

Proposal to the INTC

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Laser Spectroscopy of Cadmium Isotopes: Probing the Nuclear Structure Between the Neutron 50 and 82 Shell Closures

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We propose to study the isotopic chain of cadmium with high-resolution laser spectroscopy for the first time. Our goal is to determine nuclear spins, moments and root mean square charge radii of ground and isomeric states between the neutron 50 and 82 shell closures, contributing decisively to a better understanding of the nuclear structure in the vicinity of the doubly-magic ^{100}Sn and ^{132}Sn . On the neutron-rich side this is 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 may elucidate the role of the cadmium isotopes in the rp-process for rapidly accreting neutron stars.

keywords: cadmium, spins, moments, radii, COLLAPS

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PERSPECTIVES FOR LASER SPECTROSCOPY IN THE TIN REGION

Our current understanding of the nuclear landscape is derived from the modern nuclear models which provide the scientific language for its description and study. We commonly talk about “magic numbers” as one representation of the empirical fact that the atomic nuclei have an intrinsic structure. Behind this figurative concept lies an important natural phenomenon, which in the nuclear theories takes shape through a multitude of parameters and observable quantities. Our comprehension of nuclear matter is equivalent to the knowledge of those parameters. However, the ability of theoretical models to predict properties of nuclei away from the valley of stability is limited due to the changing nuclear structure. Experimental input is, therefore, needed for the development of such models and for enhancing our knowledge of the phenomena taking place in the exotic regions of the nuclear chart.

Collinear laser spectroscopy is a well-established experimental method for measuring model-independent parameters of nuclear ground and isomeric states, namely spins, electromagnetic moments and root mean square (rms) charge radii. These quantities are highly sensitive probes of the nuclear structure - the nuclear wave function as well as of global



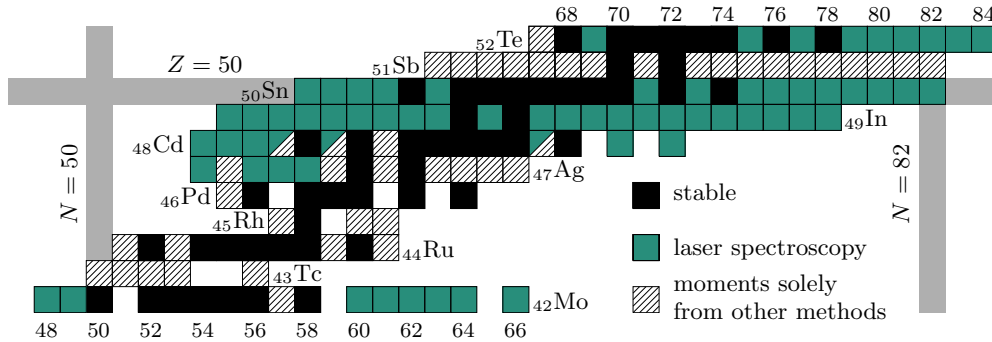


FIG. 1: Chart of experimental electromagnetic moments and radii of nuclear ground states in the tin region. Properties of stable nuclei (black) are generally known. In the absence of data from laser spectroscopy (solid color), moments from other methods (hatched) are depicted. For a number of odd-mass cadmium isotopes laser spectroscopy provides only the charge radius (see the text).

