THE POLARIZATION OF NUCLEI OF DIAMAGNETIC ELEMENTS DISSOLVED IN IRON

B. N. SAMOĬLOV, V. V. SKLYAREVSKIĬ, and E. P. STEPANOV

Submitted to JETP editor August 6, 1959

J. Exptl. Theoret. Phys. (U.S.S.R.) **38**, 359-371 (February, 1960)

The possibility of polarizing the nuclei of paramagnetic elements — indium, antimony, and gold — in weak solutions of these elements in iron is established. Samples of ferromagnetic alloys In-Fe, Sb-Fe, and Au-Fe were cooled to a temperature of ~ 0.03°K and magnetized to saturation by a not too large (~ 2000 oe) magnetic field. The gamma-ray anisotropy of In^{114m}, Sb^{122}, and Au^{198} nuclei contained in the samples was measured. Measurements showed that a strong inner magnetic field acts on the nuclei of the elements dissolved in iron; the value of this field has the following limits: for In-H $\geq 2.5 \times 10^5$, for Sb-H $\geq 2.8 \times 10^5$, for Au-H $\geq 1.0 \times 10^6$ oe. The assumption is expressed that this field is created by the conduction electrons, which have a substantial degree of polarization in a ferromagnet. At temperatures of 0.03°K the value of the polarization of the investigated nuclei is not less than 30 — 50%.

1. INTRODUCTION

In recent years a considerable number of experiments with oriented nuclei was performed. In the majority of cases a study was made of the angular distribution of the gamma rays. In these experiments, except for checking the polarization methods themselves, information was also obtained that made the decay schemes of radioactive nuclei more precise. After the widely known experiment by Wu, Ambler et al., a certain number of experiments was performed on the angular distribution of electrons and positrons released during beta decay. Some experiments were also performed to study the interaction of polarized neutrons with polarized nuclei, by observing the anisotropy of the angular distribution of alpha particles during alpha decay and of fragments in neutron-induced fission of nuclei.

In the overwhelming majority of cases two statistical and equilibrium methods, proposed in references 1 and 2, were used for orientation. Both methods are applicable to the limited number of elements that form paramagnetic compounds which retain their paramagnetic properties down to very low temperatures. This requirement is very stringent and explains why all the experiments were performed solely with the isotopes of several elements of the iron group, the rare earths, and actinides. A limitation is also inherent in two other statistical methods — the method of reference 3 and the direct method. The first of these is applicable to a narrow class of compounds whose nuclei have large quadrupole moments; the second requires the use of static magnetic fields with an intensity of 10^5 to 10^6 oe, the production of which entails at present considerable technical difficulties. The use of the method proposed in references 4 and 5 for the polarization of ferromagnetic nuclei is naturally limited to ferromagnetic elements.

The dynamic methods, proposed in references 6, 7, and by others, extend somewhat the circle of elements whose nuclei can be oriented. Thus a sufficiently large degree of orientation of As^{76} nuclei was attained in references 8 and 9; this the authors were able to measure by means of the anisotropy of the gamma radiation. However, obviously even the dynamic methods must not be considered universal. In addition their practical carrying out is more complicated than that of the statistical methods, particularly if a study of beta or alpha radiation emitted by the oriented nuclei is necessary.

We have attemped to find new methods for polarizing nuclei. Earlier we published[10,11] preliminary results of experiments on the polarization of Au^{198}, Sb^{122}, and In^{114m} in weak solutions of these elements in iron. In all three cases a relatively large degree of polarization, which was determined by the extent of the gamma-ray anisotropy, was attained. The method of polarization consists essentially of the cooling of a sample of ferromagnetic alloy, containing active nuclei magnetized to saturation, to a temperature of several hundredths of a degree. The above nuclei were chosen only because both their magnetic moments and their decay schemes[12] are known.

In this paper we publish the final results of the experiments on the polarization of Au^{198}, Sb^{122},

and In^{114m}, nuclei in weak solutions of gold, antimony, and indium in iron. Possible explanations of the polarization mechanism are discussed in Sec. 4 of this paper.

2. EXPERIMENTAL SETUP AND METHOD OF MEASUREMENT

The adiabatic demagnetization method for paramagnetic salt was used to cool the samples down to a temperature of several hundredths of a degree. Potassium chrome alum was used. The thermal contact between the salt and the sample was accomplished by means of a "heat conductor" — a copper rod ~ 150 mm long and with a diameter of 2.5 to 3 mm. The sample was soldered to one end of the "heat conductor." At the other end of the rod, copper plates, serving as the thermal contact between the rod and the salt, were soldered on with silver solder. The previously ground salt was pressed under a pressure of several thousand atm around these plates into the form of a cylinder 50 mm long and with a diameter of 20 mm. The total surface of the copper plates in contact with the salt amounted to $40 - 50$ cm^2.

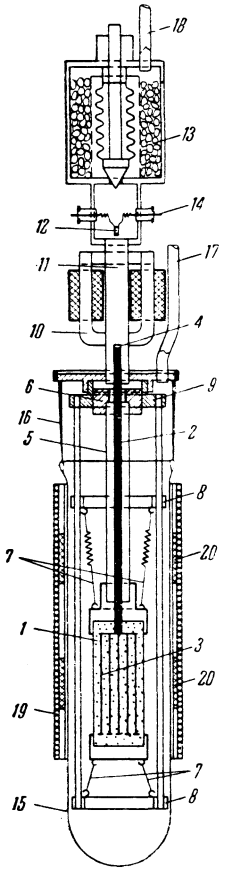


FIG. 1. Arrangement of the instrument.

