

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Precision Mass Measurements with ISOLTRAP to Study the Evolution of the $N = 82$ Shell Gap far from Stability

January 13, 2017

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Abstract

We request 8 additional shifts of radioactive beam time to perform Penning-trap mass spectrometry on neutron-rich isotopes of cadmium across $N = 82$. The requested shifts are needed to complete the initial proposal described in the INTC-P-382 document (IS574). So far the IS574 experiment has been successful in studying three out of the four exotic cadmium cases approved by the Committee and the result are published [1]. A measurement of the most neutron-rich of the isotopes under investigation, ^{132}Cd , was unsuccessful due to technical difficulties. A newly established Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR) technique was successfully installed at ISOLTRAP showed that the low lying isomeric state found in ^{129}Cd could be resolved.

Requested shifts: 8 shifts of radioactive beam by using a UCx target material, quartz insert and RILIS ion-source



1 Motivation

As discussed in the initial proposal [2], the mass measurements of silver, cadmium and indium isotopes at the crossing of the $N = 82$ are of great interest for the astrophysics and nuclear physics communities. The synthesis of over half of the heavy elements has its origin in the rapid neutron-capture process (r -process). The nuclear properties of isotopes found in this region lead to changes in the final abundance pattern. The lack of experimental data for these nuclides, however, is a limiting factor for making definitive conclusions in the astrophysical calculations. The atomic masses, when considering r -process modeling, are of particular interest [3]. In general the separation energies (given as differences in atomic masses) appear in calculations of neutron capture rates, photodissociation rates and β -decay Q -values. The largest dependence is evident by the formulation of the photodissociation rates, typically calculated from neutron capture rates and atomic masses:

$$\lambda_\gamma \propto T^{3/2} \exp \left[- \frac{S_N(Z, N)}{kT} \right] \langle \sigma v \rangle_{(Z, N-1)} \quad (1)$$

with T being the temperature, $\langle \sigma v \rangle_{(Z, N-1)}$ is the neutron capture rate of the neighboring isotope and k is the Boltzmann's constant. The neutron separation energy that appears in the exponential factor requires it to be determined with great precision to actually achieve reliable r -process modeling and thus abundance prediction. At ISOLTRAP, the required precision can be obtained by using the Penning-trap mass spectrometry, employing the conventional Time-Of-Flight Ion-Cyclotron Resonance (TOF-ICR) [4] or the novel Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR) [5] methods, or alternatively by using the Multi-Reflection Time-Of-Flight Mass Separator/Spectrometer (MR-TOF MS) [6]. Mumpower et al. [3] studied the influence of masses on the r -process abundances. Their results for the low entropy hot wind scenario are presented in Fig. 1, and show that cadmium isotopes (including the unknown mass of ^{132}Cd) have the biggest impact.

Predicting or even describing dramatic changes in nuclear structure far from stability are challenging for nuclear theory and the correct prediction of shell evolution is perhaps the strongest constraint for the different nuclear models and the corresponding nuclear interactions. The two-neutron shell gap is an empirical quantity determined by the two-neutron separation energy. Its evolution with proton number reflects the energy gap in the single-particle spectrum and the correlation energy of the nuclei whose atomic masses are used to calculate it. The mass of ^{132}Cd would allow determining the first value of the $N = 82$ two-neutron shell gap for $Z < 50$ and thus provide important information about the evolution of the $N = 82$ magic number towards the neutron dripline.

A particular property of even-odd nuclides with $N < 82$ around the tin isotopic chain is the presence of a negative-parity $I^\pi = 11/2^-$ isomer. The isomer is interpreted as resulting from an odd neutron occupying the $h_{11/2}$ orbital. The excitation energy of the $11/2^-$ isomer in the cadmium, tin and tellurium isotopic chains ($Z = 48, 50, 52$, respectively) is represented as a function of neutron number in Fig. 2. The preliminary value of the excitation energy of the isomer in ^{127}Cd , resulting from this work, is also shown (see next section for details). One notices that the trend of the excitation energy has a significant dependence with proton number and thus is sensitive to the proton-neutron interaction in the region. Interestingly, a recent shell model calculation gives the $11/2^-$ state as the ground state in ^{129}Cd [7, 8]. A measurement of the ground and isomeric states in ^{129}Cd would complete the systematics of the $11/2^-$ state above and below the tin isotopic chain and provide important information for shell-model calculations around ^{132}Sn .

