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Complete and incomplete fusion in ^{9}Be+^{124}Sn system

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Summary. Complete and incomplete fusion cross-sections for the ^{9}Be + ^{124}Sn system have been measured around the Coulomb barrier energies ($E_{\rm C.B}^{\rm lab} = 28$ MeV) using the on-line gamma ray detection technique. The complete fusion cross-sections of this system have been compared with the two stable projectiles on the same ^{124}Sn target to provide information on the projectile dependence. The brief comparison of the present ^{9}Be + ^{124}Sn data with a comprehensive and recent study of the neighbouring system ^{9}Be + ^{144}Sm is also given.

1. Introduction

Fusion cross-sections for stable nuclei have been of interest since many years [1]. Due to the recent availability of Radioactive Ion Beams (RIBs), the investigations of fusion with weakly bound stable nuclei (^{6,7}Li, ^{9}Be) have also grown up [2]. Such reactions provide the platform to establish the best experimental techniques and reaction models required for the best study of exotic nuclei available at RIB facilities with low intensities. The fusion reactions with weakly bound stable/unstable nuclei are of astrophysical interest and can give insight for super heavy element production. As far as the spectroscopy point of view is concerned, fusion-evaporation reactions are the usual way to get the high spin structure of excited nuclei. Apart from this, the ^{6,7}Li, ^{9}Be, ^{10,11}B beams are ideal for studying high spin states of stable and neutron rich nuclei produced through incomplete fusion reactions (the process in which part of the projectile is captured by the target) [3].

In this paper we have discussed the measurement of complete (CF) and incomplete fusion (ICF) cross-sections for ^{9}Be + ^{124}Sn system. We have used the online gamma ray spectroscopy method to extract fusion cross-sections, since all the evaporation residues are stable.

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2. Experimental details

The experiment was performed using the ^{9}Be beam at energies $E_{\rm lab} = 26$–46 MeV in 1 MeV steps, from the 14UD BARC-TIFR Pelletron accelerator, Mumbai. The target used was ^{124}Sn of thickness ~ 2.5 mg/cm^2, measured using the Rutherford backscattering method. The typical energy loss of the ^{9}Be beam in this 2.5 mg/cm^2 ^{124}Sn target is around 0.6–1.0 MeV, estimated from the code SRIM. The energies were corrected for the loss at half of the target thickness and used in the subsequent analysis. Two Compton suppressed clover detectors were used, one at 125°, for absolute cross-section estimation of various reaction channels and other at 90°, for identification of unshifted gamma lines. The absolute efficiency of both detectors was determined by the use of a set of calibrated radioactive sources (^{152}Eu and ^{133}Ba) mounted at the same geometry as the target. Along with the clovers two charged particle detector telescopes ($\Delta E = 20$–30 μm, $E = 1000$ μm) and one monitor detector ($= 500$ μm) were placed at 65°, 160° and 30°, respectively. The monitor detector angle is chosen in such a way that even at highest bombarding energy the elastic scattering remains in the Rutherford scattering regime. The integrated beam current deposited at the beam dump after the target has also been recorded using the high precision current integrator. The data have been acquired in the particle-gamma 'OR' condition. The coincidences between 125° clover detector and particle telescopes (TAC1, TAC2) were also recorded in ADC but the exclusive data are not discussed in this report. We have used the FERA based data acquisition system developed for INGA (Indian National Gamma Array) [4] campaign at BARC-TIFR accelerator facility, for handling these high count rates in the "OR" condition. These TAC spectra have been further utilized for putting the gates in the gamma ray spectra and identification of gamma ray lines of the residues from incomplete fusion process.

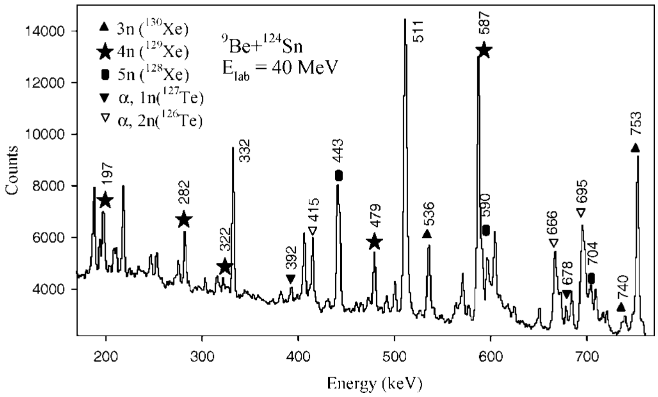

Fig. 1. Addback spectrum of the clover at 125° at $E_{\text{lab}} = 40$ MeV. The gamma lines from the possible evaporation residues are labeled. The gamma lines from the ICF channel (α, 1n and α, 2n) are also marked.

