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MILESTONE 12

Odd one out

Jun Kondo. Image courtesy of AIST, Tokyo.

Impurities are not always unwanted. With the right type and dose of impurity atoms, the bulk properties of a material can be tuned in a beneficial way, which is a technique made heavy use of, for example, in standard silicon technology. At the microscopic level, interesting questions arise about how an impurity atom interacts with its host.

In 1964, Jun Kondo resolved a long-standing question regarding the electrical resistance of magnetic impurity-doped metals. The mystery was this: the resistance of a metal should decrease with decreasing temperature, as atomic vibrations freeze out, so that conduction electrons can move more easily through the material; however, for magnetically doped metals, the resistance was found to increase again below a certain temperature. Kondo discovered that it is the intrinsic spin of magnetic impurity atoms that leads to this anomalous resistance. The amount of scattering that electrons experience at the impurities does not decrease but increases when the temperature goes down, and this leads to the observed minimum in total resistance.

Not only did this finding explain a nagging problem but it also triggered a vast amount of theoretical follow-up work. The initial issue to tackle was that the effect seemed to yield infinite resistance as zero temperature is approached — clearly an unphysical result. It was soon found that this divergence of resistance is suppressed, below a certain temperature (the Kondo temperature), by the formation of a bound state between impurity and conduction electrons, in which electron spins line up to screen the spin of the impurity atom. A later development was the extension of the theory to 'Kondo lattices' in which electrons interact not only with the odd magnetic impurity but rather with an array of localized spins, and are significantly slowed down by the strong interactions. This model can explain some of the unusual properties, such as anomalous superconductivity, displayed by so-called heavy-fermion compounds.

Another line of research is the Kondo effect in nanometre-sized structures, such as quantum dots, in which the interactions between a single magnetic impurity and its environment can be controlled. A quantum dot can be tuned to contain an odd number of electrons — that is, an unpaired spin. Below the Kondo temperature, this localized spin can form a bound state with the free electrons in the electrodes on either side of the quantum dot, similar to the classical Kondo effect. However, this 'Kondo resonance' opens an additional pathway for electrons to flow through the quantum dot and, as a result, the resistance decreases, in contrast to the original effect.

The ideas and methods developed by Kondo and his fellow theorists turned out to be relevant to a wide range of problems that involve strong interactions between particles. As a result, the 'Kondo effect' — which, in truth, comprises a range of phenomena to do with collective behaviour arising from localized magnetic impurities — is an active research topic today and one that still throws up surprises.

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