PHYSICAL REVIEW C **76**, 014302 (2007)

New levels and a lifetime measurement in ^{202}Tl

N. Fotiades,* R. O. Nelson, and M. Devlin
Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

J. A. Becker
Lawrence Livermore National Laboratory, Livermore, California 94550, USA
(Received 30 April 2007; published 2 July 2007)

The ^{203}Tl$(n, 2n\gamma)$ reaction was used to study excited states in ^{202}Tl. The data were taken using the GEANIE spectrometer. The pulsed neutron source of the Los Alamos Neutron Science Center's WNR facility provided neutrons in the energy range from 0.6 to 250 MeV. The time-of-flight technique was used to determine the incident neutron energies. γ-ray excitation functions were measured from the beam-on data, whereas half-lives of isomers were determined from the beam-off data. The level scheme of ^{202}Tl has been considerably enriched and the low-spin part of the level scheme exhibits striking similarities to that of the neighboring ^{204}Tl isotope. The previously reported first excited state in ^{202}Tl has been decomposed into two close-lying states in the present measurement. The half-life of the 7^+ isomer at 950-keV excitation energy was measured with a more precise result that differs by ~4% from the value adopted in the literature.

DOI: 10.1103/PhysRevC.76.014302 PACS number(s): 23.20.Lv, 25.40.Fq, 27.80.+w, 28.20.−v

I. INTRODUCTION

The study of excited states in the thallium isotopes that are located close to the doubly magic ^{208}Pb nucleus is important for comparison with shell-model calculations in this mass region. However, for ^{202}Tl, which is an odd-odd nucleus no shell-model calculations have been so far reported. Moreover, the experimental information on this nucleus is very limited, due mainly to its proximity to the line of stability. Generally, for ^{202}Tl the low-lying states are expected to have negative parity, and spin in the range 0 to 5 with configurations based on the $3s_{1/2}$, $2d_{3/2}$, and $2d_{5/2}$ proton orbitals and $2f_{5/2}$, $3p_{1/2}$, and $3p_{3/2}$ neutron orbitals, whereas the lowest positive-parity states involve the neutron $1i_{13/2}$ orbital.

The only information that exists for ^{202}Tl is mostly for low-spin states and was obtained in β-decay measurements [1] and in single-nucleon pickup reactions [2]. A total of eight transitions have been assigned to this isotope observed in the β decay of ^{202}Pb [1], and a total of 15 excited levels are known [2]. However, the low-spin level scheme of the neighboring ^{204}Tl isotope is much better known [3] (a total of 38 states known) and is expected to exhibit similarities with that of ^{202}Tl. Indeed, both level schemes have a 2^- ground state with half-life of 3.78 years in ^{204}Tl and 12.23 days in ^{202}Tl, and a 7^+ isomer is known in both isotopes with reported half-life of 63 μs in ^{204}Tl [3] and 572 μs in ^{202}Tl [2]. Moreover, the similarities extend to lighter odd-odd Tl isotopes. Indeed, a series of low-lying 7^+ isomeric states are known in all lighter odd-odd Tl isotopes [4] down to ^{194}Tl, whereas 2^- ground states are the case in all these isotopes. The measurement of the g factor of the 7^+ isomer in ^{202}Tl supports the $((\pi s_{1/2})^{-1}(\nu i_{13/2})^{-1})$ coupling as the main configuration for the interpretation of this state [5]. Clearly, more spectroscopic information is needed on ^{202}Tl to obtain a low-spin level scheme as rich as that in ^{204}Tl and other lighter odd-odd Tl isotopes.

In the present work we studied excited states in ^{202}Tl populated in a $(n,2n)$ reaction on the stable ^{203}Tl isotope. The previously known level scheme was considerably enriched and the half-life of the 7^+ isomer was remeasured with better accuracy.

II. EXPERIMENT

The experiment was performed at the Los Alamos Neutron Science Center Weapons Neutron Research (LANSCE/WNR) facility [6]. The γ rays produced in the bombardment of a ^{203}Tl target by neutrons were observed with the GEANIE spectrometer [7].

