Effective magnetic field at the ^{82}Kr nucleus in iron

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The effective magnetic field acting on ^{82}Kr nuclei imbedded in an iron matrix is measured by the integral perturbed-angular-correlation technique. Use is made of the 698–777 keV $\gamma\gamma$ cascade excited in ^{82}Kr following β decay of ^{82}Br. A value $B_{Kr}(Fe) = +(660 \pm 270)$ kG is obtained for the field from the experimental value of the angle of rotation of the angular correlation function $\omega_L \tau = (8.8 \pm 3.3) \times 10^{-3}$ rad by assuming that the g factor of the first excited 777-keV 2^+ level of ^{82}Kr is $g = 0.4$.

1. INTRODUCTION

The effective magnetic fields produced at atomic nuclei implanted in ferromagnets reach in some cases millions of gausses. These fields are extensively used to determine the magnetic moments of short-lived excited states of nuclei. In experiments of this type it is important to know the value of the magnetic field acting on the nucleus. The existing systematics of magnetic fields for atoms with different Z[1] points to a periodic variation of the magnitude and sign of the fields, thus indicating a connection between this field and the structure of the atomic shell. The complicated character of the phenomenon and the large number of factors that contribute to the field do not make a consistent theoretical analysis possible at present[2]. In view of the absence of a quantitative theory that makes it possible to calculate the effective magnetic field for arbitrary atoms, further experimental investigations are necessary.

The most complete experimental data are available for atoms with 3d, 4d, 5d, and 4f unfilled shells, implanted in iron, nickel, and cobalt. The effective fields for the d-elements are negative and vary relatively smoothly with Z. Balabanov and Delyagin[3] have derived a simple empirical rule that describes satisfactorily the fields of the d-elements of the periods IV, V, and VI. There are much less data for the s- and p-elements, especially in the region of noble gases. In these regions the field varies rapidly with Z, so that this empirical rule is difficult to use in this case.

We have attempted to determine the effective magnetic field at the ^{82}Kr nucleus in an iron matrix by the method of integral perturbed angular correlation[4], which makes it possible to determine both the magnitude and the sign of the field. The only data available for krypton and the neighboring elements are: $B_{Se}(Fe) > 400$ kG[5], $B_{Br}(Fe) \sim 180$ kG[6], $B_{Kr}(Fe) = 400^{+400}_{-300}$ kG[6]. The signs of the fields have not been established, nor are there any data for Rb and Sr.

2. EXPERIMENTAL PROCEDURE

The perturbed angular correlations were investigated using the $\gamma\gamma$ cascade in ^{82}Kr, which is excited by β decay of ^{82}Br ($T_{1/2} = 35.3$ hr). The decay scheme of ^{82}Br is shown in Fig. 1. The most convenient is the 698–777 keV cascade, since it has, according to[7], a large anisotropy ($A_2 = -0.27 \pm 0.06$; $A_4 = +0.25 \pm 0.08$), and the lifetime of the 777-keV 2^+ level is known, $T_{1/2} = (4.8 \pm 0.8) \times 10^{-12}$ sec[8]. The magnetic moment of the excited levels of ^{82}Kr are not known, but we can use the fact that the gyromagnetic ratio g of the first 2^+ levels of even-even nuclei have only a weak dependence on A and are close to Z/A. This is seen, for example, in Fig. 2, which shows the experimental values of $g(2^+)$ for A in the region 50–150, as given by Shirley[9]. We shall henceforth assume the value g = 0.4 for the 777-keV 2^+ level of ^{82}Kr.

Preparation of the ^{82}Br source in iron. The ^{81}Br atoms were implanted in iron foil of isotopically pure ^{56}Fe with the aid of an electromagnetic separator with ion energy 30 keV. The same separator was used for preliminary cleaning of the surface of the iron foil to rid it of the iron oxide by bombarding it with ^{56}Fe ions and to cover the surface of the foil with a protective layer of iron after the implantation of the ^{81}Br atoms. The dose of the implanted atoms was $\sim 5 \times 10^{15}$ atoms/cm^2. The iron foils were then bombarded in a reactor, in evacuated quartz ampoules, by a thermal-neutron flux of $\sim 6 \times 10^{13}$ neut/cm^2 sec for four days. The bombardment was carried out in a water channel at a temperature ~60°C. The γ spectrum of the source contained, in addition to the γ lines of ^{82}Br, only the 511 and 1340-keV γ lines belonging to ^{64}Cu (12.84), which made no noticeable contribution to the investigated ^{82}Kr cascade. Altogether we prepared 11 sources, with each of which the measurements were continued for 4–5 days. The iron foils were 11 × 5 mm in area and 3 μ thick.

