



Isomer studies in the vicinity of the doubly-magic nucleus ^{100}Sn : Observation of a new low-lying isomeric state in ^{97}Ag

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ABSTRACT

Long-lived isomeric states in ^{97}Ag and $^{101-109}\text{In}$ were investigated with the FRS Ion Catcher at GSI. In the isotope ^{97}Ag , a long-lived ($1/2^-$) isomeric state was discovered, and its excitation energy was determined to be 618(38) keV. This is simultaneously the first discovery of a nuclear isomeric state by multiple-reflection time-of-flight mass spectrometry. The measured excitation energies were compared to large-scale shell-model calculations, which indicated the importance of core excitation around ^{100}Sn . Furthermore, advanced mean-field calculations for the ^{97}Ag nucleus and relevant neighboring nuclei were performed, which have contributed to a better understanding of the repetitive appearance of certain isomeric structures in neighboring nuclei, and which have supported the discovery of the isomeric state in ^{97}Ag in a global shell-evolution scheme.

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1. Introduction

The lifetimes of isomers are much longer than those of common excited states [1]. There are several reasons for this: the shape, the spin, or the spin orientation relative to a symmetry axis of the isomeric state. The properties of nuclear isomers [2] are significant for

the understanding of nuclear structure because they provide stringent tests for nuclear models. There is a broad field of applications for nuclear isomers, ranging from new possibilities for the storage of energy to the impact on nuclear astrophysics and the synthesis of the elements in the universe [3].

The nucleus ^{100}Sn is the heaviest self-conjugate doubly-magic nucleus in the chart of nuclides, and therefore, attracts a broad interest in both experimental and theoretical nuclear physics. Since its discovery [4,5], it has been the subject of many investigations

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and measurements, leading to a better understanding of the nuclear structure in this region of the nuclear chart [6]. Because the experimental access to ^{100}Sn is still limited, most of the data obtained stems from nuclei in the neighborhood. Therefore, the knowledge of their detailed structure is indispensable in understanding this region of the chart of nuclides. Recently, new isotopes in this region were identified, and their half-lives and decay properties have been measured [7–10]. In-beam and decay spectroscopy delivered new information on single particle level energies and residual nucleon-nucleon interaction [6], especially below ^{100}Sn , in the last 20 years. ^{100}Sn , as an open spin-orbit (SO) core nucleus, allows the study of the $1g_{9/2}$ intruder-dominated states, with significantly different angular momentum from that of the neighboring states. Consequently, states that are close in energy have a large difference in spin, causing the existence of long-lived isomeric states, i.e., meta-stable states. The comparison of large scale shell model (LSSM) and mean field approaches, and their complementarity, will lead to a clearer understanding of nuclear structure evolution in this region.

The masses of nuclei reflect their total binding energy, and can be measured directly using mass spectrometry techniques. The mass reveals basic information about nuclear properties [11]. Despite experimental efforts, documented by many Penning trap measurements in this region [12–15], there is a large uncertainty still associated with the mass of ^{100}Sn ($\Delta m \approx 300$ keV) [16,17]. The heaviest $N = Z$ nuclides with a mass that is measured directly is ^{76}Sr . Those neutron-deficient nuclei are synthesized in astrophysical environments, where the rapid proton capture process (rp -process) takes place [18,19]. The modeling of the rp -process is necessary in understanding the origin of the elements and the abundances of the isotopes in the universe.

High-resolution mass spectrometry is a relatively new tool to study isomeric states. During the last two decades, isomeric states were discovered by mass measurements, using storage rings [20, 21] and Penning traps [22]. The half-lives are difficult to access in the millisecond range because established high-resolution mass spectrometry methods are either not fast enough, or have very limited mass ranges that can be simultaneously measured. For decay spectroscopy, the challenge is the requirement of long coincident-times, which result in a strongly increased background. The first discovery of a nuclear isomeric state by multiple-reflection time-of-flight mass spectrometry is presented in this paper. The multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS) of the FRS Ion Catcher [23] is, due to its unique combination of performance parameters, an ideal device for the search for new isomeric states [24]. It combines a high mass resolving power ($m/\Delta m > 600,000$), short measurement time (> 0.01 s), high accuracy (relative mass accuracy of $< 10^{-7}$), and non-scanning operation. Combined with a gas-filled stopping cell, it is applicable for production methods at the Coulomb barrier and relativistic energies. Therefore, the MR-TOF-MS of the FRS Ion Catcher has a high discovery potential for isomeric states with half-lives as low as the ms range.

