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# Study of the Energy Levels of $^{205}$Tl Using the $(\gamma, \gamma')$ Reaction

R. Moreh and A. Wolf
*Nuclear Research Centre-Negev, Beer Sheva, Israel*

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Both elastic and inelastic scatterings of monochromatic photons were used for studying the energy levels of $^{205}$Tl; the photons were produced by thermal-neutron capture in iron, and the resonantly scattered spectrum was measured using Ge(Li) detectors. The scattering isotope was identified by using an isotopically enriched thallium target. The energy of the resonance level in $^{205}$Tl was found to be 7.646 MeV. The spectral shape of the scattered radiation was found to have a strong intensity bump above about 4.5 MeV. Energies and intensities of several $\gamma$ lines were measured in the region 1.0–7.7 MeV. Assuming the high-energy lines to be primary transitions deexciting the resonance level, 25 energy levels were found from the ground state up to 3.4 MeV, 8 of which may be identified with recently reported levels. By measuring the angular distribution of the scattered radiation, the spin of the scattering level was found to be $\frac{1}{2}$. The width of the resonance level was determined and was found to be $\Gamma = 0.98 \pm 0.09$ eV, and $\Gamma_0/\Gamma = 0.58$. The E1 character of the scattered radiation was inferred from the systematics of the radiation widths of highly excited levels, and the resonance level was interpreted as being associated with the tail of the giant electric-dipole resonance. The $^{205}$Tl levels are discussed in terms of the predictions of the shell model. The anomalous intensity bump in the $\gamma$ spectrum is discussed in the light of similar bumps obtained in the $(n, \gamma)$ reaction on nuclei in the same mass region.

## I. INTRODUCTION

The technique of using monochromatic photons, obtained from thermal-neutron capture, for studying the low-lying energy levels of nuclei is relatively new.[1] In this technique, inelastic scattering of monochromatic photons is used for populating low-energy levels while angular distribution of the scattered radiation is utilized for determining the spins of the resonance level and the low-lying levels. In an earlier publication,[2] the potentialities of using the $(\gamma, \gamma')$ reaction in nuclear studies were discussed in some detail and a comparison with the use of the $(n, \gamma)$ technique was given.

In this paper, the $^{205}$Tl energy levels were studied using the $(\gamma, \gamma')$ reaction on natural thallium; the $\gamma$ source was obtained from thermal-neutron capture in iron. The scattering isotope was identified by using an enriched target scatterer as discussed in Sec. III C. The spin and the radiative width of the scattering level were determined. The decay scheme of the 7.646-MeV resonance level in $^{205}$Tl was constructed. The positioning of some new levels was made by relying on the assumption that strong high-energy $\gamma$ rays are emitted in primary transitions; an experimental test of this latter assumption is given. The character of the scattered radiation was inferred from the systematics of the radiation widths of high-energy neutron-capture $\gamma$ rays of known multipolarity as given by Bartholomew.[3]

The spectral shape of the scattered radiation was found to have a strong intensity bump above about 4.5 MeV; this bump is reminiscent of "anomalous" intensity bumps in the $\gamma$ spectra from $(n, \gamma)$ and $(d, p\gamma)$ reactions on nuclei in the mass range $180 < A < 208$. The possibility of a common origin for both phenomena is discussed.

Resonance scattering from a thallium target, using neutron-capture $\gamma$ rays of Fe, was first reported by Ben-David *et al.*[4] Only the elastically scattered component was observed and the effective cross section was found to be 370 mb.

The energy levels of $^{205}$Tl were previously measured by Hinds *et al.*[5] using the $^{206}$Pb$(t, \alpha)$ reaction and 16 energy levels were found below the 2.8-MeV excitation. In the present work, about 10 levels in the excitation region between 1.5 and 3.0 MeV were identified, whose spins are believed to be either $\frac{1}{2}$ or $\frac{3}{2}$.

## II. EXPERIMENTAL PROCEDURE

The neutron source was provided by the Israel Research Reactor-2 (IRR-2). The capture $\gamma$-ray source (Fig. 1) was about 10 kg of natural iron in the form of separated discs, placed near the reactor core along a tangential beam port. The geometrical arrangements of the source, target, filters, collimators, and the scattering system remained the same as given in a previous report.[2] The flux near the iron source is about $2 \times 10^{13}$ $n$/cm$^2$ sec yielding typical $\gamma$ intensities of the order of $10^8$ monoenergetic photons/cm$^2$ sec on the target scatterer. The temperature of the iron source is about 360°C during full-power operation. The scattered $\gamma$ rays were observed by placing a 3-mm-thick thallium target of 12-cm radius. The detectors used were either a 5-in.×5-in. NaI crystal or a 47-cm$^3$ Ge(Li) coaxial crystal. The spectrum was recorded with a 1024-channel TMC analyzer. Due to the very high counting rate of small energy pulses (see Sec. III) detected by both detectors, it was necessary to use a base-line restorer in conjunction with the normal electronics.

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[1] K. Min, Phys. Rev. **152,** 1062 (1966).

[2] R. Moreh and A. Nof, Phys. Rev. **178,** 1961 (1969).

[3] G. A. Bartholomew, Ann. Rev. Nucl. Sci. **11,** 259 (1961).

[4] G. Ben-David, B. Arad, J. Balderman, and Y. Schlesinger, Phys. Rev. **146,** 852 (1966).

[5] S. Hinds, R. Middleton, J. H. Bjerregaard, O. Hansen, and O. Nathan, Nucl. Phys. **83,** 17 (1966).

