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Ground state inversions in hole nuclei near ^{132}Sn driven by the monopole interaction

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The neutron-rich nuclei to the southwest of ^{132}Sn are studied comprehensively by large-scale, shell-model calculations with the extended pairing plus multipole-multipole force (EPQQM) model. A regular correlation driven by the monopole interaction between the neutron orbits $h_{11/2}$ and $d_{3/2}$ is found in this nuclear region for different isotonic chains with $N = 79, 80, 81$. The ground-state inversions from ^{130}In (^{129}Cd) to ^{128}In (^{127}Cd) seen experimentally are well described for the first time by this regular correlation. The regular correlation in different isotonic chains is also supported by a systematic comparison between the observed spectra of ^{126}Ag and ^{128}In, and further confirmed by the investigation of isomeric states of ^{126}Pd, ^{128}Cd, and ^{129}In the in $N = 80$ isotonic chain. This regular correlation in different isotonic chains should provide useful guidance for further experiments in this region of nuclei.

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I. INTRODUCTION

Many exotic and intriguing phenomena have been reported in neutron-rich nuclei near the doubly magic ^{132}Sn. The second abundance peak at $A \approx 130$ appears through the astrophysical rapid neutron capture process, and the doubly magic nature of ^{132}Sn was explored in experiment and also theory [1–5]. Recently, the doubly-magic nucleus ^{132}Sn was reconfirmed again by the first charge-radius measurement of a neutron-rich Sn isotope beyond $N = 82$ [6] and the investigations for nuclei near ^{132}Sn are important for the r-process study around the $A = 130$ abundance peak [7]. The strong fragmentation of single-hole strength is reported in ^{131}In from measurements of the spectroscopic factors of proton-hole states [8]. From mass measurements of the neutron-rich cadmium isotopes, the $N = 82$ shell closure was confirmed below $Z = 50$ and the $h_{11/2}$ neutron orbital near ^{132}Sn was reported to be a key for the evolution of the $N = 82$ shell gap towards $Z = 40$ [9]. A reduction of the $Z = 40$ subshell gap was suggested in the Ag isotopes approaching $N = 82$ and the tensor force was found to play a crucial role in the proton shell evolution [10]. The first spectroscopic information on the excited states in ^{125,127}Pd suggested competition between proton excitations and neutron excitations of hole nuclei in the vicinity of the doubly-magic ^{132}Sn [11] nucleus. The isomeric states in ^{128}Cd have been identified and compared to the results of large-scale shell-model calculations [12]. A microsecond isomer has been identified in ^{127}Cd, and the experimental data have been investigated by two theoretical shell-model approaches with different model spaces and interactions [13].

Note that a new β-decaying high-spin isomer has been discovered in ^{128}In at 1797.6(20) keV by using Penning-trap techniques [14]. The isotopes of neutron-rich indium can provide essential data to test the nuclear shell model and to develop the nucleon-nucleon effective interaction. The ground state of ^{128}In was suggested as $(3)^+$ by Fogelberg and Carl in Ref. [15], and the change in position of the 1^- state from ^{130}In to ^{128}In was investigated in Ref. [16]. Such ground-state inversion also exists for ^{129}Cd to ^{127}Cd. In ^{129}Cd, the ground state is assigned as $11/2^-$, while the excited $3/2^+$ level changes into the ground state in ^{127}Cd. It is very interesting to search for the nuclear structure reason for these ground-state inversions. The isomers of neutron-rich exotic nuclei have been investigated comprehensively, and a γ ray at $E_\gamma = 254.8$ keV was observed in ^{126}Ag [17]. The systematic study assigned 3^+ as the ground state of ^{126}Ag by comparison with states in ^{128}In, while the ground state of ^{126}Ag was assigned as 1^- using the jj45pna interaction. The two-body effective Hamiltonians have been well established for decades in shell-model calculations, and the monopole interaction is crucial for obtaining agreement with experiment [18]. Different effects of the monopole-driven shell evolutions are discussed for tensor forces [19] and other terms in the nucleon-nucleon interaction [20–23]. In fact, the monopole corrections are necessary for two-body interactions [24], as confirmed by the *ab initio* studies in Ref. [25].

