OBSERVATION OF THE HALL EFFECT IN SUPERCONDUCTORS

W. A. Reed, E. Fawcett, and Y. B. Kim
Bell Telephone Laboratories, Murray Hill, New Jersey
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In this Letter we report the first observation of the Hall effect in superconducting niobium[1] and indium. Shortly after the discovery of superconductivity, Kamerlingh Onnes and Hof[2] searched for the Hall effect in tin and lead and showed that in the superconducting state there was no Hall emf greater than the limit of measurement. Although they were unable to measure the Hall emf even in the normal state, their result led to theoretical speculations that the Hall effect would be unmeasurable in a superconductor. Lewis,[3] in 1953, made another attempt to detect the Hall effect in superconducting vanadium; the result was again negative. He then concluded that the absence of a Hall effect in a superconductor is not an obvious consequence of the London theory. The question was revived in 1963 when De Gennes and Matricon[4] considered the possible existence of the Magnus force on the quantized flux lines moving in a type-II superconductor. Vinen[5] remarked that the Magnus force on the flux line will lead to a large Hall angle. However, the experimental results on type-II superconductors[6-10] of short mean free path did not bear out this anticipation. Subsequently, Bardeen[11] pointed out that theoretical arguments for the Magnus force are in error in that the effect of the positive ion background is not taken into account. The present observation of the Hall effect is significant in view of this historical development.

The niobium sample is a single crystal with a residual resistance ratio [$\mathrm{RRR} = R_{300°\mathrm{K}}/R_{4.2°\mathrm{K}}(H = H_{c2})$] of 1550. The rod of Nb was first electron-beam float-zoned and then outgassed at a temperature of approximately 2000°C in a vacuum better than 10^{-9} Torr. A flat plate, 15.2 mm long by 3.2 mm wide by 0.43 mm thick, was spark planed from the rod and etched to remove the surface damage. Current leads were soldered across the ends of the sample to ensure uniform current density, and a pair of transverse (Hall) leads were soldered to the narrow edges at the middle. Resistance leads were soldered above and below the transverse pair with a separation of 9.2 mm. The indium sample (RRR = 18 300) was prepared from a zone-refined single crystal which was spark-planed into a plate 17.4 mm by 2.4 mm by 0.45 mm and etched. The current and potential leads were attached as for the Nb sample.

The measurements are made by a standard dc method on a system whose sensitivity is about 2×10^{-9} V. The potentials are recorded continuously on the y axis of an x-y recorder whose x axis is driven by a fluxmeter linear in H. Recordings of the transverse voltages are made for the four combinations of forward and reverse current and forward and reverse field. These curves are then added and subtracted in the appropriate manner to extract the Hall voltage and transverse even voltage.[12]

Some of the experimental data for the niobium sample taken in this manner are shown in Fig. 1. As the magnetic field is increased, the resistance [Fig. 1(b)] is zero up to a value H_0 of the field.[13] At fields above H_0 the resistance in the mixed state is roughly proportional to $(H-H_0)$. The slope of the resistance curve changes abruptly at the upper critical field H_{c2}, and at higher fields the resistance in the normal state increases much more slowly with increasing field and eventually approaches saturation, as one expects for an uncompensated metal. The resistive behavior in the mixed state is similar to that observed by Kim et al.[9,10] in the flow region of dirty type-II superconductors. The Hall voltage, which is one-half the difference between the two curves in Fig. 1(a), appears at the same magnetic field H_0 as the resistance. At higher fields in the mixed state the Hall voltage is roughly proportional to $(H-H_0)^2$, until the more rapid increase just below H_{c2} brings the voltage up to the normal-state value at H_{c2}. In the normal state the Hall voltage approaches the usual linear dependence on H at higher fields.

The ratio $E_\perp/E_\parallel$, i.e., the tangent of the Hall angle, is shown in a logarithmic plot as a function of H in Fig. 2. $E_\perp/E_\parallel$ is directly proportional to H in the normal state, and the slope of the curve corresponds within experimental accuracy to exactly one carrier per atom, the sign of the Hall voltage showing this to be a hole. As the field decreases below H_{c2}, the

