Analysis of fusion barrier parameters for ^{12}C+^{93}Nb reaction

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Introduction

Information about nuclear potential is the backbone of nuclear physics research. It is because, the exact barrier shape of colliding nuclei provides an understanding of their interaction phenomena. Due to miniature scale of interaction, extraction of potential parameters from the laboratory reactions is challenging. Hence indirect method that utilizes the experimental fusion data is adopted, e.g., Wong formalism [1]. Theoretical model frameworks, for instance, Proximity models, e.g., PROX 77, PROX 88, PROX 00, PROX 00DP (2000), and PROX 2010 [2, 3], have been worked upon in the past few decades and found to be reliable. These pocket-formula-based model forms have been systematically implemented on a wide range of colliding nuclei having $12 \leq Z_1.Z_2 \leq 2952$ to extract their barrier position (R_b) and height or Coulomb barrier (V_b). Using known factors like charge and mass of nuclei, specific core parameters like mean curvature radii, surface energy, surface asymmetry constants, etc., are calculated. Efforts are constantly being made to improve these parameters' accuracy. In this work, the fusion barrier parameters for ^{12}C+^{93}Nb reaction have been extracted using the experimental data on evaporation residue (ER) cross section [4]. The results have been further validated using Proximity models' predictions.

Experiment and analysis

The experiment was performed at the BARC-TIFR Pelletron facility, Mumbai, India. Stacks of self-supporting alternative ^{93}Nb target and ^{27}Al catcher foils (99.9% pure) with thicknesses 1.3-3.0 mg/cm^2 and 1.5-1.8 mg/cm^2, respectively, were bombarded by ^{12}C beam with energy 77, 73.5, 63, and 50 MeV. Considering energy loss through the target-catcher foils using SRIM software, the incident E_{lab} was found to be 39.5-75.9 MeV, while the V_b was 37.7 MeV. The pre-calibrated high-purity germanium (HPGe) detector was used to identify the radionuclides after the end of bombardment through their characteristic γ-rays. The acquisition was continued for next few days and subsequent analyses of the measured γ-ray spectra were done through GENIE-2K software.

Results and discussion

Fourteen ERs, viz., ^{103,102,101}Ag, ^{101,100}Pd, ^{101m,100,99m,97}Rh, ^{97}Ru, ^{96,95,94}Tc, and ^{93m}Mo emitting through xn, pxn, αxn, αpxn, $2\alpha xn$, and $2\alpha pxn$ channels, respectively, have been identified [4]. The total ER cross section data have been compared with the predictions of theoretical model code EMPIRE-3.2.2 with different level density forms (FIG. 1). EMPIRE incorporates the equilibrium and pre-equilibrium mechanisms for the compound nuclear reactions based on the Hauser-Feshbach and Exciton model. Reaction data are justified well by the model code with EGSM level density. The incomplete fusion and direct reaction cross section have been found to be negligible for the present case.

Wong Formulation: The total reaction cross section $\sigma_r(E_{c.m.}) = \pi\lambda^2 \sum_{\ell=0}^{\infty}(2\ell+1)T_\ell$, where T_ℓ is the absorption probability of the ℓ^{th} partial wave. Solving further, Wong finds that R$_\ell$ and $\hbar\omega_\ell$ are insensitive to ℓ [1], hence integrating it for $\ell = 0$ (s-wave), $\sigma_r(E_{c.m.})$ equals:

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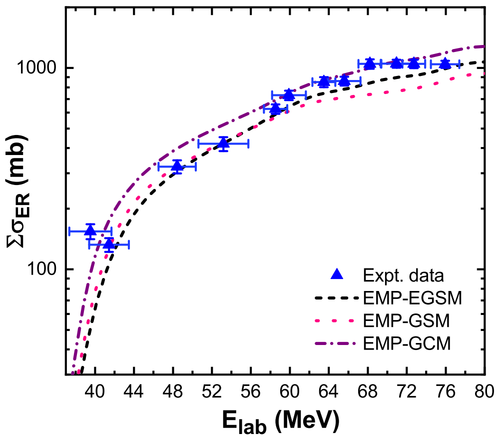

FIG. 1: Total cross section of the fourteen identified ERs populated in ^{12}C+^{93}Nb reaction.

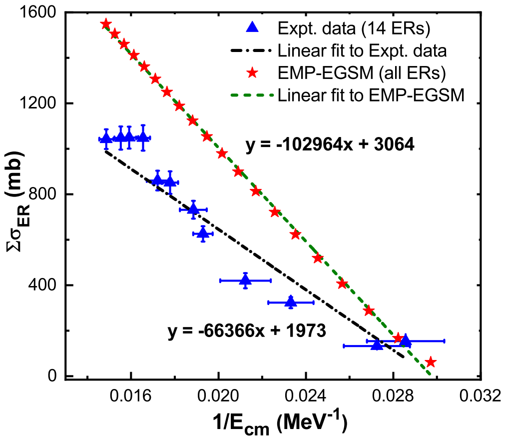

FIG. 2: Total experimental and EMPIRE predicted ER cross section as a function of $1/E_{c.m.}$.

$$\left[\frac{R_0^2\hbar\omega_0}{2E_{c.m}}\right] ln\left\{1+exp\left[\frac{2\pi}{\hbar\omega_0}(E_{c.m}-V_0)\right]\right\} \quad (1)$$

For energies much above the Coulomb barrier (V_0), i.e., $E_{c.m.}$ - $V_0 \gg \hbar\omega_0/2\pi$, the Eq: 1 results into:

$$\sigma_r(E_{c.m.}) = \pi R_0^2\left(1-\frac{V_0}{E_{c.m.}}\right) \quad (2)$$

The linear dependence of σ_r on $1/E_{c.m.}$ gives the barrier radius (R_0) and height (V_0). For systems lying in the intermediate-mass region, the contribution of direct reactions is negligible, hence $\sigma_r \approx \sigma_{fus}$. As ERs are a direct measure of fusion phenomenon, we have used the Wong formulation on total measured, and EMPIRE-EGSM predicted ER cross section data (FIG. 2). The EMPIRE predicted cross section is for all the ERs (detected+undetected); hence it is $\approx \sigma_{fus}$ and gives the fairly precise values of R_0 and V_0 (Table I). The difference in experimental value of R_0 can be attributed to a few major undetected ERs, i.e., ^{102}Pd (stable), ^{98}Rh (8.72 min), ^{98}Ru (stable), and ^{93}Nb (stable), which are contributing up to 460 mb cross section as per EMPIRE-EGSM calculations.

To further confirm our estimated barrier parameters, we have compared them with the predictions of Bass 80, Prox 00DP and Prox 2010 [2, 3], which are in mutual agreement. Our value of R_0 will be reasonably close to the above predictions, considering the missing contribution due to undetected ERs.

TABLE I: Consolidated information of the fusion barrier parameters of ^{12}C+^{93}Nb reaction

Formalism	R$_0(fm)$	V$_0(MeV)^a$
Wong (Expt. data)	7.92 ± 0.26	33.64 ± 0.36
Wong (EMP-EGSM)	9.88 ± 0.03	33.60 ± 0.09
Bass 80	9.83	33.37
Prox 00DP	9.78	33.57
Prox 2010	9.75	33.53

[a] in centre of mass frame

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