Low temperature nuclear orientation of ^{93,94,95}Tc, ^{93}Mo^{m}, ^{109,111}In, and ^{110}In^{m}

I. Berkes, G. Marest, and R. Haroutunian

Institut de Physique Nucléaire, Université Claude Bernard Lyon-I and IN2P3 43, Bd du 11 Novembre 1918-69621 Villeurbanne, France

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^{93}Tc (2.8 h), ^{94}Tc (5 h), ^{95}Tc (20 h), ^{93}Mo^{m} (7 h), ^{109}In (4.2 h), ^{110}In^{m} (5 h), and ^{111}In (2.8 day) radioactive nuclei implanted by recoil into iron foils have been oriented at low temperature in a ^{3}He-^{4}He dilution refrigerator. The following values have been established: $|\mu(^{93}\mathrm{Tc}^{g})| = [6.2(^{+11}_{-4})]\mu_N$, $I(^{94}\mathrm{Tc}^{g}) = 7$, $|\mu(^{94}\mathrm{Tc}^{g})| = [5.03(30)]\mu_N$, $|\mu(^{110}\mathrm{In}^{m})| = [4.64(35)]\mu_N$, $I^{\pi}(^{93}\mathrm{Mo}, 1520\ \mathrm{keV}) = 7/2^{+}$, $\delta(E2/M1)$ in ^{93}Mo: $\delta(1363$ keV; $7/2 \rightarrow 5/2) = 0.48(^{-8}_{+6})$, $0.7 \leq \delta(1520$ keV; $7/2 \rightarrow 5/2) \leq 1.9$; in ^{94}Mo: $\delta(449$ keV;$6^{+} \rightarrow 6^{+}) = 0.0(^{+2}_{-1})$ or 0.7(2), $\delta(916$ keV;$6^{+} \rightarrow 6^{+}) = -0.07(^{+7}_{-5})$ or 0.8(1); in ^{95}Mo: $\delta(765$ keV;$7/2^{+} \rightarrow 5/2^{+}) = 0.11(12)$; in ^{109}Cd: $\delta(205$ keV;$7/2^{+} \rightarrow 5/2^{+}) = -0.13(4)$; in ^{110}Cd: $\delta(M2/E1;997$ keV;$5^{-} \rightarrow 4^{+}) = -0.025(^{+35}_{-75})$. Measured moments are compared with j^{n} coupling predictions. Intermediate state reorientation due to randomly oriented quadrupole interaction has been observed for the 247 keV state of ^{111}Cd.

[RADIOACTIVITY ^{93,94,95}Tc from Nb(α, xn), ^{93}Mo^{m} from ^{93}Nb($\alpha, p3n$), ^{109,111}In, ^{110}Im^{m} from Ag(α, xn), implanted into iron; measured $I_{\gamma}(B, T, \theta)$ oriented nuclei; deduced magnetic moments, mixing ratios J^{π} values; Ge(Li) detectors.]

I. INTRODUCTION

In spherical odd nuclei near to closed shells, ground state nuclear gyromagnetic ratios are expected to have values close to the Schmidt values and not to vary appreciably with respect to the number of even nucleons; in odd-odd nuclei the additivity of neighboring odd moments should hold. The slight variation of g factors is expected also for $I = j - 1$ three-quasiparticle states. The $40 \leq Z \leq 50$ region offers a good tool for such investigations, as $g_{9/2}$ proton states have large nuclear moments. Recently a certain number of $g_{9/2}$ proton moments have been measured using the low temperature nuclear orientation technique.[1-3] Other values concerning In nuclei are tabulated in compilations, but some of them are still unpublished.[3,4]

The experimenter is confronted with two difficulties in measuring isotopic or isotonic chains: The lifetimes of radioactive nuclei decrease the farther they are from the stability valley, and hyperfine interactions in unknown alloys sometimes make uncertain the evaluation of magnetic moments. We will discuss these points in Secs. II B and III. Preliminary evaluations and some results of this work were presented at the International Meeting on Hyperfine Interactions in Leuven, 1975.[5]

II. EXPERIMENTAL

A. Sample preparation

^{93,94,95}Tc have been prepared by recoil implantation into 1 μm thick iron foils by the ^{93}Nb(α, xn)Tc reactions with the internal α beam of the synchrocyclotron at Lyon. Simultaneously we also produced ^{93}Mo^{m} from ^{93}Nb($\alpha, p3n$). The α-particle-produced radioactive background in the iron foil was weak as compared with Tc and ^{93}Mo^{m} activities. The only foreign atoms introduced into the iron lattice are the radioactive nuclei and elastically scattered Nb nuclei. Estimated impurity concentration in the iron host is thus five orders of magnitude lower than in the usual isotope-separator implantation, and Tc and Mo can be considered as dilute impurities in Fe. Iron foils were soft-soldered to the cold finger of the dilution refrigerator (solder being applied on the back side of the iron foil with respect to implantation), together with a ^{60}CoFe nuclear thermometer.

^{109,111}In and ^{110}In^{m} have been prepared in the same manner as radioactive Tc, with the Ag(α, xn)In reaction. In the 5 μm thick iron foils ^{56,58}Co activities have also been produced. Orientation of ^{58}Co confirmed that the temperature in the sample foil and in the ^{60}CoFe thermometer were the same.