nuclear properties such as sizes and shapes. This technique is, therefore, a key contributing factor for enriching our understanding of the atomic nuclei, in particular near closed shells, where experimental input is of critical importance for improving the nuclear models. The current availability of electromagnetic moments and data from laser spectroscopy in the vicinity of the proton-magic tin isotopes ($Z = 50$) is summarized in Fig. 1. The areas near the doubly magic $^{100}\text{Sn}_{50}$ and $^{132}\text{Sn}_{82}$ are of primary interest for studying the shell structure away from the valley of stability. On the neutron-rich side this is directly related to the duration of the r-process as it propagates along $N = 82$ over the waiting-point nuclei from zirconium to cadmium. The neutron-deficient region plays a prominent role in the rp-process for rapidly accreting neutron stars [1]. Laser spectroscopy of $^{108-132}\text{Sn}$ [2–4] has confirmed the ground-state single-particle nature of the odd-mass isotopes and derived nearly spherical shapes with slight increase in deformation towards midshell. With the production rates of ISOLDE [5, 6] and efficient resonant laser ionization [7] the measurements of neutron-rich tin isotopes can be extended beyond $N = 82$. This is expected to shed additional light on the restoration of the shell gap inferred from the mass measurements of $^{132,134}\text{Sn}$ [8] and to reveal the characteristic shell effect in the radii, which has been observed close to stability and has recently been confirmed for the neighboring tellurium isotopes [9]. Expanding the existing laser spectroscopy of indium [10] and certainly silver [11], which has not been studied on the neutron-rich side, would also be most desirable. Further down to molybdenum [12], the experimental data on nuclear ground states (Fig. 1) are rather scarce.

With only two proton holes in the $Z = 50$ shell, the isotopes of cadmium are of compelling nuclear-structure interest. The initial laser spectroscopy on these nuclei [13] has been carried out in a resonance vessel with resolution comparable to the hyperfine-structure splitting (GHz). Thus, no moments have been resolved on the neutron-rich side. Only the neutron-deficient ^{103}Cd has been assigned a magnetic and a quadrupole moment, with large relative uncertainties of 4% and 88%, respectively. Herewith, we propose to apply collinear fast-beam laser spectroscopy (linewidth = tens of MHz) and use extremely sensitive detection methods to derive spins, rms charge radii and high-precision moments for the exotic cadmium nuclei towards the neutron 50 and 82 shell closures.

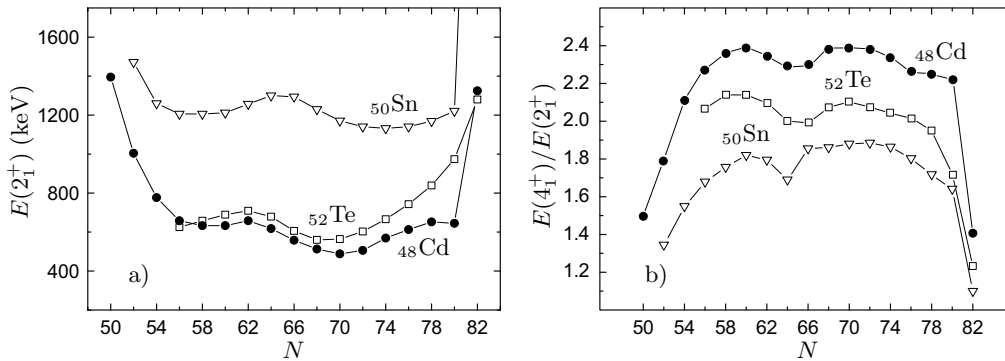


FIG. 2: Systematics of 2_1^+ states (a) and 4_1^+ over 2_1^+ energy ratios (b) of tellurium, tin and cadmium isotopes for $50 \leq N \leq 82$. The data have been adopted from Ref. [14].

PHYSICS INTEREST IN THE CADMIUM ISOTOPES

Charge radii of the even-even isotopes

The problem of studying the structure of even-even nuclei is typically approached through the knowledge on their excited states and transition probabilities. This partly solves the issue on their intrinsic deformation, which can not be addressed directly due to the unobservability of quadrupole moments in their $I = 0$ ground states. The rms charge radius, on the other hand, is a measurable quantity in all nuclei that is genuinely linked to the nuclear shape. In the case of cadmium this quantity is of particular interest.

