90 YEARS

# MAGNETIC PROPERTIES OF SUPERCONDUCTING METALS AND ALLOYS

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## 1. Methods of Measurements

Superconductors have sufficiently large magnetic moment, that is why all measurements can be executed, by using the ballistic method. The experiments were conducted with polycrystal and single crystal bars about 5 mm in diameter and 50 to 80 mm in length. In all experiments, the sample axis exactly coincided with the magnetic field direction. In order that the hysteresis effects inherent in a superconductor do not distort the observations, the magnetization curve was read only once, and then the sample was raised a little from liquid helium and warmed up to the above-critical temperature, at which the superconductivity phenomenon is completely absent. For the measurements, we used either a cryostat which was filled up with liquid helium from a liquefactor or a special instrumentation working according to Simon's [1] method (adiabatic expansion). We used two ballistic methods.

F i r s t  m e t h o d. We measured the quantity $\triangle B/\triangle H$ i.e. the induction change caused by a sudden change of the external field by small value. The field changed in small steps from 0 to $H_k$ and vice versa to fields higher than $-H_k$. After the summation of the values of $\triangle B$ obtained when the field changed by $\triangle H$, we got the continuous dependence of the induction $B$ on the external field $H$. In such a way, the total cycle of magnetization was obtained. In the middle of the tested bar, a coil having 150–700 turns of a thin varnished wire (0.05 mm in thickness) was wound. This coil was connected to an $H\&B$ ballistic galvanometer (oscillation period is 7 s) which was connected through a Moll thermorelay to a Moll galvanometer (oscillation period is 0.2 s) in order to amplify kicks. Such a connection guaranteed a greater measurement sensitivity. At each measurement, the galvanometer constant was measured with the help of a normal solenoid. At the computation of the results of measurements, it was necessary to take a small clearance for magnetic-field lines between the bar and the coil, which was due to the thickness of an isolation and a wire itself, into account. In our experiments, 98% of the coil surface was occupied by a lead bar. It is clear that this method yields reliable results only in the case where the duration of processes running in the sample under the field change is less than a quarter of the galvanometer oscillation period. At the beginning of the work, we believed that this condition occurs both in a superconductor, where excited currents do not decay, and in a normal conductor, where the decay occurs very quickly. However, the first measurements showed us that both the durations of the process of superconductivity breakup and, especially, the process of superconductivity onset in the decreasing fields are less as compared with the oscillation period of a galvanometer. Therefore, this method of measurement yields wrong results.

S e c o n d  m e t h o d. We measured the magnetic moment of a superconducting sample in the constant predetermined magnetic field. The measurement was conducted by the ballistic method. We measured the kick of a ballistic galvanometer which occurred on the fast withdrawal (or the introduction) of the bar far beyond the coil surrounding it (the elevation height was 70–80 mm). When moving, the sample was everywhere in the field with same intensity. The coil consisting of 800 turns of a thin varnished wire was connected directly to a ballistic galvanometer having its 14.4-s oscillation period. There was no necessity to use an amplifier in this method since, in contrast to the first method, the total change of the induction through the coil was measured, which caused quite great kicks of the galvanometer. The galvanometer constant was measured with the help of a normal solenoid. Measurements of the magnetic moment were conducted at different fields from 0 to fields higher than $H_k$. Therefore, the whole cycle of magnetization was completed. Then the dependence of the induction $B$ on the external field $H$ was calculated.

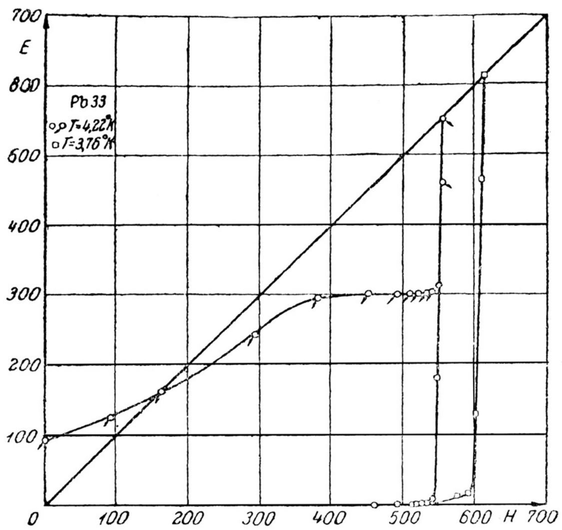


Fig. 1

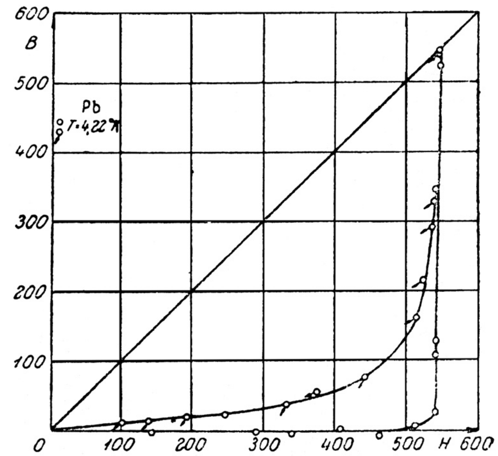


Fig. 2

In the calculations, it was necessary to consider the effect of both a quite wide clearance between the bar and the coil and the sample shape. This correction was determined experimentally. All the measurements described in this publication were conducted by using this method.

The magnetic field was created with a solenoid which had additional coils on its ends [2], which allowed us to obtain a homogeneous field on the length of 24 cm. The solenoid was cooled by liquid air that made it possible to achieve fields up to 4500 Gs at small dimensions of the solenoid.

## 2. Pure Metals

L e a d p o l y c r y s t a l. We made measurements of the same sample that we used before [3] (Pb I 33). Figure 1 presents the dependence of the induction $B$ on the field $H$ at 4.24 and 3.76 K. With increase in the field, the induction remains equal to zero (with an accuracy up to 0.2% in the wide range of the field strength). When the field subsequently increases, one can observe a small increase of the induction going further to an abrupt jump. A small increase of the induction before the abrupt jump was observed by us for each superconductor and was caused, very likely, by secondary reasons. As the onset and the end of superconductivity breakup, we take the fields $H_a$ and $H_e$, which we find from intersections of the vertical part of the curve with the $X$-axis and a straight line $\mu = 1$. Table 1 shows $H_a$ and $H_e$ at various temperatures.

