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N. Sacchetti, G. Sacerdoti, G. Sanna, F. Smriglio and A. Susanna:

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(Nota interna: n. 251)

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(Submitted to Physical Review for publication)

ABSTRACT

In a previous experiment, it was observed that the persistent current in a thin Pb superconducting ring decays when the material is subjected to α - particle irradiation from a Po^{210} source. Systematic observations of flux decay have been carried out under different experimental conditions. The effects of varying the temperature (from 1.1 to 4.2 °K), the thickness of superconducting layers (from about 10 to 40 μ), and the materials (lead, tin, and indium) have been investigated.

The flux decay law deduced from the experimental data seems to be logarithmic in time, showing a behaviour similar to that observed by Kim et al. for flux creep in hard superconductors.

I - INTRODUCTION

It is well known that in a multiply-connected superconductor, the fluxoid:

(1) $$\Phi = \iint_S \vec{H}\cdot d\vec{S} + c\oint_C \Lambda \vec{J}\cdot d\vec{l}$$

under fixed external conditions, is constant in time(1). With reference to Fig. 1, C is a closed curve located entirely within the material and enclosing one of the holes of thr superconductor. S is any surface bounded by C. $\vec{H}$ and $\vec{J}$ are, respectively, the magnetic field and the current density. Λ is a parameter introduced in the London phenomenological theory and is related to the penetration depth by the simple relation:

(2) $$\lambda = c\left(\frac{\Lambda}{4\pi}\right)^{-1/2}$$

If the superconductor is sufficiently thick, we can choose the curve C to be so deep inside its interior that the current density is essentially zero, and we can rewrite the relation (1) as follows:

(3) $$\Phi = \iint_S \vec{H}\cdot d\vec{S}$$

In such a case the fluxoid becomes identical with the magnetic flux through the hole.

We note that a superconductor containing magnetic flux is not in absolute thermal equilibrium. The persistent current must to be considered as metastable in the sense that the energy of the system is a minimum only with respect to infinitesimal variations of the current distribution.

In the particular case of superconductors of the second kind, Kim et al.(2) have shown that the superconducting currents induced by an external magnetic field in tubular samples of Nb, V and Nb-Zr are inherently unstable and slowly decay, with a decay law proportional to the logarithm of the time. In a preceding letter(3) a brief qualitative account of the effect of α-particle irradiation on a lead superconducting ring containing trapped magnetic flux was given and it was pointed out that under these conditions the trapped magnetic flux decays in time.

magnetic flux decays in time.

In the present work we have extended the previous measurements to a number of soft superconductors in which the trapped flux has the maximum value allowed by temperature and geometrical factors.

Varying certain experimental parameters such as the temperature and the ring thickness, we have carried out a systematic investigation of this decay phenomenon.

Detailed examination and discussion of the experimental results will be given in the following sections, but we can anticipate here that the decay phenomenon is proportional to the logarithm of the time.

II - EXPERIMENTAL DETAILS

A) Preparation and Calibration of α - sources.

A schematic view of a superconducting ring and the associated source is shown in Fig. 2. The latter were prepared by electrodeposition of Po^{210} from a $Po(NO_3)_2$ solution on a silver or platinum support ring, whose dimensions are also shown in Fig. 2.

In preliminary experiments we tried to prepare the α sources by spontaneous deposition of Po^{210} on the support ring, but, since the source activity was too weak for our purposes (less than 1 mC), we prepared other sources by electrodeposition at low current intensity (7 to 8 mA) for two days.

Moreover, in order to obtain good surface uniformity, we slowly rotated the support ring during the deposition. The sources prepared in this way were sufficiently uniform (about 20%) and their total activity was high enough to produce an experimentally detectable flux decay rate.

The intensity and the uniformity of the sources were measured by an apparatus especially designed for this purpose. It consists essentially of a vacuum chamber (see Fig. 3) in which we can place the source to be calibrated.

The two diaphragms D_1 and D_2 geometrically define the relevant portion of the emitting surface and the relative solid angle subtended by the crystal scintillator (a thin CsI(Tl) crystal).

The source can also be rotated and translated vertically. A photomultiplier tube with related electronic counting equipment complete the calibration unit.

In certain cases the source was protected by means of a thin metal layer (less than one micron) to prevent Po^{210} volatilization and also to separate the source from the superconducting deposit; but this has very little effect on the behaviour of the decay.

B - Preparation of Superconducting Rings.

The superconducting rings have been prepared by electrodeposition of the metal (to be studied) on the radioactive source, using a standard galvanic solution.

By weight measurements, it has been possible to estimate the ring thickness with an accuracy of about 3%. Moreover, the uniformity of the superconducting layer has been checked by analyzing the α- particle emission from different points on the surface, this analysis being made by measuring the α- particles energy spectrum by means of a pulse height analyzer.

C - Flux Measurements and Temperature Control.

A schematic view of our experimental apparatus is shown in Fig. 4.

Flux trapping was accomplished by the use of an external coil, which raised the magnetic field well above the critical field of the superconductor under study.

Flux measurements were performed by means of an electronic integration fluxmeter whose search coil was fixed while the moving element was the superconducting ring.

In a number of experiments, a non-irradiated superconducting ring was also present in the helium bath, in order to be sure that the trapped flux does not decay even in the absence of an α particle source.

Good control of the temperature (to within at least 0.01 °K) was achieved by using a cartesian manostat to stabilize the helium vapor pressure. Often, after a run of several hours, we have again raised the external magnetic field to the value at the beginning of the experiment. We always found that the trapped flux in the superconducting ring was the same as before. In other words, no permanent damage to the superconducting properties resulted from α particle bombardment.