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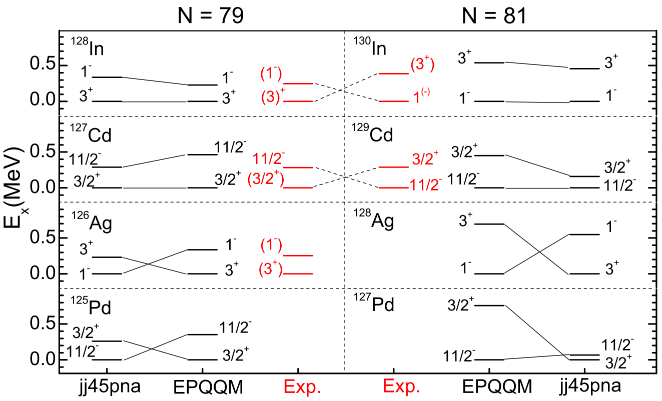

FIG. 1. The EPQQM calculations on ground-state inversions in comparison with experiment and jj45pna results.

In this paper, the neutron-rich hole nuclei of $N = 79, 80, 81$ are investigated using the extended pairing plus multipole-multipole force (EPQQM model [26–29]. This model employs monopole correction (Mc) terms that provide an advantage to study monopole effects. With ^{78}Ni as the frozen core, the present model space includes six proton orbits ($0f_{5/2}, 1p_{3/2}, 1p_{1/2}, 0g_{9/2}, 0g_{7/2}, 1d_{5/2}$) and seven neutron orbits ($0g_{7/2}, 1d_{5/2}, 2s_{1/2}, 0h_{11/2}, 1d_{3/2}, 1f_{7/2}, 2p_{3/2}$). The two orbits above $Z = 50$ ($N = 82$) added for proton (neutron) core excitations are frozen in this work, to make sure of using a uniform model space to study the nuclei a little further from the doubly magic ^{132}Sn. The single-particle energies and the two-body force strengths employed in the present work are consistent with our previous paper [30]. There is no truncation in major shell orbits, and the shell-model code NUSHELLX@MSU is used for the calculations [31].

II. THE MONOPOLE CORRECTIONS

In the present interaction, the monopole effects can be investigated using the monopole correction terms

$$\mathrm{Mc} = k(ia, i'c) \sum_{JM} A^{\dagger}_{JM}(ia, i'c) A_{JM}(ia, i'c). \qquad (1)$$

Here $A^{\dagger}_{JM}(ia, i'c)$ and A_{JM} are the pair operators, and k_{mc} is the monopole force strength (pn representation). Three monopole terms have already been employed, namely $\mathrm{Mc1} \equiv k_{mc}(\nu h_{11/2}, \nu f_{7/2}) = 0.52$ MeV, $\mathrm{Mc2} \equiv k_{mc}(\pi g_{9/2}, \nu h_{11/2}) = -0.4$ MeV, and $\mathrm{Mc3} \equiv k_{mc}(\pi g_{9/2}, \nu g_{7/2}) = -1.0$ MeV. These play crucial roles in explaining the energy spectrum to the southwest of ^{132}Sn [30,32,33]. In ^{128}In, the ground state was suggested as $(3)^+$ by Fogelberg and Carl [15], while the (3^+) state becomes an excited level in ^{130}In with the configuration $\pi g^{-1}_{9/2} \nu d^{-1}_{3/2}$, and the $1^{(-)}$ is suggested as the ground state in ^{130}In with the configuration $\pi g^{-1}_{9/2} \nu h^{-1}_{11/2}$.

III. GROUND STATE INVERSIONS

It is very interesting to see why the ground state is reversed experimentally from ^{130}In to ^{128}In. Such a ground-state inversion also exists from ^{127}Cd to ^{129}Cd (Fig. 1) with increasing neutron number. The ground state of odd Cd isotopes from ^{121}Cd to ^{127}Cd is $(3/2^+)$, while the excited level $11/2^-$ becomes the ground state in ^{129}Cd. Note that the $(3)^+$ level in ^{128}In has a main configuration of $\pi g^{-1}_{9/2} \nu d^{-1}_{3/2} h^{-2}_{11/2}$, and the 3^+ level in ^{128}In would be influenced by monopole effects involving the $\pi g_{9/2}$, $\nu d_{3/2}$, and $\nu h_{11/2}$ orbits. So, the monopole terms $\mathrm{Mc}(\pi g_{9/2}, \nu d_{3/2})$, $\mathrm{Mc}(\pi g_{9/2}, \nu h_{11/2})$, and $\mathrm{Mc}(\nu h_{11/2}, \nu d_{3/2})$ are studied as the function of the monopole force strength k_{mc} in Fig. 2. The monopole term $\mathrm{Mc}(\pi g_{9/2}, \nu d_{3/2})$ shifts the 3^+ level down about 40 keV as k_{mc} varies from 0.5 to 0 MeV, while there is a slight increase from 0 to -0.5 MeV.