**T a b l e 1**

| $T$°K | $H_a$ | $H_e$ |
|---|---|---|
| 4.22 | 547 | 557 |
| 3.76 | 602 | 614 |
| 3.28 | 656 | 664 |

In the fields higher than $H_e$, the permeability $\mu$ always exactly (up to 0.2%) equals unity. When the field decreases backward, one can observe an abrupt jump at the same critical field, but the induction does not decrease down to zero.[1] In the polycrystal, we found a strong hysteresis and a big residual magnetic moment at the field equal to zero.

L e a d s i n g l e c r y s t a l (Pb II 34). The sample was prepared from "Kahlbaum zur Analyse" lead. Its dimensions were: 81 mm in length and 4.85 mm in diameter. The single-crystal property was verified by etching the surface with acetic acid. Figure 2 illustrates the results of measurements at 4.2 K. It follows from the comparison of Fig. 1 and Fig. 2 that the process of superconductivity breakup is the same both in a polycrystal and a single crystal. The abrupt increase of the induction starts quite precisely at the same crystal field $H_k$ as in a polycrystal. It is worth to note that, in the figures and tables, we present the solenoid fields. Whereas, in reality, the true field at the surface of a superconductor is somewhat different due to its strong polarization. It equals

$$H = H' - N\frac{B-H}{4\pi},$$

[1]In all figures, except Fig. 16, the points measured in diminishing fields are marked with dashes.

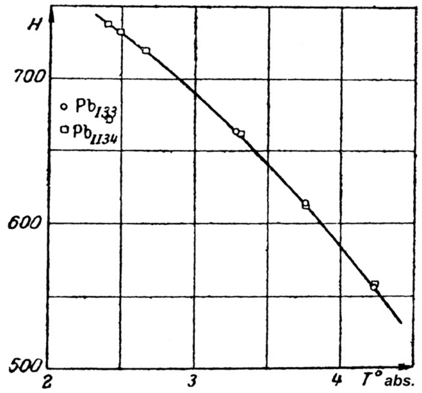


Fig. 3

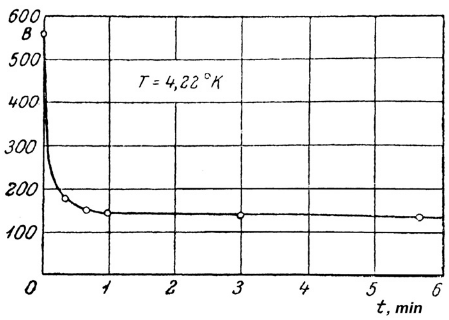


Fig. 4

where $H_1$ is the solenoid field, and $N$ is the demagnetization factor. The field at different places of the bar is not homogeneous. But, for the bars having a large length-to-diameter ratio, the inhomogeneity is not so high, and it is possible to quite precisely determine the magnetizing field when using the formula for an ovoid body. For our single crystal, the factor $N$ was about 0.12. Having calculated, we found that the true field at the onset of superconductivity breakup is by several Gs larger than the solenoid field, and, at the end of superconductivity breakup, the true field equals the solenoid field. Table 2 contains the results of measurements of the critical field at various temperatures, where $H_a$ means the solenoid field, at which the process had started, $H_{a\,\mathrm{corr}}$ is the true field at that moment, and $H_e$ is the field, at which the superconductor completely goes into the normal state.

As follows from Table 2, the superconductivity breakup occurs in a very narrow field range. The precision of our measurements allows us to state that the transition from the superconductive state to the normal one occurs in the field interval not exceeding 1–2 Gs. It is clear that this interval may be determined more precisely only by means of the measurement with samples of the shape which provides the uniform field everywhere. It is possible that, even under these ideal experimental conditions, the transition will take place not at a constant field, but in some interval of the field strength. Figure 3 shows the temperature dependence of $H_k$ for a single crystal and a polycrystal. In both cases, the fields $H_e$ are plotted, because they do not depend on the sample shape. Points for a single crystal and a polycrystal fall well onto the same curve.

The inverse process of superconductivity onset, when coming from high fields to fields lower than $H_k$, was found to differ in the single crystal and the polycrystal. It turned out that, at this transition, the induction in the crystal slowly follows the variation of the external field, and the process strongly depends on time. Figure 4 illustrates one of such measurements, where the $X$-axis is the time in minutes, and the $Y$-axis is the induction. The sample was firstly at $T = 4.22$ K in the field higher than $H_k$, and then the field was abruptly decreased to 511.3 Gs, i.e. it was considerably lower than the critical one. Starting from that moment, we observed the dependence of the induction on time. As one can see in the figure, the induction firstly decreases rapidly and then more slowly approaches the limiting value. After a half-hour delay, the decrease of the induction was almost not observed. By conducting measurements in decreasing fields, we could determine that the abrupt decrease of the induction started at the same field, at which the superconductivity breakup occurred previously (Fig. 2). The time dependence is different in different regions. For example, at the transition from the fields higher than the critical one to fields only slightly lower than the critical field, we observe the extremely slow decrease of the induction. Vice versa, at the complete switching-off of the field, the process runs extremely fast. In this case, we observe a residual magnetization which amounts to 0–2% of the maximal value of $B$ in the transition region in different experiments.

The dependence of $B$ on $H$ in decreasing fields, which is shown in Fig. 2, was obtained by connecting the points with the lowest observed induction values.

