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MIRROR ENERGY DIFFERENCE AT HIGH SPINS IN THE MIRROR PAIR ^{67}Se AND ^{67}As*

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We investigate large mirror energy differences (MED) between high-spin states in the mirror nuclei ^{67}Se and ^{67}As. By employing large-scale shell model calculations, we show that the electromagnetic spin-orbit interaction and the Coulomb monopole radial term are important for the observed large MED in this mirror pair. It is clarified that this large MED is attributed to the proton pair excitations from the $p_{3/2}$ and $f_{7/2}$ orbits to the $g_{9/2}$ orbit and the spin alignment of the $g_{9/2}$ protons at high spins.

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1. Introduction

Isospin symmetry breaking due to the Coulomb force and the strong nucleon–nucleon (NN) interaction is one of the current topics in nuclear structure physics [1]. As well known, the Coulomb effects and the isospin nonconserving NN interaction break this symmetry, leading to observable differences between energy levels of analogue states. The so-called mirror energy differences (MED) are defined by

$$\mathrm{MED}_J = E_x(J,T,T_z=-T) - E_x(J,T,T_z=T)\,, \tag{1}$$

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where $E_x(J, T, T_z)$ are the excitation energies of analogue states with spin J and isospin T, T_z. For mirror nuclei in the upper part of the fp shell, the experimental information on MED is relatively scarce. Recently, new data on the $A = 67$ mirror nuclei ^{67}Se and ^{67}As, the heaviest pair where the MED has been observed so far, have become available [2]. The positive-parity band built on the $9/2^+$ state has been observed up to high spin in ^{67}As [3, 4], and has been recently determined for the mirror partner ^{67}Se [5]. The neutron spin alignment is expected to occur at spin $25/2^+$ in ^{67}As [6, 7]. On the other hand, the proton spin alignment takes place at the same spin in its mirror partner ^{67}Se. As the response to the Coulomb field is different for the corresponding high-spin states in such mirror nuclei, one expects the Coulomb based MED contribution in ^{67}Se and ^{67}As to give large negative value suddenly at $25/2^+$ where the proton/neutron spin alignment occurs.

2. Model

Employing the recently proposed JUN45 interaction [7], the calculations are performed using the spherical shell model in the $pf_{5/2}g_{9/2}$ model space. Following Zuker's procedure [8], the Coulomb interaction is separated into a monopole term $V_{\rm Cm}$ and a multipole term $V_{\rm CM}$. While $V_{\rm Cm}$ accounts for single-particle and bulk effects, $V_{\rm CM}$ contains all the rest. The monopole term $V_{\rm Cm}$ is further divided into the single particle correction ε_{ll}, the radial term $V_{\rm Cr}$ and the spin orbit term ε_{ls}.

With inclusion of $V_{\rm CM}$, ε_{ll} and ε_{ls}, shell-model calculations are carried out in the $pf_{5/2}g_{9/2}$ shell for the $A = 67$ mirror nuclei. The Coulomb matrix elements in the valence space represent the multipole part $V_{\rm CM}$ of the Coulomb interaction. The contribution of ε_{ll} to the monopole term is given by [9]. The single-particle shift ε_{ls} takes into account the relativistic spin-orbit interaction. The radial term $V_{\rm Cr}$ reflects the change in radii along the rotational band, and in the fp shell is proportional to the change in occupancy of the $p_{3/2}$ orbit as a function of spin J. It can be expressed as $\Delta_{\rm MED}(V_{\rm Cr}) = a_m(\langle m_{p3/2}\rangle_{9/2}/2 - \langle m_{p3/2}\rangle_J/2)$, where $\langle m_{p3/2}\rangle_J$ with $m_{p3/2} = z_{p3/2} + n_{p3/2}$ is the expectation value of the proton and neutron number in the $p_{3/2}$ orbit at spin J, and a_m was fix so as to fit the experimental MED of the positive-parity high-spin states. In this work, the isospin nonconserving term was neglected. After solving the eigenvalue problem, contribution of the Coulomb monopole radial term $V_{\rm Cr}$ is included into the energy obtained in the shell model calculation.

