CERN-INTC-2020-025 / INTC-P-553
14/05/2020

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Mass measurement of the proton-rich ^{99}In and self-conjugate ^{98}In nuclides for nuclear and astrophysical studies

May 14, 2020

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Abstract:

We propose to use the ISOLTRAP high-precision online mass spectrometer to perform mass measurements of neutron-deficient $Z = 49$ indium isotopes. These masses will be used to study the evolution of nuclear structure in the immediate vicinity of the doubly magic ^{100}Sn nuclide. In addition, their impact on the composition of astrophysical X-ray burst ashes will be assessed. In a recent experimental campaign, preliminary measurements of neutron-deficient indium isotopes of mass numbers down to $A = 99$ in their ground and/or excited states have been performed with ISOLTRAP. We aim at extending this work by refining our measurement of ^{99}In, where a low-lying isomer of unknown excitation energy is expected but is yet to be experimentally observed. Pushing one neutron below $N = 50$, we furthermore aim to perform the first precision measurement of the mass of the $N = Z = 49$ self-conjugate ^{98}In nuclide, which, apart from its importance for nuclear structure and astrophysics, is a strong case of interest for weak interaction studies by nuclear beta decay.

Requested protons: 15 shifts on LaC$_x$ target with RILIS ionisation

1 Motivation

Introduction — Being the heaviest self-conjugate N=Z doubly magic nucleus bound against proton emission, ^{100}Sn is of paramount importance to refine our understanding of nuclear structure at the limits of nuclear existence. In addition, its vicinity is the convergence point for various scientific questions, notably the modeling of the astrophysical rapid-proton capture process (rp-process). Indeed, $N \sim Z \sim 50$ nuclei in this region are located so close to the proton drip-line that their properties have a direct influence on the course of the rp-process towards its end-point in the tellurium chain [1].

Impact on nuclear structure — With only one proton below the tin isotopic chain, neutron-deficient indium isotopes constitute ideal systems to pin down nuclear phenomena around ^{100}Sn. While recent β-decay spectroscopy experiments [2, 3, 4, 5, 6] have provided precious new information on half-lives and branching ratios for excited states in this region, the knowledge of nuclear ground-state properties south of ^{100}Sn is scarce. A recent experimental campaign carried out by the CRIS collaboration extended our knowledge of ground-state electromagnetic moments out to ^{101}In. Furthermore, the ground state mass and a low-lying isomeric state of ^{101}In were identified and measured both with the CSRe in Lanzhou [7] and at GSI using the FRS Ion-Catcher [8]. The masses of the ^{101g,m}In states (see Figure 1 and 3) were also recently measured with ISOLTRAP [9] using the newly commissioned Phase-Imaging Ion Cyclotron Resonance (PI-ICR) technique [10]. During the same experimental campaign, the ISOLTRAP mass spectrometer was also used to determine the ground state mass of ^{99}In for the first time, reaching an uncertainty below 100 keV and also improved the precision of the ^{100}In mass by a factor of about 100.

In the shell-model picture of the odd-even indium isotopes, the $(9/2^+)$ ground states are dominated by a proton hole in the $\pi g_{9/2}$ orbital, while the $(1/2^-)$ isomeric states (observed all along the chain) are constructed on a proton hole in the $\pi p_{1/2}$ sub-shell. The proton separation energies of the two states, especially at $N = 50$ (^{99}In) where the $\nu g_{9/2}$ shell is full, give the evolution of effective single-particle energies of the two proton orbits, a crucial

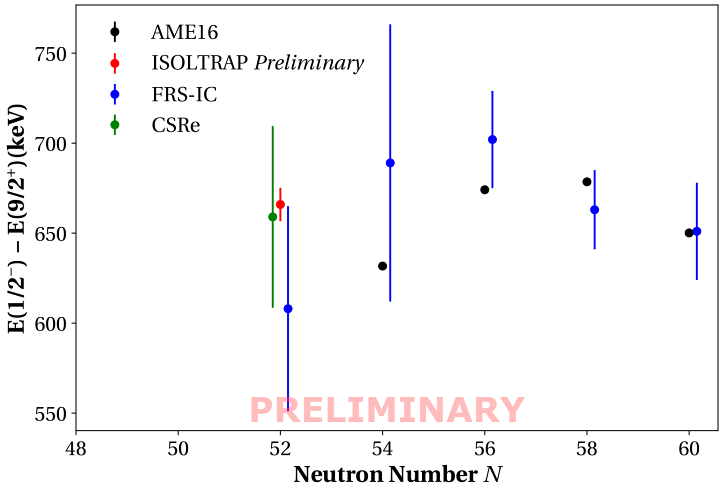

Figure 1: Evolution of the $(1/2^-)$ isomer excitation energy in odd-even indium isotopes towards $N = 50$. For ^{101}In recent measurements performed at CSRe [7] and at GSI [8] are compared to the preliminary ISOLTRAP result obtained using the recently commissioned PI-ICR technique. For ^{101}In the spin state assignment is tentative.

