Neutron Bubble Nuclei

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A detailed study of exotic phenomenon "bubble structure" [1–5] is important because it is related to (i) occupation of single particle s-state which may be impacted by the inversion of $2s_{1/2}$ & $1d_{3/2}$ and $3s_{1/2}$ & $1h_{11/2}$ states (ii) density distribution inside the nucleus and (iii) pairing correlation. The first experimental evidence for depletion of the central density of protons in ^{34}Si has been recently reported by Mutschler *et al.* [1]. Theoretically, a strong depletion in the center of the proton density was obtained in for ^{46}Ar indicating 's' and 'd' state inversion by Todd-Rudel *et al.* [3] and an explanation of this inversion was given by Grasso *et al.* [4]. In 2009, Grasso *et al.* had proposed ^{34}Si as proton bubble candidate and ^{22}O as neutron bubble candidate by applying various theoretical models including shell-model calculations, non-relativistic HF and HFB approaches, relativistic mean-field (RMF) and relativistic Hartree-Bogoliubov (RHB) calculations [6]. Recently, ab initio self consistent Green function many-body method has also been used to investigate bubble structure in ^{34}Si [2].

Here, we present a study of neutron bubble structure for magic nuclei Z = 8, 20 (O and Ca isotopes) with a theoretical calculation by employing the well established relativistic mean-field (RMF) plus BCS approach [7, 8] which is suitable and effective for wide range of masses and recently have been applied for the study of bubble structure [9, 10]. Fig. 1 shows the plots of neutron density of $^{12-28}$O and $^{34-70}$Ca isotopes as a function of radius r(fm). The bubble structure can be seen in those neutron de-

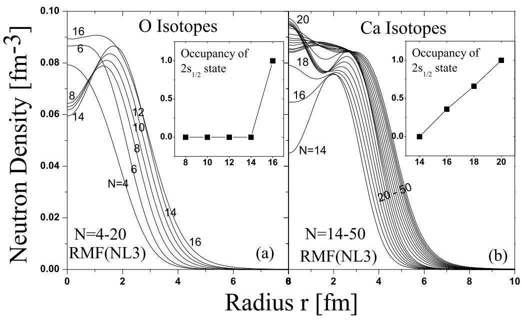

FIG. 1: Results for neutron density distributions of (a) O and (b) Ca isotopes obtained with the NL3 parameter [11] force are shown. The inset shows occupation number of $2s_{1/2}$ state in their respective chain.

ficient isotopes where the $2s_{1/2}$ state remains vacant. In the inset, we have shown occupancy of $2s_{1/2}$ state which remains zero (in Fig. 1 (a)) for O isotopes with N = 8−14 and then attains the maximum value of 1.0 at N = 16. This indicates that the whole bunch of nuclei $^{8-14}$O (Z = 8, N = 8−14) have their density depleted and qualify to be the potential candidates of bubble nuclei. However, $^{22}O_{14}$ has maximum depletion of density as compared to its neighbouring isotope/isotone and hence is a strong candidate of neutron bubble structure in accordance with the study of neutron bubble structure by Grasso *et al.* [6].

In Fig. 1(b), the bubble formation in Ca isotopes is seen where the density of ^{34}Ca is found maximum depleted. From the variation of neutron density and occupancy of $2s_{1/2}$ state, it is clear that the gradual variation of occupancy in $2s_{1/2}$ leads to bubble to semi bubble and non-bubble structures in ^{34}Ca, ^{36,38}Ca

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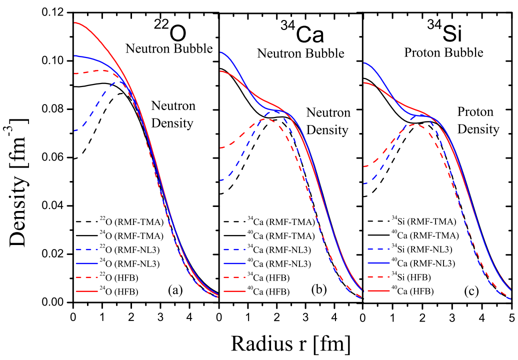

FIG. 2: (Colour online) Results of densities of (a) ^{22}O, (b) ^{34}Ca and (c) ^{34}Si along with densities of the next isotope/isotone ^{24}O, ^{40}Ca (neutron) and ^{40}Ca (proton) are shown obtained with NL3 parameter [11] along with TMA parameter [12] and with non-relativistic approach (Skyrme-Hartree-Fock method) [13].

and $^{40-70}$Ca, respectively. Hence, a bubble structure in $^{34}_{20}$Ca$_{14}$ which is a mirror nucleus of $^{34}_{14}$Si$_{20}$, is reported here (see Fig. 1(b)) which occurs due to zero occupancy of 2s$_{1/2}$ state shown in the inset of Fig. 1(b).

In order to check the parameter or model dependency on the above results, here we show the densities of few strong bubble candidates ^{22}O and ^{34}Ca along with the densities of experimentally established proton bubble candidate ^{34}Si. In the Fig. 2, densities of the next isotope/isotone in the chain are also shown to depict the difference due to unoccupied and occupied 2s$_{1/2}$ state in Fig. 2. Here we compare our results of TMA parameter [12] and NL3 parameter[11]. In addition, we show the densities calculated by a non-relativistic approach using the Skyrme-Hartree-Fock method(SHFM) [13]. It is very interesting to note from Fig. 2 that the bubble candidates ^{22}O, ^{34}Ca and ^{34}Si show very similar trends in the central densities calculated using a different parameter TMA and also using a different approach of SHFM. However in case of ^{22,24}O, the central density calculated using the Skyrme-Hartree-Fock method shows a slight upshift but the difference between two densities is still significant to establish it as a good candidate of neutron bubble. From the present study and analysis, it may be earmarked that ^{34}Ca and ^{34}Si are excellent neutron and proton bubble candidates respectively independent of the parameters of theory and models as is evident from Fig. 2. In view of a recent experiment [1] and many theoretical investigations [3, 4, 6] along with a recent communication [2] on proton bubble structure of ^{34}Si, its mirror nucleus ^{34}Ca is predicted to be a possible neutron bubble candidate as per our calculations.

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References

[1] A. Mutschler *et al.*, Nature Physics 13 (2017) 152.
[2] T. Duguet *et al.*, PRC 95 (2017) 034319.
[3] B.G. Todd-Rudel *et al.*, PRC 69 (2004) 021301(R).
[4] M. Grasso *et al.*, PRC 76 (2007) 044319.
[5] E. Khan *et al.*, NPA 800 (2008) 37.
[6] M. Grasso *et al.*, PRC 79 (2009) 034318.
[7] G. Saxena *et al.*, IJMPE 26 (2017) 1750072.
[8] G. Saxena *et al.*, PLB 775 (2017) 126.
[9] G. Saxena *et al.*, Accepted in Phys. Lett. B (2018).
[10] G. Saxena *et al.*, Submitted to JPG (2018).
[11] G. A. Lalazisssis, Phys. Rev. C 55 (1997) 540.
[12] Y. Sugahara *et al.*, Nucl. Phys. A 579 (1994) 557.
[13] S. Goriely *et al.*, PRL 102 (2009) 152503, http://www-astro.ulb.ac.be/bruslib.