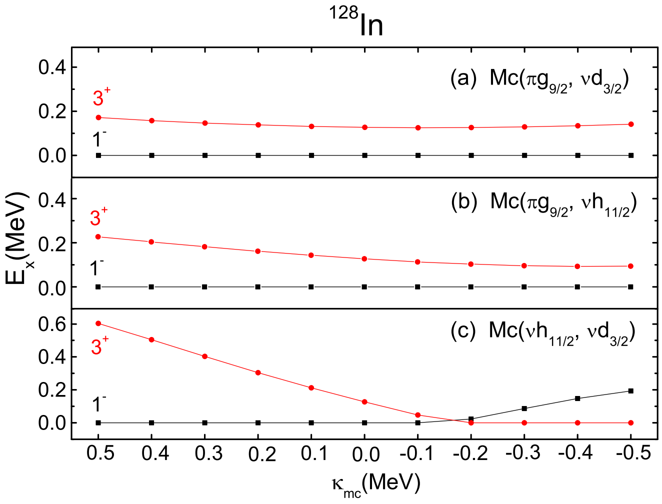

FIG. 2. The monopole effects in 3^+ and 1^- levels in ^{128}In.

For $\mathrm{Mc}(\pi g_{9/2}, \nu h_{11/2})$, the 3^+ level keeps linearly decreasing as k_{mc} varies from 0.5 to -0.2 MeV, and then is almost stable from -0.3 to -0.5 MeV. As the monopole interaction between neutron orbitals $h_{11/2}$ and $d_{3/2}$, the monopole term $\mathrm{Mc}(\nu h_{11/2}, \nu d_{3/2})$ has been found to provide influence obviously on the 3^+ level and reverses the 3^+ level into the ground state after $k_{\mathrm{mc}} = -0.1$ MeV. With two more neutron holes in ^{128}In than in ^{130}In, the additional monopole strength is quantitatively fixed as $\mathrm{Mc4}(\nu d_{3/2}, \nu h_{11/2}) = -0.4$. With this Mc4 monopole correction, the excited 3^+ level in ^{128}In reverses into the ground state, and the 1^- level becomes an excited state closer to the experimental datum 0.248 MeV (Fig. 3). The 16^+ state also has a positive change that shifts it down close to the datum 1.798 MeV.

To validate this regular correlation driven by monopole interactions, the isotone $N = 79$ is studied. In ^{127}Cd, the reversal of the excited level $3/2^+$ into the ground state is driven by Mc4 after increasing by 2 the number of neutron holes from ^{129}Cd. In experiments, the $11/2^-$ level is the ground state in ^{129}Cd, and the $3/2^+$ level is the excited one. Based on this regular correlation, the $3/2^+$ state is suggested as the ground state of ^{127}Cd in theory. As a further test, more $N = 79$ isotones are investigated. In Ref. [34], an isomeric state with a half-life of 27(6) μs is observed in ^{126}Ag, and (1^-) and (3^+) are assigned to the 254 keV and the ground-state levels based on the systematics by comparing with the level scheme of ^{128}In. In Fig. 1, both the present calculations and the jj45pna results reproduce well these reversed ground states of ^{128}In and ^{127}Cd in experiments, while the jj45pna

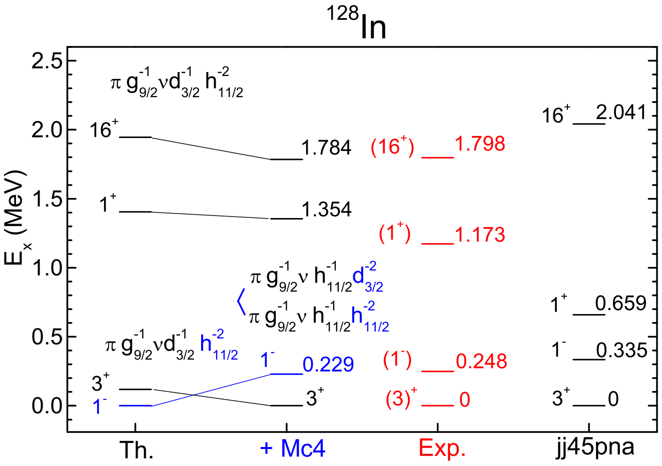

FIG. 3. The theoretical low-lying levels of ^{128}In in comparison with experimental data. "+Mc4" means considering monopole effects of Mc4 in the calculations (Th.).

interaction gives the 1^- level as the ground state of ^{126}Ag. As shown in Fig. 4, the 3^+ level in ^{126}Ag is reversed well into the ground state driven by this new monopole effect of Mc4. In this work, the ground states keep the same parity and J value, and they are connected by the same regular correlation driven by the monopole interaction. This systematic study provides evidence for extending the regular correlation from ^{128}In to ^{126}Ag, which suggests 3^+ as the ground state of ^{126}Ag.