input missing in shell-model calculations of the region [11, 12]. In addition, this evolution has been shown to be sensitive to the phenomenon of type-II shell evolution [7], a study which still needs to be extended to ^{99}In. A precision measurement of the $(1/2^-)$ state in ^{99}In is thus essential in order to draw the full picture of its excitation-energy systematics (see Figure 1).

One neutron below $N = 50$, ^{98}In would provide the missing mass for determining the one-neutron empirical shell gap at $N = 50$, one of the standard benchmarks for nuclear theory. In addition, its low-energy structure dominated by a proton and a neutron hole in the $g_{9/2}$ orbital makes ^{98}In an important testing ground for the proton-neutron interaction. A multiplet of states between $J = (0^+)$ and $J = (9^+)$ is predicted [12], with the two extremes observed experimentally as long-lived states. A recent RIKEN measurement of ^{98}In determined the (9^+) state to lie 820(730) keV above the (0^+) ground state, with a half-life of 0.99(7) s, nearly two orders of magnitude larger than the ground-state half-life of 30(1) ms [6]. This study leaves the question of the ordering and difference of energy between the states open, demanding a high-precision and high-resolution study in order to benchmark theoretical predictions.

In recent years, the ^{100}Sn region has become an important testing ground also for state-of-the-art nuclear models such as the Monte-Carlo Shell Model [13] and *ab initio* approaches [14]. The latter are currently undergoing renewed developments allowing not only to address heavy, open-shell systems, but also to include new terms from the chiral expansion. Recently, first N^{3}LO calculations have been performed, including the subleading 3N interactions [15, 16]. These exhibit interesting sensitivities for ground-state properties and are aided by new developments to extend *ab initio* calculations in 3N matrix element space, important for heavy nuclei.

Lastly, $N = Z$ nuclei are important for the understanding of the proton-neutron pairing interaction and the so-called Wigner effect. The latter, manifesting as an excess binding in self-conjugate systems, is still treated as an empirical correction even in the most advanced microscopic mass models [17]. The knowledge of the mass surface in the ^{100}Sn region is not sufficient to directly extract pairing or Wigner energies, however an indirect test of its current modeling can be obtained by computing the difference between the lowest $T = 0$ and $T = 1$ states of ^{98}In, as discussed in [18]. Remarkably, ^{98}In is proposed to be the only other case (apart from ^{58}Cu) where the lowest $T = 0$ state can become the ground state, due to the neighbouring shell closure [19]. A measurement of the two long-lived states in ^{98}In would allow improving the description and testing this prediction. In particular, it would be interesting to revisit the Wigner effect from the perspective of *ab initio* theory (see work on understanding the $T = 0$ vs. $T = 1$ pairing matrix elements [20]).

Impact on the rp-process — In addition to the nuclear-structure studies, we aim at minimizing the influence of mass uncertainties on type-I X-ray burst models. These energetic events occur in binary systems of neutron stars and main-sequence stars when the degenerate matter accumulation on the neutron-star surface results in a thermonuclear runaway fusion reaction beyond the helium and CNO cycles, leading to an explosion [21]. In rapid proton-