The instrument. The foils were mounted in the gap

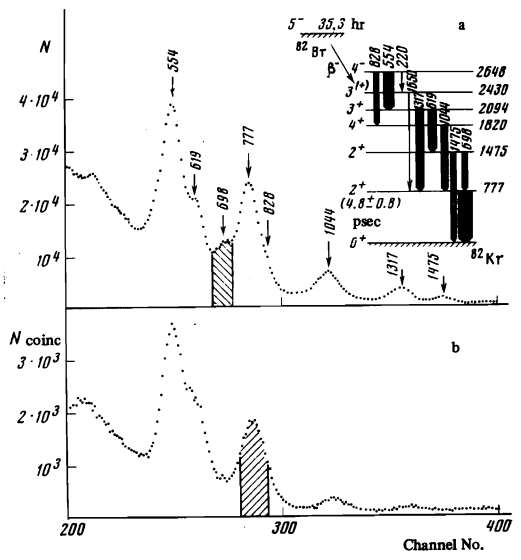

FIG. 1. Decay scheme of ^{82}Br, isolated γ spectrum (a) and spectrum of coincidences with 698-keV γ line (b).

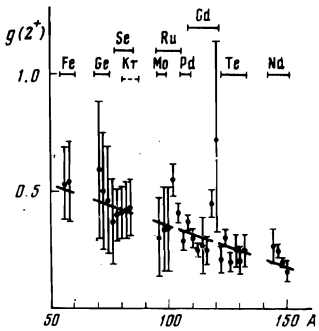

FIG. 2. The g-factors of the first 2^+ levels of even-even muclei.

of a miniature electromagnet that saturated the foil in a direction perpendicular to the plane of the detectors and of the source. The detectors were two NaI(Tl) (40 × 40 mm^2) crystals operating in conjunction with FÉU-93 photomultipliers. The photomultipliers were surrounded by permalloy screens to eliminate the effect of the stray magnetic field of the electromagnet. The distance from the source to the detector was 5 cm. We used a duplicated fast-slow coincidence circuit, in which both detectors were connected in symmetrical fashion, so that we measured the spectra of the coincidences from both counters. The spectra were registered with the 512 × 4 multichannel pulse-height analyzer of the Spectrometric Center of the Neutron Research Laboratory of our Institute. The electromagnet field direction was reversed automatically every 80 seconds and the coincidence spectra were registered separately for each direction of the field and for each counter (altogether four spectra).

Figure 1 shows the isolated γ spectrum of ^{82}Br and the spectrum of the coincidences with the 698-keV γ line. On the first of these spectra is marked the spectral region to which the window of the amplitude differential discriminator was tuned. On the second spectrum is shown the counting interval in which the summation was carried out to determine the intensity of the 777-keV line in the coincidence spectrum. The contributions of other cascade transitions to this interval did not exceed 20%. The positions of the window and of the counting interval remained unchanged in the succeeding experiments. The random-coincidence background was ~10% and was not registered separately.

3. MEASUREMENT OF PERTURBED ANGULAR CORRELATIONS

In the preliminary experiments we measured the angular correlation of the 698–777 keV cascade of ^{82}Kr (see Fig. 3). The obtained angular dependence agrees with the function $W(\theta)$ given in[7]; the point of the maximum slope of the function $W(\theta)$ is close to $\theta = 120°$. The measurements were subsequently carried out at $\theta_0 = 120°$ and $\theta_0 = 240°$. At these angles, we measured the influence of the change of the field direction on the photomultiplier by determining the intensities of the 777-keV line $n_\uparrow$ and $_\downarrow$ in the isolated spectra measured for two opposite field directions. The results were:

$$\delta(120°)=\frac{2(n_\uparrow-n_\downarrow)}{n_\uparrow+n_\downarrow}=-(3\pm5)\cdot10^{-4},\quad \delta(240°)=-(2\pm5)\cdot10^{-4}.$$

This was followed by measurements of the rotation of the total integral angular correlation in the magnetic field using ten ^{82}Br sources in Fe. The coincidences

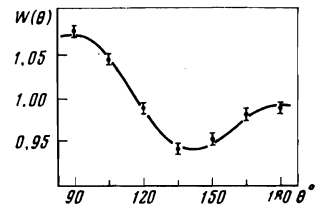

FIG. 3. Angular correlation of the 698–777 keV cascade of ^{82}Kr.

