Levels of $^{203,\,205}$Tl from the $(n, n'\gamma)$ reaction*

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The energy levels of ^{203}Tl and ^{205}Tl have been studied using the $(n, n'\gamma)$ reaction with enriched isotopes. Deexcitation γ rays were observed in a time-of-flight gated Ge(Li) detector at several neutron energies. Level schemes for ^{203}Tl and ^{205}Tl have been proposed. A substantial discrepancy between the experimental cross sections and those calculated from the compound nuclear statistical theory has been found. The magnitudes of the predicted cross sections are roughly a factor of 2 high, whereas previous results for other nuclei indicate much better agreement.

[NUCLEAR REACTIONS ^{203,205}Tl$(n, n'\gamma)$, $E = 1.1-3.2$ MeV; measured E_γ, $\sigma(E_n; E_\gamma)$; ^{203,205}Tl levels deduced, γ branching. Enriched targets; Ge(Li) detector.]

I. INTRODUCTION

The odd mass thallium nuclei exhibit energy levels which, in theoretical investigations of ^{203}Tl isotopes, have been attributed to a single-hole state coupled to a closed shell ($Z = 82$) core. The previous experimental information on ^{203}Tl was obtained from the ^{204}Pb(t, α) (Ref. 1), ^{204}Pb$(d, {}^3$He) (Ref. 2), ^{203}Tl$(\alpha, \alpha'\gamma)$ (Ref. 3), ^{203}Tl(d, d') (Ref. 4), ^{203}Tl(γ, γ') (Ref. 5), ^{203}Tl(n, n') (Ref. 6), and ^{203}Tl-$(n, n'\gamma)$ (Refs. 7 and 8) reactions and from the β

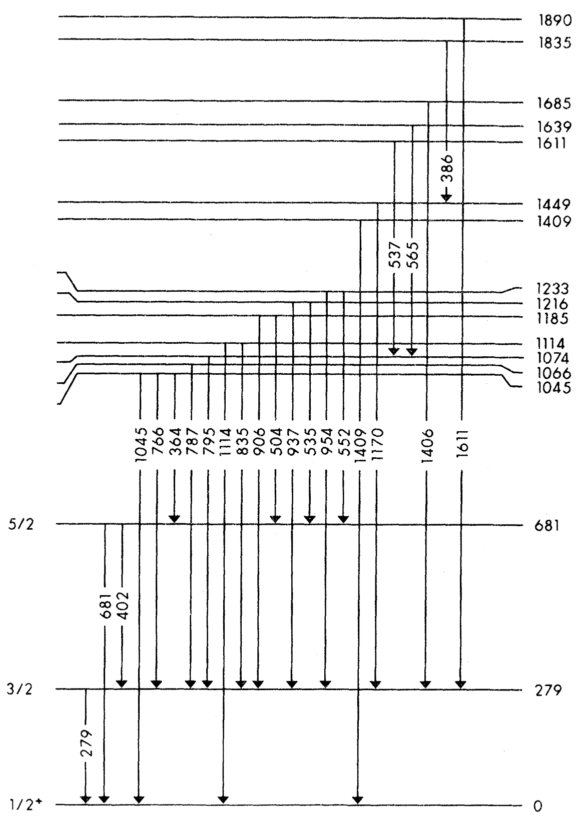

FIG. 1. The energy levels of ^{203}Tl as derived from the present studies. The J^π's are from the previous accumulated results. The energies are given in keV.

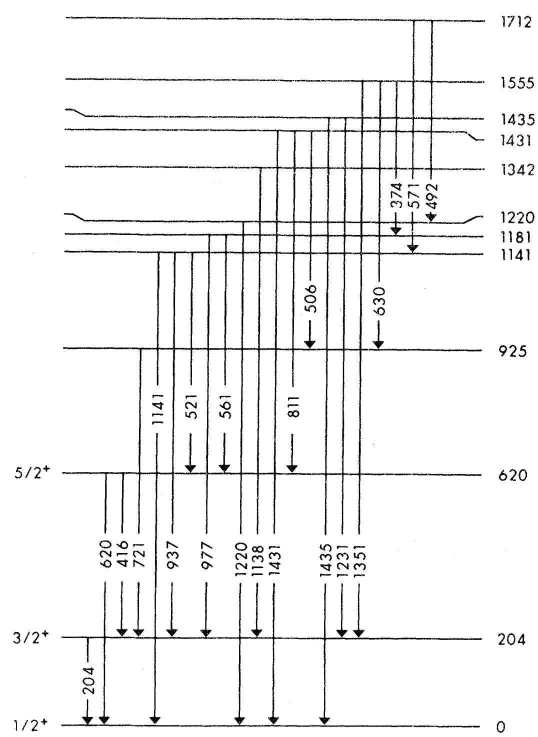

FIG. 2. The energy levels of ^{205}Tl as derived from the present studies. The J^π's are from the previous accumulated results. The energies are given in keV.

TABLE I. Excitation energies and branching ratios of the levels in ^{203}Tl.

Initial state (keV)	Final state (keV)	E_γ (keV)	Branching ratios (%)
279 ± 1	g.s.	279	100
681 ± 1	g.s.	681	16 ± 1
	279	402	84 ± 1
1045 ± 1	g.s.	1045	35 ± 2
	279	766	37 ± 2
	681	364	26 ± 2
1066 ± 1	279	787	100
1074 ± 1	279	795	100
1114 ± 1	g.s.	1114	32 ± 4
	279	835	68 ± 4
1185 ± 1	279	906	82 ± 2
	681	504	18 ± 2
1216 ± 1	279	937	74 ± 2
	681	535	26 ± 2
1233 ± 1	279	954	74 ± 2
	681	552	27 ± 2
1409 ± 1	g.s.	1409	100
1449 ± 1	279	1170	100
1611 ± 1	1074	537	100
1639 ± 1	1074	565	100
1685 ± 1	279	1406	100
1835 ± 1	1449	386	100
1890 ± 1	279	1611	100

TABLE II. Excitation energies and branching ratios of the levels in ^{205}Tl.

