Isomeric states close to doubly magic ^{132}Sn studied with the double Penning trap JYFLTRAP

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The double Penning trap mass spectrometer JYFLTRAP has been employed to measure masses and excitation energies for $11/2^-$ isomers in ^{121}Cd, ^{123}Cd, ^{125}Cd, and ^{133}Te, for $1/2^-$ isomers in ^{129}In and ^{131}In, and for 7^- isomers in ^{130}Sn and ^{134}Sb. These first direct mass measurements of the Cd and In isomers reveal deviations to the excitation energies based on results from β-decay experiments and yield new information on neutron- and proton-hole states close to ^{132}Sn. A new excitation energy of 144(4) keV has been determined for ^{123}Cd^m. A good agreement with the precisely known excitation energies of ^{121}Cd^m, ^{130}Sn^m, and ^{134}Sb^m has been found.

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I. INTRODUCTION

Long-living excited states, isomers, store energy since their decay is inhibited by nuclear structure effects: the spin, spin projection, or shape of the isomer can be such that there are no easily accessible states for a fast decay. Detailed knowledge on isomers is required for nuclear structure and astrophysics studies as well as for potential future applications, such as energy storage and γ-ray lasers, utilizing the de-excitation of isomeric states in a controlled way [1–3]. Nuclei near ^{132}Sn have typically long-living isomeric states due to the $\nu 1h_{11/2}$ and $\pi 1g_{9/2}$ shells lying close to low-j shells. Information on these isomers has been scarce since many of them decay via β decay and the excitation energies have been based on differences in β-decay energies. In the work presented in this paper, we have applied state-of-the-art cleaning methods at the JYFLTRAP double Penning trap mass spectrometer to study the isomers and corresponding excitation energies around ^{132}Sn.

The astrophysical rapid neutron capture process (r process [4]) proceeds along the $N = 82$ isotones as a sequence of β^- decays and neutron captures before running toward more neutron rich nuclei after ^{132}Sn (see, e.g., Refs. [5,6]). As a result, matter is accumulated around ^{132}Sn, which is observed as a peak at $A \approx 130$ in the abundance pattern. The β-decay properties and masses of the involved nuclei should be precisely known in order to more reliably compare the calculated r-process abundances to the observations. A recent study on the sensitivity of the r process to nuclear masses has shown that nuclei around the closed shells near $N = 50$, 82, and 126 have the largest impact on the r-process abundances irrespective of the mass models used [7]. In order to obtain accurate masses for the relevant nuclei close to ^{132}Sn, it is crucial to assign the measured value correctly either to the ground or isomeric state. Isomers play a role in the r process as such and should be taken into account in the modeling. Namely, isomers and low-lying excited states can be thermally populated if the r process operates at high temperatures, and thus the β-decay rates can significantly differ from the terrestrial rates [5,8]. Furthermore, if the r process operates at such low temperatures that thermal equilibrium cannot be achieved, it becomes necessary to independently describe the population of different isomers after neutron capture and the rates for neutron capture and decay of each isomer.

Experimental data on nuclei close to ^{132}Sn are essential for comparisons with shell-model calculations and for further development of theoretical models needed to describe the properties of the r-process nuclei unreachable by experimental methods. The shell structure at $N = 82$ is also important for determining the role of fission in the r process [9]. Recent Penning trap mass measurements [10,11] as well as a study on single-particle states in ^{133}Sn [12] have verified that ^{132}Sn is magic and that the $N = 82$ shell closure is not quenched. The level schemes of the nuclei in this region are relevant for the shell-model studies. One-particle (or one-hole) nuclei provide direct information on single-particle energies, two-particle (two-hole) nuclei provide direct information on correlations between different nucleon pairs, and various nuclei around ^{132}Sn have been used for studies of neutron-proton interaction [13–16] employing the realistic effective interaction derived from the CD-Bonn nucleon-nucleon potential [17]. Isomers in ^{128}Cd [18] and in the r-process waiting-point nucleus ^{130}Cd [19] have yielded detailed information on two-body interactions as well as on the structure of the states to which isomeric decay is selective. High-spin isomers resulting from couplings of the valence nucleons to core excitations, such as the short-lived isomers in ^{133}Sb [20] and ^{131}In [21], have been interpreted with empirical nucleon-nucleon interactions. Recently, large-scale shell-model calculations with core excitations have been performed for nuclei above ^{132}Sn providing data, e.g., for the 7^- isomer in ^{134}Sb [22].

The isomers studied in this work have spins and parities of $11/2^-$, $1/2^-$, and 7^- (see Table I). Even-Z, odd-N nuclei just below the closed neutron shell $N = 82$ typically have $3/2^+$ or

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TABLE I. Properties of the nuclides studied in this work. The values are based on Ref. [27] unless stated otherwise. Given are half-lives $T_{1/2}$, spin-parities I^{π}, and excitation energies of the isomeric states E_x. The parentheses in the third column indicate uncertain values of spin and/or parity. The values estimated from systematic trends from neighboring nuclides with the same Z and N parities are denoted by "#."

