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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Mass measurement of the neutron-deficient ^{96}Cd with ISOLTRAP

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Abstract:

We propose to use the ISOLTRAP high-precision online mass spectrometer to perform the mass measurements of the neutron-deficient $N = Z = 48$ ^{96}Cd isotope (the last even-even $N = Z$ before ^{100}Sn itself). The extracted binding energy trends are to be used to study the evolution of nuclear structure in the immediate vicinity of the doubly magic ^{100}Sn. The ground-state mass of ^{96}Cd will allow for the first time to experimentally quantify the strength of the two-neutron shell-gap right below ^{100}Sn. This quantity is of paramount importance to test virtually all nuclear models in the region. Depending on the observed relative isomeric yield ratio, a simultaneous direct measurement of the excitation energy of the 16^+ "spin-gap" ^{96m}Cd isomeric state (even with relatively low precision) should provide a stringent test of the interplay between the various components of the nuclear interaction. The measurement would benefit from yield/beam-composition information and additional mass data obtained during a production study performed earlier this year with ISOLTRAP.

Requested protons: 18 shifts on LaC_x target with RILIS ionisation

1 Motivation

1.1 Scientific context

The region around the N=Z=50 self-conjugate nucleus ^{100}Sn nucleus is the location of a plethora of physical phenomena [1, 2]. Its direct vicinity to the proton drip-line is such that the path of the astrophysical *rp*-process is very sensitive to the properties of nuclei in the neighborhood of ^{100}Sn [3, 4]. In addition, the existence of so-called "spin-gap" isomers, exhibiting large-spin difference with respect to their ground state and half-lives in the ~1s range, has been observed in several nuclei in the region. The excitation energy of these high-lying states is at times such that they β-decay to nuclear states exceeding the proton decay threshold in their respective daughter nucleus. As a result, β-delayed proton emission is often observed in the decay pattern of several isomeric states in the region [5, 6, 7, 8]. Last but not least, the large spatial overlap between protons and neutrons in nuclei located in the direct vicinity of ^{100}Sn make them probably the most suitable candidates to study the interplay between the neutron-neutron and proton-proton (T=1, $|T_z = 1|$, in isospin language) and the proton-neutron ($T = 1$, $T_z = 0$; and more importantly $T = 0$) components of the nuclear interaction.

Because of the importance of this area of the Segrè chart for nuclear sciences, considerable experimental efforts have been undertaken over the last decade to extend our knowledge of nuclear observables towards ever more neutron-deficient isotopes [2]. However, mostly decay properties have been studied via in-beam gamma-ray spectroscopy at fragmen-

