Observation of Isomeric Decays in the *r*-Process Waiting-Point Nucleus $^{130}Cd_{82}$

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The γ decay of excited states in the waiting-point nucleus $^{130}Cd_{82}$ has been observed for the first time. An 8^+ two-quasiparticle isomer has been populated both in the fragmentation of a ^{136}Xe beam as well as in projectile fission of ^{238}U, making ^{130}Cd the most neutron-rich $N = 82$ isotone for which information about excited states is available. The results, interpreted using state-of-the-art nuclear shell-model calculations, show no evidence of an $N = 82$ shell quenching at $Z = 48$. They allow us to follow nuclear isomerism throughout a full major neutron shell from $^{98}Cd_{50}$ to $^{130}Cd_{82}$ and reveal, in comparison with $^{76}Ni_{48}$ one major proton shell below, an apparently abnormal scaling of nuclear two-body interactions.

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The pioneering work of Goeppert-Mayer [1] and Haxel, Jensen, and Suess [2] in realizing that the experimental evidence for nuclear magic numbers could be explained by assuming a strong spin-orbit interaction constituted a major milestone in our understanding of the internal structure of the atomic nucleus. However, it has been recognized for more than 20 years that the single-particle ordering which underlies the shell structure (and with it the magic numbers) may change for nuclei approaching the neutron dripline. It has been argued that the neutron excess causes the central potential to become diffuse, leading to a modification of the single-particle spectrum of neutron-dripline nuclei [3,4]. In addition, a strong interaction between the energetically bound orbitals and the continuum also affects the level ordering. The consequence of these modifications can be a shell quenching; i.e., the shell gaps at magic neutron numbers are less pronounced in very neutron-rich nuclei than in nuclei closer to stability. At the extreme, these gaps may even disappear. Alternatively, the tensor part of the nuclear force has been shown to cause shell reordering for very asymmetric proton and neutron numbers [5,6].

The $N = 82$ isotones below the doubly magic nucleus ^{132}Sn are crucial for stellar nucleosynthesis due to the close relation between the $N = 82$ shell closure and the $A \approx 130$ peak of the solar *r*-process abundance distribution. Based on the mass models available at that time, it was shown in the 1990s that the assumption of a quenching of the $N = 82$ neutron shell closure leads to a considerable improvement in the global abundance fit in *r*-process calculations [7,8], in particular, a filling of the troughs around $A \approx 120$ and 140. On the other hand, recently, alternative descriptions of the phenomenon have been given without invoking shell quenching at all [9,10]. Unfortunately, the very neutron-rich $N = 82$ waiting-point nuclei are still out of reach experimentally. However, recent spectroscopic observations in nuclei close to ^{132}Sn have been interpreted as the first experimental evidence of a quenching of the $N = 82$ shell closure in ^{130}Cd [11,12], much closer to ^{132}Sn than predicted by any calculation. One such observation concerns the low excitation energy of 957 keV tentatively proposed for the 2^+ state of this nucleus [11].

In this Letter, we present the identification of an isomeric decay in ^{130}Cd, representing the most neutron-rich $N = 82$ waiting-point nucleus in which γ-ray transitions have been observed to date. The results present the most direct information with respect to any possible modification of the $N = 82$ shell gap close to ^{132}Sn.

Isomer spectroscopy was performed to search for an $I^\pi = 8^+$ isomer in ^{130}Cd. Such an isomeric state, based on a maximally aligned pair of proton holes in the $g_{9/2}$ orbit, was expected to exist in this nucleus in analogy to the 8^+ isomer observed in the valence analog Cd isotope ^{98}Cd$_{50}$ [13]. The experiment was performed at the Gesellschaft für Schwerionenforschung (GSI), Darmstadt, Germany. In the first part, ^{130}Cd was produced via 6-proton knockout from a ^{136}Xe projectile accelerated to 750 MeV/u by the SIS-18 synchrotron and impinging on a 4 g/cm^2 Be target. In the second part of the experiment, ^{130}Cd ions were produced using projectile fission of a ^{238}U beam at an energy of 650 MeV/u and a 1 g/cm^2 Be target. They were separated from other reaction products and identified ion by ion in the GSI fragment separator (FRS) [14] via the measurement of the energy loss, the magnetic rigidity, the positions in the intermediate and the final focal plane, and the time of flight in the second half of the FRS. Figure 1 illustrates the identification of the different Cd isotopes.

