α-decay spectroscopy of the chain ^{179}Tl^{g} $\rightarrow$ ^{175}Au^{g} $\rightarrow$ ^{171}Ir^{g} $\rightarrow$ ^{167}Re^{m}

A. N. Andreyev,[1,2,11,*] V. Liberati,[3] S. Antalic,[4] D. Ackermann,[5] A. Barzakh,[6] N. Bree,[2] T. E. Cocolios,[2,15] J. Diriken,[2] J. Elseviers,[2] D. Fedorov,[6] V. N. Fedosseev,[7] D. Fink,[7,16] S. Franchoo,[8] S. Heinz,[5] F. P. Heßberger,[5,17] S. Hofmann,[5,9] M. Huyse,[2] O. Ivanov,[2] J. Khuyagbaatar,[5] B. Kindler,[5] U. Köster,[10] J. F. W. Lane,[3] B. Lommel,[5] R. Mann,[5] B. Marsh,[7] P. Molkanov,[6] K. Nishio,[11] R. D. Page,[12] N. Patronis,[2,18] D. Pauwels,[2] D. Radulov,[2] Š. Šáro,[4] M. Seliverstov,[1,2,6,7] M. Sjödin,[7] I. Tsekhanovich,[13] P. Van den Bergh,[2] P. Van Duppen,[2] M. Venhart,[2,14] and M. Veselský[14]

[1]*Department of Physics, University of York, Heslington, York YO10 5DD, United Kingdom*
[2]*Instituut voor Kern en Stralingsfysica, KU Leuven, University of Leuven, B-3001 Leuven, Belgium*
[3]*School of Engineering and Science, University of the West of Scotland, Paisley, PA1 2BE, United Kingdom*
[4]*Department of Nuclear Physics and Biophysics, Comenius University, 84248 Bratislava, Slovakia*
[5]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*
[6]*Petersburg Nuclear Physics Institute, 188350 Gatchina, Russia*
[7]*CERN, CH-1211 Geneve 23, Switzerland*
[8]*IPN Orsay, F-91406 Orsay Cedex France*
[9]*J.W. Goethe-Universität, D–60054 Frankfurt, Germany*
[10]*Institut Laue Langevin, 6 Rue Jules Horowitz, F-38042 Grenoble Cedex 9, France*
[11]*Advanced Science Research Center, Japan Atomic Energy Agency (JAEA), Tokai-mura, Naka-gun, Ibaraki, 319-1195, Japan*
[12]*Department of Physics, Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[13]*Centre d'Etudes Nucleaires de Bordeaux Gradignan, F-33175 Gradignan Cedex, France*
[14]*Institute of Physics, Slovak Academy of Sciences, 84511 Bratislava, Slovakia*
[15]*School of Physics and Astronomy, University of Manchester, Manchester, M13 9PL, United Kingdom*
[16]*University of Heidelberg, Heidelberg, Germany*
[17]*Helmholtz Institut Mainz, 55099 Mainz, Germany*
[18]*Department of Physics, University of Ioannina, Ioannina, Greece*

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Detailed α-decay studies of ^{179}Tl^{g} and its daughter products ^{175}Au^{g} and ^{171}Ir^{g} were carried out in two complementary experiments at the mass separator ISOLDE (CERN) and velocity filter SHIP (GSI). First unambiguous determination of the α-decay properties of ^{175}Au^{g} was performed as follows: $E_{\alpha} = 6433(4)$ keV, $T_{1/2} = 207(7)$ ms, and α-decay branching ratio 90(7)%. First determination of the α-decay branching ratios for ^{179}Tl^{g} and ^{171}Ir^{g} was also made: $b_{\alpha}(^{179}\mathrm{Tl}^{g}) = 60(2)\%$ and $b_{\alpha}(^{171}\mathrm{Ir}^{g}) = 15(2)\%$. The spins of the ground states in ^{175}Au and ^{171}Ir are established as $1/2^{+}$.

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I. INTRODUCTION

In 1983, Schneider *et al.* reported the discovery of the isotope ^{179}Tl [1] at the velocity filter SHIP (GSI, Darmstadt) [2] by using the complete-fusion reaction ^{89}Y(^{92}Mo,2n)^{179}Tl. In total $\sim$20 α-decay events with $E_{\alpha} = 6.56(2)$ MeV and $T_{1/2} = 160^{+90}_{-40}$ ms were attributed to the ground state of ^{179}Tl, denoted further in the text as ^{179}Tl^{g} (see Table I). In addition, 10 decays with $E_{\alpha} = 7.20(2)$ MeV and a half-life of 1.4 ± 0.5 ms were observed, which were tentatively assigned to the decay of an isomeric state in ^{179}Tl, denoted further ^{179}Tl^{m}. The assignment to the decay of the isomeric and ground states was based solely on the systematics of the heavier odd-A thallium isotopes.

In later studies, based on a relatively low number of observed events, comparable data on the α-decay energy of ^{179}Tl^{g} were measured by Page *et al.* [3], Toth *et al.* [4], and Rowe *et al.* [5] (see Table I). However, the reported half-life values are different by a factor of $\sim$2.6 between the smallest and the largest values, though the experimental uncertainties are quite large. In these three experiments ^{179}Tl nuclei were produced in different complete-fusion reactions with heavy ions, followed by the separation with a recoil separator and implantation in a silicon detector where their subsequent α decays were measured. Both the longer-lived ground state and the short-lived isomeric state of ^{179}Tl were observed in these studies. By analogy with other odd-A Tl isotopes, all earlier studies proposed a spin parity of $I^{\pi} = (1/2^{+})$ due to the $\pi 3s^{-1}_{1/2}$ configuration for the ground state of ^{179}Tl. This inference was recently directly confirmed by the laser spectroscopy measurements at ISOLDE [6].