Moreover, we point out that particular care has been taken to avoid surface oxidation effects which would affect the reproducibility of data. Every set of experimental runs has been performed in such manner that the metal ring is never exposed to the air during two successive runs.

III - EXPERIMENTAL RESULTS

We give here only the most interesting results of our measurements, which we shall discuss in the next section.

A - Tin Rings.

In Fig. 5 we give the experimental points pertaining to a number of runs for a tin ring, $\sim 10\mu$ thick and 2 mC total activity, at different temperatures. The temperature ranges from 1.13 to 3.60 °K.

In Fig. 6, the same data are, plotted as a function of logt. The straight lines represent a best fit of the experimental data by the least-squares method.

The slopes of these straight lines are shown in Fig. 7 as a function of the temperature. We note that these runs have been carried out during a time interval of about one month. During this period the source activity has decreased by $\sim$20% (calculated value), but presumably this has not strongly influenced the observed data.

A second series of runs has been carried out by varying the superconducting layer thickness at constant temperature (1.12 °K) and constant source activity (1.2 mC). In this case, we have used the same support ring on which the superconducting layer thickness was increased by successive electrodepositions. Probably oxidation occurred between two successive layers. In spite of this, in Fig. 8 we have plotted the values of $d\Phi/d\log t$ as a function of thickness. We note that $d\Phi/d\log t$ becomes smaller as the layer thickness increases, but it has a maximum value when the thickness corresponds to $\sim 30\mu$. The reasons for such an effect are not very clear. We only observe that for this thickness the counting rate of our calibration apparatus was essentially zero, that is, almost of all the α- particles were absorbed inside the layers.

B - Indium and Lead Rings

The experimental data for an indium ring, analogous to that previously reported for a tin ring, are shown in Figs. 9, 10 and 11. Fig. 12 shows a logarithmic plot of the flux curves for a lead ring. In this case, the behaviour of these curves is more irregular than those previously reported for the other metals. We can ascribe this to the fact that it is very difficult to obtain good electrodeposition of lead, which are microscopically uniform, and also this metal is very sensitive to unavoidable oxidation effects.

C - Some attempt has been made to look for the influence of varying the source intensity on the decay curves. Unfortunately, with our technique it was extremely difficult to obtain two rings of the same material and thickness with the same superconducting characteristics i. e., the same initial value of the frozen-in flux and the same decay rate. Therefore, we cannot give reliable experimental data about this point.

IV - DISCUSSION.

Although quite a bit of experimental data is now available, other information is necessary in order to completely understand this phenomenon.

First, there is no precise knowledge about the penetration and current distribution in our rings. We cannot exclude the presence of chemical impurities and physical defects, and also the existence of some inhomogeneities due to local fluctuations of current during the electrodeposition.

Moreover, the interaction mechanism between α particles and superconducting currents is unknown, but it is reasonable to assume, according to Sherman(4), that the α particles, range in the superconductor is the same as in the normal metal. Cabibbo and Doniach(5) tried to interpret our preliminary experiments in terms of thermal heating due to energy losses of the α particles. The presence of "normal" zones generated in this way, together with the magnetic pressure due to frozen-in flux, gives qualitative account of the flux decay. Although this idea can lead to interesting conclusions, our experimental data does not agree in two points. The first one is that there is flux decay even for ring thicknesses well above, (almost twice as large as) the α particles range in the material.

The second is that here is no evidence of an asymptotic approach to a finite limiting value of flux, at least for the time duration of our experiments.

At first sight the decay curves exhibit a behaviour similar to that reported by Kim et al.$^{(2)}$ for flux creep in hard superconductors, to which Anderson's theory$^{(6)}$ is applicable. The law $\phi \propto \log t$, in spite of the more irregular behaviour of flux decay in lead rings, seems to be a quite general experimental relation which holds for this class of phenomena.

But, aside from this, we believe the fundamental point necessary to explain our results is the dependence of $d\phi/d\log t$ on temperature. This would enable us to relate such a quantity to other characteristic parameters of the superconducting state, such as the penetration depth λ(T), the critical field H_c(T), the critical current density J_c(T), etc., all of which are strongly influenced by the temperature.

Many attempts have been made to find a phenomenological relation between some of these latter quantities and $d\phi/d\log t$, but no simple relation seems to hold. In the case of tin, $d\phi/d\log t$ seems to be proportional to $H_c(T)^{3/2}$ in the temperature range from 1, 13 °K to 3, 18 °K, using for H_c(T) the values reported by Shoemberg$^{(7)}$, but since this is not the case for an indium ring, its significance, for the interpretation of experimental data, is very limited.

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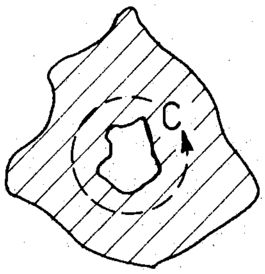

FIG. 1 - Multiply-connected superconductor for which equation (1) is valid.