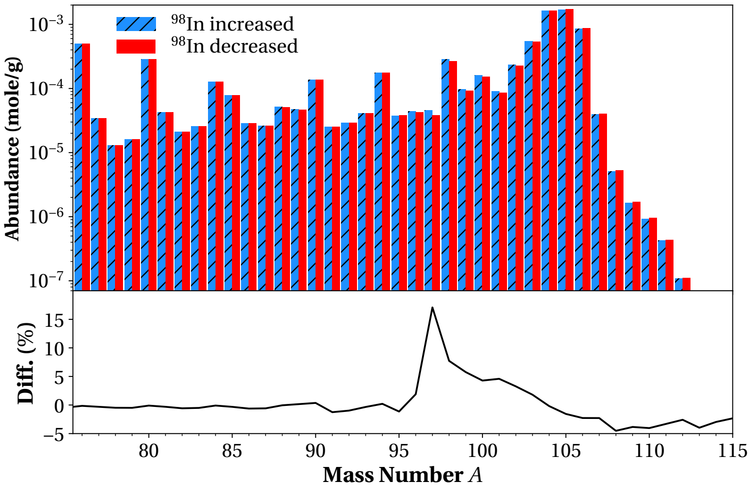

Figure 2: Top: Impact of the isotope mass variation of ^{98}In on the element abundance $\mathcal{A}$ in X-ray burst ashes where the masses are varied by 3σ up (blue bars) and 3σ down (red bars). Bottom: Fractional difference relative to the element mass number resulting from the same mass variation. The mass and mass uncertainty were taken from the *AME2012*.

capture nucleosynthesis along the proton drip line (*rp*-process), ever-heavier elements are produced. This reaction is limited by slow β^+-decays that cause waiting points, at which the relatively long half-lives of certain isotopes stem the reaction flow rate [22]. This results in an experimentally observable characteristic X-ray light curve and influences the composition of the remaining ashes in the neutron-star crust.

The proton-capture rate is competing directly with the photo-disintegration rate, depending exponentially on the quantity $Q_{(p,\gamma)}/k_BT$. This makes model calculations especially sensitive to nuclear masses while a high temperature T (on the order of $\sim 10^9$K) of the surrounding environment is also required. In a comprehensive case study [1, 23] the dependence of X-ray burst models over a range of nuclear masses and reaction rates was identified, in which neutron-deficient isotopes up to ^{101}In play an important role. Recently, the first-time mass measurement of ^{99}In at ISOLTRAP improved model calculations significantly [9].

By varying the mass of ^{98}In up and down within three standard deviations the sensitivity of the *rp*-process was studied in a scenario characterized by the accretion of material with a large initial hydrogen abundance ($\sim 0.66\%$). While no significant change in the X-ray burst light curve is observed, the abundance $\mathcal{A}$ of elements produced in X-ray burst ashes changes significantly around mass number $A = 98$ (see top of Figure 2). The fractional difference, defined as $(\mathcal{A}_{\text{down}} - \mathcal{A}_{\text{up}})/\mathcal{A}_{\text{up}} \times 100$, is plotted in the lower part of Figure 2 and shows a change in abundance of up to 20% for $A = 97$.

Weak interaction — Low-energy nuclear-physics measurements can not only probe the validity of the Conserved Vector Current (CVC) hypothesis but also determine the value of the $\mathrm{V_{ud}}$ element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, which connects the quark weak eigenstates with the mass eigenstates [24]. The $\mathrm{Q_{EC}}$-value of superallowed Fermi-type β-decays with transitions between two analog ground states is directly linked to the evaluation of the statistical rate function f which, in addition to the half-life, branching ratio, and theoretical corrections, is used to calculate the $\mathcal{F}t$-value and eventually the matrix element [25]. The ^{98}In decay has not been included in the most up-to-date evaluation of superallowed Fermi transitions due to a lack of both experimental and theoretical input [25]. Sufficient production yields and sample purity are required for a precise measurement of the branching ratio R which is further complicated by numerous weak Gamow-Teller decay branches [25]. No successful direct mass measurement has been performed so far on the parent state. Using decay spectroscopy, the half-life and Q_{EC}-value have been measured with a precision of 0.1 ms and 40 keV, respectively [6].

However, with experimental input the statistical rate function $f \sim Q_{\mathrm{EC}}^5$ and the outer radiative correction term can readily be calculated [26]. An additional important theoretical correction required to yield the corrected $\mathcal{F}t$-value is the so-called isospin symmetry breaking correction term, whose magnitude becomes more important for higher Z. A calculation of this correction was attempted in an angular momentum projected HFB approach which simultaneously predicts the Q_{EC}-value of the transition [27]. Recently, the *ab initio* approach has been successfully employed for the description from first principles of β-decay properties in the ^{100}Sn region [28], enabling future studies of isospin symmetry breaking effects, which are aided by the development of improved many-body bases. Constraining the Q_{EC}-value with a direct mass measurement of the parent state is a first but necessary step on a long journey of challenging measurements and calculations towards an improved $\mathcal{F}t$-value and, thus, an increased accuracy for the CKM matrix element V_{ud}.