More refined measurements of the α-decay properties of ^{179}Tl were performed by Andreyev *et al.* [7] at SHIP by using the complete-fusion reaction ^{144}Sm(^{40}Ca,p4n)^{179}Tl. Approximately 3000 decay events were attributed to ^{179}Tl^{m}, which is at least one order of magnitude larger than in any previous experiment. Due to the higher statistics, more precise values of $E_{\alpha} = 7207(5)$ keV and $T_{1/2} = 1.46(4)$ ms were deduced for ^{179}Tl^{m} in comparison to the earlier studies. For consistency of the discussion, the data for ^{179}Tl^{m} and its daughter products ^{175}Au^{m} and ^{171}Ir^{m} from [7] are also shown in

*Corresponding author: andrei.andreyev@york.ac.uk

TABLE I. Comparison of the α-decay energies E_α, half-life values $T_{1/2}$, and α-branching ratios b_α from our measurements and from earlier studies of $^{179}Tl^{g,m}$, ^{175}Au, and $^{171}Ir^g$. The half-life value for $^{179}Tl^g$ and α-decay energies for $^{179}Tl^g$ and $^{175}Au^g$ from the present work are weighted averages of our two independent measurements at ISOLDE and SHIP. The indicated statistical uncertainties of α-decay energies from the present work are from the Gaussian fits of the respective peaks. A typical systematical uncertainty of ~5 keV should be added due to the calibration procedures used at SHIP and ISOLDE.

Isotope, I^π	E_α (keV)	$T_{1/2}$ (ms)	b_α (%)	δ_α^2 (keV)	Reference
$^{179}Tl^g$, $1/2^+$	6560(4)	265(10)	60(2)	50(3)	This work
	6560(20)	160^{+90}_{-40}			[1]
	6568(18)	430(350)			[3]
	6569(10)	230(40)			[4]
	6568[a]	415(55)			[5]
$^{179}Tl^m$, $(11/2^-)$	7207(5)	1.46(4)	100	89(4)	[7]
	7200(20)	1.4(5)			[1]
	7201(20)	$0.7^{+0.6}_{-0.4}$			[3]
	7213(10)	1.8(4)			[4]
	7201	1.7(2)			[5]
$^{175}Au^g$, $1/2^+$	6433(4)	207(7)	90(7)	44(4)	This work
	6412[a,c]				[5]
$^{175}Au^m$, $(11/2^-)$	6432(5)	138(5)	90(3)	67(4)	[7]
	6440(10)				[8]
	6435(10)	200(22)	94^{+6}_{-25}		[1]
	6438(9)	185(30)			[3]
	6430[a]	143(8)			[9]
	6438[a,b]	158(3)			[5]
	6430[d]	139(2)			[10]
$^{171}Ir^g$, $1/2^+$	5734(7)		15(2)	43^{+12}_{-20}	This work
	5717(10)[e]	$3.2^{+1.7}_{-0.7}$ s			[5]
$^{171}Ir^m$, $(11/2^-)$	5925(8)	1.4(1) s	53(5)	54(7)	[7]

[a]No uncertainty value was quoted.
[b]Attributed to $^{175}Au^m$ in Ref. [5].
[c]Tentatively attributed to $^{175}Au^g$ in Ref. [5].
[d]Quoted value from Ref. [9].
[e]Tentatively attributed to $^{171}Ir^g$ in Ref. [5].

Table I. We mention already at this moment that our denotation of the states in the α-decay chains of $^{179}Tl^{m,g}$ as isomeric or ground state throughout this work will be justified in Sec. IV B. Based on systematics of excited states and α-decay properties of odd-A Tl isotopes, a spin-parity $I^\pi = (11/2^-)$ and a $\pi\, 1h^{-1}_{11/2}$ configuration [7] were assigned to the shorter-lived isomer, which confirmed the earlier studies.

The previously known α-decay properties of ^{175}Au, the daughter of ^{179}Tl, are summarized in Table I. Based on the observation of a few tens of α-decay events, the first study by Cabot *et al.* [8] assigned an α decay with $E_\alpha = 6440(10)$ keV to this nuclide, but no half-life could be measured. The later studies [1,3,5,9,10] reported similar α-decay energies, but the agreement between the reported half-lives is not satisfactory.

The presence of two α-decaying states in ^{179}Tl with very different configurations raises a question on the possible occurrence of two long-lived states in the daughter nuclide ^{175}Au. The unhindered nature of the 7207-keV decay of $^{179}Tl^m$ [7] establishes the same spin parity of $I^\pi = 11/2^-$ for the state in the daughter ^{175}Au fed by this decay. As shown in Table I, all previous studies except [5] observed a single α-decay line for ^{175}Au, which was indeed attributed to the decay of the high-spin $11/2^-$ state, which is dominantly populated in the complete-fusion reactions used in all previous studies. The recent in-beam study of ^{175}Au [9] provided first data on excited states above the $11/2^-$ state.

Due to the absence of the experimentally measured α-branching ratio for $^{179}Tl^g$, no conclusion was drawn in the previous studies in respect to whether the 6.56-MeV decay of $^{179}Tl^g$ is favored or hindered. This, in turn, prevented firm conclusions from being drawn on the nature of the state populated by this decay in the daughter ^{175}Au. To our knowledge, the only work which claimed the observation of α decay of the second state in ^{175}Au was the investigation by Rowe *et al.* [5]. This study tentatively identified a weak group of $\alpha(6412)$-$\alpha(5717(10))$ correlated decays and assigned it to the $^{175}Au^g$–$^{171}Ir^g$ decay. However, Rowe *et al.* [5] stated: "…Unfortunately, correlated decays preceding or following this pair, which would confirm this assignment, were not observed." Therefore this identification needed an independent confirmation, which was one of the goals of our study.

We report here on dedicated α-decay studies of $^{179}Tl^g$ and its daughter $^{175}Au^g$, performed at two experimental setups: the mass separator ISOLDE (Geneva, CERN) [11] and the velocity filter SHIP (GSI, Darmstadt) [2]. The present study will use the so far unpublished α-decay data for $^{179}Tl^g$ from the same experiment as discussed in [7]. In each experiment several thousand decays of $^{179}Tl^g$ were observed, which is at least an order of magnitude higher than in any previous study of this isotope. The complementary data from both experiments allowed for the first time the reliable decay sequence of $^{179}Tl^g$–$^{175}Au^g$ to be established. The structure of the paper is as follows: In Secs. II A and II B, the ISOLDE and SHIP experiments are described, respectively. The results are presented in Sec. III A (ISOLDE) and Sec. III B (SHIP), followed by the discussion in Sec. IV.