B. Nuclear orientation

Cooling down of samples to low temperature (down to 15 mK) was performed with a ^{3}He-^{4}He dilution refrigerator. To achieve cooling-down times comparable to the period of radioactive sources (a few hours) and to enable easy sample changing, Kerley (Oxford Instruments Co.) developed on our request a top-loading facility which allows cooling to about 20 mK in three hours. The cooling power at 26 mK was about 3 μW, and the continuous operation base temperature 15–16 mK.

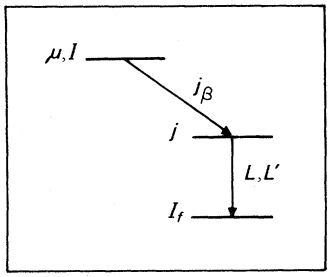

FIG. 1. Nuclear parameters entering in nuclear orientation experiments.

A split coil superconducting magnet polarized the sample with 0–6 T field.

C. Hyperfine field considerations

The hyperfine magnetic field $\underline{B}_{\rm hf}$ in dilute ferromagnetic alloys is known for a large number of elements.[6] The angular distribution of a radiation emitted by oriented nuclei is as follows:

$$W(\theta)=\sum_k B_k\left(\frac{\mu\underline{B}}{kTI}\right)U_k(j_\beta,I,j)A_k(j,L,L',I_f)P_k(\cos\theta), \tag{1}$$

where B_k are orientation parameters, T is the absolute temperature, A_k are the distribution coefficients, and U_k are attenuation factors due to unobserved intermediate transition. Other quantities are defined in Fig. 1.

In an implanted source or in an imperfect alloy the use of Eq. (1) is not unambiguous. A "bad alloy" may modify the angular distribution in several ways.

(i) The magnetic field acting on the nuclei is not the same for each site. The B_k parameters must be modified to

$$B_k=\sum_i a_i B_{ki}\left(\frac{\mu\underline{B}}{kTI}\right), \tag{2}$$

where summation on i is applied to all possible effective field values whose probabilities are a_i. An often used approximation (disregarding demagnetizing field) is

$$\underline{B}_1=\underline{B}_{\rm hf}\pm\underline{B}_{\rm ext},\quad \underline{B}_2=\underline{B}_{\rm ext},$$
$$a_1=a,\quad a_2=(1-a), \tag{3}$$

where $\underline{B}_{\rm hf}$ is the correct internal field.

(ii) Nuclei experience an electric field gradient (interstitial position with respect to iron matrix, vacancy association, or noncubic intermetallic compound in a nondilute alloy). The electric quadrupole alignment is superposed on the magnetic polarization. As this electric quadrupole interaction has random orientation, the B_k orientation parameter becomes

$$B_k'=B_k g_k,\quad \text{where } g_k\leq 1. \tag{4}$$

g_k depends on ω_m/ω_E and T, where $\hbar\omega_m=\gamma\underline{B}$ and $\hbar\omega_E=\{3eQ/[4I(2I-1)]\}V_{ZZ}$, are the magnetic and axially symmetric electric coupling energies of oriented nuclei.

(iii) If the intermediate state's lifetime τ is comparable to or longer than $1/\Omega_m$ of the intermediate state [Ω for the intermediate state is defined in the same way as ω for the oriented one in (ii)], and a randomly oriented quadrupole perturbation Ω_E is not negligible as compared with Ω_m, the distribution coefficients A_k will be attenuated on account of intermediate state reorientation[7]:

$$A_k'=A_k G_k. \tag{5}$$

In presence of (i), (ii), and (iii) the angular distribution takes the form

$$W(\theta)=1+\sum_{k=2}^{k_{\max}} aB_k g_k G_k A_k P_k(\cos\theta). \tag{6}$$

The product $aB_k g_k$ is the same for every transition of the same nucleus, whereas $G_k A_k$ depends on the considered transition.

The term $C=ag_k$ can be approached experimentally, observing simultaneously with the unknown nuclide the orientation of another isotope of the same element with known nuclear parameters, or the orientation of another element with similar metallurgical properties. The validity of this "magnetometry" is shown in Fig. 2. The spins are those of $^{110}\text{In}^m$ and ^{111}In. The figure shows clearly that the two very different assumptions [assumption α: mean effective field equals half of the correct h.f. field, assumption β: see Eq. (3)] give different orientation curves, but the deviation between $I=7$ and $I=\frac{9}{2}$ curves is negligible as long as $T>15$ mK. For $^{110}\text{In}^m$ and ^{111}In we checked the validity of assumptions α and β and only the second one was found to be compatible with experimental results. Intermediate state reorientation can be neglected for high hyperfine magnetic coupling energies or short intermediate state lifetimes.

