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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Decay spectroscopy of odd-Ag isotopes

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Abstract: We propose to study the odd-A isotopes ^{123,125}Cd by γ-ray spectroscopy following the β decay of ^{123,125}Ag. The experiment aims to establish level schemes and determine lifetimes of the excited states in the cadmium isotopes. The Coulomb-excitation experiments performed at REX-ISOLDE on the neutron-rich even-A Cd nuclei appear to show that these nuclei may possess some collectivity beyond that predicted by modern shell-model calculations. Beyond-mean-field calculations also predict these nuclei to be weakly deformed. These facets are surprising considering their proximity to the doubly magic ^{132}Sn. The experimental results may give a unique insight into the deformation-driving roles played by different orbits in this region. Such studies of the onset of collectivity become especially important in light of recent results showing that mid-shell Cd nuclei can no longer be classified as vibrational in nature. In order to correctly determine the B(E2) values connecting excited states with the long-lived $(11/2^-)$ isomer and the ground state, the level scheme of the nucleus of interest needs to be well known. Previous studies of the excited states in ^{123}Cd give contradictory results and do not agree even on the position of the isomer. High accuracy spectroscopy of the Cd isotopes is necessary for the completion of the study.

Requested shifts: 18 shifts, (split into 1 run over 1 year)

1 Physics case

The physics case was already discussed in the proposal for IS524 and will be shortly summarized here. The region around the doubly-magic nucleus ^{132}Sn is the focus of many efforts in both experimental and theoretical nuclear physics. This is because it is one of only two doubly-magic, medium-heavy, neutron-rich regions which are currently experimentally accessible, the second region being that around ^{78}Ni. Studies of the nuclei here, which have a rather simple structure, allow state-of-the-art shell-model interactions to be tested in detail. Reports of a possible reduction of the N=82 shell gap [1] have stimulated much recent work. Since the astrophysical r-process is expected to pass through this region, such an effect would have also an impact on the description of the $A\sim130$ peak in the solar element abundances. However, isomeric-decay data concerning ^{130}Cd seem to show that it appears to be a normal shell-model nucleus, without any signature of shell quenching [2]. Furthermore, mass measurements from ISOLTRAP [3] have also now removed the previous divergence between the expected mass trends and earlier experimental values, which was also cited as possible evidence of shell quenching in the past. Some questions still remain in this region, notably regarding the amount of collectivity in the Cd isotopes and a proposed weakening of the strength of nucleon-nucleon forces [4]. At REX-ISOLDE, the neutron-rich even-A isotopes ^{122,124,126,128}Cd have been successfully studied with γ-ray spectroscopy following safe Coulomb excitation (IS411 and IS477) [5, 6]. Values of $B(E2;0^+ \rightarrow 2^+)$=22.7(10), 18.8(17) and 11.9(6) W.u. (Weisskopf units) were obtained for ^{122,124,126}Cd, respectively. Such transition rates are not well reproduced by modern shell-model calculations using realistic effective interactions [7]. The calculations predict values of $B(E2;0^+ \rightarrow 2^+)$= 12.7 and 9.6 W.u. for ^{124,126}Cd, respectively, which are $\sim$30 % lower than the experimental values. A recent measurement of the quadrupole deformation in odd-Cd isotopes via laser spectroscopy at COLLAPS [8] is also in agreement with the small quadrupole moments determined for ^{122,124,126}Cd in the Coulex experiment. The large $B(E2)$ values seem to show that either some additional collectivity is present in the nuclei ^{124,126}Cd beyond that predicted by the shell model, or there are some problems with the shell-model interactions. Such discrepancies are surprising due to the relatively small number of valence holes with respect to ^{132}Sn. In order to ascertain how collectivity may arise in the hole-hole nuclei it is essential to study the odd-A nuclei, where the roles played by different orbitals can be determined. The cadmium nuclei are particularly well suited to such examinations as they have essentially two sets of accessible neutron states; low-lying, low-spin positive parity levels, which can be populated by Coulomb excitation from the $3/2^+$ ground states (strong $\nu d_{3/2}$ component), and low-lying $11/2^-$ isomeric states with half-lives of a few seconds, allowing the population of intermediate-spin levels. These isomeric states have a dominant $\nu h_{11/2}$ configuration and as these orbits are calculated as being down-sloping (deformation-driving) beyond N=78 or 76 (depending if the deformation is prolate or oblate respectively) [9] they may play an important role in generating collective behavior in these nuclei. Indeed, a recent theoretical study of the unusually low energy of the 2^+ state of ^{128}Cd, using beyond-mean-field calculations [9, 10], has proposed that instead of shell-gap quenching in a spherical nucleus, a pronounced prolate minimum is obtained for this nucleus. The even A=110-116 cadmium nuclei are often thought of classic cases of spherical vibrational nuclei containing multi-phonon excitations

