NUCLEAR SPIN RELAXATION TIME IN SUPERCONDUCTING ALUMINUM

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The nuclear spin relaxation time T_{1S} in superconductors was first measured by Hebel and Slichter[1,2] just below the transition temperature in aluminum, and by Reif[1] well below the transition temperature in mercury. These measurements indicated that T_{1S} decreases rapidly just below T_C, and then rapidly increases again well below the transition temperature, becoming greater than the normal state relaxation time at very low temperatures. Hebel and Slichter pointed out[1] that the decrease in T_1 near T_C could be easily explained only in terms of an energy gap model of superconductivity. They supported their explanation with a detailed calculation[2] based on the Bardeen, Cooper, and Schrieffer (BCS) theory of superconductivity. Comparison of the temperature dependence of T_1 as contrasted with that of acoustic attenuation provides confirmation of the spin-dependent correlation of the wave functions used in the BCS theory.[2]

Preliminary measurements of T_1 in aluminum by Anderson and the writer[3,4] were in reasonable agreement with the Hebel-Slichter-BCS theory; accuracy of these measurements has now been improved using a He^3 cryostat. The experimental method was basically the same as that used previously.[1] The sample was soaked in a 3000-gauss field for a time long compared to T_1, so that the spin magnetization built up to its equilibrium value in this field. The field was then turned off in about 1/10 sec and left off for a variable time τ; during this time the sample is in the superconducting phase and the spin polarization relaxes toward zero. The field is then turned on to 1000 gauss and within 2/10 second the spin polarization is measured in the normal state by applying suitable rf and sweep fields.

The sample was immersed in liquid He^3 to eliminate temperature changes due to the magneto-caloric effect; temperature was inferred from measurement of the magnetic susceptibility of a solid cylinder of iron ammonium alum, with an estimated error of 2%.

The recent data are plotted in Fig. 1, together with earlier data[5] taken in this laboratory, as a function of T_C/T (assuming $T_C = 1.178°K$). The signal to noise ratio was 10 or better, and the signal appeared to decrease exponentially with

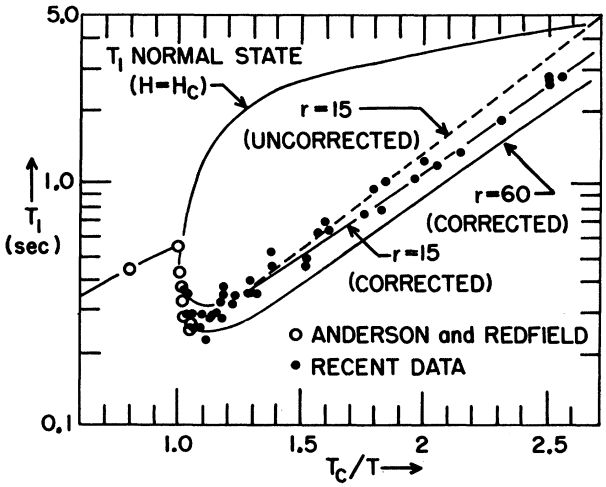

FIG. 1. Experimental and theoretical nuclear spin relaxation time in pure aluminum plotted as a function of inverse reduced temperature.

τ for all the points shown. We do not believe that possible impurities affected the data of Fig. 1, and we are currently attempting to confirm this by studying the effect of known impurity concentrations.

A possible source of error in this experiment is the presence of regions of trapped flux. Such regions would give a contribution to the observed T_1 characteristic of the normal state at $H = H_C$, which might not be resolved with the poor signal to noise ratio in the present experiment. We have plotted in Fig. 1 the semiempirical temperature dependence of T_1 in the normal state at H_C, based on actual measurements at 0.5° and on measurements of T_1 above T_C, as a function of field.[5] Since there is no noticeable correlation between the variation of the normal state T_1 and the superconducting T_1, and since they are very different over much of the range, we believe that the effect of trapped flux is small.

The data of Fig. 1 are in reasonable agreement with the earliest measurements[1] of Hebel and Slichter and of Reif, and are in detailed agreement with the predictions of Hebel and Slichter based on the BCS theory. For comparison we have plotted in Fig. 1 recent calculations of T_{1S} by Hebel,[6] based on the expressions found in

reference 2 but evaluated more accurately. There are two unknown parameters in the theory: a multiplicative constant which is determined by the requirement that T_1 be continuous at the critical temperature, and a parameter $r = \epsilon_0(0)/\Delta$, where $\epsilon_0(0)$ is the half gap width of BCS at 0°K ($3.5kT_C$) and Δ can be regarded as the half-width of the electronic energy levels. In reference 2, Δ is introduced into the theory by smearing or folding the BCS density of states function with a square function of width 2Δ and height $(2\Delta)^{-1}$. Δ can be interpreted either as an uncertainty width due to electron scattering mechanisms not accounted for in the BCS theory, or as a smearing of the BCS density of states due to anisotropy of the energy gap.[7]

The "uncorrected" curve in Fig. 1 is that calculated by Hebel directly from the BCS theory for $r = 15$; for other values of r the curve is nearly parallel to this one for $T_C/T > 1.5$. The "corrected" curves are calculated using the energy gap found experimentally by Biondi and Garfunkel from microwave measurements[8] [i.e., $\epsilon_0(T)$ proportional to, but 7.5% smaller than, the BCS prediction]. According to Hebel,[6] the calculation of T_{1S} can be corrected for an energy gap different from the BCS prediction if the form of the BCS wave functions is correct, and only their energies are assumed to be incorrect. In that case $T_{1S}T$ is a function of $\epsilon_0(T)/kT$ alone.

Agreement with theory is excellent assuming $r = 15$ [$\Delta = \epsilon_0(0)/15$]. This agreement is in contrast with the Knight-shift observations of Reif and of Androes and Knight.[9] Our measurements are made on particles large compared to the coherence length (10^{-3} cm). The parameter Δ is nearly temperature independent, consistent with the idea that it represents either the inverse electronic lifetime against boundary scattering, or more likely anisotropy of the energy gap.[7] It is probable that if Δ represented phonon scattering, it would be strongly temperature dependent, contrary to observation.

It is a pleasure to acknowledge the contribution to this research of Dr. A. G. Anderson, who collaborated on the early measurements. The writer is also indebted to many other members of this laboratory, especially Mr. W. V. Kiselewsky and Dr. H. A. Reich. Finally he wishes to thank Dr. L. C. Hebel and Professor C. P. Slichter for several interesting discussions and for communicating the progress and results of their research prior to publication.

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OPTICAL MASER DESIGN

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Schawlow and Townes[1] have discussed the possibility of operating a maser in the infrared or visible wavelength region. They point out that the difficulty of maintaining an adequate population excess in the upper of the two levels between which maser action takes place increases rapidly with the operating frequency because of the large rate of spontaneous emission. They envisage only the use of photon excitation for populating the appropriate level in the working medium.

In observing the resonance absorption of a spectral line, there exists the well-known difficulty of obtaining a large amount of light from a source without broadening the line to the point where only a fraction of the total is absorbed. In view of this, it appears difficult to employ effi-