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THE HYPERFINE MAGNETIC FIELDS AT NUCLEI OF INDIUM IN IRON AND NICKEL*

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Berkeley, California

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ABSTRACT

Hyperfine magnetic fields for In in Fe and Ni were determined by nuclear orientation of In^{114m} in Fe and Ni alloys. A Co^{57} thermometer was used in each case. The results are: H_{hf} (In in Fe) = -295(10) kG; H_{hf} (In in Ni) = -42(5) kG.

I. INTRODUCTION

The decay scheme of In^{114m} is shown in Fig. 1. This isotope was one of the first used by Samoilov et al.[1] to demonstrate the existence of large hyperfine magnetic fields at the nuclei of diamagnetic atoms dissolved in ferromagnetic lattices. They found a lower limit of H_{hf} (In in Fe) $\geq$ 175 kG for the field for In in iron. Later this value was changed to 250 kG and an attempt was made to measure H_{hf} (In in Ni), but no anisotropy was observed.[2] The sign of H_{hf} (In in Fe) was subsequently determined as negative (i.e., opposite to the polarizing field) by Kogan et al.[3] Westenbarger independently confirmed this result.[4] Thus before the present work was undertaken the hyperfine field for In in Fe was known to be approximately -250 kG.

Recent activity in this area of research has yielded rather accurate values for several hyperfine fields at nuclei of elements between Y(Z=39) and Te(Z=52) in Fe and Ni lattices, determined by the techniques of perturbed angular correlations, nuclear polarization, Mössbauer spectroscopy, and NMR. Frankel, et al.[5] have found a strikingly regular variation of H_{hf} in Fe and Ni lattices with solute atomic number; accurate experimental values for the fields at In nuclei in Fe and Ni have thereby acquired a new significance. Accordingly we have made accurate determinations of these fields, using a Co^{57} γ-ray thermometer.

II. EXPERIMENTAL METHODS AND RESULTS

The apparatus described by Westenbarger and Shirley[6] was used in these experiments. Those authors also described the portion of the theory of nuclear orientation that is relevant to this work. The recently-developed Ge(Li) γ-ray detectors enabled us to resolve the 122.0 and 136.4-keV γ rays of Co^{57} very well, and we used the 136.4-keV γ ray as a nuclear thermometer. The decay scheme and γ-ray spectrum of Co^{57} are shown in Fig. 2. Table I gives the calculated intensity of the 136.4-keV γ ray vs. temperature, for Co^{57} oriented in Fe and in Ni. These calculated values are based on the nuclear moment of 4.6 nm for Co^{57} and hyperfine fields of -286 kG and -120 kG in Fe and Ni, respectively. The Co^{57} anisotropies have been shown to obey the calculated relationship by comparison with a Co^{60} thermometer.[7] For many experiments Co^{57} should prove a more convenient thermometer because of the low intensity of potentially interfering high-energy radiations.

The Fe-In-Co alloys (two were made) were formed by evaporating solutions containing In^{114m} and Co^{57} in a small Fe pot which was then plugged and heated in a sealed evacuated quartz ampule in a preheated (1600°C) electric resistance furnace for approximately 5 minutes.

The Ni-In-Co alloys (again two were made) were formed by plating In^{114m} onto a thin strip of Ni metal, then evaporating a solution containing Co^{57} onto the surface of the strip. This was folded several times, melted, and heated to 1500°C in the same manner as the Fe alloys. Bright metallic alloys were obtained in every case.

The alloys were pounded down to a thickness of ~10 mils and cut with scissors into the desired shape. The Ni alloys were annealed at 400°C for one hour at this point. The Fe alloys were not annealed. Each alloy was then cleaned with acid to remove any residual surface activity and soldered to a copper fin assembly. The fins were embedded in a chrome alum-glycerine slurry which was adiabatically demagnetized from 1.0°K to ~0.01°K. The anisotropy of the Co^{57} γ rays was used to measure the alloy temperature. The samples were polarized by a magnetic field of 2 kG trapped during demagnetization in a short tube of pure niobium, which is superconducting under the experimental conditions.

