LEES 08

Low Energy Electrodynamics in Solids

LOW ENERGY ELECTRODYNAMICS IN SOLIDS 2008

ABSTRACT BOOKLET

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Talk Abstracts

Interface charge tunneling in La_2CuO_4-$La_{1.64}Sr_{0.36}CuO_4$ superlattices*

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We have used resonant soft x-ray scattering to quantify the distribution of doped holes in a superlattice comprising two layers of nominally insulating La_2CuO_4 (LCO) and four layers of nonsuperconducting $La_{1.64}Sr_{0.36}CuO_4$ (LSCO). Despite its nonsuperconducting constituents, this superlattice is superconducting, with a T_c = 38K. We find that the distribution of holes is measurably smoother than that of the Sr^{2+} dopant ions, indicating tunneling of charge between the layers. Surprisingly, the "insulating" layers are found to be optimally doped, with p = 0.16±0.02 holes per planar Cu atom, suggesting that they are the locus of superconductivity. Applying a linear response model we deduce a *c* axis screening length of λ_0= 8.4 Å for the LCO/LSCO system.

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Scanning tunneling spectroscopy and transport measurements in graphene

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The recent discovery of methods to isolate graphene (a single layer of graphite) has opened the way to bench-top studies of quasi-particles whose properties are governed by quantum-relativistic dynamics (Dirac fermions). I will describe scanning tunneling spectroscopy and transport experiments that give access to the unique properties of the Dirac fermions in graphene. Our findings include evidence of their chiral nature, effects of interactions and novel transport properties.

Infrared spectroscopy of correlated electron matter at the nano-scale

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One common attribute of several classes of correlated electron systems is that the onset of conducting state in these systems typically occurs in the regime of nano-scale phase separation of chemical, and/or electronic/magnetic origin. These intrinsic non-uniformities have been systematically documented using scanning probe and scattering techniques. However, the dynamical properties of multiple electronic phases coexisting in macroscopic heterogeneous samples remain unexplored because methods appropriate to study dynamics (transport, infrared/optical and many other spectroscopies) lack needed spatial resolution. To circumvent this fundamental limitation, we applied a new technique: scanning near field infrared microscopy to investigate the transition from a correlated insulator to a correlated metal driven by temperature in vanadium dioxide (VO_2) at length scales down to 10 nano-meter. In combination with more conventional far field infrared ellipsometry these studies uncover spectroscopic signatures of the Mott transition including divergent effective mass and electronic pseudogap. These findings may help to settle decades long debate on the respective roles played by the lattice and by the electron-electron correlations in the insulator-to-metal transition of VO_2 (Ref.[1]).

[1]. M. M. Qazilbash, M. Brehm, Byung-Gyu Chae, P.-C. Ho, G. O. Andreev, Bong-Jun Kim, Sun Jin Yun, A. V. Balatsky, M. B. Maple, F. Keilmann, Hyun-Tak Kim, and D. N. Basov "*Mott Transition in VO_2 Revealed by Infrared Spectroscopy and Nano-Imaging*" Science 318, 1750 (2007)

Nested Fermi Surface and Electronic Instability in $Ca_3Ru_2O_7$

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The bilayer ruthenate $Ca_3Ru_2O_7$ is a correlated semimetal with two phase transitions, a Néel transition at 56 K and a structural phase transition at 48 K [1], where the in-plane resistivity increases by about 30 %. At low temperatures the resistivity is metallic, but rather large [2, 3]. With 2.8 mJ/molK^2 the electronic specific heat of $Ca_3Ru_2O_7$ is approximately 40 times lower than in the isovalent $Sr_3Ru_2O_7$.

We present a combined photoemission and quantum oscillation study elucidating the microscopic origin of this unusual ground state. High-resolution ARPES data reveal well-defined quasiparticle bands of unusually low weight, emerging in line with the metallic phase of $Ca_3Ru_2O_7$ below 30 K. At the bulk structural phase transition temperature of 48 K, we find clear evidence for an electronic instability, gapping large parts of the underlying Fermi surface that appears to be nested [4]. Metallic pockets are found to survive in the small, non-nested sections, constituting a low-temperature Fermi surface with 2 orders of magnitude smaller volume than in all other metallic ruthenates. The Fermi velocities and volumes of these pockets are in agreement with the results of complementary quantum oscillation measurements on the same crystal batches.

[1] Y. Yoshida, et al., *Physical Review B* **72** (2005) 054412.
[2] Y. Yoshida, et al., *Physical Review B* **69** (2004) 220411.
[3] E. Ohmichi, et al., *Physical Review B* **70** (2004) 104414.
[4] F. Baumberger, et al., *Physical Review Letters* **96** (2006) 107601.

Spectral weight transfer in polaronic systems

Mona Berciu, Glen L. Goodvin, Lucian Covaci

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Finding simple, yet accurate analytical approximations for the Green's functions of various systems, especially at intermediary coupling strengths, has been a major challenge in recent years. In this talk, we will present such an approximation, called the Momentum Average (MA) approximation, relevant for polaronic systems [1]. For the Holstein polaron, the MA spectral weight has been shown to satisfy exactly the first 6 sum rules and to remain highly accurate for all higher order sum rules, for all coupling strengths. This accuracy has also been confirmed by comparison against results of numerical simulations. Moreover, the MA approximation can be systematically improved, at an increased (but still small) computational cost [2,3]. Our MA results allow us to elucidate the evolution of the spectral weight of a Holstein polaron as the electron-phonon coupling is turned on. We will also discuss recent progress in extending this approximation to other polaron Hamiltonians (e.g., coupling to breathing-mode phonons); to electron-phonons problems with multiple phonon branches and/or multiple electronic bands; to bipolaron problems; and to finite polaron concentrations.

[1]. M. Berciu, Phys. Rev. Lett. **97**, 036402 (2006).
[2]. M. Berciu, Phys. Rev. Lett. **98**, 209702 (2007).
[3]. M. Berciu and G. L. Goodvin, Phys. Rev. B **76**, 165109 (2007).

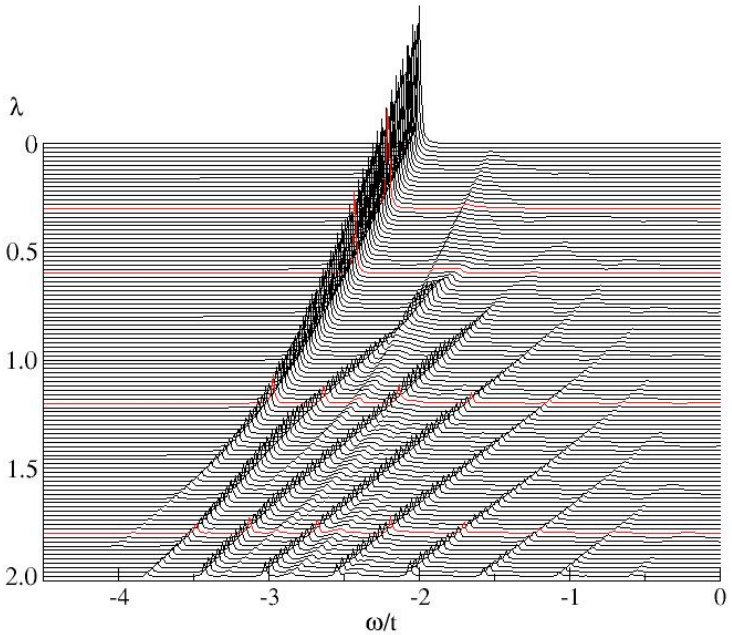

Fig.1. Evolution of the spectral weight A(k,w) of a one-dimensional Holstein polaron as the electron-phonon coupling is increased. The results shown are for the Γ-point k=0. The effective coupling is $\lambda=g^2/(2\Omega t)$, where g is the electron-phonon coupling, Ω is the phonon frequency and 4t is the one-dimensional free-electron bandwidth. From Ref. [3].

Competition between high T_c superconductivity and ferromagnetism in oxide multilayers

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Artificial multilayers offer unique opportunities for combining materials with antagonistic orders such as superconductivity and ferromagnetism. It was previously shown for multilayers of classical superconductors and ferromagnets that fascinating new quantum states can be realized by tuning the layer thicknesses or the interface properties.

In my talk, I will show that multilayers of cuprate high T_c superconductors (HTSC) and oxide-based ferromagnets provide an equally fascinating playground for studying the competition between the superconducting and ferromagnetic orders under the condition that both opponents are of comparable strength. I will present experimental results from neutron reflectometry and low energy muon spin rotation (μSR) measurements on thin film superlattices that were grown by pulsed laser deposition (PLD). These measurements establish that the interaction between superconductivity and ferromagnetism is surprisingly strong and gives rise to a number of unexpected and very unusual phenomena. In particular, our data provide evidence that a giant superconductivity-induced modulation of the vertical profile of the ferromagnetic magnetization takes place in some of these superlattices and that a magnetic spin-density-wave state is induced (due to the proximity coupling to the ferromagnetic layers) even deep inside the high T_c superconducting cuprate layers.

Recent progress in the phase diagram of YBCO

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I will review recent breakthroughs in the control over sample quality in the YBCO system, that have led to changes in our view of the phase diagram of the cuprates. The talk will focus on recent work on transport and quantum oscillations, microwave spectroscopy, and ARPES measurements of the Fermi surface.

Optical properties of lattice/spin polarons in underdoped cuprates

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The problem of a single hole in the *t-J* model interacting also with the lattice degrees of freedom bares a notable interest in relation with the physical properties of the high-*Tc* cuprates. Electron-phonon self-trapping and the magnetic interaction give rise indeed to polaronic features which have been recently claimed to explain the photoemission spectra of strongly underdoped and undoped high-*Tc* superconductors [1]. Relative less effort have been devoted to the study of the corresponding polaronic features in the optical conductivity $\sigma(\omega)$.

In this contribution we investigate the optical spectra of one hole in the Holstein-*t-J* model. We employ a dynamical mean-field theory which becomes exact in the limit of infinite connectivity. This allow us to investigate the local (incoherent) features which are related to the internal structure of the polaron, disregarding coherent motion which should be reflected in the Drude-like peak. We show that magnetic and electron-phonon interactions sustain each other in establishing polaronic regime [2]. Polaron formation is reflected in a peculiar mid-infrared (MIR) band which is however notably different in the case of a lattice or magnetic origin [3]. The dependence of $\sigma(\omega)$ on the electron-phonon coupling constant λ, on the exchange interaction J and on temperature T is investigated. We compare our results with experimental data in $Nd_{2-x}Ce_xCuO_4$ [4] showing that the doping and temperature dependences of the optical conductivity in this compounds is naturally reproduced by a spin/lattice polaronic model.

[1]. For a review see X. J. Zhou, T. Cuk, T. Devereaux, N. Nagaosa, and Z.-X. Shen, arXiv:cond-mat/0604284 (2006) and references therein.

[2]. E. Cappelluti and S. Ciuchi, Phys. Rev. B **66**, 165102 (2002)..

[3]. E. Cappelluti, S. Ciuchi, and S. Fratini, Phys. Rev. B **76**, 125111 (2007).

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Attosecond spectroscopy in condensed matter

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Electron transport on the attosecond timescale, through several atomic layers, has now been observed in single-crystal tungsten in real time [1]. This development was made possible by extension of established attosecond spectroscopic techniques developed in gas-phase targets. In tungsten, an isolated attosecond XUV pulse [2] was used to excite photoelectrons inside the crystal, while a waveform controlled, few-cycle NIR laser pulse was used to probe their emission [3]. Time-dependent photoemission spectra displayed in Figure 1 show that the overlapping laser pulse modulates the measured photoelectron kinetic energy. As the relative delay between XUV and NIR pulses is varied, the underlying field of the NIR pulse is revealed in both the 4*f* core-state and conduction-band photoemission peaks. Comparison of these "streaking" curves revealed that photoelectrons originating from the 4*f* core-states were emitted from the tungsten surface approximately 110 attoseconds after those from the delocalized conduction-band states. Delayed emission is a consequence of the material's electron transport properties, which can only be accessed in the time-domain. This result demonstrates that, in general, time-domain observation of attosecond charge dynamics in solids and surfaces – including charge transfer, charge screening, image charge formation and decay, electron-electron scattering, and collective electronic motion – is now feasible. Future research efforts utilizing the most recent technological advances in attosecond pulse generation and measurement [4] will be described.

[1]. A. L. Cavalieri, *et. al.*, Nature **449**, 1029 (2007).
[2]. A. Baltuska, *et. al.*, Nature **421**, 611 (2003).
[3]. R. Kienberger *et. al.*, Nature **427**, 817 (2004).
[4]. E. Goulielmakis, *et. al.*, Science **317**, 769 (2007).

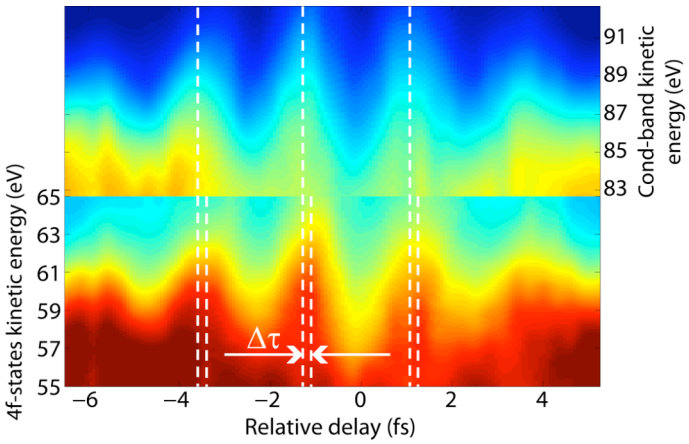

Fig.1. Tungsten photoemission induced by isolated attosecond XUV pulses is modulated by an overlapping, waveform-controlled NIR laser pulse. Oscillating curves in the spectra are observed as the relative delay between pulses is smoothly varied, revealing the vector potential of the NIR streaking pulse in both the 4*f* and conduction-band photoemission peaks. The temporal shift between these "streaking" curves, highlighted by white dashed lines, indicates that the 4*f* photoemission occurs approximately 110 attoseconds after the conduction-band photoemission.

Quasiparticle Extinction with approaching Mottness in $Bi_2Sr_2CaCu_2O_{8+\delta}$

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When a copper-oxide Mott insulator (MI) is converted into a high temperature superconductor by increasing the hole-density p, the MI states localized in real space (r-space) must evolve into momentum space (k-space) eigenstates. Recent theoretical studies of the CuO_2 Hubbard model suggest a complex phenomenology of this critically important evolution. The unique capability of quasiparticle interference (QPI) imaging to determine the electronic structure simultaneously in r-space and k-space makes it ideal for studying such effects. Here we use superconducting QPI to study them as $p \rightarrow 0$ in $Bi_2Sr_2CaCu_2O_{8+\delta}$. We find that the Bogoliubov quasiparticle states are confined to a k-space 'Bogoliubov Arc' that shrinks rapidly with p. The end points of this arc, where quasiparticle interference disappears, lie near the diagonal lines connecting $k=(0,\pm \pi/a_0)$ and $k=(\pm\pi/a_0,0)$ and occur at a weakly doping-dependent 'extinction' energy $E=\Delta_0$. The electronic excitations for $E>\Delta_0$ are dramatically different, being quasi-localized states in r-space with locally broken translational and rotational symmetries. From tunneling asymmetry contrast, we show that these r-space characteristics are most pronounced at the particle-hole symmetric 'pseudogap' energy $E=\pm\Delta_1$. Overall a novel perspective emerges. It is that a defining characteristic of the copper-oxide pseudogap excitations as $p \rightarrow 0$ is that the **k**-space eigenstates necessary for Cooper pairing are always extinguished near a plane connecting $k=(0,\pm \pi/a_0)$ and $k=(\pm\pi/a_0,0)$ even as the pairing-energy continues to rise. In such a situation, the two classes of excitation energy scales of the copper-oxides would represent: (i) the maximum energy Δ_0 of **k**-space singlets (Cooper pairs) and, (ii) the maximum excitation energy Δ_1 of the quasi-localized **r**-space states (possibly spin-singlets since maximum contrast in Z occurs symmetrically about the chemical potential at $E(\mathbf{r})=\pm\Delta_1(\mathbf{r})$). Among the most significant implications of this picture are explanations for (i) why superconducting T_c diminishes so rapidly with falling p in copper-oxides, (ii) why the antinodal momentum eigenstates become incoherent in k-space with falling p and, (iii) why the pseudogap does not close with temperature. The first and second effects would occur because the **k**-space eigenstates necessary to form delocalized singlets (Cooper pairs) are rapidly converted to **r**-space quasi-localized states as $p \rightarrow 0$. The third would occur because independent quasi-localized **r**-space states should not exhibit the temperature dependent energy-gap of a condensed electronic phase.

Infrared and Raman study of the charge-density-wave state in the rare-earth polychalcogenides $R\mathrm{Te}_n$

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The rare-earth polychalcogenides $R\mathrm{Te}_n$ (where R is the rare earth element and n=2, 2.5, 3) have recently attracted great interest due to their low dimensionality. Among the $R\mathrm{Te}_n$ families are members that variously host large commensurate distortions, ordered and disordered vacancy structures, and Fermi surface driven charge-density-wave (CDW). Optical spectroscopic methods (infrared reflectivity and Raman scattering) were applied as a function of both temperature and external pressure, in order to address the electrodynamic response and the complete excitation spectrum in these CDW materials. We establish the energy scale of the single particle excitation across the CDW gap and find that the CDW collective state gaps a large portion of the Fermi surface. The CDW gap decreases upon compressing the lattice (both with chemical and applied pressure). Furthermore based on the observation of a power law behavior in the optical conductivity, we suggest that interactions and Umklapp processes may play a role in the onset of the CDW broken symmetry ground state. We will also discuss our Raman scattering experiments as a function of chemical and applied pressure, from where we get some insights into the CDW collective state.

ARPES studies of bilayer CMR manganites (plus some cuprates)

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I will principally discuss our recent high resolution ARPES studies of bilayer CMR manganites [1-3]. We have studied a wide range of doping levels, including studying the evolution of the Fermi surfaces, temperature dependences, quasiparticle weight, etc. Our data highlight a number of surprising findings due to the strong correlations, and speak directly to the nature of the metal-insulator transitions, the charge correlation vectors, the strong electron-phonon coupling, the nature of the quasiparticle excitations, etc.

At the end I will briefly discuss some of our recent ARPES and laser-ARPES studies of high-T_c superconductors, including in particular studies of the electron-boson couplings using the isotope effect and other methods [4-5].

[1] Z. Sun et al. (submitted)

[2] Z. Sun, J.F. Douglas, A. V. Fedorov, Y.-D. Chuang, H. Zheng, J.F. Mitchell, D.S. Dessau, "A local metallic state in globally insulating $La_{1.24}Sr_{1.76}Mn_2O_7$ well above the metal insulator transition" Nature Physics 3, 248 (2007)

[3] Z. Sun, Y. -D. Chuang, A. V. Fedorov, J. F. Douglas, D. Reznik, F. Weber, N. Aliouane, D. N. Argyriou, H. Zheng, J. F. Mitchell, T. Kimura, Y. Tokura, A. Revcolevschi, D. S. Dessau "Quasiparticle-like peaks, kinks, and electron-phonon coupling at the $(\pi,0)$ regions in the CMR oxide $La_{2-2x}Sr_{1+2x}Mn_2O_7$" Phys. Rev. Lett. 97, 056401 (2006)

[4] H. Iwasawa et al. (submitted)

[5] J.F. Douglas, H. Iwasawa, Z. Sun, A.V. Fedorov, M. Ishikado, T. Saitoh, H. Eisaki, H. Bando, T. Iwase, A. Ino, M. Arita, K. Shimada, H. Namatame, M. Taniguchi, T. Masui, S. Tajima, K. Fujita, S. Uchida, Y. Aiura, D.S. Dessau "Unusual oxygen isotope effects in cuprates?" Nature 446, E5 (2007)

Two gaps scenario in HTSCs: overview and perspective

Thomas Peter Devereaux

Stanford University

In this talk I will present an overview on the issue of gaps observed in Raman, ARPES & STM spectroscopies. The behavior of the near nodal and anti-nodal gaps show distinctly different variations with temperature and doping in a variety of cuprate materials, indicating that the superconducting gap, and small and large pseudogaps may originate from different mechanisms.

Fermi surface and carrier density in hole-doped cuprates

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Recent high field measurements have convincingly demonstrated the existence of a Fermi surface made up of electron- and hole-like parts in the underdoped cuprate superconductor YBCO [1,2,3,4]. In contrast to the overdoped region where a large hole-like cylindrical Fermi surface was observed via ARPES [5] and transport [6,7] measurements, the Fermi surface pockets seen in quantum oscillation experiments are very small, covering only about 2% or so of the entire Brillouin zone. This naturally begs the question as to how electrons in cuprates go from a regime of high carrier density on the overdoped side, to one of low density on the underdoped side. Here we examine this question via a new generation of transport measurements on Nd-doped LSCO, a cuprate whose low T_c can be fully suppressed with available static magnetic fields, allowing a study of its normal state properties in the zero temperature limit. We find that a pronounced change in carrier density, as measured by the Hall number, appears to coincide with the point where the pseudogap temperature T^* vanishes, and where the electrical resistivity exhibits a linear temperature dependence as $T \rightarrow 0$.

[1]. N. Doiron-Leyraud *et al.*, Nature **447**, 565 (2007).
[2]. E.A. Yelland *et al.*, Phys. Rev. Lett. **100**, 047003 (2008).
[3]. A.F. Bangura *et al.*, Phys. Rev. Lett. **100**, 047004 (2008).
[4]. D. LeBoeuf *et al.*, Nature **450**, 533 (2007).
[5]. M. Platé *et al*., Phys. Rev. Lett. **95**, 077001 (2005).
[6]. N.E. Hussey *et al.*, Nature **425**, 814 (2003).
[7]. A.P. Mackenzie *et al.*, Phys. Rev. B **53**, 5848 (2003).