$N_\uparrow$ and $N_\downarrow$ accumulated for each field direction amounted to ~10^6. The following values were obtained:

$$R(120°)=\frac{2(N_\uparrow-N_\downarrow)}{N_\uparrow+N_\downarrow}=+(35\pm14)\cdot10^{-4},\quad R(240°)=-(21\pm15)\cdot10^{-4}$$

(the sign of the effect should change on going from 120 to 240°).

Taking into account the experiments on the influence of the field on the photomultiplier, the average value of R is $\bar{R} = (29 \pm 11) \times 10^{-4}$. Thus, the effect of the perturbation is very small. For such weak perturbations, the angular-correlation function in the presence of a static transverse magnetic field B can be written in the form

$$W(\theta,B)=\sum_k A_{kk}P_k[\cos(\theta\pm\omega_L\tau)],$$

where $\omega_L = -g\mu_{nuc}B/\hbar$. The shift of the function for two opposite field directions is therefore

$$R(\theta_0)=\frac{2(W_\uparrow-W_\downarrow)}{W_\uparrow+W_\downarrow}=2\omega_L\tau k(\theta_0),\ k=\frac{1}{W}\frac{\partial W}{\partial\theta}\Big|_{\theta=\theta_0}$$

(k is the slope of the angular-correlation function).

One of the ^{82}Br sources in Fe was used entirely for the experimental determination of the slope k. We measured here the number of coincidences $N_{+\Delta\theta}$ and $N_{-\Delta\theta}$ at counter positions corresponding to the angles $= 120° \pm \Delta\theta$ ($\Delta\theta = 7.5°$). The slope was

$$k(\theta_0)=\frac{2(N_{+\Delta\theta}-N_{-\Delta\theta})}{(N_{+\Delta\theta}+N_{-\Delta\theta})\cdot2\Delta\theta}=(0.163\pm0.013)\ \text{rad}^{-1}.$$

The slope measured by us with $\Delta\theta = 7.5°$ differs from the true one by not more than 5%. From the measured values of R and k we determined the angular shift of the correlation curve $\omega_L\tau = (8.8 \pm 3.3) \times 10^{-3}$ rad.

This method of determining $\omega_L\tau$ by measuring the shift R and the slope k under the same experimental conditions makes it possible to take into account automatically several factors: 1) the geometrical corrections connected with the finite dimensions of the detectors and the source; 2) the random-coincidence background; 3) the contribution of the coincidences of the harder 828-, 1044-, and 1317-keV γ lines, the Compton distribution of which falls in the discriminator window, with the 777-keV line. All the foregoing γ transitions, as well as the 698-keV transition, go to the 777-keV level of ^{82}Kr (see Fig. 1), meaning that the relative contributions of the corresponding cascades to R and to k will be the same.

What remains unaccounted for is the effect exerted on R by the coincidences of the 777-keV γ line, which falls in part in the discriminator window, with the 698-, 828-, 1044-, and 1317-keV lines. However, the contribution of these lines to the counting interval is 20%, and the correction to R (on the higher side) will be <20% and is disregarded.

If we assume g = 0.4, then we obtain for the effective magnetic field at the Kr nucleus in iron

$$B_{Kr}(Fe) = +(660 \pm 270)\ \text{kG}.$$

The sign of the field is determined from the direction of the rotation of the angular-correlation function relative to the direction of the external magnetic field. The measurement error, unfortunately, is large, owing to the very small lifetime of the intermediate level.

4. CONCLUSION

It is known that the method of integral perturbed correlations is now sensitive to the presence of a possible distribution of the fields at the impurity atoms, which can occur as a result of differences in the localizations of the impurity atoms in the lattice iron. The distribution of the positions of the impurity atoms is affected by a number of factors, such as the concentration of the atoms, formation of defects following implantation of the ions and neutron bombardment, the possible low-temperature annealing, and formation of an oxide film on the surface of the iron foil. The method of implanting impurity ions and the subsequent reduction of the samples can therefore influence noticeably the results of the measurements of the effective field. Consequently, the obtained value of the field is a certain average value of the effective field for the krypton atoms introduced into the iron by the method described above.

For noble gases, we have at present the following values of the effective magnetic fields in iron:

$$B_{Kr}(Le) = +(660 \pm 270)\ \text{kG},$$
$$B_{Xe}(Fe) + (1010 \pm 40)\ \text{kG}\ [^{10}],\quad B_{Rn}(Fe) = +(920 \pm 85)\ \text{kG}\ [^{11}].$$

The sign of the field in Xe has not been determined, but the data on the neighboring elements indicate that it is probably positive. Thus, it can be presently regarded as established that large positive fields are induced at the nuclei of noble gases in iron.

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