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

Laser Spectroscopy of Cadmium Isotopes Towards $N = 50$

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Abstract:

We propose to study the neutron-deficient cadmium isotopes with high-resolution laser spectroscopy for the first time. Our goal is to determine nuclear spins, electromagnetic moments and rms charge radii towards $N = 50$, contributing decisively to a better understanding of the nuclear structure in the vicinity of the doubly-magic ^{100}Sn.

keywords: cadmium, spins, electromagnetic moments, radii, COLLAPS

Requested shifts: 9 shifts of radioactive beam and 2 shifts of stable beam

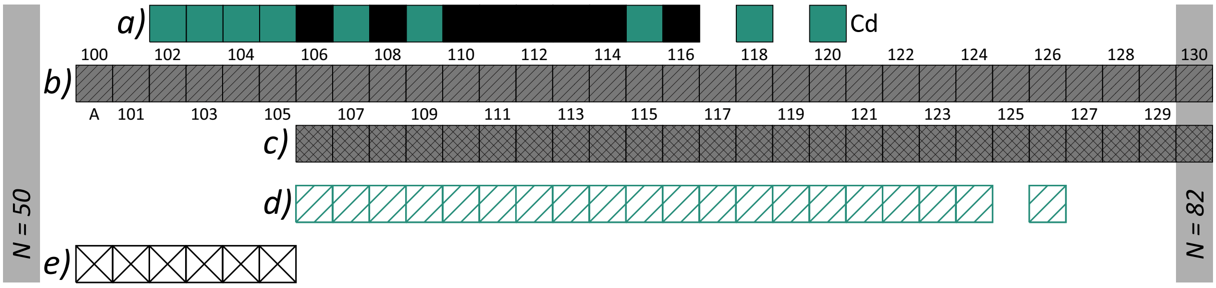

Figure 1: Progress of IS497: a) Previous work by low-resolution laser spectroscopy (green); b) Proposed range of studies [1] by high-resolution laser spectroscopy (35 shifts requested); c) Approved range of studies [2] with a reduced number of shifts (17 out of 26); d) Studied isotopes in 2011 (8 shifts); e) Range of radioactive isotopes subject of this addendum (9 shifts being requested);

1 Introduction

The original proposal "Laser Spectroscopy of Cadmium Isotopes: Probing the Nuclear Structure Between the Neutron 50 and 82 Shell Closures" [1] presented our interest to study for the first time by high-resolution laser spectroscopy the isotopic chain of cadmium. The goal was to determine nuclear spins, electromagnetic moments and root mean square charge radii of ground and isomeric states towards the neutron 50 and 82 shell closures. Thus, the nuclear structure was to be studied in the vicinity of the doubly-magic ^{100}Sn and ^{132}Sn. On the neutron-rich side this was expected to shed light on a shell-quenching hypothesis and consequently on the duration of the r-process along the waiting-point nuclei below ^{130}Cd. On the neutron-deficient side it was considered applicable for clarifying the role of the cadmium isotopes in the rp-process for rapidly accreting neutron stars. The beam-time requested for this work was 35 shifts [1], 9 of which for the neutron-deficient isotopes $^{100\text{-}105}$Cd and 26 for the neutron-rich ones $^{106\text{-}130}$Cd. The committee recommended for approval 17 shifts [2] for the investigation of the neutron-rich cases. Fig. 1 summarizes our beam-time requests in chronological order.

2 Progress of IS497

Considering the production of cadmium at ISOLDE (Fig. 3, Tab. 1) the following strategy for conducting IS497 was adopted. The allocated beamtime was divided into two parts. The first would investigate the high-yield isotopes and push towards $N = 82$ as much as the experimental method permits. In this case continuous beams would be used after the GPS separator, measuring the fluorescence in the conventional manner. In the second run the beams would be bunched with the ISCOOL Paul trap in order to increase the sensitivity to the fluorescence and cover the most exotic cases up to the shell closure at ^{130}Cd. The necessity of this division is defined by two main factors. First, the beam intensities of the less-exotic isotopes would be too high to be used in combination with ISCOOL. The reason is the occurrence of space charge effects in the trap, which alter the

