Many-Body Effects Found In Solid-State Plasma

Spin waves, which are collective periodic variations of the magnetization vector, have been found in both sodium and potassium. This is the first observation of genuine many-body effects in a solid-state plasma, and it confirms the collective Fermi-liquid model first proposed by Lev Landau ten years ago.

In ferromagnetic materials, spin waves are well known. V. P. Silin, in 1958, suggested that spin waves could be found in nonferromagnetic substances too. Using the Landau theory, he investigated spin-wave properties in neutral systems like He^3. He noted that, in principle, any normal Fermion system with a magnetic moment should propagate spin waves when placed in a dc magnetic field, if there is a finite amount of interaction.

Recently Philip Platzman and Peter Wolff investigated spin waves in charged Fermion systems and suggested that they might be observed in very pure metals by doing a conduction-electron spin-resonance experiment.

Meanwhile at the University of California in La Jolla, Sheldon Schultz and Gerald Dunifer were measuring conduction-electron spin resonance (CESR) in sodium foils at 1.4°K, and they found extra structure near the CESR peak. Both groups concluded that spin waves had been excited in the metal by the applied rf field. Results were reported in two companion papers in the 20 Feb. *Phys. Rev. Letters.*

To do CESR experiments, one applies both a static field H_0 and an rf field of frequency ω. Magnetic response of the system, Platzman noted, is determined solely by the rf susceptibility $\chi(\boldsymbol{k},\omega)$ where $\boldsymbol{k}$ is the wave vector. By varying the magnetic field, one can set up standing waves in the sample. Near a singularity of χ, induced magnetization is large, and one sees a resonance in the system response.

If one neglects interactions among electrons, the only resonance will be at $\omega_s = 2\mu H_0/\hbar$ (μ is electron magnetic moment). But in a real metal, electrons interact rather strongly with one another. In the Landau Fermi-liquid picture of this interacting electron fluid, the excited states of the system are completely described by a set of quasi-particles that interact weakly with one another.

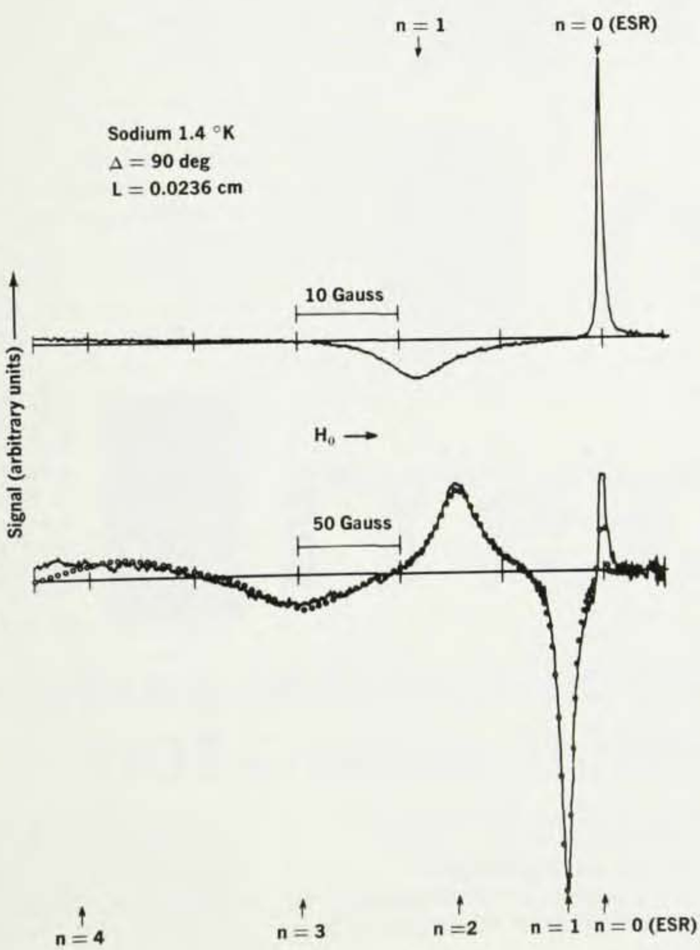
The function that describes the interaction between quasi-particles $S(\mathbf{p},\mathbf{p}',\sigma,\sigma')$ depends on the momenta, $\mathbf{p}$ and $\mathbf{p}'$ of two quasi-particles and their relative spin direction (σ and σ' are the Pauli spin matrices of the electrons). For an isotropic system one can express the function as

