Deformation versus sphericity in the ground states of the lightest gold isotopes

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The changes in mean-squared charge radii of neutron-deficient gold nuclei have been determined using the in-source, resonance-ionization laser spectroscopy technique, at the ISOLDE facility (CERN). From these new data, nuclear deformations are inferred, revealing a competition between deformed and spherical configurations. The isotopes ^{180,181,182}Au are observed to possess well-deformed ground states and, when moving to lighter masses, a sudden transition to near-spherical shapes is seen in the extremely neutron deficient nuclides, ^{176,177,179}Au. A case of shape coexistence and shape staggering is identified in ^{178}Au which has a ground and isomeric state with different deformations. These new data reveal a pattern in ground-state deformation unique to the gold isotopes, whereby when moving from the heavy to light masses, a plateau of well-deformed isotopes exists around the neutron midshell, flanked by near-spherical shapes in the heavier and lighter isotopes – a trend hitherto unseen elsewhere in the nuclear chart. The experimental charge radii are compared to those from Hartree-Fock-Bogoliubov calculations using the D1M Gogny interaction and configuration mixing between states of different deformation. The calculations are constrained by the known spins, parities and magnetic moments of the ground states in gold nuclei, and show a good agreement with the experimental results.

The shape of the atomic nucleus is a result of the interactions between its proton and neutron constituents [1]. At "magic" shell closures nucleons arrange themselves in energetically stable configurations, producing spherical ground states (except for extreme cases of neutron/proton ratios which form e.g. the island of inversion [2–6]). However, if one moves just a few nucleons away, residual, deformation-driving interactions between valence protons and neutrons come into play. These interactions scale with the number of valence particles, peaking at proton and neutron midshells where they compete with the stabilising effects of nearby shell closures. This produces coexisting spherical and deformed structures, creating striking varieties of nuclear shape phenomena.

Characterising these coexisting structures and their evolution across regions of the nuclear chart is important for furthering our understanding of the governing interactions. In this respect, isotope shift (IS) and hyperfine structure (hfs) measurements, from which changes in nuclear mean-squared charge radii ($\delta\langle r^2\rangle$) and magnetic dipole moments (μ) can be deduced, have proven a powerful tool [7–9]. Whilst μ provides insight into the orbitals occupied by unpaired nucleons, the $\delta\langle r^2\rangle$ value is sensitive to the radial charge distribution of the nucleus, and hence, to changes in its shape.

The nuclei surrounding the $Z = 82$ shell closure have been the focus of an extensive campaign of such IS and hfs measurements, and display some of the best-known examples of nuclear shape coexistence. Notably, whilst the ground states of semi-magic lead nuclei remain near spherical [10, 11], those of the mercury ($Z = 80$) [12–15], and the bismuth ($Z = 83$) [16] isotopic chains, are seen to stagger dramatically between strongly deformed and near-spherical shapes around the $N = 104$ neutron midshell, where a strong competition between co-existing spherical and prolate configurations

