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Original Article

Understanding Breakup Phenomena Using Monte Carlo Simulation for Nuclear Reaction

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Abstract *- The break up of the projectile in the case of weekly Bound nuclei is interesting to study. A Monte Carlo simulation was performed to understand the breakup of the projectile from different excited states, and a unique Dalitz Plot method was presented to help understand it.*

Keywords *- ES, CF, ICF, CN, LNL.*

1. Introduction

The breakup of the projectile in the coulomb field of the target, including the nuclear breakup, is of renewed interest in nuclear reactions involving loosely bound projectiles. It is important and interesting in the context of RIB facilities [1]. Over the last decade, many studies have been done using loosely bound projectiles (^{6,7}Li, ^{9}Be…etc.) to understand the reaction mechanics, and it has been understood up to a certain extent. Many reports [2-4] have found that the effect of the breakup is present, including the coupling of the breakup channel with the other reaction channels. As a result, the suppression and enhancement of the fusion cross-section were found. People are trying to develop theoretical models to explain this phenomenon. So far, we have a classical trajectory model [5], and CDCC is available for the calculation, not in a direct but in an indirect way. In many reports, it has also been found that the alpha cross section is higher than expected, which is far from being fully understood. It has been well established that there are contributions from the transfer and pickup channels to the reaction mechanics. Also, It has been found that the breakup of the projectile can occur near the target or far away from it (such as elastic, inelastic/Direct/sequential BU). In both situations, the projectile can break into fragments and be detected experimentally. It is important to perform simulations to understand the breakup mechanism as, till now, there has been no single model available that can incorporate all the things at the same time. This work is a continuation of our earlier work. It has been seen that there are exclusive as well as inclusive alpha events for the ^{7}Li+^{208}Pb reaction. In this paper, we have shown a Monte Carlo simulation to help us understand the breakup phenomena, especially in a situation where there are three body breakups.

1.1. Experimental Details

The experiment was performed at LNL (Laboratori Nazionali di Legnaro) Tandem Van de Graaff accelerator, using a ^{7}Li beam with beam energies varying from 31 to 39 MeV. The beam intensity was around 10 nA. A of ^{208}Pb target, which is a self-supporting thickness of 200 μg/cm^{2,} has been used for the experiment. In the exit channels, only the emitted particles have been detected in Singles and coincidence. For the measurement, the 4π array 8πLP setup has been used. It has two main parts: The "WALL" and the "BALL". In the Forward direction, there was a WALL, and the BALL was backward. Both cover the lab. angles from 3^{0} up to 163$^{0.}$ In total, 246 Telescope (ΔE and CsI(TI) as E) have been used, of which 126 numbers are in BALL and the remaining are in WALL. The wall is a matrix of an 11×11 telescope. For the particle identification, The ΔE vs Time and ΔE vs E_{res} 2d matrices have been plotted for each telescope. Different types of particles, such as α, t, d, p, and elastic ^{7}Li, have been detected and nicely separated from each other. The elastic ^{7}Li has been stopped in the ΔE part since the thickness of the ΔE was more so in the E-ΔE spectrum and all the other particles are there except the elastic one. However, the elastic is present in the ΔE vs Time graph. For the Present purpose, the ΔE vs E_{res} spectrum has been considered, and only the coincidence events have been analyzed for the full setup. There are other channels are also present, but the focus has been given to the resonant states only. An experimental observed data has been shown in Figure 1. The data analysis has been done using a VISM program, which converts the data file to different visualized files in the form of 1D and 2D histograms. The elastic particles have been stopped in the delta E, and the other particles (light particles like alpha, proton, etc.) transfer to the E part of the detector. A 2D matrix of delta E versus E has been generated, which can identify the different particles. The delta E versus time has also been generated to identify the elastic part. Then, after the gate has been done on the specific particle to generate a Coincidence Spectra.

The gates are banana gates. After that, the coincidence spectra were built by keeping the condition that if one detector detected the alpha particle, the other detector detected the triton. Sam for other detectors. The coincidence spectra are shown in Figure 1 onwards, and a Monte Carlo simulation has been done to explain these spectra, which is explained in the sections below.

