East European Journal of Physics. 4. 195-199 (2024)
DOI:10.26565/2312-4334-2024-4-18 ISSN 2312-4334

UNDERSTANDING THE PROJECTILE BREAKUP MECHANISM USING MONTE CARLO SIMULATION TECHNIQUE

M. Swain[a], Prasanta Kumar Rath[a,b]*, Balaji Padhy[a], Aditya Kumar Pati[a], Vaishali R. Patel[c], Nirali Gondaliya[c], Ami N. Deshmukh[c], Ravindra Prajapati[c], N.N. Deshmukh[c]

[a]*Centurion University of Technology and Management, Paralakhemundi, Odisha, 761211 - India*
[b]*Department of Physics, University of Naples "Federico II" and INFN, I-80125, Naples, Italy*
[c]*P.P. Savani University, Dhamdod, Kosamba, Surat, Gujarat, India*
**Corresponding Author email: prasanta.rath@cutm.ac.in*
Received July 10, 2024; revised October 8, 2024; in final form November 4, 2024; accepted November 13, 2024

The breakup of projectile has been understood using a Montecarlo simulation at low energy, which indicates a wider breakup cone is present for near target breakup whereas at far target breakup there are well localized breakup cone is present. The simulations indicate the requirement of wider solid angle in experiment and localized kinematic solid angle to study the breakup phenomena. The case study of ^{7}Li+^{208}Pb has been considered and found well agreement of simulated results with experimental data.
Keywords: *ES (Elastic scattering); CF (Complete Fusion); ICF (Incomplete fusion); CN (Compound Nucleus); BU (Break up)*
PACS: 25.60.Dz, 25.10.+s, 25.40.Hs, 25.60.Gc, 25.60.Pj, 25.60.Je, 25.70.Gh

INTRODUCTION

Study of nuclear reaction involving loosely bound projectile is a subject of current study and interest in specific [1-5]. This is because when one can use a loosely bound projectile there is a possibility that the projectile can fuse with the target or it can break before the fusion leads to an incomplete fusion (ICF) process. Including ICF there can be a break up escape, transfer and pickup can also possible [6]. Many experimental studies [7-9] has been done and found that using loosely bound projectiles if complete fusion can be measured there is a fusion suppression of complete fusion above the barrier and enhancement bellow the barrier has been reported compared to the Single barrier penetration model calculation. The exact reason is still far from understanding. Not only the enhancement and suppression has observed but there can be proton transfer and n pickup has also been observed including main breakup channel [10]. All the above-mentioned feature has been observed only by using the projectile a loosely bound projectile (^{7}Li→α+t,^{6}Li→α+d,^{9}Be→α+α+n…etc). Recently there are reports which indicates the breakup from the resonant states including the excited states of projectiles are important [20]. In addition, with the breakup the location (near/far) where the breakup occurs also effects the crossection and it is difficult to measure experimentally all the times as it requires higher solid angle coverage experiment [16-19]. To understand these phenomena presently limited theoretical models are available for example CDCC, FRESCO, CCFULL [11-12]. All the models are complex quantum mechanical models. People are trying to develop simplified model which can explain all the phenomena simultaneously.

Our work is also on the same way. In the present paper we tried to understand the reaction specially the breakup of the projectile around the coulomb barrier using a classical approach and Monte Carlo modeling.

The present approach will be helpful to understand near /far breakup mechanism. Since experimentally it is always difficult to get the data in all 4π, So a model has been adopted (using classical trajectory under Monte Carlo modeling) to understand the breakup mechanism.

Specially we tried to understand the mechanism around the coulomb barrier regions. Because around the barrier, (below the barrier) the fusion will not possible, the nuclear reaction can happen because of tunneling phenomena. So, it is interesting to see a classical approach bellow the barrier to understand the breakup mechanism.

The paper has been organized as follows in the Section 1 experimental detail has been provided, Section 2 contains the modeling (classical trajectory approach using Montecarlo modeling) with results. The Summary with future outlook has been explained in Section 3.

