Isomers from intrinsic excitations in ^{200}Tl and ^{201,202}Pb

Poulomi Roy, S. K. Tandel, Saket Suman, P. Chowdhury, R. V. F. Janssens, M. P. Carpenter, T. L. Khoo, F. G. Kondev, T. Lauritsen, C. J. Lister, D. Seweryniak, and S. Zhu

Phys. Rev. C **100**, 024320 — Published 14 August 2019

DOI: 10.1103/PhysRevC.100.024320

Isomers from intrinsic excitations in ^{200}Tl and ^{201,202}Pb

Poulomi Roy,[1] S.K. Tandel[a],[1,2] Saket Suman,[1] P. Chowdhury,[2]
R.V.F. Janssens,[3,4] M.P. Carpenter,[5] T.L. Khoo,[5] F.G. Kondev,[5]
T. Lauritsen,[5] C.J. Lister,[2,5] D. Seweryniak,[5] and S. Zhu [b5]

[1]*School of Physical Sciences, UM-DAE Centre for Excellence in Basic Sciences, University of Mumbai, Mumbai 400098, India*

[2]*Department of Physics, University of Massachusetts Lowell, Lowell, Massachusetts 01854, USA*

[3]*Department of Physics and Astronomy, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina 27599, USA*

[4]*Triangle Universities Nuclear Laboratory, Duke University, Durham, North Carolina 27708, USA*

[5]*Argonne National Laboratory, Argonne, Illinois 60439, USA*

(Dated: July 30, 2019)

Abstract

A six-quasiparticle isomer with $T_{1/2}$ = 57(2) ns has been established in the doubly-odd isotope ^{200}Tl and its level scheme is significantly extended. Half-lives of previously reported isomers in ^{200}Tl and ^{201,202}Pb have been determined and revised values are reported in a few cases, with $T_{1/2}$ = 397(17) ns and 7.0(5) ns for the $I^{\pi} = 5^{+}$ and 7^{-} states in ^{200}Tl, 52(2) ns for the $41/2^{+}$ level in ^{201}Pb, and 93(4) ns for the 16^{+} state in ^{202}Pb. Configurations for the isomers have been assigned and these predominantly involve intrinsic excitations of neutrons from the $i_{13/2}$ subshell. The inferred transition rates for the decay of these isomers compare well with single-particle estimates attesting to their intrinsic character.

PACS numbers: 21.10.Pc, 21.10.Tg, 23.20.Lv, 23.35.+g, 27.80.+w

[a] Corresponding author: sktandel@gmail.com

[b] Present address: National Nuclear Data Centre, Brookhaven National Laboratory, Upton, New York 11973-5000, USA

I. INTRODUCTION

Nuclei in the vicinity of proton magic number $Z = 82$ and with neutron numbers approaching the shell closure at $N = 126$ are characterized by excited states with predominant contributions from intrinsic excitation modes. Some of the yrast levels in these nuclei, which result, primarily, from configurations involving the intruder $i_{13/2}$ neutron and/or $h_{11/2}$ proton orbitals, have been found to be isomeric [1–6]. The half-lives of these long-lived states range from a few nanoseconds (ns) to hours, depending on the extent of the angular momentum or configuration hindrance [1–6]. Isomers have been reported in isotopes of Tl ($Z = 81$) and Pb ($Z = 82$) with $A \approx 200$. While proton-rich isotopes of these elements with $A < 200$ are characterized by moderate oblate deformation, near-spherical shapes are evident approaching $N = 126$. As a result, several isomers arising from intrinsic excitations have been observed in the $A \geq 200$ region.

A systematic study of these isomers and their decay properties is expected to yield an improved understanding of nuclear stucture in this region. By establishing the excitation energy, spin-parity and underlying configuration of these states, one can obtain insight into quasiparticle (qp) energies in the vicinity of the doubly-magic ^{208}Pb nucleus. Additionally, with the realization of multiple isomers arising from various qp configurations, it is possible to sensitively explore residual interactions between nucleons occupying different orbitals. Detailed experimental data are expected to provide stringent tests of modern shell-model calculations, and allow an evaluation of the various effective interactions that have been proposed. Isotopes of Tl and Pb with $A \approx 200$ have, thus far, been studied primarily with α-induced reactions [4–10]. In the present work, states up to quite high spin have been populated using multi-nucleon transfer reactions with heavy, energetic beams. High-fold coincidence data provide selectivity, and with precise information on various time parameters, it is possible to explore multiple isomers in a single isotope, where higher-lying ones feed the lower states.

II. EXPERIMENT AND RESULTS

Isomers in Tl and Pb isotopes with $A \approx 200$ were studied using a 1430-MeV ^{207}Pb beam, from the ATLAS accelerator at Argonne National Laboratory, incident on a ^{197}Au target of ≈ 50 mg/cm^2 thickness. Excited states in Tl and Pb isotopes were populated through multi-nucleon transfer, (1p, xn) and xn reactions, respectively, all followed by neutron evaporation. Three- and higher-fold coincidence events were recorded using the Gammasphere array comprising 100 high-purity, Compton-suppressed HPGe detectors [11]. One out of every ten beam pulses from ATLAS were incident on the target *i.e.* 1 ns pulses spaced by 825 ns. Numerous histograms with various energy and time parameters and different time conditions were created and analyzed to establish or confirm the decay schemes and to determine the half-lives of the isomers. Representative values for the detection of prompt γ rays were ±20 ns and ±50 ns with respect to when the beam is incident on the target; for delayed γ rays, these were +20 to 120 ns and +50 to 650 ns. Details about the analysis are found in Refs. [12, 13]. The software packages RADWARE [14] and TSCAN [15] were utilized in the data analysis. A summary of the properties of the isomers established from the present work, including revised values of half-lives for previously identified ones, is presented in Table I.

A. ^{200}Tl

Excited states in ^{200}Tl, including low-spin isomeric states and a weakly-deformed oblate band structure, up to I = 14 $\hbar$, had been established previously using the ^{198}Pt(^{6}Li,4n) reaction with only two Ge(Li) detectors [2]. In addition to the previously reported metastable state with $I^\pi = 7^+$ and $T_{1/2}$ = 34.0(9) ms, two other low-spin isomers with $I^\pi = 7^-$, $T_{1/2}$ = 4.8(2) ns, and $I^\pi = 5^+$, $T_{1/2}$ = 0.33(5) μs had been placed in the level scheme [1, 2]. Subsequently, the level scheme was extended up to $I = 22\ \hbar$ using the ^{198}Pt(^{7}Li,5n) reaction with 15 Compton-suppressed clover Ge detectors [3]. The present work is focused further on the exploration of isomers in ^{200}Tl.

1. A new isomer at E_x = 6007 keV

It was found that all the γ rays reported in Ref. [2] placed above the 754-keV state in ^{200}Tl have a marked delayed feeding which is attributable to a single isomer with spin-parity $I^\pi = (26^-)$. The level scheme of ^{200}Tl was extended in the present work up to a I^π=(26$^-$) isomeric level at 6007 keV (Fig. 1), based on observed coincidence relationships and intensity considerations (Fig. 2).

The half-life of this long-lived level is established in the present work to be 57(2) ns by inspecting the variation in time of the cumulative intensity of delayed γ rays (beyond the $\sim$20 ns associated with prompt radiation emitted when the beam is incident on the target) following the deexcitation of this state (Fig. 3). Coincidence intensities of the parallel 749- and 752-keV decay branches from the (24^-) state, as well as the 286-keV, $(22^-) \rightarrow (21^+)$ transition, exhibit a consistent increase with increasing width of the time coincidence gate, and lead to the inferred value $T_{1/2} = 57(2)$ ns [18]. Twelve new transitions have been identified following the decay of the isomer. The energies of the newly placed transitions are: 99, 116, 184, 196, 220, 326, 453, 649, 749, 752, 824 and 851 keV, respectively. Note that the presence of an unobserved 80-keV transition is inferred from coincidence relationships. The 99-keV γ ray is observed to directly deexcite the isomer, and intensity balance considerations, combined with theoretical values of conversion coefficients [17], exclude all multipolarities other than *E2* for this transition (Table II). Similarities are observed between the decay scheme of ^{200}Tl and that of its isotone, ^{201}Pb ($N = 119$), in terms of both the presence of a low-energy *E2* transition deexciting the isomer, and of fragmentation of the intensity into multiple pathways below this level [4, 16]. Intensity balance arguments also allow for the multipolarity assignments to the following transitions (with energies in keV): 116 (*M1*), 192 (*E1*), 220 (*M1*), and 286 (*E1*). Detailed considerations are presented in Table II. Some modifications to the previously reported spin-parity assignments [3] at high spin were found to be necessary, based on the present data. The 192-keV transition deexciting the 4049-keV level had been assigned *M1* multipolarity in Ref. [3] based on the inferred DCO (Directional Correlation from Oriented nuclei) ratio being consistent with a dipole character. However, no information on the IPDCO (Integrated Polarization Directional Correlation from Oriented nuclei) ratio was available due to the relatively low energy of the transition. The present data unambiguously support a *E1* multipolarity for this 192-keV γ ray (Table II). The 707-keV transition, deexciting the 4873-keV level, had previously been assigned *E2* character, but both its DCO and IPDCO ratios [3] are not inconsistent with the *M1* multipolarity that appears to be most likely from the present level scheme. The 286-keV transition from the 5158-keV level had been previously assigned dipole character with mixed *M1* + *E2* multipolarity, and a small negative value of the IPDCO ratio [3]. Dipole character is inferred from the present work as well, however, intensity balance considerations favor a

E1 and rule out a *M1* multipolarity (Table II).