2 Experimental techniques

As for the $^{99-101}$In masses mentioned above, the ISOLTRAP high-precision mass spectrometer [29] will be used for ^{98}In. Currently, the apparatus consists of four ion traps optimized for different purposes: accumulation, bunching, separation, cleaning, and mass determination.

In Figure 3(top) a schematic view of the apparatus is presented. The quasi-continuous ion beam provided by ISOLDE is cooled and bunched in a linear radio-frequency quadrupole (RFQ) to improve the beam's ion-optical quality. Ion bunches are ejected from the RFQ into a Multi-Reflection Time-of-Flight (MR-ToF) device [30] which is used in combination with a ToF-detector to identify (mass-spectrometry mode) and clean (mass-separation mode) undesired ion species from the ion bunch. Selected ions are then guided to the two Penning traps: The preparation Penning trap is used to further reduce the beam emittance while in the precision Penning trap the ion mass is determined by either the Time-of-Flight Ion-Cyclotron-Resonance (ToF-ICR) [31] or the Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR) [10, 32] techniques.

The bottom left plot in Figure 3 shows the $A = 99$ MR-ToF spectrum from which the mass of ^{99}In was recently determined [9]. This clearly demonstrates that the ions of interest can be separated from isobaric contaminants for the proposed measurement. In case the indium isotopes are too short-lived or cannot be transported in sufficient quantities to the Penning traps, the MR-ToF provides in mass-spectrometry mode a precision of $\delta m/m = 10^{-6}$

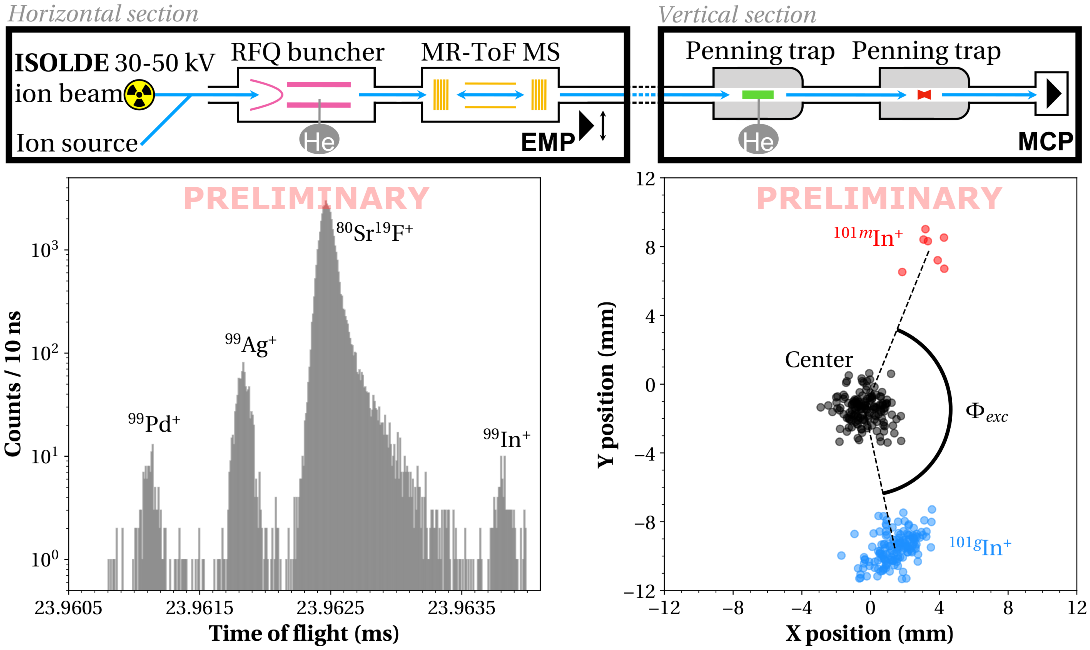

Figure 3: Top: schematic of the ISOLTRAP setup with its four ion traps and offline sources. Bottom left: ToF spectrum of $A = 99$ components of the ISOLDE beam. Bottom right: PI-ICR resonance of the ground and isomeric states of ^{101}In.

[33]. Unwanted isobaric contamination can be removed using the well-proven in-trap lift method [34]. An absolute mass measurement of the isotope of interest can be performed by using several off-line ion sources in well-established cross-reference measurements [33]. In case that species like SrF (see bottom left insert in Figure 3) delivered online from ISOLDE are not sufficient for calibration purposes, $^{12}C_8$ and $^{12}C_9$ carbon clusters from a laser-ablation source or $^{85/87}$Rb and ^{133}Cs isotopes from a surface ion source will be used as mass references to reduce mass-dependent systematical shifts.