Nuclide	$T_{1/2}$	I^{π}	E_x (keV)
^{121}Cd	13.5(3) s	$(3/2^+)$	
^{121}Cd^m	8.3(8) s	$(11/2^-)$	214.86(15)
^{123}Cd	2.10(2) s	$(3/2)^+$	
^{123}Cd^m	1.82(3) s	$(11/2^-)$	316.52(23)
^{125}Cd	650(20) ms	$3/2^+$#	
^{125}Cd^m	570(90) ms	$11/2^-$#	50(70)
^{129}In	611(4) ms	$9/2^+$#	
^{129}In^m	1.23(3) s	$1/2^-$#	370(40)[a]
^{129}In^n	670(100) ms[b]	$23/2^-$	1630(56)[b]
^{129}In^p	8.5(8) μs	$17/2^-$	1688.0(5)
^{131}In	280(30) ms	$(9/2^+)$	
^{131}In^m	350(50) ms	$(1/2^-)$	302(32)[c]
^{131}In^n	320(60) ms	$(21/2^+)$#	3764(88)[c]
^{130}Sn	3.72(7) min	0^+	
^{130}Sn^m	1.7(1) min	7^-#	1946.88(10)
^{131}Sn	56.0(5) s	$(3/2^+)$	
^{131}Sn^m	58.4(5) s	$(11/2^-)$	69(14)[c]
^{132}Sb	2.79(5) min	(4^+)	
^{132}Sb^m	4.15(5) min	(8^-)	200(30)
^{134}Sb	780(60) ms	(0^-)	
^{134}Sb^m	10.07(5) s[d]	(7^-)	279(1)[d]
^{133}Te	12.5(3) min	$(3/2^+)$	
^{133}Te^m	55.4(4) min	$(11/2^-)$	334.26(4)

[a]The value is a weighted mean of the results from [28–30].
[b]The value has been taken from [30].
[c]The value has been taken from [31].
[d]The value has been taken from [32].

$1/2^+$ ground states and $11/2^-$ isomeric states, corresponding to a neutron hole in $2d_{3/2}$, $3s_{1/2}$, or $1h_{11/2}$ shells, respectively. Odd-In ($Z = 49$) isotopes have $9/2^+$ ground and $1/2^-$ isomeric states due to a proton hole in the $1g_{9/2}$ or $2p_{1/2}$ shells. The evolution of the excitation energies of the $11/2^-$ and $1/2^-$ isomeric states toward the closed neutron shell at $N = 82$ gives us information on these neutron- and proton-hole states close to ^{132}Sn. The 7^- isomers in the two-neutron-hole nucleus ^{130}Sn and in ^{134}Sb having one proton and neutron above ^{132}Sn have also been investigated. Since these isomers are already well known via γ-spectroscopy, they provide a good consistency check of our measurements. Cd and In isotopes have also high-lying, high-spin ($I \geqslant 17/2$) isomers which usually have relatively short half-lives (see, e.g., Refs. [23–26]). Short-lived isomers are not of interest for this work and we focus on isomers with half-lives longer than 100 ms.

II. EXPERIMENTAL METHOD

The ions of interest were produced via fission reactions induced by 25-MeV protons on $^{\text{nat}}$U or ^{232}Th at the Ion Guide Isotope Separator On-Line (IGISOL) facility [33]. A 15-mg/cm^2-thick uranium target foil was used to produce neutron-rich $^{121–128}$Cd, ^{131}In, $^{130–135}$Sn, and $^{132–140}$Te in June 2009. ^{129}In and $^{131–136}$Sb isotopes were produced with a 14-mg/cm^2-thick ^{232}Th target in a second experiment in May 2010. The results for the measured ground-state mass values have already been published in Ref. [11]. This paper focuses on the isomeric states.

The fission products are stopped in the ion-guide gas cell filled with helium at a pressure of around 200 mbar. There, a good fraction of ions ends up singly charged from charge-exchange reactions. The ions are extracted from the gas cell by differential pumping and with a sextupole ion guide (SPIG) [34]. After acceleration to 30 kV and mass separation with a 55° dipole magnet, the continuous ion beam with a selected mass number A is sent to a gas-filled radio-frequency quadrupole cooler and buncher (RFQ) [35]. The RFQ cools the ions and injects them as narrow ion bunches to the JYFLTRAP double Penning trap [36,37].

JYFLTRAP consists of two cylindrical Penning traps inside a 7-T superconducting solenoid. The first trap, the purification trap, is used for beam purification via a mass-selective buffer-gas cooling technique [38]. With a typical mass-resolving power of around $m/\Delta m \approx 3 \times 10^4$, neighboring isobars can usually be separated before extracting them through a narrow diaphragm toward the second trap, the precision trap. There, high-precision mass measurements are performed by employing the time-of-flight ion cyclotron resonance (TOF-ICR) technique [39,40].

The ions in a Penning trap have three different eigenmotions: axial, magnetron, and reduced cyclotron motions with frequencies ν_z, ν_-, and ν_+, respectively. According to the invariance theorem [41], the sideband frequency $\nu_- + \nu_+$ corresponds to the true cyclotron frequency ν_c with a high precision even in a nonideal Penning trap:

$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B, \tag{1}$$

where B is the magnetic field, and q and m are the charge and the mass of the ion, respectively. In the precision trap, a dipole excitation at the frequency of the magnetron motion is first applied to increase the magnetron radius for all ions. A subsequent quadrupole excitation is used to convert the magnetron motion into a reduced cyclotron motion periodically. When the excitation frequency matches the sideband frequency $\nu_- + \nu_+$, the radial energy of the ions reaches its maximum as the initially pure magnetron motion is fully converted to reduced cyclotron motion. The gain in radial energy is observed as a shorter time of flight to the microchannel plate detector (MCP) when the ions are extracted from the trap in the strong magnetic field gradient.

The magnetic field B is calibrated with a reference whose atomic mass m_{ref} is well known. In this experiment, ^{130}Xe ($m = 129.903509351(15)$ u [42]) was used as a reference mass except for ^{131}Sn, for which ^{132}Xe ($m = 131.904155086(10)$ u [43]) was employed. Since singly-charged ions were used, the mass of the nuclide of interest can be determined as

$$m_{\text{meas}} = r(m_{\text{ref}} - m_e) + m_e, \tag{2}$$

where $r = \frac{\nu_{c,\mathrm{ref}}}{\nu_{c,\mathrm{meas}}}$ is the measured cyclotron frequency ratio between the reference ion and the ion of interest, and m_e is the electron mass.