D. Data collection and evaluation

γ-ray spectra were accumulated with two 52 cm^3 Ge(Li) counters at 0° and 90° angles with respect to the field polarization axis. The pulse height spectra collected every 5, 10, or 20 minutes were registered on a magnetic tape. Source lifetimes and cooling down time being of the same order, $I(0°)/I(90°)$ ratios were fitted to Eq. (1). This method eliminates the need for hazardous

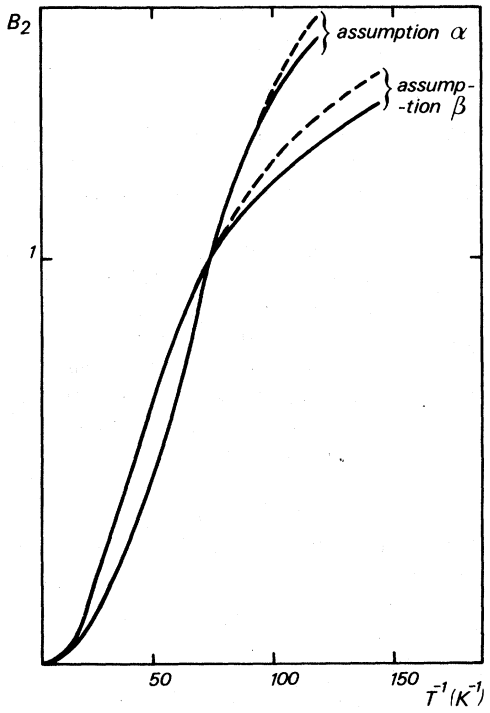

FIG. 2. B_2 orientation parameter for $I=7$ (full line) and $I=\frac{9}{2}$ (discontinuous line). α: $B_{2\alpha}=B_2(\frac{1}{2}\underline{B}_1)$: 50% effective field. β: $B_{2\beta}=\frac{1}{2}B_2(\underline{B}_1)$: $\underline{B}_1$ effective field acting on 50% of nuclei.

decay corrections. Counting ratios were corrected for the difference of dead times in the pulse height converters and the result for finite solid angles of detectors. For long-lifetime sources several cooling cycles with successive heating up to 1 K have been performed to check the absence of overall instability effects in the device.

III. RESULTS

A. ^{95}Tc ($T_{1/2}$ = 20 h) and the hyperfine field on Tc sites in Tc*Fe*

The magnetic moment of ^{95}Tc has been measured with great accuracy using resonant destruction of nuclear orientation (NMR/ON) by Hagn, Kienle, and Eska.[2] From the resonance frequency the magnetic energy is $\mu\underline{B}=9.4214\times10^{-25}$ J. This value has been used to fit the orientation of the 1074 keV $\frac{7}{2}^+\rightarrow\frac{5}{2}^+$ transition. The $\delta(E2/M1)$ mixing ratio is known from Coulomb excitation experiment[8]: $\delta=-0.72(11)$. The mean value of C for three sources, determined according to Eq. (3) is $C=0.92(5)$. This error includes also the error on δ. For the 765 keV $\frac{7}{2}^+\rightarrow\frac{5}{2}^+$ transition we can derive $\delta(E2/M1)=0.11(12)$. (The phase convention of the Delft conference is used.[9])

B. ^{94}Tc ($T_{1/2}$ = 5 h)

The simplified decay scheme used for evaluations is represented on Fig. 3. Three $E2$ transitions (the cascade $6^+\rightarrow4^+\rightarrow2^+\rightarrow0^+$) allow a simple one-parameter fit using C derived previously. Statistical accuracy of these fits is very high and the result shows a slight scatter of C (of the order of 2%) among different sources. To avoid introducing systematic error in evaluation, the C value derived for each source from ^{95}Tc is used in the corresponding fit for ^{94}Tc.

For the evaluation of the magnetic moment we supposed that $I^\pi(^{94}\text{Tc})=7^+$ or 6^+. The β transitions are assumed to be of $j_\beta=1$ nature. [A small admixture of $j_\beta=0$ would not affect the validity of the results as

$$U_2(7\xrightarrow{j_\beta=1}6)=0.96$$

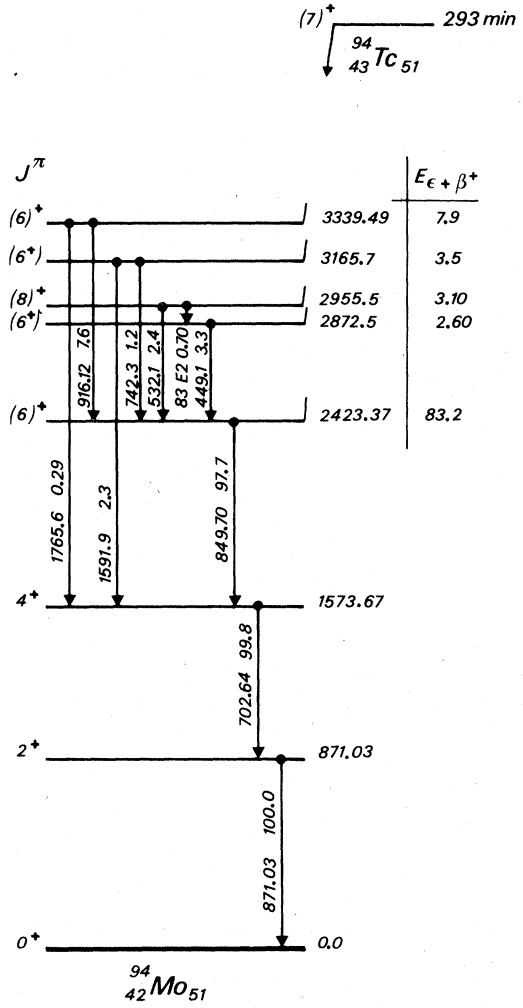

FIG. 3. Decay scheme of ^{94}Tc based on Ref. 10.

