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VIEWPOINT

Engineering magnets on the atomic scale

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The ubiquity of the prefix 'nano' (Greek: dwarf) in conjunction with metre, scale, structure, fabrication etc in present day (serious and not so serious) scientific and technical literature is startling. Clearly, this signals a great amount of activity in a field that one could quite generally call 'engineering materials on the atomic scale'.

To appreciate the length scales involved, one recalls that one nanometre, abbreviated as 1 nm, equals 10^{-9} m or one millionth of 1 mm. The atomic scale can be visualized by measuring the size of a cobalt atom in a piece of cobalt metal. If we put one of these atoms in a sphere we arrive at a radius of about 0.14 nm. Imagine that we place a number of cobalt (Co) atoms side by side like a necklace of pearls, in this way obtaining a monatomic Co chain. Can this be done in reality? Can the physical properties of such chains (or wires) be determined? The answer to these questions is quite remarkably yes.

In an attempt to assemble a necklace, one first needs a flat surface to align the pearls. The same is true for the atomic engineer who, one should hasten to say, actually is a physicist; in the experiment of interest here, Gambardella and colleagues [1–3] used the surface of platinum (Pt) oriented in such away that it consists of flat portions separated by regularly spaced steps, not unlike a staircase. Cobalt is brought onto the surface in tiny amounts by evaporation. In a certain temperature range the atoms glide about the surface like ice-skaters getting stuck at the edges because there the binding energy is larger than on the flat portions. This fabrication process, an art in itself [4], results in a very large number of regularly spaced straight Co chains glued to the edges of the Pt steps.

Indeed, we can really see all this with the scanning tunnelling microscope (STM). In 1981 this instrument was invented by Binnig and Rohrer (Nobel prize in 1986); it actually initiated the substantial progress in surface physics and the fabrication of nanostructures on surfaces. A picture of the steps and Co chains can be seen in figure 3 of Gambardella's paper [3]. A modern, very promising development of the STM is described in this Special Issue [5].

Turning now to the physical properties of the Co chains we briefly recall the phenomenon of magnetism. In various forms and guises, magnets are encountered in daily life. The compass needle is the best known example—an old one, too; much more frequently you perhaps notice the magnetic strip on your credit or bank card. Various electric motors and the starter in the automobile employ permanent magnets. Your PC's storage unit is a delicately fabricated magnetic device, where modern surface physics is being used in the magnetoresistive reading head. At the basis of these metallic magnets are generally iron, cobalt, nickel and some

elements from the group of the rare earths. Knowing that a macroscopic piece of Co is a permanent magnet (called a ferromagnet) when the temperature does not exceed 1388 K (or 1115 °C), the so-called Curie temperature, we may ask what the magnetic properties of the Co nanowire on the Pt surface are.

In a much-cited paper, Mermin and Wagner [6] showed rigorously that under some quite general assumptions a one-dimensional magnet cannot possess any long-range magnetic order except at the absolute zero of temperature. Taking this at face value, one would expect to find that a Co chain cannot be a permanent magnet. But the measurements of Gambardella and colleagues [1–3] give a different answer. They find it to be a ferromagnet with a Curie temperature of about 15 K. This is low, but not zero. The measurements by two different spectroscopic methods are unambiguous and, furthermore, reveal a giant magnetic anisotropy energy (MAE). This is the energy that keeps the magnetic moments aligned along a certain crystallographic direction and is a measure of the strength of the magnet which is estimated to be about 200 times larger than that of a Co atom in the bulk crystal.

We might now ask whether the Mermin–Wagner theorem is in error or simply not applicable here. It certainly is not in error, but we need to look at the assumptions made. One of them is the famous Heisenberg model which describes the energy changes when the magnetic moments are disordered: does it apply to the itinerant d electrons that are spectroscopically established to be responsible for the magnetism of Co chains? Although the situation is somewhat controversial, the answer is most likely to be in the affirmative. Another, crucial assumption concerns the length of the chains. In the theory of Mermin and Wagner they are assumed to be infinitely long, whereas the experimental chains are of finite length. In fact, Gambardella in his paper argues, by means of an estimate of the entropy, that finite chains could be stable magnets. But he also argues that the giant MAE, which is not part of the Heisenberg model considered by Mermin and Wagner, stabilizes the one-dimensional magnet. Here the MAE sets up an energy barrier that leads to a long relaxation time of a single-domain magnetic particle. Thus on some timescale, the magnetism of the Co chains might be a metastable affair. In summary, it is believed that the Mermin–Wagner theorem does not apply here.

The measurements by Gambardella and colleagues already initiated new theoretical work [7–9] that led to an improved understanding of the experimental results. But many problems remain, especially as regards a detailed understanding of the giant MAE together with the finite-temperature problems of the magnetic nanowires.

The work described here must, no doubt, be called fundamental research. But as has become customary, one might ask whether it has any bearings on applications. Magnetic data-storage technology comes to mind, for instance—where today some 100 000 magnetic atoms are required to provide a stable magnetic bit on a computer disk. Gambardella [3] places a limit of about 50 Co atoms on the length of the chains. Thus, if a chain is to be used for a magnetic bit, clearly, the storage density would increase enormously, provided only that they are stable at room temperature.

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