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Pairing correlations in high-spin isomers

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High-spin isomers with $J^\pi = 49/2^+$ and 27^+ have been systematically observed in a number of $N = 83$ isotones with $60 \leqslant Z \leqslant 67$ at excitation energies ~9 MeV. Based on experimental excitation energies, an odd-even binding energy staggering has been extracted for the first time for these multi-quasiparticle states. Surprisingly, the magnitude of the odd-even effect in high-spin isomers turned out to be very close to that in ground states, thus challenging conventional wisdom that pairing correlations are reduced in highly excited states. Theoretical analysis based on mean-field theory explains the observed proton number dependence of the odd-even effect as a manifestation of strong pairing correlations in the highly excited states. Mean-field effects and the proton-neutron residual interaction on the odd-even staggering are also examined.

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Nuclear high-spin isomers (HSI) are known to be excellent laboratories for observing transition from superfluid to normal motion. Because those states are formed by the blocking of single-particle levels near the Fermi surface (i.e., by consecutive increase of the degree of quasiparticle excitation or seniority), their structure reflects the gradual decrease of pairing correlations with energy and angular momentum [1–4]. There exists an extensive literature on the subject of pairing phase transition (see Ref. [5] and references therein). In particular, in the context of HSI [2], the pairing gap exhibits successive reductions with the seniority quantum number. Although the dynamics of the superfluid-to-normal transition is an interesting subject in itself, the subject of this work is to study pairing correlations in specific HSI.

Pairing energies are not directly accessible in experiment, so other kinds of data are needed to learn about their magnitude. In this work, we investigate the traditional indicator of pairing correlations, the odd-even mass difference. To this end, we employ the unique experimental data set for HSI in the $N = 83$ isotones: ^{143}Nd [6], ^{144}Pm [7], ^{145}Sm [8], ^{146}Eu [9], ^{147}Gd [10,11], ^{148}Tb [12], ^{149}Dy [13], and ^{150}Ho [14]. The excitation energies of those HSI, in particular the $J^\pi = 49/2^+$ isomers in odd-Z nuclei and the $J^\pi = 27^+$ isomers in odd-odd nuclei, are shown in Fig. 1. The level schemes were constructed based on prompt and delayed $\gamma\gamma$ coincidences. Angular momentum assignments of HSI were made by analyzing angular distributions of γ rays, and parities of the states in ^{143}Nd were determined from linear polarization measurements. Lifetimes of isomeric states have been found to be between ~10 ns and ~2 μs, and their excitation energies turned out to be almost constant, between 8.5 and 9.0 MeV.

From the measurements of g factors, the structure of HSI in odd-Z nuclei ^{143}Nd [15], ^{147}Gd [16], and ^{149}Dy [17] was experimentally determined to be a seniority-five, stretched shell-model configuration $[\nu(f_{7/2}h_{9/2}i_{13/2}) \otimes \pi h^2_{11/2}]^+_{49/2}$. The oblate deformation parameter, $\beta_2 = -0.19$, of the $J^\pi = 49/2^+$ HSI in ^{147}Gd has been deduced from the experimental static quadrupole moment [18,19].

The systematic information on the HSI excitation energy and the ground-state (GS) mass enables us to determine the absolute binding energies $B(N, Z)$ in HSI from which the odd-even binding energy staggering (OES) can be extracted, in a similar way as was done for GS [20]. In the context of pairing correlations, of particular interest is the three-point indicator $[B(N, Z) \equiv B(Z) < 0]$:

$$\Delta(Z) = \frac{(-1)^Z}{2}[B(Z-1) + B(Z+1) - 2B(Z)], \qquad (1)$$

which is often interpreted as a measure of the proton pairing gap (see Refs. [21,22] and references quoted therein). The most striking feature exhibited by the HSI data set of Fig. 1 is a constancy of excitation energies of HSI. Since $\Delta(Z)$ is not influenced by a constant shift in the binding energy, the experimental values of $\Delta(Z)$ for GS and HSI are fairly close (see Fig. 2). The exceptions are ^{144}Pm and ^{145}Sm, where the HSI values are reduced by ~30% and ~10%, respectively. Taken at face value, this result implies that the proton correlations in the $N = 83$ isotones are not reduced in HSI, that is, the blocking effect does not seem to be present. Of course, this conclusion depends critically on the interpretation of $\Delta(Z)$ as a measure of the pairing gap.

