POLARIZATION OF Sc^{46} NUCLEI IN IRON

A. V. KOGAN, V. D. KUL'KOV, L. P. NIKITIN, N. M. REINOV, I. A. SOKOLOV, and M. F. STEL'MAKH

Leningrad Physico-Technical Institute, Academy of Sciences, U.S.S.R.

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The asymmetry of the γ radiation from polarized Sc^{46} nuclei in an alloy with pure iron was measured for temperatures of $(1.5 - 3) \times 10^{-2}$ °K. The effect observed shows that the introduction of scandium into the ferromagnet results in the appearance of an effective magnetic field H_{eff} of the order of 10^5 oe acting on the nucleus. In the case of Co^{60} introduced into iron the effective field is $(3 \text{ to } 4) \times 10^5$ oe.

THE theoretical treatment[1-3] of the correlations between β particles and γ quanta, following an allowed β transition, shows that for the case of oriented nuclei, the correlation function should be asymmetric with respect to the direction of the momentum of the β particle if combined parity is not conserved and symmetric if it is.

It has by now been established in various experiments that parity is conserved within the limits of error ~10%. In order for experiments on β-γ correlation from oriented nuclei to give a result with a greater or comparable accuracy, it is necessary to choose a nucleus in which the term in the β decay corresponding to interference between the Fermi and Gamow-Teller interactions is large. Of the known nuclei, this condition is best satisfied by Sc^{46}, Mn^{52} (which has already been investigated by Ambler and co-workers[4]) and, to a lesser degree, by V^{48}. The β decays of Co^{56} and Co^{58}, which are allowed β transitions, cannot be used for experiments concerning time parity because the interference term is equal to zero.[5,6] For this same reason, one cannot use allowed β transitions which occur with a change of spin of 1 (Co^{60}), in which there is a pure Gamow-Teller interaction.

Experiments with Sc^{46}, which are the most promising in this respect, could not be done, since the scandium ions are not paramagnetic, and one therefore could not use the method of Bleaney and Gorter-Rose for orienting the nuclei. The use of the method of a strong field (Simon) requires practically unattainable steady magnetic field intensities of $10^5 - 10^6$ oe for obtaining a noticeable degree of polarization.*

The work of Samoĭlov, Sklyarevskiĭ, and Stepanov,[8-10], who polarized the nuclei of weakly magnetic elements in alloys of these elements with ferromagnets, opened the possibility for the orientation of nuclei of various new elements including scandium.

In the present paper we present the first results obtained by us on orientation of Sc^{46}, introduced into iron.

The apparatus used by us for orientation of nuclei introduced into ferromagnets is shown in Fig. 1.

The sample 1 in the form of a thin disk was cooled by adiabatic demagnetization of a mixture of chromium potassium alum and propyl alcohol 2, in a container of organic glass 3; heat was transferred from the sample to the cooling mixture by means of a "cold pipe" 4. To improve the thermal contact between the paramagnetic salt and the cold pipe a "whisk broom" 5 of small copper wires 0.5 mm in diameter was soldered to its end. The separation between the wires did not exceed 1.5 mm. The sample was soldered to the cold pipe with tin (as in the experiments of references 8 — 10) and covered electrolytically with a layer of copper. To reduce the heat flow to the working cooling mixture it was attached by means of three small quartz tubes 6 to an upper "ballast" salt pressed in the shape of a hollow cylinder 7, which was fixed into the glass collar of the envelope by two sliders 8 made of stainless steel. The container 3 was centered with respect to the surrounding removable cover of the glass envelope by stainless steel springs 9 bonded to the cylinder of the lower "ballast" salt 10. The "ballast" salt was joined to the container by a quartz tube 11.