Since the studied isomeric states lie close to the ground states, they could not be fully resolved by employing only the purification trap. A so-called Ramsey cleaning technique [44] was applied for resolving the isomers. There, the purified ions from the first trap are further cleaned by applying a dipolar excitation at reduced cyclotron frequency of the contaminant ion in the form of time-separated oscillatory fields [45–47] in the precision trap. In this way, the unwanted species are driven to a larger cyclotron orbit but the ions of interest are unaffected. After the dipolar excitation, only the ions of interest can pass through the 2-mm diaphragm back to the purification trap for recooling and recentering before the actual mass measurement in the precision trap. With this additional cleaning method, a mass-resolving power up to $m/\Delta m \approx 10^6$ or better can be achieved.

In this work, a dipolar excitation pattern of 20–40–20 ms (on–off–on) was used for Cd isotopes, 15–30–15 ms for ^{130}Sn, 20–50–20 ms for ^{131}Sn, and 10–40–10 ms for the rest. Time-separated oscillatory fields were also applied for the quadrupole excitation in the precision trap and the resulting frequency spectrum was fitted with the theoretical line shape [47,48]. An excitation pattern of 25–350–25 ms (on–off–on) was used except for In and Sn isotopes having shorter or longer half-lives than the others, respectively. The time between the 25-ms pulses was shortened to 150 ms for ^{129,131}In and increased to 725 ms for Sn isotopes. Figure 1 shows examples of TOF-ICR spectra with and without Ramsey cleaning and excitation for ^{131}In.

The data were collected interleavedly [49]: after one or two frequency sweeps for the reference ion, a few frequency sweeps were collected for the ion of interest and this pattern was repeated as long as required for sufficient statistics (typically for few hours). The interleaved scanning reduces the uncertainty due to time-dependent fluctuations in the magnetic field, which for JYFLTRAP has been determined to be $\delta_B(\nu_{\mathrm{ref}})/\nu_{\mathrm{ref}} = [5.7(8) \times 10^{-11}\ \mathrm{min}^{-1}]\Delta t$, where Δt is the time between the two reference measurements. The data files were split into smaller parts in such a way that a proper count-rate class analysis [50] was possible at least for the reference ion. If the count-rate class analysis was not possible, the number of ions was limited to 1–2 ions/bunch and the uncertainty of the obtained cyclotron frequency was multiplied by a coefficient deduced from the closest neighboring isotope possible. Frequency ratios were calculated for each data pair. The error due to the time-dependent magnetic field fluctuation was quadratically added to the statistical uncertainty of each frequency ratio. The weighted mean of the measured frequency ratios was calculated and used as the final value. The inner and outer errors [51] of the data sets were compared and the larger value of these two was taken as the error of the mean. Finally, the uncertainty due to the mass-dependent shift $\delta_{m,\mathrm{lim}}(r)/r = (7.5 \pm 0.4 \times 10^{-10}/u)\Delta m$ [52] and an additional residual relative uncertainty $\delta_{\mathrm{res,lim}}(r)/r = 7.9 \times 10^{-9}$ [52] were quadratically added to the error. The obtained frequency ratios are collected in Table II.

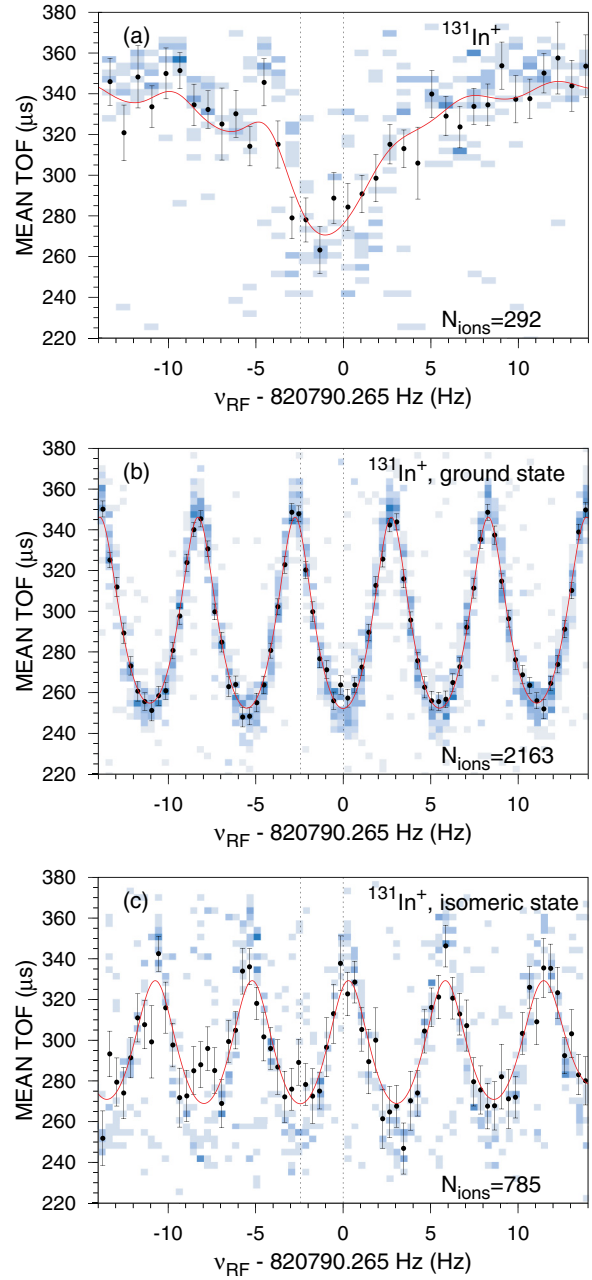

FIG. 1. (Color online) TOF-ICR spectra of ^{131}In (a) without Ramsey cleaning and with a continuous quadrupolar RF excitation of 200 ms, (b) for a Ramsey-cleaned ground state with a 25–150–15 ms (on–off–on) excitation, and (c) for a Ramsey-cleaned isomeric state with a 25–150–15 ms (on–off–on) excitation. The blue squares indicate the number of ions in each time-of-flight bin: the darker the color, the more ions there are. The dashed lines show the positions of the resonance frequencies for the ground and isomeric states.