IR Hall Effect in underdoped cuprates*

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The Hall Effect at infrared frequencies extends magneto-transport to a spectroscopic tool with energy resolution and sum rules and provides a sensitive probe of the electronic properties of strongly interacting electron metals [1-3]. Recent results on electron and hole doped cuprates will be reviewed and compared with recent reports of quantum oscillations in YBCO and the nodal metal phenomenology from ARPES measurements on Bi(2212) [1-5]. In underdoped cuprates IR Hall measurements have given two kinds of evidence for a broken symmetry ground state (spin or d- density wave). In electron doped $Pr_{2-x}Ce_xCuO_4$ direct evidence for a density wave gap is observed in the Hall Effect measured at mid infrared (100-300 meV) frequencies [3]. At far IR frequencies (~10 meV) evidence for Fermi surface reconstruction into small electron-like Fermi pockets is seen in terms of a decreasing Hall mass in the underdoped state. In hole underdoped cuprates ($La_{2-x}Sr_xCuO_4$ and $YBaCu_3O_{7-x}$) we find evidence for small hole-like Fermi pockets while no gap-like features are found throughout the infrared [1,2]. The IR Hall results suggest that Fermi surface reconstruction and the formation of small Fermi pockets is a ubiquitous feature of underdoped cuprates.

*Work done in collaboration with J. Cerne, R. Greene, G. Jenkins, A. Millis, L. Rigal, D. Schmadel, I. Tsukada and A. Zimmers and supported in part by NSF grant #DMR-0303112.

1. L. B. Rigal, et al., Phys. Rev. Lett. **93**, 137002 (2004).
2. L. Shi, et al., Cond-mat/0510794.
3. A. Zimmers, et al., Phys. Rev. B **76**, 064515 (2007).
4. N. Doiron-Leyraud, et al., Nature, **447** 565 (2007); A. F. Bangura, et al., Phys. Rev. Letters **100**, 047004 (2008) and E. A. Yelland et al., Phys. Rev. Letters **100**, 047003 (2008).
5. A. Kanigel, et. al., Nature Physics **2**, 447 (2006).

Interplay between superconductivity and charge order in β"-(BEDT-TTF)$_2$SF$_5$CH$_2$CF$_2$SO$_3$: optical study.

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Theoretical study of systems with quarter-filled conductance band and strong electron-electron correlations propose superconductivity mediated by charge order fluctuations [1]. This was our motivation to investigate IR reflectivity of a 1/4-filled organic superconductor β"-(BEDT-TTF)$_2$SF$_5$CH$_2$CF$_2$SO$_3$ (T_c=5 K) in the frequency range between 10 and 10000 cm^{-1} at temperatures down to 1.8 K. Our spectroscopic study reveals a splitting of the charge-sensitive phonons and a pseudogap in electronic spectrum at 50 cm^{-1} evidencing for the charge order present in the whole temperature range. The narrow Drude response also present at all temperatures is responsible for superconductivity, with a superconducting gap of 12 cm^{-1} at 1.8 K in good agreement with BCS predictions. A comparison with the isostructural metal β"-(BEDT-TTF)$_2$SO$_3$CHFSF$_5$ suggests that superconductivity and charge order are closely related.

[1]. J. Merino et al. Phys. Rev. Lett **87**, 237002 (2001)

X-Ray Holography: From Snapshots to Movies

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In x-ray holography, coherent scattering with short wavelength radiation ($\lambda \approx 1$ nm) is used to obtain a high resolution image of a specimen. To turn the coherent scattering pattern into a hologram, a suitable reference beam has to be coupled in. This is achieved by combining the sample with a nanofabricated x-ray mask. As a result, a Fourier Transform Hologram of the object can be recorded, which can be inverted into a high resolution image by a single Fourier transformation.[1]

By combining this lensless imaging approach with x-ray magnetic dichroism as a contrast mechanism, we are able to study the switching behavior of nanomagnets and thin magnetic films in external magnetic fields. Material science studies in the context of the development of patterned perpendicular magnetic storage media for high density recording are presented. The combination of high spatial resolution, specific contrast mechanisms (here: magnetic) and flexible sample environment (here: variable B,T) enables investigations of the structure-function relationship in nanoscale materials science. More complex object/reference structures allow spatially multiplexed experiments and the introduction of geometrical time ramps with a few fs temporal resolution in pump-probe experiments.[2,3]

A major motivation for femtosecond single-shot imaging at Free Electron X-ray Lasers is the hope to record a "movie" of a dynamic object with femtosecond time resolution and nanometer spatial resolution. As a complementary approach to time-delay holography,[4] we present proof-of-principle 2-beam experiments carried out at the FLASH free electron laser facility. Here, a soft x-ray split-and-delay unit in conjunction with a suitably designed Fourier Transform Holography mask is used to record two *independent* images of the same object at variable time delay between 15 fs and 15 ps, i.e. we take the step from a "still picture" to a "two frame movie".[5]

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Novel aspects in the physics of oxide's surfaces

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Oxides are a fascinating class of materials that continue to surprise condensed matter physicists as well as materials scientists with a wide variety of properties. A TMO surface also shows unique properties that stand out from those leveraged for the TMO surface's more traditional and technologically oriented roles, such as selective oxidation, dehydration, etc... For example, conventional density functional studies of the polar surfaces in non-magnetic band insulators, such as the (111) surface of MgO predict an insulator-metal transition with very peculiar ferromagnetic properties. Interfaces are another very distinct example where the so-called polar catastrophe plays an important role, and results in a metallic conductivity at the interface between a simple band insulator $SrTiO_3$ and strongly correlated antiferromagnetic insulator $YBa_2Cu_3O_6$.

Ultrafast X-ray Studies of Atomic and Electronic Dynamics

Kelly Gaffney,[1]

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X-ray free electron lasers present unique opportunities for studying dynamics in condensed matter. I will discuss our investigation of electronic lattice instabilities in semiconductor crystals with both ultrafast x-ray scattering and density functional theory calculations, as well as the development of x-ray emission spectroscopy as a probe of electronic dynamics in transition metal complexes.

Electronic structure studies of bilayer colossal magnetoresistant manganites

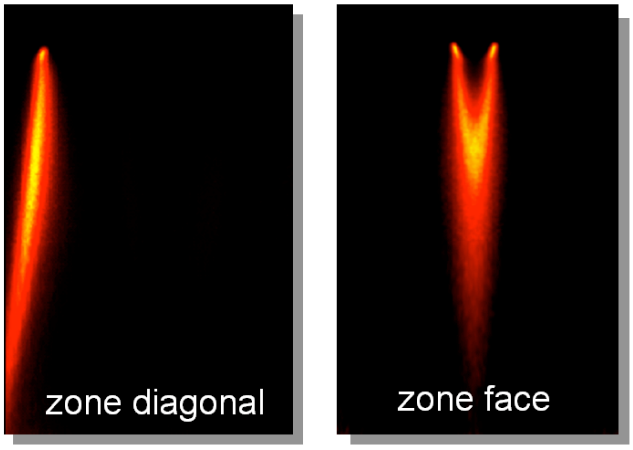
Mark S. Golden
Van der Waals-Zeeman Institute for Experimental Physics, Universiteit van Amsterdam, The Netherlands

Photoemission studies of the fermiology of the high T_c superconductors have played a pivotal role in research into the unconventional electronic behaviour of these systems. Despite this success, only relatively recently have photoemission data of high quality been coaxed from layered colossal magnetoresistant manganese oxides.

In this talk I'll present photoemission data from bilayer $La_{2-2x}Sr_{1+2x}Mn_2O_7$ systems (x=0.3, 0.35, 0.36, 0.4). Kicking off by discussing the Fermi surface topology, I'll then move on to the issues surrounding the interplay between itinerant (band-like) and local (small polaronic) behaviour in these systems. The *k*- and temperature dependence of the electronic states will be subjects of particular interest.

Time permitting, I'll present results from recent hard x-ray photoemission experiments on these materials, and also will make a connection to new UHV STM data recorded in Amsterdam from the same LSMO single crystals.

This research is carried out in collaboration with Sanne de Jong, Yingkai Huang, Freek Massee and Jeroen Goedkoop with funding from FOM, the EU and the UvA. Wing Kiu Siu, Iman Santoso, Anton Mans, Wim Koops, Huib Luigjes and Ton Gortenmulder, as well as the staff of the Swiss Light Source and BESSY are thanked for their able assistance.



ARPES data from a single cleave of
$La_{1.28}Sr_{1.72}Mn_2O_7$

Strong spin-orbit coupling effects on the Fermi surface of Sr2RuO4 and Sr_2RhO_4

M. W. Haverkort,[1] I. S. Elfimov,[2] L. H. Tjeng,[1] G. A. Sawatzky,[2,3] A. Damascelli[2,3]

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We present a first-principle study of spin-orbit coupling effects on the Fermi surface of Sr_2RuO_4 and Sr_2RhO_4. For Sr_2RhO_4 Spin-orbit coupling leads to a dramatic change of the Fermi surface with respect to non-relativistic calculations; as evidenced by the comparison with experiments on Sr_2RhO_4 (fig 1 a,b), it cannot be disregarded. For Sr_2RuO_4, the Fermi surface modifications are more subtle (fig 1 c,d). We will discuss why the effects of spin-orbit coupling look so much more apparent in Sr_2RhO_4, then for Sr_2RuO_4.. But even for Sr_2RuO_4 spin orbit coupling induces several important changes. Spin-orbit coupling modifies the k_z dispersion (fig 1 e-h) and induces a strong momentum dependence, normal to the RuO_2 planes, for both orbital and spin character of the low-energy electronic states. These findings have profound implications for the understanding of unconventional superconductivity in Sr_2RuO_4.

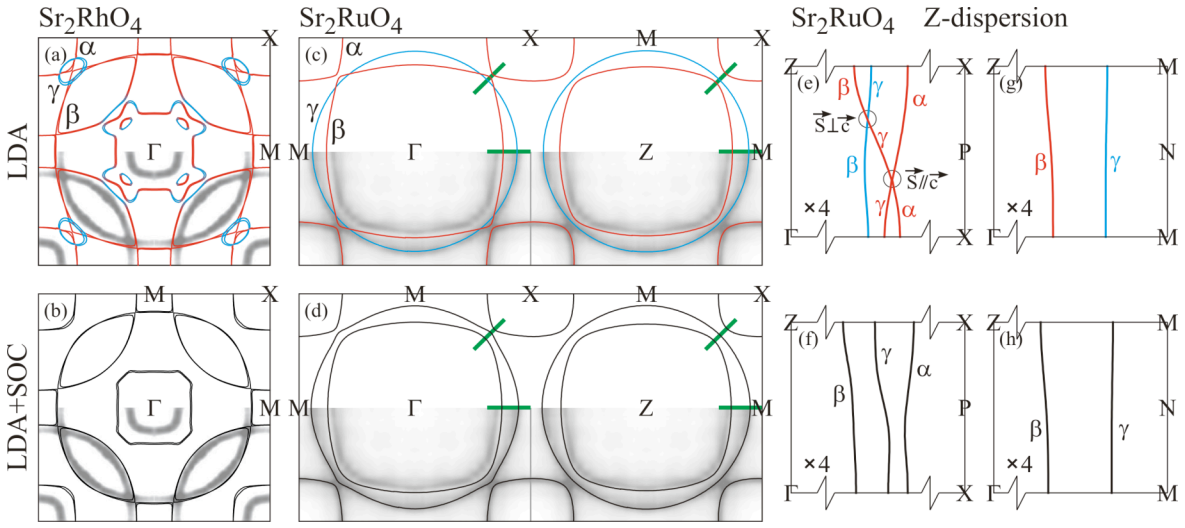

Fig.1. (a,b) LDA Fermi surface of Sr^2RhO4 and (c,d) Sr_2RuO4; (e-h) k_z electronic dispersion for the Sr_2RuO4 cuts highlighted in (c,d) by green solid bars. Calculations were performed without SOC (top panels: a,c,e,g) and with SOC (bottom panels: b,d,f,h). The grey-scale ARPES data are reproduced from (a,b) Kim *et al.* [1] and (c,d) Damascelli *et al.* [2].

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Gaps in Our Understanding of High Temperature Superconductors

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One of the main challenges in the study of the cuprates is to disentangle the rich variety of states of matter that may coexist, cooperate, or compete with d-wave superconductivity. At center stage is the pseudogap phase, which occupies a large portion of the cuprate phase diagram surrounding the superconducting dome. In this talk I will present results of our recent temperature and doping dependent scanning tunneling microscopy investigations of $Bi_2Sr_2CuO_{6+x}$ (Bi-2201). First I will focus on the existence of a new, narrow, homogeneous gap that vanishes near T_C, superimposed on the typically observed, inhomogeneous, broad gap, which is only weakly temperature dependent.[1] Its existence, especially in combination with recent ARPES and Raman measurements, points strongly toward a picture of the high temperature superconductors in which distinct superconducting and pseudogaps coexist below T_C. I will then discuss spatial 'checkerboard' patterns which have been observed widely in the cuprates. We have found a distinct doping dependence of this checkerboard pattern indicating that a charge density wave is its cause. Taken together, these results suggest a need to rethink the nature of pseudogap and its relation to high temperature superconductivity.

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Time reversal symmetry breaking in unconventional superconductors

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The search for broken time reversal symmetry (TRSB) states in the superconducting state of unconventional superconductors intensified in the past year as more systems have been predicted to possess such a state. Following our pioneering study of TRSB state in Sr_2RuO_4 [1], we embarked on a systematic study of several other systems predicted to be candidates of such novel state. The primary instrument for our studies is the Sagnac magneto-optic interferometer, which we recently developed. This instrument can measure magneto-optic Faraday or Kerr effects with unprecedented sensitivity of 10 nanorad at temperatures as low as 100 mK.

In this talk we will review our recent studies of TRSB in several systems. These include recent results on Sr_2RuO_4 [1], the pseudogap state of high temperature superconductors [2], and the heavy fermion systems $URu_2 Si_2$,and $PrOs_4 Sb_{12}$. In addition, we will show new results on the inverse proximity effect in superconductor/ferromagnet bilayer structures supporting the notion of spin screening in the superconducting layer.

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Spectroscopy of electronic reconstructions at oxide interfaces

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We will discuss recent experiments using a combination neutron reflectometry, x-ray spectroscopy, and spectral ellipsometry to probe charge transport as well as magnetic and orbital polarization at oxide interfaces. Of particular interest will be cuprate-manganate [1-3] and nickelate [4] interfaces. The latter experiments indicate an intrinsic metal-insulator transition at the interface driven by charge ordering.

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Octahedral rotation and spin-orbit coupling effects on the electronic structures of 4*d* and 5*d* transition metal oxides.

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The interplay among on-site Coulomb interactions, electronic band structure, and lattice distortions plays an important role in determining the physical properties of transition-metal oxides (TMO) and has been extensively studied. In those studies, lattice distortion effect is thought to be resulting in changes only in the hopping energy *t*. However, lattice distortion can cause a dramatic change in the electronic structure through hybridization between different orbitals.

We investigated the electronic structures of the 4*d* transition-metal oxide compound Sr_2RhO_4 by angle resolved photoemission spectroscopy (ARPES). In the measured Fermi surfaces (FS) of Sr_2RhO_4, the *xy*-band FS sheet expected from the well-established results of the FS of Sr_2RuO_4 is missing. The apparent contradiction is resolved by a careful analysis of the band structure where the rotation of octahedra results in the hybridization of e_g and t_{2g} states and thus plays a key role in the determination of the electronic structure near E_F.

The modification of the FS structure due to the distorted lattice is relevant to the metal-insulator transition in $Ca_{2-x}Sr_xRuO_4$. Band structure calculation indeed show that the RuO_6 rotation leads to orbital-dependent changes in the band structure of $Ca_{2-x}Sr_xRuO_4$. The d_{xy} band near the Fermi level is significantly modified and thereby a severely reconstructed Fermi surface with nested sections appears at x=0.5 while the d_{yz} and d_{zx} bands are found to be insensitive to the rotational distortions induced by the Ca substitution.

In spite of the overall agreement between the experimental and calculated FSs of Sr_2RhO_4, appreciable disagreement is observed between the two. Such disagreement is found to be due to the spin-orbit coupling effect which is enhanced upon the octahedral rotation. Spin-orbit coupling effect is enhanced by briefly discussed with the recent ARPES results on J=1/2 material Sr_2IrO_4.

*This work has been done in collaboration with B. J. Kim, S. J. Oh, J. Yu (Seoul Nat'l Univ.), E. J. Ko, H. J. Choi (Yonsei Univ.), and I. Nagai, S. Ikeda (AIST).

Infrared spectroscopy of electrostatically gated bilayer graphene

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There is growing evidence that electrostatic doping of bilayer graphene results not only in a shift of the Fermi level but also in a significant modification of the low-energy bands. The most important feature to be expected is the opening of a gap due to the difference of the electrostatic potential between the two layers. Provided that such a gap can be controllably tuned to large enough values this could make graphene-based transistors (GraFETs) realizable. At the moment, spectroscopic information about the bands in bilayer graphene is limited. Using infrared microscopy, we measured the optical conductivity of exfoliated bilayer flakes on top of SiO_2/Si. Our data reveal a dramatic dependence of the optical transitions between the four bilayer bands as a function of the gate voltage. The splitting of optical peaks at large gate voltages is consistent with the opening of a gap. By sweeping the voltage from positive to negative values we observe a strong electron-hole asymmetry. Tight-binding calculations including next-nearest neighbor hopping terms can explain many of the optical features. However, the peaks show a strong extra broadening which might be due to electron-electron and electron-phonon interactions.

Microscopic Origin for the Ultrafast Insulator-Metal Phase Transition in VO_2 Studied via Femtosecond Field-resolved Mid-infrared Spectroscopy

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The insulator-metal transition in VO_2 represents an intriguing phenomenon from the field of strongly correlated electron systems [1]. When cooling the compound below the critical temperature of T_L = 340 K, the high-temperature metallic phase transforms into a dielectric while dimerization of V atoms reduces the crystal symmetry from rutile to monoclinic. The microscopic driving force has been a subject of controversy. A structural Peierls instability as well as Coulomb repulsion and charge localization typical of a Mott insulator have been proposed. Ultrafast optical studies of this phenomenon have promised new insight into the time ordering of the microscopic mechanisms. Advanced techniques such as femtosecond X-ray [2] and electron scattering [3] have been applied. However, it turns out that a temporal resolution of 300 fs is not sufficient to monitor the key processes involved. Ultrabroadband THz pulses, in contrast, are able to simultaneously trace lattice polarizability and electronic conductivity on the 10 fs time scale [4]. Consequently, they might serve as an important tool to understand cooperative phenomena in solid-state dynamics. Here, we report the first multi-THz measurements of VO_2 monitoring a femtosecond insulator-metal transition initiated by a 12-fs light pulse [5]. The complex infrared conductivity is sampled via field-resolved spectroscopy with multi-THz transients [6]. The data include the spectral signatures of electronic and ionic degrees of freedom, precisely unraveling their interplay. Our findings motivate a qualitative picture for the ultrafast dynamics of the insulator-metal transition. The model is inspired by recent cluster dynamical mean-field theory treating the strong electronic correlations in the dielectric phase on a two-electron Heitler-London basis for the V-V dimers [7]. In the earliest stage, the dynamics initiated by the femtosecond pulse resembles the local excitation of the dimers into an antibonding state, triggering a coherent wave packet of a V-V stretching mode at 6 THz. At moderate excitation fluence, the strong correlations between the two binding electrons of each dimer are re-established on a subpicosecond time scale and the mid-IR electronic conductivity vanishes rapidly. However, if the density of excited lattice sites exceeds a threshold value, wave packet oscillations and thermal fluctuations drive the system to a point where electronic correlations can no longer be restored and the metallic phase is stabilized. The high speed of the phase transition is explained by the fact that the wave packet motion in the excited state automatically pushes the monoclinic lattice towards rutile symmetry. Interestingly, the electronic conductivity settles to a constant value already after one V-V oscillation cycle while the lattice oscillates coherently for approximately 1 ps. This behavior beyond the Born-Oppenheimer approximation is a clear fingerprint of the strongly correlated character of the electronic system underlying these phenomena.

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Electronically soft matter

Peter Littlewood,[1] Maria Calderon[3], Susan Cox,[1,2] Geoff Milward,[1] Neil Mathur [1], Paul Midgley[1], Ross McDonald[2], Albert Migliori[2] , John Singleton[2],

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The phenomenon of colossal magnetoresistance in manganites is generally agreed to be a result of competition between crystal phases with different electronic, magnetic, and structural order; a competition which can be strong enough to cause phase separation between metallic ferromagnet and insulating charge modulated states. Nevertheless, closer inspection of phase diagrams in many manganites reveals complex phases where the two order parameters of magnetism and charge modulation unexpectedly coexist. I will discuss how such experiments can be naturally explained within a phenomenological Ginzburg-Landau theory, where magnetic and charge modulation coexist in new thermodynamic phases, structured on the nanoscale [1]. It seems possible that this is a general phenomenon, which commonly pre-empts first-order transitions. Remarkably, it is also found that the charge modulated insulating states seem to be better regarded as charge density waves instead of the expected strongly localised striped phases [2,3]. The disjunction of the phenomenology versus the expectations from microscopic models and measurements raises some conundrums about the treatment of strong electron-phonon interactions in oxides.

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Far-infrared response of $BiFeO_3$ and $TbMnO_3$ multiferroic materials

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Mutiferroic materials are compounds that show at least two coexisting ferroic orders (ferroelectric, ferromagnetic, ferroelastic). A particular interest is present in magnetoelectric multiferroics. Those are materials showing concomitant ferromagnetism and ferroelectricity, which are unfortunately present in only a very small number of compounds. In practice, a large interest is given to systems showing ferroelectricity coexisting with *any* type of magnetic order. Although some prototype applications already exist, on the fundamental level the understanding of the physics underlying the coupling between magnetic and dielectric ordering properties is still an open question.

Ferroelectricity is often related to a renormalization of the phonon excitation spectrum, more specifically polar phonons. Far-infrared spectroscopy has a long standing history of spectacular results in the characterization of polar phonons in ferroelectric systems and, in particular, soft modes. In addition, in a magnetoelectric multiferroic, infrared spectroscopy may also be sensitive to coupling between charge (phonons) and magnetic (magnons) channels.

Here, we will present low temperature (4 K to 300 K) polarized infrared (20 cm^{-1} to 5000 cm^{-1}) data on single crystals of $BiFeO_3$ and $TbMnO_3$. In $BiFeO_3$, which has a structural induced ferroelectric transition, we will discuss the phonon dynamics and a possible role of ferroelasticity in the ferroelectric phase transition [1]. Our observations are consistent with a phonon softening in the plane perpendicular to the polar axis. Phonon trends in $TbMnO_3$, where ferroelectricity arises due to magnetoelectric coupling, are less characteristic of typical ferroelectric materials and a relaxor behavior extending into the far-infrared seems to be present. In both systems we will discuss possible magnon signatures.

