Projectile Breakup of ^{7}Be on ^{12}C at 5 MeV/u

Dhruba Gupta

Department of Physical Sciences, Bose Institute

R. Mitra, S. Samanta, S. Maity, K Kundalia, Sk M Ali, S K Saha Bose Institute, India
O Tengblad, A Perea CSIC, Madrid, Spain
I Martel Bravo Universidad de Huelva, Huelva, Spain
J Cederkall Lund University, Sweden
A.M. Moro Universidad de Sevilla, Spain

ISOLDE Workshop and Users meeting, CERN, November 27-29, 2024

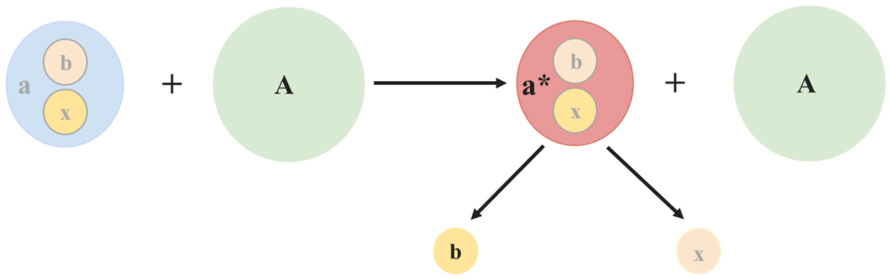
Projectile Breakup

Typical nuclei average $B.E/A \sim 8$ MeV, tightly bound nuclear structure

Weakly bound nuclei *d* has *B.E* of 2.22 MeV, ^{6,7}Li show α–cluster structures and low energy thresholds (1.47/2.47 MeV) against cluster breakup. Crucial for understanding nuclear structure, potential and reaction dynamics. An important feature of collisions of such nuclei is the high probability of **breakup reaction**.

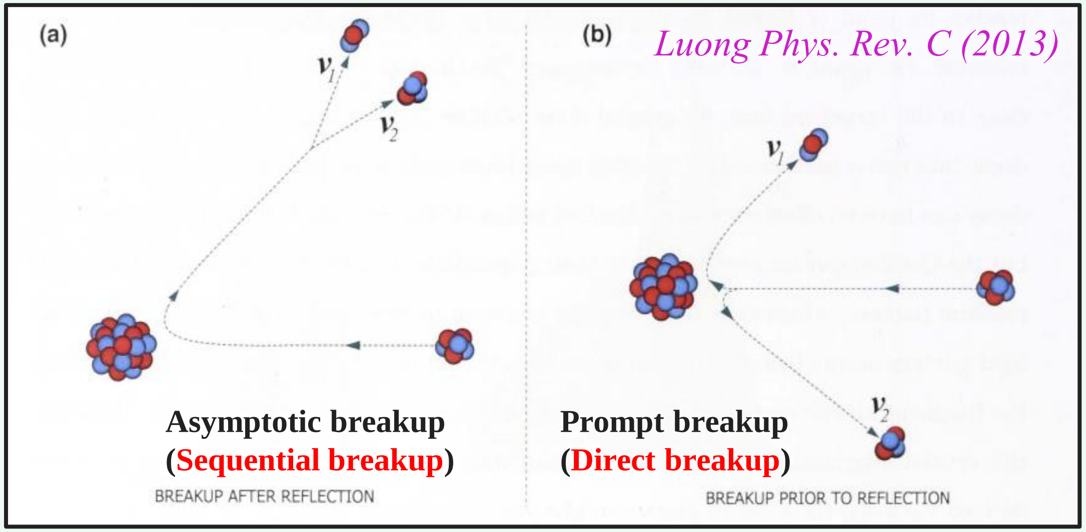
Nuclei near drip lines: more intriguing, very weakly bound, particle emission thresholds $\leq$ 1 MeV. **Exotic features** usually increase the variety of reaction mechanisms. Large enhancement of σ_R observed for reactions induced by halo nuclei.

Study of reaction dynamics of **light weakly bound RIBs** is particularly interesting at **energies near the Coulomb barrier**. Experiments indicate that for ^{6,8}He, *n*-transfer channels mainly contribute to enhancement of σ_R while for ^{8}B/^{11}Li, it is due to **projectile breakup**.



Studying the breakup mechanism crucial for understanding the reaction dynamics of weakly bound nuclear systems.

Breakup occurs when a weakly bound nucleus is excited above its breakup threshold through the long-range Coulomb or short-range nuclear interactions.



If the nucleus is populated to long-lived (narrow) resonances, the "asymptotic" breakup may occur far away from the target (**sequential breakup**). Breakup from non-resonant continuum or broad resonant states, the "prompt" breakup occurs close to the target (**direct breakup**). Projectile excitation and location of breakup can be obtained from E_{rel} of the breakup fragments:

$$E_{rel} = \frac{m_1 E_2 + m_2 E_1 - 2\sqrt{m_1 E_1 m_2 E_2}\cos\theta_{12}}{m_1 + m_2}$$

where, m_1, m_2 and E_1, E_2 are the masses and energies of the breakup fragments and θ_{12} their opening angles.

^{6}Li: **direct breakup** ^{6}Li→α+d dominant as compared to transfer-triggered breakup into $\alpha + p$, $\alpha + \alpha$, $\alpha + t$, *nearly independent of energy and target mass*. As the bombarding energy increases in the above barrier region, **sequential breakup** eventually dominates.

