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FLUX JUMP SIZE DISTRIBUTION IN LOW-κ TYPE-II SUPERCONDUCTORS

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The size distribution of noncatastrophic flux jumps in cylindrical specimens of Pb+2 at.%-In alloys in an axial, homogeneous, linearly swept magnetic field has been measured as a function of field at 4.2°K and found to approximate the form $N(\varphi)=N(0)\times\exp(-\varphi/\overline{\varphi})$, where the mean bundle size $\overline{\varphi}$ was of the order of $10^2\varphi_0$ to $10^4\varphi_0$. The fraction of the entering flux participating in the jumps was found to have a field dependence similar to that of $\overline{\varphi}$. When surface superconductivity was present, the jumping persisted up to H_{c3}.

It is well known that the magnetic flux entering or leaving a solid cylindrical specimen of a type-II superconductor in an external, time-varying, axial magnetic field may do so by means of "flux bundles" composed of many individual fluxoids. Previous papers[1-3] dealing with flux penetration have reported primarily the occurrence of giant jumps of the order $10^8\varphi_0$ ($\varphi_0\equiv$ elemental fluxoid $\approx 2\times10^{-7}$ G cm^2), which arise from thermal runaway.[4]

We wish to report the measurement of the size distribution of flux jumps over the range $\sim10\varphi_0$ to $\sim10^4\varphi_0$ as a function of magnetic field for low-κ (≈1.5) specimens of Pb+2 at.% In at 4.2°K; these specimens have an H_{c2} of 980 Oe and an H_{c1} of ~400 Oe at this temperature.

The specimens were in the form of circular cylinders approximately 60 mm long and 1.2 mm in diameter. They were prepared from 99.999%-pure metals by melting for several hours in a vacuum of 10^{-6} Torr, quenching in liquid nitrogen, and cold drawing through a die. They were then chemically polished and stored at 77°K to prevent annealing until used. The samples to be measured were placed in a homogeneous, axial magnetic field generated by a compensated copper solenoid. Flux jumps were measured with a small, tightly wound, 3600-turn pickup coil as the field was swept. Figure 1(a) is a schematic diagram of our apparatus. The flux jumps appeared as a set of irregularly shaped voltage pulses induced by flux bundles suddenly entering or leaving the sample, superimposed on a smoothly varying "dc" voltage due to flux entry via other mechanisms. These pulses were first electronically integrated and then converted into a narrow pulse whose height was proportional to the number of fluxoids in the bundle.[5] The size distribution of the bundles was then obtained directly by means of a 400-channel pulse-height analyzer. In order to accumulate good statistics over any narrow region of magnetic field, the field was swept up and down linearly from a small initial value below H_{c1} to fields above H_{c2}. Since the magnetization loops were closed, we could repeatedly take data over any convenient narrow field interval by using a gate to block the analyzer in all but the preselected region. Our basic sweep rate was 10 Oe/sec; the data were not altered by raising this rate to as high as 100 Oe/sec. The lack of dH/dt dependence indicates that thermal relaxation effects due to the heating produced by a flux jump played no significant role in our distributions.

The results of a typical run are shown in Fig. 1(b). The size distribution asymptotically approaches the form

$$N(\varphi)=N(0)e^{-\varphi/\overline{\varphi}} \tag{1}$$

which defines the mean bundle size $\overline{\varphi}$ for each curve. The two distributions shown in Fig. 1(b) were taken on the same sample at different values of H. In all cases, we observed deviations from a true exponential behavior at low values of φ. Some of this deviation can be explained by

