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ANOTHER NUCLEAR ORIENTATION MEASUREMENT OF PARITY ADMIXTURE IN THE 501-keV GAMMA TRANSITION IN $^{180}Hf^{m}$ *

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ABSTRACT

The parity non-conserving nuclear force has been investigated by measuring the asymmetry of the angular distribution of the 501-keV gamma ray following the decay of $^{180}Hf^{m}$ polarized at temperatures as low as 16 millikelvin in the ferromagnetic matrix $ZrFe_2$. A difference of 1% was observed between the gamma-ray intensities parallel and anti-parallel to the nuclear polarization direction; from this asymmetry the amplitude ratio of the parity non-conserving E2 component of the 501-keV transition to its parity conserving M2 multipole matrix element has been deduced to be $\epsilon = -0.029 \pm 0.003$. This agrees well with earlier measurements. The global average of all measurements available to date is $\epsilon = -0.032 \pm 0.002$.

I. INTRODUCTION

The current-current theory of weak interactions of Feynman and Gell-Mann[1,2] suggests that the strangeness-conserving, non-leptonic weak interaction will contribute to the internucleon potential and will result in small parity impurities in nuclear states.

In the past there have been numerous experimental studies of this effect in nuclei, either by searching for decays which would be absolutely forbidden except for the parity-nonconserving interactions, or else by searching for evidence of interference between the parity-conserving and possible nonconserving multipoles in the nuclear electromagnetic radiation field. Numerous theoretical computations of parity nonconserving effects have likewise been attempted. The experimental and theoretical situation has been most recently summarized by Gari,[3] and previous reviews have been given by Hamilton[4] and Henley.[5] Discussions of a more pedagogic nature regarding weak interactions and their relationship to possible parity nonconserving effects in nuclei may be found in the works of Blin-Stoyle[6] and Commins.[7]

The ratio F of the strength of the parity non-conserving force to that of the parity-conserving force was estimated by Blin-Stoyle[8] to be of the order of 10^{-7}; thus these parity admixtures are expected to be quite small. However, in the event that nuclear observables resulting from the parity-conserving component are strongly hindered, effects of the parity impurity may compete more successfully. The case of ^{180}Hf provides a particularly striking example of this relative enhancement. We have undertaken a measurement of the asymmetry in the angular distribution of the 501-keV gamma ray following the decay of polarized ^{180m}Hf. Earlier measurements of parity nonconserving effects in this transition had been reported in three previous studies of the circular polarization of radiation from am unpolarized sample,[9-11] as well as in one previous study of the angular distribution asymmetry from a polarized sample.[12] Nevertheless, we felt that the size of the effect in this transition and its significance for comparisons with theoretical calculations warranted an independent remeasurement under somewhat varied conditions. The original objectives of this project included reaching lower temperatures by adiabatic demagnitization, varying the method of sample preparation, and improvement of the statistical accuracy relative to earlier measurements. These objectives were only partially reached, as described below. The theory of this experiment is given in Section II, and experimental procedures are described in Section III. Section IV concerns data reduction, and the results are treated in Section V.

II. THEORY

The effect of the parity-nonconserving weak interaction is to introduce a small parity admixture into the nuclear levels, such that the nuclear wave function may be written as

$$\psi = \psi^{(\pi)} + \mathcal{F}\psi^{(\pi')}, \qquad (1)$$

where $\pi \neq \pi'$. Matrix elements of the electromagnetic field operator

H may then be written as

$$\langle \psi_f | H | \psi_i \rangle = \langle \psi_f^{(\pi_f)} | H | \psi_i^{(\pi_i)} \rangle + \mathcal{F} \{ \langle \psi_f^{(\pi_f)} | H | \psi_i^{(\pi_i')} \rangle + \langle \psi_f^{(\pi_f')} | H | \psi_i^{(\pi_i)} \rangle \} \quad (2)$$

neglecting terms of order $\mathcal{F}^2$.

The parity mixing thus gives rise to irregular electromagnetic transitions $\pi_i \rightarrow \pi_f'$ and $\pi_i' \rightarrow \pi_f$, in addition to the regular transition $\pi_i \rightarrow \pi_f$. The interference term is proportional to the ratio of the amplitudes of the irregular and regular transitions

$$\frac{\text{irregular}}{\text{regular}} = \mathcal{F} \frac{\langle \psi_f^{(\pi_f)} | H | \psi_i^{(\pi_i')} \rangle + \langle \psi_f^{(\pi_f')} | H | \psi_i^{(\pi_i)} \rangle}{\langle \psi_f^{(\pi_f)} | H | \psi_i^{(\pi_i)} \rangle}$$

$$= \mathcal{F} R. \quad (3)$$

The factor R, called the nuclear structure factor, depends on the overlap of the admixed nuclear levels and on the strengths of the electromagnetic transitions between the levels. It is apparent that if the regular transition is strongly hindered, the factor R can become large (i.e., the denominator becomes small) and give rise to a large interference term, in spite of the small value of $\mathcal{F}$.

