THE UNIVERSITY OF MICHIGAN
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Department of Physics

Progress Report

RESEARCH IN THE FIELD OF NUCLEAR SPECTROSCOPY

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FOREWORD

The progress report, covering the first eight months of operation under this contract, consists of six papers (either published or in the process of publication in various journals) as well as a report on the preliminary work on capture gamma spectra.

In addition to the research reported herein, work is being carried out on: (1) the angular correlation of the gamma rays of W^{182}, (2) the β spectra, decay scheme, and angular correlation following the decay of Dy^{165}, (3) the angular correlation of certain γ-γ cascades arising from the decay of Sm^{153}, and (4) resonance fluorescence in Mg^{24} and other nuclei.

Studies of nuclear energy levels are being continued both in the Physics Department of the University and at the Argonne National Laboratory, under their Participating University Program.

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THE LEVEL STRUCTURE OF Dy^{160}

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THE LEVEL STRUCTURE OF Dy^{160}

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Abstract: Gamma rays in Dy^{160} following beta decay of the 72 day Tb ^{160} have been studied using coincidence and angular correlation methods. The relative intensity and coincidence measurements confirm the principal features of the decay scheme proposed by Nathan [1]). Angular correlation measurements were made on six cascades. The spin and parity of the 0.087 MeV, 0.964 MeV, and 1.262 MeV levels were found to be 2+, 2+, and 2− respectively. The measurements favour spins of 4 and 3 for the 0.283 MeV and 1.359 MeV levels. These assignments are in agreement with previous assignments by Ofer [2]). The multipolarities of the main gamma transitions are given.

1. Introduction

The level structure of Dy^{160} following beta decay of the 72 day Tb^{160} has been the subject of several investigations [1–8]). The more recent of these studies have been in agreement on several features of the level structure. However, conflicts still exist in regard to the relative intensities and multipolarities of certain strong gamma transitions. The angular correlation of the 1.076 MeV—0.196 MeV cascade reported by Ofer [2]) was considerably different from that observed by Nathan [1]). In addition, Ofer found it necessary to postulate an attenuation [2, 9]) in interpreting three of his angular correlation measurements (those involving the 0.087 MeV level). Under the circumstances an attenuation is difficult to understand and further study of this aspect would seem to be of value. Thus the present coincidence and angular correlation measurements were undertaken in the hope of resolving some of the incompatible aspects of previous research on this decay.

2. Experimental Procedure

Qualitative coincidence measurements were carried out using a fast-slow coincidence circuit with multichannel recording of the "gray wedge" type (modified Beva Lab 210). The detectors were 1½″×1″ NaI(Tl) crystals mounted on RCA type 6342 phototubes.

The quantitative coincidence measurements and angular correlation

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measurements employed a conventional fast-slow coincidence circuit [10]) with an effective resolving time of 20 ns. The scintillation counters consisted of 2″ × 2″ NaI(Tl) crystals mounted on RCA type 6342 phototubes. Differential analyzers were used to provide energy selection. Lateral lead shielding was used to prevent counter-to-counter scattering.

Angular correlation data were taken in a double quadrant sequence. A least-squares fit of the data was made to the function

$$W'(\theta) = \alpha_0+\alpha_2 P_2(\cos\theta)+\alpha_4 P_4(\cos\theta).$$

The resultant expansion coefficients were then normalized and corrected for finite angular resolution by a collimated beam method [11]). This yielded a correlation function of the form

$$W(\theta) = 1+(A_2\pm\sigma_2)P_2(\cos\theta)+(A_4\pm\sigma_4)P_4(\cos\theta).$$

The σ_2 and σ_4 are the root-mean-square errors as defined by Rose (ref.[12]), eq. (30)).

High purity Tb_2O_3 powder was irradiated for 24 hour periods in The University of Michigan Ford Nuclear Reactor. The activated powder was then dissolved in HCl and the solution was diluted. No impurity activities were found to be present in the source material.

3. Results

3.1. COINCIDENCE MEASUREMENTS

In order to determine the position of the various gamma rays in the decay scheme, measurements were made of the gamma rays coincident with the following energy regions:

$$0.080 \text{ MeV} \leqq E \leqq 0.100 \text{ MeV},\quad 0.160 \text{ MeV} \leqq E \leqq 0.240 \text{ MeV},$$
$$0.250 \text{ MeV} \leqq E \leqq 0.350 \text{ MeV},\quad \text{and}\quad 0.830 \text{ MeV} \leqq E \leqq 1.00 \text{ MeV}.$$

The qualitative results are summarized in table 1.

A knowledge of the relative intensities of the 0.877, 0.960 and 0.964 MeV lines is necessary in order to interpret the angular correlation data. Hence a careful measurement was made by means of the 0.298 MeV coincidence spectrum. After correction for detector efficiency and the slight overlap of the lines, the intensity ratio 0.877: 0.964 : 0.960 was found to be 1 : 0.73± 0.06: 0.29±0.06. This ratio was confirmed by measurements in the 0.087 MeV coincidence spectrum although the presence of interfering cascades prevented reliable quantitative results. The present results are in good agreement with the ratio 1 : 0.68±0.10 : 0.35±0.10 found by Nathan. A ratio of 1 : 0.90±0.18 : 0.05±0.01 has been quoted by Ofer.

TABLE 1

Gamma-gamma coincidence measurements

Energy Region (MeV)	Transitions Selected (MeV)	Coincident Transitions (MeV)	Remarks
$0.080 \leqq E \leqq 0.100$	0.087	0.196+0.215, 0.298, 0.877, 0.960, 1.175, 1.272	The photopeak at 0.960 MeV was found to be about $\frac{1}{3}$ as strong as the 0.876 MeV photopeak after subtraction of interfering cascades.
$0.160 \leqq E \leqq 0.240$	0.196, 0.215	0.087, 0.196+0.215, 0.298, 0.681, 0.764, 0.960, 1.076	The 0.681 MeV transition was found to be about $\frac{1}{2}$ as strong as the 0.764 MeV transition. No gamma ray was found at 1.047 MeV thus ruling out the presence of a strong ground state transition from the 1.047 MeV level.
$0.250 \leqq E \leqq 0.350$	0.298	0.087, 0.196, 0.877, 0.964	The 0.964 MeV transition was found to be about $\frac{2}{3}$ as strong as the 0.877 MeV transition.
$0.830 \leqq E \leqq 1.00$	0.877, 0.960, 0.964	0.087, 0.159, 0.215, 0.298	

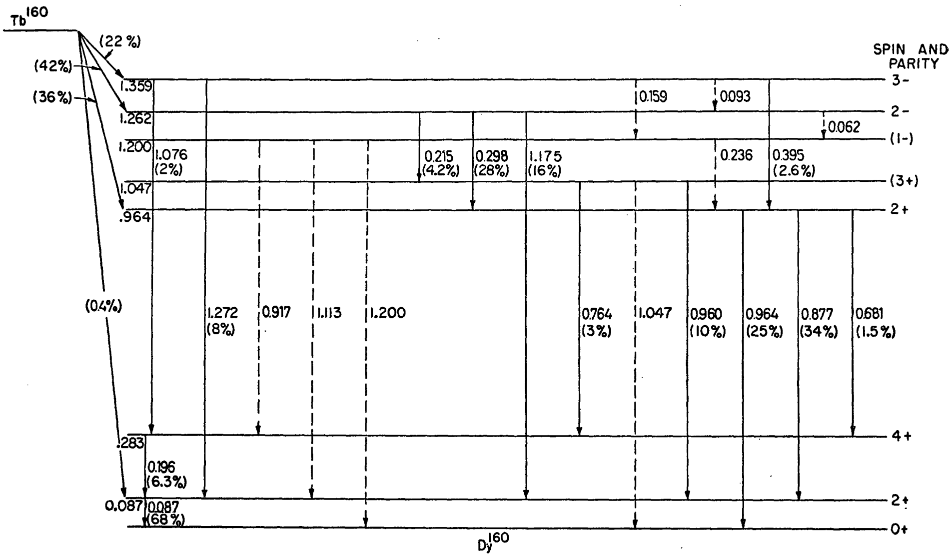

Fig. 1. Decay scheme of Tb^{160}. The beta decay data and gamma ray energies (in MeV) are according to Nathan. The relative intensities are due to Nathan except where directly measured in the present research. A number of weak transitions observed by Gregor'ev *et al.* [7]) (relative intensities unknown) have been included.

The decay scheme shown in fig. 1 is due to Nathan [1]). The relative intensities of some transitions have been modified to agree with the present measurements. An additional level at 1.200 MeV and several weak transitions have been added to the scheme on the basis of internal conversion measurements by Grigor'ev *et al.* [7]).

3.2. ANGULAR CORRELATION OF THE 0.298 MeV—0.877 MeV and 0.298 MeV—0.964 MeV CASCADES

Although the 0.877 MeV photopeak and the 0.960 MeV and 0.964 MeV combined photopeak were easily resolved by the scintillation counters, there remains a small overlap of these lines which must be considered in analyzing the angular correlation data. Two angular correlation measurements were made. In each measurement one of the differential analyzers was set to accept the upper half of the photopeak of the 0.298 MeV gamma ray. In one case the second differential analyzer was set to accept a narrow range of pulses in the upper half of the 0.964 MeV photopeak. In the other measurement, the second differential analyzer selected a narrow range of energies centered on the 0.877 MeV photopeak.

Using the measured relative intensities (without the detector efficiency correction), the 0.877 MeV and 0.964 MeV photopeaks were constructed from known shapes of single gamma rays in this energy region. The integrated contribution of both gamma rays to each correlation function was then determined. The two correlation functions were combined with special attention to the errors in the relative intensities, channel settings, and the correlation functions themselves. In this manner the 0.298 MeV—0.964 MeV angular correlation yielded expansion coefficients $A_2 = +0.259 \pm 0.042$ and $A_4 = -0.031 \pm 0.030$. These are in good agreement with the theoretical coefficients for a pure 2(D)2(Q)0 cascade, i.e., $A_2 = +0.250$, $A_4 = 0$. If the cascade is of the form 2(D, Q)2(Q)0, the limits of error will allow a maximum of 0.5 % quadrupole content in the 0.298 MeV transition. This assignment is supported by the measured K-conversion coefficients [1,7]) which indicate an E1 multipolarity for the 0.298 MeV gamma ray and E2 for the 0.964 MeV transition. It seems safe to assign a spin and parity of 2+ to the 0.964 MeV level on the basis of the conversion data. The expansion coefficients for this sequence are also consistent with a 3(D, Q)2(Q)0 cascade with a quadrupole content Q_1 for the first transition of $0.21 \leqq Q_1 \leqq 0.65$. An M2 content of this magnitude is inconsistent with experience and with the measured K-conversion coefficients. Thus a spin assignment of 3 must be ruled out for the 1.262 MeV level.

In the manner described above the corrected expansion coefficients for the 0.298 MeV—0.877 MeV sequence were found to be $A_2 = -0.126 \pm 0.026$ and $A_4 = +0.015 \pm 0.020$. The first excited state (at 0.087 MeV) can almost certainly be characterized as 2+. If the 0.298 MeV transition is assumed to be pure dipole, the data are then consistent with a 2(D)2(D, Q)2 sequence with $0.95 \leqq Q_2 \leqq 0.99$ or $0.25 \leqq Q_2 \leqq 0.35$. The latter possibility can be ruled out by the angular correlation data from the 0.877 MeV—0.087 MeV cascade which is given below. The possibility of a small M2 admixture in the 0.298 MeV transition cannot be ruled out. The graphical analysis [13]) of the data for a doubly mixed cascade is shown in fig. 2 in which the range of E1+M2 mixture for the 0.298 MeV transition is assumed from the results of the 0.298 MeV—0.964 MeV correlation. Again in accord with the results of the 0.877 MeV—0.087 MeV angular correlation, the data still require a quadrupole content of $0.925 \leqq Q_2 \leqq 0.995$ for the 0.877 MeV transition.

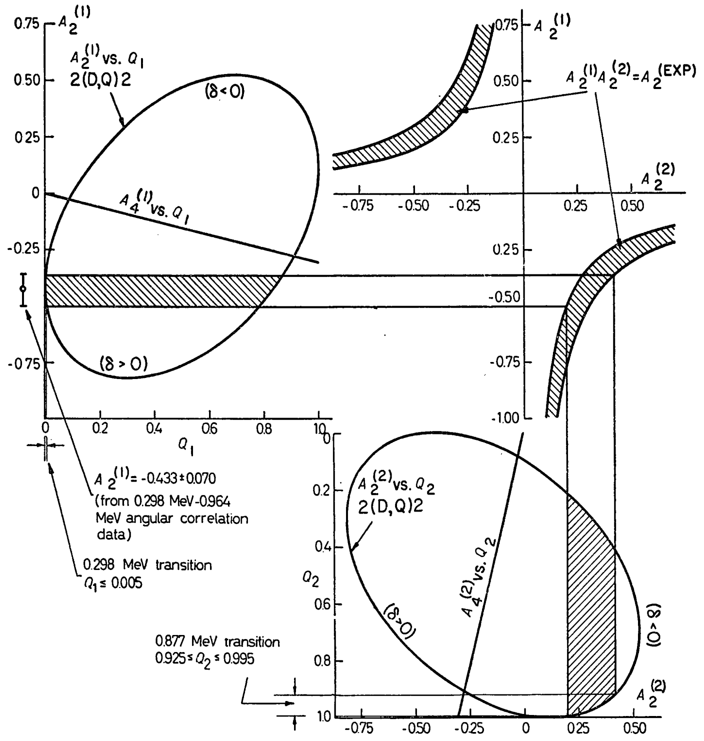

Fig. 2. Analysis of the 0.298 MeV—0.877 MeV angular correlation in terms of a 2(D, Q)2(D, Q)2 sequence. The limits of quadrupole content for the first step of the cascade are known from the 0.298 MeV—0.964 MeV angular correlation.

In summary, it has been shown that the 0.298 MeV gamma ray proceeds from a 2— level at 1.262 MeV to a 2+ level at 0.964 MeV by radiation which is predominantly electric dipole (≦ 0.5 % M2). The 0.964 MeV level decays by pure E2 radiation to the 0+ ground state and by 96±3.5 % E2 and 4∓3.5 % M1 radiation (0.877 MeV gamma ray) to the 2+ first excited state at 0.087 MeV.

3.3. ANGULAR CORRELATION OF THE 0.877 MeV—0.087 MeV CASCADE

The 0.877 MeV gamma ray is a transition from the 2+ level at 0.964 MeV to the first excited state (spin and parity of 2+) at 0.087 MeV. Angular correlation measurements on this cascade can provide information on the multipolarity of the 0.877 MeV transition, assuming that the 0.087 MeV transition is pure E2. An accurate measurement is not possible, however, due to the presence of the Compton distributions of interfering cascades. The chief contributions to this background, i.e., the 1.272 MeV—0.087 MeV, 1.175 MeV—0.087 MeV, 0.960 MeV—0.087 MeV and 0.298 MeV—0.877 MeV cascades, comprise nearly 50 % of the real coincidences measured by accepting a small portion of the 0.087 MeV and 0.877 MeV photopeaks in alternate differential analyzers. However, the range of multipolarities possible for the 0.877 MeV gamma ray is already known from the 0.298 MeV—0.877 MeV angular correlation measurement. Thus, despite the large errors introduced by the interference subtraction, the 0.877 MeV—0.087 MeV data can be used to distinguish between the two allowable ranges. The corrected data showed the negative A_2 and large positive A_4 characteristic of a 2(D, Q)2(Q)0 sequence with a large (> 90 %) quadrupole content in the first transition.

The angular correlation of this cascade was also measured by Ofer [2]. In that measurement the experimental data were corrected for interference from the 1.272 MeV—0.087 MeV and 1.175 MeV—0.087 MeV cascades and the resultant coefficients were considerably smaller than would be expected for the large quadrupole admixture present in the 0.877 MeV transition. The present measurements indicate that it is not necessary to postulate an attenuation if all interference is considered. However, the presence of some attenuation cannot be ruled out. Ofer and Cohen [9] were unable to achieve a completely satisfactory explanation for the large attenuation proposed. It will be seen below that the results of the 1.272 MeV—0.087 MeV and 1.175 MeV—0.087 MeV angular correlations can be more readily understood if no attenuation is present.

3.4. ANGULAR CORRELATION OF THE 1.272 MeV—0.087 MeV AND 1.175 MeV—0.087 MeV CASCADES

The 1.175 MeV and 1.272 MeV photopeaks are barely resolved in the scintillation spectrum, and an analysis similar to that outlined in section 3.2 must be applied in order to obtain the corrected angular correlation functions. The errors involved are large due to a poor knowledge of the relative intensities and are reflected in the increased error limits of the expansion coefficients. The corrected expansion coefficients for the 1.175 MeV—0.087 MeV angular correlation were found to be $A_2 = +0.133 \pm 0.041$ and $A_4 = +0.008 \pm 0.083$. Similarly the 1.272 MeV—0.087 MeV cascade yielded $A_2 = +0.148 \pm 0.065$ and $A_4 = -0.09 \pm 0.14$.

The 1.175 MeV gamma ray proceeds from the 2− level at 1.262 MeV to the first excited state. The cascade is certainly of the form 2(D, Q)2(Q)0. The expansion coefficients are then consistent with an E1+M2 mixture for the 1.175 MeV gamma ray with 97.5±1.5 % E1 and 2.5∓1.5 % M2. This is in agreement with the K-conversion coefficient measurements of Nathan and of Grigor'ev *et al.* If a perturbation were present, a larger M2 content could not be ruled out. Assuming an attenuation, Ofer's data ^{2}) would require an M2 content of about 65 %. This would contradict the conversion measurements and also constitute a much larger M2 admixture than is normally encountered. Hence the results tend to favor the present interpretation.

The 1.272 MeV gamma ray is a transition from a level at 1.359 MeV to the first excited state. Of the spin assignments logically available for the 1.359 MeV level, the angular correlation data is consistent only with 2 or 3. As will be shown below, the 1.076 MeV—0.196 MeV angular correlation rules out a spin assignment of 2 for the 1.359 MeV level. For a 3(D, Q)2(Q)0 sequence the data require $0.04 \leqq Q_0 \leqq 0.18$ or $0.66 \leqq Q_1 \leqq 0.86$. The K-conversion coefficient measured by Nathan favors an E1 multipolarity for the 1.272 MeV transition. Hence the 1.359 MeV level is most naturally characterized as 3− and the 1.272 MeV gamma ray is an E1+M2 mixture with 89±7 % E1 and 11∓7 % M2. Ofer, assuming a perturbation, found a quadrupole content of between 27 % and 50 % for the 1.272 MeV transition.

3.5. ANGULAR CORRELATION OF THE 1.076 MeV—0.196 MeV CASCADE

The 1.076 MeV gamma ray is a transition from the 1.359 MeV level to the second excited state at 0.283 MeV. The 0.196 MeV gamma ray is a transition between the second and first excited states. Both gamma rays involved are very weak. The window of one differential analyzer was set to accept the 0.205 MeV photopeak and the other was set with a narrow window in the region where the 1.076 MeV gamma ray should occur. It was found that interference was present due to the high energy tails of the 0.960 MeV and 0.964 MeV gamma rays as the 0.215 MeV—0.960 MeV and the 0.298 MeV—0.964 MeV cascades. No adequate method could be found for subtracting out this interference.