Initial state (keV)	Final state (keV)	E_γ (keV)	Branching ratios (%)
204 ± 1	g.s.	204	100
620 ± 1	g.s.	620	6 ± 1
	204	416	94 ± 1
925 ± 1	204	721	100
1141 ± 1	g.s.	1141	19 ± 2
	204	937	58 ± 3
	620	521	24 ± 2
1181 ± 1	204	977	60 ± 2
	620	561	40 ± 2
1220 ± 1	g.s.	1220	100
1342 ± 1	204	1138	100
1431 ± 1	g.s.	1431	17 ± 2
	820	811	16 ± 2
	925	506	66 ± 2
1435 ± 1	g.s.	1435	37 ± 3
	204	1231	63 ± 3
1555 ± 1	204	1351	29 ± 3
	925	630	42 ± 4
	1181	374	28 ± 3
1712 ± 1	1141	571	28 ± 6
	1220	492	72 ± 6

decay of ^{203}Hg (Ref. 4); while for ^{205}Tl the information came from the ^{205}Tl($p, p'\gamma$) (Refs. 9 and 10), ^{205}Tl(γ, γ') Refs. 11 and 12), ^{205}Tl(p, p') (Refs. 13 and 14), ^{206}Pb(t, α) (Ref. 1), ^{205}Tl($\alpha, \alpha'\gamma$) (Ref. 3), ^{205}Tl(n, n') (Ref. 6), ^{205}Tl($n, n'\gamma$) (Refs. 7 and 8), ^{208}Pb(p, α) (Ref. 14), and from the β decay of ^{205}Hg (Ref. 14).

The results of these studies are at variance with each other except for a few of the levels below 1.0 MeV. The previous ($n, n'\gamma$) studies of Bernard *et al.*[7] and Feicht and Göbel[8] were carried out with natural thallium isotopes and their decay schemes are different from each other. The spin and parity assignments for most of the levels are either not well known, or are in disagreement. Because of these discrepancies, it was decided to study the level structures of ^{203}Tl and ^{205}Tl from the ($n, n'\gamma$) reaction with enriched isotopes using the close geometry small scattering sample technique developed earlier.[15] This technique was found useful for the study of ($n,n'\gamma$) reactions (Refs. 16–19) where natural abundance of the element of interest is small. In this paper we are presenting the excitation energies, decay modes, branching ratio of γ rays, and neutron inelastic cross sections for levels in both ^{203}Tl and ^{205}Tl nuclei that resulted from the ($n, n'\gamma$) reaction studies.

II. EXPERIMENT AND DATA ANALYSIS

The present study of ^{203}Tl and ^{205}Tl isotopes was carried out using the close neutron source-to-scatterer geometry. In this work the neutrons were produced by the ^{3}H(p, n)^{3}He reaction. The tritium target consisted of tritium embedded in metallic erbium that had been deposited on a tantalum backing. The ^{3}H(p, n) absolute neutron flux was determined from the differential cross sections for this reaction as measured by Perry *et al.*[20]

The energy of the 0.5 ns pulsed proton beam from the 6MV van de Graaff accelerator of the University of Alberta was varied from 2.25 to 4.0 MeV, resulting in neutrons of maximum energies from 1.45 to 3.2 MeV, respectively.

The samples consisted of 5.06 g of thallium oxide enriched to 95.0% ^{203}Tl and 3.25 g enriched to 97.8% ^{205}Tl, compressed into disks (0.476 cm high, 1.584 cm diam) inside a nylon ring. The sample was placed in direct contact with the tantallum backing of the tritium target.

A 52 cm^{3}Ge(Li) detector was placed at 90° with respect to the direction of the proton beam and at a distance of 61.0 cm from the scattering sample. The detector was enclosed in a lead sleeve 5 cm thick. The energy resolution of the detector was 2.8 keV for 1.332 MeV γ rays.

A large number of γ-ray spectra were obtained for incident neutron energies between 2.25 and 3.2 MeV. At each energy background γ-ray spectra were taken with an empty nylon ring of the same dimensions as the one enclosing the scattering sample.

An on-line data collection system was used to accumulate the γ-ray spectra, and necessary corrections to the data for detector efficiency and γ-ray attenuation in the scattering sample were made while analyzing the data as described previously.[15-19]

The optical and statistical model calculations were done in the same manner as in previous work of the present authors.[15-19]

A spherical local potential

$$U(r) = -Vf(r, r_{0r}, a_r) + 4ia_i W \frac{d}{dr}[f(r, r_{0i}, a_i)] + \left(\frac{\hbar}{m_\pi c}\right)^2 V_s \frac{1}{r}\frac{d}{dr}[f(r, r_{0s}, a_s)]\vec{L}\cdot\vec{\sigma}$$

was employed to calculate optical model transmission coefficients, where V, W, V_s, r_0, a_i, and m_π are the depths of the real, imaginary, and

