LEES 2014 — Program

Sun 29	Mon 30	Tue 1	Wed 2	Thu. 3	Fri 4
	8:45 **Welcome** *Sacuto et al.*				
	9:00-10:50 **Pseudogap I** **Bourges** *Norman* *Greven* *Varma* *Yakovenko* *Mangin-Thro* *Sakai*	9:00-10:45 **Pseudogap II** **Norman** *Chubukov* *Taillefer* *Pépin* *Cyr-Choinère* *Mansart* *Cilento*	9:00-10:45 **Graphene** **Hoffman** *Basov* *Fuchs* *Orlita* *Boris* *Kuzmenko*	9:00-10:40 **URu_2Si_2** **Dressel** *Blumberg* *Coleman* *Timusk* *Maslov*	9:00-10:45 **Pnictides & Heavy Fermions** **Benfatto** *Hackl* *Gallais* *Paul* *Hall* *Okamura*
	Break				
	11:15-12:45 **Multiferroics** **Lobo** *Park* *de Brion* *Petzelt* *Nagel* *Chaix*	11:15-12:45 **Electromagnons** **Petzelt** *Hlinka* *Loidl* *Pimenov* *Kamba* *Rovillain*	11:15-12:45 **Fermi Liquids** **Timusk** *van der Marel* *Georges* *Dressel* *Scheffler*	11:10-12:45 **Topological Insulators II** **Armitage** *Hoffman* *Ishizaka* *Madhavan* *Valdés-Aguilar* *Chia*	11:15-12:35 **Hetero-structures** **Gervais** *Perez* *Todorov* *Bergeal* *Perucchi*
	Lunch		12:45 Lunch box Excursion Chenonceau Clos-Lucé Wine tasting	Lunch	12:35 **Conclusion**
	14:00 Exhibit			14:00 Exhibit	
	15:15-16:50 **Topological Insulators I** **van der Marel** *Lupi* *Perfetti* *Akrap* *Autore* *Wu* *Kalinko*	15:00-16:50 **Methods** **Roy** *Hillenbrand* *Shen* *Damascelli* *Tanner* *Martin*		15:15-16:50 **BCS & CDW** **Tanner** *Shimano* *Carr* *Méasson* *Benfatto* *Wang*	
	Break			Break	
17:00-19:00 Registration	17:20-18:50 **Optical Conductivity** **Tajima** *Homes* *Armitage* *Degiorgi* *Janod*	17:20-18:50 **Cuprates CDW** **Greven** *Blackburn* *Le Tacon* *Proust* *Comin*		17:20-18:50 **Fluctuations** **Hackl** *Giannetti* *Hinton* *Tajima* *Munzar*	
19:00 Welcome Buffet	19:00 Poster Exhibit Buffet Magsurf	19:30 **Dinner talk** **Sacuto** *Séamus Davis*	19:00 Poster Exhibit Buffet	19:30 Banquet	

Monday, June 30

Welcome

Program

Monday, 8h45–9h00 — *Chair:* A. Sacuto *et al.*

Mo1: Pseudogap I

Program

Monday, 9h00–10h50 — *Chair:* P. Bourges

9:00-9:25	M.R. Norman	What is the pseudogap?
9:25-9:50	M. Greven	New insights into the cuprate phase diagram from transport, X-ray and neutron scattering studies of $HgBa_2CuO_{4+\delta}$
9:50-10:15	C.M. Varma	Some constraints put by experiments on theories of high temperature superconductivity in cuprates
10:15-10:30	V.M. Yakovenko	Possible spiral structure in the pseudogap phase of cuprates
10:30-10:40	L. Mangin-Thro	Search for Intra-Unit-Cell magnetic order close to optimal doping in superconducting cuprates
10:40-10:50	S. Sakai	Evidences of an s-wave structure of the pseudogap in high-T_c cuprate superconductors

Mo2: Multiferroics

Program

Monday, 11h15–12h45 — *Chair:* R.P.S.M. Lobo

11:15-11:40	J.G. Park	Low energy spin dynamics of multiferroic $RMnO_3$ and $BiFeO_3$
11:40-12:05	S. de Brion	THz Magneto-Electric excitations in multiferroic compounds
12:05-12:20	J. Petzelt	Broadband dielectric spectroscopy of $BaTiO_3$-$BaZrO_3$ solid solutions
12:20-12:35	U. Nagel	Room temperature toroidal moment in multiferroic $BiFeO_3$ and its interaction with THz light
12:35-12:45	L. Chaix	Bunched modulation of the magnetic structures in chiral compounds: towards new magnetoelectric excitations

Mo3: Topological Insulators I

Program

Monday, 15h15–16h50 — *Chair:* D. van der Marel

15:15-15:40	S. Lupi	Plasmonic excitations in topological insulators
15:40-16:05	L. Perfetti	Dynamics of the electrons in surface states with strong spin-orbit coupling
16:05-16:20	A. Akrap	Magnetooptical study of giant Rashba systems BiTeBr and BiTeCl
16:20-16:30	M. Autore	Dirac plasmonics of topological insulators
16:30-16:40	Liang Wu	A sudden collapse in the transport lifetime across the topological phase transition in $(Bi_{1-x}In_x)_2Se_3$
16:40-16:50	A. Kalinko	Low temperature and high pressure lattice dynamics study of alpha and beta-$SnWO_4$

Mo4: Optical Conductivity of Superconductors and MIT

Program

Monday, 17h20–18h50 — *Chair:* S. Tajima

17:20-17:45	C.C. Homes	Optical properties of iron-based conductors and superconductors
17:45-18:10	N.P. Armitage	Optical birefringence and dichroism of cuprate superconductors in the THz regime
18:10-18:35	L. Degiorgi	Hysteretic behavior in the optical response of the underdoped Fe-arsenide $Ba(Fe_{1-x}Co_x)_2As_2$ in the electronic nematic phase
18:35-18:50	E. Janod	Optical conductivity measurements of $GaTa_4Se_8$ under high pressure: Evidence of a bandwidth-controlled insulator-to-metal Mott transition

Poster Session I

Program

Monday, 19h00 — *Chair:* A. Sacuto

Poster list

Tuesday, July 1

Tu1: Pseudogap II

Program

Tuesday, 9h00–10h45

Chair: M.R. Norman

9:00-9:25	A. Chubukov	Superconductivity, charge order, and psudogap phase in hole-doped cuprates
9:25-9:50	L. Taillefer	The three phase diagrams of cuprate superconductors
9:50-10:15	C. Pépin	Charge ordering around a Quantum Critical Point in cuprate superconductors
10:15-10:25	O. Cyr-Choinière	Anisotropy of the thermoelectric response in the pseudogap phase of the cuprate superconductor YBa2Cu3Oy
10:25-10:35	B. Mansart	Real-time observation of structural and electronic degrees of freedom in high-T_c superconductors
10:35-10:45	F. Cilento	Photoinduced antinodal metallicity in the pseudogap state of high-T_c cuprates

Tu2: Electromagnons

Program

Tuesday, 11h15–12h45

Chair: J. Petzelt

11:15-11:40	J. Hlinka	How many different indicators of direction in space can be distinguished by the space-time symmetry?
11:40-12:05	A. Loidl	Electromagnons
12:05-12:20	A. Pimenov	Electric field control of terahertz polarization with electromagnon
12:20-12:35	S. Kamba	Electromagnons in multiferroic $CaMn_7O_12$ and ε-Fe_2O_3
12:35-12:45	P. Rovillain	Iron borate multiferroics, a new way to observe the electromagnon?

Tu3: Methods

Program

Tuesday, 15h00–16h50

Chair: P. Roy

15:00-15:15	M. Dressel	Genzel Prize Ceremony
15:15-15:40	R. Hillenbrand	(Genzel Prize) Infrared nanoimaging and nanospectroscopy
15:40-16:05	Z.X. Shen	Domain walls and edge structures in quantum system: Views from scanning microwave impedance microscope
16:05-16:20	A. Damascelli	Probing spin-orbital entanglement by polarization- and spin-resolved ARPES
16:20-16:35	D.B. Tanner	Use of X-ray scattering factors for Kramers-Kronig high-frequency extensions
16:35-16:50	M.C. Martin	Ultra-broadband Synchrotron Infrared Nano-spectroscopy

Tu4: Cuprates CDW

Program

Tuesday, 17h20–18h50

Chair: M. Greven

17:20-17:45	E. Blackburn	Charge density waves in underdoped YBCO
17:45-18:10	M. Le Tacon	Competing orders in underdoped cuprates
18:10-18:35	C. Proust	Fermi surface reconstruction by charge order in underdoped copper oxides
18:35-18:50	R. Comin	Charge order, Fermi-arc instability, and d-wave bond order in underdoped cuprates

Dinner Talk

Program

Tuesday, 19h00

Chair: A. Sacuto

J.C. Séamus Davis — Visualizing (Electronic) Dragons

Wednesday, July 2

We1: Graphene

Program

Wednesday, 9h00–10h45

Chair: J.E. Hoffman

9:00-9:25	D.N. Basov	Nano-plasmonic phenomena in graphene
9:25-9:50	J.N. Fuchs	From dia- to paramagnetic orbital susceptibility of Dirac cones
9:50-10:15	M. Orlita	Massless fermions in 2D and 3D: Infrared magneto-spectroscopy studies
10:15-10:30	A.V. Boris	Fano resonances in hyperkagome iridates
10:30-10:45	A.B. Kuzmenko	Strong plasmon reflection at nanometer gaps in graphene

We2: Fermi Liquids

Program

Wednesday, 11h15–12h45

Chair: T. Timusk

11:15-11:40	D. van der Marel	Fermi liquid behaviour in strongly correlated metals
11:40-12:05	A. Georges	Fermi liquids and beyond: Non-Drude universal scaling and optical signatures of resilient quasiparticles
12:05-12:30	M. Dressel	Power-Law behavior of optical conductivity observed in strongly-correlated organic conductors
12:30-12:45	M. Scheffler	THz properties of $CaRuO_3$: Can we reconcile non-Fermi-liquid optics with Fermi-liquid concepts?

Poster Session II

Program

Wednesday, 19h30

Chair: A. Sacuto

Poster list

Thursday, July 3

Th1: URu_2Si_2 & Heavy Fermions

Program

Thursday, 9h00–10h40 — *Chair:* M. Dressel

9:00-9:25	G. Blumberg	Chiral density wave of the 'hidden order' phase in URu_2Si_2
9:25-9:50	P. Coleman	Composite and topological order in heavy fermion materials
9:50-10:15	T. Timusk	The normal state of URu_2Si_2: Spectroscopic evidence for an anomalous Fermi liquid
10:15-10:40	D.L. Maslov	Optical conductivity of Fermi-liquid and non-Fermi-liquid metals

Th2: Topological Insulators II

Program

Thursday, 11h10–12h45 — *Chair:* N.P. Armitage

11:10-11:35	J.E. Hoffman	Nanoscale band structure imaging of topological materials: Sb and SmB_6
11:35-12:00	K. Ishizaka	Giant spin splitting in inversion-symmetry broken semiconductors
12:00-12:15	V. Madhavan	Coexistence of massless and massive Dirac fermions in topological crystalline insulators
12:15-12:30	R. Valdés-Aguilar	Time-resolved terahertz dynamics in thin films of the topological insulator Bi_2Se_3
12:30-12:45	E.E.M. Chia	Terahertz conductivity of Dirac-like materials

Th3: BCS & CDW

Program

Thursday, 15h15–16h50

Chair: D.B. Tanner

15:15-15:40	R. Shimano	Observation of Higgs amplitude mode in superconductors
15:40-16:05	G. L. Carr	Strong-Field THz study of superconductivity in the time domain
16:05-16:20	M.A. Méasson	Amplitude Higgs mode in 2H-$NbSe_2$ superconductor
16:20-16:35	L. Benfatto	Spectroscopic signatures of phase and amplitude modes in superconductors
16:35-16:50	N.L. Wang	Coexistence and competition of multiple charge-density-wave orders in RTe_3 as revealed by optical probes

Th4: Fluctuations in Cuprates

Program

Thursday, 17h20–18h50

Chair: R. Hackl

17:20-17:45	C. Giannetti	Snapshots of the retarded electronic interaction with antiferromagnetic fluctuations in high-temperature superconductors
17:45-18:10	J.P. Hinton	Quasiparticle recombination dynamics in the model cuprate superconductor $HgBa_2CuO_{4+\delta}$
18:10-18:35	S. Tajima	Optical observation of precursory superconductivity in $YBa_2Cu_3O_y$
18:35-18:50	D. Munzar	Evidence for a superconducting origin of prominent features of the in-plane infrared response of underdoped cuprates and implications of their persistence above T_c

Friday, July 4

Fr1: Pnictides & Heavy Fermions

Program

Friday, 9h00–10h45

Chair: L. Benfatto

9:00-9:25	R. Hackl	A light scattering study of the pairing potential in Fe-based superconductors and related compounds
9:25-9:50	Y. Gallais	Raman scattering as a probe of charge nematic fluctuations in Iron-based superconductors
9:50-10:15	I. Paul	Nesting induced large magnetoelasticity in the iron arsenide systems
10:15-10:30	J.S. Hall	Hybridization regime and hidden order state of URu_2Si_2: Effects of doping on Fermi liquid scattering and energy gap
10:30-10:45	H. Okamura	Electron-Hole symmetry in the electronic structures of Ce and Yb compounds examined by optical study under high pressure

Fr2: Heterostructures

Program

Friday, 11h15–12h35

Chair: F. Gervais

11:15-11:40	F. Perez	Collective spin excitations in diluted magnetic quantum wells
11:40-11:55	Y. Todorov	Collective effects in 2D electron gas and Ultra-strong light-matter coupling
11:55-12:20	N. Bergeal	Multiple quantum phase transitions in a two-dimensional superconductor
12:20-12:35	A. Perucchi	Electrodynamics of hetero-structured high temperature superconductors

Concluding Remarks

Program

Friday, 12h35

Chair: LEES Committee

What is the pseudogap?*

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A bewildering array of phenomena occur in underdoped cuprates, including superconductivity, nematicity, charge order, spin order, and (perhaps) orbital currents. Often lost in this discussion of the pseudogap phase is what the large energy gap seen by spectroscopic probes is actually due to. Here, I will discuss the pros and cons of the various scenarios that address the origin of this gap, and implications this has for the physics of the cuprates.

*Work supported by the US Dept. of Energy, Office of Science, Basic Energy Sciences.

New insights into the cuprate phase diagram from transport, X-ray and neutron scattering studies of $HgBa_2CuO_{4+\delta}$ *

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We will review our extensive efforts to understand the properties of the tetragonal cuprate superconductor $HgBa_2CuO_{4+\delta}$, with particular focus on recent charge transport [1–3], resonant X-ray scattering [4] and neutron scattering experiments [5, 6] that reveal Fermi-liquid behavior, charge-density-wave correlations and an unusual magnetic response below optimal doping. The comparison with the properties of cuprates that feature a higher degree of disorder and/or lower structural symmetry leads to profound new insights into the phase diagram of the cuprates.

[1] Neven Barišić *et al.*, Proc. Natl. Acad. Sci. USA **110**, 12235 (2013)
[2] Neven Barišić *et al.*, Nature Phys. **9**, 761 (2013).
[3] Mun K. Chan *et al.*, arXiv:1402.4472.
[4] Wojciech Tabis *et al.*, manuscript in preparation.
[5] Yuan Li *et al.*, Phys. Rev. B. **84**, 224508 (2011).
[6] Mun K. Chan *et al.*, arXiv:1402.4517.

*Work supported by the US Department of Energy, Office of Basic Energy Sciences.

Some Constraints put by Experiments on Theories of High Temperature Superconductivity in Cuprates

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There is wide-spread agreement now that a phase competes with superconductivity in the under-doped region of the Cuprates. The scattering of its associated quantum-critical fluctuations determine both the strange metal properties and the high temperature superconductivity.

I will use the ARPES measurements to raise an important issue - the inelastic scattering in the normal state is independent of angle on the Fermi-surface, while scattering with maxima at ± 90 degrees is required for d-wave superconductivity.

I will also ask why the phase transition to the under-doped phase is unobserved in the specific heat measurements and what related sound-velocity measurements have to say on this issue.

Possible spiral structure in the pseudogap phase of cuprates

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We propose a novel chiral order parameter to explain recent experimental developments concerning the polar Kerr effect in underdoped cuprates. Originally, experimental observation of the polar Kerr effect in the pseudogap phase of cuprates was interpreted as a signature of a ferromagnetic-like time-reversal symmetry breaking. However, more recent measurements suggest that this interpretation is not correct, and the polar Kerr effect is more likely to originate from a chiral and inversion symmetry breaking, which results in handedness and spatial dispersion with gyrotropy. Our theoretical scenario is based on the loop-current model by Varma, which is characterized by the in-plane anapole moment N and exhibits the magnetoelectric effect. We propose a helical structure where the vector $N(n)$ in the layer n is twisted by the angle $\pi/2$ relative to $N(n-1)$, thus breaking inversion symmetry. We show that coupling between magnetoelectric terms in the neighboring layers for this structure produces optical gyrotropy, which results in circular and linear dichroism and the polar Kerr effect. Magnetic field lines produced by the loop currents get twisted and tilted in a double-helix manner reminiscent of DNA, which is consistent with tilted intra-unit-cell magnetic moments observed in neutron scattering experiments. The chiral order parameter requires only local correlations between neighboring layers and does not imply long-range translational order and additional Bragg peaks. We also discuss consequences of this peculiar symmetry breaking for non-linear optical response, such as second-harmonic generation and appearance of dc current in response to ac electromagnetic field.

[1] S. S. Pershoguba, K. Kechedzhi, and V. M. Yakovenko, PRL 111, 047005 (2013).

Search for Intra-Unit-Cell magnetic order close to optimal doping in superconducting cuprates

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After more than two decades, the origin of superconductivity in copper oxide materials is still a mystery. Several broken symmetry states could compete with superconductivity, but could also produce electronic or magnetic fluctuations potentially important for the understanding of the superconducting pairing mechanism and the anomalous electronic properties observed in the normal state. Using polarized neutron scattering in four cuprates families [1-4], including YBa2Cu3O6+x, the existence of a new magnetic order was reported. This order develops below the pseudo-gap (PG) transition temperature, Tmag. Combined with ultrasound measurements [5], it has been established that the PG is a broken symmetry state. This new magnetic phase could be induced by the staggered orbital magnetism within the unit cell as proposed in the loop current model for the PG state [6]. This Intra-Unit-Cell (IUC) magnetic order indicates that time reversal symmetry is broken in the PG state, but translation invariance is preserved. The ordering temperature matches the hole doping dependence of the PG state and is likely to vanish around a quantum critical point (QCP) close to p 0.2. The existence of the IUC magnetic order is well documented in a wide hole doping range. However, its evolution at larger hole doping (in particular, upon approaching the QCP) had not yet been addressed. Our study on YBa2Cu3O6.85 (Tc=89K, p=0.15), performed on 4F1 (Orphée), revealed that the IUC order settles in below T 200K> Tc, proving the persistence of the IUC order close to optimal doping. Compared to samples with a lower hole doping level, the measured intensity at the Bragg position is reduced by a factor of 4 [7], suggesting a shortening of the magnetic correlation length upon increasing hole doping. Interestingly, this scenario is also consistent with the fast decay of the magnetic intensity from the under-doped to optimally doped range in the Bi2Sr2CaCu2O8+d compounds [8]. In order to shed light on the evolution of the correlation length upon approaching the QCP, complementary measurements were carried out on D7 (ILL). By performing momentum scans across the Bragg reflection, we indeed report a shortening of the magnetic correlation

length in YBa2Cu3O6.85: the persistence of the signal away from the Bragg peak at low temperature means that the scattering remains short range even at temperature well below Tmag. Diffraction measurements showed also a critical slowing down of magnetic fluctuations on both sides of the transition temperature. Besides, by moving away from the Bragg reflection in momentum and in energy, we could observe for the first time low energy magnetic excitations.

[1] B. Fauqué et al, PRL 96 197001 (2006)

[2] Y. Li et al, Nature 455 372 (2008)

[3] V. Balédent et al, PRL 105 027004 (2010)

[4] S. De Almeida-Didry et al, PRB 86 020504 (2012)

[5] A. Shekhter et al, Nature 497 75 (2013)

[6] C.M. Varma, PRB 73 155113 (2006)

[7] P. Bourges and Y. Sidis, CR Physique 12 461 (2011)

[8] L. Mangin-Thro et al, PRB 89 094523 (2014)

Evidences of an s-wave structure of the pseudogap in high-Tc cuprate superconductors

S. Sakai[1], S. Blanc [2], M. Civelli[3], Y. Gallais[2], M. Cazayous[2], M.-A. Méasson[2], J. S. Wen[4], Z. J. Xu[4], G. D. Gu[4], G. Sangiovanni[5], Y. Motome[1], K. Held[6], A. Sacuto[2], A. Georges[7], and M. Imada[1]
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It is established that the superconducting gap in high-Tc cuprates is dominantly d wave, distinct from conventional superconductors, which have s-wave gap. A gap (the pseudogap) in the one-electron excitation spectra persists even above the superconducting critical temperature T_c, and its relationship with the superconducting gap has been a central issue in the search for the high-T_c superconducting mechanism. According to angle-resolved photoemission spectroscopy (ARPES), the symmetry of the pseudogap also looks like d wave. Based on this observation, a number of phenomenological theories have assumed a d-wave structure also for the pseudogap. However, since APRES in practice observes only the occupied spectra, almost nothing is actually known about the spectrum (and the gap structure) above the Fermi level. We explore this dark (unoccupied) side of the excitation spectra, by combining the electronic Raman spectroscopy experiments and a cluster extension of the dynamical mean-field theory. Our result reveals an unprecedented s-wave structure of the pseudogap, whose energy location is strongly dependent on momentum: The gap opens around the Fermi level in the antinodal region while it resides above the Fermi level in the nodal region. This s-wave pseudogap structure, which is different from the s-wave gap in a standard sense, is compatible with the ARPES observations because the gap below the Fermi level is seemingly d-wave; The main difference is in the unoccupied spectra, which have been elusive in experiments. The s-wave pseudogap furthermore explains well the electron-hole asymmetry observed in recent ARPES and STM experiments. Our results thus suggest that the pseudogap is not smoothly connected to the superconductivity gap, imposing a strong constraint on phenomenological theories of the pseudogap and the high-T_c superconductivity in cuprates.

Low energy spin dynamics of multiferroic $RMnO_3$ and $BiFeO_3$

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Multiferroic materials that have the coexistence of both magnetic and ferroelectric ground states have drawn significant attention in materials science over the past ten years or so. The underlying origin of this unusual behavior in either naturally occurring materials or artificially synthesized thin films has been a strong enough motivation for material scientists to discover or rediscover new multiferroic materials.

Among a long list of multiferroic materials, hexagonal manganites $RMnO_3$ and $BiFeO_3$ are arguably two most interesting multiferroic materials. In particular, $BiFeO_3$ has been extensively investigated for potential applications by virtue of its magnetic and ferroelectric transitions occurring above room temperature: T_N=650 K and T_C=1050 K. Moreover, it has a very interesting incommensurate magnetic phase transition with an extremely long period of 650 Å. On the other hand, the hexagonal manganite materials exhibit a natural two-dimensional triangular lattice, which provide an interesting platform to investigate low dimensional magnetism with a supposedly strong coupling to the ferroelectric order parameter.