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Low-Energy Electrodynamics and Metal to Insulator Transition in strongly correlated VO_2, V_2O_3 and V_3O_5 Vanadium Oxides

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[2] *Experimentalphysik 2, Universitaet Augsburg, D-86135 Augsburg, Germany (Eu)*
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The development of the metallic behavior from a correlated insulator represents a paradigm of modern Solid-State Physics. In correlated systems indeed, electronic delocalization is strongly reduced due to coulomb repulsion so that the interplay among competing energy scales, as for instance spin, charge and lattice interactions, might determine different metallic states with exotic physical properties. In particular, the quantum coherence of mobile quasi-particles (QP) is strongly reduced by electronic correlation. This induces at relatively high-temperature a huge loss of spectral weight at low frequency and eventually the disappearance of QP.

Vanadium oxides show rich phase diagrams displaying different low-temperature insulating ground states. These states are connected to high-temperature metallic phases by metal to insulator transitions (MIT) with jumps of conductivity up to 7 orders of magnitude. For instance, in V_2O_3 the MIT is considered as induced mainly by electronic correlation (Mott-Hubbard transition), meanwhile the microscopic mechanisms driving the MIT in VO_2 and in V_3O_5 are still unclear and probably determined by an interplay between electron-phonon (Peierls) and electron-electron (Mott-Hubbard) interactions. Moreover, all those materials show high-temperature metallic phases characterized by short-living QP.

Here we present a complete investigation of those MIT as a function of T and P, by measuring the optical properties of single crystals of VO_2, pure and Cr-doped V_2O_3 and V_3O_5. In order to cover the rich phase diagrams of those materials, reflectivity measurements have been performed in a wide range of temperature (10-600 K) and pressure (0-15 GPa), using conventional and synchrotron infrared radiation coupled with a Michelson interferomer.

The experimental data will be compared with theoretical results based on DMFT+LDA calculations as well as with photoemission and resistivity results so to better understand the microscopic MIT mechanisms associated to the peculiar properties of vanadium oxides.

Spectral properties of gated graphene

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We will report on a theoretical study [1] of the influence of electron-electron interactions on ARPES spectra in finite-carrier-density graphene sheets. The study is based on the random-phase-approximation and on graphene's massless Dirac equation continuum model. Special attention will be given to explaining the unususal character of plasmonic collective excitations in graphene sheets. We find that level repulsion between quasiparticle and plasmaron resonances gives rise to a gap-like feature in ARPES spectra near the Dirac point. ARPES spectra are sensitive to the electron-electron interaction coupling strength and might enable an experimental determination of this important material parameter. We will also comment briefly on the influence of disorder and electron-electron interactions on the ac conductivity and magnetoconductivity of graphene sheets.

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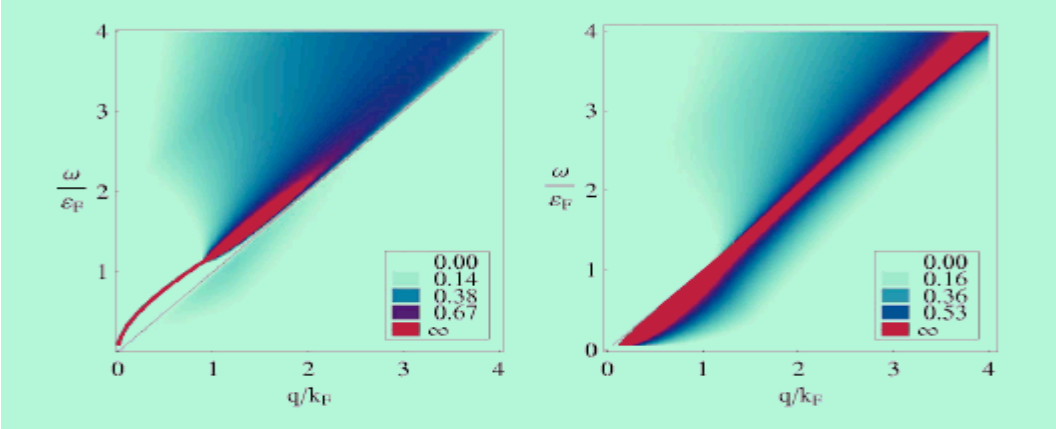

Fig.1. Excitation spectrum of a doped graphene sheet as a function of wavevector and energy. Left panel: an interacting graphene sheet with coupling constant $\alpha_{gr} = 2$. The red solid line is the plasmon dispersion relation. Right panel: The non-interacting limit.

Colossal Magnetoresistive Manganites and High Temperature Superconductors: so different, … yet so similar

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In this talk, I will discuss the results of some recent angle-resolved photoemission spectroscopy (ARPES) investigations in the prototypical colossal magnetoresistive (CMR) bilayer compound $La_{1.2}Sr_{1.8}Mn_2O_7$ (LSMO, x = 0.4) [1,2].

Our results allowed elucidating the controversial nature of the ferromagnetic metallic (FM) groundstate in LSMO by showing that the FM phase is a polaronic metal, albeit with a strong anisotropic band structure. Its electronic structure has been found to be strikingly similar to that of the pseudogap phase in heavily underdoped cuprates high temperature superconductors [3]. In particular, the distribution of spectral weight in momentum space exhibits a nodal–antinodal dichotomous character. The spectra along the parallel sections of the Fermi surface (FS) (antinodal) exhibit a pseudogap. On the other hand, quasiparticle excitations (QP) have been detected for the first time along the nodal direction (i.e. diagonal), and they are found to determine the metallic transport properties in the FM phase. This dichotomy between the electronic excitations along the nodal and antinodal directions in momentum space was so far considered a characteristic unique feature of the copper oxide high-temperature superconductors (HTSC). These findings therefore cast doubt on the assumption that the pseudogap state and the nodal-antinodal dichotomy in the copper oxides HTSC are hallmarks of the superconductivity state.

Furthermore, we found that the temperature dependent evolution of the nodal QP in LSMO tracks remarkably well the DC conductivity, thus accounting for the macroscopic transport properties and the metal to insulator transition [2]. Our results indicate that the microscopic mechanism leading to the MIT and the CMR effect in manganites is intrinsically a quantum effect linked to a crossover via the nodal QP collapse from a coherent polaronic conductor in the FM state below T_C to a hopping regime with thermally activated single polarons in the paramagnetic state above T_C. The role of the exchange interaction is crucial in controlling the competition between coherence and localization effects.

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The Electron Gas at the $LaAlO_3/SrTiO_3$ Interface: Ground State, Carrier Generation Mechanism, and First Devices

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Highly conducting electron gases can be induced at interfaces in oxide heterostructures. A prime example for such heterostructures are bilayers of $LaAlO_3$ and TiO_2-terminated $SrTiO_3$ [1]. At the interface between these layers an *n*-type electron is generated if the $LaAlO_3$ thickness exceeds 3 unit cells [2]. This electron gas is a superconductor with a T_c~200 mK [3].

In the presentation we will report on experiments that analyze the mechanism generating the electron gas and we will discuss its ground state. Further, first, exploratory devices will be presented that utilize the unique properties of these electron systems.

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IR Spectromicroscopy of Charge Injection in Graphene and Organic FETs

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We report on infrared (IR) spectromicroscopy of the electronic excitations in nanometer-thick accumulation layers in field-effect transistor (FET) devices based on grapheme [1], poly(3-hexylthiophene) (P3HT) thin films [2] and rubrene singe crystals [3]. IR imaging allows us a contact-less method to explore the charge injection landscape in these FET devices at relevant length scales for the charge accumulation layer, and/or for small single crystal samples, using the high spatial resolution of a synchrotron light source. For monolayer graphene samples, we observe significant deviations of the electromagnetic response of our transistors from predictions made for Dirac quasiparticles expected in idealized, free standing graphene. We identify and discuss several factors that may be responsible for the rather exotic quasiparticle dynamics in realistic graphene samples integrated in the FET architecture. IR spectromicroscopy of the mobile holes in the accumulation layer of rubrene-based FETs reveal that the charge transport in these devices are governed by light quasiparticles in molecular orbital bands without prominent polaronic effects at room temperature. These studies demonstrate the unique potential of IR spectroscopy for the investigation of physical phenomena at the nanoscale occurring at the semiconductor-insulator interface in variety of FET devices.

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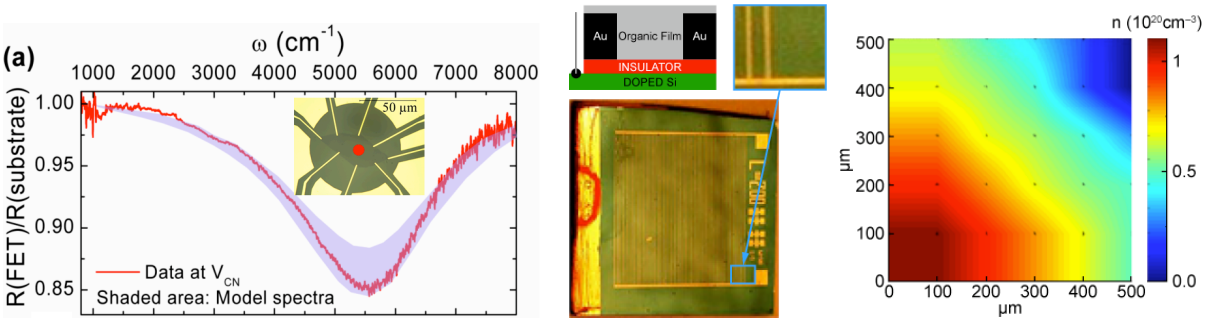

Fig.1. Left: Graphene sample and its reflectivity. Right: Organic FET is carrier density.

Neutron and ARPES evidences for 2 energy scales in $La_{2-x}Sr_xCuO_4$

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While the momentum and energy dependent susceptibility as measured by inelastic neutron scattering on optimally doped high-temperature superconductors (HTSC) can be reasonably well understood within the frame work of Fermi liquid theory, understanding that of the underdoped regime remains a challenge. Using high-resolution neutron scattering combined with high-magnetic fields, we show that the value of the spin-gap Δ_{SG} at the incommensurate wavevector $(\pi,\pi+\delta)$ in the underdoped regime of $La_{2-x}Sr_xCuO_4$ (LSCO) scales with T_c [1] (see Figure 1). This is in strong contrast with the doping dependence of the gap maximum as measured from angle resolved photoemission (ARPES). In order to resolve this apparent contradiction we performed ARPES measurements on the crystals used for the neutron experiments. Our results [2] differ considerably from what has been published earlier [3]

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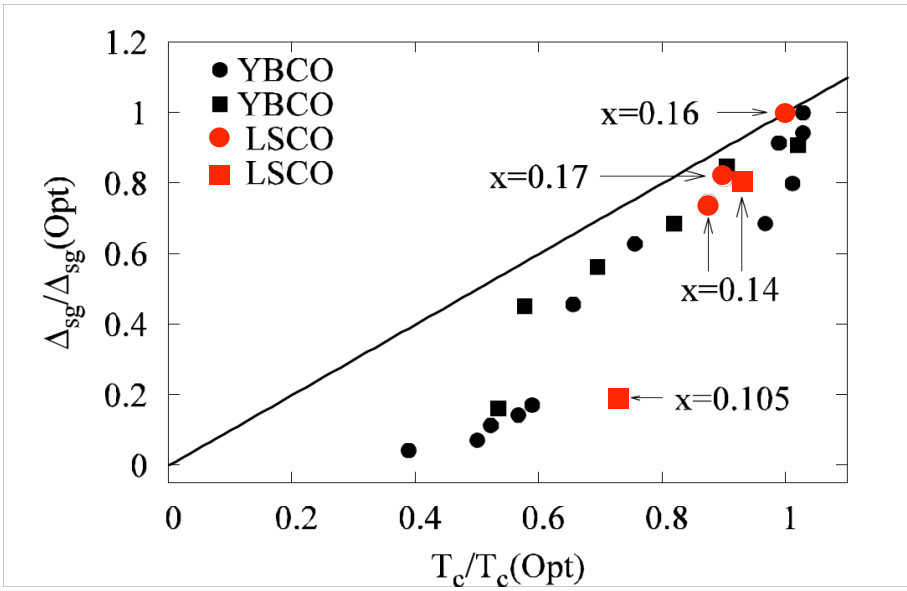

Fig.1. Normalized Δ_{SG} versus normalized T_c for LSCO (red symbols) and YBCO (black symbols) [1].

Transport at the charge neutrality point in single- and bi-layer graphene

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Single- and bi-layer grapheme are two recently discovered two-dimensional zero-gap semiconductors, which exhibit a variety of unique electronic phenomena. In this talk I will discuss the transport properties through these systems, focusing on the regime in which the Fermi level is close to the charge neutrality point where valence and conduction band touch. Despite the vanishing (for ideal systems) density of states at this point, the conductivity of single- and bi-layer grapheme is finite. This counterintuitive and unique phenomenon is of great fundamental interest, as the understanding of conduction in systems where all the bands are either completely filled or completely empty remains to be established. At the same time, the finite conductivity poses a problem for the utilization of graphene-based materials in electronic applications such as field-effect transistors, since it prevents devices to be switched off. Here, I will first show experimentally how it is possible to open a band-gap controllably in graphene bi-layers, in order to induce an insulating state. After addressing briefly the possibility to use the induced gap in bi-layer graphene to achieve topological confinement, I will proceed to show that in a single layer grapheme not only the conductivity at the charge neutrality point is finite, but also the supercurrent. I will conclude by discussing shot noise experiments in ballistic grapheme devices, providing evidence for a specific mechanism responsible for the conductivity at the charge neutrality point, namely the presence of evanescent waves.

The work presented here has been done in collaboration with a number of persons, including J.B. Oostinga, L.M.K. Vandersypen, S. Russo, M.F. Craciun, R. Donneau, P.J. Hakonen, P. Jarillo-Herrero, H.B. Heersche, and it is discussed in the following articles

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Cooperative interplay between spin-orbit coupling and electron correlation and the realization of novel J_{eff}=1/2 Mott insulator in layered iridates

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Mott physics has been successfully adopted to explain physical properties of 3*d* transition metal oxides (TMOs). The electronic ground state becomes a Mott insulator when the on-site Coulomb repulsion surpasses the bandwidth, which is the case of spatially localized 3*d* TMOs. On the other hand, 5*d* TMOs are expected to have much weaker on-site Coulomb repulsion due to their extended nature of electron wavefunctions, so we expect that most 5*d* TMOs should have metallic ground states. However, there exist numerous insulating 5*d* TMOs, including $Cd_2Os_2O_7$, Ba_2NaOsO_6, and Sr_2IrO_4 [1-3]. How can such insulating states appear in 5*d* TMOs? Can electron correlation also play an important role in spite of its small value in 5*d* TMOs?

Interestingly, anomalous insulating ground states of 5*d* TMOs were reported in layered iridates, i.e., Sr_2IrO_4 and $Sr_3Ir_2O_7$ [3, 4]. For 5*d* TMOs, the on-site Coulomb repulsion is expected to be weak, but the spin-orbit (SO) coupling is expected to be large and play a important role for their properties. However, little is known at present about the role of SO coupling for their physical properties. In this presentation, we will present how the combined effects of the SO coupling and the on-site Coulomb repulsion could make the insulating ground states of the layered iridates.

We investigated the electronic structures of Ruddlesden-Popper series $Sr_{n+1}Ir_nO_{3n+1}$ (n=1, 2, and ∞) compounds with optical spectroscopy and first-principles calculation. From the comparison between optical conductivity spectra $\sigma(\omega)$ and the results of first-principles calculation, we found that the ground states of layered iridates should have different characteristics to those of a typical S=1/2 Mott insulator. Due to the large value of the SO coupling, total angular momentum should be a good quantum number instead of the spin. We demonstrated that the ground states of layered iridates can be represented by J_{eff}=1/2 Mott insulator, which can be stabilized by the cooperative interplay between SO coupling and on-site Coulomb repulsion. This interplay might be the reason why we can observe some insulators in 5*d* TMOs.

We also performed a systematic studies on how bandwidth change can affect the electronic structures of the J_{eff}=1/2 Mott insulator system. We measured the electronic structural changes from insulator (n=1 and 2) to metal (n=∞) in $Sr_{n+1}Ir_nO_{3n+1}$, and found that they are quite different from those of 3*d* or 4*d* S=1/2 systems. These electronic structure changes provide another evidence that $Sr_{n+1}Ir_nO_{3n+1}$ should be considered as the J_{eff}=1/2 weakly correlated narrow band system. We will also discuss how the intriguing electronic structure of J_{eff}=1/2 Mott insulator can change with temperature.

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*This work has been done in collaboration with J. Yu (Seoul Nat'l Univ.), J.-H. Park (POSTECH), C. Kim (Yonsei Univ.), S.-J. Oh (Seoul Nat'l Univ.), G. Cao (Univ. of Kentucky), and H. Funakubo (Tokyo Institute of Tech.).

Fermi Arcs and Fermi Pockets

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In the pseudogap phase of underdoped cuprates, ARPES reveals that the large hole-like Fermi surface is truncated below T*, leaving behind gapless "Fermi arcs" [1]. These arcs have a linear dependence on temperature above T_c [2], but collapse suddenly to the point nodes of the d-wave superconductor below T_c [3]. Recently, de Haas – van Alphen data on underdoped YBCO have instead revealed the presence of small Fermi pockets above the resistive H_{c2} [4] associated with a negative Hall number [5]. How can these two contrasting results be reconciled? Here, we describe theories based on lifetime broadening of a paired d-wave state as a possible origin for the arcs [6,7]. On the other hand, the pockets can be reproduced if we instead assume a field induced incommensurate spin density wave state associated with the proximity to x=1/8 doping [8]. The relation between these two pictures will be speculated upon.

[1]Work supported by the US DOE, Office of Science, under Contract No. DE-AC02-06CH11357.

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Spin propagation in the two-dimensional electron gas: observation of the persistent spin helix

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Spin excitations in a nearly-free electron gas are well described by the quasiparticle picture. In particular, a spin excitation of wavevector q has a lifetime Dq^2 in the diffusive regime, *i.e.* when $ql<1$, where l is the electron mean free path. The infinite lifetime in the limit that $q \rightarrow 0$ reflects conservation of total spin. Recently, there has been tremendous interest in the modifications of spin dynamics caused by strong spin-orbit (SO) interactions, which lead to spin nonconservation. In QW's of III-V semiconductors there are two contributions to the SO Hamiltonian, known as the Rashba and Dresselhaus terms. Both operate on the electron spin as effective magnetic fields that depend on the Bloch wavevector of the electron. Spin relaxation occurs as a consequence of interrupted spin precession in these SO effective fields, which cause decay of the q=0 spin memory at the Dyakonov-Perel (DP) rate $1/\tau_s \sim \Omega^2\tau$, where Ω is the precession rate and τ is the mean-free-time between collisions. In the past, it was often assumed that the effect of SO coupling could be described, at least phenomenologically, simply by adding a spin relaxation rate $1/\tau_s$ to the diffusive lifetime Dq^2. More recently it was recognized that, in theory, certain SO interactions in QW's could result in more complex and far more interesting spin dynamics. Because of the entanglement of the spatial and spin degrees of freedom, the DP and diffusive rates do not simpy add. One of the most dramatic consequences of spin/orbit correlations is the prediction that when the Rashba and Dresselhaus terms are equal the Hamiltonian recovers SU(2) symmetry, albeit with a new set of spin operators. These operators correspond to new conserved quantities, one of which is a helical spin polarization at a specific nonzero wavevector ("a persistent spin helix"). In this talk I will report on the observation of a strongly enhanced spin lifetime at nonzero wavevector in a series of GaAs/GaAlAs QW's. The measurements are performed using the transient spin grating technique, whereby spin polarization waves are created and detected in the 2DEG by interfering two coherent, orthogonally polarized light pulses. I will describe the behavior of the spin helix lifetime as a function of both Dresselhaus and Rashba coupling, wavevector, disorder, and temperature.

Frontiers of time resolved experiments in condensed matter with EUV and X-ray Free Electron Laser

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The advent of new laser sources capable to provide very short e.m. pulses from the infrared to the extreme ultraviolet region has opened a new gate to study the radiation-matter interaction in the time domain. The large number of pioneering studies is this field is the background that stimulated the studies of new coherent synchrotron radiation light sources, based on the free electron physics, to provide sub-ps and sub-fs electromagnetic radiation pulses with unique behavior.

The advent of these new sources will open the gate to study selective excitations (charge transfer and phonons) to study transient states and photo-induced phase transitions in superconductors (dynamics of quasi-particles, photon-boson interactions and the interplay between magnetism and superconductivity), magnetic materials (dynamics of the magnetic excitations) and electron correlations in hard- and soft- condensed matter (charge transfer and phonon assisted excitations).

Magnetoelectric Effects and Excitations in Rare-Earth Manganites

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Most interactions in physics are accompanied by characteristic excitations, which can be observed with spectroscopic techniques as absorption modes. The excitations responsible for the magnetoelectric coupling are called "electromagnons" and can be observed at terahertz frequencies [1]. Contrary to the conventional magnons the electromagnons are excited by the electric component of the electromagnetic wave only and contribute to the static dielectric permittivity. The suppression of electromagnons in external magnetic field provides a natural explanation for the magnetoelectric effects in broad frequency range between dc and terahertz. The corresponding spectral weight is transferred to the lowest lattice vibration [2] demonstrating the strong coupling of phonons with electromagnons. I will compare results obtained on different multiferroics and discuss recent problems and developments in this field.

