Physics Letters B ••• (••••) •••–•••

Contents lists available at ScienceDirect

Physics Letters B

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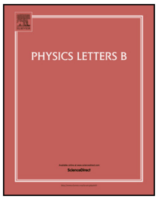

# Change in structure between the $I = 1/2$ states in $^{181}$Tl and $^{177,179}$Au

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## ARTICLE INFO

*Article history:*
Received 16 July 2018
Received in revised form 2 October 2018
Accepted 3 October 2018
Available online xxxx
Editor: V. Metag

*Keywords:*
Nuclear physics
Decay spectroscopy
Laser spectroscopy
Nuclear deformation

## ABSTRACT

The first accurate measurements of the $\alpha$-decay branching ratio and half-life of the $I^\pi = 1/2^+$ ground state in $^{181}$Tl have been made, along with the first determination of the magnetic moments and $I = 1/2$ spin assignments of the ground states in $^{177,179}$Au. The results are discussed within the complementary systematics of the reduced $\alpha$-decay widths and nuclear $g$ factors of low-lying, $I^\pi = 1/2^+$ states in the neutron-deficient lead region. The findings shed light on the unexpected hindrance of the $1/2^+ \rightarrow 1/2^+$, $^{181}\mathrm{Tl}^g \rightarrow {}^{177}\mathrm{Au}^g$ $\alpha$ decay, which is explained by a mixing of $\pi 3s_{1/2}$ and $\pi 2d_{3/2}$ configurations in $^{177}\mathrm{Au}^g$, whilst $^{181}\mathrm{Tl}^g$ remains a near-pure $\pi 3s_{1/2}$. This conclusion is inferred from the $g$ factor of $^{177}\mathrm{Au}^g$ which has an intermediate value between those of $\pi 3s_{1/2}$ and $\pi 2d_{3/2}$ states. A similar mixed configuration is

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https://doi.org/10.1016/j.physletb.2018.10.005

Please cite this article in press as: J.G. Cubiss et al., Change in structure between the $I = 1/2$ states in $^{181}$Tl and $^{177,179}$Au, Phys. Lett. B (2018), https://doi.org/10.1016/j.physletb.2018.10.005

Gold nuclei
Thallium nuclei

proposed for the $I^{\pi}=1/2^{+}$ ground state of $^{179}$Au. This mixing may provide evidence for triaxial shapes in the ground states in these nuclei.

## 1. Introduction

Low-energy shape coexistence, whereby states of differing shape compete at low-excitation energies within the same nucleus, is an intriguing and complex facet of nuclear structure [1]. This phenomenon results from an interplay between two opposing behaviours: the stabilising effect of shell closures which preserves sphericity, and residual interactions between protons and neutrons that drive deformation [2]. However, the description of such behaviour remains a challenge for contemporary nuclear theory.

To simplify the description of this complex phenomenon, theoretical models often invoke axial and reflection symmetries. However, as highlighted in e.g. Ref. [3] for germanium isotopes, the use of such restrictions may lead to problems. In particular, coexisting energy minima at different quadrupole deformations could be connected by a valley of triaxiality, along which the true energy minimum lies. Therefore, special care should be taken when modelling nuclei that inhabit known or expected regions of triaxiality.

The neutron-deficient gold ($Z=79$) isotopes have proved to be fertile ground for the study of shape coexistence and triaxiality [4–14]. The ground-state structures of odd-mass gold isotopes are seen to gradually evolve as the mass reduces down to $A=187$ ($N=108$). This is evidenced by their $g$ factors, spins and parities which change from those of near-pure $\pi 2d_{3/2}$ configurations with $I^{\pi}=3/2^{+}$ for the odd-$A$ isotopes with $A \geqslant 191$, to mixed $\pi 2d_{3/2}/\pi 3s_{1/2}$ states with $I^{\pi}=1/2^{+}$ in $^{187,189}$Au [15,4]. However, these nuclei are seen to retain weakly oblate (near spherical) shapes. A more dramatic change in structure is seen below $A=187$, with a large increase in the mean-squared charge radius indicating a sudden increase in the ground-state deformation [5–7]. This transition from weakly oblate to strongly prolate shapes makes these nuclei of particular interest for investigating coexisting structures within the region. The large increase in deformation is accompanied by a change in the ground-state configuration to the $5/2^{-}$ member of the band, based upon the strongly prolate 1/2[541] and/or 3/2[532] deformed states of a $\pi 1h_{9/2}$ parentage, as was proposed for $^{181,183,185}$Au in Refs. [4,16,17]. The ground states of the neutron-deficient gold isotopes were predicted to stay strongly deformed until $A \approx 177$, where a return to near-spherical shapes was proposed to occur (see Fig. 31 in Ref. [18]). However, results from in-beam and $\alpha$-decay studies suggest that this region of strong deformation ends earlier, at $A=179$, where it is proposed that the ground state returns to a $\pi 2d_{3/2}/\pi 3s_{1/2}$ configuration [19–21].