**Table 2**

| $T$, K | $H_a$ | $H_e$ | $H_{a\,\mathrm{corr}}$ |
|---|---|---|---|
| 4.22 | 551 | 558 | 558 |
| 3.76 | 606 | 613 | 613 |
| 3.31 | 654 | 660 | 662 |
| 2.66 | 711 | 720 | 720 |
| 2.49 | 724 | 733 | 733 |
| 2.41 | 730 | 788 | 738 |

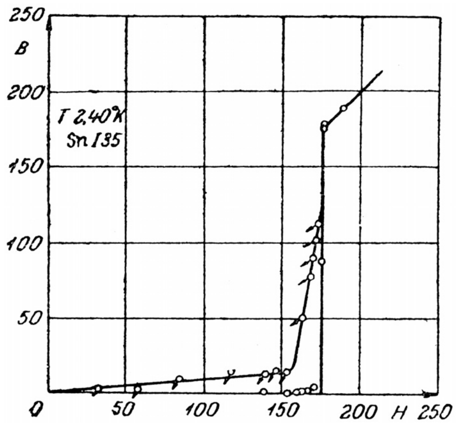


Fig. 5

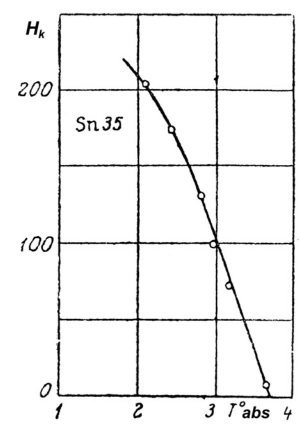


Fig. 6

We were interested in how continuous is the transition from a less stable state to a stabler one and also in the transition from the superconductive state to the normal one. It is known that, in ferromagnetic substances on the magnetization curve, one can observe a step-like change of the induction related to the quick magnetization flip in separate small areas of the crystal.

This effect was first discovered by Barkhausen with the help of a telephone and an amplifier. We used a similar instrumentation. On the lead bar, we wound about 2500 turns of a thin varnished wire, and the ends of the coil were connected through a low-frequency three-tube amplifier to a telephone. The sample was in an installation filled with liquid helium. By moving the solenoid, we can gradually increase the field from zero to fields higher than $H_k$ or decrease it. Preliminarily, the installation was tested with a bar having the same dimensions and made from nickel. When changing the magnetic field, rustle and separate clicks were well heard in the telephone. The experiments held using a single crystal and a polycrystal of lead at various temperatures (the temperature was lowered down to 2 K in order to increase $H_k$) and various rates of increase and decrease of the field did not caused any noticeable signs of the telephone membrane movement. It is not ruled out that the regions in a superconductor, in which a sudden change of the induction occurs, are small, and the effect cannot be observed with such an instrumentation.

T i n s i n g l e c r y s t a l. (Sn I 35) The sample was prepared from "Kahlbaum zur Analyse" tin. Its dimensions were: 72 mm in length and the 5.79-mm average diameter (the sample cross-section was slightly elliptical). The single-crystal property was verified by etching the crystal surface with hydrochloric acid. Figure 5 presents the results of measurements at 2.40 K.

Measurements showed that the field dependence of the magnetic induction in tin crystals is the same as that in lead crystals. We obtained similar curves at the other temperatures. Figure 6 shows the dependence of $H_k$ on the temperature. The curve well coincides with the Leyden curve for the critical field "threshold value field," at which the electrical resistance[2] appears in the superconductor.

It is interesting to point out that the field dependence of the induction remains similar at all temperatures, even at the temperatures very close to the critical one, $T_k$. At temperatures slightly higher than $T_k$, the permeability is equal to unity, and no magnetic anomalies were found within the limits of sensitivity of the ballistic method.

M e r c u r y p o l y c r y s t a l. Glass cylindrical pipes were filled up with mercury and were slowly uniformly cooled. Slow cooling should induce the appearance of a coarse-crystalline structure of samples. The samples were not free from internal stresses; in several cases, the cooling of mercury caused the rupture of thin-walled glass. Measurements were conducted with mercury of two sorts: Hg I was made of usual laboratory mercury subjected to the purification and the sixfold distillation in vacuum. The bar diameter was 6.0 mm, and its length

[2] Keeley, Mendelsohn, and Moore [4] found that the field interval for superconductivity breakup in tin constituted 10–20% of "threshold value field" and was always higher than this field. This discrepancy should be ascribed to an imperfection of the experiment performed by those authors or to a high contamination of the metal.

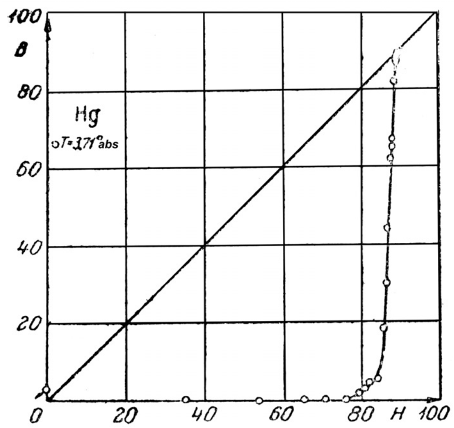


Fig. 7

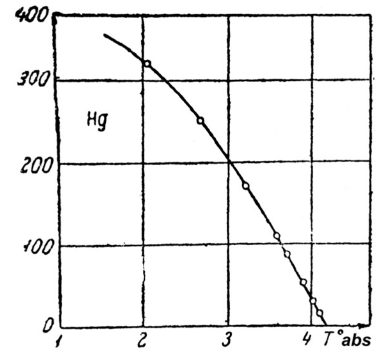


Fig. 8

was 65 mm. Hg II mercury was prepared from the same mercury but it was three times distillated.

The results of measurements with Hg I at a temperature of 3.71 K are shown in Fig. 7. Measurements at the other temperatures give a similar field dependence of the induction. Figure 8 shows the dependence of the critical field on the temperature. Our curve coincides well with the Leyden curve of "threshold value field". In increasing fields, the measurements of Hg II give the same dependence as those of Hg I; in decreasing fields, a large hysteresis was observed, which should be evidently attributed to a lower purity of Hg II. For both samples of mercury, we observed the difference between $H_e$ and $H_a$ which is considerably greater than a change of the field at the surface of the superconductor. We cannot claim at present if it is caused by the polycrystallinity and a stress inside the metal or it is a property of mercury. For both mercury and tin, no magnetic anomalies were found at temperatures slightly higher than $T_k$.

It is of interest to note that Hg I gives a very small hysteresis loop as compared with the other superconductors, which should be evidently attributed, first of all, to a high purity of mercury.

