CONFERENCE SUMMARY 2: EXPERIMENTS*

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We briefly overview the highlights of some of the experimental papers presented at SCES'02.

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1. General remarks

The visit to the museum of the Jagellonian University on the first conference day confronted some of the participants to the SCES'02 in Kraków with the first successful attempt to liquefy air components by the two Polish scientists, Karol Olszewski and Zygmunt Wróblewski, both professors of the Jagellonian University. Solid State Physics owes a lot to their discovery since the liquefaction of air was a major step in the further development of the cryogenic techniques. The deviations in the specific heat of solids from the DuLong–Petit law well below room temperature could even better be ascertained in the liquid-air temperature region. These deviations motivated Einstein in 1907 to apply the energy quantization, introduced by Planck in 1900 to describe the ultra-violet catastrophe in the emission spectra of black bodies, to the specific heat data of diamond, a model further reevaluated by Debye in 1912 in order to produce the T^3-contribution of the lattice vibrations to the specific heat of a solid at the lowest temperatures.

The specific heat plays an important role in the description of the low-temperature electronic excitations in the energy spectrum of solids and in particular, at articulating the anomously large effective electronic mass in heavy fermion systems. For that reason, specific heat data were always of central interest to the SCES community and experimental facilities have

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been developed by the same community to measure this quantity under extreme conditions at low temperatures. At this meeting, progress has been reported for measuring the specific heat along three different directions:

- Accurate specific heat data have been reported for temperatures down to 20 mK at which the nuclear contribution has been subtracted from the raw data by using Mössbauer data for the nuclear part in the specific heat.
- Specific heat data have been reported at temperatures above 300 mK under pressure up to 25 kbar.
- Low-temperature specific heat measurements have been performed in static fields up to 45 T at the National Magnet Laboratory in Tallahassee, Florida, USA.

Each of these results will be briefly commented on.

Heavy-fermion physics has its origin in the study of anomalous low-temperature properties of a selected series of cerium and uranium compounds. That selected series of compounds has been discovered in systematic studies on a large number of (pseudo-)binary and (pseudo-)ternary intermetallic cerium and uranium compounds. That is still the way the SCES-community is undertaking a continuous search of new examples of strongly correlated electron systems. The elements on which this search is based has been extended from cerium and uranium as the basic constituents to praseodymium, europium, and ytterbium. But still, the majority of the research efforts is carried out on bulk samples of compounds that are stable in nature. There is little work reported at this meeting on thin films, nanostructures or multi-layer compounds. In that sense, this meeting is different from, for instance, conferences on magnetism where mesoscopic physics starts to dominate. Only a few contributions at this conference deal with quantum-dot phenomena and related nanostructures. There is no doubt that the artificial and lower dimensional structures will also be introduced in the future programs of the SCES meetings.

Sample quality has always been an essential point of discussion at the SCES meetings. Sample quality is usually controlled in EPMA and X-ray diffraction studies, and the sample purity by the residual resistivity at zero temperature. Experiments are preferentially carried out on single-crystalline samples in order to address the anisotropy of the physical properties. Single-crystal growth of the intermetallic compounds is frequently arranged by a Czochralski three-arc melting equipment which, for congruently melting materials, is an excellent approach. Nevertheless, in some cases improved quality has been mentioned for single-crystalline samples prepared by the Travelling Solvent Floating Zone Technique in a multiple-mirror furnace. The advantage of this latter method is that non-congruently melting compounds can be prepared as well. The technique has proven its great value in the production of the ceramic high-temperature superconducting materials. In the past twenty-five years, a large part of the interest in heavy-fermion systems went to the heavy-fermion superconductors such as: $CeCu_2Si_2$, UBe_{13}, UPt_3, URu_2Si_2, UPd_2Al_3 *etc.*, *i.e.* the compounds for which the latent or the actual magnetic order is combined with the superconductivity at temperatures below 1 K. Most of these compounds are still a subject of intense studies. For the compound URu_2Si_2 the present interest is directed towards the hidden order that controls the transition at 17 K. For UBe_{13}, detailed specific heat and thermal expansion measurements on one and the same sample reveal an anomaly in the thermal expansion that could be related to the second transition in the phase-diagram of $(U_{1-x}Th_x\mathrm{x})Be_{13}$ for x-values roughly between 0.02 and 0.04. The compound UPt_3 seems to be an exception among the heavy-fermion superconductors, since, apart from a theoretical paper on the dual nature of the $5f$ states in this compound, no further developments have been reported. There are, however, two recent reviews that have been published elsewhere in Refs [1] and [2]. It is also interesting to note that some of the old materials, like $ZrZn_2$, MnSi, and Ni_3Al, that were studied in the sixties and seventies for their weak itinerant ferromagnetism, are now included in the broader discussion of non-Fermi-liquid phenomena and quantum critical points.

