Study of quasi-elastic reactions with a recoil separator

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Peripheral collisions between two heavy ions [1] populate nuclides with large range of energy, angle, nuclear charge (Z) and mass number (A). Devices with good resolution of energy, Z and A and preferrably large angular acceptance are suitable for studying such reactions. Magnetic spectrographs [2] had often been used to identify quasi-elastic events resulting from heavy ion collisions. In recent years, a new class of magnetic separators (see *e.g.*, Ref. [3]) with very large acceptance has been commissioned to study multinucleon transfer (MNT) reactions. These separators have fairly simple magnetic configurations, however, a rather complex event by event reconstruction of trajectories are essential for identification of reaction products.

Quasi-elastic reactions can be studied experimentally by detecting either the projectile-like or the target-like ions. In the case of lighter projectiles colliding with heavier target nuclei, the back-scattered projectile-like ions carry a very small fraction of the initial kinetic energy of the projectile ($E_{\rm lab}$). This makes identification and detection of the back-scattered particles quite difficult. Moreover, no measurement can be performed at the extreme backward angle ($\theta_{\rm lab} = 180^\circ$). For each back-scattered projectile-like ion, however, there is a target-like ion moving with relatively higher energy in the forward direction in the laboratory frame of reference. These targt-like ions can be separated and detected using a highly selective device like a recoil separator.

This technique was first successfully utilized in the measurement of transfer channels for ^{58}Ni+$^{\rm A}$Sn [4] at sub-barrier energies using the Daresbury recoil mass separator. Target-like ions, separated according to their mass to charge state (q) ratio $\left(\frac{A}{q}\right)$, were detected by a position-sensitive detector at the focal plane of the separator. Though a conventional recoil separator has very limited dynamic range in velocity and charge acceptances, the excellent mass resolution makes it quite useful in the study of quasi-elastic reactions. Similar method had been adopted in the study of MNT probabilities, especially at sub-barrier energies, using other recoil separators. The Heavy Ion Reaction Analyzer (HIRA) [5] at IUAC, one of the first generation recoil mass spectrometers (RMSs), had also been useful in the study of MNT channels for several medium-heavy systems.

However, all such measurements suffered from two major drawbacks. Firstly, while estimating the transfer probabilities, it had been assumed that the transmission efficiency (ϵ) of the RMS for each transfer channel was the same as that for the elastic channel. Secondly, cross sections had not been extracted from measured yields, as ϵ had not been known. Differential cross sections for a few transfer channels had been extracted, for a limited number of reactions, by equating the sum of differential elastic, inelastic and transfer cross sections to the differential Rutherford scattering cross sections, at energies near and below the Coulomb barrier.

Recently similar method of studying quasi-elastic reaction channels, by measuring the heavier target-like ions in the forward direction, has been adopted in two other types of recoil separators. The velocity filter SHIP [6] at GSI has been used for populating MNT channels in very heavy mass region [7], in which the transfer products have been identified at the focal plane by their characteristic α-decay. Fusion barrier distributions (BDs) have been extracted from quasi-elastic excita-

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tion functions for several reactions [8], to optimize $E_{\rm lab}$ for synthesizing unknown superheavy elements, using the gas-filled separator GARIS [9] at RIKEN.

It should be mentioned here that fusion BD is defined as the second derivative of the energy-weighted cross section [10] and is extracted from measured fusion excitation function using the finite difference method. Timmers *et al.* [11] showed that similar insight about the fusion dynamics may be obtained from measurement of quasi-elastic excitation function at large angles. In this case, BD can be extracted from the first derivative of the ratio of differential quasi-elastic and Rutherford cross sections. Extraction of BD from quaselastic excitation function is advantageous in cases where measuring fusion excitation function with high precision is difficult. Two examples are fusion reactions involving exotic beams and fusion leading to formation of very fissile di-nuclear systems like superheavy nuclei. Quasi-elastic excitation functions are usually measured by detecting the projectile-like ions at large backward angles [12]. Here different scattering angles correspond to different grazing angular momenta (ℓ). The effect of ℓ is corrected by shifting the energy by an amount equal to the centrifugal potential. If the excitation function is measured at $\theta_{\rm c.m.} \sim 180^\circ$, which correspond to $\ell \sim 0$, scaling of energy is not needed. Such measurements can only be carried out by detecting the target-like ions at $\theta_{\rm lab} \sim 0^\circ$, as has been demonstrated in Ref. [8].

Biswas *et al.* recently reported [13] simulation of an RMS for measurement of differential quasi-elastic scattering cross sections. The semi-microscopic Monte Carlo code, developed for this purpose, is useful for calculation of ϵ for target-like ions and unambiguous identification of elastic/inelastic and MNT channels at the focal plane of the RMS. The methodology for extracting cross sections from measured yields was verified [14] by reproducing results from the reaction ^{28}Si+^{94}Zr [15], measured with the HIRA.

Further, simultaneous measurement of fusion and quasi-elastic excitation functions were carried out for the reaction ^{16}O+^{142}Ce. For the first time, BDs were extracted from three different data sets [16] *viz.* fusion excitation function measured at $\theta_{\rm lab} \sim 0^\circ$, quasi-elastic excitation function measured at $\theta_{\rm c.m.} \sim 180^\circ$ (by detecting target-like ions) and quasi-elastic excitation function measured at large backward angles (by detecting projectile-like ions). The resulting BDs were found to be nearly identical, thus, providing the first experimental verification for validity of the scaling property and iso-centrifugal approximation [12]. Additionally one-proton ($1p$-) and two-proton ($2p$-) stripping channels were identified at the focal plane [17]. Coupled reaction channel (CRC) calculations were performed using the code FRESCO [18]. The spectroscopic information for the target-like nuclei were extracted from large-scale shell model [19] calculations. An excellent reproduction of the data by theory was achieved for $1p$-stripping whereas cluster transfer of two protons was found to have dominant contribution in case of $2p$-stripping. These results demonstrate the usefulness of a recoil separator for studying quasi-elastic reactions. The methodology presented here could be adopted for measurement of quasi-elastic BDs and study of MNT channels with similar devices.

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