# Inelastic and Transfer-Induced Breakups in $^{12}$C-$^{12}$C Collisions

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# FOOT- UOC Group

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# Outline

1. Unraveling the Nucleus..!
2. Recent Works on breakup and fragmentation
   - $^{7}$Be breakups
   - Sequential Breakups in Photo-dissociation of $^{12}$C
3. Sequential breakups in $^{12}$C-$^{12}$C Collisions
4. What We can do with FOOT Apparatus

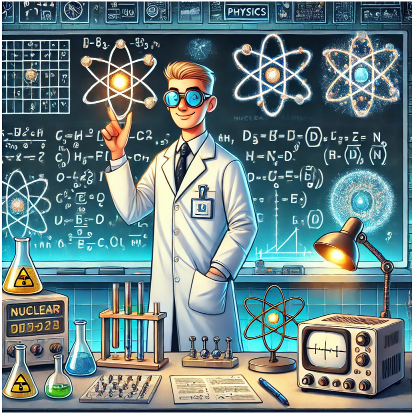
# Unraveling the Nucleus..!

**Natural phenomena reveals some basic physics of the nature**

**Experiments reveals further hidden mechanism of the nature.**

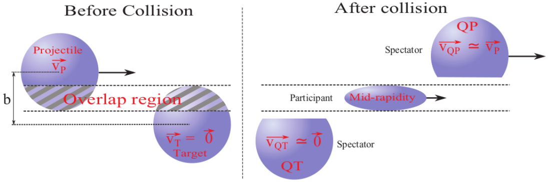
**Whatever we gain from experiments reflects the true essence of reality. However, it is merely a numerical representation of the underlying truth.**

**To uncover the actual physics, one must reproduce the results with a solid theoretical foundation. Only then will the nucleus begin to reveal its secrets.**

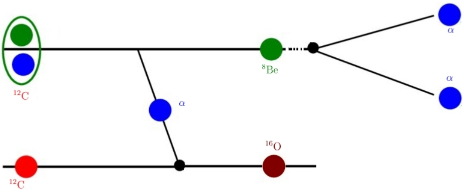


# Fragmentation - Currently in a Statistical Word..!

**Present approach to explain fragmentation is SMM.. !**




**Is this accounts for all kind of Interactions ?**



# Recent Works on breakup - Experimental and Theory

**Experimental measurement of breakup modes and cross sections followed by the theoretical calculation.**

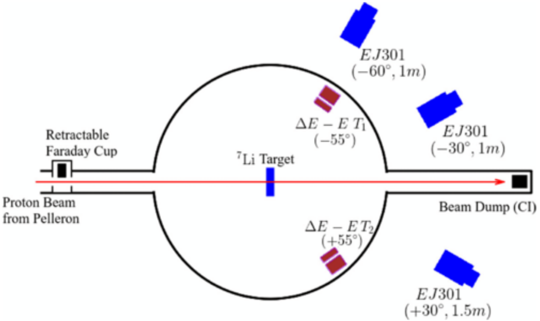
1. $^{7}\text{Be} \rightarrow ^{3}\text{He} + \alpha$ in $^{7}\text{Li}(p, n)$
2. $^{12}\text{C}(\gamma, \alpha)^{8}Be \rightarrow 2\alpha$ (Direct and Sequential)
3. $^{7}\text{Li}(\gamma, \alpha)^{3}H$

**Theoretical Interpretations at higher energies**

- Transfer induced breakup in $^{12}C -^{12}C$ collisions $[^{12}C(^{12}C,^{8}Be \rightarrow 2\alpha)^{12}C]$
- Inelastic breakup in $^{12}C -^{12}C$ collisions $[^{12}C(^{12}C,^{12}C^{*} \rightarrow 3\alpha)^{12}C]$

**$^{7}$Be breakup :** Proof for Ejectile Wavefunction Knocks the breakup modes

# Experimental Setup




For this, $20\mu g/cm^2$ Li target was made as sandwiched between $5\mu g/cm^2$ Carbon, and $5\mu g/cm^2$ Al.

# Data Conditioning and Analysis

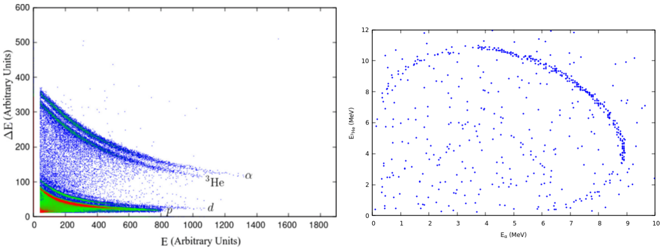



Figure: **a:**E-$\Delta E$ from Telescope **b:** $E_{^3He} - E_\alpha$ Correlation