The salt block with the "heat conductor" was suspended in the vacuum chamber of a cryostat by means of thin stainless-steel wires and was centered with the aid of a thin-walled glass tube in the upper part of the chamber (Fig. 1). On this figure, 1 is the block of paramagnetic salt, 2 — the "heat conductor" between the contact plates 3 and sample 4; 5 — the centering glass tube held by Plexiglas washers surrounding the salt, 6 — a textolite sleeve for centering. The block was suspended on the thin wires 7, whose tension was adjusted by little springs attached to brass hooks 8 sliding in a frame of thin-walled tubes coated with German silver. The tubes of the frame were soldered on to the flange 9, fixed to the lid of the vacuum chamber. A centering sleeve was screwed into the flange. The position of the salt block with the sample was chosen such that the sample was at the lower end of the polepieces of the electromagnet 10. The electromagnet produced fields up to $2 - 2.5$ koe at the position of the target. In these fields the samples used were magnetized practically to saturation. The vacuum chamber was connected by a pipe 11 to a volume where a resistance thermometer 12 was placed, and to an adsorption pump 13 (reference 13). The upper end of the "heat conductor" with the soldered-on sample was also inside this pipe. The thermometer was connected to the measuring circuit through air-tight isolated leads 14 (cf. reference 14) by means of thin constantan wires. The thermometer served as the vacuum indicator in the chamber. A glass test tube 15 served as the outer wall of the vacuum chamber. The test tube was attached to a copper cylinder 16 which was sealed to the chamber lid with low-melting-point solder. Tubes 17 and 18 served for pumping out the small pump and the chamber, and for filling the chamber with helium for heat exchange through a special measuring device placed in the cryostat lid. To measure the magnetic susceptibility of the salt, a coil with two windings, primary winding 19 and secondary winding 20, was placed over the test tube.

The vacuum chamber was fastened inside the helium Dewar flask by means of a thin-walled silver-coated tube joined to the lid of the Dewar. Inside this tube there was a second tube which served as the connection to the valve of the adsorption pump. The electromagnet was fastened to a flange equipped with three stainless-steel wire braces of about 1 mm diameter whose upper ends were attached to the lid of the cryostat, since during magnetization of a paramagnetic salt in the field of a large magnet a considerable force tends to pull the electromagnet in. The whole cryostat was placed on a swinging truss making it possible to transfer the device after demagnetization from the magnet into the measuring setup quickly and without shaking. The helium evacuation line was equipped with an oilseal packing permitting, in ad-

dition to a rotation of the truss, also the adjustment of its height above the field. The end of the evacuation line was fastened to the lid of the cryostat through a bellows which made it possible to change the distance between the axis of the device and the axis of rotation of the truss. This provided the device with a third degree of freedom. The evacuation of the helium was effected by means of a VN-4 pump with a geometric efficiency of about 60 *l*/sec. The pump was in a different room and was secured on a massive foundation. The evacuation line practically did not decrease the efficiency of the pump. With a completely open valve the pump allowed an evacuation up to 0.2 — 0.3 mm Hg above liquid helium; this corresponded to a salt temperature of 1.05 — 1.10° K before demagnetization.

A powerful magnet with an adjustable distance between the poles was used to magnetize the salt. The magnet was equipped with polepieces of "Armco" iron permitting the establishment of fields up to 22 koe in a 90 mm gap with a power dissipation of 40 kw in water-cooled windings. The polepiece diameter was 120 mm.

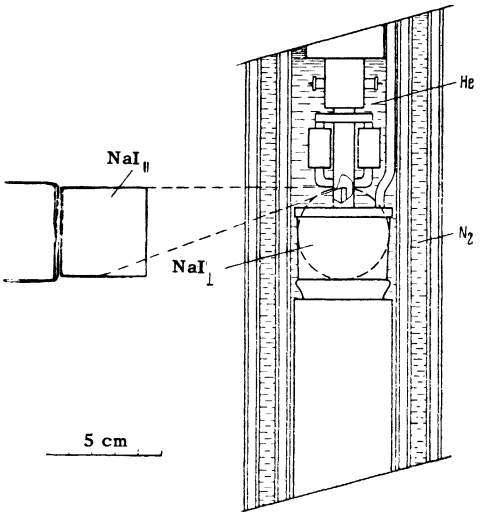


FIG. 2. The geometry of the measurements.

The angular distribution of the gamma quanta emitted by the sample was measured with two scintillation counters fastened to massive iron shields on a support which made it possible to place the counters at angles of 0, 30, 45, 60, and 90° to the direction of the sample magnetization. Inasmuch as the angular distribution of the gamma radiation for the investigated transitions was assumed to be known, the counting was performed in two directions only — parallel and perpendicular to the magnetizing field. Figure 2 shows the relative positions of the sample, the small magnet, and the crystals during the measurement of the angular distribution. As can be seen from the figure, the crystals were placed a little below the sample in order to decrease the shielding influence of the magnet poles.

Every counting channel contained a crystal (as usual, this was a NaI crystal in the form of a 40 × 40 mm cylinder), a FEU-13 photomultiplier with a power pack and a cathode follower, an amplifier, a pulse-height analyzer, and a scaler. The amplitude resolution of the system was 14% for Cs^{137} 662-kev gamma rays. In each channel there were two decade scalers. A special switching device connected each scaler in turn. As one scaler was in operation, the readings of the other one were recorded. The operating precision of the switching device was determined by a crystal-stabilized master generator of standard frequency (60 cps), and was sufficiently high. A PPCh-4 device for watch checking was used as such a generator. The same generator was used also for supplying the primary circuit of the R-56 ac bridge that served to measure the magnetic temperature of the paramagnetic salt. In addition to the secondary winding of the coil, a variable inductance was connected to the secondary circuit of the R-56 bridge; it served to determine the initial potentiometer reading.