In the next $N = 79$ isotone ^{125}Pd, the excited state $3/2^+$ is also shifted down as the ground state even in four proton-hole configurations such as $\pi g_{9/2}^{-4}$. With increasing number of proton holes from ^{128}In to ^{125}Pd, the p-n monopole interaction does not have more impact, while the neutron monopole interaction keeps dominating the ground-state inversions in $N = 79$ isotones. Figure 2 also shows the greater monopole effects of Mc($\nu h_{11/2}$, $\nu d_{3/2}$) between neutrons. The competition between 1^- $(11/2^-)$ and 3^+ $(3/2^+)$ will be determined by their configurations. As shown in Fig. 5, the 3^+ (or $3/2^+$) states of these $N = 79$ isotones have the main neutron configuration $\nu d_{3/2}^{-1}h_{11/2}^{-2}$, and the 1^- $(11/2^-)$ states have the main neutron configuration $h_{11/2}^{-1}h_{11/2}^{-2}$, as well as $h_{11/2}^{-1}d_{3/2}^{-2}$. Considering the attractive monopole correction between $\nu h_{11/2}$ and $\nu d_{3/2}$, the components of $\nu d_{3/2}^{-1}h_{11/2}^{-2}$ and $\nu d_{3/2}^{-2}h_{11/2}^{-1}$ increase in these $N = 79$ isotones, while the part of $\nu h_{11/2}^{-1}h_{11/2}^{-2}$ distinctly shrinks, as in the 1^- and $11/2^-$ levels (Fig. 5). The configurational competition is the structural reason for the ground-state inversions in $N = 79$ isotones, which are driven by the monopole interaction between $\nu h_{11/2}$ and $\nu d_{3/2}$.

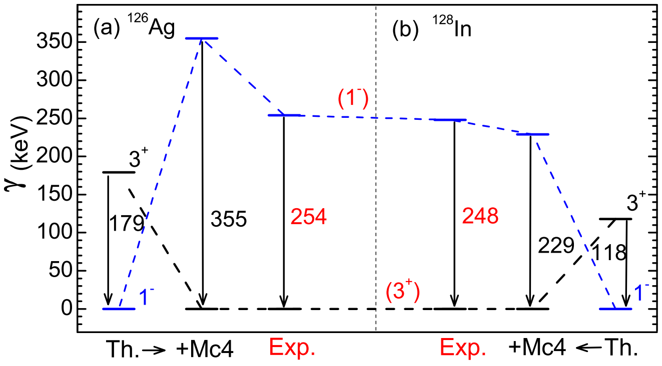

FIG. 4. The comparison of 1^- and 3^+ states in ^{126}Ag and ^{128}In with monopole effects from Mc4.

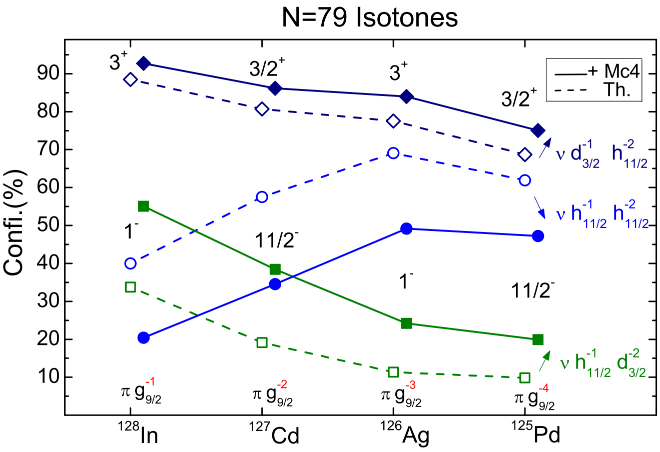

FIG. 5. The variation of configurations in the ground states of $N = 79$ isotones with the monopole effects of Mc4.

The same regular correlation is also found in $N = 80$ isotones. Three isomeric states, in ^{129}In, ^{128}Cd, and ^{126}Pd especially, shown in Fig. 6, exhibit this regular correlation driven by the monopole interaction. The calculations can reproduce well the experimental data with Mc4($\nu d_{3/2}$, $\nu h_{11/2}$) = −0.4 MeV, and the jj45pna results are listed for comparison. In the present work, the 7^- level in ^{126}Pd has 59% of $\pi g_{9/2}^{-4}\nu h_{11/2}^{-1}\nu d_{3/2}^{-1}$ (43% without Mc4), and jj45pna has about 18% of this configuration as the biggest component. For the 5^- level in ^{128}Cd, the main configuration is 74% of $\pi g_{9/2}^{-2}\nu h_{11/2}^{-1}\nu d_{3/2}^{-1}$ (58% without Mc4), while jj45pna has about 11% of $\pi g_{9/2}^{-2}\nu h_{11/2}^{-1}\nu d_{3/2}^{-1}$ and 16% of $\pi g_{9/2}^{-2}\nu h_{11/2}^{-1}\nu s_{1/2}^{-1}$.

