Hyperfine interactions of light nuclei recoil-implanted into iron

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The perturbed integral angular distribution technique has been used to study hyperfine interactions of light nuclei recoil-implanted into iron. Heavy-ion-induced fusion-evaporation reactions populated the excited states of ^{37}Ar, ^{39,40,41}K, and ^{41}Ca, whose deexciting γ rays were observed in a Ge(Li) detector. In all cases the measured shifts of the angular distributions were found much smaller than the ones calculated using the known values of g factors, lifetimes, and strengths of the internal hyperfine fields. This can be explained under the assumption that only a fraction of the nuclei feel the full internal magnetic field, while the rest of them do not feel any magnetic interaction at all. Different fractions obtained for ^{40}K and ^{41}K suggest a migration process on a ns time scale of the implanted ions in the lattice.

[NUCLEAR REACTIONS ^{28}Si(^{14}N, xn, yp)^{37}Ar, ^{39}K, ^{40}K; ^{27}Al(^{16}O, xn, yp)^{41}K, ^{41}Ca; E=30–35 MeV. Measured $I_\gamma(\theta, H)$. Deduced H_{hyp} at Ar(Fe), K(Fe), Ca(Fe).]

I. INTRODUCTION

The implantation perturbed angular correlation (IMPAC) technique is widely used for g-factor measurements.[1,2] In this method excited states are populated by means of heavy-ion Coulomb excitation, and they are recoil-implanted into a ferromagnetic material. The interaction of the magnetic moment of the implanted nuclei with a large magnetic field is measured as a perturbation of the angular correlation between a γ ray emitted from the excited state and a backscattered particle.

Many excited states with lifetimes in the nanosecond range can be produced in nuclear reactions and implanted into ferromagnetic foils. Hence, in principle, the implantation perturbed angular distribution (IMPAD) method of deexciting γ rays can be applied to the observation of hyperfine (hf) interactions and the determination of nuclear magnetic moments.

There have been very few measurements[3–5] of this type performed so far, all using light particle reactions. For lifetimes longer than a few nanoseconds, the more precise differential method would usually be preferred. The Fourier analysis of the precession frequency obtained in this way can give a complete picture of the distribution of magnetic fields acting on implanted nuclei. Unfortunately the differential method cannot be applied for excited states having lifetimes shorter than a few nanoseconds, and the only way to measure the hf interaction is to observe the integral shift of the angular distribution pattern of the deexciting γ rays.

In the experiments reported here the integral IMPAD method was used for the determination of hf interaction of some light nuclei around A = 40, recoil-implanted into iron by heavy-ion induced reactions. For the proper interpretation of the experimental results, the fate of implanted atoms should be known at least approximately.

It should be stressed that most of the methods of hf-interaction measurements, such as ME, NO, NO/NMR, PAC, deal with the lattices which have sufficient time to anneal after the implantation process. This means that atoms implanted in different lattice sites have the opportunity to migrate and to change their initial positions and surroundings. This is not the case for the IMPAD method, where the observation time after implantation is defined by the short lifetime of the nuclear excited states of implanted nuclei. This can drastically change the internal magnetic effects on implanted nuclei.

II. EXPERIMENTAL PROCEDURE

The experiments were carried out with the heavy-ion beam of the Emperor tandem accelerator of the Centre de Recherches Nucléaires in Strasbourg. The beams of ^{14}N and ^{16}O ions, of 30–35 MeV energy and 20 nA intensity, were used to bombard ^{27}Al and ^{28}Si targets. The targets evaporated on 20 mg/cm^2 iron backings were about 200 μg/cm^2 thick.

Investigated nuclear states and the reactions used for their production are listed in Table I. The target backings were magnetized in a 1.3 kG external field. The angular distributions of the γ rays were measured for up and down magnetizing field directions, the γ rays being detected with a 70 cm^3 (or 56 cm^3) Ge(Li) detector with an energy resolution of 3 keV for 1.33 MeV γ rays. The detector was placed at the angles −40°, −30°, 0°, 30°, 45°, 60°, 90°, and 120° in the reaction plane. The resulting spectra were normalized with the readings of a fixed detector. The γ-ray intensities were calculated using a Gaussian fit program. The experimental rotations of some of the angular distribution patterns are shown in Fig. 1.

III. ANALYSIS OF THE RESULTS

The experimental angular distributions were analyzed using the integral formula:

$$W(\theta, H) = 1 + \sum_k b_k' \cos k(\theta - \Delta\theta_k), \qquad (1)$$

where $\Delta\theta_k = (1/k)\arctan k\omega\tau$ are angular shifts of the distribution pattern. As b_4 coefficients were always negligible for all investigated cases in comparison with b_2, these terms were neglected in the further analysis.

