Inclusive breakup reactions in low energy unstable nuclei collisions

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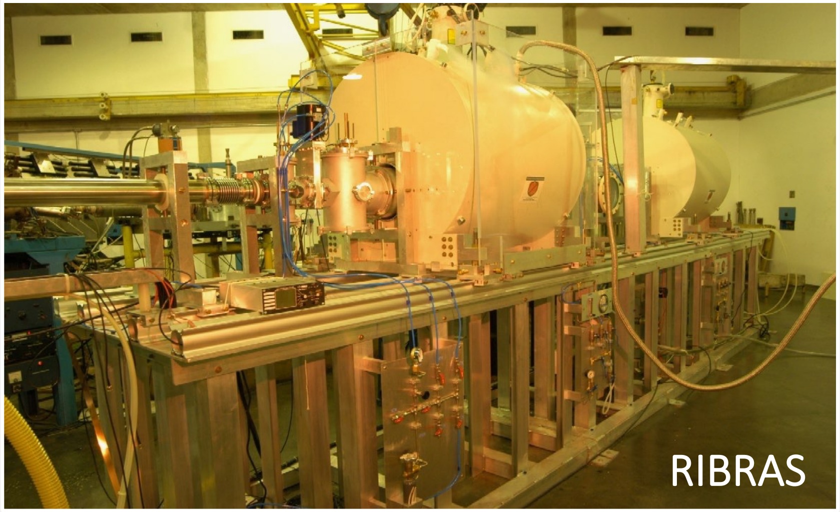
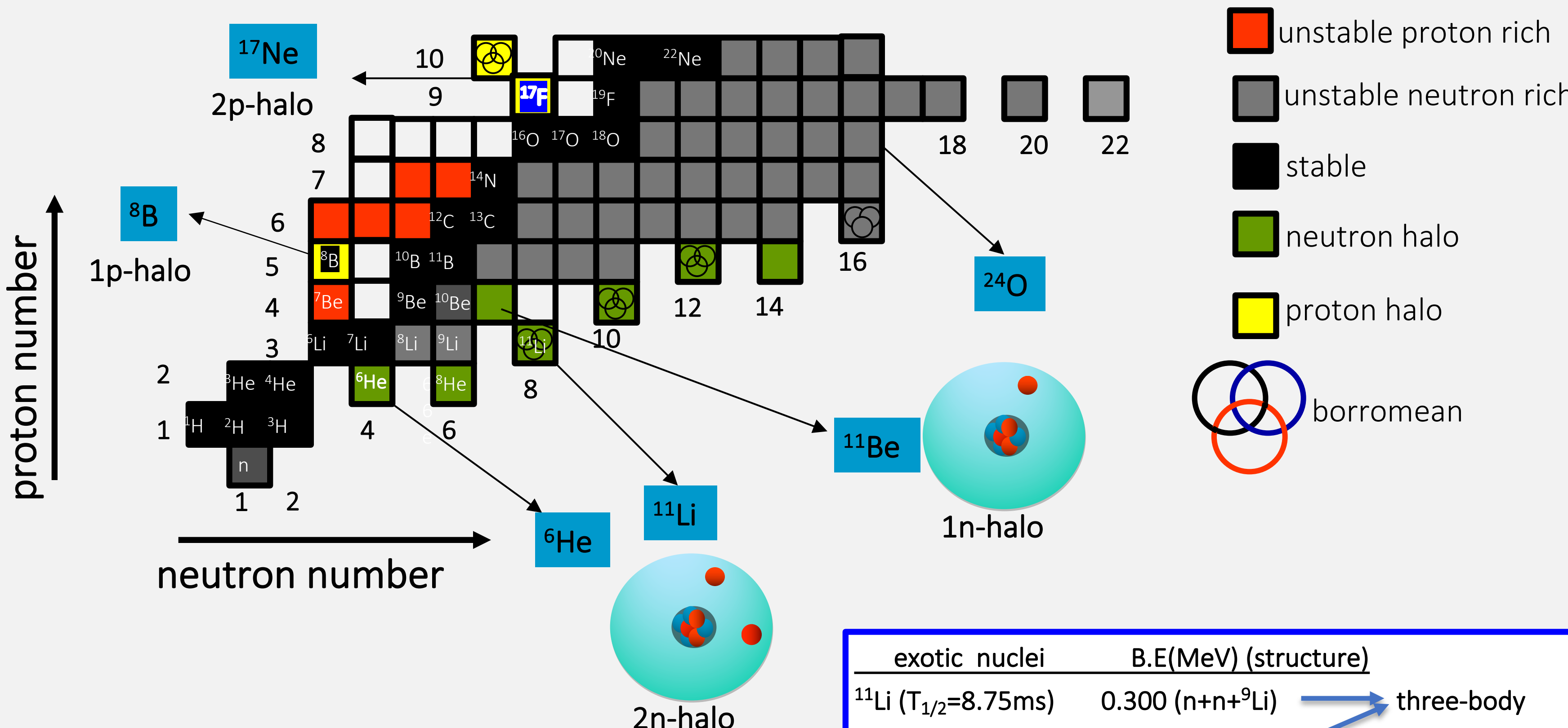
- Introduction: light exotic nuclei
- Inclusive breakup reactions induced by ^{8}Li
- Inclusive breakup reactions induced by ^{6}He
- Comparison with more exotic projectiles ^{11}Li, ^{11}Be and ^{8}B
- Conclusions