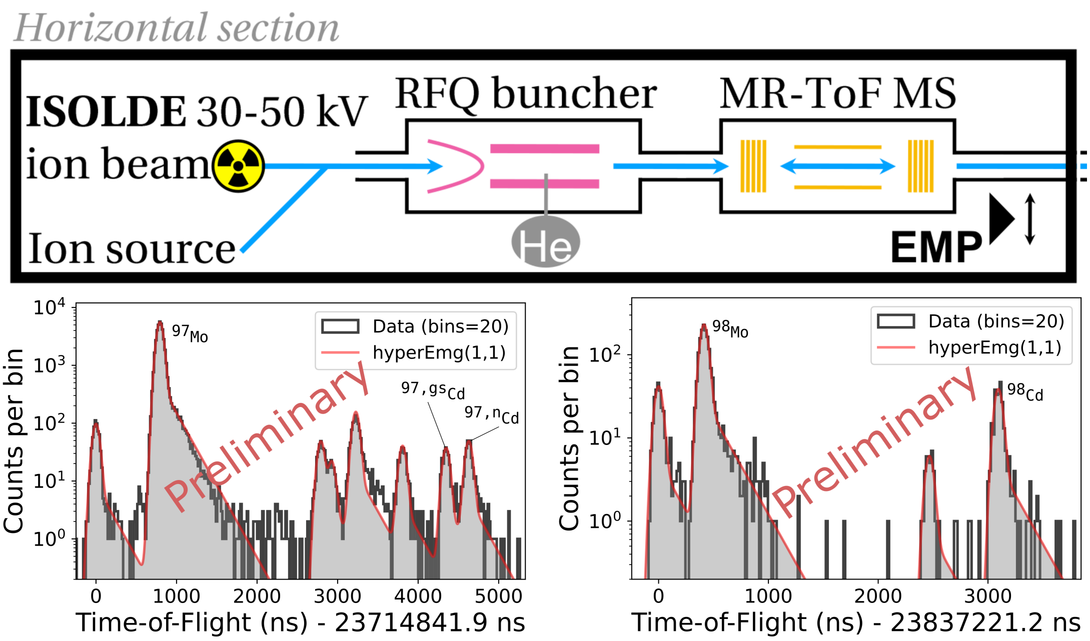

Figure 1: Top: schematic of the horizontal section of ISOLTRAP setup with its two ion traps, offline sources and electron multiplier detector (EMP) used for the ToF measurements. Bottom left: ToF spectrum of $A = 97$ components of the ISOLDE beam. Bottom right: ToF spectrum of $A = 98$ components of the ISOLDE beam. In both cases, the binwidth was set to 20ns.

tation facilities. By direct determination of the nuclear binding energy, high-precision atomic-mass measurements provide a model-independent probe of the structural evolution of exotic nuclei. Precision mass measurements are traditionally performed at isotope separation online (ISOL) facilities. The production of medium-mass, neutron-deficient nuclides at such facilities is prohibitively difficult, explaining that most of the recent mass measurements performed in the region have been undertaken at heavy-ion fragmentation facilities[9, 10, 11]. Nonetheless, the ISOLTRAP mass spectrometer has recently demonstrated its ability to measure neutron-deficient isotopes produced in the ~ 10 ion/μC range, reaching the isotopes ^{99}In (only one proton below ^{100}Sn) in two complementary campaigns, in 2018 and 2021 respectively [12, 13].

1.2 Yield study of neutron-deficient Cd isotopes

While the accepted INTC proposal [14] aims at extending our knowledge of the mass surface past N = 50 in the odd Z=49 indium chain, we suggest in the present work to focus on the even-Z=48 Cd isotopic chain. About a decade ago, the ISOLTRAP mass spectrometer already reached N=51, measuring the isotope ^{99}Cd for the first time [15]. In the 2020 edition of the Atomic Mass Evaluation (AME2020) [16, 17], the atomic mass of ^{98}Cd (N = 50) is reported with an uncertainty of 40 keV. However, it is only constrained indirectly through the β-decay Q-value reported in [18]. The first direct measurement of this isotope was performed only very recently, albeit with an uncertainty of 60 keV [11]. Crossing N = 50, the extensive β-decay studies carried out by J. Park *et al.* [7, 8] report Q-values from which atomic mass values for ^{95}Cd,^{96}Cd and ^{97}Cd can be extracted. On the one hand, the ^{97}Cd-Ag mass difference, reported in [8], yields a ground-state mass value exhibiting an uncertainty of 420 keV while the excitation energy of the long lived ($T_{1/2}$ = 3.86s) ^{97n}Cd isomeric state is reported with an excitation energy in excess of 2.5 MeV and an uncertainty of 520 keV [19, 20]. On the other hand, the ^{95}Cd and ^{96}Cd mass values, extracted from [7, 8], seem to violate the assumed smoothness of the trends of the mass surface. As a result, the AME2020 evaluators recommended replacing these two mass values by extrapolated ones (see Table F. in [16]).