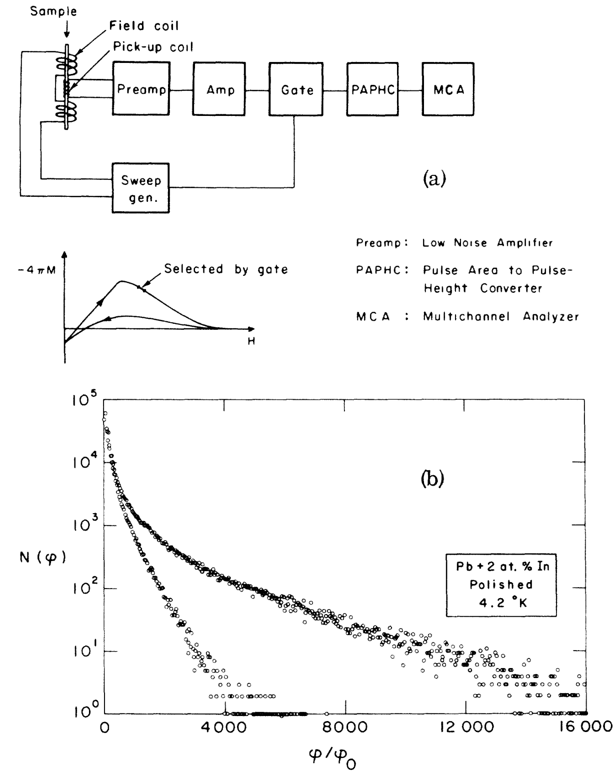

FIG. 1. (a) Block diagram of the electronics used to measure the flux-jump size. For each jump the MCA puts one count in the channel corresponding to the flux contained in that jump. The position and width of the field region selected by the gate could be selected at will. (b) Distribution of jump sizes for a sample annealed at 300°C for several hours. The data were plotted directly on a logarithmic scale after 50 sweeps. The upper curve was taken at ~550 Oe and the lower at ~850 Oe with a gate width of 20 Oe. The horizontal axis corresponds to 40 fluxoids per channel. The values of $[N(0), \overline{\varphi}]$ according to Eq. (1) are $(650 \pm 50, 2500\varphi_0 \pm 100\varphi_0)$ for the upper curve and $(400 \pm 100, 500\varphi_0 \pm 50\varphi_0)$ for the lower.

the finite length of the flux bundles.[6] As the pickup coil is 1 mm in length, there will be a geometrical factor tending to increase the number of counts at low φ values on account of having a bundle linking only part of the coil. Amplifier noise will contribute only to the first several channels, which we have omitted from the data analysis. It seems very likely to us that, even after making the corrections above, there are still excess counts (with respect to the exponential distribution) in the low channel numbers, which are most probably due to the small jumps taking part in flux flow and creep.[7]

From the mean bundle size $\overline{\varphi}$ defined by Eq. (1) and the intercept $N(0)$ of the extrapolated exponential distribution, we may derive the fraction of the flux which enters the sample in large bundles. Defining the total flux which entered the specimen up to a field H by

$$\varphi_T = \int_0^H \frac{d\varphi_T}{dH} dH, \tag{2a}$$

defining the flux which entered the sample via the jumps which followed the exponential distribution by

$$\varphi_J = \int_0^H \frac{d\varphi_T}{dH} dH, \tag{2b}$$

and noting that φ_T and φ_J can be determined from the magnetization curve and the jump-size distribution, respectively, we can then determine the contribution of the flux jumps to the total flux entering the sample $d\varphi_J/d\varphi_T$ as a function of H.

Figure 2 shows M, $\overline{\varphi}$, and $d\varphi_J/d\varphi_T$ as a function of H for flux entering an unannealed sample with a polished surface.[8] The distribution of $d\varphi_J/d\varphi_T$ vs H is quite similar in shape to the $\overline{\varphi}$ distribution, which indicates that the number of bundles entering the sample does not vary markedly as a function of H, although the proportionality factor seems to alter above H_{c2}. The rapid rise in $\overline{\varphi}$ above H_{c1} is believed to be due to the distribution of pinning forces, as a bundle cannot move unitl the driving force overcomes the pinning. Both the magnetic pressure and the average flux-line density increase sharply above H_{c1}, leading to flux jumps whose average size increases with H in qualitative agreement with our results. The rapid drop in bundle size near H_{c2} can be explained by the increasing "rigidity" of the fluxoid lattice due to the strong interaction between fluxoids at small distances. This should greatly reduce the effect of a pinning site by making it more and more energetically unfavorable to create a perturbation in the regular flux-line array as the field approaches H_{c2}.[9] Less easily understood is the observation that $\overline{\varphi}$ rises sharply again above H_{c2} in the regime of surface superconductivity, peaks, and falls sharply once more as we approach H_{c3}. Because of the critical role of surface preparation, this phenomenon has thus far only been observed in a few samples.

