High Magnetic Fields in Condensed Matter Research

It is difficult to do justice to the importance of high magnetic field research in all its applications so we shall concentrate on topics in a major area, namely condensed matter. Research using high magnetic fields seeks new effects and phenomena under extreme conditions. The magnetic field controls the orbital motion of charged particles by the Lorentz force as well as particle angular momenta or spin, thereby adjusting the energy of the system to create a new physical state which can give rise to novel properties. Magnetic fields thus have effects comparable to low temperatures, which also lead to new physical states such as superconductivity and new structural phases. In contrast, other techniques requiring major facilities (*e.g.* neutron sources, accelerators, synchrotrons) generally investigate systems without altering the physical state.

However, the effects of magnetic fields are unique and very different to those obtained by applying low temperatures since a magnetic field quantizes the motion and energy of charges and magnetic particles and destroys time-reversal symmetry.

Of course, the more spectacular effects caused by magnetic fields are not always observed in a dramatic way because application of the field often only slightly changes the state of the system. For it must be realized that, in many respects, the fields presently attainable in laboratories are never large compared with other physical quantities. A Bohr magnetron placed in magnetic field of 1 T has an energy of 0.058 meV, equivalent to 0.67 K so a state-of-the-art high magnetic field facility generating fields approaching say 100 T only yield an energy equivalent to 67 K which is small compared to room temperature. Put differently, Zeeman splitting of an electron demands several hundred tesla at room temperature and about 1000 T at the band gap — fields which are essentially inaccessible.

Similarly, the size of a cyclotron orbit in a 1 T field is 25 nm which is large compared with most naturally occurring lengths such as a typical lattice spacing (0.5 nm) or the Bohr radius (0.05 nm).

Judicious Experiments

New physical phenomena must therefore be found using judiciously chosen experiments — chosen so as to attain extreme physical conditions. In the case of condensed matter, the energy change owing to available magnetic fields must be, for example, compared with the Coulomb energy separation between different electronic configurations, magnetic anisotropies, the crystal-field interaction of surrounding charges and the spin-orbit interaction. Anisotropies are typically 0.1 to 10^3 K, and the last two on the order of 1 to 10^3 K, for rare-earth ions and Fe-group ions, making materials containing these ions well suited to studies in the 100 T range.

The fine structure of the density of states curve near the Fermi energy can also be resolved using high fields. Of particular interest are many-body phenomena that appear at low temperatures with characteristic energies of a few meV. Magnetic fields in the 10 to 100 T range thus allow the study of electron correlations in metallic systems.

Advances in Materials

In identifying new departures for high magnetic field research it must also be appreciated that the availability of high fields goes hand-in-hand with advances in materials science. Consider, for example, the orbital quantization of electrons: contrary to localized, spin-like magnetization that can be observed at quite low fields, quasi-free electrons, the origin of the more "delocalized" magnetic properties, are very sensitive to defects so in order to observe the effect of orbital quantization one needs high fields and/or very high purity materials. By combining these requirements "orbital" magnetism becomes accessible, first in exploratory work at relative high fields in specialized facilities and later at lower fields as materials technology advances and techniques become perfected (see the example described on page 162).