The first 2^+ and 4^+ states in ^{126}Cd and ^{128}Cd and tentatively the 2_1^+ state in ^{130}Cd have been identified in the β decays of the corresponding silver isotopes [15]. The two lighter nuclei have recently been produced in fragmentation as isomeric beams and their levels independently confirmed [16], whereas the result on ^{130}Cd has been modified and its scheme extended to higher-energy levels [17]. Accordingly, the systematics of 2_1^+ states in the isotopes of cadmium and tellurium, respectively one proton pair below and above the magic tin isotopes, can now be followed towards the $N = 82$ shell closure. As shown in Fig. 2 (a), both isotopic chains have very similar behavior in the middle of the shell and energies significantly lower than those of the tin nuclei. The latter is typically a signature of collectivity, which in the case of cadmium appears to be correlated with the midshell increase in deformation detected in the existing rms charge radii [13]. The isotopes of cadmium near $N = 82$, unlike those near $N = 50$ and unlike the tellurium isotopes close to $N = 82$, retain collectivity as their 2_1^+ levels remain low. The level in ^{128}Cd is even lower by 7 keV relative to ^{126}Cd . Only at the magic ^{130}Cd sphericity is restored in a step-like process. This is also apparent from the plot in Fig. 2 (b), where the energy ratios, being in most isotopes well above the empirical boundary of 2 for spherical nuclei, behave very differently towards the two shell closures. The abrupt drop at ^{130}Cd stands out in comparison with the smoothness of the tin and tellurium curves. The work of Ref. [15], offers an interpretation in terms of shell quenching in spherical nuclei, rather than departure from sphericity close to the shell closure. A smaller $N = 82$ shell gap has also been inferred from the β decay of ^{130}Cd [18], which would effectively result in longer theoretical half-lives of the waiting-point nuclei below ^{129}Ag and a better match to the solar r-process abundances near the $A \simeq 130$ peak. However, the idea of moderate deformation from beyond-mean-field calculations [19, 20] has recently been proposed as an alternative to the shell-quenching hypothesis. The excited

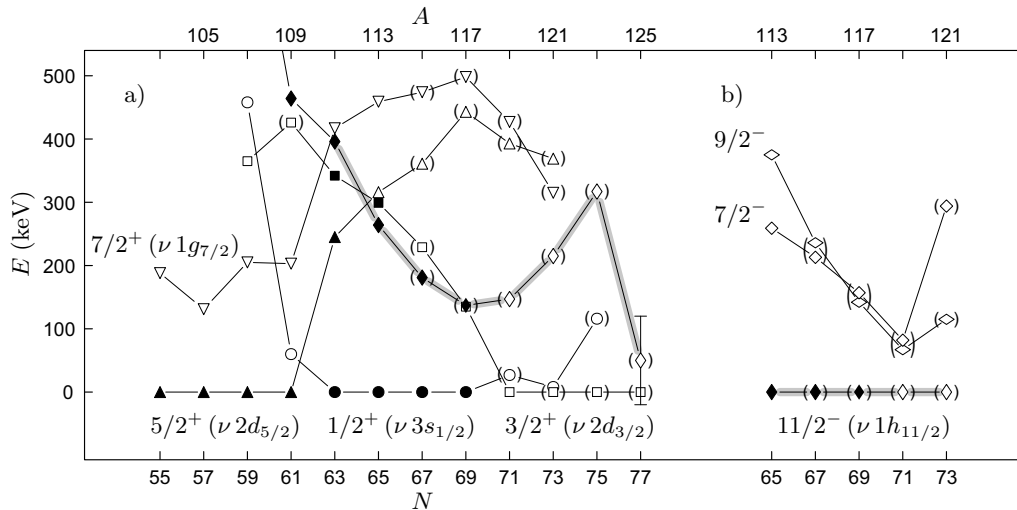


FIG. 3: Systematics of the low-lying level structure in the odd- A cadmium isotopes. Levels likely associated with the single-particle orbitals of the *sdgh* shell are shown relative to the ground state (a). “Anomalous coupling” ($J-1$ and $J-2$) collective states (b) are plotted relative to the $11/2^-$ ($\nu 1h_{11/2}$) level. Filled markers denote states with known magnetic moments. Parentheses mark levels with tentative spin assignments. Shaded lines represent the long-lived isomeric states. With the exception of ^{111}Cd , whose isomer undergoes a γ decay, the others disintegrate via β decay. Data have been compiled according to Refs. [14, 21].