In the simulation, a large number of particles were generated randomly and then thrown through the detector geometry. Coinciding particles between the different pairs of detectors were identified event by event, and the histogram was reconstructed. Here, we have focused on an exclusive breakup event.

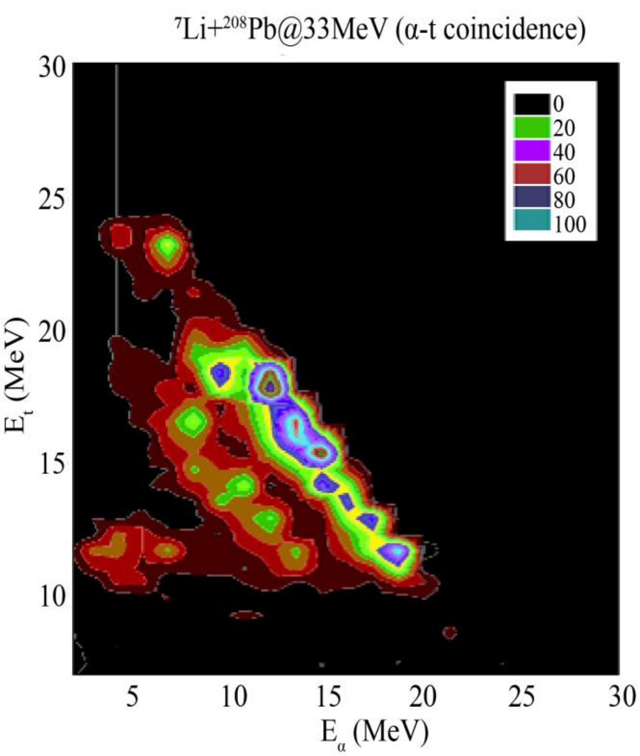

Fig. 1 Experimental E1 vs E2 in coincidence mode. E1 is the energy of the detected alpha particle where, and E2 is the energy of the detected triton in the lab frame for ^{7}Li+^{208}Pb reaction at 33 MeV

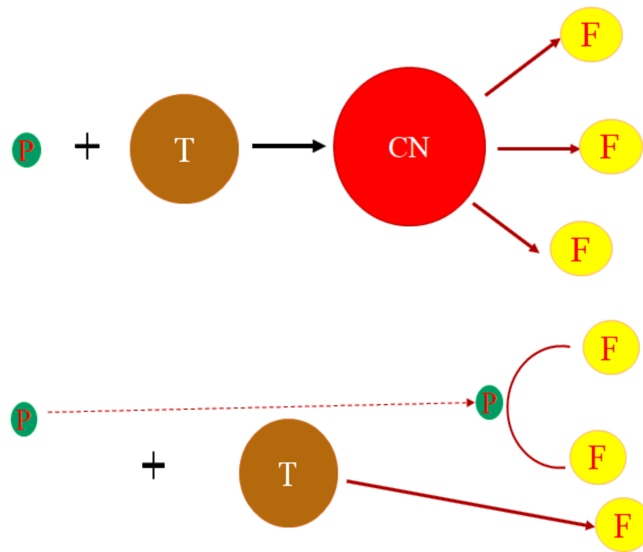

Fig. 2 (Upper) The formation of the compound nucleus and then its decay into three fragments (down). The projectiles scatter and break far from the target, which is called an elastic breakup. The recoil is the same as the target nucleus.