The parameters obtained by least squares fitting, together with other relevant data, are listed in Table II. In this table, the $(\omega\tau)_{obs}$ deduced from the experimental angular shifts of the γ-ray distributions are compared with the expected values of $\omega\tau$ calculated from the known g factors, lifetimes, and effective field strengths. The values of the internal fields in iron were taken from Ref. 9, with the exception of the argon case, for which the field value was deduced from the value obtained in nickel[10] using the ratio of iron and nickel local magnetic moments. All observed values $(\omega\tau)_{obs}$ are much smaller than the expected ones. Especially striking is the case of ^{40}K and ^{41}K, for which the $(\omega\tau)_{obs}$ are nearly equal, while the ratio of the calculated values is 18. This disagreement can be explained if it is assumed that there are at least two different magnetic fields acting on implanted nuclei. Under this assumption ($H_1 + H_2$ model) the $(\omega\tau)_{obs}$ can be expressed by the following formula:

$$(\omega\tau)_{obs} = \frac{f[1+(2\omega_2\tau)^2]\omega_1\tau + (1-f)[1+(2\omega_1\tau)^2]\omega_2\tau}{f[1+(2\omega_2\tau)^2] + (1-f)[1+(2\omega_1\tau)^2]}, \qquad (2)$$

TABLE I. Investigated nuclei and nuclear reactions used for their production.

Nucleus	E_x (keV)	E_γ (keV)	J^π	τ (ns)	Reaction
^{37}Ar	1611	1611	$\frac{7}{2}^-$	6.3 (2)	^{28}Si + ^{14}N
^{39}K	2814	2814	$\frac{7}{2}^-$	72 (7) ps	^{28}Si + ^{14}N
^{40}K	2543	1651	$5, 7^+$	1.5 (3)	^{28}Si + ^{14}N
^{41}K	1294	1294	$\frac{7}{2}^-$	10.4 (3)	^{27}Al + ^{16}O
^{41}Ca	3830	460	$(\frac{15}{2}^+)$	4.4 (5)	^{27}Al + ^{16}O

where ω_1, ω_2 are the precession frequencies in the magnetic fields H_1 and H_2, and f is the fraction of implanted atoms located in positions where atoms experience the magnetic field H_1.

It is found that the experimental value $(\omega\tau)_{obs}$ cannot be reproduced for any f unless the intensity of one of the magnetic fields is nearly zero. For the sake of simplifying further treatment, we assume that a "$H + 0$" model is adequate. This

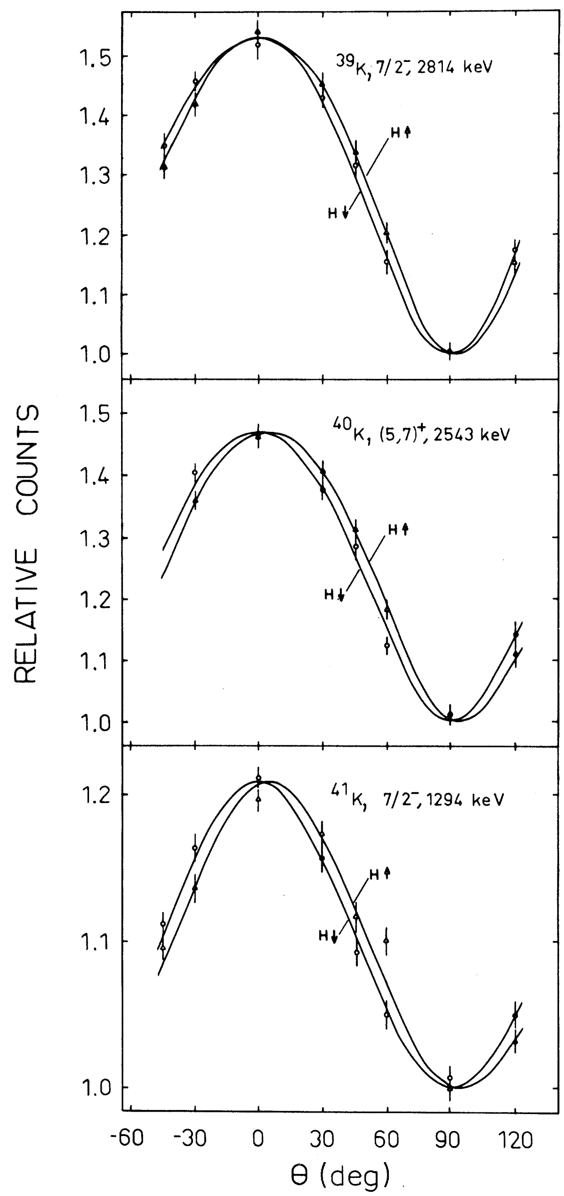

FIG. 1. Examples of γ-ray angular distributions for nuclei implanted into iron: ^{39}K, $\frac{7}{2}^-$, 2814 keV state; ^{40}K, $(5, 7^+)$, 2543 keV state, and ^{41}K, $\frac{7}{2}^-$, 1294 keV state. The curves are computer fits to the experimental points.

