

MAGNETIC FLUX JUMPS IN HARD SUPERCONDUCTORS IN PULSED MAGNETIC FIELDS

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A large number of abrupt changes are observed in the magnetic flux upon destruction of the superconductivity in Nb_3Sn and NbZr samples. The magnitudes of the jumps and their duration are measured. The durations vary from 2×10^{-5} to 5×10^{-4} sec. Each jump is connected with a partial penetration of the flux into the superconductor.

AT the present time, a great deal of attention is given to the study of the properties of hard superconductors, which possess large critical fields and currents. In the investigation of the magnetic properties of hard superconductors, a phenomenon has been discovered that has been given the name of flux jumps.^[1] When certain hard superconductors are placed in a slowly changing magnetic field, a rapid change takes place in the magnetic flux inside the superconductor with almost no change in the magnetic field intensity. This phenomenon has not yet found its complete explanation.

The present work was devoted to getting the characteristics of this phenomenon. Such an investigation can also be of practical interest, since the flux jumps play an important role in the destruction of the superconducting state in solenoids.^[2] The study of the magnetic flux jumps was carried out in pulsed magnetic fields. The objects of investigation were specimens of Nb_3Sn , NbZr , and Nb .

1. DESCRIPTION OF THE APPARATUS

The experimental setup is pictured in Fig. 1. The pulsed magnetic field is created in the coil 1, which is cooled by liquid nitrogen or hydrogen, by a discharge from a capacitor bank with a maximum energy supply of 40 kjoules. The length of the coil was 10 cm, its internal diameter 3.7 cm, and external diameter 7 cm. Fields were obtained with an amplitude up to 140 kOe and with a rise time required for the field to reach its maximum varying from 0.04 to 0.17 sec. The time rate of change of the field ranged from 10^5 to 10^6 Oe/sec. The method of obtaining strong magnetic fields of long duration was based on the work by one of the authors and Limar'.^[3] In the present work, results are reported for measurements in fields up to 70 kOe.

A German-silver cold finger of the dewar 2,

which can be filled with liquid helium or hydrogen, is placed inside the volume in which the magnetic field is produced. In this finger are located the superconducting specimen 3 and the set of measuring coils 4, which consist of two coils with a large number of turns, made of copper wire of diameter between 0.06 and 0.1 mm. The specimen is placed inside one of the coils. Both coils are mounted on a single thin-walled glass tube, rigidly connected with the rod 5. They are connected in such a fashion that when they are moved relative to the field coil by means of the rod, one can find the compensation position at which the emf at the terminals of the set of measuring coils as the external magnetic field is changed, is equal to zero if the specimen is absent or is in the normally conducting state. When the entire specimen or a part of it is in the superconducting state, the emf

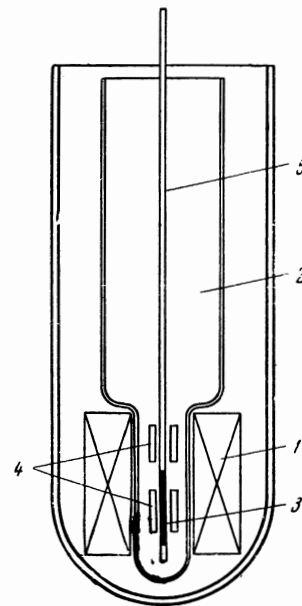


FIG. 1. Diagram of the experimental apparatus.

in the coil with the specimen is not equal to the emf in the compensating coil, since the permeability of the superconductor is less than unity. The difference between the emf's in the measuring and compensating coils is recorded by means of an oscilloscope.