2. The isomer at E_x = 1244 keV

The half-life of 4.8(2) ns previously measured for the 1244-keV state [2] was revisited in the present work using the centroid-shift technique [12, 13]. The difference in time of γ rays above this level (311 and 230 keV) and the 490-keV transition deexciting it were plotted and compared with those obtained for two prompt transitions of similar energies (Fig. 4). Respective half-lives of 6.9(5) ns and 7.1(5) ns were deduced from the shift in centroid of the distributions. A value of $T_{1/2}$ = 7.0(5) ns is, therefore, assigned to this state. This represents a revision from the previously reported value of 4.8(2) ns, which lies outside 3σ limits of the present measurement.

The spin-parity of the 1244-keV state was previously assigned as $I^{\pi} = 7^-$ by Kreiner *et al.* [2] and later revised to $I^{\pi} = 9^-$ by Bhattacharya *et al.* [3]. The $\chi^2(\delta)$, multipole-mixing analyses of the angular distribution obtained in the two measurements for the 490-keV transition deexciting this level are not in agreement. In the former case, a 9^- assignment is strongly disfavored [2], while in the latter instance [3], a 7^- assignment appears less probable. The conversion coefficient measured by Kreiner *et al.* [2] for the 490-keV transition suggests a *E1* character, while the small negative value of Δ_{IPDCO} = -0.10(2) and a DCO ratio close to unity obtained by Bhattacharya *et al.* [3] led to the inference of a *M2* character. From the present data, the DCO ratio for the 490-keV transition, obtained by gating on *E2* transitions located above the 1244-keV isomeric state (similar to the approach in [3]), is also found to be close to unity. However, it should be noted that a DCO ratio close to unity is also obtained for the 391-keV mixed *E1/M2*, $8^- \rightarrow 7^+$ transition in ^{198}Tl. In general, in cases where gating *E2* transitions are located above isomeric states, the DCO ratios for pure *E1* transitions below these long-lived levels tend to approach unity, in contrast to situations where both γ rays are in prompt coincidence with each other where these are closer to 0.5. This may be understood in terms of the gating γ ray being emitted from an oriented state, while the one deexciting the isomer is either partially or fully deoriented depending on the half-life involved. While a half-life of 7 ns is rather short, a significant deorientation effect for the deexciting 490-keV transition cannot be excluded. In ^{200}Tl, the feeding from the newly identified $I^{\pi} = (26^-)$ isomer with $T_{1/2}$ = 57(2) ns, and any resultant deorientation effect for the gating transitions in the vicinity of $I = 14\text{-}16\ \hbar$ is expected to be small, since most of the feeding around this spin value was found to be prompt.

There is further supporting evidence for the spin-parity assignments of Kreiner *et al.* [2]. Three transitions of energy 220, 358 and 490 keV deexcite the 1244-keV isomeric level [2, 3], and all are assigned *E1* character by Kreiner *et al.* [2], while *E2*, *E1* and *M2* multipolarities are proposed by Bhattacharya *et al.* [3]. The assignment of a *E1* character for the three transitions leads to an expected increase in transition rates for higher-energy transitions and is consistent with the measured branching ratios. In the latter instance of *E2*, *E1* and *M2* assignments, based on a comparison with Weisskopf estimates, the 358-keV transition would be expected to be the most intense and the 490-keV one to be the weakest branch, contrary to experiment. There may, of course, be additional considerations of configuration hindrance involved in the three cases. It may be noted that the 9^- assignment of Bhattacharya *et al.* [3] would lead to the presence of two 9^- states, originating from the same configuration, at different values of excitation energy of 1244 and 1323 keV, respectively. This situation does not occur with the 7^- assignment of Kreiner *et al.* [2]. In the former work [2], the level at 1323 keV had been assigned spin-parity $(9{+}\Delta I)^-$ with $\Delta I = 0$, 1. The observation of a weak, 195-keV transition linking the 1442- and 1247-keV levels in the latter work [3] indicates most likely a ΔI=0 spin difference. Consequently, for the 1247-keV and all higher-lying levels, the spin-parity assignments from both previous reports [2, 3] are in agreement. Therefore, the spin-parity assignments for the higher-lying levels are not affected by any uncertainty in the spin of the 1244-keV isomeric level. Based on the evidence above, it appears likely that the 490-keV transition has mixed *E1/M2* character, consistent with a 7^- assignment for the 1244-keV isomeric state (Fig. 1).

3. The isomer at E_x = 762 keV

Another ^{200}Tl isomer had been first identified through proton-induced reactions on Tl targets [1]. Although it had been assigned to ^{200}Tl and the deexciting γ ray identified, it could not be placed in the level scheme, but its half-life was determined to be 330(50) ns. In the subsequent work of Kreiner *et al.* [2], the isomer was placed at $E_x = 762$ keV and assigned $I^\pi = 5^+$, based on a measured K-conversion coefficient, $\alpha_K = 0.06(2)$, of the 221-keV transition deexciting this state. A possible configuration was not proposed at the time. In the present work, the time difference between the 262-keV γ ray feeding this state and the 221- and 541-keV transitions deexciting it yield a revised and more precise value of $T_{1/2}$ = 397(17) ns (Fig. 5). In Ref. [3], the spin-parity of this state was reassigned as I^{π} = 6^{+}, based on *E2* and *E1* multipolarity assignments for the higher-lying 220- and 262-keV transitions, though no information was available for the 221-keV γ ray deexciting this state. These multipolarity assignments were based on measured DCO and IPDCO ratios [3], and the electric character of the 220-keV γ ray and the dipole nature of the 262-keV transition appeared to be determined. However, the large errors on the DCO and IPDCO ratios of the 220- and 262-keV transitions, respectively [3], lead to considerable uncertainty; *e.g.*, a dipole nature for the former and magnetic character for the latter γ ray cannot be ruled out. Furthermore, the *M2* assignment proposed in Ref. [3] for the 221-keV transition deexciting the isomer is in stark contradiction with the measured *K*-conversion coefficient $\alpha_K(221)$ = 0.06(2) (see Ref. [2]). The calculated conversion coefficient for a *M2* transition would be $\alpha_K = 3.057$, a value quite different from the one expected for an *E1* transition: $\alpha_K = 0.049$. Hence, an *E1* assignment is the only one consistent with the conversion coefficient obtained from experiment.

Intensity balance considerations obtained from the present data support the assignments of Kreiner *et al.* (Table III). The 262-keV transition feeds the isomeric state. Both the 220- and 326-keV γ rays in turn feed the level deexcited by this 262-keV transition (Fig. 1). Data from the present work were inspected in order to check for intensity balance between the decaying 262-keV transition, on the one hand, and the sum of the total intensities of the 220- and 326-keV transitions feeding the isomer, on the other. In the work of Bhattacharya *et al.* [3], the 220-, 262- and 326-keV transitions were assigned *E2*, *E1* and mixed *M1*/*E2* character, respectively. Kreiner *et al.* [2] had assigned *E1* and *M1* character to the 220- and 262-keV transitions, however, they did not report the observation of the 326-keV transition, perhaps because it is significantly weaker than the other two. In the present work, all three transitions are observed using a 3-D energy histogram with delayed γ rays along two of the axes and prompt ones along the third (with respect to prompt timing), allowing for the transitions of interest to be clearly isolated and precise intensities to be determined. Intensity balance can only be achieved with the spin-parity assignments of Kreiner *et al.* [2]. Indeed, with the assignments of Bhattacharya *et al.* [3], the intensity of the 262-keV γ ray is lower than the sum of the intensities of the feeding 220- and 326-keV transitions by almost a factor of two (Table III). To summarize, the spin-parity of the isomer at E_x = 762 keV is firmly assigned as $I^\pi = 5^+$, and that of the state at E_x = 1024 keV as $I^\pi = 6^+$. With *E1* multipolarity for the 220-keV transition, the isomeric state at E_x = 1244 keV is assigned spin-parity $I^\pi = 7^-$, based on the discussion above. With the 9^- assignment for the E_x = 1244-keV state of Bhattacharya *et al.* [3], and 6^+ for the 1024-keV level, the 220-keV transition would have *E3* multipolarity, an unlikely scenario. Thus, as described above, spin-parity assignments to the crucial states above have been finalized, and the discrepancies between the previous reports [2, 3] have been resolved.

B. ^{201}Pb

Excited levels in ^{201}Pb, an isotone of ^{200}Tl ($N = 119$), were studied previously using the ^{200}Hg(α,3n) reaction [4, 9] and, later, with the ^{192}Os(^{14}C,5n) reaction [16]. Levels up to I^π = $41/2^+$ were established using the α-induced reaction and three isomers with $I^\pi = 25/2^-$, $29/2^-$ and $41/2^+$, and $T_{1/2}$ = 63(3) ns, 508(3) ns and 43(3) ns, respectively, were identified above the $13/2^+$ isomer at 629 keV. The experiment with the ^{14}C beam [16] did not focus on isomeric levels.

From the previous work of Ref. [4], the half-life of the $I^\pi = 41/2^+$ isomer was determined to be 43(3) ns from the time distribution of individual γ rays, namely the 728- and 287-keV transitions associated with its decay. The ^{201}Pb level scheme, displaying only the strong branches, and coincidence spectra with gates placed on delayed transitions, obtained from the present work, can be found in Fig. 6. Owing to the considerably greater population of the high-spin levels in the present data, it was possible to obtain the half-life from coincidence spectra and the time difference between γ rays feeding and deexciting the $41/2^+$ state. A revised value, $T_{1/2}$ = 52(2) ns, is deduced in the present work for the $I^\pi = 41/2^+$ state (Fig. 6).

C. ^{202}Pb

The high-spin structure of ^{202}Pb had been studied earlier with ^{200,202}Hg(α,xn) reactions [5, 6] and later with ^{192}Os(^{14}C,4n) and ^{198}Pt(^{9}Be,5n) ones [16, 19]. The reactions using the α beams were focused on isomer studies and, in the first experiment [6], three isomers with

$I^\pi = 7^-$, $T_{1/2} = 65.4(2)$ ns, $I^\pi = 12^+$, $T_{1/2} = 24.2(3)$ ns, and $I^\pi = 16^+$, $T_{1/2} = 110(5)$ ns were placed in the level scheme [6] above the $I^\pi = 9^-$, $T_{1/2} = 3.54(2)$ h isomer. In a later experiment, an additional isomeric level with $I^\pi = 19^-$ and $T_{1/2} = 107(5)$ ns was identified [5].

