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[Scientific Laboratory, Ford Motor Company, Dearborn, MI]

A model for the origin of ferromagnetism in Fe, Co, and Ni is developed that attributes the alignment of the magnetic moments to the indirect coupling of the predominantly localized d-like electrons through a small number of itinerant d-like electrons. [The *SCI*® indicates that these papers have been cited in over 160 and 145 publications, respectively.]

On the Origin of Ferromagnetism in Fe, Co, and Ni

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In the salad days of scientific research, the early 1960s, I joined the Ford Scientific Laboratory. At that time it was common practice, even in many industrial laboratories, to allow promising researchers the freedom of working on whatever problems they found of interest. So, upon coming to Ford, I began to look around for an interesting problem. Two aspects lead me to begin looking at the problem of the origin of ferromagnetism. One was that Ford already had a number of expert researchers in this area, so I felt I could learn a lot about this field, in which I had never worked and knew nothing. I was delighted to find out that the field was in a state of flux and the problem of the origin of ferromagnetism in metals was far from solved. The second aspect was that the Mössbauer effect had been recently discovered,[1] and its use for measuring hyperfine fields was being developed.

At that time the presumed mechanism for aligning the Fe moments in ferromagnetic Fe was through the s-like conduction electrons. However, there was no experimental evidence for this. So here was a problem just ripe for exploration. The result of my efforts was that, as described in the 1966 *Physical Review* paper, I developed a method for using the Mössbauer effect to measure the variation of the hyperfine field at the first few neighboring shells surrounding an Fe moment. This gave the spatial dependence of the spin polarization of the 4s conduction electrons surrounding an Fe atom. To my surprise this variation was such that it would *not* lead to Fe being ferromagnetic, but instead it would have aligned the Fe atomic spins in opposite directions, or antiferromagnetically! Thus, it was immediately obvious to me that the 4s conduction electrons were not responsible for the ferromagnetic alignment of Fe. It had to be caused by conduction electrons of a different character. A further requirement, which followed from the shape of the measured spin polarization, was that the number of electrons responsible for the alignment had to be much smaller than the number of 4s conduction electrons in Fe (about one per atom).

One of the vivid memories I have of these events is that one day I was sitting in my office trying to explain to a colleague what I was measuring. He was at the blackboard vociferously telling me that I couldn't be measuring what I claimed I was. At the time all of this seemed to be very surrealistic; he seemed to be far away and ranting in a rather incoherent way. It turned out that my preschooler had brought home the mumps, and I was developing a fever and a severe case of the mumps.

About this time other evidence had been accumulating, from a wide variety of experiments, that the 3d-like electrons in Fe had two types of character. Depending on the type of experiment, they looked either localized or itinerant. [illegible] I proposed that the conduction electrons that were responsible for the ferromagnetic alignment of the Fe moments were a few d-like conduction electrons. I then began to look in the literature for evidence of a small number of d conduction electrons in Fe, about 0.2-0.3 per atom. Sure enough, when the question was phrased in this way, there was a lot of evidence that this was indeed the case. The 1973 *Physical Review B* paper summarizes all this evidence and also discusses many other features of the 3d transition series that are consistent with this model.

In further work I was able to measure the variation of the spatial distribution of the 3d-electron spin-density oscillations surrounding solute atoms in Fe[2] and understand the hyperfine fields at any solute atom in Fe.[3] An especially gratifying feature of this whole approach is that it also allows great insight into the magnetic behavior of ferromagnetic alloys. There is still much activity in this field with one of the most recent papers[4] describing a cluster calculation that further confirms the small number of itinerant d-like conduction electrons in Fe.

1. Mössbauer R L. Kernresonanzfluoreszenz von Gammastrahlung in Ir^{191} (Nuclear resonance fluorescence with gamma radiation in Ir^{191}). *Z. Phys.* 151:124-43, 1958. (Cited 400 times.)
2. Stearns M B. Itinerant-3-electron spin-density oscillations surrounding solute atoms in Fe. *Phys. Rev. B—Solid State* 13:1183-97, 1976. (Cited 80 times.)
3. Stearns M B & Norbeck J M. Hyperfine fields at nonmagnetic atoms in metallic ferromagnets. *Phys. Rev. B—Condensed Matter* 20:3739-52, 1979. (Cited 20 times.)
4. Ting S T & Wang K P. A theoretical study of magnetism in Fe, Co and Ni. *Phys. Rev.* (In press.)

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