The characteristics of the specimens we studied are given below. The specimens of Nb_3Sn were given to us by B. G. Lazarev, and those of NbZr by B. N. Samoïlov, to whom the authors express their gratitude. All the specimens were cylindrical, with a large ratio of length to diameter. The axis of the cylindrical specimen was placed parallel to the magnetic field. The specimens of Nb_3Sn are niobium bars of 1-mm diameter, covered on top by a layer of the compound Nb_3Sn of thickness from 10 to $70\ \mu$ obtained by diffusion of tin into niobium at temperatures from 860 to 1200°C . The lengths of the specimens were from 20 to 30 mm. Details of the method of preparing these specimens are given in [4]. The specimens of NbZr that we investigated contained 50% Zr, the diameter amounted to 0.27 mm, and the length to 30 mm. The methods of preparation and treatment of these specimens are described in [5]. The treatment consisted of 99% deformation followed by annealing for three hours at 600°C .

The principal measurements were made at 4.2°K . Some of the measurements on Nb_3Sn were made in the temperature range from 14.5 to 18°K . All the oscillograms and graphs which will be shown below were made on a single specimen of Nb_3Sn of 20 mm length with a layer thickness of about $50\text{--}70\ \mu$ according to metallographic measurements. The inhomogeneity of the field along the specimen amounted to 8%.

2. SOME DETAILS OF THE EXPERIMENTAL METHOD AND THE RESULTS OF THE EXPERIMENT

Initially the $E(t)$ curve was recorded with a loop oscillograph. A characteristic oscillogram of the signal obtained on the measuring coils when a pulsed magnetic field is imposed is shown in Fig. 2. Curve 1 represents the change in the mag-

netic field with time, curve 2 the signal $E(t)$ from the measuring coil. In weak fields, when the entire specimen is in the superconducting state, its magnetic permeability is zero and E is proportional to the time derivative of the external magnetic field. At some field H_1 , a large voltage pulse is observed which is opposite in sign to the initial signal. This pulse appears as the result of the rapid penetration of the magnetic flux into the superconductor. Upon further increase in the field, another series of similar peaks in the voltage is observed. The magnitude of the flux jump can be determined from the area bounded by the voltage pulse. Thus, for the available rates of growth of the field, the entire transition is broken up into a series of separate flux jumps.

At some field H_2 , smaller than the amplitude of the external magnetic field H_{max} , the flux jumps cease. As the magnetic field is decreased from the maximum value to zero, similar voltage pulses of opposite sign are observed, connected with the transition from the normal to the superconducting state.

Inasmuch as the duration of the flux in oscillogram 1 of Fig. 2 and those similar to it is comparable with the characteristic period of oscillation of the vibrator by means of which the measurements are carried out, the duration of the peaks in this drawing are exaggerated in comparison with the actual duration, so that this oscillogram furnishes only the qualitative character of the superconducting transition, but is unsuitable for the calculation of the magnitude of the magnetic flux jumps. It is introduced here in view of its very great illustrative character and because it shows correctly the place and number of flux jumps.

The $E(t)$ curve was recorded without frequency distortion by means of cathode-ray oscilloscopes. The duration of the total process of destruction of superconductivity in our experiment amounted to about 10^{-1} sec, while the duration of the individual peaks was 3 to 4 orders of magnitude smaller. With such a great disparity of time scales of scanning and duration of individual peaks, it is difficult to obtain good resolution which would allow

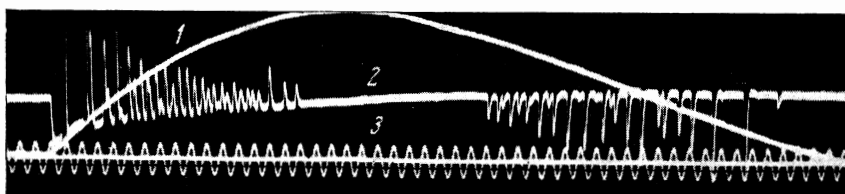


FIG. 2. Oscillogram of the signal $E(t)$, from the measuring coil, taken on the loop oscillograph with a specimen of Nb_3Sn . Maximum field is 56.1 kOe. Curve 1 — change of the magnetic field with time; curve 2 — $E(t)$; curve 3 — signal with time markers of frequency 100 cps. $T = 4.2^\circ\text{K}$.