II. EXPERIMENTAL SETUPS

A. ISOLDE experiments

The study of $^{179}Tl^g$ was performed at the mass-separator ISOLDE as a part of our extensive experimental campaign to study β-delayed fission (βDF) of $^{178,180}Tl$ [12–15] and shape coexistence phenomena in the long chain of Tl isotopes [6]. Two experiments have been performed, Run I in 2008 and Run II in 2011. The methods and the setup used in this work were described in detail in our βDF study of ^{178}Tl [14]. Thus, only a description of the most relevant features will be given here. In both Run I and II, the ^{179}Tl nuclei were produced in spallation reactions induced by a 1.5-μA, 1.4-GeV proton beam in the 50-g/cm^2-thick UC_x target of ISOLDE. The ^{179}Tl nuclei produced in the target were selectively ionized to the 1^+ charge state by using the Resonance Ionization Laser Ion Source (RILIS) [16,17] of ISOLDE, operating in the broadband mode. After ionization and extraction from the target, the ^{179}Tl ions were accelerated up to 30 keV (Run I) or 50 keV (Run II) and then mass separated with the ISOLDE High Resolution

Separator (HRS) in Run I and with the General Purpose Separator (GPS) in Run II.

The specific feature of these experiments lies in the fact that the atoms corresponding to the shorter-lived 1.46-ms isomeric state $^{179}\mathrm{Tl}^m$ were not extracted from the target of ISOLDE, due to a much longer release time. Thus, the combined use of RILIS, which gives the Z selection, and ISOLDE, which provides the A selection, allowed a pure beam of $^{179}\mathrm{Tl}^g$ to be obtained.

The measurements of decay properties were performed with the use of the Windmill system [12]. In Run I at the HRS, after the mass separation, the pure 30-keV $^{179}\mathrm{Tl}^g$ beam passed through the 6-mm-diameter central hole of an annular silicon detector of 300-μm thickness and active area of 450 mm^2. The ions were implanted into one of the 10 20-μg/cm^2-thick carbon foils installed on the rotating disk of the Windmill system. A second circular silicon detector, of 300-μm thickness and active area of 300 mm^2, was installed 2 mm behind the carbon foil. The total registration efficiency for α particles in both silicon detectors was 66% [12]. This value was deduced based on straightforward and robust GEANT Monte Carlo simulations. To detect γ- and x-ray decays a single Miniball Ge cluster [18], consisting of three HPGe crystals, was placed ~1 cm behind the circular Si detector, outside the vacuum chamber. Due to the relatively short half-lives of the studied activities and the low implantation rate, no usual automatic periodic movement of the Windmill's rotating disk was used in this run. Instead, the disk was moved manually approximately once per hour, to remove the foil with the accumulated long-lived daughter activities and introduce a fresh implantation foil.

A similar procedure was used in Run II at the GPS. However, due to the lower mass resolving power of the GPS, a small contamination from α decays of different francium isotopes (mostly around masses $A = 207$–213), abundantly produced in the target and efficiently surface-ionized in the hot cavity of the ion source, was present. Therefore, only the data from Run I were used to derive values reported in this study.

The α-decay energy calibration was performed using the tabulated α-decay energies of the daughter products of implanted $^{179}\mathrm{Tl}^g$: ^{179}Hg [$E_\alpha = 6285(3)$ keV [19]] and ^{175}Pt [$E_\alpha = 5959.5(24)$ keV [19]] and of an ^{241}Am source, $E_\alpha = 5485.56(12)$ keV [19]. An energy resolution of 40 keV [full width at half maximum (FWHM)] was measured for α decays in the energy range of 5000–7000 keV.

B. SHIP experiment

In the SHIP experiment, the isotope ^{179}Tl was produced in the complete-fusion reaction ^{144}Sm(^{40}Ca,p4n)^{179}Tl, as a by-product of the study of the new isotope ^{179}Pb [7], produced in the 5n evaporation channel of this reaction. In the same paper, a detailed discussion of the decay properties of $^{179}\mathrm{Tl}^m$ was also provided.

The typical intensity of the ^{40}Ca beam, provided by the UNILAC of GSI, was ~400 pnA. Most of the data were collected at a beam energy of 232 MeV in front of the target, corresponding to the maxima of the 5n and $p4n$ evaporation channels of the studied reaction.

Eight ^{144}Sm targets of 96.4% isotopic enrichment and ~350-μg/cm^2 thickness, were mounted on a wheel, rotating synchronously with the UNILAC macro-pulsing. The targets were produced by evaporating the $^{144}\mathrm{SmF}_3$ material onto a carbon backing of 40-μg/cm^2 thickness.

After separation by the velocity filter SHIP, the evaporation residues (ERs) were implanted into a 300-μm-thick, 35×80 mm^2 16-strip position-sensitive silicon strip detector (PSSD), where their subsequent particle decays were measured by using standard implantation and correlation techniques [20].

The energy calibration of the PSSD was performed by using known α decays of the isotopes $^{176-182}$Hg and their daughter products, having energies in the range of 5300–6800 keV. The mercury isotopes were produced via α,xn evaporation channels of the studied reaction (see Ref. [7]). A typical PSSD energy resolution of ~25 keV (FWHM) was achieved in the energy interval of 6000–7500 keV for full-energy α decays measured in the PSSD. Since α emission is a dominant decay mode of most of the nuclei produced in this reaction, the identification of nuclides was based on the observation of genetically correlated α-decay chains complemented with excitation function measurements.

III. RESULTS

A. Study of decay of $^{179}\mathrm{Tl}^g$ at ISOLDE

In total $\sim 3.4 \times 10^3$ α decays of $^{179}\mathrm{Tl}^g$ were observed ($\sim 2.4 \times 10^3$ in Run I and $\sim 10^3$ in Run II). Figure 1 shows the relevant part of the α-decay spectrum measured in Run I in both silicon detectors.

The spectrum in Fig. 1 shows the purity of the $^{179}\mathrm{Tl}^g$ beam as all the observed decays originate from $^{179}\mathrm{Tl}^g$ itself or from the decays of its daughter nuclides: $^{175}\mathrm{Au}^g$ (after α decay), ^{179}Hg (after EC/β^+ decay), ^{175}Pt (after EC/β^+ decay of $^{175}\mathrm{Au}^g$, and after α decay of ^{179}Hg) and ^{179}Au (after EC/β^+ decay of ^{179}Hg). We remind the reader that the α-decay energies of ^{175}Pt and ^{179}Hg were used to calibrate the silicon detectors; therefore their energies coincide with the tabulated values. The decay at 6038 keV was assigned to the known decay of ^{175}Pt based on its measured decay energy. The peak

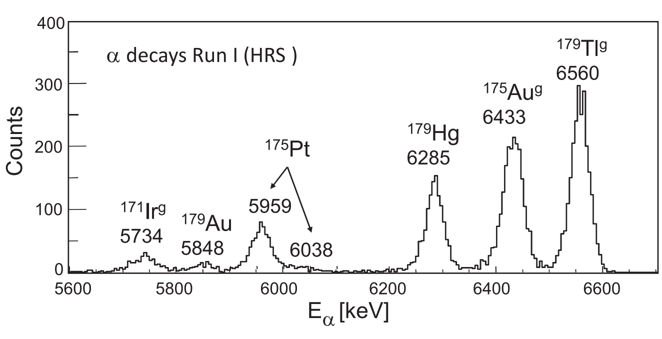

FIG. 1. A part of the α-decay spectrum collected in the silicon detectors in Run I (HRS). The α peaks are denoted with their energies in keV and the isotope to which they belong.

at 5734 keV was assigned by us to ^{171}Ir, being the daughter of ^{175}Au, and will be discussed below.