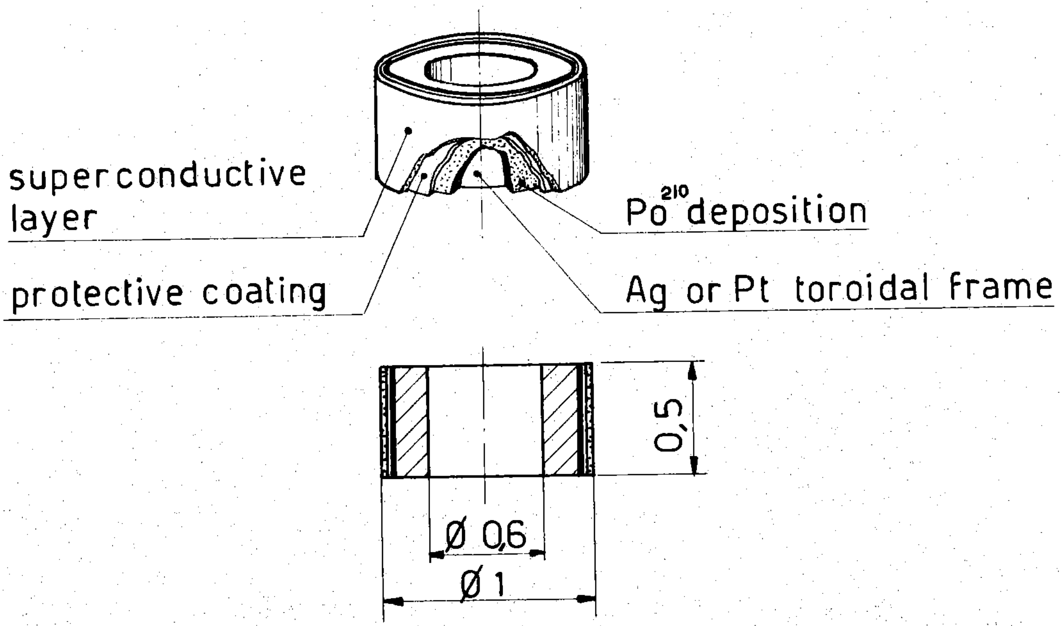

FIG. 2 - Detailed view of the cylindrical radioactive sources and superimposed superconducting rings. All dimensions are given in cm.

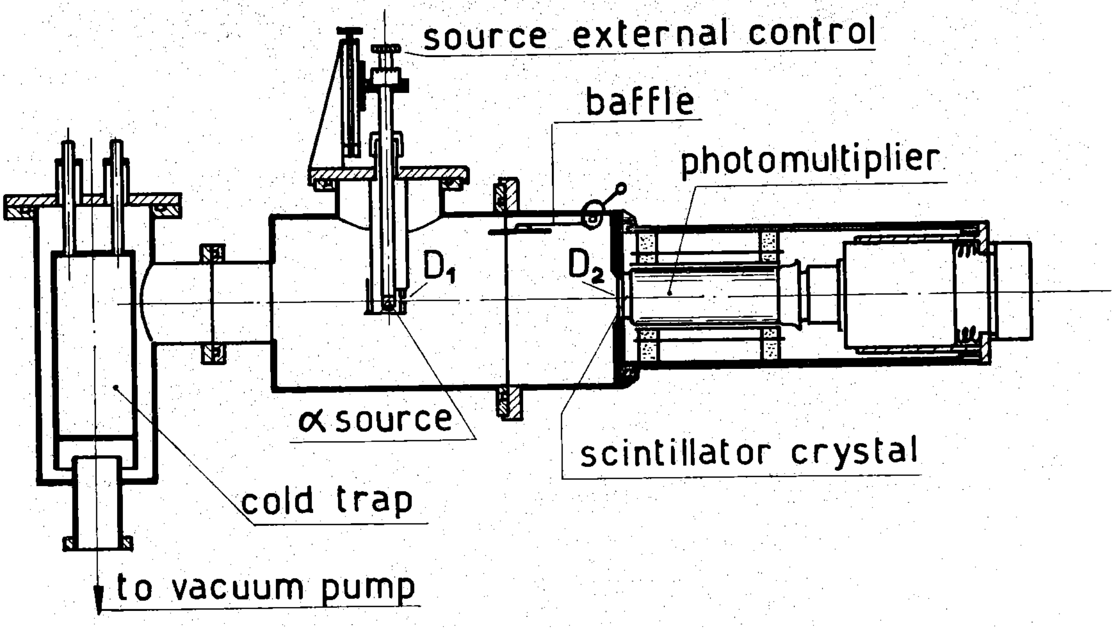

FIG. 3 - Schematic view of the source calibration apparatus showing the vacuum chamber, the crystal scintillator and the photomultiplier tube. The letters D_1 and D_2 indicate the diaphragms employed for the exact geometrical definition of counting conditions.