To get some insight into the nature of $\Delta(Z)$ in HSI, it is instructive to first consider the situation without pairing. For this, we carried out Skyrme-Hartree-Fock (SHF) calculations for GS and HSI configurations. Guided by experimental results, we assumed the following fully aligned single-particle (sp) configurations: $[\nu(f_{7/2}h_{9/2}i_{13/2}) \otimes \pi(h^2_{11/2})]^+_{49/2}$

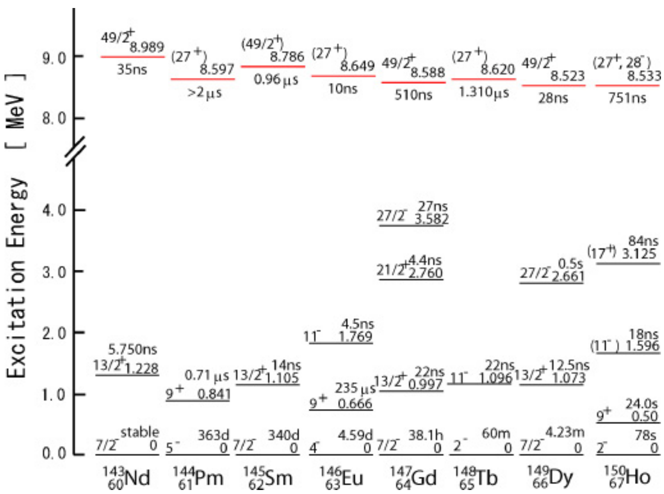

FIG. 1. (Color online) Systematics of the experimentally determined HSI in $N = 83$ isotones. These results are taken from Refs. [6] for ^{143}Nd, [7] for ^{144}Pm, [8] for ^{145}Sm, [9] for ^{146}Eu, [10,11] for ^{147}Gd, [12] for ^{148}Tb, [13], for ^{149}Dy, and [14] for ^{150}Ho.

(labeled as C$_\circ$ in the following) for odd $N = 83$ isotones and $[\nu(f_{7/2}h_{9/2}i_{13/2})\otimes\ \pi(d^{-1}_{5/2}h^{2}_{11/2})]^{+}_{27}$ for odd-odd systems (C$_{\circ\circ}$). The calculations have been carried out using the HFODD code [23] and the two different Skyrme parametrizations: SLy4 [24] and SkO [25]. Our self-consistent calculations confirm that these stretched configurations have oblate shapes with $\beta_2 \approx -0.20$, in good agreement with experiment. According to our SHF model, both HSI configurations considered are yrast, except for the heaviest nucleus ^{150}Ho, where an aligned

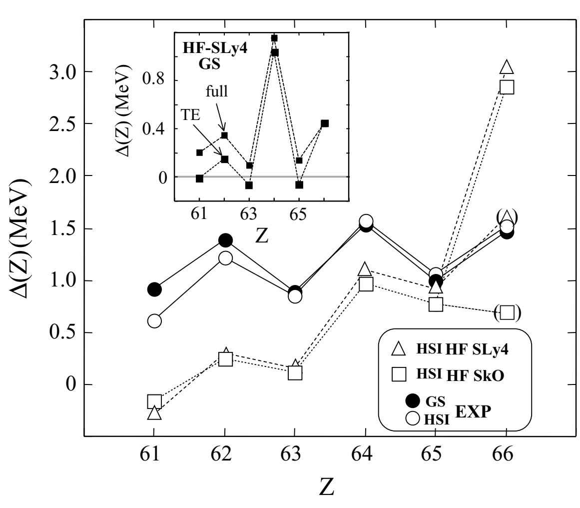

FIG. 2. Experimental (dots, solid line) and theoretical (squares) values of $\Delta(Z)$ for GS (closed symbols) and HSI (open symbols) configurations in the $N = 83$ isotones. Calculations for fixed HSI configurations C$_\text{o}$ and C$_\text{oo}$ were carried out within the SHF-SLy4 (dashed line) and the SHF-SkO (dotted line) models without pairing. The alternative results for ^{150}Ho, corresponding to a different structure of HSI, are marked by parentheses. The inset displays the GS values of $\Delta(Z)$ calculated within the SHF-SLy4 model with and without the time-odd fields. See text for details.

