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RESEARCH HIGHLIGHT

Extended quantum molecular dynamics model predicts new breathing modes in ^{36}Ar bubble nuclei

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In theoretical investigations of ^{36}Ar published by Ge Ren et al. (Phys Lett B 138990, 2024), ^{36}Ar bubble nuclei, characterized by central density depletions, were studied using the extended quantum molecular dynamics model. Three novel density distributions—microbubble, bubble, and cluster resonances—were identified, each showing distinct spectral signatures in the gamma-ray decay spectrum of the isoscalar monopole resonance. Notably, the oscillation frequency of the bubble mode mirrors macroscopic bubble dynamics, bridging classical and quantum phenomena in atomic nuclei.

The exploration of exotic nuclei, driven by advances in large-scale radioactive ion beam facilities, reshapes nuclear physics, particularly as regards the complex structures and behaviors of atomic nuclei. Exotic structures and deformations [1–3] challenge traditional models. Unique nuclear configurations such as linear chains [4] and toroidal structures [5], as well as bubble nuclei [6, 7], add to this complexity. Bubble nuclei, first proposed by Wilson in the 1940s [8, 9], feature central density depletions resembling soap bubbles, arising from the low occupancy of the $s_{1/2}$ state with no $l = 0$ contributions [10, 11]. The existence of such unusual structures raises questions about their origins and about collective behavior during heavy-ion collisions.

Wong [12, 13], Campi and Sprung [14], along with others [15, 16], have conducted substantial early work, which laid the groundwork for understanding bubble structures. Experimental evidence for bubble structures emerged with Mutschler et al.'s study of ^{34}Si in 2017 [17]. However, the dynamic behavior of the bubble structures after excitation remains unexplored.

The isoscalar monopole resonance, known as the "breathing" mode, offers a promising avenue for exploring the collective motion in bubble nuclei. In their published study examining how unique central structures influence monopole resonance behavior under varying excitation intensities [18], the authors uncovered new breathing modes and revealed a striking parallel between the quantum dynamics of bubble nuclei and the classical dynamics of macroscopic bubbles. This work links classical and quantum phenomena, advancing our understanding of exotic nuclear structures.

The extended quantum molecular dynamics (EQMD) model was employed to investigate the monopole resonance of ^{36}Ar in a bubble structure. This model offers several advantages, including the subtraction of zero-point kinetic energy, as well as the incorporation of an effective Pauli potential and a complex variable wave packet width into the Hamiltonian [19]. These enhancements enable the model to more accurately ensure the stabilities of ground state nuclei and of the bound states in excited nuclei, facilitating research on the properties of bubble structures [20].

Three distinct density distribution modes were uncovered for the first time in this research: microbubble, bubble, and cluster resonances as shown on the right side of Fig. 1, where ε serving as a measure of the initial excitation intensity. The oscillatory behavior of the root-mean-square radius $R_{\mathrm{rms}}(t)$ on the left side of Fig. 1 in microbubbles resembles conventional monopole resonances. However, as the excitation intensity increases, the oscillation patterns change, revealing the distinctively different characteristics of the bubble and cluster resonance modes. In addition, these modes show unique spectral signatures compared to the monopole resonance spectrum as the excitation intensity increases.

The probability distribution of photon energy E_γ of ^{36}Ar is shown in Fig. 2a. Typically, for conventional monopole resonances, the γ-ray emission spectra of nuclei display a pronounced peak within the energy range of 10 to 25 MeV. Instead, the spectrum of the new breathing mode corresponding to bubble nuclei does not follow this pattern. The

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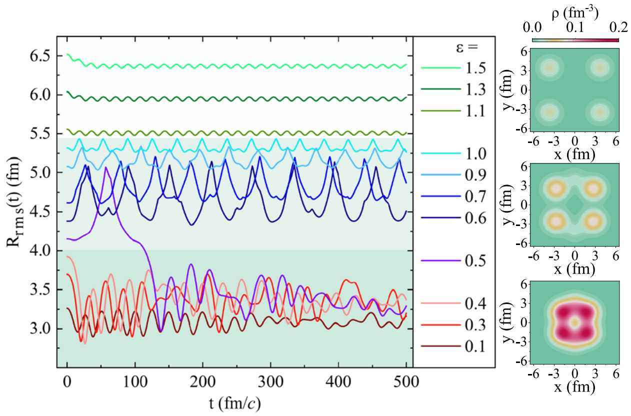