III. RESULTS AND DISCUSSION

A. $11/2^-$ isomers

$11/2^-$ isomers are typical for even-Z, odd-N nuclei below the $N = 82$ neutron shell. For example, long-lived $11/2^-$ isomers are found in ^{119,121,123,125}Cd ($Z = 48$), ^{123,125,127,129,131,133}Te ($Z = 52$), and ^{129,131,133,135}Xe ($Z = 54$)

TABLE II. Cyclotron frequency ratios ($r = \nu_{c,\mathrm{ref}}/\nu_{c,\mathrm{meas}}$), resulting mass-excess (ME) values, and comparison to the literature (LIT) values [27] for the measured isomers. ^{130}Xe was used as a reference except for ^{131}Sn for which ^{132}Xe was employed.

Isomer	r	ME$_{\mathrm{JYFL}}$ (keV)	$E_{x,\mathrm{JYFL}}$ (keV)	$E_{x,\mathrm{LIT}}$ (keV)	$\Delta E_{x,\mathrm{JYFL-LIT}}$ (keV)
^{121}Cd^{m}	0.930792072(22)	−80858.7(26)	215(4)	214.86(15)	1(4)
^{123}Cd^{m}	0.946217831(25)	−77271(3)	144(4)	316.52(23)	−173(4)
^{125}Cd^{m}	0.961647897(26)	−73162(4)	186(5)	50(70)	140(70)
^{129}In^{m}	0.992446580(27)	−72379(4)	459(5)	370(40)[a]	90(40)
^{131}In^{m}	1.007881690(59)	−67660(8)	365(8)	302(32)[b]	63(33)
^{130}Sn^{m}	1.000096653(24)	−78185(3)	1948(5)	1946.88(10)	1(5)
^{131}Sn^{x}	0.992516774(26)	−77230(4)[c]	–	69(14)[b]	
^{134}Sb^{m}	1.030925604(24)	−73740.0(29)	281(4)	279(1)[d]	2(4)
^{133}Te^{m}	1.023154364(20)	−82595.8(24)	342(4)	334.26(4)	8(4)

[a]The value is a weighted mean of the results from [28–30].
[b]The value has been taken from [31].
[c]The value is the measured value. The value corrected due to an unknown mixture of states is −77262(20) keV when $E_x = 65.1$ keV [31] is assumed for the isomer.
[d]The value has been taken from [32].

[53]. Typical excitation energies are around 100–400 keV (see Fig. 2) and a sharp rise is observed when approaching the closed $N = 82$ shell. In odd-N Sn isotopes the $3/2^+$ and $11/2^-$ states are very close to each other and the order changes from isotope to isotope. The increase in the excitation energy toward the $N = 82$ shell is also observed in Sn isotopes after $N = 77$.

1. $^{121}Cd^{m}$

^{121}Cd has a $3/2^+$ ground state with a half-life of 13.5(3) s [54–57] and an $11/2^-$ isomeric state with a half-life of 8.3(8) s [57]. The excitation energy of the isomer has been determined as 70(170) keV from the difference between the β-decay energies of the ground and isomeric states [58]. No direct evidence for the excitation energy was found from the γ-γ coincidence data [59]. However, by assuming that there should be common levels de-exciting both to the ground and to the isomeric state, three common levels could be found and an excitation energy of 214.89 keV was deduced for the isomer [59]. The JYFLTRAP value, 215(4) keV, is the first direct measurement of the excitation energy of this isomer and it confirms the deductions made in Ref. [59].

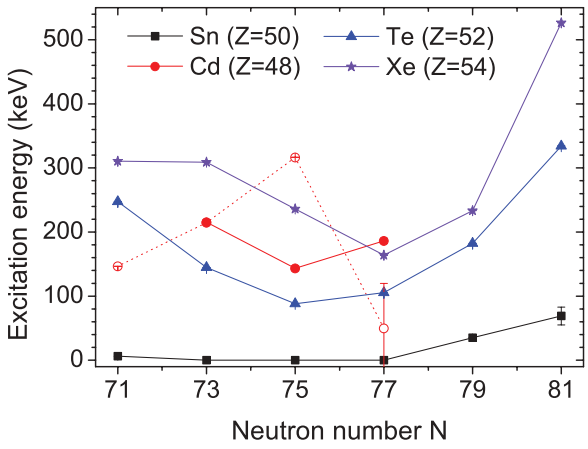

FIG. 2. (Color online) Systematics of the $11/2^-$ states in even-Z, odd-N nuclei. The open red circles and the dotted red line show the trend for the Cd isotopes with previously adopted excitation energies [29,65]. The error bars are in most cases smaller than the point size.

2. $^{123}Cd^{m}$

The existence of two long-lived states was not observed in the first measurements on ^{123}Cd [60–62] since the half-lives are so similar. The half-life for the $11/2^-$ isomer, 1.82(3) s, was determined in Refs. [63,64]. The excitation energy of the isomer, 316.52(23) keV [65], is not based on observations of γ-γ coincidences nor on a direct measurement of γ-transition energy. It was searched for by maximizing the number of shared levels de-exciting to the ground and isomeric states. Two shared levels, at 1061 and 2240 keV, were found when the γ-energy range of 260–400 keV was applied in the search. The JYFLTRAP result, $E_x = 144(4)$ keV, is below the energy range used for the search and is in a clear disagreement with Ref. [65]. Based on our result, the most probable shared level would be the state at 263.87(2) keV [65] de-exciting by 263.87(2)- and 123.67(6)-keV γ transitions to the ground and isomeric states, respectively. This yields an energy of 140.20(6) keV for the $11/2^-$ state. Since the $11/2^-$ state is below 263.87(2) keV, a spin assignment of $7/2^+$ is possible for the state at 263.87(2) keV. The spin assignment $(7/2^+)$ is further supported by the β-decay log ft value of 5.09 [65], which is compatible with an allowed decay from the $(7/2^+)$ state in ^{123}Ag. The half-life of the state at 263.87(2) keV is 80(15) ns, which is in agreement with a $7/2^+ \rightarrow 3/2^+$ $E2$ transition to the ground state when a hindrance factor of 4 is taken into account [65]. On the other hand, the intensity ratio of the 124- and 264-keV γ rays (16% [65]) should be much smaller if $M2$ and $E2$ transitions are assumed.