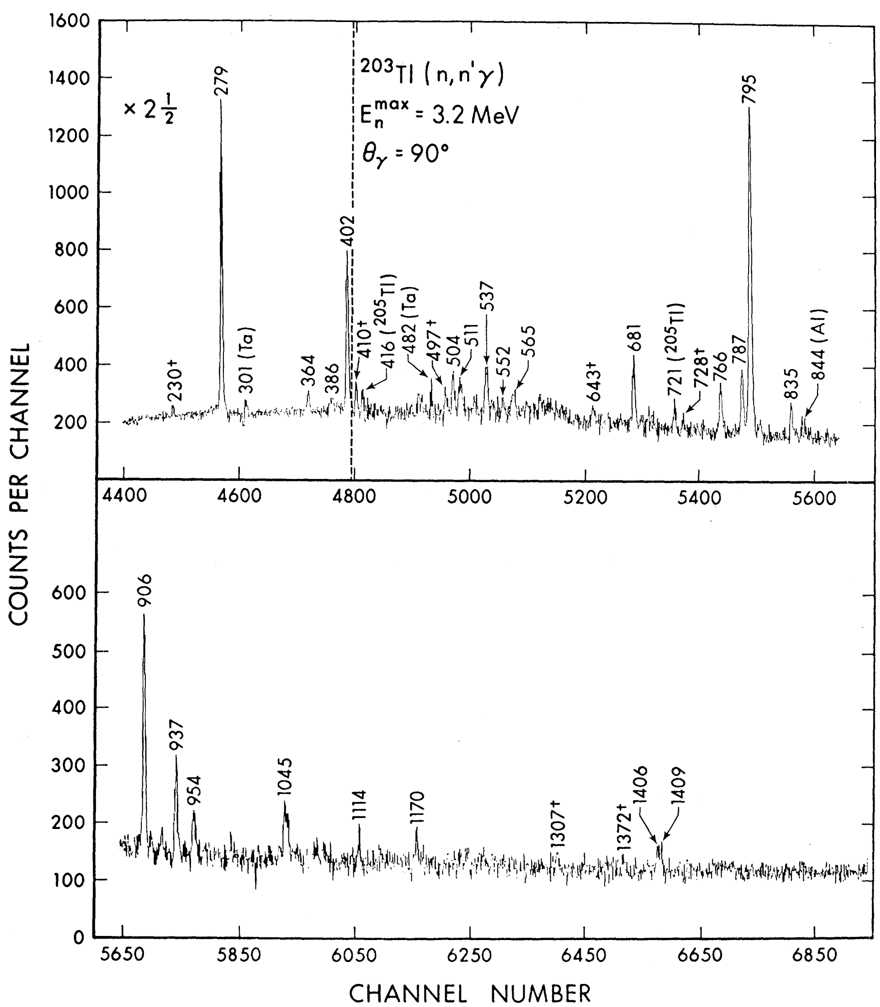

FIG. 3. A part of the time-gated Ge(Li) γ-ray scatterer-in–scatterer-out spectrum for ^{203}Tl taken at $E_n^{max} = 3.2$ MeV. The symbol † denotes unassigned γ rays observed only at this energy.

spin-orbit potentials, the radius and diffuseness parameters, and the pion mass, respectively.

In this potential

$$f(r, r_0, a) = \{1 + \exp[(r - r_0 A^{1/3})/a]\}^{-1} .$$

Calculations were made using the potential parameter values of both Rosen *et al.*[21] and Moldauer.[22] The values of these parameters were from Rosen:

$V = 49 - 0.33E_n$ MeV, $r_{0_r} = 1.25$ fm, $a_r = 0.65$ fm,

$W = 5.75$ MeV, $r_{0_i} = 1.25$ fm, $a_i = 0.70$ fm,

$V_s = 5.50$ MeV, $r_{0_s} = 1.25$ fm, $a_s = 0.65$ fm,

from Moldauer:

$V = 46.0$ MeV, $r_{0_r} = 1.25$ fm, $a_r = 0.62$ fm,

$W = 14.0$ MeV, $r_{0_i} = 1.38$ fm, $a_i = 0.24$ fm,

$V_s = 7.0$ MeV, $r_{0_s} = 1.25$ fm, $a_s = 0.65$ fm.

The transmission coefficients obtained from these potentials were used with the code NEARREX[23] to calculate inelastic cross sections corrected for the effects of width fluctuations and the radiative capture channel.

III. RESULTS AND DISCUSSION

The energy levels of ^{203}Tl and ^{205}Tl nuclei and their decay modes are shown in Figs. 1 and 2. They are derived from accurate measurement of γ-ray energies, determination of their thresholds, and from a knowledge of the level energies known from earlier studies. The γ-ray energies are the average values from all the spectra measured and the estimated uncertainties in the γ-ray energies are less than 1 keV.

The branching ratios, as measured at 90°, are presented as a percentage of total decays and have not been corrected for internal conversion and angular correlation effects, which should be small. Tables I and II list, respectively, the excitation energies, decay modes, and branching ratios of

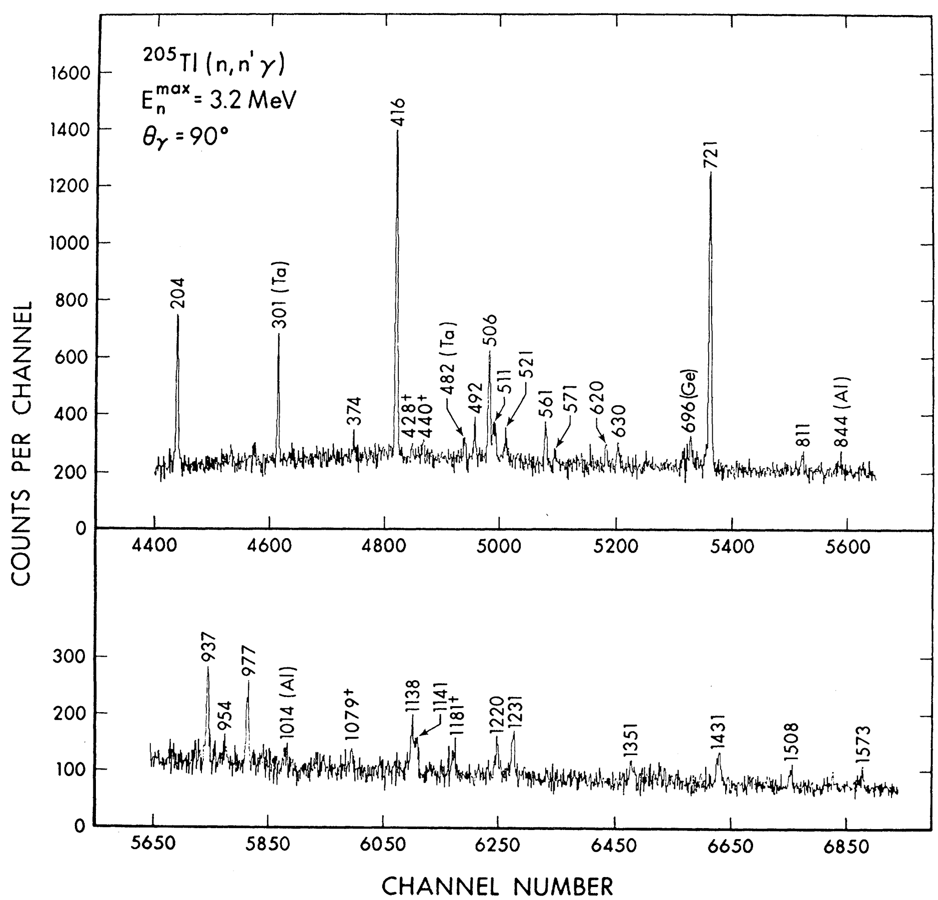

FIG. 4. A part of the time-gated Ge(Li) γ-ray scatterer-in–scatterer-out spectrum for ^{205}Tl taken at $E_n^{max} = 3.2$ MeV. The symbol † denotes unassigned γ rays observed only at this energy.