which has recently been brought into question [11, 12].
Experimentally, much less is known about the neutron-rich odd-A Cd isotopes than their even-A counterparts. The nucleus ^{123}Cd was previously investigated following the β decay of ^{123}Ag [13] and in the prompt-fission of ^{252}Cf [14]. The partial level schemes are shown in Fig. 1. Huck et al. [13] compared the excited states of the odd-A $^{115-123}$Cd isotopes to a BCS-pairing plus proton-neutron interaction calculations. In order to reproduce the

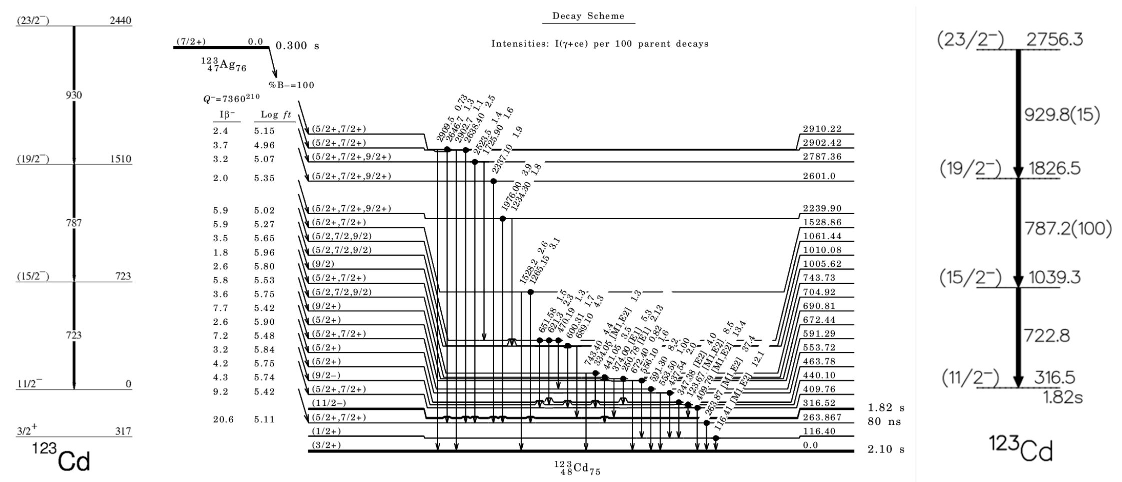

Figure 1: Partial level schemes of ^{123}Cd [4, 13, 14].

level schemes correctly the pairing force had to be increased for the $h_{11/2}$ orbit. This pairing enhancement was thought to arise from contribution of the quadrupole particle-hole neutron interaction, again pointing towards possible deformation in these nuclei. It should also be noted that a 80 ns state at 264 keV was observed in ^{123}Cd with a likely spin of $5/2^+$ or $7/2^+$ [13]. However, their calculation was unable to reproduce such a state as all levels with these possible spins were predicted to be above 1 MeV.
In May 2012 the nucleus ^{123}Cd was successfully studied in a Coulomb excitation experiment (IS524) at REX-ISOLDE [15] where the question of the evolution of collectivity in the odd-A cadmium isotopes was addressed. Only the measurement of the ^{123}Cd nucleus was approved by the INTC because the level scheme of the excited states was assumed to be well-known. In Fig. 2 the projectile Doppler-corrected spectrum from this measurement is shown. The low beam energy available at REX-ISOLDE hardly allows for multistep excitation. Therefore, most of the observed transitions correspond to one-step excitations either from the ground state or the $11/2^-$ isomer. However, low statistics γ-γ coincidences could be observed. The experimental findings differ from the known scheme given in Huck at al. [13]. During the IS524 experiment an attempt was made to assign the γ rays to states above the ground or isomeric state of ^{123}Cd by applying selective ionization. Because of the limited beam time approved for this test, only a scan with a broad-band laser was performed. In Fig. 3 the prompt γ-particle coincident spectra for two different laser settings are shown. The spectra are Doppler corrected and normalized to the target excitation. From the change in the intensity of the 116 keV transition, which depopulates the first excited state, it is obvious that the amount of g.s.-Cd is different in the two settings. From the previously observed γ rays (see Fig. 1), the multiplet structure around 660 keV could contain two transitions at 651 keV and 672 keV. As no transition