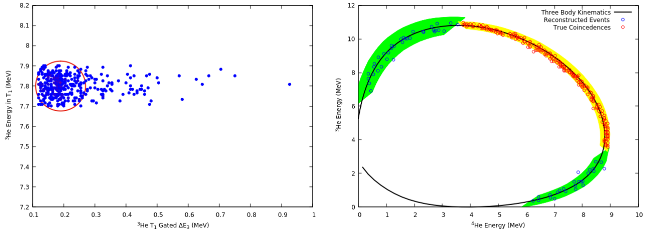
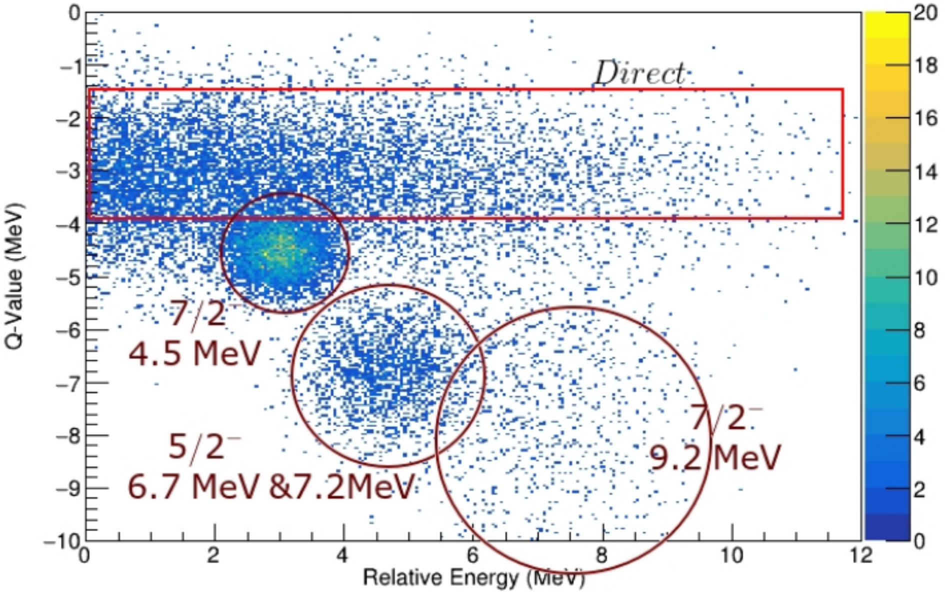
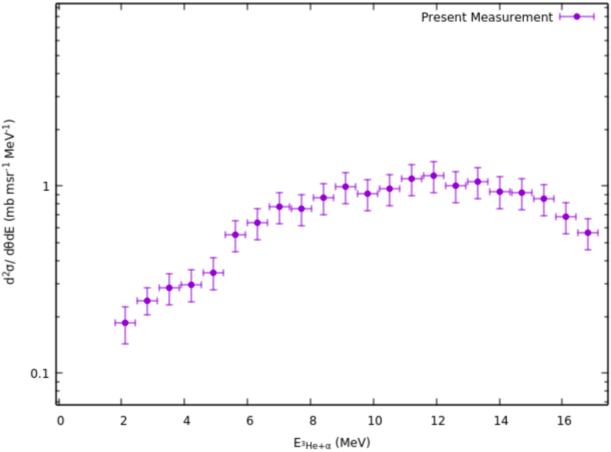



Figure: **a:**$K_{nn}$ based reconstruction of events below PI threshold **b:** Kinematic Gate