The level scheme of ^{202}Pb, with the strong transitions from the decay of the isomers, and coincidence spectra highlighting the delayed transitions, are presented in Fig. 7. The half-life of the 12^+ state is determined in the present work to be $T_{1/2} = 23.5(6)$ ns by inspecting the time difference between transitions feeding and deexciting this level (Fig. 8). This value is in agreement with the previously reported one of $T_{1/2} = 24.2(3)$ ns [6]. Similarly, the half-life of the $I^\pi = 19^-$ level is determined to be $T_{1/2} = 113(6)$ ns (Fig. 9), consistent with $T_{1/2} = 107(5)$ ns obtained from Ref. [5].

In the case of the $I^\pi = 16^+$ isomer, the previous determination of the half-life [5, 6] had relied on the inspection of the time distribution of individual γ rays from the decay of this state. In this approach, appropriate corrections are required to account for the feeding from the higher-lying, $I^\pi = 19^-$ long-lived state. In the present work, the time difference between feeding and deexciting γ rays was inspected, along with the additional selective requirement that these transitions be present in the delayed spectra, by virtue of feeding from the $I^\pi = 19^-$ isomer. This leads to a revised value $T_{1/2} = 93(4)$ ns for the $I^\pi = 16^+$ isomer (Fig. 10), which, nonetheless, overlaps within 3σ limits with the previously reported value of 110(5) ns.

III. DISCUSSION

A number of metastable states are present in isotopes of Tl ($Z = 81$) and Pb ($Z = 82$) in the $A \approx 200$ region. Odd-A Pb isotopes exhibit $I^\pi = 13/2^+$ so-called spin isomers arising from the occupation of the $i_{13/2}$ neutron orbital. Even isotopes of Pb exhibit $I^\pi = 12^+$ seniority isomers associated with a $\nu i_{13/2}^{-2}$ configuration. Other long-lived levels, both at intermediate and high spin, result from the occupation of one or more nucleons in high-j orbitals, including the $h_{11/2}$ proton subshell in Tl isotopes, and the decays are found to be either configuration hindered or retarded due to a large change in angular momentum similar to that responsible for the $13/2^+$ isomers.

A. Isomers in ^{200}Tl

Three isomers had been previously identified at $E_x = 754$, 762 and 1244 keV and assigned $I^\pi = 7^+$, 5^+ and 7^-, respectively by Kreiner *et al.* [2]. As mentioned above, in the later work of Bhattacharya *et al.* [3] the spin-parity of the latter two states was changed to 6^+ and 9^-, respectively. The configuration of the $I^\pi = 7^+$ isomer at $E_x = 754$ keV is well established as $(\pi s_{1/2}^{-1} \otimes \nu i_{13/2}^{-1})$ from the systematics of odd-odd Tl isotopes and from g-factor measurements in the cases of ^{198,202,204}Tl [7, 20, 21].

With respect to the 762-keV isomer, in the previous work [2], the state was definitely assigned as 5^+, however, its configuration was not discussed. In the later work, with a 6^+ assignment based on the spin-parity of a higher-lying level, this state was proposed to arise from the same configuration as the 7^+ isomer, but with anti-parallel coupling of the proton and neutron spins [3]. As shown above, this 6^+ assignment of Ref. [3] is ruled out by the *E1* multipolarity assigned to the 221-keV transition deexciting this state and consequent spin-parity $I^\pi = 5^+$ [2]. Further, the resulting hypothesis in Ref. [3] of the presence of a pair of closely spaced states with spin-parity 7^+ and 6^+ arising from the same configuration is also questionable, given that the energies of these two levels would be 754 and 762 keV; *i.e.* too small a difference to be accounted for by the parallel and anti-parallel couplings of the $i_{13/2}$ neutron and $s_{1/2}$ proton spins for these two levels. Further, this small relative spacing (8 keV) between the 7^+ and 6^+ states in ^{200}Tl would also be difficult to reconcile with the corresponding values of 131 and 149 keV observed in ^{198}Tl and ^{202}Tl, respectively [22, 23]. On the contrary, there is a known $I^\pi = 6^+$ level in ^{200}Tl at $E_x = 886$ keV [2]. The energy spacing between this level and the 7^+ isomer is 132 keV (Fig. 1) a difference that fits quite well with systematics. Similar energy differences of 131, 132 and 149 keV between the 6^+ and 7^+ levels in ^{198}Tl, ^{200}Tl and ^{202}Tl, respectively, can be attributed to an identical $(\pi s_{1/2}^{-1} \otimes \nu i_{13/2}^{-1})$ configuration with the 6^+ level lying higher by virtue of the anti-parallel coupling of the nucleon spins. It may also be noted that, in all the above cases, the 6^+ level decays exclusively to the 7^+ isomeric state. Thus, the above considerations strongly disfavor the 6^+ assignment of Bhattacharya *et al.* [3] for the 762-keV isomer.

The identification of 6^+ and 7^+ states in ^{198,200,202}Tl with anti-parallel and parallel couplings of spins of a $s_{1/2}$ proton and an $i_{13/2}$ neutron provides an opportunity to extract the magnitude of the energy of the residual interaction (ΔE_{res}) for this configuration. The spin-triplet (7^+) and the spin-singlet (6^+) levels are lowered/raised in energy, respectively, by an amount equal to ΔE_{res}. The average energy difference between the 6^+ and 7^+ levels in ^{198,200,202}Tl is 137.3 keV, which represents $2\Delta E_{res}$, implying ΔE_{res} = 68.7 keV. This experimental value constitutes a useful benchmark for validating different theoretical predictions. While 6^+ and 7^+ states have also been established in ^{204}Tl [24, 25], these are not included in the above calculation on account of the proximity to ^{208}Pb.

It may further be noted that with the above hypothesis of Ref. [3], the 6^+ state would be isomeric in ^{200}Tl, however, not in ^{198}Tl. On the contrary, the 5^+ assignment for the 762-keV isomer in ^{200}Tl is consistent with the measured conversion coefficient [2] for the 221-keV transition deexciting this state. Furthermore, a similar 5^+ state is observed in ^{198}Tl at E_x = 687 keV which is also found to be isomeric ($T_{1/2}$ = 150(40) ns) [22]. It is suggested that the 5^+ states in both ^{198,200}Tl result from a ($\pi d_{3/2}^{-1} \otimes \nu i_{13/2}^{-1}$), spin-triplet configuration. The spin of the 638-keV level in ^{196}Tl was not assigned. However, its half-life had been measured to be 2.5 ns [26]; a 5^+ spin-parity for this state is suggested.

The variation in energy of the 7^+ state, resulting from the ($\pi s_{1/2}^{-1} \otimes \nu i_{13/2}^{-1}$) configuration, in doubly-odd Tl isotopes mirrors the change in the energy of the $13/2^+$ isomer, arising from the occupation of the $\nu i_{13/2}^{-1}$ orbital, in odd-A Pb nuclei (Fig. 11). This is understandable since the proton Fermi surface for Tl isotopes lies at the location of the $s_{1/2}$ proton orbital. However, in the case of 5^+ levels in Tl isotopes, which also have an underlying $i_{13/2}$ neutron, a decreasing trend in excitation energy is noted for lower neutron numbers, but it is less pronounced than that for the 7^+ states. This can be attributed to higher deformation for lower-mass Tl isotopes as a result of which the $\pi d_{3/2}$ energy (with respect to the Fermi surface) increases with the decrease in neutron number. Consequently, the lowering of the 5^+ level energy is significantly less than that evident for the 7^+ state.

As mentioned previously, the $I^\pi = 7^-$ assignment [2] for the E_x = 1244 keV state in ^{200}Tl appears to be favored in comparison to the $I^\pi = 9^-$ one [3]. The configuration for this isomeric state is ($\pi h_{9/2} \otimes \nu i_{13/2}^{-1}$), as suggested in both previous works. This assignment is also consistent with systematics in odd-odd Tl isotopes.

The newly identified isomer at E_x = 6007 keV in ^{200}Tl is assigned $I^\pi = (26^-)$ and a probable 6-qp configuration. Empirical calculations using information on isomers in neighboring nuclei are consistent with the above assignment. The $N = 119$ isotone, ^{201}Pb, has a 5-qp, $I^\pi = 41/2^+$ isomer with $E_x = (4641{+}x)$ keV, where $x < 70$ keV. In ^{200}Tl, an unpaired $h_{11/2}$

proton can couple to the above state to realize the 6-qp configuration: $\pi h_{11/2}^{-1} \otimes \nu(i_{13/2}^{-3}, f_{5/2}^{-1}, p_{3/2}^{-1})$. The $\pi h_{11/2}$ qp energy from experiment is determined to be 1404 keV from an average of the corresponding energies in ^{199,201}Tl. The sum of the $\pi h_{11/2}$ and the 5-qp energy in ^{201}Pb yields (6045+x) keV, in good agreement with E_x = 6007 keV for the $I^\pi = (26^-)$ state in ^{200}Tl.