• light weakly bound nuclei – Clusters and Halos

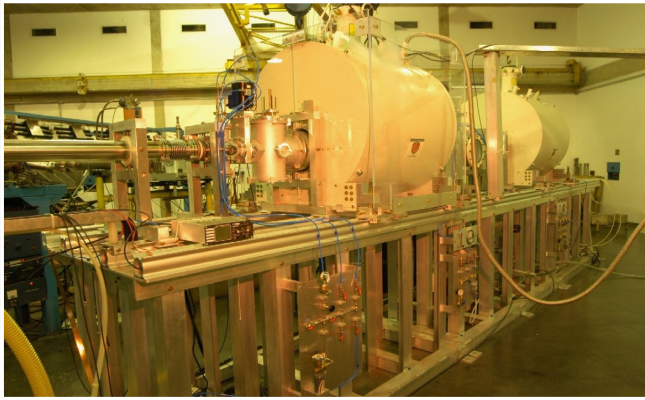


binding energies of 'normal'nuclei 7-10 MeV

weakly bound nuclei	B.E(MeV) (structure)
^{6}Li	**1.47 (α+d)**
^{7}Li	2.46 **(α+t)**
9Be	**1.67 (α+α+n)**
8Li	2.03 (7Li + n)

exotic nuclei	B.E(MeV) (structure)	
^{11}Li ($T_{1/2}$=8.75ms)	0.300 (n+n+^{9}Li)	three-body
^{6}He ($T_{1/2}$=807ms)	0.973 (n+n+alfa)	
^{11}Be ($T_{1/2}$=13.81s)	0.501 (n+^{10}Be)	
^{8}B ($T_{1/2}$=770 ms)	0.137 (p+^{7}Be)	
^{17}F (64.5 s)	0.6 MeV (p+^{16}O)	
	0.1 MeV for 1st ^{17}F excited state	

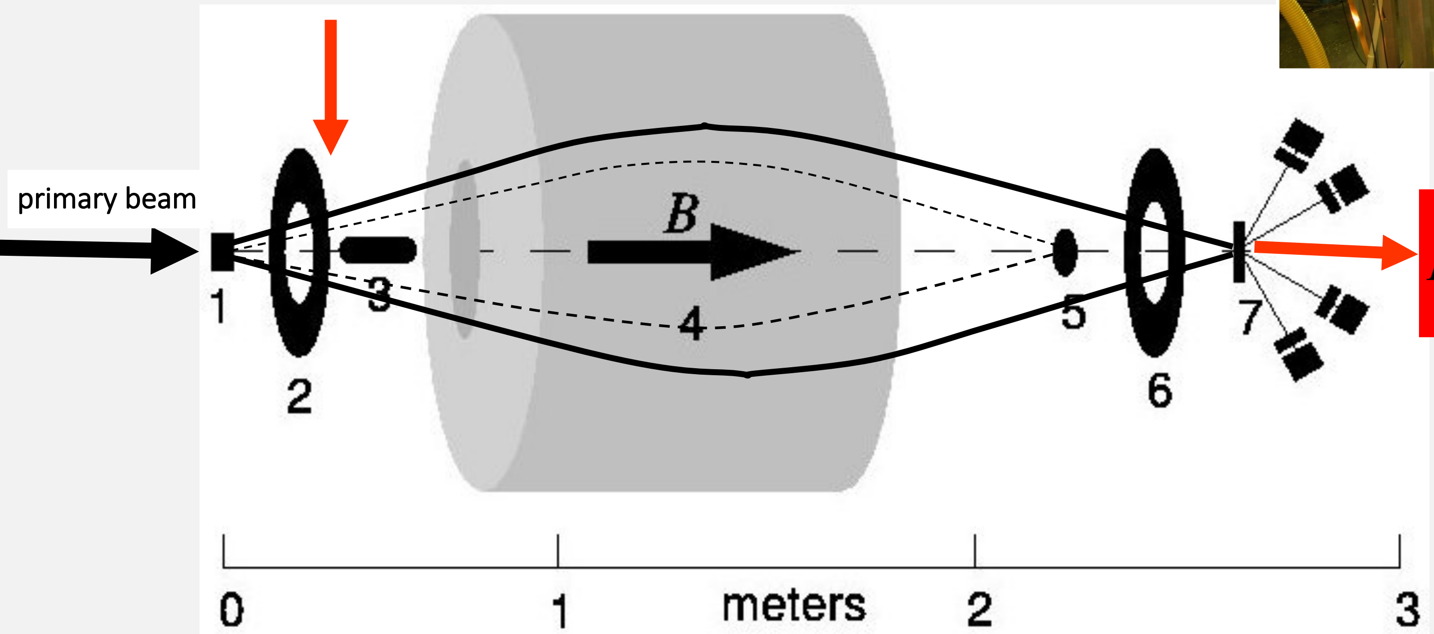
The RIBRAS system: secondary beam selection