In preparation for the present proposal, a yield investigation took place at ISOLDE in the first part of 2023. The beam was produced with a used LaCx target while the ISOLDE RILIS was employed to resonantly ionize the produced radioactive Cd atoms. The ISOLDE beam composition was studied using the ISOLTRAP multi-reflection time-of-flight mass spectrometer (MR-ToF MS) [21]. The bottom panel of Fig. 1 presents the beam components of the A = 97 and A = 98 ISOLDE beams. In both isobars, time-of-flight (ToF) peaks could unambiguously be attributed to the corresponding Cd isotopes by detuning the first step of the RILIS ionization scheme. For the A = 97 isobar, a second component was shown to react to the RILIS lasers. This second component is compatible with the expected ToF of the high-lying "spin-gap" isomer ^{97n}Cd. The duration of this yield investigation as well as the encountered production rates were such that enough statistics was gathered to extract the first direct atomic mass values for the ground-states of ^{97,98}Cd and the excitation energy of the ^{97gn}Cd "spin-gap" isomer. The analysis of the collected dataset remains at a very preliminary stage.

1.3 Extension towards ^{96}Cd

Because the binding energy is a global quantity, finite differences are commonly used for assessing changes in nuclear structure from the mass surface [22, 23]. The mass measurements performed during the reported yield study should allow extracting, for the first time with precision, the strength of the $N = 50$ one-neutron empirical shell gap in the Cd isotopic chain, thus making the Cd chain the closest isotopic chain to ^{100}Sn where this quantity is known reliably. In order to be able to benchmark a broader range of nuclear models, while removing the additional theoretical uncertainties inherent to the calculation of odd nuclei, **we propose to measure ^{96}Cd which is the last even-even $N = Z$ nucleus before ^{100}Sn**.

A direct measurement of the ground-state of ^{96}Cd will allow extracting for the first time the two-neutron empirical shell-gap which is the prime quantity to study the evolution of shell-structure far from stability. Indeed, in contrast with the one-neutron shell-gap, the contribution of the odd-even staggering of binding energies is greatly reduced when

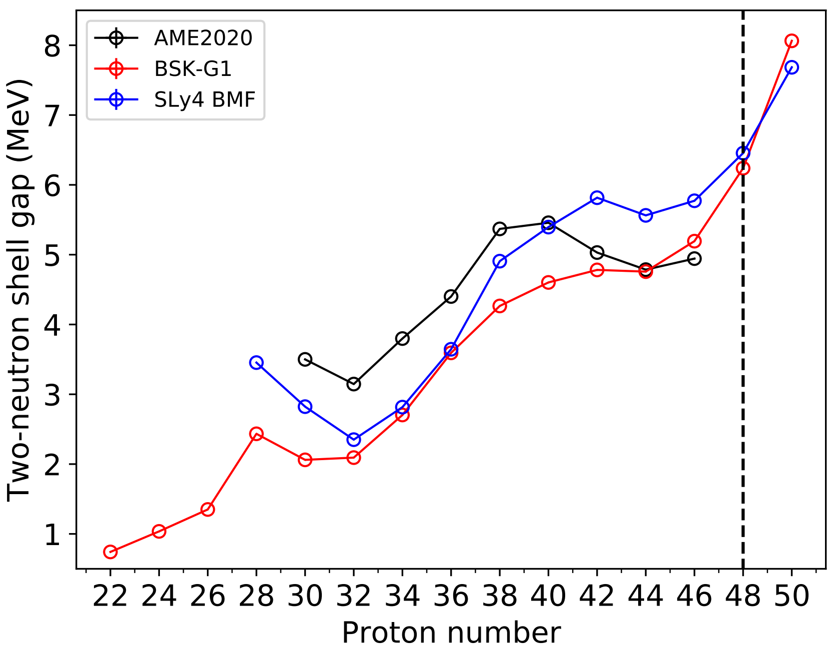

Figure 2: Evolution of the two-neutron empirical shell gap in even-even $N = 50$ isotones as a function of proton number. Data from the 2020 Atomic Mass Evaluation [16] are shown together with the predictions of two state-of-the-art self-consistent mean-field models, one of the most recent Brussels Skyrme functionals BSK-G1 [24] and the beyond mean-field calculation of [25] which uses the SLy4 interaction. The dashed line marks the abscissa of the missing data point for cadmium.