Over the past few years or so, there have been a multitude of studies done on both compounds. Largely thanks to these extensive studies, we have now come to know extremely details about the physical properties of the two materials. One of the most fruitful approaches in addressing some fundamental issues is to examine the spin dynamics. This exercise would lead to a microscopic understanding of how the magnetic moment is coupled, if ever, to the ferroelectric degree of freedom. In this talk, I will present our results obtained from high resolution inelastic neutron scattering experiments.

THz Magneto-Electric excitations in multiferroic compounds

S. de Brion[1], L. Chaix[1,2], V. Simonet[1], R. Ballou[1], J.B. Brubach[3], P. Roy3, S. Petit[4]

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[4] *CEA, Centre de Saclay, /DSM/IRAMIS/ Laboratoire Léon Brillouin, 91191 Gif-sur-Yvette,France*

Magneto-electric (ME) phenomena, involving cross coupling between electric and magnetic degrees of freedom, are attracting considerable attention. These ME couplings can also have signatures on the elementary excitations that emerge from the ordered states that prevail. The first examples, the so called electromagnons, were observed in several compounds, mainly multiferroics by Terahertz (THz), and Far Infrared spectroscopies. They are now perceived as in magnons dressed with electric charges, hence excitable via an electric field. Several microscopic mechanisms at these ME coupling have been proposed, that vary with the investigated material, and even within they same compound. Here we report on new mechanisms for ME excitations that we have evidenced combining THz/FIR spectroscopies with inelastic neutron measurements.

Broadband dielectric spectroscopy of $BaTiO_3$-$BaZrO_3$ solid solutions

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xBaZrO$_3$-$(1-x)$BaTiO$_3$ (BZT-x) solid solution is the most studied lead-free perovskite system with properties changing from ferroelectric ($x = 0$), over diffuse ferroelectric ($x = 0.1 - 0.2$), relaxor ferroelectric ($x = 0.3 - 0.8$), dipolar glass ($x > 0.8$), up to standard dielectric behaviour ($x = 1$). We have studied the dielectric response in whole composition region in the wide 100 Hz-100 THz frequency range down to 10 K using several spectroscopic techniques. The complex phonon behaviour in the far IR range is ascribed to eigenvector crossover of the lowest-frequency TO1 mode. The relaxation in the 100 GHz range is assigned to theoretically proposed (in acentric systems) anharmonic quasi-Debye losses. The main lower-frequency relaxation is thermally activated with a universal (for $x = 0.4 - 0.8$) activation energy of ~ 0.16 eV. It is assigned to local hopping of the off-centered Ti^4+ ions in the frozen microscopic $BaTiO_3$ clusters. It appears to be the first relaxor ferroelectric system with such a simple dynamics of polar clusters. First results are published [1] and submitted [2].

[1] D. Nuzhnyy, J. Petzelt, M. Savinov, T. Ostapchuk, V. Bovtun, M. Kempa, J. Hlinka, V. Buscaglia, M. T. Buscaglia, P. Nanni : Broadband Dielectric Response of Ba(Zr,Ti)O_3 Ceramics: From Incipient via Relaxor up to Classical Ferroelectric behavior, Phys. Rev. B **86**, 014106 (2012).

[2] -dtto-: Broadband dielectric spectroscopy of Ba(Zr,Ti)O_3: dynamics of relaxors and diffuse ferroelectrics, submitted (arXiv:1312.3131).

Room temperature toroidal moment in multiferroic $BiFeO_3$ and its interaction with THz light

U. Nagel,[1] and T. Rõõm,[1] and I. Kézsmárki,[2] and S. Bordács,[3] and Randy S. Fishman,[4] and Hee Taek Yi,[5] and S.-W. Cheong[5]
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Excitations in multiferroics, electromagnons [1, 2], can be used to control the polarization and intensity of THz light [3–6]. Using far infrared spectroscopy we show that spin excitations in $BiFeO_3$ simultaneously interact with the electric and magnetic field components of light because an applied static magnetic field induces a toroidal moment in the cycloidal spin structure [7]. These toroidal excitations exhibit strong direction-dependent absorption even in the room-temperature state of the material.

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Bunched modulation of the magnetic structures in chiral compounds: towards new magnetoelectric excitations

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The langasite Ba3NbFe3Si2O14 has recently attracted a lot of attention due to its unique chiral (structural, magnetic and excitations) and multiferroic properties [1–4]. The magnetic order of the Fe3+ magnetic moments is made of a 120 arrangement in triangles, helically propagated in the perpendicular direction. We report here new experimental evidence showing that this picture is incomplete. An anti-crossing of magnons leading to extinction is observed by inelastic neutron scattering. Moreover, higher order and forbidden weak magnetic and structural satellites have been evidenced using single crystal neutron diffraction measurements, with and without longitudinal polarization analysis. From a comparison with the Ba3TaFe3Si2O14 compound with the reversed structural chirality, where these experimental signatures are significant, I will show that these features can be explained by the presence of single-ion anisotropy combined with the DM interaction, and by the loss of the 3-fold axis. This results in a bunched modulation of the helical order. Moreover, the resulting symmetry lowering is a key parameter to understand the new kind of magnetoelectric excitations observed in these two compounds by THz spectroscopy as well as their multiferroic properties [3, 4].

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Plasmonic Excitations in Topological Insulators

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The quantized collective oscillations of ordinary massive electrons are since a long time basic ingredients of research in plasmonics and in optical metamaterials. Instead, plasmons of massless Dirac electrons have been recently observed in graphene and their properties applied to new tunable metamaterials from terahertz to the mid-infrared range. Apart graphene, Dirac particles have been also observed in topological insulators (TI). TI are quantum electronic material with an insulating gap in the bulk of spin–orbit origin, and metallic states at the interface with the vacuum or another dielectric. In this talk, we report on plasmonic excitations in Bi_2Se_3 topological insulator thin films patterned in different micro-structures. Propagating plasmons were observed in micro-ribbon arrays and localized plasmons instead in micro-disks and rings. In all cases plasmon excitations can be well described in terms of the electrodynamics properties of single-particle Dirac carriers. Moreover, the plasmon lineshape was found to be extremely robust vs. temperature, as expected for the excitations of topological carriers.

Dynamics of the electrons in surface states with strong spin-orbit coupling

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The realization of transistors via the transport of spin polarized electrons has attracted the interest of the solid state community for 20 years. In such devices, an applied gate voltage induces a spin torque of the injected electrons via spin-orbit (SO) interaction. The energy scale of this effect is typically 1–10 meV in the semiconductor heterostructures, but reaches values 10 times larger at surfaces of systems containing heavy elements. Therefore, the latter are considered as valuable models for future spintronic applications. This cross fertilizing field has been recently enriched by the discovery of protected edge states in topological insulators. A macroscopic spin injection in these surface states may be obtained by optically pumping the system with circularly polarized photons. Such a technique has been widely employed to optically orient the spins of bulk semiconductors and GaAs/AlAs quantum wells. Here the optical transition selection rules of the Bloch bands are inherited from their parent atomic orbits. Alternatively, the spin polarization can be entangled to valley degrees of freedom by intercellular currents. The ternary compound BiTeI is a valuable example of a noncentrosymmetric material where this process should induce an optical spin-orientation. Our time resolved detection of the electronic states out of equilibrium conditions disclose unusual scattering mechanism in the femtosecond regime and nanometric scale. Since BiTeI holds large spin-orbit coupling, the optical pumping with circularly polarized photons naturally produce a macroscopic spin orientation of the electronic states. We monitor the orbital polarization of the photoexcited system via the dichroic constrast generated by circularly polarized laser pulses on a photoelectron current. Interestingly, the dichroic contrast acquired 80 fs after photoexcitation is already different from the one expected from the point group symmetry of the crystal. We deduce that the initial spin orientation decays on a time scale faster than the electronic thermalization. The observed dichroism has been ascribed to the transport of electrons out of the photoexcitation volume within the duration of the pump pulse. In the case of BiTeI, this ultrafast transport depends on the photon helicity because of the lack of spatial inversion symmetry. We conclude that the different transport of energy density is due to chiral scattering events of an electronic distribution that does not respect detailed balanced conditions.

Magnetooptical study of giant Rashba systems BiTeBr and BiTeCl

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Layered bismuth chalchogenides BiTeX (where X=I, Br or Cl) host giant Rashba spin splitting, which makes these materials interesting for spin manipulation.

We present a comparative study of the optical properties - reflectance, transmission and optical conductivity - and Raman spectra of BiTeBr and BiTeCl at 300 K and 5 K. Despite different space groups, the optical properties of the two compounds are very similar. Both materials are doped semiconductors, with the absorption edge above the optical gap which is lower in BiTeBr (0.62 eV) than in BiTeCl (0.77 eV). The same Rashba splitting is observed in the two materials. A non-Drude free carrier contribution in the optical conductivity as well as three Raman and two infrared phonon modes are observed in each compound. There is a dramatic difference in the highest infrared phonon intensity for the two compounds, and a difference in the doping levels. Aspects of the strong electron-phonon interaction are identified. Several interband transitions are assigned, among them the low-lying absorption β which has the same value 0.25 eV in both compounds and is caused by the Rashba spin splitting of the conduction band. An additional weak transition is found in BiTeCl, caused by the lower crystal symmetry.

We performed a detailed study of reflectivity and Kerr effect on BiTeBr and BiTeCl up to a field of 7 T and in a wide energy range from 2 meV to 0.5 eV. We find a large Kerr effect in BiTeBr in the far infrared (with Kerr rotation up to 0.15 rad) and a smaller but qualitatively similar response in BiTeCl. The analysis of the Kerr BiTeBr data is done in terms of the Rashba split bands.

Dirac plasmonics of Topological Insulators

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Recently, a new developement in the field of plasmonics has been achieved by means of engineering plasmonic structures in Topological Insulators (TIs). Indeed, their peculiar properties such as 2D intrinsic transport carried out by Dirac fermions, very high surface density (n 10 13 cm -2) compared to the typical values for metallic surfaces, backscattering protection and robustness of the topological phase at room temperature, make them perfect candidates to develope and take further plasmon based technology. We performed a wide study of plasmonic excitations on topological insulator Bi2Se3-based devices in the THz range, using Fourier Transform Infrared (FT-IR) spectroscopy technique. In particular, we investigated resonances dispersion in thin film samples patterned with several shapes by means of Electron Beam Lithography (EBL) in collaboration with the Institute for Photonics and Nanotechnologies in Rome. A first study was performed on Bi2Se3 micro-ribbon arrays, enabling to trace the energy-momentum dispersion for plasmonic excitations, in good agreement with the relation expected for 2D gases p *propto* k 1/2. Most importantly, we found a very good quantitative agreement with that predicted for Dirac plasmons. Then we investigated devices patterned with microring arrays, which are interesting because they exhibit two distinct resonances (bonding and antibonding), arising from the hybridization between the resonance of a disk and the one of an anti-dot. The measured extinction coefficient has been compared to ab initio analytical model for plasmonic resonances, through a collaboration with the Institute of Photonic Sciences in Barcelona. The comparison gives an impressive agreement, given the fact that the model has no free parameter, thus opening the way for further prediction and tailoring of plasmonic devices in the THz range. Finally, we studied the excitations on Bi2Se3 micro-disk arrays, and we intend to perform transmission measurements under the effect of a strong magnetic field (up to 30 T) perpendicular to the surface, expecting to observe and charachterize the resonance splitting due to the excitation of magnetoplasmons. Moreover, we studied the quantum phase transition (QPT) from a topological insulator to a conventional band insulator exploiting the plasmonic properties of microribbon arrays of (Bi1-xInx)2Se3 . Under the effect of In-Bi substitution, this

material undergoes a QPT around x=0.05, as recently observed by means of ARPES and time domain spectroscopy measurements. The study of plasmon dispersion and width as a function of doping represent a first study of the behavior of collective excitations through the QPT.

A sudden collapse in the transport lifetime across the topological phase transition in $(Bi_{1-x}In_x)_2Se_3$ *

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AbstractText Topological insulators (TIs) are newly discovered states of matter with robust metallic surface states protected by the topological properties of the bulk wavefunctions. A quantum phase transition (QPT) from a TI to a conventional insulator and a change in topological class can only occur when the bulk band gap closes. In this work, we have utilized time-domain terahertz spectroscopy (TDTS) to investigate the low frequency conductance in $(Bi_{1-x}In_x)_2Se_3$ as we tune through this transition by indium substitution. Above certain substitution levels we observe a collapse in the transport lifetime that indicates the destruction of the topological phase. We associate this effect with the threshold where states from opposite surfaces hybridize. The substitution level of the threshold is thickness dependent and only asymptotically approaches the bulk limit $x \approx 0.06$ where a maximum in the mid-infrared absorption is exhibited. This absorption can be identified with the bulk band gap closing and a change in topological class. The correlation length associated with the QPT appears as the evanescent length of the surface states. The observation of the thickness-dependent collapse of the transport lifetime shows the unusual role that finite size effects play in this topological QPT. Possibility of realization of Weyl semi-metal near the Quantum critical point ($x \approx 0.06$) by applying a magnet field will also be discussed. THz measurements on a new generation of Bi_2Se_3 samples with low bulk carrier concentration is also investigated.

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Low temperature and high pressure lattice dynamics study of alpha - and beta-$SnWO_4$

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Tin tungstate ($SnWO_4$) exists in two polymorphs: the low-temperature orthorhombic alpha -phase (Pnna space group) [1] with the indirect band gap Eg=1.64 eV [2] and the high-temperature cubic beta -phase ($P2_13$ space group) [3] with the direct band gap Eg=2.6-2.7 eV [2]. A diffusion-controlled phase transition from alpha to beta -phase occurs upon heating under vacuum at about 670∘C, whereas the high-temperature beta -phase can be stabilized at room temperature by quenching from above 670∘C [4]. The difference in band gaps is related to the atomic structure: while tin atoms are six-fold coordinated by oxygen atoms in both phases, tungsten atoms have WO_6 octahedral coordination in alpha -$SnWO_4$, but WO_4 tetrahedral coordination in beta -$SnWO_4$ [1, 2]. The valence band in both phases is mainly composed of strongly interacting O 2p and Sn 5s states, whereas the conduction band is built up of W 5d and O 2p antibonding states with an admixture of Sn 5p states [2, 5]. These small band gaps and specific band structures allow using $SnWO_4$ in photocatalysis and gas sensing. Only a few studies of both $SnWO_4$ phases are available in the literature: their lattice dynamics has been probed by Raman and mid-infrared spectroscopies at room temperature and normal pressure [4, 6]. Nevertheless, their small band gap values and peculiar atomic structure suggest possible pressure induced phase transitions. In the present study, the lattice dynamics of alpha - and beta -$SnWO_4$ as a function of pressure (0-12 GPa) and in a wide temperature range (6-300 K) was investigated by Raman and synchrotron-based far/mid-infrared spectroscopies. The experimental results were supported by the first-principles linear combination of atomic orbital (LCAO) calculations. The alpha - and beta -phases of $SnWO_4$ were synthesized using a solid-state reaction method by heating under vacuum equimolar mixtures of SnO and WO_3 at 600∘C and 750∘C, respectively. X-ray powder diffraction was used to control the phase of the obtained samples. Far (50-650 cm_{-1}) and mid (550-8000 cm_{-1}) infrared measurements were performed in transmission mode using synchrotron

radiation combined with a IFS 125MR FTIR interferometer. The temperature and pressure control were respectively realized using a closed cycle He cryostat and a recently developed high-pressure setup based on a diamond anvil cell. The sample pressure was monitored using ruby luminescence. The high-pressure micro-Raman measurements were performed in backscattering geometry using HORIBA Jobin Yvon iHR320 spectrometer and 514.5 nm argon laser. Polyethylene and KBr pressure transmitting media were used for far- and mid-infrared experiments, respectively, whereas a methanol-ethanol mixture (4:1) was used for Raman experiments. Far-infrared measurements in the low-temperature range (6-300 K) did not reveal any phase transitions neither in alpha - or beta -$SnWO_4$. The evolution of vibrational bands upon increasing temperature can be explained by thermal lattice expansion leading to band broadening and shift to lower frequencies. The main difference between the two phases is the 250 cm_{-1} wide gap in the phonon density of states in beta -$SnWO_4$, separating high-frequency stretching modes of the WO_4^{2-} tetrahedra from other modes. High-pressure Raman and infrared measurements of beta -$SnWO_4$ indicate an almost linear increase of the frequencies of all phonon up to 10 GPa except for those at about 270 and 800 cm_{-1}, which show anomalous pressure dependence: a negative shift applying the pressure. The amorphisation of beta -$SnWO_4$ giving rise to broad phonon structures occurs above 10 GPa, and the amorphous phase remains stable after releasing the pressure. In contrast, the phonon modes of alpha -$SnWO_4$ are only broadened with pressure increasing in this pressure range while, a large shift of 25 cm_{-1} for the highest W-O stretching mode at 777 cm_{-1} appears in the Raman spectrum indicative of a distortion of the WO_6 octahedra upon lattice contraction. First-principles LCAO simulations predict changes in the structure and electronic properties of alpha - and beta -$SnWO_4$ as pressure increases up to 16 GPa. They suggest that the calculated band gap value is reduced upon increasing pressure in both phases, leading to an insulator-to-metal transition for alpha -$SnWO_4$ only. The evidence of this transition was experimentally observed in the mid-infrared region (800-1600 cm_{-1}), where an abrupt decrease of the transmission was detected in the 5-7 GPa pressure range in alpha -$SnWO_4$.

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Optical Birefringence and Dichroism of Cuprate Superconductors in the THz regime *

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The presence of optical polarization anisotropies, such as Faraday/Kerr effects, linear birefringence, and magnetoelectric birefringence are evidence for broken symmetry states of matter. The recent discovery of a Kerr effect using near-IR light in the pseudogap phase of the cuprates can be regarded as a strong evidence for a spontaneous symmetry breaking and the existence of an anomalous long-range ordered state. In this work we present a high precision study of the polarimetry properties of the cuprates in the THz regime. While no Faraday effect was found in this frequency range to the limits of our experimental uncertainty (1.3 milli-radian or 0.07°), a small but significant polarization rotation was detected that derives from an anomalous linear dichroism. In $YBa_2Cu_3O_y$ the effect has a temperature onset that mirrors the pseudogap temperature T^* and is enhanced in magnitude in underdoped samples. In $x = 1/8$ $La_{2-x}Ba_xCuO_4$, the effect onsets above room temperature, but shows a dramatic enhancement near a temperature scale known to be associated with spin and charge ordered states. These features are consistent with a loss of both C_4 rotation and mirror symmetry in the electronic structure of the CuO_2 planes in the pseudogap state.

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Hysteretic behavior in the optical response of the underdoped Fe-arsenide $Ba(Fe_{1-x}Co_x)_2As_2$ in the electronic nematic phase*

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The tetragonal-to-orthorhombic structural phase transition at T_S, coincident or preceding the onset of an antiferromagnetic ground state at T_N, in the underdoped regime of quite all families of iron-pnictide and chalcogenide superconductors breaks the four-fold rotational symmetry of the tetragonal phase, implying the onset of a nematic phase. The relevance of nematicity, either electronic in nature or spin-induced, in shaping their phase diagram is certainly one of the most debated issue nowadays. We report on an optical reflectivity study of $Ba(Fe_{1-x}Co_x)_2As_2$ with $x = 0$ and 2.5%, detwinned by uniaxial and in-situ tunable pressure acting as an external symmetry-breaking field. We discover a remarkable optical anisotropy as a function of the applied pressure, very much reminiscent of a hysteretic-like behavior. Its temperature dependence supports the analogy between pressure and external magnetic field with respect to the electronic anisotropy in iron-pnictides and magnetization in ferromagnets, respectively. We estimate the nematic susceptibility, which is Curie-like at temperatures close to and above T_S and which may hint to a ferro-orbital ordering as driving mechanism for both structural and magnetic transitions.

*Work in collaboration with: A. Dusza, C. Mirri, S. Bastelberger, A. Lucarelli

Optical properties of iron-based conductors and superconductors *

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In the high-temperature cuprate superconductors, only a single band is observed at the Fermi level; as a result the optical conductivity may be modeled using a single free-carrier component. In a simple metal the Drude model usually sufficient; however, electronic correlations and electron-boson coupling in the cuprates require a more generalized form in which the scattering rate and the effective mass are both frequency dependent [1]. The iron-based conductors and superconductors are multiband materials with several bands crossing the Fermi level, resulting in multiple hole and electron pockets at the center and corners of the Brillouin zone, respectively [2]. The presence of multiple bands requires, at a minimum, a "two-Drude" model in which the electron and hole pockets are treated as separate contributions [3]. In general, the two-Drude approach reveals: (i) a strong component associated with the hole pocket with a large scattering rate (nearly incoherent transport) that is essentially temperature independent; (ii) a weaker component associated with the electron pocket whose scattering rate has a strong temperature dependence. Some recent results using this approach in the pnictide materials $BaFe_2As_2$ ($T_N \simeq 138$ K) and $Ba_{0.6}K_{0.4}Fe_2As_2$ ($T_c \simeq 38$ K) [4] will be discussed, as well as some preliminary findings the iron-chalcogenide systems, $Fe_{1+\delta}Te$ ($T_N \simeq 68$ K) and $FeTe_{0.55}Se_{0.45}$ ($T_c \simeq 14$ K) [5].

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Optical Conductivity Measurements of $GaTa_4Se_8$ Under High Pressure: Evidence of a Bandwidth-Controlled Insulator-to-Metal Mott Transition *

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Mott insulators represent a large class of materials with half-filled d or f orbitals that should be metallic according to conventional band theory, but are actually insulators thanks to onsite electron-electron (Coulomb) repulsion U. The theoretical description of the Mott insulating state has been a long-standing problem [1,2] and only modern approaches such as the dynamical mean field theory (DMFT) have successfully predicted the whole phase diagram (U/D, T/D) of this class of materials (where D represents the half bandwidth) [3]. An interesting characteristic of Mott insulators is that external perturbations, such a chemical or physical external pressure, may provoke insulator to metal transitions (IMTs) [4]. Recently, a new family of insulators, the lacunar spinel chalcogenides AM_4Q_8 (A = Ga, Ge; M = V, Nb, Ta; Q = S, Se) has attracted attention because of their surprising electronic properties emerging in the vicinity of metal-insulator transitions. As an example, $GaTa_4Se_8$ undergoes an insulator-metal-superconductor transition under pressure [5,6]. Moreover, a resistive switching induced by electric pulses was discovered in these compounds, making these materials promising for RRAM applications [7,8,9,10]. It was argued that these compounds belong to a new class of Mott insulators where the relevant entity for electronic correlation is a cluster of transition metals M4 rather than a single atomic site as usually encountered, and that their striking resistive switching properties are related

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to a Mott IMT [11,12]. In this work,[13] we show that $GaTa_4Se_8$ behaves as a canonical Mott insulator. Our study of optical conductivity under high pressure combined with band structure calculations indeed indicates that this compound undergoes an IMT through a crossover region, in remarkable agreement with the (U/D, T/D) phase diagram predicted by the DMFT. Moreover, our measurements unravel a three components optical conductivity, including a narrow low energy contribution related to the quasiparticle peak theoretically expected on the metallic side of the Mott metal-insulator transition. To our knowledge, this is the first time that such a successful comparison between experimental and theoretical (U/D, T/D) values is obtained, with the use of optical conductivity under pressure measurements. This may result from several unique aspects of $GaTa_4Se_8$, which include (i) the high connectivity (n = 12 first neighbors) of its fcc lattice particularly well suited for a comparison with DMFT, an approach based on an infinite connectivity (n = ∞), and (ii) the absence of disorder due to chemical substitution, which plays a role in prototypical Mott insulators considered so far, in particular $(V_{1-x}Cr_x)_2O_3$ and $NiS_{2-x}Se_x$. In this context, $GaTa_4Se_8$ could become the new archetypal Mott insulator ideally suited for future in-depth comparisons between experiments and theory.