The full width at half-maximum (FWHM) of the 47-$cm^3$ detector obtained during operating conditions was 11 keV at 7.6 MeV. For angular distribution measurements, the detector was mounted on a rotating arm pivoted around a perpendicular axis passing through the scatterer. The counting time at each angle was determined by the counting rate in a 1.5-in.×1.5-in. NaI detector, which monitored the Compton-scattered $\gamma$ rays from a 6-mm-thick $B_4C$ plate inserted in the incident beam.

## III. RESULTS

### A. Background

The main source of background at the high-energy region of the $\gamma$ spectrum was found to arise from neutrons produced mainly by the ($\gamma$, $n$) reaction on the thallium target and partly by the ($\gamma$, $n$) reaction on the lead collimators and shielding. The direct beam of iron-capture $\gamma$ rays consists of strong intensity lines at 7.632, 7.646, and 9.298 MeV which are largely responsible for producing neutrons, being higher than the ($\gamma$, $n$) threshold for some of the stable isotopes of thallium and lead. The cross section for ($\gamma$, $n$) reaction produced by 9.0 MeV neutron-capture $\gamma$ rays on nuclei in the region of $A\approx 200$ was measured by Hurst and Donahue,[6] and found to be of the order of 40 mb. In fact, because of the intense $\gamma$ beam, the neutrons produced by the ($\gamma$, $n$) reaction of the thallium target and lead collimators caused a strong build up of activity in the NaI crystal. A high reduction in background was effected by shielding the NaI detector with 1 in. of paraffin with an inner and outer mantel of borated plastic.

### B. Energy Spectrum

The spectra of high- and low-energy scattered radiation were measured using 10- and 47-$cm^3$ Ge(Li) detectors. Figure 2 shows the high-energy part of the scattered-radiation spectrum from a 3-mm-thick natural thallium target with the 47-$cm^3$ Ge(Li) detector placed at a scattering angle of 150°. The energy calibration of the $\gamma$ spectrum was performed before and after each run with respect to the energies of the iron capture $\gamma$ rays of the incident beam of the high-energy region. In the low-energy region a thorium source was used. The variable energy response of the 47-$cm^3$ Ge(Li) detector was calibrated with reference to the well-known line intensities of the ($n$, $\gamma$) spectrum of chlorine[7] by employing the external thermal-neutron beam facility at IRR-2. For comparison, the scattered-radiation spectrum as measured by a 5-in.×5-in. NaI crystal is shown in Fig. 3, which also shows the background spectrum obtained using a nonresonant scatterer of Bi. The background spectrum at low energies is produced mainly by Compton scattered radiation, by bremsstrahlung of photoelectrons and electron pairs from the scatterer, and by stray neutrons emitted via the ($\gamma$, $n$) reaction on the scatterer. The steeply rising background spectrum at lower energies distorts to some extent a "bump" of strong intensity lines above 4.5 MeV. This bump, obtained by subtracting the background Bi spectrum from the resonance scattered spectrum of Tl, may be seen clearly in Fig. 4 and will be discussed later. Another remark should be added regarding the scattered-radiation spectrum. The incident $\gamma$ spectrum consists of a doublet of lines at 7.646 and 7.632 MeV of about the same intensity. However, no evidence was found for the appearance of the 7.632-MeV line in the scattered-radiation spectrum.

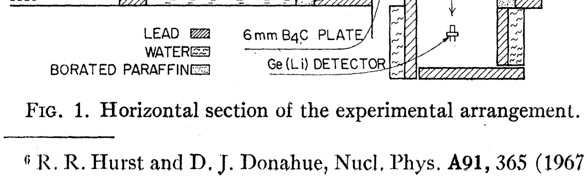

FIG. 1. Horizontal section of the experimental arrangement.

The use of a large volume Ge(Li) detector in the present technique proved to be of great advantage especially in the energy region below 4 MeV. This is due to the fact that the spectrum obtained using a large volume has relatively strong photopeaks as compared with the same spectrum obtained using small-volume detectors. Such photopeaks lie at an energy region (higher by 1.022 MeV) where the spectrum "background" is much lower than the region where second escape peaks appear. As a result, it was much easier to observe relatively weak lines at energies below 4 MeV, using a large-volume detector.

### C. Identification of the Scattering Isotope

A comparison of the energies of the inelastically scattered $\gamma$ rays with the energies of the low-lying levels indicate that $^{205}$Tl is most probably the scattering isotope. However, because the energies of the low-lying levels in $^{205}$Tl and $^{203}$Tl, as reported in the literature, are known only to within 20 keV it was formidable to draw any definite conclusion regarding the scattering isotope before independent evidence was obtained. A direct determination of the scattering isotope was made in the present work by measuring the scattered-radiation spectrum from an enriched $Tl_2O_3$ target weighing 1.0 g, of isotopic composition 92.3% $^{203}$Tl and 7.7% $^{205}$Tl using a 5-in.×5-in. NaI detector. Figure 5 shows the scattered-radiation spec-

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[6] R. R. Hurst and D. J. Donahue, Nucl. Phys. **A91**, 365 (1967).

[7] L. B. Hughes, T. J. Kennett and W. V. Prestwich, Nucl. Phys. **80**, 131 (1966).

