

CONFERENCE SUMMARY 1: LOW TEMPERATURE PHYSICS AT SCES'02*

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Focus is given on low temperature properties, with some remarks on materials, instrumentation, salient features of phase diagrams, quantum critical point and superconductivity.

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1. Materials and physics

The appearance of new materials was the driving force in SCES. Here the rush to skutterudite with the specific case of Pr compounds with singlet crystal field ground state has already led to many relevant contributions. Among them there is the discovery of the skutterudite superconductor PrOs_4Sb_2 which has led to exotic properties and to the question about the origin of the heavy fermion mass, the decoupling between orbital ordering and electronic motion, the nature of the order parameter and the intrinsic nature of the double structure of the superconductivity anomaly.

The quality of different heavy fermion compounds continues to be improved; that gives a sound experimental basis. Here, the presence of heterogeneities was suspected for a long time to play an important role, since all magnetic and electronic properties are strongly pressure dependent. Near dislocations or stacking faults, pressure gradients (few kbar) are often comparable to the critical pressure P_C of the magnetic instability *i.e.* the so called quantum critical point. Furthermore, in many cerium compounds, P_C coincides also with the point at which the crystal field splitting is wiped out and thus, the entrance in the regime where the quantum charge fluctuations occur. That may drive to the self-induced defects as proposed in high T_C oxides (in the form of stripes).

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It is worthwhile to remark that fine structural studies on intermetallic compounds are here far more difficult to realize than in oxide materials, notably reliable experiments by high resolution electronic microscopy. A new generation of experiments with microscopic probes are clearly required. One can dream of localising a dislocation and observing its magnetic and electronic response from atomic to nanometric scale, as it has been done in high- T_C materials on defects by the superconducting-gap tunnelling microscopy.

The subject of heavy fermion systems started three decades ago. Our opening to other exotic SCES materials is needed. That is the case with the pyrochlore system, where the magnetic frustration and/or small structural transformations show SCES phenomena. In the pyrochlore $\text{Cd}_2\text{Re}_2\text{O}_7$, the superconductivity appears only in the low temperature low pressure phase with a structural distortion. In the same spirit is the discovery of pressure induced superconductivity in the $\beta\text{-Na}_{0.33}\text{V}_2\text{O}_5$ bronze beyond its charge ordering. The attraction to spin ladder systems $\text{Sr}_{14-x}\text{Ca}_x\text{Cu}_{24}\text{O}_{41}$ has vanished despite the fact that no clear response is given on the appearance of superconductivity and the role of the ladder structure intermediate between the one- and two- dimensional configurations. Here, recent NMR studies up to 3.5 GPa are reported for $\text{Sr}_2\text{Ca}_{12}\text{Cu}_{24}\text{O}_{41}$.

The manganite family has a large diversity of behaviour (metal-insulator transition, spin and charge orderings, *etc.*), and thus a great opportunity for deep research at low temperature. The more difficult task appears to be to know how to pick up a particular case for a potential last comer in the field. As a main priority, we must give a better place to young researchers involved in materials sciences, young talented solid state chemists or physicists in this field are highly demanded. This is also true for the instrumentation.

2. Instrumentation and physics

The oral presentations but even posters were mainly devoted to the discussions of the results rarely on the presentation of the bare data. That eliminates information which is unfortunately lost for the community. Let us hope that the future conferences and their proceedings will be used as an unique opportunity to provide experimental details, which might be boring for a large audience but not for a meeting of specialists. A good example is the recent work on the transition intermetallic compound ZrZn_2 which does not come from the resistivity measurements regarded as the prototype of an ideal weak ferromagnet. Similar behaviour is observed for Ni_3Al . Here clearly basic thermodynamic measurements are needed. As for MnSi , there is already preliminary NMR measurement under pressure which indicates a strong heterogeneity near the first order transition at P_C .

Great progresses have been performed on extreme conditions for the (T, P, H) experiments. Examples were: the simultaneous calorimetric and transport pressure measurements for CeCu_2Si_2 , the phase diagram of URu_2Si_2 up to 40 T by calorimetric and ultrasound experiments or of the specific heat on YbRh_2Si_2 down to 10 mK.

As specific probes, let us emphasise the use of the anisotropy in the thermal conductivity with the orientation of the magnetic field to probe the gap nodes and the application to different unconventional superconductors: ruthenate, heavy fermion and organic conductors. Complementary measurements at very low temperature must be performed to test the strong theoretical statement concerning a universal limit for specific types of the order parameter.

3. Results

3.1. From single Kondo impurity to the Kondo lattice

The old debate on the problem of the electron counting (n_e) (often referred to as an exhaustion case when one goes from the single Kondo impurity problem to a regular array of Kondo centres on the lattice) is still continuing. In a rigid band picture, the number (n_e) of light conduction electrons with density of states $n(E_F)$ at the Fermi level available for a Kondo singlet (energy $K_B T_K$) is low ($K_B T_K \times n(E_F)$). In reality, the process is dynamic as electrons hybridise. There is already a large variety of experiments which demonstrate different energy scales even in the so called coherence regime *i.e.* below the temperature where the resistivity stops increasing on the cooling. The simple evidence comes from comparing thermal expansion α and specific heat C . A behaviour driven by a sole parameter leads to a temperature invariant of the ratio α/C *i.e.* a constant Grüneisen parameter; a behaviour driven by two or more parameters corresponds to a strong T variation of α/C *i.e.* a constant Grüneisen parameter may be achieved only at very low temperature. The differentiation between a coherence counting temperature, T_K^* , spin fluctuation temperature, T_{SF} , or ordering temperature will be possible only in rare cases.

