Observation of Nuclear Magnetic Resonance in Superconducting Mercury*

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THE study of the Knight shift and relaxation time for nuclear magnetic resonance in metals can yield microscopic information about the conduction electrons near the Fermi surface.[1] Such a study in superconducting metals could therefore be of considerable interest. The difficulty of the experiment lies in the requirement of metallic particles of size small compared to the superconducting penetration depth λ (430 A for Hg)[2] to insure a reasonably uniform magnetic field throughout the metal. A large Knight shift K is also desirable to make changes in this quantity more readily measurable.

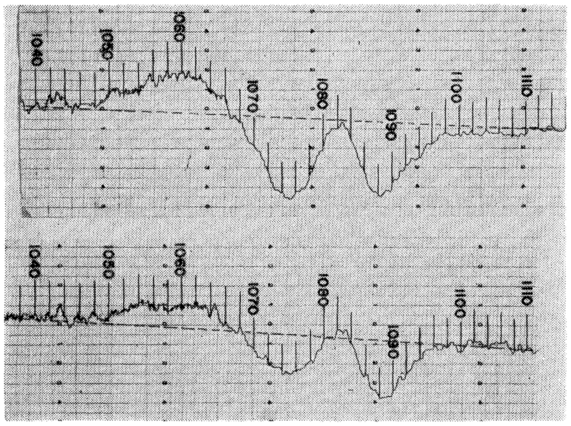

FIG. 1. Experimental curves of superconducting and normal Hg lines at 1.45°K in a magnetic field of 1390 gauss. Top: Low rf power level. Bottom: High rf power level causing partial saturation of the superconducting line. (Note that the experimental equipment plots the derivative of the absorption line. The frequency markers are spaced at 2-kc intervals.)

A preliminary experiment at 77°K on a micron-size dispersion of mercury showed that K in this metal has the large value of 2.4%.[3] A sample of colloidal Hg in albumen, similar to those used in Shoenberg's experiments,[4] was then prepared. This colloid contains about 80% by weight of Hg; electron microscope examination reveals that almost all Hg drops have diameters less than 1000 A, the most probable diameter being about 200 A. Experiments on this sample in fields of 6500 and 3300 gauss show, down to 1.45°K, only the normal metallic Hg^{199} line. At 1500 gauss, though only the normal line is observed at 4.2°K, there appears in addition at lower temperatures a second rather asymmetric line at a lower frequency. We attribute this line to nuclei in Hg drops small enough to be superconducting in this magnetic field.[5] At 1.45°K, this superconducting line increases in intensity at the expense of the normal line when the field is decreased; at 970 gauss, the normal line has disappeared. (See Figs. 1 and 2.)

The width of the normal Hg^{199} line at liquid helium temperatures appears to be due predominantly to asymmetric Knight shift[6] at high fields and to indirect nuclear exchange coupling[7] at lower fields. The width of the superconducting line is due mainly to the inhomogeneity of the magnetic field throughout the superconducting particles. Assuming the validity of London's equations, one can calculate the distribution of the magnetic field in a superconducting sphere of radius a in an external magnetic field, and thence the resonance absorption $I(\nu)$ at the frequency ν due to nuclei in this sphere. Let ν_s be the resonance frequency of a nucleus in superconducting metal as $\lambda \rightarrow \infty$, $\zeta = 30\ (\nu - \nu_s)\nu_s^{-1}$, and $a' = a/\lambda$. Then for $a' \ll 1$, one obtains the result

$$I \sim a' f((\zeta + 2a'^2)/3a'^2),$$

where $f(x) = (1 - |x|)^{\frac{1}{2}}$ for $0 < |x| < 1$ and vanishes otherwise. Summation of I over all particle radii in proportion to their size distribution then gives a line shape of the type shown in Fig. 3 and exhibiting the kind of asymmetry which is experimentally observed. The point $\zeta = 0$ is distinguished by the fact that there *all* spheres, irrespective of radius, contribute to the intensity of the line. In fact, rather general arguments seem to indicate that, except for possible small effects of microscopic broadening, $\zeta = 0$ determines the point of maximum negative slope on the absorption line. Thus the minimum on the experimental derivative plot of the line should determine ν_s and hence the value

