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The basics of 4f-electron magnetism

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Magnetism, the phenomenon by which materials assert an attractive or repulsive force or influence on other materials, has been known for thousands of years. However, the underlying principles and mechanisms that explain the magnetic phenomenon are complex and subtle, and their understanding has eluded scientists until relatively recent times. Many of our modern technological devices rely on magnetism and magnetic materials. Many materials including iron, some steels, and the naturally occurring minerals are well-known examples of materials that exhibit magnetic properties. However, it is the fact that these substances are influenced to one degree or another by the presence of a magnetic field.

It is a well-known fact that solids are characterised by a regular (almost fixed) arrangement of a huge number of atoms, which consist of the nucleus and an appropriate number of electrons which are strongly bound. Only a small number of them are mobile. Usually, these mobile electrons are primarily responsible for the thermal, electrical and magnetic properties of a solid. Charged particles are subjected to mutual interactions due to the Coulomb force which can be both repulsive and attractive, depending on the charge. Moreover, there are also forces between magnetic moments, however much smaller if compared to the Coulomb interaction. The 1022 particles are therefore exposed to complicated many-body interactions, which can be treated exactly only in terms of quantum mechanics. The latter is valid, in particular, for mobile electrons moving across the solid. Each electron is then described by its position vector and spin. Beside the negative charge, the spin of the electrons determines the magnetic properties of the solid to a substantial extent. This means that the magnetic moments of the electrons are ordered in the material over a substantial distance. The sum of the ordered moments yields then the macroscopically deduced total magnetisation.

Within the last two decades various metals have been found to possess heavy electrons which consequently are termed as heavy fermion systems or heavy electron systems. The carriers responsible for the electrical current (electrons or holes) are associated with masses up to several hundred times the mass of free electrons in simple metals like Cu or Al. However, this appearance can be found only at low temperatures ($T \approx 10$ K). At high temperatures the systems behave like normal "magnetic" metals. Heavy electron systems usually contain rare earth elements like cerium (Ce) or ytterbium (Yb) or actinides like uranium (U). These materials exhibit partially filled 4f- or 5f shells. Cerium and ytterbium possess the 4f shell which is occupied by 1 or 13 electrons, respectively (4f1 and 4f13 - state). The one electron of cerium – in case of Yb a hole – appears to be unstable and fluctuations of the spin and/or of the valence part into the conduction band may occur. These fluctuations are considered as origin of the low temperature anomalies. They behave at high temperatures like the f-electrons are completely localised, which is already well known from stable rare earth intermetallics (e.g. Gd., Ho, Er, . . .). However, while the latter show in general a phase transition into a magnetically ordered ground state (e.g., ferro- or antiferromagnetism) the former crosses over at low temperatures to a behaviour known only from simple metals, like a temperature independent Pauli susceptibility or a temperature independent Sommerfeld term in the specific heat, with the exception of strongly renormalized masses (enhanced effective masses m*). This talk provides a brief description of the origin of magnetic fields and discusses the various magnetic field

vectors and magnetic parameters. The basic phenomena of diamagnetism, paramagnetism, ferromagnetism, and ferrimagnetism due to the presence of -f electrons in solids will also be discussed.

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