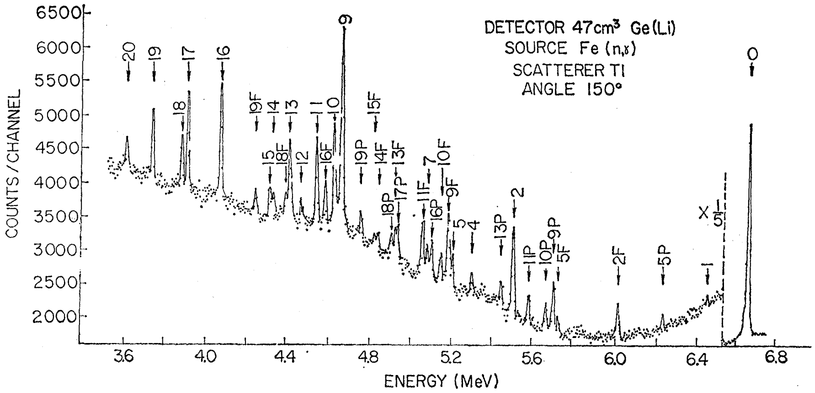

FIG. 2. Scattered $\gamma$-ray spectrum from a Tl target at an angle of 150° measured by a 47-cm³ Ge(Li) detector. The lines labelled $P$ and $F$ refer to the photopeak and first escape peak, respectively; other lines refer to double escape peaks.

trum from the enriched target, from a natural $Tl_2O_3$ target (29.5% $^{203}$Tl and 70.5% $^{205}$Tl), and from a $BiONO_3$ target, all of which contain the same weight of the heavy element. The scattered intensity of the natural sample was found to be about nine times larger than that of the enriched sample (after reducing the background intensity of the $BiONO_3$ sample). This fact shows beyond doubt that $^{205}$Tl is the isotope responsible for resonance scattering. It should be noted that this result is at variance with that expected from consideration of the $(\gamma, n)$ thresholds for the two isotopes $^{203}$Tl and $^{205}$Tl; these thresholds were reported[8] to be 7.66 and 7.53 MeV, respectively, which probably indicates that $^{203}$Tl is the isotope responsible for resonance scattering, its $(\gamma, n)$ threshold being higher than the resonance energy 7.646 MeV. This discrepancy may be due either to an inaccurate measurement of the $(\gamma, n)$ threshold for $^{205}$Tl or to the existence of an unbound level in $^{205}$Tl having a high radiative width; the latter possibility seems to be more likely.

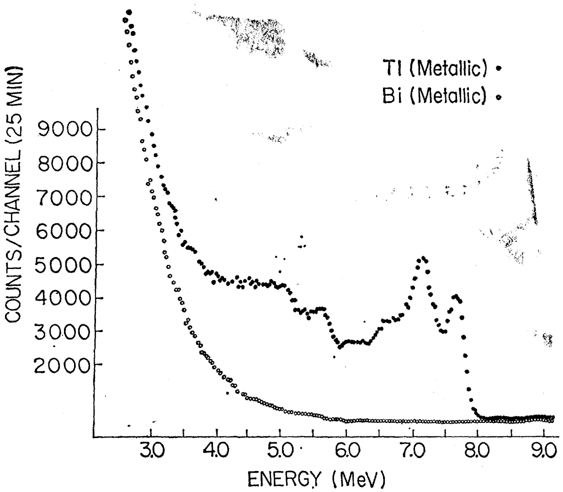

FIG. 3. Scattered $\gamma$-ray spectrum from a Tl target at an angle of 135° as measured by a 5-in. × 5-in. NaI detector. The background spectrum is obtained using a Bi scatterer.

### D. Decay Scheme

The decay scheme and hence the energy levels of $^{205}$Tl may be deduced from the resonantly scattered-radiation by making two assumptions The first is that only one resonance level is excited by the incident iron capture $\gamma$ rays and the second is that strong high-energy $\gamma$ rays are emitted in primary transitions. The first assumption may be justified by comparing the line energies of the scattered-radiation spectrum with the line energies of the direct iron capture $\gamma$-ray spectrum. It was found that only the 7.646-MeV line is common to both spectra.

It was suspected that some of the lines may arise from thermal-neutron capture in $^{203}$Tl or $^{205}$Tl, the neutrons being produced by the $(\gamma, n)$ reaction on the thallium scatterer and on the lead collimators and shielding. These neutrons are assumed to be thermalized via several scattering events by the nuclei of the surrounding material. However, the energies and intensities of the lines were not found to fit those of

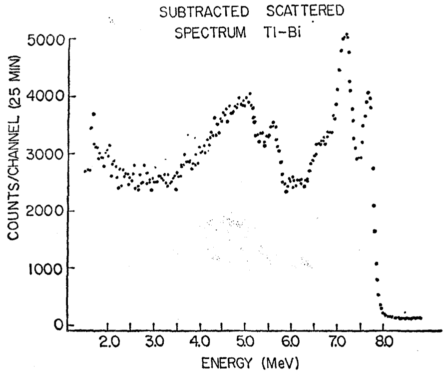

FIG. 4. Scattered $\gamma$-ray spectrum from a Tl target after substracting the contribution of a comparative Bi nonresonant scatterer of Fig. 3. The bump of strong intensity $\gamma$-rays around 5 MeV is clear.

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[8] *Nuclear Data Sheets*, edited by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington, D.C. 20025, 1959–1965); J. Solf, W. R. Hering, J. P. Wurm, and E. Grosse, Phys. Letters **28B**, 413 (1969).

the known $\gamma$ lines[9] obtained from thermal-neutron capture in $^{203}$Tl and $^{205}$Tl.

The other possibility that some of the lines are due to resonant capture of energy-degenerated photoneutrons may be eliminated by noting that the experimental dependence of the intensity of all lines on target thickness for thin targets, was found to be linear. This is to be compared with an expected variation as the square of the target thickness for a two-step process ($\gamma$, $n$) followed by ($n$, $\gamma$). It may also be noted that an overestimate of the $\gamma$-line intensities for an assumed two-step process can be obtained by taking a cross section of 100 mb for both the ($\gamma$, $n$) and the subsequent ($n$, $\gamma$) process.[6,9] The total $\gamma$-line intensity thus calculated is found to be about two orders of magnitude lower than the weakest line observed in the present work.