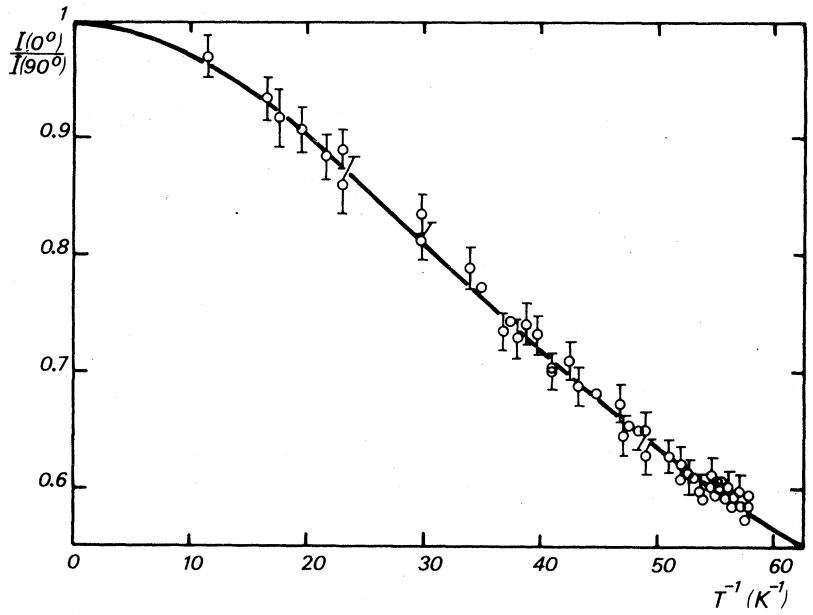

FIG. 4. $I(0°)/I(90°)$ anisotropy of the 849 keV $6^+ \rightarrow 4^+$ transition in the ^{94}Tc decay versus inverse temperature, showing best fit (one of the runs). Standard errors are shown on some measured points.

is already very close to unity.] The $\delta(E2/M1)$ ratios for the 916 and 449 keV transitions were derived from this measurement: The quoted error of $\mu(^{94}\mathrm{Tc})$ accounts for the ambiguity of these mixing ratios too (see below). From the fit of the three $E2$ transitions we find $|\mu\underline{B}| = 8.14(48)\times10^{-25}$ J, if $I(^{94}\mathrm{Tc}^g) = 7$ and with $\underline{B}_{\mathrm{hf}} = 32.03(6)$ T, $|\mu(^{94}\mathrm{Tc}, 7^+)| = [5.03(30)]\mu_N$. A similar evaluation, supposing $I(^{94}\mathrm{Tc}^g) = 6$ would yield $|\mu(^{94}\mathrm{Tc}, 6^+)| = [5.22(30)]\mu_N$.

Recently the orientation group of Munich determined by NMR/ON that the g factor of ^{94}Tc was $g(^{94}\mathrm{Tc}^g) = 0.733(8)$.[11] The ratio $\mu/g\mu_N = I$ gives the spin of the decaying ground state: Supposing $I = 7$ with $\mu = [5.03(30)]\mu_N$ we find $I = 6.86(41)$, supposing $I = 6$ with $\mu = [5.22(30)]\mu_N$ we find $I = 7.12(43)$. Only the first assumption is consistent. The spin (7) was assigned to $^{94}\mathrm{Tc}^g$ by compilers of NDS mainly on the basis of weak arguments (decay scheme intensities). Our measurement establishes this assignment definitively.

The established spin and moment values agree with those determined for ^{96}Tc by Fox *et al.*,[12] corrected for the hyperfine field used in our evaluation: $\mu(^{96}\mathrm{Tc}^g) = [4.98(10)]\mu_N$. Knowing the spin of $^{94}\mathrm{Tc}^g$, the angular distribution of the 849.7 keV radiation allows one to confirm the assignment 6^+ to the 2423.4 keV state of ^{94}Mo. Figure 4 shows a curve fitted to one series of measurements. Fitting on the 1590 keV $6^+ \rightarrow 4^+$ $E2$ radiation, whose orientation is not affected by the unobserved intermediate radiation, we find $|\mu(^{94}\mathrm{Tc}^g)| = [4.99(41)]\mu_N$, in good agreement with the previous result.

On account of the good statistical weight of the three $E2$ radiations, a two-parameter fit on $\mu(^{94}\mathrm{Tc}^g)$ and C can be also performed. It yields

$$|\mu(^{94}\mathrm{Tc}, 7)| = 4.98(^{+52}_{-28}) \quad \text{and} \quad C = 0.96(^{-10}_{+4}),$$

where the upper and lower deviations are correlated, respectively. The good agreement of these values with the preceding determinations shows the internal consistency of our magnetometry. The δ $(E2/M1)$ mixing ratios derived from the fits with above nuclear magnetic moment are as follows:

$$449 \text{ keV } (6^+ \rightarrow 6^+), \quad \delta = 0.0(^{+2}_{-1}) \text{ or } 0.7(2);$$

$$916 \text{ keV } (6^+ \rightarrow 6^+), \quad \delta = -0.07(^{+7}_{-5}) \text{ or } 0.8(1).$$