First solenoid

angular acceptance
2 deg<$\Delta\theta$ <6 deg

$\Delta\Omega$=30 msr

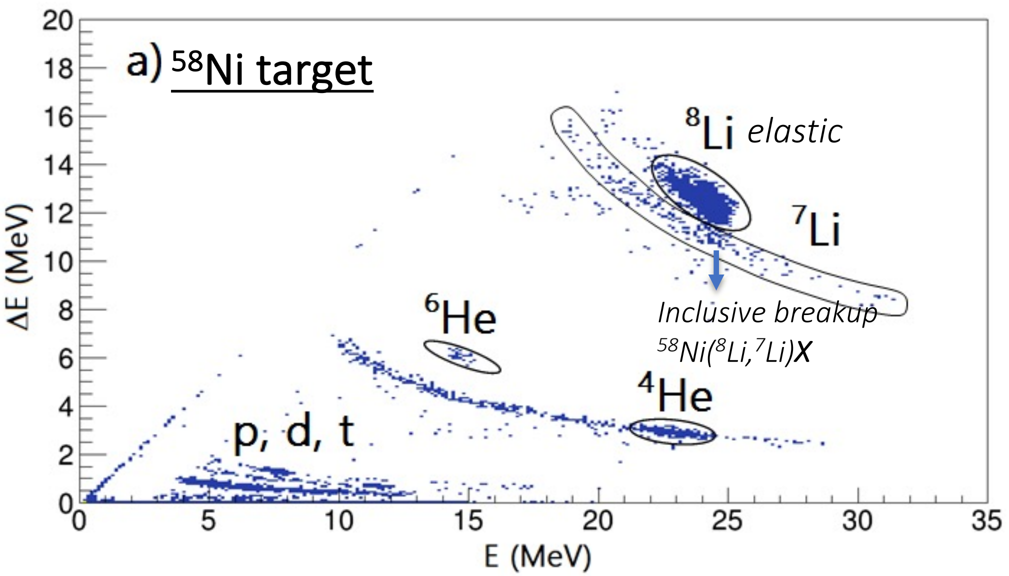


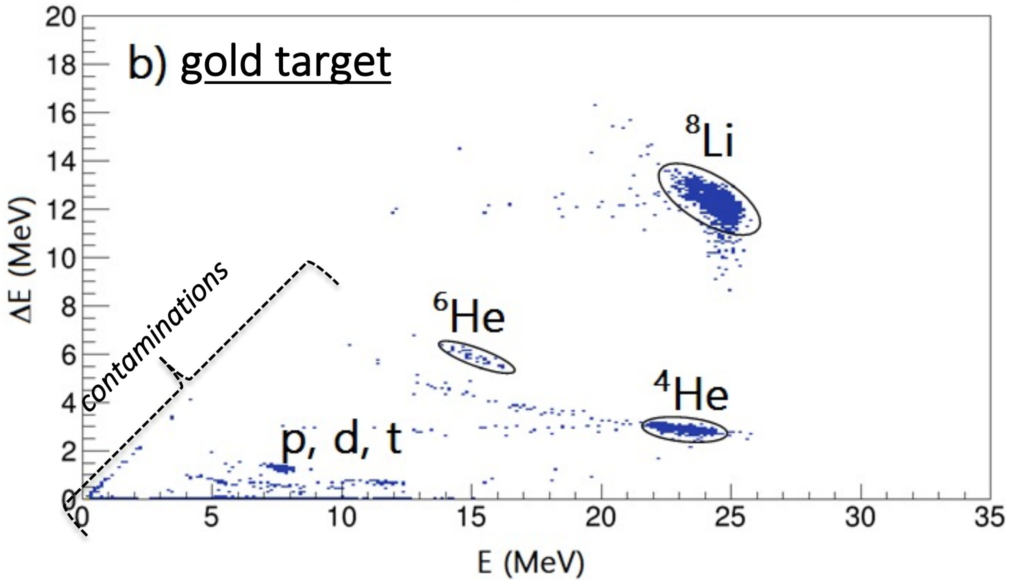
$$B\rho = \frac{mv}{q} = \frac{\sqrt{2mE}}{q}$$

1- primary target
2- collimator
3- Faraday cup
4- solenoid

5- lollipop
6-collimator
7- scattering chamber, secondary target and detectors

Inclusive breakup reactions with ^{8}Li Beam: two E-ΔE identification spectra of the ^{8}Li+^{58}Ni collision



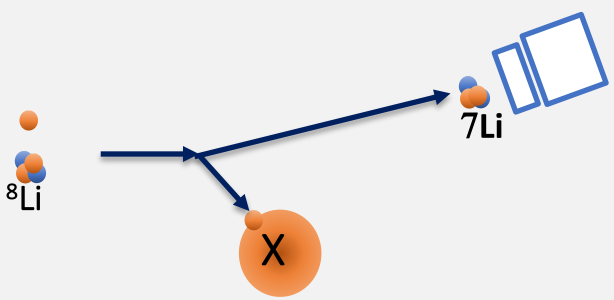


^{8}Li is a weakly bound nucleus that breaks into a ^{7}Li and a nêutron

^{8}Li → n + ^{7}Li E_{bu} = 2.03 MeV

Inclusive breakup reactions:

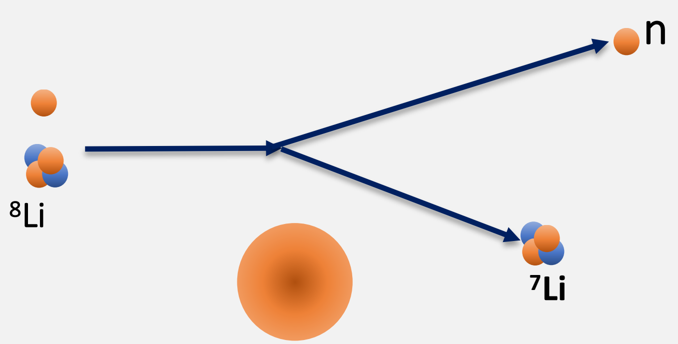
What kind of information one can get if only one of the projectiles fragment is detected



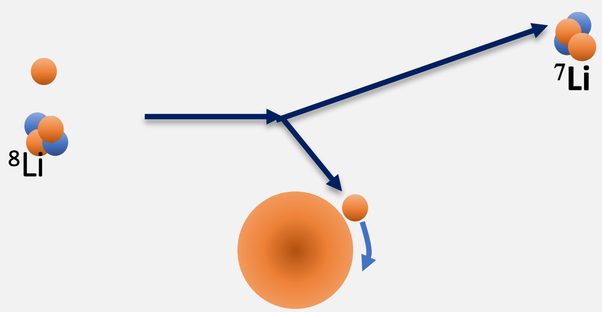
^{7}Li energy and angular distributions

Two diffferent processes are possible to produce ^{7}Li from the ^{8}Li+^{58}Ni collision:

elastic breakup



neutron transfer or non-elastic breakup (NEB)



Elastic breakup:

$^8\text{Li} \rightarrow n + {}^7\text{Li}$ $E_{bu} = 2.03$ MeV

Q-value is negative for elastic breakup

There is a threshold at E_{bu}

Neutron transfer or non-elastic breakup (NEB)

Q-value can be either positive or negative
The transfered nêutron interacts strongly with the target

Reaction Q-value can be either positive or negative depending on the final state excitation energy

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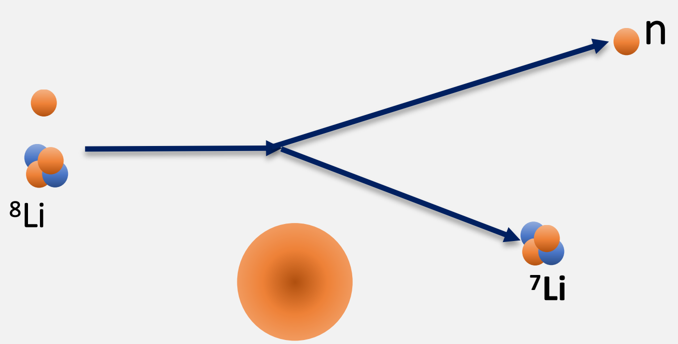

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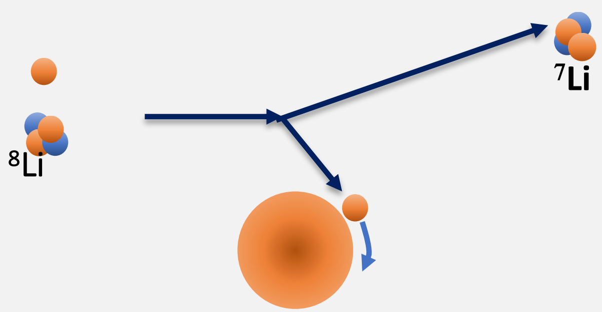

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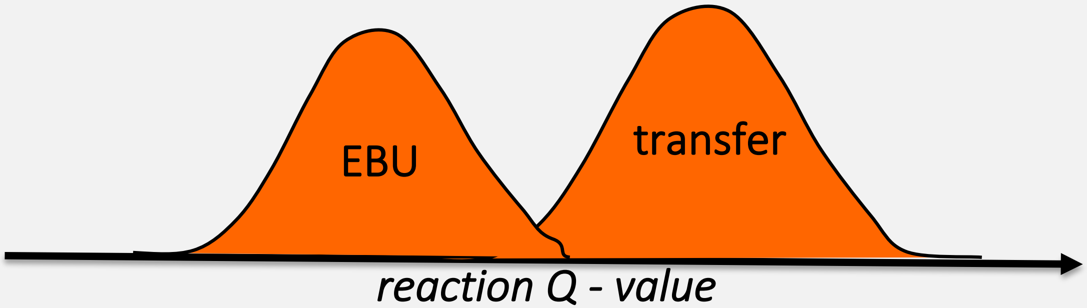
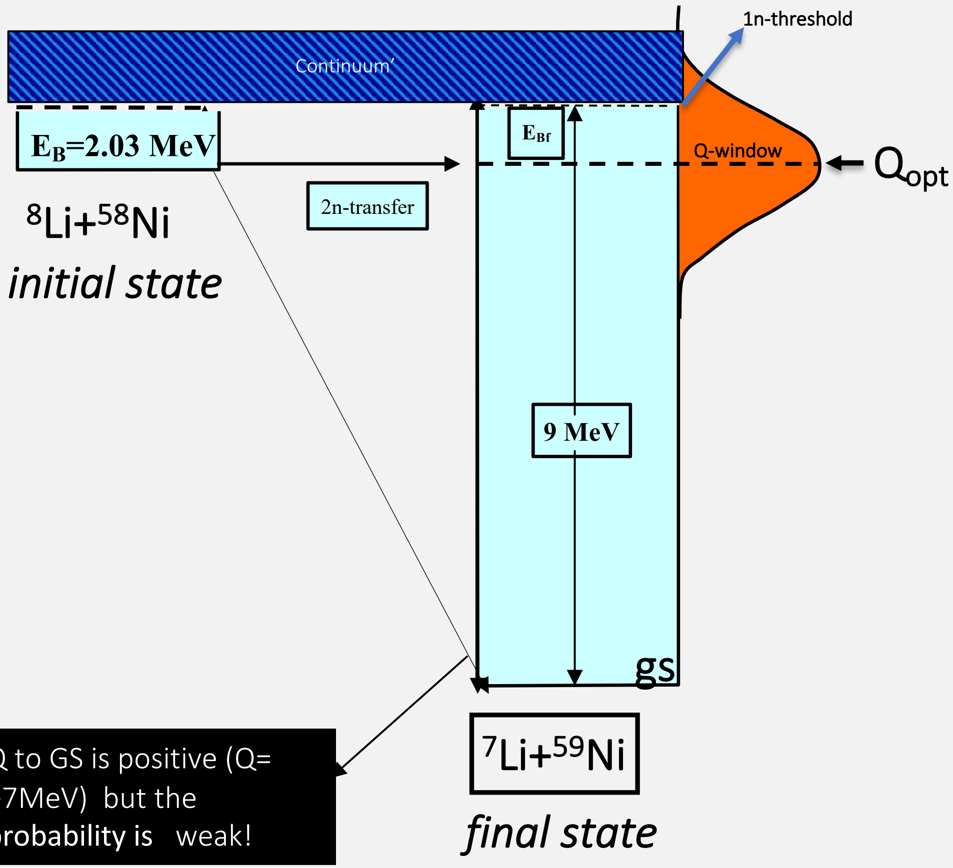


Dynamics of the neutron transfer reactions

Transfer reactions are very selective of the final states energies and angular momentum.

Q-optimum considerations
linear and angular momentum matching conditions

Seminal paper by D. M. Brink, PLB v.40, pg 37 (1972)



Q to GS is positive (Q= +7MeV) but the probability is weak!