^{7}Li: Direct breakup occurs mainly with *high-Z targets or low-Z targets at higher energies*. Predominantly driven by transfer reaction populating an unbound state in the projectile-like nucleus followed by breakup transfer-triggered breakup.

^{8}Li: Shows diverse breakup modes similar to ^{6,7}Li, processes like breakup fragment captured by the target or cluster transfer.

^{9}Be: Similar behavior as ^{7}Li, with higher breakup thresholds. Few coincident data. Transfer-triggered breakup into $\alpha + \alpha$ dominates the total breakup yield.
^{6,7}Li, ^{9}Be : yield of α exclusive << inclusive.

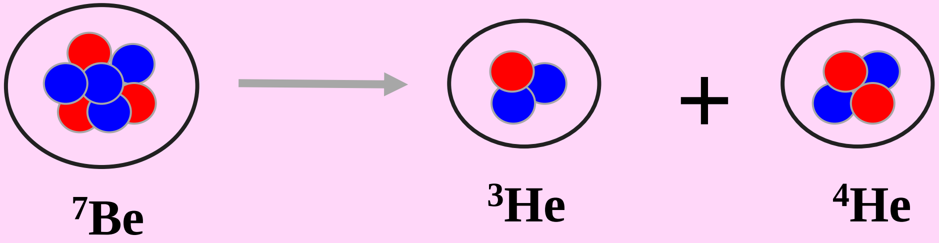
Proton halo nuclei have lower breakup probabilities than neutron halo nuclei for the same breakup threshold. Elastic breakup becomes more important for nuclei with lower breakup thresholds towards drip lines.

To understand the differences in breakup dynamics, effect of weak binding on fusion etc it is important to ***differentiate between prompt and delayed breakup***.

^{7}Be

Radioactive ($T_{1/2}$ ~ 53 days), well pronounced ^{3}He + ^{4}He cluster structure

Bound by only **1.586 MeV** with respect to ^{7}Be → ^{3}He + ^{4}He **breakup**



The direct processes induced by ^{7}Be, viz breakup, 1*n* stripping/pickup, ^{3}He/^{4}He stripping produce either one or two stable well-bound charged fragments.

Thus, in contrast to reactions induced by other light nuclei, studies of ^{7}Be reaction dynamics do not require the detection of neutrons or weakly bound/radioactive fragments (as for experiments with ^{6,7}Li, ^{6,8}He, ^{8}B, ^{11}Li)

Thus, ^{7}Be represents a kind of ideal case among all light ions where the study of the reaction mechanisms can be addressed in detail.

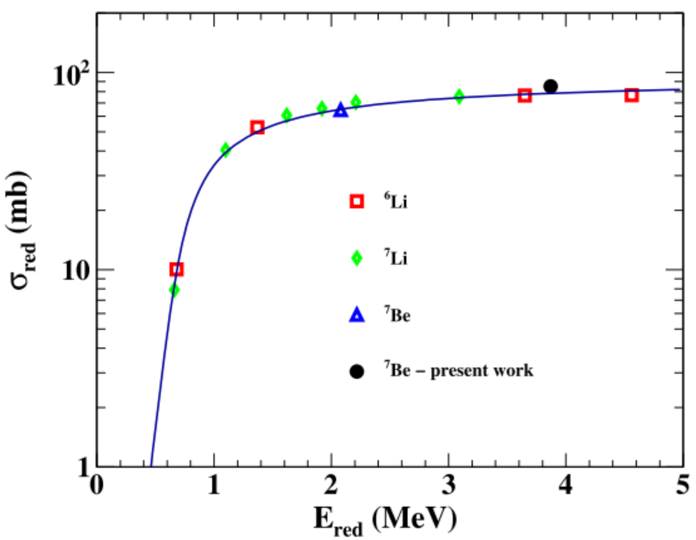
Previous Works

^{7}Be + ^{58}Ni E = 22 MeV *Mazzoco Phys. Rev. C (2015)*
^{7}Be + ^{208}Pb E = 42.2, 40.5, 37.4 MeV Mazzoco *Phys. Rev. C (2019)*
^{3}He - ^{4}He *coincidences not detected* ^{4}He yield 4-5 times more abundant than ^{3}He, exclusive breakup not dominant, mostly dominated by transfer reactions 1*n* stripping, pickup, studied elastic scattering and coupling to breakup channels.

^{7}Be + ^{12}C
E = 18.8 MeV *Zamora Phys. Rev. C (2011)*
Barioni Phys. Rev. C (2019)
E = 34 MeV *Amro Eur. Phys. J. ST (2007)*
Studied elastic scattering
Very few coincidences observed
α-transfer reaction more prominent than breakup

E = 35 MeV *Kundalia Phys. Lett. B (2022)*
From the coupled channel analysis, ^{7}Be breakup cross section ~ 10% of the reaction cross section.

Kundalia Phys. Lett. B (2022)



Reduced reaction cross section
^{7}Be + ^{12}C at E = 35 MeV

Reaction studies of the ^{7}Be nucleus on a light target like ^{12}C reported very few coincidence events from breakup. Similar results were reported on heavier targets like ^{58}Ni and ^{208}Pb. It was concluded that though ^{7}Be has a lower breakup threshold than ^{7}Li, its transfer channels are more prominent than breakup.