A sketch of the flight path and the beam time-structure is shown in Fig. 1 and is further described below: GEANIE is located 20.34 m from the WNR spallation neutron source on the 60°-right flight path. The neutrons were produced in a ^{nat}W spallation target driven by an 800-MeV proton beam with a time structure that consists of 775-μs-long "macropulses," with each macropulse containing subnanosecond-wide "micropulses" spaced every 1.8 μs. The energy of the neutrons was determined using the time-of-flight technique. The neutron flux on target was measured with a fission chamber (FC), consisting of ^{235}U and ^{238}U foils [8], located 18.48 m from the center of the spallation target. In the present experiment GEANIE was comprised of 11 Compton-suppressed planar Ge detectors (low-energy photon spectrometers; LEPS), 9 Compton-suppressed coaxial Ge detectors, and 6 unsuppressed coaxial Ge detectors.

Lifetimes for transitions observed were extracted from the beam-off data (data obtained between "macropulses"), provided that the half-lives of the states emitting them are within a range of microseconds to tens of milliseconds.

*fotia@lanl.gov

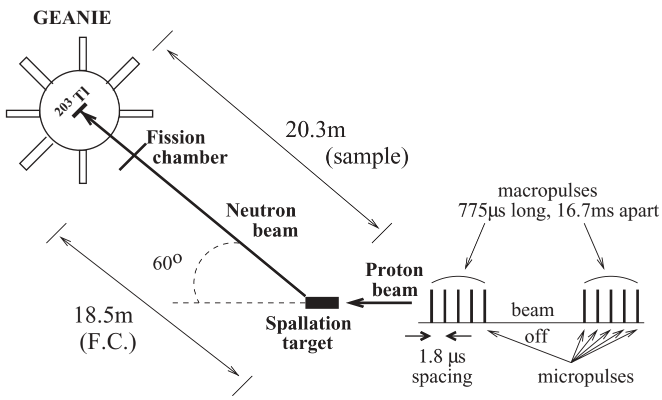

FIG. 1. A sketch of the experimental setup and the beam time structure in the present work.

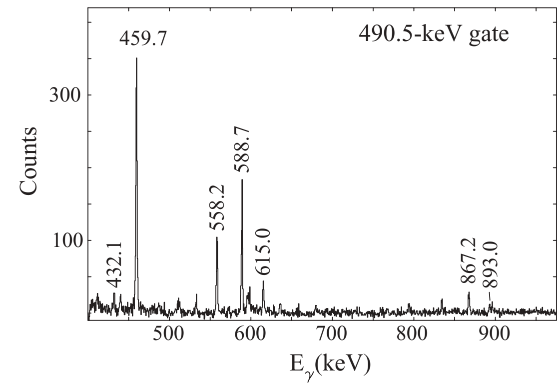

FIG. 3. Spectrum gated on the 490.5-keV transition of ^{202}Tl in Fig. 2. Only the transitions that have been placed in the level scheme of Fig. 2 are labeled (see text). The energies of the transitions are in keV.

The sample consisted of a polystyrene capsule, 2.3 cm in diameter and 0.8 mm thick, containing 2.2 g of Tl oxide powder, 97.0% enriched in ^{203}Tl. The Tl powder was tightly encapsulated in the thin-walled capsule with an inner diameter of 2.2 cm. The end faces of the sample disk were normal to the neutron beam.

