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3291-keV $J^{\pi}=\frac{25}{2}^{+}$ level in ^{205}Tl

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A $J^{\pi}=\frac{25}{2}^{+}$ isomer in ^{205}Tl has been observed using techniques of in-beam γ-ray spectroscopy and the ^{204}Hg(t,2n)^{205}Tl reaction. The decay scheme firmly establishes the yrast levels: [J^{π},E_x (keV)] $\frac{11}{2}^{-}$, 1484.02; $\frac{15}{2}^{-}$, 2054.57; $\frac{17}{2}^{-}$, 2394.18; $\frac{19}{2}^{-}$, 2551.56; and $\frac{25}{2}^{+}$, 3290.7. A candidate for a 12^{-} state in ^{204}Tl with the configuration ($\pi h_{11/2}{}^{-1}$, $\nu i_{13/2}{}^{-1}$) is identified.

I. INTRODUCTION

The orbital gyromagnetic ratio g_l of the $1h$ proton orbital has been reported[1] as $g_l=1.115\pm0.02$. This value resulted from the appropriate combination of the gyromagnetic ratios of the spin-orbit partners $g(h_{9/2})$ and $g(h_{11/2})$, and so it is relatively free of contributions due to both core polarization and spin magnetism. The value of $g(h_{11/2})$ was deduced from the magnetic moment of the 3291-keV level in ^{205}Tl; this newly reported state has spin-parity $J^{\pi}=\frac{25}{2}^{+}$ and major configuration ($\pi h_{11/2}{}^{-1}$, $\nu i_{13/2}{}^{-1}p_{1/2}{}^{-1}$). The measurement of the magnetic moment, and the deduction of $g(\pi h_{11/2})$ and $g_l(1h)$, has been described in Ref. 1; here we present the evidence for the $J^{\pi}=\frac{25}{2}^{+}$ assignment and describe the γ decay of the 3291-keV level.

As a result of investigations using the reactions (n,γ), (n,n$'\gamma$), (t,α), and (p,p$'$) to populate levels in ^{205}Tl, a good deal of information on levels in ^{205}Tl and on electromagnetic transitions between them is known. Experimental work on ^{205}Tl completed prior to 1978 is summarized by Schmorak.[2] Subsequent material particularly relevant for the work described here are the following: (1) the work of the Stockholm group[3] who initially reported the existence of an isomeric level in ^{205}Tl with excitation energy $E_x\sim3$ MeV and a lifetime in the μsec range, and (2) the work of Smith, *et al.*[4] who reported evidence for high spin states in ^{205}Tl, deduced from a measurement of the double differential cross section of the ^{208}Pb(p,α)^{205}Tl reaction done at $E_{\rm p}=35$ MeV. Among the new levels they reported, four were given $(\frac{15}{2},\frac{17}{2})^{+}$ assignments and one was assigned $(\frac{19}{2},\frac{21}{2})^{+}$ on the basis of distorted-wave Born approximation calculations of the angular distributions.

The measurements reported here were performed at the Los Alamos National Laboratory. Conventional techniques of γ-ray spectroscopy were employed to study the γ radiation produced in the ^{204}Hg(t,2n)^{205}Tl reaction. The pulsed beam technique was used to verify the isomeric level in ^{205}Tl, followed by the measurement of the isomer nuclear g factor using the time differential perturbed angular distribution technique. A decay scheme for the isomer, including spin-parity assignments, was constructed. Since the work reported in Ref. 1, we have completed γ-γ time coincidence measurements and have pursued the analyses. Finer details of the isomer decay scheme have been obtained, and we report them here for completeness. The experimental arrangement and results are presented in Sec. II, and the conclusions we draw from these results are presented in Sec. III.

