PRAMANA
— journal of
physics

Vol. 53, No. 3
September 1999
pp. 535–539

Measurement of the ground state $2n$ pickup probability for ^{28}Si + ^{68}Zn and its role in sub-barrier fusion enhancement

VANDANA TRIPATHI[1], LAGY T BABY[1], P V MADHUSUDHANA RAO[2], S K HUI[3], R SINGH[4], J J DAS[1], P SUGATHAN[1], N MADHAVAN[1] and A K SINHA[1]
[1]Nuclear Science Centre, P.B. No. 10502, New Delhi 110 067, India
[2]Department of Nuclear Physics, Andhra University, Visakhapatnam 530 003, India
[3]Department of Physics, Calcutta University, Calcutta 700 009, India
[4]Department of Physics, Delhi University, New Delhi 110 007, India

Abstract. The ground state and excited state transfer yields for the 2-neutron pickup channel in the ^{28}Si + ^{68}Zn system have been measured explicitly. The recoil mass separator at the Nuclear Science Centre, New Delhi was used for the measurement. A NaI(Tl) detector was used for detecting the de-excitation γ's from the transfer products. The kinematic coincidence technique was employed for the transfer measurement. Simplified coupled channels calculations show that out of all transfer channels the major contribution to the sub-barrier enhancement comes from the ground state 2 neutron pickup channel with a ground state Q-value of + 1.83 MeV.

Keywords. Heavy-ion fusion; sub-barrier enhancement; ground state transfer; kinematic coincidence; simplified coupled channel calculation.

PACS Nos 25.70.Hi; 25.70.Jj

1. Introduction

Heavy-ion fusion cross-sections at below barrier energies are generally enhanced by orders of magnitude in comparison to the predictions of the one-dimensional quantum mechanical barrier penetration calculations [1]. The influence of additional quasi-elastic reactions on the barrier tunneling probability is believed to be responsible for the observed increase in flux going into the fusion channel as formulated in the coupled channels calculations [2,3]. The quasi-elastic channels considered explicitly are mostly limited to the inelastic excitations of the low lying levels. Such calculations reproduce the fusion cross-sections rather well in many cases [3]. However, the variation of the measured fusion cross-section within a given projectile target combination involving different isotopes especially at energies near the barrier is not easily understood by including inelastic channels alone in the coupled channel calculations. Such variations may arise from the influence of transfer channels which have distinctly different Q-values and probabilities for various isotopes. A correlated observation is the rather dramatic increase of transfer cross-sections (mainly neutron transfer) for heavier systems at energies near the barrier suggesting a correlation between fusion and nucleon transfer. It has been pointed out that nucleon transfer with positive ground state Q-value, $Q_{\rm gg}$, favours fusion [4]. However even for the $2n$ pickup with large positive $Q_{\rm gg}$, the ground state is very weakly populated as the $Q_{\rm opt} \approx 0$. The main strength goes to states at higher excitation energies.

These observations call for experiments to measure the one and two nucleon transfer cross section with a resolution adequate to distinguish at least the ground state transfer events from the rest of the quasi-elastic transfer yield. These results can help in quantifying the role of positive Q-value transfer channels in the sub-barrier enhancement. We have attempted to measure the ground state and excited state transfer probabilities explicitly for the 2-neutron pickup reaction ^{68}Zn(^{28}Si ^{30}Si)^{66}Zn to study its influence on the sub-barrier fusion process. The above reaction has a positive ground state Q-value of 1.83 MeV and contributes significantly to the sub-barrier fusion cross-section enhancement [5,6]. We have combined the two techniques used for transfer measurement, that is identification of recoils using a recoil mass separator and the study of de-excitation γ rays in coincidence with the reaction products to estimate the ground state and quasi-elastic transfer yields.