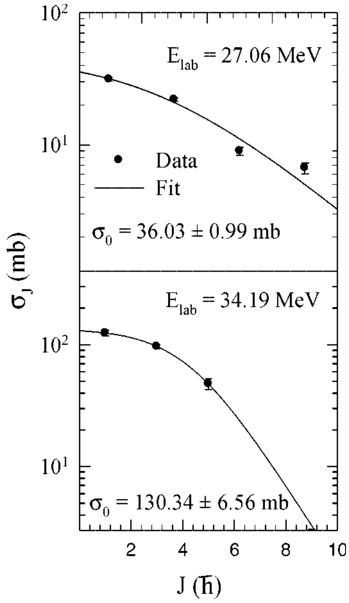

Fig. 3. The typical extrapolation method for obtaining the cross-sections for even-even ER (^{130}Xe) is shown for two energies. The function $f(x) = \frac{a}{1+e^{-\left(\frac{x-x_0}{b}\right)}}$ was used to fit the data and get the value at $J = 0$.

3. Data analysis

Fig. 1 shows the typical addback spectrum from the clover at 125° at $E_{\text{lab}} = 40$ MeV. The gamma ray lines from the evaporation residues (ERs) have been identified and labelled. The prominent gamma ray lines expected from the incomplete fusion channel residues (^{126,127}Te) are also shown. All the corresponding gamma lines cross-sections have been calculated from the relation

$$\sigma_\gamma = \frac{Y_\gamma}{Y_{\text{M}}}\frac{\text{d}\Omega_{\text{M}}}{\varepsilon_\gamma}\sigma_{\text{M}} \tag{1}$$

where Y_γ is the yield of that gamma line, Y_{M} is the monitor yield, dΩ is the solid angle of the monitor detector, ε_γ is the absolute efficiency of the gamma lines, and σ_{M} is the differential Rutherford cross-section at the relative beam energy.

The level schemes for different ERs (Fig. 2) [5–9] populated in the present experiment indicate that for even-even nuclei (^{128,130}Xe, ^{126}Te), the expected rotational structure of levels is present, and the irregular level structure in case of odd-even nuclei (^{129}Xe, ^{127}Te). Hence, for even-even nuclei the channel cross-sections can be found by extrapolating the cross-sections to $J = 0$ [10, 11]. For odd-even or odd-odd nuclei, we need to add the gamma ray cross-sections populating the ground state of residue/channel as in these cases the gamma decay may proceed through several competing rotational bands.

In the present experiment, even-even ER (^{128}Xe, ^{130}Xe) cross-sections were extracted from the extrapolated value of the gamma ray cross-sections at $J = 0$ (see Fig. 3). For the odd-mass ^{129}Xe (4n channel), there was very little known level structure (*e.g.* no heavy ion, $n\gamma$ data). Hence the cross-sections for this channel were obtained using the measured intensity of the $11/2^-$ state at 587 keV and using the statistical model code PACE [12].

The PACE calculations have been performed as follows: the excitation energy and recoil energy of compound nucleus have been given in the input along with the l-distribution corresponding to One Dimensional barrier penetration model. This l-distribution have been obtained

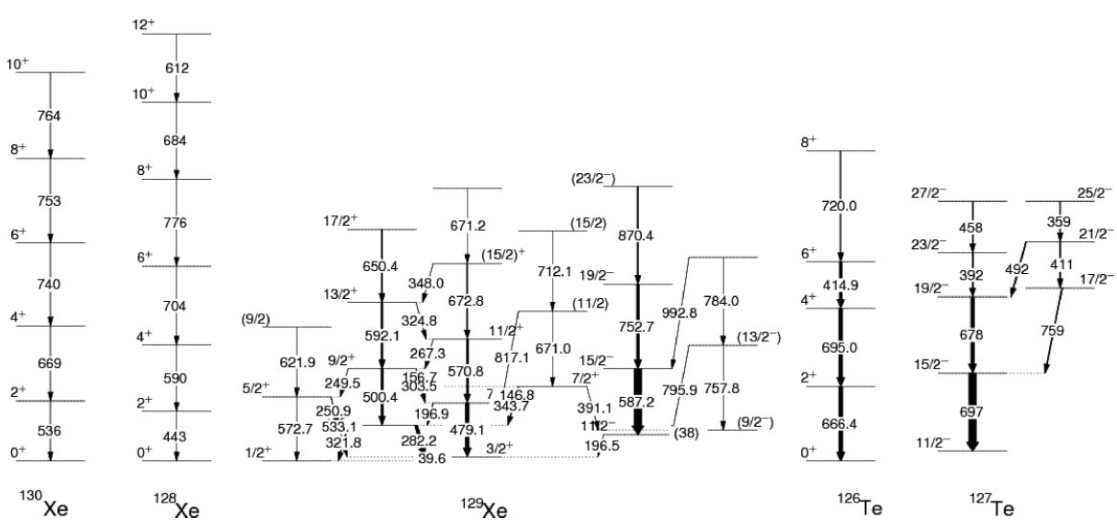

Fig. 2. Level structure of nuclei populated in the reaction. For even-even nuclei like ^{128,130}Xe and ^{126}Te, the rotational structure is seen. For odd-even nuclei like ^{129}Xe, ^{127}Te the irregular structure of gamma lines is seen.

