Shape Coexistence in N = 28 Isotones

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Shape coexistence is one of the important nuclear phenomenon which appears throughout the periodic chart from light mass nuclei to superheavy nuclei. The evolution of ground-state shapes in an isotopic or isotonic chain is governed by changes of the shell structure of single-nucleon orbitals. In recent past, evolution of shell structure guiding shape coexistence, has been observed in the N = 20 and N = 28 isotones around proton drip line [1–4] A number of experimental investigations have shown [3, 5] that in the proton-deficient N = 28 isotones below ^{48}Ca the spherical shell gap is progressively reduced and the low-energy spectra of ^{46}Ar, ^{44}S, and ^{42}Si display evidence of ground-state deformation and shape-coexistence. In this paper we have investigated shape coexistence phenomenon for N = 28 isotones in the vicinity of proton drip line using Relativistic Mean Field plus BCS approach [6, 7]. Our RMF calculations have been carried out using the model Lagrangian density with nonlinear terms both for the σ and ω mesons as described in detail in Ref. [7].

$$
\begin{aligned}
\mathcal{L} &= \bar{\psi}[\imath\gamma^{\mu}\partial_{\mu} - M]\psi + \frac{1}{2}\,\partial_{\mu}\sigma\partial^{\mu}\sigma - \frac{1}{2}m_{\sigma}^{2}\sigma^{2} \\
&\quad - \frac{1}{3}g_{2}\sigma^{3} - \frac{1}{4}g_{3}\sigma^{4} - g_{\sigma}\bar{\psi}\sigma\psi - \frac{1}{4}H_{\mu\nu}H^{\mu\nu} \\
&\quad + \frac{1}{2}m_{\omega}^{2}\omega_{\mu}\omega^{\mu} + \frac{1}{4}c_{3}(\omega_{\mu}\omega^{\mu})^{2} - g_{\omega}\bar{\psi}\gamma^{\mu}\psi\omega_{\mu} \\
&\quad - \frac{1}{4}G_{\mu\nu}^{a}G^{a\mu\nu} + \frac{1}{2}m_{\rho}^{2}\rho_{\mu}^{a}\rho^{a\mu} - g_{\rho}\bar{\psi}\gamma_{\mu}\tau^{a}\psi\rho^{\mu a} \\
&\quad - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - e\bar{\psi}\gamma_{\mu}\frac{(1-\tau_{3})}{2}A^{\mu}\psi
\end{aligned}
$$

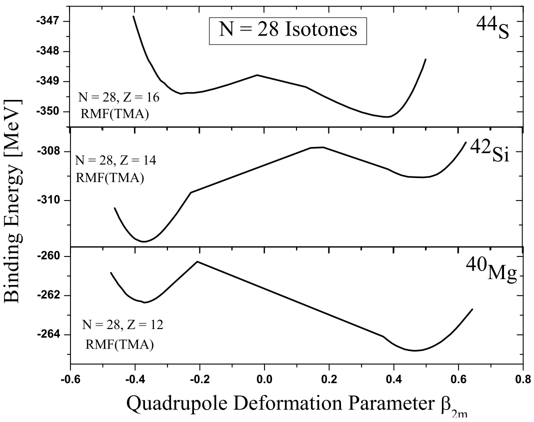

FIG. 1: The potential energy surface of N = 28 isotones (^{40}Mg, ^{42}Si, ^{44}S) as a function of the deformation parameter β_{2m}.

where the field tensors H, G and F for the vector fields are defined by

$$
\begin{aligned}
H_{\mu\nu} &= \partial_{\mu}\omega_{\nu} - \partial_{\nu}\omega_{\mu} \\
G_{\mu\nu}^{a} &= \partial_{\mu}\rho_{\nu}^{a} - \partial_{\nu}\rho_{\mu}^{a} - 2g_{\rho}\,\epsilon^{abc}\rho_{\mu}^{b}\rho_{\nu}^{c} \\
F_{\mu\nu} &= \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}\ ,
\end{aligned}
$$

and other symbols have their usual meaning.

As established, we have found spherical configuration of doubly-magic ^{48}Ca with one sharp minima at $\beta_{2m} = 0$. The binding energy maps exhibits variety of rapidly evolving shapes after successive removals of proton pairs from ^{48}Ca. This variation of binding energy is shown in Fig. 1 with respect to quadrupole deformation parameter β_{2m} for N = 28 isotones. By removing a pair of protons from ^{48}Ca, the energy surface of the corresponding isotone ^{46}Ar becomes soft with a shallow extended minimum along the oblate axis (not shown here). After another removal of proton pair we predicts a coexistence of pro-

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TABLE I: Results of excitation energy as obtained in the deformed RMF calculations using TMA force parameters. There energies are compared with other theoretical and experimental results [1, 8–10].

Nucleus	Excitation Energy (MeV)		
	RMF(TMA)	Others	
^{44}S	0.77	1.36 [8]	0.2 [1]
^{42}Si	2.6	2.5 MeV [9]	1.5 [1]
^{40}Mg	3.5	1.38 [10]	

late and oblate minima at β_{2m} = 0.38 and -0.26 respectively for the nucleus ^{44}S as can be observed from upper panel of Fig. 1. These two minima are separated only by an excitation energy of 0.77 MeV and, therefore, one expects to find pronounced mixing of prolate and oblate configurations in the low-energy collective states of this nucleus. Next, for ^{42}Si the binding energy displays a deep oblate minimum at β_{2m} = - 0.37 whereas second prolate minimum is found at β_{2m} = 0.49 with an excitation energy of 2.6 MeV as can be seen from middle panel of Fig. 1. These results are similar to the results as obtained from RHB theory by Lalazissis et al. [1] and energy Density Functional analysis of shape evolution in N = 28 isotones [4]. Moving further, with another proton pair removed, the very neutron-rich nucleus ^{40}Mg shows a deep prolate minimum at β_{2m} = 0.46 and a oblate minimum at β_{2m} = -0.37 with excitation energy of 3.5 MeV (lower panel of Fig. 1.).

Moreover, we have shown calculated results of excitation energy in Table I, which are also compared with some other theoretical and experimental data [1, 8–10]. It is gratifying to note that our results are in good agreement with other data which bear witness for shape coexistence in N = 28 isotone towards proton drip line.

This phenomenon of shape coexistence leads to disappearance of N = 28 neutron shell closure. To demonstrate it we have shown in Table II, energy difference between neutron $1f_{5/2}$ and $1f_{7/2}$ states which gives rise to N = 28 shell closure. It is evident from the Table II that the gap decreases significantly towards proton deficient side as compared to the gap in ^{48}Ca and one can conclude with this that N = 28 shell closure disappears in the vicinity of proton drip line and phenomenon of shape coexistence develops.

TABLE II: Results of energy difference between neutron $1f_{5/2}$ and $1f_{7/2}$ states responsible for N = 28 shell closure.

	Nucleus				
Energy between	^{48}Ca	^{46}Ar	^{44}S	^{42}Si	^{40}Mg
$1f_{5/2}$ and $1f_{7/2}$ (MeV)	7.49	7.43	6.79	5.12	2.62

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