The samples were prepared in the form of thin discs (to decrease the demagnetization factor) and had a diameter of 3 mm and a thickness of 0.1 — 0.4 mm. The samples were prepared by alloying "Armco" iron with some of the investigated metal, by heating them inside a high-frequency oven in a helium atmosphere. The alloying took place in quartz ampules. The bead obtained after the alloying was spread and rolled to the required thickness. A disc was punched out from the obtained strip. After this, the alloy samples were irradiated by thermal neutrons in a reactor. The irradiated samples were annealed in vacuum at a temperature of about 1000° C for 2 — 3 hours, after which they were soldered to the end of the "heat conductor" with a soft solder. To improve thermal contact, the end of the "heat conductor" with the sample was covered with an electrolytic layer of copper. Thus the samples containing Au^{198} and Sb^{122} were prepared. Samples with In^{114m} were prepared by alloying previously irradiated metallic indium with iron.

As usual, the experiment began with a calibration of the magnetic thermometer. For this purpose the susceptibility of the salt block was measured at several fixed temperatures, determined from the helium vapor pressure. To control the heat transfer by the gaseous helium, simultaneous measurements of the thermometer resistance

were made. The calibration was made in the temperature interval from 4.2 to 1.2 — 1.1°K. The helium vapor pressure was measured with a mercury manometer, small height differences being determined with the aid of a KM-6 cathetometer. After calibration, the device was placed between the poles of the electromagnet and the field was switched on. Five to ten minutes after the switching on of the field, the valve of the pump was opened. The evacuation of the heat-conducting helium continued for 10 to 15 minutes, after which the valve was shut and the field was slowly switched off (in the course of 3 — 4 minutes). The device was transferred from the magnet to the measuring setup, the field of the small magnetization magnet was switched on, and simultaneous measurements of the gamma-ray intensity along both magnetic temperature directions as a function of time began. The salt temperature was measured at equal intervals of 10 — 15 minutes; for this purpose the variable magnetic field with an amplitude of about 0.1 oe was switched on only for the short measurement time of 15 — 30 seconds. The duration of the experiment was determined by the supply of liquid helium available in the Dewar flask. And since at the end of the experiment, before all the helium had evaporated, it was essential to measure the counting rate for an isotropic gamma-ray distribution of the "warm" sample for a given position of the device relative to the counters, the duration of the experiment usually did not exceed 3 — 4 hours. During that time, in the good experiments, the salt with the sample had time to warm up from a minimum temperature of about 0.005°K to about 0.05°K. In cases where a higher temperature range was of interest, the sample and the salt were heated immediately after the demagnetization by the variable magnetic field employed for measuring the temperature. For this purpose the amplitude of this field was increased by a factor of 10 — 20 (up to 1 — 2 oe). The heat was essentially evolved in the copper contact plates and in the "heat conductor." The sample was heated in a similar manner at the end of the experiment to measure the gamma radiation of a "warm" sample.

3. MEASUREMENT RESULTS

Each experiment yielded the dependence of the counting rate from the two detectors $N(0)$ and $N(\pi/2)$ and of the salt temperature on the time after the demagnetization. These data were processed in the following manner. The background was subtracted from $N(0)$ and $N(\pi/2)$, and the values obtained (for the experiments with Au^{198} and Sb^{122} the values were first adjusted to account for the decay) were normalized by dividing them by the average counting rate for the heated sample. In the case of Au^{198} and Sb^{122} the background (amounting to about 10% of the count) was determined simply by removing the device with the sample from the detectors. In the case of In^{114m}, whose spectrum contains harder gamma rays in addition to the investigated 192-kev lines, the extent of the background was determined by measurements in which a lead filter 2.5 mm thick was placed between the sample and the detector; such a filter absorbed 192-kev gamma rays completely and allowed practically the entire passage of harder radiation. The background which was thus determined amounted to about 15 — 20%.

The sample temperature was determined by the temperature of the salt. The magnetic temperature was measured, and from it the thermodynamic temperature was calculated. For this purpose the magnetic temperature of the cylinder was first converted to the magnetic temperature of a spherical sample.[15] In these calculations the effective demagnetization factor for a salt pressed into the form of a cylindrical block was taken to be 0.95; this was determined in accordance with the data of reference 16, taking account of the change in the susceptibility of the salt with the temperature. This correction, practically constant in the temperature interval 0.01 — 0.1°K, amounted to $+2.0 \times 10^{-2}$ deg. The magnetic temperature so corrected was then converted into the thermodynamic temperature. In this conversion we made use of the data of reference 17 for the temperature region above 0.05°K, and of the data of reference 18 for temperatures below 0.05°K. The sample temperature was assumed to be equal to the temperature of the salt. The correction for their temperature difference, which is due to the energy liberated by the beta-active sample, was estimated in accordance with the data of reference 19. The correction apparently does not exceed 2 to 3×10^{-3} °K for the lowest equilibrium temperature of about 0.03°K, and lies within the limits of the error in the determination of the thermodynamic temperature of the salt, which we estimate to be about 10%. For lower temperatures this correction becomes substantial. Thus for a beta-active sample which emits energy at the rate of about 0.3 erg/sec, the temperature of the sample cannot become lower than 0.015 — 0.020°K, even when the temperature of the salt is arbitrarily low.