Another empirical estimate may be obtained with reference to the $I^\pi = 22^-$, $T_{1/2} = 90$ ns isomer in ^{204}Tl associated with a $(\pi h_{11/2}^{-1} \otimes \nu i_{13/2}^{-3})$ configuration, and the 4^+ level in ^{206}Pb arising from a $\nu(p_{3/2}^{-1}, f_{5/2}^{-1})$ excitation. The coupling of nucleons in the above orbitals leads to the 26^- state in ^{200}Tl. The energy of the residual interaction for the 4-qp configuration in ^{204}Tl is obtained as 960 keV using the $\nu i_{13/2}$ energy from the isotone ^{205}Pb (1014 keV), the average of the $\pi h_{11/2}$ energies from neighboring isotopes ^{203,205}Tl (1467 keV), and the neutron pair-gap energy (770 keV) from a five-point formula [27] of odd-even mass differences (obtained from a recent mass compilation [28]). In a similar manner, the residual interaction energy is estimated to be 234 keV for the above 2-qp configuration in ^{206}Pb. Using these residual interaction energies, and appropriate values for $\nu i_{13/2}$, $\pi h_{11/2}$, $\nu f_{5/2}$ and $\nu p_{3/2}$, 1-qp energies in ^{200}Tl obtained from neighboring nuclei, the energy of the 26^- state is calculated to be 6086 keV, also in fair agreement with the experimental value E_x = 6007 keV.

B. Isomers in ^{201,202}Pb

For some isomers in ^{201,202}Pb, revised half-life values are reported in the present work. An isomer with $I^\pi = 41/2^+$ and $T_{1/2} = 43(3)$ ns had been reported in ^{201}Pb [4]. In the present work, the value of the half-life is revised to $T_{1/2} = 52(2)$ ns. The predominant configuration proposed for this state is $\nu(i_{13/2}^{-3}, f_{5/2}^{-1}, p_{3/2}^{-1})$. This assignment is substantiated by a g-factor measurement [4]. In ^{202}Pb, an isomer with $I^\pi = 16^+$ and $T_{1/2} = 110(5)$ ns had been established [5, 6]. A revised value of the half-life, $T_{1/2} = 93(4)$ ns, has been determined in the present work. The configuration of this isomer was assigned, based on g-factor measurements [6], as predominantly $\nu(i_{13/2}^{-2}, f_{5/2}^{-2})$ with a small $\nu(i_{13/2}^{-2}, f_{5/2}^{-1}, p_{3/2}^{-1})$ admixture.

C. Transition rates

The transition rates of γ rays deexciting isomeric states in ^{200}Tl and ^{201,202}Pb have been determined and compared with Weisskopf single-particle estimates (Table IV). A few isomers in ^{201,202}Pb, where the energies of the deexciting γ rays have not been established, as well as states decaying by *E1* transitions are not included in the comparison. The bulk of the decays listed in Table IV proceed via relatively low-energy *E2* transitions (80-222 keV). In all cases, the partial half-lives and reduced transition probabilities are fairly close to the Weisskopf estimates. The single-particle nature of the states involved, including the high-spin isomer in ^{200}Tl, is thus clearly demonstrated.

IV. SUMMARY

An isomer with $T_{1/2} = 57(2)$ ns has been newly identified in ^{200}Tl and assigned the six-quasiparticle configuration $\pi h^{-1}_{11/2} \otimes \nu(i^{-3}_{13/2}, f^{-1}_{5/2}, p^{-1}_{3/2})$. The decay scheme of ^{200}Tl has been extended with the inclusion of twelve new transitions between high-spin levels. The half-lives of previously established isomers at $E_x = 762$ and 1244 keV have been revised to $T_{1/2} = 397(17)$ ns and 7.0(5) ns, respectively. The discrepancies between the spin-parity assignments for these two isomers from the previous reports [2, 3] have been resolved, and these states are assigned firm spin-parities of $I^\pi = 5^+$ and 7^-, respectively. The configuration of the 5^+ isomeric state is assigned as $(\pi d^{-1}_{3/2} \otimes \nu i^{-1}_{13/2})$. In ^{201}Pb, the half-life of the $I^\pi = 41/2^+$ state is revised to $T_{1/2} = 52(2)$ ns. In ^{202}Pb, a revised value of $T_{1/2} = 93(4)$ ns is reported for the $I^\pi = 16^+$ state. Intrinsic excitations are responsible for the observed isomeric states, and the transition rates for the decay of most of these isomers are in good agreement with Weisskopf single-particle estimates.

V. ACKNOWLEDGMENTS

The authors would like to thank I. Ahmad, J.P. Greene, A.J. Knox, D. Peterson, U. Shirwadkar, X. Wang and C.M. Wilson for assistance during the experiment. PR acknowledges support from the Board of Research in Nuclear Sciences, Department of Atomic Energy, India (Sanction Number 37/(3)/14/43/2014-BRNS). SKT would like to acknowledge support from the University Grants Commission, India, under the Faculty Recharge Programme.

SS acknowledges support from the DST-INSPIRE PhD Fellowship of the Department of Science and Technology, Government of India (Fellowship No. IF170965). This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under award numbers DE-FG02-94ER40848, DE-FG02-94ER40834, DE-FG02-97ER41033 and DE-FG02-97ER41041, and contract number DE-AC02-06CH11357. The research described here utilized resources of the ATLAS facility at ANL, which is a DOE Office of Science user facility.

---

[1] M. Ishihara, Nucl. Phys. A **179**, 223 (1972).

[2] A. J. Kreiner, M. A. J. Mariscotti, C. Baktash, E. der Mateosian and P. Thieberger, Phys. Rev. C **23**, 748 (1981).

[3] S. Bhattacharya, *et al.*, Phys. Rev. C **95**, 014301 (2017).

[4] U. Rosengard, P. Carle, A. Kallberg, L. O. Norlin, K. -G. Rensfelt, H. C. Jain, B. Fant and T. Weckstrom, Nucl. Phys. A **482**, 573 (1988).

[5] B. Fant, T. Weckstrom, H. C. Jain, L. O. Norlin, K. -G. Rensfelt, P. Carle and U. Rosengard, Nucl. Phys. A **475**, 338 (1987).

[6] H. C. Jain, P. Carle, A. Kallberg, L. O. Norlin, K. -G. Rensfelt, U. Rosengard and B. Fant, Nucl. Phys. A **458**, 225 (1986).

[7] S. Buttgenbach, K. Mohrmann, S.Penselin, E.Schrodl, W.Witte, Nucl. Phys. A **395**, 182 (1983).

[8] R. M. Diamond and F. S. Stephens, Nucl. Phys. **45**, 632 (1963).

[9] H. Helppi, S. K. Saha, P. J. Daly, S. R. Faber, T. L. Khoo and F. M. Bernthal, Phys. Rev. C **23**, 1446 (1981).

[10] H. Helppi, S. K. Saha, P. J. Daly, S. R. Faber, T. L. Khoo and F. M. Bernthal, Phys. Lett. B **67**, 279 (1977).

[11] I-Yang Lee, Nucl. Phys. A **520**, 641 (1990); R. V. F. Janssens and F. S. Stephens, Nucl. Phys. News **6**, 9 (1996).

[12] S. K. Tandel, *et al.*, Phys. Lett. B **750**, 225 (2015).

[13] S. G. Wahid, *et al.*, Phys. Rev. C **92**, 054323 (2015).

[14] D. C. Radford, Nucl. Instr. and Meth. A **361**, 297 (1995).

[15] H.-Q. Jin, TSCAN and related programs, RUTGERS-ORNL-UTK, 1992-1997.

[16] G. Baldsiefen, *et al.*, Nucl. Phys. A **592**, 365 (1995).

[17] T. Kibedi, T.W. Burrows, M.B. Trzhaskovskaya, P.M. Davidson, C.W. Nestor, Jr., Nucl. Instr. and Meth. A **589**, 202 (2008).

[18] P. Roy, S. K. Tandel *et al.*, International Conference on Recent Issues in Nuclear and Particle Physics, Santiniketan, February 3-5, 2019.

[19] A. Gorgen, *et al.*, Eur. Phys. J. A **9**, 161 (2000).

[20] O.Hashimoto, A.Sumi, T.Nomura, S.Nagamiya, K.Nakai, T.Yamazakii, K.Miyano, Nucl. Phys. A **218**, 180 (1974).

[21] K.H. Maier, Nucl. Phys. A **195**, 577 (1972).

[22] A. J. Kreiner, M. Fenzl, S. Lunardi and M. A. J. Mariscotti, Nucl. Phys. A **282**, 243 (1977).

[23] N. Fotiades, R.O. Nelson, M. Devlin, J.A. Becker, Phys. Rev. C **76**, 014302 (2007).

[24] R. Broda *et al.*, Phys. Rev. C **84**, 014330 (2011).

[25] N. Fotiades, R.O. Nelson, M. Devlin, J.A. Becker, Phys. Rev. C **77**, 024306 (2008).

[26] A. J. Kreiner, M. Fenzl, and W. Kutschera, Nucl. Phys. A **308**, 147 (1978).

[27] P. Moller and J.R. Nix, Nucl. Phys. A **536**, 20 (1992).

[28] Meng Wang, G. Audi, F.G. Kondev, W.J. Huang, S. Naimi, Xing Xu, Chinese Physics C **41**, 030003 (2017).

[29] F.G. Kondev and S. Lalkovski, Nuclear Data Sheets **108**, 1471 (2007); F.G. Kondev, Nuclear Data Sheets **108**, 365 (2007); S. Zhu and F.G. Kondev, Nuclear Data Sheets **109**, 699 (2008).

TABLE I: Half-life measurements of isomers in ^{200}Tl and ^{201,202}Pb. For each isotope, the spin-parity and excitation energy of the isomer is listed. The half-life is determined by inspecting the difference in time of γ rays ($E\gamma_1$, $E\gamma_2$) above and below the isomer. The inferred half-life from each combination, the mean value and its comparison with the adopted value in current databases [29] are presented.

