Proton bubble and robustness of neutron skin thickness

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The "Bubble Structure" or the depletion in the central density of the nucleus has renewed a lot of research interest currently. There have been increasing experimental [1] and theoretical efforts [2–4] to search and understand the phenomena of bubble which mainly arises due to the unoccupancy of the s-state because of which the density at the center becomes significantly lower than the saturation density. The first experimental evidence for depletion of the central density of protons in ^{34}Si has been recently reported by Mutschler *et al.* [1] which has opened a testing ground for already developed successful models and of course the new avenues for better and consistent understanding of the nuclear structure throughout the periodic chart. Very recently, nuclear density functional theory [5] and ab initio self consistent Green's function many-body method [2] have been applied to investigate bubble structure in in nuclei over a wide range of masses.

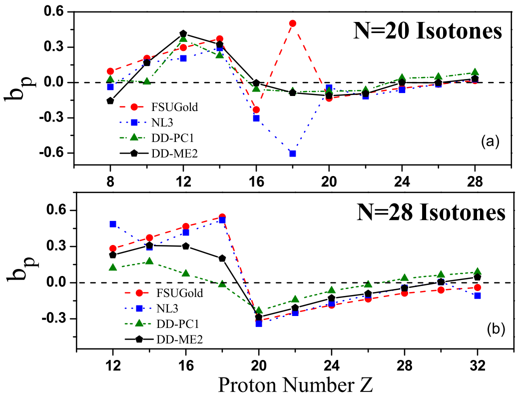

FIG. 1: (Colour online) The proton bubble parameter (b_p) for N = 20 and 28 isotones obtained with the FSUGold, NL3, DD-PC1 and DD-ME2 force parameters are shown as a function of Z.

The single particle 1s, 2s ,3s etc., orbitals in the nuclei do not have any centrifugal barrier and the radial distributions of such orbitals are peaked in the interior of the nucleus with corresponding wave functions extending into the surface region depending upon the number of nodes in the wave function. The wave functions for the single-particle states with the finite orbital angular momentum are rather suppressed in the interior of the nucleus and do not contribute to the central density. Consequently, the central density becomes depleted in the nucleus with unoccupied s-state as compared to the nucleus wherein this state is fully occupied that forms the basis for the possible existence of bubble nuclei. In this contribution, we search for the central depletion in magic nuclei with N = 20 and 28 using relativistic mean field (RMF) models such as FSUGold, NL3, DD-PC1 and DD-ME2. The influence of the bubble on the systematics of neutron-skin thickness is also studied.

The degree of central depletion can be expressed in terms of the bubble parameter $b_\tau = 1 - \frac{\rho_{\tau,c}}{\rho_{\tau,av}}$,where, $\tau = p, n$. The $\rho_{\tau,c}$ is the central density and $\rho_{\tau,av} = \frac{3N_\tau}{4\pi R^3_{\tau,d}}$ with $R_{\tau,d}$ the diffraction radius. In the case of central depletion or the bubble formation, b_τ is positive. In Fig.1 we show the results for proton bubble parameter b_p for isotonic chain of N = 20 and 28 nuclei for the different RMF models. It is evident that for the case of N = 20 isotones, the proton bubbles are present ($b_p > 0$) in ^{30}Ne,

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^{32}Mg and ^{34}Si nuclei. For nuclei with Z > 14 proton bubble is present only in the ^{38}Ar for FSUGold model. For N = 28 isotones, proton bubbles are present for nuclei with Z < 20. However, the degree of central depletion is sensitive to the choice of the model (Fig.1(b)). Among these ^{40}Mg, ^{42}Si and ^{44}S are found to be deformed for all models considered.

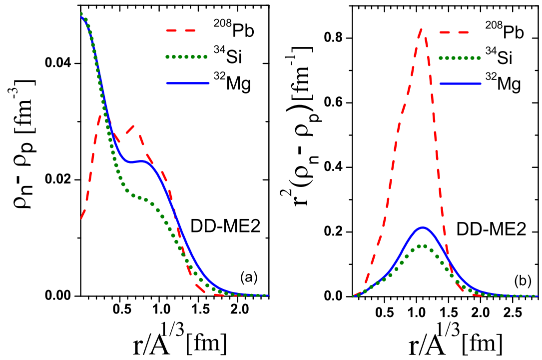

FIG. 2: (Colour online) The differences ρ_n-ρ_p and r^2(ρ_n-ρ_p) plotted as a function of $r/A^{1/3}$ for ^{32}Mg, ^{34}Si and ^{208}Pb obtained for DD-ME2.

One can also notice that among all the nuclei, ^{32}Mg and ^{34}Si are found to be the best candidates for the bubble formation. Indeed, the proton densities at the center of these nuclei are almost half the neutron density at the center (not shown here). The neutron-skin thickness is the measure of the weighted differences in the density distributions of neutrons and protons. One may expect some imprint of proton bubble on the systematics of the neutron-skin thickness. In Fig.2 we have plotted difference between neutron density and proton density (ρ_n-ρ_p) along with $r^2(\rho_n$-$\rho_p)$ as a function of r scaled by $A^{1/3}$ for these bubble nuclei. The difference between neutron to proton density ρ_n-ρ_p for ^{32}Mg and ^{34}Si at center is much larger as compared to ^{208}Pb due to central depletion in proton density. Towards the larger $r/A^{1/3}$ value the difference ρ_n-ρ_p is found similar for all these three nuclei. For bubble nuclei, because of central depletion in proton density, the neutron density adjusts itself in such a manner that neutron skin thickness might remain unaffected. It can be seen in Fig.2(b), variations of $r^2(\rho_n$-$\rho_p)$ for the bubble nuclei ^{32}Mg and ^{34}Si are similar to the normal nucleus ^{208}Pb. The values of $r^2(\rho_n-\rho_p)$ for all the three nuclei peak at almost the same value for $r/A^{1/3}$. In Fig. 3, the neutron-skin thickness δr_{np} plotted as a function of asymmetry (N-Z)/A. The nuclei ^{32}Mg, ^{34}Si and ^{46}Ar with prominent proton bubbles follow the similar trend as displayed by the normal nuclei. In conclusion, the neutron density distributions in nuclei with proton bubbles get adjusted self-consistently in such a way that the systematics of neutron skin thickness remains unaltered demonstrating the robustness of neutron skin thickness against the proton bubble.

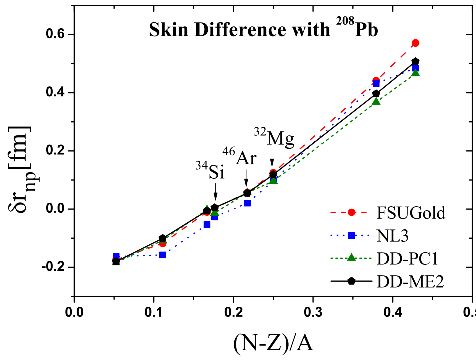

FIG. 3: (Colour online) The difference $\delta r_{np} = r_{np}(x) - r_{np}(^{208}Pb)$ with $r_{np}(x)$ being the neutron-skin thickness for the nucleus (x) plotted as a function of asymmetry $[(N-Z)/A]$ asymmetry for several RMF models as considered.

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References

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