TABLE II. Observed and calculated parameters describing the investigated hf interaction.

	E_x (keV) J^π	g	H_{int} (kOe)	$\omega\tau$ ($\times 10^{-3}$)	$(\omega\tau)_{obs}$ ($\times 10^{-3}$)	b_2' (%)	$\langle b_2\rangle$ [a] (%)	f (%) from $(\omega\tau)_{obs}$	f (%) from b_2'/b_2
^{37}Ar	1611 $\frac{7}{2}^-$	−0.377 (10)	1020	12 000	496 (87)	4.5 (4)	13.6 (8)	96^{+4}_{-7}	73^{+11}_{-10}
^{39}K	2814 $\frac{7}{2}^-$	1.5 (3)	−150 (19)	78 (18)	26 (10)	22.5 (10)	22.7 (6)	34^{+27}_{-17}	0–100
^{40}K	2543 $5, 7^+$	0.57 (10) [b]	−150 (19)	610 (160)	44 (14)	20.3 (6)	19.7 (10)	17 ± 5	0–100
^{41}K	1294 $\frac{7}{2}^-$	1.29 (3)	−150 (19)	9610 (840)	47 (14)	9.7 (5)	21.6 (8)	66^{+6}_{-12}	55 ± 6
^{41}Ca	3830 $(\frac{15}{2}^+)$	0.28 (4) [c]	−100 (9)	600 (100)	253 (48)	14.3 (14)	21.1 (8)	65^{+7}_{-9}	62^{+38}_{-21}

[a] Mean values deduced from Ref. 8.
[b] From Ref. 6, IMPAD measurement in the external magnetic field.
[c] From Ref. 7, IMPAD measurement in the external magnetic field.

means that a fraction f of the nuclei feel the full internal magnetic field H, while the rest do not feel any magnetic interaction at all. In this case Eq. (2) simplifies to the form

$$(\omega\tau)_{obs} = \frac{f\omega\tau}{1+(1-f)(2\omega\tau)^2}\,. \tag{3}$$

Figure 2 shows the dependence of $(\omega\tau)_{obs}$ vs $\omega\tau$ for different values of the fraction f.

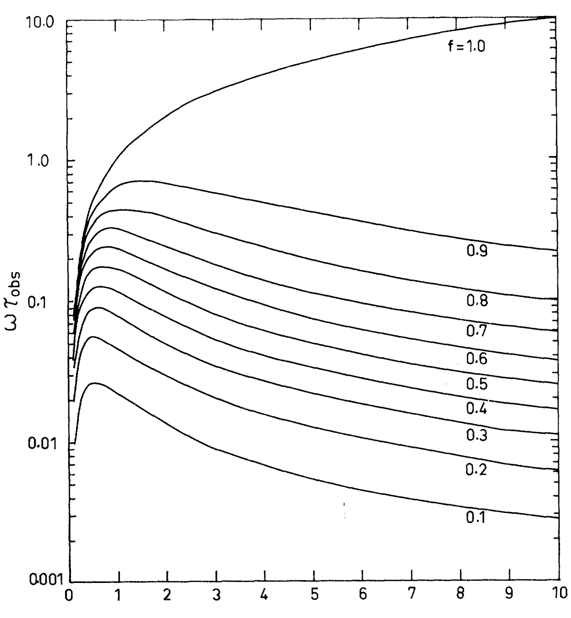

FIG. 2. Dependence of observed value $(\omega\tau)_{obs}$ vs $\omega\tau$, for different values of the fraction f, as calculated from Eq. (3).