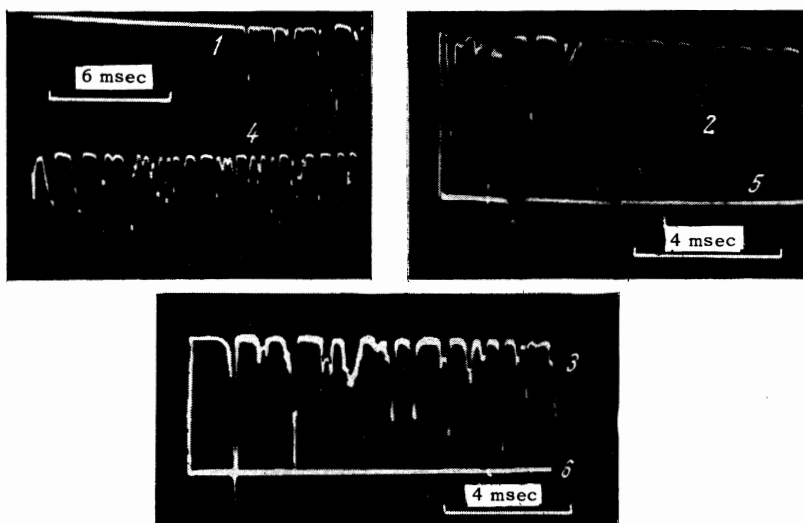


FIG. 3. Oscillograms of $E(t)$, taken on electron oscilloscopes with the same specimen of Nb_3Sn . Numbers 1, 2, ..., 6 indicate successive portions of the curve of the signal. $H_{\max} = 32$ kOe, $H_1 = 10.5$ kOe, $H_2 = 30.8$ kOe, $T = 4.2^\circ K$.

us to estimate correctly the area of the individual peak in a recording made on a single oscilloscope. A circuit was therefore developed which allowed us to record the curve on several different oscilloscopes in succession and thus increase as it were the dimensions of the oscilloscope screen in the horizontal direction by almost one order of magnitude.

The operating principle of this circuit amounted to the following. The sweep of the first oscilloscope was triggered by a signal synchronized with the initial pulse of the field. The return trace of the ray of this sweep triggered the sweep of the second oscilloscope and simultaneously shifted the beam of the first by a fixed amount in the vertical direction. The second and third oscilloscopes were triggered in the same way and the return traces of the third oscilloscope again triggered the first, but on a second line, and so forth. Thus the recording of the $E(t)$ curve was carried out on six lines. In principle, this electronic switching circuit allowed us to work with any number of oscilloscopes and for any number of lines. A detailed description of the circuit will be given separately.

Oscillograms taken on ENO-1 oscilloscopes with a specimen of Nb_3Sn in the manner described above are shown in Fig. 3. (The specimen is the same one for which the oscillogram of Fig. 2 was taken.) The field curve was simultaneously recorded on a loop oscillograph. As is seen from the oscillograms, the duration of the separate voltage peaks and consequently the duration of the flux jumps are in the range $2 \times 10^{-5} - 5 \times 10^{-4}$ sec. A check with an oscilloscope with a larger bandwidth showed that the form of the peaks is correctly reproduced but there is a small number of peaks with very short duration with which are connected flux

jumps that are quite small. Thus, the apparatus records with sufficient accuracy the process of the destruction of superconductivity of hard superconductors in pulsed fields.