Figure 3 illustrates the effect of electroplating ~1000 Å of Ni on the surface of the same specimen used to obtain the data shown in Fig. 2. The maximum value of $\overline{\varphi}$ was reduced by a factor of 6, but the contribution of the flux jumps to the

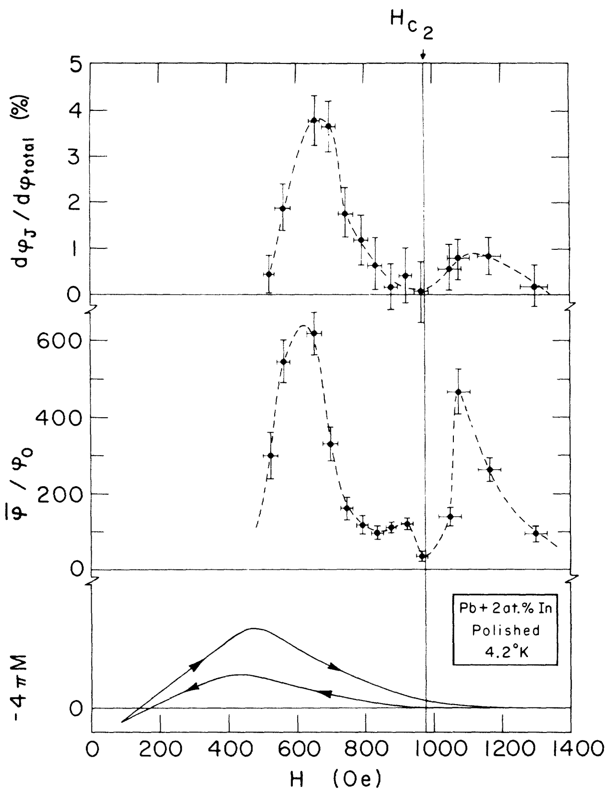

FIG. 2. The magnetization M, mean number of fluxoids per bundle $\bar{\varphi}/\varphi_0$, and the fraction of flux entering the sample via the jumps $d\varphi_J/d\varphi_T$ as a function of magnetic field for an unannealed sample exhibiting surface superconductivity. The vertical error bars represent the limits of the best fit to the slope of the asymptotic exponential distribution. The horizontal bars indicate the width of the region of magnetic field over which the data were taken.

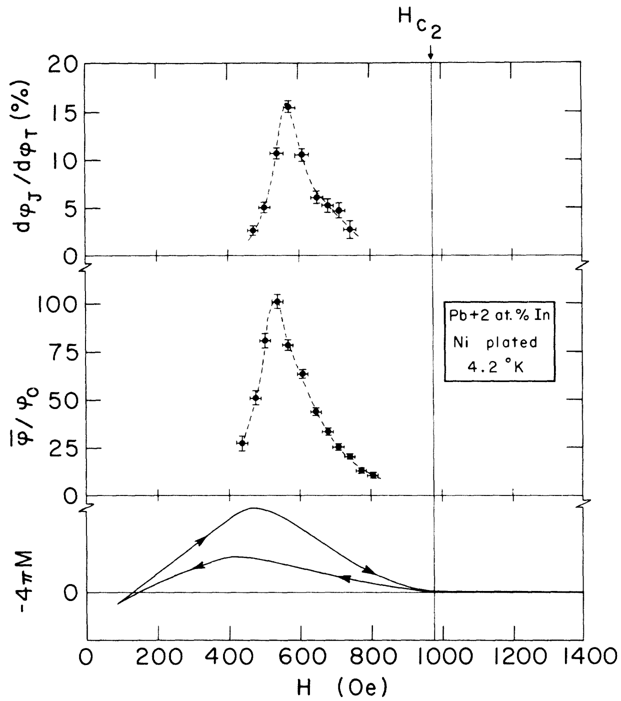

FIG. 3. The magnetization M, mean number of fluxoids per bundle $\bar{\varphi}/\varphi_0$, and the fraction of flux entering the sample via the jumps $d\varphi_J/d\varphi_T$ as a function of magnetic field when the surface of the sample has been plated with $\approx$1000 Å of Ni. These data may be compared with those shown in Fig. 2.