γ rays for ^{203}Tl and ^{205}Tl as observed in this work.

Figures 3 and 4 show the "scatterer-in–scatterer-out" spectra for ^{203}Tl$(n, n'\gamma)$ and ^{205}Tl$(n, n'\gamma)$ reactions, respectively. Some γ rays (marked †) observed only at $E_n^{max} = 3.2$ MeV were not included in the decay scheme as their origin could not be ascertained.

The experimental cross sections determined in this work are presented in Fig. 5 to Fig. 9 for ^{203}Tl and in Fig. 10 to Fig. 12 for ^{205}Tl. Also presented in these figures are the data points due to Feicht and Göbel[8] and to de Villiers *et al.*[6] It

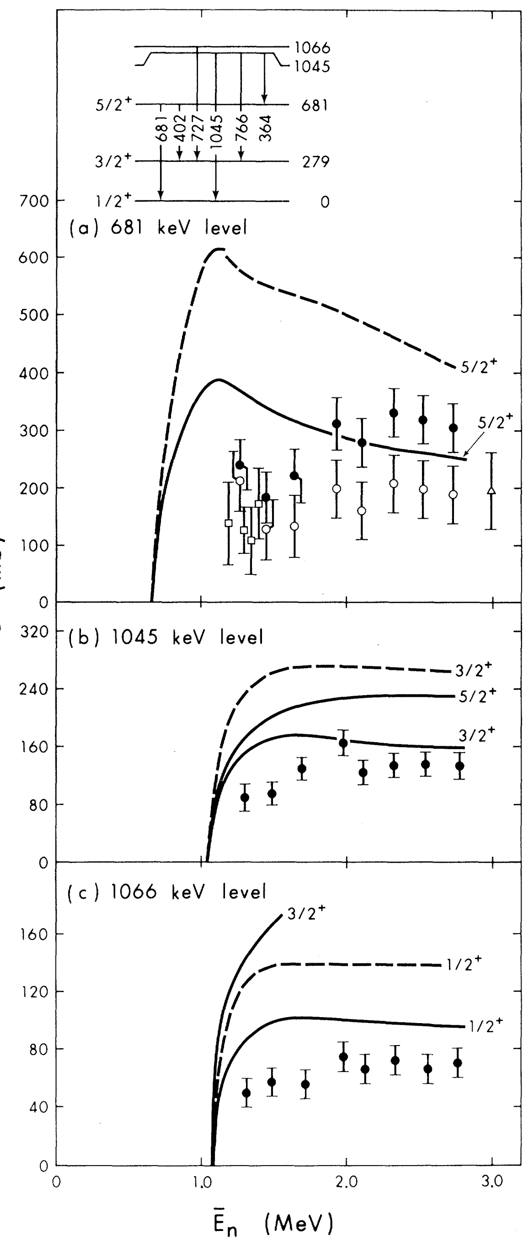

FIG. 5. Excitation curves for (a) 681, (b) 1045, and (c) 1066 keV levels. The contribution from the higher levels to these is indicated by the difference between the open and closed circles. The solid (dashed) curves represent the calculated cross sections with the predictions of the compound nuclear statistical theory using the parameter values of Ref. 22 (Ref. 21). The data points plotted with a (△) are from Ref. 8; those with a (□) are from Ref. 6.

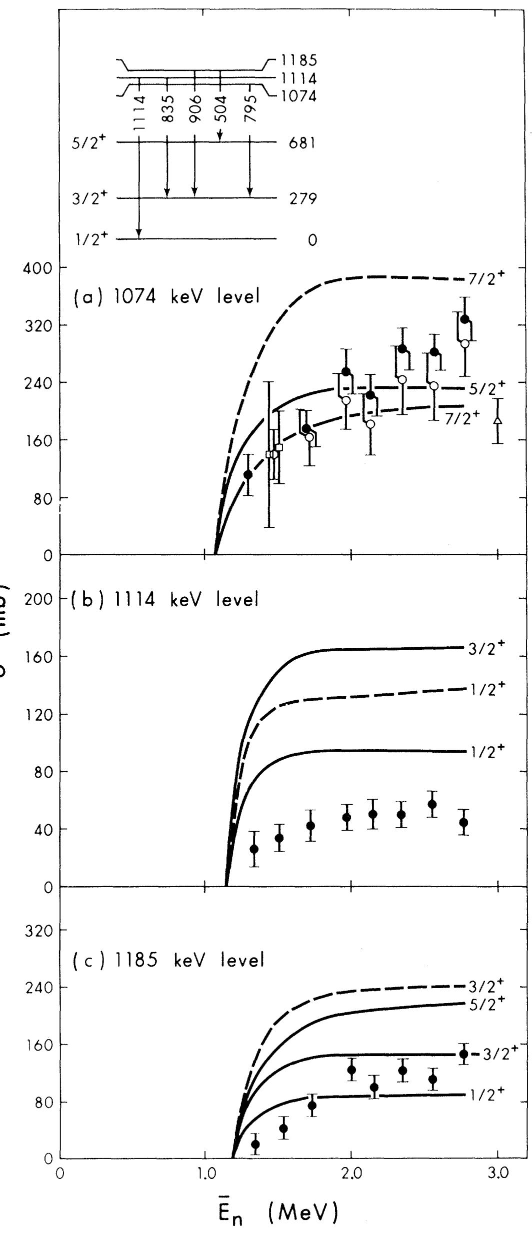

FIG. 6. Excitation curves for (a) 1074, (b) 1114, and (c) 1185 keV levels. The closed circles indicate the experimental cross sections. The open circles are the experimental cross sections after subtracting the feedings from the higher levels. The solid (dashed) curves are the cross sections calculated as in Fig. 5.