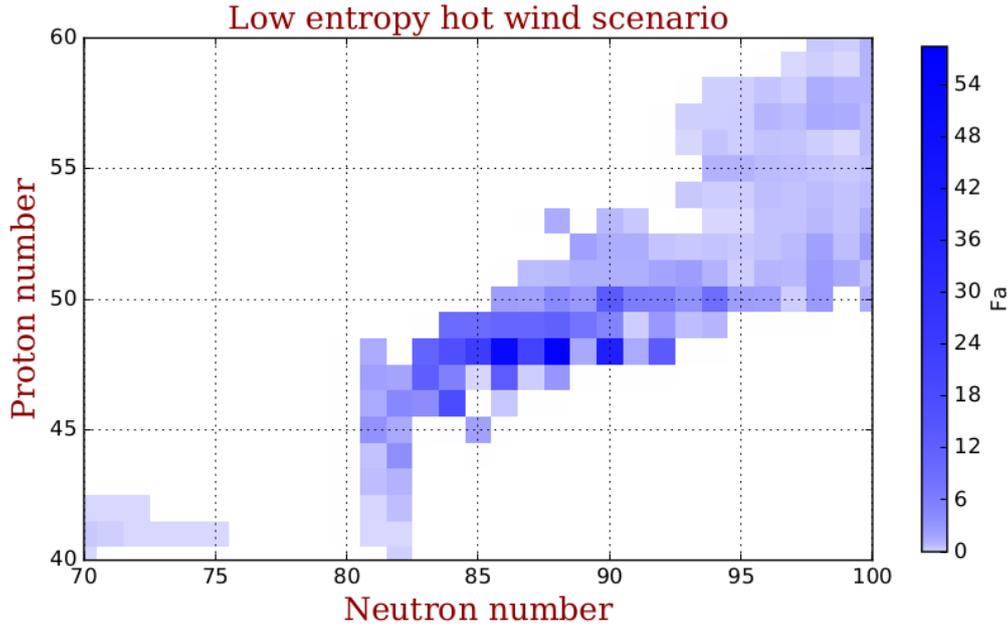


Figure 1: Region of the nuclear chart around the neutron magic number $N = 82$. The color code represents the impact parameter (Fa) of each nuclide to the final r -process abundances. The results presented here consider low entropy hot wind scenario [3]. More influential nuclides are represented by a darker color.

2 Status

The mass measurements of neutron-rich indium and silver isotopes mentioned in the proposal were not approved by the Scientific Committee in 2013. From the allocated 19 shifts requested to perform the mass measurements of the cadmium isotopes, so far 13 shifts have been used in two separate runs.

The first measurements were taken in August 2014. The suppression of the 5 orders of magnitude stable contamination present at mass $A = 130$ was achieved in this run by combining a specific target unit (which included a neutron converter, a quartz insert and a RILIS¹) with the MR-TOF MS at ISOLTRAP. This combination allowed isobarically pure beams to be transported to the Penning traps. However, due to many technical difficulties encountered in the run, the measurement time was rather limited to achieve the complete goal of the proposal.

Nevertheless, studies of the $^{129,130}\text{Cd}$ cases were achieved via TOF-ICR, while ^{131}Cd case was measured with the MR-TOF MS. During the run the determination of the excitation energy of the low lying isomeric state in ^{129}Cd was addressed. The beam of ^{129}Cd contained two nuclear states, previously identified and measured at ISOLDE. The spins of the two states were assigned to $3/2^+$ and $11/2^-$ by hyperfine structure measurements [9]. Unfortunately, the two states could not be fully resolved by using the conventional TOF-ICR technique within this beam time. Hence, it was impossible to extract the excitation energy out of the collected data. Nevertheless, the estimated energy difference between the ground and the isomeric state was inferred from the systematic trend in the cadmium chain to be about 180(100) keV. Since a definite assignment of the determined $^{129}\text{Cd}^+$ frequency ratio to one of the two nuclear states was not possible, an