considering binding differences involving two-neutrons. A direct measurement of the empirical two-neutron shell-gap in the Cd chain will provide the first direct measure of the strength of the $N = 50$ shell closure right below ^{100}Sn, which, aided by the fact that Cd is an even-Z chain, is of paramount importance to test the prediction of virtually all nuclear models. The experimental two-neutron shell gap value known so far for the $N = 50$ isotones are presented as a function of proton number in Figure 2. The missing cadmium data point is indicated by the dashed line. The predictions of two state-of-the-art theoretical models of the self-consistent mean-field family are also presented for comparison. One notices that with the approach of ^{100}Sn at $Z = 50$, the models predict an enhancement of the empirical shell gap due to the mutually enhanced proton-neutron magicity. An additional effect will contribute in reality, due to the Wigner effect (enhanced binding of $N = Z$ nuclei), which should be visible already at $Z = 48$ because of the mass of ^{96}Cd ($N = 48$). This effect is usually underestimated (or completely absent from) mean-field models,. The mass of ^{96}Cd is thus an important stepping stone towards understanding the evolution of the mass surface towards ^{100}Sn.

The presence of a 16^+ isomeric state in ^{96}Cd was established in [5] and its structure was studied using a shell-model approach based on the Gross-Frenkel interaction in a $\pi\nu(p_{1/2},g_{9/2})$ model space. Within this framework, this "spin-gap" isomer arise from a $\pi\nu(p_{1/2}^2,g_{9/2}^8)$ configuration, leaving two proton holes $\pi(g_{9/2}^{-2})$ and two neutron holes $\nu(g_{9/2}^{-2})$ to couple with the maximum attainable spin of I=16. Currently the excitation energy of this ^{96m}Cd isomer is known to be on the order of ∼ 6 MeV with an uncertainty of 1.4 MeV [8, 20]. The shell model study in [5] have demonstrated the sensitivity of this state to the isoscalar (T = 0) component of the nuclear interaction. Therefore, in addition to the ground state mass measurement, a first direct measurement of this excitation energy is expected to provide a stringent complementary test of nuclear forces and theoretical approaches in the region.

2 Experimental techniques

The ISOLTRAP high-precision mass spectrometer [26, 27] will be used for the measurement of ^{96}Cd. Currently, the apparatus consists of four ion traps optimized for different purposes: accumulation, bunching, separation, cleaning, and mass determination. However, due to the low production rates expected during the experiment, the measurement is to be carried using the ISOLTRAP MR-ToF MS. In Figure 1 (top) a schematic view of the horizontal section of the apparatus is presented. The quasi-continuous ion beam provided by ISOLDE is first cooled and bunched in a linear radio-frequency quadrupole (RFQ) to improve the beam's ion-optical quality. Ion bunches are subsequently ejected from the RFQ into the MR-ToF device [21] which is used in combination with a ToF-detector to obtain a ToF spectrum.

The mass m of an ion with charge q is related to its measured ToF t via the relation: $t = a\sqrt{m/q} + b$, where a and b are calibration parameters to be determined using ion species of well known mass. As it is typically the case, one such calibrant species will be provided by ISOLTRAP's offline ion source. While its overall abundance may constitute an