may be noted that the measured inelastic cross sections from the present work are in excellent agreement with the previous results.[6,8] The solid curves in these diagrams were calculated using the Moldauer[22] values for the optical model parameters, while the dashed curves are the results obtained using the values of Rosen *et al.*[21] It is seen

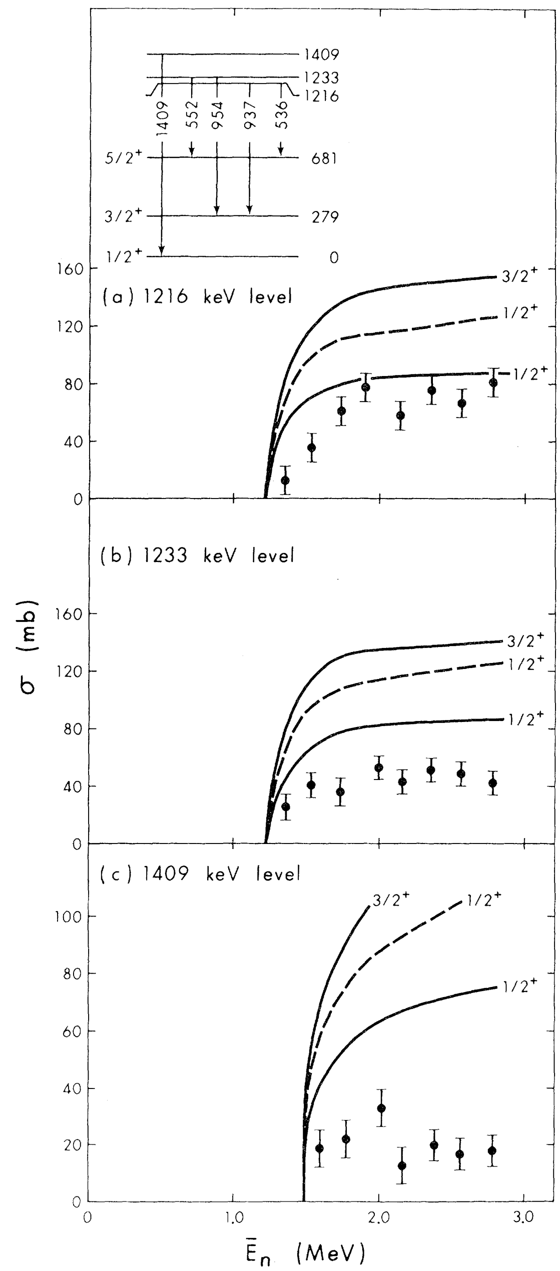

FIG. 7. Excitation curves for (a) 1216, (b) 1233, and (c) 1409 keV levels. Solid curves indicate the experimental cross sections. The solid (dashed) curves show the cross sections calculated as in Fig. 5.

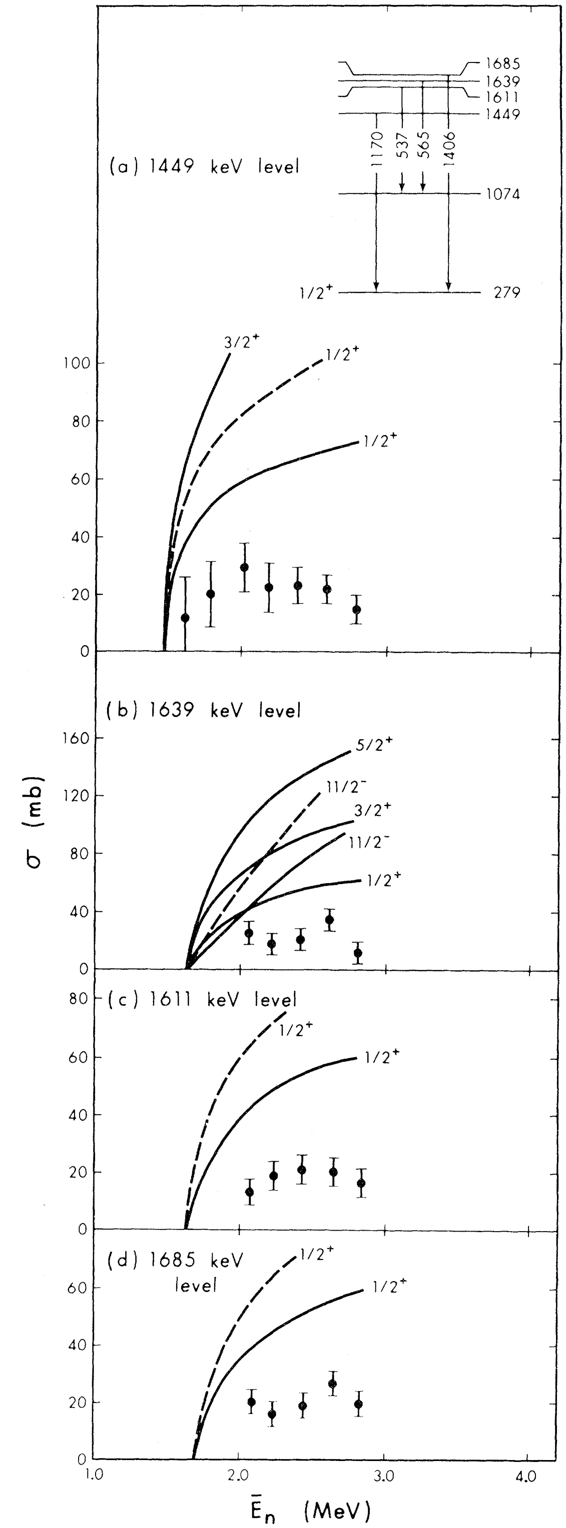

FIG. 8. Excitation function for (a) 1449, (b) 1639, (c) 1611, and (d) 1685 keV levels. The closed circles are measured cross sections. The solid (dashed) curves are calculated as were those in Fig. 5.

from these figures that neither set of parameter values produces cross sections in agreement with the experimental functions. An attempt was also made using the optical model parameters of Moldauer as altered by de Villiers *et al.*,[6] who found better fits to their differential elastic scattering cross sections for Tl by lowering the imaginary part of the potential from 14 to 7 MeV. Such a change in the potential was not made by Villiers *et al.*[6] for their Au differential cross section results. However, we found that the calculated cross sections with this changed potential were very similar to those for the Rosen parameters.