Two more difficulties suggest themselves: The first is the possibility that some of the lines may arise from elastic scattering of a weak and probably unknown line in the incident spectrum and second, it may arise from a strong inelastic component for which the elastic component is very weak and therefore unobserved. However, the probability for these processes to occur seems to be very small, as was found by a recent systematic study of the resonant scattered-radiation spectra from 50 different targets using $\gamma$ rays obtained by neutron capture in iron.[10] First, only the most intense $\gamma$ lines in the incident spectrum were found to give rise to resonance scattering and second, the intensity of the elastic component in the scattered-radiation spectra was found to be generally much stronger than the intensity of inelastic components. Only in two cases out of 40 resonances were inelastic components observed whose intensities were stronger than the elastic line. A further support for assuming that only one resonance level is excited by the incident beam was obtained by measuring the angular distribution of all strong intensity lines of the scattered-radiation spectrum as discussed in Sec. III E. The second assumption that strong high-energy $\gamma$ rays are emitted in primary transitions was justified by Bartholomew,[3] for levels formed by neutron capture, by considering the mechanism of the decay process. This assumption is further supported by the fact that 7 lines out of 24 measured high-energy lines were found to proceed to previously reported levels.

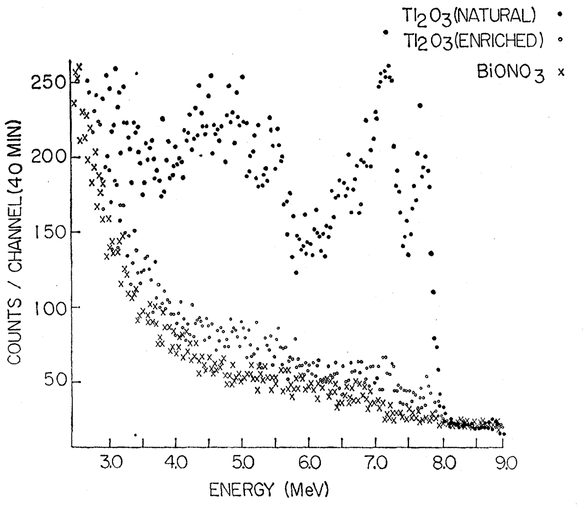

FIG. 5. Scattered $\gamma$-ray spectrum from 1 g of natural Tl$_2$O$_3$ (29.5% $^{203}$Tl, 70.5% $^{205}$Tl), an enriched Tl$_2$O$_3$ (92.3% $^{203}$Tl, 7.7% $^{205}$Tl), and BiONO$_3$ targets.

TABLE I. $\gamma$ energies from the $^{205}$Tl($\gamma$, $\gamma'$) reaction. All high-energy $\gamma$ rays were assumed to be primary transitions and were included in evaluating the branching ratios. Other $\gamma$ rays were taken as secondaries. Line energies are accurate to ±4 keV.

| No. | $\gamma$ energy (MeV) | Branching ratio (%) | No. | $\gamma$ energy (MeV) | Branching ratio (%) |
|---|---|---|---|---|---|
| 0 | 7.646 | 58.1 | 21 | 4.466 | 1.2 |
| 1 | 7.446 | 0.7 | 22 | 4.387 | 0.2 |
| 2 | 6.500 | 4.0 | 23 | 4.358 | 1.0 |
| 3 | 6.420 | 0.7 | 24 | 4.311 | 0.5 |
| 4 | 6.303 | 0.6 | 25 | 2.720 | |
| 5 | 6.210 | 0.8 | 26 | 2.616 | |
| 6 | 6.191 [a] | 1.5 | 27 | 2.558 | |
| 7 | 6.088 | 1.0 | 28 | 2.519 | |
| 8 | 6.070 [a] | 1.4 | 29 | 2.281 | |
| 9 | 5.676 | 5.8 | 30 | 2.170 | |
| 10 | 5.638 | 2.5 | 31 | 2.102 | |
| 11 | 5.548 | 2.7 | 32 | 1.967 | |
| 12 | 5.480 | 0.5 | 33 | 1.884 | |
| 13 | 5.422 | 1.9 | 34 | 1.575 | |
| 14 | 5.340 | 0.4 | 35 | 1.434 | |
| 15 | 5.327 | 0.6 | 36 | 1.389 | |
| 16 | 5.087 | 4.4 | 37 | 1.357 | |
| 17 | 4.924 | 3.0 | 38 | 1.227 | |
| 18 | 4.897 | 1.8 | 39 | 1.148 | |
| 19 | 4.753 | 2.8 | | | |
| 20 | 4.628 | 1.8 | | | |

[a] These $\gamma$ lines were observed only with the 10-cc detector.

Table I lists the results of line energies and branching ratios of scattered $\gamma$ rays from thallium as found in the present work. By considering the energies of the high- and low-energy transitions, it was possible to obtain 14 cascades, 5 of which lead to the first two excited

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[9] W. V. Prestwich, L. B. Hughes, T. J. Kennett, and H. J. Fiedler, Phys. Rev. **140,** B1562 (1965); C. Weitkamp (private communication); *Neutron Cross Sections,* compiled by D. J. Hughes and R. B. Schwartz (U.S. Government Printing Office, Washington, D.C., 1966), BNL 325, 2nd Ed., Suppl. 2.

[10] R. Moreh *et al.* (to be published).