The large interest in orbital ordering raises hope that in the future a clear example will appear of a Kondo quadrupolar effect. At this conference, there are clear examples of quadrupolar orderings in Pr compounds and discussions on the well known case of CeB_6 .

3.2. Phase diagrams

The knowledge of (H, T) or (P, T) phase diagrams is of a fundamental interest. At this conference, many endings of the transitions at $T \rightarrow 0$ K (magnetic, charge, structural) are related to a superconducting pocket. The theoretical understanding is open; new macroscopic and microscopic measurements will be soon performed.

The pressure variation of the new (H, T) phase diagram found at ambient pressure for URu_2Si_2 will be certainly precised rapidly. An attention will be given to the critical pressure $P^* = 12$ kbar, where long range ordering changes from the so-called hidden order (with a weak magnetic moment) to the classical antiferromagnetism (high magnetic moment) and simultaneously the superconducting temperature collapse.

4. Magnetic quantum critical point and universality

There are different examples where the transition from long range magnetic order to paramagnetic state is of THE first order: MnSi , UGe_2 and CeRh_2Si_2 . In the last case, the Fermi liquid T^2 law of the resistivity holds on both sides of P_C and at least in magnetic field, even though the Fermi surface (FS) is drastically different on each side of P_C .

Similar phenomena at H_C may occur in a magnetic field sweeping through the magnetic phase transition *i.e.* when going from the long-range magnetic ordered to the polarised phase. Results are presented here on the clean material YbRh_2Si_2 . As in previous works on $\text{Ce}_{1-x}\text{La}_x\text{Ru}_2\text{Si}_2$ the nature of magnetic correlations itself may change at H_C from antiferromagnetic to ferromagnetic with a deep associated modification of the Fermi surface (FS). A clear observation of the first-order magnetic transitions poses the question on the validity of second-order quantum critical point (QCP). At least, there are examples such as CeIn_3 , CePd_2Si_2 or $\text{CeCu}_{6-x}\text{Au}_x$, where a second order QCP seems to exist.

Concerning the recent debate on the occurrence of FS at QCP it seems clear that FS exist in systems like CeIn_3 and CePd_2Si_2 ($P_C \sim 25$ kbar). With the high field technique of de Haas-van Alphen experiments, the extrapolation at $H = 0$ can be discussed as well as comparison with band structure calculation realized generally at $H = 0$ can be made. Of course, the singular situation occurs when the Kondo temperature T_K is very small (in $\text{CeCu}_{5.9}\text{Au}_{0.1}$ near 1 K); the local heavy fermion quasi-particles are not completely built before interacting. Today, we cannot conclude if here the problem is mainly of experimental nature *i.e.* associated with the difficulty to reach the milli-Kelvin (very low) temperature regime ($T \ll T_K$) or really fundamental (*i.e.* the breakdown of Fermi-liquid picture). My feeling on the ω/T scaling of the dynamical function $\chi(\omega, T)$ of the form

$$\chi(\omega, T) \approx \frac{1}{T^\alpha} f\left(\frac{\omega}{T}\right),$$

is that it may be not so enlightening the picture by studying low energy, high energy, low temperature and high temperature regimes for the data. Systems where the wave vector structure is clear may be understood first.

5. Superconductivity

The theme of ferromagnetism and superconductivity in SCES is rather new. No decisive conclusions can be given however many theoretical developments have appeared. For the interplay of antiferromagnetism and superconductivity, the striking results are: (i) the superconductivity pocket near P_C may be narrower than that found by the resistivity data, (ii) the observation of finite resistivity inside a suspected superconducting domain. That suggests material problems, but also raises the question of entering the clean-limit condition which is difficult to fulfil when $T_C \rightarrow 0$ and the superconducting coherence length diverges.

The study of the vortex matter is a frontier domain, which inter-plays with nanophysics and soft matter. The link with the order parameter, the electronic anisotropy and the vortex alignment has been made for different cases, *e.g.* for Sr_2RuO_4 , UPt_3 and $\text{YNi}_2\text{B}_2\text{C}$. New ferromagnetic superconductors are appealing for the search of a spontaneous vortex state. The understanding of the vortex case may be an unique way to explore the normal phase low-temperature properties here in high- T_C oxide, but also on very strong coupling system such as UBe_{13} .

The facility to grow excellent crystals (like CeCoIn_5) of the (1.1.5) cerium family with well isolated cerium planes has led to impressive results with emphasis on the role of the planar dimensionality. Careful scans through the QCP or magnetic–non-magnetic transitions with x in $\text{CeRh}_{1-x}\text{Ir}_x\text{In}_5$ or with P on CeRhIn_5 are needed. There are few reports concerning low energy electronic spectroscopy. Let us stress the nice experiment done on CeCoIn_5 by the point-contact tunnelling.

As usual, in their talks, the experimentalists develop too extensively the theory and some theoreticians give often an up-to-date fancy presentation of the experiments. That masks often the emergence of the real improvements and the hierarchy of the various problems. I still continue to believe that each researcher must be driven by his own dynamics which must be stimulated by basic simple questions. On purpose, I have not supplied specific references since I only hope that my remarks will stimulate a careful reading of this proceedings.

Similarly as many other participants, I thank Professor J. Spalek and his colleagues for organising this stimulating conference hosted by the prestigious university. I do hope to come back some day to Kraków, a city full of many historic memorabilias, and stay at the University Guesthouse in Floriańska street. Indeed, I had a very good time in Kraków.