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Behavior of odd-even mass staggering around ^{132}Sn

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We have performed shell-model calculations of binding energies of nuclei around ^{132}Sn. The main aim of our study has been to find out if the behavior of odd-even staggering across $N = 82$ is explainable in terms of the shell model. In our calculations, we have employed realistic low-momentum two-body effective interactions derived from the charge-dependent Bonn nucleon-nucleon potential that have already proved quite successful in describing the spectroscopic properties of nuclei in the ^{132}Sn region. Comparison shows that our results fully explain the trend of the experimental staggering.

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A fundamental property of an atomic nucleus is its mass. Mass spectrometry studies started more than a century ago and since then have continued achieving higher and higher accuracy. A comprehensive historical overview of mass spectrometry since the very beginning is given in Ref. [1].

Today, the highest accuracy (parts per billion) is reached with ion traps, in particular Penning traps. With this technique, mass measurements on neutron-rich Sn and Xe isotopes were recently performed [2,3] at the CERN On-Line Isotope Mass Separator (ISOLDE) facility by using the mass spectrometer ISOLTRAP. A remarkable result of the study [2] was that the mass measurement of ^{134}Sn revealed a 0.5-MeV discrepancy with respect to previous Q_β measurements. This provided clear evidence of the robustness of the $N = 82$ shell closure, ruling out the hypothesis of an $N = 82$ shell quenching.

The ^{132}Sn region is currently the focus of great experimental and theoretical interest, especially in view of the production of new neutron-rich nuclear species at the next generation of radioactive ion beam facilities. Very recently, atomic masses of several neutron-rich nuclei around ^{132}Sn have been measured [4] using the JYFLTRAP Penning trap mass spectrometer coupled to the Ion Guide Isotope Separator On-Line (IGISOL) facility at the accelerator laboratory of the University of Jyväskylä. In this study, the masses of some nuclei, as for instance ^{135}Sn and ^{136}Sb, were measured for the first time and the precision of previously measured masses was significantly improved. Attention was also focused on the odd-even staggering (OES) of binding energies for $N = 81$ and 83 isotones. In particular, the experimental values for Sn, Te, and Xe were compared with those obtained by performing various state-of-the-art self-consistent calculations with the SLy4 Skyrme energy density functional and contact pairing force. No calculation of Ref. [4], however, was able to reproduce the experimental behavior of the staggering in the $N = 83$ isotones. This led the authors to consider this behavior anomalous and attribute it to specific effects beyond the $N = 82$ shell gap not accounted for, in their opinion, by current theoretical approaches.

Over the past several years we have conducted several shell-model studies of neutron-rich nuclei around ^{132}Sn [5–8] by using Hamiltonians with single-particle and single-hole energies taken from experiment and effective interactions derived from the charge-dependent Bonn (CD-Bonn) nucleon-nucleon (NN) potential renormalized through the $V_{\text{low}-k}$ procedure [9] with a cutoff momentum Λ of 2.2 fm^{-1}. All these studies, focused essentially on the energy spectra and electromagnetic properties, led to results in very good agreement with experiment. The findings mentioned above have challenged us to put our realistic shell-model calculations to the test also in this puzzling case.

In our calculations, we assume that the valence protons and the valence neutron holes occupy the five orbits $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $0h_{11/2}$, and $2s_{1/2}$ of the 50-82 shell while the valence neutrons have available the six orbits $1f_{7/2}, 2p_{3/2}, 2p_{1/2}, 0h_{9/2}$, $1f_{5/2}$, and $0i_{13/2}$ of the 82-126 shell. The adopted values of the single-particle and single-hole energies are reported in Refs. [8] and [7], respectively. They were taken from the experimental spectra of ^{133}Sb [10], ^{131}Sn [10,11], and ^{133}Sn [10] with the exceptions of the proton $2s_{1/2}$ and the neutron $0i_{13/2}$ energies which were from Refs. [12] and [13], respectively, since the corresponding single-particle levels are still missing in the spectra of ^{133}Sb and ^{133}Sn. We should also point out here that, as in our most recent calculations [6,8], the experimental energy of [14] is used for the neutron $2p_{1/2}$ level. The needed mass excesses are taken from Ref. [4].

As mentioned above, the two-body effective interaction V_{eff} is derived from the CD-Bonn NN potential, whose short-range repulsion is renormalized by means of the $V_{\text{low}-k}$ potential [9] with $\Lambda = 2.2$ fm^{-1}. The obtained low-momentum potential is then used, with the addition of the Coulomb force for protons, to derive V_{eff} within the framework of a perturbative approach based on the $\hat{Q}$-box folded-diagram expansion [15,16]. Some details on the calculation of the two-body interaction above and below $N = 82$ can be found in [17] and [7], respectively.

To start with, we report in Table I the calculated binding energies, relative to ^{132}Sn, of the Sn, Sb, Te, and Xe isotopes beyond $N = 82$ and compare them with the results from the mass measurements performed in [4] for the first three kinds of isotopes and in [3] for the latter. Note that the errors on the measured values are in the order of keV and therefore are not given in Table I, where the reported energies are rounded to tens of keV. We may also mention that the values of the binding energies reported in our previous papers (see, for instance, Refs. [6,18,19]) for some of these nuclei differ slightly from

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TABLE I. Calculated and experimental binding energies B, relative to ^{132}Sn, of Sn, Sb, Te, and Xe isotopes.

