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MAGNETISM

Doping rehabilitates failed materials

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Strong permanent magnets are essential for technologies from hard disk drives to hybrid cars, but they usually rely on rare-earth elements that are scarce and expensive. Now, Paul Canfield and co-workers, writing in *Physical Review Applied*, report a new strategy for converting the paramagnet $CeCo_3$, which becomes magnetic only when an external magnetic field is present, into a ferromagnet, which is always magnetic. They do this by substituting some of the Ce with Mg.

"Cerium is a rare-earth element that is relatively abundant and cheap, but in general it has not performed well in magnets so far and usually loses its magnetic moment when incorporated into many compounds, as is the case for pure $CeCo_3$," explains Canfield. "We think it is very exciting that we could take a 'failed' magnetic system and 'rehabilitate' it back into being not only magnetic, but even possibly practical for certain applications."

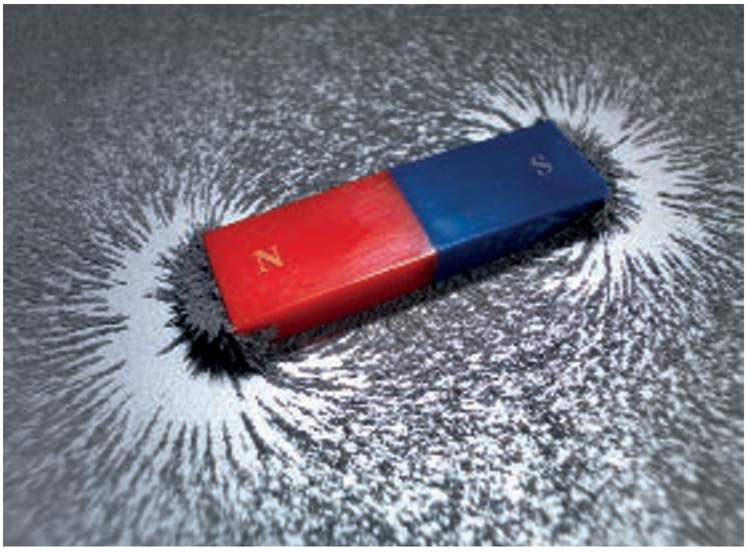
The first step in rehabilitating $CeCo_3$ as a magnetic material was to create $Ce_{3-x}Mg_xCo_9$ samples. Polycrystalline samples were prepared by arc-melting and annealing Ce, Co and Mg. Single crystals were grown from solution. As a control, $CeCo_3$ samples were also prepared using the same techniques. The composition of polycrystalline samples was checked using energy-dispersive spectroscopy, which showed that Mg doping was successful up to $x \approx 1.4$. Diffraction of the single crystal Mg-doped samples showed that the structure is rhombohedral, of the $PuNi_3$ type.

This structural study was followed by magnetic characterization. "There have been studies of Mg-doped $CeCo_3$ for hydrogen storage applications, so we knew the material could be made, but there were no reports of its magnetic properties," says Canfield. It was also necessary to confirm the characteristics of the parent material, as conflicting reports exist on its low-temperature magnetic properties. Temperature-dependent susceptibility and electrical resistivity measurements on $CeCo_3$ showed no sign of a transition to ferromagnetism.

By contrast, as the temperature dropped below the Curie temperature, the $Ce_{3-x}Mg_xCo_9$ samples showed a rapid increase in magnetization, that is, they entered the ferromagnetic phase. The Curie temperature increases with the level of Mg doping, and is above room temperature for $x > 1.2$. The coercivity field, that is, the field required to demagnetize the material, also depends on Mg doping, with a maximum value of ~0.35 T (similar to that of the permanent magnet MnBi) for $x \approx 0.8$. Single crystal $Ce_{1.66}Mg_{1.34}Co_9$ has an anisotropy energy density of 2.2 MJ m^{-3} at 2 K, which is high enough to envisage application as a permanent magnet.

The researchers hypothesize that Mg doping may work by changing the band structure of $CeCo_3$, but details of the origin of the ferromagnetism are still unclear. However, this open question leaves plenty of space for future work. "We think that this idea of rehabilitation is worthy of much greater attention, opening up a whole new strategy for finding new magnetic materials," comments Canfield. "We plan to identify as many failed magnetic compounds as we can, and apply both computation and experimentation to identify which of them may have potential for rehabilitation, and eventual application."

Zoe Budrikis



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ORIGINAL ARTICLE Lamichhane, T. N. et al. $Ce_{3-x}Mg_xCo_9$: transformation of a Pauli paramagnet into a strong permanent magnet. *Phys. Rev. Applied* **9**, 024023 (2018).