Study of Subbarrier Fusion Reaction Dynamics for 6,7Li on Light Targets with the Antisymmetric Molecular Dynamics Model

Authors: Dexin Wang, MeiRong Huang, Su-Ya-La-Tu Zhang, Su-Ya-La-Tu Zhang

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Abstract

The subbarrier fusion reaction of 6,7Li on light targets 12,13C,16O, and 24Mg using AntisymmetrizedMolecular Dynamics (AMD) model were investigated. Within the AMD framework, theground state of 6,7Li is found to exhibit an d(α) + t configuration, and possess significant deformation.Simulations are performed in the energy range of 2 - 9 MeV center-of-mass energy (Ecm),proximate to the Coulomb barrier. The computed total fusion cross-sections, as a function of incidentenergy, is found to agree favorably with experimental data at Ecm > 3 MeV. In addition, acomparison is made between the AMD predicted cross-sections of various residue channels at Ecm= 5 MeV and corresponding experimental data.

Full Text

Preamble

Study of Subbarrier Fusion Reaction Dynamics for ^{6,7}Li on Light Targets Using the Antisymmetrized Molecular Dynamics Model

D. X. Wang[1], M. Huang[1,*], and S. Zhang[1,†]

[1]College of Mathematics and Physics, Inner Mongolia Minzu University, Tongliao 028000, China

We investigate the subbarrier fusion reactions of ^{6,7}Li on light targets ^{12,13}C, ^{16}O, and ^{24}Mg using the Antisymmetrized Molecular Dynamics (AMD) model. Within the AMD framework, the ground states of ^{6,7}Li are found to exhibit a d(α) + t configuration and possess significant deformation. Simulations are performed for center-of-mass energies (E_{cm}) ranging from 2–9 MeV, near the Coulomb barrier. The computed total fusion cross sections as a function of

incident energy agree favorably with experimental data for $E_{\mathrm{cm}} > 3$ MeV. Additionally, we compare AMD-predicted cross sections for various residue channels at $E_{\mathrm{cm}} = 5$ MeV with corresponding experimental data.

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I. INTRODUCTION

The availability of radioactive beam facilities has sparked considerable theoretical and experimental interest in examining the breakup mechanisms and structure of nuclei far from the stability line. These nuclear properties play a crucial role in fusion reactions near the Coulomb barrier, particularly for weakly bound nuclei [**?**]. The fragmentation of projectiles with low binding energies significantly impacts fusion reactions, creating distinct fusion pathways. Complete fusion (CF) occurs when the entire projectile is successfully captured by the target. CF can manifest in two forms: direct CF, where fusion proceeds without prior projectile fragmentation, and sequential CF, where all projectile fragments are captured after breakup. When only some fragments are captured while others escape, the process is termed incomplete fusion (ICF). The sum of complete and incomplete fusion constitutes total fusion (TF) [**?**].

Several theoretical calculations suggest that fusion cross sections for such nuclei may be enhanced compared to well-bound nuclei due to the larger spatial extent of halo nucleons [**?**]. Conversely, the fragility of halo nuclei arising from their low binding energies can cause disintegration in the nuclear field of the target before the nuclei approach closely enough to fuse. Early calculations by Hussein et al.~[**?**] indicated that actual fusion cross sections are markedly reduced across all energies. More recent coupled-channel calculations by Hagino et al.~[**?**] revealed nuanced behavior for fusion with neutron halo nuclei: cross sections increase below the Coulomb barrier due to the halo presence but decrease above the barrier because of weak coupling of halo nucleons. Experimental verification remains challenging and continues to be debated.

Furthermore, the fusion mechanism may be influenced by the cluster structure of participating nuclei. Theoretical investigations have explored cluster structures in light nuclei from stable to exotic regions. Recent research using the antisymmetrized molecular dynamics model has identified various cluster configurations [**?**, **?**, **?**, **?**]. Distinct cluster structures have been predicted for nuclei with similar proton and neutron numbers, such as Li and Be isotopes [**?**]. When such nuclei participate in near-barrier fusion reactions, the fusion cross sections should reflect the cluster structure, particularly through variations in exit channels and fusion residue distributions. This effect may be more pronounced in light systems where the Coulomb interaction is relatively weak and nuclear proximity effects are enhanced, allowing the projectile and/or target structure to directly impact the fusion cross section, especially by enhancing certain incomplete fusion channels.

