Ferromagnetism and superconductivity strike a compromise

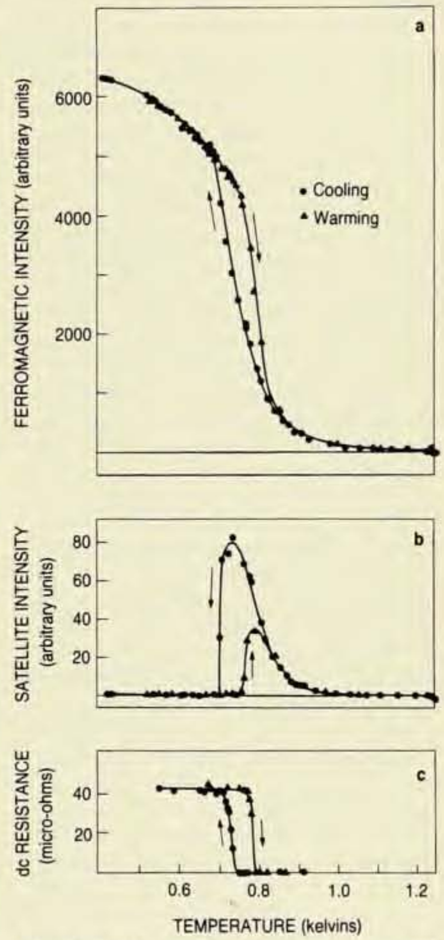
Ferromagnetism and superconductivity are two forms of long-range order that may exist in a material at low temperature. When both are present, they compete with one another, and many have wondered under what conditions they might coexist. The answer has been emerging in recent years, primarily through studies of two materials in which a compromise settlement is reached. The latest in a series of experiments—this one on a single crystal—has confirmed and further elucidated the properties of the coexistence phase seen in earlier work: This phase seems to accommodate within a single crystal both superconducting regions with sinusoidally modulated magnetic moments and normal ferromagnetic domains.

The strange phase is exhibited by erbium rhodium boride and by holmium molybdenum sulfide ($ErRh_4B_4$ and $HoMo_6S_8$)—members of two families of ternary superconductors in which one constituent is a rare-earth element. The rare-earth elements form an ordered lattice of magnetic ions within the crystal while the transition metal creates superconducting behavior. The combination of magnetic and superconducting properties has attracted much attention to this class of compounds since they were first discovered in the early 1970s. Although one might expect the spin-flip scattering of conduction electrons off the magnetic moments to destroy the pair ordering, the superconductivity persists, presumably because the localized 4f electrons in the rare-earth atoms have only a small interaction with the superconducting electrons.

The ternary compounds $ErRh_4B_4$ and $HoMo_6S_8$ both exhibit reentrant superconducting behavior; that is, they are normal paramagnets above a critical temperature T_{c1} (8.5 K and 1.8 K respectively), become superconductors below that and change again to ferromagnets below a second transition temperature T_{c2} (0.9 K and 0.64 K, respectively). Reentrant superconductivity due to onset of long-range magnetic order was first discovered in $ErRh_4B_4$ in 1977 by a group at the University of California, San Diego (see PHYSICS TODAY, April 1977, page 17) and then in $HoMo_6S_8$ by researchers at the University of Geneva. Measurements[1] of the specific heat of the family $(Er_{(1-x)}Ho_x)Rh_4B_4$ showed an anomaly at T_{c2} that suggests that the superconducting ferromagnetic transition is thermodynamically of first order. The work was done by a group at San Diego consisting of H. Bruce MacKay, Larry D. Woolf, M. Brian Maple and David C. Johnston.

The experimental work on these new compounds has revived theoretical interest in the general question of the coexistence of ferromagnetism and superconductivity. Some of the first theoretical work was done about twenty years ago by Alexei A. Abrikosov, Lev Gor'kov and A. K. Rusinov (all of the Landau Institute in Moscow) and by Philip W. Anderson (Bell Labs) and Harry Suhl (now at San Diego). The latter two predicted the existence of a sinusoidal magnetic state that they call "cryptoferromagnetism." All these theories concentrated on systems with a few magnetic impurities and assumed that the spin-exchange interaction would dominate.