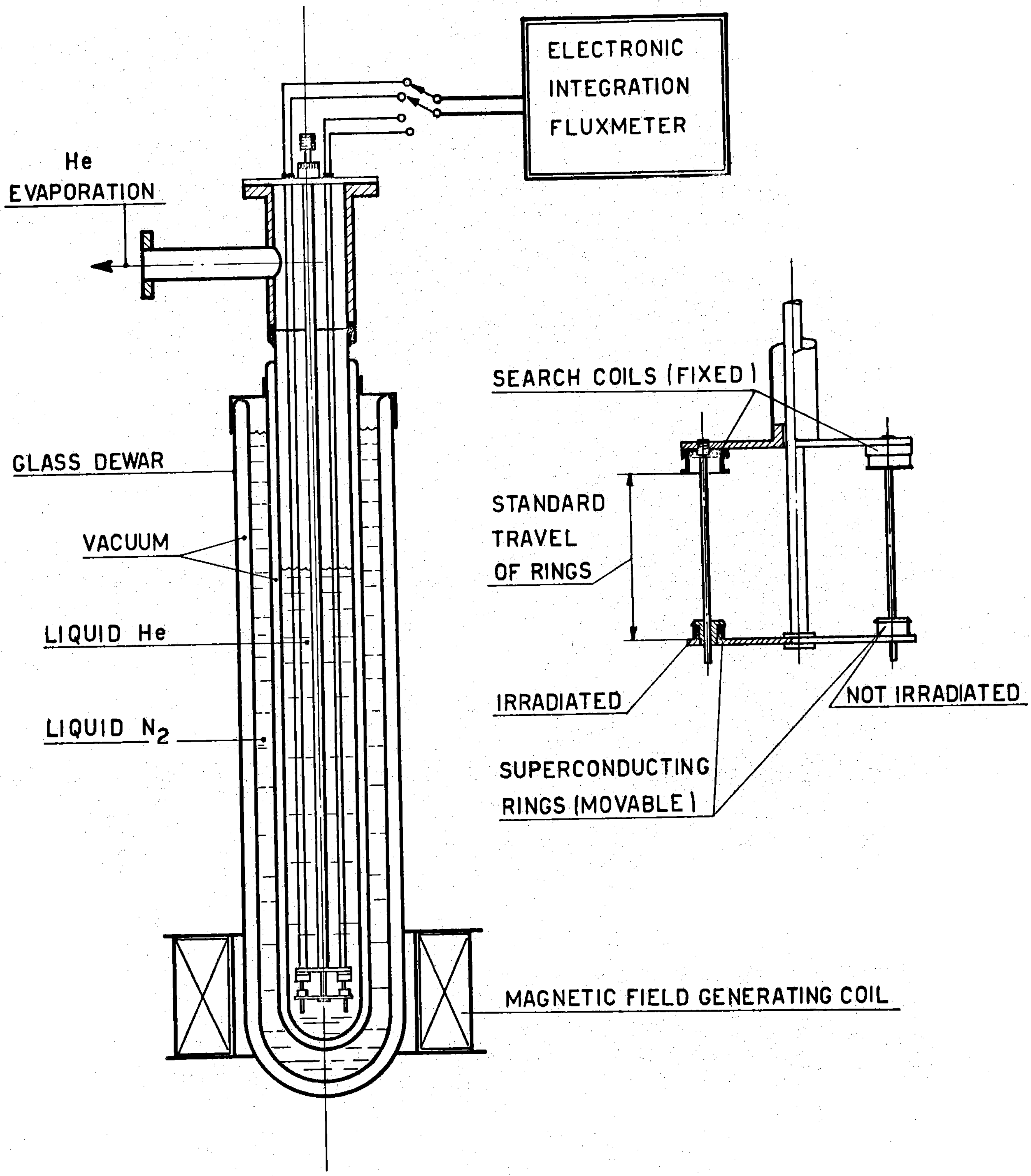

FIG. 4 - General view of the experimental apparatus. In the detail drawing, the two superconducting rings (one of which is not irradiated) and the search coils for flux measurements are shown.