TABLE II. Energy levels, spins, and parities in $^{205}$Tl from $(\gamma,\gamma')$ reaction. The energies were deduced by assuming that high-energy $\gamma$ lines are primary transitions deexciting the resonance level. For comparison, the values obtained by other workers are also shown. Spins and parities in parentheses indicate an uncertain determination.

| Present work ($\pm$4 keV) | Spin and parity | $^{208}$Pb$(t,\alpha)$ [a] ($\pm$20 keV) | Spin |
|---|---|---|---|
| 0 | $\frac{1}{2}^+$ | 0 | $\frac{1}{2}^+$ |
| 0.206 | | 0.205[b] | $\frac{3}{2}^+$ |
| 0.615 | | 0.615[b] | $\frac{5}{2}^+$ |
| 1.146 | $(\frac{1}{2}^+, \frac{3}{2}^+)$ | 1.14 | $(\frac{3}{2}^+)$ |
| 1.226 | | 1.21 | $\frac{1}{2}^+$ |
| 1.343 | | 1.34 | |
| 1.436 | | 1.43 | |
| 1.455 | | | |
| | | 1.48 | $(11/2^-)$ |
| 1.558 | | | |
| 1.576 | | | |
| | | 1.86 | |
| 1.970 | $(\frac{1}{2}^+, \frac{3}{2}^+)$ | 1.96 | |
| 2.008 | $(\frac{1}{2}^+, \frac{3}{2}^+)$ | | |
| | | 2.04 | |
| 2.098 | $(\frac{1}{2}^+, \frac{3}{2}^+)$ | | |
| | | 2.12 | |
| 2.166 | | | |
| 2.224 | | | |
| 2.306 | | | |
| 2.319 | | | |
| | | 2.43 | |
| | | 2.49 | |
| 2.559 | $(\frac{1}{2}^+, \frac{3}{2}^+)$ | | |
| | | 2.60 | |
| | | 2.61[b] | $\frac{5}{2}^-$ |
| | | 2.69[b] | $\frac{7}{2}^-$ |
| 2.722 | $(\frac{1}{2}^+, \frac{3}{2}^+)$ | | |
| 2.749 | $(\frac{1}{2}^+, \frac{3}{2}^+)$ | 2.74 | |
| 2.893 | $(\frac{1}{2}^+, \frac{3}{2}^+)$ | | |
| 3.018 | $(\frac{1}{2}^+, \frac{3}{2}^+)$ | | |
| 3.180 | $(\frac{1}{2}^+, \frac{3}{2}^+)$ | | |
| 3.259 | | | |
| 3.288 | | | |
| 3.335 | | | |
| 7.646 | $\frac{1}{2}^{(-)}$ | | |

[a] Reference 5.
[b] Reference 8.

states, and the remaining cascades to the ground state. In fact, the energies of the first and second excited states were inferred from the average of the sums of the component energies leading to these two states. The level energies thus obtained are in excellent agreement with those reported earlier.[8] The sum of the component energies of the other cascade was found to be within 7 keV of the total energy of 7.646 MeV; the average of these sums being exactly equal to 7.646 MeV. The 7-keV uncertainty is expected in view of the nonlinearities and drifts of the electronic system and the fact that the spectra were measured with a dispersion of 3.2 keV/channel. The high-energy component of each cascade was thus assumed to be a primary transition while the low-energy branch was taken as the secondary transition. The decay modes of some of the low-lying levels populated by high-energy transitions have been obtained by fitting the energy values of observed transitions to differences between level energies; these decay modes should therefore be considered tentative. Table II summarizes the excitation energies of levels in $^{205}$Tl obtained on the basis of the two assumptions made above. The level energies as obtained by others are also given. The decay scheme constructed from the data is shown in Fig. 6.

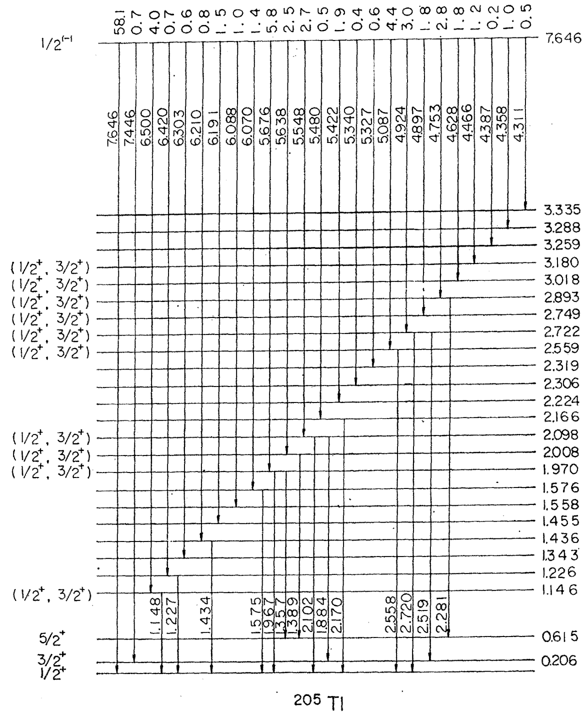

FIG. 6. Decay scheme of 7.646-MeV level of $^{205}$Tl showing level energies and corresponding branching ratios as constructed by assuming that all high-energy $\gamma$ lines in the scattered-radiation spectrum are emitted in primary transitions. Most probable spin values of some levels assigned in the present work are shown. The parity of the scattering level shown in parentheses is uncertain.

### E. Angular Distributions

Angular distribution measurements of the intense lines in the scattered-radiation spectrum were carried out at four angles using a 47-cm$^3$ Ge(Li) detector set 45 cm away from the scattering target. Corrections for the nuclear and atomic absorption of the incident beam and the atomic absorption of the scattered beam in the target scatterer were introduced. The distribution of the 7.646-MeV elastic line is seen in Fig. 7 to be isotropic, which indicates that the transition involved is dipole and that the resonance state has a spin value of $\frac{1}{2}$. It follows that the angular distribution of all inelastic lines corresponding to primary transitions should also be isotropic and therefore it is impossible in the present case to determine the spin of the intermediate levels populated via primary inelastic transitions by angular distribution measurements. It also follows that the resonantly scattered photons are not polarized[11]; thus it is impossible to find the character of the scattered radiation, and hence the parity of the resonant level by polarization measurements.