EXPERIMENTAL DETAIL

The experiment was performed long time back with the projectile ^{7}Li and a target of ^{208}Pb of thickness 200 μg/cm^2. It was a self-supporting target. The experiment was done at 8PLP set up [13]. The projectile energies vary from 31 to 39 MeV. The beam intensity was around 10 nA. The Coulomb barrier is ~31 MeV with fusion radius R_B~10.69fm provided by Proximity potential [14]. In the present paper we have focused only on one energy, that is 31 MeV which is around the barrier. The other energies are above the barrier so it has not considered presently. The detail experimental approach has been reported in [14]. There are ΔE vs Time and E vs ΔE graph has been generated to identify the particles ejected during the reaction.

Cite as: Swain, P.K. Rath, B. Padhy, A.K. Pati, V.R. Patel, N. Gondaliya, A.N. Deshmukh, R. Prajapati, N.N. Deshmukh, East Eur. J. Phys. 4, 195 (2024), https://doi.org/10.26565/2312-4334-2024-4-18

A typical experimental spectrum has been shown in Fig. 1 for 31 MeV. It can be observed from Fig. 1 that there are different particles (alpha, triton, deuteron, proton) are present which come out from the reaction because of many reactions' mechanism. The particles have been identified very clearly.

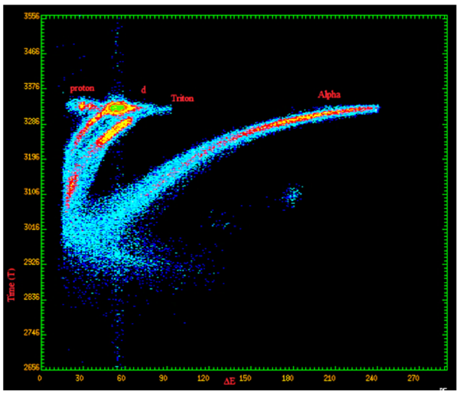

Figure 1. Typical raw spectra of particles detected during the experiment for 31MeV of ^{7}Li. All the particles are clearly visible

CALCULATION AND MODEL SIMULATIONS

A theoretical calculation including a Montecarlo modeling has been performed to understand the breakup mechanism. As a first work we have generated the coulomb barrier which is the addition of nuclear plus coulomb potential as shown in Fig. 2. The proximity potential [14] has been chosen for nuclear one which is a Wood-Saxon type in nature. The form of the wood Saxon potential is $V(r) = -V_0/(1+\exp(r-r_0)/a)$, where V_0 is the depth of the nuclear potential, a_0 is the diffuseness parameter which has taken as 0.63 fm for the present case, r is the radial distance between the interacting nuclei and r_0 is 1.02fm.

For our simulation and modeling the breakup fragments of projectile (^{7}Li→ α+t) has been detected in coincidence mode and the coincidence spectrum of alpha and triton for a beam energy of 31 MeV has been shown in Fig. 3.

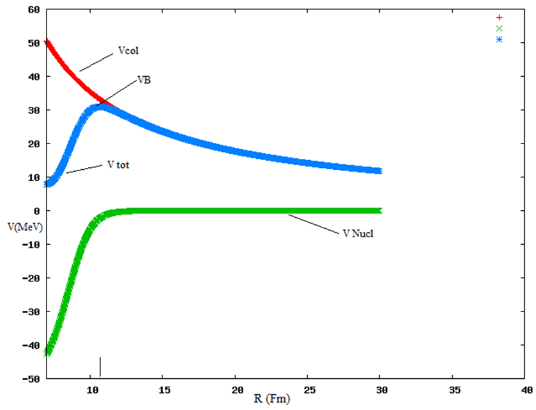

Figure 2. The effective potential for ^{7}Li+^{208}Pb using proximity potential. The barrier radius R_B and different contribution has been shown. (Vcol is the Coloumb potential; Vnucl is the nuclear potential, Vtot is the addition of Coloumb+ nuclear potential. VB – the barrier height which will be taken as the barrier of the system)