In our experiments thermal equilibrium was established within 30 — 60 minutes after the demagnetization of the salt. Up to this time the salt had time to warm up to about 0.03°K. This circumstance was not taken account of in the prelim-

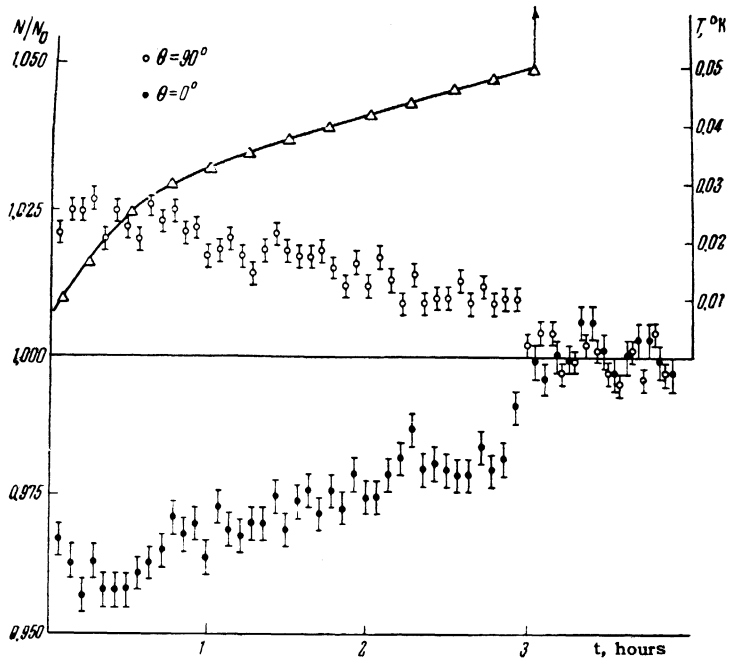


FIG. 3. The dependence of the 566-kev gamma-ray intensity of Sb^{122} on the time after the demagnetization of the salt. The counting rate of the heated sample was taken to be unity. The temperature variation of the salt is shown by the solid curve. The arrow on the temperature curve shows the time when the artificial heating of the salt began.

inary experiments,[10,11] in which the heating of the salt was carried out for 15 — 30 minutes after the demagnetization, i.e., until thermal equilibrium was established. As a result, the sample temperatures used earlier were found to be too low.

Experiments with Sb^{122}

The sample of the Sb-Fe alloy contained 0.6% Sb by weight. There are indications that antimony and iron form a solid solution with an antimony content of up to 6 — 7% (reference 20). The activity of the Sb^{122} nuclei, obtained by irradiating the sample in a reactor, amounted during the experiments to 6 — 8 μC. Only those pulses corresponding to the gamma-ray photopeak with an energy of 566 kev were registered. The fraction of the registered pulses from harder gamma rays did not amount to more than 5%.

The angular distribution of gamma rays with an energy of 566 kev (the $2^+ \xrightarrow{E2} 0^+$ transition), emitted after the beta decay of oriented Sb^{122} nuclei (the $2^- \to 2^+$ transition), is determined by the following expression:[9,21]

$$N(\vartheta) = 2[1 - \tfrac{10}{7} f_2 B_2 P_2(\cos\vartheta) - \tfrac{40}{3} f_4 B_4 P_4(\cos\vartheta)], \quad (1)$$

where ϑ is the angle between the direction of emission of the gamma rays and the axis of orientation; $P_2(\cos\vartheta)$ and $P_4(\cos\vartheta)$ are Legendre polynomials; f_2 and f_4 are orientation parameters of the Sb^{122} nuclei; B_2 and B_4 are coefficients that determine the change in the orientation of the nuclei during beta decay. For the beta transition $2^- \to 2^+$ (reference 9)

$$B_2 = 1 - \alpha_1/2 - 17\alpha_2/14,$$
$$B_4 = 1 - 5\alpha_1/3 - 5\alpha_2/7,\ \alpha_0 + \alpha_1 + \alpha_2 = 1, \quad (2)$$

where α_0, α_1, α_2, are the relative probabilities that during the $2^- \to 2^+$ beta decay the electron and the neutrino are emitted in a state with a total angular momentum L of 0, 1, and 2, respectively

Usually the anisotropy of the gamma radiation of the nuclei is determined in the following manner:

$$\varepsilon = [N(\pi/2) - N(0)]/N(\pi/2), \quad (3)$$

where $N(\pi/2)$ and $N(0)$ are the probabilities of gamma-ray emission at 90° and 0° to the axis of orientation. In our case

$$\varepsilon = (\tfrac{15}{7} B_2 f_2 - \tfrac{25}{3} B_4 f_4)/(1 + \tfrac{5}{7} B_2 f_2 - 5B_4 f_4). \quad (4)$$

The values of f_2 and f_4 are fully determined by the quantity $\beta = \mu H/kTI$, where μ is the magnetic moment of the Sb^{122} nucleus equal to 1.9 nuclear magnetons,[22] H is the effective magnetic field at the Sb nuclei, T is the absolute temperature, and I is the nuclear spin. For small values of β, $f_4 \approx 0$, and $f_2 \approx a\beta^2$, where $a \approx (\tfrac{2}{45})I(I+2)$ and consequently

$$\varepsilon \approx \tfrac{15}{7} B_2 f_2 \approx \tfrac{15}{7} B_2 a\beta^2 = \tfrac{15}{7} B_2 a (\mu H/kTI)^2. \quad (5)$$

From expressions (2) it is possible to find that $-\tfrac{3}{14} \le B_2 \le 1$. However, negative values of B_2 are excluded by the fact that the experimental value of ϵ is positive. Therefore $0 < B_2 \le 1$. Substituting in (5) the values of μ and I for Sb^{122} and taking the square root, we obtain

$$\sqrt{\varepsilon} \approx 3.0 \cdot 10^{-8} \sqrt{B_2} H/T. \quad (6)$$

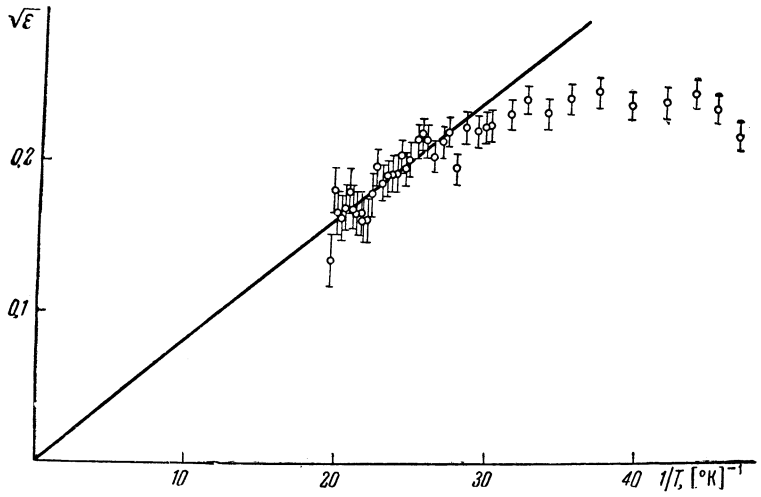


FIG. 4. The dependence of $\sqrt{\epsilon}$ on 1/T for 566-kev gamma radiation of Sb^{122}.

