Effect of microscopic nuclear potential on sub-barrier fusion cross-section for ^{30}Si+^{140}Ce reaction

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Introduction

Extensive research has been conducted on fusion reactions involving heavy nuclei to understand quantum tunnelling within complex many-body systems. A notable phenomenon in this field is the enhancement of sub-barrier fusion. In heavy-ion collision experiments, the fusion cross-section in the sub-barrier energy region shows an increment by several orders of magnitude compared to predictions from the one-dimensional barrier penetration model (1D-BPM), which incorporates quantum mechanical tunnelling during fusion [1]. So far, coupling-aided tunnelling, arising from the intrinsic degrees of freedom of the interacting nuclei [1, 2], has been identified as a critical factor. Moreover, various nuclear potentials have been proposed in the literature to calculate the fusion cross-sections across different energy ranges. The double-folding nuclear potential is a well-defined concept in which the ion-ion optical potential is derived by averaging the effective nucleon-nucleon (NN) interaction between the matter densities of the colliding nuclei [3]. The microscopic potential is calculated using the double-folding approach with relativistic mean-field density for the NL3* parameter set and the relativistic R3Y NN interaction potential [4]. This study explores the influence of structural properties and low-lying inelastic excitations of colliding nuclei on the fusion processes in the near and sub-barrier energy regions with microscopic nuclear potential. Coupled channel (CC) calculations have been performed using the R3Y NN interaction potential for the ^{30}Si+^{140}Ce reaction, about recent results obtained using the Woods-Saxon (WS) potential [5].

Theoretical Formalism

The Coupled Channel approach (CCFULL) is mainly employed to calculate the compound nucleus's average angular momenta and fusion cross-sections, accounting for the coupling between relative motion and intrinsic degrees of freedom. In the CCFULL code, the nuclear potential is typically derived from the traditional Woods-Saxon potential.

However, in this study, we will use the microscopic R3Y NN potential for the NL3* parameter set, obtained by solving the relativistic mean-field (RMF) equations for mesons. Further details can be found in Refs. [2–4]. The fusion cross-section of the compound nucleus is calculated by incorporating all intrinsic degrees of freedom, as discussed in the results section.

Result and Discussions

This study investigates the role of intrinsic nuclear degrees of freedom in enhancing the fusion cross-sections for the ^{30}Si+^{140}Ce reaction, particularly at sub-Coulomb barrier energies. The experimental data could not be accurately reproduced using the CCFULL calculations with the Woods-Saxon potential therefore, we have employed a microscopic R3Y NN potential derived from a recently developed, realistic, and self-consistent nuclear model. The densities required for this potential were generated using the relativistic mean-field (RMF) model, with the NL3* parameter set being the foundation for our calculations. We also conducted a comparative analysis using the well-established Woods-Saxon (WS) potential published by Sagwal *et al.* [5]. The fusion cross-sections obtained from both the WS and R3Y NN interaction potentials are presented in Figs. 1(a) and 1(b). For the WS potential, parameters such as excitation energies, quadrupole, and hex-

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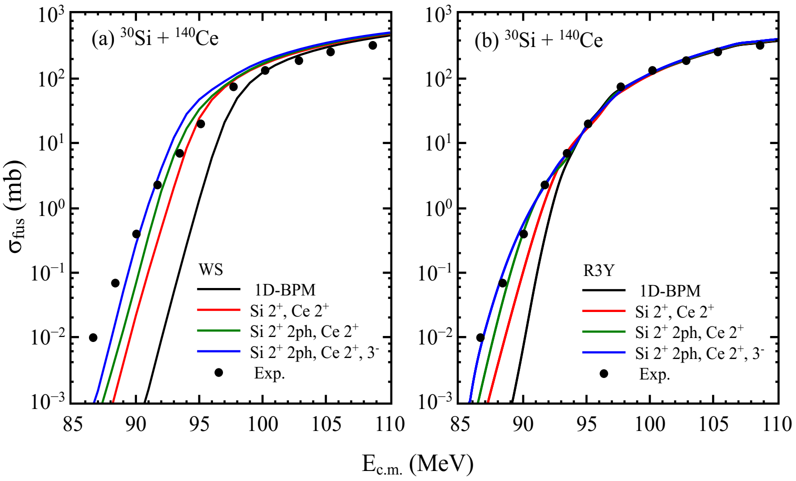

FIG. 1: (Color online) Comparison of measured fusion cross-section of ^{30}Si+^{140}Ce with CCFULL calculations for 1D-BPM (black solid line) and couplings to collective states in both projectile and target nuclei (a) WS potential (b) R3Y NN potential. (see the text for details). The experimental data is taken from Ref. [5].

adecapole deformations, necessary for coupled channel (CC) calculations, were taken from Ref. [5]. To provide an initial understanding of the fusion dynamics, we first used the one-dimensional barrier penetration model (1D-BPM) to reproduce experimental fusion cross-sections at energies above the Coulomb barrier. The solid black line in Fig. 1 illustrates these 1D-BPM results. Even the coupled channel calculations with intrinsic degrees of freedom could not explain the sub-barrier enhancement when using the WS potential, as seen in Fig. 1(a). However, when we switched to the R3Y NN potential, coupled channel calculations reduced this fusion hindrance significantly, demonstrating the potential's effectiveness in capturing sub-barrier fusion dynamics. This improvement was reported in our recent work [6], where similar trends were observed. Further analysis showed the combined effect of channel couplings from both colliding nuclei, as illustrated in Fig. 1(b). Initially, we included the 2^+ excited states of both ^{30}Si, and ^{140}Ce (solid red line), which allowed us to accurately describe the experimental data from above-barrier to near-barrier energy regions. Importantly, incorporating the 2^+ two-phonon state of ^{30}Si and the 2^+ state of ^{140}Ce further improved the agreement with experimental data, extending down to an energy of 93 MeV, as represented by the solid green line. Furthermore, including the 3^- one-phonon state of Ce with 2^+ two-phonon state of ^{30}Si and the 2^+ state of ^{140}Ce (solid blue line) successfully reproduces the experimental data [5] at sub-barrier energies. Further investigations are in progress.

Acknowledgments

This work has been supported by the Science and Engineering Research Board (SERB) File No. CRG/2021/001229 and Ramanujan Fellowship File No. RJF/2022/000140.

References

[1] M. Dasgupta *et. al.*, Annu. Rev. Nucl. Part. Sci. **48**, 401 (1998).
[2] K. Hagino, N. Rowley, and A. T. Kruppa, Comput. Phys. Commun. **123**, 143 (1999).
[3] G. R. Satchler and W. G. Love, Phys. Reports **55**, 183 (1979).
[4] M. Bhuyan and R. Kumar, Phys. Rev. C **98**, 054610 (2018).
[5] M. Sagwal, *et al.*, Eur. Phys. J. A **60**, 172 (2024).
[6] N. Jain, M. Bhuyan, and R. Kumar, Phys. Rev. C **109**, 034617 (2024).