The energy systematics of the $11/2^-$ states in even-Z, odd-N isotopes below the $N = 82$ neutron shell supports an excitation energy of around 140 keV for the isomer and the adopted value at 317 keV is clearly off the trend (see Fig. 2).

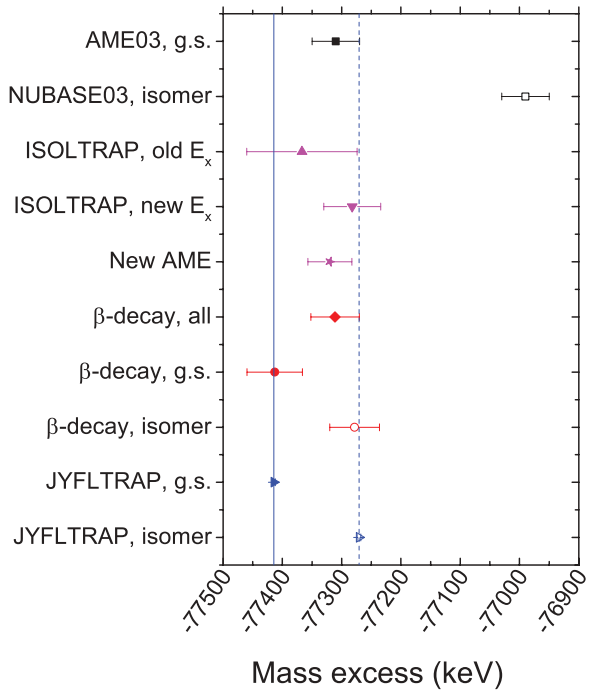

FIG. 3. (Color online) Comparison of different results for the ^{123}Cd ground state (full symbols) and isomeric state (open symbols). The ISOLTRAP data have been corrected with the old excitation energy ($E_x = 316.52(23)$ keV [65] given in the 2003 NUBASE evaluation [27]) and new excitation energy [$E_x = 144(4)$ keV, this work], respectively. The Atomic Mass Evaluation 2003 (AME03) value [68] as well as the new AME value given in Ref. [67] are mainly based on the β-decay result of Ref. [29] by assuming only one β-decaying state. The results of this work agree with the β-decay data [29,64] when ground and isomeric state are treated separately. However, JYFLTRAP disagrees with the AME03 and the updated ISOLTRAP value.

The new JYFLTRAP result also shifts the energy levels above the $11/2^-$ isomer toward lower energies. The energy levels of the $15/2^-$, $19/2^-$, $21/2^-$, and $23/2^-$ states in the band built on the $11/2^-$ isomer in ^{121}Cd and ^{123}Cd [66] are much closer to each other when the JYFLTRAP value is applied.

^{123}Cd has also been studied at ISOLTRAP but the ground and isomeric states could not be resolved [67]. Thus, the measured mass-excess value of $-77210(25)$ keV was corrected with $E_x = 316.52(23)$ keV [65] to obtain the ground-state mass value of $-77367(93)$ keV [67]. Since correcting the ISOLTRAP value with the new excitation energy yields a value higher than the JYFLTRAP value for the isomer [$-77271(3)$ keV], it most likely belongs to the isomeric state (see Fig. 3).

The mass evaluation performed in Ref. [67] yielded a new adjusted value of $-77320(37)$ keV for the ground state of ^{123}Cd. However, most of the influence in the mass evaluation still came from a β-endpoint measurement of ^{123}Cd [29]. There, six different γ-transition gates based on the results of Ref. [62] were used for determining the endpoint energies for the ground-state β decay. The obtained value of $Q_\beta = 6115(33)$ keV [29] results in a ground-state mass-excess value of $-77311(41)$ keV, around 100 keV higher than the JYFLTRAP value.

In a newer β-decay experiment [64] it was shown that many of the gating transitions used in Ref. [29] do not belong to the ground-state β decay but to the decay from the isomeric state. The used 428-, 2461-, and 2602-keV γ transitions belong to the ^{123}Cd^m β decay whereas the 1831- and 1843-keV γ transitions result from the ground-state β decay. The used 1695-keV gate is predominantly fed by the ground-state decay but there is also a small contribution from the isomeric state. The weighted mean based on the endpoint energies belonging to the ^{123}Cd^m β decay is $Q_\beta = 6148(35)$ keV. Similarly, the Q_β value for the ground-state β decay is 6013(41) keV. Thus, an excitation energy of 135(53) keV is obtained for the $11/2^-$ isomer in ^{123}Cd based on the β-decay studies [29,64]. This strongly supports the new JYFLTRAP value, also seen in Fig. 3.

