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STUDY OF $N = 16$ SHELL CLOSURE WITHIN RMF+BCS APPROACH[*]

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We have employed RMF+BCS (relativistic mean field plus BCS) approach to study behaviour of $N = 16$ shell closure with the help of ground state properties of even–even nuclei. Our present investigations include single-particle energies, deformations, separation energies as well as pairing energies *etc.* As per recent experiments showing neutron magicity at $N = 16$ for O isotopes, our results indicate a strong shell closure at $N = 16$ in ^{22}C and ^{24}O. A large gap is found between neutron $2s_{1/2}$ and $1d_{3/2}$ states for ^{22}C and ^{24}O. These results are also supported by a sharp increase in two neutron shell gap, zero pairing energy contribution and with an excellent agreement with available experimental data.

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1. Introduction

Emergence of new and disappearance of conventional shell closures throughout the periodic chart have opened various theoretical and experimental treatments in understanding the behaviour of nuclei with neutron-to-proton ratio. It has been also established that shell structure influences the locations of the neutron and proton drip lines and the stability of matter. Appearance of new magic numbers $N = 16$ in the ^{24}O [1, 2] and the emergence of an $N = 32$ sub-shell closure in ^{52}Ca [3] are some of the examples of changes in shell structure. In this paper, we have investigated $N = 16$ shell closure with the use of Relativistic Mean Field plus BCS approach [4, 5].

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2. Relativistic Mean Field Theory

Our RMF calculations have been carried out using the model Lagrangian density with nonlinear terms both for the σ and ω mesons [5]

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

where the field tensors H, G and F for the vector fields are defined by equation (1)

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

and other symbols have their usual meaning. Based on the single-particle spectrum calculated by the RMF described above, we perform a state dependent BCS calculations and continuum is replaced by a set of positive energy states generated by enclosing the nucleus in a spherical box. For further details of these formulations, we refer the readers to Ref. [5].

3. Results and discussion

The results of single-particle energy of $N = 16$ isotonic chain calculated using RMF with TMA force parameter [6] have been shown in Fig. 1. A large variation in the energies of states $2s_{1/2}$, $1d_{5/2}$ and $1d_{3/2}$ is clearly seen moving from proton rich to neutron rich (right to left). It is evident from Fig. 1 that for larger Z *i.e.* in ^{36}Ca, $2s_{1/2}$ and $1d_{3/2}$ states overlap whereas moving towards proton deficient side, $2s_{1/2}$ state creates a substantial gap with $1d_{3/2}$ state specially for $Z = 6$ and $Z = 8$, resulting in development of a new shell closure $N = 16$ in ^{22}C and ^{24}O. This gap is around 3.5 MeV and 3.3 MeV for ^{22}C and ^{24}O, respectively, as can be seen in the figure. This kind of reorganization is also observed from the calculations with other parameters NL3 and PK1 (not shown here). It is gratifying to note here that our results are showing doubly magic character of ^{24}O as observed in recent experiments [1, 2] and, in addition, the same shell closure $N = 16$ is also observed in ^{22}C.

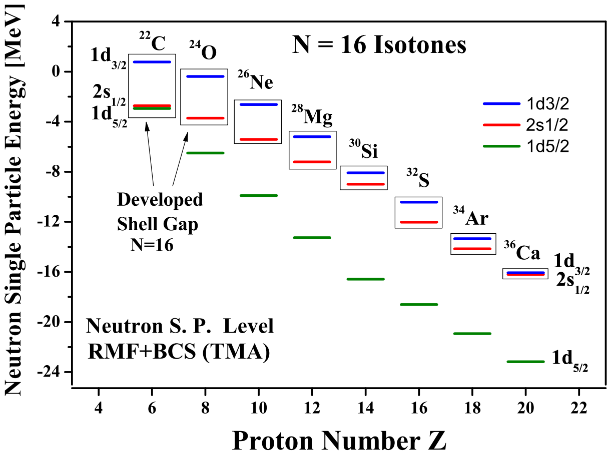

Fig. 1. Single-particle energies of neutron $1d_{5/2}$, $1d_{3/2}$ and $2s1/2$ states for $N = 16$ isotones as a function of proton number.

To get more insight, we have plotted two neutron shell gaps ($S_{2n}(N, Z)$ $- S_{2n}(N + 2, Z)$) in a lower panel of Fig. 2, for C and O isotopes calculated by RMF+BCS approach using the TMA force parameter [6] along with the experimental shell gap for O isotopes [7]. One can observe an abrupt increase in shell gap for conventional shell closure at $N = 8$. In the same way, another rise in two neutron shell gaps can be seen moving from $N = 14$ to $N = 16$ for both C and O isotopes. This rise supports occurrence of new

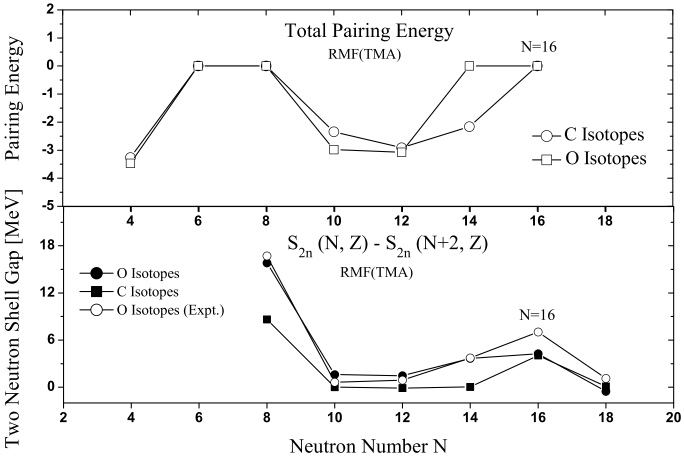

Fig. 2. Lower panel: two neutron shell gaps for C and O isotopes calculated by the RMF(TMA) [6] are compared with experimental value for O isotopes [7]. Upper panel: pairing energy for C and O isotopes calculated with TMA force parameter.

spherical shell closure at $N = 16$ for ^{22}C and ^{24}O both. From Fig. 2, it is also indulging to note that our result from RMF+BCS using TMA parameters [6] are in a good agreement with the experimental data [7]. Further, in the upper panel of Fig. 2, we have shown paring energy contribution for both C and O isotopes. For doubly magic nuclei, pairing energy vanishes and indeed it vanishes for ^{12}C, ^{14}C, ^{22}C and ^{14}O, ^{16}O, ^{24}O for $N = 6$, 8 and 16, respectively. The result in the upper panel of Fig. 2 again fortify shell closure at $N = 16$ for ^{22}C and ^{24}O and general validity of RMF approach.

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