The angular distribution of the strong intensity lines was measured and found to be isotropic. A nonisotropic distribution of any of these lines may indicate the presence of an independent resonance level (of spin different from $\frac{1}{2}$) being excited by the incident iron capture $\gamma$ rays. It may be noted that the angular distribution of a secondary transition from an intermediate level of spin $\frac{3}{2}$ is also isotropic because the spin of the resonant state is $\frac{1}{2}$. The above experimental result may therefore be regarded as a further evidence that only one resonance level is excited by the incident $\gamma$ beam, but it may in no way be considered as a conclusive evidence.

### F. Branching Ratios and Radiation Width

Since the angular distribution of the elastic transition is isotropic, it follows that the branching ratios for the decay of the 7.646-MeV level may be evaluated directly from the relative intensities as measured at any angle; the results thus obtained are given in Table II. It may be seen that the branching to the ground state is 0.58, which is equal to $\Gamma_0/\Gamma$, where $\Gamma_0$ is the radiation width to the ground state and $\Gamma$ is the total radiation width. In order to determine $\Gamma_0$, it was necessary to carry out three independent experiments.[10] In the first, the ratio between the resonant scattering cross section at liquid-nitrogen temperature (−195C°) and at room temperature (27C°) was measured. In the second, the self-absorption ratio[12] was obtained using Bi both as nonresonant scatterer and nonresonant absorber. In the third, the effective cross section for elastic resonance scattering was measured. The result of each of these measurements is a function of $\Gamma_0$, $\Gamma_0/\Gamma_t$, and $\delta$, where $\Gamma_t$ is the total width of the level (including the neutron width $\Gamma_n$) and $\delta$ is the separation energy between the incident energy and resonant line in the scatterer. The values obtained were $\Gamma_0 = 0.57 \pm 0.06$ eV, $\Gamma_t = 0.98 \pm 0.09$ eV, $\delta = 9.3 \pm 0.3$ eV. It may be noted that the value of $\Gamma_0/\Gamma_t$ as determined here is very close to the value of $\Gamma_0/\Gamma$. This fact indicates that $\Gamma_t$ is practically equal to the total radiative width $\Gamma$ and that the neutron width $\Gamma_n$ should be negligibly small.

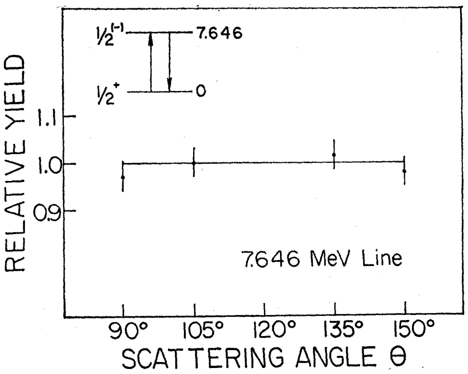

FIG. 7. Angular distribution of the elastically scattered line as measured using a 47-cm$^3$ Ge(Li) detector.

This result is not surprising in view of the angular momenta involved. The 7.646-MeV level is believed to be $\frac{1}{2}^-$ (see Sec. IV) and the $^{204}$Tl ground state is $2^-$. This would require the neutron to leave the $^{204}$Tl nucleus in the $^{205}$Tl($\gamma$, $n$) reaction with $l_n = 2$, which is very unlikely to occur, since the neutron energy is only about 115 keV after recoil corrections. The total radiative width of this level was measured earlier[13,14] and a good agreement was obtained.

## IV. DISCUSSION

### A. $\gamma$-Ray Transition Strengths

As mentioned earlier, it is not possible in the present work to make a direct measurement of the parity of the scattering level by polarization measurements of the scattered photons, because the spin of the scattering level in $^{205}$Tl is $\frac{1}{2}$. The $E1$ character of the scattered radiation was in fact inferred from the systematics of the radiation widths of high-energy primary neutron-capture $\gamma$ rays of known multipolarity in neighboring nuclei. The procedure is the same as that used by Bartholomew and Vervier[15]; it involved computing the $E1$ radiation strength $k_{E1}$ and comparing this quantity with an average value obtained from $\gamma$ transitions of known multipolarity. The radiation strength is

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[11] L. W. Fagg and S. S. Hanna, Rev. Mod. Phys. **31**, 711 (1959).

[12] F. R. Metzger, Progr. Nucl. Phys. **7**, 53 (1959).

[13] J. Balderman, M.S. thesis, Bar Ilan University, 1966 (unpublished).

[14] S. Ramchandran and J. A. McIntyre, Phys. Rev. **179**, 1153 (1969).

[15] G. A. Bartholomew and J. F. Vervier, Nucl. Phys. **50**, 209 (1964).

TABLE III. Partial radiation widths $\Gamma_i$ and $E1$ radiation strengths $k_{E1}$ of intense transitions from the 7.646-MeV resonance state in $^{205}$Tl. The level spacing $D$ was taken to be 1.0 keV.

| Transition energy (MeV) | Level energy (MeV) | $\Gamma_i$ (eV) | $k_{E1}$ ($10^{-9}$ MeV$^{-3}$) |
|---|---|---|---|
| 7.646 | 0 | 0.569 | 36.7 |
| 6.500 | 1.146 | 0.040 | 4.2 |
| 6.191 | 1.455 | 0.015 | 1.8 |
| 5.676 | 1.970 | 0.058 | 9.1 |
| 5.638 | 2.008 | 0.025 | 4.0 |
| 5.548 | 2.098 | 0.027 | 4.5 |
| 5.422 | 2.224 | 0.019 | 3.4 |
| 5.087 | 2.559 | 0.044 | 9.6 |
| 4.924 | 2.722 | 0.030 | 7.2 |
| 4.897 | 2.749 | 0.018 | 4.4 |
| 4.753 | 2.893 | 0.028 | 7.5 |
| 4.628 | 3.018 | 0.018 | 5.2 |
| 4.466 | 3.180 | 0.012 | 3.9 |
| 4.358 | 3.288 | 0.010 | 3.5 |

given by

$$k_{E1}=\Gamma_i(E_i^3A^{2/3}D)^{-1},$$

where $\Gamma_i$ is the radiative width and $D$ is the average spacing for levels of the same spin and parity near the resonance energy, $E_i$ is the $\gamma$ energy and $A$ is the mass number of the scattering nucleus.