states of ^{130}Cd [17] provide further evidence for a large shell gap. The measurements of $B(E2)$ values do not yet span the entire shell. Apart from preliminary ideas, based to a great extent on energy levels, the deformation of the exotic isotopes is still an open question. Clearly, the scarcity of experimental data has to be overcome before building a coherent picture of this interesting region. The evolution of the nuclear shape along the cadmium chain and certainly the transition to sphericity at ^{130}Cd would be detectable in the mean-square charge-radii changes from collinear laser spectroscopy.

Spins, moments and radii of the odd isotopes

Precise characterization of nuclear ground and isomeric states by laser spectroscopy is often preceded by other experimental methods. Typically, the initial information on exotic odd-mass nuclei is obtained from β -decay work. In the absence of other experimental data, properties are often assumed according to the systematics in the well-studied isotopes near stability. The chain of cadmium has been approached similarly.

Levels likely associated with the single-particle orbitals of the *sdgh* shell between the 50 and 82 neutron shell closures, are plotted in Fig. 3 (a). From the perspective for laser spectroscopy, two key observations are to be made on that figure. First, spin assignments for the ground states of the neutron-rich isotopes above ^{119}Cd are tentative (in parentheses). On the opposite side, the last firm assignment belongs to ^{103}Cd . It is important to re-emphasize that the initial measurements by laser spectroscopy [13] did not have the resolving power for determining nuclear spins. Second, nuclear moments (filled markers) are essentially not known away from stability. Clearly, high-resolution laser spectroscopy would remedy this, since it can unambiguously conclude on the ground-state spins in the entire shell as they alter from $5/2$ to $1/2$ and $3/2$, possibly $7/2$ and $11/2$, in close relation with the

corresponding single-particle orbitals. Magnetic and quadrupole moments derived from the same measurements would shed light on the composition of the wave functions, the single-particle or collective nature of the ground states and directly probe their deformation.

An important feature of the neutron-rich odd- A cadmium isotopes is the $11/2^-$ level which occurs at an energy lower than the $5/2^+$ and $7/2^+$ states. As it would not undergo a γ decay to the $1/2^+$ or $3/2^+$ states below, it disintegrates via β decay with a lifetime similar to the one of the ground state. An exception is ^{111}Cd , whose isomer γ -decays to the $5/2^+$ level below as the two get inverted towards the lighter isotopes. Ground states and long-lived isomers (shaded lines in Fig. 3) of cadmium are well produced at ISOLDE (Fig. 4), which opens up the possibility to study both in the heavier isotopes. Furthermore, next to the classical observables - spins, moments and isotope shifts, one would also get access to the isomer shifts, and in such way detect changes in the degree of collectivity between the long-lived states, not only from their quadrupole moments, but through their rms charge radii as well. Finally, laser spectroscopy would determine if the β -decaying isomer configuration in all isotopes is $11/2^-$ or, alternatively, if it is replaced by one of the competing $7/2^-$ or $9/2^-$ states in Fig. 3 (b). The negative-parity levels in ^{109}Cd have been treated successfully with the interacting boson model [22]. One more intuitive description [23] is within the particle plus rotor model, according to which these collective states arise from Coriolis coupling to an axially-symmetric core with $K^\pi = 7/2^-, 9/2^-$ and $11/2^-$, associated with oblate deformation. This is consistent with the $11/2^-$ quadrupole moments of $^{107-115}\text{Cd}$ [21], which for $I = K$ correspond to an oblate deformation in the range $-0.13 \leq \beta \leq -0.07$. The deformation parameter of the $5/2^+$ ground states in $^{105-109}\text{Cd}$, on the other hand, is positive $0.10 \leq \beta \leq 0.16$, also deduced from their quadrupole moments. This coexistence of shapes in the low-energy spectra of the neutron-rich cadmium nuclei will be followed and the results expected to be of considerable interest.