The ^{180}Hf level scheme is illustrated in Figure 1.[13] The 8^- isomeric level is characterized as K = 8; that is, with 8 units of angular momentum projection along the nuclear symmetry axis. The 501-keV transition to the 6^+ level of the K = 0 ground-state rotational band is of mixed E3/M2 multipolarity, with $\langle E3 \rangle / \langle M2 \rangle = +5.3 \pm 0.3$.[12] The parity nonconserving interaction is expected to admix a small 8^+ component into the 1.142 MeV 8^- level (a similar admixture of a 6^- component into the 0.641 MeV 6^+ level is neglected for the present discussion). To the extent that this admixture may be treated by standard methods of first-order perturbation theory, the close spacing between the 8^- level and the 8^+ level at 1.084 MeV tends to magnify the admixture; in addition, the regular (parity conserving) E3 and M2 components of the 501-keV radiation field are strongly hindered (with respect to Weisskopt estimates by $Hw(E3) = 2.0 \times 10^9$, $Hw(M2) = 1.3 \times 10^{14}$), resulting in a relative enhancement of any possible irregular component.

The angular distribution of gamma radiation from an oriented nucleus is described by[14]

$$W(\theta) = \sum_k Q_k B_k U_k A_k P_k(\cos\theta), \tag{4}$$

where the Q_k correct for the finite geometry, the orientation parameters B_k depend on the temperature and on the orienting interaction, the U_k correct for loss of orientation arising from unobserved intermediate transitions, and the A_k describe the properties of the observed gamma ray. The P_k are Legendre polynomials, and θ is the angle between the axis of orientation and the direction of emission of the gamm-ray. For the 501-keV transition, all $U_k = 1$. The parity mixing is evidenced only in the terms with odd k, which vanish in the absence of parity mixing. For odd k,

$$A_k = \frac{2\epsilon}{1+\delta^2} [F_k(L L I_f I_i) + \delta F_k(L L' I_f I_i)], \tag{5}$$

where the F_k are the F-coefficients. Here ϵ is the ratio of the irregular to regular matrix elements, in this case $\langle E2 \rangle / \langle M2 \rangle$, and δ is the $\langle E3 \rangle / \langle M2 \rangle$ mixing ratio. The asymmetry $\mathcal{A}$ is defined as

$$\mathcal{A} = 2 \, \frac{W(180^0) - W(0^0)}{W(180^0) + W(0^0)}$$

$$= -2 \, \frac{Q_1 B_1 A_1 + Q_3 B_3 A_3}{1 + Q_2 B_2 A_2 + Q_4 B_4 A_4} \, . \qquad (6)$$

In the present experiment the asymmetry $\mathcal{A}$ of the 501 keV gamma ray has been determined and the irregular-to-regular mixing ratio ϵ has been deduced.

III. EXPERIMENTAL

A. Low Temperature Apparatus

The low temperatures necessary to polarize the nuclei were produced by the demagnetization of chromium potassium sulfate (chrome alum) salt prepared in a glycerin slurry. Thermal contact to the salt slurry was achieved by means of 16 sheets of 0.13 mm (5 mil) copper foil. A schematic view of the apparatus is shown in Figure 2.

The salt pill was cooled in thermal contact with a bath of liquid helium pumped to 1°K, and was demagnetized from a field of 50 kilogauss, reaching a temperature of 10 millikelvin, as determined by a $^{60}Co(Fe)$ thermometer.

The polarizing magnets consisted of two pairs of perpendicularly oriented superconducting Helmholtz coils, made of 0.11 mm (4.5 mil) Nb-Ti wire wound on a fiberglass form. The control units for the polarizing magnets are illustrated in Figure 3. The charging and discharging of the magnets were controlled by a ramp generator and timer, and the two magnet controls could be arranged to be 90 degrees or 180 degrees out of phase, such that the effect of the ramps would be to rotate the field by 90° or 180°.

B. Detectors and Data Acquisition

The gamma-rays were observed using Ge(Li) detectors of approximately 40 cm^3 active volume. Either two detectors at 180° to each other or four detectors at 90° apart were used to collect the data. The detector preamp pulse was fed to a pole-zero compensated high-rate linear amplifier (HRLA). The slow pulse from the HRLA was used for energy discrimination, and the fast pulse was used for pile-up rejection, in which pile-up events and slow rise-time pulses resulting from partial charge collection were rejected. Energy discrimination was done using single-channel analyzers, with the fast pulse from the pile-up rejector as a strobe. The resulting pulse was routed and digitized in an analog-to-digital converter, and finally was stored in the memory of a PDP-7 computer and written onto magnetic tape.

C. Sample Preparation

The cubic ferromagnet $ZrFe_2$ provides a convenient environment in which to polarize Hf impurities. Dilute Hf impurities experience a magnetic hyperfine field in $ZrFe_2$ of 200 ± 20 kilogauss.[15] (Early attempts were made to prepare a sample of Hf(Fe), in which the Hf is expected to experience a hyperfine field larger by a factor of 3.

