Reduction of $N = 28$ shell gap in light neutron-rich nuclei

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Introduction

The nuclei in the vicinity of closed shells are generally stable and spherical. The magic number $N = 28$ originates from spin-orbit (SO) coupling in the atomic nuclei. This SO interaction lowers the $f_{7/2}$ orbital into middle of gap between sd and fp shells, resulting in the magic number between $f_{7/2}$ and $p_{3/2}$ orbitals [1]. The existence or disappearance of a shell closure is possibly linked to the evolution of SO force. The reduction of SO interaction and hence shell gaps would occur for neutron-rich nuclei with increasing in surface diffuseness. The erosion of $N = 28$ shell closure has been studied both theoretically and experimentally and is an interesting topic in nuclear physics.

Theoretical Framework

The Lagrangian density for point-coupling model can be written as [2]

$$\begin{aligned}\mathcal{L} &= \overline{\psi}(i\gamma.\partial - m)\psi - \frac{1}{2}\alpha_S(\rho)(\overline{\psi}\psi)(\overline{\psi}\psi)\\ &-\frac{1}{2}\alpha_V(\rho)(\overline{\psi}\gamma^\mu\psi)(\overline{\psi}\gamma_\mu\psi)\\ &-\frac{1}{2}\alpha_{TV}(\rho)(\overline{\psi}\vec{\tau}\gamma^\mu\psi)(\overline{\psi}\vec{\tau}\gamma_\mu\psi)\\ &-\frac{1}{2}\delta_S(\partial_\nu\overline{\psi}\psi)(\partial^\nu\overline{\psi}\psi) - e\overline{\psi}\gamma.\mathbf{A}\frac{1-\tau_3}{2}\psi,\end{aligned}$$

where m is the mass of nucleon, α_S, α_V and α_{TV} represent the coupling constants for four-fermion contact terms. The microscopic density-dependent scalar and vector self-energies are computed by using following functional form of the couplings.

$$\alpha_i(\rho) = a_i + (b_i + c_i x)e^{-d_i x}, \qquad (i = S, V, TV) \tag{1}$$

where $x = \rho/\rho_{sat}$ denotes the nucleon density in symmetric nuclear matter at saturation point ρ_{sat}. The parameters involved in point coupling CDFT model are given in Ref. [2].

It is necessary to consider pairing correlations for a quantitative description of open-shell nuclei. A separable pairing interaction has been used in the present investigation. The details about pairing interaction can be found in Ref. [3]. The calculations are performed by imposing constraints on the axial and triaxial mass quadrupole moments [4].

Results and Discussion

The evolution of proton and neutron single-particle energies are necessary to understand the role of nuclear forces involved around $N = 28$ magic shell. The middle panel of Fig. 1 shows the binding energies of the neutron states located just above and just below the $N = 28$ shell closure. The difference of the binding energy of the two states, surrounding the gaps at $N = 28$ shell closure, is shown in the upper panel of Fig. 1. A reduction of $N = 28$ spherical shell gap has been observed clearly towards the neutron-rich side. ^{48}Ca exhibits a large shell gap between occupied and valance orbits around Fermi level that prevent any excitation and lead to a spherical shape. The mixing between f and p states may result in the reduction of the spherical shell gap. Thus, the nucleus may get deformed. This change of structural behavior can partly be ascribed to the evolution of proton single-particle energies. The lower panel of Fig. 1 shows the shell structure of $1d_{5/2}$, $2s_{1/2}$, and $1d_{3/2}$ orbits as a function of proton number. The energy spacing between $\pi d_{3/2}$ and $\pi s_{1/2}$ orbitals

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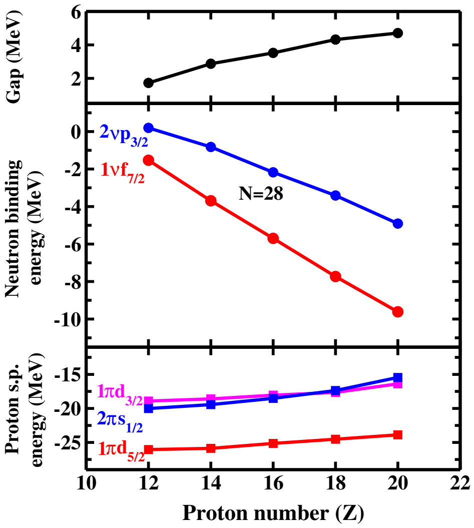

FIG. 1: (Color online) Binding energies of the neutron states located just above and just below the $N = 28$ shell closure. The difference of the binding energy of the two states is shown in upper panel. The lower panel shows the proton single-particle energies for $N = 28$ isotones.

almost vanished at N =28. The filling of neutron $1f_{7/2}$ shell induce the near degeneracy of $\pi d_{3/2}$ & $\pi s_{1/2}$ orbitals and reduction of $\pi d_{5/2}$-$\pi s_{1/2}$ splitting. These reductions are immense to develop quadrupole excitations in neutron-rich nuclei.

Fig.2 presents the 2D contour plots of potential energy surfaces (PESs) in the $\beta_2 - \gamma$ plane. The evolution of shapes and fragility of $N = 28$ shell gap can be observed in binding energy maps. A well deformed minima have been observed for these isotones. In the case of ^{40}Mg, the ground state minimum is observed along the prolate side with quadrupole deformation parameter $\beta_2 = 0.45$. While an oblate shape can be depicted for ^{42}Si. An interesting case is seen for ^{44}S exhibiting an oblate-prolate coexistence with prolate minima as the deepest solution. An oblate ground-state minimum is observed for ^{46}Ar. The spherical shape is restored in case of doubly magic ^{48}Ca nucleus. The values of absolute minima for N = 28 isotones are given in Table 1.

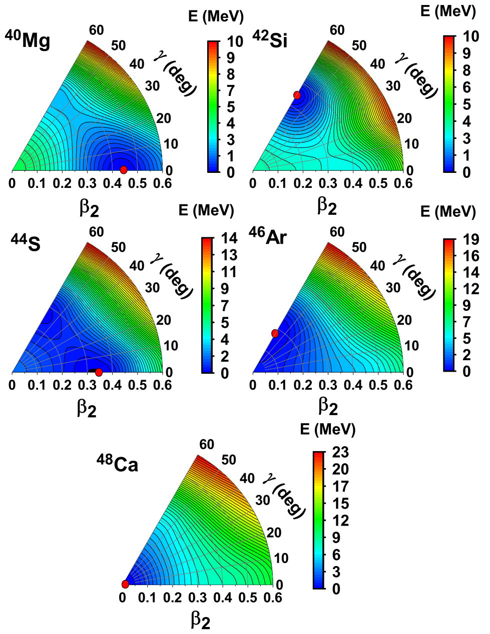

FIG. 2: (Color online) The potential energy surfaces (PESs) of $N = 28$ isotones in the $\beta_2 - \gamma$ plane.

TABLE I: The location of absolute minima (β_2, γ) of the PESs for $N = 28$ isotones.

Nucleus	β_2	γ
^{40}Mg	0.45	0°
^{42}Si	0.35	60°
^{44}S	0.34	0°
^{46}Ar	0.19	60°
^{48}Ca	0	0°

Acknowledgments

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