Fig. 1 (Color online) The evolution of the root-mean-square radius of ^{36}Ar nuclei for t= 0–500 fm/c with different excitation intensities (left), and a typical density distribution corresponding to different modes (right)—from bottom to top, the order is microbubble, bubble, and cluster

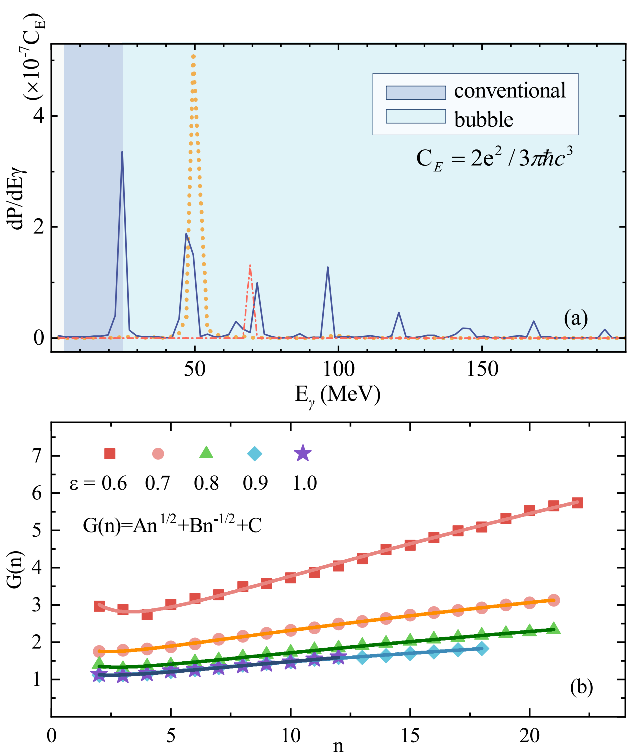

Fig. 2 (Color online) **a** The γ-ray spectra E_γ and **b** the value of F_n/f_n change with mode number n. The lines in **b** represent the correlation function $G(n)$ derived through fitting over the range of excitation intensities

bubble mode shows several peaks that decrease in intensity as the energy increases. These peaks in the γ-ray spectra provide an experimental probe to investigate bubble nuclei isoscalar monopole resonances. Microbubble and cluster resonance modes show significant peaks at around 50 and 70 MeV, respectively.

Researchers have also discovered the vibrational frequencies of the bubble mode closely resemble the dynamics of macroscopic bubbles [18]. For macroscopic bubbles, the natural frequency of the eigenmode during free vibration is related to the equilibrium radius, the surface tension coefficient, the fluid density, and the mode number n of the spherical harmonic Y_{nm} [21, 22]. In addition, the vibration frequency of the bubble mode $f_n = F_n/G(n)$ has an additional correlation function $G(n)$ in Fig. 2b compared to F_n.

The increase of excitation intensity leads to decreases in the thickness and density of the bubble's surface layer, as well as a decrease in the surface tension coefficient. This trend can be attributed to the diminishing nuclear force among clusters as their separation increases. The correlation function $G(n)$ exhibits a characteristic hook shape, indicating greater density differences between these nuclei and macroscopic bubbles near the cluster positions.

In contrast to previous research on nuclear bubble structures in neutron-rich and proton-rich nuclei, this study [18] focuses on the neutron–proton symmetric nucleus ^{36}Ar, which exhibits a bubble structure characterized by α clusters. This is distinct from proton bubbles observed in neutron-rich nuclei, where the proton density distribution is shifted. The bubble structure seen in ^{36}Ar suggests that more research into the exotic excited states of nuclei close to the β-stable line is warranted.

The three distinct density distributions discovered in ^{36}Ar, along with their unique vibrational behaviors, provide new insights into the collective behavior of excited nuclei. And the resemblance between bubble nuclei and macroscopic bubbles represents a significant milestone in unraveling the connection between classical and quantum domains within the enigmatic realm of atomic nuclei. The findings extend beyond bubble nuclei, offering insights into broader fields of nuclear physics and the response of nucleons under extreme conditions.

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