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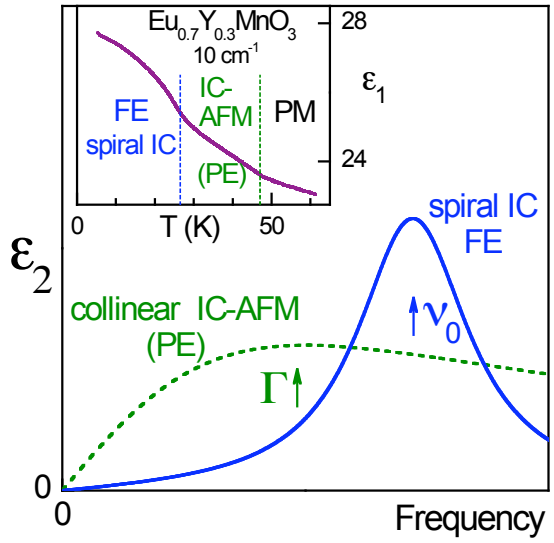

Fig.1. Schematic representation of the terahertz spectra of magnetoelectric manganites. Paramagnetic (PM) phase shows no magnetoelectric contribution; collinear incommensurate-antiferromagnetic (IC-AFM) and paraelectric (PE) phase reveals a broad Debye-like response; in a spiral ferroelectric (IC-FE) phase well-defined electromagnons are observed. Arrows indicate the damping of the relaxator Γ and the eigenfrequency of the electromagnon ν_0. The inset shows the temperature dependence of the dielectric constant of $Eu_{0.7}Y_{0.3}MnO_3$ at low-frequencies as an illustration of the discussed behavior.

Femtosecond Spectroscopy from Terahertz to X-rays: Time-resolved Studies of Phase Transition Dynamics in Strongly Correlated Electron Systems

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One of the current scientific frontiers in physics and chemistry deals with the measurement of microscopic atomic, electronic and magnetic dynamics on femtosecond timescales. Ultrashort laser, electron and x-ray pulses are allowing for increasingly sophisticated measurements, capable of exciting and probing selectively different degrees of freedom (lattice, spin, orbital, charge) on the elementary timescale of atomic motion.

In this talk, I will discuss our recent contributions in this area, motivated by the effort to understand the non-equilibrium and coherent dynamics of complex solids. We control and interrogate such dynamics by deploying the full spectral range of modern femtosecond science, from Terahertz to X-rays. I will review our time-resolved studies on insulator-metal transitions in strongly correlated electron systems, including the spin-Peierls compound VO_2 [1] and colossal magnetoresistive manganites [2]. Phase transition dynamics in these systems are studied by a combination of femtosecond visible-to-midinfrared pump-probe techniques, transport measurements and time-resolved X-ray spectroscopy. Finally, I will present our recent work which shows that an insulator-metal transition can be stimulated in manganites by selective excitation of vibrational degrees of freedom [2] (see Fig. 1 (b)). The ultrafast vibrational control of correlated-electron phases may provide new insights into the role played by lattice vibrations in determining the electronic properties of complex solids.

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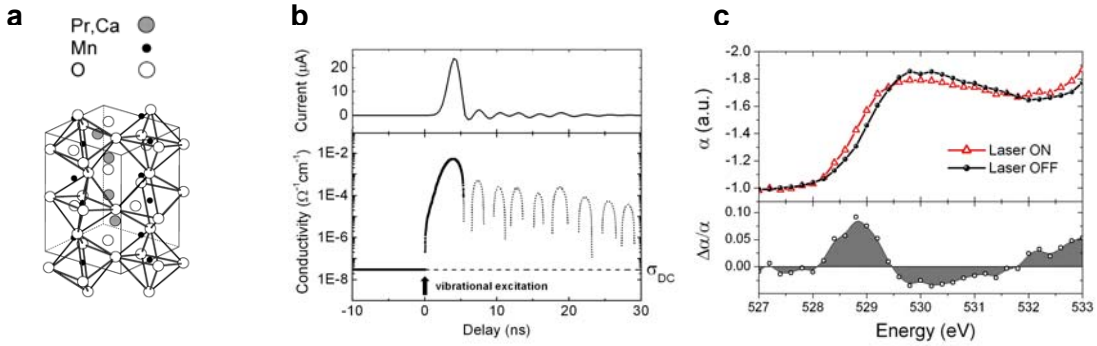

Fig.1. IM phase-transition in the CMR manganite $Pr_{0.7}Ca_{0.3}MnO_3$ (PCMO)**.** (a) Perovskite crystal structure of PCMO. (b) 5-order-of-magnitude changes in sample resistivity are observed when the Mn-O stretching phonon mode is resonantly excited by 17-μm laser pulses [2]. (c) Time-resolved XANES experiments at the O-K edge. Laser off: static O-K edge spectrum. Laser on: measured 300 picoseconds after 800-nm excitation. Lower panel: relative photoinduced change of absorption ($\Delta\alpha/\alpha$) as a function of photon energy.

Quantum dynamics and infrared absorption of H_2 molecule trapped inside a C_{60} cage.

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Encapsulation of H_2 inside C_{60} cage [1] has created an interesting quantum object where it is possible to study coupling between different degrees of freedom [2]. The surrounding C_{60} cage not only quantizes translational motion of H_2 but couples translational and rotational degrees of freedom. Quantum statistics separates H_2 into two weakly interacting subsystems: para-H_2 with total nuclear spin I=0 and ortho-H_2 where I=1.Because of symmetry para-H_2 has states with even rotational quantum number J and ortho-H_2 odd J. Isolated H_2 molecule does not have electric dipole moment and therefore vibrations and rotations are not infrared active. In the gas phase the dipole moment of H_2 is induced in binary collisions between molecules. The collisions broaden infrared absorption lines and hamper high resolution spectroscopy.

In this contribution we will show T dependence of $H_2@C_{60}$ infrared absorption spectra from 5 to 300K. Inside C_{60} the dipole moment of H_2 is induced by translational motion in a nearly spherical potential. The broadening effect of absorption lines due to anharmonic corrections to the trapping potential is small. All C_{60} cages are alike and therefore the inhomogeneous broadening of spectroscopic lines is eliminated. Main transitions are observed when vibrational and translational quantum numbers change by ±1 and rotational quantum number changes by 0 or +2. Anharmonic corrections to the trapping potential and translational-rotational coupling constants are calculated. Intensities of infrared absorption lines are in good agreement with theory.

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Many Body Effects in Graphene and Related Materials

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Graphene, a single layer of carbon atoms arranged in a honeycomb lattice, is the building block of fullerenes, nanotubes, graphite, and other mesoscopic forms of carbon. Because of the novel physics, including massless, relativistic Dirac carriers, and its excellent electronic properties, including high mobility at room temperature, graphene has received intense attention.

The many-body interactions in graphene are therefore of fundamental interest. Angle-resolved photoemission spectroscopy (ARPES) is a premier tool for determining the bandstructure and many-body interactions. Our research has focused on the relative role of electron-electron, electron-plasmon, electron-phonon interactions and defect scattering. This is because ARPES can in principle determine the complex self energy function S, whose real and imaginary parts are related through Kramers-Kronig transformation in similar fashion as the components of optical conductivity.

In this talk, I will focus on two topics: First, demonstration of self-consistency in the analysis of graphene ARPES data, from which we will conclude that many-body interactions must dominate the anomalous band dispersion[1, 2] around the Dirac crossing energy (at which the graphene density of states vanishes). Second, I will focus on the details of the electron-phonon defect scattering rates for graphene as a function of doping. Here we show that there is an anomalously strong electron-phonon coupling strength, a factor of around 5 times larger than predicted by theory. Such coupling suggests a new importance for the coupling of carbon vibrations to carbon π electrons for random and ordered K and Ca layers on graphene, which are single-monolayer models for the superconducting intercalated graphite compounds KC_8 and CaC_6. We also discuss preliminary measurements of the defect scattering rate in graphene.

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Gaps in Cuprates

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A clear identification of the superconducting gap is a fundamental open issue in the physics of high-Tc superconductors. Here, we present an electronic Raman scattering study of cuprates, as a function of both doping level and temperature. We examine both the evolution of the gaps close to the nodes and at the antinodes in the superconducting and normal states. On the deeply over-doped side, both the anti-nodal and nodal Raman responses are consistent with a picture of a single like-BCS superconducting gap. In contrast, on the under-doped side, our results reveal the existence of a break point close to optimal doping below which the anti-nodal gap is gradually disconnected from superconductivity. The nature of both the superconducting and normal states is distinctly different on each side of this breakpoint and will be discussed.

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[2]. M. Le Tacon, A. Sacuto, A. Georges, G. Kotliar, Y. Gallais, D. Colson, A. Forget, "Two Energy Scales and two Quasiparticle Dynamics in the Superconducting State of Underdoped Cuprates", Nature Physics **2**, 537, 2006.

Domain Walls as Quantum Wires in Graphene-like Structures

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We discuss under which circumstances domain walls between different patterns of dimerization in two-dimensional graphene-like structures can support low energy electron excitations. We argue that, in parity and time-reversal preserving systems, these excitations are pairs of right- and left-moving electrons which are confined to and travel along the one-dimensional domain boundaries. They in turn have strong coupling dynamics which can result in formation of a charge density wave which is confined to the boundary and gaps their spectrum, or they can remain gapless and form a Luttinger liquid with a large room temperature conductivity.

Polaron Formation in Undoped Cuprates as studied by X-Ray Absorption and ARPES

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We present recent results from x-ray absorption spectroscopy (XAS) and angle-resolved photoemission spectroscopy (ARPES) studies of a variety of undoped cuprates. In order to better understand the nature of the quantum many-body interactions of a single hole in the antiferromagnetic charge transfer insulator, we studied the temperature dependence of the XAS and ARPES spectra over a wide temperature range, work that was made possible by the high resolution soft x-ray beamline at the Canadian Light Source. By comparing the anomalously large temperature dependence of the oxygen K edge absorption with the dependence of the lower Hubbard band from ARPES, we speculate on the coupling between the photohole and both the lattice and magnetic/charge degrees of freedom.

Magnetic field phase diagram of electromagnon excitations in multiferroic manganites

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The temperature and magnetic field dependence of the far infrared (5-250 cm^{-1}) spectra of multiferroic manganites RMnO$_3$ is presented. As we pointed out before [1], for the RMnO$_3$ family, strong electromagnon absorptions only occur for applied electric field of light $e||a$, independent of the spin plane. This experimental fact is in contrast to the prediction of the spin-current model [2] that is commonly used to explain the appearance of ferroelectricity in the spiral phase of these manganites. This suggests that: 1) the electromagnon absorption does not originate from the same mechanism as the ferroelectricity and, thus, originates from the frustrated Heisenberg interactions in the system, or 2) both electromagnon and polarization in fact originate from magnetoelectric interactions of the Heisenberg type. Therefore a different mechanism for the appearance of electromagnons is required for this family of multiferroics. In H||c for both $Eu_{0.75}Y_{0.25}MnO_3$ and $TbMnO_3$ the electromagnon absorptions disappear slowly with increasing field and above 6 T electromagnons show reentrant behavior as a function of temperature. This behavior is also seen in the static polarization, which strongly suggests a common origin for electromagnons and ferroelectricity. Additionally, a magnon observed as an $h||a$ antiferromagnetic resonance (h is magnetic field of light) is observed to slowly disappear in field and around 6 T its frequency jumps suddenly indicating an additional magnetic transition at this value of field. However for H||b in TbMnO3, even though the spiral plane and polarization rotate, the electromagnons do not; confirming that the spin-current picture does not apply to electromagnons. Additional features of the phase diagrams and a discussion of the possible origin for electromagnons, and the role of the infrared active phonons will be presented.

We acknowledge support from NSF MRSEC under grant DMR-0520471.

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"Kinks", Gaps and Pseudogaps in Cuprate Superconductors

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In conventional metals, electron-phonon coupling is the pairing interaction responsible for the superconductivity. In these materials, a transition into a superconducting state is accompanied by opening of an energy gap in the electronic spectrum, indicating pairing of electrons into Cooper pairs. Both the coupling and the gap are directly observable in a modern photoemission experiment: a clear manifestation of electron-phonon coupling is a mass renormalization of the electronic dispersion ("kink") at the energy scale associated with phonons, while the gap is seen as an energy shift of an electronic state from the chemical potential.

Both "kinks" and gaps have also been detected in cuprate high temperature superconductors. However, the situation in cuprates is much more complex: there are multiple "kinks" and multiple possible explanations for them and there are gaps in both the superconducting and normal states. Here, we will discuss some elements of this complexity.

Polaron liquid in electron doped srontium titanate

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The strength of electron-phonon coupling and its possible impact on the electronic structure is subject of intensive investigation. It is particularly hotly debated in the context of high temperature superconductors, where many experiments indicate the presence of an electron-phonon coupling of intermediate strength. Nevertheless the question remains to be clarified whether electron-phonon interactions play any role at all in the pairing mechanism, in particular whether it strengthens or weakens superconducting correlations. The debate is fuelled by the observation that superconductivity in the cuprates occurs in close proximity to a Mott-Hubbard insulating state with anti-ferromagnetic order, as well as the fact that superconducting order is found to have d-wave symmetry, all of which points more in the direction of a purely electronic or spin-fluctuation driven mechanism.

Electron doped strontium titanate can in several respects be regarded as the Drosophila (or fruitfly) of electron-phonon interaction in transition metal oxides with the perovskite structure, first and foremost because a metallic state with high mobility is obtained by electron-doping the pristine material, which is an ordinary band insulator.

Our optical conductivity spectra[1] at low temperature show a narrow zero-frequency mode, representing the coherent motion of the free charge carriers, and an 'incoherent' mid infrared band the line-shape and intensity of which are traditionally associated with polaronic charge carriers. Upon increasing the temperature, our data show an increase of the mid-infrared spectral weight, and a decrease of the same amount of Drude spectral weight, contrary to the expectation that thermal fluctuations undo the self-trapping and reduce the effective mass. A similar trend has been recently reported for CMR materials using photo-emission[2] and STM [3]. This behaviour, which is opposite to that of an isolated polaron, may signal that the low temperature state of matter is a polaron liquid.

[1]. Electron-phonon interaction and charge carrier mass enhancement in SrTiO3
J.L.M. van Mechelen, D. van der Marel, C. Grimaldi, A.B. Kuzmenko,
N.P. Armitage, N. Reyren, H. Hagemann, and I.I. Mazin,
Phys. Rev. Lett., in press (2008); arXiv: 0712.1607

[2]. Polaron coherence condensation as the mechanism for colossal magnetoresistance in layered manganites
N. Mannella,W. L. Yang,K. Tanaka,X. J. Zhou,H. Zheng,J. F. Mitchell,J. Zaanen,T. P. Devereaux,N. Nagaosa,Z. Hussain,and Z.-X. Shen,
Phys. Rev. B 76, 233102 (2007)

[3]. Silvia Seiro, thèse, Université de Genève (2008)

Multiferroicity in Charge and Orbital Ordered Manganites

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I will discuss multiferroicity driven by different forms of charge and orbital ordering, with a focus on manganites. A number of generic mechanisms can induce ferroelectric ordering in magnetic charge ordered materials [1]. Multiferroic manganites include (i) the perovskites of the type $(PrCa)MnO_3$, and (ii) the complex and interesting situation in manganites of the type RMn_2O_5, where R is a rare earth element. In the former combined charge and orbital ordering leads to ferroelectricity [2], in the latter the ferroelectricity is completely induced by magnetism, but with charge ordering playing important role [3]. We show that in these materials electronic correlations decimate the intrinsic ferroelectric polarization. Such is manifest from bandstructure computations that account for the strong local Coulomb interactions between the manganese 3d electrons --the root of magnetism in these materials. When including these, the computed electronic, magnetic and lattice structure of multiferroic $HoMn_2O_5$ results in an amplitude and direction of polarization that is in accordance with experiment. The microscopic mechanism behind the decimation is a near cancellation of the ionic polarization induced by ferroelectric lattice displacements and the electronic one caused by valence charge redistributions, see Figure 1. [4].

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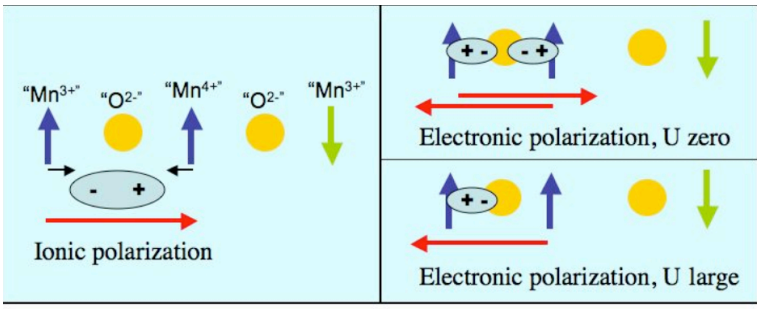

Fig 1. *Schematic view of the two contributions to the ferroelectric polarization in $HoMn_2O_5$ in the uncorrelated (U=0) and strongly correlated limit (large U). In the latter the electronic polarization nearly cancels the ionic polarization. The labels "$Mn^{4+/3+}$" indicate Mn ions that have a valence of more/less than 3.5+, respectively.*

Time-resolved ARPES Studies of Correlated Materials

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The electronic properties of highly correlated materials are often governed by strong electron-phonon coupling and correlation effects leading to phenomena like formation of charge density waves (CDW), metal insulator transitions and pairing in superconductors. When an ultrashort laser pulse induces a non-equilibrium in the system the response and relaxation of electron-electron correlations and the phonons occurs typically on different timescales.

Here we use femtosecond time-resolved photoemission (TR-PES) to investigate the time evolution of electronic structure in the Mott insulator 1T-TaS_2 and demonstrate that the photoinduced insulator to metal transition is driven directly by electronic excitation as revealed by the instantaneous collapse of the electronic gap [1]. A coherently excited lattice mode results in a periodic shift of the spectra (charge density breathing mode), which is lasting for 20 ps without perturbing the insulating phase. These findings clearly demonstrate that the metal-insulator transition in TaS2 follows a Mott-Hubbard and not a Peierls-type mechanism

In the high T_c cuprate Bi2212 we observe an ultrafast (<50 fs) electron thermalization and cooling of the electronic temperature on two distinct timescales. This observation of a bottleneck in the energy flow suggests that only a minor subset (20%) of all phonon modes contribute to the e-ph coupling with an interaction strength which is strongly anisotropic but weak [2]. Finally, I will briefly address some recent work on $TbTe_3$, where we study the anisotropic electron dynamics in this CDW compound.

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Electronic Origin of Inhomogeneous Pairing Interaction in High-Tc Superconductor BiSrCaCuO

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We have developed a number of new techniques based on variable temperature scanning tunneling microscopy/spectroscopy to visualize pair formation in BiSrCaCuO [1] and probe its origin [2] on the nanometer scale in this compound. Focusing first on optimal and overdoped side of the phase diagram, these experiments show that pairing gaps nucleates in small nanoscale puddles that form over a range of temperature above Tc. With decreasing temperature the number of nanoscale regions that show local d-wave pairing increases, the observation of which provides a microscopic explanation of the onset of Nernst and diamagnetic signals above Tc measured on the same samples. More detail analysis of the spectra as function of temperature in each of the nanoscale puddles also enable us to probe the origin of the pairing modulations. We show that the local strength of pairing is controlled by the unusual asymmetric electron-hole excitation of the normal state. With decreasing doping, the shape of the tunneling spectra no longer follows a simple d-wave form, in particular, the spectra often show a kink at lower energies. These kink have their own distinct distribution of values as compared with the larger gap features. With decreasing doping, we also observe static, non-dispersing electronic modulations [3], which further complicates the interpretation of physics of underdoped samples.

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[2] Pasupathy et al. Science 320, 196 (2008).
[3] Vershinin et al Science 303, 1995, (2004).

Poster Abstracts

Quasiparticle Evolution and Pseudogap Formation in V_2O_3: An Infrared Study

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Vanadium sesquioxide (V_2O_3) and its derivatives have been extensively studied in the past decades as the canonical Mott-Hubbard systems [1]. While vanadium oxides alloys doped with chromium $(V_{1-x}Cr_x)_2O_3$ allow to probe the metal to insulator transition (MIT) both T and P-driven without a change in crystal symmetry [2], in the pure sample the MIT is accompanied with a change in the crystal structure from a corundum to a monoclinc unit cell and induced by T only [3].

We present normal-incidence reflectivity measurements performed on single crystals of V_2O_3 in the whole phase diagram, in particular in the so-called "crossover-regime" at high T.

Quasiparticles appear above the Néel temperature T_N and eventually disappear further enhancing the temperature, leading to a pseudogap in the optical spectrum above 425 K. Comparing our spectroscopic results with theoretical calculations, we demonstrate that the high-T loss of coherence can be explained only if the temperature dependence of lattice parameters is considered.

We therefore attribute the pseudogap formation in V_2O_3 to the temperature dependence of lattice constants, which gives a small shrinkng of the LDA bandwidth upon heating. The effect is however dramatic, as the change in the lattice parameters effectively drives V_2O_3 into the "insulating" side of the Mott transition [4].

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Metamagnetic quantum criticality in $Sr_3Ru_2O_7$ probed by microwave spectroscopy

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Electrical resistivity measurements on $Sr_3Ru_2O_7$ indicate the presence of a metamagnetic quantum critical point in the temperature-field phase diagram, near a field of 7.8 tesla, for B parallel to the c axis. [1] Near this field the material undergoes a transition to a new electronic phase, a nematic fluid, that is characterized by the emergence of a spontaneous electronic anisotropy within the RuO_2 layers. [2]

Measurements of resistivity $\rho(T) = m^*(T)/ne^2\tau^*(T)$ are sensitive to the ratio of effective mass m^* to transport relaxation time τ^*, and are not able to resolve these quantities separately. By probing electrical transport at microwave frequencies, $m^*(T)$ and $\tau^*(T)$ can individually be measured, providing a new window into the electron dynamics both on the approach to the quantum critical point, and within the electronic nematic phase.

Our system for microwave spectroscopy in strong magnetic fields is the only one of its kind in the world, and is based on TiO_2 dielectric resonators. [3] Its capabilities are unique – it operates in high magnetic fields with the same sensitivity as systems based on superconducting cavity resonators. So far we have used it to make measurements on $Sr_3Ru_2O_7$ down to 1.2 K and at fields up to 8 tesla, and we plan to extend these in the near future to dilution fridge temperatures, where we will be able to determine whether the electronic nematic behaviour arises from anisotropy of relaxation dynamics or from electronic structure.

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[3]. Apparatus for high resolution microwave spectroscopy in high magnetic fields, W. A. Huttema et al., Rev. Sci. Instrum. **77**, 023901 (2006).