C. ^{93}Tc ($T_{1/2} = 2.8$ h)

The decay scheme of $^{93}\mathrm{Tc} + ^{93}\mathrm{Mo}^m$ is shown on Fig. 5. The only $E2$ transition in the decay of ^{93}Tc(1477 keV) is fed, unfortunately, also by the $^{93}\mathrm{Mo}^m$ decay formed simultaneously in the source. As our orientation measurement is incompatible with $\frac{9}{2}^+$ assignment to the 1363 and 1520 keV states, only the 1363 keV $(\frac{7}{2}^+ \rightarrow \frac{5}{2}^+)$ and the 1520 keV $(\frac{7}{2}^+ \rightarrow \frac{5}{2}^+)$ $M1 + E2$ γ rays can be used for evaluation. Thus a two-parameter fit [on $\mu(^{93}\mathrm{Tc})$ and $\delta(E2/M1)$] has been performed. On account of the correlation between μ and δ in the fit, the uncertainty of the nuclear moment determination is rather large. We find within standard deviation the following:

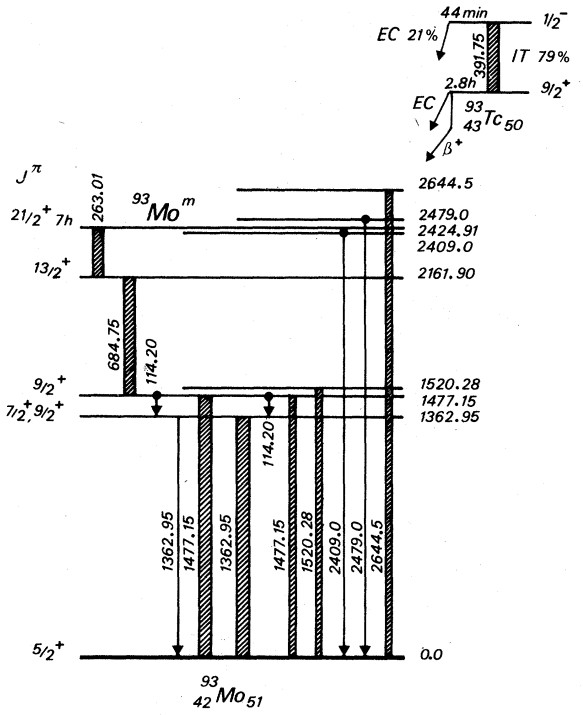

FIG. 5. Decay scheme of ^{93}Tc + ^{93}Mo^m (Ref. 13).

from the 1363 keV transition, $|\mu| = [6.0(^{+13}_{-10})]\,\mu_N$;

from the 1520 keV transition, $|\mu| = [6.4(^{+9}_{-6})]\,\mu_N$.

Comparison of these two independent evaluations yields

$$|\mu(^{93}\mathrm{Tc}^g,\ \tfrac{9}{2}^+)| = [6.2(^{+11}_{-4})]\,\mu_N .$$

The corresponding mixing parameters are as follows:

1363 keV $(\frac{7}{2}^+ \rightarrow \frac{5}{2}^+)$, $\delta(E2/M1) = 0.48(^{-8}_{+6})$;

1520 keV $(\frac{7}{2}^+ \rightarrow \frac{5}{2}^+)$, $0.7 \leq \delta \leq 1.9$.

Errors for μ and δ are not standard deviations, but maximum uncertainties corresponding to the two-parameter fit.

Duffait *et al.* determined the mean lifetimes of the 1363 and 1520 keV states with the Doppler shift attenuation method.[14] Their lifetimes, combined with our mixing ratios, allow us to deduce $B(M1)$ and $B(E2)$ values (Table I).

D. ^{93}Mo^m ($T_{1/2}$ = 7 h)

NO and NMR/ON experiments have been performed on ^{93}Mo^m in *Fe* by Kaindl, Bacon, and Shirley.[15] Fitting on three $E2$ transitions they found $|\mu B| = 12.08(20)\times10^{-25}$ J.

As Mo and Tc have very similar metallurgical behavior in *Fe*, we can suppose that C, determined from ^{95}Tc*Fe* holds also for ^{93}Mo^m*Fe*. Using this value we find $|\mu B| = 12.7(9)\times10^{-25}$ J. This value is slightly higher than that of Kaindl *et al.*, though not beyond experimental accuracy. With $I = \frac{21}{2}$ and $B_{\mathrm{hf}} = 25.6$ T we find $|\mu(^{93}\mathrm{Mo}^m)| = [10.0(7)]\,\mu_N$.

E. ^{109}In (4.2 h), ^{110}In^m (4.9 h), and ^{111}In (2.8 day)

The magnetic moments of ^{109}In, ^{110}In^m, and ^{111}In have been measured by Marino with atomic beam magnetic resonance and the results have been presented in a UCRL report.[4] While moments of ^{109,111}In, both $[5.53(6)]\,\mu_N$, are well inserted into the systematics of $g_{9/2}$ proton moments, the ^{110}In^m moment, quoted as $+[10.4(1)]\,\mu_N$ or $-[10.7(1)]\,\mu_N$ is surprisingly high. The ground and first excited states of ^{110}In must have $(\pi g_{9/2})^{-1}(\nu d_{5/2})$ configurations giving 2^+ or 7^+ assignments. In fact, $I^\pi(^{110}\mathrm{In}^g) = 2^+$, and neighboring odd-odd nuclei suggest for the metastable state $I^\pi = 7^+$. The addition of $\pi(g_{9/2})$ and $\nu(d_{5/2})$ magnetic moments, taken from the ground state moments of ^{109}In and ^{109}Cd would yield $\mu(^{110}\mathrm{In}^m) = +(4.70)\mu_N$, considerably lower than Marino's value.