The α-decay line at 6560(5) keV was attributed to the α decay of ^{179}Tl^g. Within the uncertainty this value agrees with, but is of a higher precision, than the previously reported values (see Table I). The peak at 6433(5) keV was assigned by us to the previously unknown α decay of ^{175}Au^g, since no other nuclei with such a decay energy could be present in the decay chain of ^{179}Tl^g. We note that ^{175}Au^m has practically the same α-decay energy of 6432(5) keV (see [7] and the discussion of the SHIP data). However, this isomer could not be directly implanted in the Windmill in our study, as no short-lived parent ^{179}Tl^m was extracted from the target, as described in Sec. II A. In addition, due to the large angular momentum change required, the decay of the low-spin $I^\pi = 1/2^+$ ^{179}Tl^g to the high-spin $I^\pi = (11/2^-)$ isomer ^{175}Au^m would be strongly inhibited. Therefore, we conclude that both ^{175}Au^m and ^{175}Au^g have very similar α-decay energies. Anticipating the discussion of the excitation energies of the isomeric states in Sec. IV B, we mention that despite the fact that the experimental excitation energy of ^{175}Au^m is not yet known (see also [9]), our estimate shows that it should be located ~200 keV above the ground state. This is the reason why we denote the two α-decaying states of ^{175}Au as the ground and isomeric states.

No γ rays or x rays were seen in coincidence with either the α decays of ^{179}Tl^g or ^{175}Au^g, so direct transitions from ground state to ground state in the α-decay chain ^{179}Tl^g $\rightarrow$ ^{175}Au^g $\rightarrow$ ^{171} Ir^g are suggested.

1. *Half-life value of ^{179}Tl^g*

The half-life determination of ^{179}Tl^g is based on the data from Run I. The "grow-in-decay" method described in detail in Ref. [13] was applied by using the 6560-keV α decay of ^{179}Tl^g [see Fig. 2(a)]. The "decay" part of the "grow-in-decay" curve was fitted with an exponential function, shown by the red line, and a half-life value of 263(17) ms was obtained. Within the rather large uncertainties of the previously reported values in Refs. [1,3–5], our value is in broad agreement with them. Furthermore, this value is in good agreement with the value $T_{1/2}(^{179}\mathrm{Tl}^g) = 267(13)$ ms from the independent study at SHIP (see Sec. III B). The final value of $T_{1/2}(^{179}\mathrm{Tl}^g) = 265(10)$ ms, shown in Table I, was deduced as a weighted average of the ISOLDE and SHIP measurements.

2. *Branching ratios for ^{179}Tl^g and ^{175}Au*

The purity of the ^{179}Tl^g source allows the first experimental determination of the α- and β-decay branching ratios for this isotope. By comparing the intensities of the parent ^{179}Tl^g and daughter ^{179}Hg in Fig. 1(a), and using the α-decay branching ratio $b_\alpha(^{179}\mathrm{Hg})$=75(3)% [21], a β-decay branching ratio of $b_\beta(^{179}\mathrm{Tl}^g) = 40(2)\%$ and an α-decay branching ratio of $b_\alpha(^{179}\mathrm{Tl}^g) = 60(2)\%$ were deduced. This method can be applied because ^{179}Hg is produced only via β decay of ^{179}Tl^g, as ^{179}Hg cannot be ionized either by surface ionization or by laser ionization tuned to Tl isotopes. This was proved in the βDF measurements at the mass $A = 180$, when the intensity ratios between ^{180}Tl and ^{180}Hg were compared with the laser tuned on Tl ionization and with the laser tuned off [13].

Furthermore, by comparing the numbers of α decays of ^{179}Tl^g and of the daughter ^{175}Au (after α decay) in Fig. 1(a), with necessary corrections for ^{175}Au for the recoil losses from the carbon foil, similar to those reported in Ref. [22], an α-decay branching ratio $b_\alpha(^{175}\mathrm{Au}^g) = 90(7)\%$ and a β-decay branching ratio of $b_\beta(^{175}\mathrm{Au}^g) = 10(7)\%$ were deduced. Within the uncertainty our α-decay branching ratio agrees with the less precise value of $b_\alpha = 94^{+6}_{-25}\%$ from [1].

