Does neutron transfer influence sub-barrier fusion?

Pushpendra P. Singh[1]*
[1]*Department of Physics, Indian Institute of Technology Ropar, Rupnagar - 140 001, INDIA*

The heavy-ion fusion at sub-barrier energies continue to be an outstanding issue of broad experimental and theoretical interest for the community and is particularly complex due to the interplay of couplings of inelastic excitations and transfer channels. To study the transition of nuclear reactions from well above- to deep sub- barrier energies, the fusion excitation functions for different systems have been measured for a wide energy range around the Coulomb barrier energies and interpreted in the framework of coupled-channels approach. The findings of our measurements conclusively demonstrate the phenomenon of fusion hindrance at deep sub-barrier energies in both positive and negative Q-value systems and the strong dependence of couplings of inelastic excitations and transfer channels. In this talk, the behavior of sub-barrier fusion in terms of couplings of inelastic excitations and positive Q-value neutron transfer channels will be discussed.

Heavy-ion fusion around the barrier energies is a complex phenomenon that has attracted intensive experimental and theoretical efforts in the past four decades [1–4]. In general, the fusion of two heavy nuclei occurs if the entrance-channel can overcome the effective barrier formed due to the cumulative effect of repulsive Coulomb and attractive nuclear potential. However, fusion at sub-barrier energies has been experimentally ascertained [5–8], and displayed substantial enhancement over the standard coupled-channels calculations (1-d BPM) [9]. From numerous studies, by now, there is an agreement in the community that the fusion at sub-barrier energies is attributed to the quantum tunneling [7, 10] and primarily governed by the couplings of relative motion of colliding nuclei to their internal degrees of freedom like static deformations, low-energy surface vibrations [6, 8, 11], and to the onset of transfer channels [2, 12]. In some cases, where the fusion cross-sections were measured at deep sub-barrier energies, the excitation functions drop rapidly due to the influence of (quasi-elastic/multi-nucleon) transfer reactions on fusion with a logarithmic slope much larger than that predicted by tunnelling calculations using conventional ion-ion potentials which was taken as a phenomenological signal of the presence of fusion hindrance[4].

Understanding of these degrees of freedom related to fusion and, consequently, the dynamics of fusion in the various cases has been greatly facilitated by the availability of precise fusion excitation functions [13] which have been used to extract barrier distributions, the logarithmic derivative L(E) factor, and the astrophysical S factor to interpret the behavior of fusion at sub-barrier energies. In many studies [2, 4, 11, 14, 16], heavy-ion induced reactions show different facets, reflecting several physical/dynamical situations for various projectile-target combinations, while in some cases - found to be contradictory. In order to interpret experimental fusion data, several dynamical models have been proposed, however, we are still far, generally speaking, from a complete understanding of fusion dynamics at deep sub-barrier energies. Thus continue to be an active area of investigation.

To study the behavior and dynamics of fusion at sub-barrier energies, a series of experiments have been carried out to measure fusion cross-sections in Ca+Ca, S+Ca, and Cl+Te systems around the Coulomb barrier using recoil mass separators, and analyzed in the framework of coupled-channels approach. In conclusion, the fusion below barrier is mainly governed by channel coupling, and the fusion hindrance exists in both negative and positive Q-value systems. The reduced fusion excita-

---

*Electronic address: `pps@iitrpr.ac.in`

tion functions of systems with significant variations in the number of positive Q-value nucleon transfer channels have been compared to draw some conclusions about the role of neutron transfer channels in sub-barrier fusion enhancement. It has been found that the inclusion of neutron transfer channels, especially +2n transfer and inelastic excitations couplings, explains the behavior of excitation functions in the below barrier regime. This suggests the importance of positive Q-value nucleon transfer channels in sub-barrier fusion enhancement, unlike the observations of Kohley *et al.,* [3].

Further, the qualitative signature of the valence shell effect has been noticed in our results for Cl+Te systems, which are found to be in line with the neutron flow model. It would be interesting to extend such measurements at deep sub-barrier energies for better insights into the role of deformation, nuclear structure, and transfer channel couplings for different systems. However, a deeper understanding of sub-barrier fusion dynamics requires the identification of the contribution of the individual input parameter and the channel-by-channel cross-section measurement of transfer events. The findings of these exciting measurements will be presented in light of the existing studies during the symposium.

Acknowledgments

The content of this talk is drawn from several experiments performed using Legnaro, Argonne, and Delhi accelerator and recoil mass separator facilities, and is an outcome of efforts devoted by many collaborators. I wish to acknowledge all of them for their contributions, particularly, Dr. Alberto M. Stefanini, Dr. C. L. Jiang, Dr. Lorenzo Corradi, Dr. Subir Nath, Dr. N. Madhavan, and Dr. B. J. Roy. A part of this talk comprises the findings of the Ph.D. thesis of my student Mr. Rudra N. Sahoo. I sincerely acknowledge Prof. R. G. Pillay and Prof. Vandana Nanal for their valuable inputs on the Cl+Te project, a startup research grant from the Indian Institute of Technology Ropar, and the Science and Engineering Research Board for Young Scientist Award ref. no. YSS/2014/000250.

References

[1] Proc. Int. Conf. on New Aspects of Heavy Ion Collisions Near the Coulomb Barrier, Fusion08, Chicago, Illinois, 22 - 26 September 2008, AIP Conf. Proc. 1098, edited by K. E. Rehm, B. B. Back, H. Esbensen, and C. J. Lister (AIP, Melville, NY, 2009).

[2] M. Dasgupta, *et al.*, Annu. Rev. Nucl. Part. Sci. 48, 401 (1998); Physical Review Letters 99, 192701 (2007).

[3] Z. Kohley *et al.*, Phys. Rev. Lett. **107**, 202701 (2011).

[4] B. B. Back *et al.*, Review of Modern Physics, 86, 317(2014), and the references therein.

[5] C. L. Jiang *et al.*, Phys. Rev. C **75**, 015803 (2007); Phys. Rev. Lett. **89**, 052701 (2002).

[6] R. G. Stokstad *et al.,* Phys. Rev. Lett. **41**, 465 (1978); Phys. Rev. C **21**, 2427 (1980); Phys. Rev. C **23**, 281 (1981).

[7] C. Y. Wong, Phys. Lett. B **42** 186 (1972); Phys. Rev. Lett. **31** 766 (1973).

[8] A. M. Stefanini *et al.,* Phys. Rev. C **62**, 014601 (2000); **65**, 034609 (2002).

[9] J. F. Liang *et al.,* Phys. Rev. Lett. **91**, 152701 (2003), and the references therein.

[10] L. C. Uaz *et al.,* Phys. Rev. C **10**, 464 (1974); **18**, 2152 (1978).

[11] K. Hagino, N. Rowley, and A. T. Kruppa, Comput. Phys. Commun. **123**, 143 (1999); Progress of Theoretical Physics, 128-6, 1061 (2012)

[12] V. V. Sargsyan*et al.,* Phys. Rev. C **85**, 024616 (2012); Phys. Rev. C **85**, 069903 (2012); Phys. Rev. C **91**, 014613 (2015).

[13] N. Rowley, G. R. Satchler, and P. H. Stelson, Phys. Lett. B 254, 25 (1991), and the references therein.

[14] J. G. Keller, *et al.*, Nucl. Phys. A 452, 173 (1986).

[16] Rudra N. Sahoo *et al.*, Physical Review C 99, 024607 (2019), and the references therein.

[16] Rudra N. Sahoo *et al.*, Physics Letters B (2019), under review.