The value of the magnetic flux which arises in the specimen for a single jump was calculated on the basis of oscillograms similar to those shown in Fig. 3. For simplicity of calculation, we used the following model: In a given field, part of the volume of the specimen undergoes transition to the normal state, and the flux generated in it is equal to the flux of the external field in this region. This part of the volume of the specimen or part of the cross section area of the specimen, if it is considered that the region of the new phase penetrates the entire length of the specimen (this assumption is apparently justified since the probability of formation of small regions with a large demagnetization factor is small), can be determined from the relation

$$\Delta S = \frac{1}{nH \cdot 10^{-8}} \int E dt,$$

where E is the voltage on the measuring coils, t the time, n the number of turns in the measuring coil, and H the value of the external field at the instant of appearance of the given flux jump. We neglect the change in the external field during the time of the single jump, since it is very small. The areas corresponding to the separate flux jumps are found to range from 5×10^{-7} to 3×10^{-4} cm^2 .

In some sense, it is convenient to use not the area of the region of new phase that is formed, but the change in flux $\Delta\Phi$, since the latter is not connected with any model. In individual jumps $\Delta\Phi$ changes from 1×10^{-2} to 4 $\text{G}\cdot\text{cm}^2$. The limit of sensitivity of measurement of $\Delta\Phi$ in our experiments amounts to 6×10^{-3} $\text{G}\cdot\text{cm}^2$. Upon complete

destruction of superconductivity, the sum of all the separate flux jumps $\Delta\Phi$ must equal the total flux through the cross section area of the specimen at the moment of destruction of superconductivity. Unfortunately, we still do not have oscillograms suitable for such a calculation. For the oscillogram showed in Fig. 3, $H_{\max} = 32$ kOe, $H_1 = 10.5$ kOe, and $H_2 = 30.8$ kOe. In the field $H_2 = 30.8$ kOe, the penetrating flux, i.e., the sum of flux jumps, is equal to $\Sigma\Delta\Phi_n = 70$ G-cm², which amounts to $\sim 20\%$ of that flux which would penetrate the specimen in the given field if it were in the normal state. An examination of the oscillograms showed no single large pulse which could refer to the transition to the normal state of the niobium core as a whole. It is apparently screened from the external field. The superconductivity of Nb is destroyed gradually as the field penetrates the specimen.

In the plots of the induction vs. the magnetic field of hard superconductors there are two characteristic fields—the field H_{C1} , at which penetration of the flux into the superconductor begins, and the field H_{C2} , which corresponds to complete penetration of the magnetic field. The field H_1 of the first flux jump, observed in our experiments, evidently corresponds to H_{C1} . Attention should be turned to the fact that H_1 for a given specimen changes strongly in successive pulses of the field. This is explained to a significant degree by the fact that when the magnetic field decreases from its maximum to zero part of the penetrating magnetic flux is frozen in the specimen. Therefore, each pulse occurs under different initial conditions.

To eliminate this effect, the specimen was heated between the repeated pulses of the field to a temperature above T_C (the heating was carried out by raising the specimen above the level of the liquid helium). After heating, the value of H_1 for this rate of increase of the field is repeated with a scatter not exceeding $\pm 8\%$. All the measurements whose results are given were made with heating of the specimen. But even after heating, there was no complete reproducibility of the results. Evidently, this is connected with an inaccurate repetition of the conditions of the field pulse (the structure of the flux jumps is very sensitive to the rate of increase of the field). The value of H_1 for Nb₃Sn for rates of change of the external field from 1.2×10^5 to 5.5×10^5 Oe/sec (we have in mind the value of dH/dt at the instant of the first flux jump) increases with increase in the rate of growth of the field and changes in the range from 4 to 10.5 kOe. The smallest of the values of H_1 is close to the value $H_{C1} = 4.5$ kOe measured

in [6]. The character of the dependence of H_1 on dH/dt in other intervals of change of dH/dt requires further explanation. The largest of the fields H_1 corresponds to a density of the screening current of the order of 10^6 A/cm² if one assumes that the entire current is distributed uniformly over the cross section of the superconducting layer of Nb₃Sn. It is possible that part of the screening current flows along the niobium core; then its density can be smaller.

