Study of fusion hindrance in $^{16}O+^{159}Tb$ and $^{19}F+^{159}Tb$ systems

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Fusion occurs when two atomic nuclei get close enough so that the strong nuclear forces overcome the repulsion arising from their positively charged protons, creating a fusion barrier. According to the simplest model, fusion requires the incoming projectile's energy to surpass this barrier. However, experimental evidences indicate that fusion may occur even when the center-of-mass energy ($E_{c.m.}$) of the colliding nuclei is lower than the barrier height (V_b). This phenomenon, known as sub-barrier fusion, is explained through the concept of quantum mechanical tunneling [1], via the one-dimensional barrier penetration model (1D BPM). The 1D BPM considers the wave-like behavior of particles as they attempt to pass through the fusion barrier. Jiang et al. [2] made an intriguing observation regarding fusion reactions. They noted that the fusion excitation function for certain systems exhibit an unexpected behavior characterized by a much sharper decrease than what conventional coupled-channels calculations had predicted. This phenomenon has been termed as fusion hindrance [2]. Instead of fusion excitation function, it is sometimes more convenient to discuss about the astrophysical S-factor when dealing with energies around the Coulomb barrier, where the fusion cross-section sharply declines as energy drops. Initially, fusion hindrance was observed in symmetric systems involving medium-heavy nuclei at sub-barrier energies. Its significance has been highlighted through the astrophysical S-factor [3] and the logarithmic derivative L(E) factor [4]. Both the S-factor and L(E) factor offer a means to interpret the rapid decline in fusion cross-sections at sub-barrier energies as indicative of fusion hindrance. Despite the investigations that have been done, sub-barrier fusion is still an open area of investigation.

In the present work, the S-factors for $^{16}O+^{159}Tb$ and $^{19}F+^{159}Tb$ systems have been deduced over a wide range of energies from the analysis of fusion cross-section data. The excitation functions of these systems have been measured [5,6] at energies from close to above the Coulomb barrier. The experiments have been carried out at the IUAC, New Delhi using the stacked foil activation technique. The measured fusion EFs have been compared with the theoretical predictions of code PACE4 [7] employing the quantum tunneling option and are found to agree reasonably well at above barrier energies. The same parameters have been used to compute the fusion excitation functions at below barrier energies as well. As a representative case the measured and calculated cross-sections for the system $^{19}F+^{159}Tb$ are shown in fig. 1.

The fusion cross-section is used to deduce the S-factor, defined as;

$$S(E_{c.m.}) = E_{c.m.}\, \sigma_{fus}(E_{c.m.}) \exp[2\pi(\eta - \eta_0)]$$

where, $\eta = Z_1 Z_2\, {}_e{}^2[\mu/(2h^2E_{c.m.})]^{1/2}$ is the Sommerfeld parameter, $\eta_0 = \eta$ when $E_{c.m}$

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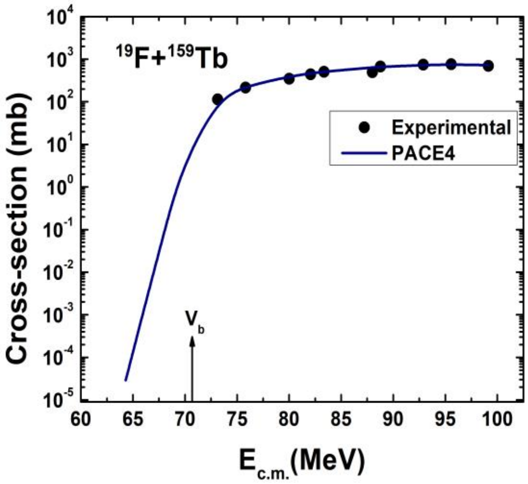

Fig.1. Experimentally measured fusion cross-sections (solid circles). The solid line represents the PACE4 calculations.

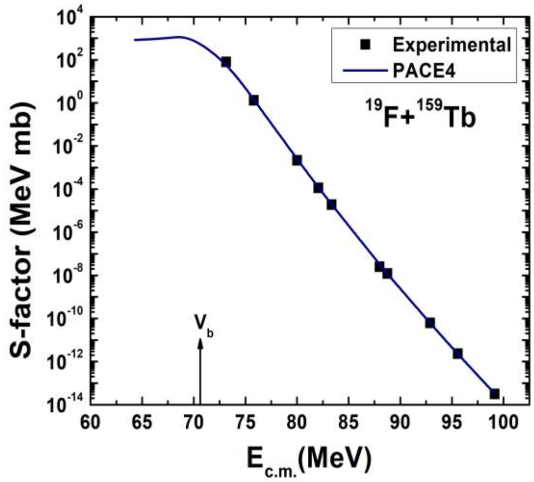

Fig. 2. Variation of S-factor with center of mass energy deduced from experimentally measured and calculated fusion excitation functions.

approaches to V_b. The Z_1 and Z_2 are the atomic numbers of projectile and target nuclei, respectively. By using the above expression, the S-factor for the systems $^{16}O+^{159}Tb$ and $^{19}F+^{159}Tb$ have been calculated. As a representative case the variation of S-factor of the system $^{19}F+^{159}Tb$ as a function of center of mass energy is shown in fig.2. Further, the fusion may occur in systems with positive Q-values even at zero center-of-mass energy. As such, the S-factor is often extrapolated to $E_{c.m} = 0$ in such cases. However, when dealing with medium-heavy systems characterized by $Z_1Z_2[A_1A_2/ (A_1 + A_2)]^{1/2} > 1500$, where the ground state Q-values are negative, it is required to interpret the S-factor. In heavy-ions induced reactions, fusion cross-sections decrease rapidly as the incident energy decreases, eventually reaching a point where fusion becomes prohibited. At a specific energy, the S-factor is expected to reach its maximum value, and below this energy, fusion cross-sections exhibit a significant decrease. This decrease in fusion cross-sections is considered as an indication of fusion hindrance [9]. As can be seen from the fig. 2, with decreasing energy the S-factor for the system $^{19}F+^{159}Tb$ attains a maximum suggesting the presence of fusion hindrance. Similar results have also been obtained for the system $^{16}O+^{159}Tb$. Further details regarding measurements and analysis will be presented.

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