The In^{114m} ($5+ \xrightarrow{E4} 1+$) and Co^{57} γ-ray intensities were measured along the axis of magnetization, using a Ge(Li) detector for Co^{57}, and both Ge(Li) and NaI(Tl) detectors for In^{114m}. The In^{114} β^- ($1+ \longrightarrow 0+$) spectrum was taken with the second Ni-In alloy, both at 0° and 180°, using a silicon surface-barrier detector mounted inside the cryostat. Intensities were measured with the alloy "cold" and were normalized to the 1°K (isotropic) values.

The data were corrected for background and solid angle, and $W(\theta)$ ($W(\theta)$ = cold intensity/warm intensity at angle θ) was calculated for each case. This was compared (Figs. 3 and 4) with theoretical curves calculated for different values of the hyperfine fields (H_{hf}), based on the known[8,9] magnetic moment $\mu_{114m} = +4.75(10)$ nm, yielding

$$|H_{hf}| = 295 \pm 5 \text{ kG (In in Fe)},$$

$$|H_{hf}| = 42 \pm 3 \text{ kG (In in Ni)}.$$

The above statistical errors are the root mean square values. They should be doubled in both cases to include miscellaneous systematic errors.

For the In^{114} β^- measurements we found thet $W(0) > 1$ and $W(\pi) < 1$, implying $\mu H_{hf} < 0$ (In in Ni). At $1/T = 25°K^{-1}$ the approximate magnitudes were

$W(0) - 1 \cong 1 - W(\pi) \cong 0.03$. This number is uncorrected for scattering and solid angle, and the magnitude is thus of doubtful accuracy, but the sign of the asymmetry is certain. For In^{114m} in Fe $\mu H_{hf} < 0$ was also found.[3,4]

III. DISCUSSION

To deduce the sign of H_{hf} from the above data we must know the sign of the relevant nuclear moment μ. Kogan et al.[3] assumed that reorientation takes place in the 72-sec ground state of In^{114}, and that the magnetic moment of this state, μ_{114}, is therefore the one in question. If this is correct we can estimate the moment theoretically as +3.4 nm, using the nuclear shell-model single particle states $g_{9/2}$ (proton) and $g_{7/2}$ (neutron). This estimate is based upon Schmidt-limit values for the single-particle moments, and more sophisticated methods of calculation would reduce its magnitude somewhat, but if the proton has mainly $g_{9/2}$ character a positive sign for μ is inescapable.

We do not agree that thermal equilibrium is established in 72-sec In^{114}; it seems to us more likely that the nuclear orientation induced in In^{114m} is retained in In^{114}. In this case the interpretation is even simpler. The magnetic moment has been measured as $\mu_{114m} = +4.75$ nm. Fortunately either interpretation yields the same result: both H_{hf} (In in Fe) and H_{hf} (In in Ni) are negative.

In Table II are listed the best values to date for H_{hf} at nuclei of elements between Y and Te dissolved in Fe and Ni. These values are plotted in Fig. 5. There now is very good evidence that this open 4d shell contributes (probably via core polarization) heavily to the negative hyperfine fields above the middle of the shell. This conclusion is supported by recnet measurements on local moments for Ru in Ni by Matthias et al.[10] The continuing large negative H_{hf} in Ag and Cd may be understood as arising from polarization of 5s "conduction" electrons.[11]

No convincing explanation exists as yet for the systematic sign change of H_{hf} in the 5p shell. The present experiment underscores the regularity of this trend. Possibly the positive Y-in-Fe point is another manifestation of this phenomenon. Certainly a successful quantitative explanation of these fields will have to account for both the <u>regularity</u> exhibited in Fig. 5 and for the pronounced <u>trends</u>.

Table I. W(θ) vs 1/T for the Co^{57} γ-ray thermometers.