Further studies required to disentangle completely several reactions producing ^{3}He and ^{4}He

(i) improving the statistical accuracy of the collected data

(ii) ensuring a larger solid angle coverage

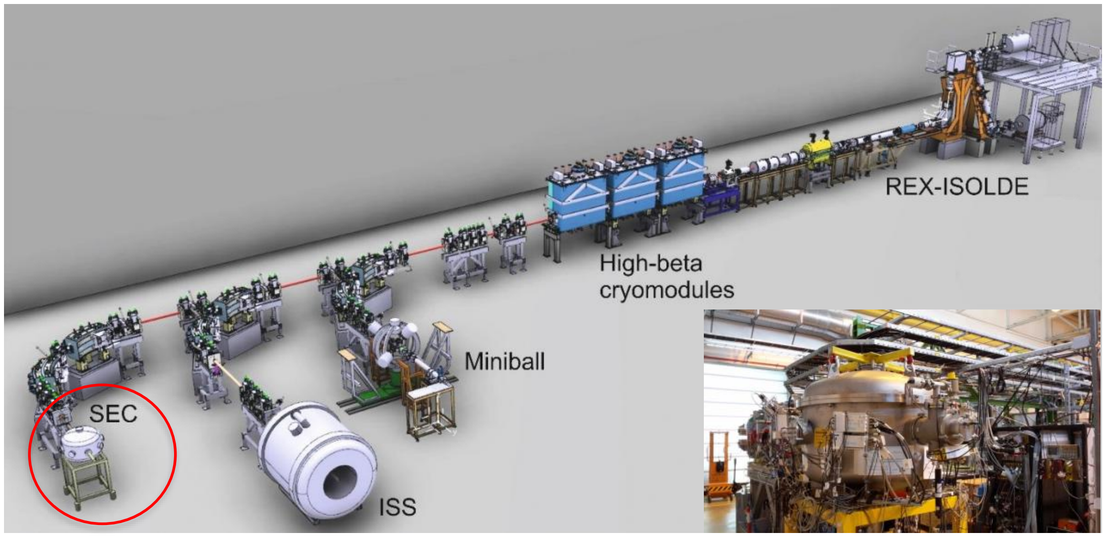
(iii) increasing the geometrical efficiency for the detection of coincidence events.

To make a detailed study of the **transfer and breakup channels** of ^{7}Be on ^{12}C target, we carried out an experiment at HIE-ISOLDE with a 5 MeV/u ^{7}Be beam.

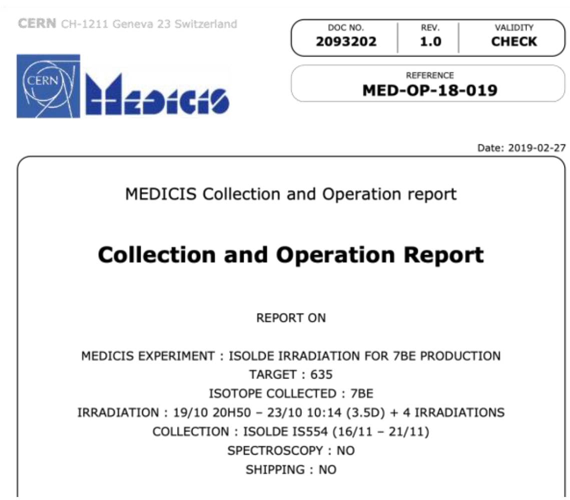
Experiment IS 554 @

^{7}**Be : E = 5 MeV/u , I ~ 5 x 10^{5} pps**

Targets: CD_2 (15 µm), CH_2 (15 µm), ^{208}Pb (1 mg/cm^2)



Scattering Chamber (SEC)