It seems highly probable that the second excited state can be characterized as 4+. Of the possible sequences 4(D, Q)4(Q)2, 2(Q)4(Q)2, and 3(D, Q)4(Q)2, the first two require a positive A_4 coefficient. The present data, even with the large interference, require an A_4 which is negative or at worst vanishing. Thus a spin of 3 must be assigned to the 1.359 MeV level but the multipolarity of the 1.076 MeV transition remains undetermined.

4. Discussion

Nathan ¹) has discussed the level structure of Dy^{160} in terms of the unified model. His spin and multipolarity assignments were based on internal conversion and relative intensity measurements. The present angular correlation measurements confirm his assignments when interpreted in accord with the internal conversion data.

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II

DECAY OF Re^{188}

DECAY OF Re^{188} *

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The gamma rays in Os^{188} following beta decay of 18-hour Re^{188} have been studied using coincidence and directional correlation techniques. The results agree with the principal features of the decay scheme proposed by Johns et al.[1] Directional correlation measurements were made on five cascades. From the directional correlation measurements, spins of 2, 2, 0, 2, 0, 2 are assigned to the levels at 0.155 Mev, 0.633 Mev, 1.086 Mev, 1.461 Mev, 1.765 Mev, and 1.941 Mev, respectively. The 0.478-Mev gamma ray is a dipole-quadrupole mixture with $Q \geqq 99\%$. The 0.828-Mev and 1.308-Mev gamma rays are pure dipole.

I. INTRODUCTION

The decay of 18-hour Re^{188} to levels in Os^{188} has been studied by a number of investigators.[1-7] Johns et al.[1] have proposed a decay scheme on the basis of external conversion and coincidence measurements. Directional correlation measurements on the 0.478-Mev — 0.155-Mev cascade[4,7] have indicated that the spins of the 0.633-Mev and 0.155-Mev levels are both 2 and that the 0.478-Mev gamma ray is mostly E2. It was felt that additional directional correlation measurements would be helpful in establishing the level structure of Os^{188}. Os^{188} is on the edge of a region in which the nuclei exhibit a well-defined rotational structure ($155 \leqq A \leqq 185$). A 4+ state has recently been found at 0.479 Mev in Os^{188} fed from the decay of Ir^{188}.[8,9] It appears that this nucleus does exhibit some rotational structure, and it is hoped that some of the higher excited levels could be related through the unified model.

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**National Science Foundation Research Participant, Jackson Junior College, Jackson, Michigan.

II. EXPERIMENTAL PROCEDURE

Samples of spectroscopically pure rhenium metal were irradiated at a flux of 2 x 10^{12} neutrons/cm^2/sec for periods of 2 to 6 hours in the Ford Nuclear Reactor. The sources used in the coincidence and directional correlation measurements consisted of irradiated rhenium powder dissolved in nitric acid and diluted. The only observed impurity was the 91-hour Re^{186}. Data for the 0.478-Mev — 0.155-Mev directional correlation were taken during the first few hours after irradiation in order to minimize possible interference from the very weak 0.631-Mev to 0.137-Mev cascade in Re^{186}. The 91-hour activity did not interfere with any of the other measurements.

The coincidence measurements employed a fast-slow coincidence circuit with a resolving time of 30 millimicroseconds. Pulses coincident with a selected energy range were fed through a linear gate and recorded on a 256-channel analyzer.

A fast-slow coincidence circuit with a resolving time of 18 millimicroseconds was used in the directional correlation measurements. The detectors in all cases consisted of 2-in. by 2-in. NaI(Tl) crystals mounted on RCA 6342 or 6342A phototubes. Differential analyzers provided energy selection in the directional correlation measurements. Lateral lead shield was used to prevent counter-to-counter scattering. Data were taken in a double-quadrant sequence at seven angles in each quadrant. The real coincidence rate was corrected for source decay and electronic drift. After making a least squares fit,[10] the expansion coefficients were normalized and corrected for finite resolution.[11]

III. RESULTS

COINCIDENCE MEASUREMENTS

Figure 1 shows the gamma ray spectrum of Re^{188} as recorded on the multichannel analyzer. The observed width of the 1.610-Mev and 1.709-Mev photopeaks indicates that these transitions are complex.

Measurements were made of the spectrum of gamma rays in coincidence with the 0.155-Mev, 0.478-Mev, 0.633-Mev, and 0.828-Mev photopeaks. Figure 2 shows the spectrum of gamma rays coincident with the 0.155-Mev photopeak. A complex peak is found which is made up of the 0.633-Mev and 0.676-Mev transitions. The weak 0.633-Mev and 0.155-Mev peaks are due to the presence of the Compton distribution of higher-energy gamma rays beneath the 0.155-Mev photopeak in the range-selecting channel. The observed complexity of the 1.133-Mev photopeak

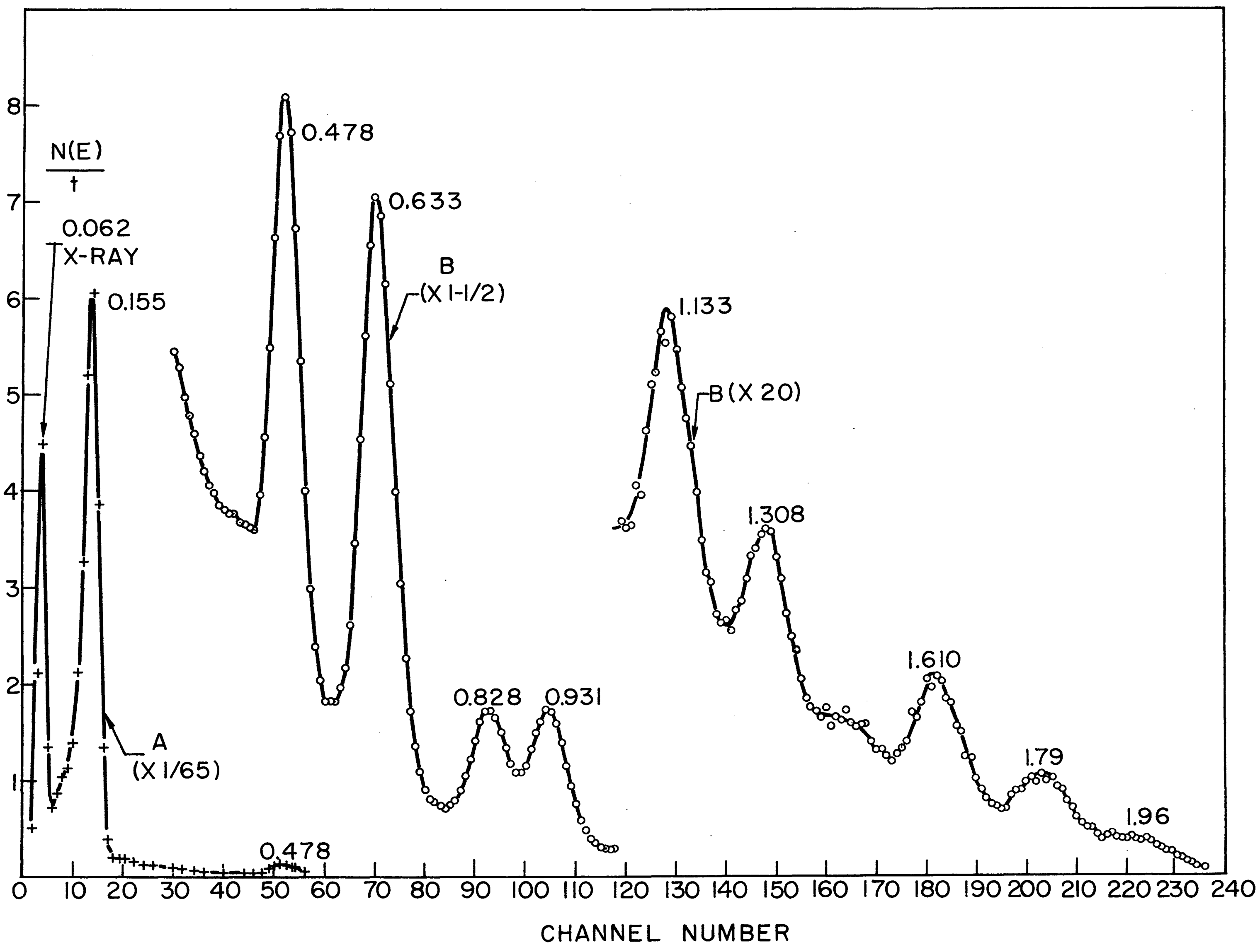

Fig. 1. Gamma ray spectrum of Re^{188}. A beta shield of 0.1-in. aluminum was used in obtaining curve A. An additional shield of 0.1-in. lead was interposed for curve B.

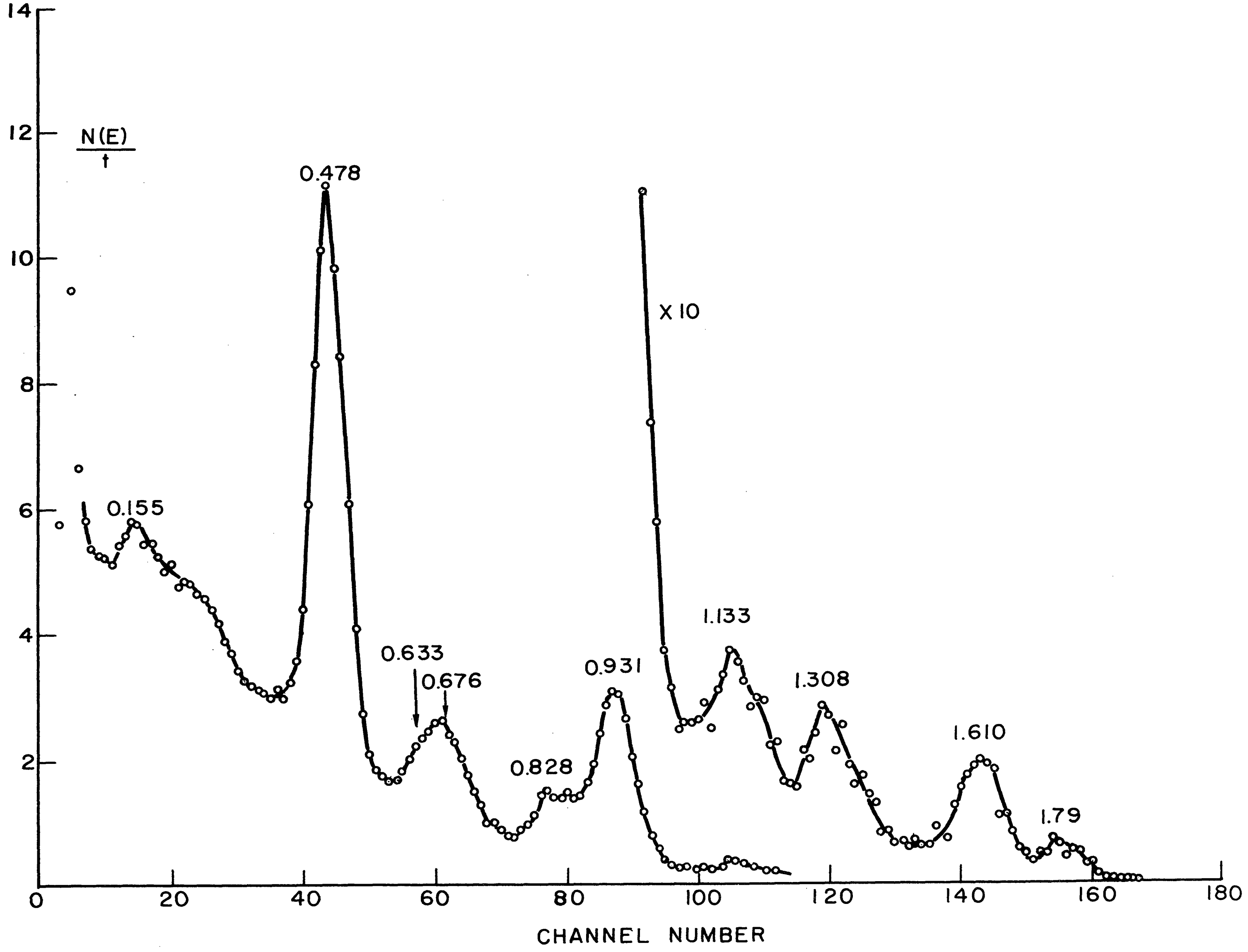

Fig. 2. Spectrum of gamma rays coincident with the 0.155-Mev photopeak. The detector which selected the 0.155-Mev gamma ray was shielded with aluminum to eliminate beta particles. An additional shield of 0.1-in. lead was used for the analyzed detector.

is attributed to the presence of a weak 1.151-Mev transition between the 1.306-Mev level and the 0.155-Mev level. The 1.609-Mev photopeak also appears to be complex. This is probably due to weakly fed level ~ 0.010 Mev above the 1.765-Mev level. Additional evidence for a second level will be discussed in regard to the 1.133-Mev → 0.633-Mev directional correlation measurement. The complexity of the 1.79-Mev peak has previously been observed by Johns *et al*.

Figure 3 illustrates the spectrum of gamma rays coincident with a narrow range of the 0.633-Mev photopeak. Curve A is the observed coincidence spectrum. Curve B shows a similar spectrum after subtraction of interference due to the Compton distribution of higher-energy gamma rays beneath the 0.633-Mev peak. The 0.676-Mev photopeak is clearly resolved. The position of the photopeak at 0.480 Mev suggests a weak transition of this energy, probably between the 1.941-Mev and 1.461-Mev levels. The 1.131-Mev photopeak is wider than would be expected for a single gamma ray.

The spectrum of gamma rays in coincidence with the 0.828-Mev photopeak is shown in Fig. 4. The peak at 0.478 Mev is relatively stronger in this spectrum than in the singles spectrum when compared with the 0.633-Mev peak. This attests to the relative weakness of the 0.454-Mev transition compared to the 0.676-Mev transition.

The spectrum of coincidences with the 0.478-Mev peak (not shown) indicates the presence of a weak peak at 0.454 Mev as proposed by Johns *et al*. in addition to the other gamma rays expected.

The results of the coincidence measurements are summarized in Table I. The proposed relative intensities were measured from the scintillation spectrometer curves and have been corrected for efficiency and correlation effects.

The proposed decay scheme is shown in Fig. 5. It agrees with the scheme of Johns *et al*. with the exception of some possible weak transitions and an additional weakly fed level at 1.775 Mev. The log *ft* values quoted have been calculated from the observed gamma ray branching, making use of the known ground-state beta intensity and conversion coefficients for the 0.155-Mev gamma ray.[1]

DIRECTIONAL CORRELATION MEASUREMENTS

0.828-Mev → 0.633-Mev Cascade.—This directional correlation was measured by accepting a narrow range of pulses on the 0.828-Mev photopeak in one differential analyzer and the full photopeak of the 0.633-Mev gamma ray in the other differential analyzer. With this arrangement, about 14.5 ± 1.5% of the real coincidences observed result from the 1.133-Mev to 0.633-Mev and 1.308-Mev to 0.633-Mev cascades. The interference was measured and subtracted from the observed correlation function. The resultant expansion coefficients, after correction for finite angular resolution, were found to be $A_2 = + .245 \pm .016$, $A_4 = 0$.

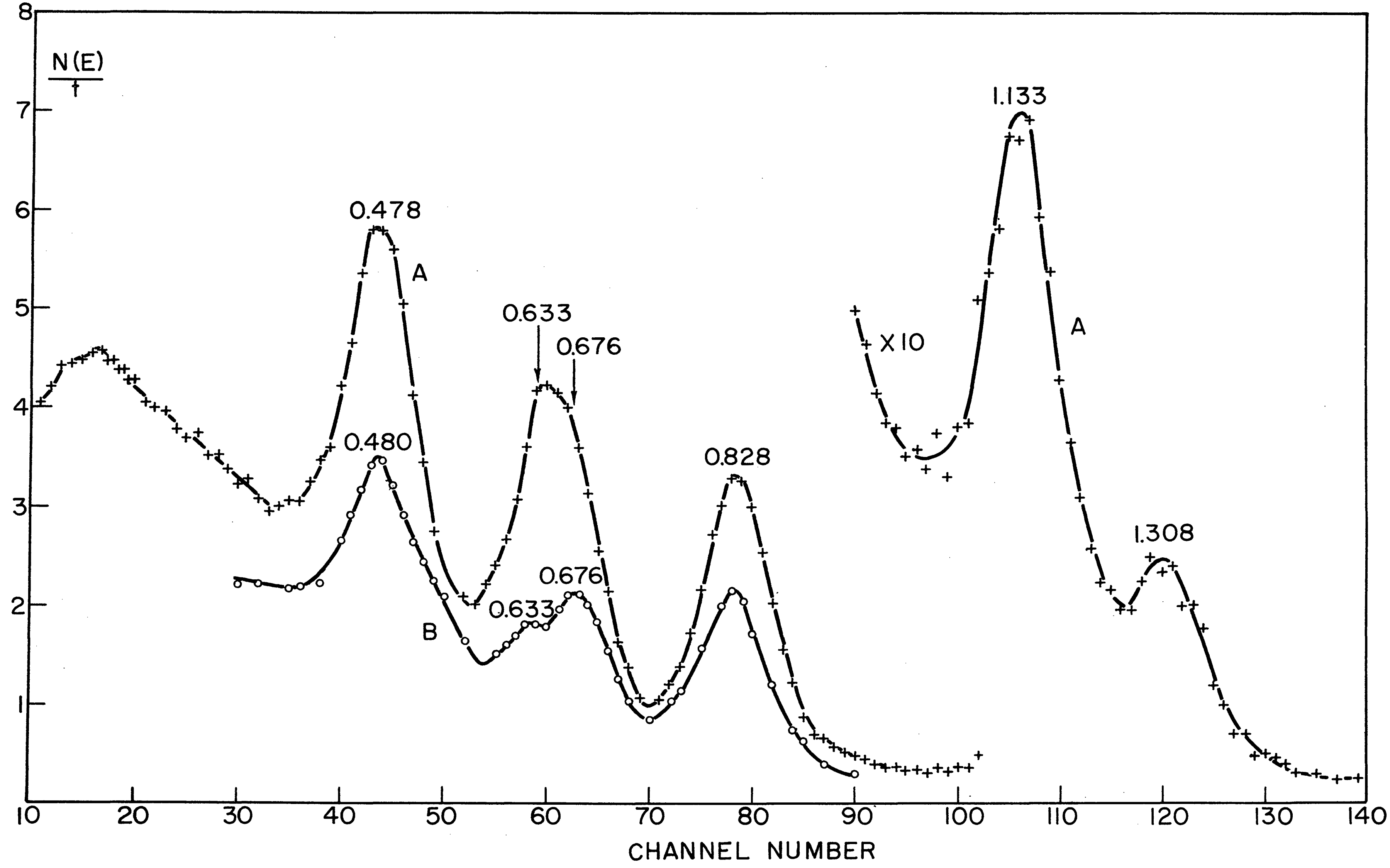

Fig. 3. Spectrum of gamma rays coincident with the 0.633-Mev photopeak. Both detectors were shielded with 0.1 in. each of aluminum and lead. Curve A is the observed coincidence spectrum. Curve B is a similar spectrum after subtraction of interference due to Compton distribution from higher-energy gamma rays beneath the 0.633-Mev photopeak.