Doping dependence of the ratio between the quasi-particles spectral weight and the slope of the superconducting gap in the cuprates: a Raman point of view

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Recent Raman experiments [1] have revealed the existence of two energy scales in the superconducting state of underdoped cuprates. One scale, observed in B_{2g} symmetry, is related to the quasi-particles in the nodal region while the other one, observed in B_{1g} symmetry is related to the antinodal region.

There exists two ways for defining the nodal energy scale as a function of the doping level using Raman scattering. The first one is to follow the peak energy observed in the Raman B_{2g} symmetry as a function of doping levels. The second one is to measure the slope of the low energy Raman response function in the same symmetry. The second approach requires the ability to compare Raman intensity observed in different samples and/or doping levels. A theoretical sum-rule derived for B_{2g} Raman scattering was previously used to achieve this goal [1,2].

In this work we compare directly the Raman slopes for different doping levels without using any theoretical assumption in Bi-based cuprates. We have developed a judicious experimental procedure which allows us to get a direct access to the evolution of the ratio between the quasi-particle spectral weight and the slope of the superconducting gap at the nodes as a function of doping level. We compare our findings with available thermal conductivity and superfluid density data and discuss them in light of a two-gap scenario in the cuprates.

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[2]. De Medici L, Georges A, Kotliar G, arXiv:08003.0752v1

Broadband Microwave Spectroscopy of Unconventional Superconductors

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Over a period spanning the lifetime of two graduate students, researchers at UBC have developed a broadband microwave apparatus to accurately measure the low-temperature surface resistance of single crystal superconductors as a continuous function of frequency from 0.1 - 25 GHz. [1] This apparatus has proven to be very versatile and this poster will briefly overview some of the past successes of the technique and then describe more recent and ongoing work. Topics include: the measured d-wave conductivity spectrum [2] and the absolute zero-temperature penetration depth of $Yba_2Cu_3O_{6+y}$ [3], the effect of Cu-O chain disorder on quasiparticle scattering in $YBa_2Cu_3O_{6.5}$, preliminary measurements of the microwave absorption spectrum of $NdO_{1-x}F_xFeAs$, the search for triplet superconductivity in Sr_2RuO_4, and the move to dilution fridge temperatures.

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[3]. T. Pereg-Barnea *et al*., Phys. Rev. B **69**, 184513 (2004).

Strong many-body effects observed by angle-resolved photoemission study in "misfit cobaltates"

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In Na cobaltates Na_xCoO_2, Co is expected to be in the low-spin state with a valence that can be tuned from Co^{4+} at x=0 (one spin ½ hole in t_{2g} per site) to Co^{3+} at x=1 (filled band). For intermediate fillings, most of these phases are metallic, but their magnetic susceptibility evolves from Pauli-like at x<0.6 to Curie-like at x>0.6. This is quite intriguing, since one would rather have expected magnetic correlations to be strong in the highly correlated state near x=0 and vanish when the number of spins ½ decreases. However, the many competing degrees of freedom coexisting in these systems makes their description challenging. Strong correlations, magnetic couplings frustrated by the triangular geometry of the Co lattice, orbital degeneracy and possibly charge ordering effects could all play a role.

A similar situation occurs in "misfit cobaltates", a family containing the same triangular Co planes than Na cobaltates but in a different 3D environment. We will present an Angle Resolved Photoemission (ARPES) study of these phases extending over a doping range equivalent to x=0.7 to 0.9 [1]. We will establish the basic similarity of the electronic structure of misfit and Na cobaltates, by mapping their Fermi Surface, measuring the Fermi velocities and comparing the lineshape structure. ARPES is a sensitive probe of correlation effects and we will argue that the spectra contain clear signatures of strong many-body effects. We will show that these many-body couplings *increase* when one approaches the band insulator regime, in parallel with the development of the Curie-Weiss susceptibility and of a large negative magnetoresistance. We will discuss possible origins of these couplings and, particularly, excitations involving a strong coupling with an orbital degree of freedom.

[1]. V. Brouet *et al.*, Phys. Rev. B **76**, 100403R (2007)

Microwave spectroscopy of highly underdoped $YBa_2Cu_3O_{6.333}$

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Following our development of a technique for continuously tuning hole doping in underdoped $YBa_2Cu_3O_{6+x}$, we have obtained a wealth of information from a series of microwave experiments as T_c is tuned to zero. [1] These results indicate conclusively the importance of phase disordering and quantum criticality. Our early experiments have focused on measuring the superfluid density ρ_s. [2] This is the most fundamental property of a superconductor, characterizing the rigidity of the superconducting order parameter to fluctuations in its phase. In carrying out a detailed study of ρ_s as T_c goes to zero, we have obtained the first glimpses of a real quantum critical point in a cuprate. These experiments have led to the following surprising discoveries:

- the absence of a Kosterlitz-Thouless-Berezinskii vortex unbinding transition, widely anticipated in the cuprate superconductors because of their large electrical anisotropy.
- a breakdown of the long-accepted Uemura phenomenology, in which $T_c \sim \rho_s$.
- instead, close to the quantum critical point we have found that $T_c \sim \rho_s^{1/2}$, the behaviour expected for a quantum phase transition in the (3+1)D-*XY* universality class,
- and that Uemura scaling is replaced by a different phenomenology, in which ρ_s grows linearly with *doping* across the whole phase diagram.

We have recently been using this and other microwave data to place tight constraints on the type and degree of competing orders present in underdoped $YBa_2Cu_3O_{6+x}$. In these experiments we probe the energy dependence of the quasiparticle excitation spectrum through the temperature dependence of the penetration depth *and* the finite-frequency quasiparticle conductivity. The microwave conductivity, which is measured with a broad-band bolometric technique, [3] gives us a window into the zero-energy excitations, which are otherwise invisible to a penetration depth experiment. This allows us to rule out certain types of competing order, such as the SDW transition, as these compete for Fermi surface and do not create a significant density of zero-energy quasiparticles.

The same experiments have been used to study the detailed doping dependence of the normal-state resistivity as T_c is tuned towards the underdoped quantum critical point. These data also reveal surprises: the resistivity remains metallic as T_c goes to zero; a T^2 term is present in $\rho(T)$, but its doping dependence rules out Fermi-liquid scattering; and the fluctuation conductivity, while 2D-like in form, is anomalously large.

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[2]. Lower critical field and superfluid density in highly underdoped $YBa_2Cu_3O_{6+x}$ single crystals, Ruixing Liang et al., Phys. Rev. Lett. **94**, 117001 (2005).

[3]. Bolometric technique for high-resolution broadband microwave spectroscopy of ultra-low-loss samples, P. J. Turner et al., Rev. Sci. Instrum. **75**, 124 (2004).

Optical spectroscopic investigations on multiferroic hexagonal RMnO$_3$ thin films

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Multiferroic oxides that have an intrinsic coupling between magnetic and electric order parameters are drawing a lot of interests these days. The magnetoelectric coupling is fascinating not only in physical point of view but also in application point of view, since, for example, they might be applied to memory devices with various switching properties. Among the magnetoelectric materials, hexagonal RMnO$_3$ (R = Sc, Y, Ho – Lu) have been attracting particularly lots of attentions due to their large ferroelectric polarization values and high ferroelectric transition temperature.

Recently, we succeeded to fabricate hexagonal RMnO$_3$ (R = Dy, Tb, Gd) thin films [1], whose bulk phase should be orthorhombic, by using epitaxial stabilization technique. Using these new compounds, we could extend the phase space for hexagonal RMnO$_3$. Such extension has provided us a new opportunities to systematically investigate how the ionic radius of the rare earth ion in hexagonal RMnO$_3$ (R = Sc, Y, Gd-Lu) could affect physical properties of this intriguing system.

From our optical spectroscopic measurements, we observed three optical absorptions in the in-plane optical conductivity spectra. Using first-principles calculations we appropriately assigned the first two optical absorptions as inter-site transitions from the strongly hybridized oxygen state with different Mn orbital symmetries to the Mn $3z^2$-r^2 state. In temperature dependent optical absorption spectra, we observed a red shift of inter-site transition peak at ~1.7 eV as we increased temperature. We could identify an anomaly at Neel temperature for all of our samples. The results indicate that coupling should exist between the magnetic ordering and electronic structure in hexagonal RMnO$_3$.

To clarify the origin of this magnetoelectric coupling, we also performed magneto-optical spectroscopy on the thin films by applying magnetic field up to 32 T. The inter-site transition peak at ~1.7 eV showed a red shift with increasing magnetic field. This suggests that the magnetic ordering influences the electronic structure of the hexagonal RMnO$_3$. When the magnetic structure is disturbed by the temperature and/or the external magnetic field the ~1.7 eV peak shifts to lower energy due to the modified electronic structure.

Finally, we show a systematic increase of the ~1.7 eV peak with the increase of the ionic radius of the rare earth ion. The optical transition at 1.64 eV for DyMnO$_3$ shifts to 1.67 and 1.81 eV for TbMnO$_3$ and GdMnO$_3$ respectively. For natural hexagonal RMnO$_3$ (R = Y, Er, Lu [2], and Sc) with smaller ionic sizes, the same optical transitions occurs at ~1.6 eV. With the help of first-principles calculations, such peak shift could be well understood in terms of the systematic change of the atomic spacing [3]. This result demonstrates that structural properties of hexagonal RMnO$_3$ could affect their electronic properties significantly.

[1] J.-H. Lee, *et al*., Adv. Mater. (Weinheim, Ger.) **18**, 3125 (2006).

[2] A. B. Souchkov, *et al*., Phys. Rev. Lett. **91**, 027203 (2003).

[3] Woo Seok Choi, *et al*., Phys. Rev. B (2008) in press.

Electron-doping a Mott insulator: Alkaline intercalation into Ti oxohalides

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The titanium-based oxohalides (TiOX with X=Cl,Br) are characterized by a strong coupling between charge, spin, and lattice degrees of freedom. Strong electronic correlations drive these materials into a Mott-insulating state [1]. Due to the nearly triangular coordination of the Ti^{3+} ions in the quasi-2D crystal structure magnetic frustration is expected and has led to speculations that the long-sought resonating valence bond (RVB) state could be realized here. However, it is found instead that an unusual spin Peierls instability occurs which results from strong spin-lattice coupling and indicates a more 1D character of the material [2]. Here I will discuss our recent attempts to drive this prototypical Mott-insulator into a metallic state by electron doping through alkaline intercalation. Photoemission data show the evolution of new states within the Mott gap which carry the signatures of strong (spin-)polaronic coupling.

[1] M. Hoinkis, M. Sing, J. Schäfer, M. Klemm, S. Horn, H. Benthien, E. Jeckelmann, T. Saha-Dasgupta, L. Pisani, R. Valentí, and R. Claessen**,** Phys. Rev. B **72**, 125127 (2005)

[2] M. Hoinkis, M. Sing, S. Glawion, L. Pisani, R. Valentí, S. van Smaalen, M. Klemm, S. Horn, and R. Claessen, Phys. Rev. B **75**, 245124 (2007)

Electronic structure of bilayered colossal magnetoresistant manganates

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The colossal magnetoresistant transition in perovskite-based (bilayered) manganese oxides such as $La_{2-2x}Sr_{1+2x}Mn_2O_7$ is seen, together with high Tc superconductivity, as one of the two flagship research directions in the investigation of complex, unconventional quantum electron matter. Just what tips the balance between the wealth of competing phases and textures in spin, charge and orbital degrees of freedom in these systems?

In this poster we'll present our latest angle-resolved photoemission data probing the occupied electronic states in bilayer manganites with x around 0.4. We will discuss their Fermi surfaces, quasiparticles and self-energies, as well as the anomalous temperature dependence seen in the data.

Optical coupling to spin waves in multiferroic materials

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Multiferroic materials are characterized by the coexistence of ferroelectric and antiferromagnetic order, with potential spintronic applications related to the electrical control of spin wave excitations. One notable example is $BiFeO_3$, a room temperature multiferroic that is currently attracting attention because of its complex optical response in bulk and thin film samples. In this talk I will describe the magnon and optical phonon spectrum of bulk [1, 2] and thin film [3] $BiFeO_3$. For bulk, the cycloidal nature of the magnetic order leads to soft mode anisotropy and magnon zone folding. The former allows electrical control of spin wave propagation via reorientation of the spontaneous ferroelectric moment. The latter gives rise to multiple magneto-dielectric resonances due to the coupling of optical phonons at zero wavevector to magnons at integer multiples of the cycloid wavevector. These results show that the optical response of a multiferroic reveals much more about its magnetic excitations than previously anticipated on the basis of simpler models.

[1]. R. de Sousa and J.E. Moore, Phys. Rev. B. **77**, 012406 (2008).
[2]. M. Cazayous, Y. Gallais, A. Sacuto, R. de Sousa, D. Lebeugle, and D. Colson (preprint), arXiv:0712.3044 (2007).
[3]. R. de Sousa and J.E. Moore, Appl. Phys. Lett. **92**, 022514 (2008).

3D Electronic Structure of Multi-layer Sr ruthenates

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X.N. Lin[3] , Gang Cao[3]

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The sequence of single, double and triple layer ruthenates, Sr_2RuO_4, $Sr_3O_2O_7$ and $Sr_4Ru_3O_{10}$, respectively, display a remarkable range of novel superconducting and magnetic ground states, either as intrinsic materials or under the effects of alloying, pressure and applied magnetic field, sometimes with quantum critical behavior. There is the suspicion that in the sequence the evolution in dimensionality is an important aspect of the variation of the ground states. Thus it is of great interest to determine the evolution of three dimensional character in the electronic structures of the sequence, in particular to extend the good general understanding of Sr_2RuO_4 to the other two compounds. Photon-dependent multi-Brillouin zone angle-resolved photoemission (ARPES) measurements are presented for $Sr_3O_2O_7$ and $Sr_4Ru_3O_{10}$. Distinct variations in band intensity and in Fermi surface topological shape and sizes are observed along k_z (photon energy) thus documenting the evolving three-dimensionality of the electronic structure. The observed k_z-periodicity corresponds to the interlayer spacing of Ru-O planes as opposed to the larger unit cell c-dimension. Quantitative comparison is made between ARPES and available LDA band structure calculations and magneto-oscillatory experiments. The possible connections between the observed electronic structures and the ground state properties of the materials are set forth.

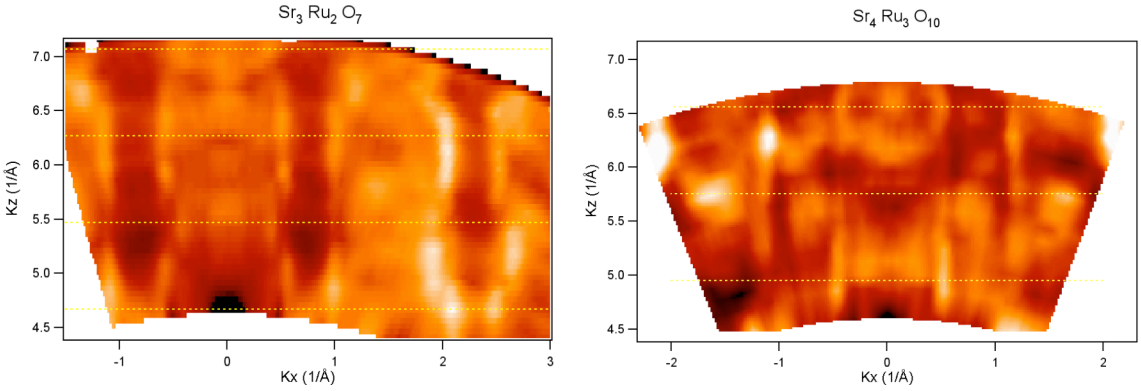

Fig.1. k_x-k_z Fermi surface slices at the BZ boundary of (left) $Sr_3O_2O_7$ and (right) $Sr_4Ru_3O_{10}$.

Quasi-Particle Dynamics in Superconducting Aluminum

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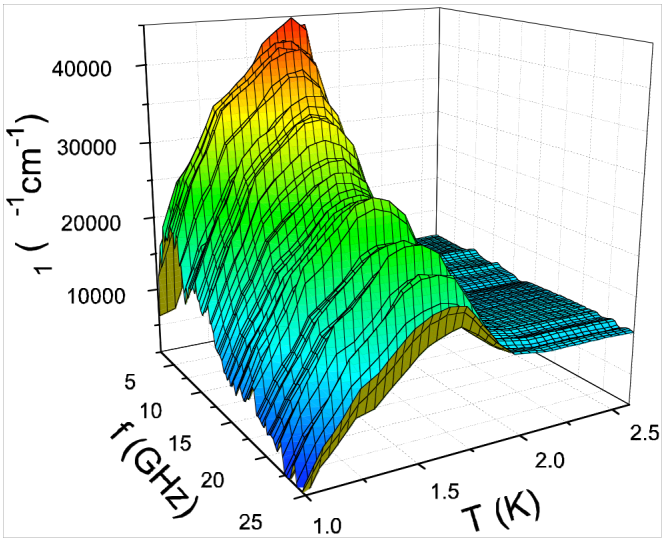
The response of superconducting aluminum to electromagnetic radiation is investigated in a broad frequency (45 MHz to 40 GHz) and temperature range ($T>T_c/2$), by measuring the complex conductivity. Thin aluminum films (10 to 50 nm) were thermally evaporated onto a sapphire substrate. The microwave conductivity was measured with a Corbino spectrometer [1] where the samples terminate a coaxial waveguide. Employing a HP 8510 network analyzer, the complex reflection coefficient was measured, from which the sample imedance and the complex conductivity could be evaluated.

For the first time we were able to map the frequency and temperature dependence of the conductivity coherence peak of aluminum [2]. While the imaginary part probes the superfluid density (Cooper-pairs), the real part monitors the opening of the superconducting energy gap and – most important here – the zero-frequency quasi-particle response. Varying the mean free path gives some insight into the dynamics, scattering and coherence effects of the quasi-particles in the superconducting state. For large mean free path, aluminum approaches a clean-limit superconductor and the coherence peak vanishes. The Tinkham-Glover-Ferrell sum rule is obeyed.

[1] M. Scheffler and M. Dressel, Rev. Sci. Instrum. **76**, 074702 (2005); M. Scheffler, S. Kilic, and M. Dressel, Rev. Sci. Instrum. **78**, 086106 (2007).

[2] K. Steinberg and M. Dressel, arXiv:0712.3391.



Real part of the conductivity of aluminum film (T_c = 1.9 K) as a function of frequency and temperature. The coherence peak decreases as the frequency increases.

In-situ doping control of the surface of high-T_c cuprates

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Central to the understanding of high-temperature superconductivity is the evolution of the electronic structure as doping alters the density of charge carriers in the CuO_2 planes. Superconductivity emerges along the path from a normal metal on the overdoped side to an antiferromagnetic insulator on the underdoped side. This path also exhibits a severe disruption of the overdoped normal metal's Fermi surface [1]. Angle-resolved photoemission spectroscopy (ARPES) on the surfaces of easily cleaved materials such as $Bi_2Sr_2CaCu_2O_{8+\delta}$ shows that in zero magnetic field the Fermi surface breaks up into disconnected arcs [2]. However, in high magnetic field, quantum oscillations at low temperatures in $YBa_2Cu_3O_{6.5}$ indicate the existence of small Fermi surface pockets [3]. Reconciling these two phenomena through ARPES studies of $YBa_2Cu_3O_{7-\delta}$ (YBCO) has been hampered by the surface sensitivity of the technique. Here, we show that this difficulty stems from the polarity and resulting self-doping of the YBCO surface. Through in situ deposition of potassium atoms on cleaved YBCO, we can continuously control the surface doping and follow the evolution of the Fermi surface from the overdoped to the underdoped regime [4]. The present approach opens the door to systematic studies of high-temperature superconductors, such as creating new electron doped superconductors from insulating parent compounds.

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[2] M.R. Norman *et al.*, Nature **392**, 157 (1998).
[3] N. Doiron-Leyraud *et al.*, Nature **447**, 565 (2007).
[4] M.A. Hossain *et al.*, Nature Physics, in press (2008); arXiv:0801.3421.

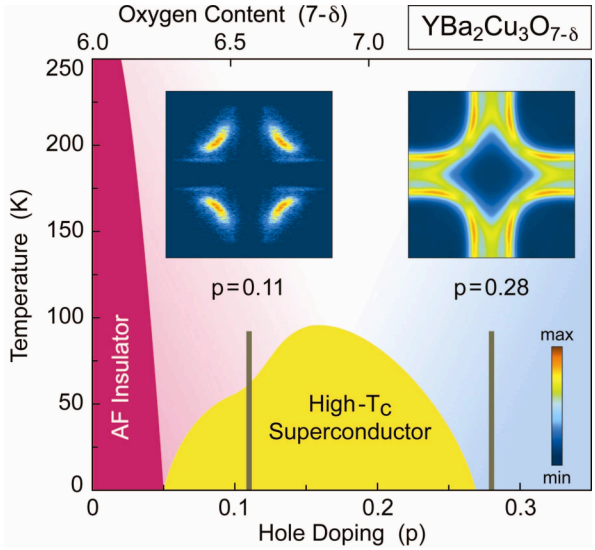

Fig.1. Phase diagram of $YBa_2Cu_3O_{7-\delta}$ as studied by ARPES.

A Resonant Soft X-Ray Powder Diffraction Study to Determine the Orbital Ordering in Half Doped A-Site Ordered Manganites

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[2] *Department of Imaging and Applied Physics, Curtin University of Technology, Perth, WA 6845, Australia*
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We present the first observation of a resonant soft x-ray orbital powder reflection [1]. The resonant powder diffraction experiments have been performed at the Mn $L_{2,3}$ edges of A-site ordered $SmBaMn_2O_6$ with the use of an in vacuum CCD camera (see figure 1). The energy and polarization dependence of the (¼ ¼ 0) reflection, compared with theoretical calculations by Mirone et al. [2] provide direct evidence for a $(x^2\text{-}z^2)/(y^2\text{-}z^2)$ type of orbital ordering. The comparison with energy scans of the layered $La_{0.5}Sr_{1.5}Mn_2O_4$ further indicated that the half doped single layer manganite exhibits a different $3x^2\text{-}r^2$ / $3y^2\text{-}r^2$ type of ordering. The temperature dependence of the orbital reflection indicates an orbital reorientation transition at $T_{RO}\approx210$ K, below which the charge and orbital ordered MnO_2 sheets show AAAA type of stacking, whereas above the transition, they show a AABB type of stacking. The concurring reduction of the ferromagnetic super exchange correlations below this reorientation transition leads to further charge localization, which is evidenced in the increase of the orbital diffraction peak below T_{RO}.