The quantitative criterion adopted here is that a $\gamma$ ray is $E1$ if its radiation strength is $k_{E1}\geq 3.9\times10^{-9}$ MeV$^{-3}$, where $E$ is in MeV while $D$ and $\Gamma_i$ are in the same units. This value of $k_{E1}$ was obtained by Carpenter[16] after averaging over 26 $E1$ transitions from neutron resonance on nuclei in the range $144\leq A\leq 202$. The value is higher than that obtained by Bartholomew ($3.2\times10^{-9}$) who averaged the results from 180 $E1$ transitions on nuclei covering almost the whole periodic table.

The $k_{E1}$ values corresponding to the elastic and the strong inelastic transitions were calculated and are listed in Table III. In this calculation, the average spacing $D$ for levels of the same spin in $^{205}$Tl and at excitations around 7.6 MeV was taken as 1.0 keV which is about the same magnitude as the average level spacings of neutron resonances[17] in $^{204}$Tl and of the spacings of $\gamma$ resonances in $^{206}$Pb as obtained by Axel[18] from analysis of experimental data of Reibel and Mann.[19] From Table III, it may be noted that the strength of the elastic transition exceeds the criterion value by a factor of about 9. In addition, 10 inelastic transitions out of 13 strong transitions have values exceeding the adopted criterion value. First this result implies that the strong intensity $\gamma$ lines forming the bump are, most probably, associated with primary $E1$ transitions from the resonance level. Second, since the ground state of $^{205}$Tl is $\frac{1}{2}^+$, the above result implies that the 7.646-MeV resonance level is $\frac{1}{2}^-$ and that all intermediate levels populated by strong primary transitions should be either $\frac{1}{2}^+$ or $\frac{3}{2}^+$ (see Table II). The remaining transitions may be either $E1$, $M1$, or $E2$ and hence the spins of the corresponding levels should be either $\frac{1}{2}$, $\frac{3}{2}$, or $\frac{5}{2}$. The probability for $M1$ or $E2$ transitions is, in general, smaller by an average factor of about one and two orders of magnitude, respectively, compared with $E1$ transitions as is known from the systematics of highly excited levels in medium- and heavy-mass nuclei.[3] In fact, the results of average neutron-resonance capture spectrum in Er$^{167}(n,\gamma)$ indicate[20] that $E1$ transitions are on the average about 6.5 times as strong as $M1$ transitions to final states in Er$^{168}$. In addition, evidence for dominant $M1$ radiation has been found in some resonance scattered $\gamma$-ray spectra from nickel and cadmium.[21] Moreover, strong $M1$ radiation has been found in some neutron-capture $\gamma$-ray spectra from tin,[22] barium,[23] and lead.[24]

It is interesting to compare the apparently large $\Gamma_i$ with the estimates of partial radiative widths as obtained from an extrapolation of the giant dipole resonance as was done by Axel.[18] Assuming that the giant resonance has a Lorentzian shape down to low energies and applying the principle of detailed balance to photonuclear reactions, the width $\Gamma_0$ for the ground-state transition is

$$\frac{\Gamma_0}{D}=3.4\times10^{-6}\frac{A}{\omega}\frac{E_0^4\Gamma_g}{(E_g^2-E_0^2)^2+E_0^2\Gamma_g^2},$$

where $\omega=(2J_f+1)/(2J_0+1)=1$ for the ground-state transition; $E_0$ and the giant resonance energy $E_g$ and also the width $\Gamma_g$ of the giant resonance are in MeV. The values of $E_g$, $\Gamma_g$ may be taken from the empirical relations $E_g=80A^{-1/3}$, $\Gamma_g=5$ MeV.

In order to find to what extent the giant dipole extrapolation reproduces the ground-state $\gamma$-ray width, the numerical constant in the above formula was calculated assuming $D=1.0$ keV and $\Gamma_0=0.57$ eV. The value obtained was $2.8\times10^{-6}$ which is considered to be in good agreement with the predicted value $3.4\times10^{-6}$. Strictly speaking, the above relation holds for ground-

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[16] R. T. Carpenter, Argonne National Laboratory Report No. ANL-6589, 1962 (unpublished).

[17] *Neutron Cross Sections*, compiled by D. J. Hughes and R. B. Schwartz (U.S. Government Printing Office, Washington, D.C. 1958), BNL 325, 2nd ed.

[18] P. Axel, Phys. Rev. **126**, 671 (1962).

[19] K. Riebal and A. K. Mann, Phys. Rev. **118**, 701 (1960).

[20] L. M. Bollinger and G. E. Thomas, Bull. Am. Phys. Soc. **12**, 1200 (1967).

[21] R. Moreh and A. Nof, Bull. Am. Phys. Soc. **13**, 1451 (1968).

[22] J. A. Harvey, M. J. Martin, and J. J. Slaughter, Argonne National Laboratory Report No. ANL-7282, 1966 (unpublished).

[23] J. Urbanec, J. Vrzal, and J. Liptak, in *Proceedings of the International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, 1965* (North-Holland Publishing Co., Amsterdam, 1966), p. 535.