## 3. Superconductive Alloys

The measurement of magnetic properties of superconducting alloys is of great interest because, in contract to pure metals, their superconductivity breaks up only in very strong magnetic fields. If the dependence of the induction on the field in alloys were the same as that in pure metals, i.e. it remained zero up to some critical field $H_k$, one should expect a huge magnetocaloric effect which would provide the heat capacity jump at $T_k$ exceeding the normal heat capacity by dozens of times. The measurements of heat capacity [5] conducted by us with the alloy consisting of 65% of lead and 35% of bismuth show that such anomalies of heat capacity in superconducting alloys are absent. Somewhat earlier, the indication of the absence of evident anomalies of heat capacity in $PbTl_2$ was published in [4], and the results of recent measurements [6] corroborate this conclusion. Since the heat capacity jump in alloys is small, this implies that the magnetic field does penetrate into alloys. De Haas and Casimir-Jonker [7] found for the first time that, for $PbTl_2$ and $Bi_5Tl_8$, there exists the critical magnetic field which penetrates into the alloy but does not break up the superconductivity; that is why it is considerably lower than the critical magnetic field, at which the alloy acquires the ohmic resistance.

Simultaneously, we also performed a complete study of the field dependence of the induction for $PbTl_2$ and PbBi alloys published somewhat later [8]. We found that the permeability remains zero up to a certain critical field $H_k$. Then, as the field increases, the permeability gradually increases and reaches unity in the field $H_{k_2}$. These results were partially confirmed in the subsequent work [9].

It was of interest to extend these measurements, to continue them with other alloys, and to investigate the dependence on the alloy composition. We performed the researches of lead–thallium, lead–bismuth, lead–indium, and mercury–cadmium alloys. In lead–thallium alloy, we conducted a systematic investigation of the dependence of magnetic properties on the alloy composition. For measurements, we used the same instrumentation which we used for the study of magnetic properties of pure metals.

L e a d – t h a l l i u m. At present time, there exists a quite extensive metallographic and X-ray examination of this alloy. However, we have still no reliable data on the state diagram, mainly because the X-ray analysis

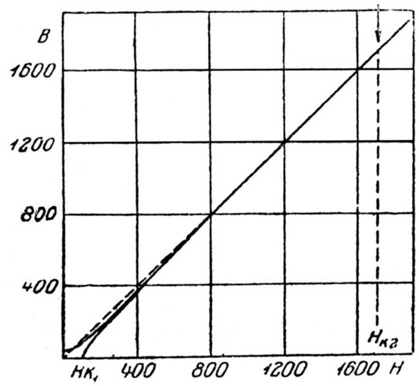


Fig. 9

cannot provide the exact information since both lead and thallium scatter X-rays identically. A melting diagram obtained in [10] contradicts the measurements of a lattice constant for different compositions done in [11]. One can undoubtedly affirm that one deals with an ordered solid solution in alloys having more than 55% of thallium. At the present time, it is difficult to say whether the ordered phase is formed from a melt (consequently, the melting diagram is incorrect), as suggests in [12] or the transition to the ordered phase takes place at lower temperatures. In any case, we can surely say that, we deal with a solid solution up to 50% of Tl. We performed a systematic investigation of magnetic properties of these solid solutions. In addition, we studied $PbTl_2$ alloy, because its superconducting properties are most well studied at present.

The measurements were conducted using single-crystal samples. During the alloy fabrication and in the process of crystallization, the metal was always in a hydrogen atmosphere. The samples prepared underwent the 100-h annealing at a temperature by 20–40°C below the melting one. The single-crystal property was verified by the light reflection from small planes which were formed on the surface of the bar and, for the samples having 15 to 30% Tl, also with the use of X-rays.

Figure 9 shows the dependence between the induction $B$ and the magnetic field $H$ for $PbTl_2$ alloy at a temperature of 2.11 K. The measurements indicate the following main characteristics of the superconducting alloy.

1. Induction $B$ remains almost zero up to a certain critical field $H_{k_1}$ which depends on the temperature. In this field interval, the alloy and the pure metal behave identically.

2. In the interval of fields from $H_{k_1}$ to $H_{k_2}$ the induction increases together with the field, by gradually

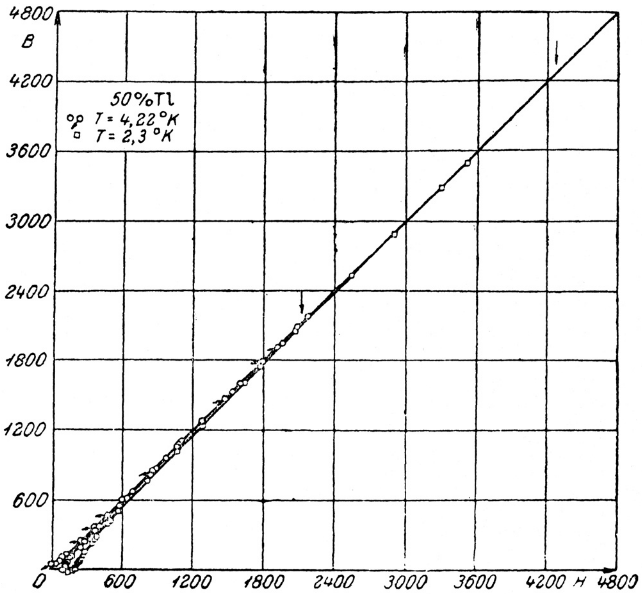


Fig. 10

approaching the value characteristic of the non-superconductive metal. Electrical measurements conducted using a wire made of the same melt showed that the potential difference remains equal to zero up to the fields close to $H_{k_2}$. Somewhat below this magnitude of the field, we observe a measurable potential difference which increases together with the field and, at the field $H_{k_2}$, takes the normal value characteristic of non-superconductors. It was also observed that the induction in this interval depends on time very weakly and approaches a quite definite limit. This means that the currents excited on the metal surface do not decay in the course of time.

3. When the magnetic field decreases, a weak hysteresis is observed in the field interval from $H_{k_2}$ to $H_{k_1}$ which substantially increases when the field $H_{k_2}$ is approached. In the zero field, a residual time-independent magnetization is observed.