II. EXPERIMENT AND RESULTS

States in ^{205}Tl were populated with the ^{204}Hg(t,2n)^{205}Tl reaction. A target of liquid ^{204}Hg ($\geq98.2\%$ ^{204}Hg) was bombarded with tritons accelerated by the Los Alamos National Laboratory tandem Van de Graaff generator. The target was thick enough to stop the beam at all the incident triton energies used, $10.8\leq E_{\rm t}$ (MeV) ≤16.5. Beam currents generally were ~1 nA. The resulting radiation was detected in Ge solid state detectors. After electronic filtering, signals were sorted and stored using an on-line computer-based data acquisition system.[5]

Several measurements were made to establish the excitation energy, decay, and J^{π} of the isomeric level. The pulsed beam technique was used to search for the isomeric level reported previously.[3] The incident 14.2-MeV beam was bunched into pulses ~1 nsec in duration, 12.8 μsec apart. For each detected γ-ray event, both its pulse height and time relative to the beam burst were stored. Gamma-ray pulse-height distributions were constructed from these data, according to (relative) event time. The event time was parametrized in five intervals, the first corresponding to beam on target, and four contiguous sequential intervals of ~1.55 μsec each. Several γ rays were observed to decay with a mean life $\tau \sim 3$–4 μsec and for these the ratio R of the yield in the prompt time interval to the yield in the first delayed time interval was formed. The γ rays associated with the isomer (listed according to increasing R) together with R are listed in the first two columns of Table I. On the basis of evidence to be described below, the 54.4- and 496.9-keV γ rays are placed appropriately in Table I, although R values are not reported for them. The low value of R identifies the 739-keV γ ray as the isomeric transition. The γ-ray energies listed in Table I were obtained using the mixed source technique; the quoted results are compiled from all the measurements we describe. A delayed γ-ray spectrum obtained during the time differential perturbed angular distribution measurements is shown in Fig. 1.

The results of γ-γ time coincidence measurements were used to confirm that the γ rays listed in Table I are the predominant decay transitions of the isomer. The measurements were done at $E_t=16$ MeV. Two Ge detectors were used to detect γ radiations. They were located at $\theta_\gamma=\pm 90°$ with respect to the incident beam direction and ~3 cm from the target center. As an example of the results, Fig. 2 illustrates the spectrum in coincidence with the 339-keV γ ray. The predominant decay γ rays of the isomer, except for the 496.9-keV γ ray, are present in this spectrum. Gamma-ray energies are included in Table I. Minor branches between low-lying states will be discussed in a forthcoming publication.[6]

The magnetic moment of the isomeric level was measured at $E_t=16$ MeV using the time differential perturbed angular correlation technique. The experimental arrangement and typical data obtained are described in Ref. 1. Data for the 497-keV γ ray were not extracted because of its low intensity. Least-squares techniques were used to fit the time distribution of γ-ray yields (cf. Fig. 1 in Ref. 1) to the expression

TABLE I. Summary of experimental data on the decay of the 3291-keV isomer in ^{205}Tl.

E_γ[a] (keV)	R[b]	I_γ[c]	$I_\gamma \times (1+\alpha_t)$[d]	E_x[a] (keV)	A_2[e] experiment; calculation	A_4[e] experiment; calculation	J_i^π	J_f^π	ML;δ[f]
739.16(10)	0.7(1)	100	100	3290.72(20)	+0.50(1)	+0.05(1); +0.03(1)	$\frac{25}{2}^{+}$	$\frac{19}{2}^{-}$	$E3$
157.38(10)	8(2)	24	82	2551.56(16)	−0.25(1)	−0.01(1); 0.00	$\frac{19}{2}^{-}$	$\frac{17}{2}^{-}$	$M1/E2$; −0.03(1)
496.94(10)		13	13	2551.56(16)			$\frac{19}{2}^{-}$	$\frac{15}{2}^{-}$	
339.61(5)	15(1)	53	66	2394.18(13)	−0.36(1)	+0.01(1); 0.00	$\frac{17}{2}^{-}$	$\frac{15}{2}^{-}$	$M1/E2$; −0.12(2)
570.55(10)	56(5)	100	99	2054.57(12)	+0.29(1); +0.28(1)	−0.06(1); −0.07(1)	$\frac{15}{2}^{-}$	$\frac{11}{2}^{-}$	$E2$
54.38(3)				1484.02(7)	−0.20(1); −0.19(1)	−0.01(1); 0.00	$\frac{11}{2}^{-}$	$\frac{9}{2}^{+}$	$E1$
505.75	110(10)	62	80	1429.64(6)	−0.32(1)	−0.01(1); 0.00	$\frac{9}{2}^{+}$	$\frac{7}{2}^{+}$	$M1/E2$; −0.10(2)
720.09(5)	227(35)	83	100	923.89(6)	+0.28(1); +0.28(1)	−0.05(1); −0.07(1)	$\frac{7}{2}^{+}$	$\frac{3}{2}^{+}$	$E2$
203.67(5)	217(10)	80	115	203.75(4)	+0.34(1)	0.00(1); 0.00	$\frac{3}{2}^{+}$	$\frac{1}{2}^{+}$	$M1/E2$; $1<\delta<3$