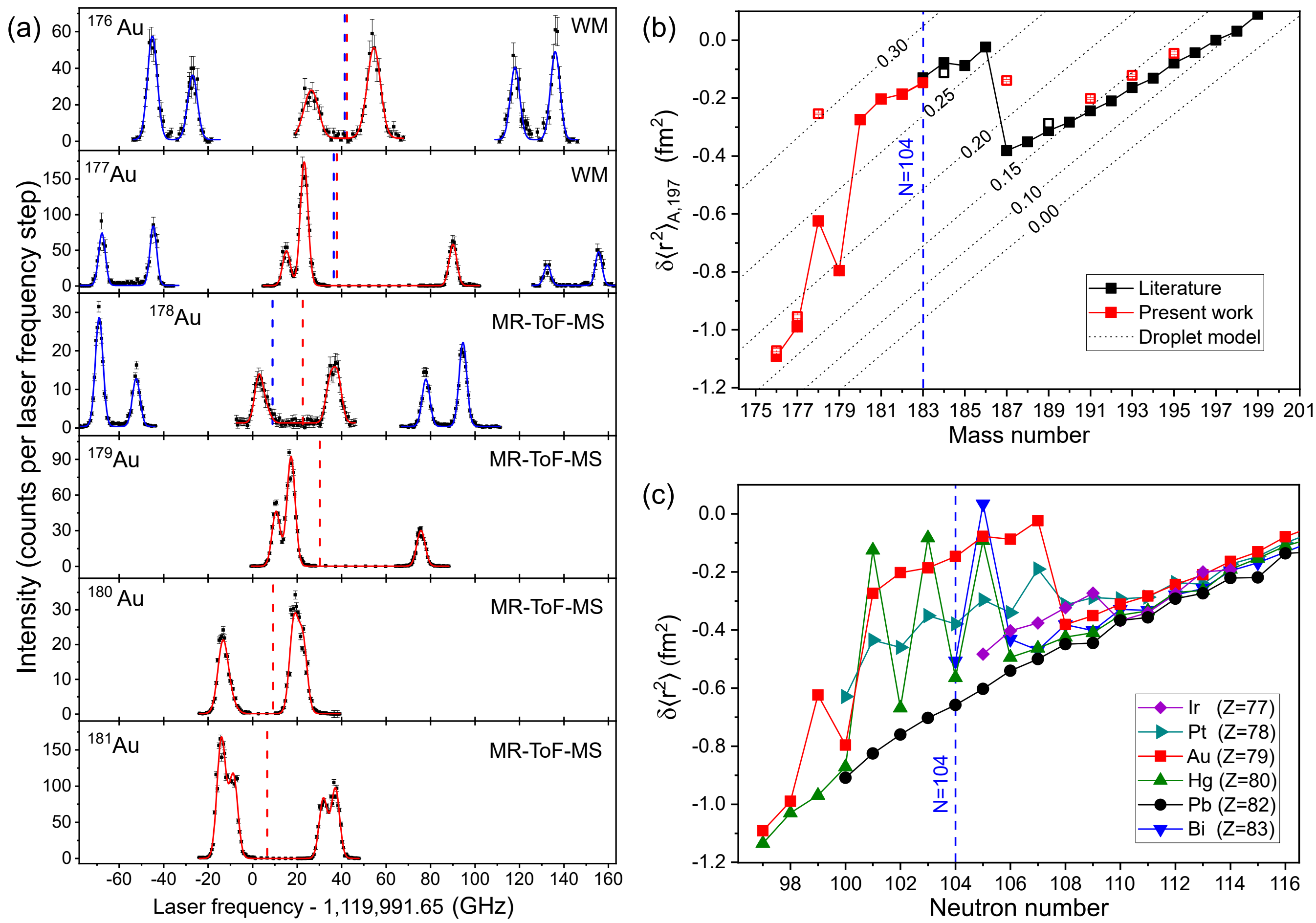

FIG. 1. (a) Examples of hfs spectra collected during the experiment (black data points) fitted with Voigt profiles (solid lines), along with the transition centroid frequencies (vertical dashed lines) and the measuring device used. The red and blue colors represent the fits and centroids for ground and isomeric states, and the low- and high-spin states in ^{176}Au, respectively. The y axis is the number of α decays, or the number of ions detected per laser step, in the WM and MR-ToF MS, respectively. (b) The $\delta\langle r^2\rangle_{A,197}$ values for gold ground (solid symbols) and isomeric (hollow symbols) states deduced from the IS extracted from the data in (a) (experimental error bars are smaller than the data points). The red and black data points are the results from the present work and literature, respectively [17–23]. The diagonal dotted lines indicate $\delta\langle r^2\rangle_{A,197}$ for fixed deformations predicted by the droplet model ($\langle\beta_2^2\rangle_{DM}^{1/2}$) [24], using the second parameterisation of Ref. [25], and assuming $\beta_2(^{197}\mathrm{Au})$=0.11 [19]. The dotted lines are labelled with their corresponding $\langle\beta_2^2\rangle_{DM}^{1/2}$ values. (c) Comparison of ground state $\delta\langle r^2\rangle$ values near N = 104, for iridium (◆) [26, 27], platinum (►) [27–30], gold (■), mercury (▲) [12–15], lead (●) [10, 11], and bismuth (▼) [16] isotopes – the chains are arbitrarily offset for the comparison. Error bars are omitted for clarity, but are typically smaller or the same size as the data points.

takes place. Above Z = 82, departures from spherical ground states are observed in the polonium (Z = 84) [31, 32] and astatine (Z = 85) isotopes [33], with smooth but rapid onsets of deformation occurring when moving away from N = 126. Meanwhile, below the proton shell closure, spherical ground states coexist with low-lying, deformed isomers in the thallium (Z = 81) chain [34, 35].