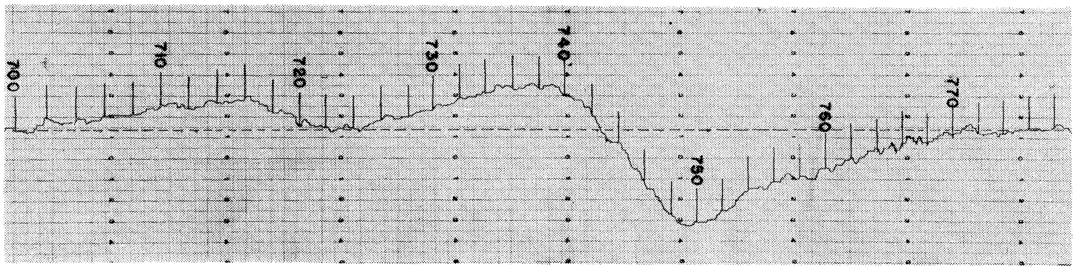

FIG. 2. Experimental derivative plot of the superconducting line at 1.45°K in a field of 970 gauss. The normal line, here missing, would occur at 757 kc/sec. (The extra hump at the low-frequency end of the line is presumably due to a group of relatively large Hg droplets.)

of the Knight shift K_s in the superconductor. On the basis of this criterion, one estimates that at 1.45°K ν_s is about 0.9% less than the resonance frequency in the normal metal, i.e., $K_s \approx 1.5\%$.

Saturation effects in the superconducting line should cause a decrease in intensity without change of shape.[8] At 1.45°K, partial saturation of the superconducting line, though not of the normal one, could indeed be observed at available power levels (see Fig. 1). This leads to an order of magnitude estimate of $T_1 \approx 0.1$ sec for the nuclear relaxation time in superconducting Hg at 1.45°K; from the Korringa relation[9] one calculates $T_1 \leq 0.01$ sec for the normal metal at this temperature. At 2.03°K, the superconducting line could not be saturated.

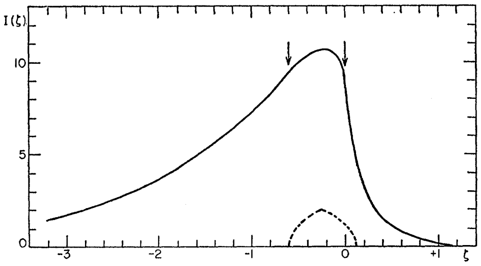

FIG. 3. Solid curve: The result of superposing the nuclear resonance absorption curves due to individual superconducting spherical particles, using for their size distribution one of our poorest (i.e., the actual sample used in the experiments contained a somewhat larger proportion of small particles). Microscopic broadening effects, such as those responsible for the width of the normal line, have not been taken into account in constructing the curve and would tend to smear it out a bit. ζ is related to the frequency ν by $\zeta = 30(\nu - \nu_s)\nu_s^{-1}$, where ν_s is the resonance frequency in a sample with infinite penetration depth. The arrows indicate the extrema on the experimentally measured derivative curve. Dotted curve: Contribution to the solid curve of particles with $0.3 < a' < 0.4$ (a' = ratio of radius to penetration depth).

More quantitative experimental work, needed for the theoretical interpretation of the results, is in progress. We wish to thank the department of meteorology, and in particular Miss B. Tufts, for generous help with the electron microscope and Miss N. Knudsen for assistance with the preparation of the samples. Numerous discussions with Professor A. B. Pippard and Dr. G. F. Dresselhaus are gratefully acknowledged.

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[3] Since then, an unpublished result of L. Sarles and H. Loeliger has come to the author's attention. They find $K = 2.5 \pm 0.1\%$.

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[5] It should be remembered that for these small particles the critical fields are much higher than for bulk superconductors. The critical temperature for Hg in zero field is 4.15°K.