3. Numerical calculations and discussions

For ^{67}Se and ^{67}As, the calculation with the JUN45 interaction reproduces well the experimental data, where the energy differences of the analogue states are in a reasonable agreement with experiment. The structure of the negative-parity states at low-excitation energies are mainly dominated by the fp shell configurations, but the positive-parity states built at higher spin mainly involve the $g_{9/2}$ orbit. The structural difference of such configurations strongly reduces the transition strengths explaining the isomeric character of the $9/2^+$ levels [6].

In Fig. 1(a), the experimental MED along the positive-parity excited band with $\Delta J = 2$ built on the $9/2^+$ state and the low-lying negative-parity states $(3/2^-, 5/2^-, 7/2^-)$ are compared with the calculations as a function of spin $2J$. The agreement is excellent and the calculation reproduces well the large negative value in the MED at the high-spin $21/2^+$ and $25/2^+$ states.

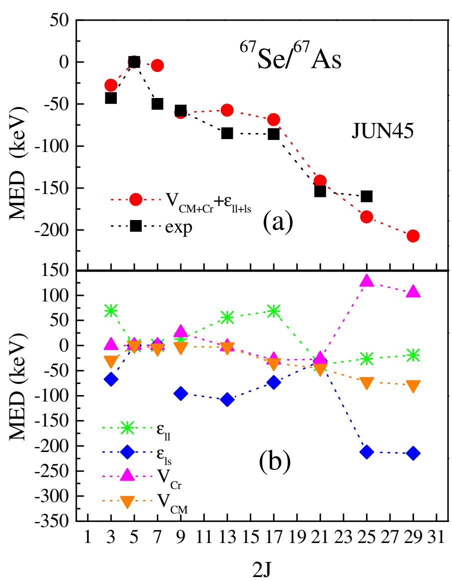

Fig. 1. Comparison of calculated MED with available data, and decomposition of theoretical MED into four terms (see text for explanation).

We now examine which terms contribute to such drastic changes in the MED. In order to see this, the four different contributions to MED have been plotted separately in Fig. 1(b). The Coulomb multipole term $V_{\rm CM}$ reflects the alignment effects at high spin and follows the negative trend of the MED. For ^{67}Se, two protons and one neutron jump up from the fp-shell to $g_{9/2}$ at spin of $25/2^+$ and $29/2^+$. The spin alignment of the two protons in the $g_{9/2}$ orbit increases the spatial separation between them, leading to a smaller Coulomb energy. Thus, the alignment effect for protons reduces the excitation energy in ^{67}Se while the same does not happen in the analogue states in ^{67}As. However, the V_{CM} term alone underestimates the MED by a factor of three (see in Fig. 1(b)). The contribution of the ε_{ll} term is only marginal, but V_{Cr} gives the largest positive contribution for the $25/2^+$ and $29/2^+$ states due to the increased occupation of the $g_{9/2}$ orbit. On the other hand, the ε_{ls} contribution to the MED is strongly negative for the $25/2^+$ and $29/2^+$ spin values. When the V_{Cr}, V_{CM}, ε_{ls} and ε_{ll} terms are all included, the theoretical MED reproduce well the experimental data.

4. Conclusion

We investigated the MED between high-spin states in the mirror pair ^{67}Se and ^{67}As using large-scale shell model calculations. It has been shown that the electromagnetic spin-orbit interaction and the Coulomb monopole radial term are responsible for producing the large MED at high-spin states, while the contribution from the Coulomb multipole term is small. The occupations of the relevant orbits and the spin alignment in the $g_{9/2}$ orbit affect the variation of the MED along the band built on the $9/2^+$ state. We obtained a good agreement with the experimental data for the MED.

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