# Nuclear structure study for the neutron-rich nuclei beyond $^{132}$Sn: In-beam gamma-ray spectroscopy of $^{136}$Sn and $^{132}$Cd

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**Abstract.** The neutron-rich nuclei $^{136}$Sn and $^{132}$Cd have been studied in the purpose of nuclear structure for the nuclei beyond the doubly-magic nucleus $^{132}$Sn. The $2^+_1 \rightarrow 0^+_{gs}$ transitions were identified for these two nuclei using in-beam $\gamma$-ray spectroscopy in coincidence with one- and two-proton removal reactions, respectively, at the RIKEN Radioactive Isotope Beam Factory. The $2^+_1$ state in $^{136}$Sn is found to be similar to that for $^{134}$Sn indicating the seniority scheme may also hold for the heavy tin isotopes beyond $N = 82$. For $^{132}$Cd, the $2^+_1$ state provides the first spectroscopic information in the even-even nuclei locating in the region "southeast" of $^{132}$Sn and the result is discussed in terms of proton-neutron configuration mixing. In both these two nuclei, it was found that the valence neutrons play an essential role in their low-lying excitations.

## 1 Introduction

Nuclear structure study for the very neutron-rich isotopes is one of major topics in nuclear physics. In particular, nuclei with a few valence particle and/or holes outside $^{132}$Sn ($Z = 50, N = 82$) have attract much attention as $^{132}$Sn is a doubly-magic nucleus while locating far away from the line of stability. It thus provides an opportunity to explore possible exotic nuclear structure beyond doubly-magic nucleus towards the neutron-drip line. In addition, elements around tin have long isotopic chains ranging from two neutron magic numbers $N = 50$ and $N = 82$ and it thus enables us to investigate systematically the structures as a function of neutron number in a wide range. However, the experimental studies are limited for the isotopes beyond $N = 82$ because of the difficulties in accessing this exotic region of the nuclear chart.

Spectroscopic information, especially the first $2^+$ states ($2^+_1$) in the even-even nuclei reveal interesting features in this region. Beyond $N = 82$, the energy of the first $2^+$ excited state [$E_x(2^+_1)$] was found to be much lower in $^{134}$Sn ($Z = 50, N = 84$) [1] than those for the lighter Sn isotopes below $N = 82$ where $E_x(2^+_1)$ keeps almost constant. At the "northeast" of $^{132}$Sn, a neutron dominance nature in the $2^+_1$ excitation was reported for $^{136}$Te ($Z = 52, N = 84$) from the decrease of both $E_x(2^+_1)$ and the reduced transition probabilities [$B(E2)$] across $N = 82$ [2]. These studies suggest that valence neutrons outside $N = 82$ may play an important role in the $2^+_1$ excitations in the neutron-rich nuclei beyond $^{132}$Sn. It is therefore intriguing to extend the spectroscopic studies in more neutron-rich side in order to investigate more on the role of neutron in the low-lying excitations.

In the present work, we report on the $2^+_1$ states in two neutron-rich nuclei: $^{136}$Sn ($Z = 50, N = 86$) following the tin isotopic chain and $^{132}$Cd ($Z = 48, N = 84$) along the $N = 84$ isotones.

## 2 Experimental Setup

The experiment was performed at the Radioactive Isotope Beam Factory (RIBF) operated by the RIKEN Nishina Center and the Center for Nuclear Study, University of Tokyo. Secondary beams were produced via in-flight fission reactions of $^{238}$U on a tungsten located at the objective

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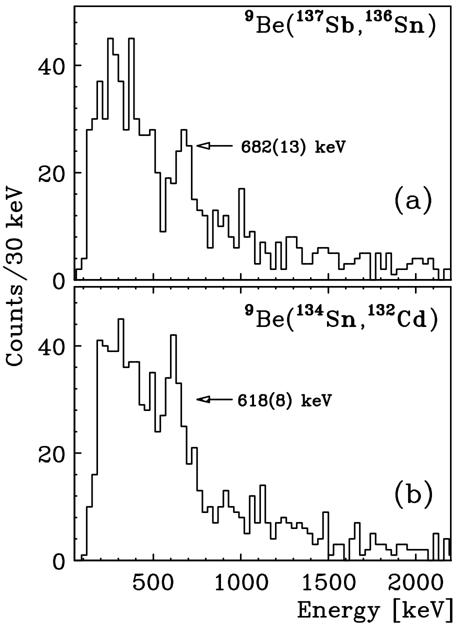


**Figure 1.** Doppler-shift corrected $\gamma$-ray energy spectra in coincidence with (a) $^{9}$Be($^{137}$Sb, $^{136}$Sn) and (b) $^{9}$Be($^{134}$Sn, $^{132}$Cd) reaction channels.

