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First spectroscopic information from even-even nuclei in the region “southeast” of ^{132}Sn: Neutron-excitation dominance of the 2_1^+ state in ^{132}Cd

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The neutron-rich nucleus ^{132}Cd has been studied at the RIKEN Radioactive Isotope Beam Factory using in-beam γ-ray spectroscopy with two-proton removal reactions from ^{134}Sn. A γ-ray transition was observed at 618(8) keV and was assigned to the $2_1^+ \rightarrow 0_{\mathrm{g.s.}}^+$ decay. The 2_1^+ state provides the first spectroscopic information from the even-even nuclei located in the region “southeast” of the doubly magic nucleus ^{132}Sn. By comparing with the 2_1^+ excitation energies in the semimagic nuclei ^{134}Sn and ^{130}Cd, it is found that neutron excitations dominate the 2_1^+ state in ^{132}Cd, in a similar manner to ^{136}Te. The results are discussed in terms of proton-neutron configuration mixing.

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The properties of nuclei with a few valence particles and/or holes outside a doubly magic core are essential for a fundamental understanding of the detailed structure of the atomic nucleus. In particular, exotic nuclei around ^{132}Sn have received much attention because ^{132}Sn contains the conventional proton and neutron magic numbers of 50 and 82, respectively, and lies relatively far from the line of β stability. Thus, it provides a key region to explore the possible modification of nuclear structure approaching the neutron drip line. Spectroscopic information from nuclei beyond ^{132}Sn is, however, very limited owing to difficulties in accessing this exotic region of the nuclear chart on the experimental forefront. Recent experimental results include spectroscopy of the $N = 82$ isotones located “south” of ^{132}Sn down to ^{128}Pd ($Z = 46$) [1–3], and the $Z = 50$ tin isotopes located in the “east” side up to ^{138}Sn ($N = 88$) [4–6]. However, experimental information in the “southeast” of ^{132}Sn is scarce. γ decays from the excited states of the odd-odd nucleus ^{132}In were reported recently [7]. No spectroscopic study has been performed for even-even nuclei in this region.

The present Rapid Communication reports on the identification of the first 2^+ state of ^{132}Cd ($Z = 48, N = 84$), located “southeast” of ^{132}Sn (see Fig. 1). This completes the measurements of 2_1^+ states for the even-even nuclei closest to ^{132}Sn in its surrounding quadrant, which is the first such instance among doubly magic nuclei that lie off the line of β stability. Such completeness enables us to investigate the proton and neutron contributions to the excitation.

In this region, the 2_1^+ states in even-even nuclei reveal interesting phenomena in their neutron excitations. For the tin isotopes ^{134,136,138}Sn, the low-lying excited states can be described well by excitations of the valence neutrons outside the ^{132}Sn core [5,6]. Also, in the “northeast” quadrant, the neutron excitation dominance of the $2_1^+ \rightarrow 0_{\mathrm{g.s.}}^+$ transition in ^{136}Te was reported [8] from the reduction in both the 2_1^+ excitation energy [$E_x(2_1^+)$] and the transition probability [$B(E2)$] relative to the $N = 80$ isotope (^{132}Te). Information on the 2_1^+ state is thus crucial for understanding the role of neutrons in the low-lying excitations in this region. It is, therefore, intriguing to extend such studies to the unexplored southeast quadrant, where the nuclei are even more neutron rich, in order to investigate the neutron contributions in the low-lying excitations of these exotic systems.