Another source of information on f is the ratio b_2'/b_2 of the observed to the unperturbed angular distribution coefficients. This ratio is given by the relation

$$\left(\frac{b_2'}{b_2}\right)^2 = (1-f)^2 + \frac{f}{1+(2\omega\tau)^2}(2-f)\,. \tag{4}$$

The fraction f for the investigated cases were calculated in both ways, using the expressions (3) and (4). The results are shown in Fig. 3. It can be seen that the observed angular shifts give a more precise value of f, but in general, the values deduced in the two ways agree reasonably well. The exception is ^{37}Ar, for which the dis-

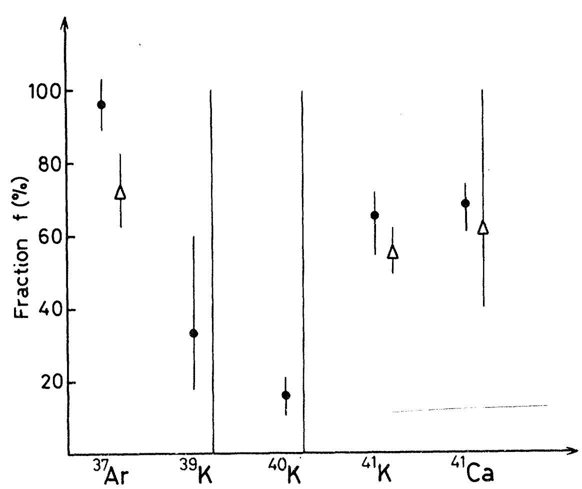

FIG. 3. Experimental values of fraction f deduced from observed values $(\omega\tau)_{obs}$ (black points) and from observed b_2' coefficients of the angular distributions (triangles).

agreement is well outside the error limits. Agreement can be achieved by assuming that the internal magnetic field acting in iron on argon nuclei is lower than the 1020 kOe used for the evaluation of the results. It should be about 300 kOe. The fraction f found for ^{41}Ca in our experiment is slightly larger than that obtained in a channeling experiment (cited in Ref. 5). In experiments [5,10] using light particle reactions it was also suggested that a large fraction of the implanted nuclei do not experience the hyperfine field. Marmor, Cochavi, and Fossan[11] pointed out that strong relaxation processes possibly due to radiation damage could also be responsible for the observed attenuation of the correlation coefficients.

For the two potassium isotopes ^{40}K and ^{41}K different f values were obtained. This was unexpected, as the recoil-implantation conditions were similar. It should be noted, however, that the higher value of f corresponds to the longer-lived nuclear state. It may be that the location of implanted ions changes in less than 10 ns, which is the lifetime of the ^{41}K excited state. During the 1.5 ns corresponding to the lifetime of the ^{40}K excited state, a smaller number of nuclei may reach positions where the full magnetic field acts.

Unfortunately the results for ^{39}K cannot be used to check this suggestion because of large statistical errors, and also because of the contribution of γ-ray cascades from higher lying states having lifetimes of the same order as that of the 2814 keV state.

Assuming that the migration of nuclei from the position without magnetic field to one of full magnetic field is responsible for the observed difference in f for the potassium isotopes, and that this migration follows an exponential law characterized by a mean migration time τ_m, the following formula for $(\omega\tau)_{\text{obs}}$ can be derived:

$$(\omega\tau)_{\text{obs}} = \omega\tau \frac{1-(\tau_\mu/\tau)^2(1-f_0)[1+(2\omega\tau)^2]/[1+(2\omega\tau_\mu)^2]}{1+(\tau_\mu/\tau)(1-f_0)(2\omega\tau_\mu)^2[1+(2\omega\tau)^2]/[1+(2\omega\tau_\mu)^2]}. \quad (5)$$

Here f_0 is the initial fraction of implanted atoms located in the positions where they experience the magnetic field, so that $f=1-(1-f_0)e^{-t/\tau_m}$ and $\tau_\mu = \tau\tau_m/\tau + \tau_m$.

Using the potassium data and formula (5) one finds a migration time of a few nanoseconds and an initial fraction of nuclei experiencing the full field close to zero. This result is disquieting in view of the wide use of the Coulomb-excitation implantation for determining $\omega\tau$. One has to notice that in the case of nuclear reactions the investigated states can be fed by several energetic γ-ray transitions. If this feeding time is longer than the stopping time of implanted nuclei, the recoil due to the preceding γ-ray emission could influence the final location of the implanted ion in the lattice.

The results of this work show that the proper evaluation of data for recoil-implanted nuclei obtained by integral measurements can be performed only for small $\omega\tau$. For $\omega\tau$ higher than about 0.2 rad, even with the knowledge of the fraction f, the analysis of experimental data becomes ambiguous as can be seen on Fig. 2. The existence of time dependence of fraction f in the nanosecond region implies that the determination of the g-factor ratio for two excited states of the same element cannot be deduced with confidence when the lifetimes are different.

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