The cross sections calculated from Moldauer potential parameters have been found to be closer to the present experimental values. A number of levels, however, have experimental cross sections substantially lower than any of the theoretically calculated values so that agreement cannot be assumed. A thorough search was made for γ rays that might account for this missing strength but none were found. A small fraction of the transitions may be accounted for by internal conversion

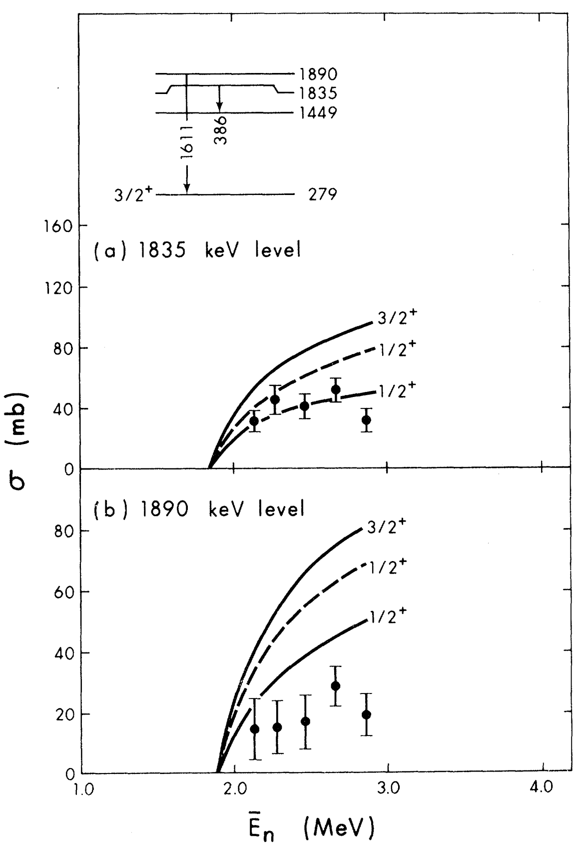

FIG. 9. Excitation curves for (a) 1835 and (b) 1890 keV levels. The closed circles are experimental cross sections. The solid (dashed) curves are the cross sections obtained as in Fig. 5.

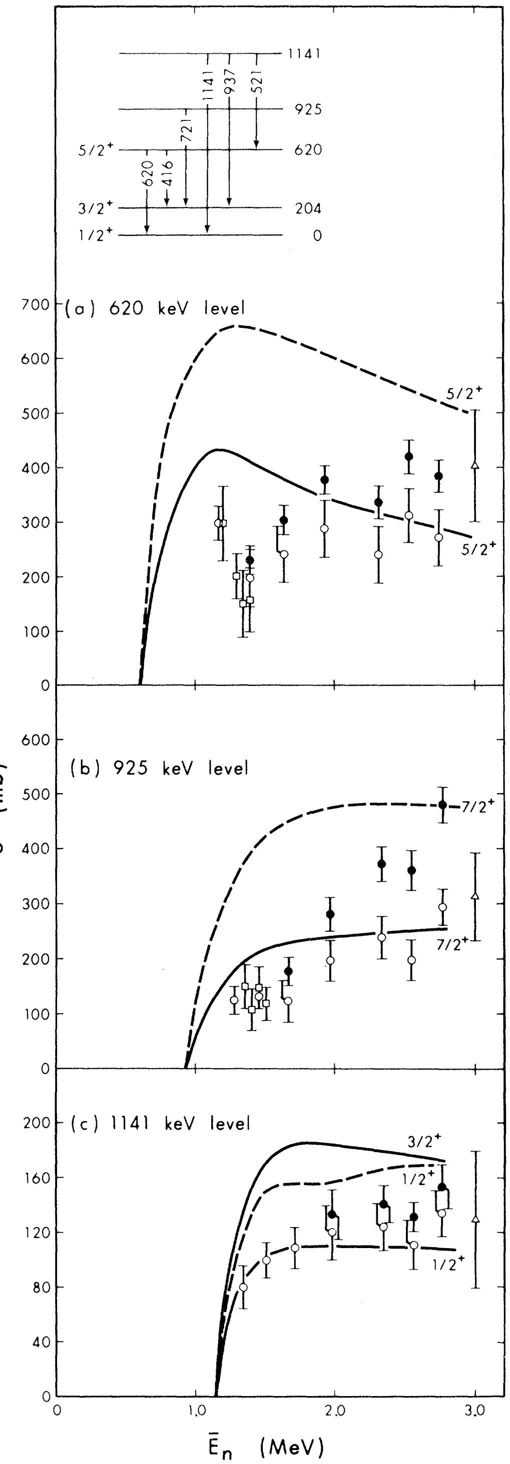

FIG. 10. Excitation curve for (a) 620, (b) 935, and (c) 1141 keV levels. The contributions due to deexcitation of the higher levels to these are indicated by the difference between the open and closed circles. The solid (dashed) curves were calculated as in Fig. 5. The data points plotted with a (△) are from Ref. 8 and those with (□) are from Ref. 6.

not observed in this work, however, this is unlikely to be larger than a few percent. Figures 13 and 14 show the energy levels of ^{203}Tl and ^{205}Tl as deduced from the present study compared with schemes from other sources and from theoretical predictions.

