# Photoexcitation of $Pb^{207m}$

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The 0.8-sec isomeric activity in lead has been excited by the photoneutron reaction in $Pb^{208}$ and the relative cross section has been calculated from the measured yield. The cross section presents an extremely sharp peak in the giant resonance region with half-width not greater than 2 Mev.

The isomeric level excitation efficiency, $\sigma(\gamma,n\gamma')/\sigma(\gamma,n)$, has been calculated: it reaches a maximum value of 5%, which may be compared with the same quantity relative to inelastic neutron scattering in $Pb^{207}$, that already at the energy of 11 Mev, in the compound system, assumes a 14% value.

A discussion is given to explain the complete disagreement between the above two values of the excitation efficiency, which is attributed to the difference in angular momentum transferred to the compound system in the above two reactions.

## 1. INTRODUCTION

THE study of $Pb^{207}$ appears to be particularly interesting from the point of view of the shell model, as this nucleus is "magic" in protons and has a single hole in the neutron shell.

A 0.8-sec metastable state of $Pb^{207}$ has been found to follow $\beta^-$ decay of $Tl^{207}$, $K$-capture in $Bi^{207}$, and decay of $Po^{211}$. This isomeric state can also be excited directly in many nuclear reactions.[1,2] Among them, the following have been used:

(I) $Pb^{208}(d,t)Pb^{207m}$,

(II) $Pb^{207}(n,n')Pb^{207m}$.

In particular, the $(n,n')$ reaction has been elegantly employed by Campbell and Stelson[3] in studying the characteristics of this metastable state, measuring the half-life (0.83 sec), and determining the excitation function of reaction (II) at various energies up to 3.2 Mev of the incoming neutron [see Fig. 1(b)]. In their paper we also find the excitation function calculated on the assumption of formation of the compound nucleus and with the energy level scheme of Fig. 1(a), as proposed independently by different authors.[4] The calculated curve fits the experimental points very well, indeed.

In principle this metastable state can also be excited in at least two types of nuclear photoreactions:

(III) $Pb^{207}(\gamma,\gamma')Pb^{207m}$,

(IV) $Pb^{208}(\gamma,n\gamma')Pb^{207m}$.

Since natural lead contains both $Pb^{207}$ (21%) and $Pb^{208}$ (52%), the contribution of reaction (III) could be detectable below the $(\gamma,n)$ threshold, while reaction (IV) should become predominant at higher energies.

A preliminary study of processes (III) and (IV) in Pb was done by Bendel *et al.*[5] in 1955 using the bremsstrahlung x-rays from the betatron at the Naval Research Laboratory. These authors found that the threshold of process (IV) was well above what could be predicted, and also that any yield from reaction (III), if present, was below the sensitivity of their apparatus and could not be detected.

In the present work we have tried to investigate further the same processes (III) and (IV) in order to contribute quantitative data for what had been presented mostly in a qualitative way. For this purpose, we have proceeded to measure accurately the excitation function leading to $Pb^{207}$ metastable state, to determine the absolute value of the yield and to calculate the relative cross sections.

## 2. EXPERIMENTAL APPARATUS

We used for these measurements the x-rays from the betatron of the University of Turin. The betatron was operated at a fixed amplitude of the magnetic field and the energy of the electrons at the time of expansion was controlled manually by adjusting the phase of the expander circuit. A special device[6] was used to obtain a convenient energy stability ($\pm$30 kev at 15 Mev); it uses a megavoltmeter, giving a dc signal proportional to the flux at the moment of the x-ray burst multiplied by the frequency of the ac line. This voltage is measured by means of a potentiometer whose output is not constant but strictly proportional to the line frequency. The potentiometer was checked periodically with a Weston standard cell.

The x-ray dose was measured by a parallel-plate ionization chamber, connected to a direct-reading electrometer, with a 5-cm thick Al converter in front of the chamber.[7] The sensitivity of this chamber, calculated by Flowers *et al.* and measured in this

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[1] J. A. Harvey, Can. J. Phys. **31**, 278 (1953).
[2] E. C. Campbell and M. Goodrich, Phys. Rev. **78**, 640 (A) (1950).
[3] E. C. Campbell and P. H. Stelson, Phys. Rev. **97**, 1222 (1955).
[4] M. Goldhaber and R. D. Hill, Revs. Modern Phys. **24**, 179 (1952).
[5] Bendel, Toms, and Tobin, Phys. Rev. **99**, 672 (A) (1955).
[6] Farinelli, Ferrero, and Malvano, Nuclear Instruments **3**, 218 (1958).
[7] Ferrero, Malvano, and Tribuno, Nuovo cimento **5**, 510 (1957).