III. EXPERIMENTAL RESULTS

The level scheme of ^{202}Tl was considerably enriched and is shown in Fig. 2. Only eight transitions were known in this isotope [1] before the present work. Seventeen new transitions were assigned to ^{202}Tl based on their excitation functions peaking between 10- and 20-MeV neutron energies and were placed in the ^{202}Tl level scheme based on the γ-γ coincidence data and/or on previous knowledge of states in this isotope from single-nucleon pickup reactions [2]. Comparison with the level scheme of the neighboring ^{204}Tl isotope was also very helpful in assigning tentative spins and parities for some levels. The quality of the γ-γ coincidence data is shown in Fig. 3, where a gate on the 490.5-keV transition of Fig. 2 is shown. Only the transitions for which the excitation functions matched the $(n,2n)$ reaction threshold and shape were assigned to ^{202}Tl and placed in the level scheme. The peaks in the spectrum of Fig. 3 that are not labeled did not satisfy this condition and, hence, are deemed as contaminants. Moreover, the two transitions that deexcite the first two excited states in Fig. 2 can be clearly seen in the gated spectra in Fig. 4. The levels in Fig. 2 are summarized in Table I.

The half-life of the previously known 7^+ isomer at 950-keV excitation energy (see Fig. 2) was remeasured in the present work from the beam-off data (data obtained between macropulses). This level deexcites by the 459.72-keV $E3$ transition to the 4^- level, which in turn deexcites to the ground state via the 490.5-keV transition in Fig. 2. The decay curves of both these transitions were obtained in the beam-off data and are shown in Fig. 5. A 592(4) μs half-life is obtained from the decay curve of the 459.72-keV transition and a 589(4) μs half-life from that of the 490.5-keV transition. In Fig. 2 only the 459.4-keV transition directly deexcites the 7^+; however, because $T_{1/2}(490.5\text{ keV}) \leqslant T_{1/2}(459.4\text{ keV})$, both values can be used to obtain an average lifetime value for the isomer. Hence, the value adopted here as the lifetime of the 7^+ isomer is $T_{1/2}(7^+) = 591(3)\ \mu$s.

The 10-MHz clock (Stanford Research Systems Model SC10) used in the present lifetime measurements has good accuracy and long-term stability. By obtaining the decay curves of transitions from known long-lived isomers, it was determined that a dead-time correction is not necessary after the first ~200 μs of the macropulse, hence, in Fig. 5 the decay data below 200 μs have been omitted as unreliable due to potential dead-time issues.

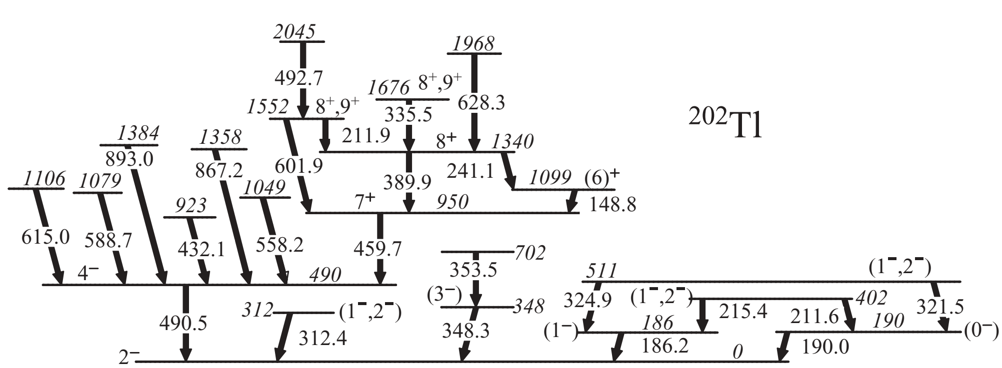

FIG. 2. Level scheme assigned to ^{202}Tl in the present work. Transition and excitation energies are given in keV.

TABLE I. Excitation energies, spin-parities, half-lives, and energies of the γ rays de-exciting all levels in Fig. 2.