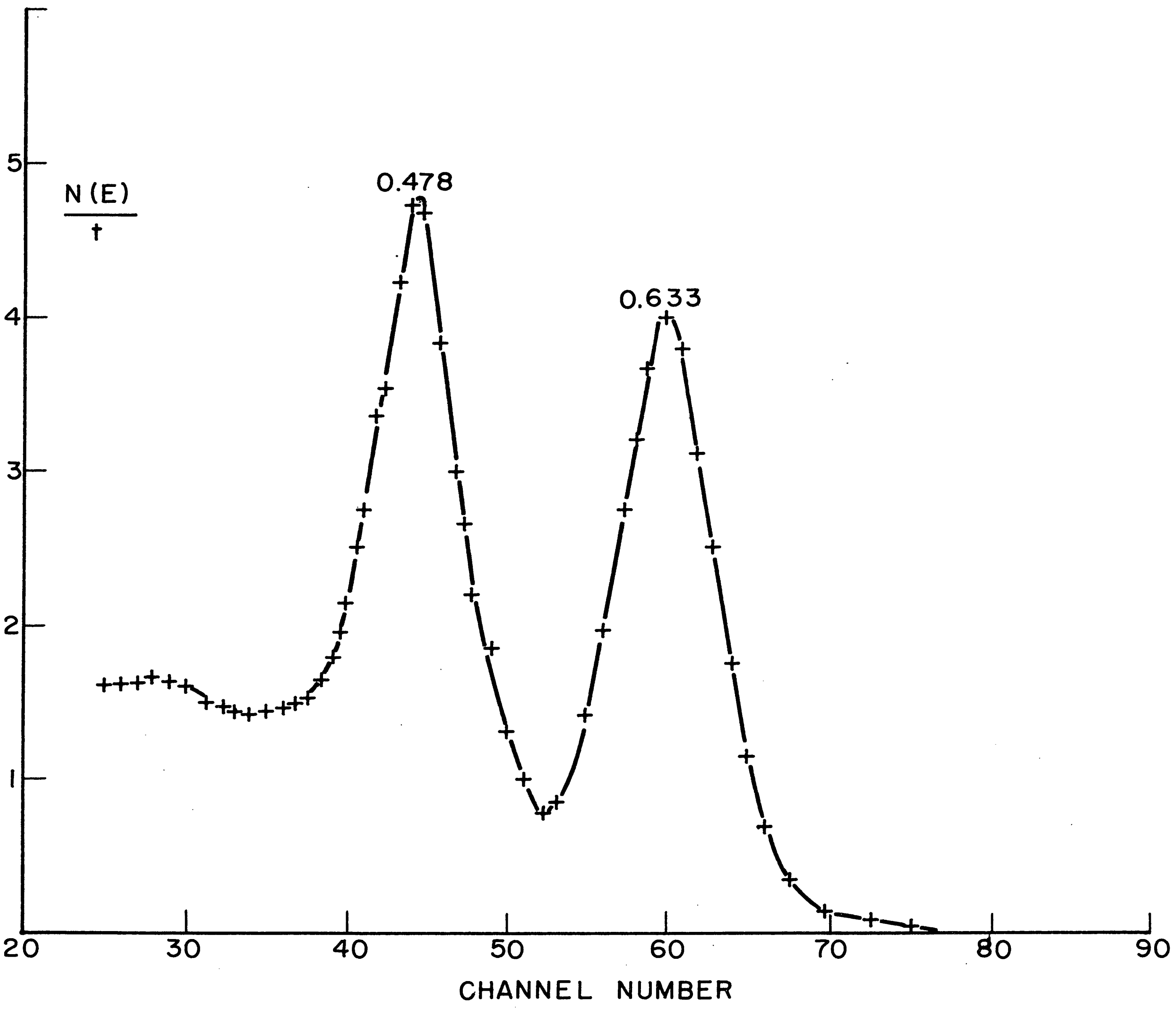

Fig. 4. Spectrum of gamma rays coincident with the 0.828-Mev photopeak. Both detectors were shielded with 0.1 in. each of aluminum and lead.

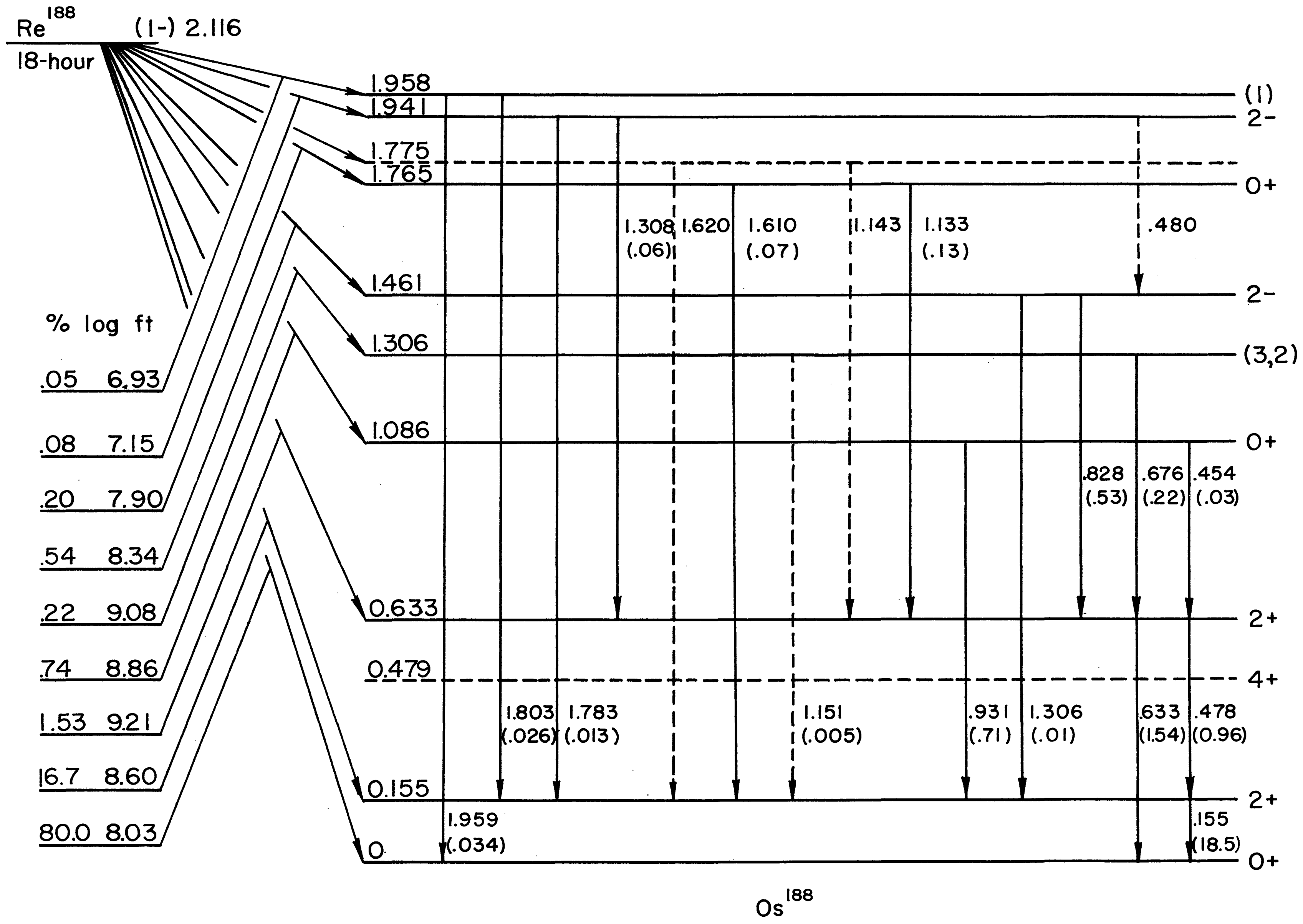

Fig. 5. Decay scheme of Re^{188}. The energies (in Mev) are taken from Johns *et al.*[1] The relative intensities (in percent) are the result of the present measurements.

TABLE I

RELATIVE INTENSITIES OF THE GAMMA RAYS OF Re^{188}

(The intensities have been normalized to the 0.633-Mev transition and are expected to be accurate within ± 20%.)

E_γ (Mev)	Intensity
0.155	7.2[a]
0.454	.02
0.478	.62
0.633	1.00
0.676	.14
0.828	.35
0.931	.46
1.133[b]	.086
1.151	.003
1.306	.007
1.308	.040
1.610[b]	.046
1.783 1.805	.024
1.959	.022

[a] Unconverted gamma ray intensity

[b] Complex

Assuming that the 0.633-Mev gamma ray is pure 2(Q)0, these coefficients are in good agreement with the theoretical coefficients of a pure 2(D)2(Q)0 sequence, $A_2 = +.250$, $A_4 = 0$. The error limits will allow a quadrupole content of no more than Q = .001 in the 0.828-Mev gamma ray. The coefficients will not fit sequences of the form 3(D,Q)2(Q)0 or 1(D,Q)2(Q)0.

1.308-Mev — 0.633-Mev and 1.133-Mev — 0.633-Mev Cascades.—Although the 1.308-Mev and the 1.133-Mev photopeaks were easily resolved by the scintillation counters, there remained a slight overlap of these lines which was considered in analyzing the directional correlation data. Two directional correlation measurements were made. In both cases one differential analyzer was set to accept the full photopeak of the 0.633-Mev gamma ray. In one case the second differential analyzer was set on the 1.308-Mev photopeak and in the other case it was set on the 1.133-Mev photopeak.

Using the relative intensities measured in the coincidence experiments, the pair of peaks was constructed from known shapes of single gamma rays in this region. The contribution of both gamma rays to each correlation function was then determined. The two correlation functions were combined with special attention to the errors in the relative intensities, and channel settings. In this manner the 1.133-Mev — 0.633-Mev cascade yielded corrected expansion coefficients of $A_2 = +.150 \pm .046$, $A_4 = +.702 \pm .060$. The observed A_4 coefficient is too large to allow a spin assignment of 2 to the 1.765 level. Thus the spin of this level must be zero although the observed coefficients do not agree well with the theoretical coefficients for a 0(Q)2(Q)0 sequence, i.e., $A_2 = +.3571$, $A_4 = +1.143$. The source was in solution and no attenuation is expected to be present. Potnis et al.[4] observed the full correlation for the 0.478-Mev to 0.155-Mev cascade using a metallic source. The lifetime of the 0.633-Mev level is expected to be shorter than that of the 0.155-Mev level and this, together with the fact that the full correlation is observed for other cascades involving the 0.633-Mev level, tends to rule out a perturbation due to extranuclear fields. The present discrepancy can be explained if it is assumed that another level lies close to the 1.765-Mev level and decays via an unresolved gamma ray with energy near 1.133 Mev. Similarly, the possibility exists for a 0.635-Mev gamma ray between the 1.941-Mev level and the 1.306-Mev level in cascade with a possible transition between the 1.306-Mev level and the 0.155-Mev level. These possibilities do not change the fact that the 1.765-Mev level must be assigned a zero spin.

In the manner described above, the corrected expansion coefficients for the 1.308-Mev — 0.633-Mev cascade were found to be $A_2 = +.309 \pm .065$, $A_4 = +.044 \pm .089$. These coefficients agree well with the theoretical coefficients for a 2(D)2(Q)0 cascade, namely, $A_2 = +.25$, $A_4 = 0$. If this sequence is of the form 2(D,Q)2(Q)0, the coefficients limit the quadrupole content of the 1.308-Mev transition to $Q \leqq .035$. The experimental coefficients will also fit a 3(D,Q)2(Q)0 sequence if the quadrupole content is in the range $Q = .42 \pm .13$. This degree of mixing is highly improbable and therefore the 1.941-Mev level is assigned a spin of 2.

0.931-Mev — 0.155-Mev Cascade.—In this directional correlation the window of one differential analyzer was set to accept the 0.155-Mev photopeak. The second analyzer was set to accept a narrow range of pulses on the upper portion of the 0.931-Mev photopeak. With this arrangement a small fraction of the real coincidences accepted were due to 0.828-Mev — 0.155-Mev cascade and an additional small interference resulted from coincidences of the 0.155-Mev gamma ray with the Compton distributions of higher-energy gamma rays beneath the 0.931-Mev gamma ray. The interfering correlations were measured and subtracted from the observed coefficients. After correction for finite angular resolution, the expansion coefficients were found to be $A_2 = .35 \pm .05$, and $A_4 = +1.06 \pm .17$. These are in good agreement with the theoretical coefficients for a 0(Q)2(Q)0 sequence, i.e., $A_2 = +.3571$ and $A_4 = +1.143$. The observed coefficients will not fit any other spin sequence.

0.478-Mev — 0.155-Mev Cascade.—For this cascade, each of the differential analyzers was allowed to accept the full-energy peak of one of the gamma rays. Due to the complexity of the decay, about 47.5 ± 5.0% of the real coincidences accepted were due to other cascades which were measured and subtracted from the basic correlation function. This yielded corrected expansion coefficients of $A_2 = -.079 \pm .054$ and $A_4 = +.402 \pm .083$. These coefficients will fit a 2(D,Q)2(Q)0 sequence with a large ($Q \geq .99$) quadrupole content in the first transition. There appears to be good evidence for other gamma rays at energies near .478 Mev in coincidence with the 0.155-Mev transition. Hence, the quadrupole content derived above may be somewhat in error, although the spins of the 0.633-Mev and 0.155-Mev levels are certainly 2. Neither of the previous directional correlation measurements on this cascade[4,7] took the interference into consideration.

IV. SUMMARY AND DISCUSSION

As a result of directional correlation measurements, spins of 2, 2, 0, 2, 0, and 2 have been assigned to the levels at 0.155 Mev, 0.633 Mev, 1.086 Mev, 1.461 Mev, 1.765 Mev, and 1.941 Mev, respectively. The transition from the second 2+ state to the first excited state (spin = 2+) has been shown to be mostly E2 with a small M1 admixture. A 4+ state has recently been found at 0.479 Mev (fed from Ir^{188}).[8,9] This state and the first excited state are interpreted as members of the ground-state rotational band.

A directional correlation measurement was attempted on the weak 0.676-Mev — 0.633-Mev cascade. However, the interference from other cascades were rather large and this resulted in large errors on the expansion coefficients. The expansion coefficients were consistent with a spin of 3 or 2 for the 1.306-Mev level in agreement with the observed gamma ray branching.

The second 2+ state at 0.633 Mev may be considered as a member of the ground-state rotational band in terms of the interpretation of the unified model due to Davydov and Filippov.[12] Many of the high-energy gamma rays observed following the decay of Ir^{188} do not occur in the decay of Re^{188}. This indicates that a different set of levels are fed by the two decays. An attempt to interpret the higher excited states of Os^{188} may be more reasonable when more is known concerning the levels fed from Ir^{188}.

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III

DECAY OF Sm^{155}

DECAY OF Sm^{155}*

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Sm^{155} was found to decay to Eu^{155} with a half-life of 21.9 ± .2 minutes. Directional correlation measurements were made on the 105-kev — 141-kev cascade in Eu^{155}, and possible spin assignments are discussed. In addition, the gamma rays were studied by using magnet spectrographs, well crystal spectra, and coincidence measurements with the x-ray, 104-kev gamma ray, 141-kev gamma ray, and 246-kev gamma ray. A number of new, weak transitions are proposed.

I. INTRODUCTION

A 21-minute activity from samarium was first observed by Pool and Quill.[1] Inghram _et al._[2] and Winsberg[3] assigned this activity to Sm^{155}. Rutledge _et al._[4] observed gamma rays of 104.6 kev and 245.8 kev on internal conversion and photoelectron spectrograms. Schmid and Burson[5] obtained coincidences between the 105-kev gamma ray and a gamma ray of 141 kev, and proposed the decay scheme shown in Fig. 1.

Because of the position of Sm^{155} in the region of $150 < A < 185$, it is expected that the excited levels in Eu^{155} conform to those of deformed nuclei. The present investigation was undertaken in order to study more completely the excited levels occurring in Eu^{155}.

II. EXPERIMENTAL METHOD

Samples of samarium oxide enriched to 99.1% in Sm^{154} were irradiated in a flux of 2×10^{12} neutrons/cm^2/sec in the Ford Nuclear Reactor.

The decay of Sm^{155} was followed for 31 hours. All other data were taken during the first 30 minutes after irradiation.

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*Supported in part by the Michigan Memorial—Phoenix Project and United States Atomic Energy Commission.

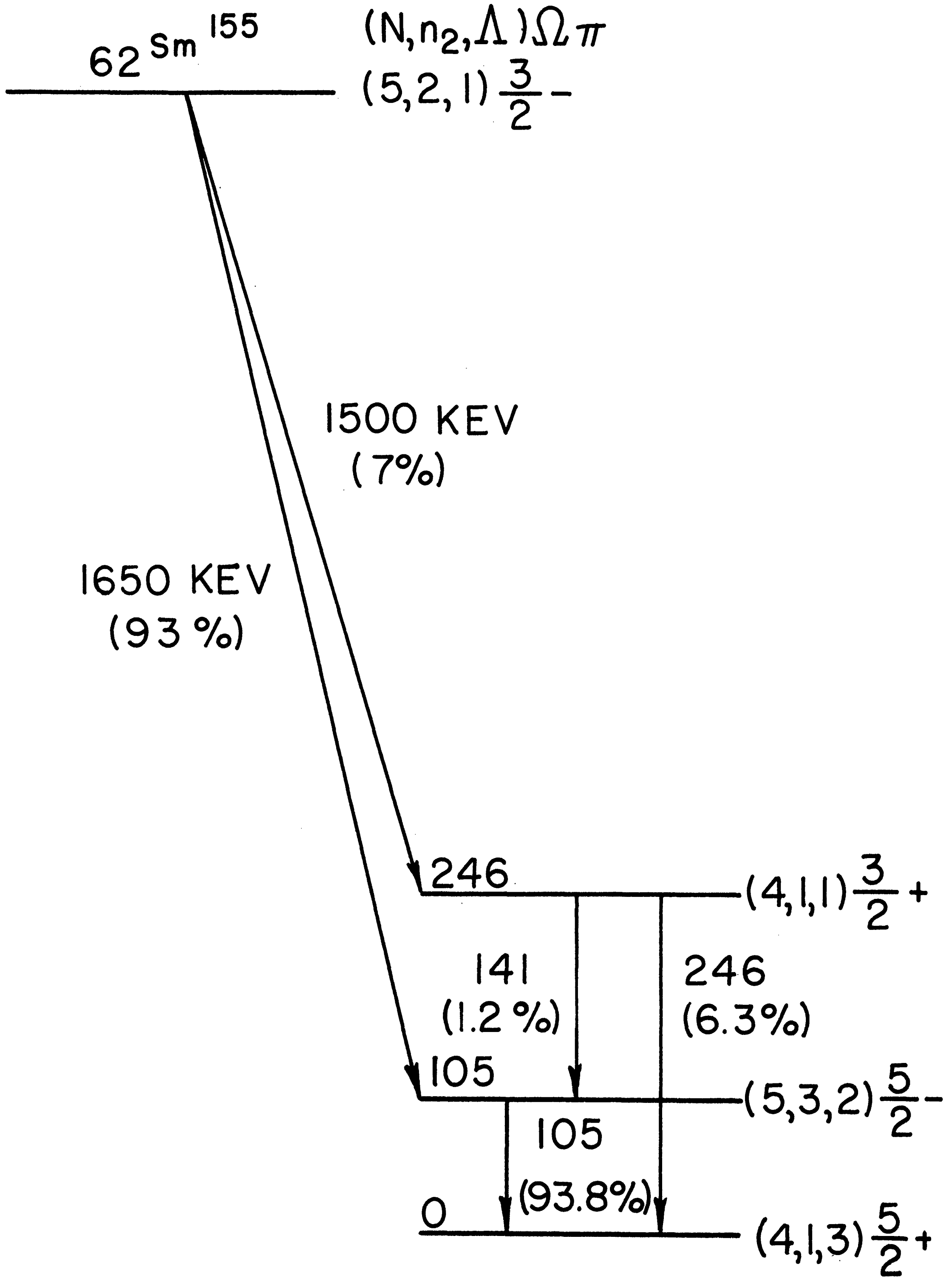

Fig. 1. Decay scheme of Sm^{155}, due to Schmid and Burson.