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Storage-Ring Synchrotron: Device for High-Energy Physics Research*

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As accelerators of higher and higher energy are built, their usefulness is limited by the fact that the energy available for creating new particles is that measured in the center-of-mass system of the target nucleon and the bombarding particle. In the relativistic limit, this energy rises only as the square root of the accelerator energy. However, if two particles of equal energy traveling in opposite directions could be made to collide, the available energy would be twice the whole energy of one particle. Kerst, among others, has emphasized the advantages to be gained from such an arrangement, and in particular of building two fixed-field alternating gradient (FFAG) accelerators with beams interacting in a common straight section.

It is the purpose of this note to point out that it may be possible to obtain the same advantages with any accelerator having a strong, well-focused external beam. Techniques for beam extraction have been developed by Piccioni and Ridgway for the Cosmotron, and by Crewe and LeCouteur for lower energy cyclotrons.

In the scheme proposed here (see Fig. 1), two "storage rings," focusing magnets containing straight sections one of which is common to both rings, are built near the accelerator. These magnets are of solid iron and simple shape, operating at a high fixed field, and so can be much smaller than that of the accelerator at which they are used.[1] The full-energy beam of the accelerator is brought out at the peak of each magnet cycle, focused, and bent so that beams from alternate magnet cycles enter inflector sections on each of the storage rings. In order to prevent the beams striking the inflectors on subsequent turns, each ring contains

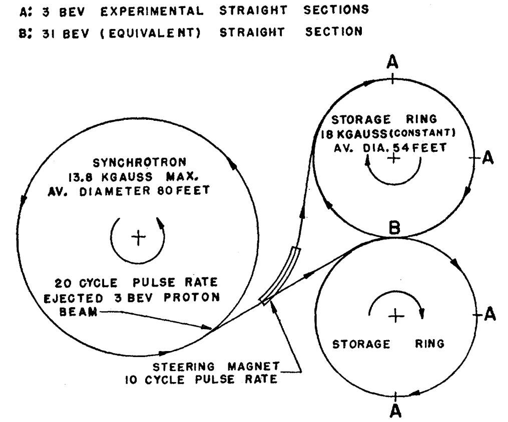
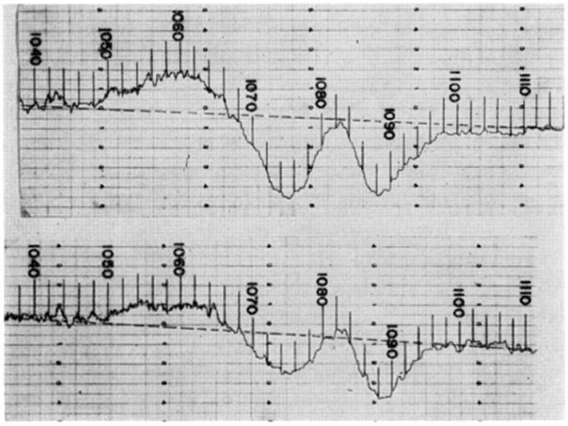


FIG. 1. Plan view of particle orbits in a hypothetical arrangement of storage rings at a 3-Bev proton synchrotron.



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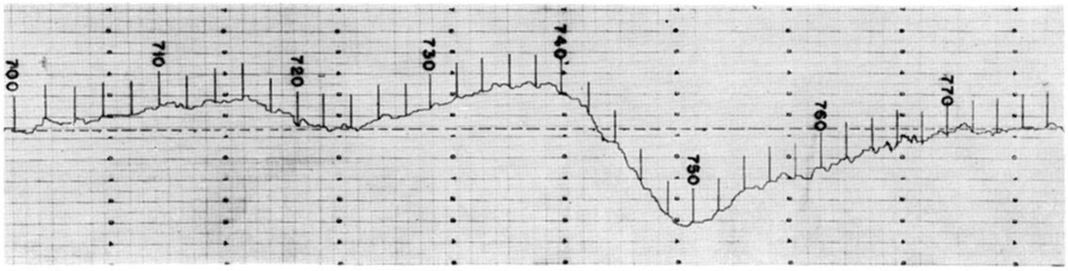

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