CERN CH-1211 Geneva 23 Switzerland

DOC NO.	REV.	VALIDITY
2093202	1.0	CHECK

REFERENCE
MED-OP-18-019

Date: 2019-02-27

MEDICIS Collection and Operation report

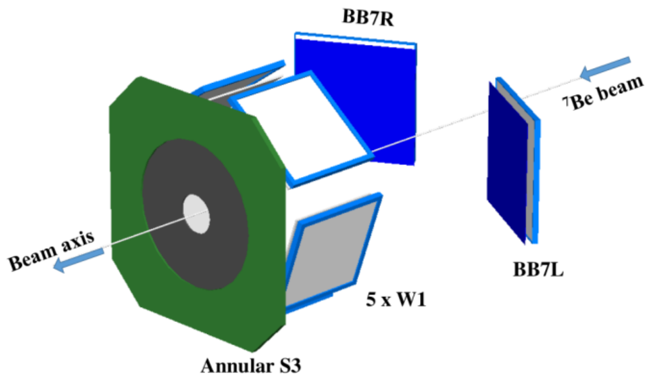
Collection and Operation Report

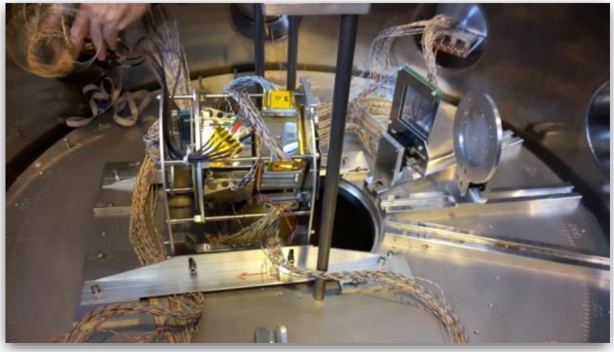
REPORT ON

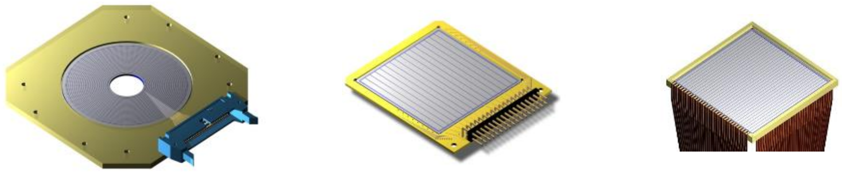
MEDICIS EXPERIMENT : ISOLDE IRRADIATION FOR 7BE PRODUCTION
TARGET : 635
ISOTOPE COLLECTED : 7BE
IRRADIATION : 19/10 20H50 – 23/10 10:14 (3.5D) + 4 IRRADIATIONS
COLLECTION : ISOLDE IS554 (16/11 – 21/11)
SPECTROSCOPY : NO
SHIPPING : NO

The target (UCx) was irradiated with 0.37 µA of 1.4 GeV **protons from the PS-booster offline during 3 days**. The activated target was then mounted on the GPS target station, heated and the ^{7}Be was extracted using the **RILIS laser ion-source**, and accelerated using the HIE-ISOLDE post accelerator. A stripping foil and a dipole before the experimental station was used to clean the beam to ^{7}**Be**$^{4+}$

Experiment IS 554 @

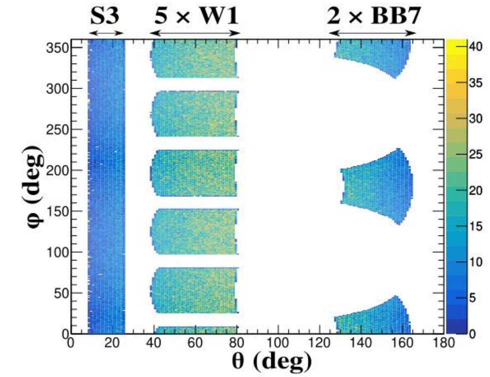






http://www.micronsemiconductor.co.uk/

Compact Silicon detector array with ΔE - E telescope configuration. Total solid angle coverage **~32% of 4π**



Charge particle detector setup

1 x S3 annular DSSD (24 x 32 strips, 1000 μm) covering front angles 8º – 25º

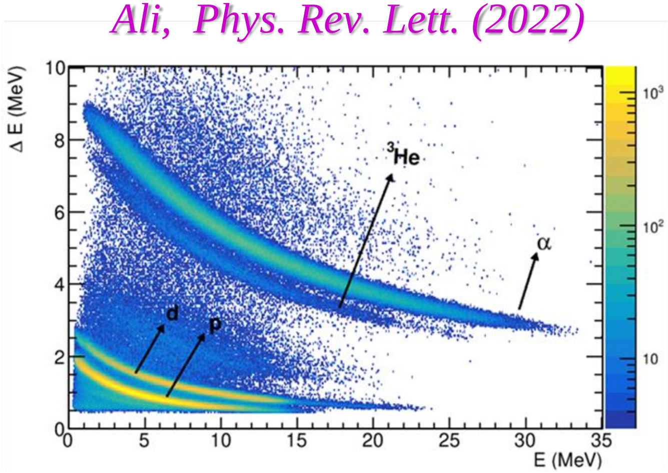
5 x W1 DSSD (16 x 16 strips, 60 μm) in pentagon geometry covering angles 40º – 80º

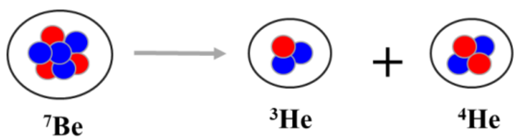
2 x BB7 DSSD (32 x 32 strips, 60 μm and 140 μm) at backward angles 127º – 165º

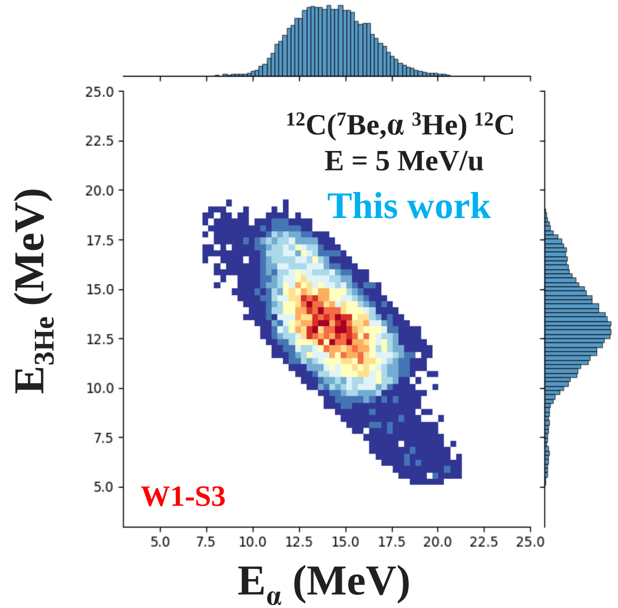
W1 and BB7 DSSDs are backed by 1500 μm thick unsegmented pads MSX25/MSX40