The results of one of the experiments with Sb^{122} are shown on Fig. 3. Figure 4 gives the experimental dependence of $\sqrt{\epsilon}$ on 1/T for Sb^{122}, calculated from Fig. 3. It can be seen that the experimental points fit well on a straight line. The deviations from the straight line for small T are essentially due to the fact that in this temperature region the temperature of the sample differs from that of the salt. From expression (6) and from the slope of the linear portion of the experimental curve of Fig. 4, it can be found that $H \approx 2.8 \times 10^5/\sqrt{B_2}$ oe. Since $0 < B_2 \leq 1$, H must be greater than or equal to 2.8×10^5 oe. Unfortunately, we still do not have data which would enable us to narrow the bounds of B_2, although it is almost obvious that very small (~ 0.1) values of B_2 are highly improbable. Thus from the results obtained it is possible to determine only the lower limit of the field value on the Sb nuclei in the Sb-Fe alloy, namely $H \geq 2.8 \times 10^5$ oe. The degree of polarization of the Sb^{122} nuclei is $f_1 = \bar{I}_z/I \geq 30\%$ for $T = 0.03°K$.

Experiments with Au^{198}

The sample of Au-Fe alloy contained 0.3% Au by weight. It is known that the solubility of gold in iron at 600° C is 0.6% (reference 20). The activity of the Au^{198} nuclei, which were produced in the sample as a result of irradiation in a reactor, amounted during the experiments to $2-3\,\mu C$. The anisotropy of the gamma radiation with an energy of 411 kev (the $2^+ \overset{E2}{\rightleftarrows} 0^+$ transition), emitted after the beta decay (the $2^- \rightarrow 2^+$ transition) of oriented Au^{198} nuclei, was measured. This case is completely identical with the above case of Sb^{122} and therefore expressions (1) — (5) are applicable to Au^{198}. Substituting in (5) I = 2, and the value of μ for Au^{198} which is 0.5 nuclear magnetons,[22] we obtain for small β

$$\sqrt{\bar{\epsilon}} \approx 0.79 \cdot 10^{-8} \sqrt{B_2} H/T. \qquad (7)$$

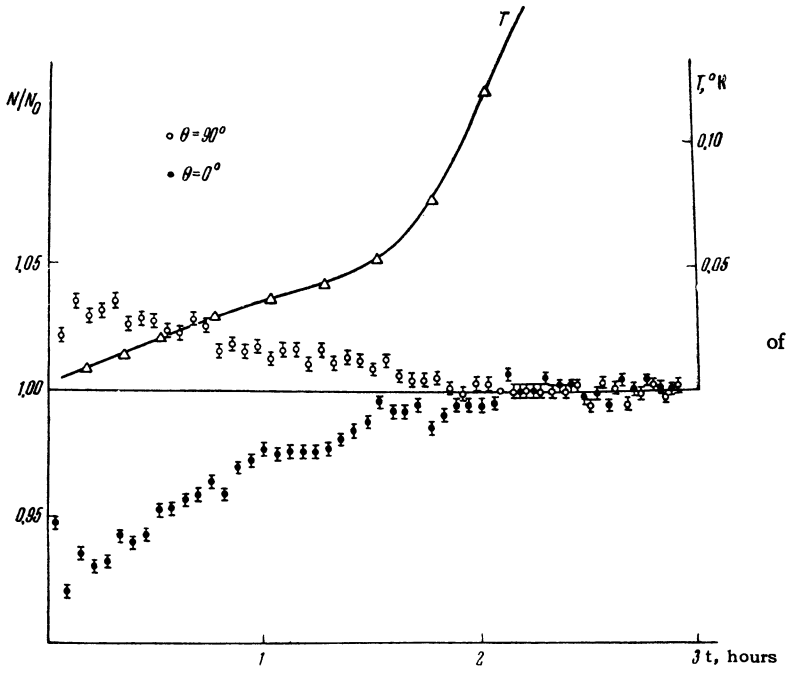


FIG. 5. The dependence of the gamma-ray intensity of Au^{198} on the time after the demagnetization of the salt.

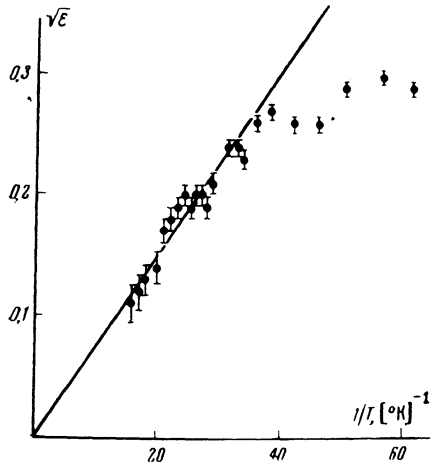


FIG. 6. The dependence of $\sqrt{\epsilon}$ on 1/T for 411-kev gamma radiation of Au^{198}.