Dynamics of the neutron transfer reactions

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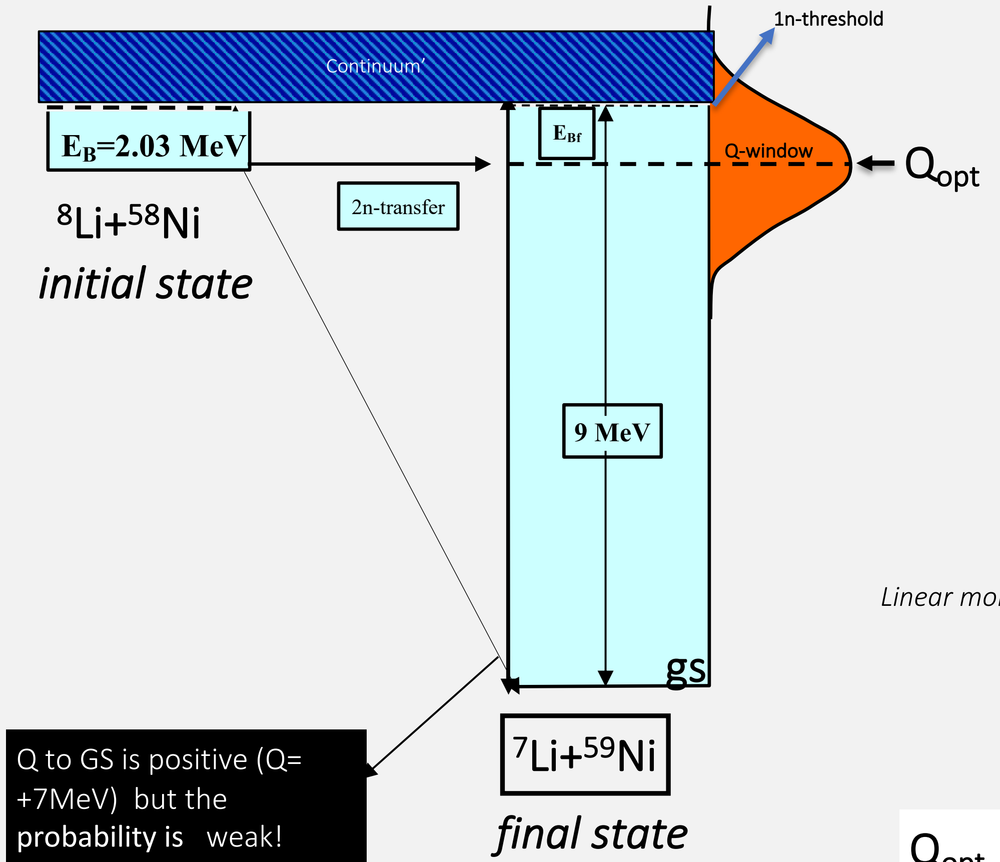

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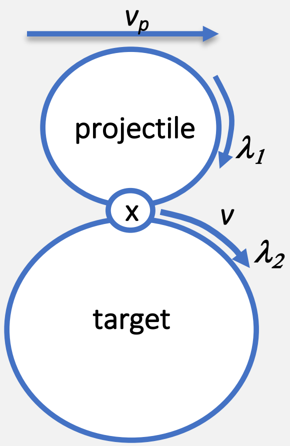


