Investigation of structural analysis of proton-halo nuclei and related aspects

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Introduction

The development of radioactive ion beams has brought around tremendous opportunities to investigate properties and structure of light nuclei beyond the drip lines. Such nuclei with weak binding-interaction may exhibit nuclear halo structures in which the valence nucleons extend outside the binding potential. Most of the halo nuclei are confirmed as neutron halos, while proton halos observed are rather scarce. Since Coulomb barrier inhibits a wider proton distribution, therefore the investigations on the formation mechanism of proton halo nuclei are relatively less as compared to those of neutron halos. Consequently, 1p-halo structures, so far observed, are for ^{8}B, ^{11}N and ^{17}F, and the 2p-halo only for ^{17}Ne.

Very recently, we investigated [1] the neutron-halo status of all the observed and proposed halo candidates and advocated the relevance and importance of nuclear deformations and associated various proximity interactions in the dynamics of such exotic nuclear systems. In this paper, we extend this work to analyze the 1p-halo status of nuclei near the proton-drip line, which include the observed cases of ^{8}B, ^{11}N, ^{17}F and five other experimentally/ theoretically proposed cases of ^{12}N, ^{23}Al, ^{26}P, ^{27}P and ^{28}P, using the cluster-core model (CCM) [2]. The halo nature of these nuclei is studied via the minima in potential energy surfaces (PES), which in turn correspond to the most probable (i.e., with relatively larger preformation probabilites, compared with the neighbors) cluster-core configurations formed in the collective clusterization process. The main aim of the present work is to analyze the influence of nuclear deformations and orientations on the halo structure (fragmentation path) of these rare proton-rich light nuclei. Since the fragmentation process in CCM is based on the collective clusterization method, the calculation depends not only on the shapes of halo nuclei, but also on all other possible fragments that a halo nucleus could be made up of. It is certainly of great interest to see that in what way the angular momentum, deformation and orientation effects of the decay fragments influence the PES behavior of one-proton halo nuclei.

Methodology

In the Cluster-Core Model (CCM), the potential energy of a nucleus A is calculated simply as a sum of the Coulomb interaction, the nuclear proximity potential, the centrifugal potential and the ground-state binding energies of two nuclei:

$$\begin{aligned} V_R(\eta) &= -\sum_{i=1}^{2} B(A_i,Z_i) + V_C(R,Z_i,\beta_{\lambda i},\theta_i) \\ &\quad + V_P(R,A_i,\beta_{\lambda i},\theta_i) + V_\ell(R,A_i,\beta_{\lambda i},\theta_i) \end{aligned} \tag{1}$$

with B's taken from the 2003 experimental compilation of Audi and Wapstra [3] and, wherever not available in [3], from 1995 calculations of Möller *et al* [4]. Here the binding energy for a cluster with x protons is defined as

$$B(A_2 = xp) = x\Delta m_p - a_c A_2^{\frac{5}{3}} \tag{2}$$

with $\Delta m_p = 7.2880$ MeV, the one-proton mass excess (equivalent of the one-proton binding energy) and $a_c = 0.7053$ MeV. The last term in equation (2) represents the disruptive Coulomb energy between x protons.

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Calculations and discussion

We have calculated the PES $V(A_2)$ for proton-rich nuclei which include the cases of ^{8}B, ^{11}N, ^{12}N, ^{17}F, ^{23}Al, ^{26}P, ^{27}P and ^{28}P, using CCM with effects of deformations and orientations of nuclei included. It is important to note here that all the 1p-halo nuclei considered are deformed and hence the deformation and orientation effects are expected to play significant role. Interestingly, it has been found that the choice of either spherical or deformations up to β_2 alone in the fragmentation potential do not influence the 1p-halo status for all the cases investigated here, except for ^{11}N.

Figures 1(a) and 1(b) show the calculated fragmentation behavior for the above noted ^{11}N nucleus, for the cases of spherical and quadrupole deformations β_2 alone at $\ell = 0$ and $\ell \neq 0$ (ℓ = 1, 2, 3, chosen arbitrarily). The orientations of nuclei are fixed by using the "optimum" orientation θ_i^{opt} of "hot" configurations, taken from Table I of Ref. [5]. At ℓ = 0, it is cleary evident from Figure 1 that for ^{11}N the 1p + core minimum is nearly as deep as 3p + core, irrespective of the use of spherical or deformed β_{2i} fragmentation. Furthermore, we notice from Figures 1(a) and (b) that the most probable cluster configuration gradually changes to 3p-halo structure with the increase in ℓ value which signifies that the angular momentum ℓ effects are important in the context of halo nature of this nucleus. Thus, ^{11}N provides an interesting case and further experiments/ calculations may impart necessary information regarding the debatable halo status of this nuclear system.

In order to look for the possible role of higher multipole deformations, calculations are performed for the fragments taken with quadrupole, octupole, and hexadecapole deformations (β_{2i}, β_{3i}, β_{4i}) having "compact" orientations θ_i^c as per Ref. [6]. The fragmentation path is studied explicitly for ^{23}Al, ^{26}P, ^{27}P and ^{28}P cases of 1p-halo nuclei, depending on the availability of estimated β_4 values [4] for their cluster-core products. We observe that although the PES are modified for the use of deformations up to β_4, but the deepest minima for each case occurs at 1p + core configuration, except for ^{26}P. However with the inclusion of β_2-β_4 deformations in ^{26}P, the decay fragments show emergence of 2p-halo structure alongwith the expected 1p-halo configuration.

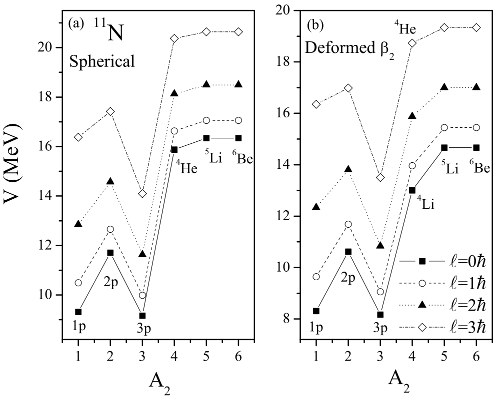

FIG. 1: The potential energy V as a function of light cluster mass A_2 for ^{11}N nucleus plotted at different ℓ values for (a) spherical and (b) β_2-deformed choice of fragmentation.

In summary, one may conclude that proper understanding of nuclear shapes along with the relative orientations is essential to make concrete predictions regarding the halo structure of proton-rich nuclei.

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