configuration $[\nu(f_{7/2}h_{9/2}s_{1/2})\otimes\ \pi(d^{-1}_{5/2}h^{4}_{11/2})]^{+}_{27}$ appears to be favored energetically.

The SHF values of $\Delta(Z)$, shown in Fig. 2, are very similar in both Skyrme parametrizations used. For the primary configurations C$_\text{o}$ and C$_\text{oo}$, $\Delta(Z)$ increases from $Z = 61$ ($\approx$0) to $Z = 66$ ($\approx$3 MeV), exhibiting a clear OES. This overall increase can be easily understood within the extreme sp scenario of Refs. [21,22]. Since the occupancy of the $\pi h_{11/2}$ shell is fixed (with the two lowest proton routhians originating from the spherical $h_{11/2}$ shell occupied), the SHF value of $\Delta(Z)$ simply reflects the difference between the energy of the highest occupied positive parity sp level and the energy of the Nilsson [402]5/2 hole orbital originating from $d_{5/2}$. In $Z < 64$ the highest lying positive-parity proton moves within the $d_{5/2}$ shell; hence $\Delta(Z) \approx 0$. However, for greater values of Z, the valence proton moves in the $s_{1/2}$ and $d_{3/2}$ orbits and this leads to larger values of $\Delta(Z)$. This sp mechanism behind the steep increase in $\Delta(Z)$ versus Z is fairly robust. Indeed, within the sp model, the only way to overturn this (unobserved) trend is by breaking more proton pairs and occupying more aligned $\pi h_{11/2}$ orbitals. Our SHF calculations admit such a possibility but only for ^{150}Ho (see Fig. 2).

The inset in Fig. 2 shows $\Delta(Z)$ extracted from the unpaired GS binding energies obtained in SHF-SLy4. The calculated GS values of $\Delta(Z)$ show a characteristic staggering behavior, reflecting the sp shell structure [21,22,26]. Namely, $\Delta(Z)$ is small for odd-Z systems whereas it is appreciable for even values of Z, where it is related to the energy splitting between the single-proton levels at the Fermi surface. [The large value of $\Delta(Z)$ at $Z = 64$ can be associated with the proton subshell closure at this particle number.] This result clearly indicates that, particularly in the weak-pairing regime, experimental values of $\Delta(Z$ even) may contain a large sp contribution. According to Ref. [26], which establishes a relation between self-consistently calculated average pairing gaps and $\Delta(Z$ odd), the average proton pairing gap around $A = 144$ is $\Delta_p = 4.52/A^{1/3} \approx 0.860$ MeV. This estimate is consistent with experimental values for odd-Z nuclei shown in Fig. 2. Hence, a large part of OES in $\Delta(Z)$ seen in the $N = 83$ data set is, most likely, due to the sp contribution. Although the sp contribution to $\Delta(Z)$ in GS may be reduced by centering the mass filter at odd values of Z, the SHF calculations do not provide any simple ansatz for extracting the sp component to $\Delta(Z)$ in HSI.

The residual proton-neutron (pn) interaction between the valence nucleons in odd-odd nuclei, $\delta_{pn}(A)$, is known [20] to lower the OES with respect to the pairing gap: $\Delta(Z) = \Delta_\text{pair}(Z) - \delta_{pn}(A)$. [For even Z, $\delta_{pn}(A)$ should be understood as the arithmetic average over the neighboring o-o nuclei.] The values of $\delta_{pn}(A)$, extracted directly from the binding energies using a nine-point mass filter [20], are shown in the inset in Fig. 3. They vary between 150 and 250 keV, consistent with phenomenological estimates [20,27].