The sources used in the half-life determination, well crystal spectrum, directional correlation measurement, and coincidence measurements were made by dissolving the Sm_2O_3 powder in dilute nitric acid and irradiating the samples from 10 seconds to 3 minutes.

A conventional fast-slow coincidence circuit with a resolving time of 70 millimicroseconds was used in the coincidence and angular correlation measurements. The detectors were 2-in. by 2-in. NaI(Tl) crystals mounted on Dumont 6292 phototubes.

Differential analyzers and lateral lead shielding provided energy selection in the directional correlation measurements. Data were taken at five angles and in a double quadrant sequence. The real coincidence rate was corrected for source decay. After making a least squares fit,[6] the expansion coefficients were normalized.

The coincidence measurements employed a linear gate circuit, which allowed pulses in coincidence with gamma rays in a selected energy range to be recorded on a 256-channel analyzer. A Compton shield of 6.4-mm-thick lead surrounded by .8 mm of Cd was placed between the two detectors.

The magnetic spectrograph sources consisted of about 1 mg/cm^2 of samarium oxide powder mounted on Scotch tape. Two identical sources were used. The elapsed time between removing the sources from the reactor and starting the exposure on the photographic plate was about 3 minutes. While one source was in the camera, the other sample was irradiated. The irradiation time averaged about 25 minutes and the exposure time was about 30 minutes. A total of 25 exposures were made. After the Sm^{155} had decayed sufficiently, a photographic plate was exposed for a long time with one of the samples to determine which lines were due to the 47-hour Sm^{153}. Sources of Eu^{152m} and Dy^{165} were used for calibrating the plates.

III. RESULTS

HALF-LIFE MEASUREMENT

The half-life was followed for 31 hours, and the 47-hour Sm^{153} activity did not become significant until after approximately eight half-lives had elapsed. The counting rates were corrected for background, the Sm^{153} activity, and Geiger tube dead time. A least squares fit was made on two sets of data, and a value of 21.9 ± .2 minutes was determined for the half-life. The error includes the probable error and also an estimate of the systematic error.

ANGULAR CORRELATION MEASUREMENTS

The angular correlation was measured by accepting a range of energies from 95 kev to 150 kev in both pulse-height analyzers. The interference between the gamma rays in this energy range and the Comptons of higher-energy gamma rays was found to be 10.5 ± 1.1%. After subtracting this interference and correcting for finite resolution,[8] the expansion coefficients were found to be $A_2 = -.086 \pm .028$ and $A_4 = -.057 \pm .050$.

For a nuclear deformation of .33 for $_{63}Eu^{155}$, the Nilsson model[7] predicts a ground-state spin of 5/2+. The measured spin[9,10] of 5/2+ for Eu^{153} supports this. The spin[9,10] of 5/2- for Eu^{151} is due to the small deformation and the corresponding change in the position of the energy levels. For $_{62}Sm^{155}$, the Nilsson calculations[7] predict a spin of 3/2- or 5/2+ for the ground state. A spin[11,12] of 3/2- for the ground state of $_{64}Gd^{157}$, and the lack of a beta transition between the ground state of Sm^{155} and Eu^{155} support a spin of 3/2- for the ground state of Sm^{155}.

The log <u>ft</u> values are 5.7 for the 1.65-Mev beta ray and 6.7 for the 1.50-Mev beta transition.[5] The internal conversion coefficients[5] of .27 ± .06 for the 105-kev gamma transition and .16 ± .06 for the 141-kev gamma ray indicate that both transitions are predominantly E1. These data indicate that the spin of the 246-kev level is 1/2+, 3/2+ or 5/2+, and that the spin of the 105-kev level is 5/2- or 3/2-. If the experimental internal conversion coefficients are interpreted with the K conversion coefficients calculated by Sliv[13] the 105-kev transition is found to be an E1 + M2 mixture with $Q \leqq .011$, and the 141-kev transition is E1 + M2 with $.001 < Q \leqq .032$. The graphical analysis[14] of the directional correlation data in terms of a 3/2(D,Q)5/2(D,Q)5/2 sequence is shown in Fig. 2. The limits of quadrupole content consistent with the internal conversion data are indicated. A 3/2(D,Q)3/2(D,Q)5/2 sequence is also allowed by the angular correlation and conversion data. For a deformation of .33 and a ground-state spin of 5/2+ for Eu^{155}, the Nilsson model[7] predicts low-lying excited states of 3/2+ and 5/2-. Therefore the 3/2(D,Q)5/2(D,Q)5/2 cascade is favored. Other spins for the ground states of Sm^{155} and Eu^{155} would allow different interpretations of the angular correlation data.

MAGNETIC SPECTROGRAPH MEASUREMENTS

Nine conversion electron lines corresponding to five gamma ray transitions were observed in the spectrograph measurements. The conversion electron energies for Sm^{155} and their interpretation are given in Table I. The line with electron energy of 56.9 was on the order of a hundred times weaker than the K line from the 105-kev transition and could possibly be explained by external conversion of the 105-kev transition in Sm. This weak line together with internal conversion lines from the 105-kev and 246-kev transitions has been observed previously.[4] The remaining lines are somewhat weaker than the L line of the 105-kev gamma ray.

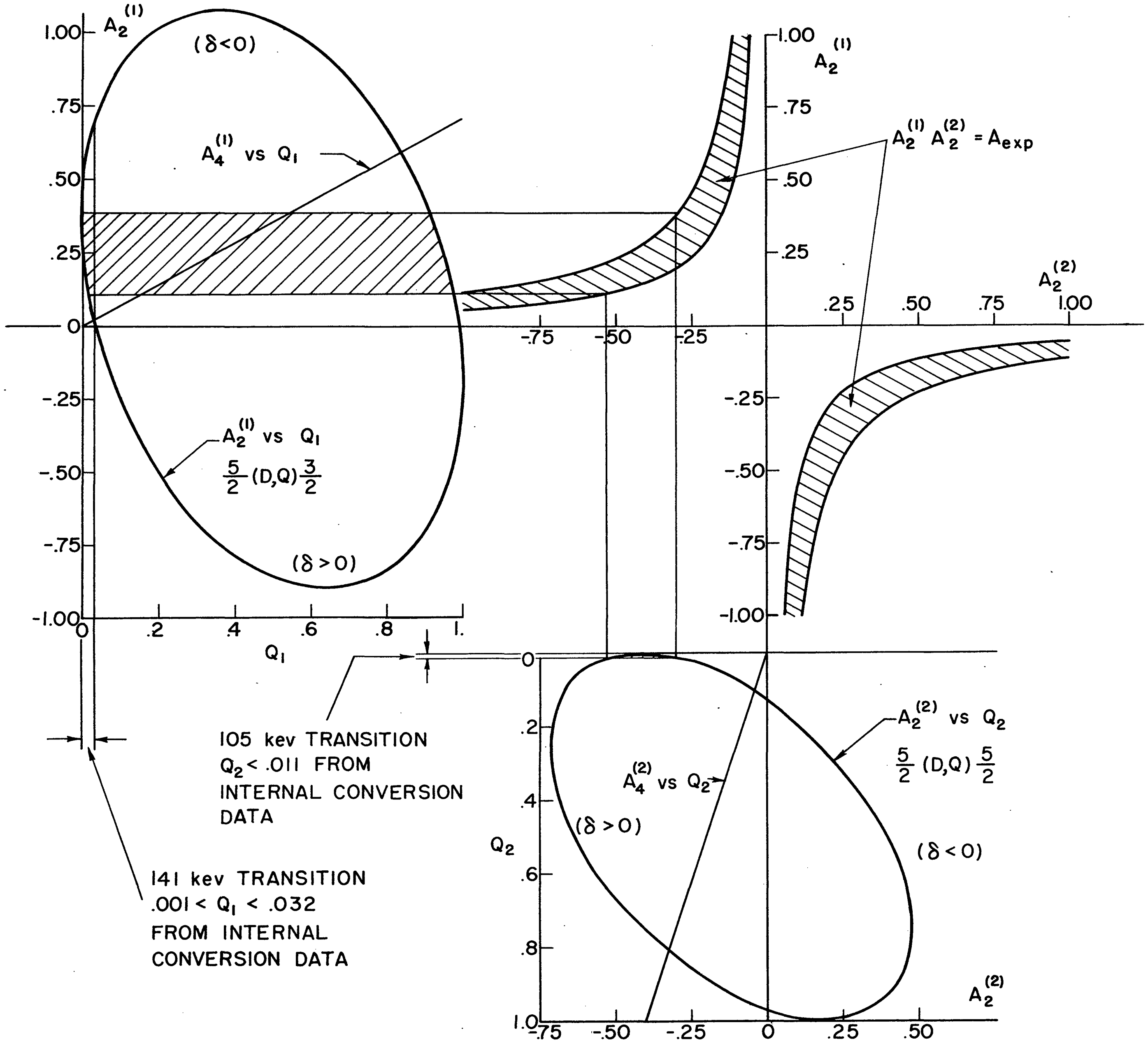

Fig. 2. Analysis of the 141-kev — 105-kev angular correlation in terms of a 3/2 (D,Q) 5/2 (D,Q) 5/2 sequence.

TABLE I

MAGNETIC SPECTROGRAPH MEASUREMENTS FOR Sm^{155}

Electron Energy (kev)	Interpretation	Energy Sum (kev)
55.8	K	104.3
56.9	K (Eu)	105.4
	or K (Sm)[a]	103.8
70.7	K	119.2
75.3	K	123.8
92.	K	141.
96.8	L	104.9
103.1	M	104.7
197.3	K	245.8

[a] Possibly photoelectrons from Sm.

A spectrogram of blank Scotch tape sources taken under similar conditions to the samarium sources showed no lines.

WELL CRYSTAL

Figure 3 shows the gamma ray spectrum as recorded on a 256-channel analyzer. Figure 4 is a spectrum taken with a weak source in a 2-in. NaI(Tl) well crystal. The well crystal shows an enhancement of the 246-kev gamma ray, corresponding to a sum of the 104-kev and 141-kev transitions. There is also a peak at 288 kev from the 246-kev gamma ray summing with the x-ray.

The peak at about 75 kev in the spectra could be caused by the iodine x-ray from the 105-kev gamma ray escaping from the crystal. The ratio of the 75-kev peak to the 105-kev peak was 7% in the "singles" spectrum and 3% in the well crystal. The theoretical value for the relative intensity of the iodine X-ray escape peak to the total peak for gamma rays entering perpendicular to an infinite NaI surface is about 4% for a 105-kev gamma ray.[15] The experimental ratios for a source distance of .4 cm are somewhat larger than the calculated values.[15]

The change in the x-ray intensity in the two spectra is due to the difference in the thickness of absorbers between the source and the crystal.

COINCIDENCE MEASUREMENTS

The result of coincidence measurements with the 246-kev gamma ray is shown in Fig. 5, and indicates coincidences with the x-ray and with weak gamma rays of about 65 kev and 104 kev. The coincidence spectrum with the x-ray is shown in Fig. 6; it shows coincidences with gamma rays of 105 kev, 141 kev, and 246 kev and with x-rays. A weak coincidence with 65 kev is possible. In both cases the accidental spectra were small and were subtracted to get the coincidence curves shown. Coincidence measurements with the 105-kev gamma ray show the x-ray and 141-kev transition are the prominent coincidences. Similarly, the x-ray and 105-kev transition are the strong coincidences with the 141-kev gamma ray.

IV. DISCUSSION

The data support the main features of the decay scheme reported by Schmid and Burson.[5] They explained the lack of a beta transition to the ground state of Sm^{155} in terms of the selection rules for deformed nuclei proposed by Alaga.

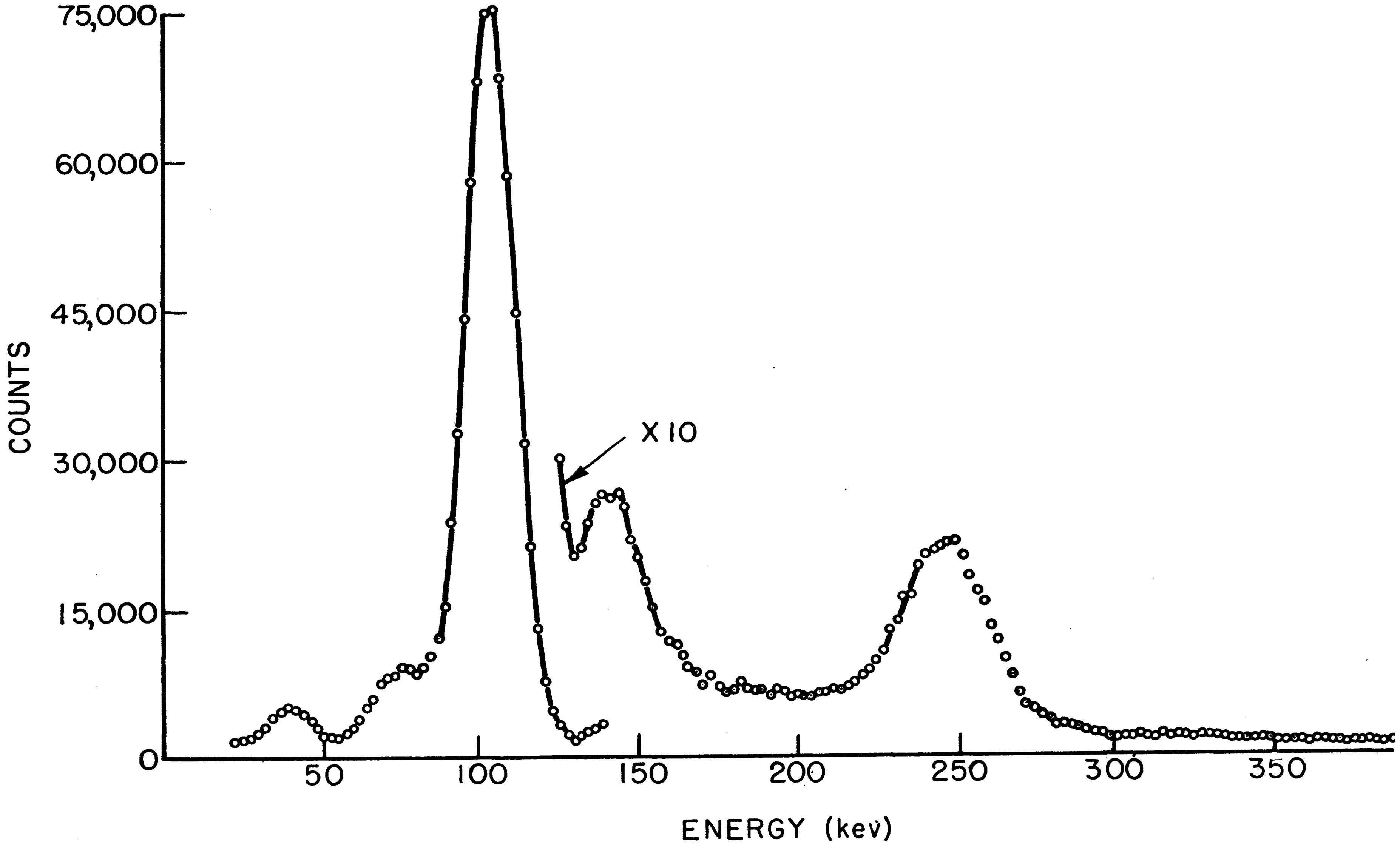

Fig. 3. Scintillation spectrum of gamma rays in Eu^{155}.

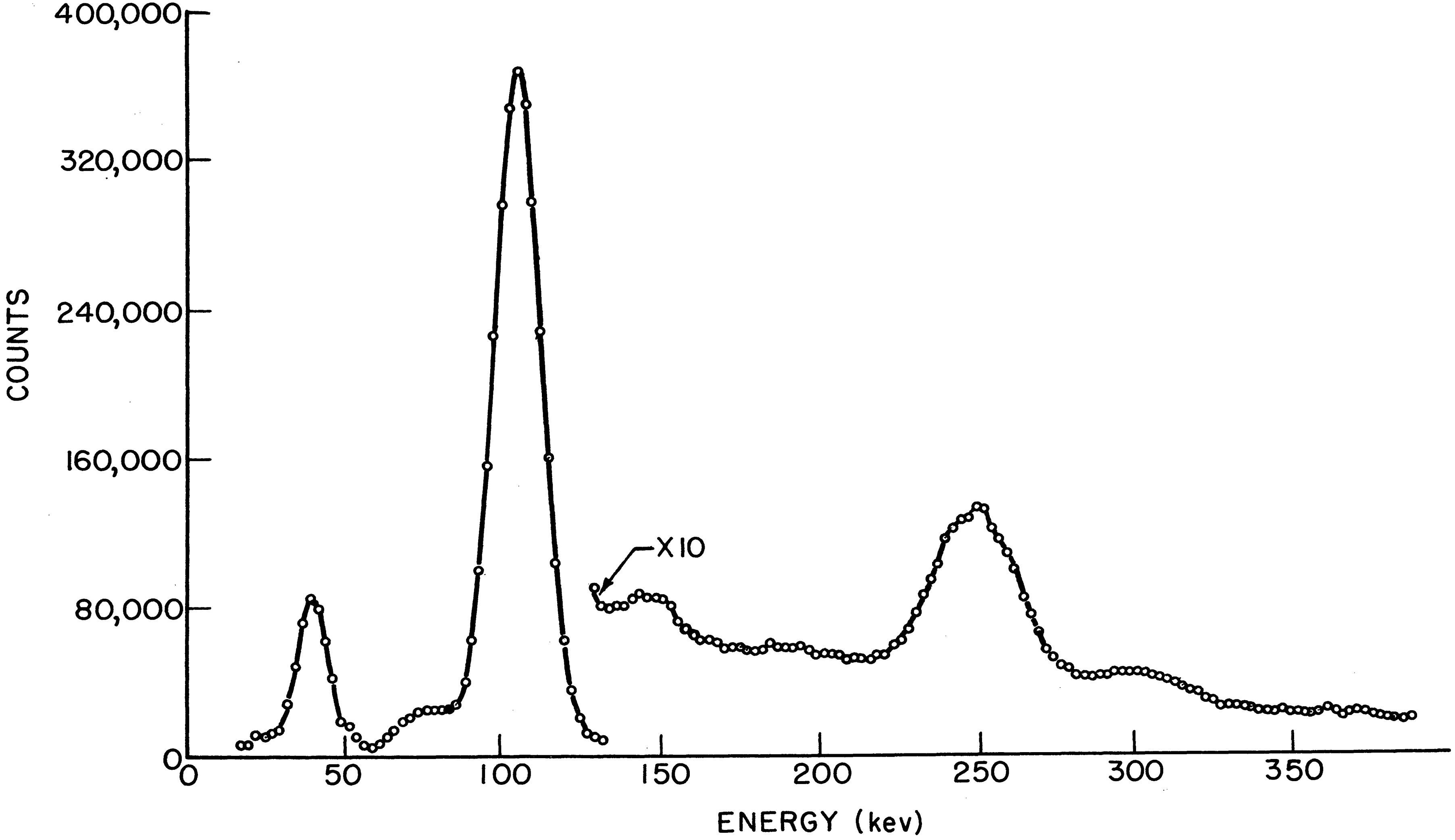

Fig. 4. Spectrum of gamma rays in Eu^{155} taken with source in a 2-in. well crystal.