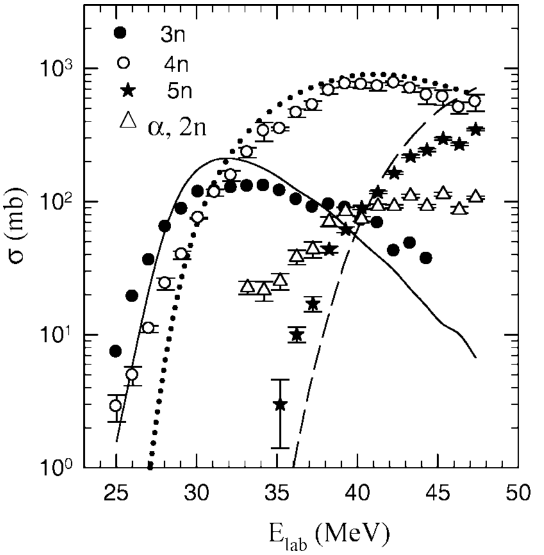

Fig. 4. Measured excitation functions for $^{9}Be + ^{124}Sn$ evaporation channels. The lines represent the statistical model predictions. The open triangles denote the cross-sections from incomplete fusion process $(\alpha, 2n)$.

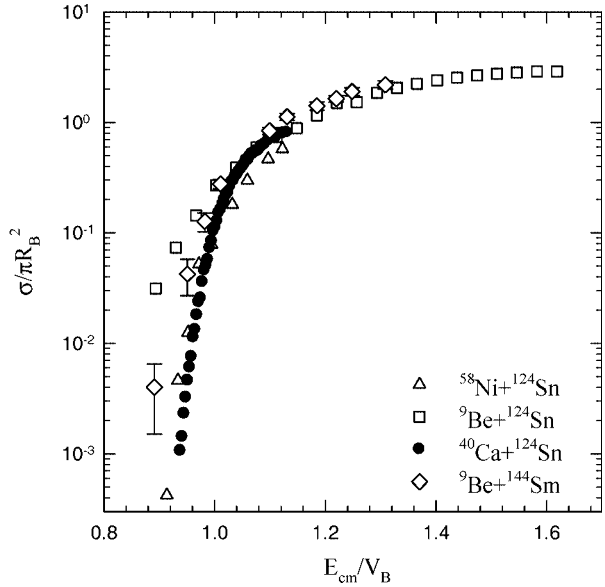

Fig. 5. Comparison of reduced cross-sections for three different systems ^{9}Be, ^{40}Ca, $^{58}Ni + ^{124}Sn$ [14, 15]. For ^{9}Be, enhancement due to low breakup threshold is seen at below barrier energies. Also the comparison with the nearby $^{9}Be + ^{144}Sm$ (CF data) [16] is shown. The enhancement at below barrier energies is seem to be more for ^{124}Sn than with ^{144}Sm target with the same projectile, ^{9}Be.

from the code CCFULL [13] for all the bombarding energies. The resulting calculated ER cross-sections from PACE are shown in Fig. 4 along with the data. To get the fusion cross-sections, a correction for small unobserved ER channels must be made. This has been done using PACE.

The ERs populated *via* incomplete fusion process are $^{126,127}Te$. Out of which the cross-sections for even-even ^{126}Te (shown in Fig. 4) have been extracted from the extrapolated value at $J = 0$. Again since the level structure of ^{127}Te is little known, we could not extract the cross-section for this channel.

The complete fusion cross-sections from the present $^{9}Be + ^{124}Sn$ reaction have been compared with two systems: $^{40}Ca + ^{124}Sn$ [14] and $^{58}Ni + ^{124}Sn$ [15], containing same target (^{124}Sn) to see the projectile dependence on fusion. This is shown in Fig. 5. The comparison shows that at below barrier energies there is an enhancement in reduced cross-sections for $^{9}Be+^{124}Sn$ which can be attributed to the low breakup threshold for ^{9}Be.

Recently the comprehensive study of reaction mechanisms for the nearby system $^{9}Be + ^{144}Sm$ has been reported in Ref. [16]. The CF data of this system is compared in Fig. 5, which shows that the enhancement at below barrier is more for ^{124}Sn than with ^{144}Sm target, when bombarded with ^{9}Be projectile.

In the study of $^{9}Be + ^{144}Sm$, they could get complete information of CF and ICF channels and hence get the total fusion (CF + ICF) cross-sections. They conclude that the total fusion cross-sections do not get affected by breakup at energies above the barrier. In the present study of $^{9}Be + ^{124}Sn$, we could not get one of the prominent ICF (^{127}Te) channel cross-section. We plan to measure this unobserved ICF channel along with 1n transfer (^{125}Sn) cross-sections by offline gamma ray technique. This will allow us to have a measure of total fusion and 1n transfer. From this complete data on fusion and transfer, we could conclude on the role of breakup in more details.

4. Conclusion

The fusion cross-sections for $^{9}Be + ^{124}Sn$ system have been obtained from online gamma ray spectroscopy. The complete fusion cross-sections from this system have been compared with the two reactions containing same target and an enhanced below-barrier cross section was observed for the $^{9}Be + ^{124}Sn$ system.

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