tially longitudinal until particle energies become relativistic. One- and two-dimensional numerical simulation of the cases treated here by a fully electromagnetic simulation method[8] and with an initial electron temperature of 17 keV ($V_{the}/c=0.25$), i.e., an electron $\beta_e=(5/4)^2$ when $\omega_p/\Omega_e=5$, have shown the development of the instability to be essentially unchanged by finite β_e effects.

The reader may be interested to know that the instability presented here was initially found with the numerical simulation code.

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Magnetic Field Splitting of the Quasiparticle States in Superconducting Aluminum Films

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Magnetic field splitting of the quasiparticle energy states in superconducting aluminum films has been observed in a tunneling experiment. The magnitude of the splitting was found to be $2\mu H$, and is attributed to the magnetic moment of the quasiparticles. The observed tunneling conductance is in qualitative agreement with theory.

We have observed splitting of the quasiparticle states in thin superconducting aluminum films in a parallel magnetic field. The density of states was obtained[1,2] by measuring the tunneling conductance, dI/dV, of Al-Al_2O_3-Ag junctions as a function of voltage V for various applied magnetic fields, H.

In the absence of a magnetic field the quasiparticle energy spectrum in a superconductor is given by the Bardeen, Cooper, and Schrieffer (BCS) theory[3] to be $E=(\epsilon^2+\Delta^2)^{1/2}$, where ϵ is the kinetic energy measured from the Fermi surface and 2Δ is the energy gap. A magnetic field applied to a thin superconducting film will act on the spins of the electrons as well as on their orbits. Both interactions will change the quasiparticle spectrum. If the film is thin enough, however, the effect of the field on the electron orbits will be negligible compared with the effect on the electron spins, provided the spin-orbit scattering rate is sufficiently small. In this case the quasiparticle spectrum becomes simply $E_{\uparrow,\downarrow}=(\epsilon^2+\Delta^2)^{1/2}\pm\mu H$, where μ is the electron magnetic moment. It will be shown later that our samples fulfill the above conditions. As a consequence we would expect the total tunneling density of states to consist of the addition of two BCS-type density-of-states curves shifted in voltage by $\pm\mu H/e$ with respect to the curve in the absence of field.[4]

This behavior has been observed experimentally as shown in Fig. 1, where $(dI/dV)_s$ is plotted versus V for various values of H. The magnitude of $(dI/dV)_s$ has been normalized to the normal-state conductance, $(dI/dV)_n$. According to theory we expect that the energy change of the peaks in the spin-up and spin-down density of states should be proportional to $\pm H$. Figure 2 shows a plot of the positions of these peaks as a function of H. The spin splitting agrees well with the simple theory given above over the entire range of field.

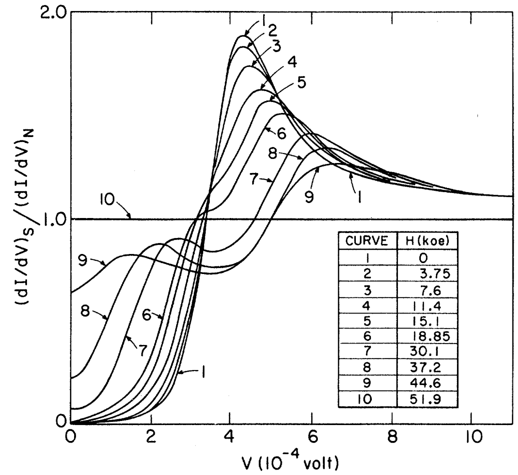

FIG. 1. Experimental plots for several values of magnetic field of the superconducting conductance $(dI/dV)_s$ divided by the normal-state conductance $(dI/dV)_n$.

In order to determine the energy separation of the two spin states it was found useful to resolve the measured conductance curves into two identical curves which when displaced in voltage and added gave the original curve. Such a resolution of one curve is shown in Fig. 3(a), the dashed curves being a trial density of states for spin up and spin down. The curve resulting from the addition of these trial curves (open circles) agrees well with the measured (solid) curve over the entire energy range. This method of graphical resolution allowed an objective determination of the splitting even for small fields. In addition, this graphical method gave the density-of-states curve for each spin direction with little ambiguity. Figure 3(b) shows such density-of-states curves for four values of the magnetic field, placed in each case midway between the two resolved curves. It should be noted that the peaks of these curves do not change with field within the accuracy of the measurements and the analysis. Each of the curves with the exception of that at the highest field (No. 9 at $H=0.93H_c$) approximates a somewhat broadened BCS density-of-states curve, the broadening increasing slightly with magnetic field. Curve (9) resembles more closely a density of states with considerable depairing.[5-7]

The Al films used in this investigation were about 50 Å thick and were formed by evaporation through a mask onto a liquid-nitrogen–cooled substrate. The transition temperature T_c was 2.4 K and $2\Delta/kT_c$ was 3.7. The critical field, extrapolated to 0 K, was about 48 kOe. The normal