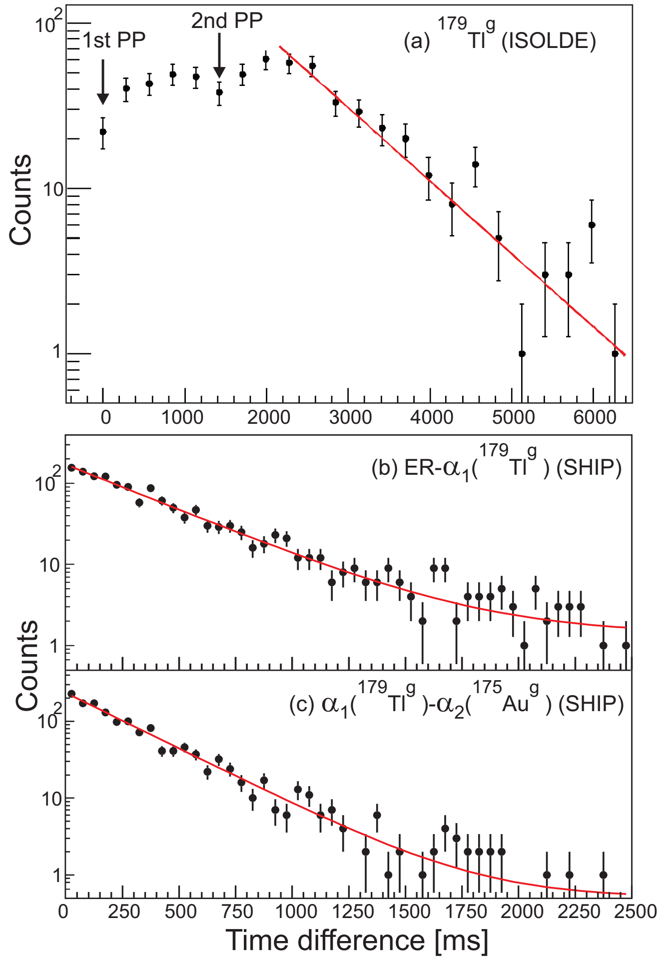

FIG. 2. (Color online) (a) Time distribution for the 6560-keV α decay of ^{179}Tl^g from ISOLDE data, determined using as reference the times of two consecutive proton pulses indicated as 1st PP and 2nd PP in the figure, respectively. The "decay" part of the time distribution was fitted with an exponential function, shown by the red line, resulting in the half-life value of 263(17) ms; (b) time distribution between the recoil implantations and subsequent α_1(6561-keV) decays of ^{179}Tl^g from the SHIP experiment by using the triple correlation events ER-α_1(6561)-α_2(6433). The fit, shown with a red solid line, was performed with a combination of an exponential decay and a constant background, resulting in a half-life value of 267(13) ms; (c) time distribution between the two correlated α decays from the ER-α_1(6561)-α_2(6433) analysis of the SHIP data. The same fit as for panel (b) was performed, giving the half-life value of 207(7) ms for ^{175}Au^g.

3. α decay of ^{171}Ir

As mentioned earlier, we attributed the 6433-keV α peak in Fig. 1 to ^{175}Au. This was also confirmed in the study at SHIP, in which an energy $E_\alpha = 6433(5)$ keV was measured for this isotope (see Sec. III B).

Let us now turn to the discussion of the peak at 5734(7) keV seen in Fig. 1. As no other activity with a similar α-decay energy is expected in the decay chain of ^{179}Tl^g, we tentatively assign this decay as originating from ^{171}Ir, populated by the 6433-keV α decay of ^{175}Au. It is important to stress that this relatively strong peak cannot be due to some contaminant, as the spectrum in Fig. 1 was measured with the HRS, which provides a strong suppression of neighboring masses and contaminants.

By comparing the number of the 6433-keV α decays of ^{175}Au^g and of the 5734-keV decays of ^{171}Ir^g in Run I, branching ratios of $b_\alpha(^{171}\mathrm{Ir}^g) = 15(2)\%$ and $b_\beta(^{171}\mathrm{Ir}^g) = 85(2)\%$ were deduced for the first time. The necessary corrections to account for the recoil escape from the carbon foils were also applied. No half-life determination was possible for ^{171}Ir^g due to the relatively low statistics and a complex "grow-in-decay" pattern for this isotope produced via a sequence of preceding decays.

As mentioned earlier, Rowe *et al.* [5] observed a weak correlated α-decay pair α_1(6412 keV)-α_2(5717 keV) and tentatively attributed it to the decay $^{175}\mathrm{Au} \rightarrow {}^{171}\mathrm{Ir}$, despite the fact that no correlations preceding or occurring after this pair of decays were observed.

The 6433-keV α peak, attributed by us to ^{175}Au, is up-shifted by ∼21 keV with respect to 6412 keV quoted for ^{175}Au in Ref. [5]. Furthermore, our energy of 5734(7) keV for ^{171}Ir^g is also up-shifted by 17 keV relative to the value of 5717(10) keV, proposed in Ref. [5] for the α decay of ^{171}Ir^g. On the other hand, we note that the α-decay energies for, e.g., ^{175}Au^m (6438 keV), ^{179}Hg (6285 keV), ^{179}Tl^{m,g} (7201 and 6568 keV) reported in [5] are all within ∼8 keV of the tabulated values and the values measured in the present work. Therefore, if one indeed assigns the 6412-keV events in Ref. [5] to the decay of ^{175}Au^g, the reason for the shift by ∼21 keV relative to our value of 6433(5) keV is not presently clear. A possible reason for this could be the much lower statistics in Ref. [5] in comparison with our study.

4. Production yield of ^{179}Tl^g at ISOLDE

An average production rate of ∼1.3 atoms/s (∼0.9 atoms/μC) for ^{179}Tl^g over the two ISOLDE runs was estimated based on its measured α-decay counting rate in the silicon detectors of the Windmill. The necessary corrections for the α-decay branching of ^{179}Tl^g, deduced in this work, and α-decay detection efficiency of 66% were implemented. A ^{179}Tl^g transport efficiency of 100% through the ISOLDE beam line to the Windmill system was assumed.

This production rate of ^{179}Tl^g is ∼115 times lower than the production rate of ∼150 atoms/s of its neighboring heavier isotope ^{180}Tl [12]. The sharp drop in the production yield is both due to the much smaller spallation cross section in the target and also due to a relatively long release time of thallium isotopes from the thick ISOLDE target [16]. The latter effect strongly suppressed the production of the shorter-lived 260-ms ^{179}Tl relative to 1.09-s ^{180}Tl. As shown in [14], a further drop to 0.15 atoms/s occurs for the 250-ms ^{178}Tl.

We also note that the measured production yield for ^{179}Tl^g is approximately a factor of 6 higher than the production rate achieved in the SHIP experiment (see discussion below).

B. α decay of ^{179}Tl^g at SHIP

In this section, the study of ^{179}Tl^g at SHIP is discussed. Figure 4(a) shows a part of the energy spectrum of α decays collected within the time interval of $\Delta T(\mathrm{ER}\text{-}\alpha_1) \leqslant 2000$ ms after the ER implantation in the PSSD. The relatively large background from the low-energy scattered beam projectiles is due to the long correlation time interval used in the present analysis. We note that a much cleaner subset of the same data for the time window of 25 ms was shown in Ref. [7], which concentrated on the decay of the shorter-lived 1.4-ms isomer in ^{179}Tl. The peaks marked in Fig. 4(a) are due to ^{179}Tl^m[7207(5) keV], ^{176}Hg [6758(5) keV], and ^{179}Tl^g[6561(5) keV]. The latter peak has a small contribution from ^{177}Hg [6582(5) keV]. The measured α-decay energies of ^{179}Hg [6287(5) keV, not shown in Fig. 4(a)], of ^{176}Hg [6758(5) keV], and its daughter ^{172}Pt [6322(5) keV; see Fig. 4(b)] are in a good agreement with the tabulated evaluated values [19] of 6285(3) keV for ^{179}Hg, 6751(5) keV for ^{176}Hg, and 6315(3) keV for ^{172}Pt. This confirms that the energy calibrations used in our ISOLDE and SHIP experiments are mutually consistent and also consistent with the tabulated data.