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Superconductivity, charge order, and psudogap phase in hole-doped cuprates

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I discuss the interplay between superconductivity and charge order within the magnetic scenario for hole-doped cuprates I show that the magnetically-mediated interaction, which is known to give rise to d-wave superconductivity, is also attractive in the charge-density-wave channel with diagonal momenta $Q_x = (2Q, 0)$ and $Q_y = (0, 2Q)$, as seen in the experiments. I show that the emerging charge order with Q_x/Q_y is of stripe type (it appears with Q_x or Q_y, but not with both). I further show that a stripe charge order parameter has two components: one is incommensurate density variation, another is an incommensurate current. Such an order breaks time reversal symmetry and generates an oscillating magnetic field. I show that, before CDW order develops, the system develops a pre-emptive composite order, in which the two CDW components form a bound state. Such an order does not break $U(1)$ symmetry associated with CDW, but it breaks time-reversal symmetry. I also show that CDW order develops in parallel with pair-density-wave order in the particle-particle channel. I hope that this theory provides the "missing link" in the spin-fluctuation scenario for the cuprates.

The three phase diagrams of cuprate superconductors *

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I present three phase diagrams for superconductivity in the high-T_c cuprate YBCO. For the temperature-doping ($T-p$) phase diagram, with its characteristic T_c dome, important new information has emerged since the discovery of quantum oscillations [1] and a negative Hall coefficient [2] showed that the Fermi surface undergoes a reconstruction in the underdoped regime. This reconstruction is caused by the onset of charge order, and was shown to be universal in cuprates, occurring in YBCO [3], Eu-LSCO [3] and Hg-1201 [4]. Its onset coincides with the fall of T_c below its maximal value [5] – so it is responsible for shaping the T_c dome. We used thermal conductivity to directly detect the upper critical field $Hc2$ [6] and map out the field-temperature ($H-T$) phase diagram, revealing that in the $T=0$ limit $Hc2(T)$ becomes equal to the resistive critical field $H_{vs}(T)$ where the vortex solid melts. In other words, there is no vortex liquid at $T=0$ [6]. Finally, I present the full ($H-p$) phase diagram of $Hc2$ *vs.* doping, using data from both YBCO and Tl-2201 [6]. It shows two peaks. Below the upper peak, located at $p=0.18$, the condensation energy drops by a factor 20. We attribute this dramatic drop to the mechanisms that cause Fermi-surface reconstruction, namely charge order and pseudogap formation.

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*In collaboration with G. Grissonnanche, O. Cyr-Choinière, F. Laliberté, S. René de Cotret, A. Juneau-Fecteau, S. Dufour-Beauséjour, M.-È. Delage, D. LeBoeuf, J. Chang, B.J. Ramshaw,D.A. Bonn, W.N. Hardy, R. Liang, S. Adachi, N.E. Hussey, B. Vignolle, C. Proust, M. Sutherland, S. Krämer, J.-H. Park, D. Graf and N. Doiron-Leyraud.

Charge ordering around a Quantum Critical Point in cuprate superconductors

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Recent experiments in Cuprate superconductors have unveiled the existence of charge ordering in the underdoped regime, inside the pseudo gap phase. This new order, first observed by Nuclear Magnetic Resonance and Scanning Tunneling Microscopy, was confirmed through quantum oscillation measurements leading to Fermi surface reconstruction, soft and hard X-ray scattering. The phase diagram of the cuprate is thus becoming more and more complex, with the hope that the charge order will shed light on the still mysterious pseudo-gap regime. In our theoretical investigation, we address this issue starting from a minimal model where commensurate anti-ferromagnetic fluctuations become increasingly strong around a QCP. A recent solution of the critical region around the QCP [1] showed the emergence of a pseudo-gap with an unusual composite SU(2) symmetry relying a Quadrupolar Density Wave (QDW) and pairing (SC) fluctuations. The issue of charge ordering and relations to experiments will be discussed in the framework of this new theoretical findings.

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Anisotropy of the thermoelectric response in the pseudogap phase of the cuprate superconductor $YBa_2Cu_3O_y$

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We recently reported evidence of a broken rotational symmetry in the pseudogap phase of the cuprate superconductor $YBa_2Cu_3O_y$ [1]. This broken symmetry was inferred from the onset of a large in-plane anisotropy of the Nernst signal N below the pseudogap temperature $T^\star$, attributed to an anisotropy in the longitudinal coefficients: the electrical conductivity σ and/or the Seebeck coefficient S. It was pointed out that an anisotropy in N could also come from an anisotropy in the transverse coefficients: the Hall conductivity σ_{xy} and/or the off-diagonal Peltier conductivity α_{xy} [2]. Here we report a complete study of the anisotropy of all transport coefficients in a single crystal of underdoped $YBa_2Cu_3O_y$ with a hole doping $p = 0.12$ [3]. The measurements were performed first with the sample length along the b-axis direction and then along the a-axis direction of the orthorhombic crystal structure, the change being achieved by rotating the CuO chain direction via detwinning. We therefore extract the anisotropy of the transport coefficients without uncertainty from geometric factors or sample variation. We disentangle the various contributions to the anisotropy of N, and find that there is a strong anisotropy in both the longitudinal and transverse thermo-electric coefficients, *i.e.* in both S and α_{xy}. We discuss the implications for our understanding of the pseudogap phase and the Fermi-surface reconstruction, attributed to charge order [4].

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Real-time observation of structural and electronic degrees of freedom in high T_c superconductors

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Unraveling the complex interplay between electronic and lattice degrees of freedom is one of the keys towards understanding the unconventional superconductivity mechanism in cuprates. In these complex systems, the applicability of conventional pairing theories, based on retarded interactions between electrons mediated by low energy glue bosons, has been doubted and a completely different framework has been proposed involving non-retarded interactions associated with high-energy electronic scales [1].

Electron-phonon interactions, leading to superconductivity in conventional systems, are accessible by ultrafast pump-probe techniques which allow to distinguish thermally activated phonons from those emitted by conduction band electrons. Separating the electronic from the out-of-equilibrium lattice subsystems, we probed their re-equilibration by monitoring the transient lattice temperature through femtosecond X-ray diffraction in $La_{2-x}Sr_xCuO_4$ single crystals with x=0.1 and 0.21. The temperature dependence of the electron-phonon coupling is obtained experimentally and shows similar trends to what is expected from the *ab-initio* calculated shape of the electronic density-of-states near the Fermi energy. This study evidences the important role of band effects in the electron-lattice interaction in solids, in particular in superconductors [2].

Time-resolved spectroscopies also allow the coherent excitation and real-time observation of atomic motions and elementary electronic excitations. We performed broad-band pump-probe optical spectroscopy measurements in $La_{2-x}Sr_xCuO_4$ (x=0.15), where a polarized ultrafast laser pulse excites the superconductor through the Impulsive Stimulated Raman Scattering (ISRS) effect [3]. The coherent oscillations of the Cooper pairs condensate are detected via delayed supercontinuum pulses and enable a new technique, Coherent Charge Fluctuation Spectroscopy (CCFS), to distinguish the electronic excitations that couple to the superconducting quasiparticles. These results reveal strong resonance effects between the oscillating condensate and high energy electronic transitions attributed to the Cu-O charge transfer excitation,

suggesting the importance of non-retarded interactions in the superconductivity mechanism of cuprates [4].

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Photoinduced antinodal metallicity in the pseudogap state of high-Tc cuprates

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A major challenge in understanding the cuprate superconductors is to clarify the nature of the fundamental electronic correlations that lead to the pseudogap phenomenon. We used ultrashort light pulses to prepare a non-thermal distribution of excitations, and we performed time-resolved broad-band reflectivity measurements in order to capture novel properties that are hidden at equilibrium. Our framework unveils a universal pseudogap-like region in the temperature (T) and hole-doping (p) phase diagram, delimited by a well-defined T*neq(p) line. In this region the photoexcitation process leads to a quench of local correlations triggering the evolution of antinodal excitations from gapped (localized) to metallic (delocalized) quasi-particles characterized by a longer lifetime. This photoinduced antinodal metallicity finds a natural explanation in terms of the single-band Hubbard model, in which the short-range Coulomb repulsion leads to a k-space differentiation between "nodal" quasiparticles and antinodal excitations, whose self-energy diverges as in the insulating state.

How many different indicators of direction in space can be distinguished by the space-time symmetry?*

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This talk aims to draw the attention to the spatiotemporal symmetry of various vector-like physical quantities. It will be argued that along with the canonical polar vector, there are still another 7 symmetrically distinct classes of stationary physical quantities, ("direction indicators") that can be – and often are – denoted as standard three-components vectors, even though they do not transform quite as the static polar vector shoud do [1]. Many of them are familiar to us as from discussion of excitations and order-parameters of magnetically ordered crystals, but the concept is general and the application can go beyond the scope of magnetism and multiferroic physics only. I shall try to demonstrate the result using both simple arguments and example as as well as using the concepts of group theory.

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Electromagnons *

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Electromagnons are generic excitations of multiferroics and can be characterized as spin waves carrying dipolar weight via a strong magnetoelectric coupling. In many cases, in the magnetically ordered phases optical weight is transferred via magneto-electric coupling from low-lying optical phonons to magnons. Electromagnon excitations were theoretically predicted already more than 40 years ago [1] and only recently were experimentally observed in spin-driven multiferroic rare-earth manganites [2]. Theoretical models to explain character and nature of electromagnons include purely electronic processes like spin currents, small lattice distortions via an inverse Dzyaloshinskii-Moriya interaction or Heisenberg exchange coupling.

In this talk I will discuss and review the recent status of experiments and theoretical modeling of the dynamics of multiferroics, reporting on recent experimental observations of magnetoelectric excitations in different classes of multiferroics, like in pure and mixed multiferroic rare earth manganites, or in triangular lattice antiferromagnets like calcium chromate.

Here I will focus on and raise a number of so far unsolved and open questions: **(i)** What are the important ingredients of electromagnons? How to explain the typical twin-peak structure of multiferroic manganites? **(ii)** How to distinguish electromagnons from multimagnon excitations and AFM resonances? **(iii)** Do different types of electromagnons exist, e.g. driven by spin currents or by Heisenberg exchange, or possibly are of other origin and nature? **(iv)** Do electromagnons exist also in the magnetic but paraelectric state? **(v)** Why is electromagnon response often so broad and is accessible throughout the Brillouin zone, while antiferromagnetic resonances are sharp and well defined?

Finally, concerning the wording of electromagnons we advise caution: Not every excitation below TN is an electromagnon!

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Electric field control of terahertz polarization with electromagnon

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Magnetoelectric effect in multiferroics has attracted much interest recently because of possibility to modulate electric polarization by external magnetic field. A related effect, control of magnetization by electric voltage is more difficult to realize experimentally but is strongly desirable especially from the point of view of applications. A promising way to solve this task is to use novel magnetoelectric excitations (electromagnons) which determine the terahertz dynamics of several multiferroic systems. In the first part of the talk we discuss an all-electrical control of a dynamic magnetoelectric effect in a classical multiferroic manganite $DyMnO_3$, a material containing coupled antiferromagnetic and ferroelectric orders. Due to off-diagonal elements of the dynamic magnetoelectric susceptibility a linearly polarized terahertz light rotates upon passing through the sample. The amplitude and the direction of the polarization rotation is defined by the orientation of ferroelectric domains and can be controlled by static voltage. These results can be explained within the model of a dynamic magnetoelectric susceptibility of a cycloidal magnet with inverse Dzyaloshinskii-Moriya coupling.

In the second part of the talk recent results on the terahertz dynamics in (i) multiferroic borate $SmFe_3(BO_3)_4$ with record values of magneto*di*electric effect and (ii) in triangular lattice antiferromagnet $CuCrO_2$ will be presented.

Electromagnons in multiferroic $CaMn_7O_{12}$ and ε-Fe_2O_3

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The spin waves are usually excited by the magnetic component of the electromagnetic radiation and they contribute to the magnetic susceptibility. In multiferroics, spin waves can be also excited by the electric component of the electromagnetic radiation; therefore, they contribute to the dielectric permittivity. Such electrically active excitations are activated due to the dynamic magnetoelectric effect and they are called electromagnons.

The properties of electromagnons and the reasons of their activation in the THz permittivity spectra will be discussed for two different compounds, which will be compared with the canonical spin-induced ferroelectric $TbMnO_3$. There, the ferroelectricity is induced by the inverse Dzyaloshinskii-Moriya interaction, but two electromagnons are activated by the magnetostriction [1]. The first example is $CaMn_7O_{12}$, whose ferroelectric polarization is the highest among all spin-induced ferroelectrics [2]. In this material, we observed three infrared-active excitations below $80\,cm^{-1}$, which change their frequencies and split in the external magnetic field. Their intensities show remarkable anomalies at the magnetic phase transitions occurring at $T_{N1} = 90\,K$ and $T_{N2} = 50\,K$. The frequencies of these absorption peaks correspond to the maxima in the magnon density of states obtained by inelastic neutron scattering. These facts provide an evidence of a magnonic origin of these excitations. Furthermore, these magnons receive the strength from the polar phonons observed in the infrared spectra; therefore they must be electromagnons. Surprisingly, two of them persist in the paramagnetic phase, 100–150 K above T_{N1}, due to short-range magnetic correlations which we observed by means of quasielastic neutron scattering.

Further, we will demonstrate that the electromagnons are not restricted to spin-induced ferroelectrics. We have observed an electromagnon in nanograin ceramics of the ε phase of Fe_2O_3 [3]. Below 490 K, this material is a ferroelectric ferrimagnet. The infrared-active electromagnon activates in the spectra

only below 110 K, at the same time as the magnetic structure becomes incommensurately modulated. Inelastic neutron scattering spectra provide an evidence of the magnetic character of the electromagnon. Simultaneously, they show that the electromagnon corresponds to a magnon from the Brillouin-zone boundary.

Finally we will show how, by combining infrared, THz and inelastic neutron scattering experiments, the electromagnons can be generally discerned from magnons or phonons. In ε-Fe_2O_3, this was achieved for the first time using ceramics, i.e. without using single crystals. In a broader perspective, the electromagnons are sensitive not only to the static external magnetic field, but also to the external electric field. This opens a promising route for electrically controlled magnonics in the THz region.

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Iron borate multiferroics, a new way to observe the electromagnon? *

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In the last years, multiferroics, have attracted much attention worldwide because of their large magnetoelectric effects. They open a myriad of possibilities in spintronics applications as tuning the polarization direction with a magnetic field and/or change the magnetization direction via an applied voltage. A particularly exciting prospect in the field of spintronics is to use the wave like excitations of a magnetic material as a means to transmit and process information.

We used infrared scattering to probe excitations as phonons and electromagnons, the dynamical coupling between spin and lattice degrees of freedom in rare earth iron borates. These materials have interesting magnetic properties due to the subtle interactions between the rare earth and the iron moments. Among these materials, Nd, $Nd_{0.75}Dy_{0.25}$, $Sm_{0.5}Nd_{0.5}$ and Dy $Fe_3(BO_3)_4$ are multiferroics or become multiferroics under magnetic field. The iron moments order antiferromagnetically below $T_N \approx 36$ K. For all of these compounds we observe a renormalisation of some phonons at the magnetic transition. Dy $Fe_3(BO_3)_4$ shows a structural phase transition at 280 K that we observe by the change of the phonon mode numbers.

In Nd, $Nd_{0.75}Dy_{0.25}$, $Sm_{0.5}Nd_{0.5}$ $Fe_3(BO_3)_4$ a splitting of the lowest frequency mode in the *ab* plane appears at low temperature. This splitting can be the signature of change in the lattice around the magnetic transition but no structural phase transitions are expected in these compounds. Moreover, along the *c* direction the lowest phonon mode has its frequency decreasing with temperature and the total dielectric function for the *c* axis comes from this phonon. This is the typical behaviour of a soft phonon mode in a ferroelectric compound. These materials are good candidates to observe the electromagnon.

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Infrared nanoimaging and nanospectroscopy

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With the development of scattering-type scanning near-field optical microscopy (s-SNOM), the analytical power of visible, infrared and THz imaging has been brought to the nanometer scale. The spatial resolution of about 10 - 20 nm opens a new era for modern nano-analytical applications such as chemical identification, free-carrier profiling and plasmonic vector near-field mapping. After a brief overview of fundamentals and applications of s-SNOM, recent achievements such as broadband infrared-spectroscopic mapping of polymers and proteins will be presented, as well as the launching and mapping of propagating and localized plasmons in graphene nanostructures.

Domain Walls and Edge Structures in Quantum System – Views from Scanning Microwave Impedance Microscope

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Understanding and controlling local conductivity have been a corner stone for important scientific breakthroughs and technological inventions, as exemplified by transistor, integrated circuit, Anderson localization, quantum hall effect and fractional quantum hall effect. In these cases, local visualization and control of doping, mobility, gating, dielectric, heterostructure, and interdiffusion are important. Microwave Impedance microscope provides a new platform to measure local electrical properties.

Microwave has several inherent advantages. It is coherent so both amplitude and phase information can be analyzed to gain quantitative insight. Its high frequency naturally leads to efficient capacitive coupling, thus no contact is needed for electrical measurement. It has much higher inherent contrast for electrical properties than optical microscopy, for conductivity diverges for metal but approaches zero for insulator. However, it also has two disadvantages – relatively poor spatial resolution and stray field coupling that compromises quantitative analysis.

In this talk, we will report our progress in developing a scalable (batch processed and shielded tip) non-resonance microwave impedance microscope that achieves a resolution $\sim$ 30-50 nm, approaching the interesting physics length scales: localization and coherence length, the edge state width of topologically ordered systems, etc. The non-resonance approach and merge with the AFM platform also greatly reduce many of the "practical problems" that severely compromises advances of the earlier resonator based scanning microwave microscope, such as thermal drift, height control, and tip consistency – all critical for quantitative and repeatable measurements.

The highlight of this talk will be the physics insight we gain by applying this technique to investigate topological structures of novel quantum systems, including edge state of topological order in quantum hall states of semiconductors and graphene, as well as a rich hierarchy of domain wall physics in charge ordered oxides.

Probing spin-orbital entanglement by polarization- and spin-resolved ARPES

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Novel phases of matter, such as topological and relativistic-Mott insulating behavior, are being discovered as a result of spin-orbit coupling effects in solids. These emergent phenomena stem from the strong momentum-dependent spin-orbital entanglement of the low-energy electronic wavefunction. A complete microscopic description critically hinges on the availability of techniques that can probe the entangled spin and orbital quantum numbers, with momentum resolution. This can be achieved, as I will illustrate using Bi2Se3 [1,2] and Sr2RuO4 [3] as examples, by taking advantage of novel developments in angle-resolved photoemission spectroscopy (ARPES). I will show in particular how polarization- and spin-resolved ARPES can be used to reveal the layer-by-layer entangled spin-orbital texture of the topological surface state in Bi2Se3 [1], and how 3-dimensional photoelectron spin-polarization control can be achieved – via quantum interference – by varying experimental configuration and photon energy [2]. Finally, I will show how spin-resolved ARPES with circular polarization can be used to measure the strength of the effective spin-orbit coupling in Sr2RuO4, and reveal the spin-orbit-induced breakdown of pure singlet and triplet Cooper pairing, necessitating a description of the superconductivity of Sr2RuO4 in terms of the newly found spin-orbital entangled eigenstates [3].

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Use of X-ray scattering factors for Kramers-Kronig high-frequency extensions

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Kramers-Kronig analysis, of — for the most part — reflectance data, is commonly used to estimate the optical conductivity, dielectric function, sum rules, and other optical functions for new materials. The experimenter typically has data from far infrared through near ultraviolet, covering, say, 40 to 40,000 cm^{-1}. This is a reasonably wide bandwidth, but of course the Kramers-Kronig integral extends from zero to infinity, so that extrapolations need to be made outside the measured range. The high frequency extrapolation is especially problematic and can cause significant distortions to the conductivity near the end of the measured range, with consequences for sum rules as well. The approach used by most is to use a slow power law in $1/\omega$, transitioning to $1/\omega^4$ at a considerably higher frequency and continuing this free-carrier extension to infinity. The mid-range power law is adjusted to match the slope of the data and to give pleasing curves, but the choice of power (typically between 0.5 and 2) is arbitrary. Here, I will present an analysis using X-ray atomic scattering functions presented by Henke and co-workers [1, 2]. These basically treat the solid as a linear combinations of its atomic constituents and, knowing the chemical formula and the density, allow the computation of dielectric function, reflectivity, and other functions. The "Henke reflectivity" can be used over 10 eV–30 keV, after which a $1/\omega^4$ continuation is perfectly fine. The bridge between experimental data and the Henke reflectivity as well as two corrections that needed to be made to the latter will be discussed.

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Ultra-broadband Synchrotron Infrared Nano-spectroscopy *

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Characterizing and ultimately controlling the heterogeneity underlying quantum behavior of complex matter, photonic materials, or catalysis requires large scale, spectroscopic imaging with simultaneous specificity to structure, phase, and chemical composition at nanometer spatial resolution. However, as with any ultrahigh spatial resolution microscopy technique, the associated demand for an increase in both spatial and spectral bandwidth often leads to a decrease in desired sensitivity. We overcome this limitation in infrared vibrational scattering-scanning probe nearfield optical microscopy (*s*-SNOM) using synchrotron midinfrared radiation. Tip-enhanced localized light-matter interaction is induced by low-noise, broadband, and spatially coherent synchrotron light of high spectral irradiance, and the nearfield signal is sensitively detected using heterodyne interferometric amplification. We achieve sub-40 nm spatially resolved, molecular and phonon vibrational spectroscopic imaging, with rapid spectral acquisition, spanning the full mid-infrared (700–5000 $cm^{-}1$) with few $cm^{-}1$ spectral resolution. We demonstrate the performance of synchrotron infrared nanospectroscopy (SINS) on boron nitride, semiconductor, biomineral, and protein nanostructures, providing vibrational chemical imaging with subzeptomole sensitivity. With a spatial resolution 100-1000 times better than conventional FTIR microscopy, SINS enables the investigation of nanoscale phenomena in both hard- and soft-matter systems.

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Charge density waves in underdoped YBCO

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The notion of competing order is central to many theories of unconventional superconductivity, where superconductivity emerges on tuning between phases governed by much larger energy scales. An example of this is the widely-discussed "stripe order" observed in some HTSs and related compounds [1]. Recently, charge density waves (CDWs), as sampled by a range of different probes, [2–7] have been shown to be a widespread competitor to superconductivity in YBCO and other high-Tc materials. These CDWs appear to originate in the CuO2 planes, but also affect the lattice dynamics [8–10]. This talk will discuss these observations, their relationship with other experimental probes, and will report on new investigations by both elastic and inelastic X-ray techniques of the energy-, wavevector- and temperature-dependences.