The magnetic field H_0 needed for magnetization of the iron was produced by means of a superconducting cylinder[11] 12 in the helium dewar. The niobium cylinder, which during the adiabatic demag-

*A description of the various methods for orienting atomic nuclei can be found in the survey paper of G. R. Khutsishvili.[7]

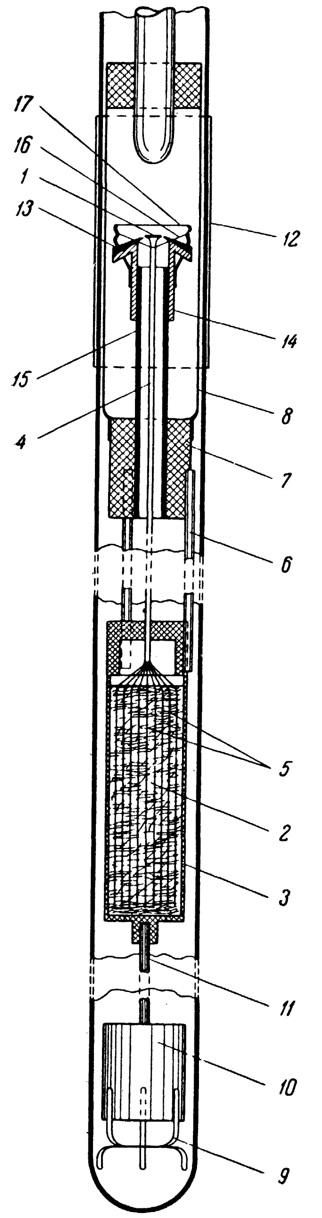

FIG. 1. Schematic drawing of the equipment.

netization is in a quite high field, preserves within its volume, after demagnetization to zero field, a field which is close to the critical value. For the niobium which we had at our disposal this residual field was ~ 900 oe. To increase the magnetic field in the neighborhood of the sample up to ~ 1600 to 1800 oe, we used wedge-shaped "concentrators" 13 of Armco iron. The "concentrators" were fixed to bracket supports 14 attached with BF-4 adhesive to a silvered glass tube 15, pressed into the upper "ballast" salt 7. The upper end of the cold pipe was centered with respect to the "concentrators" by means of caprone tension members 16 bonded to the housing 17 of stainless steel; the housing had a temperature close to the temperature of the "ballast" salt.

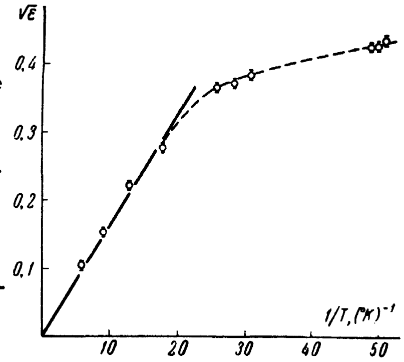

FIG. 2. Dependence of the asymmetry ε of γ radiation of Co^{60} on thermodynamic temperature T. The points shown on the graph are the average values of $\sqrt{\varepsilon}$ in a certain temperature interval.

The use of "ballast" salts enabled us to mount the apparatus in an envelope with small clearances (internal diameter 20 mm) and to reduce the heat leak to a value < 10 erg/min at temperatures ~ 0.01°K.

EXPERIMENTS WITH Co^{60}

To check the operation of the equipment, we carried out experiments on orientation of Co^{60} nuclei dissolved in pure iron obtained by heating in vacuum. The cobalt content of the iron did not exceed 0.02%. In Fig. 2 we show the dependence of the square root of the asymmetry of the γ-radiation

$$\varepsilon = [I(\pi/2) - I(0)]/I(\pi/2)$$

on the thermodynamic temperature T of the cooling mixture. For low values of the nuclear polarization, when the condition $\mu H_{eff}/kTI \ll 1$ is satisfied, where μ is the magnetic moment of the nucleus, H_{eff} is the effective magnetic field acting on the nucleus and I is the nuclear spin, we have $\sqrt{\epsilon} \sim H_{eff}/T$. Then the relation between $\sqrt{\epsilon}$ and T^{-1} should be represented by a straight line if the thermodynamic temperature T of the cooling mixture is correctly determined and the temperatures of sample and salt coincide. The magnetic temperature was determined from the susceptibility of the cooling mixture by using a mutual inductance bridge. As in the papers of Samoĭlov and coworkers, to change from magnetic to thermodynamic temperature we used the old scale for a single crystal of chromium potassium alum.[12-13] Later it was shown that this scale is not exact for low temperatures (1/T > 20).