# Direct, Resonant states in Breakup

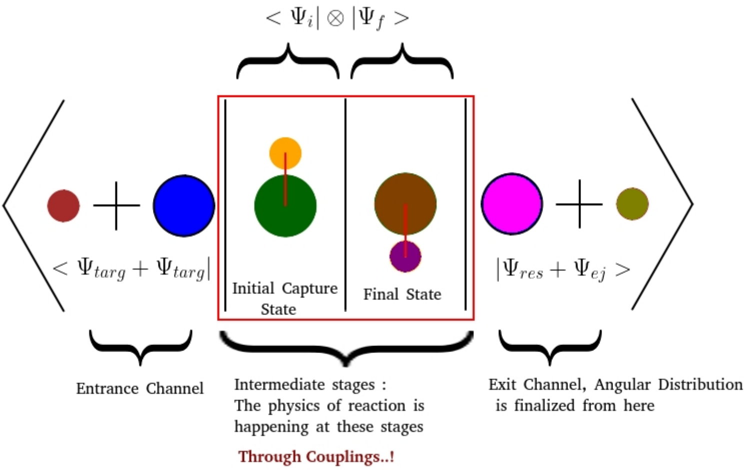


# Breakup Cross Sections

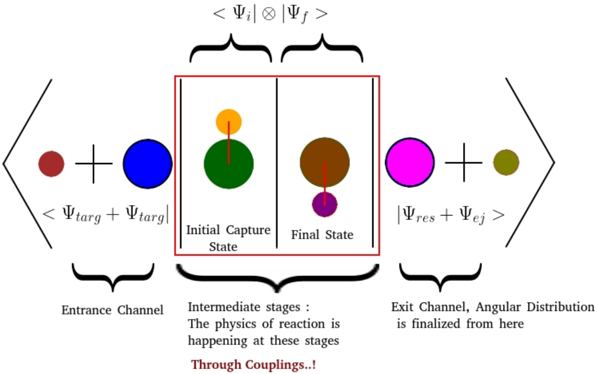


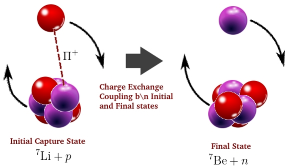

**Need theoretical support to understand the physics....!**

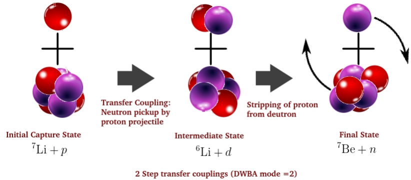
# Reaction Systematics



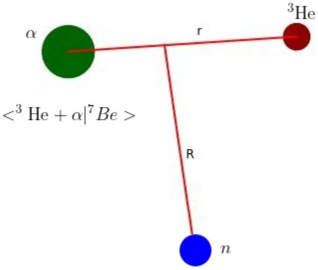
# Reaction Systematics

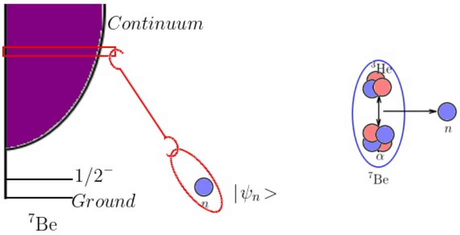


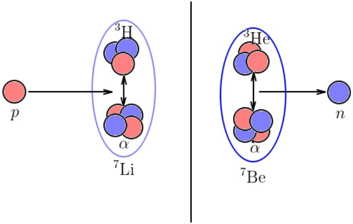
# Expected Physics : Continuum Coupling to Ejectile Neutron wave function

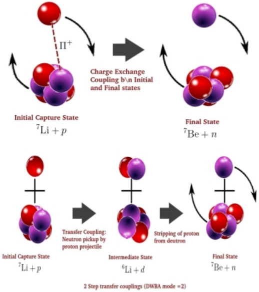


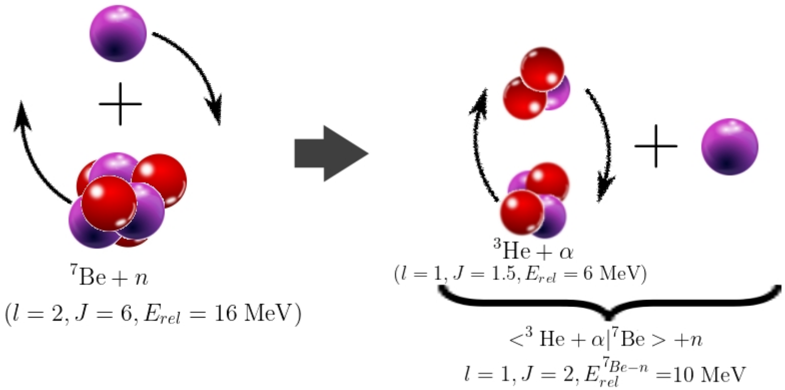
1. Mass Partitions
   - Entrance Channel: $^7$Li + p, where $^7$Li as Core = $\alpha$ Valance = $t$;
   - Exit Channel : $^7$Be + n, where $^7$Be as Core = $\alpha$; Valance = $^3$He
2. Coupling between Entrance and Exit Channel Mass Partitions
   - Charge Exchange Coupling
   - 2-Step DWBA Transfer

Both are coherently added for considering the $^7$Be.