Isotope	I_i^π	E_x (keV)	$E\gamma_1$-$E\gamma_2$ (keV)	$T_{1/2}$ (ns)	$\overline{T}_{1/2}$ (ns)	$T_{1/2}^{ENSDF}$ (ns)
^{200}Tl	5^+	762	262-221	417(28)	397(17)	330(50)
			262-541	386(21)		
	7^-	1244	311-490	7.1(5)	7.0(5)	4.8(2)
			230-490	6.9(5)		
	(26^-)	6007	g1-286	57(2)	57(2)	-
			g1-749	56(3)		
^{201}Pb	$41/2^+$	4641+x	902-827	52(4)	52(2)	43(3)
			902-728	51(4)		
			447-728	56(3)		
			447-827	49(3)		
^{202}Pb	12^+	3238	853-888	23.5(6)		24.2(3)
	16^+	4091+x	797-853	98(9)	93(4)	110(5)

Isotope	I_i^π	E_x (keV)	$E\gamma_1$-$E\gamma_2$ (keV)	$T_{1/2}$ (ns)	$\overline{T}_{1/2}$ (ns)	$T_{1/2}^{ENSDF}$ (ns)
			354-853	92(7)		
			1151-853	92(6)		
	19^-	5242+y	g2-354	115(9)	113(6)	107(5)
			g2-797	111(8)		

Gating transitions

g1: 217, 230, 311, 348, 490

g2: 689, 841

TABLE II: Multipolarity assignments for transitions in ^{200}Tl based on intensity balance arguments. The total intensities feeding and deexciting a given level populated in the delayed regime from the decay of the $T_{1/2} = 57(2)$ ns have been considered. Theoretical conversion coefficients [17] have been used. For relatively high-energy transitions ($\geq$ 600 keV), the choice of multipolarity does not significantly affect the value of the total intensity (I_{total}) inferred from the γ-ray intensity (I_γ). In the case of lower-energy, weak transitions, the choice of multipolarity does not significantly alter the sum of intensities. The procedure has been used to assign multipolarity to transitions with relatively low energy ($\approx$ 100-300 keV), which potentially have significant conversion coefficients, depending on their character. Gating transitions appropriate to the intensity balance for each level have been used. Level and transition energies, relative γ intensities, multipolarities, theoretical conversion coefficients, total transition intensities corrected for internal conversion, and sums of feeding (Sum*) and deexciting (Sum$^\#$) intensities for each level are listed.

E_x (keV)	E_γ (keV)	I_γ	Multipolarity	α_t	I_{total}	Sum*	Sum$^\#$
5907	**99***	13(2)	*E1*	0.44	19(3)	**93(14)**	**101(5)**
			M1	8.84	128(20)		
			E2	6.18	93(14)		
			M2	75.29	992(153)		
	749$^\#$	100(5)	*E2*	0.01	101(5)		
4165	271*	7(1)	*M1*	0.52	11(1)	**90(3)**	**96(6)**
	707*	31(2)	*M1*	0.04	32(2)		

E_x (keV)	E_γ (keV)	I_γ	Multipolarity	α_t	I_{total}	Sum*	Sum#
	779*	18(1)	*E2*	0.01	18(1)		
	909*	29(2)	*E2*	0.01	29(2)		
	116#	14(1)	*E1*	0.30	19(1)		
			***M*1**	5.62	96(6)		
			E2	3.19	61(4)		
			M2	41.75	618(41)		
4049	271*	10(1)	*M1*	0.52	15(2)	**110(5)**	**108(3)**
	707*	31(2)	*M1*	0.04	32(2)		
	779*	18(2)	*E2*	0.01	18(2)		
	824*	11(1)	*E2*	0.01	11(1)		
	909*	34(3)	*E2*	0.01	34(3)		
	192#	100(3)	***E*1**	0.08	108(3)		
			M1	1.35	235(7)		
			E2	0.47	147(4)		
			M2	6.77	777(23)		
4873	749*	100(8)	*E2*	0.01	101(8)	**101(8)**	**96(7)**

E_x (keV)	E_γ (keV)	I_γ	Multipolarity	α_t	I_{total}	Sum*	Sum#
	220#	30(3)	*E1*	0.06	32(3)		
			***M*1**	0.92	58(6)		
			E2	0.30	39(4)		
			M2	4.21	156(16)		
	436#	9(2)	*M1*	0.14	10(2)		
	707#	17(3)	*M1*	0.04	18(3)		
	824#	10(2)	*E2*	0.01	10(2)		
5158	749*	99(3)	*E2*	0.01	100(3)	**100(3)**	**103(2)**
	286#	100(2)	***E*1**	0.03	103(2)		
			M1	0.45	145(3)		
			E2	0.13	113(2)		
			M2	1.73	273(5)		

Sum* : I_{total}(feeding)

Sum# : I_{total}(deexciting)

TABLE III: Intensity balance considerations for the spin-parity assignment of the $T_{1/2}$ = 397(17) ns isomer at E_x = 762 keV and the $T_{1/2}$ = 7.0(5) ns state at E_x = 1244 keV in ^{200}Tl. Cases 1 and 2 correspond to $I^\pi = 7^-$ and 9^- assignments of Kreiner *et al.* [2] and Bhattacharya *et al.* [3], respectively, for the E_x = 1244 keV state. Transition energies, relative γ intensities, multipolarities, theoretical conversion coefficients [17], and total transition intensities corrected for internal conversion are listed. The 262-keV γ ray deexcites the E_x = 1024 keV level while the 220- and 326-keV transitions feed this state.

Case	E_γ(keV)	I_γ	Multipolarity	α_t	I_t	Sum 1	Sum 2
1	262	90(7)	$M1$	0.57	**141(11)**	**147(10)**	**140(9)**
	220	100(7)	$E1$	0.06	106(7)		
	326	31(5)	$M1$	0.31	41(7)		
			$E2$	0.09	34(5)		
2	262	90(7)	$E1$	0.04	**94(7)**	**171(11)**	**164(11)**
	220	100(7)	$E2$	0.30	130(9)		
	326	31(5)	$M1$	0.31	41(7)		
			$E2$	0.09	34(5)		

Sum 1 : $I_t(220) + I_t(326_{M1})$

Sum 2 : $I_t(220) + I_t(326_{E2})$

TABLE IV: Decays of isomeric states in ^{200}Tl, ^{201,202}Pb and comparison with Weisskopf estimates. Excitation energy, spin-parity, level half-life, transition energy and multipolarity, partial γ-ray half-life (experiment and Weisskopf estimate) and reduced transition probability (in Weisskopf units), respectively, are listed.

Isotope	E_x (keV)	I_i^π	$T_{1/2}$ (ns)	E_γ (keV)	*Mult (Eλ)*	$T^\gamma_{1/2}$ (s)	$T^W_{1/2}$ (s)	*B(Eλ)* (W.u.)
^{200}Tl	6007	(26^-)	57(2)	99	*E2*	4.09 x 10^{-7}	8.56 x 10^{-7}	2.09(7)
^{201}Pb	2719	$25/2^-$	63(3)*	222	*E2*	8.18 x 10^{-8}	1.49 x 10^{-8}	0.18(1)*
	4641+x	$41/2^+$	52(2)	80	*E2*	0.94 x 10^{-6}	2.46 x 10^{-6}	2.62(10)
^{202}Pb	2208	7^-	65.4(2)*	168	*E2*	1.21 x 10^{-7}	0.60 x 10^{-7}	0.50(5)*
				825	*E3*	2.62 x 10^{-6}	1.92 x 10^{-6}	0.7(3)*

* Values adopted from ENSDF [29]

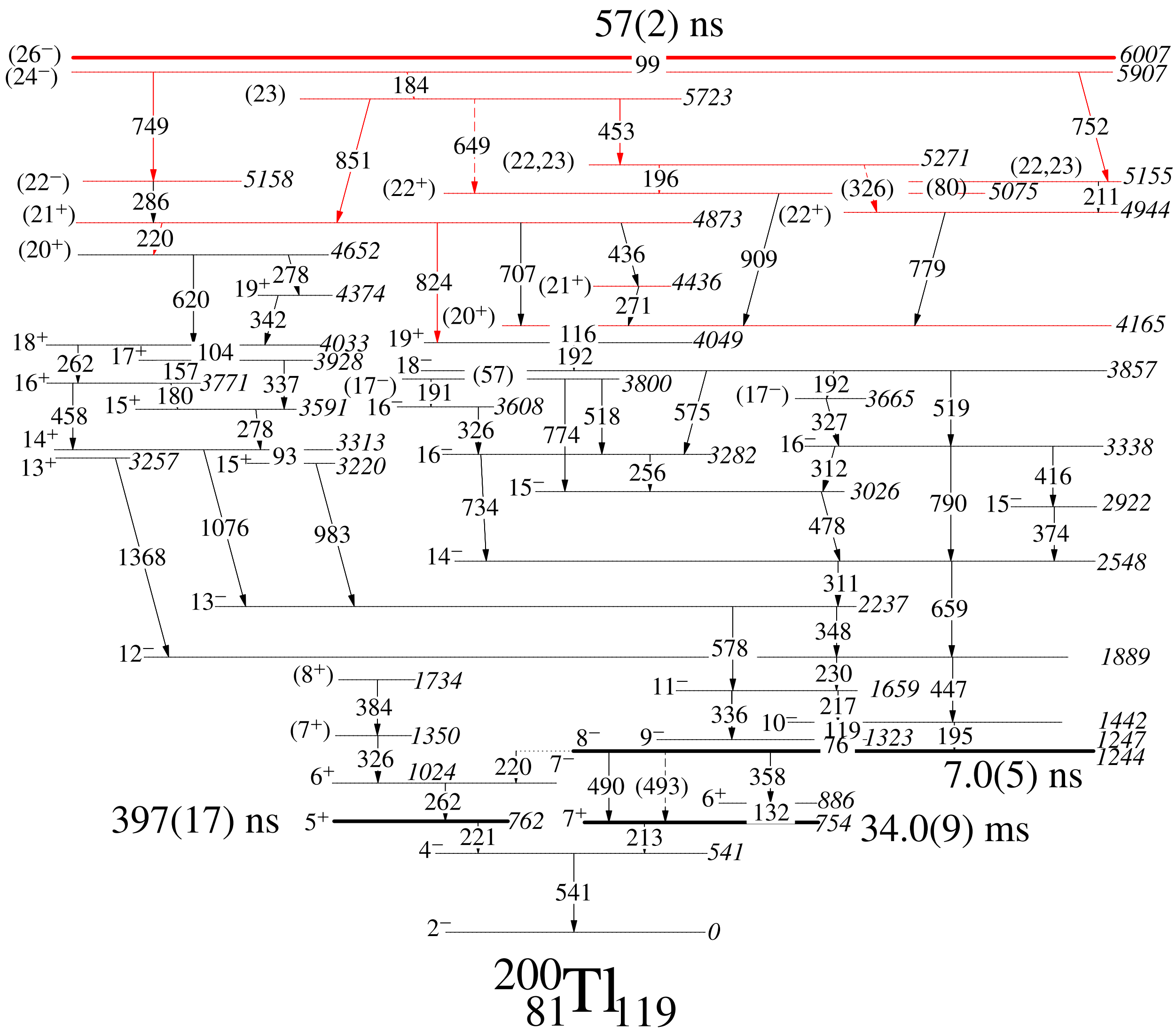

FIG. 1: Partial level scheme for ^{200}Tl displaying transitions observed in the decay of the newly established, $T_{1/2}$ = 57(2) ns isomer in ^{200}Tl. Note that the half-lives of two of the previously established isomers at low spin have been revised (see text). The levels and transitions marked red are newly established in the present work. The half-life of the 7^+ level is adopted from earlier work [29].