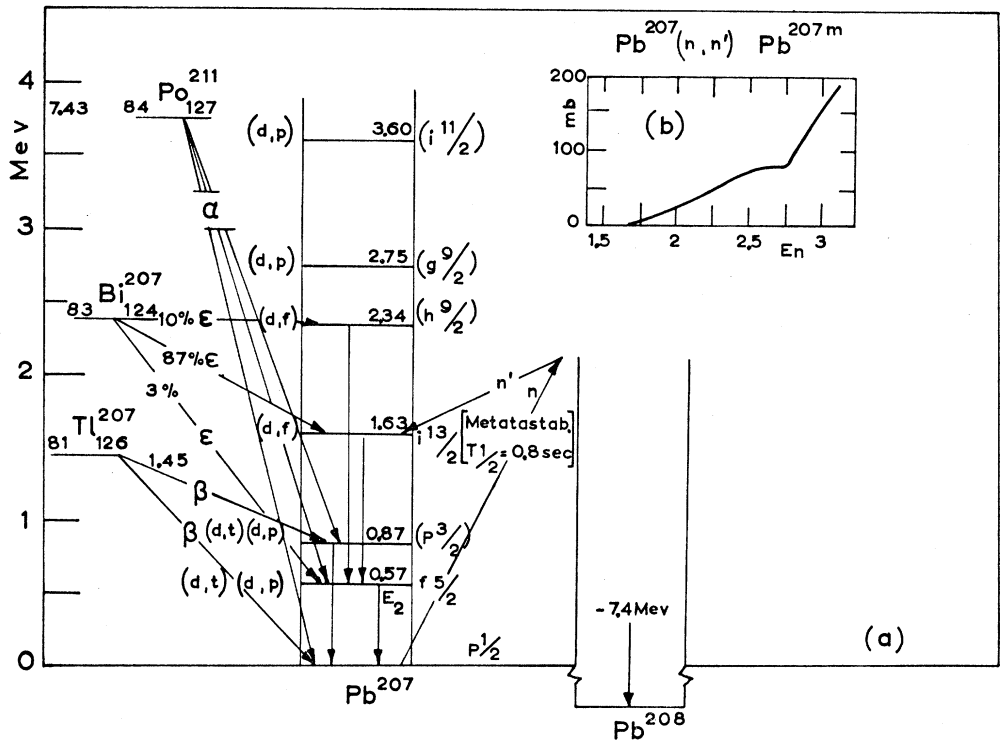


FIG. 1. $Pb^{207}$ level scheme (a) and excitation function of the $Pb^{207}(n,n')Pb^{207m}$ reaction (b).

laboratory, is very accurately proportional to the x-ray beam intensity.

The $\gamma$ activity from the target was detected by a cylindrical NaI(Tl) crystal (2-in. diameter, 1-in. thick) locked by a 6292 Dumont photomultiplier. The output of the photomultiplier was connected to a linear amplifier and a "one-channel" differential discriminator. The stability of the whole apparatus was periodically checked with a standard $Na^{22}$ annihilation radiation source. The output from the discriminator was connected to a five-channel time analyzer made up of five gates operated cyclically by a stable pulse generator followed by a multistage scaler and a mechanical selector. The same selector also operated the betatron injector periodically at the end of each counting time.

The whole cycle consisted of 2 sec of irradiation, 0.4 sec of waiting, and five channels of 0.8 sec each. The photomultiplier was cut off during irradiation time by applying a negative voltage to the shield (pin 13), a gradual decrease of pulse height at the output of the multiplier having been observed, caused by damage due to the intense light delivered by the crystal during irradiation.

In order to reduce the background as far as possible, the irradiation room was carefully shielded from the betatron by means of a thick water wall and a convenient frame of boric acid. The x-ray beam, after passing through the Pb scatterer ($\sim$20 g/cm$^2$), was caught in a cavity in a large tank full of water (beam catcher).

## 3. MEASUREMENTS

The activity from $Pb^{207m}$ was easily recognized. Before proceeding to measure the yield, two preliminary tests were made. First, the gamma-ray spectrum from the target was analyzed by means of the pulse-height selector and the results are shown in Fig. 2. The arrows in this figure indicate the positions of the annihilation radiation and the two photoelectric peaks of the 0.67-Mev line from $Cs^{137}$ and the 1.28-Mev line from $Na^{22}$, respectively. The results show the very well-known 0.57- and 1.06-Mev lines.

