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Quadrupole collectivity in neutron-rich Cd isotopes

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Abstract. The proximity to the closed shells at $Z = 50$ and $N = 82$ makes the neutron-rich Cd isotopes a perfect test case for nuclear theories. The energy of the first excited 2^+-state in the even $^{122-128}$Cd shows an irregular behaviour as the Cd isotopes exhibit only a slight increase for ^{122}Cd to ^{126}Cd and even a decrease from ^{126}Cd to ^{128}Cd. This anomaly can so far not be reproduced by shell model calculations. Only beyond mean field calculations with a resultant prolate deformation are capable to describe this anomalous behaviour. In order to gain more information about the neutron-rich Cd isotopes a Coulomb excitation experiment was performed with MINIBALL at REX-ISOLDE, CERN. The extracted transition strengths $\mathrm{B}\left(E2, 0^+_{gs} \rightarrow 2^+_1\right)$ for ^{122,124,126,128}Cd agree with beyond mean field calculations. The spectroscopic quadrupole moments $Q_s\left(2^+_1\right)$ are compared with measurements on odd neutron-rich Cd isotopes.

1. Motivation

The neutron-rich Cd isotopes provide a perfect test for nuclear theory, as they are only two protons away from the shell closure at $Z = 50$ and close to the $N = 82$ magic number. Already twenty years ago a quenching of the shell gap at $N = 82$ has been proposed by Dobaczewski et al. [1]. However, the astrophysical r-process path is expected to pass this region with the waiting-point nucleus ^{130}Cd. Experimental investigations of this semi-magic nucleus found a high Q_β value of ^{130}Cd which supports the idea of a shell gap reduction [2], whereas information on the isomeric decay found no evidence of a total shell quenching [3]. However, the solar abundance peak at $A \approx 130$ is better described including a quenching of the shell gap at $N = 82$ [4]. Such an effect should be reflected in lowered excitation energies and an enhanced transition strength.

The excitation energy of the first excited 2^+-state in the neutron-rich Cd isotopes show an irregular behaviour. The rise towards the $N = 82$ shell closure is not as steep as expected from comparison to the isotones Ba, Te, Xe and Pd, and even decreases from ^{126}Cd ($\mathrm{E}(2^+_1) = 652$ keV [5]) to ^{128}Cd ($\mathrm{E}(2^+_1) = 645$ keV [5, 6]). The 2^+_1 energy for ^{128}Cd lies lower than for both the isotones $^{132}_{52}$Te ($\mathrm{E}(2^+_1) = 974$ keV [7]) with two protons above $Z = 50$ and $^{126}_{46}$Pd ($\mathrm{E}(2^+_1) = 974$ keV [8]) with two protons less than $^{128}_{48}$Cd. This anomaly is so far not explained by shell model calculations. Nevertheless, beyond mean field calculations are able to reproduce these findings with a resultant prolate deformation for ^{122,124,126,128}Cd.

The cross section for a Coulomb excitation depends on the transitional and diagonal matrix elements of the nuclear states involved in the excitation process. These matrix elements can be used to determine the transition strength $\mathrm{B}\left(E2, 0^+_{gs} \rightarrow 2^+_1\right)$ and the spectroscopic quadrupole moment $Q_s\left(2_1^+\right)$ of a nucleus. In order to shed light into the region around doubly-magic ^{132}Sn a Coulomb excitation experiment was performed at the REX-ISOLDE facility located at CERN.