2. Calculation

2.1. Simulation Method

To understand the breakup process, we have assumed two different situations. I) Once the projectile fuses with the target, it forms the Compound Nucleus (CN) and then CN breaks into three equal fragments (like ternary decay). II) The exit channel will be the same, but the formation of three fragments is not the CN decay but the elastic breakup. The schematic representation is shown in Figure 2, and the result of the calculation is shown in Figure 3. The above situation has been explained graphically in Figure 2. One can see that the projectile, after fusion with the target, makes the compound nucleus, and then the compound nucleus undergoes decay to the same three mass masses. On the other hand, in the second case, the projectile scatters and goes far from the target; it breaks into two fragments, and the recoil can be considered the third fragment. In both situations, the final state and the exit channel are the same (three fragments). A Monte-Carlo simulation of the decay of the CN to an equal three fragments has been performed using its program code, which is shown in the figure below. The x-axis is X, and the Y-axis is the Y value, as described in [6]. It is clear from Figure 3 that all the events are equally probable, whereas the three fragments can have equal mass. The distribution is shown as the three lobes close to the center. In contrast, the situation completely changes when we go to an elastic breakup, which is shown in Figure 2. It is assumed that before the formation of the CN, the incident projectile scatters and breaks into two fragments, and the heavy Evaporation Residue (ER) stays inside the target foil. One can see from Figure 4 that the distribution is now focused on the specific position and not distributed like earlier.

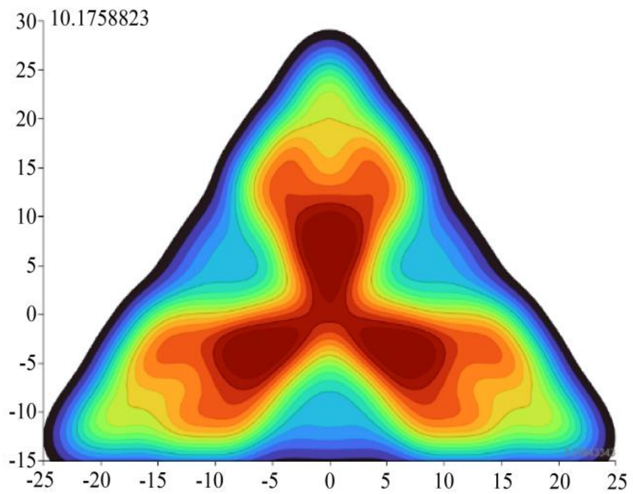

Fig. 3 A Monte-Carlo simulation of the decay of the CN to an equal three fragments. The x-axis is X, and the Y-axis is the Y value, as described in [6]

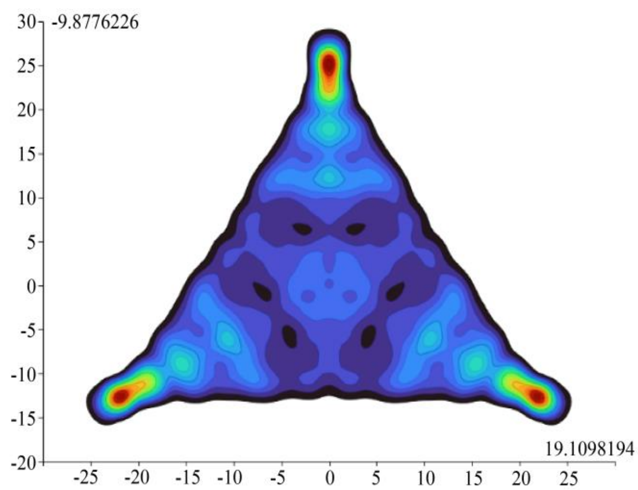

Fig. 4 A Monte-Carlo simulation of the decay of the CN to an equal three fragments. The x-axis is X, and the Y-axis is the Y value, as described in [8]. Here, the 1st excited state has been considered (Ex=4.630 MeV, $7/2^-$ for ^{7}Li)

Since it is an elastic breakup, one can expect that the distribution of emitted particles with their energy will be different from that of CN emission. The energy of each fragment has been converted to X and Y as prescribed above (Dalitz plot Mechanics) and shown in Figure 3. It has been observed from Figure 3 that the distribution of particles with energy for CN is completely different from the elastic breakup of the same projectile, where the exit channel is the same for both cases. One can also observe that for CN emission, the distribution of fragments is equally populated around the center, whereas the lobes are localized in different locations, as shown in Figure 4, indicating that the breakup of the projectile has happened and not the emission of the fragments from the CN. The graph is plotted using a Dalitz plot mechanism [6], which is very important, and it is interesting to understand the breakup process of a compound nucleus into three or more fragments. For the elastic breakup, it has been assumed that the projectile has scattered at any angle sampled randomly. Also, the breakup cone of the projectile after scattering has been taken into consideration by taking the geometry of the detector array.