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[3]. U. Staub, V. Scagnoli, A. M. Mulders, K. Katsumata, Z. Honda, H. Grimmer, M. Horisberger, and J. M. Tonnerre, Phys. Rev. B **71**, 214421 (2005).

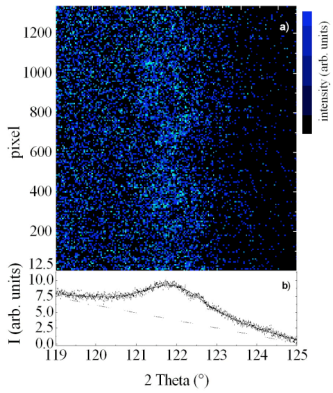

Figure 1 a) Image of a section of the resonant orbital powder diffraction ring (¼ ¼ 0) taken at the Mn L_3 edge (643.25 eV) at 14K with π incident radiation located at 2θ of approximately 120 degree of $SmBaMn_2O_6$. b) Integrated intensity (vertical) of the image as a function of 2θ.

Electronic Raman Scattering in Magnetite: Spin vs. Charge gap

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Magnetite (Fe_3O_4) is the first magnetic material known to manifest charge-ordering transition discovered by Verwey in 1939. [1] Fe_3O_4 has been extensively studied for more than six decades, however driving mechanism of the Verwey transition remains an unsolved puzzle. The value of the charge gap in magnetite is an interesting question that may hold a key to this puzzle. Raman scattering is one of the experimental techniques capable of addressing it.

We report Raman scattering data on single crystals of magnetite (Fe_3O_4) with the Verwey transition temperature of 123 and 117K. Measured single crystals reveal broad electronic background extending up to 900 wavenumbers (~110 meV). Redistribution of this background is observed when the samples are cooled below the transition temperature. In particular, spectra of the low temperature phase show diminished background below 300 wavenumbers followed by an enhancement of the electronic background between 300 and 400 wavenumbers. To display the effect of the background distribution we divide the spectra just below the Verwey transition by the spectra just above the transition, Fig.1, inset. The resultant broad peak-like feature is centered at 368 ±5 wavenumbers (45 meV). The peak position of this feature does not scale with the transition temperature. We discuss two alternative assignments of this feature to a spin or charge gap in magnetite.

[1]. E. J. W. Verwey, Nature (London) **144**, 327 (1939).

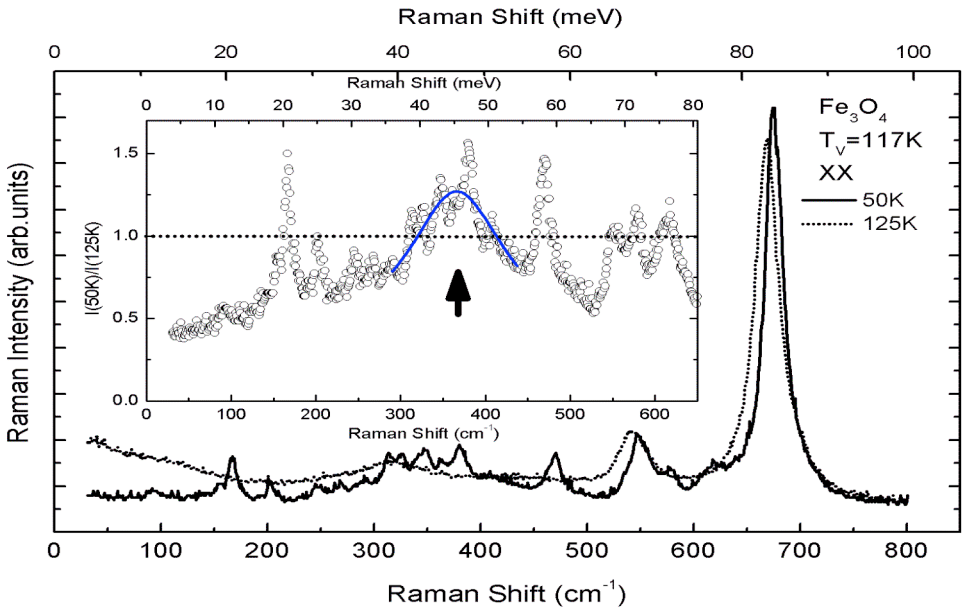

Fig.1. Polarized Raman spectra of Fe_3O_4 (magnetite) well below the Verwey transition (solid line) and just above the transition (short-dash line). Inset displays the ratio of the below-to-above the transition spectra. Dashed line in the inset represents unity. Blue solid line in the inset is a guide to the eye to emphasize the "gap" feature.

Local quasiparticle lifetimes in a *d*-wave superconductor

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Scanning tunneling spectroscopy (STS) measurements find that the surface of Bi-2212 is characterized by nanoscale sized regions, ``gap patches," which have different magnitudes for the *d*-wave energy gap . Recent studies have shown that the tunneling conductance can be fit using a BCS-type density of states for a *d*-wave superconductor with a *local* quasiparticle scattering rate. The fit is made with a scattering rate which varies linearly with energy and has a slope that is positively correlated with the local value of the gap. We consider first the question of what is actually measured in such an experiment[1]. To this end we revisit a model of quasiparticle scattering by impurities and spin fluctuations which was previously used to describe the lifetimes of nodal quasiparticles measured by angle-resolved photoemission (ARPES). We argue that the broadening of the local density of states is determined, except in the case of localized impurity bound states, by the imaginary part of the self-energy of the system averaged over a small region. The size of this region is set by a mean free path which depends upon the energy. At low energies, this region is found to be significantly larger than a gap "patch", so that the density of states measured by STS is homogeneous in this energy range. At higher energies where the mean free path is comparable with the patch size, the density of states is inhomogeneous. We show that a local self-energy in the impurity-plus-spin fluctuation model, while not strictly linear, yields a local density of states (LDOS) nearly identical to the full theory, and argue that it is consistent with the STS data as well as the phenomenological linear scattering rate extracted from experiment. We also explore the qualitative consequences of this phenomenology for the spectral widths observed in ARPES and predict the existence of Fermi arcs in the superconducting state.

[1]. S. Graser, P.J. Hirschfeld, and D.J. Scalapino, arXiv:0801.0101

Optical properties of the first high-temperature superconductor: $La_{2-x}Ba_xCuO_4$

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$La_{2-x}Ba_xCuO_4$ (LBCO) was the first material in which high-temperature superconductivity was observed [1]. Unfortunately, difficulties with crystal growth restricted early work to powders, and attention quickly shifted to single crystals of $La_{2-x}Sr_xCuO_4$ (LSCO). However, recent advances at BNL have resulted in the ability to grow large single crystals of LBCO over a wide doping range. Superconductivity exists in this material from x=0.04 to about 0.25 with a maximum superconducting transition temperature (T_c) of about 32 K. In the x=1/8 doping static charge- and spin-stripe order are observed, and the superconductivity is almost totally destroyed [2]; however, only a small anomaly in T_c is observed in LSCO at the 1/8 doping. The temperature-dependent reflectance of single crystal LBCO has been examined over a wide frequency range for x=0.095, 0.125 and 0.155 for light polarized in the copper-oxygen (*a*-*b*) planes, as well as along the poorly conducting *c* axis. The optical properties have been calculated from a Kramers-Kronig analysis of the reflectance.

In the slightly underdoped x=0.095 material with T_c=32 K, the optical properties are similar to LSCO at comparable doping. The transition into the superconducting state results in a noticeable increase in the low-frequency reflectance (with a commensurate reduction of the low-frequency conductivity), signaling the formation of a condensate. A striking optical effect upon entry into the superconducting state along the *c* axis is the formation of a sharp plasma edge in the reflectance due to Josephson coupling. The *c*-axis plasma edge is also present in the x=0.155 sample, although it is broader and shifted to higher frequency. In the x=1/8 material, the superconductivity is so strongly suppressed ($T_c \cong 3$ K) that no *c*-axis superconducting plasma edge is observed. In addition, the *ab*-plane results for x=1/8 are dramatically different than for the underdoped or optimally-doped materials – in these materials the low-frequency reflectance increases with decreasing temperature. However, in the 1/8-doped material the low-frequency reflectance increases only until about 60 K; below this temperature charge and spin order develop and the reflectance over much of the far- and mid-infrared regions is suppressed with decreasing temperature [3]. An analysis of the conductivity reveals a dramatic decrease in the coherent "Drude-like" contribution, indicative of a loss of free carriers and suggestive of a "nodal metal" with an anisotropic gapping of the Fermi surface. This work is in agreement with recent ARPES studies of this material that show a *d*-wave like gap developing at or below about 50 K [4], despite the absence of bulk superconductivity [5].

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[3]. C. C. Homes, S. V. Dordevic, G. D. Gu, Q. Li, T. Valla, and J. M. Tranquada, Phys. Rev. Lett. **96**, 257002 (2006).
[4]. T. Valla, A. V. Federov, Jinhoe Lee, J. C. Davis, G. D. Gu, Science **314**, 1914 (2005).
[5]. Q. Li, M. Hücker, G. D. Gu, A. M. Tsvelik, and J. M. Tranquada, Phys. Rev. Lett. **99**, 067001 (2007).

Crystal-field level inversion in lightly Mn-doped $Sr_3Ru_2O_7$

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$Sr_3(Ru_{1-x}Mn_x)_2O_7$, in which 4*d*-Ru is substituted by the more localized 3*d*-Mn, is studied by x-ray dichroism and spin-resolved density functional theory. We find that Mn impurities do not exhibit the same 4+ valence of Ru, but act as 3+ acceptors; the extra e_g electron occupies the in-plane $3d_{x2-y2}$ orbital instead of the expected out-of-plane $3d_{3z2-r2}$. We propose that the 3*d*-4*d* interplay, via the ligand oxygen orbitals, is responsible for this crystal-field level inversion and the material's transition to an antiferromagnetic, possibly orbitally-ordered, low-temperature state [1].

[1] M.A. Hossain *et al.*, Phys. Rev. Lett. in press (2008); arXiv:0801.2995.

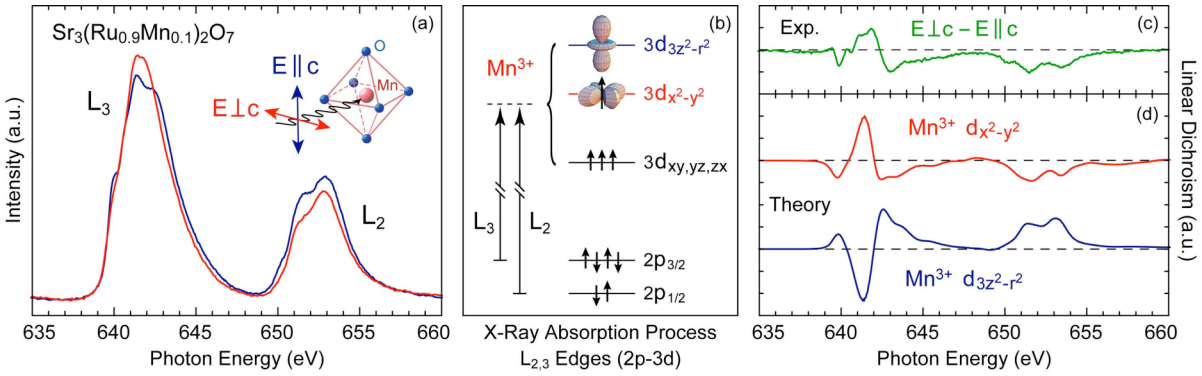

Fig.1. (a) Polarization-dependent Mn L2;3-edge XAS spectra from $Sr_3(Ru_{1-x}Mn_x)_2O_7$ at T = 295 K. (b) Scheme of the XAS process: the L2 (L3) edge corresponds to the excitation of a Mn $2p_{1/2}$ ($2p_{3/2}$) electron to the Mn 3d valence shell. The L3-L2 energy separation is due to the 2p core level spin-orbit coupling. (c) Experimental and (d) theoretical linear dichroism two possible eg-orbital occupations.

Direct observation of dispersive Kondo resonance peaks in a heavy-fermion system

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We have performed Ce 4d-4f resonant angle-resolved photoemission spectroscopy to study the nature of strongly correlated Ce 4f-electrons in a quasi-two-dimensional non-magnetic heavy-fermion system $CeCoGe_{1.2}Si_{0.8}$. For the first time, the dispersive coherent peaks of f-state crossing the Fermi level, the so-called Kondo resonance, are directly observed together with the hybridized conduction band. Furthermore, the experimental band dispersion is quantitatively in good agreement with a simple hybridization-band picture based on the periodic Anderson model. The obtained physical quantities, i.e., coherent temperature, Kondo temperature, and mass enhancement, are comparable to the results of thermodynamic measurements. These results undeniably manifest an itinerant nature of Ce 4f-electrons in heavy-fermion systems and clarify their microscopic hybridization mechanism.

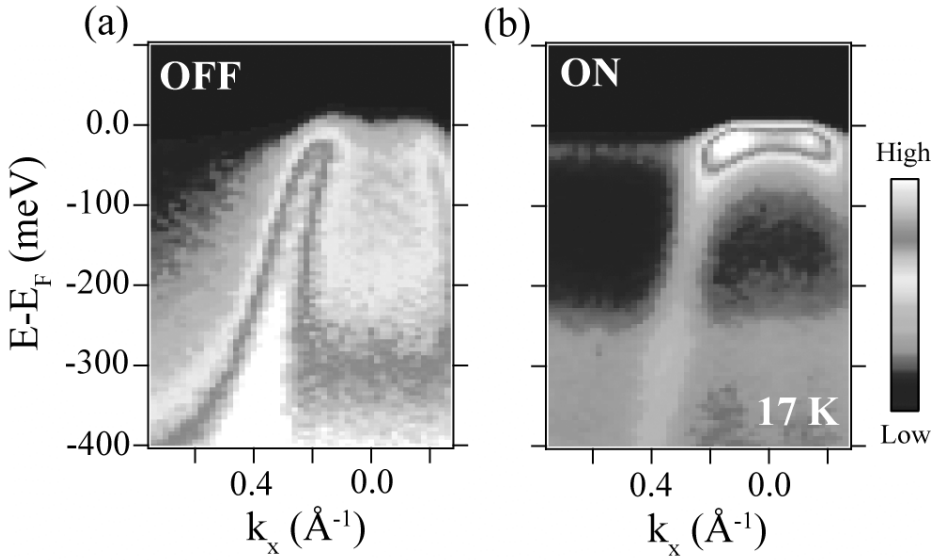

Fig.1. Intensity plots of (a) off- and (b) on-resonant ARPES spectra of $CeCoGe_{1.2}Si_{0.8}$ represent the band dispersion of conduction and f-electrons, respectively.

Cleaving temperature dependence of layered-oxide surfaces

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The surfaces generated by cleaving non-polar, two-dimensional oxides are often considered to be perfect or ideal surfaces. However, single particle spectroscopies on Sr_2RuO_4, a archetypal non-polar two dimensional oxide, show significant cleavage temperature dependence. We show that this is not a consequence of the intrinsic characteristics of the surface: lattice parameters and symmetries, step heights, atom positions, and density of states. Instead, we find a marked increase in the density of defects at the mesoscopic scale with increased cleave temperature. The potential generality of these defects to oxide surfaces may have broad consequences to the interpretation of surface sensitive measurements.

VUV Three-Dimensional Angle-Resolved Photoemission Study on $CeTe_2$

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Low-dimensional electronic structure is believed to be an important essence to understand the anomalous physical properties, such as a charge/spin density wave formation, high-Tc superconductivity, etc., originating from the anisotropic electronic/magnetic structure. In turn, the investigation of the three-dimensional effect in the electronic structure is essentially important to understand the anomalous physical properties of low-dimensional compounds. To demonstrate the importance of three-dimensionality to insight into the anomalous physical properties, we have performed three-dimensional angle-resolved photoemission spectroscopy (3D-ARPES) on quasi-two-dimensional charge-density-wave (CDW) compound $CeTe_2$[1] where the existence of three-dimensional anomaly at the Fermi surface (FS) has been reported [2]. The 3D-ARPES was performed at the beamline 7U of UVSOR-II, the Institute for Molecular Science, which has been developed in 2007's for bulk-sensitive ARPES on strongly correlated electron systems in the VUV region [3]. Taking account of the inner potential of V~16.4 eV [2], we set the measurement axis along (110) plane of Te 5p hole-like FS (see hatched area in Fig. 1).

Figure 2 shows the evolutions of the hole-pocket around the MR line as a function of photon energy $h\nu$, in other word, of the k_z line in the Brillouin zone. We clearly observe that the Te 5p band (solid line) folds at the E_F crossing point (dashed line) at $h\nu = 19$ eV (ΓM line), i.e., the Fermi surface of the Te 5p band is nested due to the CDW formation. Furthermore, with decreasing photon energy, the separation between the Te 5p band and the folded band gradually increases. This result suggests that the nesting condition becomes imperfect from the ΓM to ZR lines gradually. The observed change of the folded band certainly indicates the existence of the unexpected three-dimensional CDW vector in quasi-two-dimensional $CeTe_2$.

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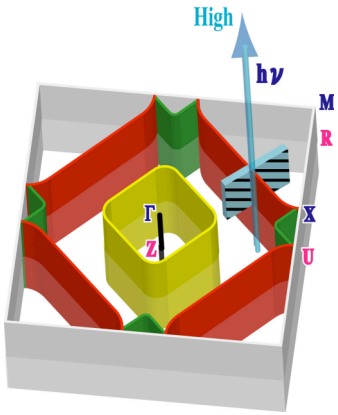

Fig.1. Schematic Fermi surface of $CeTe_2$.

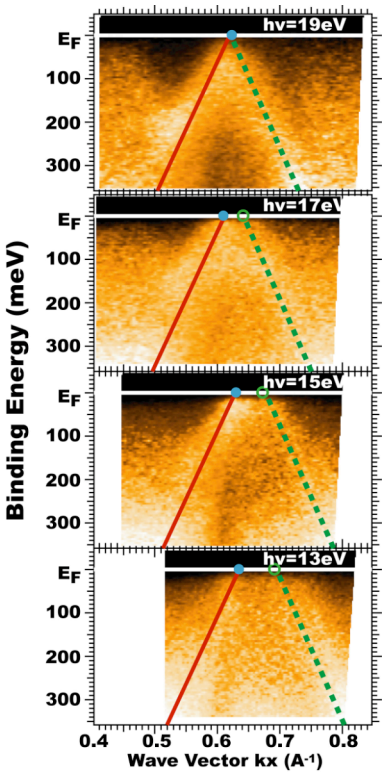

Fig.2. $h\nu$-dependent experimental band structure of $CeTe_2$ The images of $h\nu = 19$ and 13 eV correspond to the band structure in the ΓM and ZR lines, respectively. See the text for details.

Raising the bars in vacuum FT-IR spectroscopy: design advances and research applications

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When the bar for research FT-IR spectrometers was set, we knew that some day we would feel obliged to raise it. For the new VERTEX 80v Bruker Optics provides an innovative interferometer concept and a very flexible vacuum optics layout, which is the culmination of everything that have been pioneered and developed in over 30 years. The new research vacuum FT-IR spectrometer is based on the true-aligned UltraScan^{TM} interferometer (see fig. 1), which provides the highest spectral resolution achievable on a bench top FT-IR spectrometer. The precise linear air bearing scanner and high quality optics guarantees the ultimate sensitivity and stability.

The rugged and stable cast aluminium optics bench enables demanding experiments such as high spectral resolution (better than 0.07 cm^{-1}), ultra fast time resolved spectroscopy (ms down to low ns temporal resolution), or ultra-violet spectral range (up to 50,000 cm^{-1}) measurements. The two optional external detector ports accommodate liquid He dewars of bolometer and/or hot electron-detectors (see beam exits OUT 2 and OUT 5 in fig.1). In combination with the external water cooled high power Hg-arc source, the terahertz spectral range is accessible (down to less than 5 cm^{-1}). The evacuated optics bench eliminates atmospheric moisture absorptions and provides extreme sensitivity and stability, especially in the far IR spectral regions.

In this contribution we will demonstrate the instruments resolving power $\nu/\Delta\nu$ of better than 300.000:1 on iodine vapour absorption lines in the visible spectral range. In addition from the area of nano-science research, water vapour free IR spectra of molecular mono layers on gold surfaces with signal intensities below 10^{-3} absorbance units will be presented: such a performance can be achieved by use of a vacuum optics bench only [1]. Furthermore, using a Hyperion infrared microscope adapted to the Vertex, we show that the achievable spatial resolution of such a system is practically only limited by Abbe's diffraction barrier.

[1] A. Schlapka, U. Käsberger, D. Menzel, and P. Jakob, Surface Science 502-503 (2002) 129-135.

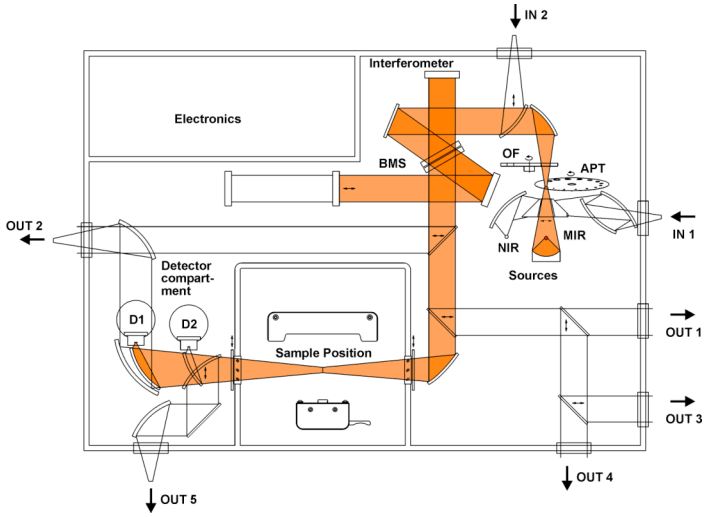

Fig.1 Optics layout of the new vacuum research FT-IR spectrometer VERTEX 80v.