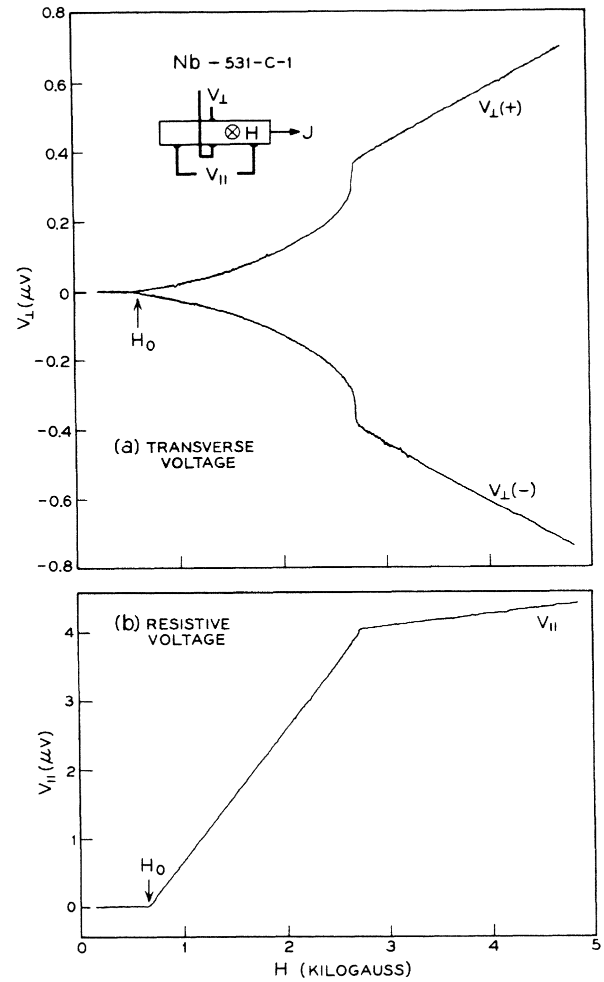

FIG. 1. The experimental data for the transverse ($V_\perp$) and resistive ($V_\parallel$) voltages for the niobium sample at 4.2°K with a current density of 460 A/cm^2. The two transverse voltage curves labeled $V_\perp(+)$ and $V_\perp(-)$ are taken with positive and negative magnetic field, respectively; and their difference is equal to twice the Hall voltage. Their sum is always less than 5% of the Hall voltage, which shows that any spurious transverse voltage due to misalignment of the transverse leads (and any true transverse-even voltage) is small.

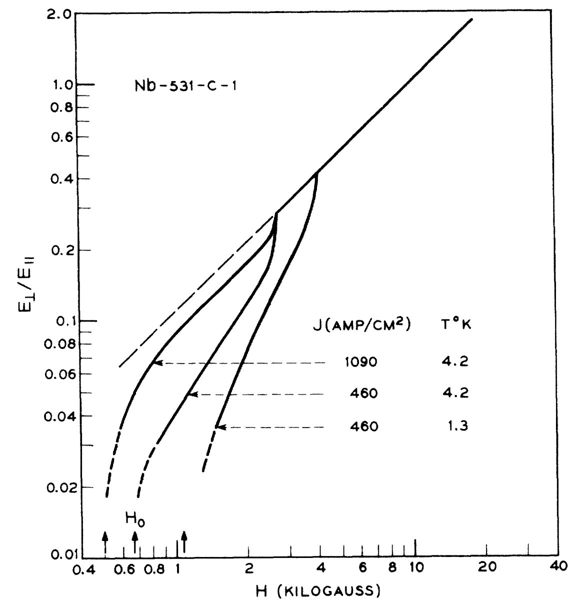

FIG. 2. The ratio $E_\perp/E_\parallel$ of the Hall field to the resistive electric field for the niobium sample in magnetic fields up to 18 kG for three combinations of current density J and temperature T. In the normal state the ratio is directly proportional to H and is independent of J and T.

value of $E_\perp/E_\parallel$ in the mixed state falls rapidly away from the extrapolated normal-state curve. At low current densities J and low temperatures T, $E_\perp/E_\parallel$ continues to decrease rapidly with decreasing field until it vanishes at H_0. But for increasing values of J and T, $E_\perp/E_\parallel$ in the mixed state progressively approaches the extrapolated normal-state value until, for the highest values of J and T, there is a direct proportionality between $E_\perp/E_\parallel$ and H for values of H between about 1 and 2 kG. These results suggest that, although the measurements close to H_{c2} are taken in the flow region where the resistive voltage is proportional to J, there is still some residual pinning to oppose the motion of the flux vortices.[14] We anticipate that, when this pinning is overcome by the use of higher purity samples or higher current densities, the Hall angle in the mixed state will coincide with the extrapolated normal-state Hall angle.