The field H_2 which corresponds to the last flux jump must evidently correspond to H_{C2} , if the amplitude of the external field is much greater than H_{C2} . In fields with an amplitude smaller than H_{C2} , however, H_2 is never identical with H_{\max} . This is explained by the fact that the rate of its increase close to the maximum field, is much less, and evidently the probability of appearance of the flux jump becomes small. The fact that the pulses on the curve $E(t)$ are always absent close to the maximum field gives evidence on behalf of this assumption. For a sufficiently large rate of change of the field, the interval between individual flux jumps amounts to more than several hundred Oe (up to 1 kOe); close to the maximum, there cannot be a single jump of 3.5 kOe. In order to measure the actual value of the field at the end of the destruction of the superconductivity H_{C2} , it is necessary to make the measurements in sufficiently large fields, where the dependence of the field H_2 on H_{\max} disappears. Preliminary measurements show that the dependence of H_2 on H_{\max} saturates in the region of large fields.

The field in which the inverse transition—from the normal to the superconducting state—begins (with decreasing external magnetic field) is always smaller than H_2 , which testifies to the presence of hysteresis.

As was mentioned above, the inhomogeneity of the field for the shortest of the specimens amounted to about 8%. However, in the case of longer specimens, for which the inhomogeneity exceeds 10%, the results do not differ qualitatively from those obtained by us. It is interesting that the difference in the fields at the two ends of the specimen was sometimes larger than the field difference between the individual jumps.

Measurements were also carried out on the alloy NbZr (50% Zr) at 4.2°K. The picture of the transition in these specimens does not differ qualitatively from the transition in Nb₃Sn.

In the study of Nb₃Sn at temperatures close to T_C , it was discovered that the character of the transition changes. In the region of temperatures above 14.5°K, the individual flux jumps are not ob-

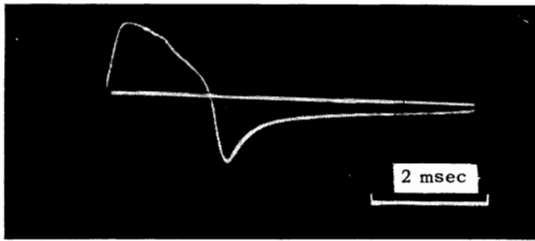


FIG. 4. Oscillogram of $E(t)$ with the same specimen of Nb_3Sn , taken on an electron oscilloscope. $T = 16.8^\circ K$. Maximum field 61 kOe.

served. The oscillogram of $E(t)$ taken at a temperature of $16.8^\circ K$ is shown in Fig. 4. All the results in other specimens of Nb_3Sn with a very thin layer of the compound are qualitatively the same as those obtained in the present work. For specimens of Nb at a temperature of $4.2^\circ K$, the flux jumps are absent.

3. DISCUSSION OF THE RESULTS

The dependence of the flux generated in the specimen (or the sum of the flux jumps) $\Sigma\Delta\Phi_n$ on the external field is shown in Fig. 5. This curve is constructed from the oscillogram of Fig. 3. As is seen from this curve, and from the calculation of the value of the flux jump obtained earlier, each flux jump is considerably less than the total flux of the external field through the cross section of the specimen. However, the flux jumps observed by us are so large that they cannot be connected with the quantization of the magnetic flux in the superconductor, but are a macroscopic phenomenon. Inasmuch as the quantum of the magnetic flux is equal to $2.07 \times 10^{-7} \text{ G-cm}^2$,^[7] the minimum of the observed flux jumps corresponds to a value of the order of 5×10^4 quanta. Let us also turn our attention to the fact that the jumps do not lead to an identical field inside and outside the superconductor, and that the curve of the dependence of $\Sigma\Delta\Phi_n$ on H has a small slope. For measurements on such superconductors in quasistationary fields,^[8,9] at an increase of the external field H with a rate of the order of 10 Oe/sec, the field H' inside the specimen also remains equal to zero, up to some value of the external magnetic field; the jump of the field in the superconductor does not occur. However, in contrast with the results obtained by us in pulsed fields, the flux jump would be complete, i.e., the field H' inside the superconductor would be equal to the external field. Upon further increase in the field, the internal field undergoes no further change until the next jump, at which H' again becomes equal to H . The pres-

ence of similar total flux jumps is evidence that, at the moment of the jump, a transition takes place from the superconducting to the normal state. The duration of such jumps did not change. In contrast with the experiments on quasistationary fields, the transition to the normal state beginning in a pulsed field does not develop into a complete transition. Qualitative results similar to ours for measurements in pulsed fields were also obtained in^[10].

