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Letters to the Editor

Nuclear Relaxation in Superconducting Aluminum*

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NUCLEAR relaxation in metals arises principally from energy exchanges with electrons at the top of the Fermi distribution. One would therefore expect the relaxation rate in superconductors to be significantly different from that in normal metals. In this letter we report the results of measurements of the nuclear spin-lattice relaxation time in superconducting aluminum between 0.94°K and the critical temperature (1.17°K), and of calculations of the relaxation time using the microscopic theory of superconductivity recently given by Bardeen, Cooper, and Schrieffer.[1] The experimental results are in direct conflict with simple two-fluid models, are qualitatively explained by a one-electron, energy gap model, and are in essential agreement with the theory of Bardeen, Cooper, and Schrieffer.

The major difficulty in studying nuclear relaxation in superconductors arises from the Meissner effect. Reif[2] and Knight[3] have observed resonances directly in superconductors by working with particles of size small compared to the superconducting penetration depth. In contrast, our technique involves a cycling process in which we observe the resonance in the normal state, but allow the nuclei to relax while in the superconducting state.

The Al resonance was observed at a frequency of 500 kc/sec in a field of about 500 gauss. The powdered sample sat in a liquid helium bath. The following cycle was followed. The static field was left at a value of about 500 gauss for a time long enough to achieve thermal equilibrium between the nuclear spins and the lattice. In this field the sample was in the normal state. The field was then turned to zero, cooling the nuclear spin system (adiabatic demagnetization) and making the aluminum superconducting. The field was left at zero for a time, t, and then turned back up to a value somewhat larger than that appropriate for resonance. The resonance was observed "on the fly," i.e., as the field passed through the resonance value. The decrease in amplitude of the resonance as t is increased is simply related to the relaxation time in the superconducting phase.

The method described in the foregoing is similar to that used by Sachs and Turner,[4] Pound and Ramsey,[5] and Abragam and Proctor[6] in other connections, and has been proposed independently for the superconducting problem by Redfield[7] (who has also suggested several interesting modifications).

To compare the relaxation rate in the normal and superconducting phases, we have measured the normal relaxation time in *zero* field, and find that it is proportional to temperature as predicted by Redfield.[8] Extrapolating the normal relaxation rate, R_n, below the critical temperature, and comparing it with the superconducting rate, R_s, we find that at 0.94°K, $R_s \cong 2R_n$. Thus, just below the critical temperature, T_c, the relaxation is faster in the superconductor. Reif,[9] studying mercury, and using the saturation technique, has one point at $T/T_c = 0.27$ for which $R_s \cong 0.1R_n$. Thus, well below the critical temperature the relaxation rate is slower in the superconductor. Reasonable assumptions for a two-fluid model would make the relaxation rate always slower in the superconductor (or in any event *either* slower or always faster), so that the experiment does not seem capable of interpretation in these terms.

From a one-electron theory one can show that the temperature dependence of the relaxation rate arises solely from the electron statistics. Hence one finds

$$R \propto \int |M|^2 \rho(E_f)[1-f(E_f)]f(E_i)\rho(E_i)dE_i, \qquad (1)$$

where $\rho(E)$ is the density of electron states in energy, $f(E)$ is the Fermi function, and E_i is the initial energy of an electron which is scattered, relaxing the nuclei, to a final energy, E_f. Thus $E_f \cong E_i$. M is the magnetic matrix element between electron and nucleus, and in the normal metal is virtually independent of energy. If one introduces a gap in $\rho(E)$ with the "missing states" piled on the edge of the gap [so that $\rho(E)$ is higher than usual just above and below the gap], one finds qualitative agreement. The faster relaxation just below T_c arises because peaking ρ has the double effect of increasing the number of initial electrons *and* the number of vacant final states *at the same energy*. At very low temperatures relaxation is slow since electrons find no nearby empty states to permit relaxation.