The fact that $E_\perp$ is observed in close association with $E_\parallel$ suggests that the observed Hall effect is an integral part of the dissipative processes taking place in the mixed state. According to Kim et al.,[9,10] the dissipative effect in the flow state of dirty type-II superconductors ($l \ll \xi$) can be quantitatively accounted for if the current density is approximately uniform throughout the superconductor, including the vortex-core regions which are essentially in the normal state. Apparently the current does not avoid the normal core when the vortices are flowing. In this model $E_\parallel$ observed in the flow state is $bE_\parallel{}^n$, where $b(\simeq H/H_{c2})$ is the volume fraction of the normal cores and $E_\parallel{}^n$ is the electric field in the core. Since the same consideration should apply also for the Hall emf,

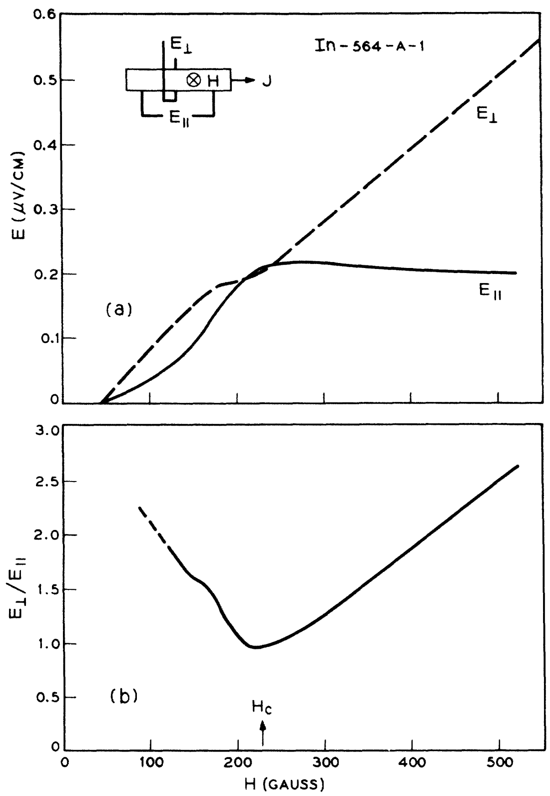

FIG. 3. The Hall ($E_\perp$) and resistive ($E_\parallel$) electric fields and their ratio ($E_\perp/E_\parallel$) for the indium sample measured in a magnetic field H perpendicular to the plate at 1.38°K with a current density of 600 A/cm^2. The dashed line at low fields indicates the trend of the ratio $E_\perp/E_\parallel$ as $V_\perp$ and $V_\parallel$ approach the noise level.

one would expect $E_\perp$ to equal $bE_\perp^n$ in the flow state and $E_\perp/E_\parallel$ to equal the Hall angle in the normal state at the appropriate field. Although in the present niobium sample the mean free path l is much longer than the coherence length ξ, i.e., the size of the vortex core, Anderson[15] points out that the scattering mechanisms are effectively the same as in dirty type-II superconductors since the density of vortex cores is very large.

Since the Hall voltage occurs in close association with the resistance in the mixed state of a type-II superconductor, we also measured a type-I superconductor in the intermediate state where the resistance is nonzero at high current densities.[16] The results are shown in Fig. 3 for an indium sample, which is uncompensated like niobium. The resistance in the intermediate state below the critical field H_c falls with decreasing H more rapidly than that of the niobium sample [Fig. 1(b)]. Both the Hall voltage and the resistance vanish at the same field, but the field dependence of the Hall voltage in the intermediate state appears to be quite different from that in the mixed state. The ratio of $E_\perp/E_\parallel$ shown in Fig. 3(b) rises above the extrapolated normal-state curve, and indeed increases with decreasing field. We do not understand this behavior in the intermediate state, which will be the subject of further experimental and theoretical investigations.

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[1]Observation of the Hall effect in superconducting niobium was first reported as a post-deadline paper by W. A. Reed, E. Fawcett, and Y. B. Kim at the March 1965 meeting of The American Physical Society in Kansas City, Missouri.

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[13]The magnitude of H_0 decreases as pinning effects are reduced by either increasing J or increasing T; for a given value of T the limiting value of H_0 at high J presumably is determined by the demagnetization factor of the sample.

[14]In one outgassed polycrystalline sample of niobium having RRR = 350, the behavior was essentially similar to that of the higher purity sample. But in another sample, which was not heat treated, pinning effects were much greater; and although the value of RRR was 500, the flow region could not be reached even at the highest value of J.

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