In this work, we present our results from IS and hfs measurements for neutron-deficient gold (Z = 79) nuclides, using the in-source, resonant-ionization laser spectroscopy technique. The study was performed at the ISOLDE facility in CERN, for which partial results for the nuclear spin (I), μ values and decay properties of some gold isotopes have been presented [36–41]. Previous IS studies of gold isotopes found a remarkable transition from near-spherical ground states in $^{187-199}$Au (N = 108 – 120), to strongly deformed, presumably prolate configurations in $^{183-186}$Au (N = 104 – 107) [17–23]. However, questions remain; what happens to the ground states in the lightest isotopes of gold? Do they remain strongly deformed, or do they return towards sphericity? This letter will answer these questions.

The gold nuclei were produced in spallation reactions induced by impinging a beam of protons with an energy of 1.4 GeV and a maximum current of 2.1 μA, onto a 50 g/cm^2 UC$_x$ target. After proton impact, reaction products diffused out of the target matrix and effused towards a hot cavity ion source [42], kept at a temperature of ≈2300 K. Inside the cavity, gold isotopes were selectively ionized using the three-step ionization scheme shown in Fig. 1 of [43] (see also Supplemental Materials). The ions were extracted by a 30 kV potential and mass separated by the ISOLDE General Purpose Separator (GPS) [44], before transportation to either the Windmill (WM) system [45, 46], or ISOLTRAP's [47] multi-reflection time-of-flight mass spectrometer (MR-ToF MS) [48] for ion counting. To construct hfs spectra, the number of characteristic alpha or gamma decays measured in the WM, or of mass-resolved ions of interest detected by the MR-ToF MS were recorded for each frequency step (see Ref. [33] for details). The IS measurements were made by scanning the 267.6 nm atomic transition ($6s\,^2S_{1/2} \rightarrow 6p\,^2P^o_{1/2}$), using a frequency-tripled titanium sapphire laser operated in a narrowband mode (≈ 600 MHz bandwidth before frequency tripling), with the laser wavelength recorded using a High-Finesse/Angstrom WS7 wavemeter. References for the IS measurements were made regularly, using a Faraday cup to record hfs spectra of stable ^{197}Au.

Examples of the measured hfs spectra are shown in Fig. 1(a). Voigt profiles are fitted to the different components, with positions determined by the standard relation [7], and intensities using the procedure described in Ref. [46] (see Supplemental Materials for further details). The fits were made assuming fixed I values taken from available data [49] and our previous studies [36–41], whilst the IS relative to stable ^{197}Au ($\delta\nu_{A,197} = \nu_A - \nu_{197}$), and the magnetic hfs constants for the atomic levels of the scanned transition (a_{6s} and a_{6p}) were left as free parameters.

The measured $\delta\nu_{A,197}$ value is related to the $\delta\langle r^2\rangle_{A,197}$ via $\delta\nu_{A,197} = (k_{\mathrm{NMS}} + k_{\mathrm{SMS}})(\frac{1}{M_A} - \frac{1}{M_{197}}) + \mathcal{F}\delta\left\langle r^2\right\rangle_{A,197}$, where the field shift constant $\mathcal{F}$, the normal (k_{NMS}) and specific (k_{SMS}) mass shift constants needed to be calculated, and M_A is the atomic mass of the isotope with mass number A.

For this work, new atomic physics calculations have been performed employing relativistic coupled cluster theory, using the Dirac-Coulomb Hamiltonian, with a correction on the Gaunt interelectron interaction. Up to perturbative quadruple cluster amplitudes are taken into account for the correlation treatment which is quite new for IS problems [50–54]. The constants k_{NMS} and k_{SMS} are calculated using fully relativistic operators (see Supplemental Material) [55–58]. In the calculations, the locally modified relativistic electronic structure codes [59–68] have been used as well as our method of constructing compact basis sets [52, 69]. The results give $\mathcal{F} = -40.1(11)$ GHz/fm^2, $k_{\mathrm{NMS}} = 600(40)$ GHz u and $k_{\mathrm{SMS}} = 103(93)$ GHz u, giving a total mass shift constant is $k_{\mathrm{NMS}} + k_{\mathrm{SMS}} = 703(101)$ GHz u.