As we see from Fig. 2, when 1/T ≈ 25 — 30 one already observes a significant deviation of the experimental points from a straight line. This effect is mainly caused by a temperature drop between the sample and salt. If we use the results of references 14 and 15 for the change to the thermodynamic temperature scale, the curve $\sqrt{\epsilon} = f(T)$

deviates from the straight line at the smallest values of 1/T. However, for the determination of the effective internal field one can use the straight line for values $1/T < 20$, and the difference between the temperature scales has practically no effect on the value of H_{eff} obtained in the experiment.

From Fig. 2 it follows that the effective magnetic field acting on a Co^{60} nucleus in an alloy with iron is equal to 3.5×10^5 oe, for cobalt content < 1%. This value is in good agreement with results for H_{eff} for the case of an alloy of iron with 5% cobalt, obtained both from the asymmetry of the γ radiation of Co^{60} and from the nuclear specific heat of Co^{59} (reference 16) ($H_{eff} = (3.1 - 3.2) \times 10^5$ oe). The values for alloys with low cobalt content are somewhat higher than for permendur[17] ($H_{eff} = 2.4 \times 10^5$ oe) and for a cobalt single crystal[18,19] ($H_{eff} = (1.8 - 2.0) \times 10^5$ oe).

These data were interpreted by Kurti[16] as a confirmation of the theoretical estimate made by Marshall of the effect of the main component of the cobalt-iron alloy on the internal field produced by the d-shell electrons of the cobalt ion. However, recently Daniels and Le Blanc[20] found that the internal field in a hexagonal single crystal of cobalt is $H_{eff} = 2.7 \times 10^5$ oe; this value practically coincides with the data for alloys with low cobalt content. It was shown that the values $H_{eff} \approx 2 \times 10^5$ oe found in earlier work are explained by the presence in the cobalt crystals of the high-temperature cubic crystalline phase.

It is obvious that for a satisfactory comparison of experimental data with theory it is necessary to increase significantly the accuracy of the experiment. We note that the quite sizeable differences between data obtained in various laboratories may arise simply because of errors in the determination of the absolute temperature of the sample in the range $\sim 10^{-2}$ °K.

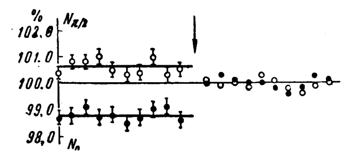

FIG. 3. Asymmetry of γ radiation of Sc^{46} nuclei polarized in an alloy with iron. On the graph we indicate (in percent) the ratios of the number of pulses recorded by scintillation counters over a time interval of 64 sec, in the direction of the axis of orientation, N_0, (solid dots), and at an angle of $90°-N_{\pi/2}$, (open circles), to the average number of pulses recorded in the corresponding counters after heating of the sample. The arrow shows the time when the sample was heated from 0.03°K to 1.2°K. The mean square statistical errors of the measurements are indicated.

EXPERIMENTS WITH Sc^{46}

Scandium irradiated with neutrons was introduced into pure iron in the form of a metal. The scandium content in the iron did not exceed 0.5%, the activity of the sample was equivalent to ~ 1 μC of Sc^{46}.

The solubility of scandium in iron has not yet been investigated and it was not known whether a solid solution of scandium in iron occurs*.

We carried out a long series of measurements of the asymmetry of the γ radiation of Sc^{46} for a temperature of the cooling mixture down to 0.015°K. The asymmetry obtained at these temperatures was $\epsilon = 2.5\%$. Its sign is in agreement with the known dipole character of the cascade γ transitions in Ti^{46}. As was already stated above, the thermal contact used by us did not achieve equality of temperatures of sample and cooling mixture for $1/T > 25$.

