Role of nuclear surface diffuseness in investigating the structure of ^{35}Mg

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Introduction

The shell inversion in the nuclei at the N=20 island of inversion (IoI) causes unusual exotic features such as the disappearance of shell gap and strong deformation. Recent studies also show the shape coexistence of many particle-many hole (mpnh) configurations within a small excitation energy [1]. Understanding the shell structure and ordering is important to reveal such features in these nuclei. Particularly in odd-mass nuclei, the characteristics of the single-particle orbit of the valence particle or hole are significantly manifested in the overall system. However, there is limited knowledge about the ground state spin-parity of most of these nuclei. ^{35}Mg, which lies at the edge of N=20 IoI, is one such example. The ordering of the single-particle levels is important to elucidate the driving mechanisms of shell evolution of nuclei in this region.

Nuclear surface diffuseness can be useful in identifying the particle-hole configurations and spin-parity. Diffuseness can be correlated with the single-particle orbits of the valence nucleons. Nuclei with valence nucleons occupying weakly bound lower angular momentum orbits show larger diffuseness [2]. Again, the proton-elastic scattering is a useful tool to probe the nuclear surface, and one can estimate the diffuseness from the first diffraction peak of the differential cross-section [3]. Thus, by studying diffuseness, it is possible to indirectly estimate the particle-hole configurations.

In this work, we use the microscopic antisymmetrized molecular dynamics (AMD) model with the generator coordinate method (GCM) [4] to investigate the low-lying states of ^{35}Mg and study their density profile to investigate the relation between the diffuseness and the particle-hole configurations.

Formalism

In AMD, the intrinsic wave function is defined by a slater determinant $\Phi_{int} = \mathcal{A}\{\varphi_1, \varphi_2, ..., \varphi_A\}$, with $\varphi_i(\mathbf{r}) = \phi_i(\mathbf{r})\chi_i\xi_i$ being the single particle wave function consisting of the spatial, spin, and the isospin parts,

$$\phi_i(\mathbf{r}) = \exp\left[-\sum_{\sigma=x,y,z} \nu_\sigma \left(r_\sigma - \frac{Z_{i\sigma}}{\sqrt{\nu_\sigma}}\right)^2\right],$$

$$\chi_i = a_i\chi_\uparrow + b_i\chi_\downarrow,\ \xi_i = \text{proton or neutron},$$

respectively. Here, the Gaussian centroids $Z_{i\sigma}$, the spin directions a_i and b_i and the width parameters ν_x, ν_y, and ν_z are the variational parameters. We employ the parity projection, $\Phi^\pi = \hat{P}^\pi\Phi_{int}$, where $\hat{P}^\pi$ is the parity projector. The energy variation is done by optimizing the variational parameters using constraint over the quadrupole deformation parameter β. Then, we project the wave function to the eigenstate of the total angular momentum to obtain $\Phi^{J\pi}_{MK}(\beta) = \hat{P}^J_{MK}\Phi^\pi(\beta)$. In this method, we employ the Gogny D1S force as effective nucleon-nucleon interaction, and the Coulomb force is approximated by the sum of seven Gaussians. We finally apply GCM to describe the ground state wave function by superposing all $\Phi^{J\pi}_{MK}(\beta)$ for the same J and π but different K and β values

$$\Psi^{J\pi}_{Mn} = \sum_{iK} c^{J\pi}_{iMKn}\Phi^{J\pi}_{MK}(\beta_i). \tag{1}$$

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The coefficients and the eigenenergies are calculated using Hill-Wheeler's equation [5]. All the physical quantities discussed here are calculated using the GCM wave function.

Results and Discussion

Figure 1 displays the excitation spectra of ^{35}Mg featuring the low-lying states below 1 MeV. Our calculations show that different particle-hole configurations coexist within small excitation energy. The ground state of ^{35}Mg is not well-known. The study reported in [6] based on nucleon removal reactions suggests a few low-lying states with little information about the ground state. The shell model calculations with SDPF-M and SDPF-M+$p_{1/2}$ interactions predict a $3/2^-$ ground state. On the other hand, our calculations predict a $3/2^+$ state with a 4p1h configuration, while the $5/2^-$ (5p2h) and $3/2^-$ (3p0h) states lie within 800 keV. Since we are interested in different particle-hole configurations, we chose these states to discuss their density distributions.

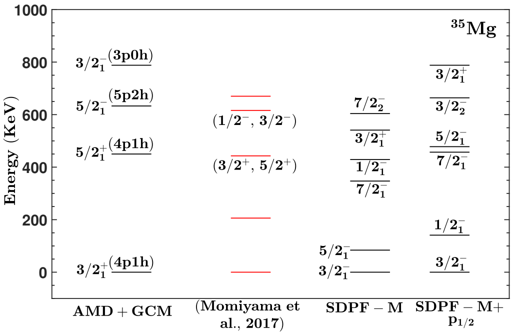

FIG. 1: Excitation energies of low-lying states of ^{35}Mg.

Figure 2 shows the the plot for $r^2\rho$, ρ being the matter density distribution, as a function of the radial distance r, for the above-mentioned states. The diffuseness is distinctive for each particle-hole configuration, and increases as more particles occupy the pf shell and more holes form in the sd shell. This is because deformation causes the mixing of the f- and p-waves in the pf shell, and valence particles occupying more weakly bound, p-wave mixed orbits exhibit larger diffuseness.

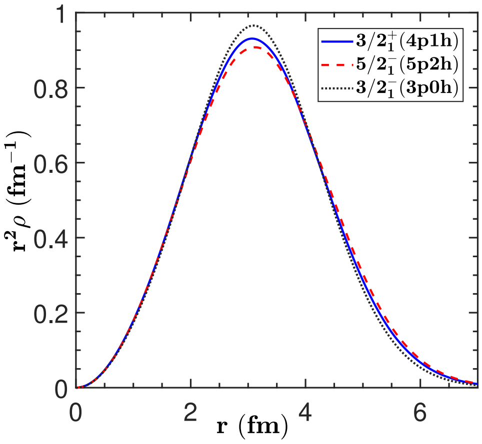

FIG. 2: r^2 multiplied by matter density distributions for the selected states of ^{35}Mg.

As the diffuseness is also sensitive to the first diffraction peak of the angular distribution of proton-elastic scattering cross-sections, one can extract the diffuseness by fitting the cross-sections with a suitable density distribution. This could be a powerful tool for an indirect probe of the particle-hole configuration or the spin-parity of the nuclei.

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