3. $^{125}Cd^m$

The first β-decay experiments on ^{125}Cd did not resolve the ground and isomeric states [29,61,62]. The half-lives for both states were determined in Refs. [63,64]. The β-decay schemes obtained separately for the ground and isomeric state β decays [64] showed that three out of the four γ transitions used to gate the β spectra in Ref. [29] belong to the isomeric β decay. The difference in the β-decay energies of Ref. [29] gated by the transitions following the isomeric β decay (191-, 262-, and 1614-keV transitions) and the ground state β decay (the 1701-keV transition) gives an estimate of 50(70) keV for the isomer. The JYFLTRAP result, 188(5) keV, is the first direct measurement of the excitation energy of the $11/2^-$ isomer. With the new JYFLTRAP values, the trend between the $N = 73$–75 odd-N isotopes is very similar for Cd ($Z = 48$) and Te ($Z = 52$), as shown in Fig. 2. Recently, more attention has been paid on the microsecond isomers in ^{125}Cd [23–25,69]. γ lines de-exciting the $19/2^+$ and $15/2^-$ levels above the $11/2^-$ isomer have been observed in all recent experiments [23–25,69]. Weak delayed γ transitions with energies of 486 and 667 keV were observed only in Ref. [25]. Interestingly, the difference between these transitions (181 keV) is close to the observed isomeric energy.

4. $^{131}Sn^x$

For ^{131}Sn, the isomeric state could not be resolved with JYFLTRAP. The excitation energy of the isomer was determined as 160(100) keV and suggested as a level at 241.8 keV in an early β-decay study [70]. A recent β-decay experiment yielded an excitation energy of 69(14) keV [31]. A more precise value of 65.1 keV not confirmed by coincidence measurements may also be deduced from the level scheme of ^{131}Sn [31]. The latter excitation energies were too low to be resolved with the current JYFLTRAP facility. ^{131}Sn has also been studied at ISOLTRAP [10,71,72]. The measured mass-excess values ($-77242(15)$ keV [71,72] and $-77222(4)$ keV [10]) agree with the value determined at JYFLTRAP [$-77230(4)$ keV]. Therefore, it is likely that the same state or a similar mixture of states has been measured with both traps.

The β decay of the $11/2^-$ isomer in ^{131}Sn feeds the $15/2^-$ state at 1606.7 keV in ^{131}Sb [73]. On the other hand, the $3/2^+$ ground state feeds the $(5/2^+)$ state at 798.494 keV in ^{131}Sb [73]. In the future, the different γ rays related to the isomeric (447.4-, 450.03-, 1226.03-, and 1229.23-keV γ rays) and ground-state β decay (798.494-keV γ rays) of ^{131}Sn could be used to identify the isomer to ground-state ratio of the measured state. Another possibility would be the identification via laser spectroscopy or selective laser ionization. Laser spectroscopy on the ground and isomeric states of ^{131}Sn has already been performed and laser ionization has been used to ionize the Sn isotopes [74]. In addition, the resolving power of JYFLTRAP could be enhanced via doubly-charged or more highly charged ions in the future.

5. $^{133}Te^m$

The $11/2^-$ isomer in ^{133}Te decays mainly via β decay to ^{133}I but a good fraction [$b = 16.5(20)\%$] proceeds via an $M4$ internal transition to the ground state. The isomeric transition has been studied carefully via γ spectroscopy [75–78] and an excitation energy of $E_x = 334.27(4)$ keV has been determined. The JYFLTRAP result, $E_x = 342(4)$ keV, deviates from the measured excitation energy by 8(4) keV. No clear explanation for the discrepancy has been found. New mass measurements of the ground and the isomeric state of ^{133}Te would be desirable in the future.

B. $1/2^-$ isomers in ^{129}In and ^{131}In

Proton-hole states close to doubly magic ^{132}Sn can be probed by even-N In ($Z = 49$) isotopes. They all have $(9/2^+)$ ground states and $(1/2^-)$ isomeric states, corresponding to a proton hole in the $\pi 1g_{9/2}$ or in the $\pi 2p_{1/2}$ shell. The evolution of the $1/2^-$ states in odd-A In isotopes (see Fig. 4) gives us interesting information on the single-particle energies when approaching $N = 82$.

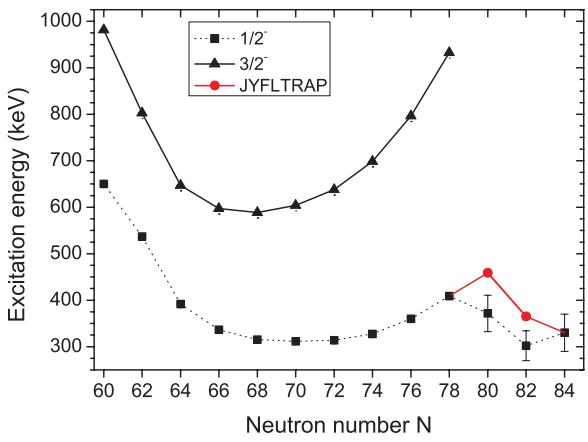

FIG. 4. (Color online) Systematics of the lowest $1/2^-$ and $3/2^-$ levels in even-N In isotopes. The ground state for these isotopes is always $9/2^+$.

1. ^{129}In

Previously, the excitation energy of the $1/2^-$ isomer in ^{129}In ($E_x = 200(600)$ keV [28], $E_x = 380(70)$ keV [29], and $E_x = 369(46)$ keV [30]) has been based on differences in the Q_β values between the isomeric and ground-state β decays. In this work, JYFLTRAP yields the first directly measured value for the excitation energy of the isomer: $E_x = 459(5)$ keV. It is around 90 keV higher than the values based on β-decay experiments but, given the uncertainties related to the β-decay studies, the difference is not surprising. Further support for the result is given by the observed γ rays following the β decay of ^{129}Cd [79]. Several energy differences of the γ rays are close to 458(1) keV (858.1 − 400.5, 1020.3 − 561.7, 1561.5 − 1103.4, and 2918.5 − 2460.2 keV). The new value changes the trend in the excitation energies of the $1/2^-$ isomeric states in odd-A In isotopes. With the previously adopted value, the excitation energy started to decrease already at $N = 78$ but now it increases until $N = 80$ (see Fig. 4). The β-decaying $(23/2^-)$ isomer with a half-life of about 0.67 s [30] was not searched for in the JYFLTRAP experiment, and thus it could not be confirmed. The $17/2^-$ isomer with a half-life of 8.5(8) μs was too short-lived for a measurement in a Penning trap.