1/T ($^{o}K^{-1}$)	Fe lattice		Ni lattice	
	W(0)	W(π/2)	W(0)	W(π/2)
10	0.980	1.010	0.995	1.002
20	0.927	1.036	0.986	1.007
30	0.851	1.070	0.968	1.016
40	0.767	1.106	0.947	1.026
50	0.682	1.138	0.920	1.039
60	0.602	1.165	0.890	1.053
70	0.531	1.185	0.856	1.068
80	0.465	1.202	0,822	1.083
90	0.404	1.216	0.786	1.098
100	0.353	1.225	0.750	1.113

Table II. The known values of H_{hf} for Y-Te in Fe and Ni. Errors are given parenthetically.

Element	T(^{o}K)	H_{hf} in Fe	T(^{o}K)	H_{hf} in Ni	Reference[a]
Y	<1	+205			b
	4.2	286(5)			c
Nb		258	1.4	39	d,e
Mo	4.2	256(5)			b
Ru		-505(20)	300	-178(7)	b,f
Rh	4.2	545(8)			c
Pd	4.2	600(10)			c
Ag	<1	-272(19)		-84(5)	b
Cd	300	348(10)	300	-65.3(1.6)	b
In	<1	-295(10)	<1	-42(6)	
Sn	100	-81(4)	100	+18.5(1.0)	b
Sb		193(3)			b
	<1	+205			b
	<1	170(8)			b
		230	4.2	+88(5)	c,e
Te	4.2	+620(20)	4.2	+195(10)	b

[a] Signs of hyperfine fields are given where known. Error limits are stated parenthetically for some cases. Original references should be consulted.

[b] D. A. Shirley and G. A. Westenbarger, Phys. Rev. <u>138</u>, A170 (1965).

[c] M. Kontani, K. Asayama, and J. Itoh (private communication).

[d] K. Asayama, M. Kontani, and J. Itoh, J. Phys. Soc. Japan <u>19</u>, 1984 (1964).

[e] Y. Koi, et al. (private communication quoted in Ref. c).

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FIGURE CAPTIONS

Fig. 1. Decay scheme of In^{114m}.

Fig. 2. Gamma-ray spectrum of Co^{57} as recorded with a Ge(Li)-detector. The decay scheme of Co^{57} is also shown.

Fig. 3. $W(0)$ for 191-keV γ ray from In^{114m} in Fe as a function of temperature. Each point represents one demagnetization. Curves are for various values of the hyperfine field. □ -source 1[NaI(Tl)], O-source 2[Ge(Li)], ●-source 2[NaI(Tl)].

Fig. 4. $W(0)$ for 191-keV γ ray from In^{114m} in Ni as a function of temperature. Each point represents the average of several demagnetizations. Curves are for various values of the hyperfine field. □ -source 1[Ge(Li)], O-source 2[Ge(Li)], ●-source 2[NaI(Tl)].

Fig. 5. Hyperfine fields at nuclei of atoms ($Z=39-52$) dissolved in Fe (circles) and Ni (squares) hosts. Cases for which the sign is known are shown as filled points.