Secondly, the half-life of the activity was carefully measured; the result found was 0.797 sec, in excellent agreement with the last result of reference 5.

Very accurate measurements of yield were performed

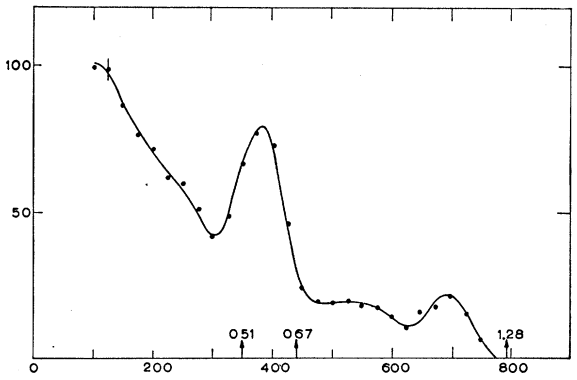


FIG. 2. $\gamma$-ray spectrum from 0.8-sec lead isomeric activity.

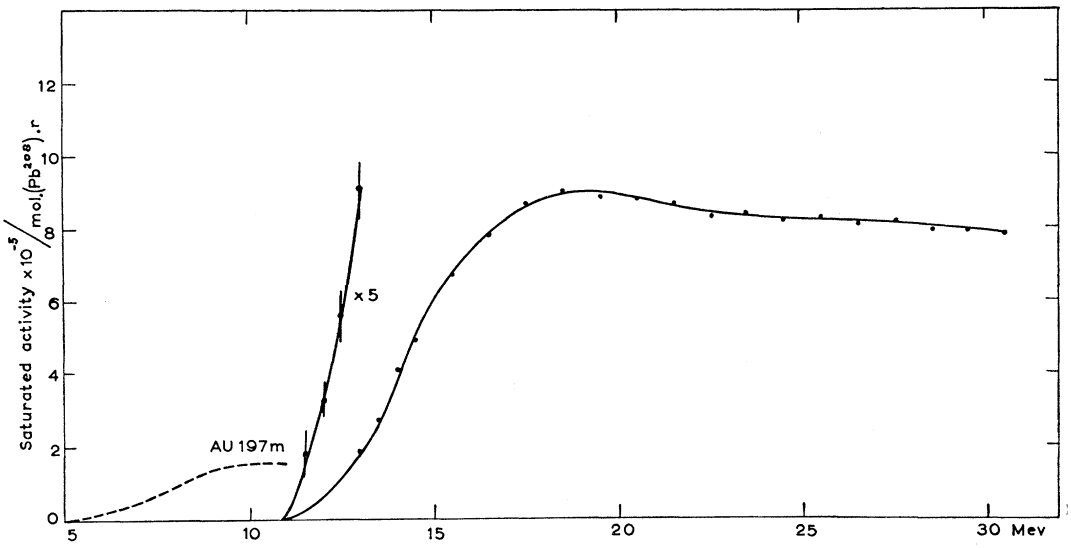


FIG. 3. Photoexcitation yield of 0.8-sec isomeric activity in lead.

in the region of threshold. The experimental results are shown in Fig. 3. The calibration of the energy scale was obtained through a measurement of thresholds of the $(\gamma,n)$ reactions in $Cu^{63}$ (10.61 Mev), $Si^{28}$ (16.8 Mev), and $C^{12}$ (18.73 Mev). The low-energy region of the curve is shown in the same figure multiplied by a convenient factor. The apparent threshold of the yield can be located quite well at 10.8 Mev.

The absolute calibration of the yield was obtained by making a comparison with the annihilation radiation emitted by the activity induced in a Ca sample by irradiation at 30 Mev. This last value is known from measurements by Braams and Smith.[8]

By applying the photon difference method, the cross-section curve shown in Fig. 4 (solid line) was obtained. The maximum is very close to 14 Mev. The full width at half height is not greater than 2 Mev. The dashed line in the same figure is the cross section, having a width of 2.4 Mev, of the total photoneutron reaction in Pb, as measured at the U. S. Naval Research Laboratory.[9] However, a higher value of the width (3.8 Mev) was obtained at the National Bureau of Standards by Fuller and co-workers.[10] The cross-section shape above 15 Mev can be easily understood if we take into account the competition of the $(\gamma,2n)$ process whose threshold is 14.2 Mev.