The experiment was carried out at the Radioactive Isotope Beam Factory (RIBF) [9] operated by the RIKEN Nishina Center and the Center for Nuclear Study, University of Tokyo. A primary beam of ^{238}U with an energy of 345 MeV/nucleon was incident on a 0.5-mm-thick tungsten target located at the entrance of the BigRIPS fragment separator [10] to produce the secondary beams from in-flight fission reactions. The U beam intensity was about 1.8 particle nA on average. The fission products around ^{134}Sn were selected and purified in BigRIPS by employing two wedge-shaped aluminum energy

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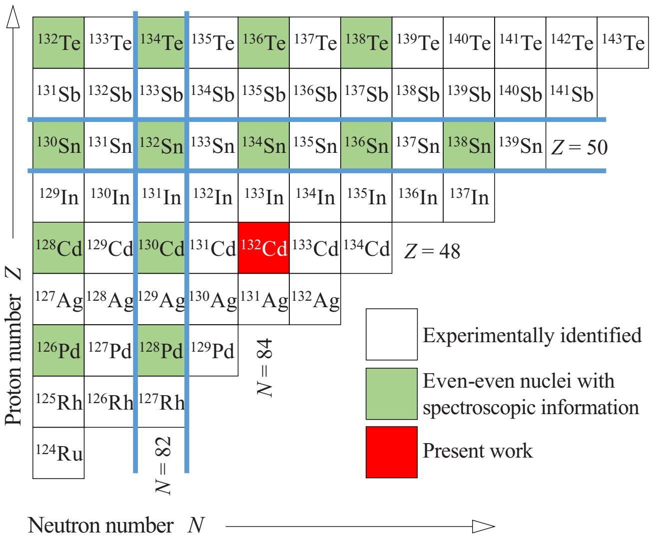

FIG. 1. Part of the nuclear chart showing the exotic isotopes identified experimentally so far in the vicinity of ^{132}Sn. Proton and neutron magic numbers are highlighted by the thick blue lines. Highlighted by the green color are the even-even nuclei which have available spectroscopic information. The present work reports on the excited 2_1^+ state in ^{132}Cd (red).

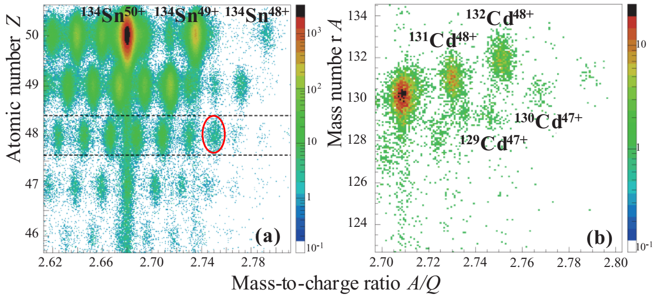

FIG. 2. Particle identification plots for the ZeroDegree spectrometer. (a) Two-dimensional plot of Z vs A/Q for the reaction residues produced from ^{134}Sn. The horizontal dashed lines show the Z gate that was adopted for selecting the Cd isotopes. The red circle indicates the mixture of $^{132}\mathrm{Cd}^{48+}$ and $^{129}\mathrm{Cd}^{47+}$. (b) Two-dimensional plot of A vs A/Q for the Cd isotopes. The fully stripped $^{132}\mathrm{Cd}^{48+}$ ions could be separated from the $^{129}\mathrm{Cd}^{47+}$ fragments using this technique.

degraders with thicknesses of 0.8 and 0.4 g/cm^2, located at the F1 and F5 dispersive foci, respectively. Secondary cocktail beams were identified event-by-event by measuring the time of flight (TOF), magnetic rigidity ($B\rho$), and energy loss (ΔE) as described in Refs. [11,12]. The average intensity for the ^{134}Sn beam was 3.0×10^2 particles per second.