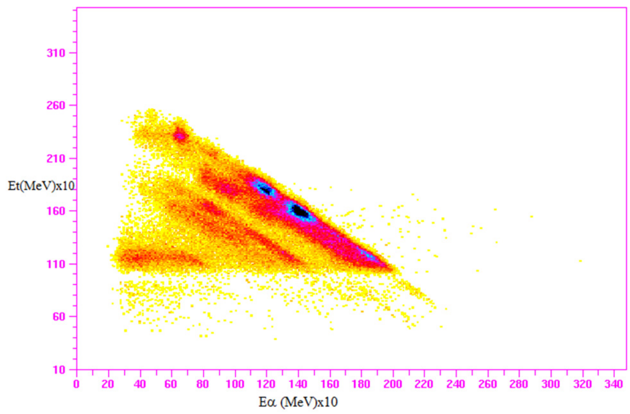

Figure 3. Coincidence experimental data of alpha and triton for 31 MeV projectile energy

From Fig. 3 one can see that there are different bands and the different bands results from the different break up process. (breakup from GS, breakup from excited state, breakup from resonant state, Ex: Ex = 4.630 MeV, $7/2^-$ for ^{7}Li …etc). The same structure of the band in coincidence mode keeping the detector geometry in mind has been simulated using Montecarlo technique and shown in Fig. 4.

In the simulation the target excitation has not included as our aim is to see the effect of projectile breakup only. If we see the value of the loci of the 2d spectra (Fig. 4) and compare with the loci of Fig. 3 for the projectile breakup we will see the patches matches at the same values which indicates the reproduction of the experimental data for the projectile breakup. No contribution of the target excited states has considered as it makes the situation complex. The same can be tried later.

In the present case to understand the interaction/breakup mechanism of the projectile we have considered only around the barrier points i.e 31 MeV data only. From Fig. 2 one can see that the barrier radius (R_B) ~ 10.6 Fm. This indicates that if the projectile wants to fuse with the target it has to cross that barrier radius and below the barrier energy it is difficult for the projectile to reach that barrier radius. So, it has assumed that the maximum break up point after which the particle can fuse with the target is the barrier radius (R_B). In the below barrier energy in addition with tunneling the projectile can scattered to different direction. For each scattering the scattered angle has been randomly samples between the angle 0° to 180^0. For a given randomly generated scattering angle the distance of closest approach has been calculated as prescribe in [15]. The randomly generated scattering angle with the distance of closet approach has been shown in Fig. 5.

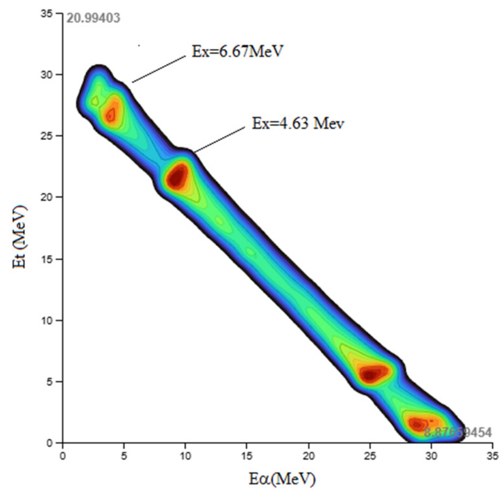

Figure 4. Montecarlo simulation keeping the geometry in mind. The coincidence of alpha and triton has been considered only. The different patch leads to the different excited states of the projectile

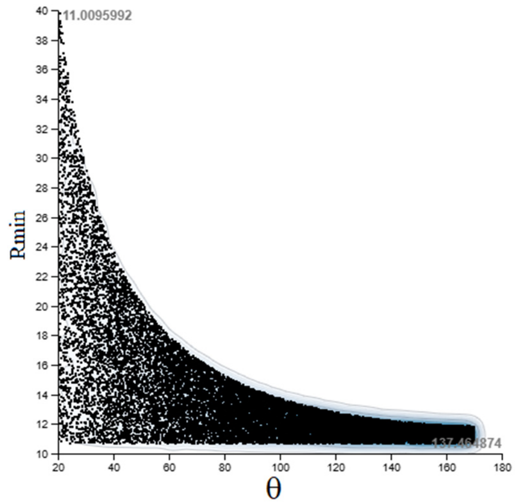

Figure 5. Randomly generated R_{min} w.r.t. the scattering angle for a given energy