Indium recoil-implanted into iron may occupy badly defined sites and experience uncertain hyperfine field and quadrupole perturbation as well. On account of the short lifetime of ^{110}In^m and the thickness of the iron foil, no thermal treatment was attempted on the source. Measurements were normalized on the orientation of the 173 keV $\frac{7}{2}^+ \rightarrow \frac{5}{2}^+$ $M1+E2$ transition of ^{111}Cd in the ^{111}In decay, which should not be attenuated by an intermediate state reorientation. The $E2/M1$ mixing ratio determined by Steffen is $\delta = -0.146(3)$[16] (sign

TABLE I. Reduced transition probabilities in ^{93}Mo.

Level (keV)	Spin	Lifetime (Ref. 14) (fs)	Transition	$B(M1)$ (μ_N^2)	$B(E2)$ ($e^2\,\mathrm{cm}^4\times10^{-50}$)
1363	$\frac{7}{2}$	$150(^{+50}_{-30})$	$\frac{7}{2} \rightarrow \frac{5}{2}$	$0.12(^{+4}_{-3})$	$2.1(^{+9}_{-7})$
1477	$\frac{9}{2}$	$460(^{+280}_{-130})$	$\frac{9}{2} \rightarrow \frac{5}{2}$		$2.5(^{+9}_{-7})$
1520	$\frac{7}{2}$	$900(^{+800}_{-250})$	$\frac{7}{2} \rightarrow \frac{5}{2}$	$(2-16)\times10^{-3}$	0.2–1.2

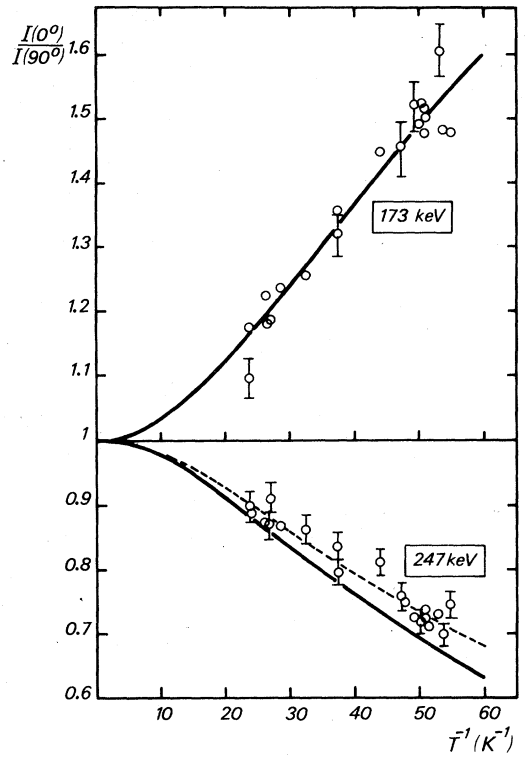

FIG. 6. $I(0°)/I(90°)$ ratio of the 173 keV ($M1+E2$) transition and the 247 keV $E2$ transition in the ^{111}In decay versus inverse temperature. Best fit for the 173 keV transition $C=0.675(25)$. Best fit for the 247 keV transition is shown in broken line; calculated curve without intermediate state reorientation in full line. Standard errors are shown on some measured points.

in the Delft phase convention). The magnetometry, as described in II B yields $C=0.675(25)$. The fit on the 173 keV transition is shown in Fig. 6.

The evaluation of the nuclear moment of $^{110}In^m$ is based on the NDS decay scheme.[17] The moment was derived from the orientation of the 937, 884, and 658 keV pure $E2$ transitions ($6^+\rightarrow 4^+\rightarrow 2^+\rightarrow 0^+$ cascades). The attenuation of orientation due to unobserved intermediate transitions is calculated taking into account the angular distribution of the 641 and 707 keV transitions. The spin of the 3187 keV level in ^{110}Cd can be 6, 7, or 8. The correlated values of I(3187 keV), δ(641 keV), δ(707 keV), and $\mu(^{110}In^m)$ are given in Table II. As long as no other independent measurement exists between the quantities listed in this table, we accept the extreme values for the magnetic moment: $4.29\leq|\mu(^{110}In^m)|\leq 4.97\mu_N$, i.e., $|\mu(^{110}In^m)|=[4.64(35)]\mu_N$. The error quoted in this latter case is higher than the standard deviation. The measured value is in an excellent agreement with that obtained from the addition of neighboring moments ($4.70\mu_N$) and is very different from Marino's value.[4] The $M2/E1$ mixing ratio of the 997 keV $5^-\rightarrow 4^+$ transition in ^{110}Cd is δ(997 keV) $=-0.025(^{+35}_{-75})$, in agreement with the limit given in Ref. 17.

The comparison of the orientation of the 173 and 247 keV γ transitions in ^{111}Cd shows that the orientation of the latter, emitted from the $\tau=121$ ns lifetime 247 keV state, is attenuated [$G_2=0.86(3)$]. This value corresponds to a randomly oriented quadrupole coupling of about $eQV_{zz}/\hbar\approx 100-150$ MHz, which gives an electric field gradient at the site of the implanted nucleus of $V_{zz}\approx(1.5-2)\times 10^{17}$ V/cm^2. Such a rather weak field gradient can exist if implantation yields defect sites.