¹Resonance Ionization Laser Ion Source

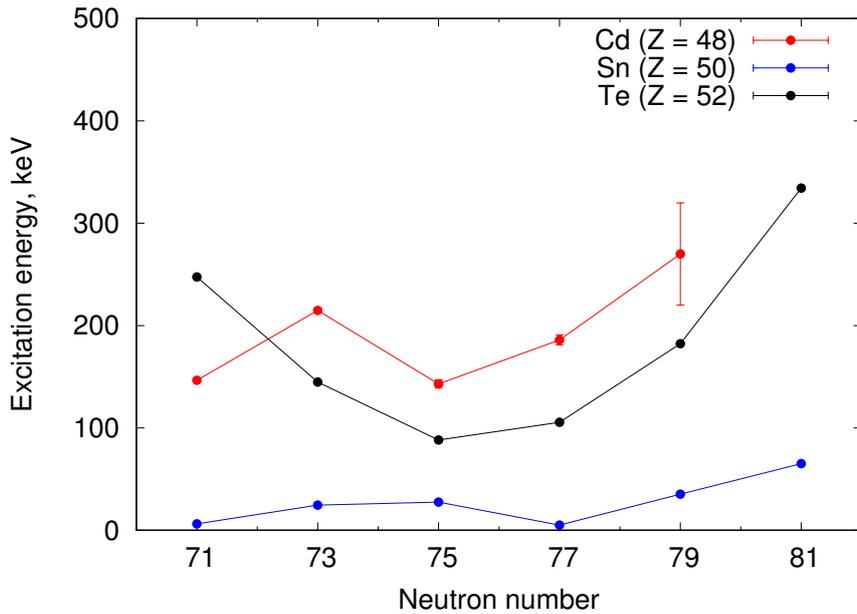


Figure 2: Systematic trends of the excitation energy of the $11/2^-$ states in cadmium, tin and tellurium nuclei at the crossing of $N = 82$. The value for ^{127}Cd ($N = 79$) has been determined by using the PI-ICR measurements done during the 2016 run.

estimation for the pure ground state mass excess was determined according to Appendix B of [10] which lead to an increase of the uncertainty from 17 keV to 74 keV. Furthermore, the most challenging case, ^{132}Cd , could not be attempted due to the time constraints.

In the more recent experimental campaign in July 2016 our aim was to measure the mass of ^{132}Cd by using the MR-TOF MS and the excitation energy of the isomer in ^{129}Cd by using the PI-ICR technique, which has been under development at ISOLTRAP in the period 2015-2016. Due to a number of technical problems the beam intensity was lower than in 2014, therefore the ^{132}Cd beam could not be measured. Concerning the isomer separation, the available time allowed only performing a proof-of-principle PI-ICR study of ^{123}Cd (where the excitation energy of the isomer is known) and a first-time study of ^{127}Cd . In Figure 3 the first isomeric separation by using the PI-ICR detection method for the ^{127}Cd case is presented alongside the corresponding TOF-ICR spectrum. Since the experiment, a number of upgrades in the ion-optical arrangement and the timing-pattern generation for the PI-ICR technique have been carried out. These interventions allowed significantly improving the method's resolution and accuracy. An resulting, improved six-spot imaging of the cyclotron frequency of ^{85}Rb ions is shown in Fig. 4.

In conclusions, part of the original goal of the proposal INTC-P-382 was not achieved. In order to consolidate the conclusion of the first experiment and to fully complete the program for this proposal, we would like to attempt measurements of both ^{132}Cd and ^{129}Cd in the next run. However, the remaining 6 shifts of IS574 are not sufficient to achieve that goal.