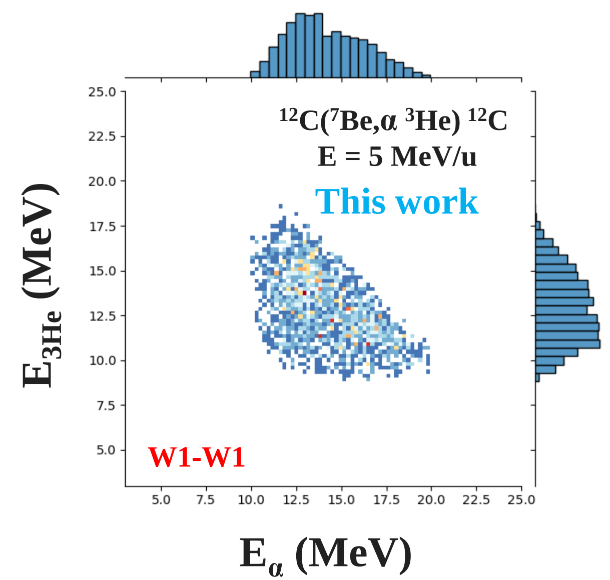
Energy Correlation

Ali, Phys. Rev. Lett. (2022)









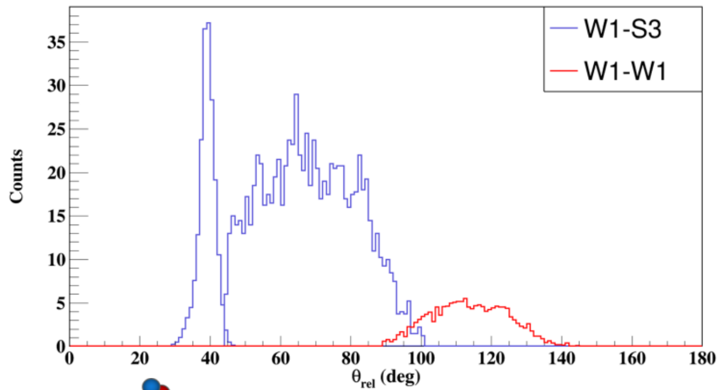
Energy correlations of coincident α and ^{3}He from breakup of ^{7}Be

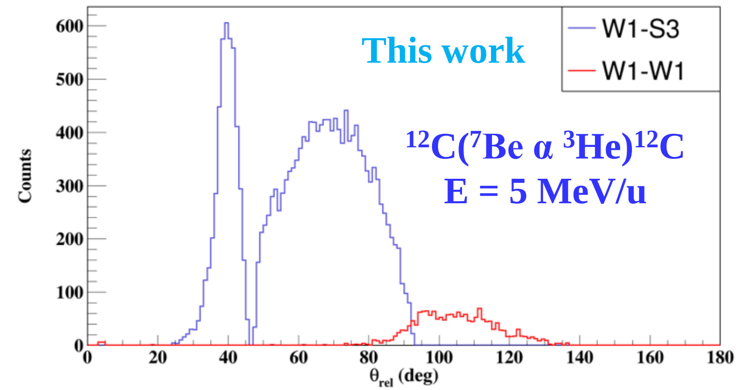
Prominent signature of breakup

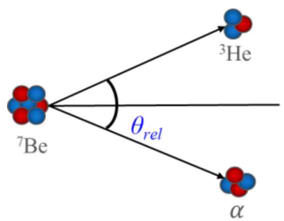
Significant breakup events from the reaction ^{12}C(^{17}Be,α ^{3}He)^{12}C at 5 MeV/u

Opening angle distribution

$$\cos\theta_{rel} = \cos\theta_1\cos\theta_2 + \sin\theta_1\sin\theta_2\cos(\phi_1-\phi_2)$$







Coincident ^3He and ^4He from ^7Be breakup over a wide angular range

Simulation

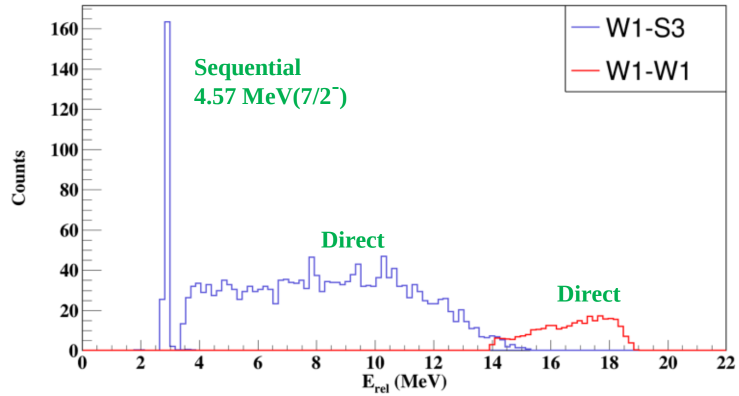
Data

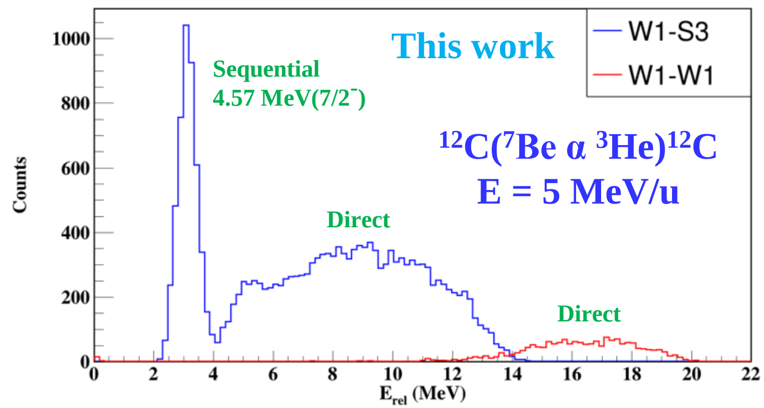
Relative Energy Distribution

$$E_{rel} = \frac{m_2E_1 + m_1E_2 - 2\sqrt{m_1E_1m_2E_2}\cos\theta_{12}}{m_1+m_2}.$$