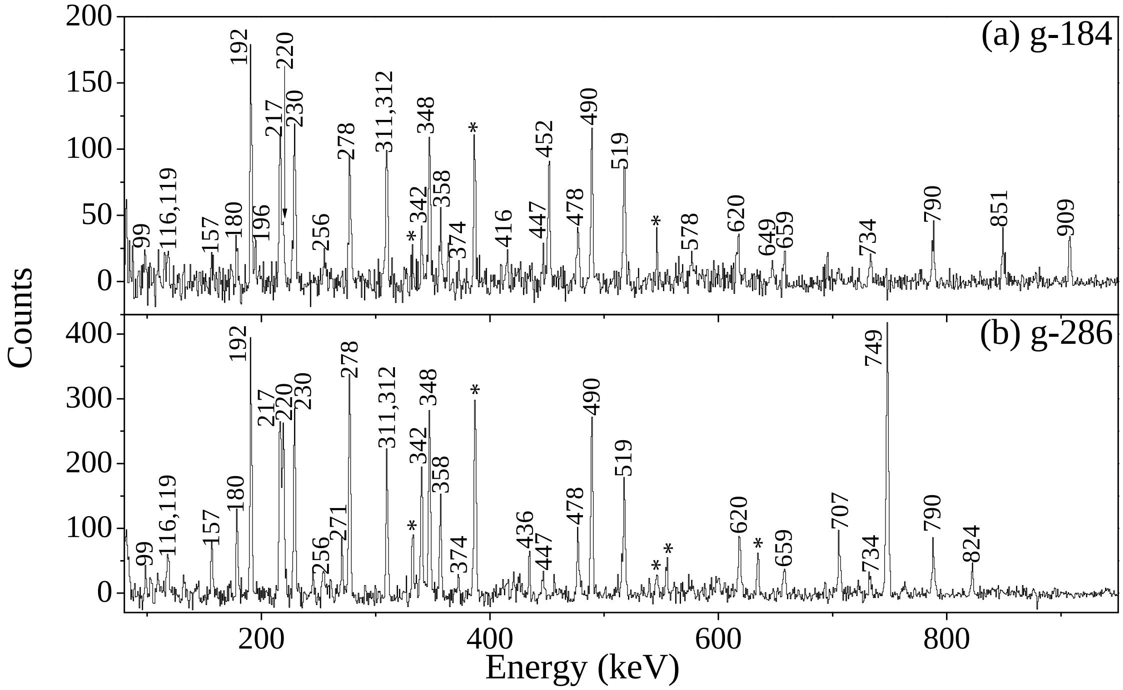

FIG. 2: Double-gated coincidence spectra showing delayed γ rays following the deexcitation of the $T_{1/2} = 57$ ns isomer in ^{200}Tl. The label g corresponds to the 217-, 230-, 311-, 348- and 490-keV γ rays, herewith indicating that the spectra are sums with the coincidence gates placed on all these transitions. The γ rays marked with an asterisk are contaminant peaks.

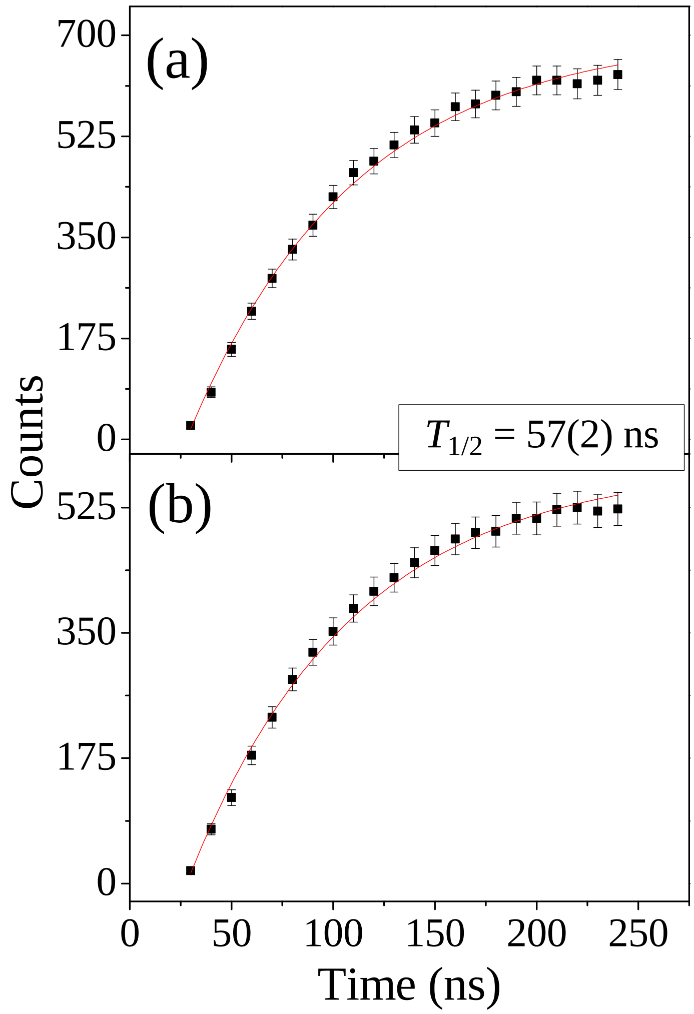

FIG. 3: (Color online) Variation with time of the cumulative intensity of delayed transitions from the newly observed $I^{\pi} = (26^{-})$ state in ^{200}Tl. A half-life of 57(2) ns is inferred. The summed coincidence intensity, in delayed spectra, of the (a) 286-keV γ ray and (b) the 749-keV transition, with the 217-, 230-, 311-, 348- and 490-keV γ rays, is plotted.

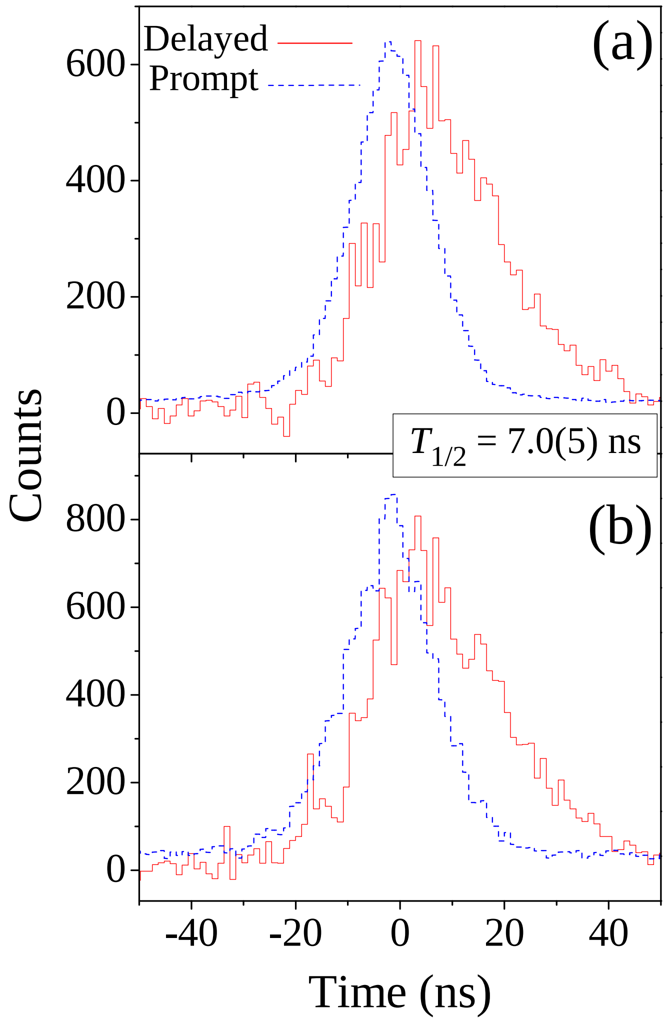

FIG. 4: (Color online) Half-life of the $I^{\pi} = 7^{-}$ isomer in ^{200}Tl measured using the centroid-shift technique. Energies of gating transitions are: (a) 311 and 490 keV; (b) 230 and 490 keV. A value of $T_{1/2} = 7.0(5)$ ns is inferred, which lies outside 3σ limits of the previously reported value of 4.8(2) ns [2]. The solid (red) curve displays the time difference between transitions deexciting and feeding the isomer, while the dashed (blue) one is that characteristic of prompt transitions with similar energies.