Figure 4(b) shows the two-dimensional plot of α_1-α_2 correlated events, observed within the time interval of $\Delta T(\alpha_1\text{-}\alpha_2) \leqslant 1200$ ms after the ER-α_1 correlated events from Fig. 4(a). The strongest groups marked in the spectrum are due to known α_1-α_2 correlations of ^{179}Tl^m-^{175}Au^m, ^{176}Hg-^{172}Pt, ^{177}Hg-^{173}Pt. In the following, we will concentrate on the correlation group of 6561-keV–6433-keV decays, which we attributed to the decay chain ^{179}Tl^g-^{175}Au^g. The measured α-decay energies coincide well with the values deduced in our ISOLDE experiments for these nuclides and weighted average values of $E_\alpha(^{179}\mathrm{Tl}^g) = 6560(4)$ keV and $E_\alpha(^{175}\mathrm{Au}^g) = 6433(4)$ keV were derived, as quoted in Table I and Fig. 3.

Figure 2(b) shows the time distribution of the α_1(6561 keV) decays after the ER implantation in the PSSD deduced from the analysis of the triple correlation events of the type ER-α_1(6561)-α_2(6433) from Fig. 4(b). A wider time interval of $\Delta T(\mathrm{ER}\text{–}\alpha_1) \leqslant 2500$ ms was used in this analysis for a better definition of a small background due to random correlations. The time distribution was fitted using a combination of an exponential function and a constant background, but the choice of the fitting function for the background component did not influence the final half-life value within the quoted uncertainty. A half-life value of $T_{1/2}(^{179}\mathrm{Tl}^g) = 267(13)$ ms was deduced from such an analysis, which is in good agreement with the value of 263(17) ms from our ISOLDE study.

As the two measurements are independent, we evaluated a weighted average of $T_{1/2}(^{179}\mathrm{Tl}^g) = 265(10)$ ms, which is given in Table I and in Fig. 3.

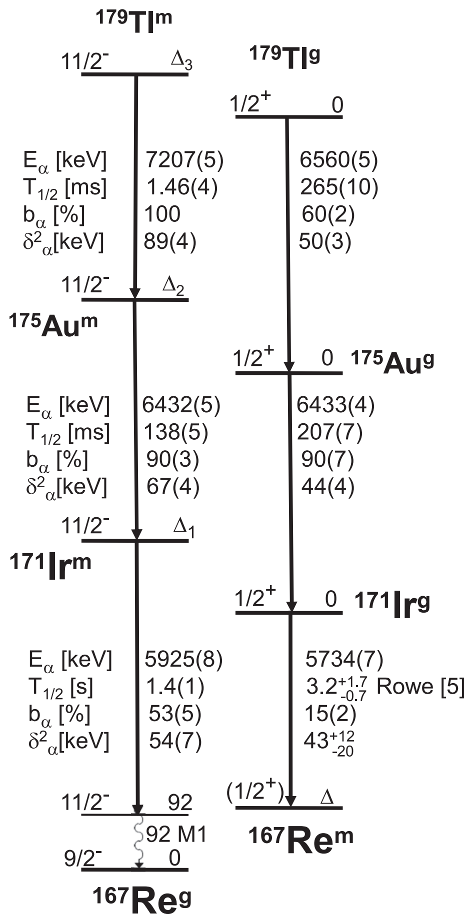

FIG. 3. (Right-hand side) The decay scheme of ^{179}Tl^g deduced in the present study. For comparison and to support the discussion, the decay scheme of ^{179}Tl^m from [7] is shown on the left-hand side of the figure. The α-decay energies E_α, the half-life values $T_{1/2}$, the α-decay branching ratios b_α, and the reduced α-decay widths δ^2_α are indicated for each isotope. The quoted α-decay energies for ^{179}Tl^g and ^{175}Au^g are weighted averages from the SHIP and ISOLDE experiments. The α-decay branching ratios of ^{179}Tl^g and ^{175}Au^g are from the ISOLDE data. The half-life value of ^{175}Au^g is from the SHIP experiment. The tentative estimates of the excitation energies of the isomeric states (the Δ values) are given in the text. The indicated statistical uncertainties of α-decay energies from the present work are from the Gaussian fits of the respective peaks. A typical systematical uncertainty of ~5 keV should be added due to the calibration procedures used at SHIP and ISOLDE.

Figure 2(c) shows the time distribution of the α_2(6433 keV) decays from the analysis of the triple correlated events ER-α_1(6561)-α_2(6433) from Fig. 4(b). Similar to the case of ^{179}Tl^g, the time distribution was fitted with a combination of an exponential function and a constant background, resulting in the half-life value of 207(7) ms for ^{175}Au^g. To our knowledge, this is the first determination of the half-life for this α-decaying state in ^{175}Au.

Due to an admixture of the 6582-keV α decay of ^{177}Hg in the peak at 6561 keV in Fig. 4(a), the determination of the α-branching ratio for ^{175}Au^g was not possible using the SHIP data. The search for correlations with the 5734 keV of the granddaughter ^{171}Ir^g was also not feasible, due to both

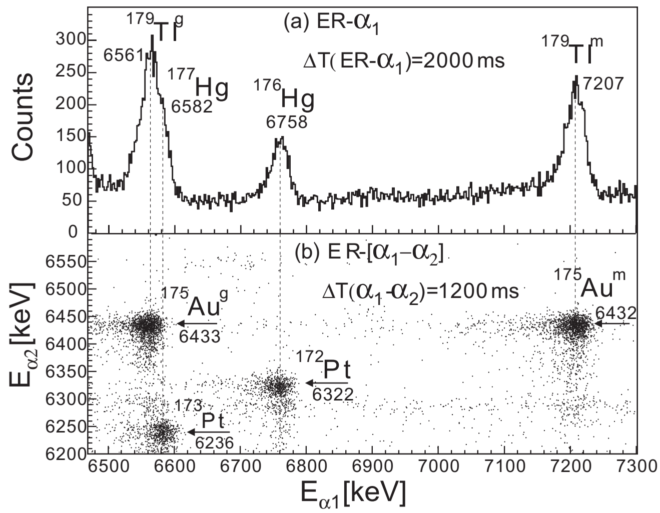

FIG. 4. (a) Part of the α_1-energy spectrum from the reaction ^{40}Ca + ^{144}Sm → ^{184}Pb* registered within 2000 ms after the ER implantation in the PSSD. α-decay energies are given in keV. (b) The α_1-α_2 correlation plot for the α_1 decay from the panel (a), measured within the time interval of $\Delta T(\alpha_1\text{-}\alpha_2) \leqslant 1200$ ms.

the relatively low α branching of ^{171}Ir^g and a large random background, which arose when a time window of ~6 s was applied to accommodate the half-life of ~3.2 s, proposed in Ref. [5].