Our $\delta\nu_{A,197}$ and corresponding $\delta\langle r^2\rangle_{A,197}$ results for gold nuclei are given in Table I. The accompanying $\langle\beta_2^2\rangle^{1/2}_{DM}$ values are root-mean-squared deformation parameters based on comparison of our $\delta\langle r^2\rangle_{A,197}$ values with droplet model (DM) predictions, using the second parameterisation of Ref. [25], and assuming $\beta_2(^{197}\mathrm{Au}) = 0.11$ [19].

Our new $\delta\langle r^2\rangle_{A,197}$ values are plotted in Fig. 1(b), along with literature values for $^{183-199}$Au taken from [19–21, 23, 39]. The literature values display a large jump in deformation at ^{186}Au, followed by a plateau of strongly deformed ground

TABLE I. Values for the IS ($\delta\nu_{A,197}$) and $\delta\langle r^2\rangle_{A,197}$ relative to ^{197}Au extracted from the experimental data, assuming different I assignments. The I values in parentheses represent cases where the assignment is not certain, or has not been directly measured. Statistical uncertainties from fits to the data are given in round parentheses, whilst systematic uncertainties stemming from the atomic calculations are given in curly brackets. The $\langle\beta_2^2\rangle^{1/2}_{DM}$ values are taken from comparison to predictions from the DM. Our values of $\mu(^{181,183}\mathrm{Au})$ are presented here for the first time, whilst the other values are included for completeness – all μ values are calculated taking the hyperfine anomaly into account as described in [41].

Isotope	I	$\delta\nu_{A,197}$ (MHz)	$\delta\langle r^2\rangle_{A,197}$ (fm^2)	$\langle\beta_2^2\rangle^{1/2}_{DM}$	μ (μ_N)
^{176}Au^{ls}	(3)	43340(640)	−1.091(16){31}	0.17	-0.823(48) [40]
	(4)	42860(660)	−1.079(16){31}	0.17	-0.853(54) [40]
	(5)	42520(700)	−1.071(16){31}	0.17	-0.873(55) [40]
^{176}Au^{hs}	(8)	42580(310)	−1.072(8){31}	0.17	5.14(20) [40]
	(9)	43070(370)	−1.085(9){31}	0.17	5.18(20) [40]
^{177}Au^{g}	1/2	39290(220)	−0.990(5){29}	0.18	1.257(64)[a]
^{177}Au^{m}	(11/2)	37860(250)	−0.954(6){28}	0.19	6.519(38) [41]
^{178}Au^{g}	(2)	24650(260)	−0.624(7){18}	0.24	-0.884(68) [38]
	(3)	23800(260)	−0.603(7){18}	0.25	-0.962(77) [38]
^{178}Au^{m}	(7)	9790(140)	−0.254(3){8}	0.30	4.84(8) [38]
	(8)	10300(140)	−0.266(3){9}	0.30	4.89(8) [38]
^{179}Au	1/2	31570(200)	−0.796(5){23}	0.19	1.050(30)[a]
^{180}Au	(1)	10650(200)	−0.274(5){9}	0.28	-0.830(90) [37]
^{181}Au	(3/2)	7820(230)	−0.203(6){7}	0.28	1.238(67)[b]
^{182}Au	(2)	7160(200)	−0.186(5){6}	0.27	1.664(91) [37]
^{183}Au	(5/2)	5620(120)	−0.147(3){5}[c]	0.27	2.057(39)[d]
^{187}Au^{m}	(9/2)	5380(160)	−0.139(4){4}[e]	0.23	3.529(53) [39]
^{191}Au^{m}	(11/2)	7950(180)	−0.201(4){6}	0.16	6.326(37) [41]
^{193}Au^{m}	11/2	4780(180)	−0.121(4){4}	0.15	6.320(37) [41]
^{195}Au^{m}	11/2	1760(220)	−0.045(5){1}	0.13	6.316(37) [41]