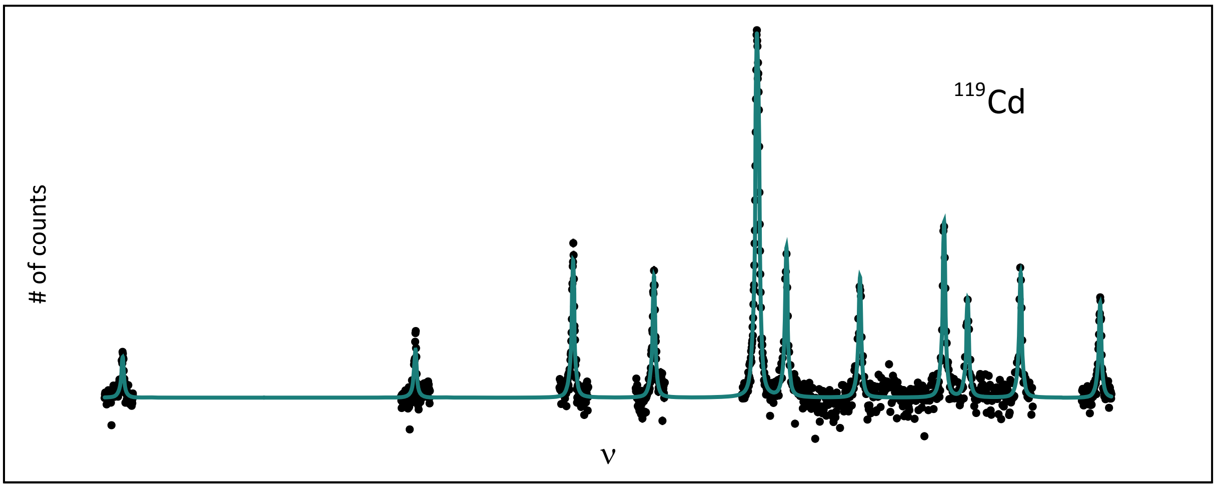

Figure 2: Hyperfine-structure spectrum of ^{119}Cd.

beam velocity depending on the isotope production. This yield dependence of the beam energy is undesirable for charge-radii measurement as it introduces systematic uncertainties that are difficult to quantify. When using ISCOOL laser spectroscopy experiments have to ensure a beam current of about 10^6 ions/s or less. This would mean one has to reduce the intensity by one or two orders of magnitude for most cadmium isotopes, when it is perfectly possible and uncertainty-free to use the full beam intensity at GPS. The second factor is related to the time necessary for mass changes with the HRS separator. As reference measurements with ^{114}Cd have to take place very often mass changes of 10-15 min would accumulate into an appreciable amount of time (1 shift on a run of 8 shifts). Considering the above points a decision was made to split the beam time in two runs, respectively 8 shifts at GPS and 9 shifts at HRS.
The first run of IS497 was scheduled in August 2011 at GPS. It was the first study of the isotopic chain of cadmium by high-resolution laser spectroscopy. Within 8 shifts measurements were carried out in $^{106\text{-}124,\,126}$Cd, hence covering 19 ground states and 7 isomers. Spins, electromagnetic moments, and charge radii of the odd isotopes in the range $^{117\text{-}123}$Cd, as well as the charge radii of the even cases ^{122,124,126}Cd, were measured for the first time. The most intriguing discovery from this dataset is the evolution of the quadrupole moment of the $11/2^-$ isomers, which is correlated with the measured isomer shifts. Analysis and interpretation are ongoing. We do not present more explicit information in this addendum. However, presenting such at the time of the defense is being considered.
One final point that needs to be discussed here concerns determination of the nuclear spins. In the case of ^{119}Cd (Fig. 2) the measurements conclusively show that the ground-state spin quoted in the literature without brackets [9] is wrong. This exposes the necessity of direct spin measurements even for cases not very far from stability. Typically, spin assignments are then propagated to other nuclei by other means, for instance by β-decay studies. In this respect high-resolution laser spectroscopy, with its ability to measure nuclear spins, is essential for extending our knowledge to the most exotic nuclei.