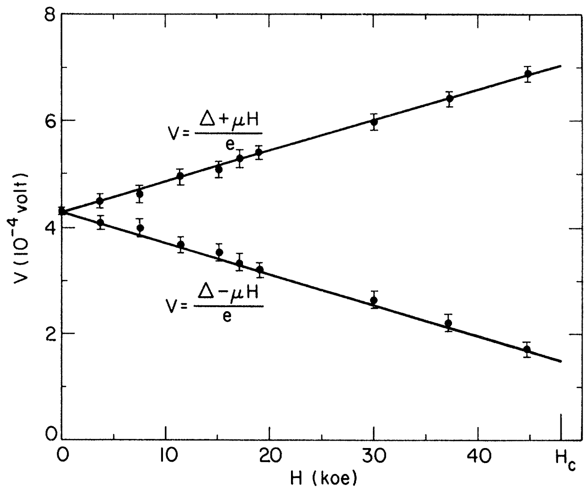

FIG. 2. Voltage corresponding to the maxima of the spin-up and spin-down density-of-states curves determined from Fig. 1 by the graphical method illustrated in Fig. 3. The lines represent the theoretically expected result that $eV=(\epsilon^2+\Delta^2)^{1/2}\pm\mu H$.

resistance was 200 Ω/square. The junctions were cooled by immersion in pumped He^3 and were aligned parallel to H within 0.1°. The conductance was measured in a conventional way

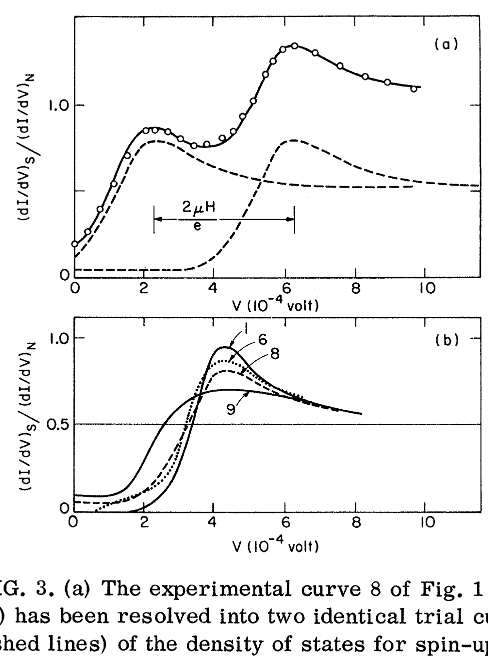

FIG. 3. (a) The experimental curve 8 of Fig. 1 (solid line) has been resolved into two identical trial curves (dashed lines) of the density of states for spin-up and spin-down particles. The sum of the two trial curves is shown by the open circles and agrees well with the experimental curve. The energy separation determined by this graphical procedure is equal to $2\mu H$. (b) Normalized density of states for one direction of spin if it were not affected by H. The numbering of the curves corresponds to that in Fig. 1.

with a phase-sensitive detector operating at 500 Hz. The data shown in Figs. 1 and 2 were obtained at the lowest temperature, about 0.4 K. At temperatures above about 0.7 K, splitting could not be observed, probably because of thermal broadening of the peak in $(dI/dV)_s$.

Here it is appropriate to comment on the influence of spin-orbit scattering. Generally a spin-orbit scattering rate, $1/\tau_{so}$, will lead to a broadening of the effects discussed above. If it is small enough ($\tau_{so}\Delta \gtrsim 1$), the two peaks in the tunneling conductance will be correspondingly broadened, but still well separated. If the scattering rate is large ($\tau_{so}\Delta \ll 1$), the two peaks are smeared into one which is of the type found in other pair-breaking situations. Thin aluminum films are known to have sufficiently small spin-orbit scattering[8,9] rates to make the splitting effect observable. However, Fig. 3(b) indicates that the broadening effect due to spin-orbit scattering[10] is not negligible and a detailed comparison between experiment and theory will be made in a future publication. Another cause for broadening of the density-of-states curves can be the effect of the magnetic field on the electron orbits. However, the estimated effect for the aluminum film under consideration is very small. The pair-breaking parameter with which one can calculate the broadening of the BCS type of density-of-states curves[6,11] is given by $\alpha = \frac{1}{2}[H/H_{c\parallel}{}^0(0)]^2$, where $H_{c\parallel}{}^0(0)$ is the critical field the film would have at $T=0$ if the field would act on the electron orbits only. One can estimate that $H_{c\parallel}{}^0(0)$ is 3.7 times bigger than the measured critical field $H_{c\parallel}{}^0(0)$, thus leading to rather small values for α.

Consistent with this reasoning is the fact that the order parameter $\Delta(H)$ was found not to vary significantly with H up to the highest fields, indicating that the films were in the paramagnetic limit.

In conclusion, we have observed splitting of the quasiparticle states of superconducting Al by a magnetic field. The magnitude of the splitting as well as the shape of the density-of-states curve are consistent with theory.

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Plastic Flow in Normal and Superconducting Indium*

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Changes in flow stress, which occur in indium at the transition from the normal to the superconducting states, have been studied in a series of experiments in which strain rate, state, and temperature are changed independently. The results are consistent with a simple theory which associates the changes in flow stress with changes in activation volume and thus with the nature of the interaction between moving dislocations and obstacles.

In recent experiments by Kojima and Suzuki,[1] by Pustovalof, Startsev, and Fomenko,[2] and by Alers, Buck, and Tittmann,[3] a difference in macroscopic flow stress between the normal and superconducting states in lead, niobium, and indium has been revealed and studied. In the experiments by Alers, Buck, and Tittmann[3] the chief characteristics of the change in flow stress are these:

(a) The flow stress is higher in the normal state by up to 5%. A small correction can be applied to the difference to take account of speci-