After determining the distance of closest approach, a breakup point has been chosen randomly between the distance of closest approach and the barrier radius by doing a random sampling with a probability of breakup exponential decaying in nature ($P_{bu} \alpha e^{Rand(R_{min}-R_{BU})}$). Once the breakup point has been identified then the particle can be scattered and two break up fragments can be detected in coincidence. Here two types of break up has been considered 1) near target breakup 2) far or asymptotic breakup. In the above expression α is the proportionality constant, P_{bu}- breakup probability, Rand (R_{BU} - R_{min}) is the randomly generated point between breakup radius (R_{BU}) and R_{min}. R_{min} is the distance of closest approach for a given energy and angle.

In case of near target breakup, the influence of the coulomb potential may provide a wider breakup cone which translates to a wider Δθ, where as in case of asymptotic breakup the influence of the coulomb potential will be negligible and the breakup may have a narrow breakup cone as shown in Fig. 6.

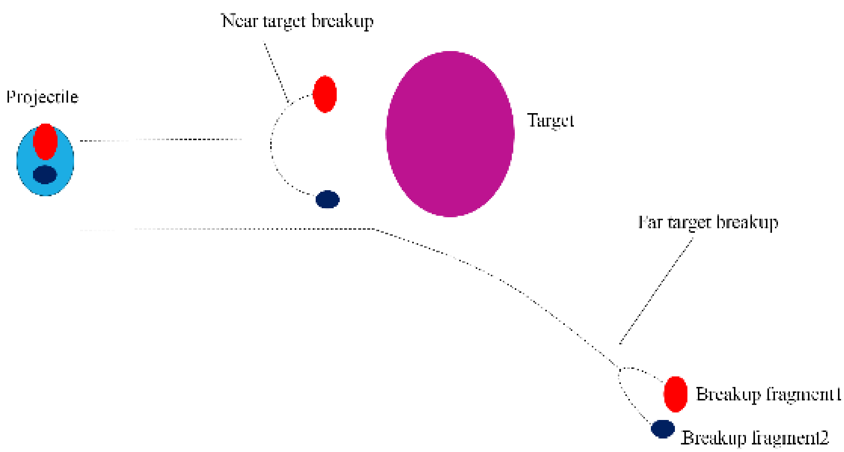

Figure 6. Pictorial diagram of the breakup of the projectile near target and far away from the target

When the projectile breaks near the target it has assumed that it breaks instantly from the breakup point. where as when breakup happens asymptotically, far from target, its breakup happens from the excited state of a specific energy and time. So, when the projectile breaks from the excited states or resonance states (For ^{7}Li the resonance state considered for simulation are 4.652 MeV, $7/2^-$, & 6.67 MeV, $5/2^-$). The Δθ with the breakup angle (β) has been shown schematically in Fig. 7.

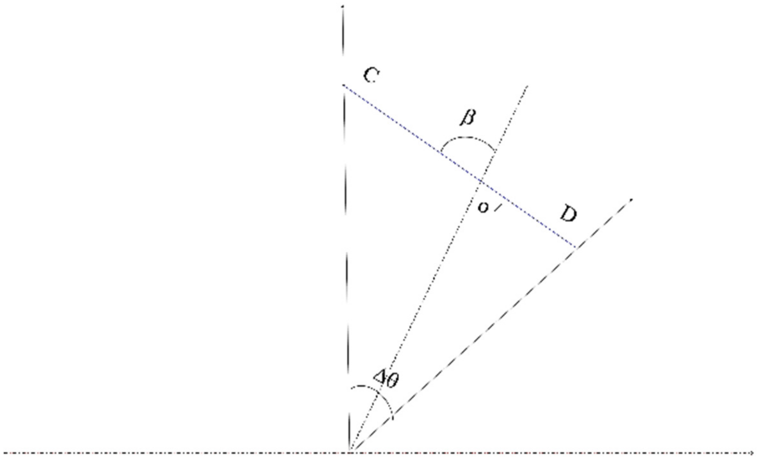

Figure 7. Schematic diagram to represent the Dq and b (b). The ejectile can break in to two fragment C, D and the fragments move in opposite direction in their c.m. frame of projectile from the point o/