total flux entry increased by roughly a factor of 4. The disappearance of surface superconductivity as seen on the M-H curve correlated with the vanishing of visible flux jumping above H_{c2}. The similarity of the curve of $\bar{\varphi}$ vs H to the curve of $d\varphi_J/d\varphi_T$ vs H was preserved. The differences between Figs. 2 and 3 are presumably due to the destruction of the superconducting surface sheath by the Ni plating, which should also drastically reduce any surface pinning.

The ultimate sensitivity of our apparatus is limited by amplifier noise to ~$10\varphi_0$ at present. The actual sensitivity varied from sample to sample, depending on the height-to-width ratio of the pulses induced in the pickup coil by the jumps.[10] On samples with long low pulses (slowly entering bundles) the sensitivity decreases because the pulse integrator cannot trigger until the leading edge of the pulse exceeds the noise. This will also tend to increase our counts in low channels, as the integrator will then tend to start late and stop early. Also, for low pulses, noise may cause the amplitude to drop below the threshold momentarily, causing a single pulse to be counted as several smaller ones. Another possible source of error is the accidental coincidence of two or more jumps. At our basic sweep rate of 10 Oe/sec, however, the probability of such an occurrence is extremely small, as the spacing between pulses as observed directly on an oscilloscope is much greater than the width of a single pulse. The lack of dependence of $\bar{\varphi}$ on sweep rate further reinforces this observation.

For flux leaving the specimen, $\bar{\varphi}$ is greatly increased for all samples when compared with $\bar{\varphi}$ for entering flux at the same H values. Although the size distribution appears to exhibit an exponential behavior, the small number of events requires what is presently an excessively long time to obtain good statistics.

Further investigation of these phenomena, particularly the dependence on temperature and the possibility of size effects, are under way and we hope that these will give us a better understanding of the mechanisms governing these effects.

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EVIDENCE FOR INTERSHEET SCATTERING IN CADMIUM AND CADMIUM-ZINC SINGLE CRYSTALS

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Measurements of the Hall resistivity in cadmium and cadmium-zinc–alloy single crystals (up to 1.5 at.% Zn) indicate that scattering of carriers between two adjacent branches of the hole surface is possible and that this intersheet scattering can affect the galvanomagnetic properties very markedly.

Discarding oscillatory effects that are observed in crystals of high purity,[1,2] the published data on the Hall resistivity of cadmium single crystals do not agree, even though the purity of the crystals is of the same order. In particular the field dependence of the Hall resistivity $\rho_{21}(H)$ seems to be influenced by relatively small differences in purity of the investigated samples. In order to check the impurity effects a number of single crystals cut from the same ingot have been alloyed with Zn by electroplating and subsequent diffusion for several days at 200°C. Samples were cut so that the electric current was along $[10\bar{1}0]$ and the magnetic field was along $[0001]$. Results representative of the general behavior are plotted in Fig. 1: The $\rho_{21}(H)$ curves for three samples with different impurity contents are characterized by their residual resistance ratios ($r = R_{273}/R_{1.5}$). The lowest value $r = 240$ is for a sample having approximately 1.5 at.% Zn.

Investigations by Tsui and Stark[3] have ruled out magnetic breakdown effects between the first- and second-zone sheets below 32 kG in samples of similar purity. It would be very difficult to explain the observed sign reversals in ρ_{21} as being caused by a magnetic breakdown effect. Firstly magnetic breakdown would cause transitions between orbits of the same character (namely holes) which would not influence the Hall resistivity greatly. Secondly a gap widening with increasing impurity content is in itself not impossible but one would expect this to occur for fields larger than the lowest limit indicated by Tsui and Stark's work.

In order to understand theoretically how the scattering between well-defined regions of the Fermi surface can influence the galvanomagnetic properties in such a drastic way, we have constructed a model which resembles cadmium in its structural properties and whose galvanomagnetic tensor can be calculated analytically. This