2. Experiment

The FRS Ion Catcher [25] is installed at the final focal plane of the fragment separator FRS [26] at GSI. The FRS Ion Catcher consists of three main parts: (i) the gas-filled cryogenic stopping cell (CSC) [27–30], which executes the complete slowing-down of the exotic nuclei produced at relativistic energies, (ii) a radio frequency quadrupole (RFQ) beamline [30–33], which is used for mass-selective transport and differential pumping, and (iii) the MR-TOF-MS [23,34,35], which performs direct mass measurements.

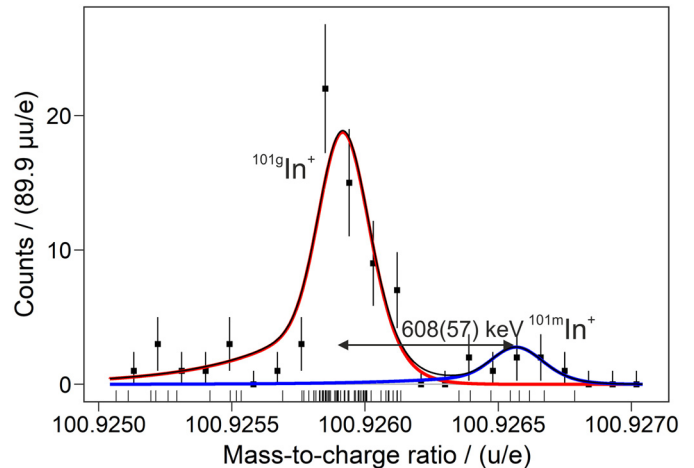


Fig. 1. Measured mass-to-charge spectrum of $^{101}\text{In}^+$ ions. The fit of the ground state and the $(1/2^-)$ isomeric state are shown by the red and blue line, respectively. The histogram of the measured spectrum is drawn only to guide the eye. The evaluation was based on measured unbinned data (“rug” graph below the histogram).

In this experiment, the exotic nuclei and their isomeric states were produced via projectile fragmentation using a 600 MeV/u ^{124}Xe projectile beam on a beryllium production target with an areal density of 1.622 g/cm 2 . The intensity was approximately 3×10^8 ions per second, with a typical spill length of 500 ms and a spill period of approximately 4 s. The mono-energetic degrader at the central focal plane [36] had an areal density of 737.1 mg/cm 2 . The CSC had an areal density of 4.6 ± 0.15 mg/cm 2 helium, corresponding to a pressure of 75 mbar at a temperature of 82 K. The extraction time for this experiment was approximately 200 ms [37]. The molecular background, generated in the CSC, was suppressed in the RFQ beamline by the isolation-dissociation-isolation method [38].

The measurements in the MR-TOF-MS were performed with a time-of-flight of approximately 19 ms (typically about 600 isochronous turns in the analyzer) and a mass resolving power of up to 450,000. The mono-energetic degrader at the mid-focal plane of the FRS ensured that the isotopes had only a narrow range distribution; this feature was used as an additional identification tool [39]. The measurements were done using different settings of the aluminum degrader at the final focal plane of the FRS. In addition, a measurement with one more turn in the time-of-flight analyzer was performed. This measurement, which had a different number of reflections, served as further confirmation of the particle identification [40].

The details of the MR-TOF-MS data-analysis procedure were reported in a separate publication [40]. The procedure allows accurate mass determination, even in the most challenging conditions, including very low numbers of events and overlapping mass distributions. In the mass measurements reported in Ref. [40], a relative uncertainty as low as 6×10^{-8} was achieved. Further details on the experiment and the data evaluation employed for the nuclides reported here, and their isomeric states, are provided in Ref. [39, 41].

3. Experimental results

The mass-to-charge spectrum for $^{101}\text{In}^+$ ions in the ground and isomeric state, measured with the MR-TOF-MS, is shown in Fig. 1. The ground and isomeric states were fitted with a so-called double hyper-EMG [44] (red line for $^{101g}\text{In}^+$ and blue line for $^{101m}\text{In}^+$) with one exponential tail on both sides. The peak shape was determined from a high statistical peak. For the isomeric state 9 counts

Table 1

Measured mass excess $ME_{\text{FRS-IC}}$ values of the ground states and excitation energies $E_{\text{exc,FRS-IC}}$ of the $(1/2)^-$ and $(19/2)^+$ isomeric state ^{109}In . The measured data are compared with the literature values (ME_{Lit} , atomic mass evaluation (AME) [16], and $E_{\text{exc,Lit}}$, the atlas of isomers [42]). In the last column, the difference between the measured and literature values is given. # The values and uncertainties are extrapolations obtained from [43].

