Bubble structure in $N = 28$ isotones

Pankaj Kumar[1],* Virender Thakur[1], Vikesh Kumar[1], Smriti Thakur[1], Anupriya Sharma[1], Raj Kumar[1], and Shashi K. Dhiman[1]
[1]*Department of Physics, Himachal Pradesh University, Summerhill, Shimla-171005, INDIA*

Introduction

In general, the density of most nuclei is saturated ($\rho_0 \approx 0.16 fm^{-3}$) in the central region and is smoothly decreasing at the surface. However, this trend of nucleon density distribution shows a different behavior in some cases. In some nuclei, the density at the center is depressed with a hump nearby it, followed by a smooth decrease towards the surface region. This type of density distribution is known as "bubble" structure. The bubble structure is characterized by the central depression of nucleonic density and is currently a hot topic in nuclear physics.

The concept of reduction of density in the nuclear interior was first considered by Wilson [1]. By now, there exists appreciable literature to understand the occurrence of bubble-like structures in different mass regions. The degree of central depletion in proton or neutron densities can be quantified in terms of depletion fraction (DF), defined as

$$DF = \frac{\rho_{max} - \rho_{cen}}{\rho_{max}} \times 100\%, \qquad (1)$$

where ρ_{max} and $\rho_{cen} = \rho(r = 0)$ represent the values of maximum and central nucleon density, respectively.

Theoretical Formalism

A. Meson exchange model

The Lagrangian density for meson exchange model can be written as [2]:

$$\begin{aligned}\mathcal{L} &= \sum_i \overline{\psi_i}(i\gamma_\mu\partial^\mu - m)\psi_i + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma \\ &-\frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{2}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu \\ &-\frac{1}{4}\vec{\mathbf{R}}_{\mu\nu}\vec{\mathbf{R}}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu.\vec{\rho}^\mu - \frac{1}{4}\mathbf{F}_{\mu\nu}\mathbf{F}^{\mu\nu} \\ &-g_\sigma\overline{\psi}\psi\sigma - g_\omega\overline{\psi}\gamma^\mu\psi\omega_\mu - g_\rho\overline{\psi}\vec{\tau}\gamma^\mu\psi.\vec{\rho}_\mu \\ &-e\overline{\psi}\gamma^\mu\psi A_\mu, \qquad (2)\end{aligned}$$

where the first term represent the Lagrangian of free nucleons. m_σ, m_ω, m_ρ represents the masses of σ, ω, and ρ mesons with corresponding coupling constants g_σ, g_ω, g_ρ for the mesons to the nucleons, respectively. $\Omega_{\mu\nu}$, $\vec{R}_{\mu\nu}$, $F_{\mu\nu}$ are field tensor of the vector fields ω, ρ, and the photon. The coupling of σ field and ω field to the nucleon field reads

$$g_i(\rho) = g_i(\rho_{sat})f_i(x) \qquad \text{for} \quad i = \sigma, \omega \quad (3)$$

with

$$f_i(x) = a_i\frac{1 + b_i(x + d_i)^2}{1 + c_i(x + d_i)^2}, \qquad (4)$$

with $x = \rho/\rho_{sat}$. Here, ρ_{sat} (=$0.152 fm^{-3}$) is the baryon density at saturation in symmetric nuclear matter.
For density dependence of ρ-meson coupling is given by

$$g_\rho(\rho) = g_\rho(\rho_{sat})e^{-a_\rho(x-1)} \qquad (5)$$

This model is represented in the present investigations by the parameter set DD-ME2 [2].

The inclusion of pairing correlations is significant for the description of open-shell nuclei quantitatively. A separable pairing interaction has been used in the present investigation. The details about pairing interaction can be found in Ref. [3]. The present calculations have been performed by using DIRHB code developed by Niksic and others [4].

---

*Electronic address: `pankajdhiman659@gmail.com`

Results and Discussion

Fig. 1 presents the neutron and proton density distributions of ^{40}Mg, ^{42}Si, ^{44}S, and ^{46}Ar nuclei. In this figure, an attenuated bubble is observed in neutron density distributions, while a pronounced bubble can be seen in the proton density profiles. The calculated values of neutron and proton depletion fractions are given in Table 1.

