Validation of molecular structure in the ^{10}Be ground-state†

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Cluster structure within exotic nuclei is an intriguing phenomenon that requires a complete understanding of the fundamental nuclear interactions. Calculations in various frameworks have predicted that the ground- and low-lying states of light neutron-rich nuclei may possess a molecular-like structure with a core formed by an assembly of light clusters (typically α particles) around which excess neutrons orbit. Despite these longstanding theoretical conjectures, experimental validation of the molecular character of light neutron-rich nuclei remains elusive. Neutron-rich beryllium isotopes are considered promising candidates for such investigations. In particular, theoretical studies[1,2] suggest the ^{10}Be ground state has a molecular structure, configured as an α-α core, hosting two valence neutrons that orbit perpendicular to the axis of the core. An analogue system can be found at the atomic scale when two atoms share two electrons through covalent bond to form a diatomic molecule.

The SAMURAI-12 experiment, performed at the RI Beam Factory (RIBF) at RIKEN Nishina Center, aimed to investigate the cluster structure of the neutron-rich ^{10}Be via the α-cluster knockout reaction in inverse kinematics. The ^{10}Be$(p,p\alpha)^6$He reaction was induced by ^{10}Be beam at 150 MeV/nucleon impinging on a 2-mm-thick pure solid hydrogen target, with recoil protons detected by a two-arm Recoil Proton Spectrometer, and knocked-out α detected by telescopes at forward angles. Furthermore, the detection of ^{6}He residues was achieved using the SAMURAI spectrometer and its standard detectors. In this process, known as quasi-free scattering, an α-cluster is "knocked out" by a proton, transferring nearly zero momentum to the residue.

The recent theoretical work[1] highlights the remarkable sensitivity of the triple differential cross section (TDX) of the α knockout reaction to the α-cluster wave function, thereby reflecting the spatial distribution of the α-cluster within the ground-state of ^{10}Be. Experimental TDXs for ^{10}Be$(p,p\alpha)^6$He(g.s.) reaction are shown in Fig. 1, extracted at the coplanar angle pair $\theta_p/\theta_\alpha = 65°/-7.7°$ to fulfill the recoilless condition of the residual nucleus. These TDXs were compared to distorted-wave impulse approximation (DWIA) calculations integrated with the Tohsaki-Horiuchi-Schuck-Röpke wave-function,[1] and the wave-function deduced from Antisymmetrized Molecular Dynamics.[2] Remarkably, the measured TDXs exhibited excellent agreement in shape and magnitude with both

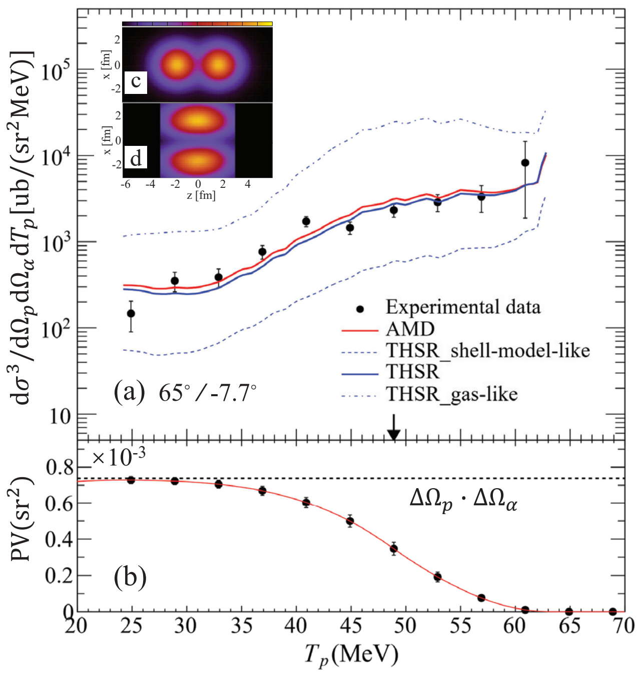

Fig. 1. (a) TDX distribution of ^{10}Be$(p,p\alpha)^6$He(g.s.) reaction, compared with theoretical predictions, details in the text; (b) The corresponding phase volume distribution. The horizontal dashed line indicates the product of solid angles $\Delta\Omega_p \cdot \Delta\Omega_\alpha$. (c) and (d) are the density distribution of the protons and valence neutrons in the ground state of ^{10}Be predicted by the THSR model.

state-of-the-art calculations. The TDX calculations using the two "extreme" cases of a compact shell-model-like and a loosely bound gas-like configuration of ^{10}Be nucleus described in Ref. 1), required very large normalization factors to match the magnitude of the data, far beyond the cross-section uncertainties.

Altogether, these results directly validate the molecular structure description of the ^{10}Be ground-state, configured as an α-α core with two valence neutrons occupying π-type molecular orbitals. This study provides a distinctive perspective that complements the classic shell model of nucleons bound within an attractive mean-field induced by the interactions among all nucleons. The experiment employing α-knockout reaction in inverse kinematics, combined with state-of-art nuclear structure and reaction theories, presents an innovative and quantitative approach for probing the α-cluster's spatial distribution in the ground state.

References

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