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Competing orders in underdoped cuprates

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I will present an overview of recent results obtained in high temperature superconducting cuprates obtained by various photon scattering experiments. The greatly enhanced sensitivity of resonant x-ray scattering to the valence electron system led us to the discovery of a fluctuating charge density wave (CDW) competing with the superconducting order at low doping levels [1–3]. Direct evidences for CDW were also observed using inelastic scattering of visible light (Raman scattering) [4]. Trying to get more insights about the mechanism leading to the CDW formation, we have used high resolution inelastic x-ray scattering to study low energy phonons with wavevectors near the CDW ordering vector. We found that they exhibit large superconductivity induced lineshape renormalizations, attributed to strongly anisotropic electron-phonon interaction [5]. This provides important insights regarding the long-standing debate of the role of this interaction, which is a major factor influencing the competition between collective instabilities in correlated-electron materials. Finally, combination of resonant scattering studies on Bi-based compounds with surface sensitive techniques (ARPES and STM) allow us to locate, in the reciprocal space, the electron involved in the CDW phenomena. These studies suggest that the CDW might be driven by a nesting of the tip of the Fermi arcs [5, 6].

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[2] A. J. Achkar *et al.*, Phys. Rev. Lett. 109, 167001 (2012).
[3] S. Blanco-Canosa *et al.*, Phys. Rev. Lett. 110, 187001 (2013).
[4] M. Bakr *et al.*, Phys. Rev. B 88, 214517 (2013).
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[7] E. da Silva Neto *et al.*, Science 343, 393 (2014).

Fermi surface reconstruction by charge order in underdoped copper oxides

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25 years after the discovery of high temperature cuprate superconductors, the observation of quantum oscillations [1] has deeply changed the theoretical landscape relevant to these materials. The measurements of quantum oscillations on both sides of the phase diagram of cuprates show that the Fermi surface has suffered a drastic modification on the underdoped side. Indeed, the small Fermi pocket inferred from quantum oscillations combined with the negative Hall and Seebeck coefficients pointing to an electron pocket show that the Fermi surface of underdoped $YBa_2Cu_3O_y$ undergoes a reconstruction because the translational symmetry of its lattice is broken at low temperature.

In underdoped $YBa_2Cu_3O_y$, many studies such as NMR measurements [2], x-ray scattering [3, 4] point to a reconstruction of the Fermi surface due to charge order. After providing the context for charge order in underdoped cuprates, I will present transport and ultrasonic measurements in magnetic fields large enough to suppress superconductivity at low temperature in underdoped $YBa_2Cu_3O_y$ and $HgBa_2CuO_{4+\delta}$. These results point to an universal Fermi surface reconstruction at a critical doping in underdoped cuprates. I'll also discuss Fermi surface reconstruction scenarios with the aim to provide information on the Fermi surface in the pseudogap phase.

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Charge Order, Fermi-Arc Instability, and d-wave bond order in underdoped cuprates

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The phase diagram of cuprates features a rich diversity of exotic electronic states characterized by broken symmetries which induce corresponding orders: antiferromagnetism (AFM), pseudogap (PG), charge-density-wave (CDW). Recent experiments in YBCO have revamped the debate around the importance and universality of a charge-ordered electronic ground state emerging in the normal phase above the critical temperature T_c. In our work [1, 2], we investigated the origin and characteristics of charge-ordered states in single- (Bi2201) and bi-layer (YBCO) compounds, using a suite of complementary real- and momentum-space, and surface and bulk probes – resonant X-ray scattering (REXS), scanning-tunnelling microscopy (STM), and angle-resolved photoemission spectroscopy (ARPES). By bringing together these techniques, we identify the connection between charge order and the Fermi arcs to occur via the hot spots, and detect an onset of charge modulations right below T^* – thus pointing to an intimate relationship between the coexisting CDW and PG orders [1]. In addition, we have also explored the local symmetry of charge modulations, and reveal it to correspond to a d-wave bond order [2]. This discovery implies that the same mechanism which drives particle-particle pairing is also active in the particle-hole channel, and is suggestive that the CDW and SC instabilities originate from the very same attractive interactions.

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[2] R. Comin et al., submitted (2014).

Visualizing (Electronic) Dragons

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High-T_c superconductivity is found in strongly correlated (repulsive electron-electron interaction) systems exhibiting antiferromagnetic 'parent' states. Examples include the copper-based, iron-based and heavy-fermion superconductors. However, the **terra incognita** between the superconductivity the antiferromagnetic phase often harbors very exotic states whose identification/explanation has proven extremely challenging. Motivation for the introduction of atomically resolved spectroscopic imaging STM [RSI **70**, 1459 (1998)] came from my desire to directly visualize these **electronic dragons**. I will discuss the history of this technique and explain how it was used to first reveal the cuprate $\mathbf{Q} \neq 0$ density wave [Science **266**,455 (2002)] along with its detailed microscopic structure [Science **315**, 1380 (2007)], the cuprate $\mathbf{Q} = 0$ intra-unit-cell nematic state [Nature **466**, 374 (2010)] and its intimate relation the $\mathbf{Q} \neq 0$ density wave [K. Fujita *et al.*, Science (2014)], and the pnictide $\mathbf{Q} = 0$ nematic state [Science **327**, 181 (2010)]. Time permitting; I will discuss a model conceptual framework within which to understand the relationship between AF electron–electron interactions, these exotic states, and the correlated SC [PNAS **110**, 17623 (2013)].

Nano-plasmonic phenomena in graphene

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The term "plasmonics" often carries an applied connotation owing to remarkable successes in controlling and manipulating light at the nanoscale in artificial structures. Infrared nano-spectroscopy and nano-imaging experiments on graphene carried out in our group [Nano Letters 11, 4701 (2011), Nature Nano 8, 821 (2013)] have uncovered a rich variety of plasmonic effects that may enable functionalities not attainable through metal-based plasmonics. Applications aside, the nano-scale exploration of surface plasmons has offered an entirely new perspective on fundamental physics behind electronic phenomena in graphene. For example, by interferometric infrared imaging of plasmonic standing waves we were able to quantify the electronic losses in graphene. This latter result highlights the important role of many body effects [Nature 487, 82 (2012)] that were not anticipated theoretically. By examining the sub picosecond dynamics of plasmons in a setting of a unique pump-probe nano-spectroscopy apparatus we were able to discriminate between the roles of several photo-induced processes in mono-layer and few layer graphene [Nano Letters 14, 894 (2014)]. Unexpectedly, infrared photo-excitation enables ultrafast control of plasmons with the efficiency rivaling that of electrostatic gating. Confined surface waves that can travel over macroscopic distances are generic to other classes of two-dimensional atomic crystals [Science **343**, 1125 (2014)].

From dia- to paramagnetic orbital susceptibility of Dirac cones

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We study the orbital susceptibility of multiband systems with a pair of Dirac points interpolating between honeycomb and dice lattices. Despite having the same zero-field energy spectrum, these different systems exhibit spectacular differences in their orbital magnetic response, ranging from dia- to paramagnetism at Dirac points. We show that this striking behavior is related to a topological Berry phase varying continuously from π (graphene) to 0 (dice). The latter strongly constrains interband effects, resulting in an unusual dependence of the magnetic response also at finite doping.

Massless fermions in 2D and 3D: infrared magneto-spectroscopy studies

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Solid-state physics and quantum electrodynamics, with its relativistic (massless) particles, meet to their mutual benefit in steadily expanding class of materials. Those include, 1D carbon nanotubes, 2D graphene or topological-insulator surfaces, and, most recently, the systems with an isotropic conical dispersion in 3D - with Weyl, Dirac or Kane fermions. In this talk, I will review how the linear dispersion impacts the basic (magneto-) optical properties of these systems.

To illustrate this, we focus on two representative materials: a 2D graphene and bulk HgCdTe which displays the 3D conical dispersion when tuned to the point of the semiconductor-to-semimetal topological transition. We demonstrate that it is the number of dimensions, which defines the (joint) density of states, and in consequence, the simple physical quantities such as absorption of light - dispersionless in graphene but displaying a linear-in-photon-energy dependence in HgCdTe.

In magnetic fields, the conical dispersion is transformed into Landau levels (LLs) and the optical response is determined by electronic excitations between discrete (in 2D) or dispersed (in 3D) LLs, both, however, with a typical for relativistic particles, square root dependence on the magnetic-field. Further relativistic effects may appear, depending on the strength of spin-orbit coupling. Spin-related effects are rather absent in the optical response of graphene which exhibits a weak spin-orbit coupling. Instead, we observe a pronounced spin splitting of LLs in HgCdTe, which follows the $\sqrt{B}$-dependence – a well-established signature of relativistic particles, but never observed in any condensed-matter system up to now.

Fano resonances in hyperkagome iridates

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Iridates exhibit enhanced spin-orbit coupling and their 5d electrons have reduced on-site Coulomb repulsion, compared to 3d-electron systems, giving rise to novel electronic phases, including relativistic Mott insulators with antiferromagnetic and spin liquid ground states, for geometrically unfrustrated and frustrated lattices, respectively. Geometrical frustration and spin-orbit interaction imply a strong spin-lattice coupling in a sublattice of Ir ions, but the effects of electron-phonon interactions have not been explored in the system.

One of the most striking manifestations of the electron-phonon interaction is the quantum interference between discrete phonons and the continuum of electron-hole excitations. Drawing on a spectroscopic ellipsometry study, we report evidence that conditions favorable for Fano interference are met in the three-dimensional hypekagome lattice of $Na_3Ir_3O_8$ [1], the semimetallic counterpart of Mott-insulating $Na_4Ir_3O_8$, one of the best candidates for a three-dimensional (3D) spin-liquid state [2]. The entire set of well-defined phonon modes in the ellipsometric IR spectra of $Na_3Ir_3O_8$ single crystals exhibit highly asymmetric line shapes characteristic of Fano resonances. With decreasing temperature, we observe a sharp increase of the infrared intensity of the resonances followed by concomitant changes in the underlying electronic background, formed by electronic transitions between Ir 5d t_{2g} bands of a mostly $J_{eff} = 1/2$ character. Because of the lack of inversion symmetry the four $J_{eff} = 1/2$ bands have linear Rashba-type dispersion in the vicinity of the Gamma point. These bands originate from strong spin-orbit coupling and intersect near the Fermi level, resembling the Dirac cone in graphene. An analysis of the dipole matrix elements has shown that interband transitions between these partially filled bands have a high probability. This provides high density of electron-hole excitations which interfere with superimposed discrete phonon states, in a similar manner as discussed for graphene.

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Strong Plasmon Reflection at Nanometer Gaps in Graphene

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Graphene plasmons attract much attention as they exhibit a remarkable electrostatic tunability and the ability to strongly concentrate electromagnetic energy, potentially useful for applications. We used tip-enhanced infrared near-field microscopy (s-SNOM) to study propagating plasmons in epitaxial quasi-free-standing monolayer graphene on silicon carbide. We observe that plasmons are strongly reflected at tiny graphene gaps formed at the steps between the atomically flat substrate terraces. For the step height of only 1.5 nm, which is two orders of magnitude smaller than the plasmon wavelength, the plasmon reflection reaches 20 percent, and it approaches 0.5 for steps of 5 nm. We support this observation with numerical simulations and provide physical rationale for this intriguing phenomenon. Our results suggest that in general plasmon propagation can be controlled using ultracompact nanostructures.

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Fermi liquid behaviour in strongly correlated metals *

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A reference point for research on a wider range of correlated behaviour is provided by the so-called Fermi-liquids, characterized by a relaxation rate $1/\tau \propto \omega^2 + (p\pi k_B T)^2$. The theoretical prediction for the relaxation rate appearing in the optical conductivity is $p = 2$ when considering the experimentally most accessible range $\omega > 2\pi k_B T$. A number of recent optical studies have addressed the issue of Fermi-liquid characteristics, reporting indeed ω^2 and T^2 for the optical scattering rate of a number different materials. However, a perfect match to the prediction $p = 2$ has not been observed. One possible scenario that has been proposed to explain this discrepancy is the presence of magnetic impurities. In a recent study we have investigated Sr_2RuO_4, a material which can be synthesized in very pure form, with well established T^2 resistivity below 25 K. Here we observe a perfect scaling collapse of $1/\tau$ as a function of $\omega^2 + (p\pi k_B T)^2$ for with $\omega < 36$ meV, and temperature below 40 K, with $p = 2$. We also observe features in the spectrum at higher energy, which are manifestly beyond the Fermi-liquid model. The sign and size of these features agree quantitatively with the notion of resilient quasiparticles predicted by dynamical mean field theoretical calculations for this compound.

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Fermi liquids and beyond: non-Drude universal scaling and optical signatures of resilient quasiparticles *

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*Based on:X.Deng et al. Phys Rev Lett 100, 086401 (2013); C. Berthod et al. Phys Rev B 87, 115109 (2013); D. Stricker et al. arXiv:1403.5445

Power-Law Behavior of Optical Conductivity Observed in Strongly-Correlated Organic Conductors

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Organic charge-transfer salts are highly conducting one- or two-dimensional electron systems which exhibit unusual physical behavior due to significant electron-electron interactions. The best known example are the one-dimensional metals of the TMTSF family which show significant deviations from a Drude metal and been established as the model compound of a Luttinger-liquid. The optical properties provide insight into the dynamics of the correlated electrons and energy dependence of the interactions. In two-dimensional metallic k-(BEDT-TTF) salts the effective Coulomb repulsion can be tuned be pressure until the Mott-insulating state is reached. With increasing correlations, the Fermi-liquid behavior becomes more pronounced, the effective mass grows and the prefactor in temperature- and frequency dependent scattering rate increases. The ratio between the temperature and frequency dependent contributions corresponds to Landau's predictions of a Fermi liquid. On the insulating side of the Mott transition, frustration on the triangular lattice causes a spin-liquid behavior with no magnetic order down to lowest temperatures. The optical conductivity of k-(BEDT-TTF)2Cu2(CN)3 reveals a large in-gap absorption where the excess conductivity exhibits a power-law behavior $\sigma(\omega) = \omega^n$ that grows stronger as the temperature decreases. With $n \sim 0.8$ to 1.5, the exponent is significantly smaller than predicted for spinon contributions to the optical conductivity.

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THz properties of $CaRuO_3$: can we reconcile non-Fermi-liquid optics with Fermi-liquid concepts?

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Landau Fermi liquid (FL) theory is the established framework to describe the many-particle system of electrons in metals within a single-particle picture. In particular, the existence of well-defined Landau quasiparticles is taken as hallmark that renders a metal a Fermi liquid. While experiments have verified FL predictions for many different physical quantities, the situation for the optical properties of a FL remains under debate. Furthermore, it is not clear how optical properties of metals that contradict FL predictions and that are often phenomenologically termed non-FL optics should be interpreted or analyzed quantitatively. $CaRuO_3$ has long been established as a non-FL metal in a wide temperature range, including non-FL optical properties [1, 2], but with recent improvements in the growth of $CaRuO_3$ thin films using metalorganic aerosol deposition we could document a FL ground state for $CaRuO_3$ by observation of Shubnikov-de Haas oscillations and a quadratic temperature dependence of the dc resistivity below 1.5 K [3]. Metallic thin films allow optical measurements at frequencies well below the conventional infrared range, and this low-frequency range is particularly suitable to address optical FL and non-FL properties, which are usually confined to low energies both in temperature and frequency. Here we present the results of phase-sensitive THz transmission measurements on high-quality thin films of $CaRuO_3$ at frequencies 0.2 - 1.4 THz and temperatures 2 - 300 K [3]. When cooled below 100 K, the optical scattering rate of our $CaRuO_3$ films moves into our spectral range, and we can observe the charge dynamics. Below 40 K, the metallic response clearly develops a frequency-dependent scattering rate, i.e. cannot be described in simple Drude terms. In particular, we find a pronounced increase of the scattering rate for frequencies above 0.6 THz, and this increase is much stronger than predicted in the context of FL theory. However, the temperature-dependent response below 0.6 THz, which exhibits only weak deviations from Drude behavior, can be described within FL concepts as recently suggested by Berthod *et al.* [4]. We discuss how the optical response

of $CaRuO_3$ in the non-FL temperature range fits into the present discussion of FL optics, and how future studies on $CaRuO_3$ at even lower temperatures or in magnetic field could further elucidate the situation.

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Chiral density wave of the 'hidden order' phase in URu_2Si_2 *

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A second-order phase transition is associated with emergence of an "order parameter" and a spontaneous symmetry breaking. For the "hidden order" phase below 17.5 K in the heavy fermion superconductor URu2Si2, the symmetry of the order parameter and its associated collective modes has remained ambiguous despite 30 years of research. Here we use polarization resolved Raman spectroscopy to specify the symmetry of low energy excitations above and below the hidden order transition. These excitations involve transitions between interacting heavy uranium 5f orbitals, responsible for the broken symmetry in the "hidden order" phase. From the symmetry analysis of the collective mode, we determine that the hidden order parameter breaks local vertical and diagonal reflection symmetries at the uranium sites, resulting in crystal field states with distinct chiral properties, which order to a chiral density wave.

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Composite and Topological Order in Heavy Fermion Materials *

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Heavy Electron materials provide a low energy realization of many of the emergent properties of correlated electron systems, providing a readily tuneable research test-bed for research into correlated electron materials. In this talk I shall talk about two aspects of these materials that are ripe for new spectroscopic study: topological order and composite pairing.

Topological order appears to be present in some of the Kondo insulators, such as SmB6 and high pressure SmS, but it may also be present in the quantum critical material YbAlB4 and could even be present in fully gapped scenarios of composite paired heavy electron superconductivity, such as in Yb doped CeCoIn5. I shall review these three possibilities and discuss ways in which STM, optical and ARPES spectroscopy may be able to shed new light on our understanding.

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The normal state of URu_2Si_2: spectroscopic evidence for an anomalous Fermi liquid.**

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The Landau Fermi liquid, is recognized experimentally by an electrical resistivity that is proportional to the square of the absolute temperature. There is also a frequency dependent term which has received less attention since the experiments have to be performed in the difficult far infrared region of the spectrum. Calculations show that, if electron-electron scattering dominates the electron lifetime, in a Landau Fermi liquid, $\rho(T,\omega) = A'(\omega^2 + b\pi^2T^2)$ where $b = 4$. Using an optical technique that minimizes interference artifacts, we find the coefficient $b = 1.0 \pm 0.1$ in the normal state of the heavy Fermion metal URu_2Si_2. This unexpected result implies that the electrons are experiencing a novel scattering process. This scattering is intrinsic and we suggest that, above 17.5 K, the uranium f electrons do not hybridize with the free *spd* electrons to form a coherent Fermi liquid but instead act like a dense array of elastic impurities, interacting incoherently with the charge carriers. Calculations by Maslov and Chubukov [1] show that resonant elastic scattering in a Fermi liquid can yield a scattering rate where $b = 1$. This behavior is not restricted to URu_2Si_2. Fermi liquid like states with $b \neq 4$ have been observed in a number of disparate systems but the significance of this result has not been widely recognized.

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Optical conductivity of Fermi-liquid and non-Fermi-liquid metals *

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In the first part of the talk, I will discuss the robustness of the Fermi-liquid (FL) theory results for the imaginary part of the single-particle self–energy, $\mathrm{Im}\Sigma \sim \omega^2 + \pi^2 T^2$, and for the real part of the (inverse) optical conductivity, $\mathrm{Re}\sigma^{-1} \sim \omega^2 + b\pi^2 T^2$ with $b = 4$. I will show that these scaling forms follow from exact analytic properties in the complex plane (the "first-Matsubara-frequency rules"), and also that the result for the optical conductivity is valid to any order in the electron-electron interaction and with all vertex corrections taken into account [1, 2]. However, optical measurements on a number of strongly correlated metals indicate that the scaling form of $\mathrm{Re}\sigma^{-1}$ differs from the FL prediction: the coefficient b is closer to 1 than to 4. We propose a phenomenological model in which electrons, in addition to inelastic electron-electron interaction, are also scattered elastically by resonant levels. This model explains the data on URu_2Si_2 [3]. In the second part of the talk, I will discuss the optical conductivity of a 2D metal at the onset of the spin-density-wave instability [4]. It will be shown that composite scattering of "lukewarm fermions" results in a non-FL behavior of $\mathrm{Re}\sigma$, which scales as $\omega^{-1/3}$ and ω^{-1} below and above some characteristic frequency, correspondingly.

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*In collaboration with A. V. Chubukov and V. I. Yudson.

Nanoscale Band Structure Imaging of Topological Materials: Sb and SmB_6*

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We use STM to study the topological semimetal Sb(111), and report the first simultaneous observation and quantitative reconciliation of Landau level spectroscopy and quasiparticle interference imaging. We thus establish the technique of band structure tunneling microscopy (BSTM), and use it to reconstruct the multi-component surface states band structure of Sb with nanoscale spatial resolution, and to quantify essential metrics for spintronics applications. We also conduct the first atomic resolution spectroscopic study of the proposed topological Kondo insulator SmB_6. We disentangle the tunneling interference between two distinct bands, to reveal a robust hybridization gap which universally spans the Fermi level on four distinct surface morphologies, paving the way for more detailed understanding of the purported topological surface states.

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Giant spin splitting in inversion-symmetry broken semiconductors

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There has been increasing interest in emerging phenomena from relativistic electrons in a solid, which gives a potential impact on spintronics and magnetoelectrics. One such example is the Rashba and/or Dreselhaus effect that lifts the electron-spin degeneracy as a consequence of spin-orbit interaction (SOI) under the broken inversion-symmetry. A high-energy scale spin-splitting is highly desirable for enhancing the coupling between electron-spins and electricity relevant for spintronic functions. In my talk, I will present the findings of huge SOI effects in several inversion-symmetry broken semiconductors. One is a polar semiconductor composed of heavy elements, BiTeI, where the whole bulk carriers are ruled by big Rashba-like spin-splitting. The band splitting and its spin polarization obtained by spin- and angle-resolved photoemission spectroscopy are well in accord with relativistic first-principles calculations, confirming the spin-splitting indeed derived from bulk atomic configurations. At the same time, the emergence of a strongly spin-orbit coupled 2-dimensional (2D) electron gas is also found in BiTeI, BiTeBr, and BiTeCl, arising from the 2D confinement of conduction electrons due to the surface band bending effect. I will also show the recent result on another inversion-symmetry broken semiconductor, transition metal dichalcogenide MoS_2, clearly indicating the nearly full spin polarization of valence band electrons at the Brillouin zone corners.

Coexistence of Massless and Massive Dirac Fermions in Topological Crystalline Insulators

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Topological crystalline insulators (TCIs) are recently discovered topological materials [1,2] where topology and crystal symmetry intertwine to create linearly dispersing Dirac surface states similar to graphene. Among the theoretical predictions for TCIs is the possibility of imparting mass to the massless Dirac fermions by breaking crystal symmetry, as well as a Lifshitz transition with a change of Fermi surface topology. In this talk I will discuss our recent experimental and theoretical investigations of a TCI, $Pb_{1-x}Sn_xSe$ [3]. We performed scanning tunneling microscopy (STM) studies at low temperatures and as a function of magnetic field. By analyzing two types of STM data: Fourier transforms of interference patterns and Landau level spectroscopy, we reveal two distinct regimes of fermiology separated by a Van-Hove singularity at the Lifshitz transition point. Our studies reveal the coexistence of zero mass Dirac fermions protected by crystal symmetry with massive Dirac fermions resulting from crystal symmetry breaking. In addition, I will discuss our recent data on the evolution of the mass as well as the Dirac surface states as we go through a quantum phase transition from the topological to trivial regime.

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Time-resolved terahertz dynamics in thin films of the topological insulator Bi_2Se_3 *

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We use optical pump–THz probe spectroscopy at low temperature to study the hot carrier response on thin films of Bi_2Se_3 of several thicknesses to separate the bulk from the surface response. We find that for thinner films the photo excitation changes the transport scattering rate and reduces the THz conductivity, which relaxes within 10 picoseconds (ps). For thicker films, the conductivity increases upon photo excitation and scales with the increase in both the film thickness and optical fluence, with a decay time of approximately 5 ps, as well as a much larger scattering rate. The different dynamics between surface and bulk electrons indicate a decoupling of surface and bulk carriers, and present the possibility of accessing long-lived surface photo-carriers for optoelectronic applications.