[a]Including data from Ref. 6.
[b]R is defined in the text.
[c]Measured delayed γ intensities (±10%) normalized to I(739 keV)=100 from the g factor measurement.
[d]Total delayed transition intensities (±20%) including electron conversion and corrected for known parallel branches (Ref. 6). Conversion coefficients are from Ref. 12 except for $\alpha_t(203)=0.44$ (Ref. 13).
[e]See the text, Eq. (1).
[f]Gamma-ray multipolarity (ML) and mixing ratio (δ).

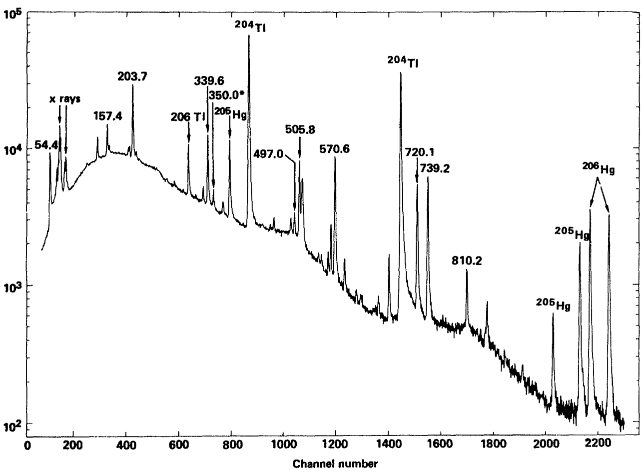

FIG. 1. Delayed γ-ray energy spectrum measured in the time interval $2.56<\tau$ (μsec) <5.13 following the bombardment of ^{204}Hg with 16-MeV tritons. Decays of the ^{205}Tl isomer are marked by their energies (in keV); other decays that have been identified are labeled by the decaying nuclide. The energies of these are ^{206}Tl, 304.75(10); ^{205}Hg, 379.40(5); ^{204}Tl, 413.82(10); ^{204}Tl, 690.01(10); ^{205}Hg, 966.57(10); ^{205}Hg, 1015.46(15); ^{206}Hg, 1034.01(10); and ^{206}Hg, 1068.54(10). The 350-keV transition marked with an asterisk may belong to the decay of a 12^- isomer in ^{204}Tl.

$$N(t)=A_0e^{-\lambda t}[1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)]\ , \qquad (1)$$

with

$$\theta=\omega_L t+\psi+\gamma\ .$$

From this procedure we deduced the decay constant $\lambda=1/\tau$, the Larmor frequency ω_L, possible phase shifts ψ, and the angular distribution coefficients A_2 and A_4. The detector angle with respect to the beam direction ($\pm135°$) is expressed by γ. Angular distribution coefficients are summarized in Table I. Apart from the 497-keV γ ray, the γ radiations listed in Table I exhibited within experimental errors the mean lifetime 3.7 ± 0.3 μsec and the same Larmor precession frequency. The large error quoted for the lifetime is due to uncertainties in these data associated with background, dead time, and pileup effects, present since the yield of the isomer is $\sim1\%$ of the prompt 203-keV γ radiation and because high count rates were used during data collection.