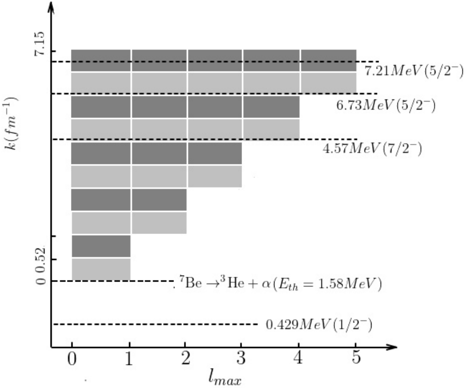


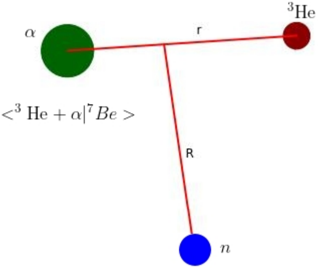
# Residual Breakup : Coupling Scheme



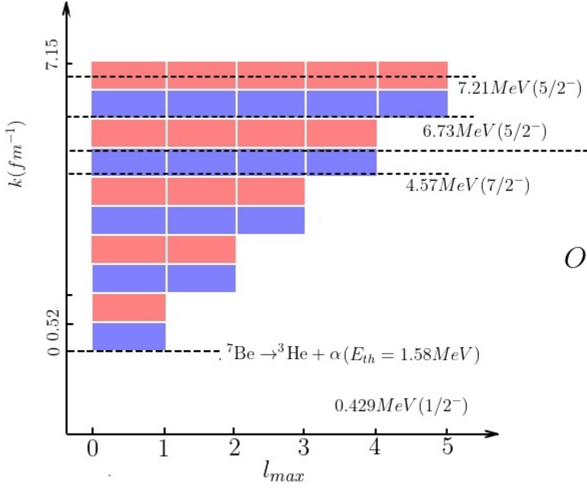
# &States : CDCC + CRC

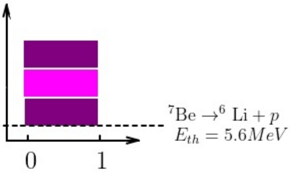



$$k^2 = \frac{2\mu E_{rel}}{\hbar^2}$$



# &Overlaps

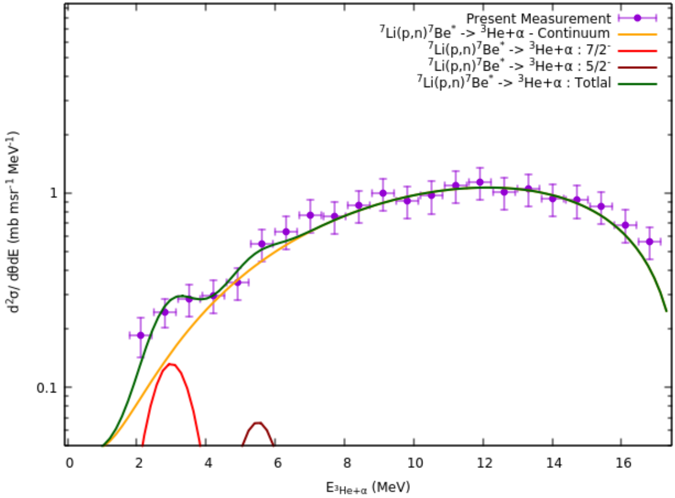



$Overlaps : \, < {}^6\mathrm{Li}_{(0)} + p \, | {}^7\mathrm{Be} >$

$$k^2 = \frac{2\mu E_{rel}}{\hbar^2}$$

# Cross Sections with Fresco Results

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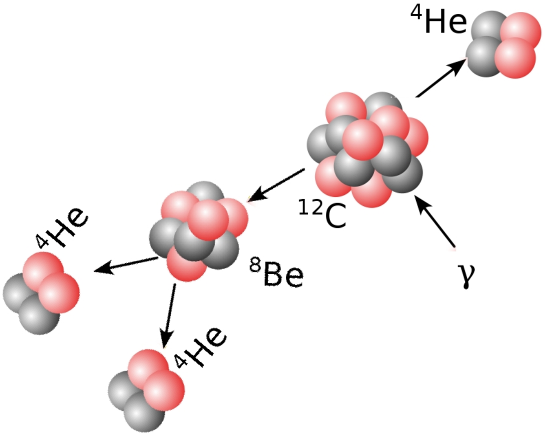
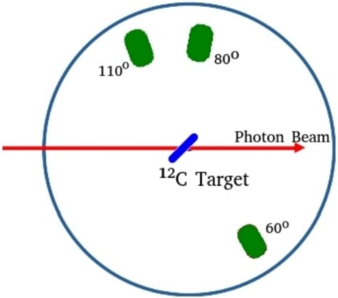
[1] *Midhun et al.*, PhysRevC.104.054606(2021)

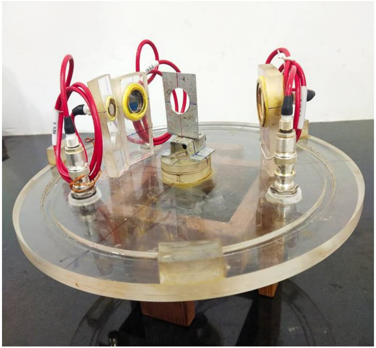
# Sequential Breakups in Photo-dissociation of $^{12}C$

