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Determination Of Breakup Cross-Sections Using A 3-body Simulation Code Based On Monte Carlo Method

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An array of double sided Silicon strip detectors has been used to measure the events for elastic scattering and different breakup channels like direct, resonant and transfer reactions involving ^{7}Li as a projectile. The aim is to quantify the differential cross-section for above breakup channels to understand the high yield of inclusive alpha contribution. Precise determination of the detection efficiency for the events in coincidence is required for that purpose. A simulation code has been developed based on Monte Carlo method involving 3-body kinematics to extract out the coincidence efficiency of the binary breakup events. This paper explains the method of extraction of breakup cross-section using the extracted efficiency.

KEYWORDS: Breakup Reactions, Monte-Carlo Simulation, Detector efficiency, Differential Cross-Sections

1. Introduction

The study of nuclei near the neutron drip-line has been drawing tremendous interests due to the observations of many exotic features like extended matter distribution, halo and Borromean structure, low lying continuum etc [1]. The weakly bound stable nuclei like ^{6,7}Li,^{9}Be show somewhat similar behaviour (such as low breakup threshold, core+valence cluster structure, etc.) as that of the exotic nuclei [2–6], one can study the reactions involving these stable nuclei to get the taste of the unstable nuclei. The projectile dissociation of weakly bound nuclei serves as an input to the determination of radiative capture cross section of astrophysical interest. The information of radiative capture cross-section provides an input to the determination of reaction rate of various nucleosynthesis processes in stellar burning astrophysical sites. Therefore, by studying the reaction mechanism involving ^{6,7}Li and ^{9}Be nuclei, which are available easily and abundantly from the stable beam accelerators, one can predict a number of fascinating properties of the weakly bound exotic nuclei and understand the elemental abundances of various stars.

The accurate identification of different breakup processes requires the detection of breakup fragments in a large angular range as much as possible. With the advent of Silicon technology, now a days large area segmented silicon strip detector arrays such as GLORIA, STARS, MUST2, TIARA, BALIN have been built for the study of breakup reaction processes.

The determination of detection efficiency for coincident breakup fragments is needed to quantify the contribution of different breakup processes leading to large inclusive α production. The coincidence efficiency can be determined either by Jacobian co-ordinate transformation [7] or by Monte-Carlo based simulation. Monte Carlo based simulation code has the advantage over Jacobian method because of the proper consideration of energy resolution, angular resolution of the detector and detection threshold. However the equivalence of the two methods has been discussed in Ref [8]. In the present work, a simulation code based on Monte Carlo method has been developed to estimate the coincidence efficiency of the breakup fragments and to interpret the dynamical observables of the breakup processes.

2. Experimental Details

Exclusive measurements have been carried out for the ^{7}Li+^{112}Sn reaction at beam energy and intensity of 30 MeV and 2 pnA respectively using the 14-UD Pelletron-Linac facility in Mumbai. A self-supporting enriched(>99 %) ^{112}Sn target of thickness ~540 μg/cm^2 has been used. The details of the experimental set-up has been discussed in [4–6]. The typical inclusive two-dimensional energy-calibrated spectrum of ΔE vs E_{total} obtained from a strip telescope, given in [5], shows a good separation of the particles with different masses (A =1-7) and charges (Z = 1-3) produced by different reaction mechanisms. The direct, resonant and transfer breakup channels are identified event by event through kinematical reconstruction method [5, 6].

3. Monte Carlo Simulation

A Monte Carlo simulation code has been developed based on 3-body kinematics to estimate the efficiency of the binary breakup fragments in coincidence. Any two body nuclear reaction can be expressed as A(a,b)B, where any projectile 'a' is incident on target 'A', forming ejectile 'b' and recoil 'B'. For the case of quasi-bound ejectile 'b', the final product will be the binary breakup fragments from 'b', say particle 'c' and 'd'. The binary breakup fragments 'c' and 'd' will be emitted in the opposite direction in the center of mass frame of the projectile-like fragment (PLF) 'b'.

For isotropic distribution of breakup in the center-of-mass frame of PLF, the magnitude of the velocity of the fragment 'd' is given by

$$v^{d}_{c.m.} = \sqrt{\frac{2Q}{m_d(1+\frac{m_d}{m_c})}} \tag{1}$$

and, the $v^{c}_{c.m.}$ can be found from the following relation

$$v^{c}_{c.m.} = \frac{m_d}{m_c} v^{d}_{c.m.} \tag{2}$$

From the velocity vector diagram, it is clear that,

$$\vec{v}^{\,c,d}_{lab} = \vec{v}^{\,b}_{lab} + \vec{v}^{\,c,d}_{c.m.} \tag{3}$$

Now, $\vec{v}^{\,c,d}_{c.m.} = \left\{v^{c,d}_{1}, v^{c,d}_{2}, v^{c,d}_{3}\right\}$, where $v^{c,d}_{1}$, $v^{c,d}_{2}$, $v^{c,d}_{3}$ are the x, y and z components of the vector $\vec{v}^{\,c,d}_{c.m.}$. We considered isotropic breakup $b \rightarrow c + d$ in center of mass frame and randomly selected the breakup direction θ, ϕ for 'c', such that θ lies between [0,π] and ϕ lies between [-π,π], then automatically the conservation of linear momentum suggests that the direction of 'd' will be $\pi - \theta$ and $\phi + \pi$ for each trial. The velocity vector of products 'c' and 'd' in the lab frame $\vec{v}^{\,c}_{lab}$ and $\vec{v}^{\,d}_{lab}$ are then reconstructed from the equation 3 for each possible values of θ^{b}_{lab}, ϕ^{b}_{lab}, Q-value and E_{rel}. The intersection points of the two vectors with the detector plane were then determined. A trial was treated as unsuccessful when (i) any of the two intersecting points lies out of the detector boundary, (ii) both the intersecting points are lie on a same vertical strip and (iii) any of the energies for c and d lies below the detection threshold. The efficiency thus provides the number of successful events out of total number of events. The conversion of the energy and scattering angle from the laboratory frame to the c.m. frame of the projectile-target in event-by-event mode automatically takes care of the Jacobian of the transformation.