Activated $^{180}Hf^m$ metal was arc-melted with Fe to prepare Hf(Fe) alloys with 0.01-0.1 atomic % Hf. The resulting alloys were rolled into a foil and cooled in the low-temperature apparatus. The resulting effective field on the Hf was deduced to be in the neighborhood of 200 kilogauss; this reduced effective hyperfine field is likely due to the presence of a substantial fraction (2/3) of the Hf impurity atoms being in non-magnetic sites.) The compound $Hf_{0.1}Zr_{0.9}Fe_2$ was prepared in an arc furnace in an argon atmosphere, using Fe and Zr metals of 99.99% purity along with Hf enriched to 87% in ^{179}Hf. The alloy was produced by first melting together Zr and Fe in stoichiometric ratios to make $ZrFe_2$; the resulting ingot was remelted several times to assure homogeneity. An x-ray powder diffraction spectrum of a portion of the ingot is shown in Figure 4. The lines shown are characteristic of $ZrFe_2$ in the face-centered cubic structure; no evidence is seen for other possible phases such as Zr_2Fe (2.35Å) or $ZrFe_3$ (2.07Å, 2.25Å) in the limit of 10% of the $ZrFe_2$. The resulting alloy was then remelted in stoichiometric ratios with Hf and Fe to form $Hf_{0.1}Zr_{0.9}Fe_2$. Disks of the alloy were spark-cut and mechanically polished to thickness of 0.6-0.8 mm (25-34 mils); the disk diameter was in the range 5-7 mm (195-275 mils).

Three different types of samples were employed. In one method, the compound was annealed at 750°C for 12 hours following melting in the arc furnace. The compound was then neutron-irradiated for 30 min. at a flux of 1×10^{13} neutrons-cm^{-2}-sec^{-1}. A second method similarly employed unannealed samples. Finally, the alloy was prepared using previously activated Hf in order to avoid the problems associated with radiation damage following neutron capture. Within experimental error, no differences in the nuclear polarization properties were observed between the various ways of sample preparation.

IV. DATA REDUCTION

A. Thermometry

The sample temperature was monitored using a $^{60}Co(Fe)$ thermometer; the anisotropy of the angular distribution of the gamma rays following the ^{60}Co decay was used to deduce the temperature.[16] It was also possible to use the ^{180}Hf gamma rays for thermometry purposes, since the $^{180}Hf^{m}$ hyperfine splitting has been previously measured to be 7.9± 0.5 mK.[12] The temperature deduced from the ^{60}Co in the 20-30 mK range was consistently 2-3 mK lower than that obtained from the ^{180}Hf. In addition, it proved impossible, despite repeated attempts using various source mounting arrangements, to cool the Hf sample below 16 mK, even when the cold finger was in the neighborhood of 10 mK. The irreducible thermal gradient was interpreted as arising from a lack of sufficiently good thermal contact between the Hf sample and the cold finger. Thus the temperature deduced from the Hf has been used in analyzing the 501-keV angular distribution asymmetry. Specifically, the angular distribution of the pure E2 444-keV transition has been employed, assuming the unobserved 57-keV transition to be pure E1 multipolarity.[17]

B. Data Analysis

The data were written onto magnetic tape in the form of 1024-channel gamma-ray spectra. Each spectrum correspond to the results of counting with a single detector at a given position of the applied field for a period of approximately 10 minutes. Also written onto the magnetic tape were markers defining the positions of the 444-keV and 501-keV peaks along with the positions of appropriate regions of background.

The data were reduced using a CDC 6600 computer. A linear background was assumed, and a straight line was drawn between the selected background regions on either side of both the 444- and 501-keV peaks. Following background subtraction, the spectra were integrated between the two selected limits of each peak, and the photopeak intensities were normalized according to the analyzer live times. The asymmetries were computed according to Eq. (6) by comparing the counting rate for each counting period with the average of those of the previous and subsequent periods having the field directed 180° opposite. Finally the deduced asymmetries were corrected for small count-rate nonlinearities of the electronics and effect which results from the high count rates during the early counting periods. These correction factors were deduced empirically from the performance of each detector and associated electronics. An illustration of this nonlinearity is shown in Figure 5. Such nonlinearities not only can lead to erroneous conclusions regarding the counting rate asymmetry, but they also result in incorrect deductions of the sample temperature.

V. RESULTS

The results of this experiment represent data from 4 different samples, each of which was counted during two half-lives. Representative temperatures at which three of the four samples were run were 16 mK, 17 mK, and 22 mK; a fourth sample was observed at temperatures in the range 16-28 mK. The results are summarizied in Table I. For sample #1, the reasonably rapid warm-up rate necessitated a point-by-point calculation of the parity mixing ratio ϵ; hence no average value of the asymmetry was obtained. The detector code refers to the choice of a selection of detectors available at this Laboratory. The asymmetries are defined according to Eq. (6), and the mixing ratio ϵ was deduced from Eq. (5). The orientation parameters B_1 and B_3 may be either positive or negative according to the sign of the hyperfine splitting parameter Δ; since we deduced the odd-order orientation parameters from the even-order ones (which are always positive, independent of the sign of Δ), the sign of ϵ may not be deduced unambiguously from $\mathcal{A}$. The deduced sign of the moment and hyperfine field[15] indicate, however, that B_1 is positive, and thus that $\epsilon < 0$.