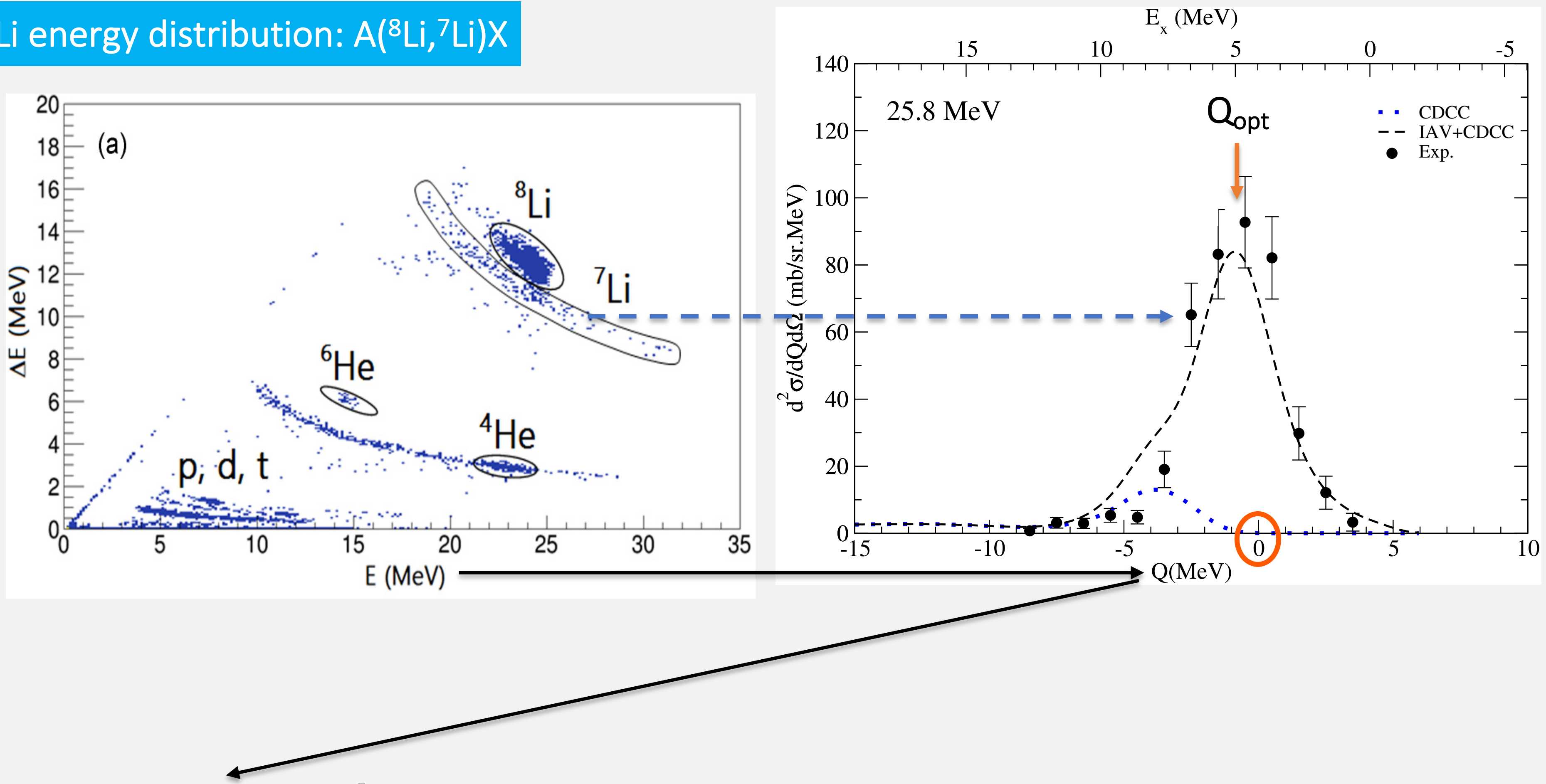
Classical selection rules

Linear momentum of the transfer particle stays constant during the transfer

for nêutron transfers Q_{opt} ~ 0

Q_{opt} shifts to negative values as more and more angular momentum is transfered in the collision

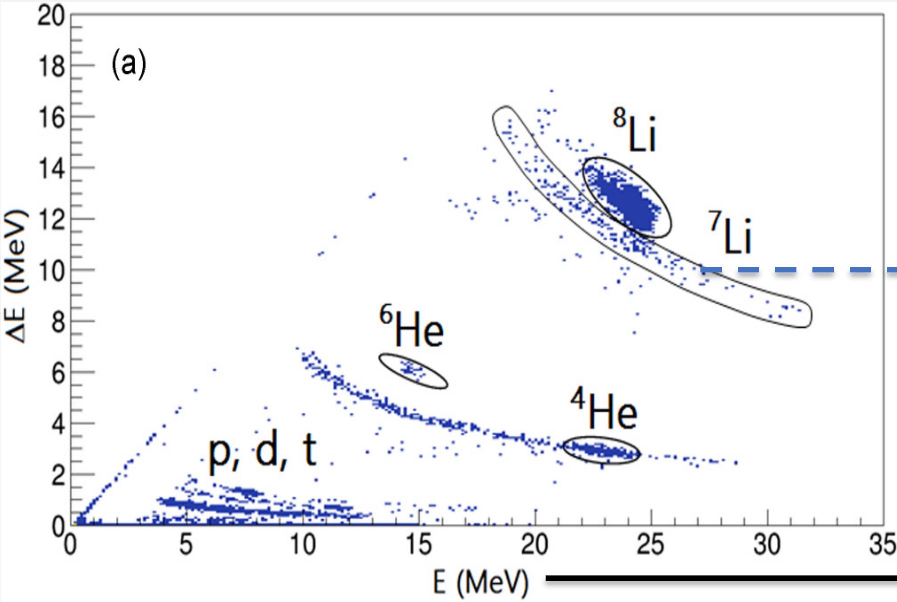
^{7}Li energy distribution: A(^{8}Li,^{7}Li)X