A critical temperature $T_k$, at which the superconductivity begins, was determined by the measurements of electrical conductivity and magnetic properties; both methods gave the same result, $T_k$=3.75 K. At all temperatures below $T_k$, the $B$-to-$H$ ratio remains the same. At temperatures above $T_k$, the magnetic permeability is equal to unity, which means that no free lead grains are present in the alloy.

Figures 10–15 show the field dependence of the induction for alloys having 50, 30, 15, 5, 2.5, and 0.8 wt.% of thallium, respectively. The basic peculiarities

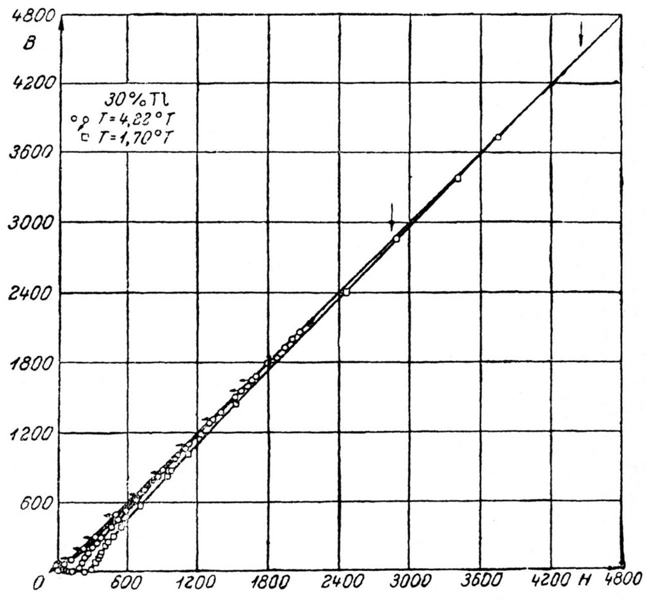


Fig. 11

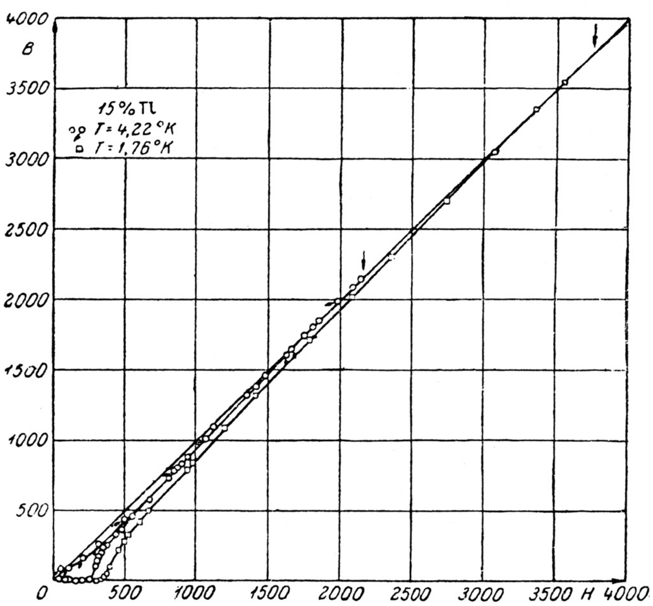


Fig. 12

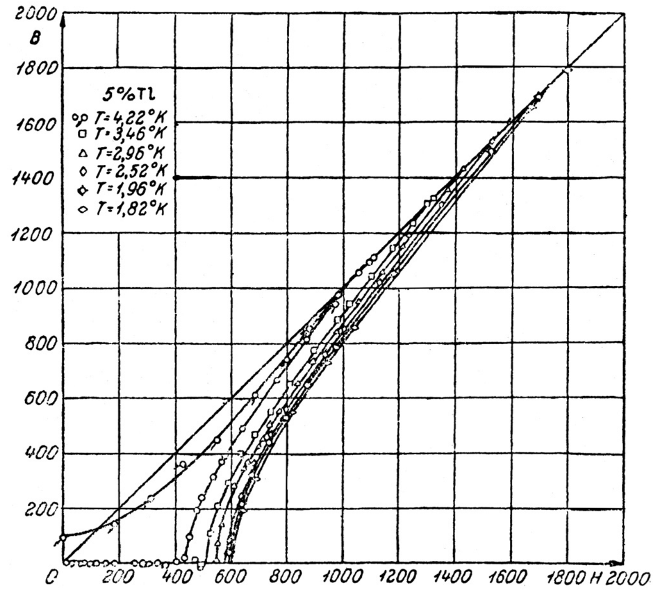


Fig. 13

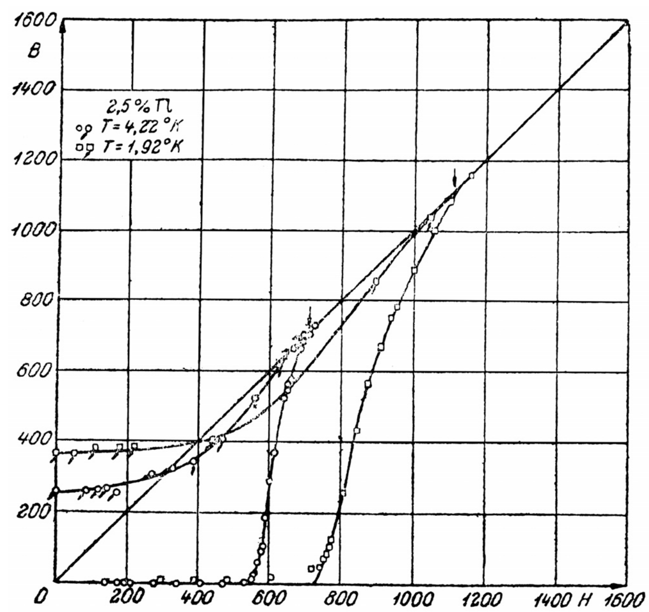


Fig. 14

that we observed for $PbTl_2$ alloy are also characteristic of alloys with the other compositions. It is worth to note that already comparatively small admixtures of thallium in the amount of 2.5 and 5% produce the field dependence of the induction characteristic of the alloy. Thus, in a crystal having 2.5% of thallium at a temperature of 1.92 K, the breakup of the superconductivity occurs in the field interval of 734–1110 Gs. At the same time, $H_k$ only slightly differs from the values for pure lead becoming slightly smaller than these values when the temperature decreases. It is obvious that the influence of admixtures has effect only by starting from some limit value, since the alloy having 0.8% of Tl behaves in the magnetic field as pure lead. Since such