E_x(keV)[a]	J^π	$T_{1/2}$	E_γ(keV)[a]
0.0	2^-	12.23 *d* [2]	
186.2	(1^-)		186.2
190.0	(0^-)		190.0
312.4	$(1^-,2^-)$		312.4
348.3	(3^-)		348.3
401.6	$(1^-,2^-)$		211.6, 215.4
490.5	4^-		490.5
511.2	$(1^-,2^-)$		321.5, 324.9
701.8			353.5
922.6			432.1
950.2	7^+	591(3) μs	459.7
1048.7			558.2
1079.2			588.7
1099.0	$(6)^+$		148.8
1105.5			615.0
1340.1	8^+		241.1, 389.9
1357.7			867.2
1383.5			893.0
1552.1	$8^+,9^+$		211.9, 601.9
1675.7	$8^+,9^+$		335.5
1968.4			628.3
2044.8			492.7

[a]The uncertainty on the γ-ray and excitation energies varies from 0.2 to 0.5 keV.

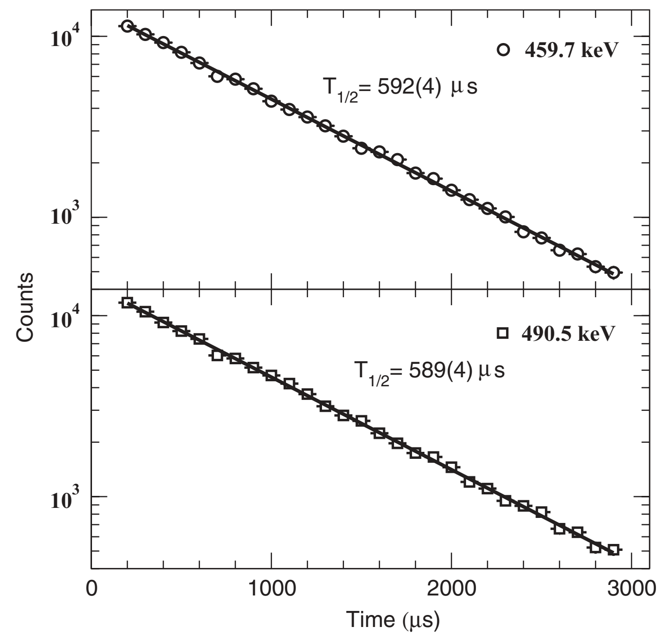

FIG. 5. Decay curves obtained from the beam-off data in the present experiment for the 459.7- and 490.5-keV transitions in Fig. 2. The half-life deduced from the fitting of the curves is shown in both cases. The vertical-axis error bars are smaller than the size of the symbols.

IV. DISCUSSION

The 591(3) μs value obtained in the present work differs by $\sim$4% from the 572(7) μs value adopted in the literature [2] for the half-life of the 7^+ isomer in ^{202}Tl. This latter value is the result of evaluation from all previous measurements of the half-life of this isomer. All these measurements are illustrated in Fig. 6 together with the present result. It is clear from Fig. 6 that the present measurement has a smaller statistical error than any previous measurement and that of the evaluation. Moreover, the present result is in agreement, within uncertainties, with four of the previous six measurements (the 57, 58, 67, and 75 measurements in Fig. 6).

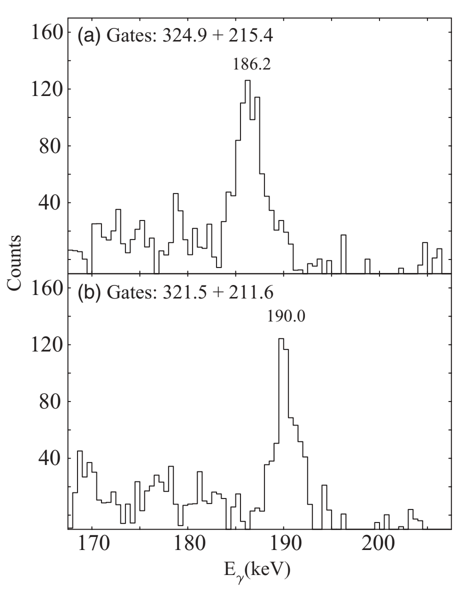

FIG. 4. Spectra each produced by summing two gates on the transitions that feed directly the (a) 186-keV and (b) 190-keV levels of ^{202}Tl in Fig. 2. All transition energies are in keV.