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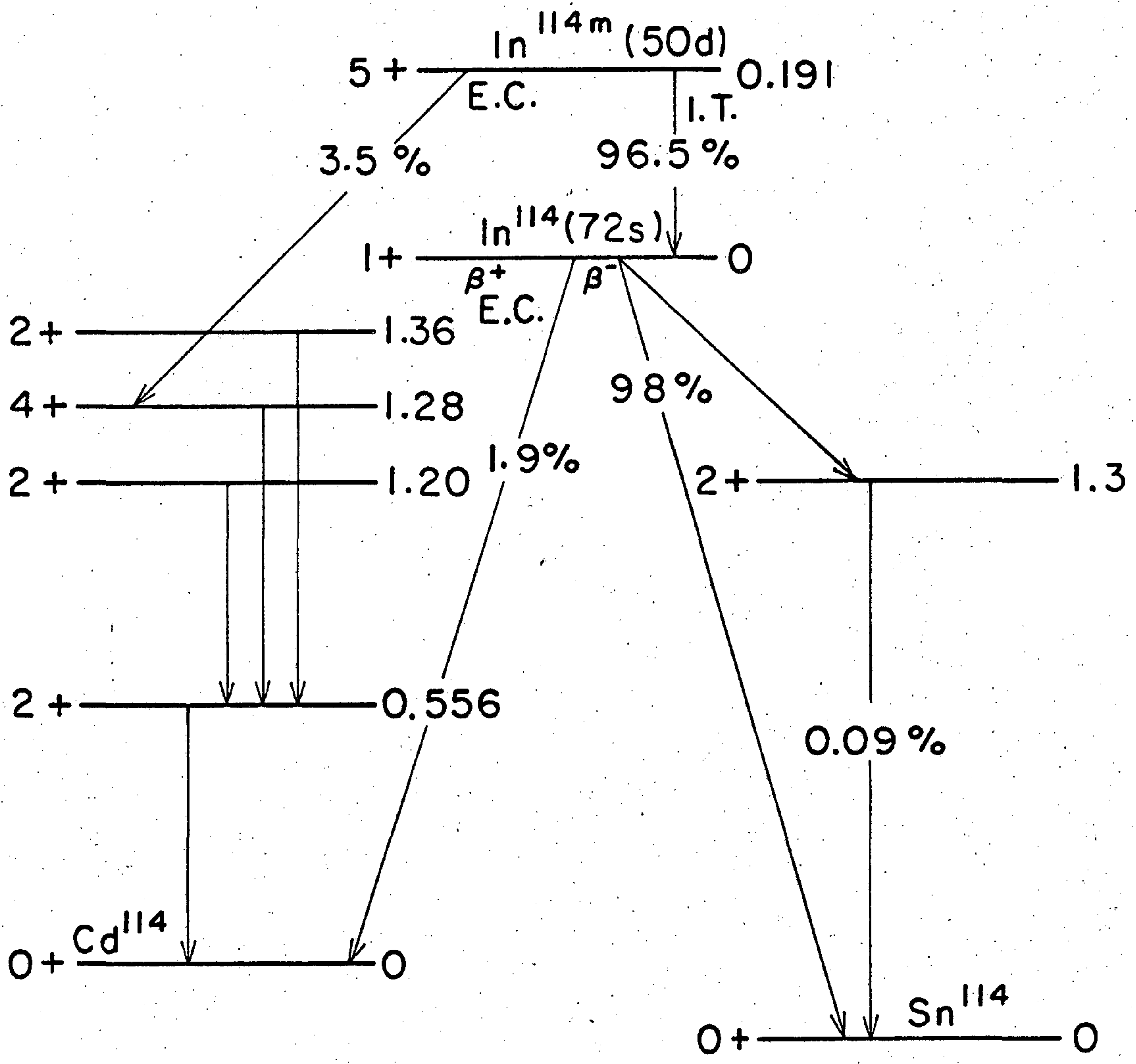