The fraction of the nuclei implanted in an excited isomeric state in a passive stopper at the spectrometer focal point was 10%–20% of the total population. These isomeric states then decay to the ground state by γ-ray emission. These γ rays were detected by 15 large volume Ge cluster detectors [15] from the former EUROBALL [16] spectrometer arranged in close geometry around the stopper. With the requirement of a delayed coincidence relationship between the implanted ion and the detected γ ray, the radiation can be unequivocally assigned to the decay of an isomeric state of a particular isotope. It should be stressed that only the unprecedented high gamma detection efficiency and granularity of the Ge array [17] available within the rare isotope spectroscopic investigation at GSI experimental campaign, in conjunction with the clean identification after fragmentation reactions at relativistic energies, allowed for the first time observation of isomeric decays in ^{130}Cd despite its very low production cross section.

The data for ^{130}Cd obtained from the two parts of the experiment have been combined. Figure 2 (top row) shows the spectrum of γ rays observed in delayed coincidence with a total of about 6300 identified and implanted ^{130}Cd ions. In this spectrum, four transitions are clearly observed with energies of 128, 138, 539, and 1325 keV, respectively.

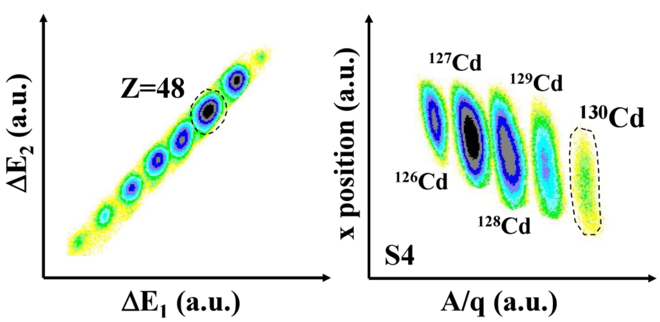

FIG. 1 (color online). Example of particle identification plots from the fragmentation of ^{136}Xe. Left: Z identification from the energy losses measured in two multiple sampling ionization chamber ionization chambers. Right: Isotope identification from the positions of the Cd ions in the final focal plane S4 of the FRS shown as a function of A/Q.