## 4. DISCUSSION

The first observation to be made on the experimental results concerns the absence of any detectable activity below 10.8 Mev. This indicates that $(\gamma,\gamma')$ excitation in $Pb^{207}$ gives no appreciable contribution to the yield. More accurate measurements with a new system that will greatly increase the detection efficiency are in progress; however, a cross section for the $(\gamma,\gamma')$ reaction of the same order of that observed in $Au^{197m}$ can already be ruled out. This clearly appears from Fig. 3, where the excitation curve obtained by Schutzmeister and Telegdi[11] with $Au^{197}$ is shown (dashed line) in comparison with our curve in the same scale. As a matter of fact, we easily observed at 11 Mev the 7.5-sec activity excited by the $(\gamma,\gamma')$ reaction in gold and the result is consistent with the curve obtained in reference 11.

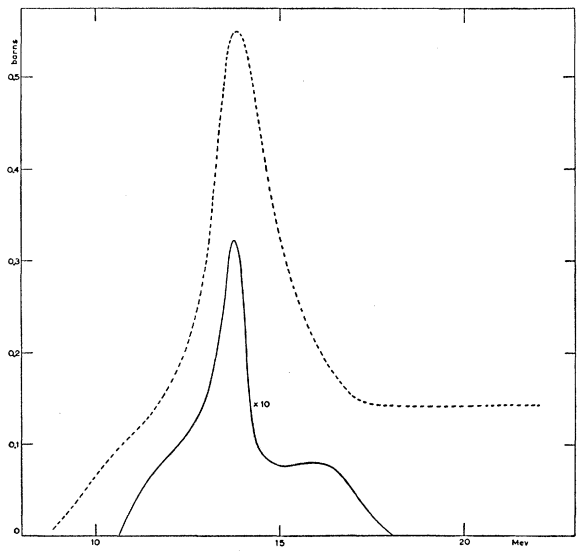


FIG. 4. Cross section of the $Pb^{208}(\gamma,n\gamma')Pb^{207m}$ photoreaction (solid line), and that of the photoneutron reaction in lead (dashed ilne—from reference 10).

[8] R. Braams and C. L. Smith, Phys. Rev. **90**, 995 (1953).
[9] M. E. Toms and W. E. Stephens, Phys. Rev. **108**, 77 (1957).
[10] National Bureau of Standards Report NBS-5686, December, 1957 (unpublished).
[11] M. Schutzmeister and V. L. Telegdi, Phys. Rev. **104**, 185 (1956).

The reason for this fact can probably be ascribed (a) to the high value (13/2) of the metastable state spin, and (b) to the small level density in $Pb^{207}$ in the region just above the metastable state.

The $(\gamma,\gamma')$ metastable state excitation (all other conditions being the same) is proportional to the value of the inelastic $\gamma$-ray cross section. Now inelastic scattering seems to be complementary to elastic scattering in the region below threshold for particle emission. In fact, as is observed by Fuller and Hayward,[12] the value of the elastic cross section depends in part on the number of alternative modes of decay available for the excited nucleus, and therefore on the details of the level structure in the particular scattering nucleus. The experiments show that the elastic scattering is much stronger in lead than in gold: the inelastic scattering (and consequently the metastable state excitation) should be much smaller in lead than in gold, as was indeed found.

The yield curve effectively begins at 11 Mev. The calculated threshold of the $Pb^{208}(\gamma,n\gamma')$ process should be located at 9.0 Mev or 9.7 Mev, according to which value is chosen for the $(\gamma,n)$ threshold in $Pb^{208}$: either the value of 7.37 Mev from $(n,\gamma)$ measurements[13] or the 8.1 Mev found from $(\gamma,n)$ measurements in a pure 31-g sample of $Pb^{208}$.[14–16]

We tried therefore to deduce the calculated yield curve of the isomeric state starting from the known values of the $(\gamma,n)$ cross section, which however refers to the natural isotopic constitution of lead rather than pure $Pb^{208}$.[17] The cross section for the excitation process of the isomeric state can be calculated, in the framework of the compound nucleus formation, assuming that the

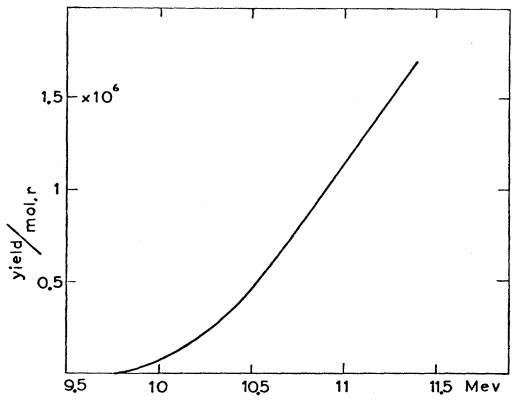


FIG. 5. Calculated yield of the $Pb^{208}(\gamma,n\gamma')Pb^{207m}$ reaction.