Average production rates in the target of ~0.15 recoils/s for ^{179}Tl^g and ~0.1 recoils/s for ^{179}Tl^m were estimated based on the measured α-decay counting rates from Fig. 4. The necessary corrections for the α-decay branching ratios, the PSSD detection efficiency ϵ(PSSD)~ 50% for α decays, and calculated SHIP transmission efficiency of ~40%, were implemented.

It is interesting to stress the fact that the $1/2^+$ ground state is populated approximately 50% more strongly than the $11/2^-$ isomer. This is in contrast to the well-known fact of a stronger population of the higher-spin states, typically observed in the fusion-evaporation reactions. For example, based on Fig. 1 from [25], one can estimate that the $11/2^-$ isomeric state of ^{177}Tl is produced approximately a factor of 7–10 times more strongly than the $1/2^+$ ground state. The higher apparent population of the $1/2^+$ state in ^{179}Tl might indicate that there exists an internal transition or proton-decay branch in the decay of the $11/2^-$ isomer, but no evidence for either could be found in our data.

IV. DISCUSSION

A. Spin-parity assignment for ^{175}Au^g and ^{171}Ir^g.

By using the experimentally determined α-decay branching ratios for ^{179}Tl^g, ^{175}Au^g, and ^{171}Ir^g, it is possible for the first time to calculate the reduced α-decay widths δ^2_α for the respective α decays (see Table I and Fig. 3). This was done with the Rasmussen approach by assuming $\Delta L = 0$ transitions [23] and screening correction. The δ^2_α values for the 6560-keV decay of ^{179}Tl^g and 6433-keV decay of ^{175}Tl^g are in the range of 45–70 keV, which is comparable to the typical values for the unhindered α decays in this region of neutron-deficient nuclei [7,24–26,28]. This signifies both the unhindered nature of these two α decays and the same spin-parity and similar configurations for the three states connected by the α-decay chain ^{179}Tl$^g \rightarrow {}^{175}$Au$^g \rightarrow {}^{171}$Ir^g.

Presently, experimentally measured information on the spin of the nuclides in this decay chain is available only for ^{179}Tl^g. Namely, the recent laser spectroscopy measurements at ISOLDE [6] established a spin parity of $I^\pi = 1/2^+$ for the ground state of ^{179}Tl. Based on the measured magnetic moment and by analogy with other odd-A thallium isotopes, the $\pi 3s_{1/2}^{-1}$ configuration can be assigned to the ground state of ^{179}Tl. Therefore, the unhindered nature of the 6560-keV and 6433-keV decays unambiguously establishes a spin parity of $I^\pi = 1/2^+$ for ^{175}Au^g and ^{171}Ir^g.

Earlier α- and proton-decay studies suggested a spin parity of $(1/2^+)$ for ^{171,173}Au^g [24–26]. Furthermore, the recent laser spectroscopy studies firmly point to a spin-parity assignment of $I^\pi = 1/2^+$ for ^{177,179}Au^g [27]. Therefore, it now appears that the lightest odd-A isotopes ^{171,173,175,177,179}Au have ground-state spins of $1/2^+$.

Similarly, based on α- and proton-decay studies, a spin parity of $(1/2^+)$ was earlier suggested for ^{165,167,169}Ir^g [24,25]. On the other hand, a spin of $(3/2,5/2)^+$ was proposed for ^{173}Ir [19]. Thus, apparently ^{171}Ir^g establishes the border between the two different proton configurations, which determine the ground-state spin. While the most probable configuration of ^{165,167,169,171}Ir^g is based on $3s_{1/2}$, the $2d_{3/2,5/2}$ configurations (or their mixture) are the most feasible candidates for the ground state of ^{173}Ir^g.

The reduced α-decay width of the 5734-keV α decay of ^{171}Ir^g was calculated by using the α-decay energy and branching ratio from the present work and the half-life value of $3.2^{+1.7}_{-0.7}$ s from [5]. On the one hand, the resulting value of $\delta_\alpha^2 = 42^{+12}_{-20}$ keV is consistent, within the experimental uncertainties, with the values for unhindered α decays in this region. This would also establish a spin parity of $1/2^+$ for the state ^{167}Re, fed by the 5734-keV decay. However, if one calculates the lowest possible reduced α-decay width value defined by the uncertainty, this α decay should be considered as slightly hindered. This could signify a change of spin value and/or underlying configuration. Overall, in view of a rather tentative determination of the decay properties of ^{171}Ir^g, based on a combination of data from the present work and from [5], we prefer not to draw definite conclusions and propose only a tentative spin assignment of $I^\pi = (1/2^+)$ for the low-spin state in ^{167}Re.

Based on α- and proton-decay studies, a spin parity of $(1/2^+)$ was earlier proposed for the ground states of ^{161,163,165}Re [24,25,28], while, tentatively, a spin of (3/2,5/2) was proposed for the low-spin α-decaying isomeric state in ^{169}Re [19]. Therefore, the $(1/2^+)$ state in ^{167}Re also appears to lie in the transitional zone between the two proton configurations.

The knowledge of the magnetic moments for ^{175}Au^g, ^{171}Ir^g, and ^{167}Re would definitely shed more light on their underlying proton configurations.

B. Relative position of the $11/2^-$ and $1/2^+$ states in ^{179}Tl, ^{175}Au, ^{171}Ir, and ^{167}Re

In this subsection we provide the reasons for our classification of the $11/2^-$ and $1/2^+$ states as being isomeric or ground states in the decay chain ^{179}Tl $\rightarrow {}^{175}$Au $\rightarrow {}^{171}$Ir $\rightarrow {}^{167}$Re (see Fig. 3).