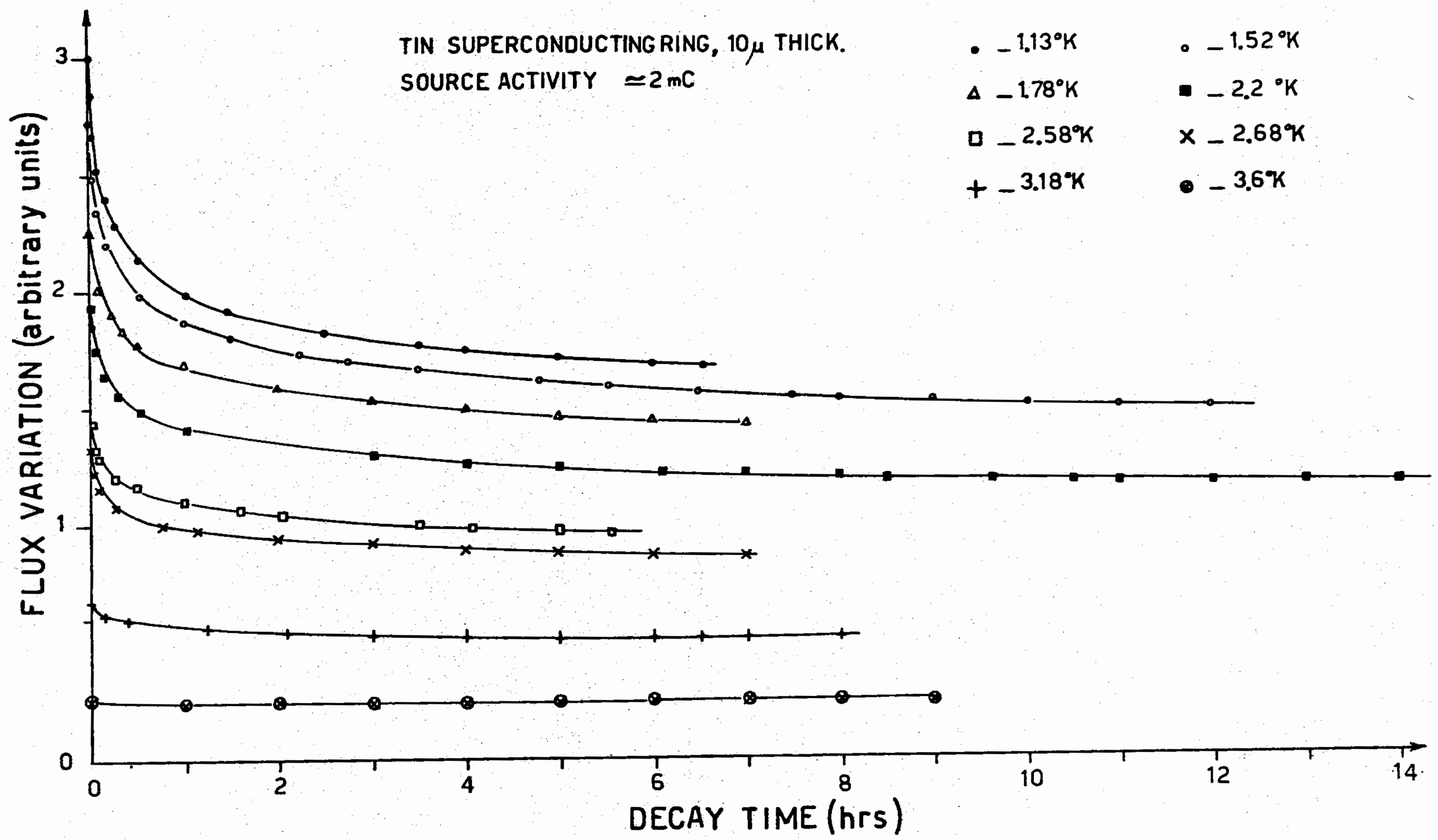

FIG. 5 - Flux decay curves for a tin superconducting ring at various temperatures.

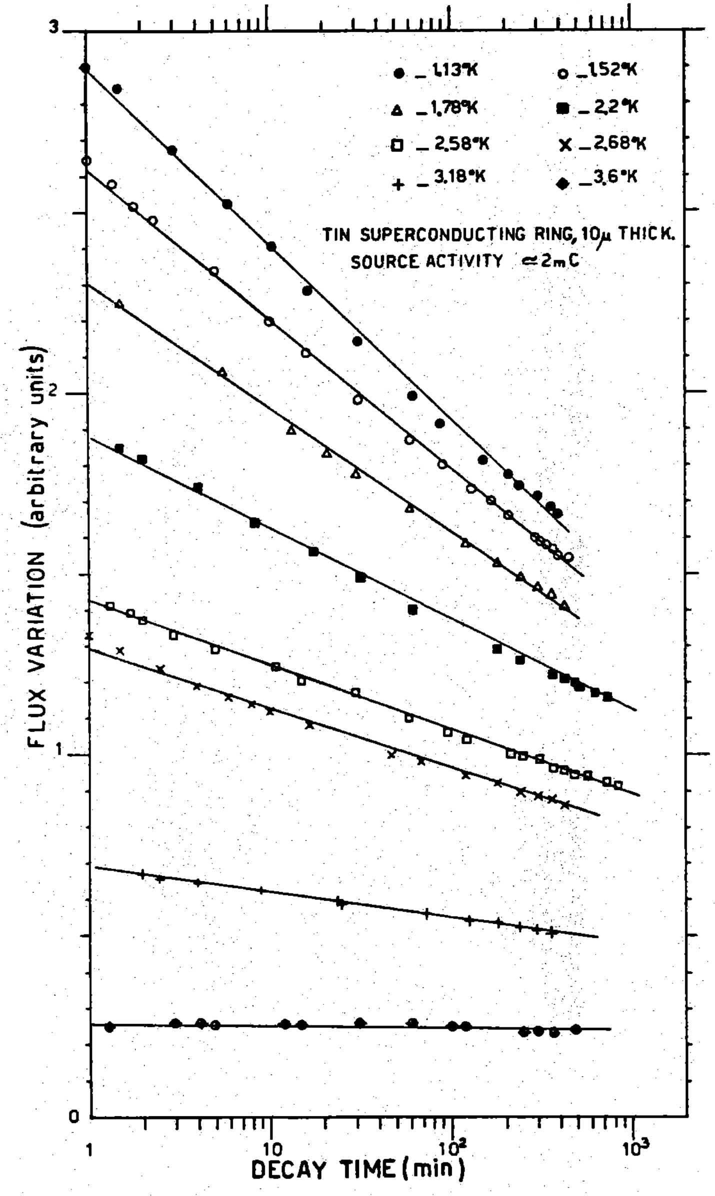

FIG. 6 - The same experimental data as in fig. 5 plotted on a logarithmic time scale. The straight lines are the least-squares best fits of the experimental points.