The errors in the branching ratios and the cross sections presented (Tables I and II, Figs. 5 to 12) are statistical only. Systematic errors in the

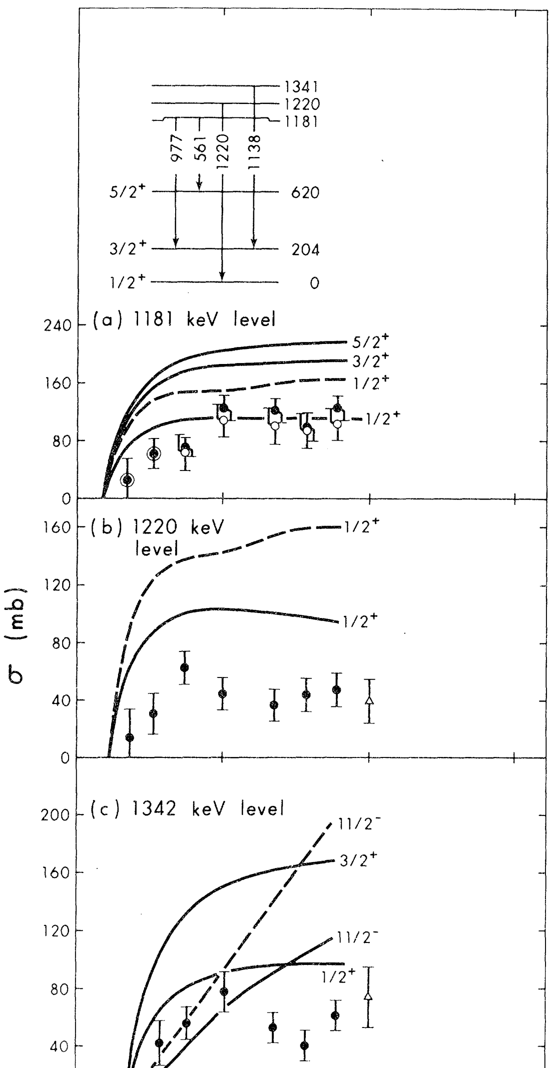

FIG. 11. Excitation curve for (a) 1181, (b) 1220, and (c) 1342 keV levels. The closed circles are the experimental cross sections and the open circles are those after subtracting the feedings from the higher levels. The solid (dashed) curves represent the calculated cross sections as in Fig. 5.

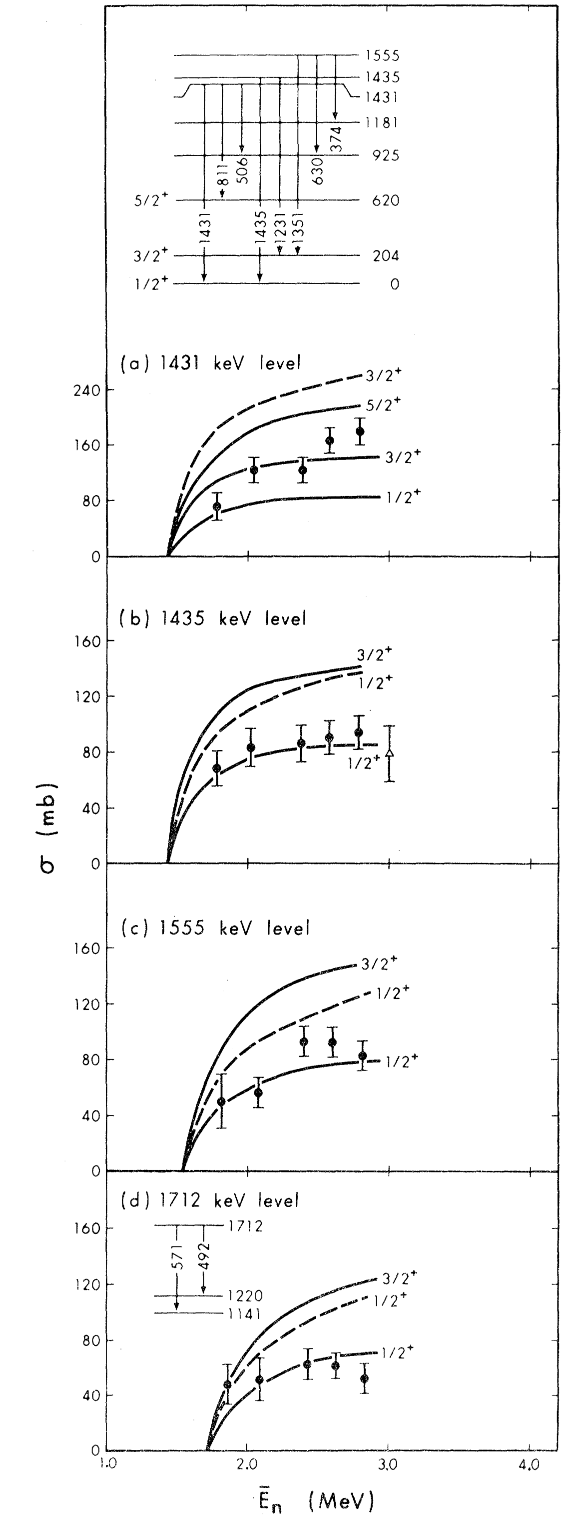

FIG. 12. Excitation curve for (a) 1431, (b) 1435, (c) 1555, an d (d) 1712 keV levels. The solid circles indicate the experimental cross sections and the solid (dashed) curves are from the calculated cross sections as in Fig. 5.