2. Experiment

The experiment was performed at the Nuclear Science Centre, New Delhi using the ^{28}Si beam of energy 78 MeV from the 15UD Pelletron. The target used was 109 μg/cm^2 ^{68}Zn with 15 μg/cm^2 carbon backing. The ^{68}Zn target was 99.3% enriched (0.25% ^{66}Zn and 0.11% ^{67}Zn). The target-like reaction products, moving in the forward direction were separated out from the beam-like particles by the Heavy Ion Reaction Analyser (HIRA) and detected at the focal plane by a detector system consisting of a multi-wire proportional counter followed by an ionisation detector. HIRA was kept at 10 degree with respect to the beam for better beam rejection. The 'kinematic coincidence technique' was employed for the transfer measurement which involved detection of the kinematically correlated reaction products in coincidence. To detect the back scattered projectile-like particles a 8×47 mm^2 position sensitive detector (PSD) was placed at roughly 145 degree with respect to beam in the scattering chamber of HIRA at a distance of 80 mm from the target. The angle was optimised for maximum coincidence efficiency. A time-of-flight (TOF) arrangement was set up using the start signal from the PSD and stop from the focal plane timing. This was helpful in completely eliminating the beam background. Two monitors were kept at $\pm$ 25 degrees from the beam direction for beam monitoring. A $3'' \times 3''$ NaI(Tl) detector was put at a distance of 30 mm from the target. A 4 mm thick lead shielding was put around the detector to attenuate the X-rays and low energy γ rays. The timing signal from the γ detector was used to set up the coincidence between the prompt γ rays and the recoils at the focal plane.

3. Analysis

A typical projection of TOF vs focal plane position is shown in figure 1(a). The three peaks marked correspond to the elastic, $1n$- and $2n$-pickup channels. The pickup channels turn out to be mainly neutron channels from Q-value considerations. Elastically scattered recoils from the contaminants in the target (^{67}Zn and ^{66}Zn) also add to the transfer product yields from ^{68}Zn. An estimate of the contribution from these isotopes was obtained and

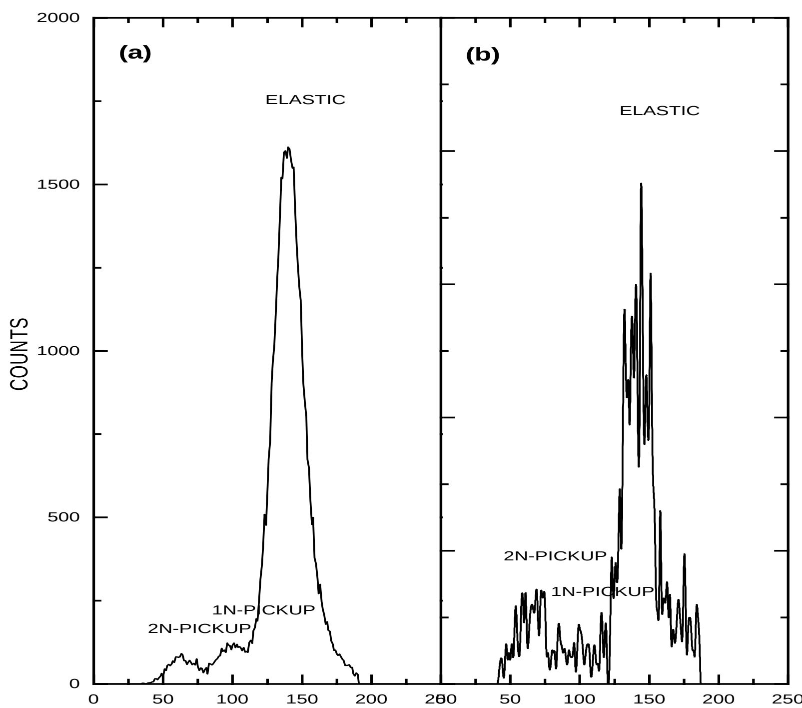

Figure 1. (**a**) Projected mass spectra at the focal plane of HIRA, (**b**) gated with the prompt timing between the recoils and the γ's. X axis is the position in both cases.

was subtracted from the transfer yields. Since HIRA detection efficiency is same for all channels and the solid angle factor being identical, the yields in the channels can be directly used for obtaining the transfer probabilities. The transfer probability for a particular transfer channel has been calculated as the ratio of the yield in that channel to the sum of the yields in elastic plus transfer channels. These correspond to the total quasi-elastic transfer probabilities for the $1n$- and $2n$- pickup.