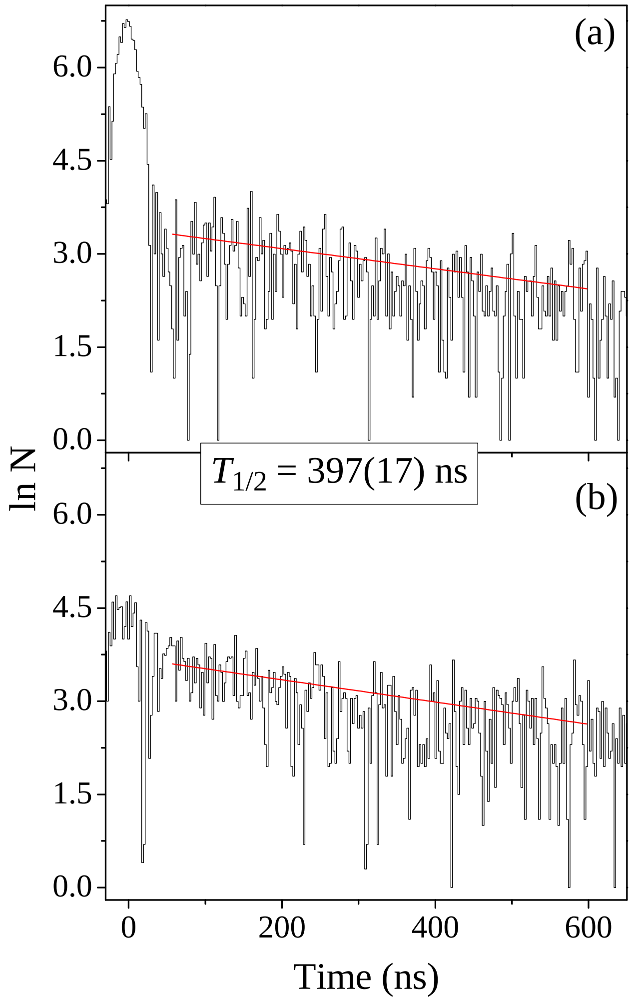

FIG. 5: (Color online) Determination of the half-life of the $I^{\pi} = 5^{+}$, $E_x = 762$ keV state in ^{200}Tl based on the time difference between: (a) the 541- and 220-keV and (b) the 541- and 262-keV transitions. A value of 397(17) ns is inferred in contrast to the previously reported 330(50) ns value [1]. A prompt coincidence peak is visible in (a) since the 220-keV transition above the isomer cannot be fully resolved from the deexciting 221-keV γ ray.

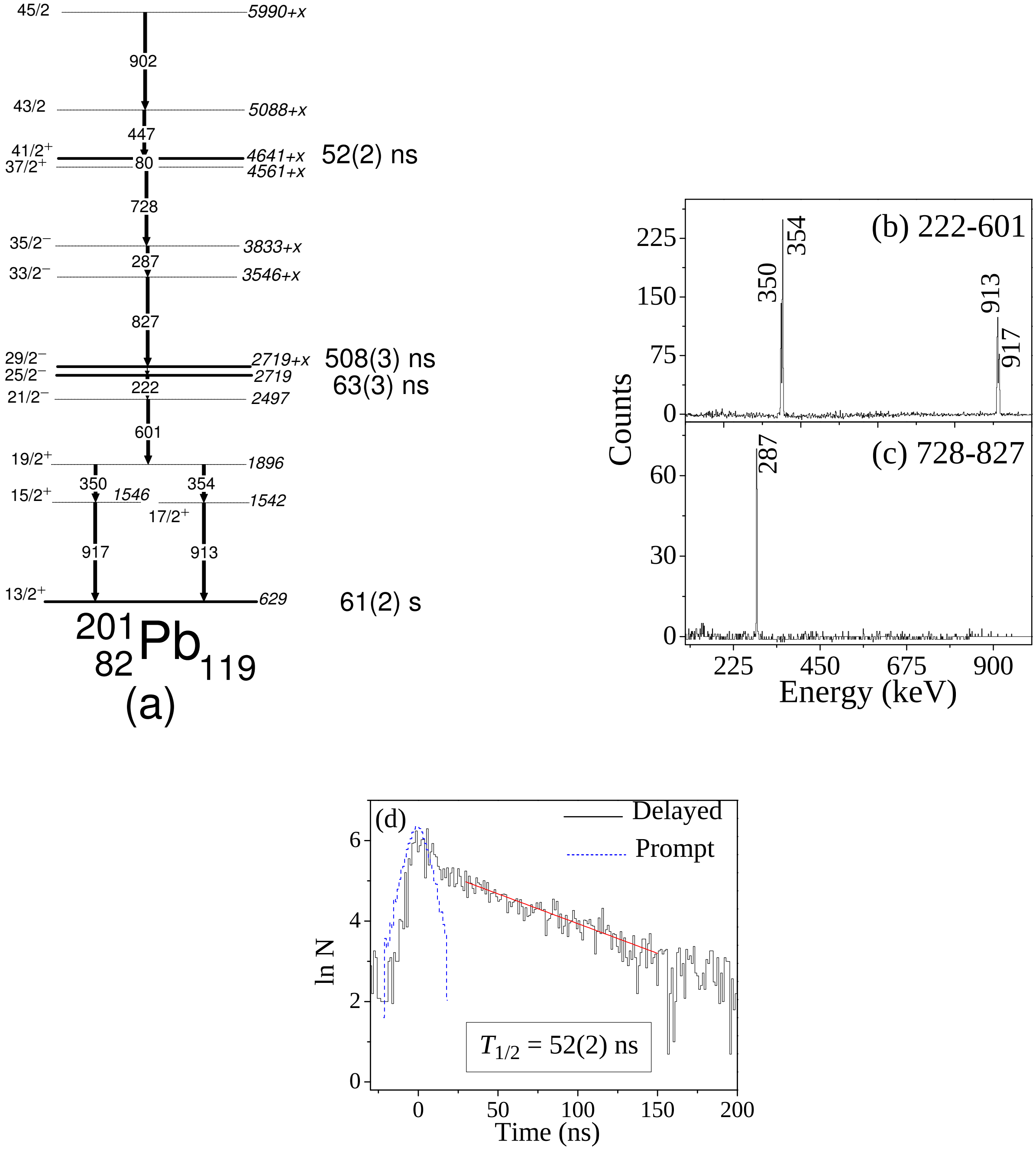

FIG. 6: (Color online) (a) Partial level scheme for ^{201}Pb illustrating the most intense decay paths. The half-lives of the $13/2^+$, $25/2^-$ and $29/2^-$ levels are adopted from earlier work [29]; (b), (c) Delayed coincidence spectra with gates on the transitions indicated; (d) Half-life determination of the $I^\pi = 41/2^+$ state in ^{201}Pb. A value of 52(2) ns is inferred which represents a slight revision of the previously reported 43(3) ns value [4]. For comparison, the time difference spectrum of two prompt γ rays with similar energies is overlaid in blue.

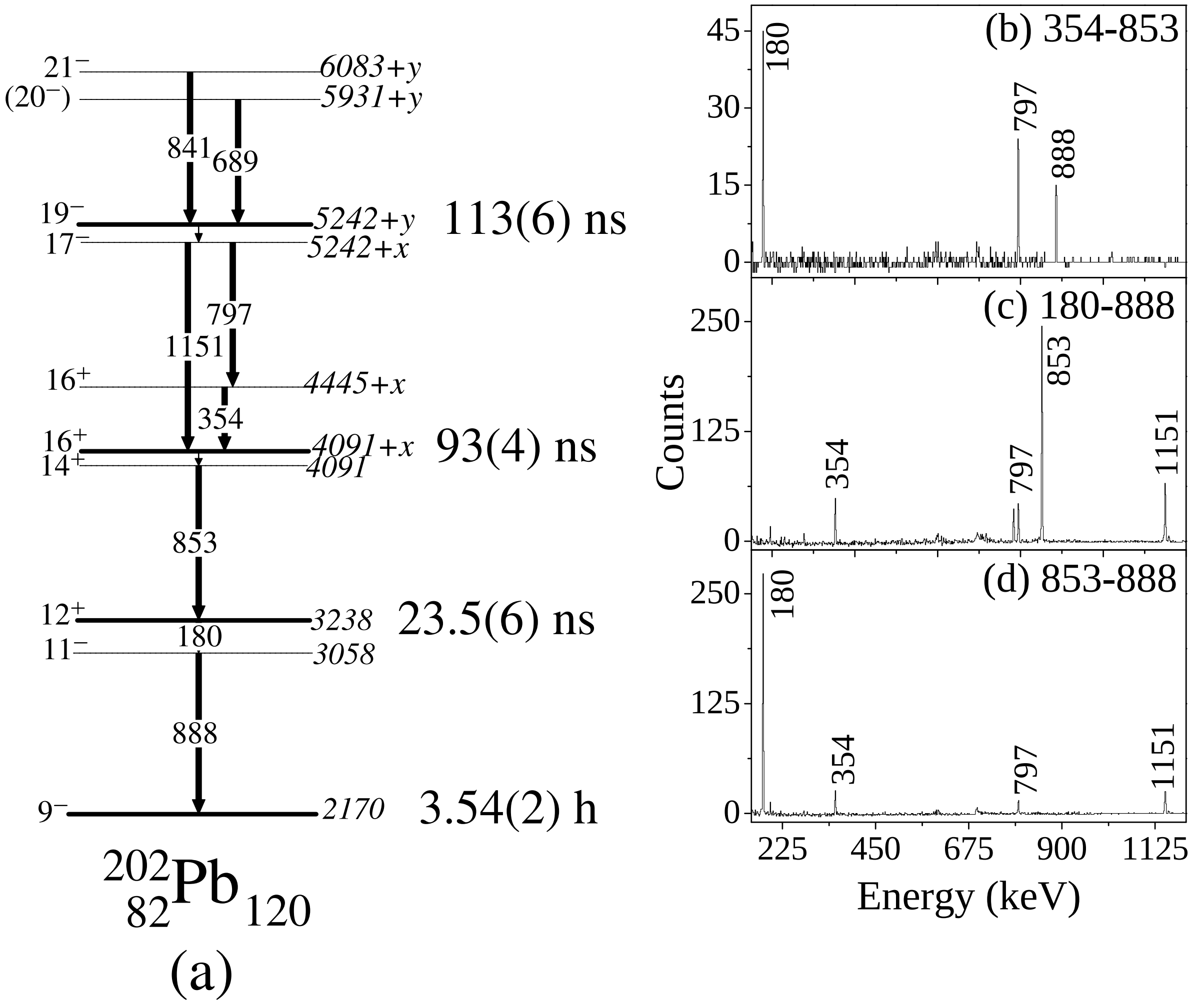

FIG. 7: (a) Partial level scheme for ^{202}Pb illustrating the strongest transitions observed in the present work. The half-life for the 9^- level is adopted from earlier work [29]; (b), (c), (d) Delayed coincidence spectra with gates on the γ rays indicated in the insets.