Spins and parities of the levels above the known $\frac{11}{2}^-$ state at $E_x=1484$ keV will be inferred from these data. The isomeric 739-keV transition is assigned $(J\rightarrow J-3,E3)$, based upon its lifetime and angular distribution. Assuming a pure multipole transition, the alignment of the isomer can be determined from the measured coefficient A_2(739 keV). Attenuation coefficients are found to be $\alpha_2=0.71(2)$ for A_2(739 keV) and $\alpha_4=0.38(5)$ with the assumption of a Gaussian distribution of the population of the magnetic-substates.[7] The A_2 and A_4 coefficients for all members of the γ-ray cascade were then calculated; these are given in Table I. Transitions of pure multipolarity show excellent agreement between calculation and experiment in both A_2 and A_4 coefficients for the adopted spin sequence. Multipole mixing ratios, δ, for $M1/E2$ transitions have been deduced from the measured A_2 coefficients; here the values of the A_4 coefficients eliminate second solutions with $|\delta|\gg1$.

Further experimental evidence supports the spins and parities of the states involved in the cascade, namely: (1) Agreement with the $\frac{1}{2}^+$, $\frac{3}{2}^+$, $\frac{7}{2}^+$, and $\frac{11}{2}^-$ assignments, which have been established before.[2] (2) The measured g factor suggests the isomer is $\frac{25}{2}^+$ or, much less likely, $\frac{23}{2}^+$. (3) Intensity balance requires a conversion coefficient >2 for the 157-keV transition; therefore we assign it multipolarity $M1$. (4) Since the 339-keV transition has mixed multipolarity, it has multipolarity $M1/E2$ and not $E1/M2$. The decay scheme is presented in Fig. 3. In conclusion, we regard the spin-parity assignments and multipolarities as firmly established by these experiments. We have established from the coincidence measurements[6] that the isomer decays predominantly by a single cascade, and except for the 54-keV transition, the sequence of γ rays is determined by the prompt-to-delayed intensity ratios; the 54-keV line is unambiguously placed by coincidences in agreement with Ref. 3. (See also Ref. 4.) The weak $(\frac{19}{2}^-\rightarrow\frac{15}{2}^-)$ 496.9-keV crossover transition is placed on the basis of coincidence measurements, its energy sum, and its lifetime. The g-factor data for this γ ray were not evaluated because of the low γ-ray intensity. The decay scheme presented in Fig. 3 includes some weak branches between the lowest levels. These are placed by an analysis of prompt γ-γ coincidences.[6] The intensities of these weak branches and corrections for internal conversion account for the missing intensity of the main cascade.

A weak 349.97 ± 0.10-keV γ ray was also observed; it exhibits the following properties: $\tau_m=(4.1\pm1.0)$ μsec, a precession frequency corresponding to a nuclear level with a g factor $g=0.486\pm0.010$, angular distribution coefficient $A_2=0.44\pm0.02$, and relative intensity

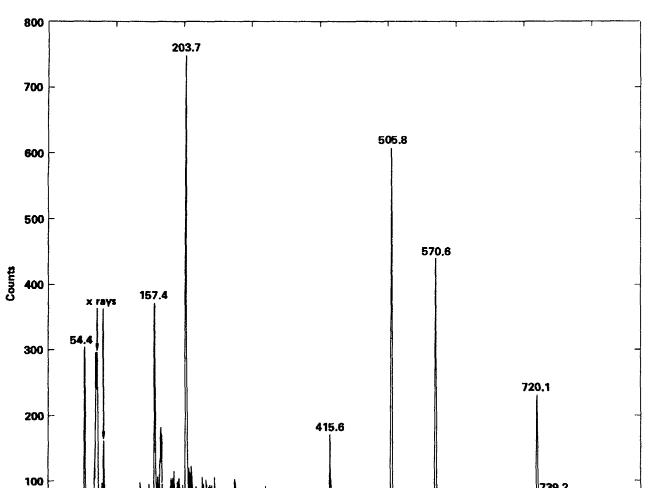

FIG. 2. Spectrum in coincidence with the 339-keV γ ray produced in the bombardment of ^{204}Hg with 16-MeV tritons.