If the production yield and the beam purity is sufficient, isotopes can be transported to the precision Penning trap. In the bottom right panel of Figure 3 a plot for a PI-ICR resonance of the resolved isomeric and ground states of ^{101}In proves the precision and the resolving power of the measurement procedure.

3 Beam time request

From systematical trends, we expect the isomeric state to lie about 500 keV above the ^{99}In ground state. Hence, a resolving power of merely 200 000 is required to separate the two states. During our measurement of ^{101}In, a mass resolving power in excess of 10^6 was achieved with ~ 65 ms of phase accumulation time and a total ISOLTRAP cycle length under 1 s. The isomeric state is expected to be long-lived ($\gg 1$ s) while the ground state's half-life is 3.1(1) s [4]. As such, the half-lives are not expected to be a limiting factor in our measurement. From our 2018 data, we can estimate the yield of ^{99}In in CA0/tape-station to be about 10 ions/s. Assuming an overall transport efficiency from CA0 to our positionsensitive detector of 1% (including detection efficiency) and typical beam gate opening time of 500 ms, we would record one count of ^{99g,m}In mixture every 20 s. If the observed ratio of isomer and ground state stays similar to that of ^{101}In, we should expect 1 count of the isomer per 25 counts of the ground-state. Our measurement of ^{101g,m}In shows that with the PI-ICR technique as little as 5 counts are sufficient to perform a reliable mass measurement. Nonetheless, the mass of each state will be measured independently to keep our systematic uncertainties under control. Hence, we believe that 4 shifts are required to perform the complete measurement of the masses of the ^{99}In ground and isomeric states. — If the production yield is too low to allow for a Penning-trap measurement, the measurement will be performed with the ISOLTRAP MR-ToF MS. With the recent implementation of an active and passive voltage stabilisation system [35], a resolving power in excess of 200 000 can be readily and reliably achieved with a total trapping time inside the device just under 50 ms (corresponding to ~ 2000 revolutions). In this case, the PI-ICR technique would be used to study the isomeric to ground state ratio in ^{101,103,105}In allowing to estimate this ratio for the ^{99}In case. With this value fixed, we are confident we would be able to extract an excitation energy from our MR-ToF MS measurement. In this case, 4 shifts would also be required.

While we do not foresee strong contamination in the ISOLDE beam, we expect ^{98}SrF$^+$ to be present in the beam where its isotopic counterparts with A=99, 100 and 101 were observed in the 2018 run. Once again, this molecule would offer a perfect reference species for our measurement. For ^{98}In, we can estimate the production yield to be approximately 0.5 ions/s [36]. Doubling the frequency of the first RILIS ionisation scheme step should allow boosting the ionisation efficiency by another factor of 2 [37]. Quite remarkably, the ground state of ^{98}In is short-lived (~ 30 ms) while the (9^+) isomeric state is a long lived state (~ 1 s). Given the poor precision with which the excitation energy is known, we are confident that if the isomeric states does not lie below 500 keV we can optimise our MR-ToF MS measurement such that a measurement of both states is possible. Nonetheless, the PI-ICR technique would allow measuring the long-lived isomeric state in the Penning trap. For this case, 9 shifts would be necessary.

Finally, two shifts are required to study the ISOLDE beam composition and to optimise the neutron-deficient indium production prior to the actual mass measurement.

Table 1: Detailed summary of the shift request. The production yields marked with # are extrapolated values.

Isotope	Half-Life [ms]	Yield in CA0 [ions/s]	Target / Ion source	Method	Shifts (8h)
^{99}In	3100(200)	10	LaC$_x$/RILIS	PI-ICR and/ or MR-ToF MS	4
^{98}In	30(1)	0.5#	LaC$_x$/RILIS	PI-ICR and/ or MR-ToF MS	9
Beam optimization					2

Summary of requested protons: 15 shifts in one run with a LaC$_x$ target and RILIS ionisation.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: ISOLDE central beam line and ISOLTRAP setup. The ISOLTRAP setup has safety clearance, the memorandum document 1242456 ver.1 "Safety clearance for the operation of the ISOLTRAP experiment" by HSE Unit is released and can be found via the following link: `https://edms.cern.ch/document/1242456/1`.

Part of the	Availability	Design and manufacturing
ISOLTRAP setup	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT

Hazards named in the document relevant for the fixed ISOLTRAP installation.