The weighted average value of ϵ based on the data of Table I is $\epsilon = -0.029 \pm 0.002$. Computing the normalized chi-squared value of the 14 individual measurements of ϵ, we obtain $\chi^2 = 2.3$. This value is somewhat large, and perhaps suggests a systematic source of error in the data. A careful examination of each individual data point revealed no systematic effect which could be correlated with the detector identity, its orientation relative to the polarizing magnets, the distance from the cryostat, and so forth. However, we allow for the possibility of some as yet unknown source of systematic error by increasing the individual statistical uncertainties by a factor of 1.5 ($=\sqrt{2.3}$). The final result of the present experiment is compared with those of previous studies in Table II. In doing the comparison, all results have been evaluated using $\delta = +5.3$. The weighted average of the six results to date is $\epsilon = -0.032 \pm 0.002$ ($\chi^2 = 1.0$).

The case of ^{180}Hf thus represents the only nucleus for which consistent evidence of parity nonconservation has been obtained from different methods and from independent investigations. As the summary by Gari[3] suggests, possible evidence has been found in other cases, but there is in general a lack of agreement among the various results. The present results are entirely consistent with the other published results for ^{180}Hf and support the evidence for parity nonconserving effects in this nucleus. The chief value of the present measurement is to confirm the earlier measurements under somewhat altered experimental conditions.

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Footnotes and References

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Table I. Parity nonconserving asymmetry of the ^{180}Hf 501-keV gamma-ray.

Sample No.	Temperature	Detector No.	Source-to-Detector Distance(cm)	Detector Orientation	Asymmetry[a]	$\|\epsilon\|$[a]
1	16-28 mK	A	22	270°		0.0464 (59)
		B	20	0°		0.0378 (68)
		C	10	90°		0.0464 (64)
		D	11	180°		0.0252 (63)
2	16 mK	A	30	180°	0.0160 (40)	0.0293 (75)
		E	11	270°	0.0100 (28)	0.0184 (52)
		C	12	90°	0.0138 (27)	0.0252 (50)
		D	13	0°	0.0162 (44)	0.0296 (81)
3	22 mK	A	27	270°	0.0111 (30)	0.0244 (67)
		E	10	180°	0.0068 (25)	0.0151 (55)
		C	12	0°	0.0131 (23)	0.0290 (52)
		D	13	90°	0.0111 (33)	0.0244 (73)
4	17 mk	A	17	270°	0.0127 (47)	0.0281 (89)
		E	9	90°	0.0129 (49)	0.0283 (92)

[a]The statistical uncertainties of the last two digit are indicated in parenthesis.

Table II. Comparison of results on parity nonconservation in the 501-keV transition of ^{180}Hf.

Method[a]	$\epsilon = \langle E2 \rangle / \langle M2 \rangle$	Reference
P_γ	-0.041 ± 0.007	Jenschke and Bock, ref. 9
P_γ	-0.033 ± 0.009	Lipson, Vanderleeden, and Boehm, ref. 10
P_γ	-0.029 ± 0.006	Kuphal, ref. 11
$\gamma(\theta)$	-0.038 ± 0.004	Krane, Olsen, Sites, and Steyert, ref. 12
$\gamma(\theta)$	-0.031 ± 0.003	Krane, Olsen, and Steyert, ref. 17
$\gamma(\theta)$	-0.029 ± 0.003	present work

[a] P_γ = circular polarization of gamma radiation from a randomly source; $\gamma(\theta)$ = angular distribution asymmetry from a polarized source.

FIGURE CAPTIONS

Fig. 1. Decay scheme of $^{180}Hf^{m}$.

Fig. 2. The low-temperature cryostat and dewar system.

Fig. 3. Schematic of polarizing magnet control cycle. Upon command from the timer, the field was rotated in a time t_r in the range 0.5-2.0 min. The effects of this slow rotation were (a) to reduce eddy current heating, and (b) to maintain the sample in magnetic saturation. The field directions are defined such that when $i_A > 0$, the field is in the direction of detector 1 and when $i_B > 0$, in the direction of detector 2.

Fig. 4. The x-ray powder spectrum of $Hf_{0.1}Zr_{0.9}Fe_2$.

Fig. 5. Integral count-rate nonlinearity of a typical detector. The solid line represents the extrapolation of the data from the region of low counting rates; the points are experimental data.