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Fig. 1

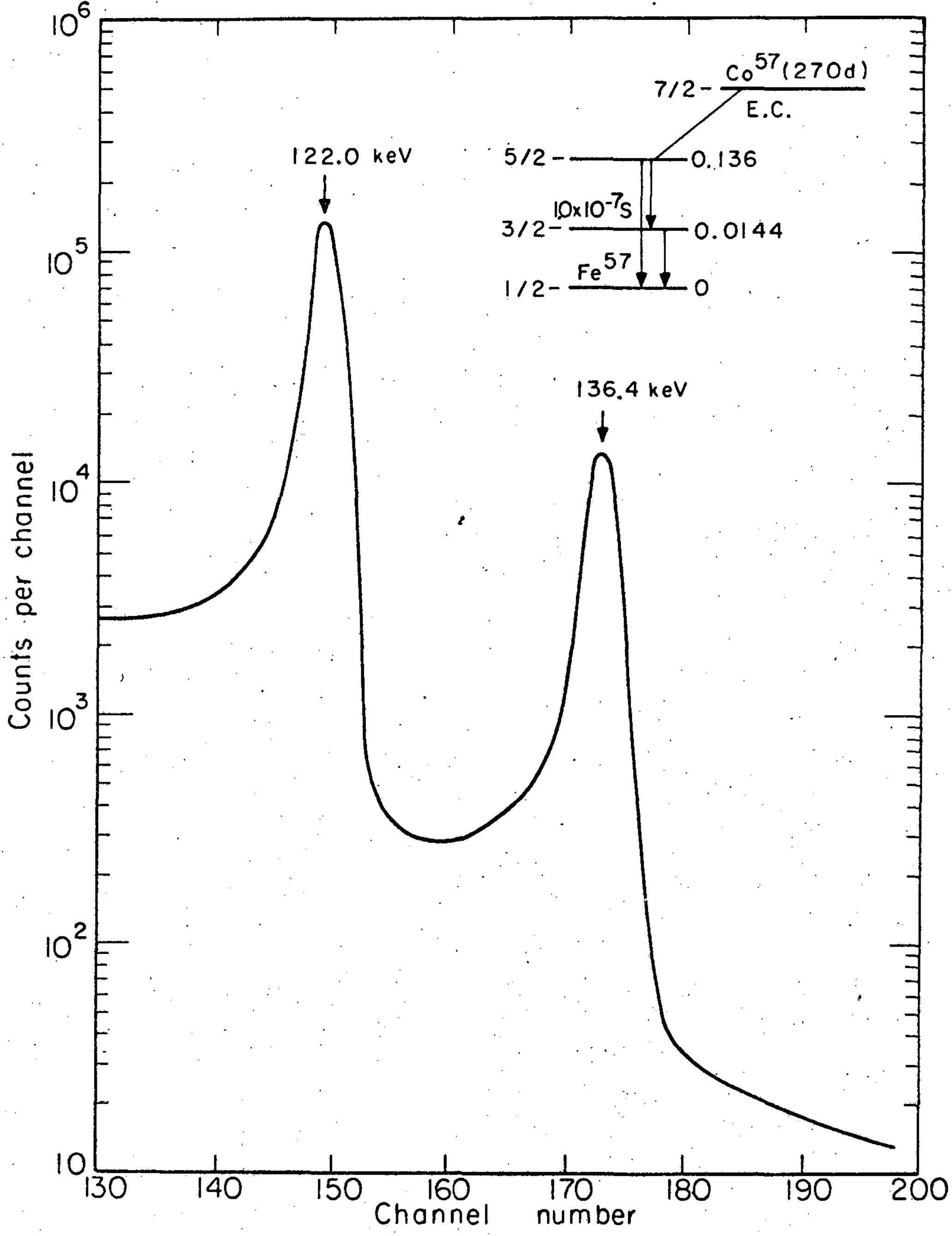
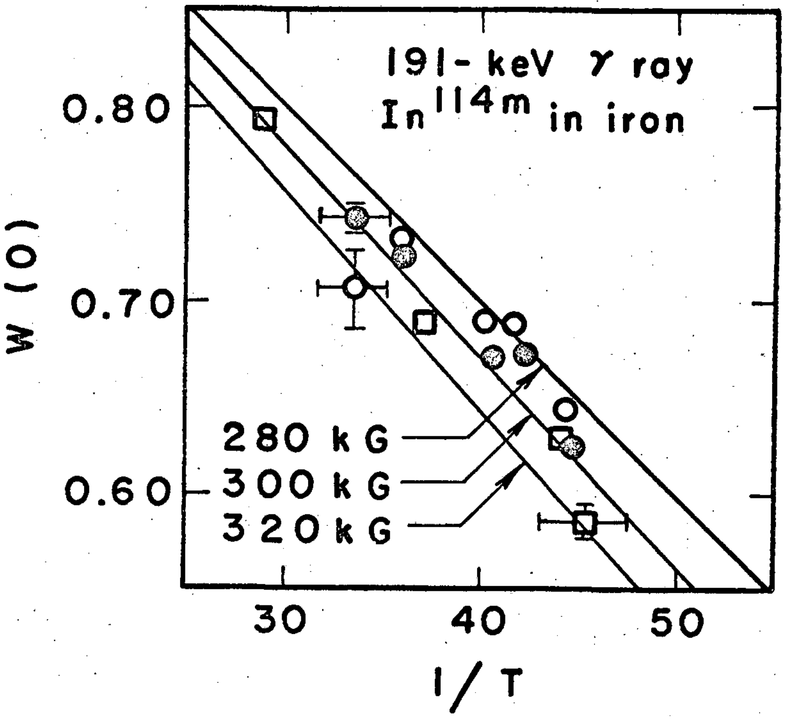