[a] Recalculated from the experimental hfs a constants from [36].
[b] Derived from experimental data $a_{6s} = 22900(100)$ MHz, $a_{6p}/a_{6s} = 0.1155(45)$ (present work).
[c] Our value differs to $\delta\langle r^2\rangle_{A,197}(^{183}\mathrm{Au}) = -0.130(9)$ [20], partially due to the different electronic factors used.
[d] Derived from experimental data $a_{6s} = 23037(40)$ MHz, $a_{6p}/a_{6s} = 0.1148(15)$ (present work). The small difference between ours and the literature value of 1.972(23) μ_N [20] is due to the treatment of the hyperfine anomaly.
[e] $\delta\langle r^2\rangle_{A,197}(^{187}\mathrm{Au}^m)$ is calculated using the new electronic factors, with $\delta\nu_{A,197}(^{187}\mathrm{Au}^m)$ taken from [39].

states for $^{183-186}$Au, extending down to $N = 104$. Our results show that this plateau continues down to ^{180}Au, with a large and sudden step back towards sphericity at ^{179}Au ($N = 100$). Apart from ^{178}Au^{g,m} which display a case for shape coexistence, and shape staggering relative to their spherical neighbors[1], the lightest gold isotopes evolve towards near sphericity, down to the extremely neutron-deficient case, ^{176}Au ($N = 97$).

In Fig. I(c) we compare the $\delta\langle r^2\rangle$ for ground states of gold, bismuth, mercury, iridium and platinum nuclides (isomeric

[1] The large increase in deformation for ^{178}Au^m relative to ^{178}Au^g and heavier gold isotopes is related to the occupation of a different proton orbital. As discussed in [38], the last proton in ^{178}Au^m occupies a 9/2[514]$_{h_{11/2}}$ orbital, whereas for all other strongly deformed cases (^{178}Au^g included) it is in either a 1/2[541]$_{h_{9/2}}$ or 3/2[532]$_{h_{9/2}}$ state.

states are omitted for clarity) to those of the spherical lead isotopes. The data for thallium ground states are not included here as they follow the same trend as the lead isotopes (see Refs. [34, 35]). The gold, mercury and bismuth chains display dramatic changes in ground state deformation relative to the lead nuclides around $N = 104$, with large increases in $\delta\langle r^2\rangle$ indicating sudden transitions from near spherical to strongly deformed configurations. Though the staggering patterns in the mercury and bismuth radii bear a resemblance, the trend followed by the gold nuclei is notably different. Here, similar to the platinum and iridium isotopes, the increase in $\delta\langle r^2\rangle$ values around $N = 104$ indicates a transition to deformed ground state configurations for both the odd- and even-N gold isotopes. However, the observed step in the charge radii in the gold chain is significantly larger than that in the platinum and iridium cases. Furthermore, the transition from spherical to strongly deformed shapes is much sharper in the gold compared to that seen in the platinum chain, and whilst a prominent odd-even staggering is observed in the latter, the trend followed by the strongly-deformed gold cases is much flatter. This sharp and large jump between near spherical ground states, to a plateau of strongly deformed ones at the neutron midshell, is a pattern that is unique to the gold isotopes within the chart of nuclides.

As well as $\delta\langle r^2\rangle_{A,197}$ values, Table I gives values for μ, most of which were published in our previous works [36–41] but are included for completeness. All μ values have been calculated using the approach to the hyperfine anomaly (hfa) described in [41], including $\mu(^{177,179}\mathrm{Au})$ which have been recalculated from [36]. Our value for $\mu(^{183}\mathrm{Au})$ agrees reasonably with $\mu(^{183}\mathrm{Au})$=1.972(23) μ_N [20], with the small difference due to the different treatment of the hfa. Our new result for ^{181}Au assumes $I = 3/2$, which gives an experimental μ in good agreement with that expected of a single-particle $\pi h_{9/2}$ state ($\mu_{eff}(\pi h_{9/2}) = 1.185$, using an effective spin g factor $g_{s,eff} = 0.6 g_s$).

To further explore our experimental results, we have performed Hartree-Fock-Bogoliubov (HFB) calculations following the protocol of Ref. [70]. The candidates for the empirical ground states are chosen from the calculations for having:

- The same I^π as that assigned experimentally.
- The value of μ in best agreement with the experimental data.
- An excitation energy of < 1 MeV relative to the theoretical ground state.