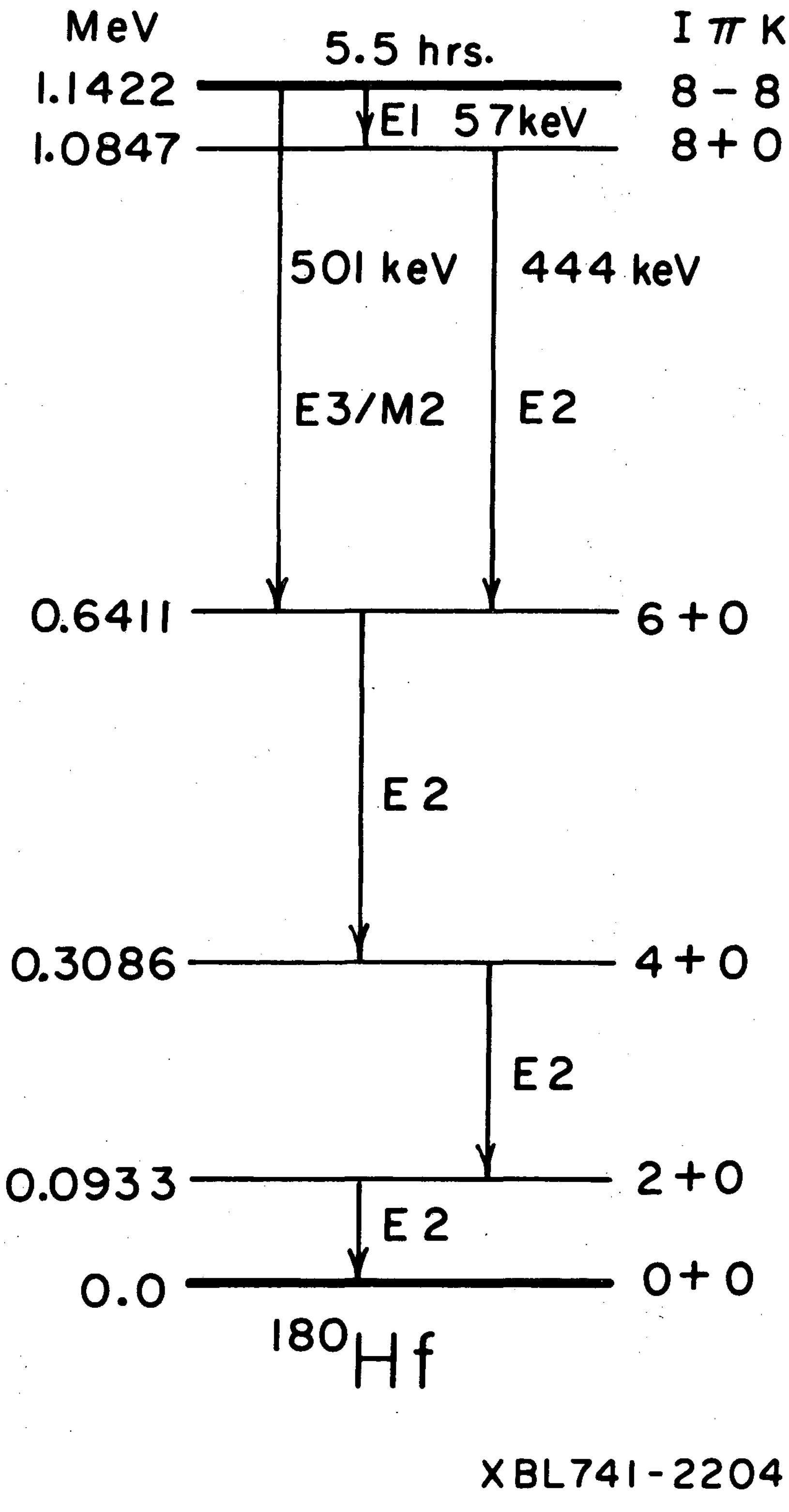
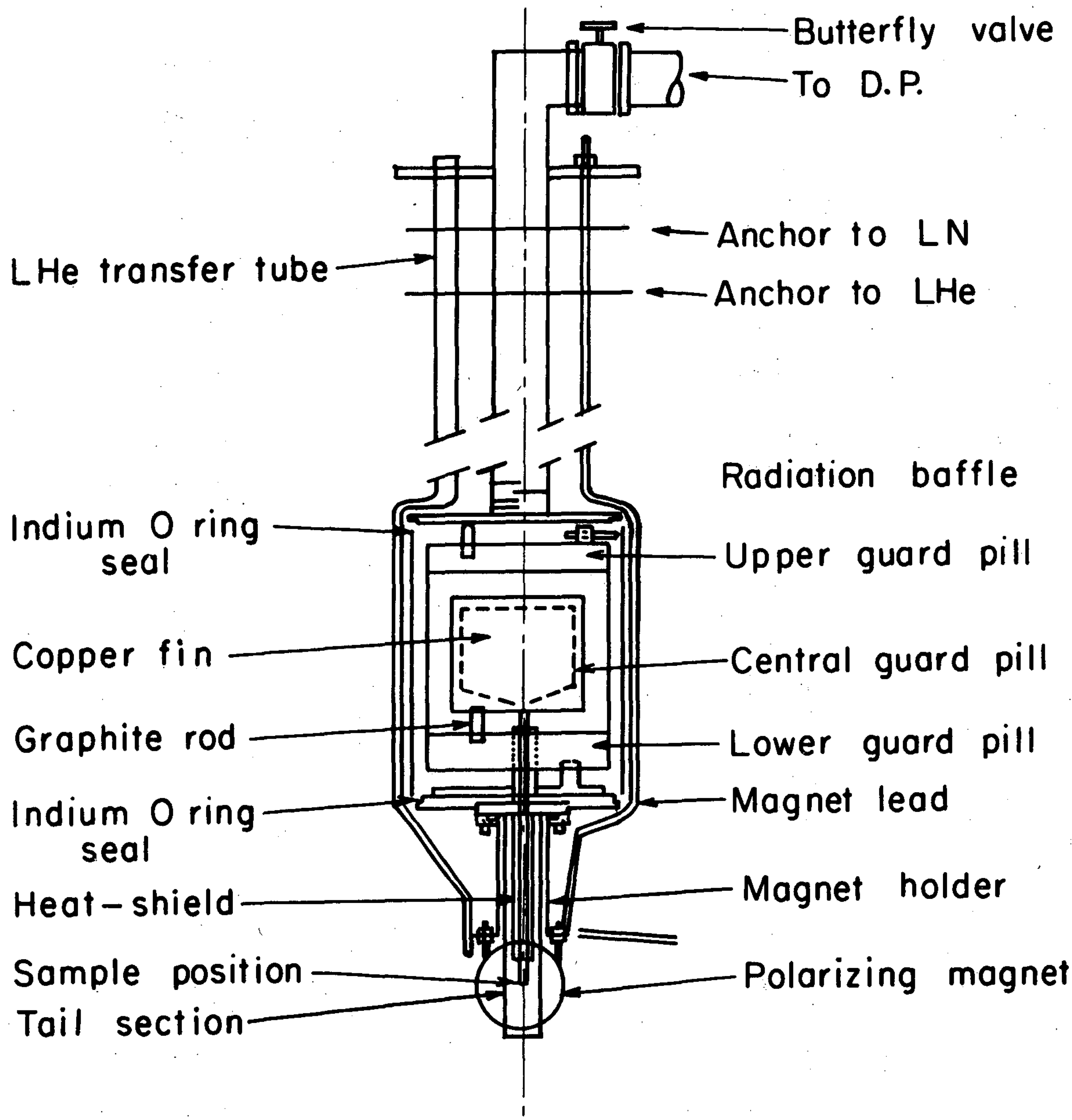