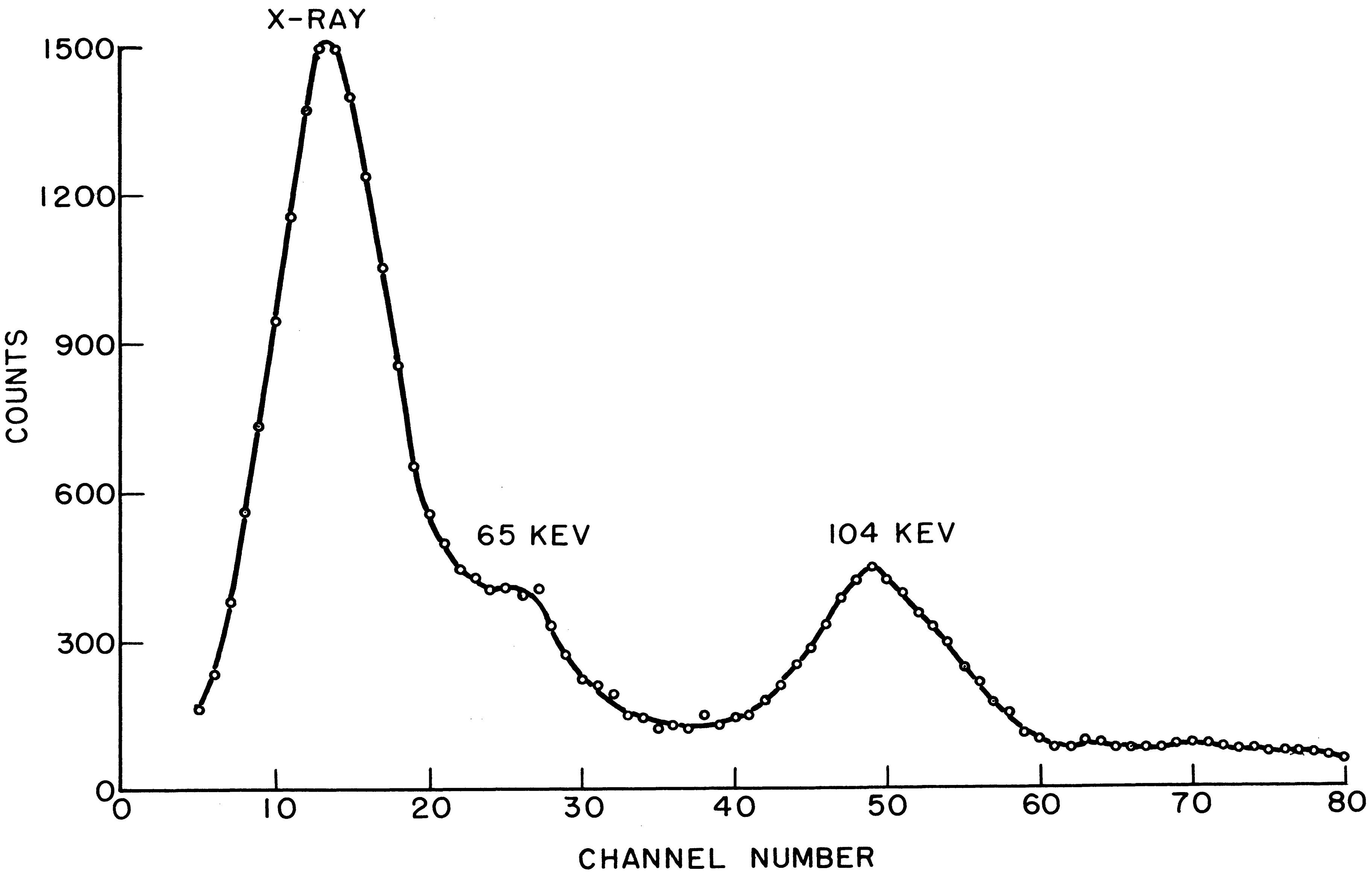

Fig. 5. Gamma rays in coincidence with 246-kev transition.

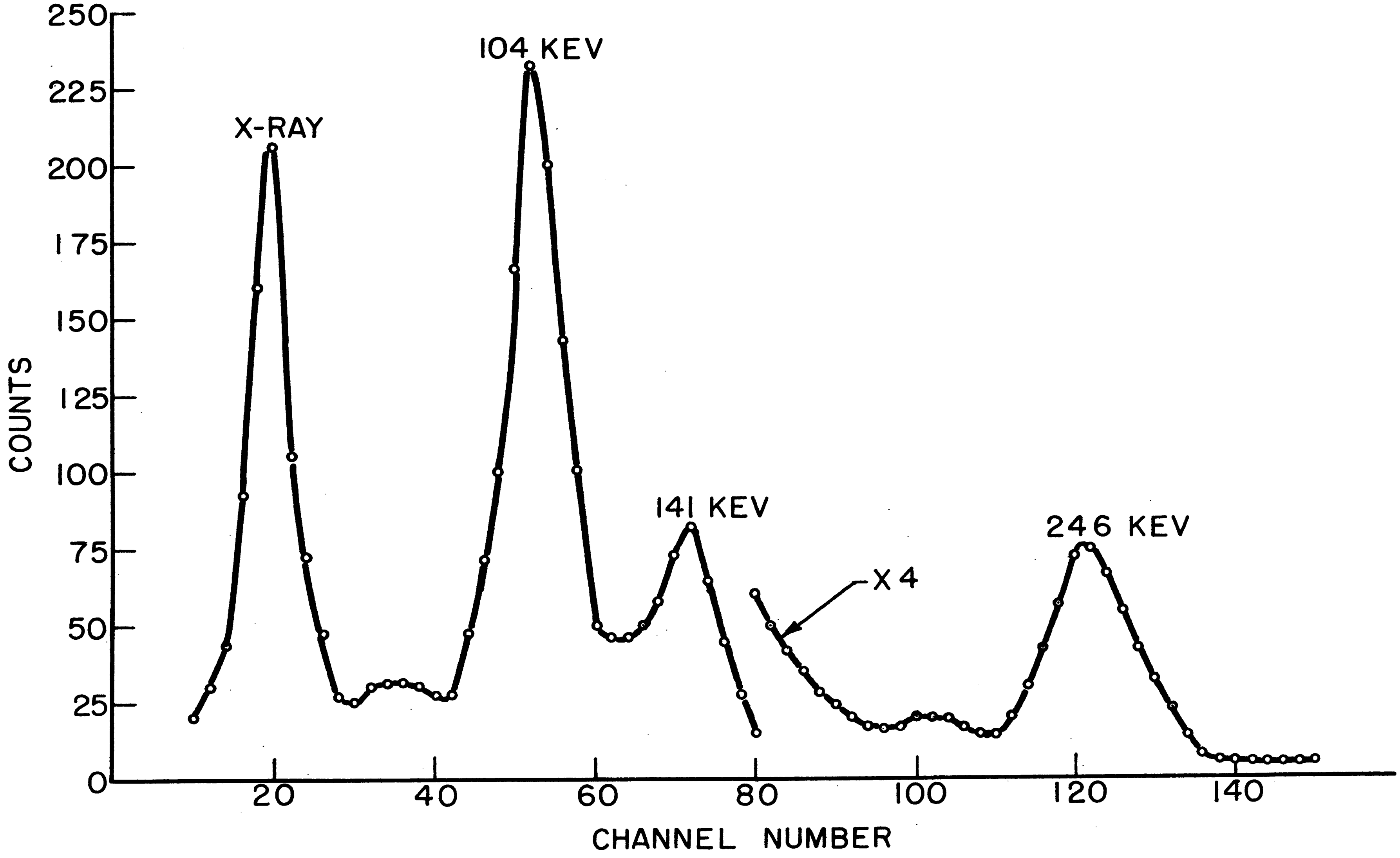

Fig. 6. Gamma rays in coincidence with the x-ray.

The internal conversion, well crystal, and coincidence measurements indicate the existence of several additional weak transitions. A possible decay scheme is shown in Fig. 7. The additional gamma rays shown are supported by the coincidence measurements and by the sum peak observed between the X-ray and 246-kev transition. A possible transition at 39 kev is based on the energy fit and on the strong transition at the x-ray energy found in the coincidence spectrum with the 246-kev gamma ray. These additional weak transitions are not intense enough to have a significant effect on the angular correlation results.

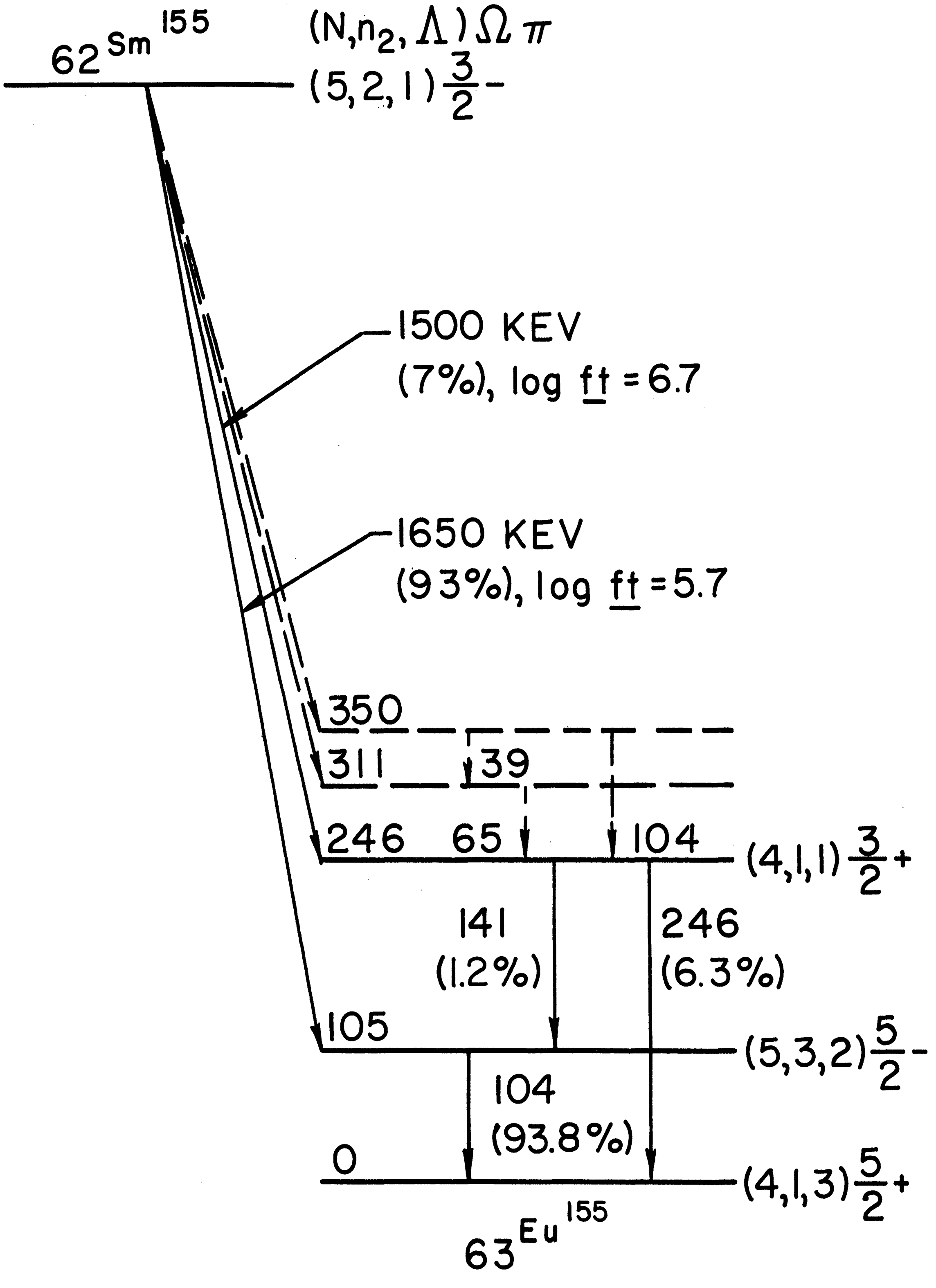

Fig. 7. Decay scheme of Sm^{155}.

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IV

ENERGY LEVELS OF Cs^{133}

ENERGY LEVELS OF Cs^{133}[*]

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Gamma rays in Cs^{133} following decay of the 7.5-year Ba^{133} have been studied in magnetic spectrographs. A total of 22 conversion electron lines have been observed corresponding to nine gamma transitions. The observed gamma rays fit the decay scheme proposed by Stewart, Lu, and Clikeman.[1]

I. INTRODUCTION

The levels in Cs^{133} following K-capture decay of Ba^{133} have been studied by a number of investigators.[1-7] The recent work of Stewart _et al_.[1,6] has led to a consistent decay scheme and has shown the positions of the main gamma transitions. The present investigation was undertaken to provide precise measurements of the gamma ray energies and to search for possible new lines.

A quartz ampoule containing 7 mg of barium carbonate, enriched to 12% in Ba^{132}, was irradiated with an accumulated flux of 4×10^{20} neutrons per cm^2 in the MTR facility at Idaho Falls. The Ba^{131} ($t_{1/2}$ = 11.6 day) impurity produced in the irradiation was allowed to decay for 4 months. The irradiated material was then dissolved in HCl. Line sources for the magnetic spectrographs were made by ruling the solution on Scotch tape backing. Several spectrograms were obtained in magnetic fields of 105 and 270 gauss with exposures ranging from 1 to 8 weeks. The spectrographs were calibrated using the 121.8-kev line in Sm^{152} and the 344.3-kev line in Gd^{152}.

II. RESULTS

Table I shows the conversion electron energies observed and the corresponding gamma ray assignment. The gamma ray energies listed are a weighted average of all observed conversion lines for the particular transition.

The decay scheme is shown in Fig. 1. The errors quoted for the gamma ray energies are the statistical errors in the observations. The energies are expected to be accurate within 0.2%.

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[*] Supported in part by the U. S. Atomic Energy Commission.

TABLE I

INTERNAL CONVERSION LINES IN Cs^{133}

E_c	Assignment	Strength*
16.2	K 52.2	vw
44.0	K 79.9	w
45.3	K 81.2	vs
46.9	L 52.2	m
74.0	L 79.9	vw
75.5	L 81.2	vs
80.2	M 81.2	s
123.9	K 160.1	vs
154.5	L 160.1	s
159.	M 160.1	vw
185.7	K 221.7	m
239.1	K 275.1	s
265.9	K 301.7	s
269.3	L 275.1	m
273.2	M 275.1	vw
295.7	L 301.7	s
300.0	M 301.7	w
319.3	K 354.8	s
345.7	K 382.8	w
349.4	L 354.8	s
353.3	M 354.8	w
377.2	L 382.8	m

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*v = very, s = strong, m = medium, w = weak

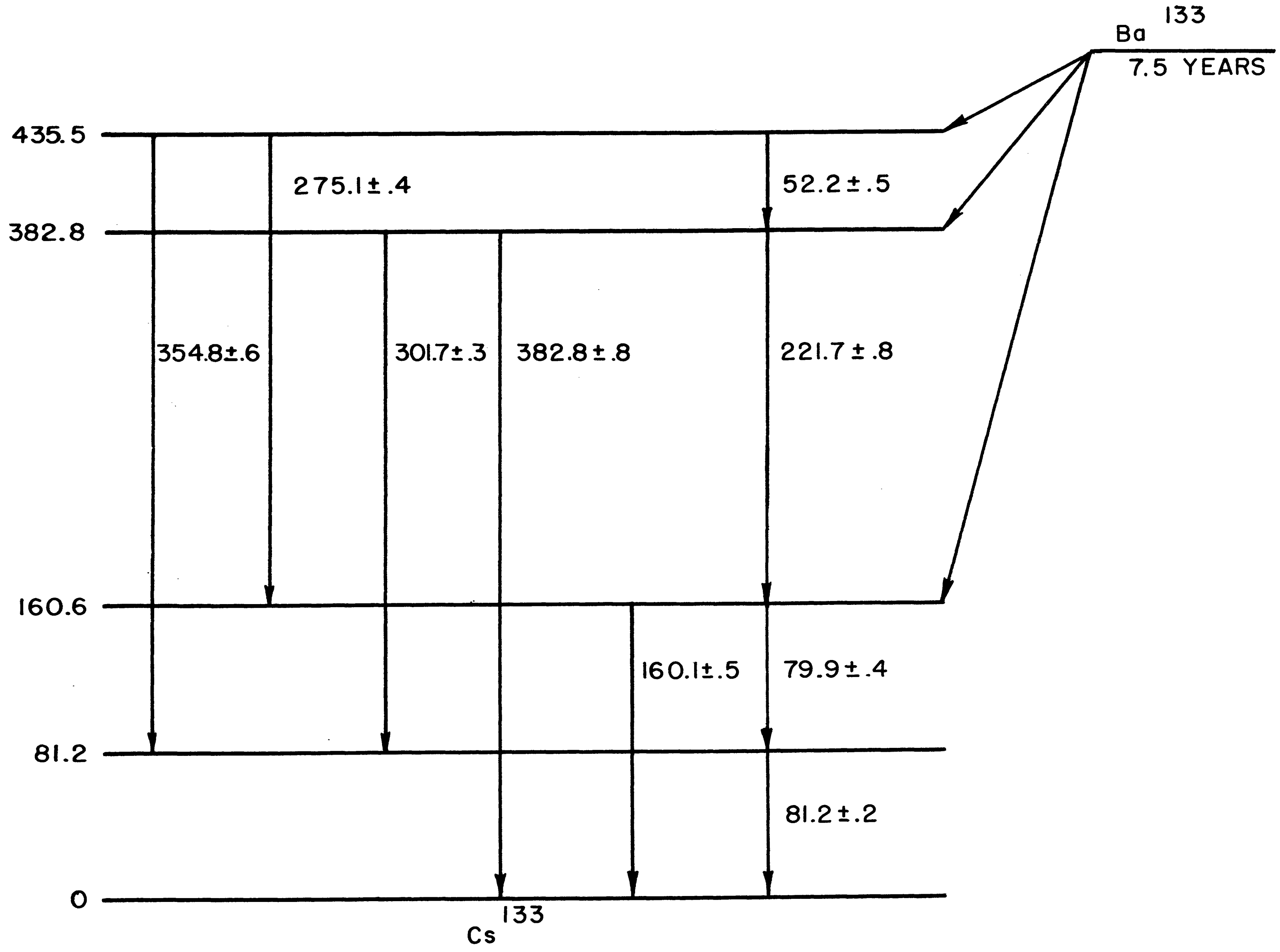

Fig. 1. Decay scheme of Cs^{133}.

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V

DECAY OF Eu^{152m}

DECAY OF Eu^{152m} [*,†]

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The gamma rays in Sm^{152} and Gd^{152} following the decay of the 9.3-hour metastable state of Eu^{152} have been studied in permanent magnet spectrographs. A number of new weak transitions have been observed, and a decay scheme is proposed. Directional correlation measurements have been made on two cascades in Sm^{152} and on one cascade in Gd^{152}. The measurements confirm the spin and parity assignments of 1- and 2+ for the .963-Mev and .122-Mev levels in Sm^{152}.. Possible spin assignments for the 1.511-Mev levels in Sm^{152} are discussed. The 1.315-Mev and .344-Mev levels in Gd^{152} have a spin and parity of 1- and 2+ respectively. Multipolarities are given for the principal gamma transitions.