A ^{9}Be target with a thickness of 1.1 g/cm^2, located at the eighth focal plane of BigRIPS, was used to induce the secondary reactions. Reaction residues were transported through and analyzed by the ZeroDegree spectrometer [10]. The particle identification process was performed event by event by measuring the TOF, $B\rho$, ΔE, and total kinetic energy (TKE) to deduce the atomic number Z, mass-to-charge ratio A/Q, and mass number A. The TOF was deduced using plastic scintillators located at the entrance and final focal points of the ZeroDegree spectrometer. Each $B\rho$ value was determined from a reconstruction of the ion trajectory using the positions and angles of the reaction residues at the dispersive focus. An ionization chamber was located at the final focus for the ΔE measurement. A LaBr$_3$(Ce) scintillation detector, located downstream of the ionization chamber, was used for the TKE measurement. The atomic number Z was deduced from the ΔE and TOF information, A/Q was obtained from the correlation between TOF and $B\rho$, and A was obtained from the TKE-TOF correlation. Resolutions [given here as FWHM] in Z, A/Q, and A were 0.47, 6.5×10^{-3}, and 1.5, respectively.

A two-dimensional plot of Z versus A/Q, measured by the ZeroDegree spectrometer for the fragmentation products of the ^{134}Sn beams, is displayed in Fig. 2(a). It is noted that the fully stripped ions are contaminated by lighter fragments with hydrogen-like ($Q = Z - 1$) charge states, for example, $^{129}\mathrm{Cd}^{47+}$ ($A/Q = 2.7447$), which has an A/Q value similar to that of the fully stripped $^{132}\mathrm{Cd}^{48+}$ ($A/Q = 2.7500$). In Fig. 2(b), a two-dimensional plot of A versus A/Q for the Cd isotopes is shown. It was obtained by selecting the events within $Z = 48.0 \pm 0.4$, as indicated by the horizontal dashed lines in Fig. 2(a). Using this technique, the fully stripped Cd^{48+} ions and the hydrogen-like Cd^{47+} ions can be separated, and the $^{132}\mathrm{Cd}^{48+}$ fragments unambiguously distinguished from the $^{129}\mathrm{Cd}^{47+}$ contaminants.

To detect γ rays emitted from the excited states of the reaction residues, the secondary target was surrounded by the DALI2 spectrometer [13], which consisted of 186 NaI(Tl) scintillators positioned at the polar angle from 14° to 148° relative to the beam direction. The energy resolution and full energy peak efficiency at 1.3 MeV measured using a ^{60}Co γ-ray source were 6% (FWHM) and 12%, respectively.

The Doppler-shift corrected γ-ray energy spectrum measured in coincidence with selecting the ^{134}Sn projectile and the ^{132}Cd ejectile is provided in Fig. 3. A prominent peak is

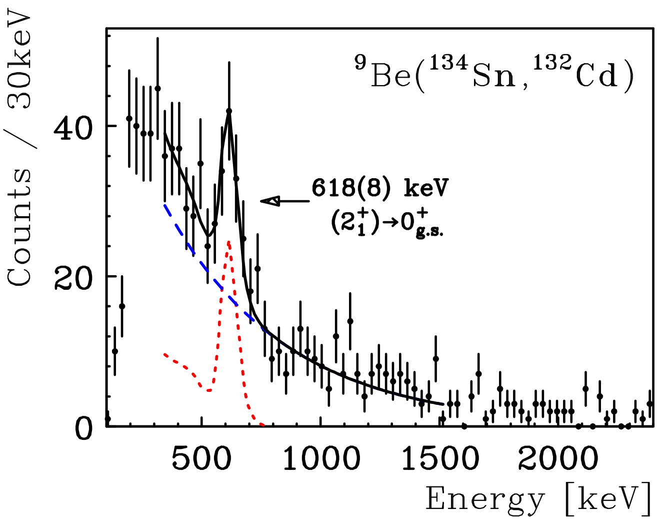

FIG. 3. Doppler-shift corrected γ-ray energy spectrum deduced from the ^{9}Be(^{134}Sn, ^{132}Cd) reaction. The solid line represents the total fit resulting from a sum of the DALI2 simulated response function (red dotted line) and an exponential background (blue dashed line).