2. Experimental setup and data analysis

At REX-ISOLDE the radioactive ion beams are produced with the ISOL (Isotope Separation OnLine)-technique. Every $n \times 1.2$ s a pulsed 1.4 GeV proton beam from the PS-BOOSTER hits a primary target (in this case UC$_x$), which undergoes fission. The products diffuse through the target and a transfer line into an ion source, where the beam is purified by a selective multistep laser ionisation with the resonant ionisation laser ion source (RILIS). Subsequently the beam is extracted into the beam line and a mass separation is applied. After cooling, bunching, charge breeding and a second mass separation (A/q $\approx$ 4.3) the beam containing the Cd isotopes was further accelerated to 2.8 MeV/u and delivered to the experimental area, where it hits a secondary target. This was chosen to be ^{108}Pd for ^{122}Cd, ^{104}Pd for ^{124}Cd and ^{64}Zn for ^{124,126,128}Cd. The beam energy is considered "safe" for each of the used beam/target combinations, as it is always much below the safe energy. This ensures the nuclear interaction being small and therefore the nuclear potential can be neglected. The average intensity of the beam was between $10^3 - 10^4$ pps. In the scattering process both target and projectile nuclei interact electromagnetically and get excited. The deexcitation γ-rays are detected with the MINIBALL detector array [9]. It consists of eight high purity Germanium triple cluster detectors, each being 6-fold electronically segmented. The array has an efficiency of ~ 7 % at 1.3 MeV. The deexcitation γ-rays are emitted in-flight, which leads to a Doppler shift of their energy. To correct for this effect the angular information of the scattered particles, which is obtained with a double-sided silicon strip detector (DSSSD) [10] with a 16-fold segmentation in θ and 12-fold segmentation in ϕ placed in forward direction, is used. The covered angular range in the laboratory frame was between $\theta_{Lab} \approx 16° - 53°$. Note, that the beam delivered to the secondary target often is not completely pure as it contains impurifications from the production of the beam and from β-decay of the beam particles (*i.e.* indium in the case of a cadmium beam). For the experiments with ^{122,124,128}Cd surface ionised isobaric Cs was present. In the measurement of ^{126}Cd and for parts of ^{124}Cd a quartz transfer line was used, which reduced the Cs contamination to a negligible amount. In the measurement of ^{122,124,126}Cd the deexcitation γ-ray spectrum obtained in the period when the RILIS laser was turned off can be subtracted from the γ-ray spectrum when the laser was turned on. During the laser off period no transitions in Cd are visible in the γ-ray spectra. Therefore the surface ionised Cs as well as the isobaric contaminant In are eliminated [11]. In the ^{128}Cd experiment the Cs contamination was not constant over the time of the measurement and could only be subtracted from the spectra by applying time gates. A gate on late times T (1300 ms $\leq$ T $\leq$ 2300 ms) after proton pulse impact reveals only contributions to the γ-ray spectra from the Cs contamination. Subtracting this from the γ-ray spectrum with a gate set on early times T (200 ms $\leq$ T $\leq$ 1200 ms) after proton pulse impact cancels the Cs contaminant. The isobaric In contamination from the decay of Cd and directly from ISOLDE can be deduced also from the γ-ray spectrum after β-decay. Therefore the beams of ^{124,126,128}Cd were stopped in a thick target and the γ-rays detected. The relative amount of each isotope is extracted by simultaneously fitting it and the efficiency to the γ-ray yields after β-decay. In the case of ^{128}Cd the relative intensities for the γ-ray transitions in ^{128}In and ^{128}Sn were determined. A deviation from literature for transitions in ^{128}Sn was found [12]. In all the experiments a contamination of the 8^- isomeric state of In was present in the beam, which had to be taken into account. The relative amount of Cd for the different experiments are displayed in table 1.

The prompt Doppler-corrected γ-ray spectra show the expected deexcitation of the 2_1^+ state of the used target and the investigated Cd nucleus. Note, that in the case of ^{128}Cd the deexcitation peak at 645 keV proofs the 2_1^+ state of ^{128}Cd being at this energy, which was not clear before.

Table 1. Beam purity and contaminating nuclei for each experiment. ^{122,124,126}Cd see: [11], ^{128}Cd see: [13].

Experiment	$\mathcal{P}$ [%]	Isobaric contaminant
^{122}Cd on ^{108}Pd	58(1)	Cs, In, ^{m}In
^{124}Cd on ^{104}Pd	18(1)	Cs, In, ^{m}In
^{124}Cd on ^{64}Zn (use of quartz transfer line)	79(4)	In, ^{m}In
^{126}Cd on ^{64}Zn (use of quartz transfer line)	45(1)	In, ^{m}In
^{128}Cd on ^{64}Zn	47	Cs, In, ^{m}In

For the experiments with ^{126}Cd and ^{128}Cd an additional Doppler corrected peak at 243 keV and 324 keV, respectively, is visible. This stems out of the excitation of the isobaric beam contaminant In [11, 13].