The 186.2-, 190.0-, 312.4- and 348.3-keV transitions were placed as feeding the ground state in Fig. 2 because 188-, 315- and 351-keV states were previously known in this isotope [2] and, moreover, the excitation functions for these transitions indicate that the levels emitting them are low-spin states.

More specifically, for the splitting of the previously reported 188(20)-keV, $(0^-,1^-)$ level [2] into two levels in the present work, the following comments can be made: In ^{204}Tl the first two excited states are $(1)^-$ and (0^-) states at 140- and 146-keV excitation energies, respectively [3]. Both states deexcite to the ground state and a weak 6-keV transition linking these states has been reported [3]. In ^{202}Tl a 188(20)-keV, $(0^-,1^-)$ state with $L = 1$ has been observed in (p,d) reactions [2]. The present results support that the latter state is actually two states with 3.8-keV excitation energy difference (see Fig. 2). Two transitions (186.2 and 190.0 keV) deexcite these states to the ground state of ^{202}Tl, whereas the possible existence of a linking transition between the two states cannot be established in the present experiment because the thresholds were set above 15 keV. Furthermore, the existence of the two states at 186- and 190-keV excitation energy is supported by the deexcitation of the newly observed 402- and 511-keV levels to both lower excited states through the newly observed 211.6-, 215.4-, 321.5-, and 324.9-keV transitions in Fig. 2. The 186.2- and 190.0-keV transitions are shown in Fig. 4, whereas their

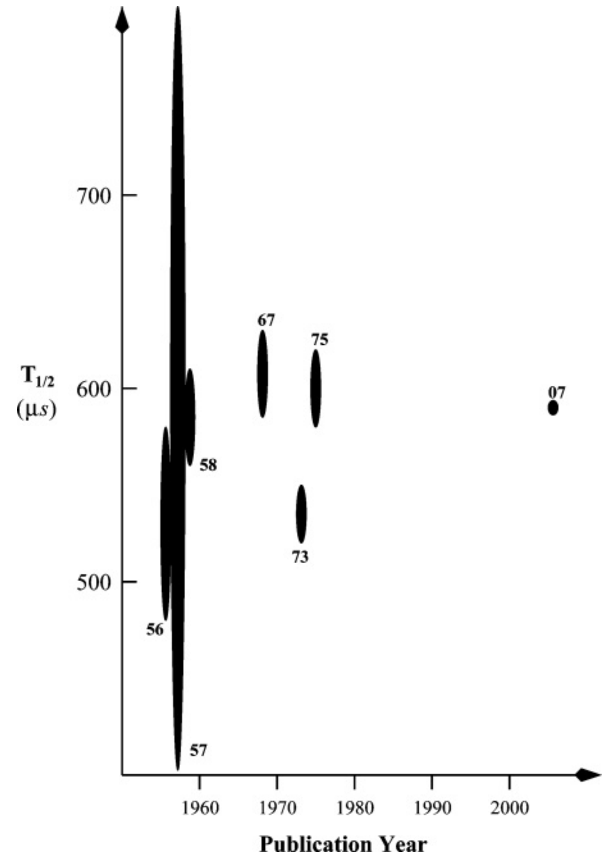

FIG. 6. Comparison of the present result (07) on the half-life of the 7^+ isomer (591(3) μs) with the results of previous measurements from the following references: 56 [9], 57 [10], 58 [11], 67 [12], 73 [13], and 75 [14]. From the previous measurements the value of 572(7) μs was adopted in the literature [2], a value that differs by ~4% from the present result.