There are other effects that can impact the calculated values of $\Delta(Z)$. In particular, a contribution to OES can come from the time-odd (TO) terms (nuclear magnetism) present in the nuclear mean field in odd and odd-odd nuclei or at high spins (see Ref. [28] for an overview). For GS configurations, our unpaired SHF calculations predict the TO contribution to

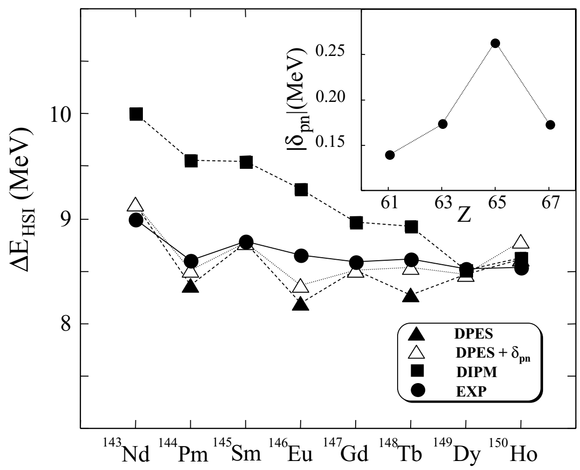

FIG. 3. Experimental (filled circles) and theoretical (DIPM: squares; DPES: triangles) excitation energies of HSI in the $N = 83$ isotones. Open triangles show the DPES calculations corrected by the pn residual interaction δ_{pn}. The inset displays $\delta_{pn}(A)$ in o-o nuclei extracted from nuclear binding energies using the nine-point indicator of Ref. [20].

$\Delta(Z)$ to be ~200 keV (see inset in Fig. 2). Interestingly, the TO effect on $\Delta(Z)$ in HSI is about -220 keV, that is, the nuclear magnetism contributes differently to OES in low- and high-spin states by effectively reducing the difference between corresponding $\Delta(Z)$ values.

Pairing correlations usually give a large contribution to $\Delta(Z)$ [21,22]. In this study, pairing properties of GS and HSI configurations have been studied using two different theoretical approaches: The deformed independent particle model (DIPM) [29] and the diabatic potential energy surface model (DPES) [30]. In DIPM, high-J multi-quasiparticle states are obtained by means of an axially symmetric deformed Woods-Saxon potential with empirically deduced spherical single-particle energies. The pairing energy is calculated by using the seniority monopole pairing Hamiltonian treated self-consistently, including blocking within the exact particle-number projection to prevent pairing collapse. The pairing strength has been obtained according to the average gap method with $\tilde{\Delta} = 14/\sqrt{A}$ MeV [31], and the excitation energy of HSI is calculated using the Strutinsky shell-correction method.

The DPES method is also based on the shell-correction method but it approximates the nuclear mean field by a triaxially deformed Woods-Saxon potential with the parameter set of Ref. [32]. The many-quasiparticle configuration is tracked diabatically over the entire potential energy surface by using the average asymptotic quantum numbers of the blocked levels. In the pairing channel, DPES employs the seniority monopole pairing interaction with blocking treated self-consistently using the approximate particle-number projection [33]. Usually, the strength of the monopole pairing interaction ($G_{\rm MN}$) is calculated using the average gap method of Möller and Nix [34]. It was, however, pointed out in Refs. [30,35] that an explicit inclusion of shape and blocking effects results in systematically larger pair gaps. To obtain correct excitation energies of the HSI, we were forced to enhance the strength by ~15%, that is, slightly more than the ~10% enhancement advocated in Refs. [30,35].

For the $N = 83$ isotones, both DIPM and DPES methods yield fairly consistent results. Namely, both methods predict (i) weakly deformed ground states (ii) well-deformed, oblate ($\beta_2 \approx -0.2$) HSI states (without triaxiality in the case of DPES), and (iii) C_o and C_{oo} yrast HSI configurations. The only exception is ^{150}Ho, where DPES predicts the C_{oo} configuration to lie ~150 keV above the HSI configuration involving four aligned $h_{11/2}$ protons.