Nuclide	Half-life	$ME_{\text{FRS-IC}}$ [keV]	ME_{Lit} [keV]	$ME_{\text{FRS-IC}} - ME_{\text{Lit}}$ [keV]
^{97}Ag	$(25.5 \pm 0.3) \text{ s}$	-70904 ± 12	-70830 ± 110	-74 ± 111
^{101}In	$(15.1 \pm 1.1) \text{ s}$	-68535 ± 20	-68610 ± 200 #	75 ± 201
^{103}In	$(60 \pm 1) \text{ s}$	-74631 ± 25	-74633 ± 10	2 ± 27
^{105}In	$(5.07 \pm 0.07) \text{ m}$	-79677 ± 31	-79641 ± 10	-36 ± 33
^{107}In	$(32.4 \pm 0.3) \text{ m}$	-83583 ± 27	-83564 ± 11	-19 ± 29
^{109}In	$(4.167 \pm 0.018) \text{ h}$	-86522 ± 34	-86490 ± -4	-32 ± 34

Nuclide	Half-life	$E_{\text{exc,FRS-IC}}$ [keV]	$E_{\text{exc,Lit}}$ [keV]	$E_{\text{exc,FRS-IC}} - E_{\text{exc,Lit}}$ [keV]
^{97m}Ag	100 ms #	618 ± 38	400 ± 200 #	218 ± 204
^{101m}In	10 s #	608 ± 57	550 ± 100 #	58 ± 115
^{103m}In	$(34 \pm 2) \text{ s}$	689 ± 77	631.7 ± 0.1	57 ± 77
^{105m}In	$(48 \pm 6) \text{ s}$	702 ± 27	674.08 ± 0.25	28 ± 27
^{107m}In	$(50.4 \pm 0.6) \text{ s}$	663 ± 22	678.5 ± 0.3	-16 ± 22
^{109m}In	$(1.34 \pm 0.07) \text{ m}$	651 ± 27	650.1 ± 0.3	1 ± 27
^{109n}In	$(209 \pm 6) \text{ ms}$	2098 ± 11	2101.8 ± 0.2	-4 ± 11

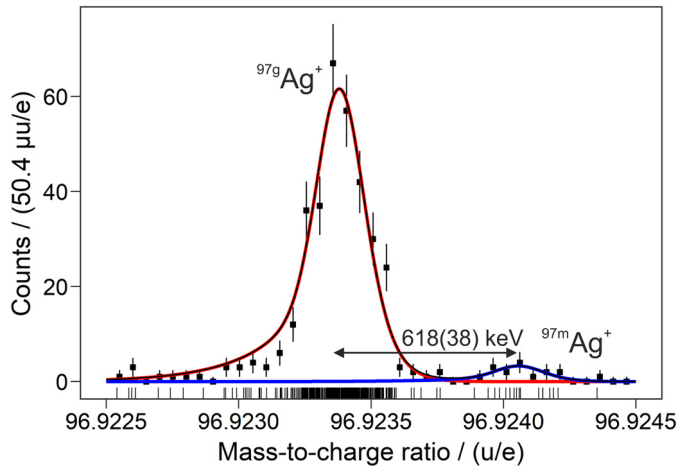


Fig. 2. Measured mass-to-charge spectrum of $^{97}\text{Ag}^+$ ions. The fit of the ground state and the $(1/2)^-$ isomeric state are shown by the red and blue line, respectively. The histogram of the measured spectrum is drawn only to guide the eye. The evaluation was based on measured unbinned data ("rug" graph below the histogram).

were detected. The background in the spectrum was 1 count per 3 FWHM. The estimated spins of the ground and isomeric states were $(9/2^+)$ and $(1/2^-)$, respectively. This was the first mass measurement for the isotope ^{101}In . A mass excess value for the ground state was determined to be $-68535(20)$ keV for ^{101}In . The extrapolated value in the AME 2016 [16] is $-68610(200)$ keV. Our measured value is expected to have an impact on the nucleosynthesis in the rp -process [45]. The excitation energy of the $(1/2^-)$ isomeric state was determined to be $608(57)$ keV. The $(1/2^-)$ isomeric state of ^{101}In was recently confirmed by an isochronous mass spectrometry measurement at the HIRFL-CSR facility in Lanzhou [46]. An excitation energy of $659(50)$ keV was reported, which is in agreement with the result presented in this paper.