Recently Bardeen, Cooper, and Schrieffer have developed a microscopic theory of superconductivity. We find, using their many-electron theory, that we get a result identical to Eq. (1), the "matrix element" being now slightly energy-dependent, and the density of states displaying an energy gap $2\epsilon_0$ and a strong peak at the edge, $E=\epsilon_0$, proportional to $E/(E^2-\epsilon_0^2)^{\frac{1}{2}}$. The peak is so great that the integral diverges if one simply sets $E_i = E_f$. The magnetic energy given up by the nuclear system prevents this catastrophe, but probably a more important factor is the breadth of the electron levels. A frequency width of 10^9 cycles/sec for the electron states makes $R_s \cong 2R_n$ at 0.94°K. The same value makes $R_s = 0.13R_n$ at $T = 0.27T_c$, in substantial agreement with Reif's data. The results depend only logarithmically on the level width.

We are indebted to Professor Dillon Mapother, Professor John Wheatley, and Mr. Frank Witt for extensive aid and advice in the design and construction of the cryogenic apparatus. We wish to thank Dr. Alfred Redfield for several interesting conferences concerning the basic experimental method. Mr. John Spokas has kindly aided us in performing the experiment. We wish to acknowledge our great debt to Professor John Bardeen, Dr. J. R. Schrieffer, and Dr. Leon Cooper for instructing us in their theory, and giving freely of their time and advice. It should be emphasized that they extended this generous aid during the very period when they were busy developing the details of their theory.

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Maser Noise Measurement*

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THE noise figure of an ammonia-beam maser amplifier at 24 000 Mc/sec has been measured with the experimental setup shown in Fig. 1. Since the bandwidth of the amplifier is about 300 cps at 20 db gain and the noise figure is low, special techniques are needed. The success of the technique used here is due to the use of an ammonia-beam oscillator, which has the stability of a primary frequency standard, as a local oscillator. This converts the noise spectrum of the amplifier to 1000 cps with a stability such that the position of any noise component in the audio strip is constant within a few cps. Thus a linear receiver is obtained with a 50-cps bandwidth.

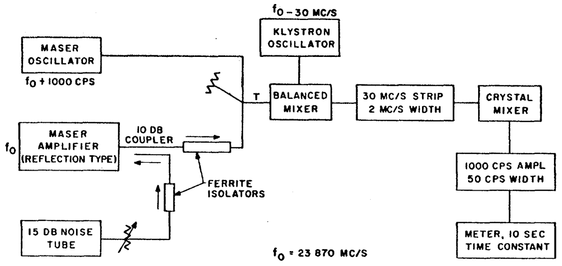

FIG. 1. Block diagram of apparatus.

Recent theoretical developments have shown that maser amplifiers should generate very little internal noise.[1–3] This experiment represents a first attempt to verify the theory. The theoretical noise figure of this maser amplifier, computed from the ratio of the external Q of the cavity coupling to the cold-loaded Q, is 3.5±0.1 db relative to room temperature, assuming a noiseless beam.[4] A lower noise figure could be obtained with greater coupling to the cavity. However, it was not possible to increase the coupling and still obtain high grain. The measured noise figure as a function of amplifier gain is shown in Fig. 2. The values given represent what would be obtained in practice if the amplifier were connected to a circulator which separates the input and output signals. The experimental scatter is caused by fluctuation in the reading of the output meter. The amount of this fluctuation has been analyzed by Dicke and a 4% observed fluctuation agrees with this analysis.[5] The apparent increase in noise figure at low gain may be the result of an interaction between the oscillator and amplifier, the amplifier bandwidth being inversely proportional to gain. If these two points are omitted, the average noise figure becomes 3.52 db with 0.5 db standard deviation. It is thus concluded that within the limits of the experiment the spontaneous-emission noise in the beam is not observable.

This is as it should be, for on the basis of the idealized situation which is assumed by theory the contribution of spontaneous emission should amount to only 0.04 db. On the other hand, it can be shown[6] that a small background gas pressure in the cavity, arising from collisions of the beam with the cavity and finite pumping speed plus a poor separation of states by the focuser,

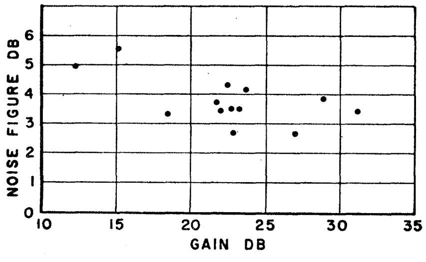

FIG. 2. Noise figure measurement.