IV. DISCUSSION

The nuclei investigated in this paper have $Z=42$, 43, 48, and 49, $N=50-52$ and 60–62. The parent nuclei are odd-proton or odd-odd nuclei with $\pi(g_{9/2})\nu(d_{5/2})$ ground state configuration. In a previous communication we published nuclear orientation of $^{106}Ag^m$ (Ref. 18) belonging to the same group of nuclei.

The additivity of neighboring odd-proton and odd-neutron moments to form the moment of odd-odd nuclei can be checked on a certain number of nuclei in this region; it holds within the precision of a few percent. For example,

$$g(^{96}\text{Tc}, 7^+) = g(^{95}\text{Tc}, \tfrac{9}{2}^+) \oplus g(^{95}\text{Mo}, \tfrac{5}{2}^+),$$

$$0.710 = 1.294(17) \oplus -0.366 = 0.701(11);$$

$$g(^{110}Ag^m, 6^+) = g(^{109}\text{Ag}, \tfrac{7}{2}^+) \oplus g(^{109}\text{Cd}, \tfrac{5}{2}^+),$$

$$0.601(1) = 1.22(4) \oplus -0.331 = 0.571(2).$$

TABLE II. Correlation between $\mu(^{110}In^m)$ and spin and mixing ratios in ^{110}Cd.

I(3187 keV)	δ(641 keV)	δ(707 keV)	$\lvert\mu(^{110}In^m)\rvert$ (μ_N)
6	$-0.05(^{+16}_{-10})$ or $0.74(^{+17}_{-25})$	$-0.14(^{+10}_{-7})$ or $0.87(^{+13}_{-17})$	4.66(31)
7	$-0.05(^{+16}_{-10})$ or $0.74(^{+17}_{-25})$	$0.39(^{+5}_{-4})$ or 3.6(4)	4.66(31)
8	$-0.02(^{+18}_{-11})$ or $0.70(^{+18}_{-27})$	∞	4.54(25)

TABLE III. Known odd-proton g factors in the $1g_{9/2}$ shell. Errors are not indicated where they are smaller than 0.1%.

I^π	Nucleus state	g factor	Reference
$\frac{9}{2}^+$	$^{93}Nb^g$	1.478(1)	Calculated
		1.3712(1)	2
	$^{93}Tc^g$	$1.38(^{24}_{-8})$	This paper
		1.41(7)	This paper, calculated
	$^{95}Tc^g$	1.312(17)	2
	$^{99}Tc^g$	1.2633	3
	$^{101}Rh^m$	1.22(2)	3
	$^{103}Rh^m$	1.38(20)	3
	$^{109}In^g$	1.23(1)	3
	$^{113}In^g$	1.2286	3
	$^{115}In^g$	1.2313	3
$\frac{7}{2}^+$	$^{103}Rh^m$	1.36(3)	3
	$^{105}Rh^g$	1.265(4)	1
	$^{103}Ag^g$	1.28(1)	3
	$^{105}Ag^m$	1.27(4)	Calculated from Ref. 18
	$^{109}Ag^m$	1.22(4)	3
	$^{109}Ag^m$	1.267	Calculated from Ref. 12

Where errors are not quoted, they are negligible as compared with quoted ones. The $\oplus$ sign signifies that the addition is to be performed according to the shell model formula

$$g(I) = \tfrac{1}{2}(g_\pi + g_\nu) + \tfrac{1}{2}(g_\pi - g_\nu) \times \frac{j_\pi(j_\pi+1) - j_\nu(j_\nu+1)}{I(I+1)} .$$

This fact can be used to derive odd-proton moments, which either have not yet been measured, or measured with low precision:

$$g(^{93}\mathrm{Tc}, \tfrac{9}{2}^+) = g(^{94}\mathrm{Tc}, 7^+) \ominus g(^{91}\mathrm{Zr}, \tfrac{5}{2}^+)$$

which yields

$$g(^{93}\mathrm{Tc}, \tfrac{9}{2}^+) = 1.41(7)$$

in good agreement with direct determination;

$$g(^{105}\mathrm{Ag}, \tfrac{7}{2}^+) = g(^{106}\mathrm{Ag}, 6^+) \ominus g(^{105}\mathrm{Cd}, \tfrac{5}{2}^+)$$

yielding

$$g(^{105}\mathrm{Ag}, \tfrac{7}{2}^+) = 1.27(4),$$

still not measured. $\ominus$ is defined in the same way as $\oplus$.

In Table III we summarize known proton g factors of the $1g_{9/2}$ shell. For $I = \frac{9}{2}$ nuclei the magnetic moment is constant except at the beginning of the shell (for Nb and somewhat less for Tc). We do not find the same increase at the end of the shell for closed-shell-minus-one In isotopes.

The $\frac{7}{2}^+$ states appear as ground or low excited states in the second half of the shell. They are interpreted in terms of $\alpha(p_{1/2}{}^2 g_{9/2}{}^3) + (1-\alpha) g_{9/2}{}^5$ mixed configuration,[19] or by phonon plus quasiparticle coupling with pairing plus quadrupole force (Alaga model[20] and dressed quasiparticle model[21]). In any case, the predictions of magnetic moments are not very different. Kuriyama, Marumori, and Matsuyanagi[21] calculated with $g_\pi(\frac{9}{2}) = 1.23$ for $^{107,109}\mathrm{Ag}(\frac{7}{2}^+)$ $g = 1.21$ which agrees rather well with the measured value. For the $\frac{7}{2}^+$ state of ^{93}Nb they found a similar increase of g factor, as exhibited by $\frac{9}{2}$ states; this prediction has not yet been checked experimentally.