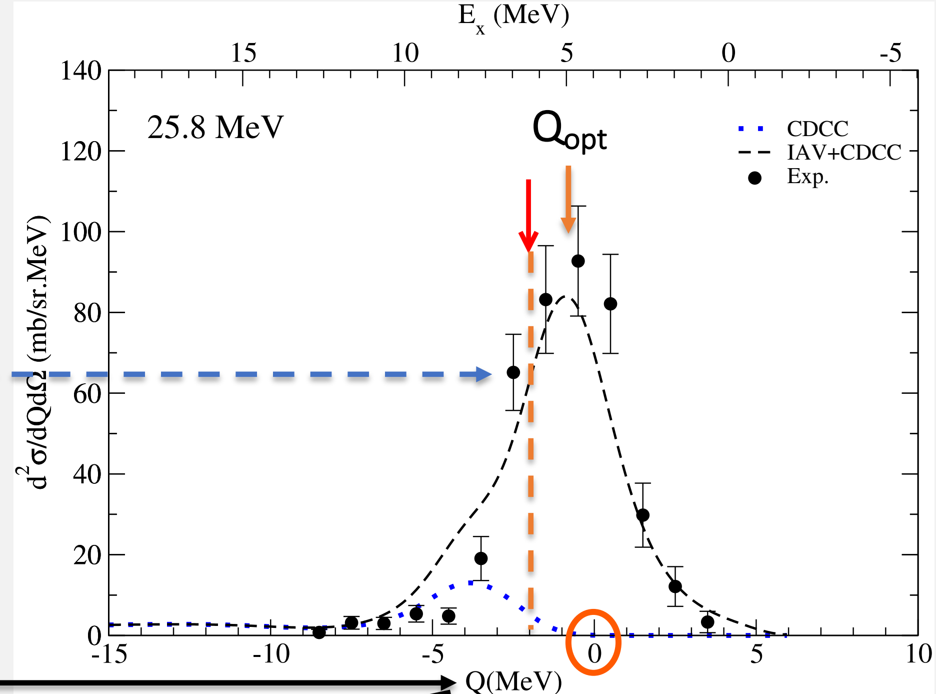


Transformation E_{7Li} → reaction Q-value

using the kinematics of the ^{58}Ni(^{8}Li,^{7}Li)^{59}Ni* reaction

^{7}Li energy distribution: $A(^{8}Li,^{7}Li)X$





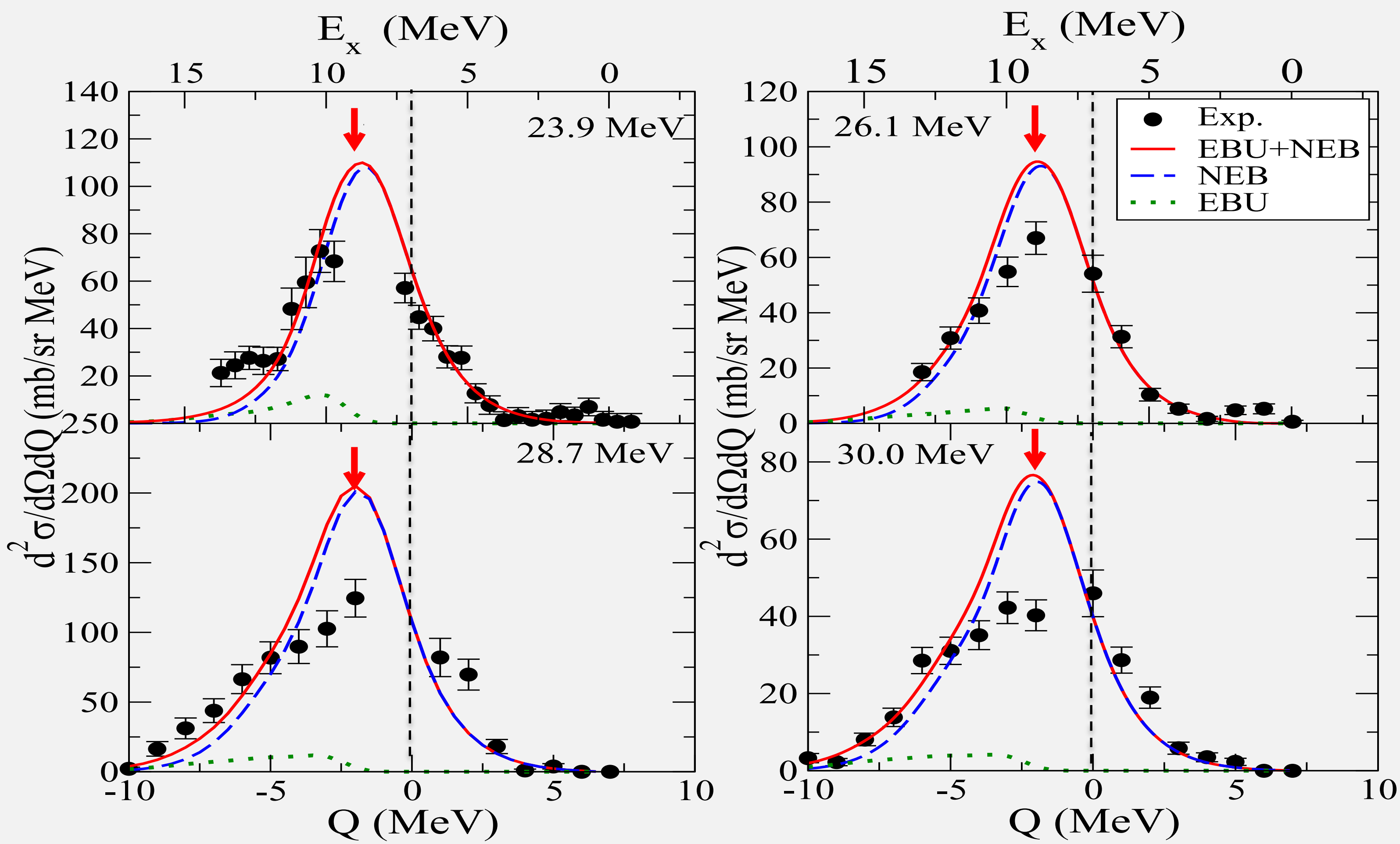
Transformation $E_{7Li} \rightarrow$ reaction Q-value

using the kinematics of the $^{58}Ni(^{8}Li,^{7}Li)^{59}Ni^*$ reaction

Why?
because the E_{7Li} distribution depends on the scattering angle but Q does not.

missing mass spectrum

$^{8}Li + ^{58}Ni$ at 4 energies: energy distributions of ^{7}Li from the $^{58}Ni(^{8}Li,^{7}Li)^{59}Ni^{*}$ reaction



About one-half of the flux goes to bound states (transfer) and one-half to unbound states (breakup)