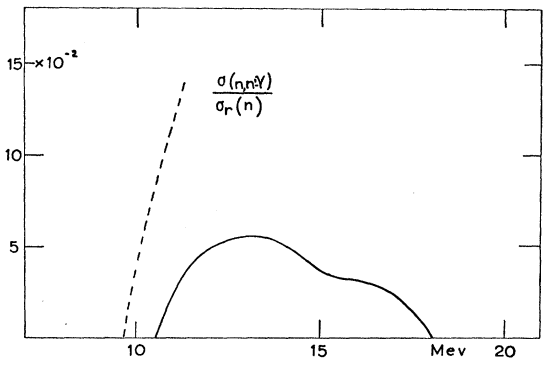


FIG. 6. Excitation efficiencies of the 0.8-sec metastable level in $Pb^{207}$ following photoneutron reaction (solid line), and inelastic neutron scattering (dashed line).

probability for the compound nucleus decay through the isomeric-state channel is the same as the ratio between the $\sigma(n,n'\gamma')$ and the total reaction neutron cross section $\sigma_r(n)$.[18]

The yield was then calculated by averaging the cross section over the bremsstrahlung spectrum according to the relation

$$Y_{\gamma,n\gamma'}(E_0)=\int_{E_{\rm th}}^{E_0}P(E,E_0)\sigma(\gamma,n)\left[\frac{\sigma(n,n'\gamma')}{\sigma_r(n)}\right]dE,$$

where $P(E,E_0)$ represents the bremsstrahlung spectrum. The calculated results, given in Fig. 5, are in striking disagreement with experiment, the calculated yield at 11 Mev being $\sim$50 times the observed yield. It should be pointed out that in the calculation the rather high value of 8.1 Mev has been assumed for the $(\gamma,n)$ threshold. Had we chosen, instead, the lower value of 7.4 Mev, the disagreement would have been even greater.

We have calculated the excitation efficiency $\sigma(\gamma,n\gamma')/\sigma(\gamma,n)$ of the isomeric level from the curve of Fig. 4, obtaining the results shown in Fig. 6. We see that the observed excitation efficiency reaches a maximum value of $\sim$5%, whereas in the case of excitation by neutron scattering already at an energy of 11 Mev, in the compound system, this quantity attains a value of 14%, as can be seen from Fig. 6. A still higher value would most certainly be found for the inelastic scattering of higher energy neutrons: unfortunately no data are available at present to extend this comparison.

The experimental results, now presented, could be explained in two different ways:

(a) The excitation of the metastable level in $Pb^{207}$ follows essentially a direct process, namely, the $Pb^{208}$ compound system[19] decays before it reaches thermal equilibrium.

[12] E. G. Fuller and E. Hayward, Phys. Rev. **101**, 692 (1956).
[13] P. B. Kinsey *et al.*, Phys. Rev. **78**, 77 (1950).
[14] Parson, Lees, and Collie, Proc. Phys. Soc. (London) **63**, 915 (1950).
[15] R. Palevsky and A. O. Hanson, Phys. Rev. **79**, 242 (A) (1950).
[16] The value found by Palevsky and Hanson[15] for the same threshold is however, 7.44 Mev.
[17] In reference 15 it has been found that the contributions to the $(\gamma,n)$ yields from $Pb^{206}$, $Pb^{207}$, and $Pb^{208}$ in the threshold region are, respectively, in the ratio 1:0.8:1.
[18] D. J. Hughes and J. A. Harvey, *Neutron Cross Sections*, compiled by D. J. Hughes and J. A. Harvey, Brookhaven National Laboratory Report BNL-325 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1955).
[19] V. F. Weisskopf, Physica **22**, 952 (1956).

(b) The decay to the isomeric level follows the formation of the $Pb^{208}$ compound nucleus.

The states of the compound nucleus differ, however, in the two cases, in the value of their angular momentum, the compound system formation being different. In the case of the photonuclear process, $J=1$; while in the case of inelastic neutron scattering (3-Mev neutrons), $J$ is of the order of 3.