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Terahertz conductivity of Dirac-like materials *

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I will discuss terahertz conductivity results of two Dirac-like materials using terahertz time-domain spectroscopy, as a function of temperature in the frequency range 0.3 – 3 THz. In twisted bilayer graphene, on top of a Drude-like response, we see a strong peak in the real conductivity $\sigma_1(\omega)$ at ∼2.7 THz. We analyze the overall Drude-like response using a disorder-dependent (unitary scattering) model, then attribute the peak at 2.7 THz to the presence of van Hove singularities arising from a small-angle commensurate twisting of the two graphene layers [1]. In the three-dimensional topological insulator $Bi_{1.5}Sb_{0.5}Te_{1.8}Se_{1.2}$,the complex conductivity was analyzed using the Drude-Lorentz model [2]. By calculating the Drude spectral weights of the sample, we found, compared to other bismuth-based topological insulators, that the topological surface states are more clearly discerned with the three-dimensional bulk states being suppressed. An impurity band is present about 30 meV below the Fermi level. We compare the calculated surface and bulk carrier densities with those obtained from transport data. From the surface Drude contribution, we obtained a ∼98% transmission through one surface layer — this is consistent with the transmission through single-layer or bilayer graphene, which shares a common Dirac-cone feature in the band structure. We also show that the temperature dependence of the experimental parameters is not the result of aging effects. The low-frequency real conductivity follows a thermally-activated behavior.

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Observation of Higgs Amplitude Mode in Superconductors*

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Superconductivity is a striking example of the spontaneous symmetry breaking (SSB) phenomena. In general, when a phase transition occurs associated with the SSB, two kinds of collective excitations emerge; the gapless phase mode and the gapped amplitude mode of the complex order parameter. The latter is also called as the Higgs mode from its analogy to the Higgs bosons in elementary particle physics. The nature of the Higgs amplitude mode in superconductors has been intensively studied theoretically in the framework of a quench problem, according to which the Higgs amplitude mode can be thought of as the collective Rabi oscillation of the Anderson's pseudo-spins. Within the mean-field approximation, a variety of collective mode dynamics such as collision-less damping, power-law decay, persistent oscillation, has been investigated. On the other hand, since the Higgs mode does not couple directly to the electromagnetic field within the linear response, the experimental investigation of the Higgs mode in superconductors has remained as an open issue. In this presentation, we report on the observation of Higgs amplitude mode in s-wave superconductors, $Nb_{1-x}Ti_xN$ films, by using THz-pump and THz-probe spectroscopy technique. In order to excite the Higgs amplitude mode with suppressing the heating effect, we irradiated the sample by an intense monocycle THz pulse whose center frequency was tuned to the superconducting gap. When the excitation pulse width was short enough compared to the inverse of superconducting gap energy, namely in a non-adiabatic excitation regime, a damped oscillation was observed in the transmission of the electric field of THz probe pulse as a function of pump-probe delay. The oscillation frequency obtained from the damped-oscillation fits coincides with the value of asymptotic BCS gap energy after the THz excitation, which behavior indicates the character of Higgs amplitude mode. When the excitation pulse width is comparable to the inverse of superconducting gap energy, the Higgs mode becomes less prominent, as the non-adiabatic excitation condition is not satisfied. In the presentation, the dynamics of pseudo-spins arising from the coherent interaction with the THz electric field will also be discussed.

*This work is done in collaboration with R. Matsunaga, Y. I. Hamada, A. Sugioka, H. Fujita, K. Makise, Y. Uzawa, H. Terai, Z. Wang, N. Tsuji, and H. Aoki.

Strong-Field THz Study of Superconductivity in the Time Domain *

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We have developed a time-domain methodology for determining the THz response of BCS superconductors [1]. The method, based on a finite difference (FDTD) calculation of electromagnetic fields, includes a time-domain susceptibility function valid for the superconducting state with T«Tc. We demonstrate the method's validity by comparing calculation results for the transmission and reflection properties of superconductors with their known frequency-domain counterparts. We also calculate the E-field waveform observed experimentally in a time-domain THz study of superconducting NbTiN.

Some of the advantages of the time-domain approach include calculating instantaneous quantities such as the induced current density that, in turn, affect other quantities. For example, it is known that a superconductor carrying a current has a reduced energy gap under equilibrium conditions, and that equilibrium is established through inelastic electron scattering. We have explored the limits on how fast this process can occur using a strong-field THz pulse to disrupt the superconducting state of a NbN film and modeled the behavior using our time-domain methodology. Comparison between the two suggest that strong currents can destroy superconductivity on a 100 fs time scale.

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Amplitude 'Higgs' mode in 2H-$NbSe_2$ Superconductor

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When a spontaneous breaking of a continuous symmetry takes place, as happens during a superconducting transition, collective excitations of the order parameter emerge among which the massive amplitude Higgs mode. Here, we report experimental evidences for the observation of the such superconducting (SC) amplitude mode, so-called 'Higgs' mode in the charge density wave (CDW) superconductor 2H-$NbSe_2$ using Raman scattering. By comparing 2H-$NbSe_2$ and its iso-structural partner 2H-NbS_2 which shows superconductivity but lacks the charge density wave order, we demonstrate that the superconducting mode in 2H-$NbSe_2$ owes its spectral weight to the presence of the coexisting charge density wave order. In addition temperature dependent measurements at ambient pressure in 2H-$NbSe_2$ show a full spectral weight transfer from the charge density wave mode to the superconducting mode upon entering the superconducting phase. Finally, thanks to the technical development of a new set-up for electronic Raman scattering at low temperature (3 K) and high pressure (20 GPa), we show that when the charge density wave order disappears (at 7GPa) the superconducting collective mode turns into a pair breaking peak as observed in 2H-NbS_2. All these observations are consistent with a superconducting amplitude mode or Higgs mode. Moreover, we have finely followed the CDW and the SC modes with pressure. Whereas the CDW mode softens and enlarges until it collapses at $\sim$5 GPa, the SC mode hardens and gains spectral weight up to 3.5 GPa before losing intensity and softening up to 5 GPa. We will discuss these intriguing results in the context of the quantum critical point theory.

Spectroscopic signatures of phase and amplitude modes in superconductors

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The formation of a superconducting state leads to the appearance of two collective modes associated with the amplitude and phase fluctuations of the SC order parameter. A direct observation of these two modes is usually elusive, since in a standard BCS superconductor they do not couple to the current or density fluctuations, which are the ones probed by the different spectroscopic techniques. However, specific mechanisms able to break a fundamental symmetry of the system can make these mode observable. Here we discuss two paradigmatic cases suggested by recent experiments in conventional superconductors. The first example is the visibility of phase fluctuations in a strongly disordered superconductor: we show that phase modes become optical active in the presence of disorder, giving rise to additional optical absorption below the gap edge [1], probed recent by microwave spectroscopy [2]. In particular, we show that the optical response is tightly connected to the spontaneous emergence of SC islands (embedded in a bad SC background) probed recently by STM [3] in several conventional superconductor (as e.g. NbN, TiN, InOx) near the superconductor-insulator transition. Indeed, isolated SC islands act as micro-antennas via the accumulation of a finite phase gradient across their edges [1, 4]. The second example in the visibility of the Higgs (amplitude) mode in the Raman response of a SC state formed on top of a CDW state. Indeed, the CDW state breaks the particle-hole symmetry leading to a finite direct coupling between amplitude fluctuations of the SC order parameter and density fluctuations, probed by Raman scattering [5]. Such a purely electronic mechanism can explain the emergence of an additional peak below T_c in 2H-NbSe2, without assuming a direct coupling between the phonon and the amplitude fluctuations. We finally comment on the consequences of all these findings within the context of other SC systems, as SC interfaces and cuprate superconductors.

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Coexistence and competition of multiple charge-density-wave orders in RTe3 as revealed by optical probes

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The rare-earth tri-telluride RTe3 (R = rare earth elements) is among the most well-known and representative CDW compounds driven by the nesting of Fermi surfaces. It is widely accepted that the compounds with light R ions in the series experience a single CDW phase transition, while the four heavy R ion compounds (R=Dy, Ho, Er, Tm) undergo two CDW transitions. The second transition occurs at lower temperature with a nesting wave vector perpendicular to the first one. Moreover, the two CDW phase transition temperatures involve in an opposite trend. Optical measurement on a heavy R compound ErTe3 indeed revealed two CDW energy gaps [1] which matches fairly well with the established results by other experimental probes. However, optical measurements (including ultrafast pump-probe) on light and intermediate rare-earth compounds CeTe3 and TbTe3 revealed puzzling results: an additional CDW energy gap still develops at low temperature [**?**], which is at odds with other experimental measurements. Moreover, the gap values for CeTe3 and TbTe3 do not follow the trend observed for the four heavy rare-earth RTe3 compounds.

To resolve the puzzle, we grew single crystals of the whole series of the rare-earth RTe3 and performed systematic optical spectroscopy studies on all eleven different compounds, which unexpectedly reveals the presence of a third CDW order which also evolves systematically in the series. The first and third CDW orders cooperate with each other and show similar suppressions with decreasing the radii of R ions (or increasing chemical pressure). Meanwhile, both compete with the second CDW order by depleting the low energy spectral weight. The energy gaps observed previously in CeTe3 and TbTe3 at lower energies actually belong to this third CDW order (this order had never been reported by any other probes before). On the basis of those results, we established a complete electronic phase diagram for the multiple CDW orders in RTe3 system [4]. The compounds offer a precious opportunity to study the interplay among the multiple order of the same type.

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Snapshots of the retarded electronic interaction with antiferromagnetic fluctuations in high-temperature superconductors

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One of the pivotal questions in the physics of high-temperature superconductors is whether the low-energy dynamics of the charge carriers is mediated by bosons with a characteristic timescale. This issue has remained

elusive since electronic correlations are expected to dramatically speed up the electron-boson scattering processes, confining them to the very femtosecond timescale that is hard to access even with state-of-the-art ultrafast techniques. Here we simultaneously push the time resolution and the frequency range of transient reflectivity measurements up to an unprecedented level that enables us to directly observe the $\sim$16 fs build-up of the effective electron-boson interaction in hole-doped copper oxides. This extremely fast timescale, together with the outcome of calculations for the t-J model and the repulsive Hubbard model, indicates that short-range antiferromagnetic fluctuations are the bosons that likely mediate the retarded electron interactions in copper oxides close to optimal doping, where the largest critical temperature is reached.

Quasiparticle recombination dynamics in the model cuprate superconductor $HgBa_2CuO_4 + \delta$ *

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The cuprate family of high temperature superconductors is characterized by a variety of electronic phases which emerge when charge carriers are added to the antiferromagnetic parent compound. In recent years, it has been established that various forms of charge ordering at temperatures proximate to the superconducting transition temperature are a universal feature of underdoped cuprates. The structural simplicity of the single layer cuprate system $HgBa_2CuO_4 + \delta$ (Hg1201) makes it an ideal system for studying subtle interactions between charge order and superconductivity.

In this work, we investigate the recombination dynamics of photo-excited quasiparticles in Hg1201 as a function of doping, temperature, and magnetic field using pump-probe optical reflectivity. We observe two distinct onset temperatures above T_C in the underdoped part of the phase diagram, corresponding to T* and T** as observed in transport and neutron scattering experiments. We also measure a suppression of the recombination rate near T_C. This suppression can be modeled as a crossover from fluctuating charge density wave to superconducting quasiparticle coherence.

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Optical observation of precursory superconductivity in $YBa_2Cu_3O_y$ *

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We have systematically studied the c-axis polarized optical spectra for Zn-doped $YBa_2Cu_3O_y$ over a wide range of oxygen and Zn-contents. Subtracting the normal components carefully, we found finite superconducting condensates at the temperatures far above T_c but below the pseudogap temperature T^* [1]. This temperature for precursory superconductivity (T_p) is sensitive to the Zn-doping like T_c, which indicates that this phenomenon is linked to superconductivity but different from the pseudogap. On the other hand, the doping dependence of T_p is similar to that of T^*, namely, T_p increases with underdoping. These results suggest that as the system approaches a Mott insulator the pairing interaction becomes stronger but the simultaneously developed competing order (pseudogap) suppresses superconductivity. Although these two (superconductivity and pseudogap) are distinct order, they may originate from the same interaction. Strong electron correlation is a possible candidate for this interaction. Since our recent study of oxygen isotope effect in $YBa_2Cu_3O_y$ suggests that the charge channel is involved in the competing order [2], the coexistence of spin and charge order such as the stripe order could be the origin of the pseudogap.

[1] E. Uykur *et al.*, to be published in Phys. Rev. Lett.

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Evidence for a superconducting origin of prominent features of the in-plane infrared response of underdoped cuprates and implications of their persistence above Tc

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The possible persistence of some form of superconductivity many tens of K above the bulk superconducting transition temperature Tc in underdoped cuprate superconductors belongs to the most vividly discussed topics in the field of high-Tc superconductivity. Surprisingly high (up to 100 K above Tc) values of the temperature Tons of the onset of an increase of coherence, presumably due to an onset of a precursor superconducting phase, have been deduced from the data of the c-axis infrared response of underdoped YBa(2)Cu(3)O(7-delta) (Y-123) [1]. The interpretation of the Tons scale in terms of a precursor superconductivity, however, has not yet been widely accepted. The main reasons are: (i) The c-axis response of Y-123 is a fairly complex quantity due to the specific bilayer structure. See, however, Ref. [2]. (ii) Underdoped cuprates are known to exhibit ordered states distinct from superconductivity, in particular, charge modulations have been reported [3] that set on at temperatures comparable to Tons. It is thus possible to speculate that the Tons scale is determined by an order competing with superconductivity rather than by superconducting correlations themselves. In this context it is of high importance to address manifestations of the increase of coherence below Tons in the in-plane response and to ascertain their relation to superconductivity.

We report on results of our analysis of published experimental data of the in-plane infrared response of two representative underdoped high-Tc cuprate superconductors (Y-123, Tc=59 K, data from [4]; HgBa(2)CuO(4+delta), Tc=67 K, data from [5]) focusing on a characteristic gap feature in the spectra of the real part of the conductivity and the corresponding structures of the memory function/optical selfenergy, that develop below Tons. Several

arguments based on comparisons of the data with results of our calculations will be provided indicating that these features are due to superconductivity and that Tons marks the onset of a precursor superconducting phase: (i) The low temperature data of the two moderately underdoped cuprates will be shown to be consistent with results of our calculations based on a well established model [6] of the in-plane response of a d-wave superconductor. This has not been recognized earlier and it strongly suggests that the features are due to superconductivity. (ii) The onset of the gap feature in the data, below Tons, will be shown to be similar to that of our calculated spectra below Tc and to that of optimally doped cuprates below Tc [7]. This finding supports the assignment of the Tons scale to precursor superconductivity. (iii) It will be demonstrated that the temperature dependence of the features cannot be simply accounted for in terms of a normal state pseudogap independent of superconductivity. (iv) Our interpretation of the infrared data will be shown to be consistent with the precursor superconductivity based interpretation of the photoemission data proposed by D. Dessau and coworkers [8,9]: The above Tc spectral functions, as parametrized in [9], provide a reasonable profile of the conductivity only when complemented with the corresponding off-diagonal components. Preprint on cond-mat [10].

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A light scattering study of the pairing potential in Fe-based superconductors and related compounds *

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We present results of light scattering experiments on Fe-based superconductors. The main focus will be placed on superconducting gap excitations in $Ba_{1-x}K_xFe_2As_2$ (BKFA). It is shown that the response in A_{1g} and B_{2g} symmetry is dominated by pair-breaking. In contrast to $Ba(Fe_{1-x}Co_x)_2As_2$ the energy gaps derived for the various bands are only slightly anisotropic. In B_{1g} symmetry we find a sharp mode inside the gap that is most naturally explained in terms of an exciton-like excitation resulting from the final state interaction between the two electrons of a broken Cooper pair. Here, as opposed to the original prediction by Bardasis and Schrieffer, the interaction does not originate in an intraband anisotropy but rather in a subdominant contribution to the pairing potential from the interaction between the electron bands. The subdominant coupling is found to be almost as strong as the dominant one between the electron and hole bands. In BKFA the identification of the in-gap mode is straightforward for the temperature dependence of the energy and the transfer of spectral weight. The position and the intensitiy of the mode can be reproduced by a semi-quantitative calculation on the basis of model assumptions for the pairing potential. In addition to the Bardasis-Schrieffer modes, there exist various other collective excitations inside the gap allowing conclusions as to the interactions in the superconducting state. We give some examples of results observed earlier in superfluid He, A15 compounds, $NbSe_2$, and MgB_2 and propose an identification in terms of Bardasis-Schrieffer, Higgs and Leggett modes, respectively.

*The work was supported by the DFG via the Priority Program SPP 1458 (project no. HA 2071/7), by the Bavarian Californian Technology Center BaCaTeC (project no. A5 [2012-2]) and, partially, by the Transregional Collaborative Research Center TRR 80.

Raman scattering as a probe of charge nematic fluctuations in Iron-based superconductors *

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In this talk, I present recent Raman scattering results showing the presence of dynamical charge nematic fluctuations in the tetragonal phase of electron doped (Ba,Sr)$(Fe_{1-x}Co_x)_2As_2$ and hole doped $Ba_{1-x}K_xFe_2As_2$ Iron-based superconductors. The diverging Raman response at low temperatures unveils an underlying charge nematic state that extends to superconducting compositions and which has hitherto remained unnoticed. Comparison between the extracted static charge nematic susceptibility and elastic modulus measurements allows to disentangle the charge contribution to the nematic instability. Key differences between hole and electron-doping will also be highlighted.

* Work performed in collaboration with R.M. Fernandes, I. Paul, L. Chauvière, Y.-X. Yang, M.A. Méasson, M. Cazayous, A. Sacuto, D. Colson, A. Forget. Financial support from Agence National de la Recherche through ANR grant 11 "PNICTIDES" is acknowledged.

Nesting Induced Large Magnetoelasticity in the Iron Arsenide Systems

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AbstractText An interesting feature of the iron arsenides is the magnetoelastic coupling between the long wavelength in-plane strains of the lattice and the collective spin fluctuations of the electrons near the magnetic ordering wavevectors. We study the microscopic origin of this feature from an electronic model with nested Fermi pockets and a nominal interaction. We find the couplings diverge with a power-law as the system is tuned to perfect nesting, thereby implying the magnetoelasticity in these systems is a nesting induced feature. We also elucidate how this nesting induced singularity plays a role in triggering a spin fluctuation driven nematic instability that gives rise to the orthorhombic phase of these materials. These results show the microscopic connection between the nesting of the bands with the nematic and the magnetoelastic properties of the iron arsenides.

Hybridization regime and hidden order state of URu_2Si_2: Effects of doping on Fermi liquid scattering and energy gap

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We present new optical data on the heavy fermion metal URu_2Si_2 doped with Re and Fe. The un-doped material shows a Drude peak and a developing hybridization gap above 17.5 K. Below this temperature there is a second order phase transition to the "hidden order state". A gap develops in the incoherent part of the conductivity but the Drude peak remains. By doping Re into URu_2Si_2 the hybridization and hidden order states can be changed considerably. In the former, the Fermi liquid behaviour onsets at a lower temperature and persists over a broader temperature range. In the latter, the hidden order gap is weakened with a corresponding decrease in the transition temperature. Doping with Fe, by contrast, causes an increase in the hidden order transition temperature before pushing URu_2Si_2 into an antiferromagnetic state. The effect of these dopings on the hybridization and hidden order states, as revealed by optical conductivity, offers significant insight into the electrodynamics of this mysterious system.

Electron-Hole Symmetry in the Electronic Structures of Ce and Yb Compounds Examined by Optical Study under High Pressure

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The electron-hole symmetry is one of the most fundamental concepts in condensed matter physics. Electron-hole symmetry exists between Ce^{3+} and Yb^{3+} ions, since the former has one f electron while the latter has one f hole. Accordingly, many common properties are found between Ce and Yb compounds. For example, heavy fermion (HF) states with large effective mass have been observed for both Ce and Yb compounds. However, there are also differences between them. For example, there have been much fewer Yb-based HF superconductors than Ce-based ones [1]. Therefore, it is interesting to compare the microscopic electronic structures of Ce and Yb compounds. Their properties under high pressure are particularly interesting, since external pressure is possible to tune the hybridization between the conduction and f electrons (c-f hybridization). We have compared the electronic structures of $CeRhIn_5$ (Ce115) [2] and $YbNi_3Ga_9$ (Yb139) [3] by measuring their optical conductivity $\sigma(\omega)$ under high pressure with diamond anvil cell. Ce115 is tuned by pressure from a localized state (antiferromagnet) to a delocalized HF state for $P \geq 2.5$ GPa, while Yb139 is tuned from a delocalized HF (intermediate valence) state to a localized state (magnetic order) for $P \geq 9$ GPa. In the measured $\sigma(\omega)$ of both Ce115 and Yb139, a characteristic mid-infrared (mIR) peak shows marked pressure evolution. This peak results from a c-f hybridized state [4], and hence its pressure evolution results from that of the c-f hybridized state. It is found that the peak shift with pressure is *opposite* between Ce115 and Yb139: the mIR peak shifts to higher energy for Ce115 and to lower energy for Yb139. This result should reflect the electron-hole symmetry, i.e., pressure evolutions of f electron state toward opposite characteristics between Ce and Yb compounds. On the other hand, the mIR peak becomes broader with pressure for *both* Ce115 and Yb139, in contrast to what is expected from a simple electron-hole symmetry. We will discuss these results on the basis of microscopic electronic structures in Ce and Yb compounds under high pressure.

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Collective spin excitations in diluted magnetic quantum wells *

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We present ten years work on collective spin excitations in electron gas confined in diluted magnetic quantum wells made of $Cd_{1-x}Mn_xTe$. The giant Zeeman effect due to the sd-exchange coupling between the conduction electron and the magnetic impurities introduce a high spin-polarization degree of the electron gas with low magnetic fields rendering the Landau orbital quantization negligible. Hence a model spin-polarized electron gas (SP2DEG) is formed. By Raman scattering, we studied the spin waves of the SP2DEG, which propagates in the plane of the quantum well [1] thanks to the spin-resolved Coulomb interaction [2]. The sd-coupling introduce spin mixed modes in which the Mn spin precession is coherently coupled to the electron spins precession [3]. The spin-mixture of the spin motion was observed in the transient THz radiation that follows the coherent spin precession induced by an optical pulse [4]. More recently, we observed huge spin-orbit fields, reinforced by the Coulomb interaction and acting as a unique field on the spin waves [5]. This effect might have applications in spin-wave based spintronics.

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*All the people who contributed to this work : F. Baboux, J. Gomez., C. Aku-Leh, J. Tignon, R. Rungsawang, S. Dhillon, T. Wojtowicz, G. Karczewski, D. Scalbert, M. Vladimirova, S. Cronenberger, B. Jusserand, D. Richards

Collective effects in 2D electron gas and Ultra-strong light-matter coupling *

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The resonant interaction between light and a quantum structure is commonly described as a process between two electronic levels. However, in solid-state physics this simple picture must be revised when a large number of particles are involved in the process, as many-body effects can modify profoundly the optical response of the system. One such example are the intersubband transitions between the quantized states of a semiconductor quantum well, hosting high density electron gas. In such system, the optical response is provided both by the quantizing effects of the heterostructure potential and by the plasmonic nature of the electronic oscillations excited by the impinging photon.