Nucleus	B_{calc} (MeV)	B_{expt} (MeV)
^{134}Sn	5.98	6.03
^{135}Sn	8.37	8.30
^{134}Sb	12.74	12.84
^{135}Sb	16.32	16.58
^{136}Sb	18.81	19.47
^{134}Te	20.81	20.57
^{135}Te	23.82	23.83
^{136}Te	28.26	28.60
^{137}Te	31.15	31.55
^{136}Xe	40.32	39.04
^{137}Xe	43.83	43.06
^{138}Xe	48.89	48.73

the present ones. This is because here we use a different energy value for the the neutron $2p_{1/2}$ level and the mass excesses measured in [4]. From Table I, we see that the experimental data are remarkably well reproduced by the theory, the largest discrepancy not exceeding 3%. It should be emphasized that for all 12 nuclei considered we have used a unique Hamiltonian with a realistic two-body effective interaction containing no free parameters.

Making use of the binding energies of ^{134}Sn, $^{134-136}$Te, and $^{136-138}$Xe reported in Table I and of those obtained for ^{130}Sn, $^{132-133}$Te, and $^{134-135}$Xe, we have calculated the neutron OES, as given by the three-point formula [20,21]

$$\Delta^{(3)}(N,Z) = \tfrac{1}{2}[B(N+1,Z) + B(N-1,Z) - 2B(N,Z)], \quad (1)$$

for the $N = 81$ isotones ^{131}Sn, ^{133}Te, and ^{135}Xe and for the $N = 83$ isotones ^{133}Sn, ^{135}Te, and ^{137}Xe.

In Fig. 1 we compare the calculated OES values with the experimental ones. We see that the agreement between theory and experiment is very good. In particular, our calculations quantitatively describe the gap between the $N = 81$ and 83 lines at $Z = 50$ as well as its decrease when adding two and four protons, which confirms the reliability of the various components of our effective interactions.

The drop of about 0.5 MeV in the observed OES for Sn when crossing $N = 82$ is accounted for by the different pairing properties of our effective interaction for neutron particles and holes with respect to the $N = 82$ closed shell. In fact, the $J^\pi = 0^+$ matrix elements, which are the only ones entering the calculation of the ground-state energies of ^{134}Sn and ^{130}Sn, are overall less attractive for the former. For instance, the $J^\pi = 0^+$ diagonal matrix element for the $(1f_{7/2})^2$ configuration, which dominates the ground-state wave function of ^{134}Sn, is -0.65 MeV, namely, about 0.5 MeV less attractive than that for

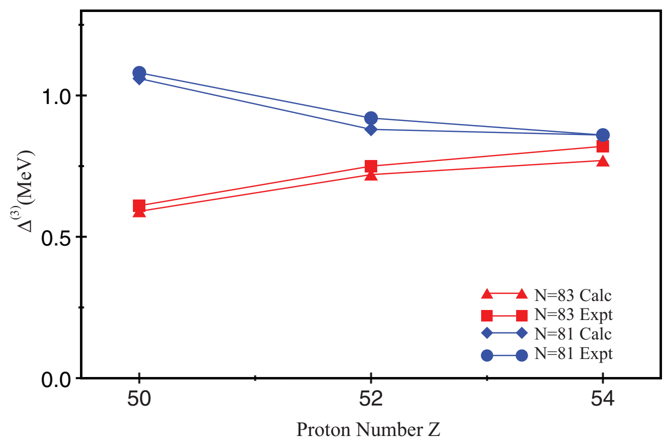

FIG. 1. (Color online) Calculated and experimental odd-even staggering for the $N = 81$ and 83 isotones.

the $(0h_{11/2})^{-2}$ configuration, whose role is very relevant to the ground state of ^{130}Sn. In previous works [5,22] we have investigated the microscopic origin of the paring force above the $N = 82$ shell within our derivation of the effective interaction. We have analyzed the various perturbative contributions and found that the reduction of the pairing component is due to the minor role played by the one-particle–one-hole excitations, which are instead responsible for a "normal" pairing below this shell. It is worth mentioning that the difference in the pairing force across $N = 82$ was also shown to be crucial in reproducing the asymmetric behavior of the yrast 2^+ state in tin and tellurium isotopes with respect to $N = 82$ [23,24].

When going to Te and Xe, the $N = 81$ and 83 lines come closer to each other as a result of the proton-neutron effective interaction. The two lines would be indeed parallel should one ignore this interaction. From Fig. 1, we see that the p-n interaction has an opposite effect on the $N = 81$ and $N = 83$ isotones, which is clearly related to its repulsive and attractive nature in the particle-hole and particle-particle channel, respectively. On the other hand, this effect is not very large either in ^{133,135}Te or in ^{135,137}Xe, since it results essentially from the difference between the contributions of the p-n interaction to the energies of the odd and neighboring even isotopes. It makes, however, the OES almost equal in ^{135}Xe and ^{137}Xe, as is experimentally observed.

In summary, we have shown that there is no anomaly in the OES of binding energies around ^{132}Sn, as it is fully explained in terms of the shell model with realistic effective interactions which are just the same as those employed in our previous studies [5–7] in the ^{132}Sn region.

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