A definite answer to these questions cannot be given without a detailed calculation of the excitation efficiency based on the two assumptions we have suggested above.


### ACKNOWLEDGMENTS

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# Positron Spectra of $Eu^{152}$ and $Eu^{152m}$†

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An intermediate-image beta-ray spectrometer equipped with spiral baffles has been used to investigate positrons in the decays of $Eu^{152}$ and $Eu^{152m}$. Thirteen-year $Eu^{152}$ emits a positron group to the 0.122-Mev 2+ first excited state of $Sm^{152}$ with an end-point energy of $0.715\pm0.010$ Mev and an intensity of $1.6\times10^{-4}$ per disintegration (log $ft=11.9$) and a positron group to the 0.366-Mev 4+ second excited state with an end point of $0.47\pm0.03$ Mev and an intensity of $0.8\times10^{-4}$ per disintegration (log $ft=11.5$). 9.3-hr $Eu^{152m}$ emits a positron group to the ground state of $Sm^{152}$ with an end-point energy of $0.895\pm0.005$ Mev and an intensity of $7\times10^{-5}$ per disintegration (log $ft=8.65$) and a positron group to the 0.122-Mev state with an intensity of $4\times10^{-5}$ per disintegration (log $ft=8.6$). The shape of the latter group has not been established. However, its end point, when the alpha shape factor is applied, gives better agreement with the 0.122-Mev energy separation from the ground-state beta ray than the end point of the uncorrected spectrum. The result is consistent with, but not positive proof of, the assumed spin of 0− for $Eu^{152m}$. The $\beta^-$ end-point energies of $Eu^{152}$ and $Eu^{152m}$ are $1.470\pm0.010$ Mev and $1.855\pm0.010$ Mev respectively. An energy separation of $0.050\pm0.015$ Mev between $Eu^{152m}$ and $Eu^{152}$ is derived from the various $\beta^+$ and $\beta^-$ end-point measurements. No $L$-conversion electrons could be found in $Eu^{152m}$ decay corresponding to a 0.05-Mev isomeric transition. An upper limit of $3\times10^{-5}$ per disintegration was obtained for the fractional decay of $Eu^{154}$ by positron emission.

## INTRODUCTION

THE helicity of the neutrino has been determined recently by Goldhaber, Grodzins, and Sunyar[1] in an experiment using 9.3-hr $Eu^{152m}$. A combined measurement of circular polarization and resonant scattering of gamma rays following orbital electron capture showed that the neutrino is left-handed. In the analysis, one assumption, based largely on plausibility arguments with respect to existing experimental information, was that the spin of $Eu^{152m}$ is 0−. Aside from a direct measurement of the spin of $Eu^{152m}$, which has not been carried out thus far, there are several other ways in which the spin assignment can be made. Studies could be made of the beta-ray branching to the 0.344-Mev 2+ first excited state of $Gd^{152}$ or of the positron branch emitted to the 0.122-Mev 2+ first excited state of $Sm^{152}$ (see Fig. 5). In either case a unique first-forbidden or so-called "alpha" shape should occur in the distribution if the spin-parity of $Eu^{152m}$ were actually 0−.

An experiment on $Eu^{152m}$ was carried out early in the present work with the intermediate-image spectrometer in which beta rays focused by the spectrometer were measured in coincidence with 0.344-Mev gamma rays detected by means of a 2×2 inch NaI scintillation crystal behind the source. Owing to the weakness of the branch to the first excited state of $Gd^{152}$ (~2%), the coincidence yield with a reasonable real-to-chance rate was found to be too small to permit a spectrum shape determination.

Positrons are known[2] to occur in the decay of $Eu^{152m}$ with an end-point energy of $0.83\pm0.05$ Mev and an intensity of ~0.02% per disintegration, as established by means of a three-crystal pair spectrometer. It was presumed that the end point corresponded to the decay to the ground state of $Sm^{152}$. The approach followed in the present work was to make a magnetic analysis of the $Eu^{152m}$ positron spectrum with the hope of detecting a branch to the 2+ first excited state of $Sm^{152}$, and of determining its shape if possible. Another aim of the experiments was to make a more accurate measurement

* Guest scientist on leave from the Hebrew University, Jerusalem, Israel.

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[1] Goldhaber, Grodzins, and Sunyar, Phys. Rev. **109**, 1015 (1958).

[2] L. Grodzins and H. Kendall, Bull. Am. Phys. Soc. Ser. II, **1**, 163 (1956).