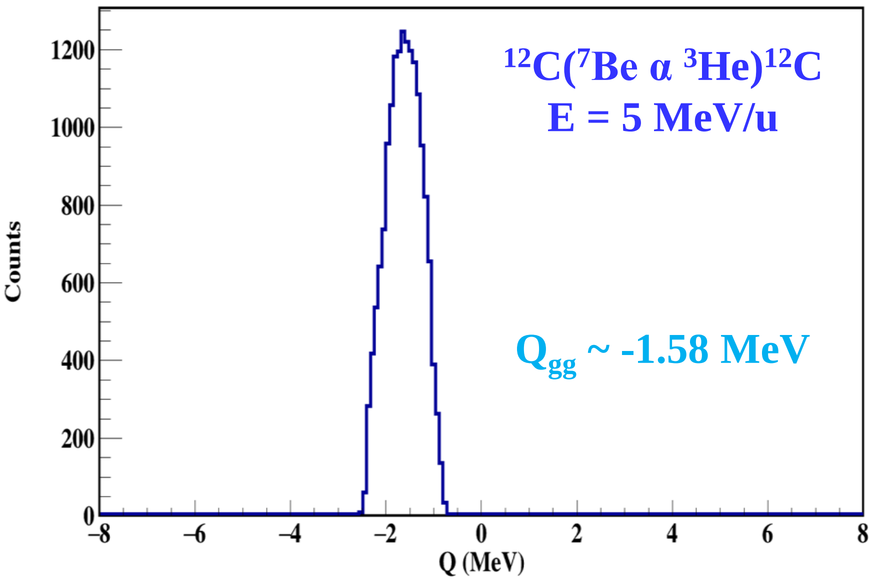
Direct breakup (79%) dominant over Sequential breakup (21%) from 4.57 MeV state

Width of the 4.57 MeV excited state is : ~ 980 keV

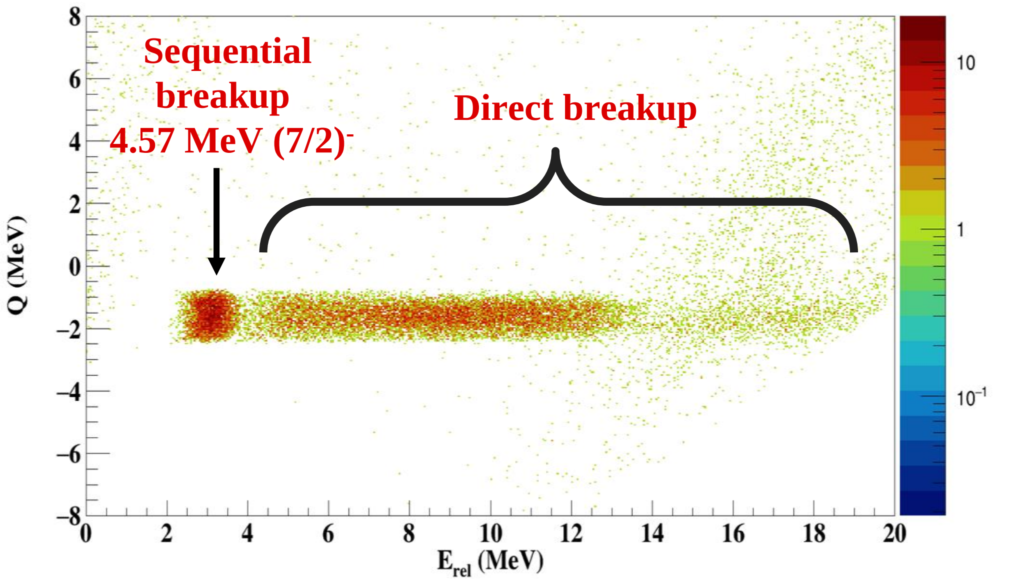




$Q - E_{rel}$ correlations



***Q* value distribution**

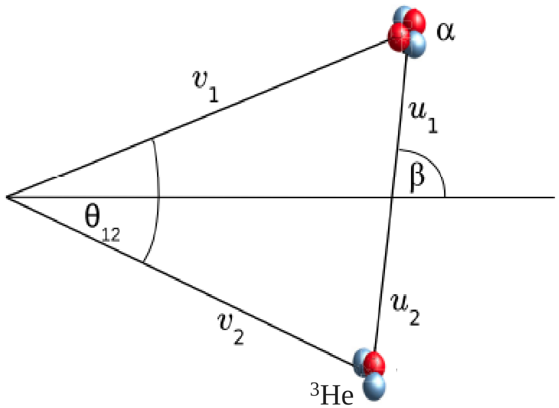


***Q* vs *E*$_{rel}$ spectrum**
Complete picture of breakup
Separation between different breakup modes

$Q = Q_{gg} - E_{ex}$, information about target excitation. Here Q value is peaking around -1.58 MeV (breakup threshold of ^{7}Be). Breakup events correspond to the ground state of the ^{12}C.