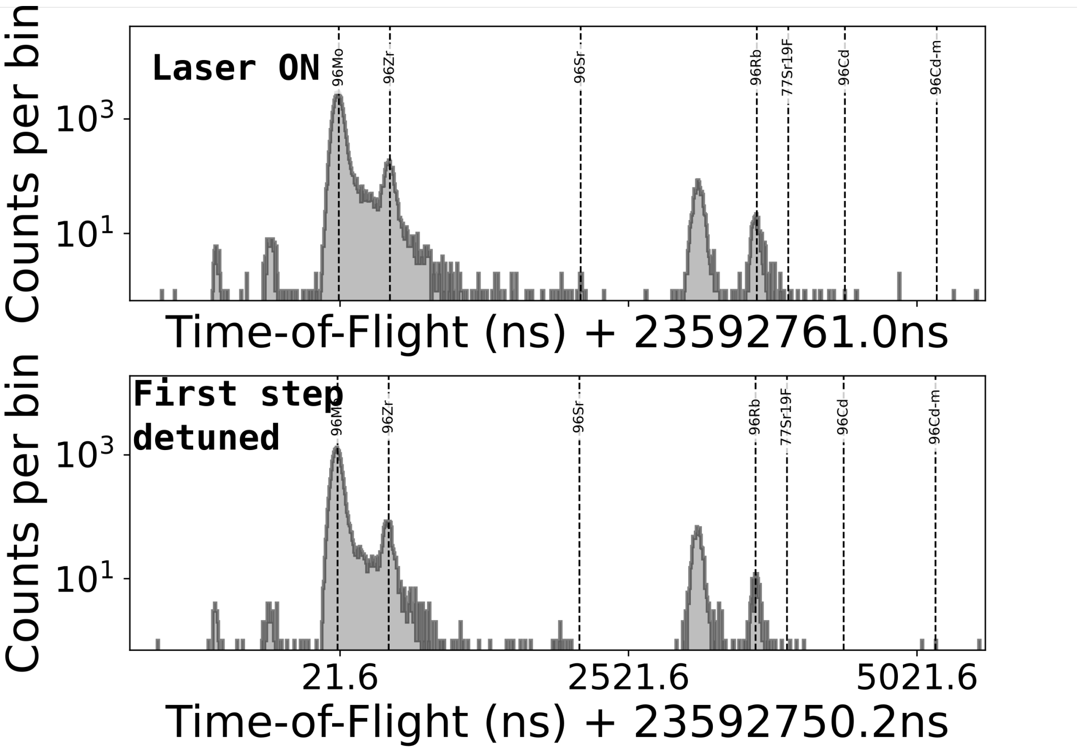

Figure 3: ToF spectrum of $A = 96$ components of the ISOLDE beam displayed with a binning of 20ns. Top: Spectrum with the first step of the RILIS ionisation scheme ON. Bottom: Spectrum with the first step of the RILIS ionisation scheme detuned.

obstacle, the presence of ^{96}Mo isobaric ion species in the ISOLDE beam, see Figure 3, is expected to be used as the second (online) calibrant.

3 Beam time request

Both the ground and isomeric states in ^{96}Cd are long-lived. The ground state's half-life is 1003(47) ms [28, 8] while that of the 16^+ "spin-gap" isomer [5, 8] is 511(26) ms. As such, the half-lives are not expected to be a limiting factor in our measurement. From our yield study, we can extrapolate the yield of ^{96}Cd in CA0 to be on the order of 10^{-2} ions/μC in CA0 (see Figure 4). Assuming a 1% transport efficiency between CA0 and our ToF detector (including losses due to processing the beam through the MR-ToF MS) and an average proton beam current of 2μA on target, 15 shifts should allow collecting ~ 80 ^{96}Cd ions. As ^{96}Cd ions will be produced through spallation reactions of LaCx, 9 protons and 34 neutrons will be ejected from the target material. This should result in a relatively wide distribution of possible spin states. As a result, we can hope for 1-10% 16^+ relative isomeric ratio between the two states [29]. As the ground and isomeric states of ^{96}Cd are measured simultaneously no additional shifts are specifically requested to measure this state.