In 1979, Eugene I. Blount and Chandra M. Varma (Bell Labs)[2] and independently M. Tachiki (Tohoku University) and Hideki Matsumoto and Hiroomi Umezawa (University of Alberta)[3] analyzed the ternary superconductors, which are characterized by lattices of magnetic moments rather than random magnetic impurities, and predicted the magnetic spins could be ordered in a long wave-length spiral within the superconducting phase. Blount and Varma showed that for these compounds the electromagnetic rather than the spin-exchange interaction was the important one. Varma explained to us that, while superconductivity acts to expel a uniform magnetic field, it can tolerate a field whose spins are modulated in a periodic fashion. He and Blount calculated that the wavelength of the oscillation would depend on the characteristic lengths of the two competing phenomena—the London penetration depth and the magnetic stiffness length. This wavelength would be on the order of 100 Å for the $ErRh_4B_4$ compound. The Bell Labs team further predicted that the transition from the coexistence state to ferromagnetism would be first order, as observed. Other theories have predicted different forms of coexistence states, such as a superconducting state with a



Magnetism and superconductivity coexist over a narrow temperature range in $ErRh_4B_4$. Neutron diffraction studies on a single crystal by an Argonne–Oak Ridge collaboration confirm features seen earlier; the satellite intensity (**b**) signals that a region of modulated magnetic moments is present simultaneously with the ferromagnetic domains (**a**). Direction of the hysteresis shows that the modulated moments are associated with the superconducting phase (**c**).

0031-9228 / 82 / 030017-06 / $01.00

vortex lattice.

The first experimental evidence for the oscillatory state came from neutron-diffraction studies of powdered samples of $ErRh_4B_4$. The work[4] was done by David E. Moncton (Brookhaven and Bell Labs), Denis B. McWhan and Paul H. Schmidt of Bell Labs, Gen Shirane and William C. Thomlinson of Brookhaven and Maple, MacKay, Woolf, Johnston and Zachary Fisk, then at San Diego. Working at the High-Flux Beam Reactor at Brookhaven, this team investigated the small-angle neutron scattering and found that a peak developed in a narrow temperature region (of about 0.5 K) just above T_{c2}. The angle at which the peak occurred corresponded to a periodic structure with a wavelength of about 100 Å. An important feature of this peak was the hysteresis it displayed: The peak was larger when the system was cooled down through the superconducting region than when the system was warmed up from the ferromagnetic region. The ferromagnetic Bragg peak exhibited similar hysteresis but in the opposite direction, being smaller upon cooling. Such behavior implied that both superconducting and ferromagnetic regions are present and that the magnetic fluctuations are associated with the superconducting regions. The other reentrant superconductor—$HoMo_6S_8$—manifests similar properties except that the oscillatory magnetic phase is completely absent when the sample is warmed up from below T_{c2}. Research on this compound was done[5] by Jeffrey W. Lynn (University of Maryland), Shirane and Thomlinson, and Robert M. Shelton (Ames Lab, Iowa State University). They also do not see the ferromagnetic peak in conjunction with the oscillatory phase when the sample is cooled.

Recently, David Hinks (Argonne) succeeded in growing a single crystal of $ErRh_4B_4$ on which he and Sunil K. Sinha and George W. Crabtree, also of Argonne, together with Herbert Mook (Oak Ridge Labs) conducted neutron diffraction measurements at the High Flux Isotope Reactor at Oak Ridge. Sinha reported the results at the Sixteenth International Conference on Low Temperature Physics in Los Angeles last August. As in the preceding studies on this compound, they saw both the modulated magnetic phase with a period of about 100 Å and the hysteretic behavior (see figure). The appearance in a single crystal of both the ferromagnetic domains and the superconducting regions with modulated magnetic spins establishes more definitively that these regions are simultaneously present. The narrowness of the scattering peaks implies that these regions are at least 2400 Å wide. By studying the intensities of diffraction peaks in different planes, the researchers concluded that the magnitudes of the magnetic spins must vary sinusoidally and the vectors cannot spiral. They furthermore established the direction of the propagation vector. Finally, this team ruled out the possibility that the magnetic superconductor might consist of a lattice of vortices, as some theories have predicted. A vortex lattice would give rise to higher harmonics and hence more satellite peaks, and its wavelength would shrink as the temperature was lowered to preserve flux quantization. Neither of these effects was observed. Lynn and his collaborators had earlier ruled out the possibility of vortex lattices for $HoMo_6S_8$ by studying the variation of the wave vector with the applied magnetic field.