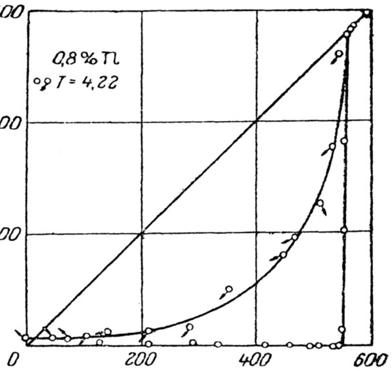


Fig. 15

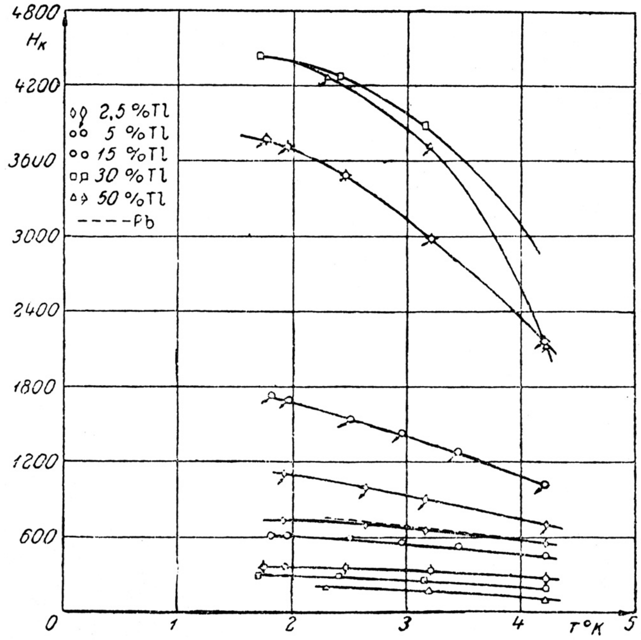


Fig. 16

small admixtures could be displaced from the metal body to the surface during the crystallization, we examined the alloy composition by means of chemical analysis in three places: at the end of the bar where the growth of a crystal started, in the middle, and at another end of the bar where the crystallization finished. The analysis gave, respectively, 0.84, 0.78, and 0.80% of thallium, i.e. a quite uniform distribution of thallium in the sample. In Fig. 16, the temperature dependence of the critical fields $H_{k_1}$ and $H_{k_2}$ is shown for all PbTl alloys. For comparison, there is shown the observed dependence of pure lead.

L e a d – b i s m u t h. The X-ray examination of the structure of alloys of different compositions was done by Solomon and Morris-Jones [13]. They have found that, in alloys with up to 20% of bismuth, there exists a solid solution having a face-centered cubic lattice. If the alloy contains 25 to 33% Bi, there exists a new phase with hexagonal close packing, and, for more than 33% Bi, the alloy consists of crystals of two kinds: with hexagonal closely packed and rhombohedral face-centered lattices. The X-ray examination contradicts the known presently melting diagrams. Since this system is not quite well studied nowadays, we limited our investigation of magnetic properties only to the alloy having 35% Bi, which was previously used by us for the measurement of heat capacity at helium temperatures and which is remarkable by the fact that its electrical resistance appears only in very large fields. For example, on the basis of data obtained at the Leiden laboratory, the superconductivity is broken up at 1.88 K only by the field of 27,000 Gs. The measurements of the field dependence of the induction up to 2,000 Gs showed that this alloy behaves absolutely similar to PbTl alloy. We do not present the results of measurements because we failed to get fields sufficient for the complete breakup of the superconductivity with the available solenoid.

L e a d – i n d i u m. According to the melting diagram determined by Kurnakow and Puschin [10], PbIn forms a continuous series of solid solutions; the reliability of this diagram is quite doubtful. We performed measurements with two alloys having 2 and 8 wt.% of indium.

Measurements were performed using single-crystal samples made of "Kahlbaum zur Analyse" lead and indium, whose purity is unknown. The single-crystal property was verified by the light reflection from small crystalline planes (bubbles) on the bar surface. The prepared samples were subjected to 100-h annealing at 250–270°C.

These alloys (Figs. 17, 18) demonstrate the field dependence of the induction, which is quite similar to that observed in PbTl. The measurements of samples with 2% of indium indicate the extremely great role of admixtures whose amount is relatively small. For example, $H_k$ = 735 Gs at 1.95 K in this alloy, which differs insignificantly from the value for pure lead, whereas $H_{k_2}$ approaches the value of 1540 Gs.

M e r c u r y – c a d m i u m. The melting diagram is determined by Bijl [14] and Mehl and Barrett [15]. Unfortunately, we cannot get the results of the last authors. Bijl indicated that a solid solution is formed with up to 51% of cadmium. We examined the alloys with 5 and 10% of cadmium. Liquid amalgam was poured in thin-walled glass pipes, whose size was approximately equal to the ordinary bar size.