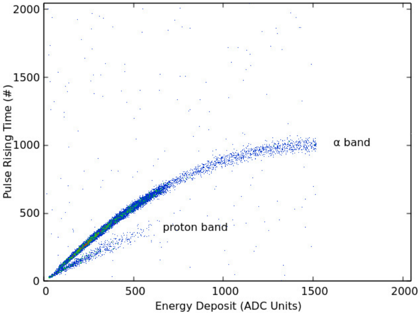


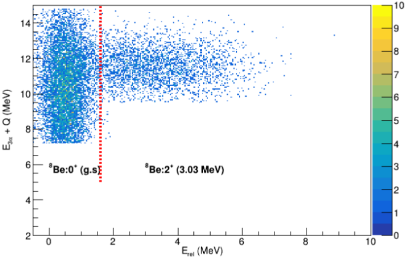

**Proof for the sequential breakups in Coulomb potentials**

# Sequential Breakups in Photo-dissociation of $^{12}C$

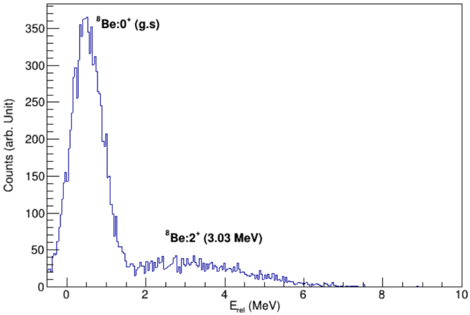


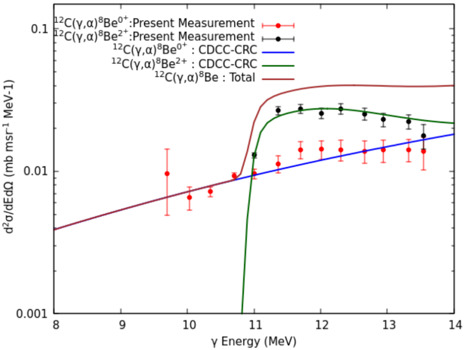





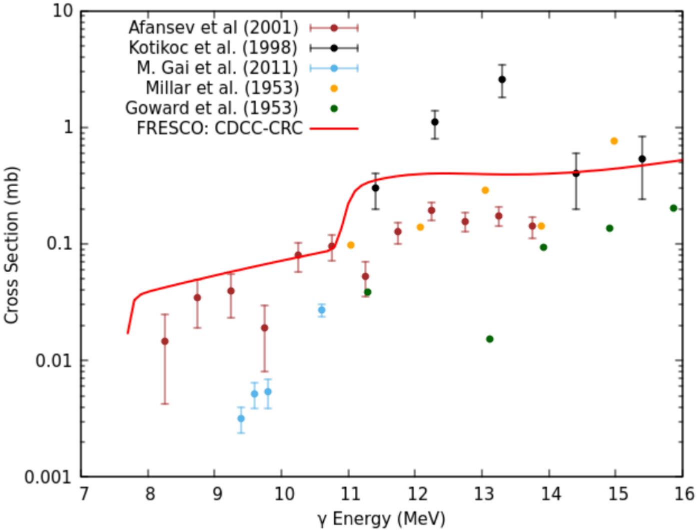



# Sequential Breakups in Photo-dissociation of $^{12}$C



# Sequential Breakups in Photo-dissociation of $^{12}C$

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[2] *Resmi et al.*, Phys. Rev. C - Accepted(2024)

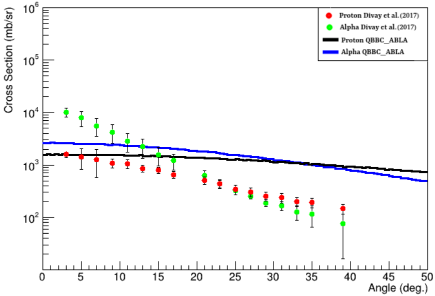
# Understanding $\alpha$ production in $^{12}$C-$^{12}$C collisions

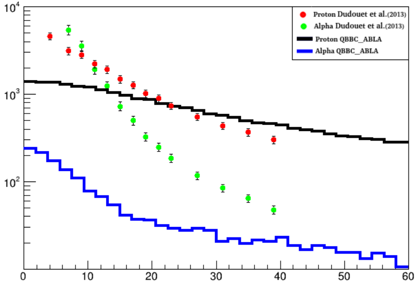
The $\alpha$ production in $^{12}$C-$^{12}$C can originate from

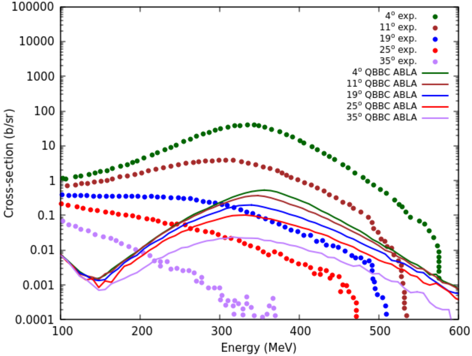
1. Compound Nuclear Component
2. Direct Reactions
   a. Knock-out
   b. Break-up

   There the modes of the breakup will be a question..

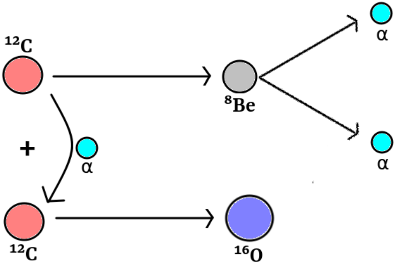
# Existing Measurements in $^{12}C$-$^{12}C$ : Mentioning a few..!



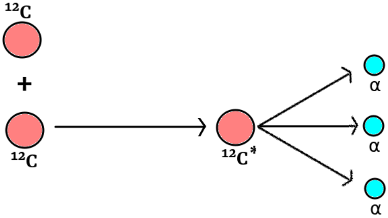



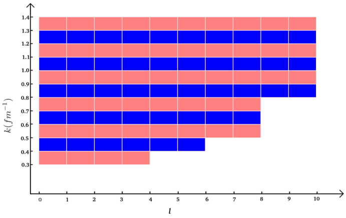
- The unaccounted Direct Reactions include:-