In such systems, one direct physical effects of the collective electronic response is the possibility to gain very large oscillators strengths for the many-body state as compared to the single particle electronic states. Such gain results in a considerable acceleration of the absorption and emission of light in these systems. For instance, when highly doped quantum wells are coupled with a resonant microcavity, one reaches the ultra-strong light-matter coupling regime, recently demonstrated experimentally by our group [1]. In these regime, the light-matter coupling strength, the Rabi splitting $2\Omega_R$ becomes a sizeable fraction of the intersubband transition frequency ω_{12} [2], and fractions as large as $2\Omega_R/\omega_{12} = 73\%$ have been recently achieved at room temperature [3]. Beyond the fundamental physical concepts, we are now exploring the large oscillator strength of the quantum plasmons for building novel devices operating in the infrared spectral range. In particular, I will present our recent investigations on electrically driven supper-radiant emitters [4] and low-dark current microcavity-coupled quantum detectors [5].

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*ERC grand "Adequate"

Multiple Quantum Phase Transitions in a two-dimensional superconductor

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Transition metal oxides display a great variety of quantum electronic behaviors where correlations often play an important role. The achievement of high quality epitaxial interfaces involving such materials gives a unique opportunity to engineer artificial materials where new electronic orders take place. It has been shown recently that a two-dimensional electron gas 2DEG could form at the interface of two insulators such as $LaAlO_3$ and $SrTiO_3$ [1], or $LaTiO_3$ (a Mott insulator) and $SrTiO_3$ [2]. We study the magnetic field driven Quantum Phase Transition (QPT) in electrostatically gated superconducting in $LaTiO_3/SrTiO_3$ and $LaAlO_3/SrTiO_3$ interfaces [3]. Through finite size scaling analysis, we show that it belongs to the (2+1)D XY model universality class. The system can be described as a disordered array of superconducting islands coupled by a 2DEG. Depending on the 2DEG conductance tuned by the gate voltage, the QPT is single (corresponding to the long range phase coherence in the whole array) or double (one related to local phase coherence, the other one to the array). By retrieving the coherence length critical exponent, we show that the QPT can be "clean" or "dirty" according to the Harris criteria, depending on whether the phase coherence length is smaller or larger than the island size [4]. The overall behaviour is well described by a model of coupled superconducting puddles in the framework of the fermionic scenario of 2D superconducting QPT [5].

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Electrodynamics of hetero-structured high temperature superconductors

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Both the iron-based and the cuprate high temperature superconductors, are intrinsically multi-layered materials. Particular efforts have thus been devoted to the deposition of thin superconducting films and to artificially synthesize heterostructures based onto different superconducting materials. The study of these systems can provide new clues to the understanding of the general mechanism of high temperature superconductivity while offering the possibility to tailor important superconducting properties. An important example is provided by Co-doped Ba122 superlattices, where it was shown that heterostructuring the pristine superconducting compound can result in a substantial enhancement of the upper critical field, due to controlled flux pinning. On the other hand, in cuprates, the fabrication of artificial interfaces between the insulating $CaCuO_3$ and $SrTiO_3$ compounds, results in superconducting interfaces, analogous to the Copper-Oxide planes of the cuprates. We address here the electrodynamics of both these classes of heterostructured superconductors. Optics allows to probe the electronic structure of these new superconducting states, thereby addressing important issues as the number and symmetry of the gaps, the density of the charge carriers and their effective masses.

Posters

Monday – 19:00

Wednesday – 19:00

#	Presenter	Title
1	Autore	Dirac plasmonics of Topological Insulators
2	Badoux	Evidence of an Additional Frequency in the Shubnikov-deHaas Measurements of Underdoped YBa2Cu3Oy
3	Benhabib	Collapse of the Pseudogap in Cuprate superconductors at a Lifshitz Transition
4	Boehm	Subdominant d-wave coupling in $Ba_{0.6}K_{0.4}Fe_2As_2$
5	Buhot	Electronic gaps and signature of the hidden order of URu2Si2 revealed by Raman scattering spectroscopy
6	Chaix	Bunched modulation of the magnetic structures in chiral compounds: towards new magnetoelectric excitations
7	Chauviere	Probing the electron-boson coupling in the overdoped regime of cuprates
8	E. Chia	Interface-Induced Magnetic Coupling in Multiferroic/Ferromagnetic Bilayer: An Ultrafast Pump-Probe Study
9	Cilento	Photoinduced antinodal metallicity in the pseudogap state of high-Tc cuprates
10	Colson	Crystal Growth of High-Tc Superconductors and Multiferroics
11	Cyr-Choiniere	Anisotropy of the thermoelectric response in the pseudogap phase of the cuprate superconductor $YBa_2Cu_3O_y$
12	Forcella	Optical properties of viscous electron fluids
13	Frenzel	Semiconducting-to-metallic photoconductivity crossover and temperature-dependent Drude weight in graphene
14	Gagel	Universal post-quench dynamics at quantum critical points
15	Geffroy	High-energy branch of the spin-excitation spectrum of cuprates: impact on quasiparticle and optical properties in the context of the spin-fermion model
16	Goian	Strain engineering of EuO thin films
17	Grissonnanche	The upper critical magnetic field of cuprate superconductors
18	Gu	Crystal growth and physical property of Bi-Sb-Te-Se topological insulator materials, and Cu-Bi-Se and Sn-In-Te topological superconductors
19	Han	Extraction of Optical Constants Using Multiple Reflections in the THz Emitter-sample Hybrid Structure
20	Kalinko	Low temperature and high pressure lattice dynamics study of alpha - and beta-$SnWO_4$

#	Presenter	Title
21	Levallois	Broad-band helicity-resolved infrared spectroscopy of bismuth
22	Mangin-Thro	Search for Intra-Unit-Cell magnetic order close to optimal doping in superconducting cuprates
23	Mansart	Real-time observation of structural and electronic degrees of freedom in high T_c superconductors
24	Massat	Charge nematic fluctuations and superconducting gap in $Ba_{1-x}K_xFe_2As_2$ probed by Raman scattering
25	Matsunaga	Collective pseudospin precession in a superconductor NbN driven by sub-gap THz electric fields
26	Mravlje	Waterfalls and resillient quasiparticles in ruthenates
27	McLeod	Cryogenic Infrared Nano-Imaging of the Metal-Insulator Transition in the Canonical Mott Insulator V2O3
28	Mitrano	Pressure-Dependent Relaxation in the Photoexcited Mott Insulator ET–F_2TCNQ: Influence of Hopping and Correlations on Quasiparticle Recombination Rates
29	Morris	A hierarchy of bound states in the 1D ferromagnetic Ising chain $CoNb_2O_6$ investigated by high resolution time-domain terahertz spectroscopy
30	Moskvin	Pseudospin $S = 1$ description of the cuprate complexity: ground state, phase diagrams, and excitations
31	Najera	Study of spin-orbit effects in the Mott-Hubbard metal-insulator transition
32	Pan	Low energy electrodynamics of novel spin excitations in the quantum spin ice $Yb_2Ti_2O_7$
33	A. Perucchi	TeraFERMI - The THz beamline of the FERMI Free-Electron-Laser
34	Riccardi	Combined Raman scattering and TEM study of suspended graphene
35	Rõõm	Directional Dichroism of THz Radiation at Elevated Temperatures in the Paraelectric and Paramagnetic State of Multiferroic $Sr_2CoSi_2O_7$
36	Roskos	Time-Resolved THz Spectroscopy of Charge-Density Waves in Blue Bronze ($K_{0.3}MoO_3$
37	Rovillain	Iron borate multiferroics, a new way to observe the electromagnon?
38	Sandilands	Spin-orbit coupling in RuCl3: Evidence for a relativistic Mott insulator on the honeycomb lattice
39	Sakai	Evidences of an s-wave structure of the pseudogap in high-Tc cuprate superconductors
40	Shuvaev	Room temperature electrically tunable terahertz Faraday effect in a topological insulator
41	Skiadopoulou	Spin and lattice excitations in BiFeO3 ceramics compared with epitaxial thin film of $BiFeO_3/TbScO_3$

#	Presenter	Title
42	Sopracase	Thz excitations of several magnetoelectric (multiferroic) compounds under strong magnetic field
43	Subedi	Theory of nonlinear phononics for coherent light-control of solids
44	Thiemann	Microwave measurements on superconductors at mK temperatures: heavy-fermion $CeCu_2S_2$ versus conventional superconductors
45	de la Torre	ARPES study of the doping evolution of the strong spin-orbit insulator $Sr_3Ir_2O_7$
46	Toulouse	Driving the spins in BiFeO3 single crystals with hydrostatic pressure
47	Tran	Infrared- and Raman-Spectroscopy Measurements of a Transition in the Crystal Structure and a Closing of the Energy Gap of BiTeI under Pressure
48	Z. Wang	Orbital-selective metal–insulator transition and gap formation above T_c in superconducting $Rb_{1-x}Fe_{2-y}Se_2$
49	Liang Wu	A sudden collapse in the transport lifetime across the topological phase transition in $(Bi_{1-x}In_x)_2Se_3$
50	Bing Xu	Charge dynamics in $BaFe_2(As_{0.7}P_{0.3})_2$ superconductor as revealed by optical spectroscopy
51	Yang	Weak coupling between orbitals and E_g phonon mode in $Ba(Fe_{1-x}Co_x)_2As_2$
52	Zhu	Polarity-driven surface metallicity in the Kondo insulator SmB_6

Evidence of an Additional Frequency in the Shubnikov-deHaas Measurements of Underdoped YBa2Cu3Oy

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In 2007, the discovery of quantum oscillations in underdoped YBa2Cu3O6.51 [1] show the presence of a closed and coherent Fermi surface at low temperature in contradiction with Fermi arcs seen by ARPES. Combined with the observation of the negative Hall and Seebeck coefficients at low temperature in underdoped YBa2Cu3Oy [2-3], those results strongly suggest that a Fermi surface reconstruction from the large hole pocket into small electron pocket(s) occurs within the underdoped side of the phase diagram. Charge order, as evidenced by NMR measurements [4] is believe to be responsible for this reconstruction.

In order to get more insight on the Fermi surface reconstruction, it is important to well characterize the Fermi surface. We have recently carried out quantum oscillations measurements in underdoped YBCO showing the presence of a new frequency in the oscillation spectra for two different dopings. The presence of this new frequency reconciles a number of experimental facts. We will also discuss Fermi surface reconstruction based on a bi-axial charge order as seen by X-ray measurements and compared it to our experimental results.

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Collapse of the Pseudogap in Cuprate superconductors at a Lifshitz Transition

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In the under-doped side of the hole doped cuprate phase diagram, the loss of well defined low energy excitations described as the pseudogap develops above the critical temperature T_c [1]. The relation between pseudo- and superconducting gaps has been a controversial issue whose understanding may provide long-sought insights into the mechanism of high temperature superconductivity [2]. Although intensely studied in the underdoped regime, relatively less is known about the pseudogap on the over-doped side, where it weakens and eventually disappears at a critical doping p_c [3]. Here, we handle a carful finely tuned Electronic Raman study of $Bi_2Sr_2CaCu_2O_{8+\delta}$ in a large range of doping from under doped to heavy over doped, (the doping was controlled by oxygen insertion). We succeed by combining experiment and theoretical calculations to determine the critical doping p_c , which correspond to the pseudogap closing at $p_c = 0.22$ and we reveal that it coincides with a Lifshitz transition where the underlying hole-like active Fermi surface becomes electron-like at a van Hove singularity [4]. Interestingly, the superconducting critical temperature T_c is unaffected by this transition. Comparing our results with existing photoemission and tunnelling data, we demonstrate that the microscopic origins of the pseudogap and the superconductivity are different on the over-doped side. Only the former is tied to the change in the Fermi surface topology, a feature universal across several hole doped cuprates [4].

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Subdominant d-wave coupling in $Ba_{0.6}K_{0.4}Fe_2As_2$

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An analysis of the light scattering spectra of optimally doped $Ba_{0.6}K_{0.4}Fe_2As_2$ is presented. On the basis of LDA band structure calculations it is shown that the narrow feature found experimentally in the B_{1g} ($d_{x^2-y^2}$) Raman spectra in the superconducting state can be reproduced quantitatively and be identified as a Bardasis-Schrieffer exciton. The binding energy of the exciton relative to the gap edge shows that the coupling strength in the subdominant $d_{x^2-y^2}$ channel is as strong as 60% of that of the dominant s_{+-} channel.

Electronic gaps and signature of the hidden order of URu_2Si_2 revealed by Raman scattering spectroscopy

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The heavy fermion compound URu2Si2 exhibits a so-called Hidden Order (HO) phase (T0=17.5K) coexisting with superconductivity. Despite almost 30 years of research, the microscopic origin of the Hidden Order is still the subject of intense debate [1]. Thanks to its ability to unveil the symmetry of the electronic excitations, Raman spectroscopy is making an important contribution to this longstanding question. We have performed polarized electronic Raman scattering on single crystals of URu2Si2 in all the allowed Raman symmetries. In addition to a peculiar temperature dependence of the B1g phonon mode, we report the opening of two electronic gaps consistently with the optical conductivity measurements [2]. One gap appears below TK and below 85meV, most probably related to the formation of the hybridization gap. Using the calculated Raman vertices, its specific symmetry will allow us to discuss the k-dependence of the Kondo physics. In addition, in the HO

state, an electronic gap opens below 6.8meV, on top of which a sharp excitation emerges at 1.75meV. Both of them have the specific A2g symmetry with chiral character. This chiral character of the gapped electronic excitations in URu2Si2 gives new strong constrain for theoretical survey. Comparison between the sharp excitation and the resonance at E0 observed by neutron scattering at Q0=(0,0,1) [3], the up-to-now major signature of the HO phase, will be done. Consequences of the close relation between these two HO signatures observed at different Q vector on the Hidden Order parameter will be discussed.

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Probing the electron-boson coupling in the overdoped regime of cuprates

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In cuprate high-T_c superconductors, it is still unclear why T_c decreases upon doping on the overdoped side of the superconducting dome, where the superconducting state emerges from a Fermi liquid normal state. In the picture of a boson-mediated interaction leading to electron Cooper pairing, the value of T_c could depend on the disappearance of the bosonic excitations themselves and/or the weakening of the electron-boson coupling. To unveil the evolution of the electron-boson interaction in the overdoped regime of cuprates, we have recently grown high-quality single crystals of $Tl_2Ba_2CuO_{6+x}$ to cover a wide range of hole doping, from close-to-optimally doped (T_c=85K) to strongly overdoped (T_c=15K), with the cleanest cuprate material available. We have performed ultrafast pump-probe reflectivity measurements in the energy window 0.75 – 2.4eV with an unprecedented experimental time resolution of 15fs, to gain direct insights into the coupling strength and excitation dynamics of both phononic and magnetic excitations. These results indicate an extremely rapid dynamic, which saturates upon heavy overdoping and which will be discussed in the context of short-range spin-fluctuations.

Interface-Induced Magnetic Coupling in Multiferroic/Ferromagnetic Bilayer: An Ultrafast Pump-Probe Study

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By use of optical pump-probe measurement, we study the relaxation dynamics of a muliferroic-ferromagnetic $TbMnO_3/La_{0.7}Sr_{0.3}MnO_3$ bilayer. The relaxation dynamics of both layers are well separated in time allowing us to investigate the magnetic coupling across the bilayer. We observe that the relaxation dynamics of the individual layers in the bilayer sample are the result of the interplay between the intrinsic magnetic order and the induced interfacial effect. Our data suggest the existence of induced ferromagnetic order in the $TbMnO_3$ layer, and antiferromagnetic order in the $La_{0.7}Sr_{0.3}MnO_3$ layer.

Crystal Growth of High-Tc Superconductors and Multiferroics

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We will detail the procedures used to grow good single crystals which allowed us to undertake very thorough studies of their physical properties in collaboration with different labs.

Concerning cuprates, our activity has been mainly focused on the synthesis of single crystals of mercury compounds with different hole dopings. Using Raman spectroscopy, A. Sacuto et al. (MPQ-Paris7) observed two distinct energy scales for the superconducting gap induced by the pseudogap in the underdoped regime. After the discovery of superconductivity in iron-pnictides in 2008, an intense activity has been devoted to the study of different compounds on the 122 family (as BaFe2As2) with different types of substitution. We developed an active synergy between material synthesis and various advanced experimental techniques on the same samples (Transport, Mössbauer spectroscopy at CEA-SPEC; NMR, ARPES in collaboration with LPS-Orsay, Raman spectroscopy in collaboration with LMPQ-Paris 7, optical measurements with ESPCI-Paris).

Concerning the multiferroics, we achieved to synthesize high quality single crystals of BiFeO3 and measured its intrinsic polarization at room temperature in excess of 100 μC/cm2. This record polarization among all ferroelectrics had been eluding researchers for about 40 years. Using neutron scattering in the LLB on similar crystals, we evidenced for the first time a strong coupling between magnetic and ferroelectric orders in bulk BiFeO3. We then demonstrated the significant magnetic exchange between the antiferromagnetic lattice of BiFeO3 crystals and a soft ferromagnetic layer deposited on top, which could also be manipulated with the polarization state of the multiferroic, hence allowing an electric control of the magnetic anisotropy. More recently we have discovered that BiFeO3 is photostrictive, i.e., it changes size when illuminated by visible light.

Optical properties of viscous electron fluids

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Interactions or long-range correlations among the constituents of a system could appear as collective behaviors of the system itself. An example of this is the finite viscosity of a fermionic liquid that have been indeed predicted and measured, for example in the normal state of 3He. Viscosity has also recently played a major role in the study of charged fluids in high energy physics. The existence of a small but finite value of the viscosity was fundamental to understand the strong coupling phase of certain plasmas formed in high energy colliders: the quark-gluon plasma. One of us (DF) has shown in this context [1, 2] that finite viscosity leads to multiple modes of evanescent electromagnetic waves at a given frequency. For a certain range of frequencies one of these modes is characterized by a negative index of refraction: its energy flux and phase velocities are in opposite directions. The role of the viscosity for charged fluids in condensed matter system, and in particular its effects on the electromagnetic properties of the media, is a quite unexplored topic. Here we provide the first results on this subject [3], and we concentrate on the way in which viscosity is manifested in the optical properties of a charged fluid. We confirm the possible presence of multiple evanescent waves and of negative refraction in condensed matter systems. We obtain analytical expressions for the reflection coefficient of electromagnetic waves at the vacuum/fluid interface, and show that the viscosity is manifested by a decrease of the reflection coefficient. The model requires no particular assumptions regarding the corpuscular nature of the charge liquid, neither a particular dependency of viscosity on wave frequency or sample temperature.

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Semiconducting-to-metallic photoconductivity crossover and temperature-dependent Drude weight in graphene

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We investigated the transient photoconductivity of graphene at various gate-tuned carrier densities by optical-pump terahertz-probe spectroscopy. We demonstrated that graphene exhibits semiconducting positive photoconductivity near zero carrier density, which crosses over to metallic negative photoconductivity at high carrier density. Our observations are accounted for by considering the interplay between photo-induced changes of both the Drude weight and the carrier scattering rate. Notably, we observed multiple sign changes in the temporal photoconductivity dynamics at low carrier density. This behavior reflects the non-monotonic temperature dependence of the Drude weight, a unique property of massless Dirac fermions.

Universal post-quench dynamics at quantum critical points

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We consider a quench in a system initially located in the vicinity of a quantum critical point and that is suddenly moved to the critical point. In this regime one finds a universal exponent that is not related to the equilibrium exponents and that governs the post-quench short time dynamics. We calculate this exponent for an open quantum system and discuss the implications for the dynamics of the order parameter and response functions. The approach demonstrates that quantum-quenches can be efficient tools to manipulate and study quantum many body systems.

High-energy branch of the spin-excitation spectrum of cuprates: impact on quasiparticle and optical properties in the context of the spin-fermion model

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Thomas Dahm and coworkers have shown that the strength of the coupling of charged quasiparticles of the copper-oxygen planes to spin excitations, inferred from the photoemission (nodal cut) and neutron scattering data of the high-temperature superconductor YBa2Cu3O(6.6) by using the Eliashberg theory, is large enough for the coupling to cause high-Tc superconductivity [1]. The high-energy branch of the spin-excitation spectrum has been found to play a crucial role in determining the position of the kink in the nodal dispersion.

We report on results of our study based on an extension of the approach of [1]. The same treatment of the underlying bare dispersion and the same experimental spectrum of the spin susceptibility involving the high-energy branch from [1] have been employed, but in contrast to [1], the fully selfconsistent solution of the generalized Eliashberg equations [2] has been used to describe the superconducting state. In addition to the quasiparticle properties, the spectra of the in-plane infrared conductivity have also been calculated and analyzed.

The profile and magnitude of the calculated conductivity are consistent with experimental data [3, 4], provided a value of the coupling constant considerably lower than that needed to reproduce the nodal kink and reported in [1] is used. Possible reasons for this discrepancy will be discussed. Important features of the calculated quasiparticle spectra (in particular the kink, including its angular dependence [5, 6]) and of the calculated optical spectra (in particular the gap feature) will be presented, and their relation to the high-energy branch of the spin-excitation spectrum will be discussed.

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Strain engineering of EuO thin films *

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Several years ago, it was demonstrated that biaxial strain can induce the ferroelectric and ferromagnetic state in epitaxial thin films of $EuTiO_3$, a material that is paraelectric and antiferromagnetic in the bulk [1]. We found that 1% tensile strain in $EuTiO_3/DyScO_3$ induces ferroelectricity at 250 K and ferromagnetism at 4.2 K [1]. Here, we will focus on the study of EuO thin films, in which first principles calculations [2] predicted the emergence of a multiferroic state under expitaxial strains larger than +4%. Note that bulk EuO is paraelectric at all temperatures and becomes ferromagnetic below 69 K. Strained EuO films with ferroelectric and ferromagnetic orders should exhibit a strong magnetoelectric coupling, much stronger than in most multiferroics with antiferromagnetic and ferroelectric orders [3].

Direct low-frequency dielectric measurements are impossible due to a leakage current present in the strained thin films. Therefore we have used IR spectroscopy, which is not influenced by electrical leakage. The predicted ferroelectric phase transition should be proper and displacive, therefore a strong soft mode anomaly should be observed at T_C.

We have investigated using IR spectroscopy EuO thin films grown by molecular beam epitaxy on three different substrates leading to three different strain states. We also measured several $(EuO)_n(BaO)_m$ superlattices deposited on $YAlO_3$ and Si substrates. The films deposited on yttrium-stabilized ZrO_2 (YSZ) are virtually lattice-matched whereas the films deposited on $LuAlO_3$ and $YAlO_3$ are biaxially strained in an anisotropic way with in-plane tensile strains up to +1.5% and +2.2%, respectively. The EuO cubic crystal has only one IR active phonon with frequency lying as function of the sample quality between 180 and 200 cm^{-1} [4,5]. Stronger phonon shifts were observed in the $EuO/YAlO_3$. In this case, phonon frequency shifts down to 149 cm^{-1} (300 K), with a further softening to 144 cm^{-1} on cooling to 10 K while in EuO/YSZ and $EuO/LuAlO_3$ a small influence of the strain on the optical phonon was observed. The strain influence on the soft mode is

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smaller than predicted in Ref. [2] which leads to the conclusion that the strain required to induce the ferroelectric phase induction may also be higher than the previously predicted 4%.