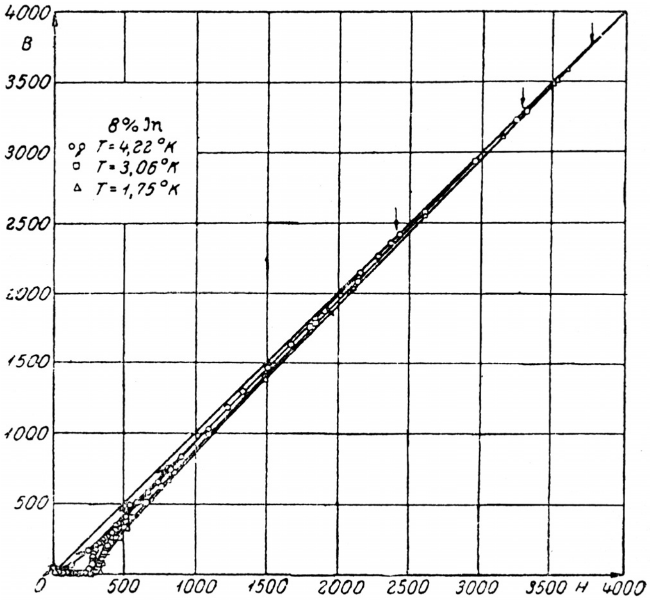


Fig. 17

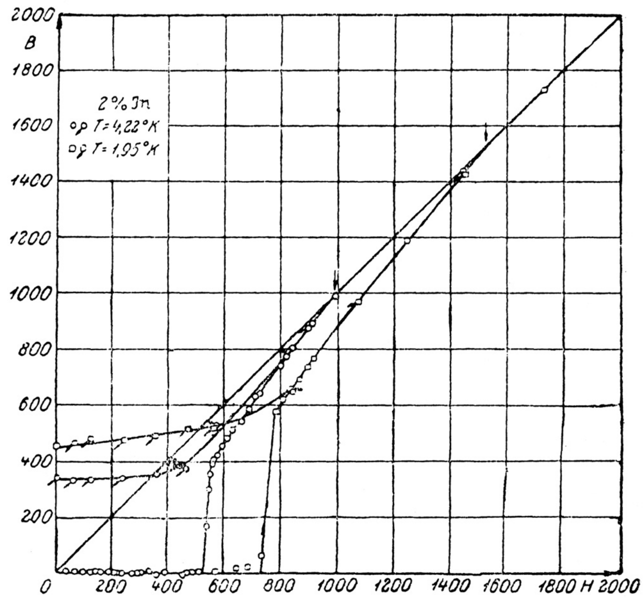


Fig. 18

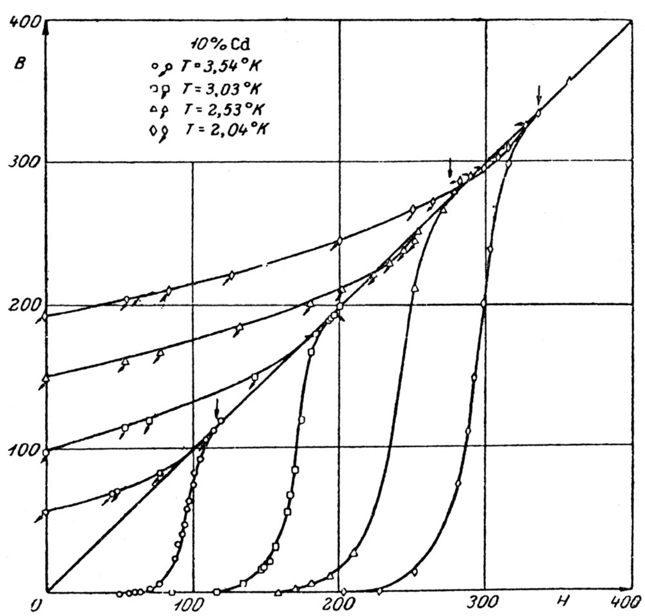


Fig. 19

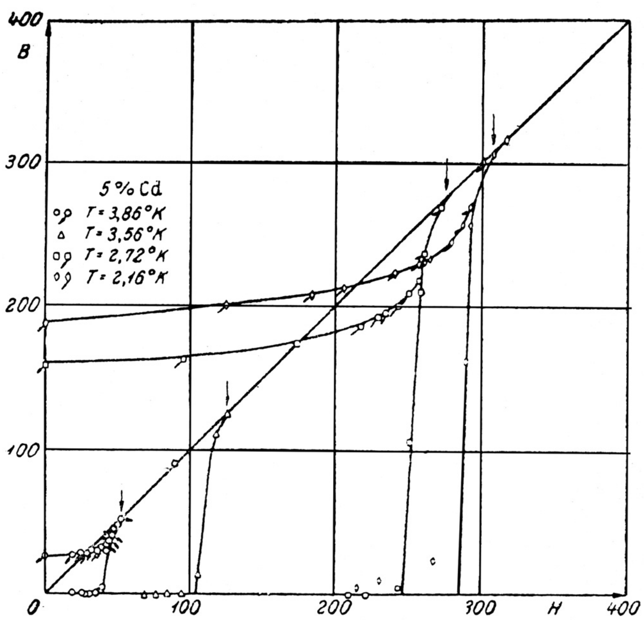


Fig. 20

The samples were fast cooled down to the liquid helium temperature, and that is why the measurements were conducted using polycrystalline non-annealed samples. The increase of the admixture concentration in this alloy (Figs. 19 and 20), as well as in the other alloys, leads to an increase of the field interval $H_{k_1} - H_{k_2}$; however, in contrast to the earlier alloys, the role of the admixture is insignificant. For example, the alloy having 5% of Cd behaves itself almost in the same way as pure mercury. Adding the admixture only strongly increases the hysteresis; and $H_{k_2}$ is only by 10–20% more than $H_{k_1}$.

The studies of various alloys, the majority of which form solid solutions, show that a quite identical dependence of the induction on the field is observed in all cases. Below some threshold field $H_{k_1}$, the permeability remains close to zero. Then it increases with the field and gradually approaches the value equal to unity. The field interval $H_{k_1} - H_{k_2}$ increases when the amount of the admixture in the superconductive metal increases. Such unusual magnetic properties of superconductors cannot be explained by the effect of hysteresis, because it is just in high increasing and decreasing fields that the observed behavior is quite well reversible, and the hysteresis is rather small.