Figure 5 shows the results of one of the experiments with Au^{198}, and Fig. 6 shows the experimental dependence of $\sqrt{\epsilon}$ on 1/T obtained from these results. From (7) and the slope of the linear portion of the experimental curve of Fig. 6 it can be found that $H \approx 1.0 \times 10^6/\sqrt{B_2}$ and since $0 < B_2 \leq 1$, $H \geq 1.0 \times 10^6$ oe for Au^{198}. For $T = 0.03°K$ the degree of polarization of Au nuclei is $f_1 = \bar{I}_z/I \geq 30\%$.

Experiments with In^{114m}

The sample of the In-Fe alloy, containing In^{114m} radioactive nuclei, was prepared by alloying metallic indium, previously irradiated in a reactor, with iron. About the solubility of indium in iron, unfortunately, nothing is known. The indium content of the sample was 0.12% by weight, and the activity of the In^{114m} nuclei (the number of decays) was $\sim 10\,\mu C$. In^{114m} nuclei disintegrate basically (96.5%) by gamma transition ($5^+ \xrightarrow{E4} 1^+$) with an energy of 192 kev. The anisotropy of the quanta emitted during this transition was measured. Because of the large conversion coefficient, the number of these quanta per decay is only equal

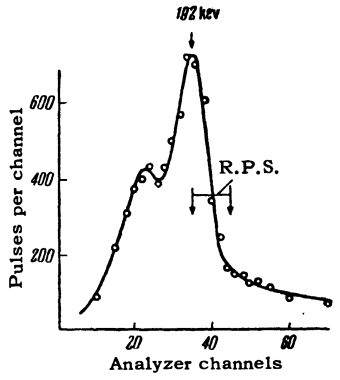


FIG. 7. The gamma-ray spectrum of In^{114m} (R.P.S. – the registered portion of the spectrum).

to 0.18. Figure 7 shows the gamma spectrum of the sample when it is in its operating position inside the Dewar flask. The spectrum was measured by a detector placed at an angle of 0° with respect to the field of the small magnet. As can be seen from Fig. 7, only pulses corresponding to the right half of the gamma-ray photopeak with an energy of 192 kev were registered. This was done in order to exclude the effect of gamma rays scattered by various parts of the device near the source.

The angular distribution of gamma rays with an energy of 192 kev, emitted by oriented In^{114m} nuclei, is of the following form:*

$$N(\vartheta) = 1 - 2.61 f_2 P_2(\cos\vartheta) + 4.97 f_4 P_4(\cos\vartheta) + 1.71 f_6 P_6(\cos\vartheta) - 75 f_8 P_8(\cos\vartheta). \quad (8)$$

For small values of β all terms, except the one depending on f_2, can be neglected, and, using the value of the nuclear magnetic moment for In^{114m}, equal to 4.7 nuclear magnetons,[22] and I = 5, it is possible to obtain the following expression for the anisotropy of the gamma rays:

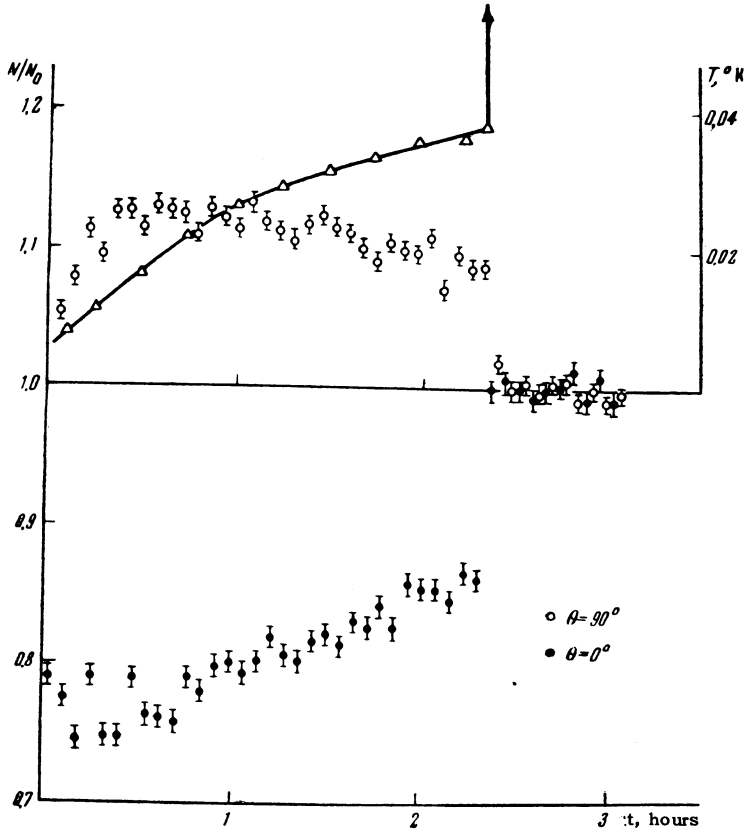
$$\sqrt{\epsilon} \approx 8.5 \cdot 10^{-8} H/T. \quad (9)$$

The results of two experiments with In^{114m} are shown on Figs. 8a and b. Soon after the start of the second experiment, the sample was heated from ~ 0.01 to $\sim 0.03°K$. It can be seen that this heating was accompanied by a sharp decrease in the anisotropy of the gamma radiation. From a comparison of the temperature curve after the heating with the change in the counting rate, it is possible to conclude that the time for the establishment of thermal equilibrium between the sample and the salt was ~ 20 min.