The calculated excitation energies of HSI, $\Delta E_{\rm HSI}$, slightly depend on the model used (see Fig. 3). The DIPM model predicts a smooth decrease in $\Delta E_{\rm HSI}$ as a function of Z against the empirical trend. For the lighter isotones, DIPM overestimates experimental data by ~1 MeV yielding, however, very good results for ^{149}Dy and ^{150}Ho. The DPES model does very well on $\Delta E_{\rm HSI}$, especially for even-Z nuclei. For odd-Z nuclei, the agreement is slightly worse, suggesting that the blocking effect is probably too strong. Part of this odd-even dependence can be, however, related to the residual pn interaction. Indeed, correcting the GS energies by empirical values of δ_{pn} (see inset in Fig. 3) leads to a reasonably good overall agreement between experiment and DPES. It is worth noting, that the reduction in pairing strength to $1.1G_{\rm MN}$ shifts the entire $\Delta E_{\rm HSI}(Z)$ curve down by ~450 keV, without affecting its pattern.

Figure 4 (top) displays experimental and DPES values of $\Delta(Z)$. Although theory overestimates experimental data, the OES in $\Delta(Z)$ is reproduced very well. Phenomenological corrections resulting from the pn residual interaction lower the difference between the experiment and the theory by ~200 keV but do not cure the problem. In particular, the empirically observed similarity $\Delta^{\rm (exp)}_{\rm GS}(Z) \approx \Delta^{\rm (exp)}_{\rm HSI}(Z)$ is not reproduced. To see the effect of the pairing channel alone, DPES and DIPM proton pairing gap parameters, $\Delta_p^{\rm proj}$, are displayed in Fig. 4 (bottom). Both calculations incorporate particle-number fluctuations by means of an exact or approximate projection and the resulting $\Delta_p^{\rm proj}$ values are very close.

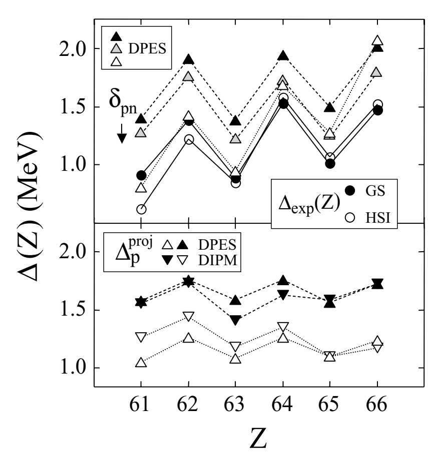

FIG. 4. Top: $\Delta(Z)$ of Eq. (1) calculated in DPES filled (open) symbols denote GS (HSI) values. The effect of δ_{pn} on GS DPES values is indicated (gray triangles). Experimental values of $\Delta(Z)$ are marked by dots. Bottom: Calculated values of the proton pairing gap parameter, $\Delta_p^{\rm proj}$, in DIPM and DPES.

It is seen that the amount of pairing reduction in DPES when going from GS to HSI seen in Δ_p^{proj} is close to that in $\Delta(Z)$. This suggests that reduction of pairing caused by blocking is slightly overestimated by theory.

In summary, the HSI with $J^\pi = 49/2^+$ and 27^+ were systematically observed at very similar excitation energies, $\Delta E_{\mathrm{HSI}} = 8.5$–$9.0$ MeV, in the $N = 83$ isotones with $60 \leqslant Z \leqslant 67$. The OES of binding energies of HSI was extracted empirically for the first time and has been found to be very close to that of the GS. A theoretical analysis has been carried out in terms of the self-consistent unpaired SHF formalism and the deformed mean-field theory with pairing, involving self-consistent blocking and particle-number projection. Only when the dynamical pairing and the mean-field effects are simultaneously included in DPES does one obtain excellent reproduction of experimental particle-number dependence of the OES in $\Delta(Z)$. These experimental and theoretical results suggest that the pairing effects are substantially strong in HSI, in spite of their high seniority. The role of the residual proton-neutron interaction is also examined in the $\Delta(Z)$ values. Although the observed particle-number dependence of the OES both in GS and HSI well reproduced, the theoretical models give somewhat stronger reduction of the OES in HSI than in GS. This problem is still requires future work.

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