Exploring two-neutron halos in $N = 28$ isotones ^{40}Mg and ^{39}Na[1)]

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The development of radioactive ion-beam facilities has enabled the study of shell evolution near the neutron dripline, revealing exotic nuclear behaviours such as shell-gap quenching, shape coexistence, and halo formation.[2)] The spin-orbit force plays a crucial role in determining the magic numbers for heavier nuclei, with $N = 28$ being the lightest closure sensitive to its effects. Experimental evidence suggests that the shell gap at $N = 28$ weakens in neutron-rich nuclei, forming a "big island of inversion" (B-IOI) in neon, sodium, and magnesium isotopic chains.[3,4)] Recent observations of two-neutron Borromean halo, such as ^{29}F[5)] have inspired exploration of the neutron-rich Na and Mg isotopes. The weakly bound nucleus ^{37}Mg[6,7)] has been identified as a one-neutron halo nucleus, while ^{39}Mg is unbound, highlighting the role of neutron pairing in binding ^{40}Mg. This study investigates the potential formation of a two-neutron Borromean halo structure in neutron-rich isotones ^{40}Mg and ^{39}Na, situated at the periphery of the B-IOI. In addition, we predict separation energies and matter radii for ^{39}Na and provide Glauber-model cross-section predictions, which further probe halo formation at the limits of nuclear stability.

Our work employs a three-body model using a hyperspherical formalism with a transformed harmonic oscillator (THO) basis for analyzing the ground states of ^{40}Mg and ^{39}Na. The ^{40}Mg nucleus is modeled as a ^{38}Mg core with two valence neutrons, incorporating effective neutron-neutron (n-n) and phenomenological three-body interactions, along with a core-neutron interaction built to describe available data on ^{39}Mg. These core-neutron interactions are modeled as Woods-Saxon potentials with central and spin-orbit terms. The parameters are selected to match theoretical predictions for ^{39}Mg, with ^{38}Na assumed to follow similar trends. There remains sufficient leeway to explore alternative scenarios for the single-particle spectrum, which includes a normal, degenerate, and inverted ordering of p- and f-wave resonances.

Figure 1 illustrates the variations in matter radii along the Mg and Na isotope chains. Experimental data for $^{20\text{–}32}$Mg and $^{20\text{–}32}$Na (black circles) are obtained from Ref. 8), while those for $^{32\text{–}35}$Mg (blue circles) are from Ref. 9) and that for ^{37}Mg (red circle) are obtained from Ref. 6). The findings indicate that, depending on the choice of interaction parameters, the matter radius of ^{40}Mg and ^{39}Na are larger by 0.1-0.5 fm than that of their respective core nuclei. This effect strengthens as the $p_{3/2}$ intruder orbital gains occupancy, indicating the breakdown of the $N = 28$ shell gap. These findings highlight the role of intruder orbitals in shaping the halo structure in neutron-rich nuclei as previously discussed for ^{29}F.[10)] The enhanced total reaction cross-sections observed in these systems (Fig. 5[1)]) support the existence of the two-neutron halo structure in ^{40}Mg and ^{39}Na.

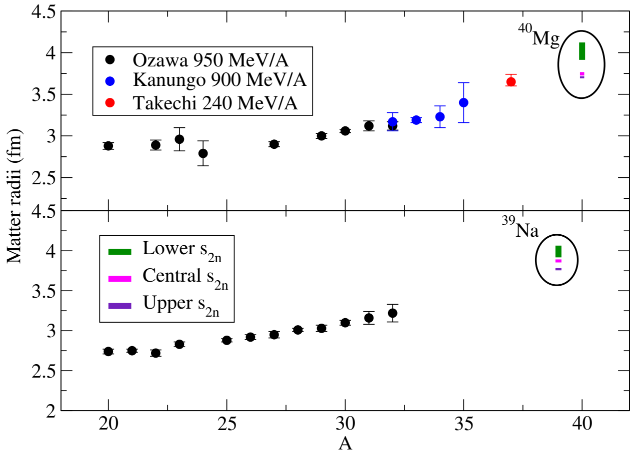

Fig. 1. Variation in the matter radii (R_m) for Mg (upper panel) and Na (lower panel) isotopes with mass number A. The figure is adopted from the original article.[1)]

In summary, our work provides the first theoretical indication for such halos, highlighting the role of increased matter radii and orbital inversions in shell evolution near the neutron dripline. The results offer valuable insights for future experimental campaigns that explore the structure of neutron-rich nuclei.

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