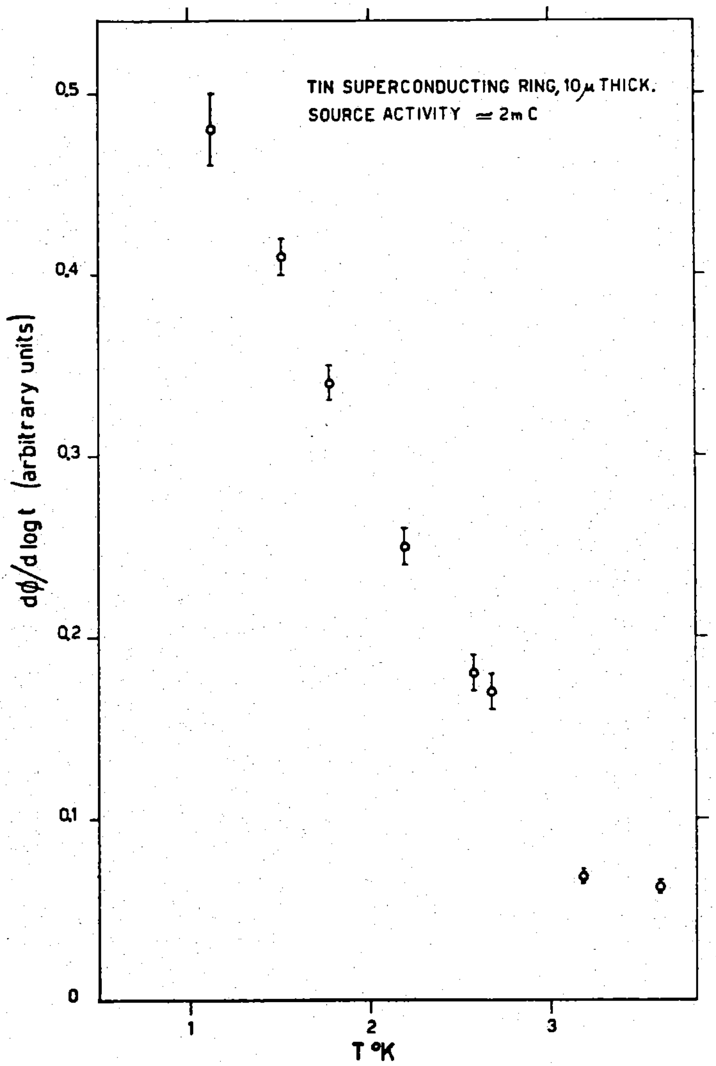

FIG. 7 - Slopes of the best fit lines of fig. 6 versus temperature.

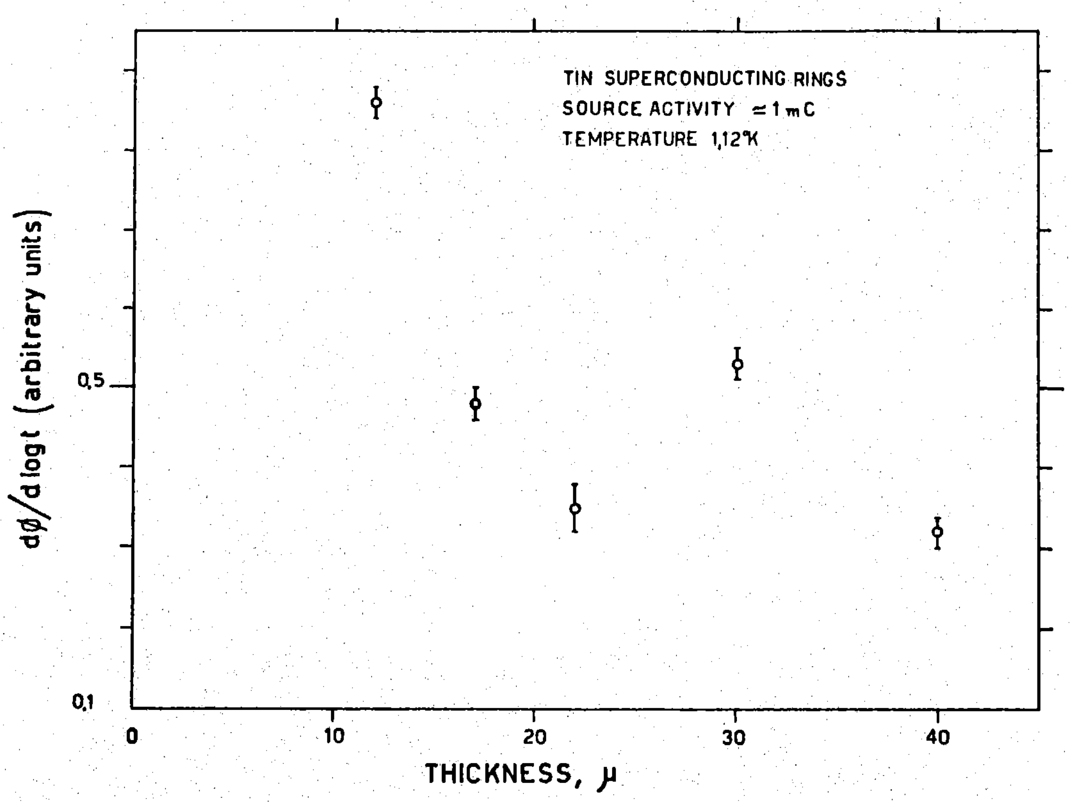

FIG. 8 - Values of dϕ/dlogt versus ring thickness, for a Sn ring under constant irradiation conditions and at fixed temperature.