The present study employs the AMD/DS version [?], which incorporates both diffusion (D) and wave packet shrinking (S) effects in the mean-field propagation through the selection of a finite coherence time. We present results from our investigation of ^{6,7}Li + ^{12,13}C, ^{6,7}Li + ^{16}O, and ^{6,7}Li + ^{24}Mg fusion reactions near the Coulomb barrier using AMD simulations.

II. AMD SIMULATIONS

The AMD/DS code with the Gogny interaction was utilized to generate the initial nuclei ^{6,7}Li, ^{12,13}C, ^{16}O, ^{24}Mg, and ^{28}Si. The computed binding energies and root-mean-square radii are compared with experimental values in Table~1 . The calculated values agree well with experimental data, except for the RMS radius of ^{6,7}Li, which is approximately 20% larger than the experimental value. However, more advanced calculations in Ref.~[?] successfully reproduce the experimental binding energy of ^{6,7}Li and demonstrate distinct d(α) + t structures.

Density distributions of these nuclei are shown in Fig.~1 [Figure 1: see original paper], with symbols indicating nucleon positions. The plots reveal clear spatial clustering of nucleons. For ^{6}Li and ^{7}Li, two clusters are evident: a larger α-cluster and a smaller deuteron or triton cluster, resulting in highly deformed nuclei. In contrast, ^{12,13}C [?, ?], ^{16}O [?], and ^{24}Mg exhibit no developed cluster structure, appearing compact and significantly more spherical.

Using these initial nuclei, we simulated ^{6,7}Li + ^{12,13}C, ^{6,7}Li + ^{16}O, and ^{6,7}Li + ^{24}Mg reactions at center-of-mass energies from 2 to 9 MeV with AMD/DS. The calculations were performed up to 2000 fm/c and clusterization was applied at the end using a phase-space coalescence technique with a coordinate-space coalescence radius of 5 fm at all energies. The charge (Z), mass (A), excitation energy, angular momentum, and velocity vector of each cluster were calculated. Simulations covered impact parameters b from 0 to 7 fm; no fusion reactions were observed for $b > 7$ fm.

Figure~2 [Figure 2: see original paper] compares experimental fusion cross sections (open circles) with calculations filtered for Z greater than the target' s Z (open squares) and for Z equal to the sum of projectile and target Z values (closed triangles). Experimental data were taken from Refs.~[?, ?, ?, ?]. The AMD simulations reproduce the experimental data well within experimental uncertainties for $E_{\text{cm}} > 3$ MeV. Absolute cross sections were determined from the number of events generated in the given impact parameter range. At $E_{\text{cm}} \leq 3$ MeV, AMD underestimates fusion cross sections because tunneling through the Coulomb barrier, which becomes important at these energies, is not incorporated in the present AMD formulation.

The figure also shows ^{19}F formation cross sections from primary AMD events (open squares). As discussed below, there is an additional 20-30% incomplete fusion contribution in the primary fusion process.

Figure~3 [Figure 3: see original paper] illustrates the time evolution of density distributions for typical complete and incomplete fusion reactions in the ^{7}Li + ^{12}C system. The left panel shows complete fusion, the middle panel shows α-particle transfer to ^{12}C with triton escape as a spectator, and the right panel shows triton absorption with the α-particle as a spectator. The latter two cases occur primarily at larger impact parameters. Several thousand to ten thousand events were generated at each incident energy, depending on the fusion cross section and impact parameter range.

Figure~4 [Figure 4: see original paper] displays the fusion channel distribution at the primary stage as a probability distribution, showing only the three major channels. ^{19}F formation and the ^{15}N + α channel dominate at all energies. Complete fusion occurs in approximately 80% of cases at lower incident energies, decreasing to about 70% at higher energies. The third channel varies with incident energy but contributes only a few percent at most.

SUMMARY

The fusion cross sections for ^{6,7}Li + ^{12,13}C, ^{6,7}Li + ^{16}O, and ^{6,7}Li + ^{24}Mg reactions were studied using AMD simulations.

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* Email: huangmeirong@imun.edu.cn
† Email: zsylt@imun.edu.cn

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Note: Figure translations are in progress. See original paper for figures.