The nucleus ^{101}In was produced in fragmentation, with a production cross section of 230 nbarn [47]. An isomer-to-ground state ratio of 0.14 ± 0.03 was measured. Therefore, an effective production cross section of approximately 30 nbarn can be deduced for the isomeric state. This sensitivity was recently reported to be sufficient for the discovery of isotopes [48]. The $(1/2^-)$ isomeric state was measured at a rate of 2 per hour. The high sensitivity, mass resolving power, and dynamic range make the MR-TOF-MS an ideal

tool to measure and identify exotic nuclei in their ground and isomeric states.

The masses of the ground and $(1/2^-)$ isomeric states of the odd nuclides $^{103}\text{--}^{109}\text{In}$ were determined, as seen in Table 1. In this isotopic chain, all odd isotopes have a $9/2^+$ ground state and a $1/2^-$ isomeric state [16]. The mass excess values are in good agreement with previous storage ring and Penning trap measurements [49,50]. The results for the excitation energies are in good agreement with previous experiments [51].

The measured mass-to-charge spectrum of $^{97}\text{Ag}^+$ ions is shown in Fig. 2. Ground and isomeric states were fitted with a double hyper-EMG [44] (red line for $^{97g}\text{Ag}^+$ and blue line for $^{97m}\text{Ag}^+$), with one exponential tail on both sides. The peak shape was determined from a high statistical peak. For the isomeric state, 14 counts were detected. The background in the spectrum was measured at 1 count per 3 FWHM. The mass excess values of the ground state were determined to be $-70904(12)$ keV. Previously, the $(9/2^+)$ ground state of ^{97}Ag was measured indirectly by γ -spectroscopy [52]. The first direct mass measurement is reported in the current paper. The uncertainty of the mass value was reduced by almost an order of magnitude.

For the $(1/2^-)$ isomeric state, an excitation energy of $618(38)$ keV was determined from the mass measurement. Recently, new information was added to the level scheme [53]. The measurement of the excitation energy now allows the correct positioning of the negative parity states, i.e., the $(3/2^-)$ state had an energy of $1853(57)$ keV, and therefore, above the second $(9/2^+)$ state.

The nucleus ^{97}Ag was produced in fragmentation, with a production cross section of $1.2 \mu\text{barn}$ [47]. An isomer-to-ground state ratio of 0.078 ± 0.005 was measured, corresponding to an effective production cross section of approximately 90 nbarn for the isomeric state.

The decay properties of ^{97}Ag were investigated in β -delayed γ -spectroscopy, and shell model calculations were performed [54]. The decay properties and with this, the half-life of the $(1/2^-)$ state crucially depends on its excitation energy. Assuming an excitation energy of approximately 600 keV, de-excitation would be only possible via an M4 transition to the ground state, or a Gamow-Teller decay, leading to a predicted half-life up to several hundred seconds. This is in agreement with our expectations, based on the measured extraction time from the CSC of approximately 200 ms, because the isomeric state survived the transport to the MR-TOF-MS. The isomer-to-ground state ratio for the $(1/2^-)$ isomeric state of ^{101}In was measured to be approximately a factor of 2 larger. If