Note, similar selection criteria were recently used successfully for modelling the radii of mercury isotopes using the Monte-Carlo shell model (MCSM) [14, 15]. However, odd-odd nuclei such as those in the gold chain remain a challenge for the MCSM approach.

Our HFB calculations use the D1M Gogny interaction [71] with the equal filling approximation for the odd-A and odd-odd gold nuclei. Similarly to our recent works [16, 70, 72, 73], potential energy surfaces are calculated whilst blocking quasiparticles that are compatible with the I^π for the ground and

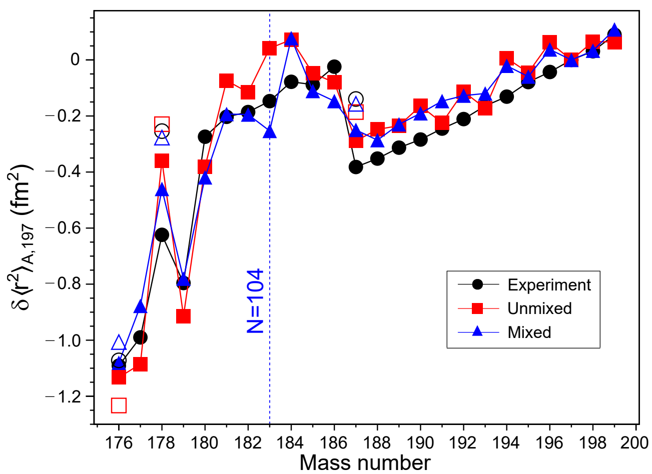

FIG. 2. Comparison between experimental $\delta\langle r^2\rangle_{A,197}$ values (●) for gold isotopes with HFB calculations without (■) and with (▲) CM included. The filled symbols connected by lines indicate ground states, whilst the hollow symbols represent the isomers in ^{178,187}Au and the high-spin state in ^{176}Au. The $11/2^-$ isomers have been excluded for clarity.

isomeric states deduced from experiment, and for ^{183,185}Au, the known $K^\pi = 1/2^-$ assignments were used (see Ref. [74] and references therein).

Magnetic moments are calculated with the method described in Ref. [70], using an effective operator $\hat{\mu}^{eff} = 0.82 g_s \hat{s} + 1.25 g_\ell \hat{\ell}$, where g_ℓ is the orbital g factor for the free nucleon. Effective coefficients are used to account for beyond mean-field and core-polarization effects [75], which are required to reproduce experimental values. For strongly deformed cases, rotational contributions are also included.

The calculated and experimental $\delta\langle r^2\rangle_{A,197}$ values for gold isotopes are compared in Fig. 2 (a similar comparison for μ is provided in the Supplemental Material). The main features of the experimental results are reproduced well: moving from heavier to lighter masses, the jump from near-spherical to well-deformed at $A = 186$; a retention of strongly-deformed ground states for $A = 180 - 186$; a return towards sphericity for ^{176,177,179}Au; and the shape staggering and large isomer shift in ^{178}Au.

However, at points there remain discrepancies between experiment and theory which may be due to configuration mixing (CM) between states of different deformation, as was recently seen in the bismuth isotopes [16]. The possible influence of CM in the gold isotopes was explored following the same method used in Ref. [16], taken from statistical physics [76, 77]. Here, several states of different deformations (q) are mixed, and the average value of an observable (O) is calculated using the expression:

$$\langle O\rangle = \frac{\int O \exp[E(q)/T]\, dq}{\int \exp[E(q)/T]\, dq}, \tag{1}$$