excitation functions can be seen in Fig. 7(a) and exhibit a different shape at neutron energies above the threshold to $E_n \sim 11$ MeV (the excitation function for the 190.0-keV transition exhibits a more rapid increase in this neutron energy interval), suggesting that the 186- and 190-keV levels have different spin. The relative intensity of the 190.0-keV transition is ~42% of that of the 186.2-keV transition (without correcting for internal conversion differences due to possible different multipolarities for these transitions, and while the attenuation of both γ rays inside the thick target in the present experiment is assumed practically identical). Because the $(n,2n)$ reaction channel proceeds through a compound nucleus that is expected to populate a channel entry region at a higher spin and excitation energy, a more intense population of the 1^- state is expected. Hence, the stronger 186.2-keV transition suggests that the 186-keV level in Fig. 2 is the 1^- state, and thus the 190-keV level is the 0^- state (however, these spin-parity assignments remain tentative). It is worth noting here that, following these spin-parity assignements, an intensity correction for internal conversion of the 186.2- and 190.0-keV transitions will result in an even smaller relative intensity for the 190.0-keV transition (e.g., assuming $M1$ and $E2$ multipolarities for the 186.2- and 190.0-keV transitions,

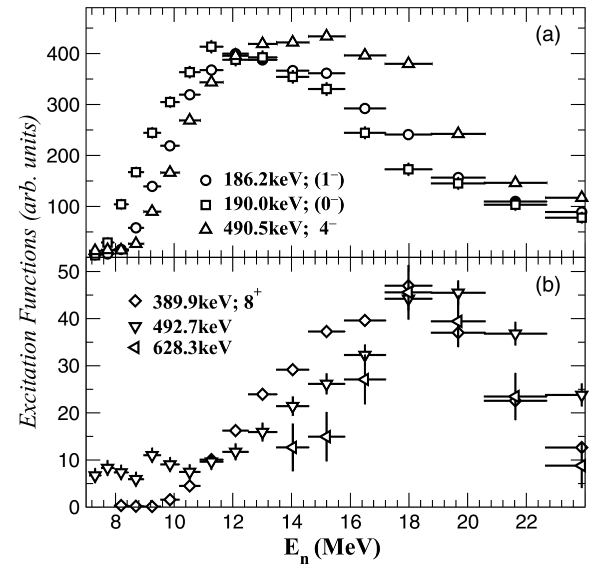

FIG. 7. Excitation functions (up to 24-MeV neutron energy) obtained in the present experiment for (a) three γ rays (186.2-, 190.0- and 490.5-keV transitions in Fig. 2) that feed directly the ground state of ^{202}Tl, and (b) three γ rays (389.9-, 492.7- and 628.3-keV transitions in Fig. 2) emitted from higher-spin states.

respectively, the relative intensity of the 190.0-keV transition is now ~25% of that of the 186.2-keV transition). Thus, after the present work, the first two excited levels in ^{202}Tl exhibit striking similarities to the first two excited states in ^{204}Tl. The $((\pi s_{1/2})^{-1}(\nu p_{1/2}))$ configuration has been evoked to interpret the first two excited states in ^{204}Tl, an interpretation that seems quite likely for the 186- and 190-keV levels in ^{202}Tl.

The third and fourth excited states in ^{204}Tl, which lie at excitation energies of 300 and 319 keV with $(1,2)^-$ spin-parity assignments in both cases [3], have been interpreted using the $((\pi s_{1/2})^{-1}(\nu p_{3/2})^{-1})$ configuration. Only one candidate for these states has been observed in the present data for ^{202}Tl. This is the 312-keV level, which is the third excited state observed in the present experiment and lies very close to the 315(20)-keV level observed in (p,d) reactions [2]. The $L = (1)$ value obtained in the (p,d) reactions for this level is in agreement with the $(1^-,2^-)$ tentative spin-parity assignment in Fig. 2.

