Simulating measurement of differential quasi-elastic scattering cross-sections in an RMS

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Modern recoil mass spectrometers (RMSs) like the Heavy Ion Reaction Analyzer (HIRA) [1] belong to a special class of recoil separators which are suitable for identification of weak reaction channels amidst dominant background events. The HIRA is based on QQ-ED-MD-ED-QQ configuration where Q, ED and MD stand for quadrupole magnet, electrostatic dipole and magnetic dipole, respectively. In the conventional mode of operation, non-zero mass dispersion along with space focus and energy achromaticity is achieved at the focal plane of the HIRA.

One of the major applications of an RMS is to detect fusion reaction products, *viz.* evaporation residues (ERs), at its focal plane. It is well known that the single potential barrier between two heavy ions splits into a distribution of barriers because of coupling between the relative motion and other degrees of freedom *e.g.* static deformation and inelastic excitations of the collision partners and exchange of nucleons between them. The barrier distribution (BD), bearing signatures of channel coupling, can be extracted from measured fusion cross sections (σ_{fus}) around the barrier:

$$BD_{\mathrm{fus}}(E) = \frac{\mathrm{d}^2}{\mathrm{d}E^2}\left[E\sigma_{\mathrm{fus}}(E)\right]. \qquad (1)$$

σ_{fus} needs to be measured with high recision at small intervals of projectile energy (E) in order to obtain a reliable BD.

BD can also be extracted from measurement of differential quasi-elastic scattering cross sections $\left(\frac{\mathrm{d}\sigma_{\mathrm{qel}}}{\mathrm{d}\Omega}\right)$ at large angles [2]:

$$BD_{\mathrm{qel}}(E) = -\frac{\mathrm{d}}{\mathrm{d}E}\left[\frac{\mathrm{d}\sigma_{\mathrm{qel}}(E)}{\mathrm{d}\sigma_{\mathrm{Ruth}}(E)}\right], \qquad (2)$$

where $\left(\frac{\mathrm{d}\sigma_{\mathrm{Ruth}}}{\mathrm{d}\Omega}\right)$ is the differential Rutherford scattering cross section. Detection of the back-scattered projectile-like ions at $\theta_{\mathrm{lab}} \simeq 180°$, though, is extremely difficult. For each back-scattered ion, however, there is a forward-moving target-like ion which can be detected using a device with high selectivity like an RMS. Feasibility of such a measurement was first demonstrated using the Daresbury recoil mass separator [3].

We present a semi-microscopic Monte Carlo code to simulate measurement of quasi-elastic scattering cross section in the HIRA. The present approach is based on the existing code TERS [4], which can simulate measurement of ER cross sections in the HIRA and calculate the transmission efficiency (ϵ_{HIRA}). This code is very effective for planning and performing a scattering experiment in an RMS. It can be customized for similar devices by necessary modification in the ion-optical layout.

The code has two major parts. Ion-optical parameters of the reaction products are generated in the first part. Angular distribution of the target-like ions in the laboratory frame of reference can be provided by the user. This feature helps in adapting the code to various kinds of direct nuclear reactions. The code generates scattering angle θ_{lab}, event by event, based on the user input, using acceptance-rejection Monte Carlo technique. The azimuthal angle (ϕ_{lab}) is sampled randomly from a uniform distribution in the range of 0 to 2π. The divergences in the dispersive (x–z) and the non-dispersive (y–z) planes, ϑ and φ, respectively, are obtained by suitable trans-

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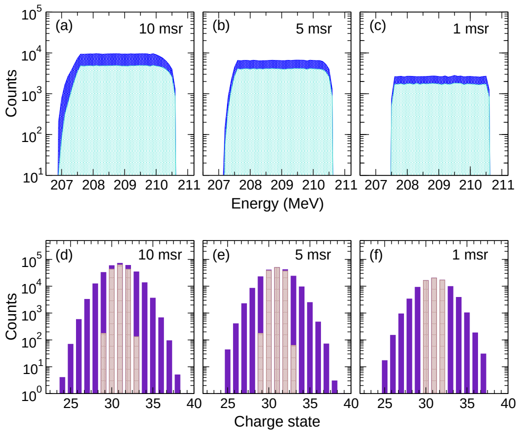

FIG. 1: Simulated energy and charge state distributions of scattered ^{116}Sn ions within the entrance aperture (darker shade) and at the focal plane (lighter shade) of the HIRA. Simulation has been carried out for 300,000 events.

formations. Here, z is the direction of the beam in the laboratory frame of reference. Energy of each scattered ion ($\mathcal{E}$) is calculated using the non-relativistic two-body kinematics. Each ion is next assigned a charge state. Finally χ and y, the displacements in x–z and y–z planes, respectively, are sampled randomly from the user-defined size of the beam. Each scattered ion is thus characterised by six ion-optical parameters: χ, ϑ, y, φ, $\mathcal{E}$ and q.

Trajectories of the scattered target-like ions are calculated using first-order ion-optical transfer matrices in the second part of the code. $\epsilon_{\rm HIRA}$ is defined by the ratio of the number of trajectories reaching the focal plane ($\mathcal{N}_{\rm FP}$) to the number of trajectories entering the entrance aperture ($\Omega_{\rm HIRA}$) of the HIRA ($\mathcal{N}_{\rm AP}$), which is used to calculate the differential scattering cross-section.

We consider the reaction ^{58}Ni+^{116}Sn to illustrate the methodology of calculation [5]. ^{58}Ni projectiles ($E_{\rm lab}$ = 237 MeV) are assumed to collide with a thin self-supporting taget (100 μg/cm^2) of ^{116}Sn. We consider Rutherford scattering and detection of forward-moving target-like ions are simulated. Dimensions of the forcal plane detector is taken to be 15 cm in x and 5 cm in y. Simulated energy and charge state distributions of ^{116}Sn ions are shown in Fig. 1. Trajectories of the ions through the HIRA are shown in Fig. 2. Finally, calculated $\epsilon_{\rm HIRA}$ for different values of $\Omega_{\rm HIRA}$ are presented in Table I.

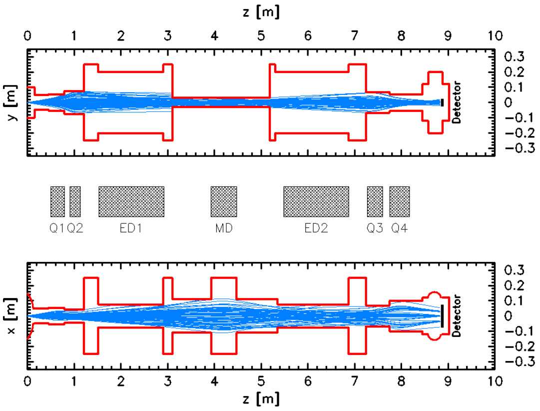

FIG. 2: Simulated trajectories for scattered ^{116}Sn ions in x–z and y–z planes of the HIRA. Contours of the vacuum chambers are denoted by the thick (red) lines. The HIRA is set for the reference particle with $\mathcal{A}_0$ = 116 amu, $\mathcal{E}_0$ = 208.7 MeV and $q_0 = 31^+$. Only 100 trajectories are shown.

TABLE I: Calculated $\epsilon_{\rm HIRA}$ for forward-moving target ions for different values of $\Omega_{\rm HIRA}$.

$\Omega_{\rm HIRA}$ (msr)	$\mathcal{N}_{\rm AP}$	$\mathcal{N}_{\rm FP}$	$\epsilon_{\rm HIRA}$ (%)
10	300,000	156,744	52.2
5	209,912	132,022	62.9
1	87,254	57,293	65.7

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