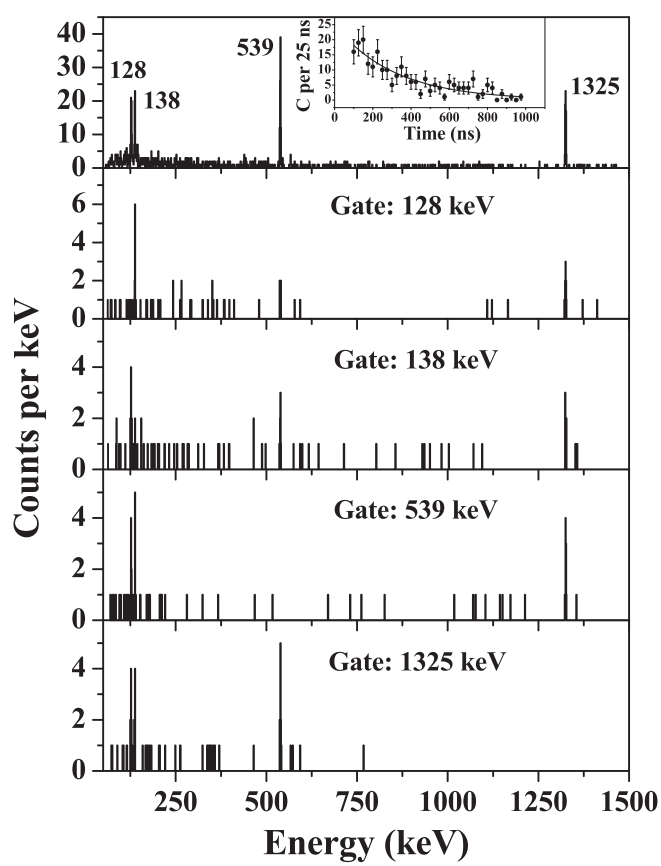

FIG. 2. Delayed γ-ray spectrum (75 ns–1 μs) in coincidence with identified ^{130}Cd ions implanted in the stopper. The inset shows the time distribution between the ion implantation and the detection of one of the four γ rays. The lower panels show the γ spectra observed in coincidence with the 128, 138, 539, and 1325 keV transitions, respectively.

TABLE I. Energy, half-life, relative intensity, and experimental and theoretical conversion coefficient for the transitions observed in delayed coincidence with implanted ^{130}Cd ions.

E_γ (keV)	$T_{1/2}$ (ns)	I_{rel}	α_{exp}	α_{theo} $E1$	α_{theo} $M1$	α_{theo} $E2$
128	216(48)	2.06(26)	0.63(26)	0.08	0.23	0.62
138	216(48)	2.16(27)	0.56(25)	0.07	0.19	0.48
539	214(33)	3.21(43)	...	...	...	...
1325	186(29)	3.62(56)	...	...	...	...

Since all of these transitions are observed in mutual coincidence as evidenced by the coincidence spectra included in Fig. 2, we may assume that they form a single cascade from one isomeric state to the ground state. Assuming that the transitions within the cascade have identical intensities, the missing gamma yield for the two low-energy transitions can be attributed to internal conversion. In Table I, we summarize the observed relative intensities of the four transitions and compare the experimental conversion coefficients for the 128 and 138 keV transitions with the theoretical ones for $E1$, $M1$, and $E2$ multipolarity. From this comparison, we conclude that $E2$ character is the most probable assignment for the two low-energy transitions.

In the $N = 50$ isotope ^{98}Cd$_{50}$ [13], the transition energies in the $E2$ cascade from the maximally aligned 8^+ isomeric state to the antialigned 0^+ ground state are 147, 198, 688, and 1395 keV. We therefore assign the 1325 keV transition as the ground state transition and the 539 keV line as the $4^+ \to 2^+$ transition. The 128 and 138 keV γ rays form the $8^+ \to 6^+ \to 4^+$ sequence. Their order cannot be firmly established because their energies are so similar. The time distributions of the four transitions have been fitted separately with a single exponential decay. The resulting half-life values agree within their statistical uncertainties (see Table I). Assuming pure $\pi(g_{9/2})^{-2}$ configurations for the 2^+ to 8^+ states, the 6^+ state is expected to be an isomer with a nanosecond half-life, too. Unfortunately, the low statistics of the observed time distributions do not allow an independent determination of $T_{1/2}(6^+)$. We therefore deduced a single decay time of $T_{1/2} = 220(30)$ ns by performing a least-squares fit to the summed time spectra of all four transitions shown in the inset in Fig. 2. In ^{98}Cd, a 12^+ isomeric state has been observed feeding the 8^+ isomer [18]. We cannot exclude the existence of such a second, higher-lying isomer in ^{130}Cd.