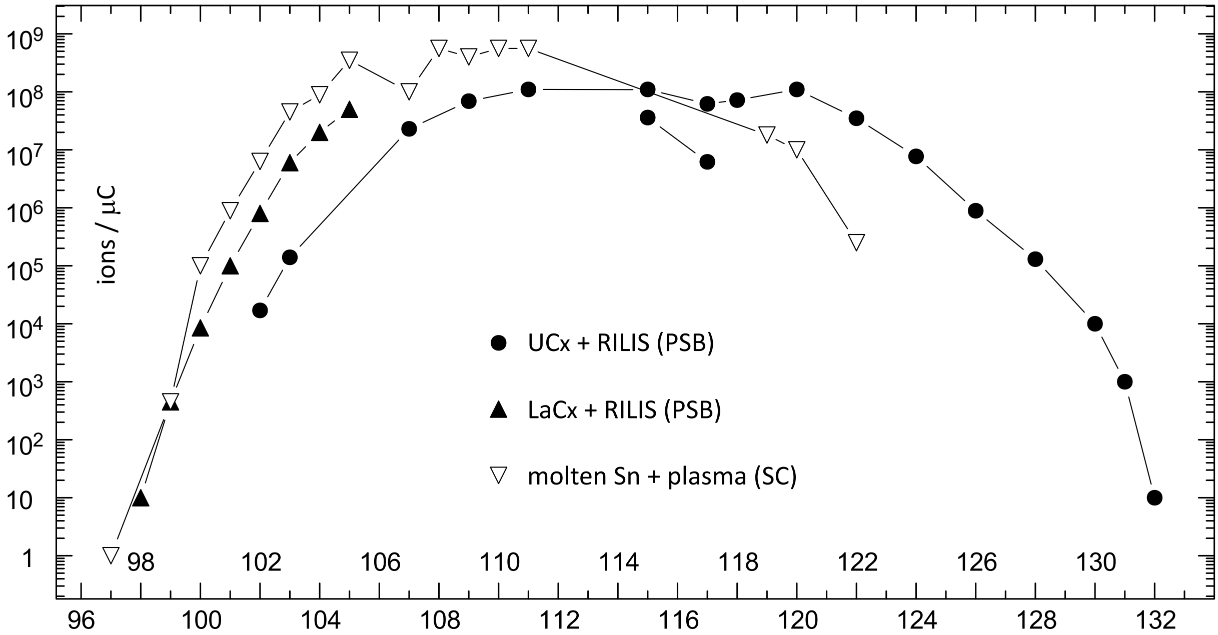

Figure 3: Yields of cadmium ions from UC_x and LaC_x targets [3] after resonant laser ionization [4], next to SC yields from a molten Sn target with a plasma-discharge ion source [5]. The numerical data are given in Tab. 1.

3 Physics case

Considering the results from the first experiment, the general outline of the physics case is now better defined. In the initial proposal [1] we hypothesized about shape coexistence. Now there are data that may support or deny this idea. It is important to continue the study by measuring the two long-lived states in ^{125}Cd. Further on towards the $N = 82$ shell closure there is an additional physics interest based on the low-lying 2_1^+ states in ^{126}Cd and ^{128}Cd, which could be attributed to a retained deformation close to the shell closure [10, 11], or to a shell-quenching effect [12]. It is expected that electromagnetic moments and charge radii will be of great help to resolve the problem. Furthermore, measurements in that range will help to improve theory and therefore the understanding of the r-process through the bottleneck region below ^{130}Cd. The INTC approved part of the beam-time requested for this study (9 out of 18 shifts).

The interest on the neutron-deficient side is defined to a large extent by the need to explore the structure of nuclei in the vicinity of the doubly magic ^{100}Sn. Currently, using the bunched-beam method measurements are possible down to ^{100}Cd, already in the domain of ^{100}Sn $\pm$ 2 protons and neutrons. Measuring further down towards the $N = 50$ shell closure could be possible by the use of the collisional ionization method [13]. This option needs to be tested offline as the cross sections for collisional ionization are unknown. This is not a subject of the current addendum, but it could be considered in the future when the ionization conditions are understood and quantified (possibly in 2013).

The neutron-deficient cadmiums are important to study also in connection with other