Rutgers [16] gave the relation between the derivative of the critical field with respect to the temperature and the heat capacity jump at $T_k$, which is well satisfied for a number of superconductive metals. Gorter [17] gave the derivation of this formula, by assuming the existence of two phases: the superconducting phase with permeability $\mu = 0$ and the normal one with $\mu = 2$. We would like to point out that the derivation of this formula is not related to the assumption about the existence of two phases, because the magnetocaloric effect in superconductors, as well as in ferromagnets where there is no ground to take the existence of two phases to be real, is determined only by the form of the magnetization curve and the temperature dependence of the magnetization. The difference of the free energies of magnetized and normal superconductors is given by the area under the curve

$$\triangle F = \int \frac{H\,dB}{4\pi},$$

and the difference of the entropies is determined by the derivative

$$\triangle S = -\left(\frac{\partial F}{\partial T}\right)_B .$$

For pure metals, the magnetic moment $\sigma$ changes by a rather abrupt jump from $\sigma_k$ to zero, owing to what the thermodynamic values can be related to critical magnetic values. For alloys, the corresponding areas can be calculated graphically. In this case, similarly to pure metals, we take the curve in increasing fields as the equilibrium curve. The calculation of the entropy difference for alloys shows that, in this case and in the case of pure metals, we obtain the value of the same order, which similarly depends on the temperature.

The heat capacity jump for $PbTl_2$ alloy at $T_k$ (3.75 K) calculated in the same manner equals approximately $3.5 \times 10^{-3}$ that makes up about 7% of the heat capacity at this temperature. It is evident that the calculation is not very accurate, because the determination of the second-order derivative of the magnetization area with respect to the temperature can introduce a considerable error. Unfortunately, the measurements of the $PbTl_2$ heat capacity [9], are not enough accurate to be compared with the calculated quantities.

In our first paper on the study of superconducting alloys, we pointed out the possibility to explain the unusual magnetic properties of superconducting alloys by the disintegration of solid solutions at low temperatures. In this paper, we have not yet managed to obtain any indications of the disintegration of solid solutions. For example, regardless of the cooling rate and the holding duration of a sample at a low temperature, it was found that the effect is well reproducible. The X-ray studies performed at room temperatures on samples cooled down to the liquid-helium temperature gave no signs of the decay of a solid solution. X-ray investigations at low temperatures were not done as yet.

We obtained the interesting results for the breakup of superconductivity in alloys by a current. Keesom [18] found that superconductivng alloys are not suitable to obtain high magnetic fields using a solenoid, because a slight current destroys the superconductivity. Simultaneously, we also published the detailed investigations of the superconductivity breakup in $PbTl_2$ alloy by a current [8].

The measurements were made, by using wires with diameters of 0.71, 0.33, and 0.26 mm. After the preparation, the wires ought to be well annealed and slowly cooled, because the thermal hysteresis disappears only after the thorough annealing. The measurements on various wires showed that, at a constant temperature, the critical current which breaks up the superconductivity is proportional to the wire diameter. Hence, the superconductivity breakup occurs when the magnetic field or, what is the same, the surface current density reaches its critical value on the surface. The critical values of the field of a current $H_{kj} = 2j/R$ for various temperatures are shown in Fig. 21. The points calculated in this manner lie well on the same curve. For comparison, the critical values $H_{k_1}$ and $H_{k_2}$ are shown in the same figure as functions of the temperature.

We see that $H_{kj}$ is always somewhat lower than $H_k$ and amounts to about 65% of the latter. This result was completely confirmed in [19]. It was interesting to compare all three critical values. For example, $H_{kj}$ is about 68 Gs at 2.11 K; $H_{k_1}$, at which the field starts to

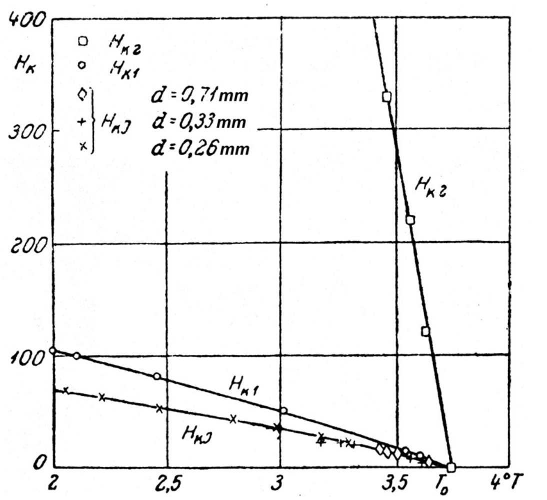


Fig. 21

penetrate into the sample, is equal to 100 Gs; and the magnitude of longitudinal magnetic field $H_{k_2}$, at which the permeability becomes equal to 1 and the normal electrical conductivity completely recovers, is equal to 1700 Gs. For pure superconductive metals, the measurements performed at the Leiden laboratory gave approximately equal magnitudes of the critical values of the field of a current and the external longitudinal field, at which a sample acquires the normal ohmic resistance. For alloys, the critical value of circular magnetic field is lower by a factor of tens than the critical value of the longitudinal field.


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**SHUBNIKOV LEV VASIL'EVICH**
**(29.09.1901–10.11.1937)**

Lev Vasil'evich Shubnikov was the outstanding physicist-experimentalist, the co-author of some Nobel-prize-level publications, had worked at Leiden University during 1926–1930; from 1930 till 1937, he worked at the Ukrainian Physical-Technical Institute (UPhTI), Kharkov (now NSC "Kharkov Institute of Physics and Technology" of the NAS of Ukraine). L.V. Shubnikov was Professor of the Kharkov State University (1934–1937). L.V. Shubnikov was a founder and the first head of the cryogenic laboratory at UPhTI.

In 1930, L.V. Shubnikov and W. De Haas have discovered the effect of electric resistance oscillations of bismuth at low temperatures (the Shubnikov–de Haas effect). During his work at UFTI, L.V. Shubnikov together with his colleagues had performed a number of high-priority works on superconductivity (1934–1938) and antiferromagnetism (1936–1938) that gained a worldwide recognition. Together with I.V. Obreimov, he had developed a new method for growing single crystals of metals (the Obreimov–Shubnikov method) [1, 2]. For the first time in the USSR, he had performed the researches of liquid helium, hydrogen, and other liquefied gases (1931–1934). In 1937, Shubnikov was subjected to repressions without any reasons, and therefore his name was absent in papers [6, 7] under the conditions of that time. He was a founder of the scientific school of low-temperature physics.


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