The resolution of the NaI(Tl) was not good enough to resolve the individual gamma's. This was due to the high count rate which was essential for getting sufficient coincidence counts. So the prompt timing between the de-excitation gamma rays from the transfer products and the recoils was used to gate the TOF vs position plots. Figure 1(b) shows such a plot. The yields in the pickup channels after subtracting the background correspond to transfer to excited states. Corrections have been made for the excitation of the target impurities. After correcting for efficiency the transfer probability to the excited states was extracted as before .The ground state probability is given by the difference of the total and the quasi-elastic transfer probabilities. Table 1 gives the transfer probabilities for the $1n$ and $2n$ channels.

When the ground state and excited states can be treated separately [7], the total transfer probability will be the sum of ground state strength and strength to the excited states.

Table 1. Measured transfer probability for the $1n$ and $2n$ pickup channel at 78 MeV.

	$(P_{\rm tr})_{\rm tot}$	$(P_{\rm tr})_{\rm ex.}$	$(P_{\rm tr})_{\rm gs}$
+ $1n$	0.0580 $\pm$ 0.0006	-	-
+ $2n$	0.0450 $\pm$ 0.0006	0.041 $\pm$ 0.002	0.004 $\pm$ 0.002

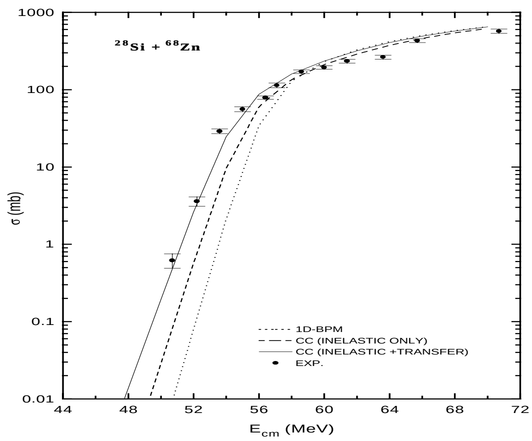

Figure 2. Simplified coupled channel calculations for the system ^{28}Si + ^{68}Zn.

Since the probabilities to both ground state and excited states are known experimentally for the $2n$ pickup channel, the form factors Fo and $\bar{F}$ [7] for the ground state and excited states respectively were calculated. For the $1n$ channel an average form factor was calculated. Coupled channels calculations were performed using a modified version of the code CCMOD [8]. The experimental fusion cross sections were taken from ref. [8]. A plot of the cross section vs energy is shown in figure 2. Inclusion of excitation of low lying 2^+, 3^- states of ^{28}Si and ^{68}Zn gives substantial enhancement but not enough to reproduce the data (figure 2). The negative Q-value transfer channels do not have any significant effect on the fusion result. The inclusion of $2n$ pickup to excited states of ^{30}Si and ^{66}Zn with an effective Q-value which is negative, does not improve the fit. Large asymptotic barrier shift of 2.52 MeV is obtained on coupling the ground state $2n$ transfer. This reproduces the below barrier data quite well (thick solid line in figure 2).

In summary, we have measured the ground state and quasi-elastic transfer strength for the reaction ^{68}Zn(^{28}Si ^{30}Si) ^{66}Zn. Simplified coupled channels calculations show that the major contribution to the sub-barrier enhancement apart from the inelastic couplings comes from the ground state 2 neutron transfer which has a positive Q-value, even though it is weakly populated. The results also point to the need for experiments to measure transfer yields to individual states, which will lead to a better understanding of sub-barrier fusion dynamics.

References

[1] M Beckerman, *Phys. Rep.* **129**, 145 (1985)
[2] H Esbensen, *NPA* **352**, 147 (1981)
[3] C H Dasso, S Landowne and A Winther, *NPA* **405**, 381 (1983); *NPA* **407**, 221 (1983)
[4] R A Broglia, C H Dasso, S Landowne and A Winther, *Phys. Rev.* **C27**, 2433 (1983)
[5] S Saha and Y K Agarwal, *Nucl. Phys.* **A601**, 251 (1996)
[6] D O Kataria *et al*, *Phys. Rev.* **C56**, 1902 (1997)
[7] Lagy T Baby *et al*, *Phys. Rev.* **C56**, 1936 (1997)
[8] M Dasgupta, A Navin, Y K Agarwal, C V K Baba, H C Jain, M L Jhingan and A Roy, *Nucl. Phys.* **A539**, 351 (1992)