Orientation of the Relative Momentum of Breakup Fragments

To examine the effects of target proximity on the observed energy and angular distribution of breakup fragments, a new breakup observable was constructed, that of the orientation β of relative momentum of the fragments w.r.t the direction of the centre of mass of the nucleus undergoing breakup. Thus, segregation of **direct** and **sequential** breakup can be verified further.



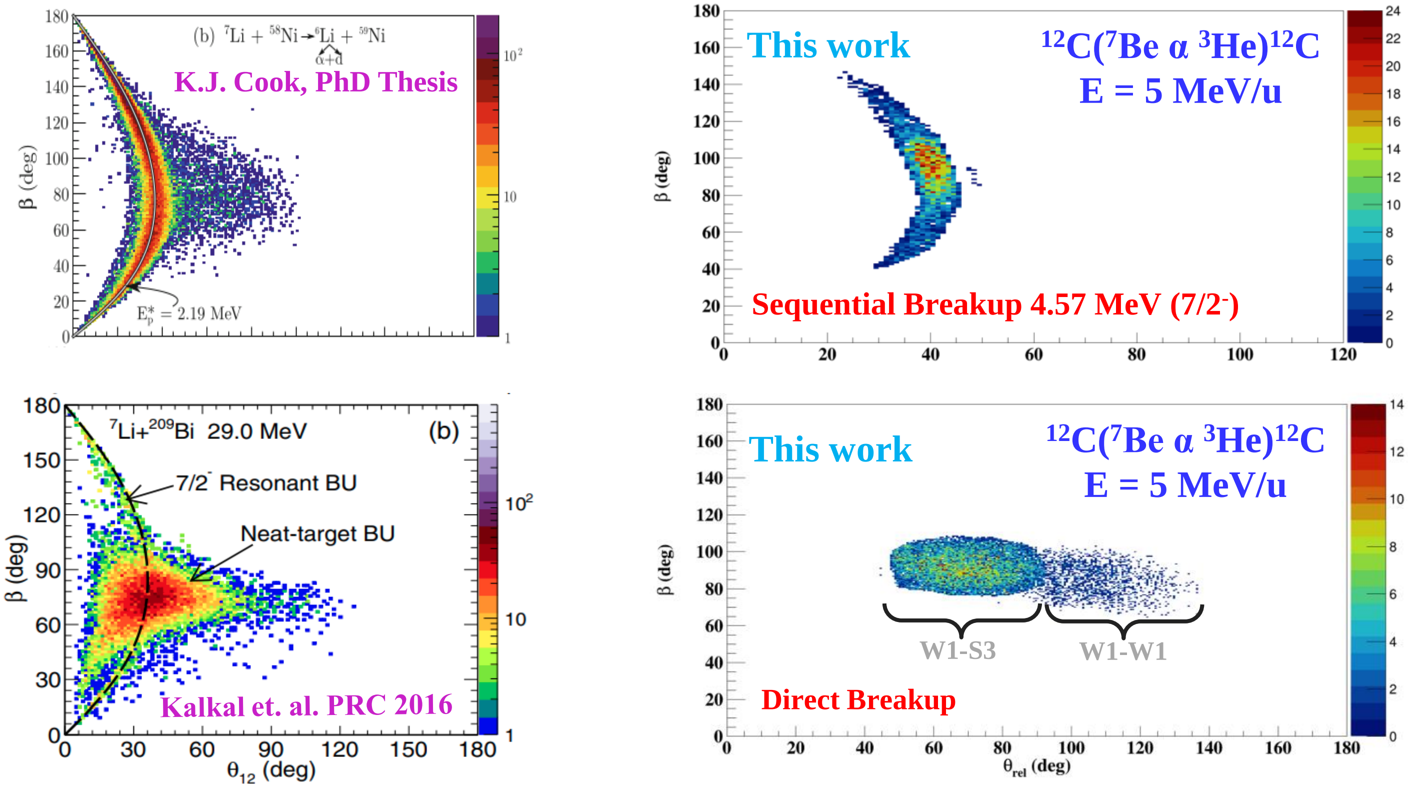
$$\sin\beta = \frac{v_1 v_2 \sin\theta_{12}}{\left(v_2^2 u_1^2 + v_1^2 u_2^2 + 2u_1 u_2 v_1 v_2 \cos\theta_{12}\right)^{1/2}},$$

v_1, v_2 = velocity of breakup fragments in lab frame
u_1, u_2 = velocity of breakup fragments in CM frame