[24] J. A. Biggerstaff, J. R. Bird, J. H. Gibbons, and W. M. Good, Phys. Rev. **154**, 1136 (1967).

state transitions only; however, it was theoretically found[25] that the same relation may also be applied to transitions to excited states. The calculation of the numerical constants for inelastic transitions suffer from an uncertain spin value of the excited levels (being either $\frac{1}{2}$ or $\frac{3}{2}$) corresponding to an uncertain $\omega$ value. Nevertheless, if one abruptly assumes $\omega=1$ for all strong inelastic transitions, an average value of $1.0\times 10^{-6}$ is obtained for the numerical constant to be compared with the predicted value of $3.4\times 10^{-6}$. This is probably not a bad agreement in view of all approximations and uncertainties involved.

### B. Intensity Anomaly of $\gamma$ Lines

The anomalous intensity lines in $\gamma$ spectra are usually encountered in $(n,\gamma)$ reactions using thermal, epithermal, and fast neutrons[26] on nuclei in the mass range $180<A<208$. This bump is centered at about 5 MeV and is about 1 MeV wide. It was demonstrated that this phenomenon is associated with resonance reactions and was extensively studied[27] using the $(d, p\gamma)$ reaction. This reaction is closely related to neutron capture and in effect permits capture below the neutron threshold. Few important features of the bump were noted[28]: (a) Its energy is fixed near 5 MeV irrespective of the excitation energy of the emitting nucleus, (b) its radiation is associated with primary transitions from the resonance state, and (c) the character of the radiation is mainly $E1$ and only a small portion is believed to be $M1$. The main characteristics of this phenomenon seem to be preserved by the $\gamma$ spectrum observed in the present work (Fig. 4) using the $(\gamma,\gamma')$ reaction. However, it was impossible to check whether the energy of the bump in the present case is fixed as a function of excitation energy because the incident photon energy cannot be varied in the present technique. It is of course unsafe to draw general conclusions regarding a $\gamma$ bump obtained from one isotope using the $(\gamma,\gamma')$ reaction. However, it is tempting to consider the implications of this result due to the striking similarity between the spectrum obtained here and that obtained by $(n,\gamma)$ reactions on nuclei such as $^{203}$Tl.[9] These bumps are now believed to be due to $E1$ energy differences of the single-particle energies across the shell-model orbits. These energy differences such as $s$ shell to $p$ shell, $d$ to $p$, or $d$ to $f$ are all separated by roughly 5.0 MeV and are of course favored $E1$ transitions. It was suggested[28] that these bumps are obtained by the decay of doorway states of the final nucleus. The corresponding configurations are formed in the $(n,\gamma)$ and $(d, p\gamma)$ reactions through a semidirect process. It may be noted that most of these configurations may be alternatively formed by one-particle–one-hole excitations through $E1$ absorption by the same final nucleus. One therefore expects the $\gamma$ spectrum to display the same characteristics in the $(d, p\gamma)$ or $(n,\gamma)$ and $(\gamma,\gamma')$ reactions provided that the same final nucleus is involved.

### C. Energy Levels of $^{205}$Tl

Table II summarizes the present information regarding the $^{205}$Tl levels. Apart from the results obtained in the present work, Table II shows levels obtained using the $^{206}$Pb$(t,\alpha)$ reaction.[5] It also shows two other levels ($\frac{5}{2}^-$, $\frac{7}{2}^-$) observed using $^{205}$Tl$(p,p')$ reaction[8] and believed to be a doublet originating from a $3s_{1/2}$ proton hole coupled weakly to the $3^-$ state at 2.65 MeV in $^{206}$Pb. As expected, no direct transition was found to occur between the 7.646-MeV resonant level ($\frac{1}{2}^-$) and any level whose spin is larger than $\frac{3}{2}$. In particular, no transition was observed to levels at 0.605, 1.48, 2.61, and 2.69 MeV which are believed to be $\frac{5}{2}^+$, $\frac{11}{2}^-$, $\frac{5}{2}^-$, and $\frac{7}{2}^-$, respectively.

According to the simple shell model, the $^{205}$Tl nucleus consists of one proton hole and two neutron holes in the $^{208}$Pb doubly magic core; it may also be viewed as consisting of a single proton hole in the $^{206}$Pb core. The levels populated by the $^{206}$Pb$(t,\alpha)$ reaction correspond, most probably, to single proton-hole states coupled to the core states of $^{206}$Pb. In fact, very recent calculation[29] of the $^{205}$Tl energy levels was made by assuming a simple model in which the single-hole states of the proton were coupled to quadrupole and octupole vibrations of the core. In this manner, energy levels of $^{205}$Tl below 2-MeV excitation were obtained and the results seemed to agree satisfactorily with some of the levels obtained by the $^{206}$Pb$(t,\alpha)$ reaction. It is very likely that the description of levels around 2.8 MeV may require additional degrees of freedom and hence more complex configurations than that assumed by this simple model. It is possible therefore that the group of levels around 2.8 MeV strongly populated by the $(\gamma,\gamma')$ reaction are associated with neutron-core excitation of $^{205}$Tl. A partial confirmation of this assumption may be found in the fact that among the 16 proton-hole levels observed by the $^{206}$Pb$(t,\alpha)$ reaction, only 3 levels were strongly excited by the $(\gamma,\gamma')$ reaction.

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[25] N. Rosenzweig, Nucl. Phys. **A118**, 650 (1968).

[26] N. Starfelt, *Nuclear Structure* (North-Holland Publishing Co., Amsterdam, 1966), p. 160.

[27] G. A. Bartholomew, E. D. Earle, A. J. Ferguson, and I. Berqvist, Phys. Letters **24B**, 47 (1967).

[28] G. A. Bartholomew, Bull. Am. Phys. Soc. **13**, 1461 (1968).

[29] N. Azziz and A. Covello, Nucl. Phys. **A123**, 681 (1969).