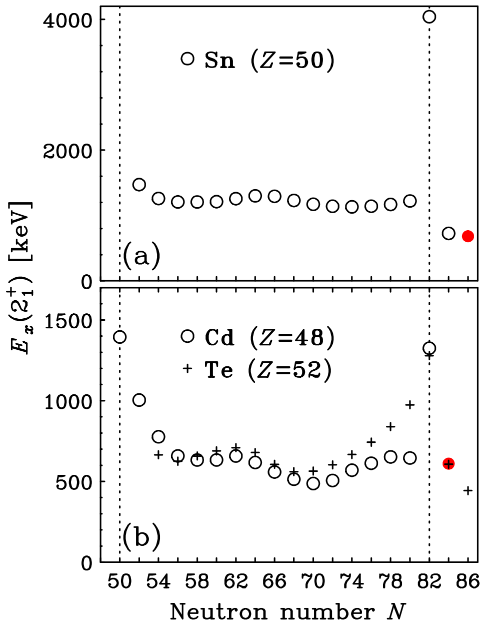


**Figure 2.** $E_x(2_1^+)$ systematics for (a) Sn and (b) Cd isotopic chain. In Panel (b), the $E_x(2_1^+)$ values for Te are displayed for comparison. The results obtained in the present work are highlighted by red color in both panels.

point of the BigRIPS separator [3]. The fission products including nuclei around $^{137}$Sb and $^{134}$Sn were selected and purified in the first stage of BigRIPS by inserting a wedge-shaped aluminum degrader with thicknesses of 0.8 g/cm$^2$. Further purification for the secondary beams was made in the second stage of BigRIPS using a 0.4-g/cm$^2$-thick degrader. The particles were identified event-by-event by using the TOF-$B\rho$-$\Delta E$ method, in which time of flight (TOF), magnetic rigidity ($B\rho$) and energy loss ($\Delta E$) were measured to deduce the atomic number ($Z$) and mass-to-charge ratio ($A/Q$) [4, 5].

The secondary reactions were induced by a $^9$Be target with a thickness of 1.1 g/cm$^2$. Reaction residues were collected and analyzed by the ZeroDegree spectrometer [3]. The particle identification was made using again the TOF-$B\rho$-$\Delta E$ method in a similar way to BigRIPS. In addition, the total kinetic energy was measured to deduce the mass number ($A$) for the identification of different charge states for these heavy ions. Detailed information on the experimental setup and particle identifications can be found in Refs. [6, 7].

Gamma rays emitted from the decay of the excited states of the reaction products were detected by the DALI2 array [8] surrounding the secondary target. DALI2 consisted of 186 NaI(Tl) scintillation detectors and covered the polar angle from 14 to 148 degrees with respect to the beam direction. The energy resolution and full energy peak efficiency were 9% (FWHM) and 22%, respectively, for the 0.662 MeV $\gamma$-ray measured using a $^{137}$Cs source.

## 3 Results and Discussions

The $\gamma$-ray energy spectra in coincidence with the respective one- and two-proton removal reactions to $^{136}$Sn and $^{132}$Cd are displayed in Fig. 1. Prominent transitions observed at 682(13) and 618(8) keV in Fig. 1(a) and (b), respectively, correspond to the $2_1^+ \rightarrow 0_{gs}^+$ transitions for $^{136}$Sn and $^{132}$Cd.

The experimental $E_x(2_1^+)$ values as a function of neutron number are shown for the even-even Sn and Cd isotopes in Fig. 2(a) and (b), respectively. As displayed in Fig. 2(a), the $E_x(2_1^+)$ value for $^{136}$Sn is close to that for $^{134}$Sn. In another word, $E_x(2_1^+)$ keeps constant in the Sn isotopes beyond $N = 82$. This behavior is similar to that for the lighter Sn isotopes below $N = 82$, where $E_x(2_1^+)$ is almost constant reflecting the consequence of the seniority $\nu = 2$ configuration [9]. The similar $E_x(2_1^+)$ values in $^{136}$Sn and $^{134}$Sn suggest that the seniority scheme holds also for the tin isotopes beyond $N = 82$. The similar $E_x(2_1^+)$ values as well as the constant $4_1^+$ and $6_1^+$ states are also found by identifying the $6^+$ seniority isomers in $^{136,138}$Sn [10], supporting further the dominant seniority $\nu = 2$ scheme.

For $^{136}$Sn, a mixed seniority is suggested in the $4_1^+$ state from the $B(E2; 6^+ \rightarrow 4^+)$ value [10]. To reproduce the $B(E2; 6^+ \rightarrow 4^+)$ systematics in $^{134,136,138}$Sn, shell-model calculations with an empirically redued neutron-pairing strength was applied and such shell-model calculations suggest that the $4_1^+$ state in $^{136}$Sn has mixed seniority $\nu = 2$

and $\nu = 4$ components. The reduction of $\nu = 2$ component in the $4^+_1$ is supported by another shell-model calculations [11]. While the $4^+_1$ state in $^{136}$Sn has mixed seniority, the $2^+_1$ and $6^+_1$ states are predominant seniority $\nu = 2$ as demonstrated by the shell-model calculations [11].