The Coulomb excitation cross section of the projectile nucleus σ^{proj} can be determined with the information from the obtained γ-ray spectrum

$$\sigma^{proj} = \frac{1}{\mathcal{P}} \frac{N_\gamma^{proj}}{\varepsilon_\gamma^{proj}} \left(\frac{N_\gamma^{targ}}{\varepsilon_\gamma^{targ}} \right)^{-1} \cdot \sigma^{targ}, \tag{1}$$

with N_γ^i being the γ-ray yield of the projectile/target excitation, respectively, ε_γ^i is the efficiency of the MINIBALL detectors obtained with a ^{152}Eu source and σ^{targ} is the Coulomb excitation cross section for the target excitation, which can be calculated from the already known target properties. The normalisation to the target excitation is performed in order to reduce systematic uncertainties. The Coulomb excitation cross section is proportional to the matrix elements of the states involved in the excitation. For all the here discussed experiments these states are only the 0^+ ground state and the first excited 2^+ state. This leads to the important matrix elements being the reduced transitional matrix element M_{02} and the diagonal matrix element M_{22}

$$\begin{aligned} M_{02} &= \langle\, 0^+_{gs} \parallel \mathcal{M}(E2) \parallel 2^+_1 \rangle, \\ M_{22} &= \langle\, 2^+_1 \parallel \mathcal{M}(E2) \parallel 2^+_1 \rangle, \end{aligned} \tag{2}$$

with $\mathcal{M}(E2)$ being the electric quadrupole operator. Varying these matrix elements in the input for the programs CLX/DCY until the cross section reproduces the experimentally found one gives sets for possible combinations of (M_{02}, M_{22}). Because the cross section exhibits a different sensitivity to the matrix elements at different angles, a division of the scattered particles into distinct center of mass angular ranges restricts the possible combinations of the matrix elements. By performing a maximum likelihood analysis the transition strength

$$B\left(E\lambda, I_i \rightarrow I_f\right) = \frac{1}{2I_i+1} \left|\langle I_i \parallel \mathcal{M}\left(E\lambda\right) \parallel I_f \rangle\right|^2 \tag{3}$$

and the spectroscopic quadrupole moment

$$eQ_s(I) = \sqrt{\frac{16\pi}{5\left(2I+1\right)}} < II20|II > \langle I \parallel \mathcal{M}(E2) \parallel I \rangle \tag{4}$$

can be extracted.

3. Results, discussion and outlook

The reduced transition strength $\mathrm{B}\left(E2, 0^+_{gs} \rightarrow 2^+_1\right)$ has been determined in Coulomb excitation experiments at REX-ISOLDE for the nuclei ^{122,124,126,128}Cd [11, 13]. The values seem to follow the beyond mean field predictions rather than the shell model calculations, where the configuration space is based on a ^{78}Ni core. The proton orbits $\pi\left(1f_{5/2}, 1g_{9/2}, 2p_{1/2}, 2p_{3/2}\right)$ and the neutron orbits $\nu\left(1g_{7/2}, 1h_{11/2}, 2d_{3/2}, 2d_{5/2}, 3s_{1/2}\right)$ were included. In a laser spectroscopy measurement of odd neutron-rich Cd isotopes at COLLAPS [14] small quadrupole moments for the ground state were found. The small spectroscopic quadrupole moments for ^{122,124,126}Cd follow this trend.

Additional information from direct lifetime measurements provide a further constraint on the transitional matrix element. This could already be included in the analysis of ^{122}Cd and ^{126}Cd. However, for ^{124}Cd and ^{128}Cd these information are not available so far. The lifetime of the first excited 2^+ state in these nuclei coud be investigated in the future with a plunger measurement at HIE-ISOLDE [15]. A high source of uncertainty is the lack of statistics in the γ-ray spectrum for such highly exotic beams. The upgrade of ISOLDE to HIE-ISOLDE will in the future provide beams of highly exotic nuclei with a higher intensity and energy to increase the γ-ray yield in the deexcitation spectrum.

To answer the question of which orbitals contribute to the collectivity a campaign to measure the odd Cd isotopes via Coulomb excitation has been started at REX-ISOLDE. In these nuclei the low-lying, high-spin states are accessible via the isomeric $\frac{11}{2}^-$ state, whereas the low-lying, low-spin states can be populated from the $\frac{3}{2}^+$ ground state. ISOLDE provides a beam containing the ground as well as the isomeric state of these nuclei, whose relative amount can be varied with the RILIS. A first successful investigation of ^{123}Cd has been performed already [16].

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