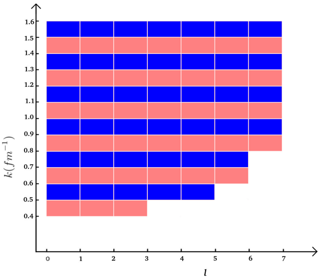

Transfer-Induced Breakup
$^{12}C(^{12}C,^{8}Be \rightarrow 2\alpha)^{16}O$



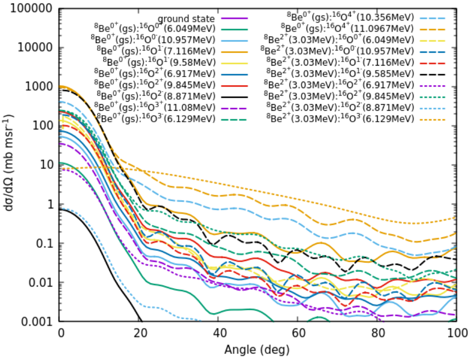

Inelastic Breakup
$^{12}C(^{12}C,^{12}C^{*} \rightarrow 3\alpha)^{12}C$



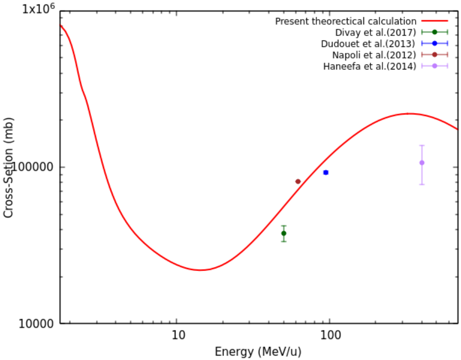
k(fm^-1)
l

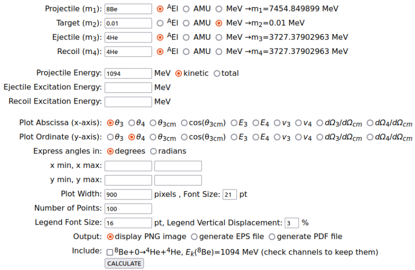
k(fm^-1)
l

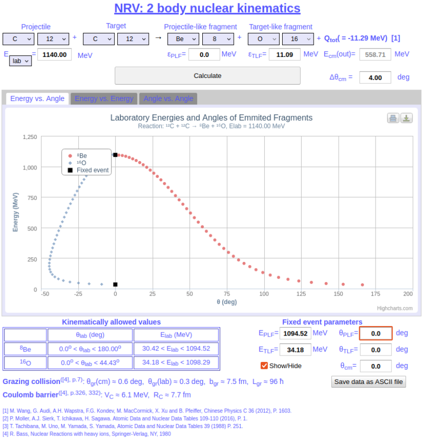
dσ/dΩ (mb msr^-1)
Angle (deg)
ground state
8Be0+(gs):16O0+(6.049MeV)
8Be0+(gs):16O0-(10.957MeV)
8Be0+(gs):16O1-(7.116MeV)
8Be0+(gs):16O1-(9.58MeV)
8Be0+(gs):16O2+(6.917MeV)
8Be0+(gs):16O2+(9.845MeV)
8Be0+(gs):16O2-(8.871MeV)
8Be0+(gs):16O3+(11.08MeV)
8Be0+(gs):16O3-(6.129MeV)
8Be0+(gs):16O4+(10.356MeV)
8Be0+(gs):16O4+(11.0967MeV)
8Be2+(3.03MeV):16O0+(6.049MeV)
8Be2+(3.03MeV):16O0-(10.957MeV)
8Be2+(3.03MeV):16O1-(7.116MeV)
8Be2+(3.03MeV):16O1-(9.585MeV)
8Be2+(3.03MeV):16O2+(6.917MeV)
8Be2+(3.03MeV):16O2+(9.845MeV)
8Be2+(3.03MeV):16O2-(8.871MeV)
8Be2+(3.03MeV):16O3-(6.129MeV)

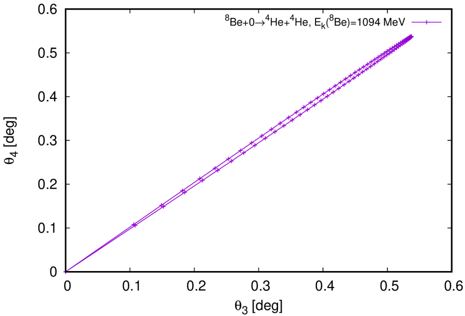
Cross-Setion (mb)
Energy (MeV/u)
Present theorectical calculation
Divay et al.(2017)
Dudouet et al.(2013)
Napoli et al.(2012)
Haneefa et al.(2014)



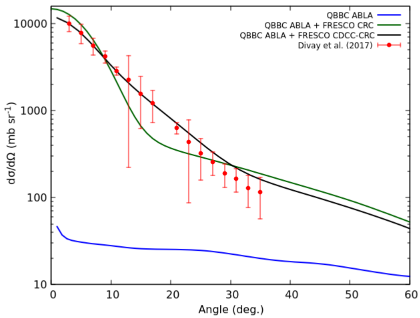
Projectile (m1): 8Be AEl AMU MeV →m1=7454.849899 MeV
Target (m2): 0.01 AEl AMU MeV →m2=0.01 MeV
Ejectile (m3): 4He AEl AMU MeV →m3=3727.37902963 MeV
Recoil (m4): 4He AEl AMU MeV →m4=3727.37902963 MeV
Projectile Energy: 1094 MeV kinetic total
Ejectile Excitation Energy: MeV
Recoil Excitation Energy: MeV
Plot Abscissa (x-axis): θ3 θ4 θ3cm cos(θ3cm) E3 E4 v3 v4 dΩ3/dΩcm dΩ4/dΩcm
Plot Ordinate (y-axis): θ3 θ4 θ3cm cos(θ3cm) E3 E4 v3 v4 dΩ3/dΩcm dΩ4/dΩcm
Express angles in: degrees radians
x min, x max:
y min, y max:
Plot Width: 900 pixels , Font Size: 21 pt
Number of Points: 100
Legend Font Size: 16 pt, Legend Vertical Displacement: 3 %
Output: display PNG image generate EPS file generate PDF file
Include: 8Be+0→4He+4He, Ek(8Be)=1094 MeV (check channels to keep them)
CALCULATE