2. ^{131}In

^{131}In has three different states with rather similar half-lives of around 300 ms. In addition to the $(9/2^+)$ ground state and the $(1/2^-)$ isomeric state at 302(32) keV [31], a high-spin isomer $(21/2^+)$ has been observed at 3764(22) keV [31]. The JYFLTRAP measurement focused on the ground state and the $(1/2^-)$ isomer of ^{131}In. Since the excitation energy of the high-spin isomer is almost 4 MeV, it was already cleaned away with the purification trap and thus it does not interfere with the mass measurements of the other two states. The JYFLTRAP mass-excess value for the $1/2^-$ isomeric state, $E_x = 365(8)$ keV, disagrees with the value based on the differences in the Q_β values [31]. On the other hand, when the Q_β results for different gating transitions [31] are compared with the JYFLTRAP value, an agreement is found with one of the results (see Fig. 5).

C. 7^- isomers in ^{130}Sn and ^{134}Sb

1. ^{130}Sn

Even-Z, $N = 80$ isotones, such as ^{130}Sn, ^{132}Te, ^{134}Xe, ^{136}Ba, ^{138}Ce and ^{140}Nd have a 7^- isomeric state at around 2 MeV. This state can be explained by the $(\nu 1h_{11/2})^{-1} \otimes (\nu 2d_{3/2})^{-1}$ configuration, which results in a quartet of states with spins and parities $7^-, 6^-, 5^-$, and 4^-. In ^{130}Sn, the 7^- state is located above the 0^+ ground state and the 2^+ first excited state, thus forming an yrast trap. The β decay of the (7^-) isomer was studied for the first time and an excitation energy of around 1.8 MeV was estimated in Ref. [80]. Later, a more precise value of 1946.88(10) keV has been obtained based on γ spectroscopy following the β decay of ^{130}In Ref. [81]. The JYFLTRAP result, $E_x = 1948(5)$ keV, agrees with this precise

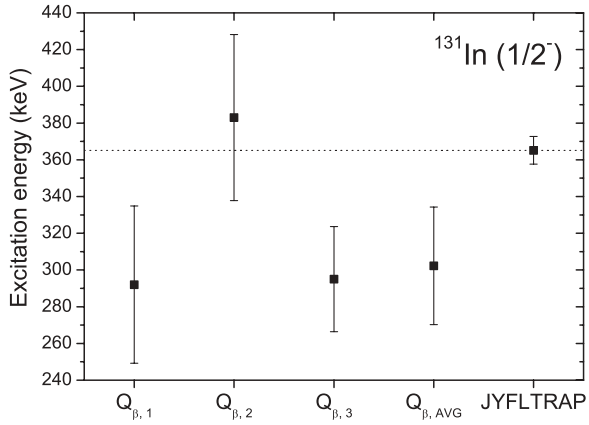

FIG. 5. The excitation energies for the $(1/2^-)$ isomer in ^{131}In based on the difference between the Q_β value for the $1/2^-$ isomer [$Q_\beta = 9524(26)$ keV] and Q_β values for the $9/2^+$ ground state of ^{131}In gated by (1) 4487-keV [$Q_\beta = 9232(34)$ keV], (2) 3990-keV [$Q_\beta = 9141(37)$ keV], and (3) 2434-keV γ transitions [$Q_\beta = 9229(12)$ keV] [31]. $Q_{\beta,\mathrm{AVG}}$ is calculated using the weighted mean of the ground-state β-decay results [31].

value and gives further support that the JYFLTRAP Penning trap works well for the studies of isomeric states.

The ground and isomeric states of ^{130}Sn have also been measured at ISOLTRAP [71,72]. The ISOLTRAP value for the ground-state mass excess [−80134(16) keV] is almost in perfect agreement with JYFLTRAP. The ISOLTRAP mass-excess value for the 7^- isomer [−78190(11) keV] is in good agreement with the JYFLTRAP value. The excitation energy of the isomer [$E_x = 1944(19)$ keV] obtained at ISOLTRAP agrees with JYFLTRAP but is less precise.

2. ^{134}Sb

^{134}Sb, having one proton and neutron above the closed $Z = 50$ and $N = 82$ shells, offers an ideal test case to study the proton-neutron interaction near doubly magic ^{132}Sn. In this respect, ^{134}Sb is similar to the well-studied nucleus ^{210}Bi above the closed $Z = 82$ and $N = 126$ shells in the ^{208}Pb region. Whereas the lowest energy levels in ^{210}Bi are members of a $0^-, 1^-, \ldots, 9^-$ multiplet resulting from the configuration $(\pi 1h_{9/2})^1 \otimes (\nu 2g_{9/2})^1$, ^{134}Sb has a multiplet of states $0^-, 1^-, \ldots, 7^-$ corresponding to the $(\pi 1g_{7/2})^1 \otimes (\nu 2f_{7/2})^1$ configuration.

The levels of ^{134}Sb have been intensively studied at the OSIRIS facility in Studsvik [82–84]. The 0^- ground state and the 7^- isomeric state were observed already in the 1970s [82]. In 1990, a 318-keV γ transition was detected and assigned to a 1^- state in ^{134}Sb [83]. Later, it was found that the 1^- state is located only 13 keV above the ground state and the previously proposed 1^- state matches with the 2^- level [84]. In addition, 3^- and 4^- levels were identified [84]. The last members of the multiplet were recently observed at CERN/ISOLDE in a γ-spectroscopy experiment [32]. There, an energy of $E_x = 279(1)$ keV was found for the 7^- state based on γ-γ coincidence relations. The JYFLTRAP value, $E_x = 281(4)$ keV, agrees nicely with this precise result and confirms the position of the 7^- isomer. Interestingly, the shell-model calculations carried out in Ref. [84] yield an excitation energy identical to the experimental value for the 7^- state. There, the residual interaction was based on the Kuo-Herling matrix elements deduced from the ^{208}Pb region [85].