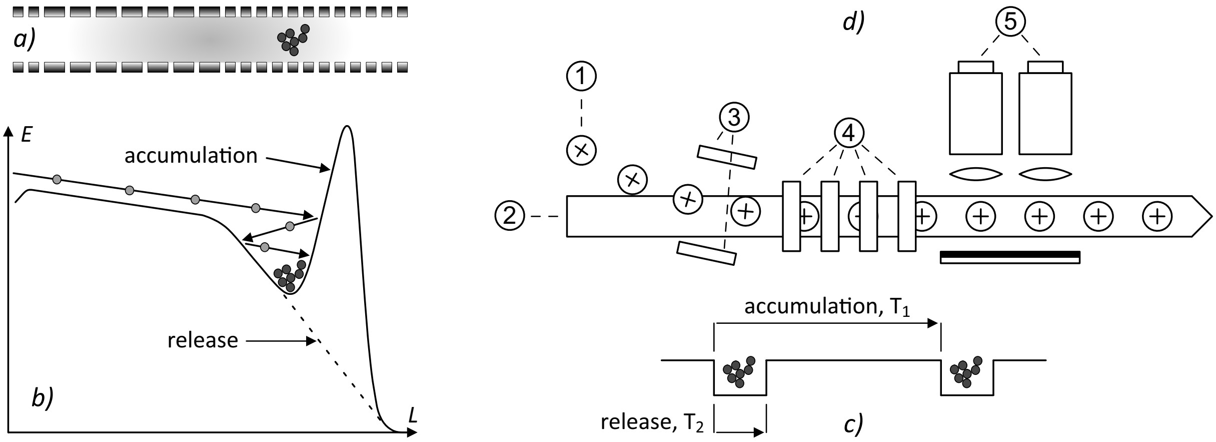

Figure 4: Principle of the experiment: (a) bunch of ions in the buffer gas of ISCOOL; (b) basic concept of cooling and bunching; (c) time structure of the emerging beam; (d) sketch of the setup for collinear laser spectroscopy configured for optical detection: (1) incoming ions, (2) laser beam, (3) deflection plates, (4) post-acceleration lenses, (5) optical detection;

effects. High-resolution laser spectroscopy has never been applied to the isotopes below ^{106}Cd, meaning that the $5/2^{+}$ states, based on the $d_{5/2}$ orbital, have never been investigated in this manner. Reliable spin assignments will be made to ^{101,103,105}Cd, magnetic and quadrupole moments will be extracted and the sequence of measured charge-radii will be extended to cover nearly the entire *sdgh* shell. Providing such sensitive nuclear probes will certainly enhance the general understanding and the theoretical modeling of the entire region. This may also contribute to a better understanding of the rp-process for rapidly accreting neutron stars [14].

4 Experiment

Isotope production (Fig. 3, Tab. 1), beam purity and the experimental technique have already been discussed in detail [1]. For the sake of completeness here we present a somewhat shorter description. The beams will be accumulated in ISCOOL and then released in bunches. The concept is outlined in Figs. 4 (a), (b) and (c). T_1 and T_2 represent respectively the accumulation time and the bunch width. By gating the optical detection (Fig. 4 (d)) on the bunched beam structure (Fig. 4 (c)) one can reduce the background from laser scattering and dark noise of the phototubes by a factor of T_1/T_2 and therefore the signal-to-noise ratio with the square root of that factor. Typical time constants are $T_1 = 100$ ms and $T_2 = 10$ μs. As a result, this method can cope with two orders of magnitude lower yields than conventional fluorescence spectroscopy. Our experience with continuous beams shows a feasibility limit of 10^5 ions/s ($\approx 10^5$ ions/μC) for even-even isotopes and 10^6 ions/s for isotopes with hyperfine structure. Indeed, assuming an efficiency for fluorescence detection of 10^{-4}, laser background of 2 kHz, and 30 points in a spectrum, the fluorescence signal from 10^5 ions/s would exceed the noise in the

Table 1: ISOLDE-database yields [6] of the cadmium according to Refs. [3, 5].

	$\tau_{1/2}$	ions/μC LaC$_x$ (PSB)	ions/μC UC$_x$ (PSB)	ions/μC Sn (SC)
^{97}Cd	2.8(6) s	×	×	1.0×10^{0}
^{98}Cd	9.2(3) s	1.0×10	×	×
^{99}Cd	16(3) s	4.5×10^{2}	×	4.5×10^{2}
^{100}Cd	49.1(5) s	8.5×10^{3}	×	1.0×10^{5}
^{101}Cd	1.36(5) m	1.0×10^{5}	×	8.9×10^{5}
^{102}Cd	5.5(5) m	8.0×10^{5} [a]	1.7×10^{4}	6.3×10^{6}
^{103}Cd	7.3(1) m	6.0×10^{6}	1.4×10^{5}	4.5×10^{7}
^{104}Cd	57.7(10) m	2.0×10^{7}	×	8.9×10^{7}
^{105}Cd	55.5(4) m	5.0×10^{7}	×	3.5×10^{8}
^{107}Cd	6.50(2) h	×	2.3×10^{7}	1.0×10^{8}
^{108}Cd	stable	×	×	5.6×10^{8}
^{109}Cd	462.6(4) d	×	6.9×10^{7}	4.0×10^{8}
^{110}Cd	stable	×	×	5.6×10^{8}
^{111}Cd	stable	×	×	5.6×10^{8}
^{111}Cd^{m}	48.54(5) m	×	1.1×10^{8}	×
^{115}Cd	53.46(5) h	×	3.6×10^{7}	×
^{115}Cd^{m}	44.56(24) d	×	1.1×10^{8}	×
^{117}Cd	2.49(4) h	×	6.2×10^{6}	×
^{117}Cd^{m}	3.36(5) h	×	6.2×10^{7}	×
^{118}Cd	50.3(2) m	×	7.2×10^{7}	×
^{119}Cd	2.69(2) m	×	×	1.8×10^{7}
^{120}Cd	50.80(21) s	×	1.1×10^{8}	1.0×10^{7}
^{122}Cd	5.24(3) s	×	3.5×10^{7}	2.5×10^{5}
^{124}Cd	1.25(2) s	×	7.7×10^{6}	×
^{126}Cd	506(7) ms	×	8.9×10^{5}	×
^{128}Cd	340(30) ms	×	1.3×10^{5} [b]	×
^{130}Cd	162(7) ms	×	1.0×10^{4}	×
^{131}Cd	68(3) ms	×	1.0×10^{3}	×
^{132}Cd	97(10) ms	×	1.0×10	×