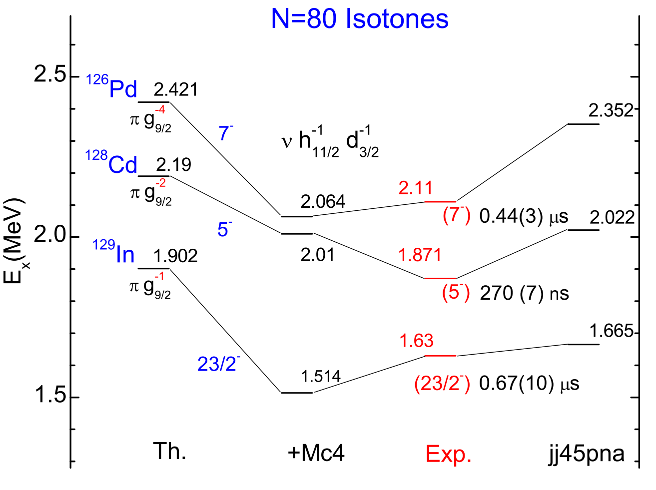

FIG. 6. The Mc4 monopole effects in negative-parity levels of the $N = 80$ isotones. The present results are compared to experimental data and jj45pna calculations.

If we sum up the just the proton configurations in this 5^- level, the jj45pna model predicts about 33% of $\pi g_{9/2}^{-2}$ and 25% of $\pi g_{9/2}^{-1} p_{1/2}^{-1}$, while 70% of $\pi g_{9/2}^{-1} p_{1/2}^{-1}$ is reported in Ref. [12]. As a further transitional test, the $B(E2, 7^- \rightarrow 5^-)$ in ^{126}Pd is 2.76 W.u. with Mc4 (almost zero before) compared with 2.13(14) W.u. experimentally [35], while jj45pna provides 6.27 W.u. for this transition. In ^{128}Cd, the value of $B(E2, 7^- \rightarrow 5^-)$ is 0.89 W.u. with Mc4 (1.08 W.u. before) compared with the datum 1.5(3) W.u. [12]. The value is 2.87 W.u. for the jj45pna interaction. These isomeric states with $B(E2)$ transitions provide more evidence for the regular correlation in this region of hole nuclei.

IV. THEORETICAL PREDICTIONS

In ^{128}In, the reversed ground state is driven by the monopole correction Mc4 between $\nu h_{11/2}$ and $d_{3/2}$. This regular correlation dominates the ground-state inversions in these $N = 79$ isotones and supports the systematic analogy between ^{128}In and ^{126}Ag that assigned the isomeric state (1^-) and the ground state (3^+) in ^{126}Ag experimentally. As a theoretical prediction, the reversed ground state of ^{126}Ag will change back to (1^-) in ^{128}Ag. For odd mass nuclei, with two more neutron holes in ^{129}Cd (^{127}Pd), the regular correlation reverses the excited $3/2^+$ level into the ground state in ^{127}Cd(^{125}Pd). The ground state of ^{127}Cd has already been suggested as $3/2^+$ in Ref. [36], and then the theoretical prediction in ^{125}Pd will become more reasonable.

V. SUMMARY

The neutron-rich isotones of $N = 79$, 80, 81 are studied comprehensively with large-scale shell model calculations to the southwest of ^{132}Sn. A regular correlation driven by the monopole interaction between the neutron orbits $h_{11/2}$ and $d_{3/2}$ is found and quantified with the extended pairing plus multipole-multipole force model. The data on the ground-state inversion from ^{130}In to ^{128}In can be well described by this regular correlation, as well as the inversion from ^{129}Cd to ^{127}Cd. The configurational competition between 1^- $(11/2^-)$ and 3^+ $(3/2^+)$ provides the structural reason for these ground-state inversions in the $N = 79$ isotones. Furthermore, this regular correlation agrees with the fact that ^{126}Ag and ^{128}In have the same parity and J value in their ground states. The study of isomeric states with $B(E2)$ transitions in the $N = 80$ isotones provides more evidence, and such a regular correlation in different isotonic chains should provide useful guidance for further experiments in this region of nuclei.

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