With increasing strain and film thickness, relaxation of the strain in the films, e.g. by formation of edge dislocations, becomes more pronounced. In case of EuO, ultrathin ($\ll$ 5 nm) films are required to achieve homogeneous strains higher than 4%. Phonons from such thin films give a very weak signal in IR spectra. For this reason we have decided to study EuO/BaO superlattices, where the BaO interlayers help to keep the strain. Higher tensile strain values of almost +5.6% for the EuO layers were obtained in a $(EuO)_2(BaO)_6$ superlattice (28 stacks) deposited on silicon. In this case, the EuO layers had total thickness of 15 nm, and the BaO layers had total thickness of 46 nm and were compressively strained by -1.6% In case of this sample, we were able to see two stiffened BaO phonons near 177 (300 K) and 164 cm^{-1} (10 K) while the EuO phonon softened from 97 cm^{-1} (300 K) down to 89 cm^{-1} (10 K).

We observed a strong influence of strain on the phonon modes in EuO and $(EuO)_n(BaO)_m$ superlattices. However, higher strains than 5.6% seem to be necessary for the induction of ferroelectricity in EuO thin films and superlattices. New first-principles calculations that are able to better describe the experimental situation suggest that strain values above 6% may indeed be sufficient to induce ferroelectricity in $(EuO)_n(BaO)_m$ superlattices. Deposition of new EuO/BaO superlattices with higher strain values is in progress.

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The upper critical magnetic field of cuprate superconductors

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In the quest to increase the critical temperature Tc of cuprate superconductors, it is essential to identify the factors that limit the strength of superconductivity. The upper critical field H_{c2} is a fundamental measure of that strength, yet there is no agreement on its magnitude and doping dependence in cuprate superconductors. Owing to its high sensitivity to vortex scattering, we show that the thermal conductivity κ_{xx} can be used to directly detect H_{c2} in the cuprates $YBa_2Cu_3O_y$, $YBa_2Cu_4O_8$ and $Tl_2Ba_2CuO_{6+?}$. Using resistivity measurements in high magnetic fields, we demonstrate that there is no vortex liquid phase at T = 0, allowing us to map out H_{c2} across the doping phase diagram [1]. It exhibits two peaks, located at dopings $p_1 = 0.08$ and $p_2 = 0.18$, where the Fermi surface of $YBa_2Cu_3O_y$ is known to undergo a transformation. Below p_2, the condensation energy, obtained directly from H_c2, suffers a sudden 20-fold collapse. This reveals that phase competition – associated with Fermi-surface reconstruction and charge-density-wave order - is a key limiting factor in the superconductivity of cuprates. In addition, we investigate the thermal Hall conductivity κ_{xy} in magnetic fields up to 35 T and show that the Wiedemann-Franz law is satisfied above H_{c2} in

underdoped $YBa_2Cu_3O_y$. Thereby demonstrating the Fermi-Liquid normal state of underdoped cuprates, and moreover confirming no trace of long range superconductivity above H_{c2}. This also confirms that the Fermi surface is dominated by an electron pocket, as inferred from prior Hall [2] and Seebeck [3] data.

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Crystal growth and physical property of Bi-Sb-Te-Se topological insulator materials, and Cu-Bi-Se and Sn-In-Te topological superconductors *

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AbstractText The discovery of 3D topological insulator materials and topological superconductor opens up a new research field in the condensed matter physics. We have grown a number of Bi-Sb-Te-Se topological insulator, and Cu-Bi-Se and Sn-In-Te topological superconductor single crystals. We have measured the physical properties on these single crystals. We have studied the effect of growth condition and impurity on the bulk electrical conductivity of these single crystals. We try to answer two questions for the topological insulator materials if it is possible to grow the bulk-insulating topological insulator single crystals and Which maximum resistivity of these topological insulator single crystals we can grow. For the topological superconductor, we have got the bulk superconducting single crystals with a maximum $T_c = 4.5$ K.

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Extraction of Optical Constants Using Multiple Reflections in the THz Emitter-sample Hybrid Structure

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To extract optical constants of non-transmitted samples in the terahertz (THz) spectral region, we employ a THz emitter-sample hybrid structure where THz pulses are generated from the emitter and reflected at the emitter-sample interface. We applied this technique for extracting optical constants of doped semiconductors and noble metals, and found that obtained results are in good agreement with literature values or the results obtained by using other THz techniques. We will introduce details of the experimental set-up implemented in conventional THz time-domain spectroscopy and the data extracting algorithm from temporally resolved electric field.

Broad-band helicity-resolved infrared spectroscopy of bismuth

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Bismuth is a canonical and widely studied semimetal, and yet its electronic and optical properties keep surprising the research community. Due to 3D Dirac-like electron dispersion, strong spin-orbit interaction, a possibility of doping induced topological phase transitions and long mean-free path, this 'old' material is an interesting playground for modern solid-state studies. We present infrared spectra of reflectivity and magneto-optical Kerr angle of a high-quality bismuth crystal. We generalize the conventional (zero-field) Kramers-Kronig analysis to this case and extract the diagonal and the Hall optical conductivity spectra, as well as the optical conductivity for left- and right-handed circular polarizations in a broad range of frequencies. This allows us to distinguish the intraband and interband cyclotron resonances in the electron and hole pockets. With the Kerr angle measurements, we can directly distinguish between helical (magneto-active) and non-helical transitions. We present a calculation based on the extended Dirac model for electrons and parabolic-band model for holes, and critically compare it with the experimental spectra.

Charge nematic fluctuations and superconducting gap in $Ba_{1-x}K_xFe_2As_2$ probed by Raman scattering

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We report an electronic Raman scattering study of hole doped $Ba_{1-x}K_xFe_2As_2$ over a wide doping range. In the tetragonal phase we study the development of charge nematic fluctuations as a function of doping and temperature in the B_{1g} symmetry channel. At optimal doping (T_c = 38 K), the enhancement of nematic fluctuations upon lowering temperature is significantly weaker than in the case of electron optimally doped $Ba(Fe_{1-x}Co_x)_2As_2$ (T_c = 24 K). The asymmetry in the behavior of nematic fluctuations between electron and hole doped $BaFe_2As_2$ parallels the significantly reduced transport anisotropy found in the hole doped side [**?**]. It is also consistent with recent shear modulus measurements suggesting a reduced impact of nematic fluctuations in the phase diagram of $Ba_{1-x}K_xFe_2As_2$. We also report a doping dependence study of the superconducting gap structure and compare it with the case of $Ba(Fe_{1-x}Co_x)_2As_2$. The behaviour of the gap across the coexistence region between magnetism and superconductivity sheds light on the interplay between both orders.

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Collective pseudospin precession in a superconductor NbN driven by sub-gap THz electric fields

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Spontaneous gauge-symmetry breaking is hallmarked by an emergence of collective excitation modes associated with phase and/or amplitude fluctuations of the order parameter ?. The amplitude mode in a superconducting state, analogous to the Higgs boson, does not directly couple with electromagnetic fields in the linear response regime because of the absence of charge fluctuations. Therefore the collective amplitude mode has evaded detection in pure s-wave superconductors. With recent advances of ultrafast pump-probe spectroscopy with intense terahertz (THz) pulse generation techniques, temporal oscillations of the order parameter amplitude with frequency of 2 have been clearly observed after a nonadiabatic perturbation by a monocycle THz pulse. However, dynamical behavior of the superconducting state during a strong THz electric field irradiation remains to be elucidated. Specifically, the nonlinear interaction between a superconducting state and strong sub-gap ac electric fields is a highly intriguing subject. Here we study ultrafast dynamics of the order parameter in a superconductor NbN under multi-cycle sub-gap THz electric fields by using THz pump-THz probe spectroscopy. In the nonlinear response regime we reveal that the sub-gap electric field induces the order parameter oscillation with twice the frequency of the THz field. The result is well described microscopically by collective precession of the Anderson's pseudospins driven by the squared vector potential.

Cryogenic Infrared Nano-Imaging of the Metal-Insulator Transition in the Canonical Mott Insulator V2O3

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We report on temperature-dependent (20K-300K) near-field infrared imaging of the canonical Mott insulator V2O3 across its temperature-driven metal-insulator transition. This was accomplished using a home-built s-SNOM (scattering-type scanning near-field optical microscope) affording unprecedented spatial sensitivity (10 nm resolution) to surface optical properties with simultaneously acquired AFM topography at cryogenic temperatures. Our V2O3 thin film is found to exhibit extreme nano-scale electronic heterogeneity near the Mott transition (170K) from paramagnetic metal to antiferromagnetic insulator. Through a sequence of near-field infrared images acquired across the transition, we resolve dynamic spatial correlations and competition between electronic phases, offering a direct probe of the metal/insulator fill fraction in strong agreement with macroscopic transport and magnetic susceptibility. A statistical analysis of our near-field images in comparis on with X-ray diffraction imply decoupled electronic and structural transitions, enabling a nano-scale assessment of bandwidth and many-body effects within our film, while also resolving long-standing controversies surrounding the Mott physics of V2O3.

Pressure-Dependent Relaxation in the Photoexcited Mott Insulator ET–F_2TCNQ: Influence of Hopping and Correlations on Quasiparticle Recombination Rates *

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We use ultrafast reflectivity measurements under pressure to investigate the quasiparticle recombination in a photoexcited Mott insulator as function of bandwidth (t) and electronic on- and inter-site interaction energies (U, and V) [1]. Our measurements are performed on bis-(ethylendithyo)-tetrathiafulvalene-difluorotetracyano-quinodimethane (ET-F_2TCNQ), a room-temperature quasi-1D half filled Mott insulator (U/t 20) with weak electron

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phonon coupling [2,3]. It has been previously shown that photoexcitation induces a metallic state due to spin-charge separation [3]. Probing the coherent evolution of the photoinduced double occupancies (doublons) and empty sites (holons) reveals the importance of nearest neighbour interactions. Quantum interference along different excitation path between bound and free holon-doublon pair states takes place during the melting of the Mott insulating state [4]. Here we investigate the influence of the relative electronic interactions on the relaxation of the photo-induced metal back into the Mott insulator. We apply external pressure in order to tune the electronic bandwidth t and nearest neighbour interaction V. Broadband reflectivity measurements under pressure of the Mott gap and charge transfer band reveal the full equilibrium optical response. From that we were able to extract effective U, V, and t parameters by fitting the optical spectra with an extended Hubbard Model. The photo-doping dynamics is measured in a pump probe experiment. We excite quasiparticles with a short laser pulse tuned resonant to the charge transfer band and measure the lifetime of the photo-excited state of holons and doublons with a subsequent time-delayed laser pulse [1,3,4]. We find that their recombination takes place via local interactions with a dissipative bath, likely intramolecular vibrations. As we increase the pressure, the recombination accelerates and for each pressure value we can connect the rates to the previously extracted interaction parameters U, V, t. Simulating this recombination dynamics using a time dependent effective multiple site Hubbard model suggests a competition between the local recombination of bound holon-doublon pairs and the delocalization of holons and doublons right after photoexcitation. Both these processes are found to be highly dependent on the relative ratios among the U, V, and t electronic parameters. Through this connection between electronic interactions and non-equilibrium response, our experiments provide a deeper insight into the non-equilibrium dynamics of Mott insulators and constitute a valuable test-bed for new theoretical work in this growing and interesting field.

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A hierarchy of bound states in the 1D ferromagnetic Ising chain $CoNb_2O_6$ investigated by high resolution time-domain terahertz spectroscopy *

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Kink bound states in the one dimensional ferromagnetic Ising chain compound $CoNb_2O_6$ have been studied using high resolution time-domain terahertz spectroscopy in zero applied magnetic field. When magnetic order develops at low temperature, nine bound states of kinks become visible. Their energies can be modeled exceedingly well by the Airy function solutions to a 1D Schrödinger equation with a linear confining potential. This sequence of bound states terminates at a threshold energy near two times the energy of the lowest bound state. Above this energy scale we observe a broad feature consistent with the onset of the two particle continuum. At energies just below this threshold we observe a prominent excitation that we interpret as a novel bound state of bound states – two pairs of kinks on neighboring chains.

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Pseudospin $S = 1$ description of the cuprate complexity: ground state, phase diagrams, and excitations *

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A large body of experimental data points towards a charge transfer instability ofparent insulating cuprates to be their unique property [1]. We introduce a minimal model for 2D cuprates with the on-site Hilbert space reduced to only three effective valence centers $[CuO4]^{7-,6-,5-}$ (nominally $Cu^{1+,2+,3+}$) and make use of the $S = 1$ pseudospin formalism and familiar spin algebra. Effective spin-pseudospin Hamiltonian does incorporate all the on-site and inter-site meaningful couplings. All the charged and neutral excitations in the pseudospin systems are related with $S_z = +1$ (hole creation) and $S_z = -1$ (electron creation) (pseudo)magnons or (pseudo)bimagnons with $S_z = 0$, $S_z = +2$, and $S_z = -2$. The 2D pseudospin system is prone to a topological phase separation, in particular, to creation of the Mott skyrmion-like excitations which form a topologically protected inhomogeneous distribution both the of conventional spin density and eight local pseudospin order parameters including charge density and superfluid order parameters. We suppose that both thermally activated skyrmions and skyrmions pinned on the impurity centers associated with a nonisovalent substitution are present in doped cuprates such as La2-xSrxCuO4. The conventional spin degree of freedom seems to play merely negative effect in high-T_c superconductivity due to anticorrelation or intertwinning effects of spin and charge/superconducting degrees of freedom. Despite its seeming simplicity the model is believed to capture the salient features both of the hole- and electron-doped cuprates. The pseudospin formalism elucidates an unique fermion-boson duality of the doped cuprates, does provide an unified standpoint for classification of the "myriad" of electronic phases in cuprates and the evolution of the CuO2 planes under a nonisovalent doping, introduces the on-site mixed valence quantum superpositions and order parameters to be novel features of the cuprate physics, does provide a comprehensive description of the correlated one- and two-particle transport, coexistence of p- and n-type carriers, electron-hole asymmetry, anticorrelation of conventional spin, charge, and superconducting order parameters. Concept of the electron and hole centers, differing by a composite local

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boson, and electron-hole pairing are shown to explain central points of the cuprate puzzles, in particular, the HTSC itself, pseudogap, and Fermi surface reconstruction. Model of the charge triplets is believed to provide a self-consistent description both for the normal and superconducting states of the cuprates based on physically clear, fundamental assumptions.

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Waterfalls and resillient quasiparticles in ruthenates

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Few years ago there was a burst of theoretical activity spurred-on by ARPES experiments on cuprates that revealed occurence of high-energy anomalies (near vertical, waterfall-like dispersions). Very recently, similar behavior was found experimentally in Sr2RuO4, too. We considered Sr2RuO4 within the dynamical mean-field theory. The calculated ARPES spectra are in excellent agreement with the observed ones. As other experimental quantities that we calculated are also in excellent quantitative agreement with experiment, the origin of the waterfall is to be attributed to the local correlations. The calculated self-energies have pronounced particle-hole asymmetry. On the unoccupied side, the relatively long-lived strongly dispersing states are found at 0.2eV above the Fermi energy. The consequences of these "resillient quasiparticle" excitations for the recently observed optical spectra are discussed.

Study of spin-orbit effects in the Mott-Hubbard metal-insulator transition

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The spin–orbit interaction, although usually considered as a small relativistic correction, has indeed shown to be able to drive systems into new states of matter, like the topological insulators, whose nature has remained unnoticed up to now. An interesting question, recently arising in the context of 5d-electron system (like Sr2 IrO4), is whether the spin-orbit interaction may also act in conjunction or competition with the Mott strong correlation and determine unusual ground-state properties.

In this work a three-orbital Hubbard model is taken as playground to study 5d-electron physics. We map the phase-diagram as a function of the spin-orbit and electronic correlation within the framework of the slave-spins mean-field approximation. The out coming behaviour is used to cast some light over the physical behaviour of Sr2IrO4

Low energy electrodynamics of novel spin excitations in the quantum spin ice $Yb_2Ti_2O_7$ *

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In condensed matter systems, the establishment of long range order (LRO) with broken symmetry is often accompanied by new types of excitations. However, in many magnetic pyrochlore oxides, geometrical frustration suppresses the formation of conventional LRO while at the same time non-trivial spin correlations are observed. For such materials, a natural question to ask then is what is the nature of the excitations in this highly correlated state without broken symmetry? Frequently the application of a symmetry breaking field can stabilize excitations whose properties reflect certain aspects of the anomalous state without long-range order. Here we report evidence of novel magnetic excitations in the quantum spin ice material $Yb_2Ti_2O_7$, obtained from time-domain terahertz spectroscopy (TDTS). At large fields, both magnon and two-magnon-like excitations are observed in a <001> directed magnetic field. The unique ability of TDTS to measure complex response functions allows a *direct* study of magnetic responses in different polarization channels, revealing the existence of an unusual *left*-hand polarized magnon states. In the low-field limit, we observe a cross-over of these one and two-magnon states into features consistent with the quantum string-like excitations proposed to be present in the quantum spin ice in a <001> applied field.

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TeraFERMI - The THz beamline of the FERMI Free-Electron-Laser

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TeraFERMI is the THz beamline for pump-probe studies on the femtosecond time-scale, to be constructed at the FERMI Free Electron Laser (FEL) facility in Trieste (Italy). The beamline will make use of the coherent radiation emitted by the electrons already spent from the FEL undulators, before being damped. This will result in short, coherent, high power THz pulses to be used as a "pump" beam, in order to modulate structural properties of matter, thereby inducing phase transitions. The intense THz pulses are also associated with a remarkably large transient magnetic field, to be used for controlling and manipulating magnetic states of matter. The modifications produced to the ionic and magnetic structures and the corresponding changes induced in the electronic properties will be probed by means of infrared spectroscopy from THz to visible. The domains of application of TeraFERMI will cover very different fields from solid-state physics to biochemistry. We discuss here the choice of the source, the optical layout as well as the expected performances of the novel TeraFERMI beamline.

Combined Raman scattering and TEM study of suspended graphene

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The electronic, thermal and mechanical properties of graphene are exceptionally sensitive to lattice imperfections and doping. In our work we combine HRTEM and micro-Raman investigations on the same micron large area of CVD grown graphene sample suspended on TEM grid. Our work allows a deeper undertanding of the evolution of the Raman spectrum with disorder and dopants such as Nitrogen. We will also show complementary Raman spectroscopy results on electronic properties of suspended graphene transistor devices produced by transfer of exfoliated graphene flakes.

Directional Dichroism of THz Radiation at Elevated Temperatures in the Paraelectric and Paramagnetic State of Multiferroic $Sr_2CoSi_2O_7$

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Directional dichroism is the property of material to have different absorption coefficient for counterpropagating light beams. Recently strong directional dichroism has been found in the THz spectral range of light in multiferroic materials with magnetic and charge order [1–5]. In these materials the collective magnetic excitations, spin waves, are coupled to charge oscillations, similarly to dc magnetoelectric effect where the coupling is between static magnetization M and electric polarization P. Because of optical (ac) magnetoelectric coupling the spin wave acquires electric dipole activity and interacts not only with magnetic (B) component but as well with electric (E) component of THz radiation. In theory, one-way transparency is possible when there is no absorption of light travelling in one direction and light is absorbed strongly when travelling in the opposite direction. The condition of one-way transparency requires certain balance between electric and magnetic dipole activity of a given spin wave resonance and some of the multiferroics belonging to åkermanite family, $Ba_2CoGe_2O_7$, $Ca_2CoSi_2O_7$ and $Sr_2CoSi_2O_7$, are not far from the ideal case of one-way transparency [5]. Since the condition of one-way transparency is sensitive to the direction of applied magnetic field the directional light switch can be realized **1**. However, the simultaneous magnetic and charge order in materials with strong directional dichroism happens well below the room temperature rendering their use in device applications impractical.

The recent study of multiferroic $Sr_2CoSi_2O_7$ has demonstrated that the dc magnetoelectric effect re-appears in strong magnetic field above the magnetic ordering temperature [6, 7]. Electric polarization was induced by applied magnetic field even at room T although the magnetic ordering T of $Sr_2CoSi_2O_7$ is as low as $T_N = 7\,\mathrm{K}$. As was pointed out by Akaki et al. [6] the microscopic mechanism of magnetoelectric coupling in $Ba_2CoGe_2O_7$ and

$Sr_2CoSi_2O_7$ is different than other known mechanisms, spin-current [8,9] and exchange striction [10]. It does not depend on the relative angle of adjacent spins and therefore the electric polarization is induced at a single spin site because of hybridization of electron orbitals of magnetic ion and ligands [11,12].

Here in this paper we present the results of directional dichroism studies of $Sr_2CoSi_2O_7$ in the THz spectral range and in magnetic fields up to 17 T. We show that the directional dichroism, the hallmark of optical magnetoelectric effect, is present well above the magnetic ordering temperature when sufficiently strong magnetic field is applied and explain it with the theory of magnetoelectric effect in the paramagnetic phase.

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Time-Resolved THz Spectroscopy of Charge-Density Waves in Blue Bronze ($K_{0.3}MoO_3$)

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We present the first time-resolved optical-pump/THz-probe study of the one-dimensional conductor blue bronze in the insulating state below the Peierls transition at 180 K. We detect the transient changes of the reflectivity of THz pulses covering the spectral range 0.3 – 2.7 THz following strong excitation of the single-crystalline sample by 100-fs optical pulses at 775 nm (pump pulse fluences of one to several hundred μJ/cm2). The measurements allow us to derive pump-pulse-induced complex ac conductivity changes in the THz spectral range. Although the amplitude mode of the charge-density waves (CDWs) at 1.7 THz is expected to be only Raman-active, we can derive a pronounced ac conductivity change of this mode from the THz data together with similar signatures of neighboring zone-folding modes (at 2.25 and 2.7 THz). The infrared activity of the amplitude mode may be a result of interactions with impurities, for which evidence has also been found in Raman studies [1], and which may break the A_g symmetry. A weak increase of the spectrally broad background conductivity is likely to result from the pump-pulse-induced rise of the lattice temperature; the increase of the conductivity occurs within the first picosecond and remains fairly constants thereafter over the time range (70 ps) probed in the measurements. In the past, the temporal evolution of the amplitude mode following (partial) photo-induced destruction of the CDW state has been investigated by all-optical measurements, tracing the pump-induced coherent modulations observed on the transient reflectivity signal of optical probe pulses [2–4]. While the precise origin of the reflectivity oscillations at the frequencies of the amplitude CDW mode and of phonon modes is still somewhat speculative, they are usually assigned to pump-pulse-*generated* coherent population density enhancements whose *decay* is monitored by the all-optical measurements. In contrast, the analysis of the imaginary part of our THz-reflectivity-change data indicates that we observe a *decrease* of the ac conductivity at 1.7 THz, 2.2 and 2.7 THz and its subsequent recovery, as one would expect it to occur for a partial destruction and re-formation of the CDW state. Transient THz-reflectivity and optical-reflectivity measurement

thus provide complementary information on CDW physics. While a number of features concerning the dynamics of the amplitude mode are found to be quite similar, the THz and the optical experiments differ with respect to one aspect: The transient THz conductivity reveals an additional modulation of the amplitude of the 1.7-THz signal during the first few picoseconds. Recent theoretical work has described the dynamics of the amplitude mode on femto- and picosecond time scales in the framework of a phenomenological Ginzburg-Landau theory [4] and with a microscopic theory with a mean-field description of electronic correlations [5]. Important aspects of the optical reflectivity change measurements could be reproduced. A characteristic feature of both theoretical treatments is a complex relaxation kinetics resulting from the cooperativity of electron and lattice degrees of freedom, which leads to non-exponential and even non-monotonic relaxation behavior of the order parameter and a strong dependence on the excitation fluence. We currently explore whether the modulation of the THz conductivity of the amplitude mode can be explained in the framework of this theories.