Figure 5 shows the systematics of experimental excitation energies and estimates for the $11/2^-$ states in the light odd-A isotopes ^{161,163,165}Re, ^{165,167,169}Ir, ^{171,173,177}Au, and ^{177,183}Tl, relative to the respective $1/2^+$ states. We stress that in the heavier rhenium, iridium, and gold isotopes, the $1/2^+$ state has either not yet been identified, or the experimental energy difference $\Delta E(11/2 - 1/2)$ is not known. Furthermore, here we use only a subset of the data for the thallium isotopes, while the full systematics, including the data on the parabolic behavior of the excitation energy of the intruder $9/2^-$ states in the odd-A $^{181-201}$Tl, can be found in Fig. 5 of Ref. [29].

To start, an excitation energy of $E^*(11/2^-, {}^{179}\mathrm{Tl}) \sim 830$ keV (shown by an open circle in Fig. 5 and by a Δ_3 symbol in Fig. 3) can be derived from the interpolation between the known values for ^{177,181,183}Tl; see also [7,29]. In passing we note, that based on these systematics, the $9/2^-$ state in ^{179}Tl is expected at $\sim$1170 keV [7], which is higher than the estimated position of the $11/2^-$ state; see Fig. 5. Furthermore, by using the measured α-decay energies in the respective α-decay chains of ^{179}Tl^{m,g}, the excitation energies of the $11/2^-$ states in ^{175}Au and ^{171}Ir can be estimated as

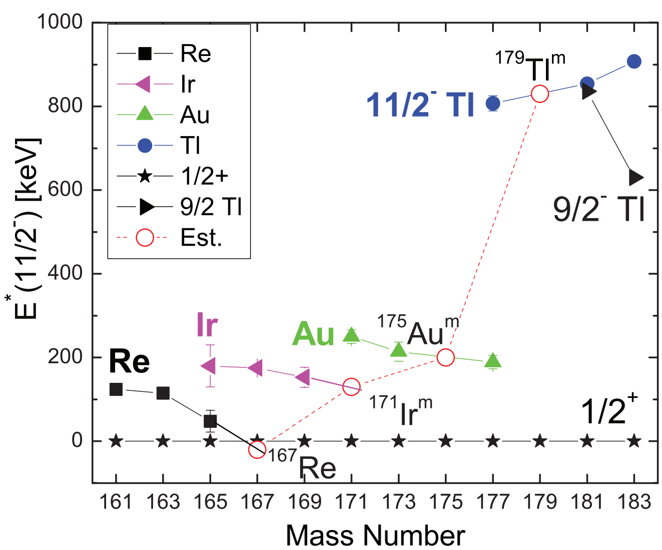

FIG. 5. (Color online) Experimental excitation energies of the $11/2^-$ states in the lightest odd-A Re, Ir, Au, and Tl isotopes, relative to the $1/2^+$ states, where known. Data are from [19,29–31]. Open red circles mark the expected position of the $11/2^-$ states in ^{179}Tl^m and ^{175}Au^m, obtained from the linear interpolation, and in ^{171}Ir^m and ^{167}Re^g from the linear extrapolation of the energies of known $11/2^-$ states in the respective isotopic chains. The dashed red line connects the states in the α-decay chain ^{179}Tl$^m \rightarrow {}^{175}$Au$^m \rightarrow {}^{171}$Ir$^m \rightarrow {}^{167}$Re^g. The $9/2^-$ intruder states in ^{181,183}Tl are also shown. See the text for further details.

$\Delta_2 = \Delta_1 = E^*(11/2^-,{}^{175}\text{Au}) = E^*(11/2^-, {}^{171}\text{Ir}) \sim 168$ keV. By extending the same procedure to ^{167}Re, one finds that its known $9/2^-$ state becomes the ground state, with the $1/2^+$ state lying at an estimated excitation energy of ~120 keV, or ~30 keV above the known $11/2^-$ state. Due to this, we denoted the $1/2^+$ state in ^{167}Re as isomeric throughout our text. Clearly, the latter conclusion will remain valid provided the excitation energy of the $11/2^-$ state in ^{179}Tl is below ~950 keV.

We can further check these inferences by using the systematics of the $11/2^-$ states in rhenium, iridium, and gold isotopes in Fig. 5, without relying on ^{179}Tl. Namely, by interpolating the data for the isotopes ^{171,173,177}Au, an expected excitation energy $\Delta_2 = E^*(11/2^-, {}^{175}\text{Au}) \sim 200$ keV can be derived, shown by an open circle in Fig. 5, which is in good agreement with the above estimate of ~178 keV. Similarly, by extrapolating the ^{165,167,169}Ir data to ^{171}Ir, an expected excitation energy $\Delta_1 = E^*(11/2^-, {}^{171}\text{Ir}) \sim 130$ keV can be obtained, which is also in satisfactory agreement with the estimate of ~178 keV, when starting from the data for ^{179}Tl.

Finally, in the chain of the rhenium isotopes, the $11/2^-$ state is known to lie above the $1/2^+$ ground state in ^{161,163,165}Re, with decreasing excitation energy when moving towards the heavier isotopes (see Fig. 5). By extrapolating the decreasing trend towards the heavier isotopes, the $11/2^-$ state is expected to become ~20 keV lower than the $1/2^+$ state in ^{167}Re ((see the respective open circle in Fig. 5). This value is also in good agreement with the above-mentioned estimate. That is why throughout this work, the presumed $(1/2^+)$ state in ^{167}Re was denoted as an isomeric state.

V. CONCLUSIONS

To conclude, a detailed α-decay study of the neutron-deficient isotope ^{179}Tl has been performed in two complementary experiments at the mass separator ISOLDE (CERN) and velocity filter SHIP (GSI). A first reliable measurement of the decay properties of the ground state in ^{175}Au has been achieved. Based on the unhindered nature of α decays in the decay chain $^{179}\text{Tl}^g \rightarrow {}^{175}\text{Au}^g \rightarrow {}^{171}\text{Ir}^g \rightarrow {}^{167}\text{Re}^m$, the spins of the ground states in ^{175}Au and ^{171}Ir were established as $1/2^+$. Further laser spectroscopy studies of the lightest Tl and Au isotopes initiated at ISOLDE [6,27] and, in particular, the determination of the magnetic moments will shed more light on the nature of these states.

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