The breakup fragments have been detected coincidently for both the case near target and far away from the target. The full simulation has been done using the present geometry in consideration and the result has been shown in Fig. 8.

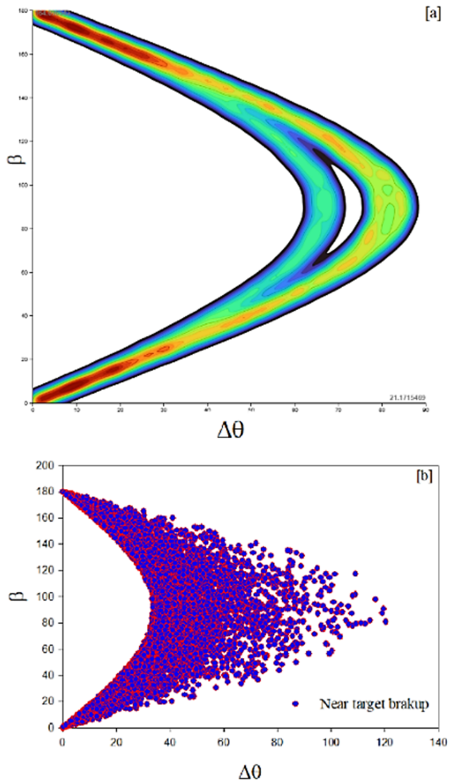

Figure 8. [a] – the result of Montecarlo simulation for the two resonant states of ^{7}Li. i.e. the breakup has happened far away from the target and one can see a well-defined localized distribution of the fragments with narrow detection cone; [b] - The breakup near the target which indicates wider angle of detection cone w.r.t β breakup angle).

One can see from the Fig. 8 that if we consider the near target breakup then there is a wider distribution of the Δθ with respect to β. In case of a far or asymptotic breakup the breakup fragments have a narrow angle of detection that means the Δθ will be more localized whereas the near target breakup the distribution is wider as shown from Fig. 8.

SUMMARY & FUTURE WORK

A Montecarlo simulation has been performed to understand the breakup at low energy and it has found that there are wider cones for near target breakup compared to asymptotic breakup. This provides an important input to experimentalist to setup their experimental apparatus for experiment to catch the breakup fragments. In addition, a coincidence energy spectrum has also simulated and presented. In future the time evolution of the trajectory will be simulated under the potential surface.

Acknowledgment

The author expresses his gratitude to SERB-CRG -2021-005100 for financial support. In addition, a special thank goes to CUTM-PKD for required support.

ORCID

Prasanta Kumar Rath, https://orcid.org/0000-0002-3869-9705, **Balaji Padhy**, https://orcid.org/0000-0002-3447-2917
Aditya Kumar Pati, https://orcid.org/0000-0003-0966-5773