3. Multi-Scattering Effects on Nuclear Reaction Spectrum

When the projectile strikes the target, the target has a certain thickness, and in this case, it is 200 μg/cm$^{2.}$ So, there are a large number of target nucleuses present. When the projectile interacts with the target, it may interact with any of the targets, or it can interact with the different targets sequentially (one after another). Due to a large number of targets, multiple scattering can happen, which leads to the loss of incident energy from the projectile. It can be called energy loss after passing through the target material. To understand the energy loss and the passage of particles inside the target, a Montecarlo-based program was used (SRIM/TRIM[7]. The results are shown in Figure 5 below. The accumulative effect of this multiple scattering from these different targets is basically the loss of energy, as mentioned above and shown in Figure 5. From Figure 5, one can see that the range of these particles or the projectile is large compared to the target thickness. So, the projectile can pass through the target by doing energy loss.

4. Angular Distributions and Correlations Between the Breakup Fragments

Out of many, one important observation of the exit channel is the angular distribution of the eject tiles. It has been observed that the angular distribution is different for the breakup fragments and also different for the compound nucleus emission. Suppose the emitted particles can come out from the compound nucleus. In that case, the angular distribution will be isotropic, which means, in all directions, the number of ejected particles per solid angle will be the same so that one can find an isotropic angular distribution in the center of the mass system of the projectile target. In the case of a breakup, which happens due to elastic breakdown, the breakup fragments ejected are highly forward-focused, and one can see that there will be no isotropic distribution of the breakup fragments. Practically, it is difficult to measure the forward-focused breakup angular distribution as the projectile or the beam contribution is very large in the forward direction. So, in the forward direction, if one puts normal particle detectors like silicon, they will go bad because of the high radiation dose of the projectile. However, in any case the correlation spectra can be measured. It has been measured for the present reaction mechanism and presented in Figure 6. one can observe from Figure 6 that the breakup fragments correlation spectrum for the ^{7}Li+^{208}Pb reactions. The alpha particle was detected in one detector, whereas the Triton was detected in the other detector in coincidence mode. It has been found that there is a correlation between them because the opening angle for the alpha and triton is very low, and in case of an elastic breakup, the detected cone is within 20-30^0.

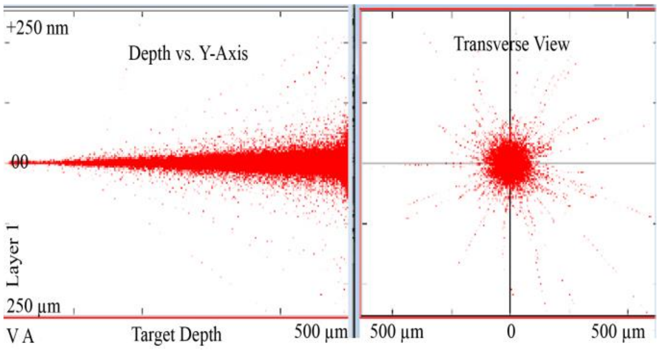

Fig. 5 A SRIN-TRIM circulation of ^{7}Li+^{208}Pb system at 33 MeV of beam Energy