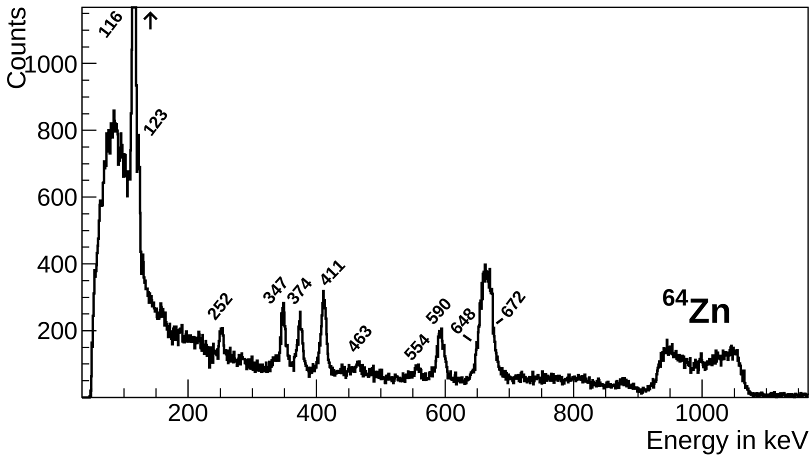

Figure 2: Projectile Doppler- and efficiency-corrected γ-ray spectrum from the IS524 experiment (Coulex of ^{123}Cd on a ^{64}Zn target).

at 470 keV or 621 keV is seen, and assuming that the level scheme reported by Huck et al. is correct, one can deduce that the state at 1061 keV is not populated and no transition at 651 keV is present. Therefore, the structure, which apparently consists of more than one transition, should contain besides the 672 keV line also unknown ones. This is proven by the fact that the shape of the structure changes in the different laser settings. The 672 keV transition is reduced similar to the 347 and 411 keV (both above the g.s.). The remaining transition(s) could be assigned to the excitation of the states above the isomer. The transition at 374 keV (marked as ?) was previously assigned to a decay feeding the

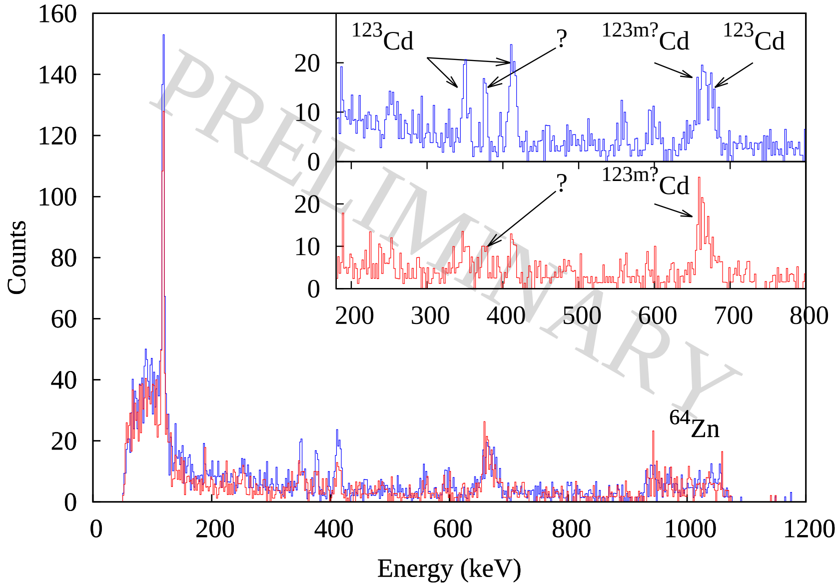

Figure 3: Projectile Doppler-corrected γ-ray spectra after an attempt for selective ionization of the beam with a broad-band laser at two different laser settings (blue and red spectra).