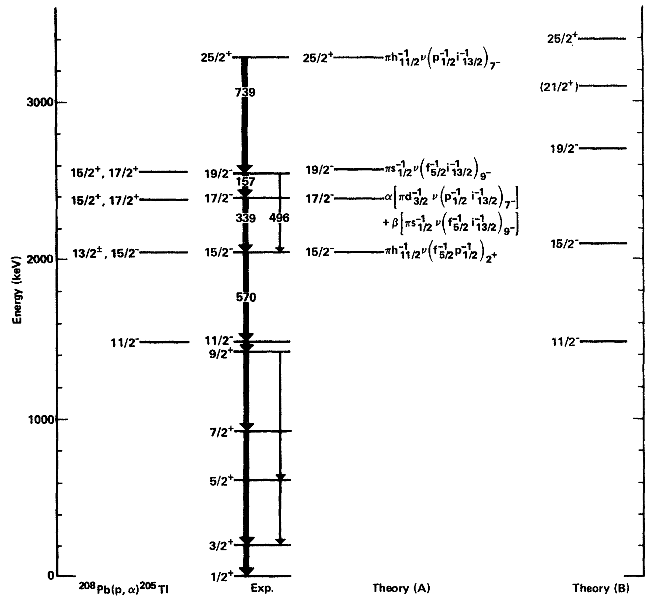

FIG. 3. Decay scheme of the $\frac{25}{2}^{+}$ isomer compared both with levels deduced in Ref. 5 and levels predicted theoretically. The columns labeled Theory (A) and Theory (B) were produced by the authors, and Silvestre-Brac and Boisson (Ref. 11), respectively. Theoretical level energies are normalized to the experimental location of the $\frac{11}{2}^{-}$ level.

$$I(350\ \text{keV})/I(339\ \text{keV})=0.12\ .$$

A list of γ rays in coincidence with this γ ray is presented in Table II. None of these γ rays fit within the known low-lying levels of either ^{204}Tl, ^{205}Tl, or ^{206}Tl. We speculate that these radiations represent the decay of a $(\pi h_{11/2}\nu i_{13/2};12^{-})$ isomer in ^{204}Tl, in analogy to the known[8] 12^{-}, $\tau_m=5.2$-min level in ^{206}Tl. [^{204}Tl is produced copiously with the ^{204}Hg$(t,3n)$ reaction; e.g., the 414- and 690-keV decay transitions of the $E_x=1104$ keV, $J^{\pi}=7^{+}$ ^{204}Tl isomer are observed in the delayed spectra.[6]] A calculation of the g factor using the values of $g(h_{11/2})$ from Ref. 1 and $g(i_{13/2})$ from Ref. 9 results in $g=0.495\pm0.013$, which agrees with the measured value. The decay would be expected to proceed via the 7^{+}, $\tau_m=92$-μsec isomer in ^{204}Tl, and thus none of the known transitions between the low-lying states in ^{204}Tl are expected to be in coincidence with the 350-keV γ ray. The lifetime of the 350-keV transition is typical of an $M2$ or $E3$ transition to a 10^{+} or 9^{+} state. The energy difference between such a 10^{+} or 9^{+} state and the proposed 12^{-} isomer in ^{204}Tl may be sufficiently large to yield the mean life observed here, relatively short compared to the mean life of the known 12^{-} isomer in ^{206}Tl. However, the energy difference between the 12^{-} and 7^{+} levels is estimated as ~ 1 MeV and thus two to four cascading transitions are expected in the isomeric decay. Therefore, it is likely that some of the transitions listed in Table II do not belong to the ^{204}Tl 12^{-} decay. An experiment in which the 350-keV γ ray is produced with greater intensity than in the present experiment is required to confirm the speculation made here, as well as to clarify the decay scheme of such an isomer.