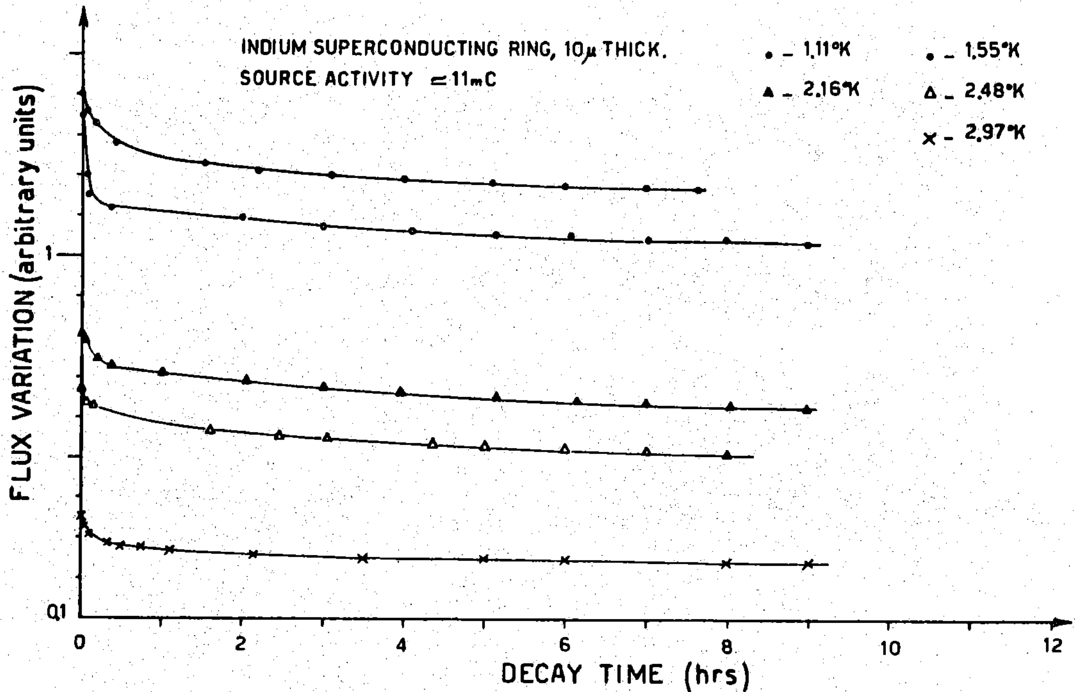

FIG. 9 - Flux decay for an indium superconducting ring at various temperatures.

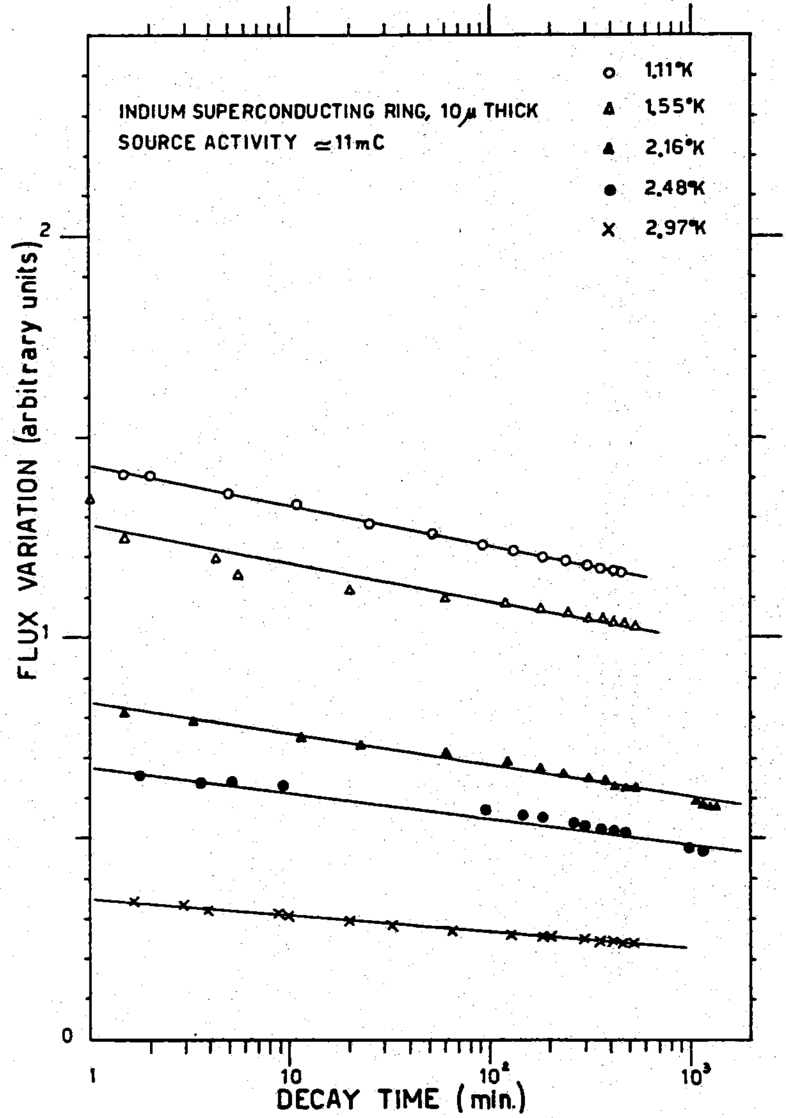

FIG. 10 - The same experimental data as in fig. 9 plotted on a logarithmic time scale. The straight lines are least-squares best fits of the experimental points.