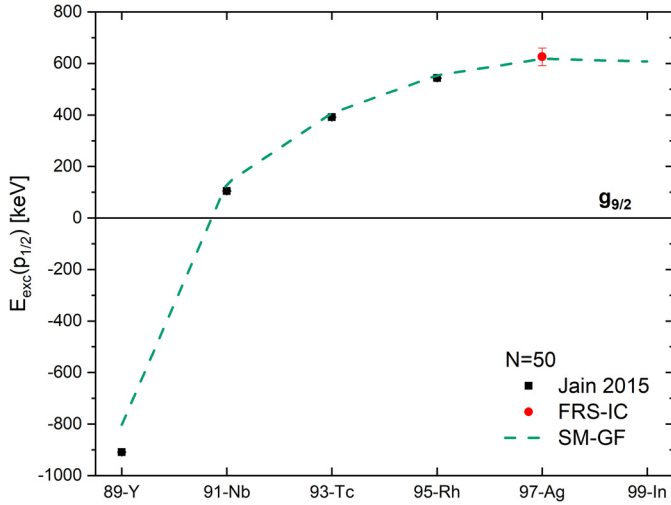


Fig. 3. Excitation energy of the $1/2^-$ isomeric state in odd-even $N=50$ nuclei. The excitation energy measured with the MR-TOF-MS at the FRS Ion Catcher is shown as a red circle. In addition, the values taken from the atlas of nuclear isomers [42] are shown by black squares, and SM-GF calculations [55] by the green dashed line. The ^{89}Y value is negative because it is still in the $\pi p_{1/2}$ sub-shell and $1/2^-$ is the ground state.

we assume a similar ratio for ^{97}Ag , it can be concluded that the half-life of ^{97m}Ag should be approximately 200 ms.

The measured masses provide information on the evolution of the mass excess values in the region below the double magic nucleus ^{100}Sn . From the mass measurement of ^{97}Ag and ^{101}In , the Q_α -value of ^{101}In was directly measured for the first time at $-56(23)$ keV. The extrapolated value stated in the AME [16] was $-210(220)$ keV. Due to the reduction of the error by an order of magnitude, an energetically possible α -decay can now be excluded with a two-sigma confidence-level. In addition, the Q_α -values of ^{105}Sb were directly determined to be $2095(30)$ keV and the error for ^{97}Ag has been reduced, approximately by an order of magnitude, to $-4317(13)$ keV. These three Q_α -values are necessary for the rp -process calculations [45].

4. Theoretical results

A comparison of the measured excitation energies of ^{97}Ag and the odd isotopes of $^{101-109}\text{In}$, along the isotonic and isotopic chains, with shell-model calculations provide interesting results. In particular, new data validates the need to include core excitations across $N=50$ in the calculations.

For the nuclei in the neighborhood of the doubly-magic spherical ^{100}Sn , the leading mechanism of the decay hindrance is associated with the axial symmetry, resulting from the polarization of the core by a few particles (or holes) on top of the closed main shells at $Z=50$ and/or $N=50$. The closed shell structures give rise to the strictly spherical geometry; however, the neighboring nuclei are expected to manifest a competition between the slightly oblate ($\beta_2 < 0$) and prolate ($\beta_2 > 0$) quadrupole deformations. Such shape distortions can be described using the nuclear mean-field approach.

4.1. Shell model calculation

The evolution of the proton $p_{1/2}$ and $g_{9/2}$ single-hole energies was studied using various shell model (SM) approaches, and compared to the experimental results.

For the $N=50$ isotones, an empirically determined isospin-asymmetric interaction (GF) [55] was used in a $\pi\nu(p_{1/2}, g_{9/2})$

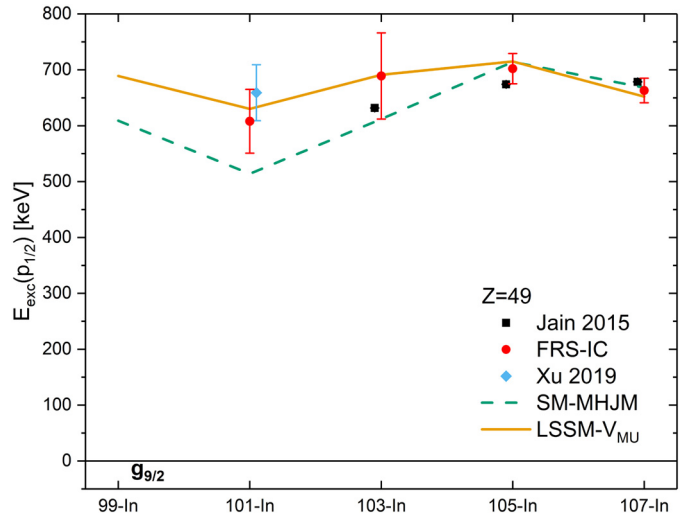


Fig. 4. Excitation energy of the $1/2^-$ isomeric state in odd indium nuclei. The excitation energies, measured with the MR-TOF-MS at the FRS Ion Catcher, are indicated by red circles and the values taken from the atlas of nuclear isomers [42], by black squares. The value measured at the HIRFL-CSR facility in Lanzhou [46] is indicated by the blue diamond, SM-MHJM calculations [56], by the green dashed line, and LSSM- V_{MU} calculations [57], by the yellow solid line.

model space, outside a hypothetical ^{76}Sr core. Two-body matrix elements (TBME) and single particle energies (SPE) were fitted to energy spectra and binding energies in $N, Z \leq 50$ nuclei.