I. INTRODUCTION

The 9.3-hour metastable state of Eu^{152} decays via beta emission to Gd^{152} and via K-capture to Sm^{152}.[1-3] Recent studies have led to a consistent decay scheme involving the strong gamma transitions in Sm^{152} and Gd^{152}.[4-8] The .963-Mev level in Sm^{152} has been excited by nuclear resonance flourescence,[9-11] and a spin and parity of 1- has been assigned to this level. Angular correlation measurements[9,12] have confirmed the spin of this level and the 2+ character of the .122-Mev level in Sm^{152}. Similarly, these measurements[12] have indicated that the spin of the 1.511-Mev level in Sm^{152} is 1 or 3, and that the 1.315-Mev and .344-Mev levels in Gd^{152} have spin and parity of 1- and 2+ respectively. Experimental evidence[7,10,13,14] indicates that the spin of Eu^{152m} is 0-.

Angular correlation measurements[15-17] have been made on gamma rays in Sm^{152} and Gd^{152} following decay of the 13-year ground state of Eu^{152}. Spins of 2, 4, 2, 3, and 3 were assigned to levels in Sm^{152} at .122 Mev, .366 Mev, 1.081 Mev, 1.240 Mev, and 1.531 Mev. Likewise the spin and parity of the .344-Mev and 1.128-Mev levels in Gd^{152} were found to be 2+ and 3- respectively. The spin of the Eu^{152} ground state is 3.[18,19]

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[†] Presented at the 1959 Spring Meeting of the Am. Phys. Soc. [Bull. Am. Phys. Soc., Ser. II, 4, 292 (1959)].

The levels at .122 Mev (in Sm^{152}) and .344 Mev (in Gd^{152}) are found in the decay of both Eu^{152} and Eu^{152m}. In view of the difference in spin between Eu^{152} and Eu^{152m}, some of the higher excited states occurring in the decay of Eu^{152} are not expected to be excited in the decay of Eu^{152m}. The present investigation was undertaken to relate the levels occurring in the Eu^{152m} decay to those following Eu^{152} and to the nuclear systematics of this region. Also, since Sm^{152} is a deformed nucleus, whereas Gd^{152} exhibits a spherical equilibrium in the ground state, this decay affords an opportunity for comparing different level structures.

II. EXPERIMENTAL METHOD

Samples of very pure natural Europium Oxide were irradiated in the Ford Nuclear Reactor for two-hour periods. The magnetic spectrograph sources consisted of powder mounted on Scotch tape or aluminized Mylar. The angular correlation sources were made by dissolving the irradiated powder in dilute hydrochloric acid. The decay of the 9.3-hour activity was followed by 12 half-lives. The weak long-lived activities were not observed until about 10 half-lives had elapsed. No other activities were present. All data were taken during the first 45 hours of decay of each sample.

A conventional fast-slow coincidence circuit with a resolving time of 20 millimicroseconds was employed in the angular correlation measurements. The detectors consisted of 2-in. by 2-in. NaI(Tl) crystals mounted on 6342 phototubes. Differential analyzers and lateral lead shielding provided energy selection. Data were taken in a double quadrant sequence. Measurements were performed at five angles for the .970-Mev ← .344-Mev cascade and the 1.389-Mev ← .122-Mev cascade, and at seven angles for the .842-Mev ← .122-Mev cascade. The real coincidence rate was normalized for source decay and electronic drift. After making a least squares fit,[20] the expansion coefficients were normalized and corrected for finite resolution.[21]

III. RESULTS

MAGNETIC SPECTROGRAPH MEASUREMENTS

Sixteen conversion electron lines corresponding to 8 gamma ray transition energies were observed on the photographic plates. Several spectrograms were taken during a period of 5 half-lives, and all the lines appeared to decay with the proper half-life. The conversion electron energies and their interpretation are given in Table I. The .430-Mev K line has an intensity of the same order as

TABLE I

MAGNETIC SPECTROGRAPH MEASUREMENTS

Electron Energy (kev)	Interpretation	Energy Sum (kev)*
75.0	K Sm	121.8
114.0	L_1 Sm	121.7
114.6	L_2 Sm	121.9
115.1	L_3 Sm	121.8
119.3 ± 1.0	M Sm	121.0 ± 1.0
121.6	N Sm	121.9
220.0	K Sm	266.9
	or K Gd	270.2
294.1	K Gd	344.3
336.0	L Gd	344.3
382.7	K Sm	429.6
	or K Gd	432.9
565.4	K Gd	615.6
608.	L Gd	616.
636.8	K Sm	684.
	or K Gd	687.
795.	K Sm	842.
834.	L Sm	842.
916.	K Sm	963.

*Normalized to 121.8-kev and 344.3-kev lines measured by Marklund.[8]

the .344-Mev L line. The .270-Mev, .616-Mev, and .684-Mev internal conversion lines are weaker. These gamma rays will fit the decay scheme in several places. The proposed decay scheme is shown in Fig. 1. The intensities and gamma ray energies for the strong transitions are taken from the crystal spectrometer and photoelectric conversion measurements made by Marklund.[8] The log *ft* values have been computed using these values and the total transition energies for Eu^{152m} given by Alburger, Ofer, and Goldhaber.[7] The .616-Mev state has been proposed by Marklund, Nathan, Nielsen, and Wood.[22] The 2+ level at 1.081 Mev occurs in the Eu^{152} ground-state decay. The absolute intensity of about .15% for the .430-Mev transition was determined on the basis of the approximate intensity of the K conversion line, possible internal conversion coefficients, and the intensity allowed by the gamma ray spectrum. The line found at .684 Mev corresponds to the .685-Mev, 0+ level in Sm^{152} proposed by Marklund *et al.*[22]

A re-examination of the spectrograms of the Eu^{152} ground-state decay taken by Cork *et al.*[23] indicates that the gamma rays of .616 Mev and .271 Mev also occur following the ground-state decay. Bobykin and Novik[24] have likewise observed a .6155-Mev transition from the 13-year activity. If the .616-Mev and .271-Mev gamma rays occupy the position assigned to them in the proposed decay scheme, this would then require the .616 Mev, 0+ state to be fed by higher levels in Gd^{152} following the Eu^{152} ground-state decay.

ANGULAR CORRELATION MEASUREMENTS

.842-Mev — .122-Mev Cascade in Sm^{152}.—After correction for finite angular resolution, the expansion coefficients were found to be $A_2 = -.203 \pm .008$ and $A_4 = -.003 \pm .012$. Interference from other cascades was small (< 2%) and did not significantly affect the results. The presence of a strong crossover transition to the ground state requires that this sequence be of the form 1(D,Q)2(Q)0. The expansion coefficients then require a quadrupole content in the first transition of $.001 \leq Q_1 \leq .002$. The presence of a small quadrupole content is to be expected since the measured lifetime of the .963-Mev level ($\tau = 7 \times 10^{-14}$ sec)[10,11] is about 300 times larger than the single proton estimate. Angular correlations involving the .122-Mev level ($\tau = 1.4 \times 10^{-9}$ sec) in the 13-year decay were found to be independent of the viscosity of the source.[16] Hence it can be assumed in the present work that the measurements involving this intermediate level will not be attenuated by extranuclear fields. The present data are in agreement with the spin and parity of 1- previously assigned to the .963-Mev level.[9,12]

1.389-Mev — .122-Mev Cascade in Sm^{152}.—The corrected expansion coefficients were found to be $A_2 = -.178 \pm .014$ and $A_4 = -.013 \pm .022$. These are consistent with a sequence of the form 1(D,Q)2(Q)0 or 3(D,Q)2(Q)0, but not with a 2(D,Q)2(Q)0 sequence. A systematic search for a ground-state transition from the 1.511-Mev level was undertaken in an attempt to reconcile a spin 1 assignment for this level. Gamma ray singles and coincidence spectra were taken on a

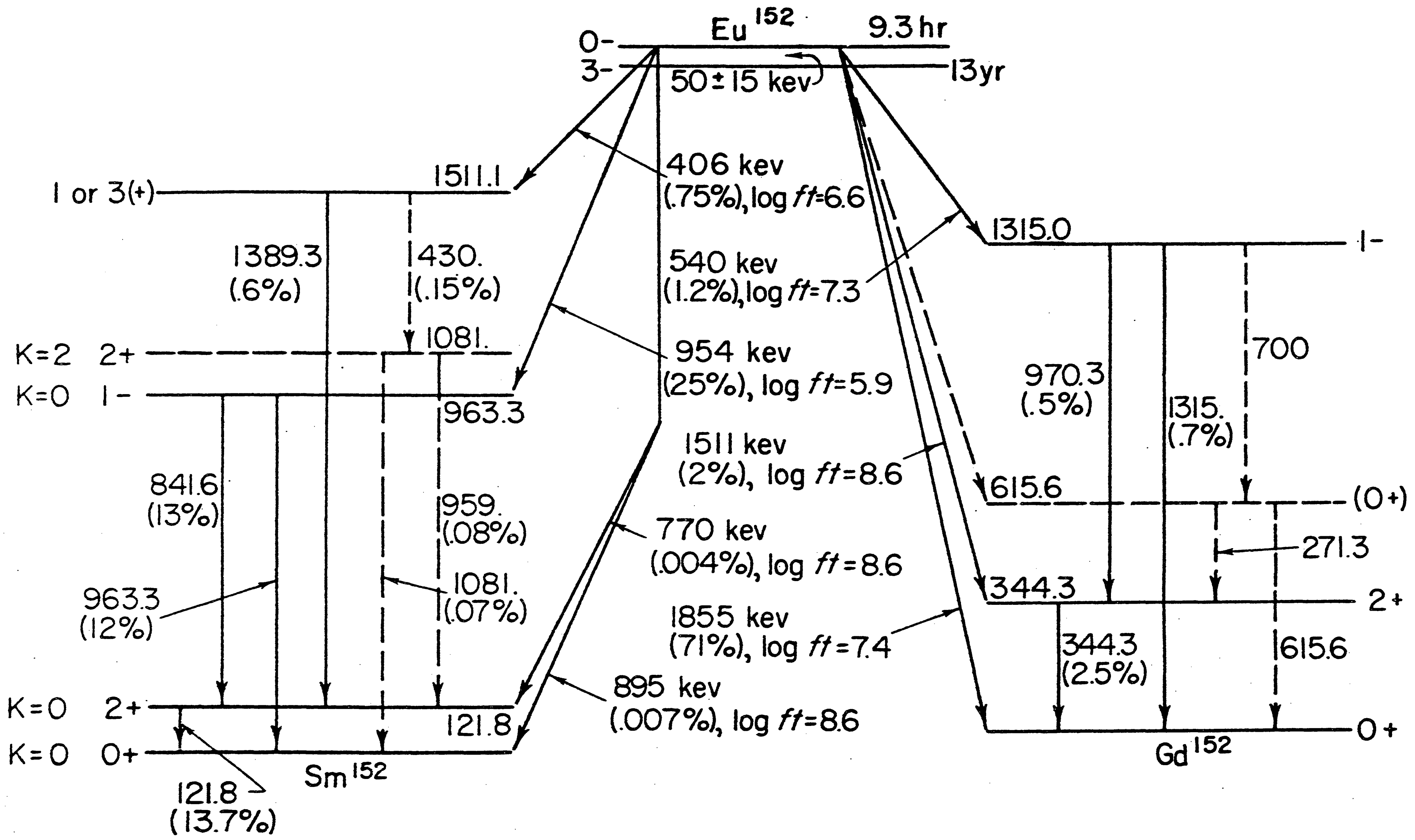

Fig. 1. Decay scheme of Eu^{152m}.

256-channel analyzer at Argonne National Laboratory. The spectrum of known gamma rays was subtracted from the singles spectrum to uncover a possible 1.511-Mev photopeak. None was observed and it was concluded that the proposed ground-state transition had an intensity at least 50 times weaker than the cascade intensity. Similar results were obtained by Wood and Nathan[12] and by Marklund.[8] For a 1(D,Q)2(Q)0 cascade, the expansion coefficients would require a quadrupole content of $.002 \leqq Q_1 \leqq .005$ in the first transition.

If this cascade is of the form 3(D,Q)2(Q)0, it is difficult to understand the low log ft value (= 6.6) of the K-capture decay to this level from Eu^{152m} (spin = 0). For this case, the expansion coefficients require a mixture with $.014 \leqq Q_1 \leqq .024$ in the first transition.

Internal conversion measurements[12] for the 1.389-Mev transition favor M1 or a mixture of M1 and E2, in agreement with an assignment of 1+ or 3+ for the 1.511-Mev level in Sm^{152}.

.970-Mev — .344-Mev Cascade in Gd^{152}.—The corrected expansion coefficients for this cascade were found to be $A_2 = -.230 \pm .019$ and $A_4 = -.016 \pm .032$. These are consistent with sequences of the form 1(D,Q)2(Q)0 and 3(D,Q)2(Q)0. The presence of a strong ground-state transition from the 1.315-Mev level rules out a spin assignment of 3 for this level. For a spin 1 assignment, the coefficients require a quadrupole content in the first transition of $Q_1 \leqq .001$.

The results of the angular correlation measurements are summarized in Table II. These results agree with those obtained by Wood and Nathan[12] within experimental error. However, since the previous measurements were taken at three angles, whereas the present data were taken at five angles, the present measurements are expected to be statistically more valid.

IV. DISCUSSION

The levels in the 9.3-hour decay at 1.081 Mev in Sm^{152} and at .616 Mev in Gd^{152} are proposed mainly on the basis of energy considerations. The position of the .616-Mev level below the .757-Mev level occurring in the 13-year activity argues against the possibility that the 0+ level is a member of a degenerate triplet of a quadrupole vibration. The 0+ excited state could possibly result from raising a proton pair from the filled $d_{5/2}$ level to a higher configuration.[25]

A possible alternative decay scheme is shown in Fig. 2. The level at 1.128 Mev occurs in the decay of the 13-year activity. The gamma rays of .270 Mev, .701 Mev, and 1.403 Mev and the levels at 1.045 Mev and 1.747 Mev were pro-

TABLE II

ANGULAR CORRELATION RESULTS

Cascade	A_2	A_4	Assignment	Q_1 = Quadrupole Content in First Transition
Sm^{152} .842 Mev — .122 Mev	-.203 ± .008	-.003 ± .012	1(D,Q)2(Q)0	.001 ≦ Q_1 ≦ .002
Sm^{152} 1.389 Mev — .122 Mev	-.178 ± .014	-.013 ± .022	1(D,Q)2(Q)0 or 3(D,Q)2(Q)0	.002 ≦ Q_1 ≦ .005 .014 ≦ Q_1 ≦ .024
Gd^{152} .970 Mev — .344 Mev	-.230 ± .019	-.016 ± .032	1(D,Q)2(Q)0	Q_1 ≦ .001

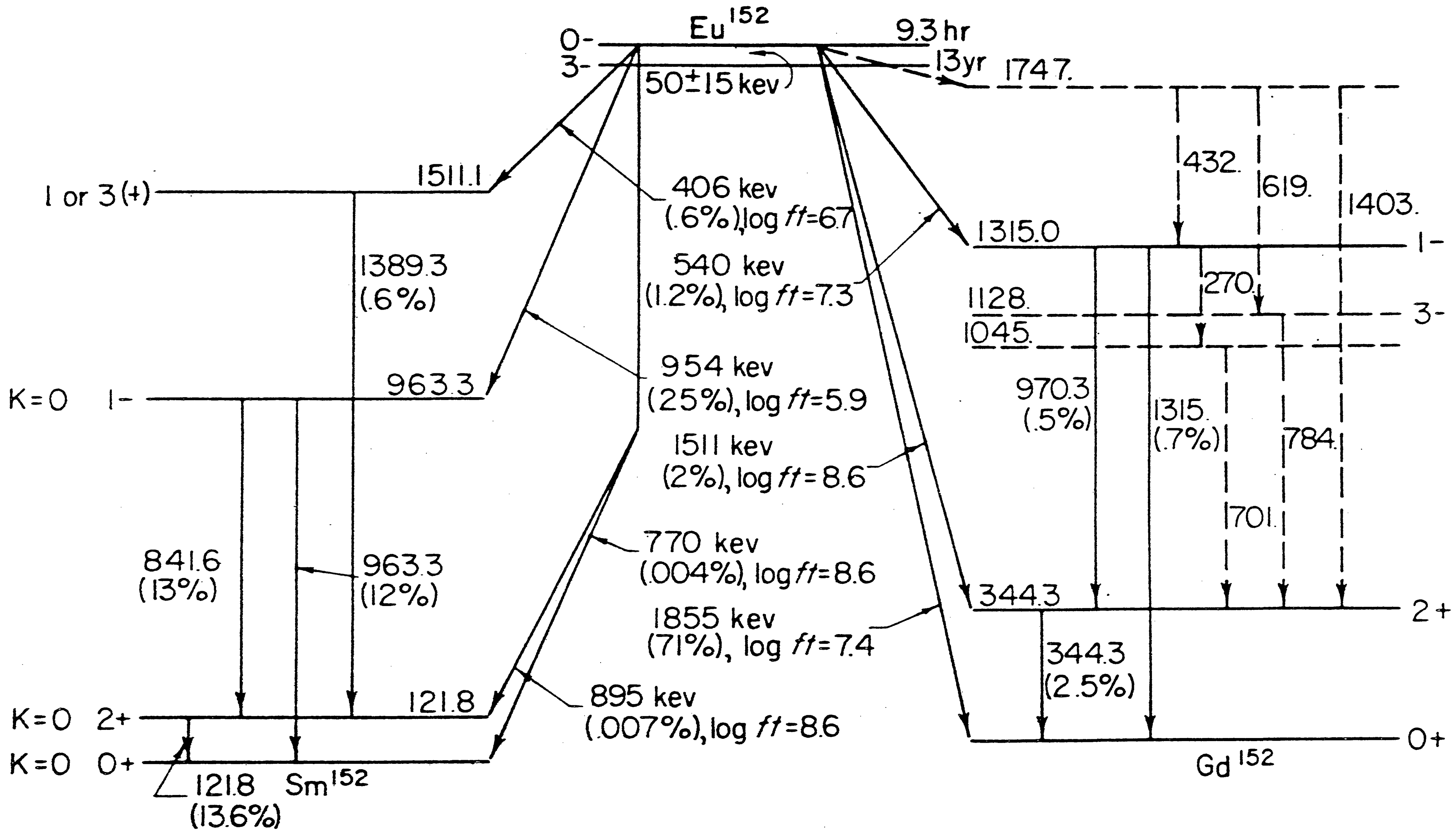

Fig. 2. Alternate-decay scheme of Eu^{152m}.

posed by Grodzins and Kendall.[5,6] The .432-Mev gamma ray intensity and log ft considerations limit the possible spin and parity of the proposed 1.747-Mev level to 0- or 1-, which do not seem likely. In addition, the occurrence of the .619-Mev gamma ray in the 13-year Eu^{152} decay and the lack of an observation of a .432 Mev transition in this decay makes a level at 1.747 Mev doubtful. Therefore, the decay scheme proposed in Fig. 1 seems much more reasonable.