In Fig. 3 we give the data on the asymmetry of the γ radiation of polarized Sc^{46} nuclei for temperatures of the cooling mixture of 0.025 — 0.03°K. The counting of the γ quanta lasted ten minutes on the cold sample, during which time the temperature of the sample hardly changed. After forced heating, measurements for this same length of time were made at a temperature ~ 1.2°K. The asymmetry value $\epsilon = 1.8\%$ obtained here was somewhat lower than the maximum value given above which was obtained for a temperature of the cooling salt T ~ 0.015°K. For a temperature ~ 0.04 — 0.05°K, the value of ϵ for Sc^{46} is only 1%, so that the temperature dependence of the asymmetry of the γ radiation cannot be investigated for low values of 1/T with sufficient accuracy. The magnetic moment of Sc^{46} has not been determined experimentally, but its value can be estimated sufficiently well on the basis of the shell model. The values of μ obtained from the formulas for a spherical and an elongated nucleus are close to one another, and their average is 3.5 nuclear magnetons, with an error not exceeding 0.5 magnetons. The comparison of the theoretical formula for the asymmetry of the γ radiation of Sc^{46} with the experimental value for $1/T = 25$ enables us to determine the effective magnetic field acting on the scandium nucleus in the alloy of scandium and iron: $H_{eff} \approx 10^5$ oe.

*L. M. Shestopalov of the Physico-Technical Institute, Academy of Sciences, U.S.S.R., made a study of microslices of two samples of iron-scandium alloy with contents ~ 1% and ~ 8% Sc, obtained by melting without crucible in vacuum. The results obtained show that formation of a solid solution occurs at normal temperature for a scandium content somewhat less than 1%. For large scandium content the more clearly observed phase inhomogeneities indicate a limited solubility.

EXPERIMENTAL ERRORS

Errors in the determination of H_{eff} are caused by: a) error in the determination of the magnetic moment of the nucleus, b) error in the measurement of ϵ (the asymmetry of the γ radiation), c) error in the determination of the absolute temperature, and d) possible error because of incomplete orientation of domains.

For Co^{60} the first and second sources of error are unimportant since its magnetic moment is known to high accuracy and the precision of the measurement of the asymmetry of the γ radiation is sufficiently high.

The error in determining the absolute temperature results from: 1) errors in going from magnetic temperature to thermodynamic temperature (according to the estimate of the authors it amounts to ~10%) and 2) errors in converting from magnetic temperatures measured for the cylindrical sample to magnetic temperatures for spherical samples for which all the computations were made. The overall error is around 15%.

The error mentioned in point d) is related to the fact that the external magnetic field used by us may not have completely oriented the domains of the ferromagnetic sample.

One might assume that iron with a small impurity of cobalt will be practically saturated for a field of 1500 oe; for the alloy of iron with scandium the situation may be somewhat worse since the magnetic properties of the iron-scandium alloy are not known. The inclusion of the corresponding correction would require additional investigations.

Taking account of all this we may state that the values of effective magnetic field measured by us lie within the following limits:

1) for Co^{60}: $3.0 \cdot 10^5 \leqslant H_{eff} \leqslant 4.0 \cdot 10^5$ oe,

2) for Sc^{46}: $0.70 \cdot 10^5 \leqslant H_{eff} \leqslant 1.30 \cdot 10^5$ oe.

POSSIBILITY OF INVESTIGATION OF β-γ CORRELATION FOR ORIENTED Sc^{46} NUCLEI

According to computation, the limiting anisotropy of γ radiation for completely oriented Sc^{46} nuclei is 80%. It is obvious that, for the insignificant degree of orientation achieved by us, experiments on β-γ correlation can give no information concerning the conservation of combined parity. However, if one achieves temperatures of the sample of 0.01°K or lower, one can obtain up to 25% polarization of the nuclei and then the precision of the experiment will increase significantly. There is information in the literature concerning indirect cooling which reached a temperature of 0.015°K.[21] If one succeeds in obtaining still lower temperatures and maintaining them sufficiently long, one may count on successful correlation measurements with Sc^{46}.

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