Although $E_x(2^+_1)$ keeps constant below and above $N = 82$ along the Sn isotopic chain, the $E_x(2^+_1)$ systematics show an asymmetric pattern around $^{132}$Sn. The $E_x(2^+_1)$ values in $^{134,136}$Sn are about 500 keV lower than those for the lighter ones below $N = 82$. Such reduction in $E_x(2^+_1)$ beyond $N = 82$ might be due to a quenching of neutron pairing in the $N > 82$ region, because the $2^+_1$ excitation is mainly determined by the strength of neutron pairing under the seniority scheme. Indeed, the neutron gap was suggested to be reduced from the mass measurement for the Sn isotopes above $N = 82$ [12]. The reduction of neutron pairing is also supported by Ref. [10] because a reduced neutron-pairing strength was used to reproduce the $B(E2; 6^+ \rightarrow 4^+)$ systematics as mentioned above.

The $2^+_1$ state in $^{132}$Cd provides a further insight on the role of neutrons in the low-lying excitation in more neutron-rich region. In order to investigate the nature of the $2^+_1$ state in $^{132}$Cd more quantitatively, a simple seniority-two empirical model was employed [2, 13]. With respect to $^{132}$Sn, $^{132}$Cd has a two-proton-hole ($\pi^{-2}$) and two-neutron-particle ($\nu^2$) configuration. As $^{132}$Sn exhibits a robust doubly-magic nature [14], the wave function of the $2^+_1$ state in $^{132}$Cd can be therefore described by taking the $2^+_1$ states of $^{130}$Cd ($\pi^{-2}$) and $^{134}$Sn ($\nu^2$) as the basis states. In this model, an interaction of $|V|$ = 275 keV is required to generate the 618-keV state in $^{132}$Cd from the mixing of the 1325- and 725-keV levels in $^{130}$Cd and $^{134}$Sn, resulting in the relationship

$$|2^+_1;{}^{132}\mathrm{Cd}\rangle = 0.93|\nu^2\rangle \pm 0.36|\pi^{-2}\rangle.$$

The respective neutron- and proton-excitation contributions were determined to be 87% and 13%, indicating a neutron dominance nature of the $2^+_1$ state in $^{132}$Cd.

Neutron excitation is also known in the $N = 84$ isotone $^{136}$Te [2] from the asymmetric $B(E2)$ pattern in the Te isotopes around $N = 82$. By using the same seniority-two model, the neutron contribution and the interaction of $|V|$ were deduced to be 85% and 282 keV, respectively, for $^{136}$Te by taking the experimental $2^+_1$ states of $^{134}$Te and $^{134}$Sn as the basis states [2]. In addition, it is worth to note that the $E_x(2^+_1)$ values in Cd and Te agree with each other beyond $N = 82$ as displayed in Fig. 2(b). The similarities of the $E_x(2^+_1)$ value, the interaction and the neutron contributions between $^{132}$Cd and $^{136}$Te suggest that the neutrons play a similar role in the $2^+_1$ excitation in these two isotopes.

The neutron-dominance nature might be attributed to the reduction of neutron pairing strength as suggested by the QRPA calculations [15, 16]. As shown by these calculations, the neutron-pairing gap becomes smaller across $N = 82$ while the proton one remains almost the same. The reduction in the neutron-pairing gap lead to an enhancement in the neutron amplitudes in the wave function of the $2^+_1$ state, resulting in a predominant neutron contribution to the $2^+_1$ excitation. Both the $2^+_1$ states in $^{136}$Sn and $^{132}$Cd suggest a quenching of neutron-pairing strength above the $N = 82$ gap. The pairing weakening might be related to the nature of nuclear structure around $N = 82$. One possible reason for the neutron-pairing decrease might be a lower level density above $N = 82$ [12, 15].

## 4 Summary

In summary, the $2^+_1$ states in $^{136}$Sn and $^{132}$Cd were studied using the in-beam $\gamma$-ray spectroscopy in coincidence with one- and two-proton removal reactions, respectively. The measured $E_x(2^+_1)$ value of $^{136}$Sn is found to be similar as that for $^{134}$Sn, indicating the seniority scheme holds beyond $N = 82$ for the tin isotopes. Neutron-excitation dominance of the $2^+_1$ state in $^{132}$Cd is suggested from the proton-neutron configuration mixing and, is supported by a seniority-two empirical model. Both the asymmetric $E_x(2^+_1)$ pattern around $N = 82$ in Sn and the neutron-dominance nature in $^{132}$Cd suggest a reduction of neutron-pairing strength above $N = 82$. Such reduction might be due to a lower level density above $N = 82$. Further studies on the neutron-pairing gap are encouraged to explore more on the neutron dominance in the low-lying excitations.

## 5 Acknowledgment

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