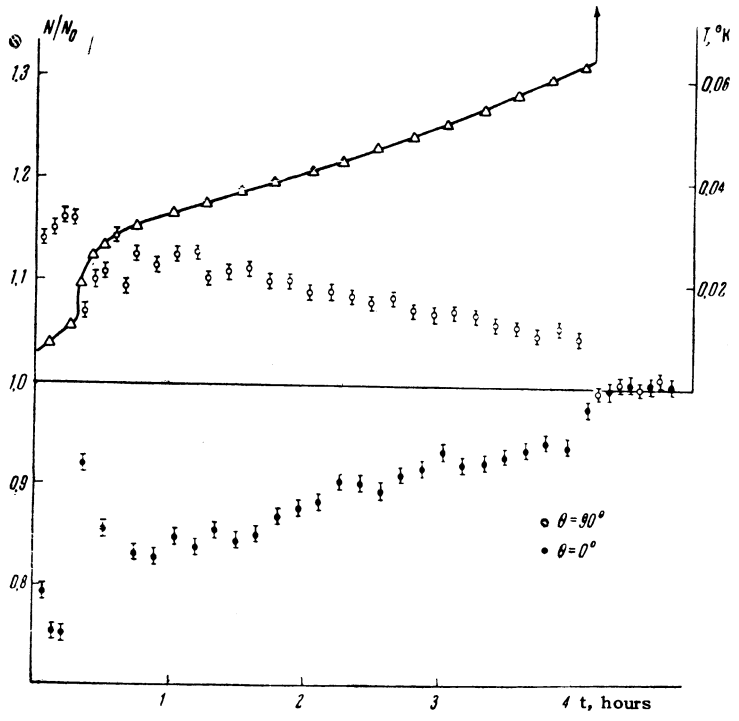
From the results of the experiment shown in Figs. 8a and b the experimental dependence of $\sqrt{\epsilon}$ on 1/T for In^{114m}, shown in Fig. 9, was obtained. Figure 9 also shows the theoretical curve $\sqrt{\epsilon}(1/T)$ calculated with formula (8), taking into account terms which contain f_2 and f_1. The initial portion of this curve coincides with the experimental points and from its slope, using (9), it is possible to obtain the value of the field on the In^{114m} nuclei $H = 2.47 \times 10^5$ oe. The polarization of the In nuclei is $f_1 = \bar{I}_z/I = 50\%$ at $T = 0.03°K$.

Measurements of the anisotropy were also carried out with Cd^{114} for gamma rays with energies of 540 and 720 kev that are emitted after K capture in In^{114m}. Since the angular distribution of the quanta of these two gamma transitions is the same (a case analogous to the emission of 1170- and 1330-kev gamma quanta in the decay of Co^{60}), they were registered simultaneously. From these measurements a value $H = 2.3 \times 10^5$ oe, coinciding within 10% with that given earlier, was obtained.

*This formula was obtained by L. D. Puzikov.



a



b

FIG. 8. The dependence of the 192-kev gamma-ray intensity of In^{114m} on the time after the demagnetization of the salt in various temperature intervals: a – first experiment, b – second experiment. The notation is the same as in Fig. 3.

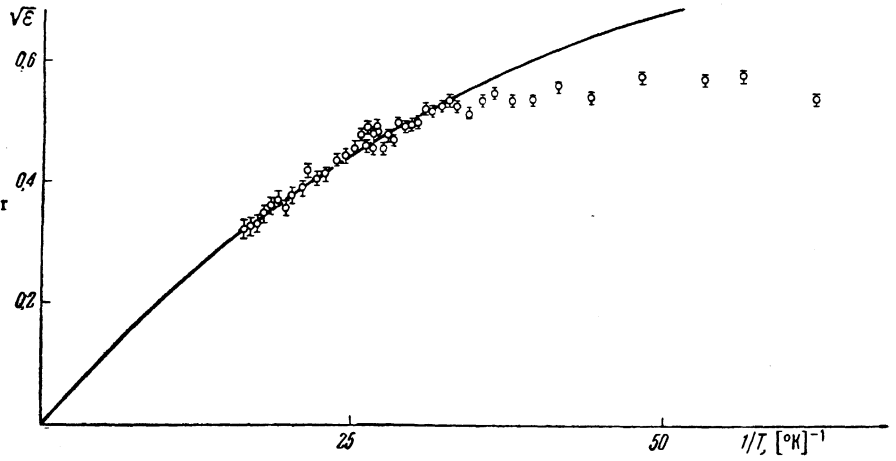


FIG. 9. The dependence of $\sqrt{\epsilon}$ on 1/T for 192-kev gamma radiation of In^{114m}.

Inasmuch as it remains unknown what portion of the indium entered into the alloy with iron, the values obtained can only be considered the lower limit of the magnetic field on the indium nuclei in the In-Fe alloy. We also carried out experiments with a sample of In-Fe alloy which contained 0.6% In by weight. The value of the anisotropy at 0.03°K turned out to be 10%. From this it is possible to conclude that the solubility of indium in iron is less than 0.6% but hardly less than 0.12%, i.e., the true value of the magnetic field on the In nuclei in the In-Fe alloy does not differ greatly from that found in the experiments with the In-Fe alloy containing 0.12% In.

A summary of the results obtained is given in the table.

The element dissolved in the iron	Au	Sb	In
Content of the element by weight	0,3	0,6	0,12
The radioactive nucleus	Au^{198}	Sb^{122}	In^{114m}
ε_γ, % for $T = 0.03°$ K	6	8	28
f_1	$\geqslant 0.3$	$\geqslant 0.3$	$\geqslant 0.5$
H, oe	$\geqslant 1\cdot 10^6$	$\geqslant 2.8\cdot 10^5$	$\geqslant 2.5\cdot 10^5$

4. DISCUSSION OF RESULTS

It follows from the stated results that the introduction of weakly magnetic elements into a ferromagnet is, apparently, a universal method for the polarization of nuclei. This method is based on the fact that a strong magnetic field on the order of 10^6 oe acts upon the nuclei of weakly magnetic elements dissolved in the ferromagnet. As was already stated in an earlier paper,[11] the most probable explanation of the source of this field (first shown to us by E. K. Zavoĭskiĭ) is that it is created by the conduction electrons, which in ferromagnets have a substantial degree of polarization. The determination of the value of this field is of independent interest for the theory of ferromagnetism.