$$S(\mathbf{p},\mathbf{p}',\sigma,\sigma') = \sum_{n=0}^{\infty} A_n P_n(\cos\theta) + \sum_{n=0}^{\infty} B_n P_n(\cos\theta)\,\sigma\cdot\sigma'$$

where θ is the angle between $\mathbf{p}$ and $\mathbf{p}'$ and the magnitudes of $\mathbf{p}$ and $\mathbf{p}'$ are both equal to the Fermi momentum.

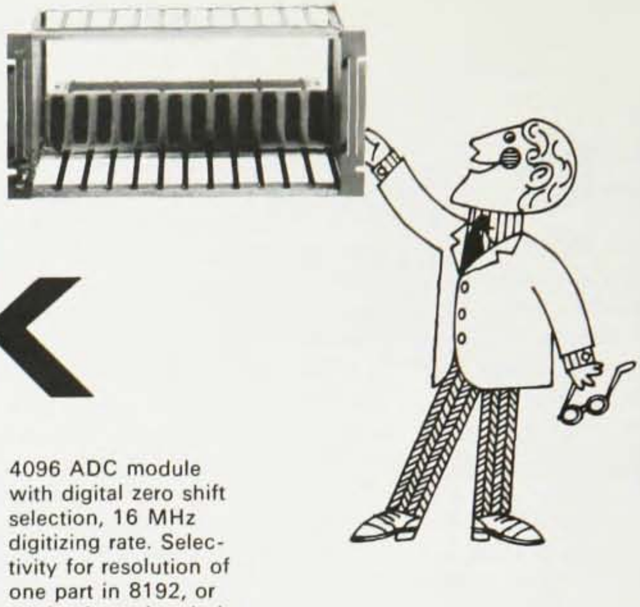
Without the parameters B_n the magnetization obeys a diffusion equation. When one includes the B_n, one introduces correlation effects that modify the susceptibility; then the magnetization can obey a wave equation. The equation has a whole branch of singularities for large $\omega\tau$ (τ is orbital collision time); these singularities are the spin waves. Position of these singularities depends on the magnitude and direction of the wave vector $\boldsymbol{k}$ with respect to H_0 and on all of the parameters B_n. In an experiment with a slab of thickness L, the k values are quantized at $k = n\pi/L$, and each mode resonates at a different frequency.

The B_n parameters have to be found experimentally. For thick enough slabs (about 0.1 mm), the sus-



SPIN RESONANCE of conduction electrons in sodium foils near 1.4°K. Extra structure near peaks corresponds to spin waves. The solid curves are experimental data and the points are from theory.

Rack up your own system



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ceptibility depends only on B_0 and B_1. One can determine B_0 and B_1 by looking at the first few sidebands.

Technique. In the La Jolla experiments, Schultz and Dunifer put a slab between a pair of X-band cavities tuned to the same frequency and apply a uniform dc field. Microwave power is coupled into one cavity and a sensitive superheterodyne receiver is connected to the second cavity. External power leakage is carefully controlled; so power found in the receiver cavity has been transmitted through the sample. Near a magnetic resonance, electrons absorb power within a skin depth on the transmitter side of the sample; the disturbance in electron spin then propagates through the bulk of the metal and power is radiated at the far end.

The figure shows a typical set of data, taken with the dc field parallel to slab. The solid curve is experimental; circles are theoretical values. With such a field orientation spin-wave structure appears on the low-field side of the main CESR signal. As the angle with respect to the surface is increased, structure moves towards the main CESR signal and eventually appears on the high-field side. The distance between the main CESR line and the spin-wave peaks is almost inversely proportional to the square of sample thickness; separation between successive harmonics is proportional to the square of the harmonic number. Schultz and Dunifer note that agreement between theory and experiment is generally excellent for the first two harmonics. —GBL

Ion Implantation Aids Solid-State and Nuclear Research

Recently a technique has been developed that uses the recoil energy of Coulomb-excited nuclei to implant them in a crystal lattice. The excited nuclei can easily be aligned, and useful information about the nuclear levels themselves, as well as the crystal in which they are implanted, can be extracted from the characteristic gamma-ray angular distributions. Magnetic moments of excited 2+ and 4+ states have been determined in this way. Useful information about the lattice also can be obtained by studying the emitted gamma rays with the Mössbauer effect.