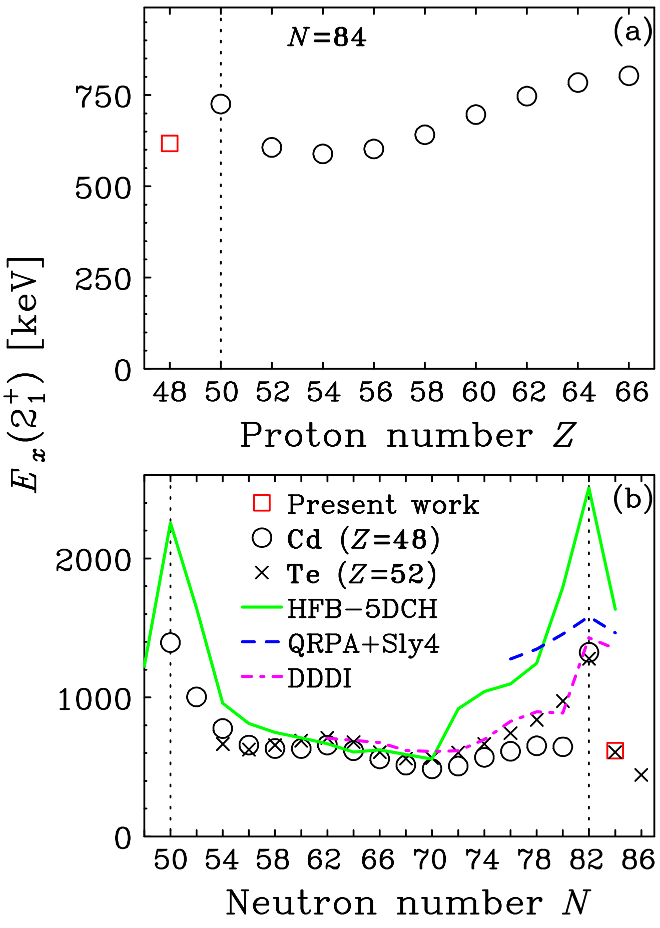

FIG. 4. Systematics of 2_1^+ excitation energies for (a) the even-even $N = 84$ isotones, and (b) the Cd and Te isotopic chains. The result of the present work is indicated by the square in both panels. Other experimental values are taken from Ref. [17]. In (b), mean-field calculations using a mapped collective Hamiltonian and the D1S Gogny interaction [18] (solid line), QRPA [19] (dashed line), and SHF method with pairing forces DDDI [20] (dot-dashed line) are displayed for comparison. It is noted that the error bars are smaller than the symbol sizes, and the vertical dotted lines represent the magic numbers in both panels.

located at 618(8) keV, which is assigned as the $2_1^+ \rightarrow 0_{\text{g.s.}}^+$ transition. The errors in the energy of the peak include both statistical and systematic contributions. The latter is attributed to the uncertainties in the energy calibration (2.5 keV), and the ambiguities in the positions of the γ-ray emission points and the projectile velocities caused by the unknown lifetimes of the excited states [14,15]. The experimental spectrum was fitted with a DALI2 response function, simulated using GEANT4 [16], and an exponential background.

The systematic trend of excitation energies of the 2_1^+ states for the even-even $N = 84$ isotones are shown as a function of proton number in Fig. 4(a). It was found that the energy of the 2_1^+ state in ^{132}Cd is similar to that of ^{136}Te, which lies at 606.62(5) keV [17]. It seems that the similar value in $E_x(2_1^+)$, found at Ba, Xe, and Te [21,22], continues to Cd in the $N = 84$ isotones. Similarity in $E_x(2_1^+)$ between the Cd and Te isotopic chains holds also for the light-mass region in general as displayed in Fig. 4(b). A deviation appears at $N = 78,80$ where the $E_x(2_1^+)$ value stays almost constant in Cd [23,24] while smoothly increasing in Te. With the result in ^{132}Cd, it is found that the deviation disappears beyond $N = 82$, in other words, the $E_x(2_1^+)$ values in Cd and Te come back to agree with each other. This $E_x(2_1^+)$ deviation between Cd and Te at $N = 78,80$ should be further investigated [24,25].