The observed differences in the value of the flux jumps and the character of the dependence of the flux inside the specimen on the magnetic field can be related to the difference in the thermal regime of the specimens in stationary and pulsed fields. Let us compare the duration of the jumps in our experiments and the propagation times for the thermal wave in the specimen. The time of equalization of the temperature over the cross section of the cylinder should be of the order of R^2/D , where R is the radius of the cylinder, D the coefficient of temperature conductivity. An exact knowledge of the quantity D for Nb_3Sn is not available; however, it can be estimated in order of magnitude. If one estimates the thermal conductivity on the basis of the Wiedemann-Franz law, we get a value of $1.5 \times 10^{-3} \text{ W/cm-deg}$. (The value of the specific electrical resistance is taken from^[11] and is equal to $7 \times 10^{-5} \text{ ohm-cm}$.) If we take into account the lattice thermal conductivity, the total thermal conductivity at $4.2^\circ K$ lies in the range from 2.4×10^{-3} to $5.7 \times 10^{-3} \text{ W/cm-deg}$.^[12] The heat capacity of Nb_3Sn per gram of matter should obviously be close to the heat capacity of Nb, the value of which is taken from^[13] for the normal state at $4.2^\circ K$.

In using the values given for the specific heat capacity and thermal conductivity, the time of equalization of the temperature over the entire cross section of the specimen is shown to be of the order of 10^{-2} sec , since the duration of the individual jump in flux lies in the range 2×10^{-5} to $5 \times 10^{-4} \text{ sec}$. The possibility is not excluded that

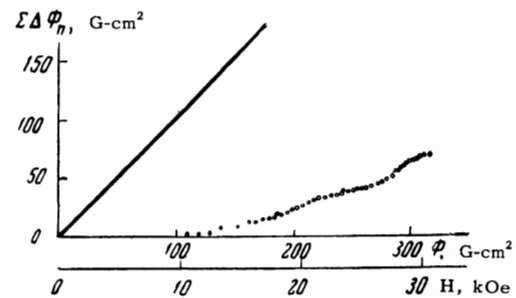


FIG. 5. Dependence of the sum of flux jumps on the external field and on the flux of the external field inside the specimen.

one should consider the time of equalization of the temperature not over the entire sample, but only inside the layer of the superconducting compound. Then it will be about 10^{-4} sec, i.e., it is seen to be comparable with the time of only the very long flux jumps. On the basis of the discussions given above, one can draw the conclusion that the process of destruction of superconductivity in pulsed fields is adiabatic under our conditions rather than isothermal, which can lead to a decrease in temperature, an increase in this connection of the critical field, and a stopping of the transition.^[14] We note that a communication has appeared on the experimentally observed fluctuations of temperature in NbZr in the mixed state,^[15] for which no convincing explanation has been found. Insofar as one can judge from the description of the experiment, the conditions in^[15] are close to adiabatic and the same explanation applies as for our experiments.

However, one must not reject the possibility that the superconductor should be regarded as a set of regions characterized by different critical fields, and that the jumps are brought about by the destruction of the superconductivity in such individual regions.

Thus, so far the experimental data do not permit us to draw an exact conclusion as to whether the observed flux jumps are associated with the existence of individual regions of superconductivity with different parameters, or whether they are connected with some macroscopic processes which limit the rate of the phase transition.

In conclusion, the authors take the occasion to express their gratitude to Prof. M. I. Kaganov for a discussion of the research.

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