Precessing distributions. For example, Gabi Goldring, Rafi Kalish and H. Spehl of the Weizmann Institute, have Coulomb-excited osmium nuclei with 35-MeV oxygen ions. These gave the target nuclei up to 10-MeV recoil energy, which is enough to drive them out of the target foil and implant them in the lattice of an adjacent foil.

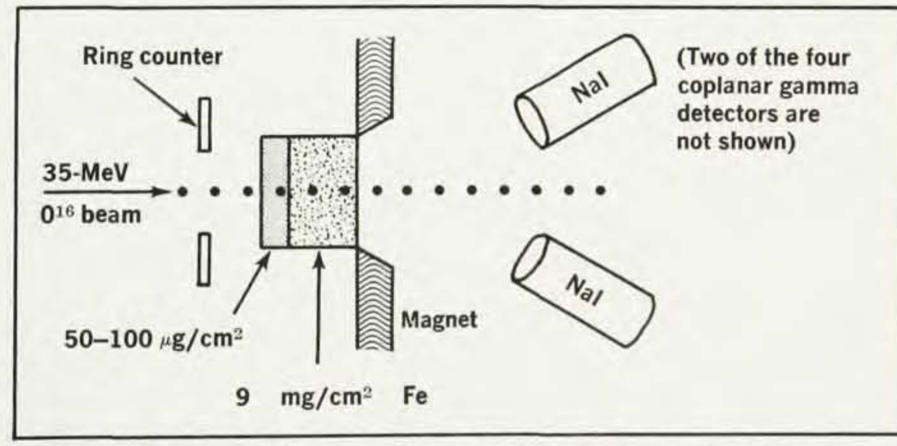
By detecting only gammas in coincidence with oxygen ions scattered through 180 deg it is possible to restrict the experiment to nuclei in the magnetic substate $m = 0$. Actually some compromise is necessary because of the difficulty of detecting particles scattered through 180 deg. A common technique, and the one used by the Weizmann group, is to place a ring counter around the incident beam and detect particles scattered through approximately 165 deg. Despite this compromise, alignment is still about 90% complete.

If an external magnetic field is applied to the aligned nuclei, they will precess about the field. Consequently their gamma-ray angular distribution will also precess. When the field is reversed, the nuclei precess in the opposite direction. Goldring and colleagues measured the angular difference $\Delta\theta$ between distributions taken with the field in opposite directions.

This shift $\Delta\theta$ is simply the product of the precession frequency ω and the lifetime of the state τ, $\Delta\theta = \omega\tau$. But the precession frequency is just the Larmor frequency $\omega = -\mu_N gB/\hbar$. Thus $\Delta\theta$ depends on τ, the magnetic field B in which the aligned nuclei are precessing and the magnetic moment of the state involved, $\mu_N g$.

Because they wished to determine the magnetic moments of 2+ excited states of known lifetime, Goldring and his collaborators needed to know accurately the magnetic field in which the nuclei precessed. To ensure they were dealing with a known field, they wanted to have their nuclei in a nonmagnetic environment. Hence they designed their experiment so that recoiling osmium nuclei would lodge in an adjacent copper foil, which would of course be nonmagnetic. Using the known magnetic-field strength and the known lifetimes of the states; they extracted the magnetic moments from the measured angular shifts.

At about the same time, Lee Grodzins, Robert Borchers and Gudrun Hagemann, working at the Niels Bohr Institute, Copenhagen, independently performed a similar experiment with a different purpose. They arranged their geometry so that recoiling Coulomb-excited nuclei, Sm^{152}, Gd^{156} and Dy^{164}, imbedded themselves in an iron foil. Because iron is ferromagnetic, the local magnetic field in which the nuclei precess is much greater than the externally applied field. It was this local field that Grodzins and his colleagues sought to measure. They also measured the angular shift of the gamma-ray distributions and used known values of the magnetic moments and lifetimes to determine the effective local magnetic field. Thus by ion implantation they made the first measure-



RECOIL NUCLEI from thin target imbed in backing foil. Setup permits measuring precession of gamma distribution in applied magnetic field.