The 2_1^+ state in ^{132}Cd can be considered as a mixture of two-proton-hole (π^{-2}) and two-neutron-particle (ν^2) excitations around the ^{132}Sn core because ^{132}Sn is a robust, doubly-magic nucleus [4]. It has been shown that the structures of ^{134,136,138}Sn [5,6,21] can be described well by configurations with valence neutrons, and that the low-lying states in the $N = 82$ isotones ^{130}Cd and ^{134}Te can be treated as pure excitations of valence proton holes [3] and valence proton particles [26], respectively. Thus, the nature of the 2_1^+ state in ^{132}Cd can be investigated by comparing its $E_x(2_1^+)$ value to those in the nuclei with π^{-2} (^{130}Cd) and ν^2 (^{134}Sn) configurations.

Because the $E_x(2_1^+)$ value for ^{132}Cd lies much closer to the energy of the first 2^+ state of ^{134}Sn (725 keV) than it does to ^{130}Cd (1325 keV), the mixture of proton excitation is expected to be small, resulting in a neutron-dominant character of the 2_1^+ level in ^{132}Cd. To quantitatively understand the nature of the 2_1^+ state in ^{132}Cd, a simple seniority-two empirical model [8,27,28] was employed for the description of the wave function of the 2_1^+ state in ^{132}Cd. The mixing of the π^{-2} and ν^2 configurations with a residual interaction of V can be considered by taking the experimental 2_1^+ states of ^{130}Cd and ^{134}Sn as the basis states. In the model, an interaction of $|V| = 275$ keV is required to generate a 618-keV state in ^{132}Cd from the mixing of the 1325- and 725-keV levels, resulting in the relationship

$$|2_1^+; {}^{132}\text{Cd}\rangle = \sqrt{0.13}|\pi^{-2}\rangle \pm \sqrt{0.87}|\nu^2\rangle.$$

Thus, contributions of the proton and neutron excitation are 13% and 87%, respectively. This result, therefore, indicates that the 2_1^+ state in ^{132}Cd is predominantly a neutron excitation.

In fact, neutron dominance of the 2_1^+ state in the $N = 84$ isotone ^{136}Te [8] has already been suggested from the asymmetric $B(E2)$ pattern around $N = 82$ in the Te isotopes. With the same seniority-two empirical model using the 2_1^+ states of ^{134}Te and ^{134}Sn as the basis states [8], a dominant neutron excitation contribution (85%) and an interaction strength of $|V| = 282$ keV have been deduced for ^{136}Te [8]. Note that these values are very similar to those deduced in the present work for ^{132}Cd. A neutron excitation dominance in ^{136}Te was also suggested by Monte Carlo shell-model calculations [29] as well as QRPA calculations with a separable quadruple-plus-pairing Hamiltonian [30,31], being consistent with the result of the empirical seniority-two model. The similarities of the neutron contributions and the interaction strengths between ^{132}Cd and ^{136}Te suggest that the neutron in these two isotopes plays a similar role. For the heavy $N = 84$ isotones, the neutron dominance of the 2_1^+ state has been suggested by the interacting boson model-2 [22] as well as the regular behavior in the 2_1^+, 4_1^+, and 6_1^+ systematics [21]. Our results indicate that the neutron dominance known in the $N = 84$ isotones with $Z > 50$ continues in those with $Z < 50$.

The neutron dominance in the $N = 84$ isotones is in contrast with the nature of the 2_1^+ states in the $N = 80$ isotones. Using similar analysis, the proton and neutron contributions in ^{128}Cd (^{132}Te) are found to be 0.46 (0.45) and 0.54 (0.55), respectively, indicating a strong mixing, which is consistent with the results of large-scale shell-model calculations [24]. It seems that the neutron dominance appears only in the east side of ^{132}Sn, namely, for the nuclei with $N > 82$.