MeV
5.5 hrs.
I π K
1.1422
8 - 8
E1 57keV
1.0847
8 + 0
501 keV
444 keV
E3/M2
E2
0.6411
6 + 0
E2
0.3086
4 + 0
E2
0.0933
2 + 0
E2
0.0
0 + 0
180Hf
XBL741-2204

Fig. 1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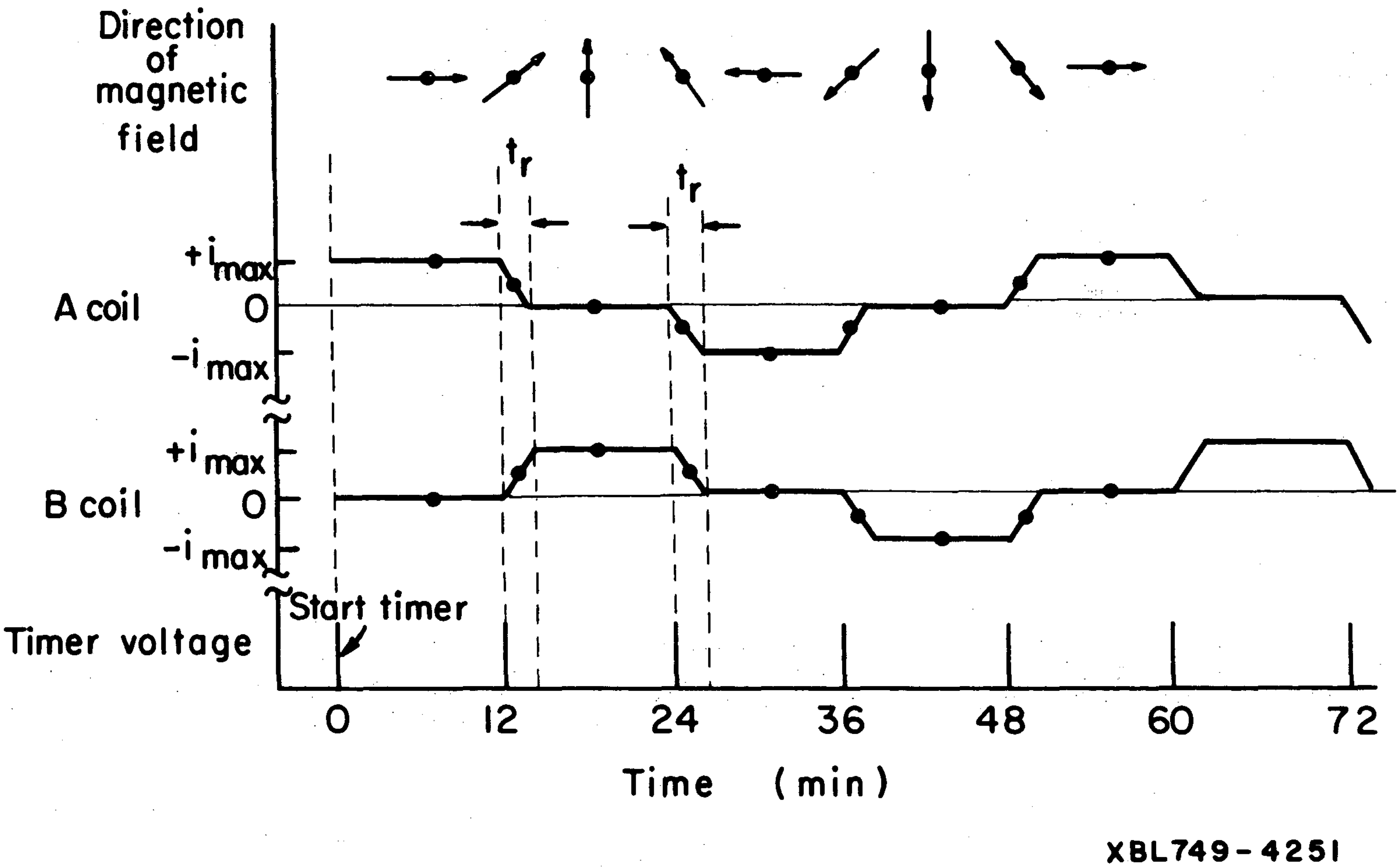
To D.P.
Anchor to LN
LHe transfer tube
Anchor to LHe
Radiation baffle
Indium O ring seal
Upper guard pill
Copper fin
Central guard pill
Graphite rod
Lower guard pill
Indium O ring seal
Magnet lead
Heat-shield
Magnet holder
Sample position
Polarizing magnet
Tail section
XBL741-2063