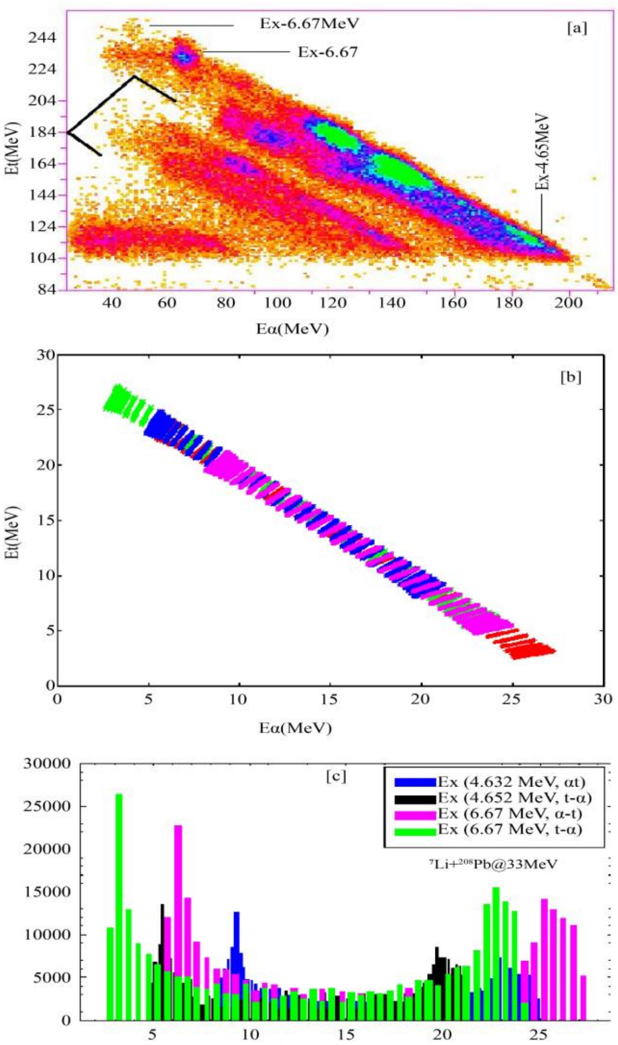

Fig. 6 (a) Alpha–triton coincidence events (b) The calculation for the resonant breakup (c) The 1D histogram of exclusive alpha

It has also been observed in Figure 6 that the co-relation energy spectra have been generated using a Monte Carlo simulation, where the geometry of the detector setup has been considered.

Furthermore, the Monte Carlo simulation was done considering the geometry of 8PLP, and the results are shown in Figure 6. Different scenarios are represented by various patches. In the case of the breakup of ^{7}Li into alpha and triton particles, one detector is capable of identifying alpha particles, while the other can identify tritons, and vice versa. As a result, for a specific type of breakup (occurring from a particular resonant state), two plots have been presented, resulting in the detection of alpha/triton in the same detector. The 1D histogram for the alpha is shown in Figure 6, and the peaks for the different resonant states are seen. Higher resonant states make the breakup cone larger, which is required to cover the larger solid angle in practical.

5. Results and Discussions

The coincidence between two breakup fragments (alpha and triton in this case) indicates the presence of different breakup channels whose origins are different. Such as (DB), Direct Breakup of ^{7}Li from its different resonance, different origins have been detected in coincidence, and the spectrum for 33 MeV has been shown in Figure 6.

It has been seen that there are breakups from the resonant states (4.652MeV, E_{rel}=2.18 MeV & 6.67 MeV, E_{rel}= 4.2 MeV). states, elastic/inelastic breakup. The alpha and the triton with different statistics indicated different patches in the coincidence band between alpha and triton.

However, other patches also indicate the presence of different excited states of the targets, as shown in Figure 1. To understand the resonant breakup, a Monte Carlo simulation was done considering the geometry of 8PLP, and the results are shown in Figures 3 and 4 for the direct breakup and the elastic breakup. There are different patches indicated as different situations.

For the breakup of ^{7}Li to alpha-triton, one of the detectors can detect alpha, whereas the other can detect the triton and vice versa. So, for one mode of breakup (breakup from one resonant state), two plots have been shown, leading to two detection alpha/triton in the same detector. The 1D histogram for the alpha has been shown in Figure 6(c), and one can see the different peaks for the different resonant states. More investigation will be required to understand the resonant state's contributions.

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