As suggested by the QRPA calculations [30,31], the neutron dominance originates from a reduction of the neutron pairing gap. According to these calculations, beyond $N = 82$, the neutron pairing gap decreases while that for the proton stays rather constant. These unbalanced pairing gaps lead to an increase in the neutron amplitude in the 2_1^+ state and a decrease for proton, resulting in a significant enhancement in the neutron contribution to the 2_1^+ excitation. Indeed, a considerable quenching in the neutron pairing gap was reported from recent mass measurements of the Te and Sn isotopes [32]. The reduction in the neutron pairing energy beyond ^{132}Sn was also suggested from the $E_x(2_1^+)$ difference between $N = 84$ and $N = 80$ in the Sn isotopic chain [5]. This pairing-strength change beyond doubly magic nucleus is not seen in the ^{208}Pb region, where both the proton and neutron pairing energies stay almost constant below and above $Z = 82$ and $N = 126$, respectively [33]. The weakening of the neutron pairing gap beyond $N = 82$ might be related to the nature of the nuclear structure in the ^{132}Sn region. As discussed in Ref. [32], one possible reason for such quenching is a low level density beyond $N = 82$. To investigate the suggested neutron dominance in ^{132}Cd further, measurements of the $B(E2)$ value and the pairing gap on the experimental forefront are encouraged.

The 2_1^+ excitation energies over a wide range of Cd isotopes calculated by several different mean-field approaches [18–20] are shown in Fig. 4(b). The solid line represents the constrained-Hartree-Fock-Bogoliubov calculations using a mapped five-dimensional collective Hamiltonian and the D1S Gogny interaction (HFB+5DCH) [18]. The HFB+5DCH predictions overestimate the experimental data from $N = 72$ to $N = 84$. A quasiparticle random-phase approximation (QRPA) calculation using the Skyrme force (Sly4) that includes the particle-particle residual interaction [19] overestimates the experimental data. The Skyrme-Hartree-Fock (SHF) model using a short-range pairing force, namely, the density-dependent δ interaction (DDDI) [20], predicts a much higher 2_1^+ excitation energy at $N = 84$ than those below $N = 82$. Both DDDI and HFB+5DCH calculations show a good agreement with the data for the lighter Cd isotopes (around $N = 60$–70). Thus, it is apparent that the $E_x(2_1^+)$ systematics along the entire Cd isotopic chain cannot be reproduced well by the calculations presented here. Shell-model calculations were employed to analyze the ^{132}In data [7] mentioned above. Further development of theory in that direction should also be useful for a comprehensive understanding of Cd isotopes in their $E_x(2_1^+)$ systematics.

In summary, the 2_1^+ state in the neutron-rich nucleus ^{132}Cd has been identified at 618(8) keV by measuring γ rays in coincidence with the ^{9}Be(^{134}Sn, ^{132}Cd) two-proton removal reaction. The result provides the first spectroscopic information on the even-even nuclei located southeast of the doubly magic nucleus ^{132}Sn. It was found that the $E_x(2_1^+)$ value in ^{132}Cd is similar to those in the heavy $N = 84$ isotones with $Z > 50$. Neutron excitation dominance of the 2_1^+ state in ^{132}Cd is suggested by comparing the $E_x(2_1^+)$ values of ^{134}Sn and ^{130}Cd, and, moreover, is supported by a seniority-two empirical model. Our result indicates that the structure in ^{132}Cd, which is located at the present experimental forefront in the nuclear physics study, can be understood as a continuation of those in the heavier $N = 84$ isotones located at the less neutron-rich region. Additional studies on ^{132}Cd, for example, measurements of the $B(E2)$ value and the neutron pairing gap, are encouraged to investigate further the suggested neutron dominance in the low-lying states.

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