The theory is in agreement with the measured data for the $N=50$ isotones, as seen in Fig. 3. As a result of the first measurement of the ^{97}Ag ($1/2^-$) state, a reliable extrapolation of the ^{99}In value was possible. The extrapolation of the ^{99}In was used as an anchor point for further calculations along the indium isotopic chain.

The spectra of $N \geq 50$ In isotopes were calculated in a $\pi(p_{1/2}, g_{9/2})\nu(g_{7/2}, d_{3/2}, d_{5/2}, s_{1/2}, h_{11/2})$ model space, with an ^{88}Sr core employing a realistic interaction based on a G-matrix, inferred from the charge dependence (CD-Bonn) nucleon-nucleon potential. The interaction was renormalized with respect to the ^{88}Sr SM core, using many-body theory techniques (MHJM) [56], and monopole tuned to reproduce the ^{100}Sn single particle/hole neutron/proton energies [58]. The $\pi\pi$ and $\nu\nu$ TBME were marginally monopole corrected to optimize total binding energies in the $N > 50$ nuclei. It should be noted that in the overlapping $N=50$ isotones, both approaches yield identical $p_{1/2} - g_{9/2}$ excitation energies.

The $\pi\nu$ interaction results in a kink in the $A=99-101-103$ evolution of the excitation energy of the $1/2^-$ state, as can be observed in Fig. 4. This may result from an overestimation of the effect of the $\pi\nu$ interaction for $N > 50$. In the present model space, the $A=99-101$ decrease was due to the strong $\nu g_{7/2} - \pi g_{9/2}$ monopole interaction, as compared to $\nu g_{7/2} - \pi p_{1/2}$, which pulled the proton orbitals closer together. The saturation of the excitation energy, up to ^{107}In , was well reproduced.

An inspection of the wave functions indicated that the $1/2^-$ state was dominantly comprised of $\pi p_{1/2}$ coupled to the 0^+ ground state of the Sn isotone; however, in the case of the $9/2^+$ state, coupling to the $2^+ - 8^+$ states was also allowed. The effect of core excitations caused the latter states to increase their excitation, relative to the 0^+ ground state, as known from ^{98}Cd [59] and ^{102}Sn [60].

Therefore, as an alternative to the LSSM approach, core excitations across the $Z, N=50$ closed shells were included in a $\pi\nu(p_{1/2}, g_{9/2})\nu(g_{7/2}, d_{3/2}, d_{5/2}, s_{1/2}, h_{11/2})$ model space. The interaction was V_{MU} [57] in the $\pi\nu(gdsh)$ space, and was from [61]. The interaction was implemented by $\pi\nu V_{MU}$, quenched by a fac-

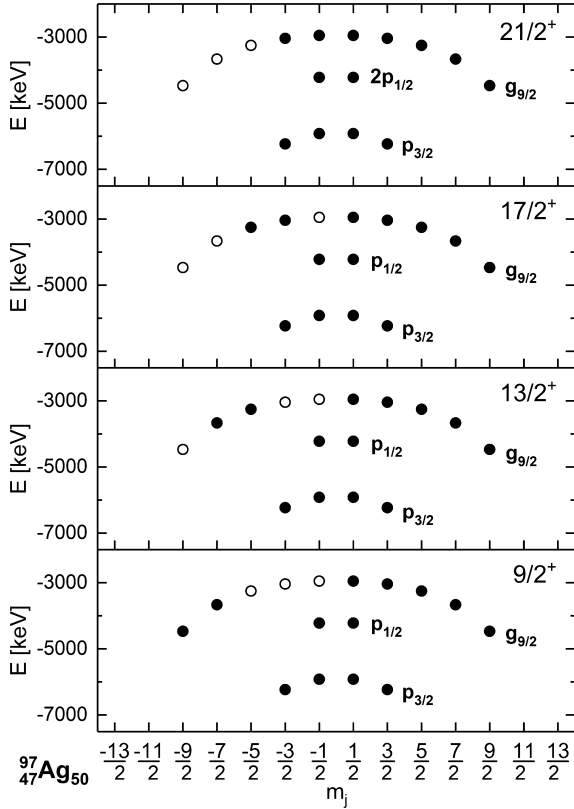


Fig. 5. Sequence of deformed mean-field proton configurations (proton single particle levels dependent on the angular momentum projections m_j) corresponding to the maximum alignment state $I^\pi = 21/2^+$ and the other states, which can be connected to it via non-collective E2-transitions, down to the ground-state at $I^\pi = 9/2^+$. Full circles represent the occupied orbitals; open circles, the unoccupied orbitals. All the orbitals, down to the bottom of the potential well (not shown in the figure), were presumed occupied. A deformation of $\beta_2 = -0.09$ and $\beta_4 = +0.02$ were used.