In summary, we propose to study the *sdgh* shell by collinear laser spectroscopy of the isotopes of cadmium and derive model-independent ground and isomeric-state properties. In such a way we will contribute to a better description and understanding of the entire region. The proposed work is also expected to be of significance for the modeling of the stellar nucleosyntheses.

EXPERIMENT

Yields

The ISOLDE yields of cadmium from laser ionization [7], as shown in Fig. 4 and Tab. I, are considerable over the entire *sdgh* shell. While this is an apparent advantage for any experimental work, the beam purity in this region is known to present problems. For cadmium there are several major sources of surface-ionized isobaric contamination: the neighboring indium isotopes, proton-rich spallation products of cesium and barium as well as molecular beams. Typically, collinear laser spectroscopy based on optical detection is relatively insensitive to contaminants, as the signal of interest consists of photons that can only originate from the studied isotope or the laser. To some extent, random collisions of the isobaric beams with the residual gas in the apparatus may generate a detectable background, but in most cases this effect is negligible. In order to study the exotic isotopes of cadmium we intend to employ the radio-frequency Paul trap of ISOLDE (ISCOOL) [28–30] for bunching the ion beam. This high-sensitivity method, on the other hand, sets a constraint on the intensity of beams that can be handled as a large amount of ions in the trap would cause them to expand into a larger volume and therefore lead to beam losses. Recent tests indicate

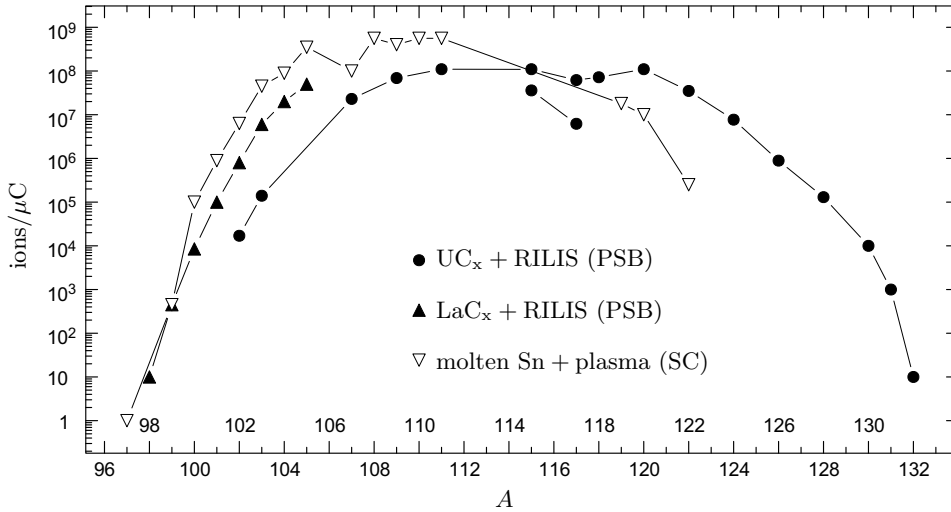


FIG. 4: Yields of cadmium ions from UC_x and LaC_x targets [24] after resonant laser ionization [7], next to SC yields from a molten Sn target with a plasma-discharge ion source [25]. The numerical data is given in Tab. I.