The fourth excited state in the present experiment is the 348.3(4)-keV level in Fig. 2 with tentative spin-parity assignment of (3^-). This is the 351(20)-keV state, with $L = (3)$, previously observed in (p,d) reactions [2]. A very similar state exists in ^{204}Tl at 347.9(4)-keV excitation energy. The excitation energy of both states is equal within uncertainties, which is an exception to the usually larger excitation energies observed in ^{202}Tl for corresponding states. The $((\pi s_{1/2})^{-1}(\nu f_{5/2})^{-1})$ configuration can be used for the interpretation of both states. It should be noted here that the assignment of the 348.3-keV transition to ^{202}Tl was confirmed in a recent ^{205}Tl$(n, xn\gamma)$ GEANIE experiment, where the excitation function obtained for the 348-keV transition is a doublet, peaking at neutron energies characteristic of the $(n,2n)$ channel (from the 347.9-keV transition of ^{204}Tl) and of the $(n,4n)$ channel (from the 348.3(4)-keV transition assigned to ^{202}Tl in the present work), thus, excluding the possible presence of the 348.3(4)-keV transition in the present data set due to contamination of the ^{203}Tl target with ^{205}Tl, which is the only other stable Tl isotope.

The existence in ^{202}Tl of the previously known 490.5-keV, 4^- level has been confirmed in the present experiment. The excitation function obtained for the 490.5-keV transition is shown in Fig. 7(a). The corresponding level in ^{204}Tl is at 414.06-keV excitation energy [3] and is the first configuration that involves a proton hole in the $d_{3/2}$ orbital, namely $((\pi d_{3/2})^{-1}(\nu f_{5/2})^{-1})$.

The new ^{202}Tl levels mentioned above at 402- and 511-keV excitation energies, have (1^-,2^-) tentative spin-parity assignments in Fig. 2. The 211.6-keV transition is lying very close in the spectra with the stronger previously known 211.9-keV transition in Fig. 2, rendering the determination of the branching ratio for the 402-keV level impossible from the present data. For the 511-keV level the 321.5-keV transition is lying very close in the spectra with a stronger transition from the $(n,3n)$ channel; however, by gating in the neutron energies below 20 MeV one can obtain a relative intensity for the 321.5-, and 324.9-keV transitions, thus determining that the latter transition is the stronger one and accounts for ~73% of the decay of the 511-keV level ($E2$ and $M1$ multipolarities were assumed for the 321.5- and 324.9-keV transitions, respectively, whereas the attenuation of both transitions inside the thick target in the present experiment is assumed to be the same for both transitions). Both levels are very similar in the deexcitation pattern to the 425.06-keV, (2^-,1^-), 432.5-keV, $(1,2)^-$, and 471.93-keV, $(1)^-$, levels of ^{204}Tl [3], for which there has been no firm configuration assignment. A direct transition from the 511-keV level to the ground state (as the 425.0- and 471.9-keV transitions in ^{204}Tl [3]) would overlap in the present data with the strong contamination from the 511-keV transition from electron-positron annihilation; hence, the existence of such a transition cannot be excluded, and cannot be confirmed either, in the present experiment.

From the discussion above it is evident that the low-spin structure in both ^{202}Tl and ^{204}Tl is very similar at least up to ~500-keV excitation energies. This is illustrated in Fig. 8.

Two more levels at 1968- and 2045-keV excitation energy were added in the present work in the structure above the 7^+ isomer. For the previously known levels of this structure, a very similar excitation function was deduced for the 211.9- and 389.9-keV transitions, supporting the previously reported [2] spin-parity assignment of 8^+,9^+ for the 1552-keV level. However, the excitation functions for the 492.7- and 628.3-keV transitions, which deexcite the new levels of the structure, have a less steep increase with neutron energy supporting higher spin assignments ($>8\hbar$) for both 1968- and 2045-keV levels in Fig. 2. Hence, both levels can be characterized as high-spin states. The excitation functions for the 389.9-, 492.7-, and 628.3-keV transitions are shown in Fig. 7(b) and exhibit a much slower rise with increasing neutron energy compared to the excitation functions for the transitions in Fig. 7(a), which are emitted by low-spin states.