Figure 3 shows the composition of the $A = 96$ ISOLDE beam. We expect stable ^{96}Mo$^+$ to be present in the beam. While it is very well separated from the species of interest, its relative abundance may constitute a significant obstacle for the experiment. As a result we would like to request the ISOLDE target and ion source development team to assess the feasibility of assembling a target unit free from parts made out of molybdenum. Furthermore, we would like to request a target similar to the target prototype #819 that was used during the test measurements as the yields were consistently higher than the previously reported ones. In one shift, with the first step of the RILIS ionisation on, see top panel of Figure 3, about 4 ions were observed in the ToF region where ^{96gs}Cd ions are expected. With the first RILIS step detuned, no ions where observed in that region within a similar time frame. In the present case, the expected ToF of both ^{96gs,m}Cd are located in a relatively background free region. Nevertheless, owing to low production rates expected, shifts have to be dedicated to assess and quantify the background in that ToF region. Thus, 3 shifts are required to tune the ISOLDE beam and assess the composition of the background in the region of interest. With such low production rates, the temporal stability of the ions ToF is of paramount importance. The technical improvements implemented and the data analysis methods developed in [13] have shown that such long data collection with the ISOLTRAP MR-ToF MS is possible while still maintaining a high mass accuracy.

Summary of requested protons: 18 shifts in one run with a LaC_x target and RILIS ionisation.

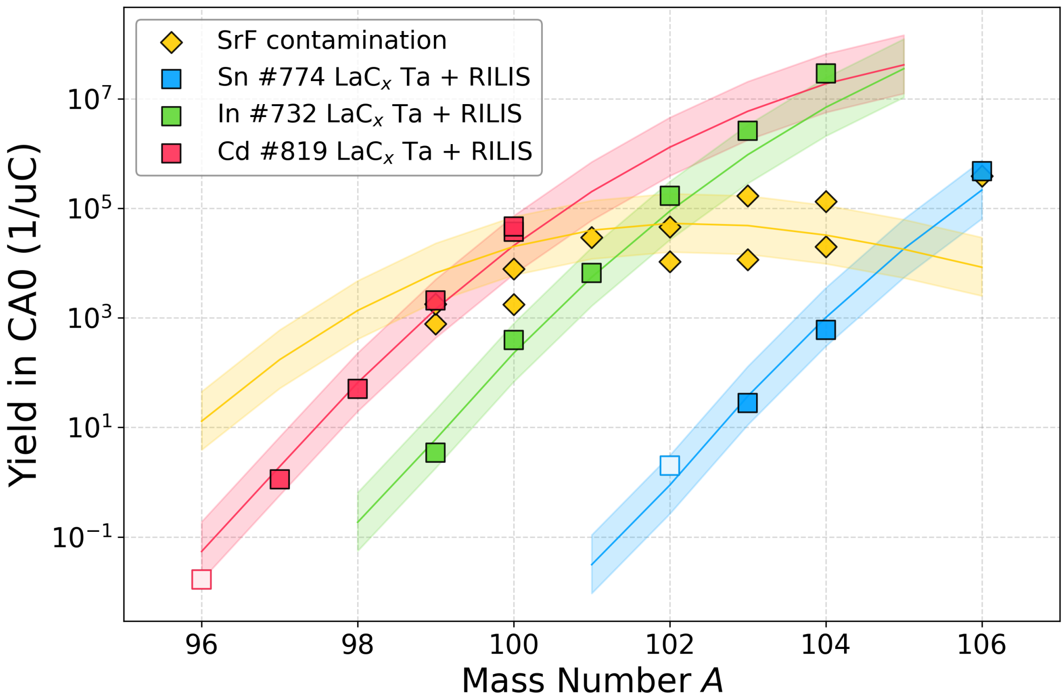

Figure 4: Yield (in ions/μC) in CA0 as measured using the ISOLTRAP MR-ToF MS for isotopes in the ^{100}Sn region. The open symbols represent upper limits based on observed statistics within the expected ToF windows.

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)
^{96}Cd	1003(47)	0.01#	LaC$_x$/RILIS	MR-ToF MS	15
^{96}Cd,m	511(26)	0.001#	LaC$_x$/RILIS	MR-ToF MS	/
Beam optimization and background studies					3

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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.