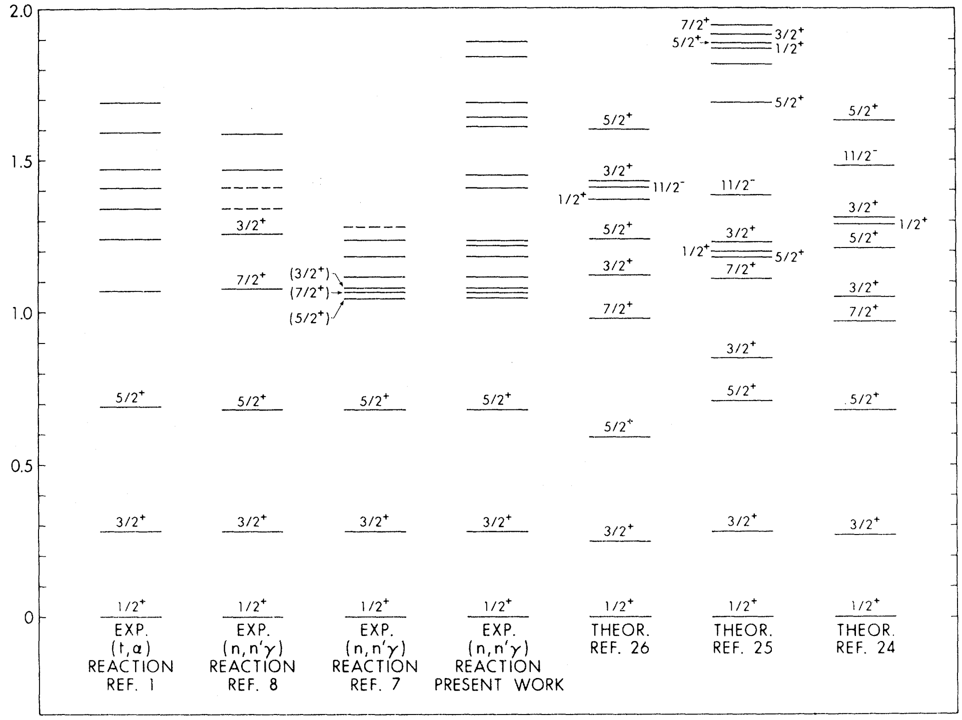

FIG. 13. Energy levels of ^{203}Tl as deduced from the present measurements and compared with the level schemes from other sources and with theoretical predictions.

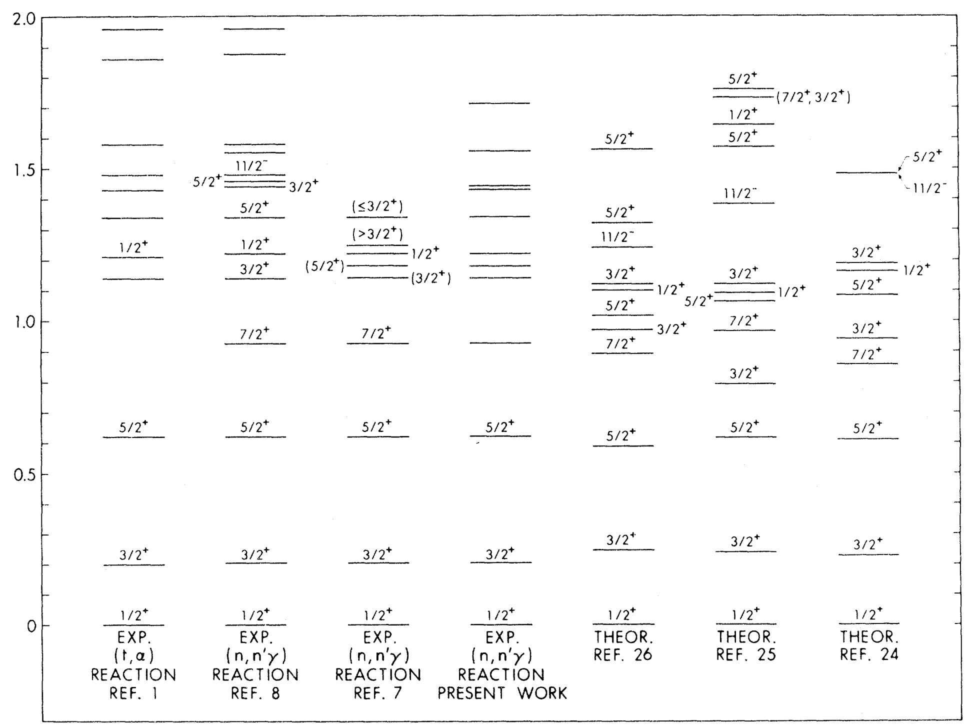

FIG. 14. Energy levels of ^{205}Tl as deduced from the present measurements and compared with the level schemes from other sources and with theoretical predictions.

branching ratios are ≤10% and for the cross sections ≤15%. These estimates have been made as in previous studies.[15-19]

It should be noted that we do not observe certain γ-ray transitions from the 1074, 1185, and 1233 keV levels in ^{203}Tl and the 1181 keV level in ^{205}Tl which were previously reported by Barnard *et al.*[7] We estimate the branching ratios for the unobserved transitions to be less than 10% and believe that the discrepancy is due to the fact that natural targets were used in the earlier work.

IV. CONCLUSION

The present study of ^{203}Tl and ^{205}Tl nuclei has revealed many of the deexcitation γ rays from the previously reported energy levels. In addition, several new levels are proposed, in particular at 1216, 1611, 1639, 1685, 1835, and 1890 keV in ^{203}Tl and at 1712 keV for ^{205}Tl. No definitive spin and parity assignments are made, however, due to the inability of the compound nuclear statistical theory to reproduce the experimental excitation function. The magnitude of this discrepancy must be noted for the results using the Rosen parameters, particularly in the light of how successful this approach has been in previous studies of ^{114,116}Cd, ^{160}Gd, and ^{154}Sm isotopes.[16-19] It should be emphasized that the experimental method and the data analysis techniques used here were identical to those employed in the earlier work. In fact all of the data for ^{203}Tl and ^{205}Tl isotopes were obtained during the same running period as the ^{114}Cd and ^{116}Cd data[17,18] and other indications that the experimental results are valid is the agreement with the previous (n,n') (Ref. 6) and $(n,n'\gamma)$ (Ref. 8) data. For these reasons, it seems unlikely that an experimental error is responsible for the discrepancy between our results and the statistical model predictions.

It is worth noting that we are dealing with odd mass nuclei in the present case, whereas the previous studies were for even-even nuclei. Also ^{203,205}Tl lie very close to the closed shell at ^{208}Pb. The discrepancies between theory and experiments in this case may in some way be due to these facts.

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