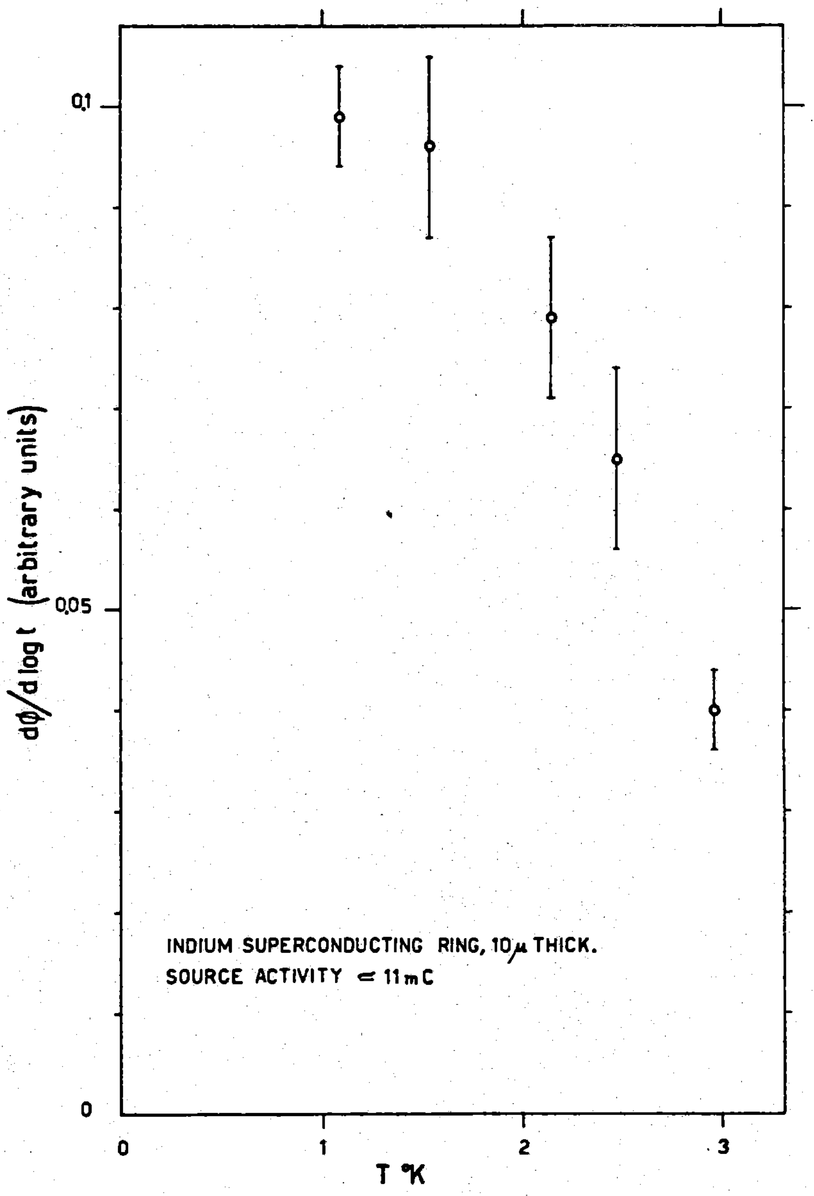

FIG. 11 - Slopes of the best fit lines of fig. 10 versus temperature.

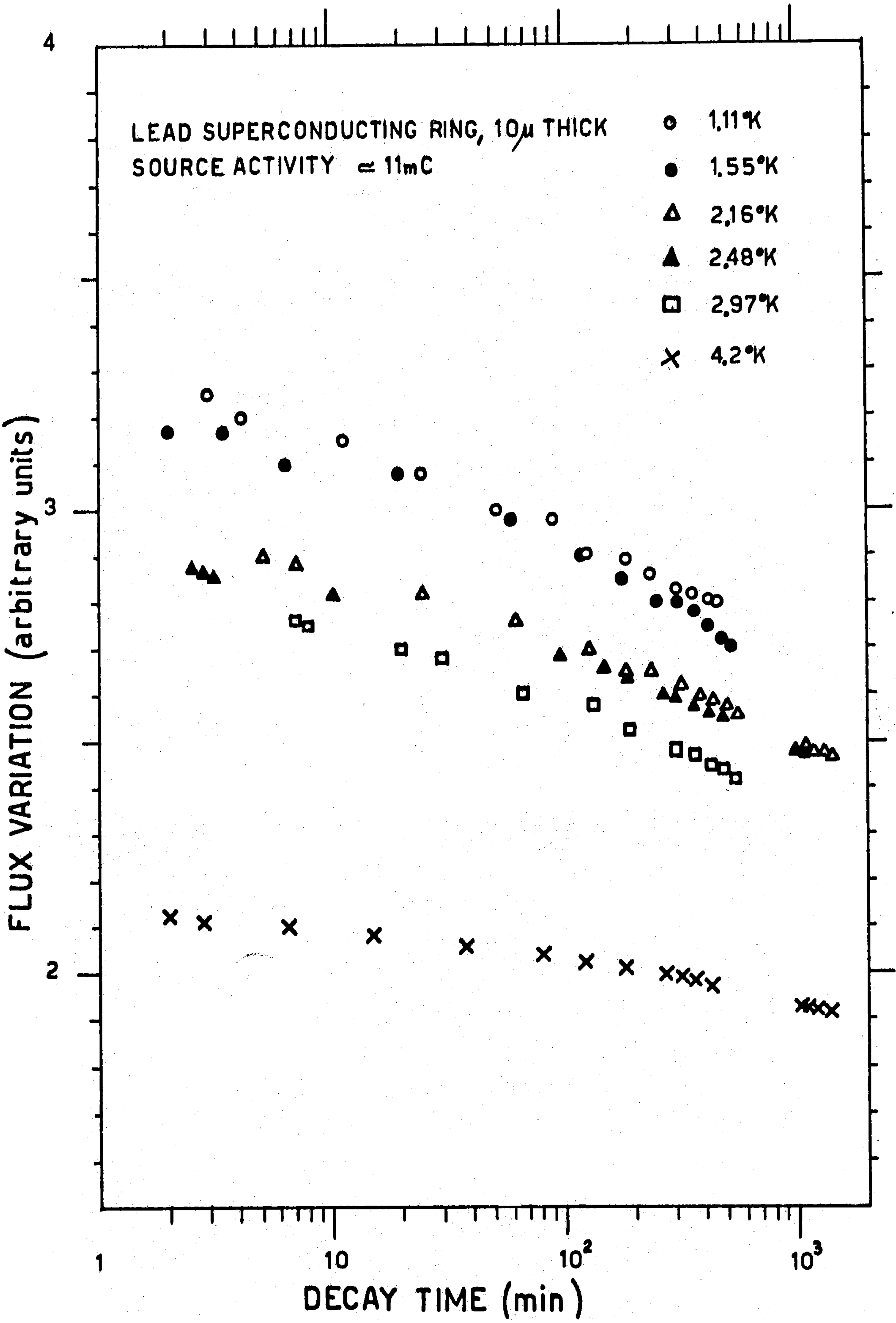

FIG. 12 - Flux decay in a lead superconducting ring plotted on a logarithmic time scale for various temperatures.