RMF+BCS Description of N = 16 Shell Closure

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Introduction

One of the most important problems in nuclear physics today is to understand how shell structure changes with neutron-to-proton ratio throughout the nuclear chart. It has been established now that shell structure influences the locations of the neutron and proton drip lines and the stability of matter. Few examples of changes in shell structure are the 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]. In this paper we have investigated N = 16 shell closure with the use of Relativistic Mean Field plus BCS approach [4, 5]. 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. [5].

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

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.

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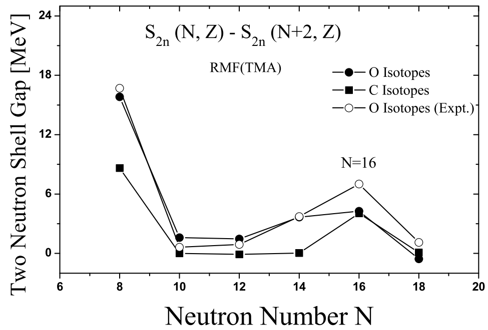

FIG. 1: Two Neutron Shell Gap for C and O isotopes calculated by RMF(TMA) [6] as a function of neutron number N. Experimental value of shell gap is also given for O isotopes [7].

In Fig. 1, we have plotted two neutron shell gap for C and O isotopes calculated by RMF+BCS approach using TMA force paramenter [6]. The two neutron shell gap is calculated by the following formula:
Shell Gap = S_{2n} (N, Z) - S_{2n} (N+2, Z)
In the Fig. 1, we have also plotted experimental shell gap for O isotopes [7]. For C isotopes the data for shell gap for N = 16 are not available. The abrupt increase in shell gap for shell closure can be seen from the figure for N = 8 which is a conventional shell closure. Moreover, from the Fig. 1, it is also evident that another rise in two neutron shell gap can be seen moving from N = 14 to N = 16 for both C and O isotopes. This gives rise to new spherical shell closure at N = 16 for ^{22}C and ^{24}O. For higher Z isotopes like Ne, Mg etc. this shell gap at N = 16 is not so pronounced (not shown here). From the Fig. 1, it is also gratifying to note that our result from RMF+BCS using TMA parameters [6] are in good agreement with the experimental data [7].

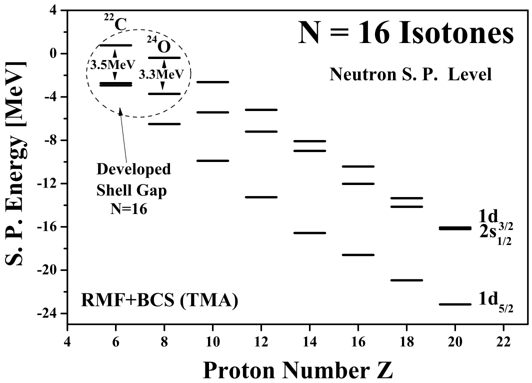

FIG. 2: Neutron single particle energy (sd shell) for N = 16 isotones as a function of proton number.

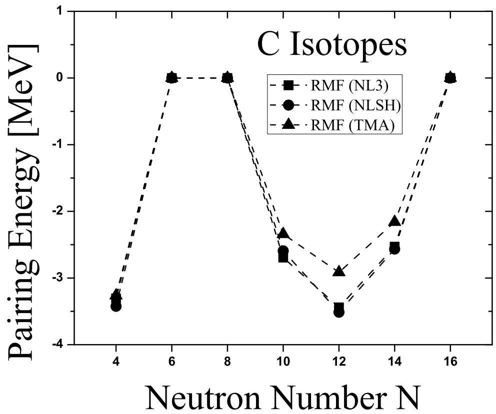

FIG. 3: Pairing Energy for C isotopes calculated from NL3, NLSH and TMA force paramenters

To get into more insight, we have plotted neutron single particle energy for N = 16 isotones as a function of Z ranging from 6 to 20 in Fig. 2. It can be seen from the figure that this shell closure at N = 16 is due to gap between $2s_{1/2}$ and $1d_{3/2}$ state which is more than 3 MeV for Z = 6 and 8. For Z = 6, $1d_{5/2}$ and $2s_{1/2}$ are nearly at same energy as reflected from the figure, and for higher Z the $2s_{1/2}$ state moves towards $1d_{3/2}$ state resulting a decrease in energy gap for N = 16. Even for Z = 20, $2s_{1/2}$ state almost overlaps with $1d_{3/2}$ state. Therefore, towards proton rich side i.e. at Z = 20 for Ca isotopes these two states $2s_{1/2}$ and $1d_{3/2}$ get separated from $1d_{5/2}$ state in this fashion that they develop a new shell gap at N = 14. Hence, moving towards neutron rich to proton rich side this reorganization of sd shell results N = 16 shell closure to N = 14 shell closure as has been depicted in Fig. 2.

Since now shell closure at N = 16 in ^{24}O is experimentally established [1, 2] and from this paper we predict that the same shell closure N = 16 should also occur in ^{22}C. To clarify the above statement we have plotted pairing energy contribution in the next Fig. 3, for C isotopes with the use of TMA [6], NLSH [8] and NL3 [9] parameters. It can be seen from the Fig. 3 that pairing energy vanishes at N = 6, 8 and 16 giving rise to two new shell closure at N = 6 and N = 16. From figure it is important to note that our results form three different parameters i.e. TMA, NLSH and NL3 are similar and provide support to the doubly magic character of ^{22}C.

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