where $E(q)$ is the HFB energy of the potential energy surface

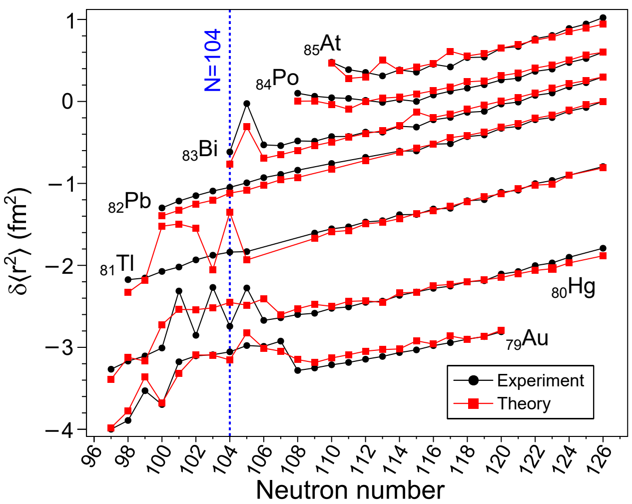

FIG. 3. Comparison between experimental (●) and theoretical (■) results for ground state $\delta\langle r^2\rangle$ values along isotopic chains. The isotopic chains are arbitrarily offset from each other for clarity, and are labelled with their chemical symbol and proton number.

at deformation q, and T is a parameter which allows mixing between low-lying states. For our calculations, a value of T = 0.5 MeV was used.

The calculated results including CM are shown in Fig. 2. An improved agreement is observed in the region of strong ground state deformation, whilst the description of the near-spherical cases remains comparable to those without CM. Overall, though differences remain, a good agreement between experiment and calculation is observed, especially considering the odd-A and odd-odd nature of gold isotopes.

The general applicability of our approach was investigated by performing calculations for neutron-deficient nuclei from mercury (Z = 80) to astatine (Z = 85). These nuclides are a hotbed of shape phenomena, transitioning from the staggering in ground state deformation of the mercury isotopes that lie below spherical lead nuclei [10, 11], to the polonium [31, 32] and astatine nuclides [33] with their early onsets of deformation as the neutron number moves away from N = 126. All of this comes in addition to the cases of shape coexistence that are commonplace throughout this region. This variety in behavior poses a significant challenge to any theoretical approach, particularly when attempting to tackle them in a consistent manner.

For these calculations CM was included, and the same I^π, μ and excitation energy (<1 MeV) selection criteria were used. The results are compared to experimental data in Fig. 3. A good overall agreement is seen across the region, however, there are large discrepancies between for some thallium and mercury isotopes. For the former, strong deformations are calculated in a number of the lightest isotopes that are known to have near-spherical shapes, whilst for the latter, the dramatic staggering is not reproduced.

Closer inspection of the calculations for thallium isotopes show that when a state with strong deformation is selected, it has only a fractionally better μ relative to experiment than a spherical candidate. Thus, our selection criteria do not work in these particular cases. For the mercury chain it was shown in Ref. [70] that the staggering was only reproducible by selecting states in the even-even isotopes with correct deformations. In our calculations the staggering can only be reproduced if an extra constraint on the $\delta\langle r^2\rangle$ is used for state selection (see Supplemental Material). This indicates that there are candidates present at low excitation energies in the HFB calculations with a set of properties consistent with experimental data, however, the present ingredients of the D1M Gogny interaction are not sufficient to correctly predict them as ground states.

To summarize, the $\delta\langle r^2\rangle$ values of ground and isomeric states in neutron-deficient gold isotopes have been measured using the in-source, resonant ionization technique. Advanced atomic calculations of the electronic factors with the refined correlation treatment enable us to decrease systematic theoretical uncertainties in $\delta\langle r^2\rangle$ down to 2.7%, which is comparable in many cases to the experimental uncertainties. An end to the region of strongly deformed ground states has been observed, and a move towards sphericity is seen in ^{176,177,179}Au. Our results reveal a unique pattern in the ground-state shape evolution of gold isotopes, that so far, has not been observed elsewhere in the nuclear chart.

HFB calculations were performed for gold isotopes using the D1M Gogny interaction and a schematic approach to CM between states of different deformations, with the experimental μ and I^π used as criteria for selecting candidate states. A good agreement between these calculations and experimental results was obtained. Further $\delta\langle r^2\rangle$ calculations were performed for the ground states of neutron-deficient nuclides near Z = 82. A good agreement with experiment was observed, with candidates for ground states with correct I^π and μ values found for almost all cases across the region. However, the criteria needed for selecting appropriate states from the calculations highlight that further refinement of the present interaction is required. In this respect, $\delta\langle r^2\rangle$ and μ values can play an important role in constraining the development of future interactions. In addition, though the schematic statistical approach towards CM used was successful, it indicates the necessity to include such mixing at a microscopic level in the future works.

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