Many of the levels in Sm^{152} and Gd^{152} may be explained in terms of collective rotations and vibrations.[4,10,12,26,27]

Sm^{152} has 90 neutrons and is on the edge of a region of even-even, spheroidal nuclei with $90 \leqq N \leqq 108$. In such deformed nuclei, the low-lying levels are of the rotational type, with spins 0+, 2+, 4+, 6+, ... The energy of the first excited state is on the order of .100 Mev,[28] and the theoretical energy ratio of the first two excited states is 10/3. In Sm^{152} the .122-Mev, 2+ level and the .366-Mev, 4+ level (from the 13-year activity) exhibit rotational characteristics. Nuclei in this region are also expected to have collective vibrational levels. The 1- level at .963 Mev is an octupole vibrational level with K = 0.[10] In addition, the study of the decay of the 13-year Eu^{152} activity has indicated that the levels at 1.081 Mev and 1.240 Mev are gamma vibrational states with K = 2 and with spins 2+ and 3+, respectively.[4,26]

In contrast to the deformed shape of Sm^{152}, Gd^{152} is in the region of even-even nuclei with $36 \leqq N \leqq 88$. These nuclei exhibit collective vibrational excitations about a spherical equilibrium shape. The first excited state has a spin of 2+ and an energy between about .330 Mev and 2 Mev.[28] The energy ratio of the second excited state to the first excited state is 2.0 - 2.5. The .344-Mev, 2+ level and the .757-Mev level (from decay of the 13-year Eu^{152} activity) in Gd^{152} are the first two states in such a quadrupole vibrational spectrum. The 3- level at 1.128 Mev (from the Eu^{152} ground-state activity) and the 1- level at 1.315 Mev correspond to octupole vibrational levels.[27] The 3- level lies below the 1- level, as predicted by theory. In contrast, in the deformed Sm^{152}, the coupling between the quadrupole deformation and the octupole mode results in a lowest odd-parity state of 1-.

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VI

ANGULAR CORRELATION OF GAMMA RAYS IN Sc^{47}

ANGULAR CORRELATION OF GAMMA RAYS IN Sc^{47}*

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Gamma rays in Sc^{47} following beta decay of Ca^{47} were studied with angular correlation techniques. These measurements and the results of previous research favor spin and parity assignments of 5/2-, 3/2-, and 7/2- for the 1.31-Mev, .480-Mev (or .830-Mev) and ground-state levels, respectively. The multipolarities of gamma transitions are given.

The decay of Ca^{47} has been the subject of several investigations.[1-6] Part of the decay scheme proposed by Lidofsky and Fischer[1] is shown in Fig. 1. They have assigned the spins on the basis of log <u>ft</u> values, intensities of gamma rays in Sc^{47}, the measured ground-state spin of Ti^{47}, and the coulomb excitation[7] of the first excited state in Ti^{47}. The present angular correlation measurements on the gamma rays in Sc^{47} were undertaken to study more completely the spins and parities of the levels.

A 12-mg sample of $CaCO_3$ powder, isotopically enriched to 2.3% in Ca^{46}, was irradiated with an accumulated flux of 4×10^{20} neutrons per cm^2 in the MTR facility at Idaho Falls. The irradiated powder was dissolved in HCl, and the solution was diluted. No gamma rays other than those in Sc^{47} and Ti^{47} were found in the irradiated sample. The only known impurity was Ca^{45}, a pure β emitter with an endpoint of .25 Mev.

The angular correlation measurements employed a fast-slow coincidence circuit[8] with a resolving time of 2×10^{-8} seconds. The scintillation counters were 2-in. by 2-in. NaI(Tl) crystals mounted on RCA 6342 photomultipliers. Pulse-height analyzers were set integrally to accept energies greater than .450 Mev. With this setting, no coincidences would be produced from the counter-to-counter scattering of the 1.31 crossover gamma ray, which has an intensity about thirteen times greater than the cascade intensity.[1] Further protection was afforded by lateral lead shielding.

Data were taken in a double quadrant sequence. The real coincidence rate was normalized for source decay and electronic drift. After making a least

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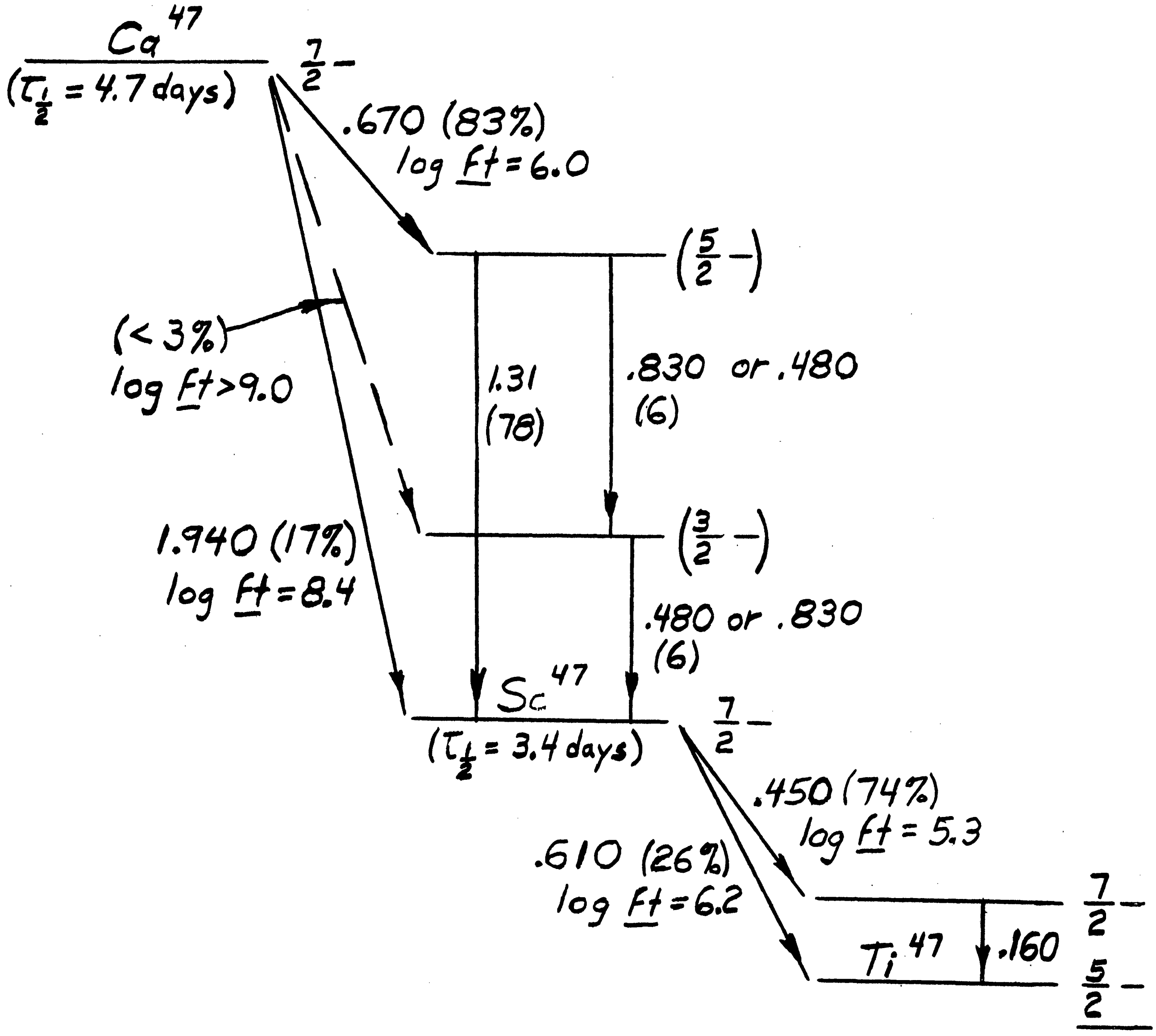

Fig. 1. Decay scheme of Ca^{47}.

squares fit, the expansion coefficients were normalized and corrected for finite resolution.[9] The resulting coefficients were found to be $A_2 = -.0015 \pm .0102$ and $A_4 = +.004 \pm .016$.

An attenuation of the angular correlation by extranuclear fields is not expected since the source was in a dilute solution and the lifetime of the intermediate state is presumably short.

The shell model indicates that the ground states of Ca^{47} and Sc^{47} should be 7/2- states. Shell model predictions of 7/2- for the ground states of Ca^{43} and Sc^{45} agree with the measured values.[10,11] The allowed log <u>ft</u> value for the β transition to the second excited state of Sc^{47} and the absence of β decay to the first excited state[1] suggest that the second excited state is 5/2- or 7/2-, and that the first excited state is 3/2- or 1/2-. The relative intensities of gamma rays are consistent with the 1.31-Mev gamma ray being M1 and the other transition from the second excited state in Sc^{47} being M1 or E2.[1]

Since the measured angular correlation is isotropic within the small error limits, a spin and parity assignment of 1/2- is possible for the intermediate state. However, this would require an E3 transition to the ground state (assumed to be 7/2-) and a correspondingly long lifetime for the intermediate state. This is contradictory to the observed coincidence rate and can be ruled out.

For a 5/2 (D,Q) 3/2 (Q) 7/2 cascade, the expansion coefficients are consistent with a quadrupole content in the first transition of $Q_1 = .008 \pm .005$ or $Q_1 = .911 \pm .019$. If both the Ca^{47} and Sc^{47} ground states are 7/2-, it is difficult to understand the high log <u>ft</u> value for the ground-state β transition. Lidofsky and Fischer[1] have explained this on the basis of the poor overlap of wave functions between the first and last particle in the 7/2 subshell. A systematic increase with A in log <u>ft</u> values has been noted for transitions between odd-A Ca and Sc ground states.[12] The possibility of different ground-state spins would allow other interpretations of the angular correlation data.

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VII

NEUTRON-CAPTURE GAMMA RAYS

NEUTRON-CAPTURE GAMMA RAYS

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A. INTRODUCTION

The program to be described is aimed at obtaining some information about the structure of some nuclei occurring as product or compound nuclei in neutron-capture reactions. In most cases, neutron capture leaves the product nucleus in a highly excited state which decays by gamma-ray cascades to the ground state. [The principal exceptions are the very light nuclei where (n, particle) reactions predominate, and the very heavy ones where the neutron may induce fission.]

The techniques of gamma-ray spectroscopy may be applied to this class of nuclei just as is done for the products of radioactive decay, with the difference, of course, that the experiments must be conducted while the sample remains in the neutron beam. Another difference which is significant experimentally is that some of the gamma rays involved will have energies of several Mev, so that special detection techniques may be required.

Gamma-ray spectra from (n,γ) reactions in nearly all the elements have been studied principally by one Canadian and one Russian group,[1,2] using external-conversion spectrometers. In most cases these spectra are so complex that unambiguous level schemes cannot be constructed. For only a few nuclei, gamma-gamma coincidences studies have been made[3,4,5] and have proved very valuable in establishing the level structure. Only in very rare cases have angular correlation measurements been performed.[6]

The object of the present program is to extend coincidence measurements to a larger number of nuclei, and eventually to measure angular correlations in such cases as this may be feasible. In the following sections, the instrumentation which has been completed to date will be described. The principal problems have been the extraction of a suitable neutron beam from the reactor, and the construction of a 3-crystal pair spectrometer for high-energy gamma rays.

B. BEAM EXTRACTION AND SHIELDING

The Ford Nuclear Reactor is very similar to the ORNL Bulk Shielding Reactor. The reactor assembly proper is approximately a 3-foot cube sitting in a pool of demineаralized water surrounded by a concrete shield. Several beam ports are provided, running from points just outside the reactor core through the water and concrete to the reactor face, i.e., the outside of the concrete wall; the length of a beam port is about 10 feet. If a beam port were left completely open, the flux at the reactor face would be approximately 1.0 x 10^8 neutrons/cm^2 sec,* with a gamma ray intensity of approximately 100 R/hr.

To perform the contemplated experiments, it was necessary to reduce the gamma ray beam to a few mR/hr while preserving as much neutron intensity as possible. The use of a Bragg-scattering crystal to deflect a neutron beam away from the port axis was considered at some length, but it was decided that, under the given conditions of geometry, a sufficiently high intensity could not be realized. Consequently the bismuth-filter method, used by several of the groups referred to above, was adopted.

In essence this consists of placing a thick piece of bismuth in the beam port; the bismuth ($Z = 83$) has a high absorption cross section for gamma rays, while its neutron-capture cross section is only 32 mb. Thus it is possible to improve the ratio of neutrons to gamma rays. It is essential that the bismuth be placed close to the reactor core, for otherwise the neutrons will be lost by scattering ($\sigma = 9$ barns). This in fact places a limit on the amount of bismuth that may be effectively used.

To meet the mechanical requirements of the reactor, the filter had to be supported independently of the beam-port casing, so the beam-port insert (plug) illustrated in Fig. 1 was constructed and installed. The first 6 in. of filter (actually lead instead of bismuth) are fixed on the end of the plug, with provision for sliding in additional pieces of shielding from the open end. At present, 5 in. of bismuth are being used in addition to the lead. Other inserts shown in the tube aid in shielding against gamma rays entering the sides of the plug, while the long boric acid cylinder is used to collimate the neutron beam. Additional shielding and collimating material is also shown. The system terminates in a 1/2-in.-diameter round hole at the reactor face. The plug may be flooded with water to shut off the beam as required.

Figure 2 shows the effect of various thicknesses of filter on the neutron and gamma intensities. (Points below 6 in. are taken from preliminary experiments made before the plug was installed.) As can be seen from this figure, addition of material beyond about 8 in. does little to improve the neutron/gamma ratio; nevertheless it was found necessary to use a total of 11 in. to reduce the gamma ray background sufficiently. The final neutron flux is about

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*Fluxes in this discussion are given in terms of the standard operating power of 1 megawatt. Most of the measurements were made at power levels of from 50 to 1000 watts. Neutron fluxes are measured by gold-foil activation or counters normalized to gold-foil measurements. Gamma ray fluxes are in terms of free-air ionization chamber measurements. Figures are specifically for the beam port in use, nominally 6 in. in diameter.

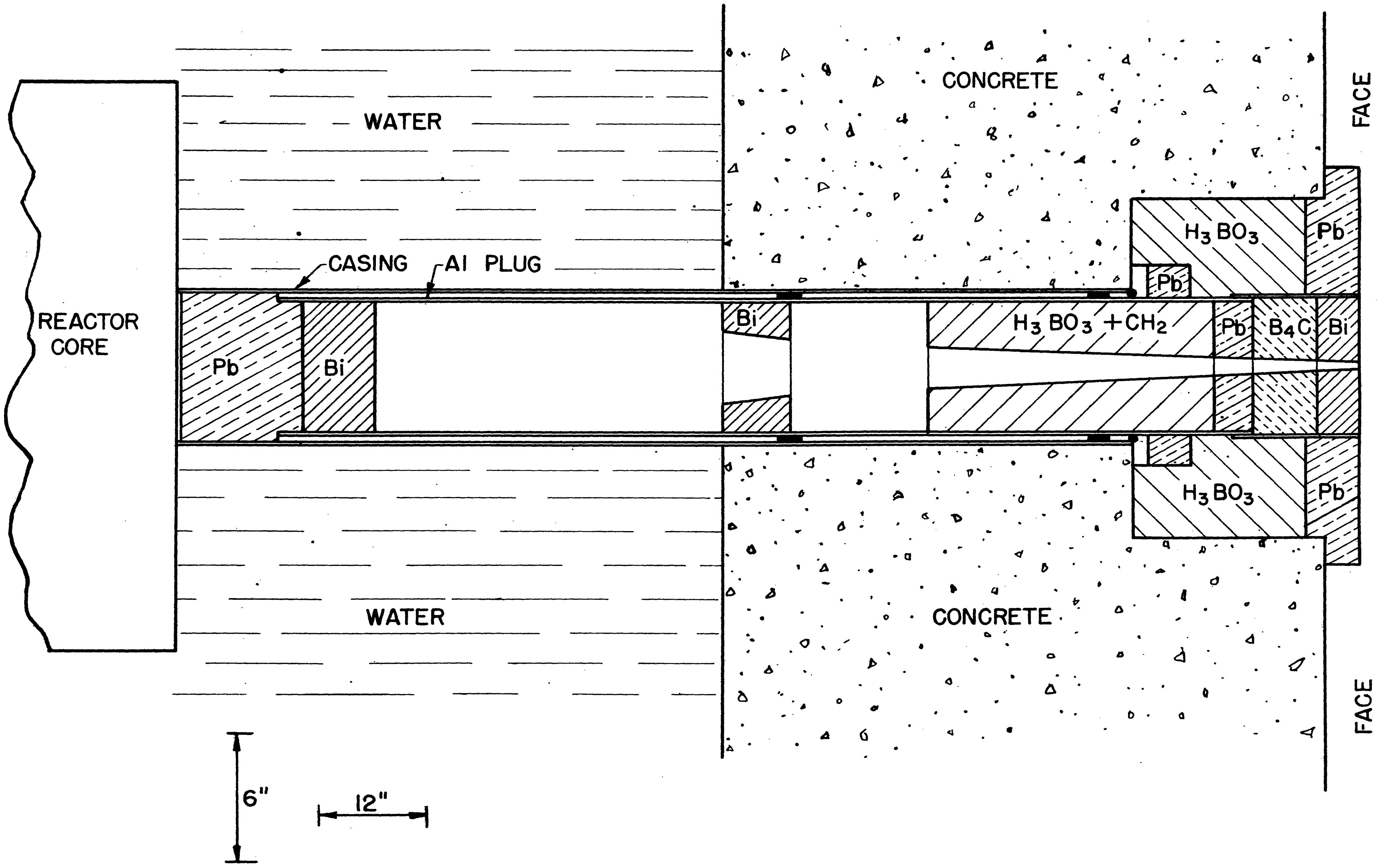

Fig. 1. Sketch of neutron beam extraction and shielding arrangement.

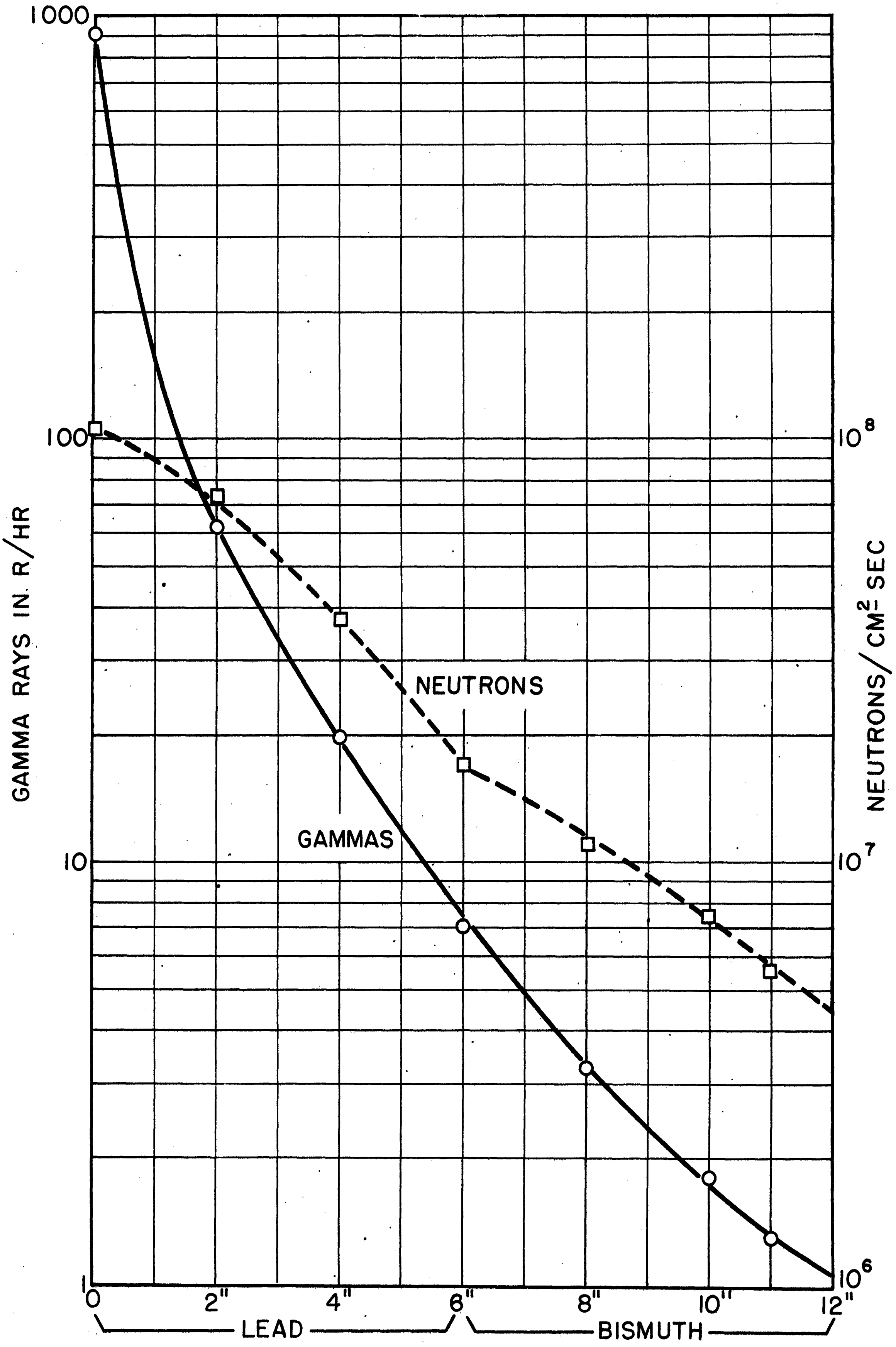

Fig. 2. Attenuation of gamma rays and neutrons by lead and bismuth beam-port inserts.