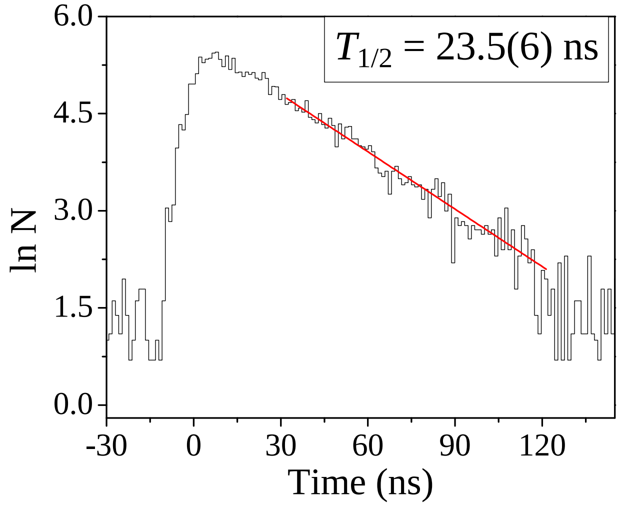

FIG. 8: (Color online) Half-life of the $I^{\pi} = 12^{+}$ state in ^{202}Pb. The measured value of 23.5(6) ns is in agreement with the previously reported 24.2(3) ns one [6].

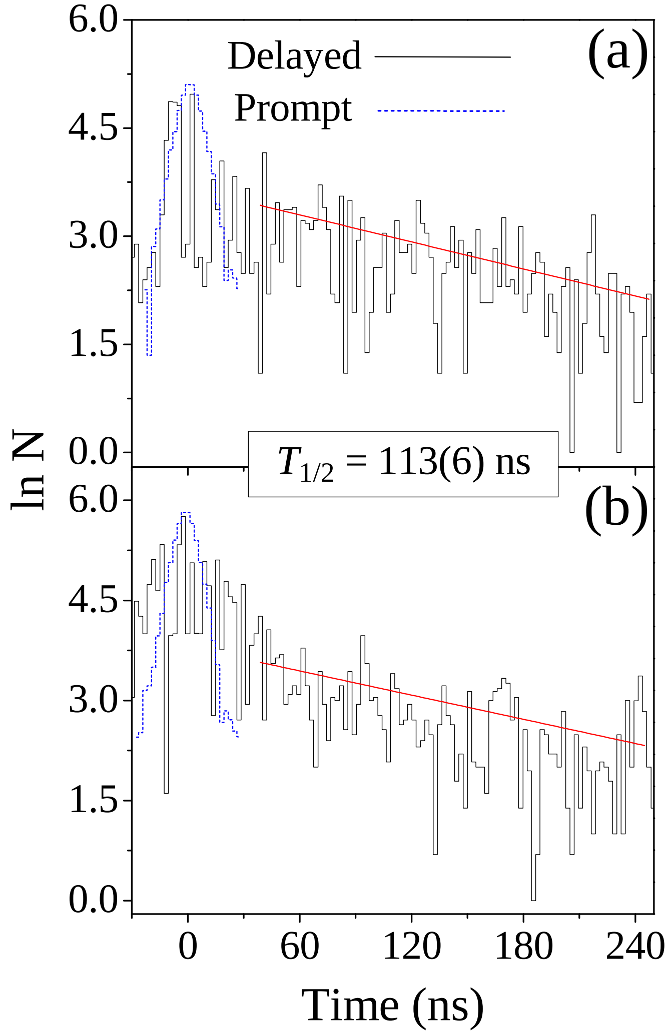

FIG. 9: (Color online) Half-life of the $I^{\pi} = 19^{-}$ state in ^{202}Pb. The measured value of 113(6) ns is consistent with the previously reported one of 107(5) ns [5]. The time difference between the 689- and 841-keV transitions and the (a) 797-keV, and (b) 354-keV γ rays is presented.

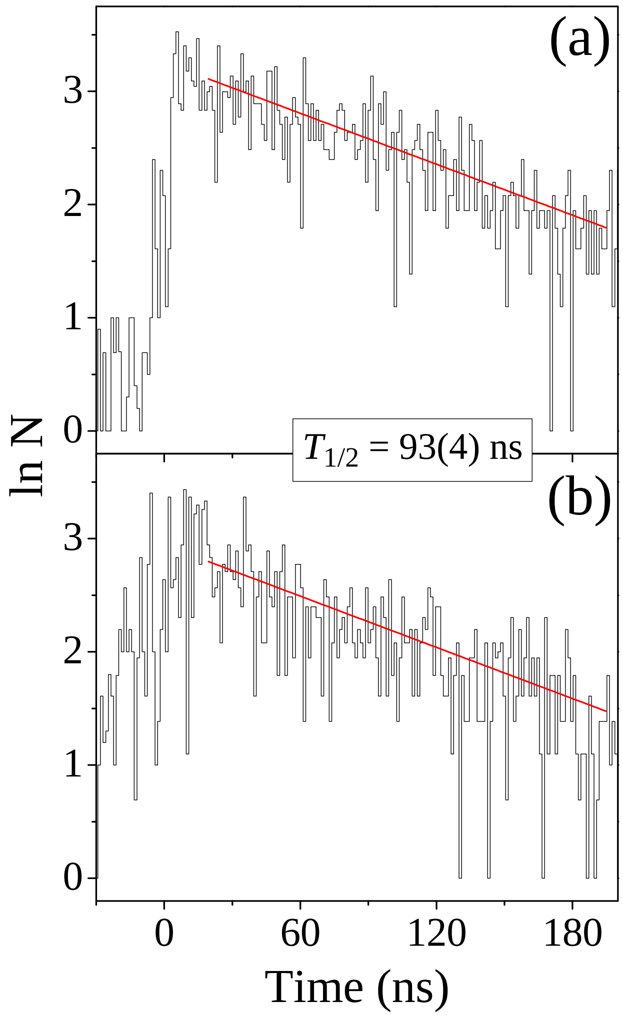

FIG. 10: (Color online) Half-life of the $I^{\pi} = 16^{+}$ state in ^{202}Pb. The time difference between delayed transitions fed in the decay of the higher-lying, 19^{-} isomer is given. The measured value of 93(4) ns represents a revision of the previously reported 110(5) ns one [6]. The time difference between the (a) 797-keV, and (b) 354-keV γ rays and the 853-keV transition is plotted.

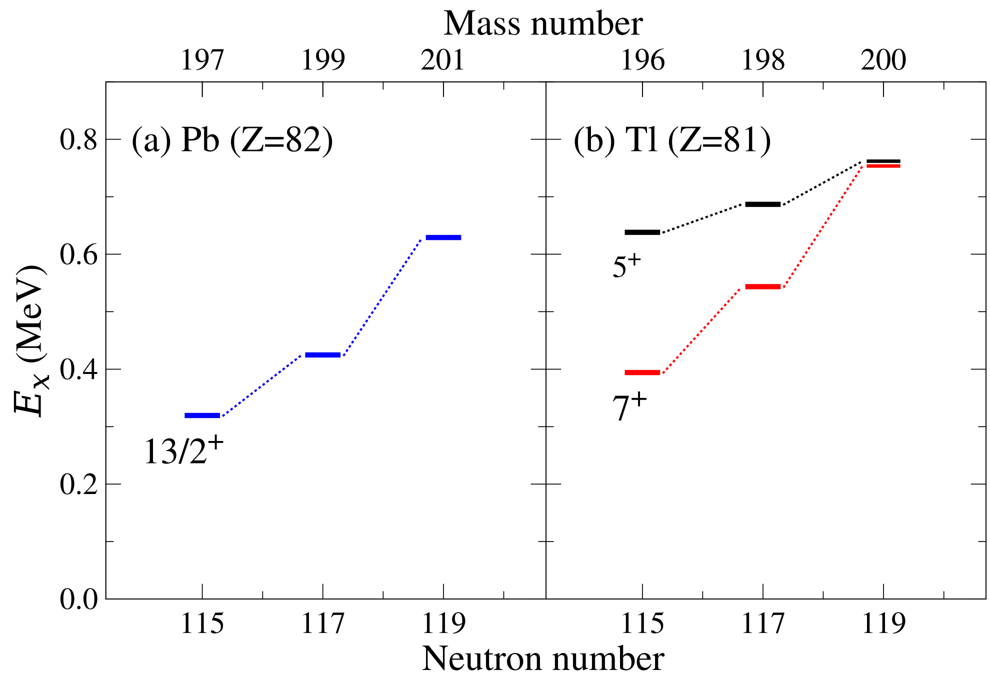

FIG. 11: (Color online) Systematics of level energies of: (a) $13/2^+$ isomers in odd-A Pb isotopes associated with a $\nu i_{13/2}^{-1}$ configuration; (b) 5^+ and 7^+ isomers in doubly-odd Tl isotopes with $(\pi d_{3/2}^{-1} \otimes \nu i_{13/2}^{-1})$ and $(\pi s_{1/2}^{-1} \otimes \nu i_{13/2}^{-1})$ configurations, respectively (see text for detailed discussion).