III. DISCUSSION

Our results agree with previous work[2] on the levels below the 1484-keV $\frac{11}{2}^{-}$ state, and the $\frac{9}{2}^{+}$ and $\frac{11}{2}^{-}$ assignments are now firm. Levels of higher spin have been observed in ^{208}Pb(p,α) by Smith *et al.*[4] and are shown in Fig. 3 for comparison. Our present assignments are in agreement with the l transfers deduced in Ref. 4, except for the 2394- and 2551-keV levels where the earlier work indicated $l=8$ transfer instead of the $l=9$ transfer required by the present data.

The shell model predicts the energies of the high spin state for the configurations indicated in Fig. 3 very well. The isomeric 739-keV transition rate is 1.5 Weisskopf units (W.u.); a major contribution to the strength probably comes from the $\pi h_{11/2}{}^{-1}\rightarrow\pi d_{5/2}{}^{-1}$ transition to a component of $(\pi d_{5/2}{}^{-1}\nu p_{1/2}{}^{-1}i_{13/2}{}^{-1})$ in the $\frac{19}{2}^{-}$ level. If the strength of the $h_{11/2}\rightarrow d_{5/2}$ transition is assumed to be 30 W.u. then the 1.5 W.u. strength observed would require 5% admixture. Similar transitions are observed in ^{206}Hg (Ref. 10) and ^{206}Tl (Ref. 8), namely:

$$(\pi h_{11/2}{}^{-1}s_{1/2}{}^{-1};5^{-})\rightarrow(\pi d_{3/2}{}^{-1}s_{1/2}{}^{-1};2^{+})+\epsilon(\pi d_{5/2}{}^{-1}s_{1/2}{}^{-1};2^{+})\ ,$$

$$(\pi h_{11/2}{}^{-1}\nu p_{1/2}{}^{-1};5^{+})\rightarrow(\pi d_{3/2}{}^{-1}\nu p_{1/2}{}^{-1};2^{-})+\epsilon(\pi d_{5/2}{}^{-1}\nu p_{1/2}{}^{-1};2^{-})\ .$$

Both transitions are about 0.2 W.u. in strength and, hence, indicate considerably less mixing. The $\frac{19}{2}^{-}\rightarrow\frac{17}{2}^{-}$ transition to the second component of the $\frac{17}{2}^{-}$ level is allowed, while the $\frac{17}{2}^{-}\rightarrow\frac{15}{2}^{-}$ decay again requires some admixture, most likely $(\pi s_{1/2}{}^{-1}\nu i_{13/2}{}^{-1}p_{1/2}{}^{-1};\frac{15}{2}^{-})$. The $\frac{15}{2}^{-}\rightarrow\frac{11}{2}^{-}$ decay is analogous to the $2^{+}\rightarrow0^{+}$ transition in ^{206}Pb. We have made a shell model calculation of the energies of yrast states from $\frac{15}{2}^{-}$ to $\frac{25}{2}^{+}$ based on empirical interaction matrix elements derived from ^{206}Tl and ^{206}Pb. The proton-neutron interaction induces strong con-

TABLE II. Gamma rays in coincidence with the 350-keV transition.[a]

E_γ (keV)[b]							
153.9[c]	195.9	276.9	467.3	663.6	669.2	739.0	839.5

[a]Tl x rays are also coincident.
[b]Energy uncertainties are estimated as ±0.3 keV.
[c]Tentative.

figuration mixing and corresponding energy shifts for some of these states; for this reason the accuracy of the calculated energies is not expected to be better than about 50 keV. A calculation with the Kuo-Herling interaction has been performed by Silvestre-Brac and Boisson.[11] The resulting level energies are also shown in Fig. 3. They reproduce the $\frac{15}{2}^-$, $\frac{19}{2}^-$, and $\frac{25}{2}^+$ levels well. On the other hand, the $\frac{17}{2}^-$ state is not predicted and the parity of the spin $\frac{21}{2}$ state quoted as plus in Ref. 11 should probably be minus.

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