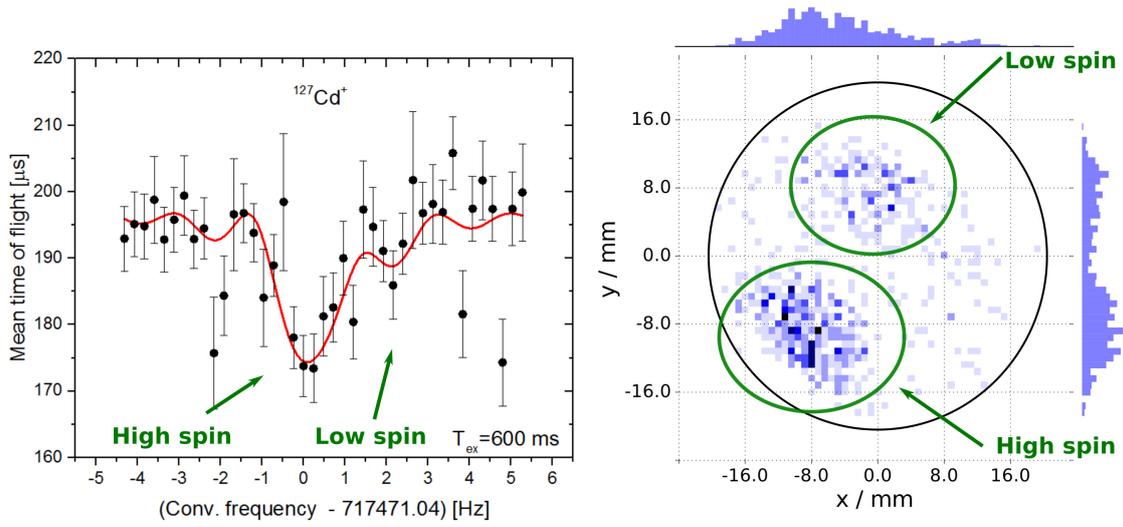


Figure 3: Spectra for ^{127}Cd obtained during the run in July 2016 showing the capabilities for isomeric separation of two detection techniques available at ISOLTRAP. On the left the TOF-ICR using excitation time of 600 ms and on the right PI-ICR with accumulation time of 300 ms. The excitation energy in this system was determined to be 270(50) keV. The black circle indicates the size of the detector.

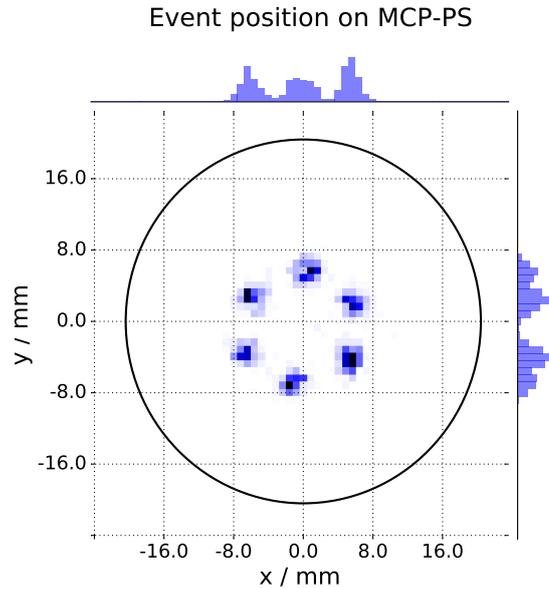


Figure 4: An improved PI-ICR six-spot image of ^{85}Rb ions.

3 Beam-time request

We would like to request 8 shifts of radioactive beam in addition to the 6 remaining shifts of the IS574 experiment. Within the requested shifts we have included 2 shift for stable beam tuning and target and ion-source optimization, 2 shifts for improving the precision for the ^{127}Cd case

and 4 shifts that will be used for the measurements of $^{129,132}\text{Cd}$ cases. The summary of shifts (requested and remaining) is given in the list below. The total shifts are to be requested in one run using RILIS and a UCx target with a Ta ionizer, a quartz insert and a neutron converter.

Isotope	Half-life (ms)	Yield (ions/ μC^{-1})	Method	Shifts (8h)
$^{127\text{g,m}}\text{Cd}$	330(20),200#	$1.0 \cdot 10^5$	Penning trap	2
$^{129\text{g,m}}\text{Cd}$	151(15),146(8)	$1.2 \cdot 10^4$	Penning trap	4
^{132}Cd	97(10)	$1.0 \cdot 10^1$ #	MR-TOF MS	6

Value has been extrapolated

References

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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	<input checked="" type="checkbox"/> Existing	<input checked="" type="checkbox"/> To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed ISOLTRAP installation.