Among the novel compounds that are claimed to exhibit anomalous properties, characteristic for strongly correlated electron systems, are the Pr-based filled skutterudites. In contrast to most of the other heavy-fermion compounds that borrow their importance from a further development of the description of strongly correlated electron systems, the rare-earth based filled skutterudites have specific thermo-electric properties which could be useful for applications. Sufficiently large values for the figure of merit Z ($Z = S^2/\kappa\rho$, with S standing for the thermopower, κ for the thermal conductivity, and ρ for the electrical resistivity) are required in order to have the product of Z and T, the temperature, larger than one, which is a condition of their applicability. Especially for these novel compounds, large collaborations have been formed that transform the competition into a co-operation. In any case, the speed with which this topic is developed is enormously high.

2. Magnetic order in heavy-fermion systems

Magnetic interactions form an essential feature for the heavy-mass electrons that reveal effective electron masses which are two to three orders of magnitude larger than the free-electron mass. In some cases, these interactions give rise to short-range magnetic fluctuations which can be investigated in neutron scattering experiments. In other cases, extremely small values, of the order parameter, in the range of 0.01 μ_B, are observed in muon–spin rotation experiments, whereas in other compounds, magnetic moments of macroscopic values are found with sizeable values for the magnetic ordering temperature. For the uranium intermetallics these observations pose the question under which conditions magnetic moments are formed on the uranium ions. Magnetism and superconductivity in the uranium intermetallics were very much discussed in the seventies in terms of what was called the Hill plot: a classification of compounds following the inter-uranium distance. The Hill limit with a value of about 4.5 Å, distinguishes compounds that show superconductivity from those exhibiting some type of magnetic order. Famous examples for superconductivity are the UX_6 compounds with X = Mn, Fe, Co, Ni and inter-uranium distances well below the Hill limit, whereas compounds like the U_3X_4 series with X= As, Se, Te, and inter-uranium distances well above the Hill limit show magnetic order. Special interest attracted compounds close to the Hill limit and UAl_2 appeared to be one of them. In any case, superconductivity was not expected in compounds like UBe_{13} and UPt_3, since in both compounds the value for the inter- uranium distance largely exceeds the Hill limit, these compounds are placed in the magnetic half of the Hill plot. The actual observation of a lack of magnetic order and the discovery of superconductivity in these two compounds instead, was a big surprise. An immediate answer to this problem was the hybridisation of uranium f-states with the Pt $5d$-states in case of UPt_3 although that solution is certainly less effective for UBe_{13}. Anyhow, a new category of compounds was born: the uranium-based heavy-fermion superconductors. Compounds that later were discovered and which fit in this category are: URu_2Si_2 and UPd_2Al_3. For all four compounds superconductivity develops in the presence of strong magnetic interactions or even a magnetic order. One of the series of compounds in which the effects of hybridisation have been systematically investigated is the UTX series, with T a d-transition metal in the second half of the d series and X a p-element. In case we choose for X the element Al and for the d series the $3d$ elements Fe, Co and Ni we find paramagnetic behaviour over the full temperature range for UFeAl, strongly enhanced paramagnetism for UCoAl with a metamagnetic transition in high magnetic field just as was found in YCo_2, and antiferromagnetic order below 19 K with a value for the uranium moment of

0.5 μ_B, approximately that for UNiAl. The two latter compounds show large values for the electronic specific heat coefficient γ of 65 and 164 $mJ/mol\,K^2$, respectively, in contrast to the relatively low value of 21 $mJ/mol\,K^2$ for UFeAl. The way magnetism develops in this series is ascribed to the characteristics of the $5f$–$3d$ hybridisation.

Another example can be discussed for a fixed d-element and a series of p elements with the increasing ionic radius. In the series UCoX with X equal to Al, Ga or Sn, magnetism develops from enhanced paramagnetism in UCoAl to ferromagnetic order below 48 K and magnetic moments of 0.2 μ_B, approximately for UCoGa and a T_c value of 80 K with a uranium moment of 0.9 μ_B, approximately for UCoSn. This development of magnetic order is ascribed to the variation in the $5f$–$3d$–p hybridisation.

High-pressure and alloying experiments have further elucidated these systematics.

REFERENCES

[1] J.J.M. Franse, *Acta Phys. Pol. A* **100**, 153 (2001).

[2] A. de Visser, *Physica B* **319**, 233 (2002).