that beam intensities in the range of 10^5 - 10^6 ions/ μC would be acceptable. We consider here the solutions readily available in order to comply with this limit and discuss the example of $A = 130$, as perhaps, the most challenging. Highly beneficial would be the use of a quartz transfer line [5] which at a certain temperature allows the more volatile cadmium atoms to diffuse out of the target, whereas the indium contamination condenses onto its surface. Moreover, microscopic cavities in the quartz traps alkalis, in particular cesium, sufficiently long to form oxides or decay before being released. Yield measurement with quartz-line target UC338 [26] showed a suppression of ^{130}Cs down to 9.3×10^5 ions/ μC , which can be tolerated by our experiment. According to equivalent measurements with UC183, it is possible to reduce this number further by a factor of 100 with the use of a neutron converter. This would decrease the yields of cadmium by only a factor from 3 to 10. However, the latter may not be required as long as the cesium does not saturate the radio-frequency quadrupole cooler and buncher (RFQCB) of ISOLDE. Indium is on the level of a few percent from a quartz-line target and protons impinging on converter [27]. With protons on the target the indium-to-cadmium ratio would not change significantly. In all cases a reduction for indium ionization by a factor of 10 can be achieved with the use of a tantalum instead of a tungsten cavity [26]. Synchronizing a fast ion-beam gate with the pulse repetition of the laser ion source (microgating), would provide an additional suppression of surface ions. On the neutron-deficient side the beam is expected to be relatively clean in terms of our experimental method.

Experimental technique

Preliminary test measurements on $^{114}, ^{116}, ^{117}, ^{118}, ^{120}, ^{122}\text{Cd}$ [31] carried out at ISOLDE in the late 80-ies provide accurate information on the challenges associated with this experiment. We will benefit from recent technical developments which remove much of the limitations related to the beam quality and clear the way for studying the exotic cases.

Collinear laser spectroscopy on bunched beams with optical detection is a relatively un-

complicated and yet very efficient way of investigating the isotopic chain of cadmium. The beams will be accumulated in the RFQCB and then released as short bunches. The concept is outlined in Figs. 5 (a), (b) and (c). The accumulation time T_1 is selected short enough to prevent saturation of the trap and decay losses. The bunch width T_2 is a property of ISCOOL, provided that the device is not overfilled. This depends on the yield and to some extent can be controlled by the time of accumulation. By gating the optical detection (Fig. 5 (d)) on the bunched beam structure (Fig. 5 (c)) one can reduce the background from laser scattering and dark noise of the phototubes by a factor of T_2/T_1 and therefore the signal-to-noise ratio with the square root of that factor. Typical time constants are $T_1 = 100$ ms and $T_2 = 10$ μ s. As a result, this method can cope with two orders of magni-

TABLE I: ISOLDE-database yields [6] of cadmium according to Refs. [24, 25].

	$\tau_{1/2}$	ions/ μ C		
		LaC _x (PSB)	UC _x (PSB)	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/ μ C from a recent measurement with LaC_x target #387 [26].

^b to be compared to 1.3×10^4 ions/ μ C from a recent measurement with UC_x target #362 and protons on converter [27].