tor of 0.75 in the $T = 1$ central force channel. The SPE were chosen to reproduce the present interaction and those of reference [61]. The $p_{1/2}$ SPE in ^{99}In was adjusted to reproduce the general trend. Truncation was applied to allow for up to $3p3h$ excitations across $Z, N = 50$ and $1p1h$ from $(g_{7/2}, d_{5/2})$ to $(d_{3/2}, s_{1/2}, h_{11/2})$. The results show a relatively flat trend along the indium chain, and a reduced kink for ^{101}In . This is in agreement with the experiment (Fig. 4) and documents the impact of core excitations in low-lying, dominantly single hole states.

4.2. Mean-field calculation

Large scale nuclear mean-field calculations have been performed for several nuclei in the discussed region. The calculations employed minimization individually, over the axial deformations of each nuclear particle-hole excited-state energy (the deformations, β_2 and β_4 , were used). The choice of the employed mean-field Hamiltonian considers that in contemporary nuclear structure physics, special attention is paid to the control of uncertainties of the modeling, and in particular, of the prediction capacities, of nuclei away from the nuclear areas, which served for the parameter adjustments (as seen in [63–66]). For reasons discussed in some detail in [67–70], the phenomenological Woods-Saxon Hamiltonian was chosen, with the universal parameterization of its potential. With a single set of parameters, it describes, on average, all the individual-nucleonic energy levels in nuclei, throughout the chart of nuclides; the relevant information is summarized in [71].

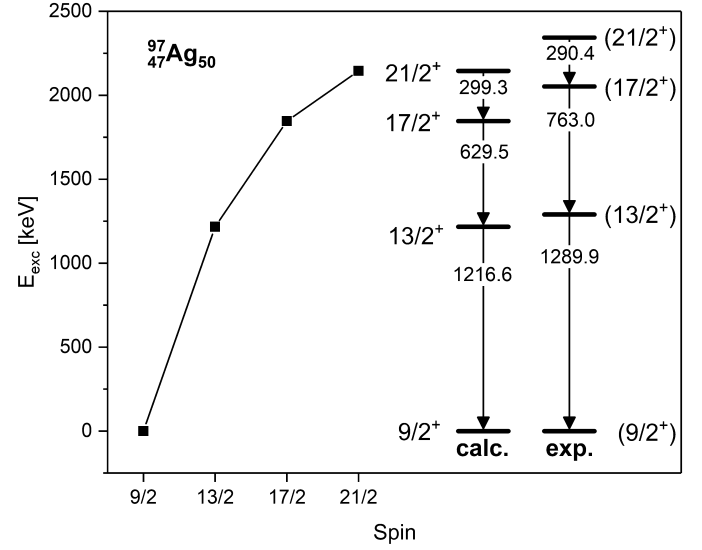


Fig. 6. Comparison between the calculated energies of the $I^\pi = 9/2^+, 13/2^+, 17/2^+$, and $21/2^+$ sequence, discussed in the text (with regard to the calculations). The experimental data was obtained from the National Nuclear Data Center database [62]. A close correspondence of the two sequences can be observed, at the slightly oblate quadrupole deformation, as indicated in the field of Fig. 5.

This section is limited to illustrating just a few selected results from the large-scale mean-field calculations addressing K-isomerism in the nuclear mass region, discussed in an upcoming article [72]. The results presented below are parameter-free – no readjustments, related to either the isomers or the excitation spectra in the discussed nuclei, have been performed.

In constructing the nuclear spectra, with the help of mean-field theory, the maximum-alignment configurations are significant, usually located at, or close to, the yrast lines (the term “alignment” relates to the nucleonic angular momenta). An effective approach to finding these lowest energy configurations has been proposed by the Copenhagen School, and is known in the literature as the “tilted Fermi surface method” [73–75]. One of the by-products of the tilted Fermi surface approach are the diagrams, similar to those in Fig. 5, which display the single-nucleon energy positions versus angular momentum projections. They also allow a qualitative discussion on the structures of the configurations, and the varying quadrupole or higher multipolarity axial deformation.

