# Multi-nucleon transfer cross sections in $^{28}$Si+$^{90,94}$Zr

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Multi-nucleon transfer (MNT) reactions [1] are characterized by broad distributions of angle, energy, charge and mass of the reaction products. Transfer of nucleons are known to influence the dynamics of sub-barrier fusion between two heavy ions. MNT reactions are also crucial for production of nuclides away from the valley of stability. Reaction products from quasi-elastic channels can be identified by detecting the projectile-like ions at large angles. Conversely, MNT channels can also be studied by detection of target-like ions at small angles around the direction of beam. Feasibility of measurement of MNT channels by the latter method, using a recoil separator, had first been demonstrated by Betts *et al.* [2]. Kalkal *et al.* [3] measured MNT probabilities in $^{28}$Si+$^{90,94}$Zr using the recoil mass spectrometer (RMS) at IUAC, *viz.*, Heavy Ion Reaction Analyzer (HIRA) [4].

Recently, Biswas *et al.* [5] developed a methodology to extract differential quasi-elastic cross sections, $\left(\frac{d\sigma}{d\Omega}\right)^{\rm qel}$, from measured yields of reaction products at the focal plane of an RMS. Transmission effiency ($\epsilon$) of the RMS for specific channel(s) was obtained using a semi-microscopic Monte Carlo code [6].

Here we report differential cross sections for MNT channels at centre-of-mass (c.m.) angle, $\theta_{\rm c.m.} \simeq 168^\circ$ for the systems $^{28}$Si+$^{90,94}$Zr, which were calculated using the relation [5]:

$$\left(\frac{d\sigma}{d\Omega}\right)^{\rm qel}_{168^\circ} = \left(\frac{Y_{\rm H}}{Y_{\rm mon}}\right)\left(\frac{\Omega_{\rm mon}}{\Omega^{\rm eff}_{\rm H}}\right)\frac{1}{\epsilon}\left(\frac{d\sigma}{d\Omega}\right)^{\rm R}_{\theta_{\rm mon}} . \quad (1)$$

Here $Y_{\rm H}$ is the yield recorded at the focal plane of the HIRA operated at $\theta_{\rm lab} = 6^\circ$ and $Y_{\rm mon}$ is the geometric mean of yields recorded by two monitor detectors placed at c.m. angle $\theta_{\rm mon}$. $\Omega_{\rm mon}$ is the solid angle subtended by each of the monitor detectors and $\left(\frac{d\sigma}{d\Omega}\right)^{\rm R}_{\theta_{\rm mon}}$ is differential Rutherford scattering cross section. $\Omega^{\rm eff}_{\rm H}$ is the effective solid angle of the HIRA, which was obtained from the experiment by recording target-like recoils at $E_{\rm lab} = 70$ MeV [7].

The excitation functions for neutron pickup and proton stripping channels for the systems $^{28}$Si+$^{94}$Zr and $^{28}$Si+$^{90}$Zr at $\theta_{\rm c.m.} \simeq 168^\circ$ are shown in Fig. 1 and 2, respectively. Location of the Coulomb barrier is indicated by an upright arrow in each panel.

Experimental transfer probabilities ($P_{\rm tr}$) as a function of the distance of closest approach ($D_0$), shown in Fig. 3, were obtained directly from the focal plane yields using the relation:

$$\mathrm{P}^{\alpha}_{\rm tr}(D_0) = \frac{\mathrm{Y}^{\alpha}/\epsilon^{\alpha}_{\rm HIRA}}{\sum_{i=89,90,91,92,93,94,95,96}\mathrm{Y}^{\rm i}/\epsilon^{\rm i}_{\rm HIRA}}; \quad (2)$$

$$\alpha \in \{89, 90, 91, 92, 93, 94, 95, 96\} .$$

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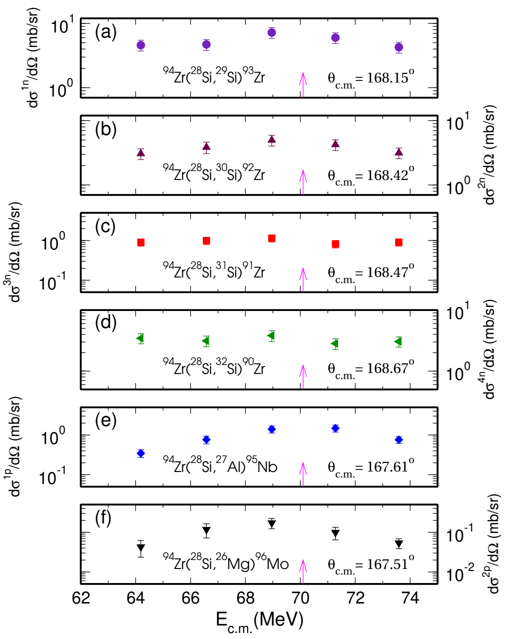


FIG. 1: Experimental differential cross sections for (a) $1n$-pickup, (b) $2n$-pickup, (c) $3n$-pickup (d) $4n$-pickup, (e) $1p$-stripping and (f) $2p$-stripping channels for the reaction $^{28}$Si+$^{94}$Zr.

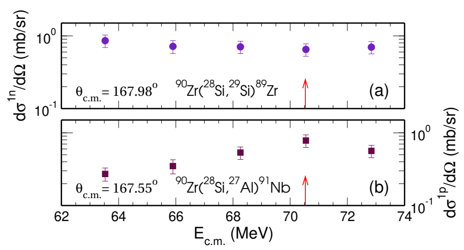


FIG. 2: Experimental differential cross sections for (a) $1n$-pickup and (b) $1p$-stripping for the reaction $^{28}$Si+$^{90}$Zr.

$D_0$ was calculated by assuming a very weak nuclear potential in such a way that the incident particle followed Coulomb trajectory:

$$D_0 = \frac{Z_p Z_t e^2}{2E_{c.m.}}\left[1 + \mathrm{cosec}\left(\frac{\theta_{c.m.}}{2}\right)\right] \quad (3)$$

where $Z_p$ and $Z_t$ are the atomic numbers of the projectile and the target, respectively, $e^2 = 1.44$ MeV fm and $E_{c.m.}$ is the energy available in the c.m. frame of reference.

The methodology presented here can be adopted to study MNT reactions using other recoil separators. Theoretical investigation within the framework of coupled reaction channel model would be important to understand the mechanism of MNT in heavy ion-induced reactions.

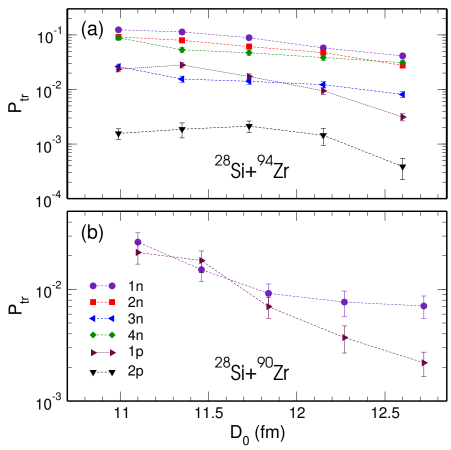


FIG. 3: Experimental transfer probabilities as a function of the distance of closest approach for (a) $^{28}$Si+$^{94}$Zr and (b) $^{28}$Si+$^{90}$Zr. The lines are for guiding the eye.

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