Our experimental results are not consistent with the previous tentative assignment [11] of a 2^+ state at 957 keV in ^{130}Cd. In Fig. 3, the new level scheme for ^{130}Cd is compared to two different nuclear shell-model (SM) calculations based on a ^{88}Sr$_{50}$ core and G-matrix realistic interactions derived for different model spaces from a CD-Bonn nucleon-nucleon potential [19] following the method outlined in Ref. [20]. The first, called SM-I in the following, uses a model space $p_{1/2}$, s, d, g for protons and $g_{7/2}$, s, d, $h_{11/2}$ for neutrons. This implies that excitations across the closed $Z = 50$ proton shell are included, whereas neutron excitations across the $N = 82$ shell closure are not. The effective interaction was monopole tuned to experimental data between $N = 50$ and 82 to reproduce single-particle and hole energies in ^{132}Sn [21]. It was first successfully applied to the study of the effects of ^{100}Sn core excitations in the $A = 102$–130 tin isotopes [22] and to β decay half-life predictions for $N = 82$ isotones [23]. Further details on the single-particle energies and effective operators used are given in Refs. [22–24]. The calculations were performed with the code ANTOINE [25]. The second shell-model calculation, SM-II, uses a model space $p_{1/2}$, $g_{9/2}$ for protons and, as in SM-I, $g_{7/2}$, s, d, $h_{11/2}$ for neutrons. Therefore, proton core excitations across $Z = 50$ and neutron core excitations across $N = 82$ are not considered in this approach. Starting from the G matrix for this valence space, an effective interaction was derived by applying monopole corrections to describe the evolution of experimental single-particle energies for ^{88}Sr to proton hole and neutron particle energies in ^{100}Sn as adopted from Refs. [9,26]. The interaction was found to describe both high-spin states and Gamow-Teller decay in the ^{100}Sn region very well [27]. For the ^{132}Sn region, besides $A^{-1/3}$ scaling, additional monopole corrections were applied to describe the single hole energies [9,26] in ^{132}Sn without modifying the ^{100}Sn results. For ^{130}Cd, proton and neutron effective charges of 1.5 e and 0.5 e, respectively, were used to calculate $E2$ transition strengths. Further details about these calculations, which were performed

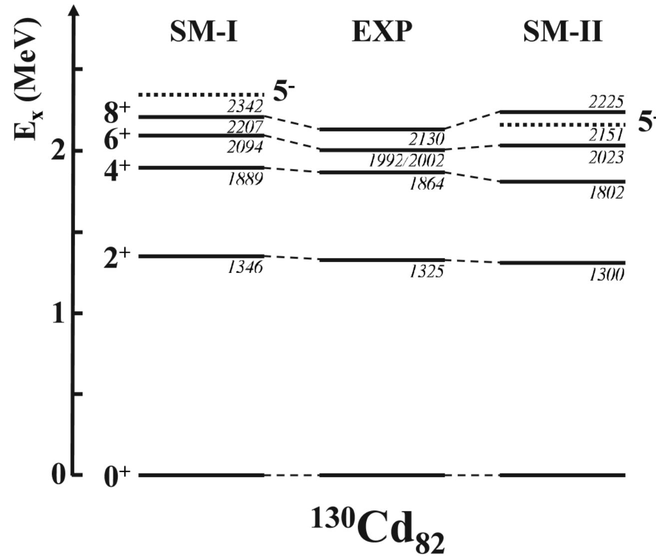

FIG. 3. Proposed level scheme of ^{130}Cd compared to two different shell-model calculations (see text for details). The isomeric 8^+ state [$T_{1/2} = 220(30)$ ns] at an excitation energy of 2130 keV is connected to the ground state via a cascade of four $E2$ transitions.

with the shell-model code OXBASH [28], are given in Ref. [27]. The calculated $B(E2)$ transition strength for the $8^+ \rightarrow 6^+$ transition, $B(E2)^{\text{SM-I}} = 1.5$ W.u. and $B(E2)^{\text{SM-II}} = 1.2$ W.u., compare well with the experimental values of 1.7(2) and 1.3(2) W.u., respectively, obtained assuming either the 128 or the 138 keV γ ray to be the $8^+ \rightarrow 6^+$ transition. Note that these values are also in good agreement with the corresponding experimental value of 1.3(4) W.u. in ^{98}Cd [18]. Since both shell-model calculations employing modern interactions describe the level sequence and the decay properties of the 8^+ isomeric state, we conclude that our new experimental results on ^{130}Cd provide no evidence for a quenching of the $N = 82$ shell closure.