5×10^6 neut/cm^2 with 1.3 R/hr of gamma rays.

The arrangement of counters and the remainder of the shielding is shown in Fig. 3. A steel tank, 4 ft on a side, filled with boric acid and water, is used as a beam catcher. Personnel shielding is completed with concrete blocks. The counters are enclosed in lithium fluoride to exclude scattered neutrons, and shielded with lead. The radiation level is monitored by a fixed ionization chamber which records in the reactor control room.

C. THE 3-CRYSTAL SPECTROMETER

Hofstadter[7] in 1950 proposed the use of a scintillation spectrometer consisting of three separate counters for detection of high-energy gamma rays. Briefly, the idea is to select, of all the possible interactions of a gamma ray with the detecting crystal, only one interaction, namely, pair production followed by escape of both annihilation quanta. This results in only one peak in the pulse-height distribution for each line in the gamma ray spectrum.

In the model constructed for this program (Fig. 4) two scintillation counters in parallel (A and A', B and B') are used on each side of the primary detecting crystal (P). In order for a count to be recorded, a fast (10^{-8} sec) coincidence is required among the three sets of counters; in addition, the pulses from the side counters must pass through single-channel discriminators set over the annihilation peak. If all these requirements are met, the pulse from P passes through a linear gate and is recorded on the multichannel pulse-height analyzer. The block diagram is shown in Fig. 5.

The efficiency of the spectrometer, of course, increases with energy, approximately in proportion to the pair-production cross section. At 5 Mev the efficiency is about 2%. Resolution is about 4% at 5 Mev. One cannot hope to resolve all the lines that have been recorded with conversion spectrometers, but the efficiency of the latter (of the order of 10^{-5}) would be entirely too low for coincidence work.

A spectrum of Na^{24} taken with this instrument is shown in Fig. 6.

D. PRESENT STATUS

Neutron-capture gamma ray spectra of several elements have already been obtained, some of which are illustrated in Fig. 7. So far, no extensive survey of the elements has been made; rather, the spectra of chlorine or mercury have been used to test various counter arrangements, shielding, electronic adjustments and the like. Considerable time has been spent eliminating fatigue effects in the photomultipliers, attributed to the high background counting rates (5×10^5 cts/sec).

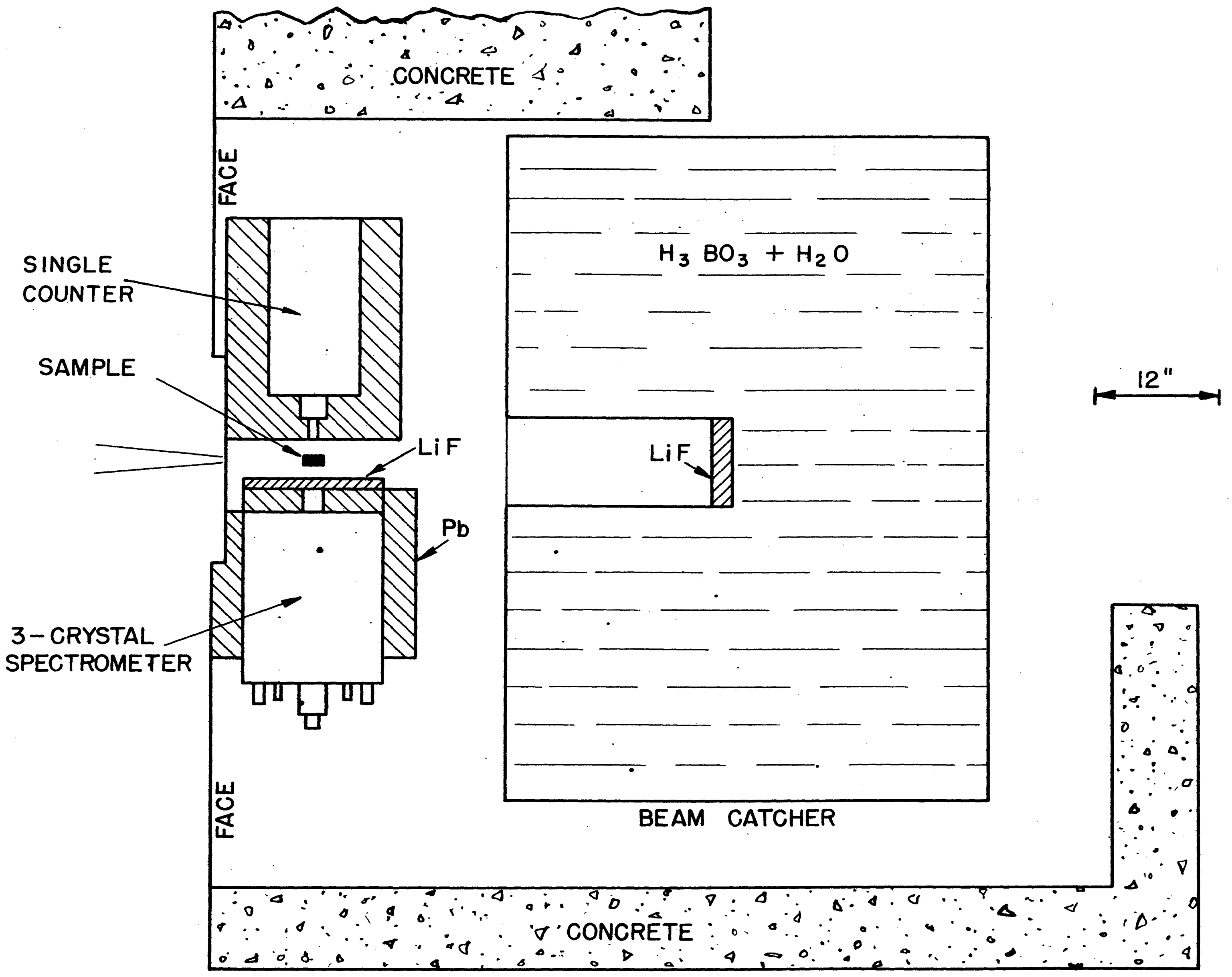

Fig. 3. Sketch of counter arrangement and beam stopper.

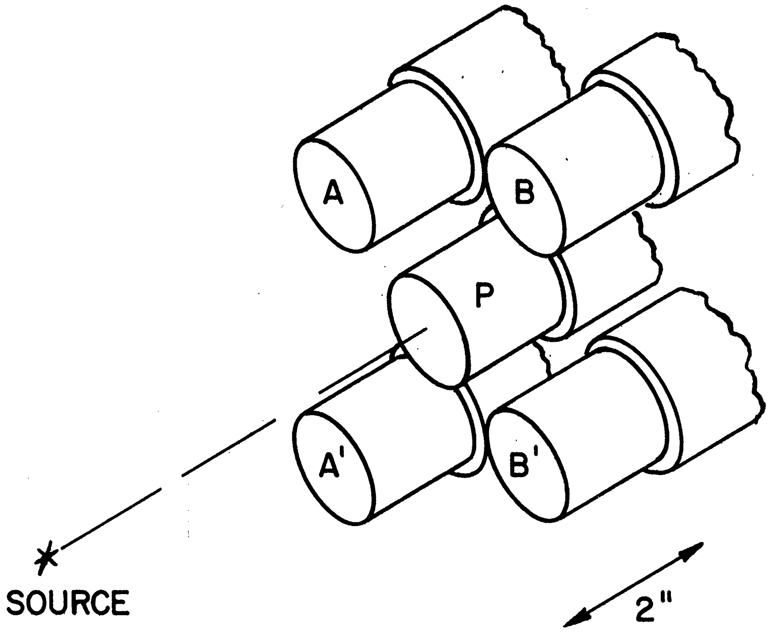

Fig. 4. Scintillation crystal geometry in the 3-crystal spectrometer. The primary crystal is 1-1/4 in. by 1-1/2 in., the others are 2 in. by 2 in.

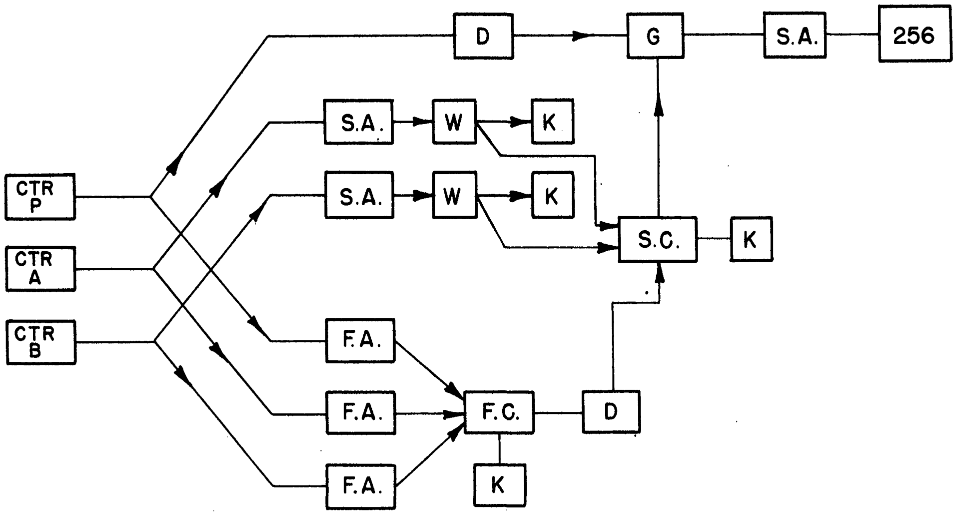

Fig. 5. Block diagram of 3-crystal spectrometer. F = fast, S = slow, A = amplifier, C = coincidence circuit, D = delay line or circuit, G = gate, K = scaler, W = single channel analyzer, 256 = multichannel analyzer.

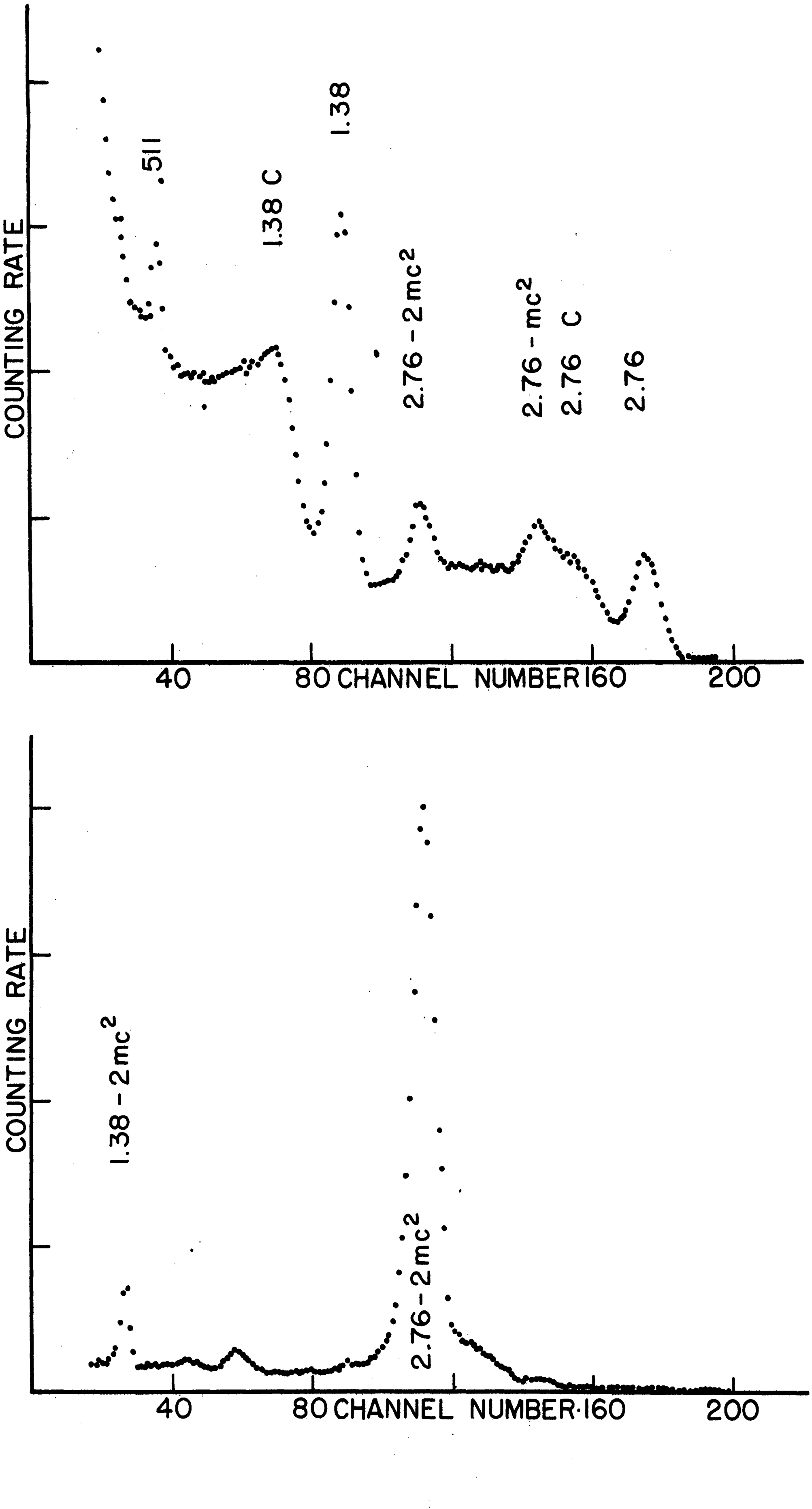

Fig. 6. (a) Singles spectrum of a Na^{24} source. (b) Spectrum of the same source taken with the 3-crystal spectrometer.

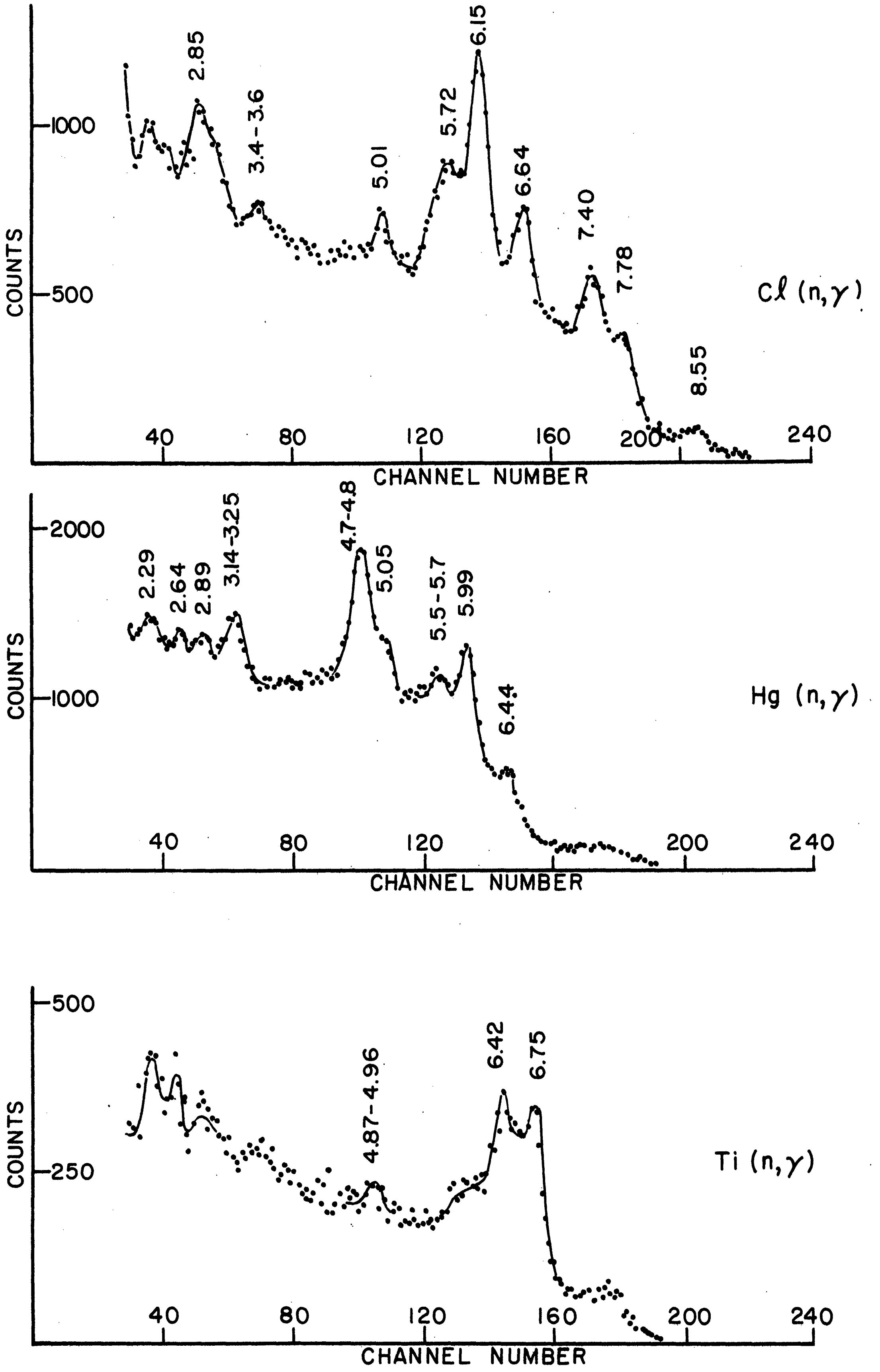

Fig. 7. (a) Cl (n,γ) spectrum. (b) Hg (n,γ) spectrum. (c) Ti (n,γ) spectrum. All taken with the 3-crystal spectrometer. Energies are from Refs. 1 and 2.

The next step will be to observe the spectra from various elements to determine which ones seem most suitable for coincidence measurements, and then to search for gamma-gamma coincidences. The coincidence and gate circuits have already been provided with extra channels for this purpose.

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