Excitonic Instability in SmS: An Infrared Study on the Black-to-Golden Phase Transition under Pressure

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Samarium monosulfide (SmS) is a semiconductor with an energy gap size of about 1000 K (~ 90 meV) and its color is black (namely, the "black phase") at ambient pressure. Above the critical pressure (P_c) of 0.65 GPa, the sample color changes to goldenyellow (the "golden phase") and the electrical resistivity then suddenly drops to one-tenth that in the black phase. [1] To clarify the origin of the black-to-golden phase transition, we performed the pressure-dependent optical reflectivity spectra of SmS in the far- and middle-infrared regions. (Fig. 1) Both of the pressure dependent Drude weight and the peak shift of the interband transitions indicate that the energy gap becomes narrow with increasing pressure in the black phase. However, the gap is not closed at P_c but becomes the same as the binding energy of the exciton at the energy gap. This result suggests the origin of the black-to-golden phase transition is an excitonic instability. [2]

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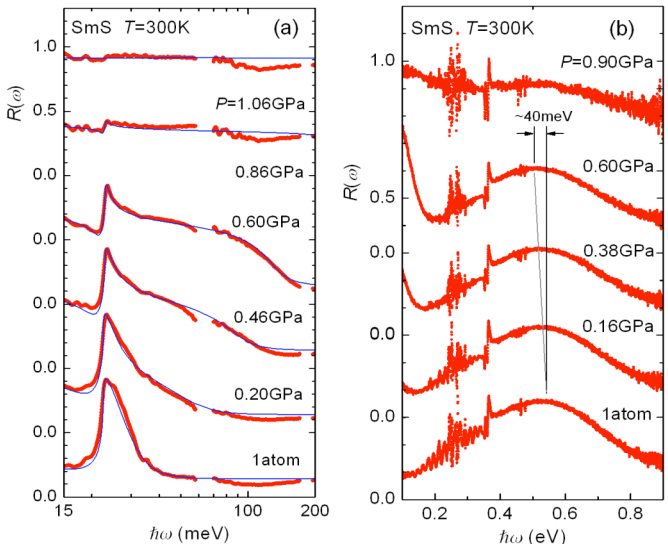

Fig.1. (a) Pressure dependence of the reflectivity spectrum [$R(\omega)$] of black SmS (thick lines) in the energy region of 15 - 200 meV at 300 K. The fitting curve of the combination of Drude and Lorentz functions (thin lines) are also plotted. Successive curves are offset by 0.5 for clarity. (b) Same as (a) but in the region of 0.1 - 0.9 eV. Successive curves are offset by 0.3 for clarity except for P = 0.90 GPa. The vertical line indicates the peak at ambient pressure and 0.6 GPa. The peak shifts to the low energy side with increasing pressure.

Scanning Tunneling Microscopy on $La_{2-2x}Sr_{1+2x}Mn_2O_7$

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The layered colossal magnetoresistant manganites $La_{2-2x}Sr_{1+2x}Mn_2O_7$ (LSMO) have recieved much attention in an effort to understand the microscopic mechanism behind the CMR phenomena in these systems. The quasi-2D nature of the materials makes them ideal for surface sensitive measurements like STM and ARPES. Although an increasing number of papers have appeared regarding ARPES measurements on bilayer LSMO, very little STM/STS data have been published to date. In the x=0.3 composition, atomic resolution has been reported in patches of only 30 Å in extension, that have been interpreted as being trapped polarons [1]. Here we present our STM data on these systems, for the same doping levels as have been studied recently with ARPES. For example, for x = 0.36, we report data showing atomic resolution over micrometer-sized terraces. Our findings could shed new light on the ongoing discussion within the ARPES and STM groups working on the manganites, and might help explain a number of the anomalous and seemingly contradictory results in the literature.

[1]. H.M. Rønnow et al., Nature **440**, 1025 (2006)

Direct photoelectrical observation of electronic structure modification of EuO due to the ferromagnetic ordering

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EuO is a ferromagnetic semiconductor with the Curie temperature (T_C) around 70 K [1]. In the electron doping case by the Eu-excess, T_C increases up to 150 K and a metal-insulator transition (MIT) appears [2]. To clarify the origin of the MIT and the mechanism of the increasing T_C, we have performed the temperature dependent three-dimensional angle-resolved photoemission spectroscopy (3D-ARPES) on single crystalline EuO thin films using tunable synchrotron radiation source. EuO thin films have been grown by a molecular beam epitaxy (MBE) method. Epitaxial growth of single crystalline EuO thin films has been confirmed by observing 1 x 1 EuO (100) patterns in LEED and RHEED measurements and T_C = 71 K by a SQUID measurement [3]. The photoemission spectra of the thin films were accumulated at the beamline 5U of UVSOR-II, Institute for Molecular Science, Okazaki, Japan, after transferring the films from the MBE system without breaking the vacuum. Figure 1 shows the temperature dependence of the Eu 4*f* photoemission spectra at the Γ point ($h\nu$ = 78 eV) and X point ($h\nu$ = 38 eV). The main Eu 4*f* peaks shifts to the lower binding energy side by about 0.2 eV with decreasing temperature. These energy shifts originate from the lowering of chemical potential due to the ferromagnetic transition. An additional Eu 4*f* peak appears only at the Γ point and it rapidly shifts to the lower binding energy side than the chemical potential shift. The observed features can be explained by the strong hybridization interaction between the Eu 4*f* and O 2*p* states in the ferromagnetic phase.

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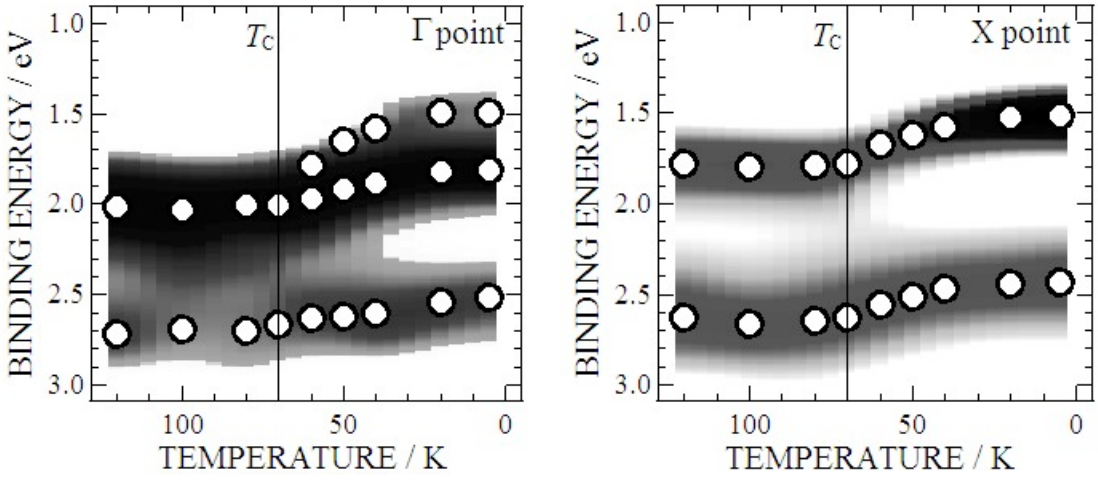

Fig.1. Temperature dependence of the energy levels of the Eu 4*f* states at the Γ point (a) and X point (b) derived from the 3D-ARPES data. Open circles indicate peak energies of the 4*f* states.

Optical Conductivity of Biased Bilayer Graphene

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We have calculated the frequency-dependent optical conductivity of bilayer graphene[1] in the presence of an asymmetry gap and finite chemical potential due to charging. The optical conductivity is found to have very rich structure and this can be understood from optical transitions in the band structure. We will discuss the physics of the graphene bilayer, with and without the asymmetry gap, and show how the important energy scales can be seen in the optics.

[1] E.J. Nicol and J.P. Carbotte, arXiv:0801.1836 (2008)

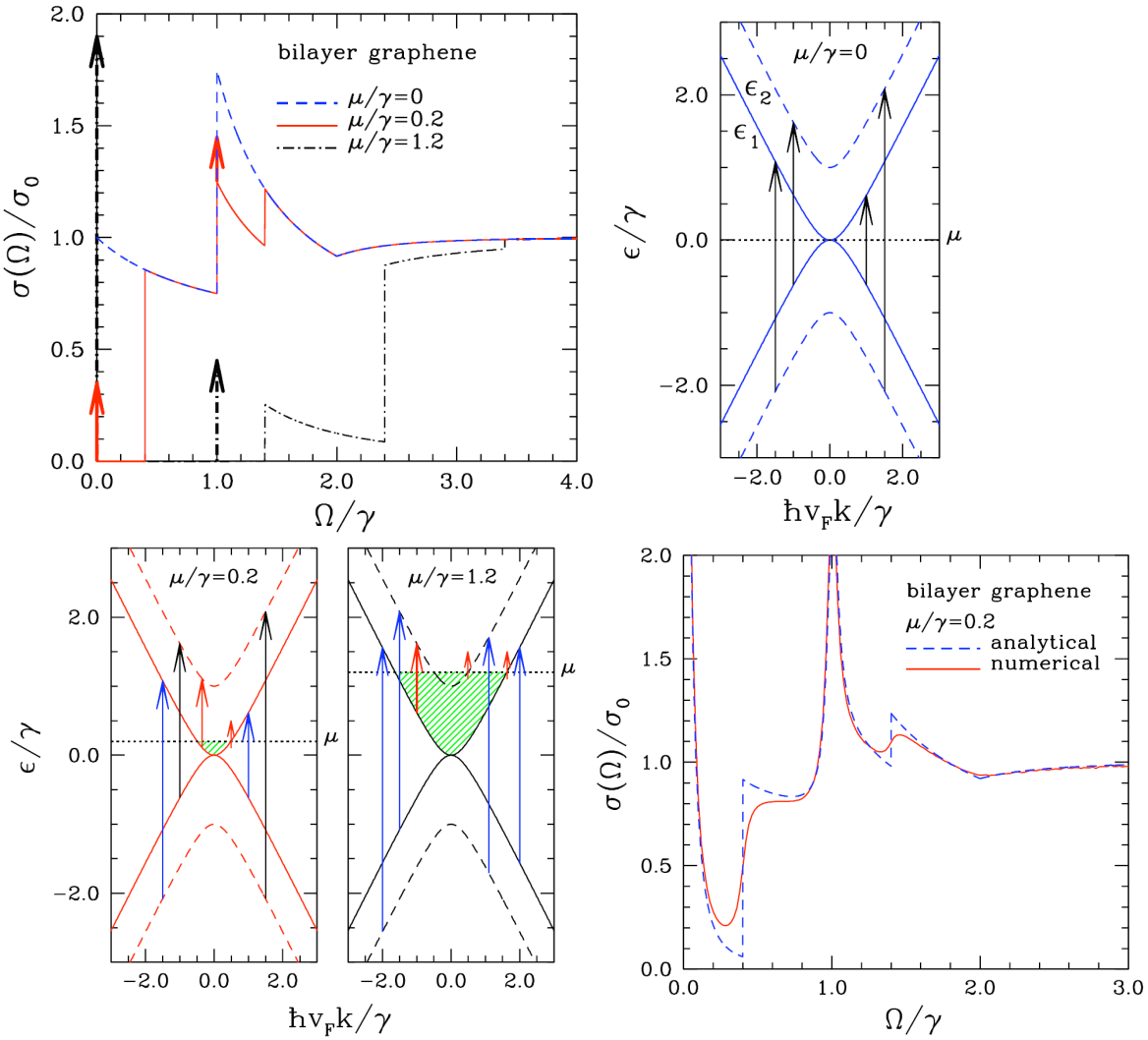

Fig. 1 Upper left: conductivity for bilayer graphene in the case where Δ=0, where arrows represent delta functions. Upper right: band structure and optical transitions for μ=0 case. Lower frames: band structure and optical transitions for other two values of μ and full calculation with impurity scattering.

Metal-Insulator transition in "misfits" cobaltates investigated by angle-resolved photoemission

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The interpretation of the phase diagram of Na cobaltates, from the Mott-insulator limit at X=0 (one spin ½ hole per Co) to the band insulator limit at X=1, is still far from being understood. Surprisingly, these materials seem to behave like a non correlated metal when many magnetic holes are present, whereas magnetic orderings and magnetic correlations appear when more than 60% of the magnetic Co holes are filled, and increase as the number of holes is further reduced. In this region of the phase diagram, Curie-Weiss susceptibility and high thermoelectric-power (TEP) are observed, despite the fact that they remain good metals [1]. Moreover, the possible influence of the different Na orderings on the CoO_2 planes further complicates the situation [2,3]. We present an angle-resolved photoemission (ARPES) study on a parent family of compounds, the "misfit" cobaltates. In these materials, the same CoO_2 layers are present, but they are separated by a rigid rock-salt structure, instead of a Na layer. The "misfits" are located in the "magnetic part" of the phase diagram (x=0.7-1) and they show high TEP and a Curie-Weiss susceptibility, as for the Na cobaltates with the same doping. However, some properties are different: some misfits show a negative magneto-resistance, no magnetic ordering is reached at low temperature, and the transport properties suggest an evolution toward an insulating phase before the band insulator limit [4,5].

By ARPES, we have established the similarity of the electronic structure between the two families [6]. In two different compounds, we have observed a narrow quasi-particle peak (QP) crossing the Fermi level, and tracing a Fermi surface qualitatively similar to that of Na cobaltates. Moreover, by using different polarizations of the light, we were able to select the band that crosses the Fermi level, and to extract precisely its lineshape. It has a peak-dip-hump structure, which indicates the presence of strong many-body effects. We have further observed the progressive disappearance of the QP when the number of holes decreases, which is not observed in Na cobaltates. This suggests that the metal-insulator transition present in the "misfits" is due to increasing many-body effects.

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[6]. V. Brouet, A.Nicolaou et al. Phys. Rev. B 76 100403 (2007)

Pressure-tuning of the *f* electron localization and hybridization probed with infrared spectroscopy under high pressure

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The duality between localized and itinerant characteristics of the *f* electrons in "heavy fermion" (HF) compounds is one of the most important problems in modern condensed matter physics. A hybridization between the otherwise localized *f* electrons and the conduction electrons ("*c-f* hybridization") leads to a heavy Fermi liquid formation and other interesting phenomena. Infrared (IR) spectroscopy has provided much information about the nature of the *c-f* hybridized electronic states in various HF compounds. For example, a characteristic mid-IR peak has been commonly observed in their optical conductivity $\sigma(\omega)$ [1–4], and its peak energy has shown a universal scaling with the *c-f* hybridization energy over many HF compounds [4]. However, if one could *continuously tune and control* the hybridization in a given compound by, e.g., applying external pressure, one may obtain further insight into the microscopic nature of *c-f* hybridized states.

We have carried out IR spectroscopic studies of Yb, $YbAl_2$, and YbS under high pressure up to 400 kbar to probe the evolution of their electronic structure as the *c-f* hybridization is tuned by the pressure. Since a trivalent Yb ($4f^{13}$) with local *f* moment has a smaller ionic radius than a divalent Yb ($4f^{14}$) without local moment, an external pressure induces a crossover toward a trivalent and localized *f* electron state [5], meaning that the *c-f* hybridization is also tuned by pressure. The experiments were done with an IR synchrotron radiation source at SPring-8 to overcome the technical difficulties in high-pressure IR spectroscopy. The measured $\sigma(\omega)$ spectra have shown drastic changes with pressure, corresponding to the evolution of electronic structures. For Yb [6] and $YbAl_2$, significant red shifts of mid-IR peak have been observed, which explicitly demonstrates a tuning of the *c-f* hybridization with pressure. For YbS, with increasing pressure, $\sigma(\omega)$ evolves from an insulator-like spectrum with a phonon peak into a highly metallic one above ~ 100 kbar with both Drude and mid-IR peaks. Our results show that the high pressure phase of YbS above 100 kbar can be well understood as a mixed-valent metal. We will discuss in detail the pressure-tuned evolution of microscopic electronic structures in these compounds.

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Single-Crystal Growth and X-ray Absorption Spectroscopy of $Tl_2Ba_2CuO_{6+x}$

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We have grown single crystals of $Tl_2Ba_2CuO_{6+x}$ (Tl-2201) by a self-flux method and investigated the polarization- and doping-dependence of their electronic structure by X-ray absorption spectroscopy. The spectra agree well with LDA band structure calculations, and are particularly straightforward, suggesting that Tl-2201 may offer a unique toehold of understanding amongst the otherwise perplexing high-temperature cuprate superconductors.

Ultrafast transient photoconductivity of the undoped cuprate $Sr_2CuCl_2O_2$

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[3] *Canadian Institute for Advanced Research, Toronto, Canada*

We present new experimental results on the mobility of photoexcited carriers in $Sr_2CuCl_2O_2$, an undoped cuprate. We use ultrafast laser pulses to excite photocarriers in the antiferromagnetic insulating lattice. We then probe the low-frequency dynamical conductivity of the resulting nonequilibrium state with time-domain terahertz spectroscopy. The prompt onset of photoconductivity is followed by a non-exponential decay on picosecond timescales. Assuming all photoexcited carriers are free we observe a peak mobility of ~0.1cm^2/Vs, much lower than the Hall mobility in chemically doped systems with similar carrier concentrations. Such a low mobility suggests the formation of polarons or excitons after photoexcitation. We examine the nature of the photoexcited carriers as a function of temperature and carrier concentration.

A High Resolution X-ray Absorption Investigation of the Polyaromatic Hydrocarbons

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Aromatic carbon rings are the fundamental building block of many interesting organic electronic materials[1,2]. Traditional electronic devices fabricated using these materials have shown potential for replacing silicon based devices and novel devices made from these systems have also been demonstrated[3]. Along with the considerable investment being made to build and characterize devices that employ these materials, theoretical studies into the basic principles governing the behaviour of these systems are required. To this end a program employing synchrotron radiation from the Canadian Light Source (CLS) has been undertaken to study the electronic structure of the linear polyacenes; benzene, naphthalene, anthracene, tetracene and pentacene. The carbon K-edge NEXAFS spectra of the linear polyacene series, from benzene to pentacene have been measured with high resolution (~20 meV) on the SGM beamline at the CLS. Ab initio calculations on all molecules were performed and used to determine the contributions to the NEXAFS spectra from electronic transitions. The high resolution NEXAFS measurements are shown in Fig. 1. The spectra are dominated by strong □* features that separates into two distinct manifolds with increasing molecular size. Previous studies of benzene[4] and naphthalene[5] have shown that the fine structure seen in the NEXAFS spectra of these molecules occurs from vibronic excitations of the form C 1s(□ = 0) □ 1□* (□ = 1). Our results show that these vibronic contributions exist in the larger polyacenes as well. The results of the ab initio calculations support this conclusion as they show that the features seen in the spectra cannot be accounted for through electronic transitions alone. Furthermore, the peak spacings seen in the fine structure are consistent with previously reported C-C stretching modes[4].

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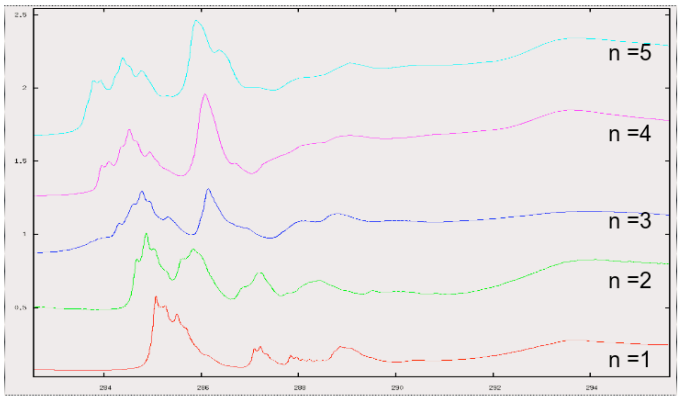

Fig.1. NEXAFS spectra of the linear polyacenes where n is the number of aromatic rings in the structure.

Frequency-Dependent Hopping Transport in Si:P

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At low energy scales charge transport in the insulating Si:P is dominated by activated hopping between the localized donor electron states. Thus, theoretical models for a disordered system with electron-electron interaction are appropriate to interpret the electric conductivity spectra. With a newly developed technique we have measured the complex broadband microwave conductivity of Si:P from 100 MHz to 5 GHz in a broad range of phosphorus concentration n/n_c from 0.56 to 0.95 relative to the critical value $n_c = 3.5 \cdot 10^{18}$ cm^{-3} corresponding to the metal-insulator transition driven by doping. The microwave conductivity was measured with a Corbino spectrometer [1] where the samples terminate a coaxial waveguide. Employing a HP 8510 network analyzer, the complex reflection coefficient was measured, from which the sample impedance and the complex conductivity of Si:P could be evaluated [2].
At our base temperature of T = 1.1 K the samples are in the zero-phonon regime where they show a super-linear frequency dependence of the conductivity indicating the influence of the Coulomb gap in the density of the impurity states. At higher doping $n \rightarrow n_c$, an abrupt drop in the conductivity power law $\sigma_1(\omega) \propto \omega^{\alpha}$ is observed. The dielectric function ε_1 increases upon doping following a power law in $(1-n/n_c)$. Dynamic response at elevated temperatures has also been investigated. [2,3]

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[3]. E. Ritz and M. Dressel, phys. stat. sol. (c) (2008); arXiv:0711.1256.

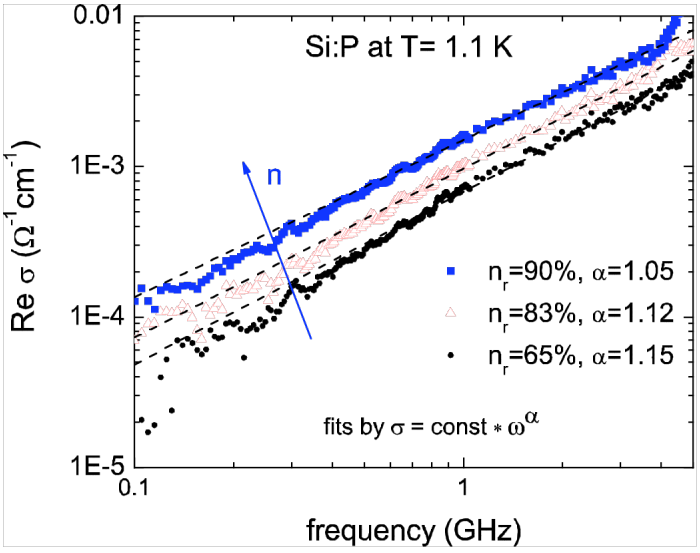

Fig.1. Typical spectra of the measured real part of the conductivity for Si:P with relative donor concentrations n/n_c of 0.65, 0.83 and 0.90. The dashed lines are the fits by a two-parameter power law function.