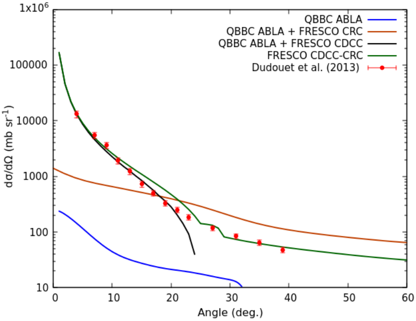



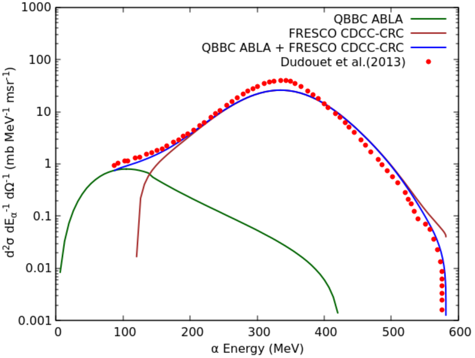
NRV: 2 body nuclear kinematics
Projectile Target Projectile-like fragment Target-like fragment
C 12 + C 12 → Be 8 + O 16 + Qtot( = -11.29 MeV) [1]
Elab = 1140.00 MeV εPLF= 0.0 MeV εTLF= 11.09 MeV Ecm(out)= 558.71 MeV
Calculate
Δθcm = 4.00 deg
Energy vs. Angle Energy vs. Energy Angle vs. Angle
Laboratory Energies and Angles of Emmited Fragments
Reaction: 12C + 12C → 8Be + 16O, Elab = 1140.00 MeV
8Be
16O
Fixed event
Energy (MeV)
θ (deg)
Highcharts.com
Kinematically allowed values
θlab (deg) Elab (MeV)
8Be 0.0° < θlab < 180.00° 30.42 < Elab < 1094.52
16O 0.0° < θlab < 44.43° 34.18 < Elab < 1098.29
Fixed event parameters
EPLF= 1094.52 MeV θPLF= 0.0 deg
ETLF= 34.18 MeV θTLF= 0.0 deg
Show/Hide θcm= 0.0 deg
Grazing collision[4], p.7): θgr(cm) ≈ 0.6 deg, θgr(lab) ≈ 0.3 deg, bgr ≈ 7.5 fm, Lgr ≈ 96 ħ
Save data as ASCII file
Coulomb barrier[4], p.326, 332): VC ≈ 6.1 MeV, RC ≈ 7.7 fm
[1] M. Wang, G. Audi, A.H. Wapstra, F.G. Kondev, M. MacCormick, X. Xu and B. Pfeiffer, Chinese Physics C 36 (2012), P. 1603.
[2] P. Moller, A.J. Sierk, T. Ichikawa, H. Sagawa. Atomic Data and Nuclear Data Tables 109-110 (2016), P. 1.
[3] T. Tachibana, M. Uno, M. Yamada, S. Yamada, Atomic Data and Nuclear Data Tables 39 (1988) P. 251.
[4] R. Bass, Nuclear Reactions with heavy ions, Springer-Verlag, NY, 1980

8Be+0→4He+4He, Ek(8Be)=1094 MeV
θ4 [deg]
θ3 [deg]

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[3] *Arunima, Anagha, Midhun et al.*, arXiv:2409.07090(2024)

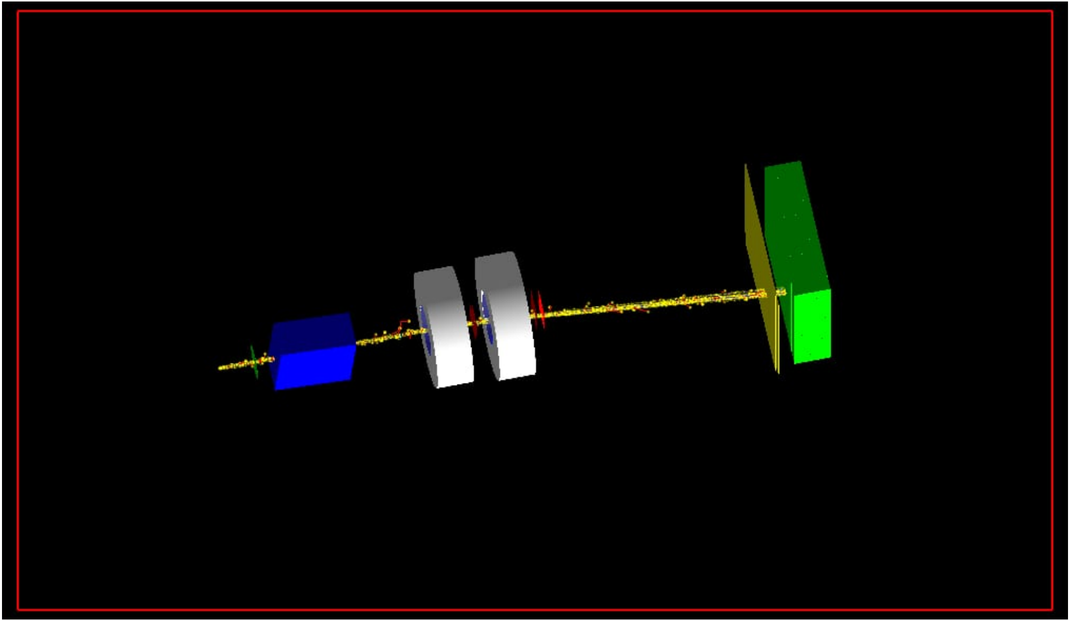
# Possibility of Exploring the Breakup Modes with FOOT Apparatus

To explore the breakup modes, we need to construct $E_{rel} - Q_{value}$ correlations for each events.