Evidence for triaxial shapes has been found in the neighbouring platinum isotopes. In particular, the magnetic moments of the lowest $3/2^{-}$ states in the odd-$A$ isotopes $^{187-193}$Pt were shown in Ref. [22] (see Fig. 6 therein) to have a strong dependence on the triaxial deformation parameter, $\gamma$. Gold isotopes, which can be viewed as a proton coupled to a platinum core, may also display such behaviour. Signatures of triaxiality have been seen in the excited states of some gold isotopes (see Refs. [23,11–13] and references within). Thus, it may be possible to observe signs of triaxiality in ground-state magnetic moments of gold nuclei, similar to those seen in the neighbouring platinum isotopes.

This article reports on a two-pronged experimental study of the ground and isomeric states of thallium and gold isotopes. First, an $\alpha$-decay study of the $I=1/2^{+}$ ground state in $^{181}$Tl ($T_{1/2}=3.2(3)$ s [24]) was performed to investigate the unexpected hindrance to the decay observed in a study by Andreyev et al. [25], at the velocity filter SHIP (GSI). In this work, the authors deduced an upper limit for the $\alpha$-decay branching ratio of $b_{\alpha}(^{181}\mathrm{Tl}^{g}) < 10\%$, which resulted in an upper limit for the reduced $\alpha$-decay width of $\delta_{\alpha}^{2} < 19$ keV. The latter is notably smaller than those of other unhindered $1/2^{+} \rightarrow 1/2^{+}$ $\alpha$ decays in the region, which typically have values of $\delta_{\alpha}^{2} = 45-90$ keV. This raises the question as to the possible cause of hindrance in the $^{181}$Tl$^{g}$ $\alpha$ decay. Recent mean-squared charge radii measurements by Barzakh et al. [26] show $^{181}$Tl$^{g}$ to be nearly spherical, with a magnetic moment in good agreement with values for the $I=1/2^{+}$ states in other odd-$A$ thallium isotopes, which have near-pure $\pi 3s_{1/2}$ configurations. This proves that there is nothing unusual with the underlying structure of $^{181}$Tl$^{g}$. Therefore, the main goals of the present work were to extract a value for $b_{\alpha}$ and the half-life ($T_{1/2}$) of $^{181}$Tl$^{g}$, in order to confirm or disprove the hindrance observed in Ref. [25].

On the other hand, a difference in configurations between $^{181}$Tl$^{g}$ and its $\alpha$-decay daughter nucleus, $^{177}$Au$^{g}$, could explain this hindrance. Prior to this work, $^{177}$Au$^{g}$ was tentatively assigned a spin of $I^{\pi}=(1/2^{+},3/2^{+})$, based on the in-beam study by Kondev et al. [21], with the most likely configuration being either $1/2^{+}[411](d_{3/2})$ at oblate deformation with some admixture from $\pi 3s_{1/2}$, or a prolate $3/2^{+}[402](d_{3/2})$ state.

Therefore, in-source laser spectroscopy measurements of $^{177}$Au$^{g}$ were performed. The present work provides the first unambiguous measurements of the spins and magnetic moments of $^{177,179}$Au$^{g}$. The new results for $^{181}$Tl$^{g}$ and $^{177,179}$Au$^{g}$ will be discussed within the context of the systematics of reduced $\alpha$-decay widths for $1/2^{+} \rightarrow 1/2^{+}$ $\alpha$ decays and nuclear $g$ factors of $I=1/2$ states within the region.

## 2. Experiment

Two experimental campaigns were performed for the isotopes $^{181}$Tl$^{g}$ and $^{177,179}$Au$^{g}$. In both cases the experimental method was the same as that employed in the studies of the thallium isotopic chain presented in Refs. [26,27]. Additional details pertinent to the present work are given below. The radioactive thallium and gold nuclei were produced at the ISOLDE facility [28,29], in spallation reactions induced by a 1.4-GeV proton beam, impinged upon a 50 g/cm$^2$-thick UC$_x$ target. The proton beam was delivered by the CERN PS Booster with an average current of 2.1 μA, in a repeated sequence known as a supercycle that typically consisted of 35–40, 2.4-μs long pulses, with a minimum interval of 1.2 s between each pulse.

After proton impact the reaction products diffused through the target matrix and effused towards a hot cavity ion source, kept at a temperature of ≈2000 °C. Inside the cavity, the thallium or gold atoms were selectively ionised by the ISOLDE Resonance Ionization Laser Ion Source (RILIS) [30,31]. The ions were then extracted from the cavity using a 30 kV electrostatic potential and separated according to their mass-to-charge ratio by the ISOLDE GPS mass separator. The mass-separated beam was then delivered to either the ISOLTRAP Multi-Reflection Time-of-Flight Mass Spectrometer (MR-ToF MS) [32] or the Windmill decay station [33,34], for photoion monitoring during RILIS laser-wavelength scans across the hyperfine structure (hfs) of an atomic transition used in the

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