REFERENCES

[1] L.F. Canto, P.R.S. Gomes, R. Donangelo, and M.S. Hussein, Phys. Rep. **424**, 1 (2006). https://doi.org/10.1016/j.physrep.2005.10.006
[2] P.K. Rath, *et al*., Phys. Rev. C, **79**, R051601 (2009). https://doi.org/10.1103/PhysRevC.79.051601
[3] P.K. Rath, *et. al*., Phys. Rev. C, **88**, 044617 (2013). https://doi.org/10.1103/PhysRevC.88.044617
[4] P.K. Rath, *et al*., Nuclear Physics A, **874**, 14 (2012). https://doi.org/10.1016/j.nuclphysa.2011.10.004
[5] C.S. Palshetka, *et al*., Phys. Rev. C, **82**, 044608 (2010). https://doi.org/10.1103/PhysRevC.82.044608
[6] L Morelli, J. Phys. G: Nucl. Part. Phys. **43**, 045110 (2016). https://doi.org/10.1088/0954-3899/43/4/045110
[7] V.V. Parkar, *et al*., Phys. Rev. C, **82**, 054601 (2010). https://doi.org/10.1103/PhysRevC.82.054601
[8] S. Santra, Phys. Lett. B, **677**, 139 (2009). https://doi.org/10.1016/j.physletb.2009.05.016
[9] R. Rafiei, Phys. Rev. C, **81**, 024601 (2010). https://doi.org/10.1103/PhysRevC.81.024601
[10] D.H. Luong, Phys. Lett. B, **695**, 105 (2011). https://doi.org/10.1016/j.physletb.2010.11.007
[11] K. Hagino, *et al*., Comput. Phys. Commun. **123**, 143 (1999). https://doi.org/10.1016/S0010-4655(99)00243-X
[12] I.J. Thompson, Comput. Phys. Rep. **7**, 167 (1988). https://doi.org/10.1016/0167-7977(88)90005-6
[13] E. Vardaci, *et al*., Eur. Phys. J. A, **57**, 95 (2021). https://doi.org/10.1140/epja/s10050-021-00400-3
[14] W. Reisdorf, J. Phys. G: Nucl. Part. Phys. **20**, 1297 (1994). https://doi.org/10.1088/0954-3899/20/9/004
[15] A. Diaz-Torres Com. Phy. Comm, **182**, 1100 (2011). https://doi.org/10.1016/j.cpc.2010.12.053
[16] K.J. Cook, *et.al*., Nature Communications, **14**,7988 (2023). https://doi.org/10.1038/s41467-023-43817-8
[17] E.C. Simpson, *et al*., EPJ Web of Conferences, **163**, 00056 (2017). https://doi.org/10.1051/epjconf/201716300056
[18] S. Kalkal, *et.al*., Phys. Rev. C, **93**, 044605 (2016). https://doi.org/10.1103/PhysRevC.93.044605
[19] L. Yang, *et al*., Fundamental research, (2023). https://doi.org/10.1016/j.fmre.2023.10.006
[20] D. Chattopadhyay, *et al*., Nuclear Physics A, **1053**, 122296 (2025). https://doi.org/10.1016/j.nuclphysa.2024.122965

РОЗУМІННЯ МЕХАНІЗМУ РОЗПАДУ ЯДРА ЗА ДОПОМОГОЮ МЕТОДИКИ МОДЕЛЮВАННЯ МОНТЕ-КАРЛО

М. Суейн[a], Прасанта Кумар Рат[a,b], Баладжі Падхі[a], Адітья Кумар Паті[a], Вайшалі Р. Патель[c], Нірaлі Гондалія[c], Амі Н. Дешмук[c], Равіндра Праджапаті[c], Н.Н. Дешмух[c]

[a]*Університет технології та менеджменту Центуріон, Паралахемунді, Одіша, 761211 - Індія*
[b]*Факультет фізики Неапольського університету «Федеріко II» та INFN, I-80125, Неаполь, Італія*
[c]*П.П. Університет Савані, Дхамдод, Косамба, Сурат, Гуджарат, Індія*

Розпад ядра був з’ясований за допомогою моделювання Монте-Карло при низькій енергії, що вказує на наявність ширшого конуса розпаду для розпаду поблизу цілі, тоді як при розпаді далекої цілі присутній добре локалізований конус розпаду. Симуляції вказують на необхідність ширшого тілесного кута в експерименті та локалізованого кінематичного тілесного кута для вивчення явищ розпаду. Було розглянуто приклад $^{7}Li+^{208}Pb$ і виявлено добре узгодження результатів моделювання з експериментальними даними.

Ключові слова: *ES (пружне розсіювання); CF (повний синтез); ICF (неповний синтез); CN (складне ядро); BU (розпад)*