Fig. 2



Direction of magnetic field
t_r
t_r
$+i_{max}$
A coil
0
$-i_{max}$
$+i_{max}$
B coil
0
$-i_{max}$
Start timer
Timer voltage
0
12
24
36
48
60
72
Time (min)
XBL749-4251

Fig. 3

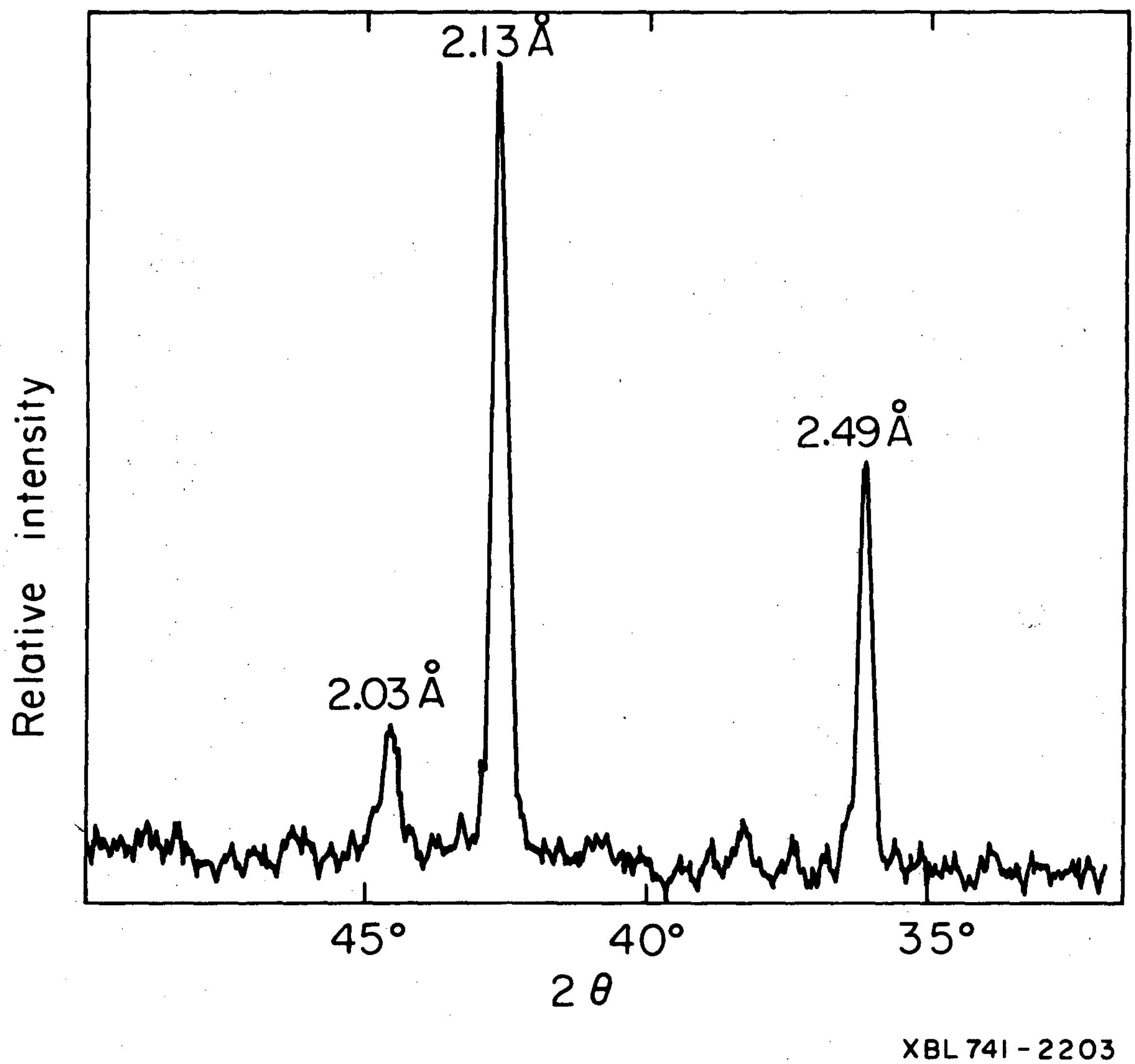
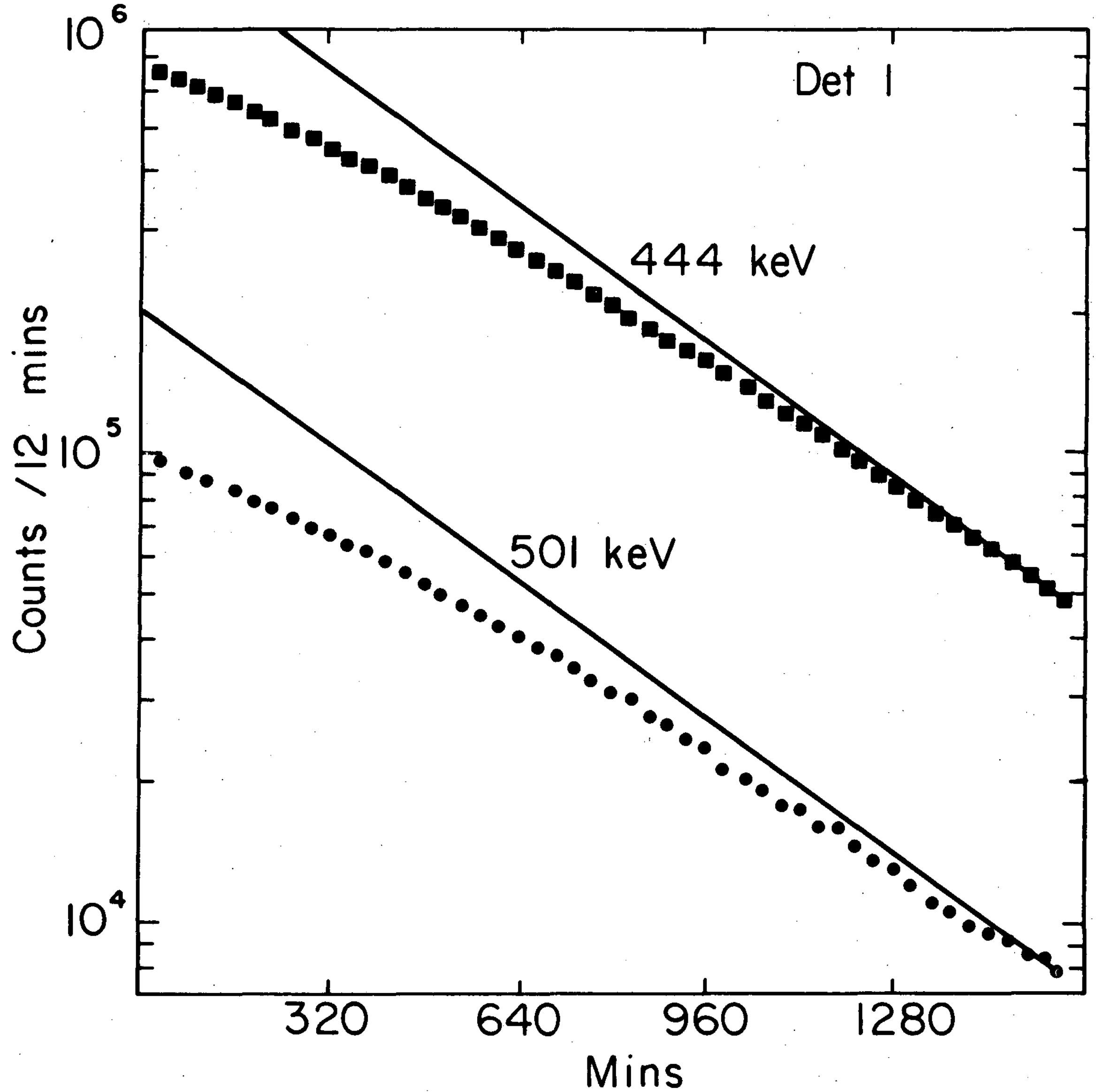


Fig. 4



XBL741-2200

Fig. 5

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