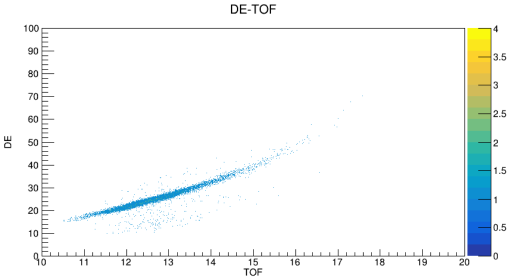
**Challenges :**

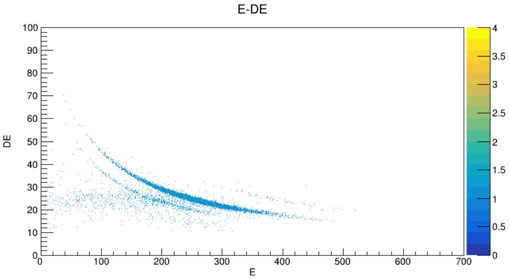
a. Isotopic Identification
b. Energy Resolution to Construct $E_{rel}$
c. Detection of all fragments for Constructing $Q_{Value}$

# Simulation of FOOT Apparatus in Geant4

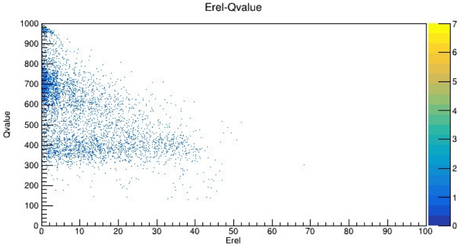


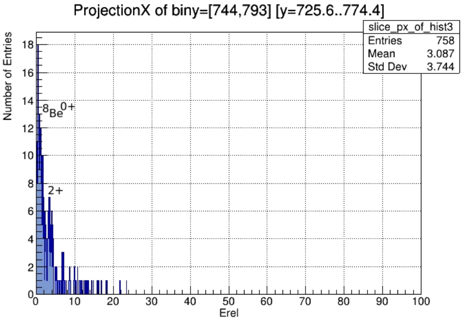
# Energy Resolution of Three-Body Events



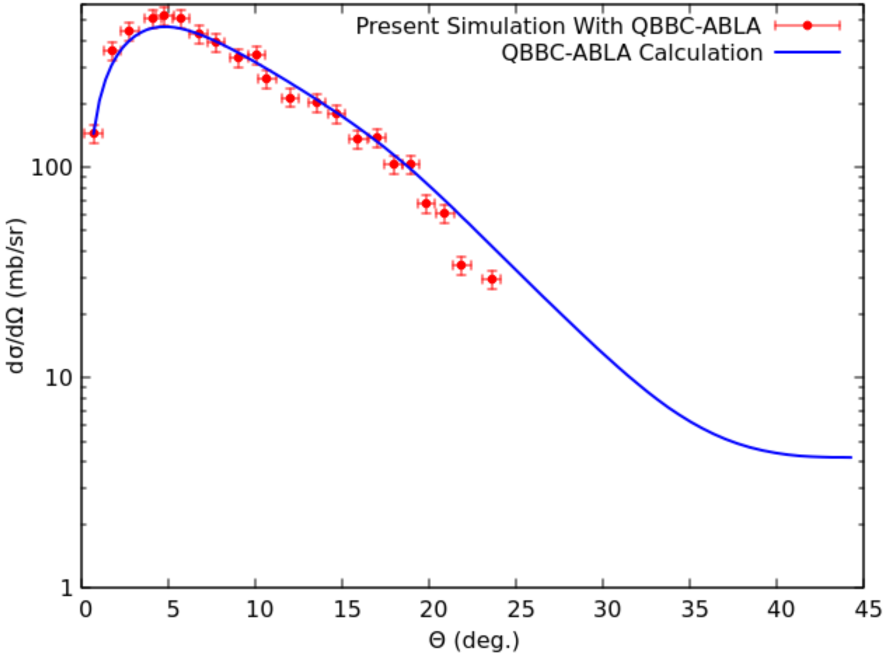



# $E_{rel} - Q_{value}$ Correlation



# Sensitivity for sequential alpha cross sections



# Where we are limited ..!

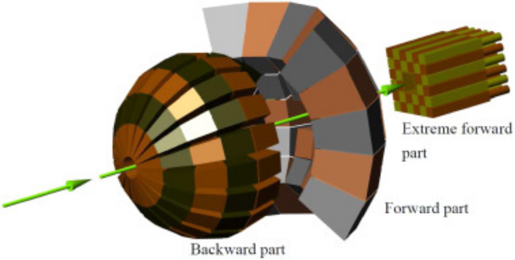
The current setup limits us on some points..

a. Target Thickness → Mean Free Path

b. Event Rates

c. Random Coincidences

However, physics is important, hence we have to go for an optimum solution.



# In Summary

1. **Physics-driven approaches** are essential, than the **numerical data-driven PhysicsList** for explaining particle correlations and particle multiplicities, which makes stronger impact in the dosimetry.
2. The term **fragmentation** is so far treated as **statistical average** of meany processes. It made into **distinct** and **desecrate** by identifying the breakup modes.
3. The $E_{rel} - Q_{Value}$ correlations can resolve different breakup modes. The FOOT apparatus is capable of the same, with optimization of the target thickness and event rates.
4. The angular distribution of individual breakup mode has to be reproduced by **CDCC-CRC** calculations, which will serve a great physics explanation.

# THANK YOU..!

**Do You Have Any Questions?**