We close this Letter with a stunning observation. In an empirical shell-model approach [26], the $I = 2^+ - 8^+$ levels are pure $(g_{9/2})^{-2}$ states, while the 0^+ ground state is mixed with the $(p_{1/2})^{-2}$ configuration. Our new results on ^{130}Cd, in comparison with ^{98}Cd and ^{76}Ni$_{48}$ [29], therefore allow one for the first time to extract an empirical j^2 two-body interaction, namely, for $g_{9/2}$ protons and neutrons, over a wide range of atomic mass A. Apparently, the $2^+ - 8^+$ energy spread scales with A^{-1} (as indicated by solid arrows in Fig. 4), which seems to be at variance with the common assumption [25,30] of a scaling with the harmonic oscillator quantum $\hbar\omega_0 = 41A^{-1/3}$ (indicated by dashed arrows in Fig. 4). This result should not be affected by Coulomb effects as, for $I \neq 0$, Coulomb shifts are essentially constant in this model space [31]. However, this $g_{9/2}^{-2}$ interpretation of the $2^+ - 8^+$ energy difference could be altered when extended model spaces are considered. In the first approximation, the $2^+ - 8^+$ spreading can

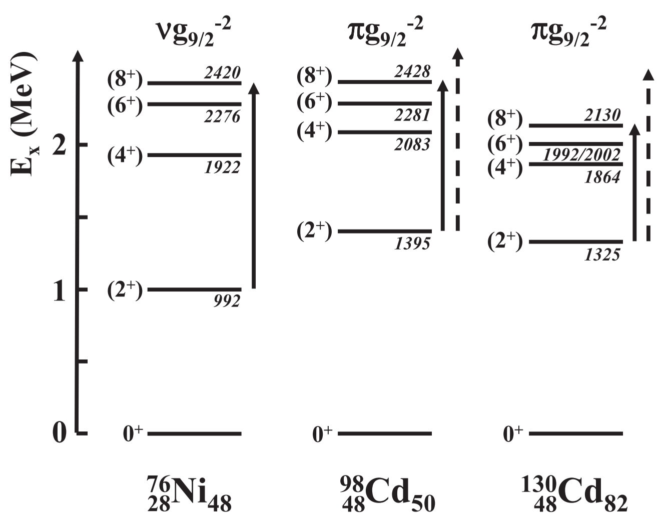

FIG. 4. Proposed level scheme of ^{130}Cd compared to the known level schemes of ^{76}Ni [29] and ^{98}Cd [13]. The solid arrows indicate the observed A^{-1} scaling, whereas the dashed arrows correspond to an $A^{-1/3}$ scaling of the $2^+ - 8^+$ energy spread.

be estimated by considering only the quadrupole part of the effective interaction for which a scaling law $E_q \sim m^2/(D \cdot A^{1/3})$ has been derived that warrants shell structure and saturation [25]. Here m and D denote the number of particles at the Fermi level and the shell degeneracy. For both $T = 1$ excitations from the lower pf shell and across the $Z, N = 50$ magic shell closure to the sdg shell (proton excitations in the case of Cd, neutron excitations in the case of Ni), for which m and D are identical for all three isotopes, the familiar $A^{-1/3}$ scaling is preserved. However, for core excitations of the $Z = 28$ (^{76}Ni), $N = 50$ (^{98}Cd) and 82 (^{130}Cd) *closed shells* which involve strong proton-neutron ($T = 0$) interactions, an additional downscaling occurs with increasing major shell and D leading to the observed deviation from the $A^{-1/3}$ scaling.

In conclusion, the question of whether and how far below ^{132}Sn an erosion of the $N = 82$ shell closure occurs will be answered only when lighter $N = 82$ waiting-point nuclei become accessible for both mass measurements and spectroscopic investigations at future radioactive beam facilities. The new results on the level scheme of ^{130}Cd, however, give no evidence for $N = 82$ shell quenching in this nucleus.

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