Doping cobaltate with electrons: $La_{1-x}Ce_xCoO_3$

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Electron doping of lanthanum cobaltate, $LaCoO_3$, with doping levels exceeding small values has recently become possible by the synthesis of epitaxial thin films of the system $La_{1-x}Ce_xCoO_3$ ($0.1 \leq x \leq 0.4$) using pulsed laser deposition [1]. In these thin films, ferromagnetic order has been observed within the entire doping range, with the maximum of the Curie temperature, T_C, occurring around $x \approx 0.3$. This results in a magnetic phase diagram similar to that of hole-doped lanthanum cobaltates. The measured spin values suggest an intermediate-spin state of the Co ions which has been also found in the hole-doped system. Unlike for the hole-doped material where T_C is well above 200 K, we observe a suppression of the maximum T_C to about 30 K possibly related to structural distortions [2].

The element-specific electronic and magnetic structure of epitaxial thin films, both electron-doped and strained undoped ones, was studied by NEXAFS and SXMCD mainly at the Co $L_{2,3}$ edges, and by multiplet calculations. Results include a doping-dependent charge transfer energy as well as a high ratio of the orbital vs. spin moment for all doping levels. Implications for spin state and interplay between structure and magnetism in these thin-film systems will be discussed.

[1]. D. Fuchs et al., Phys. Rev. B **72**, 014466 (2005).

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Infrared spectroscopy on oxide superlattice of a Mott insulator $LaTiO_3$ and a band insulator $SrTiO_3$: An evidence of metallic interface

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Oxide superlattices have been attractive in searching for a noble physical property at an interface, which is not attainable in a single-phase. Ohtomo *et al.* demonstrated an atomically abrupt interface state between a $3d^1$ Mott insulator ($LaTiO_3$) and a $3d^0$ band insulator ($SrTiO_3$) [1]. They also reported that the valence state of titanium ion changes across the interface. By model theory, Okamoto and Millis suggested that the varying valence state at the interface is unique and totally different from the bulks, i.e. metallic not insulating. They introduced a new terminology, 'the electronic reconstruction' [2].

Here, by infrared spectroscopic ellipsometry, we investigated the electronic properties of the $LaTiO_3$ and $SrTiO_3$ superlattices that were grown by pulsed laser deposition technique. We observed a clear signature showing highly conducting property of the superlattice. Extracted conducting carrier densities depended not to the La/Sr ionic concentration ratio but to the number of interface, and the scattering rates were surprisingly reduced. Temperature-dependence of the spectra also revealed an unusual behaviour that the conducting carrier density increased as decreasing temperature due to the reduced screening of electrostatic potentials by increasing the dielectric permittivity of $SrTiO_3$ [3]. The results of our study supported the idea of electronic reconstruction and suggested that the dominating factors of this phenomenon are the discontinuous polarity at the interface of $LaTiO_3/SrTiO_3$ and the strongly correlated *d*-electrons of $LaTiO_3$.

[1] A. Ohtomo, D. A. Muller, J. L. Grazul, and H. Y. Hwang, Nature **419**, 378 (2002).
[2] S. Okamoto and A. J. Millis, Nature **428**, 630 (2004).
[3] S. S. A. Seo *et al*., Phys. Rev. Lett. **99**, 266801 (2007).

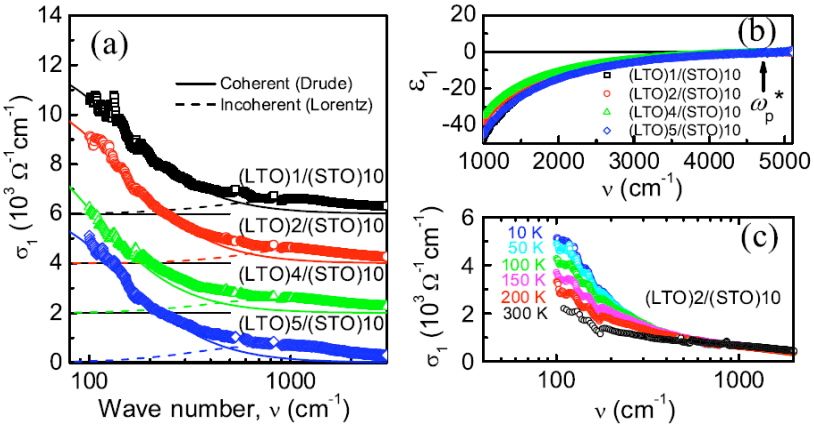

Fig.1. (a) Optical conductivity spectra of $LaTiO_3/SrTiO_3$ superlattices at 10 K (with vertical offsets), containing the coherent (Drude) and incoherent (Lorentz) contributions. (b) Superlattices' real dielectric constant spectra at 10 K. The arrow indicates the screened plasma frequency. (c) Temperature-dependent optical conductivity spectra of $(LaTiO_3)2/(SrTiO_3)10$ superlattice.

Electronic structure of triangular lattices in $NiGa_2S_4$, $FeGa_2S_4$, and $Fe_2Ga_2S_5$

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$NiGa_2S_4$ and $FeGa_2S_4$ have the Ni^{2+} (S=1) and Fe^{2+} (S=2) triangular lattice layer and found to have spin-disordered ground states [1,2]. The spins of both compounds basically obey two-dimensional antiferromagnetic Heisenberg-type interactions and have no long-range order even at the lowest temperature. The electronic structures of $NiGa_2S_4$, $FeGa_2S_4$, and $Fe_2Ga_2S_5$ with the NiS_2 and FeS_2 triangular lattices are investigated using photoemission experiments and model calculations. The Ni 2*p* spectra and the cluster model calculation show that the ground state has the $d^9\underline{L}$ character [Fig. 1(a)]. $\underline{L}$ is a S 3*p* hole. The strong S 3*p* hole character of the ground state provides the enhanced superexchange interaction between the third nearest neighbor sites [See Fig.1(b)]. On the other hand, the Fe 2*p* spectra indicate that the d^6 states are dominant in $FeGa_2S_4$ and $Fe_2Ga_2S_5$. The charge-transfer energies are positive. The e_g - e_g direct hopping and e_g-S 3*p*-e_g superexchange give the strongest interaction between the first nearest neighbor sites in the $FeGa_2S_4$.

[1]. S. Nakatsuji, *et al.*, Science **309**, 1697 (2005).
[2]. S. Nakatsuji, *et al.*, Phys. Rev. Lett. **99**, 157203 (2007).

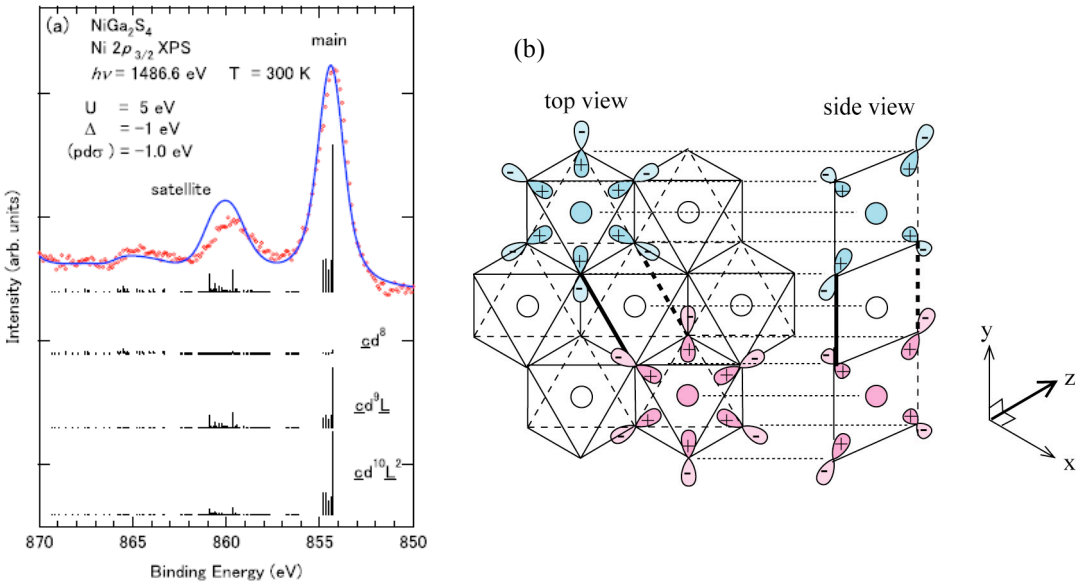

Fig.1. (a) Ni $2p_{3/2}$ core-level XPS of $NiGa_2S_4$. The calculated line spectra are compared with the experimental results. In the lower panel, the line spectrum of Ni 2*p* is decomposed into the cd^n, $\underline{c}d^{n+1}\underline{L}$, and $\underline{c}d^{n+2}\underline{L}^2$ components. (b) Top and side views for two superexchange pathways between the third nearest neighbor NiS_2 clusters.

Charge ordering phenomena and superconductivity in cuprates

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The electronic Raman response was studied in underdoped $La_{2-x}Sr_xCuO_4$ (LSCO) and $Y_{1-y}Ca_yBa_2Cu_3O_{6+x}$ (Y-123) single crystals. New low-energy excitations were found that are interpreted in terms of dynamical stripes [1, 2]. Below the onset point of superconductivity p_{sc1} the stripes are oriented along the diagonal of the CuO_2 planes for both LSCO and Y-123. The Raman data indicate that diagonal stripes compete with superconductivity. Apparently, stripes along the Cu-O direction lead to a relatively low-T_c such as in LSCO, while two-dimensional ordering such as observed by neutron scattering in Y-123 leads to high-T_c of the order of 100 K [2].

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[1]. L. Tassini, F. Venturini, Q.-M. Zhang, R. Hackl, N. Kikugawa, and T. Fujita, Phys. Rev. Lett. **95**, 117002, (2005).
[2]. L. Tassini, W. Prestel, A. Erb, M. Lambacher, and R. Hackl, cond-mat/0705.3635, (2007).

Electron-phonon interaction and charge carrier mass enhancement in electron doped alkali earth titanate semiconductors

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We have studied the electron-phonon coupling in electron doped $SrTiO_3$ for which the carrier concentration ranges from a dilute gas of polarons to a polaron liquid. Here we report a comprehensive THz, infrared and optical study together with DC conductivity, Hall effect and specific heat measurements. Our THz spectra at 7 K show the presence of a very narrow (< 2 meV) Drude peak, the spectral weight of which shows approximately a factor of three enhancement of the band mass for all carrier concentrations. The missing spectral weight is regained in a broad 'mid-infrared' band which originates from electron-phonon coupling. Analysis of the results yields an electron-phonon coupling parameter of an intermediate strength, $\alpha \approx 4$. Specific heat measurements below 4 K show the mass enhancement to be about eight times the band mass for all carrier concentrations. The ostensible discrepancy with the optical mass is interpreted together with the temperature dependence of the Hall constant, the optical spectral weight and the dc scattering rate within the framework of a polaron liquid.

Electronic structure of the $SrTiO_3/LaAlO_3$ interface revealed by resonant soft x-ray scattering

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The interfaces of hetero-junctions composed of transition-metal oxides have recently attracted great interest. Among them, the interface between two band insulators $SrTiO_3$ (STO) and $LaAlO_3$ (LAO) is especially interesting due to the metallic conductivity [1] and even superconductivity [2]. There has been intense debate on the origin of this metallicity, that is, whether it is due to oxygen vacancies ("extrinsic") or due to the polar nature of the LAO structure ("electronic reconstruction"). In this study we investigated the electronic structure of the STO-LAO superlattice by resonant soft x-ray scattering, which has recently been used to study $SrMnO_3$-$LaMnO_3$ superlattices [3]. Our superlattice consisted of seven periods of 12 unit cells (uc) of STO and 6 uc of LAO grown on a STO (001) substrate. Figure 1 shows the photon-energy dependence of the (003) peak at the Ti 2p edge. The (003) peak is only allowed if the interface differs from a bulk termination. Both (002) and (003) peaks show resonant enhancement at the Ti 2*p*, O 1*s*, and La 3*d* absorption edges. From the peak position analyses taking into account the effects of refraction, we found disagreement between experiment and calculation based on a simple model consisting of just STO and LAO and obtained evidence for electronic reconstruction of Ti 3*d* and O 2*p* occurring at the interface without interdiffusion of La atoms. From reflectivity analyses, highly asymmetric properties of the STO/LAO superlattice were concluded, which means that the n-type interface (AlO_2/LaO/TiO_2/SrO) is different from the p-type (TiO_2/SrO/AlO_2/LaO).

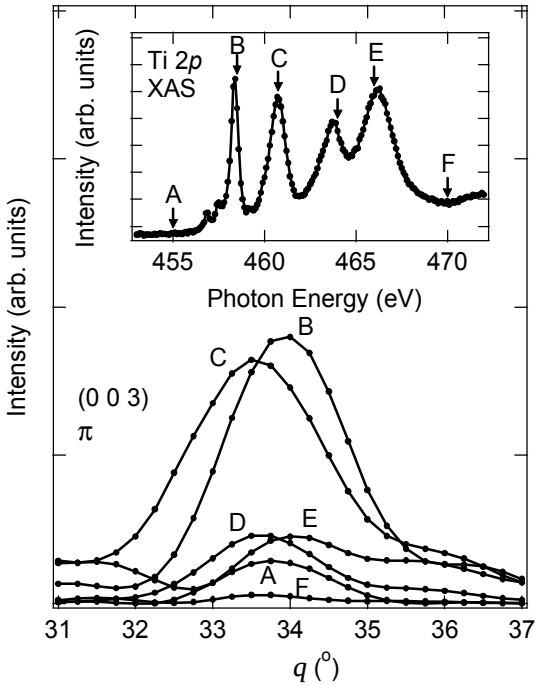

Fig.1. Photon-energy dependence of the (003) peak at the Ti 2*p* edge. The inset shows the Ti 2*p* absorption spectrum and the arrows show the photon energies at these measurements.

[1] A. Ohtomo and H. Y. Hwang, Nature **427**, 423 (2004).
[2] N. Reyren *et al*., Science **317**, 1196 (2007).
[3] S. Smadici *et al*., Phys. Rev. Lett. **99**, 196404 (2007).

Prime-Numbers Sequence in Vanadium Oxides

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Recent high pressure studies have demonstrated that a series of quasi-one-dimensional (q1D) conductors b-$A_{0.33}V_2O_5$ (A = Li, Na and Ag) reveal peculiar pressure-temperature (P-T) phase diagrams with a common characteristic; charge ordering (CO) and superconducting (SC) phases compete with each other [1,2]. Successively, we have explored high pressure properties in residual members of b-vanadium bronzes, di-valent compounds (A = Ca, Sr and Pb) using A-cation stoichiometry controlled single-crystals. In spite of absence of pressure induced superconductivity, we unexpectedly observed enormous rich P-T phase diagrams only up to 2 GPa, especially in b-$Sr_{0.33}V_2O_5$. XRD measurements at synchrotron radiation facility (KEK-PF) and precise electro-magnetic measurements showed robust four phases meet at a quite narrow P-T region [3]. At the center of region, we surprisingly discovered "Devils Stare Case"-type phase transitions [4]. The P-T phase diagram itself demonstrates profound and new physics even in non-SC di-valent b-vanadium bronzes. Because well known "Devils Stare Case" always appears when two different phases which have two different periodicities compete, meanwhile the b-vanadium bronzes does not meet the case. The most wonderful thing is that all charge modulation periodicities in all observed CO phases are prime numbers within present experimental resolution[4]. We will propose a mechanism to explain this delightful "prime numbers sequence" phenomenon taking the group theory into account. In this mechanism we will also claim a new aspect of ordered electrons (charges); the electrons are strongly coupled with crystal symmetry itself. In other words, many higher order CO patterns preserve one particular symmetry operation which is naturally included in starting crystal structure symmetry. In substantially higher pressure region above 2.0 GPa where the charge order completely collapses and the charge disorder states are sufficiently stabilized down to lowest temperature, we observed two kind of crossovers; quasi-1-dimensional to 2-dimensional conduction and randomness driven strong localization to weak localization with increasing pressure. In b-$Pb_{0.33}V_2O_5$, pressure induced anti-ferromagnetic ordering was observed at around 50 K above 0.5 GPa.

[1] T. Yamauchi, Y. Ueda, and N. Môri, Pressure-induced superconductivity in b-$Na_{0.33}V_2O_5$ beyond charge ordering, *Phys. Rev. Lett.*, **89**, 057002 (2002).

[2] T. Yamauchi, and Y. Ueda, Superconducting b(b')-vanadium bronzes under pressure, to be published in *Phys. Rev. B*.

[3] T. Yamauchi, H. Ueda, J. -I. Yamaura, and Y. Ueda, Multiple Ground State Competition under Pressure in b-$Sr_{0.33}V_2O_5$, *Phys. Rev. B,* **75**, 99 (2007).

[4] H. Ueda, T. Yamauchi, K. Ohowada, H. Sawa and Y. Ueda, Stepwise Evolution of Symmetry Reduction, *in preparation*

Quantum metamaterials: Electromagnetic waves in a Josephson qubit line

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We consider the propagation of a classical electromagnetic wave through a transmission line, formed by identical superconducting charge qubits inside a superconducting resonator. Since the qubits can be in a coherent superposition of quantum states, we show that such a system demonstrates interesting new effects, such as a "breathing" photonic crystal with an oscillating bandgap, and a "quantum Archimedean screw" that transports, at an arbitrary controlled velocity, Josephson plasma waves through the transmission line. The key ingredient of these effects is that the optical properties of the Josephson transmission line are controlled by the quantum coherent state of the qubits.

[1]E-print: arXiv:0709.1314v2 [cond-mat.supr-con].

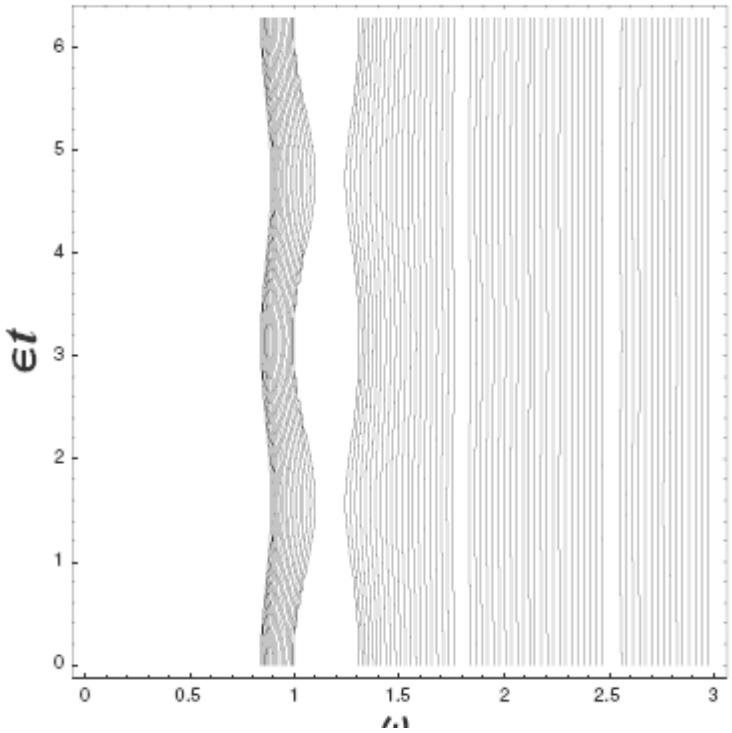

Fig.1. Breathing photonic crystal: contour curves of the wave vector k as a function of frequency, ω, and scaled time, εt, in a line of qubits in a coherent superposition of states. The time-dependent gaps in the spectrum are clearly seen.

Microwave flux-flow resistivity of $YBa_2Cu_3O_{6.333}$ and $Tl_2Ba_2CuO_{6+\delta}$ across the cuprate phase diagram

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The theoretical description of superconductivity is rooted in the understanding of the ground state from which superconductivity arises, information about which can be obtained by measuring the electrical resistivity in the normal state of the material. The high transition temperatures and upper critical fields of cuprate superconductors make it extremely difficult to measure the DC resistivity in the zero-temperature limit. Previous measurements on underdoped cuprates have revealed an apparent metal-insulator transition at low temperatures when superconductivity is suppressed by very large magnetic fields, with the resistivity showing a characteristic $\log(T_0/T)$ divergence as T goes to zero known as the Ando-Boebinger effect. [1] Until now, this insulating low-temperature behaviour was widely thought to be extrinsic, being due either to disorder or strong magnetic fields, and not essential to the cuprate problem. So far, no theoretical explanation of this effect has been proposed, despite its prominence in cuprate phenomenology.

We have recently extended these ideas substantially by carrying out high resolution microwave measurements of the flux-flow resistivity of $YBa_2Cu_3O_{6.333}$ and $Tl_2Ba_2CuO_{6+\delta}$ at temperatures down to 1.2 K. Very surprisingly, these show an insulating-like electrical response of the vortex cores, deep within the superconducting phase, with an effective resistivity that has a logarithmically diverging form below approximately 10 K. The behaviour is seen in the highest quality samples and in magnetic fields as low as 0.1 tesla, and is strikingly similar to that first observed by Ando and Boebinger in the normal state. The effect persists across the phase diagram, even in highly overdoped material in which the normal-state resistivity is metallic down to the lowest temperatures. Our observations show conclusively that the Ando-Boebinger upturn is neither an artifact of disorder nor of high magnetic fields, and strongly suggest that the anomalous log T resistivity is intrinsic to the cuprates. The measurements also provide some indication as to the origin of the effect: now that we have observed it in highly overdoped material, it seems likely that the Ando-Boebinger effect stems from the HTSC vortex cores themselves, which is a new and very interesting idea. We are currently investigating a number of theoretical scenarios including exotic Kondo scattering, in which an internal degree of freedom causes the vortex core to act as a Kondo scatterer; and the effect on vortex viscosity of Andreev bound-states in a *d*-wave vortex core.

[1]. Logarithmic divergence of both in-plane and out-of-plane normal-state resistivities of superconducting $La_{2-x}Sr_xCuO_4$ in the zero-temperature limit Y. Ando et al., Phys. Rev. Lett. **75**, 4662 (1995).


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