The estimated detection efficiency of different coincidence events depends on relative energy of the breakup fragments, energy of the projectile-like fragment prior to breakup, mass asymmetry of the breakup fragments, detection threshold, and geometric solid angle of the detection setup. Since the energy of the projectile-like fragment prior to breakup depends on the reaction Q-value and the loss of kinetic energy due to the excitation of the target, detection efficiency will also be affected by these parameters.

4. Extraction of breakup cross-section

The differential cross sections for each of the measured breakup channels has been obtained as follows. Consider the following reaction:

$$a + A \rightarrow b + B \rightarrow c + d + B \tag{4}$$

Where, 'a' is weakly bound nucleus moving into the field of target 'A'. 'b' represents the inelastic states of 'a' above the breakup threshold or the intermediate quasi-bound projectile-like fragment formed through the exchange of nucleon between projectile and target. Using events reconstruction for a particular breakup channel $c + d$, a distribution of events corresponding to different θ, ϕ of the outgoing cluster particle just before breakup, i.e., 'b' was generated. Now, for each $\theta(b)$ bin, the efficiency corrected relative energy distribution ($Y_i^{eff}(\theta) = Y_i^{raw}(\theta)/\zeta_i$) was obtained by summing over all $\phi(b)$ coverage of detector array corresponding to same $\theta(b)$ bin. Here, $Y_i^{raw}(\theta)$ represents the yield of 'i^{th} bin of the relative energy between ϵ_i and $\epsilon_i + d\epsilon_i$ without efficiency correction and ζ_i is the efficiency of the detector array for the same relative energy bin. For a particular θ bin, the coincidence yields under the peaks corresponding to resonances in relative energy distribution have been extracted individually by integrating $Y_i^{eff}(\theta)$ in steps of $d\epsilon_i$ over the respective relative energy range ($\Delta\epsilon = N d\epsilon_i$).

Differential breakup cross-sections for each of the resonance states is extracted from the following relation,

$$\frac{d\sigma^{br}}{d\Omega}(\theta) = \frac{\sum_{i=1}^{N} Y_i^{eff}(\theta)}{Y_{el}(\theta)} \frac{d\sigma^{el}}{d\Omega}(\theta) \tag{5}$$

where, $Y_{el}(\theta)$ is the yield of elastic scattering in the solid angle corresponding to the element $\Delta\theta(b)$, $\Delta\phi(b)$ and $\frac{d\sigma^{el}}{d\Omega}(\theta)$ is the differential elastic scattering cross section. The latter was obtained by normalizing (i) $Y_{el}(\theta)$ to the monitor yield $Y_m(\theta_m)$ corresponding to Rutherford scattering and (ii) their solid angles. The differential breakup cross-sections obtained from the simulation code has been compared with the Jacobian transformation method [7]. The cross-section obtained by both the methods are found to be of the same order as shown in Fig. 1 below. Similar conclusions have also been drawn by Y. Tokimoto and H. Utsunomiya [8] while comparing the results of two methods. The above comparison and the results shows that the efficiency corrections in the present manuscript are proper.

5. Summary and Conclusions

In summary, the details of the Monte Carlo based simulation code involving three body kinematics were reported. The simulation code successfully explains the kinematical correlation between the binary breakup fragments. The cross-sections for direct, resonant and transfer breakup channels were extracted using the coincidence efficiency obtained from the simulation code developed in the present work. The simulation will be extremely useful for designing an efficient experimental setup required to study the nuclear reactions with two or more fragments in the exit channel.

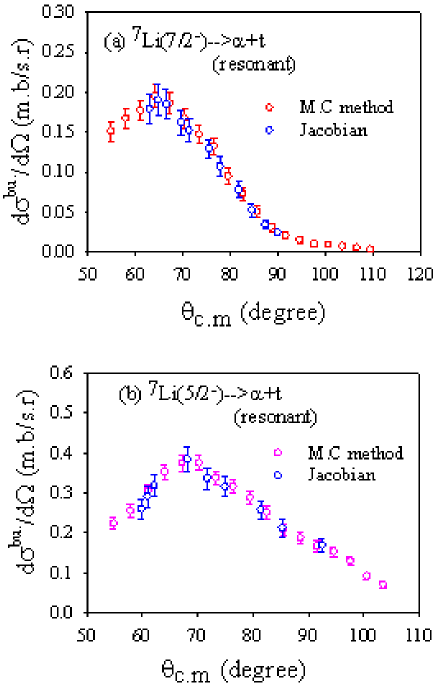

Fig. 1. Comparison of experimental $\alpha + t$ breakup cross-sections obtained by two methods: (1) using Jacobian transformation and (2) using efficiency correction by Monte-Carlo simulation for (a) $7/2^-$ and (b) $5/2^-$ resonance states of ^{7}Li

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