It should be emphasized that $g(6^+)$ can be well estimated by means of the $\pi(g_{9/2})^{-3}\nu(d_{5/2})$ coupling. This means that in spite of the small energy difference between $I = \frac{9}{2}$ and $I = \frac{7}{2}$ states the $\pi(g_{9/2})^{-3}$ coupling is sufficiently strong as to be unbroken by the addition of odd neutrons.

The lower excited states of ^{93}Mo show the well-known one-particle plus core multiplet structure. The $B(E2;$ multiplet $\rightarrow$ ground) values, listed in Table I agree well with the $B(E2; 2^+ \rightarrow 0^+)$ of ^{92}Mo: $B(E2; 1530\ \mathrm{keV}) = 0.234.10^{-49}\ e^2\ \mathrm{cm}^4$.[22] The enhancement of the quadrupole speed is thus the reason of the high $\delta(E2/M1)$ admixture in the 1363 keV transition in ^{93}Mo.

The existence of j^3 configuration discussed above is evident also in the ^{95}Mo nucleus. The three $d_{5/2}$ neutrons coupled to the vibrational core do not give the well defined weak coupling multiplet. The $\delta(E2/M1)$ admixture of the 765 keV $\frac{7}{2}^+ \rightarrow \frac{5}{2}^+$ transition is very small, indicating the weakness of quadrupole enhancement.

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[1] J. Wese, E. Hagn, and P. Kienle, in *Proceedings of the International Conference on Hyperfine Interactions Studied in Nuclear Reactions and Decay, Uppsala, 1975*, edited by E. Karlsson and R. Wäppling (Almqvist and Wiksells, Stockholm, 1974-75), Vol. 2, p.112.

[2] E. Hagn, P. Kienle and G. Eska, in *Proceedings of the International Conference on Nuclear Structure and Spectroscopy, Amsterdam*, 1974, edited by H. P. Blok and A. E. L. Dieperink (Scholar's Press, Amsterdam, 1974), pp. 138, 139.

[3] V. S. Shirley, C. M. Lederer, Table of Nuclear Moments in *Proceedings of the International Conference on Hyperfine Interactions Studied in Nuclear Reactions and Decay, Uppsala*, 1975 (see Ref. 1), Vol. 1, p. 1.

[4] L. L. Marino, UCRL Report No. UCRL-8721, 1959 (unpublished).

[5] I. Berkes, R. Haroutunian, and G. Marest, Hyperfine Interactions 2, 297 (1976); R. Haroutunian, G. Marest,

and I. Berkes, *ibid.* 2, 306 (1976).
[6]G. N. Rao, in Proceedings of the International Meeting on Hyperfine Interactions, Heverlee, 1974, Supplement (unpublished).
[7]M. Kaplan, P. D. Johnston, P. Kittel, and N. J. Stone, Nucl. Phys., A212, 478 (1973).
[8]J. Barrette M. Barrette, R. Haroutunian, G. Lamoureux, S. Monaro, and S. Markiza, Phys. Rev. C 11, 171 (1975).
[9]R. M. Steffen, in *Angular Correlations in Nuclear Disintegration*, edited by H. Van Krugten and B. Van Nooijen (Rotterdam U.P., Rotterdam, 1971), p. 1.
[10]D. C. Kocher, Nucl. Data B10, 241 (1973).
[11]E. Hagn, E. Zech, and G. Eska, Hyperfine Interactions, 2, 297 and 306 (1976) International Conference on Nuclear Orientation, Oxford, 1976 (unpublished); E. Hagn, Ph.D. thesis, Technische Hochschule, München (unpublished).
[12]R. A. Fox, P. D. Johnston, C. J. Sanctuary, and N. J. Stone, in *Hyperfine Interactions in Excited Nuclei* (Gordon and Breach, New York, 1971), p. 339.
[13]A. Charvet, R. Chéry, Do Huu Phuoc, R. Duffait, and M. Morgue, J. Phys. (Paris), 35, 199 (1974).
[14]R. Duffait, A. Charvet, T. Negadi, M. Morgue, J. Caro, and R. Chéry, J. Phys. (Paris), 37, L-103 (1976).
[15]G. Kaindl, F. Bacon, and D. A. Shirley, Phys. Rev., C 8, 315 (1973).
[16]R. M. Steffen, Phys. Rev. 103, 116 (1956).
[17]F. E. Bertrand and S. Raman, Nucl. Data, B5, 487 (1971); A. H. Lumpkin, A. W. Sunyar, and Y. K. Lee, Phys. Rev. C 9, 252 (1974).
[18]R. Haroutunian, I. Berkes, and G. Marest, Phys. Rev. C 14, 2016 (1976).
[19]N. Auerbach and I. Talmi, Nucl. Phys. 64, 458 (1965).
[20]V. Paar, Nucl. Phys. A211, 29 (1973).
[21]A. Kuriyama, T. Marumori, and K. Matsuyanagi, Prog. Theor. Phys. 47, 498 (1972).
[22]P. H. Stelson and L. Grodzins, Nucl. Data A1, No. 21 (1965).