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Spin-orbit coupling in RuCl3: Evidence for a relativistic Mott insulator on the honeycomb lattice

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Spin-orbit coupling in correlated electron systems has attracted significant interest as of late due to the possibility of realizing a variety of exotic electronic phases[1]. A notable example is the suggestion that the combined action of spin-orbital entanglement and Mott physics on the honeycomb lattice could realize the Kitaev model and therefore a quantum spin liquid ground state[2]. With this in mind, we have studied the electronic structure of the honeycomb magnet RuCl3 using optical and x-ray spectroscopies together with density functional theory. A comparison of the calculated band structure and the optical data shows that this material is a relativistic Mott insulator and that spin-orbit coupling plays a decisive role in determining the electronic structure. The importance of spin-orbit coupling is further confirmed by x-ray absorption spectroscopy. Taken together, these considerations suggest that RuCl3 is a promising system in which to investigate Kitaev physics. Indeed, our Raman scattering experiments have detected unusual magnetic excitations in this material, hinting at an unconventional magnetic ground state.

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Room temperature electrically tunable terahertz Faraday effect in a topological insulator *

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AbstractText We demonstrate electrical control of the room temperature Faraday effect in a 100-nm-thick film of strained HgTe, which is a topological insulator. A high carrier mobility together with unusual gate voltage dependences of the conductivity and cyclotron resonance unambiguously indicate that the terahertz (THz) response of our device is dominated by the carriers in the topological surface state. The electrical control is achieved by gating the carrier density in a static magnetic field, opening new perspectives for the application of topological insulators as high-speed amplitude and phase modulators in the THz frequency range.

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Spin and lattice excitations in BiFeO3 ceramics compared with epitaxial thin film of $BiFeO_3/TbScO_3$ *

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We investigated infrared reflectivity and time-domain THz transmission spectra of $BiFeO_3$ ceramics and an epitaxial thin film. The ceramics were measured at temperatures from 10 to 900 K, the thin film was studied only below room temperature. In the ceramic samples, we observed all 13 polar phonons (4A1 + 9E symmetries) allowed by the factor group analysis in the rhombohedral R3c space group. Their transverse frequencies are similar to those reported by Kamba et al. in 2007 [1]. Nevertheless, the intensities of the reflection bands are much higher than in Ref. [1], giving evidence that the longitudinal phonon frequencies (and therefore the Born effective charges) are higher than in the previous report. Thanks to this fact, the static permittivity at 10 K is more than 50, significantly more than the value of 25 published in Ref. [1]. This discrepancy is probably created by a high porosity of the previously studied ceramics, which caused diffuse scattering of the infrared beam and effectively deteriorated the mirror reflectivity. Phonons exhibit small softening on heating and due to the Lyddane-Sachs-Teller relation the static permittivity slightly increases with increasing temperature. The epitaxial (001) $BiFeO_3$ film with a thickness of 300 nm was deposited on orthorhombic (110) $TbScO_3$ substrate. It exhibits ferroelastic and ferroelectric stripe domains separated by (010) vertical domain walls [2]. The directions of spontaneous polarization in adjacent domains are rotated by 109°. Thanks to this, all 13 polar phonons are allowed in the infrared spectra in contrast to (010)cub single-crystalline infrared spectra published by Lobo et al. [3], who observed only 9 E-symmetry modes. Some phonon frequencies in the thin film exhibit a remarkable increase in comparison to the bulk ceramics

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and single crystal. This cannot be easily explained only by the $\sim 0.2\%$ compressive strain present in the film. Possible reasons for the phonon frequency shifts will be discussed. Time-domain THz transmission spectra of the thin film do not show any magnetic excitations because of a low interaction with the radiation. By contrast, the THz spectra of ceramics reveal 6 magnons which soften on heating. Their damping is much larger than that reported recently by Nagel et al. [4] in a $BiFeO_3$ single crystal. This is probably due to the unpolarized character of our THz spectra and to a limited resolution (~ 0.7 cm^{-1}) of our THz spectrometer.

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Thz excitations of several magnetoelectric (multiferroic) compounds under strong magnetic field

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We have studied the absorbance of many magnetoelectric (multiferroic) compounds (orthorhombic and hexagonal ABO^3; A=Pr, Er,Nd,Lu,Mn,Sm; B=Mn,Cr,Fe,Ni) in the THz range in function of temperature and magnetic field. As some compounds present no absorption in that range, other exhibit strong absorbing lines with often deep changes (shifting, splitting, ...) as the consequence of the field or some internal (structural, magnetic, ...) reordering. We interpret these excitations as crystal-field transitions and hybrid magnetic states.

Theory of nonlinear phononics for coherent light-control of solids

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The use of light to control the structural and electronic properties of solids is an area of great interest for both basic research and potential applications. I will present our recent work on a microscopic theory for ultrafast control of solids with high-intensity Tera-Hertz frequency optical pulses. Our theory predicts the dynamical path taken by the crystal lattice using first principles calculations of the energy surface and classical equations of motion, as well as symmetry considerations. We identify two classes of dynamics. In the perturbative regime, displacements along the normal mode coordinate of the symmetry preserving Raman active mode can be achieved by cubic anharmonicities. This explains the light-induced insulator-to-metal transition in manganites observed experimentally. Furthermore, we predict a new regime in which ultra-fast instabilities that break crystal symmetry can be induced. This non-perturbative effect involves a quartic anharmonic coupling and occurs above a critical threshold below below which the nonlinear dynamics of the driven mode displays softening and dynamical stabilization.

Microwave measurements on superconductors at mK temperatures: heavy-fermion $CeCu_2S_2$ versus conventional superconductors

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Microwave measurements on superconductors can reveal the temperature dependence of the penetration depth, which can indicate the presence of nodes in the superconducting gap function. While numerous superconductors have been studied with microwaves at ^{4}He temperatures, few such experiments are documented at mK temperatures, performed in dilution refrigerators. $CeCu_2S_2$ is a heavy-fermion superconductor with critical temperature $T_c \approx 0.6$ K. Though $CeCu_2S_2$ for a long time was believed to be a d-wave superconductor, at present it is under debate whether its order parameter features nodes or not.[1] Therefore, we have performed microwave measurements to study the penetration depth, but we address the microwave surface resistance as well. To be able to probe superconducting bulk samples at mK temperature, we have developed a new experimental approach based on superconducting stripline resonators.[2] We evaluate the performance of this technique at temperatures down to 30 mK by studying two conventional superconductors, namely zirconium (T_c similar to that of $CeCu_2S_2$) and iridium ($T_c \approx 0.1$ K). Comparing our data on the penetration depth of a $CeCu_2S_2$ single crystal with that of zirconium, we find evidence for an unconventional temperature dependence of the penetration depth in $CeCu_2S_2$, which shall be discussed in the context of the different order parameters proposed for this compound. Furthermore, we discuss the microwave surface resistance of $CeCu_2S_2$ within the context of unconventional charge dynamics that heavy fermions exhibit already in the metallic state.

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ARPES study of the doping evolution of the strong spin-orbit insulator $Sr_3Ir_2O_7$

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The insulating ground state of the layered perovskite iridates is often described in a single band $j_{eff} = 1/2$ Hubbard model [1, 2]. Iridates were thus proposed as analogues to the cuprates and as such, a potential platform for engineering high-temperature superconductivity [2]. Yet, little is known about their doping evolution. Here, we present an Angle Resolved Photoemission (ARPES) study of stoichiometric insulating $Sr_3Ir_2O_7$ [3] and lanthanum doped $Sr_{3(1-x)}La_{3x}Ir_2O_7$. We find that samples with La concentrations above 3% show a quasiparticle-like band dispersion around the "nodal" (π,π)-direction of the undistorted Brillouin Zone and a strong suppression of spectral weight along (π,0). Yet, unlike in cuprates, the Fermi surface of doped $Sr_3Ir_2O_7$ consists of closed, lens-shaped pockets. Moreover, it is qualitatively reproduced by band structure calculations that do not treat correlations explicitly. This suggests that $Sr_3Ir_2O_7$ does not behave fundamentally different from a doped narrow gap semiconductor and that correlations play a secondary role only, merely leading to moderate inter-orbital charge transfer and a renormalization of Fermi velocities.

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Driving the spins in BiFeO3 single crystals with hydrostatic pressure

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BiFeO3 exhibits ferroelectric and magnetic orders at room temperature, which makes it an ideal candidate for spintronics, electro-optics and data storage applications [1]. Most of its properties are related to its ferroelectric character, especially studied under electric or magnetic fields [2]. The antiferromagnetism hasn't been extensively investigated in particular under pressure. Here, we bring insight into the rich spin physics of BiFeO3 in a detailed study of the dynamic magnetic response of BiFeO3 bulk under pressure. The magnetic and structural properties are tracked simultaneously by Raman spectroscopy under pressure up to 20 GPa. Thanks to the Raman set-up we developed, we have been able to measure the spins excitations down to 0.6 meV. Following the phonon modes, we observe four structural phase transitions occurring around 3, 5, 8 and 11 GPa, respectively, from R3c to Pmna through three orthorhombic phases. These results are consistent with previous studies [3] and are supported by our effective Hamiltonian simulations. Below TNéel=640K, BiFeO3 exhibits an incommensurate antiferromagnetic cycloidal spin order with wavelength ?=62 nm. The cycloidal modulation results in a specific magnonic response with two types of magnon modes corresponding to excitations in and out of the cycloid plane. These excitations are associated to several peaks at low energy in the Raman spectra. Increasing the hydrostatic pressure, the energies of these peaks shift and converge

towards two distinct values at the first structural transition. These measurements and the associated simulations show that a 2nd order transition from a cycloidal spin order to a canted antiferromagnetic state takes place in the R3c structure. Such a magnetic transition is also observed in BiFeO3 thin films for compressive epitaxial strain [4]. Whereas for thin films, we have only access to discrete misfit strain accordingly to the substrate, the hydrostatic pressure allows, here, a continuous tuning of the spin state.

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Infrared- and Raman-Spectroscopy Measurements of a Transition in the Crystal Structure and a Closing of the Energy Gap of BiTeI under Pressure *

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BiTeI is a giant Rashba spin splitting system, in which a noncentrosymmetric topological phase has recently been suggested to appear under high pressure. We investigated the optical properties of this compound, reflectivity and transmission, under pressures up to 15 GPa. The gap feature in the optical conductivity vanishes above $p \sim 9$ GPa and does not reappear up to at least 15 GPa. The plasma edge, associated with intrinsically doped charge carriers, is smeared out through a phase transition at 9 GPa. Using high-pressure Raman spectroscopy, we follow the vibrational modes of BiTeI, providing additional clear evidence that the transition at 9 GPa involves a change of crystal structure. This change of crystal structure possibly inhibits the high-pressure topological phase from occurring.

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Orbital-selective metal–insulator transition and gap formation above T_c in superconducting $Rb_{1-x}Fe_{2-y}Se_2$ *

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We report on a hierarchy of temperatures $T_c < T_{gap} < T_{met}$ in superconducting $Rb_{1-x}Fe_{2-y}Se_2$ observed by THz spectroscopy. Above T_met ∼90 K the material reveals semiconducting characteristics. Below T_met a coherent metallic THz response emerges. This metal-to-insulator type, orbital-selective transition is indicated by an isosbestic point in the temperature dependence of the optical conductivity and dielectric constant at THz frequencies. At T_{gap} ∼61 K, a gap opens in the THz regime and then the superconducting transition occurs at T_c ∼32 K. This sequence of temperatures seems to reflect a corresponding hierarchy of the electronic correlations in different bands. See Nature Communications 5, 3202 (2014) for details.

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Charge dynamics in $BaFe_2(As_{0.7}P_{0.3})_2$ superconductor as revealed by optical spectroscopy *

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We present the optical properties of an optimally doped superconducting $BaFe_2(As_{0.7}P_{0.3})_2$ single crystal with $T_c = 28$ K. In the normal state, the optical conductivity can be decomposed into a broad temperature-independent background Drude component and a coherent narrow Drude component. The narrow Drude component dominates the low frequency optical conductivity, and its spectral weight is almost temperature independent whereas its scattering rate varies linearly with temperature. The presence of multiple carriers with distinct temperature-dependent characters can well explain the transport properties observed in optimally doped Ba122 iron-based superconductors. In the measurement temperature range, the transport properties of $BaFe_2(As_{0.7}P_{0.3})_2$ was solely determined by the narrow Drude conducting subsystem. Upon entering the superconducting state, the low frequency optical spectrum response and the temperature dependence of penetration depth are different between $BaFe_2(As_{0.7}P_{0.3})_2$ and the similar compound $Ba_{0.6}K_{0.4}Fe_2As_2$, suggests that the superconducting state responses for different doped Ba122 compounds may not be universal.

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Weak coupling between orbitals and E_g phonon mode in $Ba(Fe_{1-x}Co_x)_2As_2$

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We report electronic Raman scattering measurements of $Ba(Fe_{1-x}Co_x)_2As_2$ ($x = 0.065$ and 0.2) single crystals with Raman shifts from 9 cm^{-1} up to 600 cm^{-1} in the symmetry of B_{1g} with respect to 1 Fe unit cell. Upon cooling down, evident quasielastic peaks emerge only in the Raman response of the crystal with $x = 0.065$ which is due to the contribution of orbital ordering between xz and yz Fe $3d$ orbitals. Here, we analyze the E_g phonon at 128 cm^{-1} which has the same function formate of its Raman tensors as xz and yz Fe $3d$ orbitals in these two crystals respectively. While, unlike their electronic continuums, nothing anomalies are found in the E_g phonons of these two samples, which simply follows the expressions corresponding to the anharmonic phonon decay into acoustic phonons with the same frequencies and opposite momenta. Our results indicate a weak coupling between Fe $3d$ orbitals and E_g phonon mode.

Polarity-driven surface metallicity in the Kondo insulator SmB_6

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The Kondo insulator SmB_6 has been long known for its anomalous residual conductivity at low temperatures. This behavior has remained mysterious for the past 40 years, until the recent proposal that SmB_6 could be the realization of a topological Kondo insulator [1], in which case the topology-driven metallic surface states would be responsible for the finite low-temperature conductivity. Even though various experiments on SmB_6 have provided evidence for the existence of metallic surface states, no consensus on their microscopic origin has been reached. Here, by a combined angle-resolved photoemission spectroscopy and density functional theory study, we discover a polarity-driven surface metallicity in SmB_6 aside from the proposed topology-driven contribution [2]. Two surface states, not accounted for by the bulk band structure, are reproduced by slab calculations for coexisting B_6 and Sm surface terminations (consistent with the lack of a natural cleavage plane in SmB_6). Our analysis reveals that a metallic surface state stems from an unusual property, generic to the (001) termination of all hexaborides: the presence of boron 2p dangling bonds, on a polar surface [2]. The discovery of polarity-driven surface metallicity sheds new light on the long-standing puzzle of the low temperature residual conductivity of SmB_6, and raises a fundamental question in the field of topological Kondo insulators regarding the interplay between polarity and nontrivial topological properties.

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Author List

Contrib.	Presenter	Title
Oral	Akrap	Magnetooptical study of giant Rashba systems BiTeBr and BiTeCl
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Rapid	Autore	Dirac plasmonics of Topological Insulators
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Invited	Coleman	Composite and Topological Order in Heavy Fermion Materials
Poster	Colson	Crystal Growth of High-Tc Superconductors and Multiferroics
Oral	Comin	Charge Order, Fermi-Arc Instability, and d-wave bond order in underdoped cuprates

Contrib.	Presenter	Title
Rapid	Cyr-Choiniere	Anisotropy of the thermoelectric response in the pseudogap phase of the cuprate superconductor $YBa_2Cu_3O_y$
Oral	Damascelli	Probing spin-orbital entanglement by polarization- and spin-resolved ARPES
Invited	Davis	Visualizing (Electronic) Dragons
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Poster	Gu	Crystal growth and physical property of Bi-Sb-Te-Se topological insulator materials, and Cu-Bi-Se and Sn-In-Te topological superconductors
Invited	Hackl	A light scattering study of the pairing potential in Fe-based superconductors and related compounds

Contrib.	Presenter	Title
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Oral	Kuzmenko	Strong Plasmon Reflection at Nanometer Gaps in Graphene
Invited	Le Tacon	Competing orders in underdoped cuprates
Poster	Levallois	Broad-band helicity-resolved infrared spectroscopy of bismuth
Invited	Loidl	Electromagnons
Invited	Lupi	Plasmonic Excitations in Topological Insulators
Oral	Madhavan	Coexistence of Massless and Massive Dirac Fermions in Topological Crystalline Insulators
Rapid	Mangin-Thro	Search for Intra-Unit-Cell magnetic order close to optimal doping in superconducting cuprates
Rapid	Mansart	Real-time observation of structural and electronic degrees of freedom in high T_c superconductors
Oral	Martin	Ultra-broadband Synchrotron Infrared Nanospectroscopy
Invited	Maslov	Optical conductivity of Fermi-liquid and non-Fermi-liquid metals
Poster	Massat	Charge nematic fluctuations and superconducting gap in $Ba_{1-x}K_xFe_2As_2$ probed by Raman scattering

Contrib.	Presenter	Title
Poster	Matsunaga	Collective pseudospin precession in a superconductor NbN driven by sub-gap THz electric fields
Oral	Measson	Amplitude 'Higgs' mode in 2H-$NbSe_2$ Superconductor
Poster	Mravlje	Waterfalls and resillient quasiparticles in ruthenates
Poster	McLeod	Cryogenic Infrared Nano-Imaging of the Metal-Insulator Transition in the Canonical Mott Insulator V2O3
Poster	Mitrano	Pressure-Dependent Relaxation in the Photoexcited Mott Insulator ET–F_2TCNQ: Influence of Hopping and Correlations on Quasiparticle Recombination Rates
Poster	Morris	A hierarchy of bound states in the 1D ferromagnetic Ising chain $CoNb_2O_6$ investigated by high resolution time-domain terahertz spectroscopy
Poster	Moskvin	Pseudospin $S = 1$ description of the cuprate complexity: ground state, phase diagrams, and excitations
Oral	Munzar	Evidence for a superconducting origin of prominent features of the in-plane infrared response of underdoped cuprates and implications of their persistence above Tc
Oral	Nagel	Room temperature toroidal moment in multiferroic $BiFeO_3$ and its interaction with THz light
Poster	Najera	Study of spin-orbit effects in the Mott-Hubbard metal-insulator transition
Invited	Norman	What is the pseudogap?
Oral	Okamura	Electron-Hole Symmetry in the Electronic Structures of Ce and Yb Compounds Examined by Optical Study under High Pressure
Invited	Orlita	Massless fermions in 2D and 3D: infrared magneto-spectroscopy studies
Poster	Pan	Low energy electrodynamics of novel spin excitations in the quantum spin ice $Yb_2Ti_2O_7$
Invited	Park	Low energy spin dynamics of multiferroic $RMnO_3$ and $BiFeO_3$
Invited	Paul	Nesting Induced Large Magnetoelasticity in the Iron Arsenide Systems
Invited	Pepin	Charge ordering around a Quantum Critical Point in cuprate
Invited	Perez	Collective spin excitations in diluted magnetic quantum wells
Invited	Perfetti	Dynamics of the electrons in surface states with strong spin-orbit coupling

Contrib.	Presenter	Title
Oral	Perucchi	Electrodynamics of hetero-structured high temperature superconductors
Oral	Petzelt	Broadband dielectric spectroscopy of $BaTiO_3$-$BaZrO_3$ solid solutions
Oral	Pimenov	Electric field control of terahertz polarization with electromagnon
Invited	Proust	Fermi surface reconstruction by charge order in underdoped copper oxides
Poster	Riccardi	Combined Raman scattering and TEM study of suspended graphene
Poster	Rõõm	Directional Dichroism of THz Radiation at Elevated Temperatures in the Paraelectric and Paramagnetic State of Multiferroic $Sr_2CoSi_2O_7$
Poster	Roskos	Time-Resolved THz Spectroscopy of Charge-Density Waves in Blue Bronze ($K_{0.3}MoO_3$
Rapid	Rovillain	Iron borate multiferroics, a new way to observe the electromagnon?
Poster	Sandilands	Spin-orbit coupling in RuCl3: Evidence for a relativistic Mott insulator on the honeycomb lattice
Rapid	Sakai	Evidences of an s-wave structure of the pseudogap in high-Tc cuprate superconductors
Oral	Scheffler	THz properties of $CaRuO_3$: can we reconcile non-Fermi-liquid optics with Fermi-liquid concepts?
Invited	Shen	Domain Walls and Edge Structures in Quantum System – Views from Scanning Microwave Impedance Microscope
Invited	Shimano	Observation of Higgs Amplitude Mode in Superconductors
Poster	Shuvaev	Room temperature electrically tunable terahertz Faraday effect in a topological insulator
Poster	Skiadopoulou	Spin and lattice excitations in BiFeO3 ceramics compared with epitaxial thin film of $BiFeO_3/TbScO_3$
Poster	Sopracase	Thz excitations of several magnetoelectric (multiferroic) compounds under strong magnetic field
Poster	Subedi	Theory of nonlinear phononics for coherent light-control of solids
Invited	Taillefer	The three phase diagrams of cuprate superconductors
Invited	Tajima	Optical observation of precursory superconductivity in $YBa_2Cu_3O_y$
Oral	Tanner	Use of X-ray scattering factors for Kramers-Kronig high-frequency extensions
Invited	Timusk	The normal state of URu_2Si_2: spectroscopic evidence for an anomalous Fermi liquid

Contrib.	Presenter	Title
Oral	Todorov	Collective effects in 2D electron gas and Ultrastrong light-matter coupling
Poster	de la Torre	ARPES study of the doping evolution of the strong spin-orbit insulator $Sr_3Ir_2O_7$
Poster	Toulouse	Driving the spins in BiFeO3 single crystals with hydrostatic pressure
Poster	Tran	Infrared- and Raman-Spectroscopy Measurements of a Transition in the Crystal Structure and a Closing of the Energy Gap of BiTeI under Pressure
Oral	Valdes-Aguilar	Time-resolved terahertz dynamics in thin films of the topological insulator Bi_2Se_3
Invited	van der Marel	Fermi liquid behaviour in strongly correlated metals
Invited	Varma	Some Constraints put by Experiments on Theories of High Temperature Superconductivity in Cuprates
Oral	N.L. Wang	Coexistence and competition of multiple charge-density-wave orders in RTe3 as revealed by optical probes
Poster	Z. Wang	Orbital-selective metal–insulator transition and gap formation above T_c in superconducting $Rb_{1-x}Fe_{2-y}Se_2$
Rapid	Liang Wu	A sudden collapse in the transport lifetime across the topological phase transition in $(Bi_{1-x}In_x)_2Se_3$
Poster	Bing Xu	Charge dynamics in $BaFe_2(As_{0.7}P_{0.3})_2$ superconductor as revealed by optical spectroscopy
Oral	Yakovenko	Possible spiral structure in the pseudogap phase of cuprates
Poster	Yang	Weak coupling between orbitals and E_g phonon mode in $Ba(Fe_{1-x}Co_x)_2As_2$
Poster	Zhu	Polarity-driven surface metallicity in the Kondo insulator SmB_6