With the help of the aforementioned diagrams, some quantitative or semi-quantitative predictions were formulated in a simple, pedagogical manner. For example, the spin-parity characteristics of the ground-state must be $I^\pi = 9/2^+$, because the proton orbital closest to the Fermi level in $^{97}_{47}\text{Ag}_{50}$ is $1g_{9/2}$. According to the distribution of the mean-field proton orbitals, shown in Fig. 5, an illustration, which is characteristic to the maximum alignment analyses, inherent to the tilted-Fermi-surface method, can be given. There were 6 protons placed in pairwise antiparallel-spin orbitals, with spin projections denoted $\pm m_j$, the seventh one giving rise to the actual value of the ground state spin (Fig. 12 and 33–35 of [75]).

The lowest energy solutions, obtained with the tilted-Fermi-surface algorithm, often give rise to the yrast-trap configurations and related isomers (Fig. 32 in [75] and references therein).

The maximum alignment configuration possible without breaking the $Z = 50$ core using the tilted-Fermi-surface approach was $I^\pi_{\text{max}} = 21/2$. A sequence of low-lying positive parity states, with spins satisfying $9/2 < I < 21/2$, corresponding to different placements of the protons within the $1g_{9/2}$ configuration, were simul-

taneously pedagogically constructed. Some of these states are represented in Fig. 5.

Moreover, there exist low-energy excited states, characterized by $(1/2)^-$ that were obtained by promoting one of the protons residing in the $2p_{1/2}$ orbital, and occupying one of the three empty states of $1g_{9/2}$. Because the mean-field calculations showed that transitions de-exciting those latter states are of the type $\Delta I = 4$ or higher, and required a parity change, it was expected that such states would form long-living isomers.

The energies of the characteristic “inverted parabola” sequence, composed of configurations from Fig. 5, were compared to the presently known experimental data in Fig. 6. Because there was no intervention of parameter adjustments, the correspondence can be considered satisfactory, providing confidence in the underlying mean-field algorithm and its more advanced applications, which are not discussed here because it is outside the scope of the paper. The correspondence particularly provides the possibility of formulating some semi-qualitative conclusions about the nature of the $(1/2)^-$ isomer. Within the mean-field interpretation, and depending on which member of the $1g_{9/2}$ orbital is occupied by the proton originating from the $2p_{1/2}$, calculations suggested that there may exist several structures with 8 protons on $1g_{9/2}$, giving rise to a sequence of energies centered about the average position $E_{\text{aver.}}^{1/2} \approx 0.6$ MeV, within a ± 0.4 MeV interval. This estimate corresponded satisfactorily, to our experimental findings, at least on the semi-quantitative level.

5. Summary

The first discovery of a nuclear isomeric state by multiple-reflection time-of-flight mass spectrometry was achieved by measuring the $(1/2)^-$ isomeric state in ^{97}Ag . The excitation energies of the $(1/2)^-$ isomeric states in the isotopes ^{97}Ag and $^{101-109}\text{In}$ were determined from direct mass measurements of the ground and isomeric states of these isotopes, at the FRS Ion Catcher, involving cross sections as low as approximately 30 nbarn. The excitation energy of the $(1/2)^-$ isomeric state in ^{97}Ag was determined to be 618(38) keV. For ^{109}In , a second isomeric state was measured, the half-life of which is only 209 ms. In order to resolve the low-lying isomeric states, the MR-TOF-MS was operated with a mass resolving power of up to 450,000 at a duty cycle of 20 ms. Moreover, the mass of ^{101}In was measured for the first time, and the uncertainty of the ^{97}Ag ground state mass was reduced by more than an order of magnitude. These results show that the MR-TOF-MS of the FRS Ion Catcher is an efficient tool for discovery of isomeric states with half-lives in the millisecond range, which have not been well studied so far because of the difficulty to access them using existing techniques.

The measured excitation energies were compared with shell-model calculations, indicating the need to include core excitations to describe the excitation energies of the $1/2^-$ isomeric states along the Indium chain. Furthermore, results obtained within the mean-field approach for the nucleus ^{97}Ag were shown, allowing a better understanding of the level scheme from the “universal parametrization” point of view, and supporting the discovery of the isomeric state in ^{97}Ag .

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