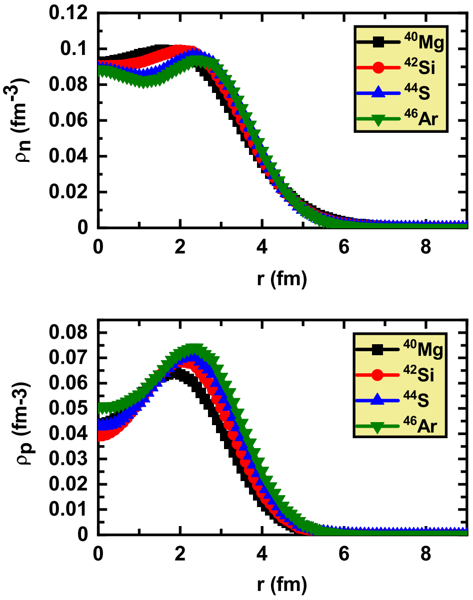

FIG. 1: (Color online) Neutron and proton density distributions for ^{40}Mg, ^{42}Si, ^{44}S, and ^{46}Ar.

TABLE I: The depletion fraction (DF) for neutron and proton bubbles for $N = 28$ isotones.

Nucleus	$DF_n(\%)$	$DF_p(\%)$
^{40}Mg	5.45	31.76
^{42}Si	7.87	42.91
^{44}S	6.73	39.49
^{46}Ar	4.88	31.46

The main reason accounting for bubble structure is the un-occupancy of $s_{1/2}$ orbital. The wavefunction of s-state contributes to the nuclear density at the center. The depopulation of s-state leads to a depressed nuclear density at the center of the nucleus, and hence a bubble may form. Fig. 2 presents the proton single-particle levels with their respective occupation probabilities for $N = 28$ isotones. In ^{40}Mg and ^{42}Si, the proton $2s_{1/2}$ orbital is empty, as all the protons are filled in $1d_{5/2}$ orbital. In case of ^{44}S and ^{46}Ar, the $2s_{1/2}$ level become depopulated due to the inversion of $2s_{1/2}$-$1d_{3/2}$ orbitals. This inversion results due to the weakening of spin-orbit strength.

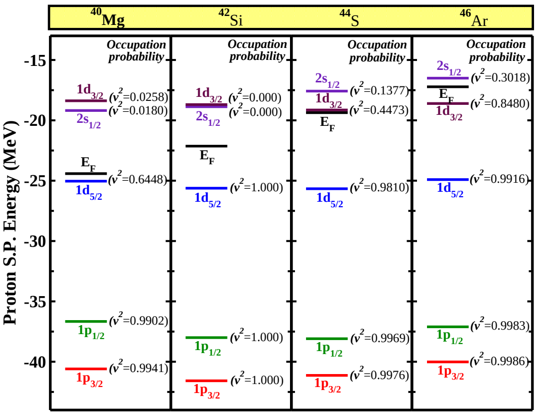

FIG. 2: (Color online) Proton single-particle energy levels for ^{40}Mg, ^{42}Si, ^{44}S, and ^{46}Ar nuclei. The value of occupation probabilities are given in the paranthese.

The bubble structure gets altered by the deformation. Deformation leads to overlapping the states, leading to a less pronounced shell effect and the depletion fraction becomes smaller. The $N = 28$ isotones are known to exhibit a deformed ground state. However, the effect of deformation on bubble structure, in $N = 28$ isotones, shall be carried out in future.

Acknowledgments

PK would like to acknowledge the financial support provided by CSIR, New Delhi under Senior Research Fellowship scheme vide reference no. 09/237(0165)/2018-EMR-I.

References

[1] H.A. Wilson, *Phys. Rev.* **69**, 538, (1946).

[2] G.A. Lalazissis, T. Niksic, D. Vretenar, P. Ring, *Phys. Rev. C* **71**, 024312 (2005).

[3] Y. Tian, Zhong-yu Ma, P. Ring, *Phys. Lett. B* **676**, 44-50 (2009).

[4] T. Niksic, N. Paar, D. Vretenar, P. Ring, *Comput. Phys. Comm.* **185**, 1808 (2014).