D. Isomeric to ground-state intensity ratios

Before each mass measurement, TOF-ICR spectra were measured by applying continuous quadrupole excitation (200, 400, or 800 ms) in the precision trap without Ramsey cleaning. The resulting TOF-ICR spectrum is thus composed of two identical superimposed TOF-ICR curves, offset in frequency by their cyclotron frequency difference, and thus their intensity ratio is obtained from the weight of the two curves. Since these spectra were only collected for setting up proper excitation schemes for the actual mass measurements, there were only a few files containing enough data to obtain the isomer to ground-state intensity ratios from the resonance fits. However, a general trend was observed in the intensities: the higher-spin states dominate the resonances of Cd and In isotopes. The (7^-) isomer in ^{134}Sb was also produced in much more abundance than the (0^-) ground state.

Isomeric yield ratios for determining the angular momenta of primary fission fragments have been intensively studied at the ion-guide isotope separator on-line facility in Tohoku [86,87]. There, it has been shown that the higher-spin states are typically favored in fission but, on the other hand, sudden changes occur in the isomeric yield ratios, e.g., due to shell effects or deformation. This is also observed at JYFLTRAP. For instance, the intensity of the $(11/2^-)$ isomer in ^{133}Te ($N = 81$) was about the same as for the ground state whereas in ^{121}Cd, located further away from ^{132}Sn, it was more than four times the ground-state intensity.

Due to lack of time, the isomeric state for the one-proton and a neutron-hole nucleus ^{132}Sb was not measured in this work by using the Ramsey cleaning and excitation schemes as was done for the ground state [11]. Nevertheless, the isomeric state was observed in a collected time-of-flight spectrum with a 800-ms quadrupole excitation (see Fig. 6). The frequency

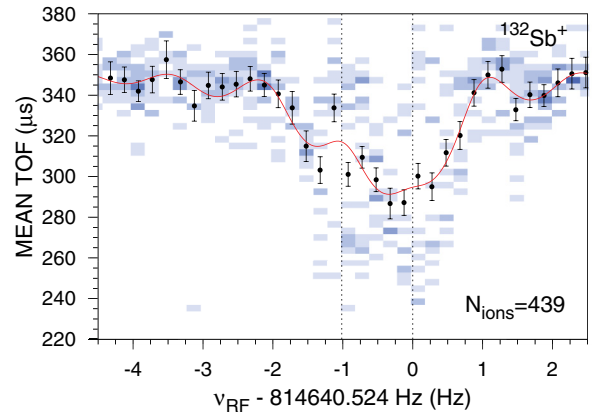

FIG. 6. (Color online) Time-of-flight spectrum for ^{132}Sb after a quadrupole excitation of $T_{RF} = 800$ ms in the precision trap. Both the ground and the isomeric state can be seen in the spectrum.

ratio between the isomer and the ground state yields an excitation energy of around 153(14) keV for the (8^-) isomer. This preliminary value, which should be confirmed in future measurements, agrees with the suggested excitation scheme shown in Fig. 4(a) of Ref. [88]. There, the (8^-) isomer lies just below the (5^+) level at 162.8 keV. Contrary to the general trend, the lower-spin (4^+) ground state was produced in greater quantities than the higher-spin isomer. In the future, the measured states should be identified by measuring their β-decay half-lives after the trap.

IV. SUMMARY AND OUTLOOK

In this work, we have utilized the JYFLTRAP Penning trap for measuring the energies of the $(11/2^-)$ neutron-hole states in ^{121,123,125}Cd and $(1/2^-)$ proton-hole states in ^{129,131}In. In addition, the energies of the (7^-) isomers in ^{130}Sn and ^{134}Sb were measured and an agreement with the precisely known adopted values was found. The new excitation energy of the isomer in ^{123}Cd suggests that the decay scheme of Ref. [65] should be revised. For ^{131}Sn, resolving the ground and isomeric states was not possible in this work. In order to identify the measured state, laser or post-trap spectroscopy would be useful in the future. In addition, an isomeric state observed in ^{132}Sb should be verified and measured more precisely. The long-lived high-spin isomers in ^{129}In and ^{131}In should also be searched for in forthcoming mass measurements.

The new excitation energies determined in this work are more precise than the previously adopted values and large discrepancies have been found for some isomers. Precise information on energy levels around doubly magic ^{132}Sn is important for the description of these nuclei within the nuclear shell model. Moreover, the exact knowledge of the masses of the ground and isomeric states is crucial for modeling of the astrophysical *r* process, which proceeds via the region of the studied nuclei. Although the effect of the isomeric states on the *r* process or the potentially increased role of high-spin isomers populated via fission of heavier *r*-process nuclei have not yet been studied in detail, the measurements of both the ground and isomeric states have improved the accuracy of the ground-state masses used in the modeling of the *r* process. The impact of the measured ground-state masses on the *r* process depends on the used model and the assumed astrophysical conditions. Calculations performed by varying the AME03 mass values of the nuclei measured in this work by 3σ upward or downward have not shown significant changes in the final abundances since the main *r*-process path flows through slightly more neutron rich nuclei in the model used in Ref. [89]. On the other hand, Brett *et al*. [7] have demonstrated that, e.g., ^{132}In, ^{133,134,135,136}Sn, and ^{134,135,136,137}Sb are among the nuclei whose neutron separation energies have the strongest influences on the final *r*-process abundances in their model. The measurements of this work have given more accurate data for the determination of these neutron separation energies and for extrapolations of the masses of more neutron-rich nuclei relevant for the *r* process. These new data should be taken into account in future calculations.

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