[a] to be compared to 6×10^{5} ions/μC from a recent measurement with LaC$_x$ target #387 [7].
[b] to be compared to 1.3×10^{4} ions/μC from UC$_x$ target #362 and protons on converter [8].

background by three standard deviations after 2 hours. Odd isotopes, on the other hand, have weaker transitions and fit in a much larger scanning range, therefore the required intensity in order to satisfy the $3\times\sigma$ condition is higher by a factor of about 10. Following this well-established guideline we are certain that the cadmium isotopes in the mass range $100 \leq A \leq 130$ are well within the reach of the bunched method.

The concept of collinear laser spectroscopy is sketched in Fig. 4 (d). The measurements will be carried out in the transitions: $5s\ ^2S_{1/2} \rightarrow 5p\ ^2P_{1/2}$ and $5s\ ^2S_{1/2} \rightarrow 5p\ ^2P_{3/2}$ in Cd II, D_1 and D_2 lines at 226.6 nm and 214.5 nm [15, 16], respectively. These wavelengths will be generated by frequency quadrupling the output of a Ti-sapphire laser, pumped at 532 nm from a diode-pumped solid-state laser. For enhanced sensitivity so deep in the UV spectrum we rely on photomultiplier tubes with thin windows of fused silica (cut off at 160 nm) and bialkali photocathode, e.g. 9829QSA from Electron Tubes , with an excellent quantum efficiency close to 30% at the above-mentioned wavelengths. In addition, we consider the atomic transition $5s5p\ ^3P_2 \rightarrow 5s6s\ ^3S_1$ at 508.7 nm, which is more favorable for resolving the spin of the isomer in ^{125}Cd. The laser system for producing the UV light is currently being tested off-line. Results from these tests will be presented at the time of the INTC meeting.

5 Beam-time request

Herewith, we request **9 shifts of radioactive beam** and **2 shifts of stable beam** for measuring spins ,electromagnetic moments and rms charge radii of the isotopes of cadmium. If approved the total beam time of IS497 will sum up to 26 shifts of radioactive beam. This is less than our original request of 35 shifts necessary for completing the program. With the permission of the INTC the remaining 9 shifts of that program will be justified separately with a status report or an addendum, which would present the results from 2012 and based on those will reassess the need for further beam time. This work is aimed to be carried out as follows:

• one experiment of 9 shifts for the neutron-deficient isotopes $^{100\text{-}105}$Cd, using a molten tin target, HRS and ISCOOL;

• the approved run on the neutron-rich isotopes and the requested run on the neutron-deficient cases need to use 1 shift of stable beam each in order to do calibration measurements over the long sequence of stable isotopes;

• we request the permission to present the status of IS497 at the earliest regular INTC meeting after the 2012 running period in order to reassess the need for further beam time up to the original request of 35 shifts;

The beam-time requests of IS497 have been summarized in Fig. 1.

Summary of requested shifts: 9 shifts of radioactive beam are being requested for the study the neutron-deficient cadmium isotopes. We consider presenting the progress of IS497 after the 2012 running period in an addendum or a status report to the INTC and justify the use of an additional beam time within the original request of 35 shifts.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT
The experimental setup comprises:

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

HAZARDS GENERATED BY THE EXPERIMENT
Hazards named in the document relevant to the fixed COLLAPS installation.