isomer, but here it has an intensity consistent with a decay to the ground state. A recent direct measurement of the mass of the ground and isomeric states in ^{123}Cd by Kankainen et al. [16] gives an energy for the isomer of 144 keV which is also in disagreement with

the literature value of 316.5 keV. In conclusion, these experimental observations show the necessity to examine the level scheme of ^{123}Cd again.
The nucleus ^{125}Cd has been studied in several μs-isomer experiments following fission or fragmentation of uranium [4, 7, 17, 18], (only γ-rays reported in [19, 20]). The observation of some of the reported γ-ray transitions is not consistent in [4, 17] and there seem to actually be two isomers in this nucleus, as explained in [17]. Only excited states built on the $(11/2^-)$ isomer are known. The relative order of the sequence of the transitions at 719 keV and 743 keV cannot be deduced from the experimental data. The excitation energy of the isomeric state, deduced from the β endpoint energy [21] is only poorly known to be 50(70) keV and it could feasibly be the ground state.
A further peculiarity of the neutron-rich, odd-A Cd nuclei is the disappearance of the $19/2^+$ μs isomer in ^{123}Cd, when moving away from N=82. The reason why this isomer is absent in ^{123}Cd is not clear, but one explanation would be that the $19/2^-_1$ state lies below the $19/2^+$ isomer, eliminating the spin trap. This isomeric state has been reported for ^{125,127}Cd [17, 18, 22]. The sudden appearance of isomers in ^{125,127}Cd was proposed to be due to a weakening of the neutron-neutron interaction strength when going beyond N=76 [4], similar to the interpretation proposed in [1]. If this hypothesis is true then there should be an abrupt difference in the structure of ^{123}Cd and ^{125}Cd. The absence of the $19/2^+$ isomer in ^{123}Cd remains an intriguing question to which there is no simple answer without more experimental evidence. New data from a β-decay of ^{123}Ag and ^{125}Ag combined with the results from the Coulomb excitation experiment give an excellent opportunity to solve this puzzle.

2 Experimental setup

For the measurement, the newly installed decay station (IDS) at ISOLDE will be used which offers ideal conditions decay spectroscopy. It is equipped with four Ge Clover detectors and four $LaBr_3$(Ce) fast scintillators. The nuclei will be implanted on a movable tape. Coincident γ rays will be measured and the decay patterns in Cd and In nuclei can be determined. In addition, lifetimes of excited states in the nanosecond and subnanosecond range can be determined with the fast scintillators using the generalized centroid difference method [23].

3 Rate estimate and beam time request

The isotopes are produced with a standard UC_x/graphite target irradiated with the proton beam from the PS Booster with the use of RILIS for ionization. The ions from ISOLDE are delivered to the experimental setup. The expected yields are $10^4/\mu$C for ^{123}Ag and $10^2/\mu$C for ^{125}Ag. With the total efficiency of the Clover detectors of 4 % a rate of γ-γ coincidences of 5/min and 70/day for a state with 1 % feeding for the ^{123}Cd and ^{125}Cd is expected. The efficiency of the four $LaBr_3$(Ce) detectors at 10 cm distance is ~0.5 % at 500 keV. Therefore, for a lifetime measurement of a state populated by a transition with 5 % feeding in ^{123}Cd one needs 2 days. In ^{125}Cd, subnanosecond lifetimes only for states with more than 50 % feeding can be determined within a reasonable beamtime of 3 days.

Therefore we ask for 7 shifts for the measurement with ^{123}Ag beam, 9 shifts with ^{125}Ag beam and 2 shift to prepare the beams.
Summary of requested shifts: In total we request **18** shifts (**6** days).

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: (*name the fixed-ISOLDE installations, as well as flexible elements of the experiment*)

Part of the	Availability	Design and manufacturing
IDS	☒ Existing	☒ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[Part 2 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed [COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH] installation.

Additional hazards:

Hazards	[Part 1 of experiment/ equipment]	[Part 2 of experiment/ equipment]	[Part 3 of experiment/ equipment]
Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum			
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]		
Static electricity			
Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		

Ionizing radiation			
Target material [material]			
Beam particle type (e, p, ions, etc)			
Beam intensity			
Beam energy			
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☐ [ISO standard]		
• Isotope			
• Activity			
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300 MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chem. agent], [quant.]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chem. agent], [quant.]		
Corrosive	[chem. agent], [quant.]		
Irritant	[chem. agent], [quant.]		
Flammable	[chem. agent], [quant.]		
Oxidizing	[chem. agent], [quant.]		
Explosiveness	[chem. agent], [quant.]		
Asphyxiant	[chem. agent], [quant.]		
Dangerous for the environment	[chem. agent], [quant.]		
Mechanical			

Physical impact or mechanical energy (moving parts)	[location]		
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			
Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): [make a rough estimate of the total power consumption of the additional equipment used in the experiment]