With this additional detail about the magnetic, superconducting state, the theoreticians have both greater input and greater constraints. Henry S. Greenside (Bell Labs), Blount and Varma had shown that the coexistence state can be linearly polarized if the magnetic anisotropy is sufficiently great. Tachiki discussed at the Los Angeles meeting the idea of a laminar structure of vortices that would not be subject to flux quantization. Other theories are being discussed. A critical but difficult feature that all must eventually explain is the relation between the ferromagnetic phase and the magnetic superconducting phase. —BGL

References

1. H. B. MacKay, L. D. Woolf, M. B. Maple, D. C. Johnston, Phys. Rev. Lett. **42**, 918 (1979).
2. E. I. Blount, C. M. Varma, Phys. Rev. Lett. **42**, 1079 (1979).
3. M. Tachiki, H. Matsumoto, H. Umezawa, Phys. Rev. **B20**, 1915 (1979).
4. D. E. Moncton, D. B. McWhan, P. H. Schmidt, G. Shirane, W. Thomlinson, M. B. Maple, H. B. MacKay, L. D. Woolf, Z. Fisk, D. C. Johnston, Phys. Rev. Lett. **45**, 2060 (1980).
5. J. W. Lynn, G. Shirane, W. Thomlinson, R. N. Shelton, Phys. Rev. Lett. **46**, 368 (1981).

How long does the tau lepton live?

The often-quoted remark of I. I. Rabi, made when the muon was discovered—"Who ordered that?"—is again an apt commentary about the third charged lepton to be found, the tau. A recent experiment, by Gary Feldman, George Trilling and their collaborators at the PEP electron–positron collider at SLAC has determined the lifetime of the tau. They find it to be $(4.6 \pm 1.9) \times 10^{-13}$ sec, a value entirely consistent with the universality of the weak interaction. That is, the weak interaction between the tau and other particles appears, within experimental limits, to be the same as that of the electron and muon. They're all spin-½, charged, pointlike particles, differing only in mass: the electron with 0.511003 MeV, the muon with 105.6595 MeV and the tau with 1782 MeV.

Since the first evidence for the tau lepton was found by Martin Perl and his collaborators in 1975, the tau has been widely studied (PHYSICS TODAY, November 1977, page 17). Although the electron neutrino was observed by Clyde Cowan, Frederick Reines and their collaborators in 1956 and the muon neutrino by Gordon Danby and his collaborators in 1962, no direct observation of the tau neutrino has been made yet.

In August, at the International Symposium on Lepton and Photon Interactions at High Energies, held in Bonn, Germany, J. G. Branson reported on an experiment at PETRA using the Tasso detector. This group reported a tau lifetime measurement of $(-0.25 \pm 3.5) \times 10^{-13}$ sec, corresponding to an upper limit of 5.7×10^{-13} sec at the 95% confidence level. In 1980 they had reported an upper limit of 14×10^{-13} sec at the 95% confidence level.

The new experiment at PEP, done with the Mark II detector (previously used at SPEAR), was a collaboration among physicists from SLAC, Berkeley and Harvard, who say that theirs is the first measurement[1] of the tau lifetime that has a statistically significant nonzero value. As Feldman pointed out at the APS Division of Particles and Fields meeting in Santa Cruz in September, previous evidence is consistent with the tau decay occurring through the normal $V-A$ charged current. But does the tau couple to this current with the same strength as the muon? The answer can be found unambiguously by measuring the tau lifetime, τ_τ. If the coupling strength is the same, τ_τ is given by:

$$\tau_\tau = (m_\mu / m_\tau)^5 \tau_\mu B_e$$
$$= (2.8 \pm 0.2) \times 10^{-13} \text{ sec}$$

where B_e is the branching ratio for $\tau \to e\nu\bar{\nu}$.

The Mark II experimenters measured the tau lifetime by reconstructing the vertex of three-pronged tau decays and calculating the flight distance between the interaction point and the vertex projected along the direction of the tau momentum. Because the expected mean flight distance of the tau (0.7 mm) is smaller than their resolution, the group had to do statistical averaging and achieve good control