122.0 keV
136.4 keV
7/2-
Co^{57}(270d)
E.C.
5/2-
0.136
1.0×10^{-7}s
3/2-
0.0144
Fe^{57}
1/2-
0
Counts per channel
10
10^2
10^3
10^4
10^5
10^6
130
140
150
160
170
180
190
200
Channel number
MUB-8248

Fig. 2



MUB-8259

Fig. 3

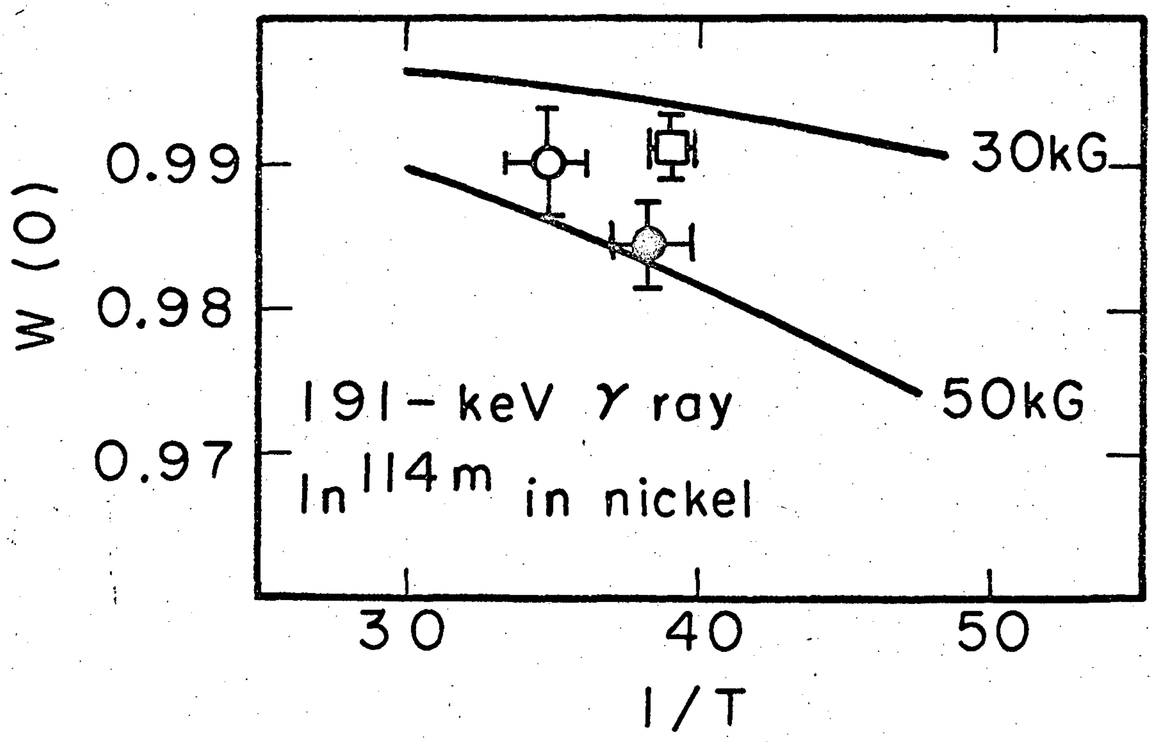


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Fig. 4

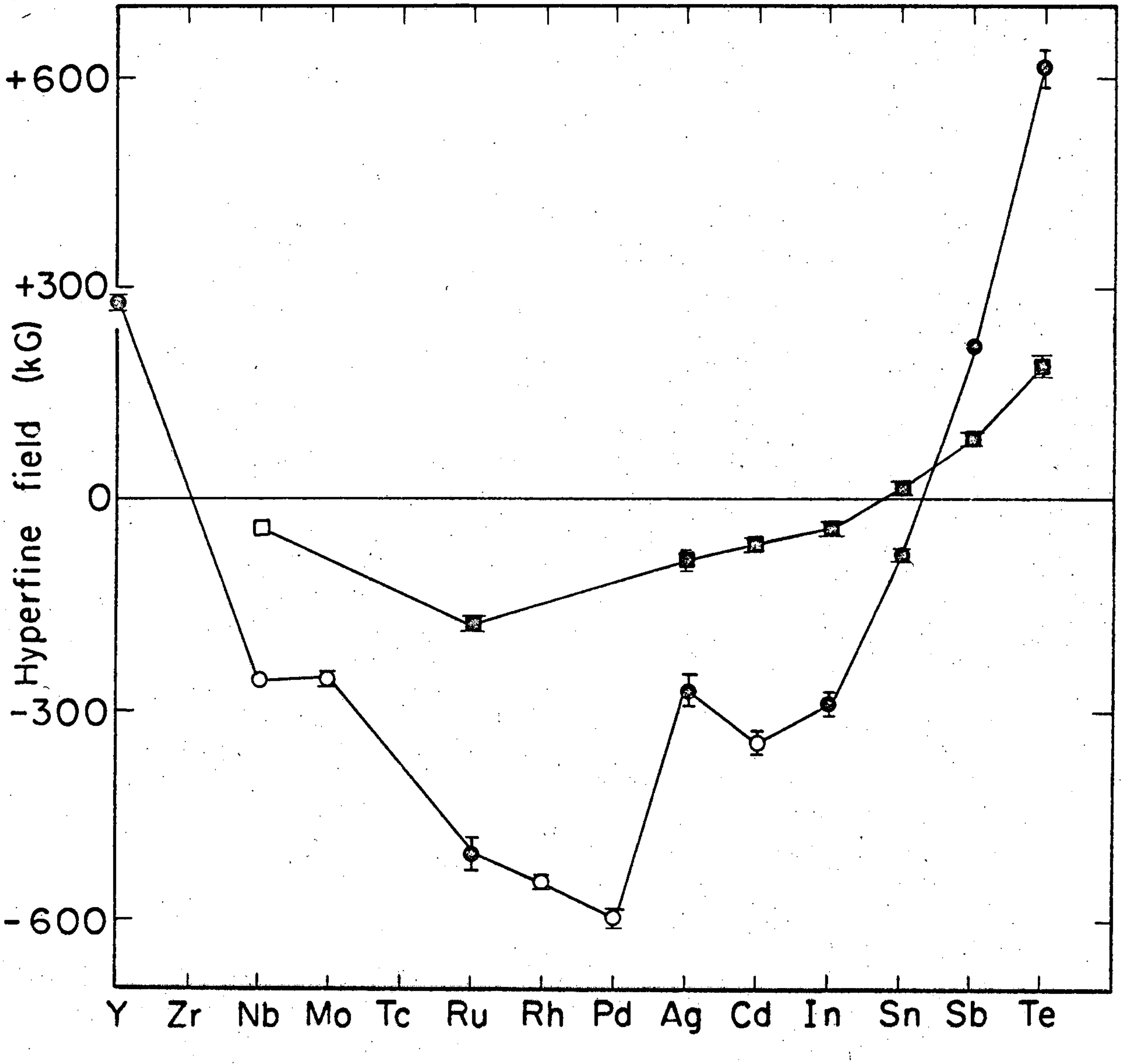

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Fig. 5