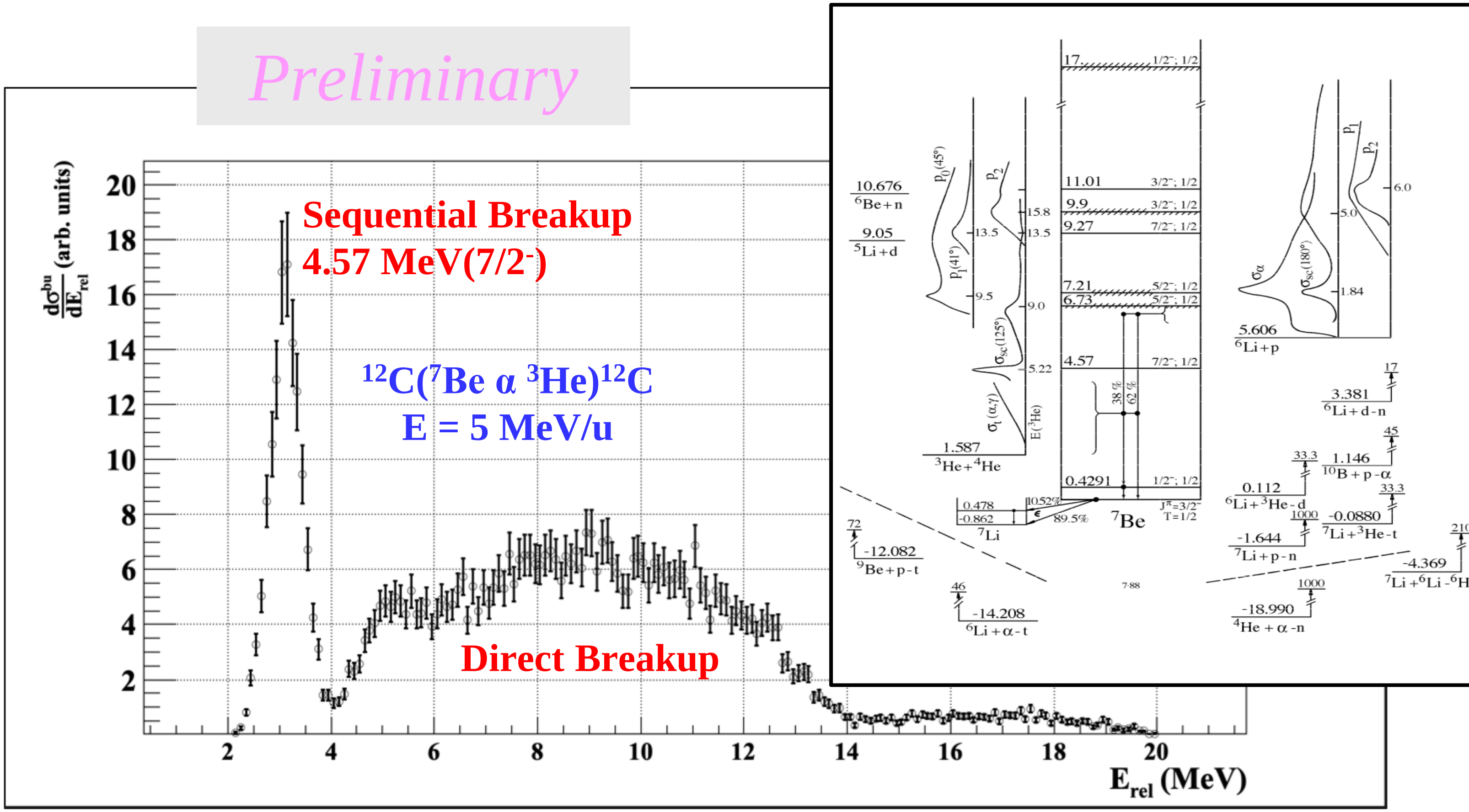
β vs θ_{rel} : crucial insight into the **location of breakup**. β can also be described as the breakup angle in the projectile like nucleus rest frame.

From E_{rel}, it is essentially impossible to identify any evidence of sequential breakup. However, when the same events were plotted in β-θ_{rel} representation, a **clear band of events** appear corresponding to the asymptotic breakup as well as a region of near-target breakup

Location of Breakup: β vs θ_{rel}



The β and θ_{rel} distribution for **sequential breakup** of ^{7}Be from 4.57 MeV ($7/2^{-}$) resonant state shows ***strong correlation*** since breakup occurs **asymptotically far from the target**. For breakup occurring near the target, post-breakup acceleration will distort this correlation - ***featureless***. The concentration of β at ~ 90 indicates **direct breakup close to the target**.



$\underline{1^{st}\ \text{component}}$ - peak at low E_{rel} centred at $E_{rel} = E^* + Q_{BU}$ associated with breakup on the outgoing trajectory and thus cannot suppress fusion.

$\underline{2^{nd}\ \text{component}}$ consists of events extending to high E_{rel} associated with breakup close to the target nucleus and may be responsible for the suppression of fusion observed at above-barrier energies.

Outlook

Measurement of exclusive breakup of ^{7}Be + ^{12}C at 5 MeV/u
with ^{3}He and ^{4}He detected in coincidence over a wide angular range.

Contribution of **direct** and **sequential** breakup have been identified.
Direct breakup of ^{7}Be at comparatively high energies (4 MeV < E_{rel} < 20 MeV) with a very large opening angle distribution.

Earlier work at similar energy inferred that transfer reaction is more prominent than breakup of ^{7}Be. Further work and CDCC calculations underway to compare transfer-breakup channels with direct exclusive breakup.

Further exclusive breakup data for drip-line nuclei. Investigations of ***p*-rich** nuclei like ^{7}Be, ^{9}C, ^{10}C, ^{12}N, will provide valuable insights on reaction dynamics and also contribute to nuclear reaction theory.

Acknowledgements

ISOLDE engineers in charge, RILIS team, Target Group

Grant agreement no. 654002 (ENSAR2)

Grant ISRO/RES/2/378/15-16 (ISRO, Govt. of India)

Thank You