Recently, Marschall[23] investigated the "contact" magnetic field created on the nuclei of a ferromagnet by the conduction electrons. For the value of this field he used the following expression:

$$H_c = -(8\pi/3)\mu_0 |\psi(0)|^2 n P_{\text{eff}},$$

where μ_0 is the Bohr magneton, $|\psi(0)|^2$ is the mean square value of the s-electron wave function at the nucleus, which can be estimated from the value of the atomic hyperfine-structure constants of a free atom, P_{eff} is the polarization of the conduction electrons. According to Marschall, P_{eff} consists of two terms. The first is due to the direct effect of the d-shell magnetic moments of the atoms on the conduction electrons; the second term is due to the exchange interaction of s and d electrons. A comparison of Marschall's estimates with the results of experiments on the polarization of Co^{60} nuclei in metallic cobalt leads to a value $P_{\text{eff}} \sim 10\%$.

The mechanism investigated by Marschall is, apparently, also applicable to our case, if it is assumed that the conduction electrons are polarized near the iron atoms and go over to the neighboring impurity atoms without reorientation. Unfortunately, it is still impossible to compare the experimental values of the fields on the nucleus with the theoretical values, which are merely estimates. Concerning the experimental values, it was possible in the cases which we investigated to determine only their lower limits. However, we propose later on to find in a number of cases the actual values of the fields (accurate within 10 — 20%) both by measuring the anisotropy of the gamma radiation emitted after allowed beta transitions, and by measuring the anisotropy of the beta radiation.

We intend also to investigate the value of the field on nuclei of elements introduced into various ferromagnets. The measurements of the gamma-ray anisotropy of In^{114m} in an indium-nickel alloy

which have already been carried out yielded a negative answer (accurate within 0.5%). This result is of interest from the point of view of recent widely discussed ideas[24] about two different types of electron structures of transition metals. According to these ideas, the d shells of the atoms of such metals as nickel and cobalt differ little from the d shells of free Ni and Co atoms, and the total number of conduction electrons per atom is only ~ 0.5. Iron and, apparently, the rare earths belong to another type. In iron atoms, for instance, six of the eight d electrons are collectivized and are in the conduction band.

The authors consider it their pleasant duty to express their deep gratitude to E. K. Zavoĭskiĭ and L. V. Groshev for their constant interests in the work, to L. D. Puzikov for help in the theoretical calculations, to V. M. Galitskiĭ and D. P. Grechukhina for a discussion of the work, to G. P. Mel'nikov for the construction of the necessary radio devices, to V. N. Agureev, I. B. Filippova, and N. V. Razzhivina for help in carrying out the experiments, and also to N. E. Yakovich, V. A. Drozdov, and V. D. Sheffer who provided an uninterrupted supply of liquid helium.

Note added in press (January 18, 1960): Until very recently we, unfortunately, did not know the paper by Beun et al.[25] on the connection between the magnetic and thermodynamic temperatures in potassium chrome alum. If in the processing of our results we had used the data of the above paper, the values of the fields on the nuclei of gold, antimony, and indium, would have been lower by 25 — 35%.

[1] B. Bleaney, Proc. Phys. Soc. **A64**, 315 (1951).
[2] C. J. Gorter, Physica **14**, 509 (1948); M. E. Rose, Phys. Rev. **75**, 213 (1949).
[3] R. V. Pound, Phys. Rev. **76**, 1410 (1949).
[4] G. R. Khutsishvili, JETP **29**, 894 (1955), Soviet Phys. JETP **2**, 766 (1956).
[5] Grace, Johnson, Curti, Scurlock, and Taylor, Comm. Conf. de Physique de basses Temperatures, Paris, 1955, p. 263.
[6] A. W. Overhauser, Phys. Rev. **92**, 411 (1953).
[7] C. D. Jeffries, Phys. Rev. **106**, 164 (1957).
[8] F. M. Pipkin and J. W. Culvahouse, Phys. Rev. **109**, 1423 (1958).
[9] F. M. Pipkin, Phys. Rev. **112**, 935 (1958).
[10] Samoĭlov, Sklyarevskiĭ, and Stepanov, JETP **36**, 644 (1959), Soviet Phys. JETP **9**, 448 (1959).
[11] Samoĭlov, Sklyarevskiĭ, and Stepanov, JETP **36**, 1944 (1959), Soviet Phys. JETP **9**, 1383 (1959).
[12] B. S. Dzhelepov and L. K. Peker, Схемы распада радиоактивных ядер, (Decay Schemes of Radioactive Nuclei), Acad. of Sciences Press, 1958.
[13] B. N. Samoĭlov, Dokl. Akad. Nauk SSSR **86**, 281 (1952).
[14] B. N. Samoĭlov, J. Tech. Phys. (U.S.S.R.) **22**, 888 (1952).
[15] N. Kurti and F. Simon, Phil. Mag. **26**, 849 (1938).
[16] K. Warmuth, Arch. Elektrotech. **33**, 747 (1939).
[17] A. H. Cooke, Proc. Phys. Soc. **A62**, 269 (1949).
[18] de Klerk, Steenland, and Gorter, Physica **15**, 649 (1949).
[19] Kurti, Robinson, Simon, and Spohr, Nature **178**, 450 (1956).
[20] M. Hansen, The Structure of Binary Alloys, Russ. Transl., 1941.
[21] H. A. Tolhoek and J. A. M. Cox, Physica **19**, 101, 673 (1953).
[22] Strominger, Hollander, and Seaborg, Revs. Modern Phys. **30**, 585 (1958).
[23] W. Marschall, Phys. Rev. **110**, 1280 (1958).
[24] N. Mott and K. Stevens, Phil. Mag. **2**, 1364 (1957).
[25] Beun, Miedema, and Steenland, Physica **23**, 1 (1957).

Translated by Z. Barnea
83