Finally, for the six new levels that were observed to feed directly the 490-keV, 4^- level in Fig. 2, spins of $\sim 4\hbar$ are supported by the excitation functions of all the corresponding transitions that deexcite these states, which were found to be similar to that of the 490.5-keV transition in Fig. 7. Hence, all six levels can be characterized as medium-spin states.

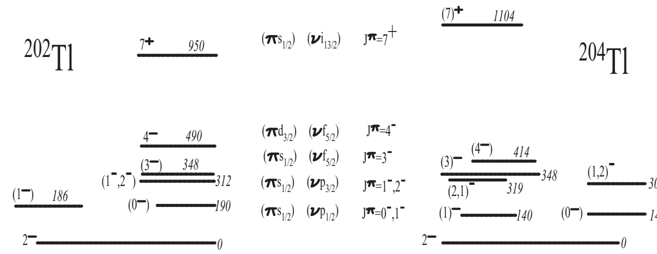

FIG. 8. Partial level schemes of ^{202}Tl (present work) and ^{204}Tl (Ref. [3]) showing the low-spin structure in both isotopes together with the particle-hole configurations used to interpret these levels (see text).

V. SUMMARY

In summary, states of ^{202}Tl with up to ~2 MeV excitation energy have been studied using the ^{203}Tl$(n,2n\gamma)$ reaction. The data were taken using the GEANIE spectrometer and the neutron beam of the Los Alamos Neutron Science Center's WNR facility. The deduced excitation functions combined with γ-γ coincidence information were used to considerably enrich the low-spin part of the level scheme, which now exhibits similarities to that of the neighboring ^{204}Tl isotope up to at least ~500 keV excitation energy. Two states, 3.8-keV apart in excitation energy, were observed very close to the previously reported first excited state of ^{202}Tl observed in a (p,d) reaction. The half-life of the previously known 7^+ isomer at 950-keV excitation energy was remeasured with the result differing by ~4% from the value adopted in the literature.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy under contracts DE-AC52-06NA25396 (LANL) and W-7405-ENG-48 (LLNL). This work has benefited from use of the LANSCE accelerator facility supported under DOE contract DE-AC52-06NA25396.

[1] J. Guile, R. E. Doebler, W. C. McHarris, and W. H. Kelly, Phys. Rev. C **5**, 2107 (1972).
[2] M. R. Schmorak, Nucl. Data Sheets **50**, 669 (1987).
[3] M. R. Schmorak, Nucl. Data Sheets **72**, 409 (1994).
[4] R. M. Diamond and F. S. Stephens, Nucl. Phys. **45**, 632 (1963).
[5] O. Hashimoto, A. Sumi, T. Nomura, S. Nagamiya, K. Nakai, T. Yamazaki, and K. Miyano, Nucl. Phys. **A218**, 180 (1974).
[6] P. W. Lisowski, C. D. Bowman, G. J. Russell, and S. A. Wender, Nucl. Sci. Eng. **106**, 208 (1990).

[7] J. A. Becker and R. O. Nelson, Nucl. Phys. News Int. **7**, 11 (June, 1997).
[8] S. A. Wender, S. Balestrini, A. Brown, R. C. Haight, C. M. Laymon, T. M. Lee, P. W. Lisowski, W. McCorkle, R. O. Nelson, and W. Parker, Nucl. Instrum. Methods A **336**, 226 (1993).
[9] S. H. Vegors, Jr. and P. Axel, Phys. Rev. **101**, 1067 (1956).
[10] B. Åström, Ark. Fys. **12**, 237 (1957).
[11] R. B. Duffield and S. H. Vegors, Jr., Phys. Rev. **112**, 1958 (1958).
[12] P. Scheimbauer and P. Hille, Nucl. Phys. **A102**, 534 (1967).
[13] G. N. Salaita and P. K. Eapen, J. Inorg. Nucl. Chem. **35**, 2139 (1973).
[14] J. Uyttenhove, K. Heyde, H. Vincx, and M. Waroquier, Nucl. Phys. **A241**, 135 (1975).