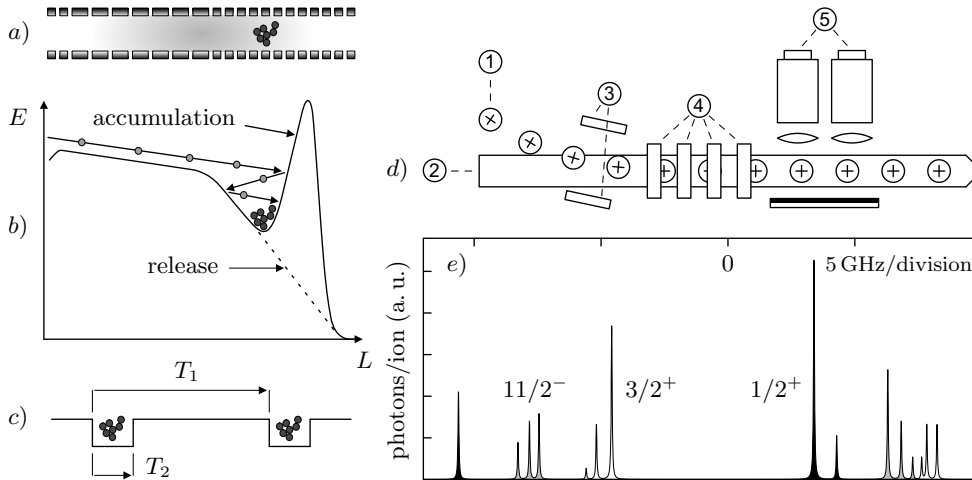


FIG. 5: Principle of the experiment: (a) bunch of ions in the buffer gas of ISCOOL, two of the four segmented rods are depicted; (b) basic concept of cooling and bunching; (c) time structure of the emerging beam; (d) sketch of the setup for collinear laser spectroscopy configured for optical detection, (1) incoming ions, (2) laser beam, (3) deflection plates, (4) post-acceleration lenses, (5) optical detection; (e) hfs in the D_2 line of the ground state and isomer in ^{111}Cd , black and gray respectively, compared with expected pattern for $I^\pi = 3/2^+$ in white (see the text).

tude lower yields than classical 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 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. Even if we are forced by overwhelming contamination to use the neutron converter and lose a factor of 10 in the cadmium yields, measurements on the nuclei in that range are still feasible.

The setup for collinear laser spectroscopy will be configured as sketched in Fig. 5 (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 [32, 33], respectively. These wavelengths will be generated by frequency doubling the output of a ring dye laser, using Stilbene 3 as an active medium, pumped with multi-line ultraviolet light from an Ar-ion laser. For enhanced sensitivity so deep in the UV spectrum we will rely on photomultiplier tubes with thin prismatic windows of fused silica (cut off at 160 nm) and bi-alkali photocathode, e.g. 9829QSA from Electron Tubes, with an excellent quantum efficiency close to 30% at the above-mentioned wavelengths. Measurements will be carried out in both transitions in order to optimize the discrimination of the nuclear spin and the sensitivity to the quadrupole moment. In addition, for some cases we consider the atomic transition $5s5p^3P_2 \rightarrow 5s6s^3S_1$ at 508.7 nm, which is more favorable for the high spin of the isomers.

Simulated hfs spectra in the D_2 line for the expected ground-state spins are depicted in Fig. 5 (e). The $1/2^+$ and $11/2^-$ configurations represent ^{111}Cd , whose magnetic moments

[21] and hyperfine parameter in the $^2S_{1/2}$ multiplet are known [34]. The ratio of the A factors in $^2P_{3/2}$ and $^2S_{1/2}$ is estimated at 3%, based on the systematics. The quadrupole splitting in the excited state is neglected due to the lack of experimental B factors. The width of the lines is approximated by the natural linewidth. Isomer shifts which are expected to be considerable, have been neglected. The $3/2^+$ magnetic moment has been substituted with the effective Schmidt value of a $d_{3/2}$ neutron. Finally, the height of the resonances has to be scaled relative to the yields of the different states. Fig. 5 (e) is given as representative of the capability of the method to distinguish between different spins and to resolve the moments and radii of ground and isomeric states in the isotopes of cadmium.

BEAM-TIME REQUEST

Herewith, we request **35 shifts** of radioactive beam for measuring model-independent nuclear properties in the isotopes of cadmium, namely: rms charge radii, spins, magnetic dipole and electric quadrupole moments. This study is aimed to cover 8 stable and more than 26 radioactive states in the range $100 \leq A \leq 130$ the vast majority of which has never been investigated with high-resolution laser spectroscopy. This work is aimed to be carried out as follows:

- one experiment of 8 shifts on the intense beams of $^{106-120}\text{Cd}$, using a UC_x target, RILIS and GPS;
- one experiment of 9 shifts for the neutron-deficient isotopes $^{100-105}\text{Cd}$, using a molten tin target or RILIS with a LaC_x target, HRS and ISCOOL;
- two experiments of 9 shifts each for the neutron-rich isotopes $^{121-130}\text{Cd}$, using a UC_x targets, RILIS, HRS and ISCOOL;

Considering the size of this program, 35 shifts of radioactive beam represents the minimum required for its successful completion. Taking into account the high number of stable isotopes which have to be linked to the radioactive ones, every experiment must be preceded by at least one shift of stable beam.

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