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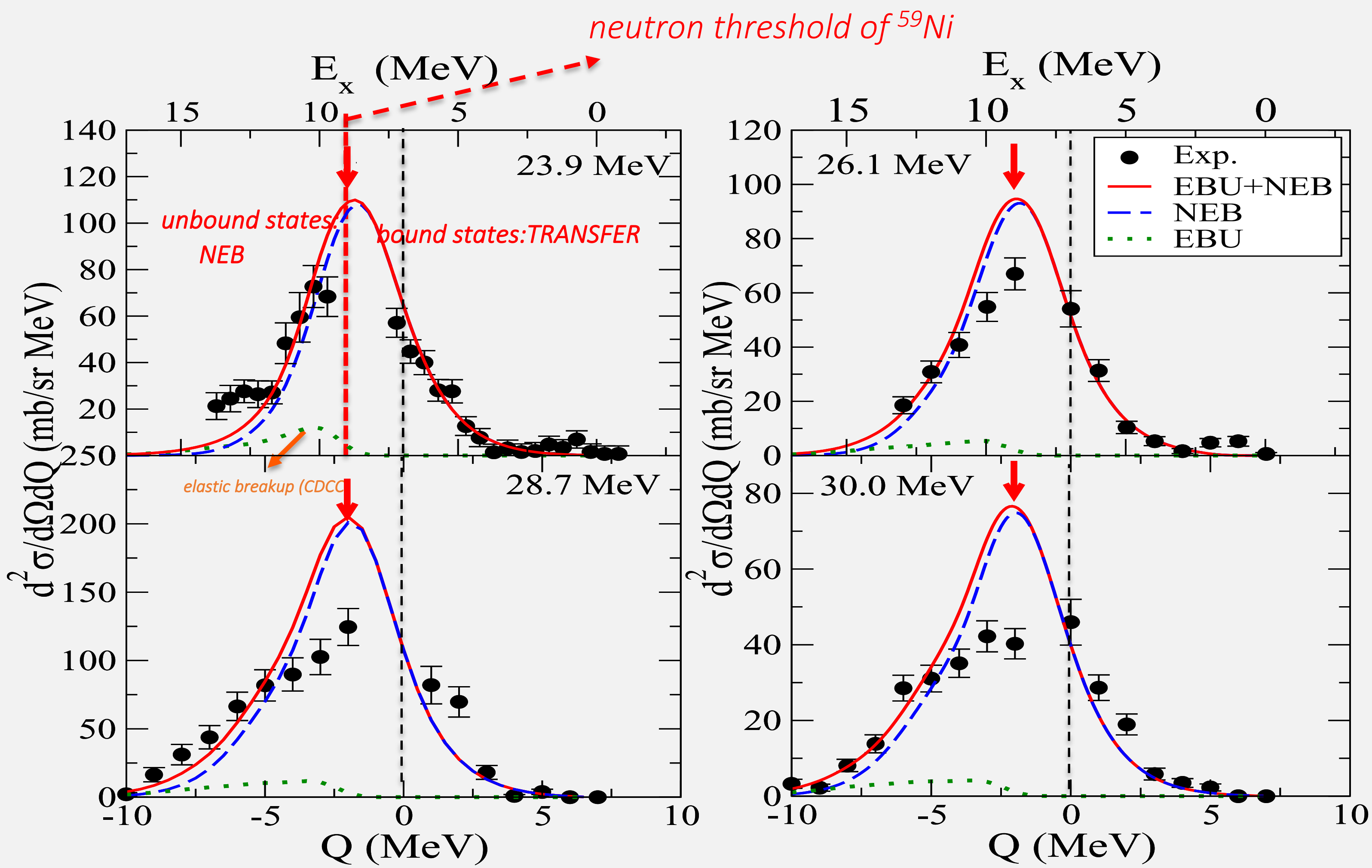

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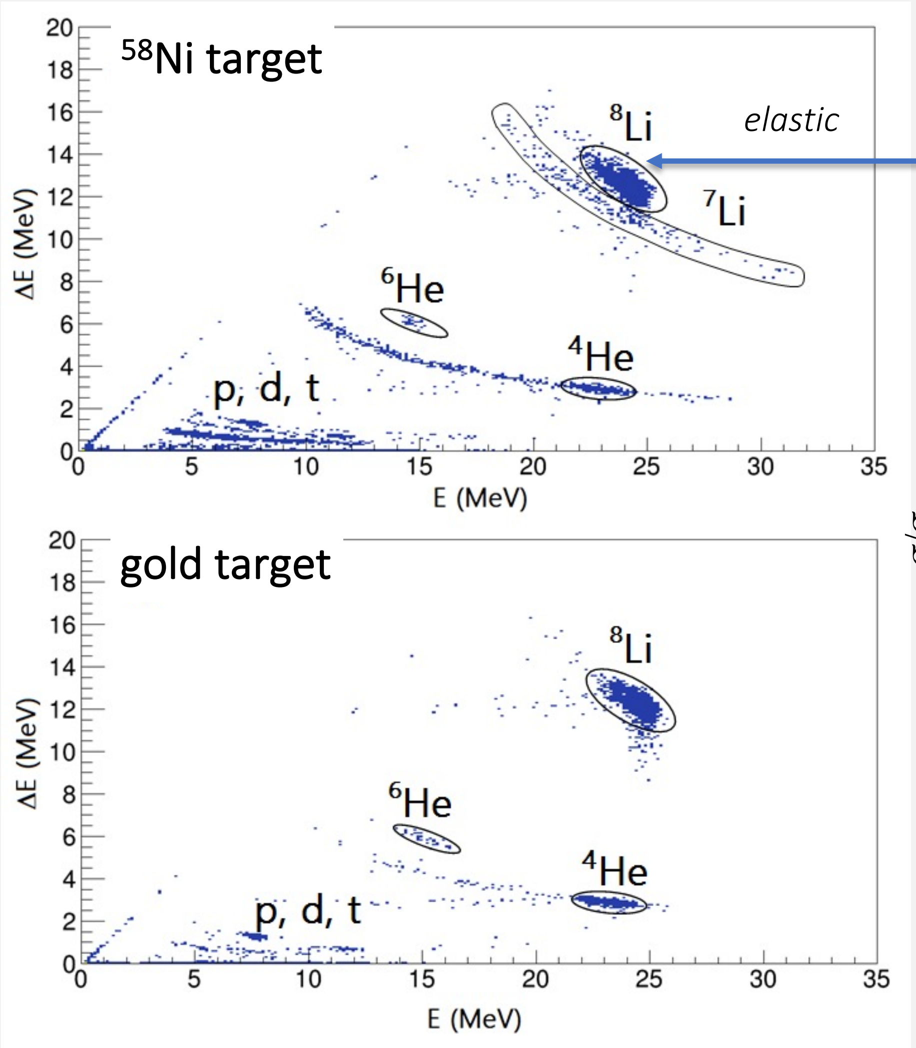
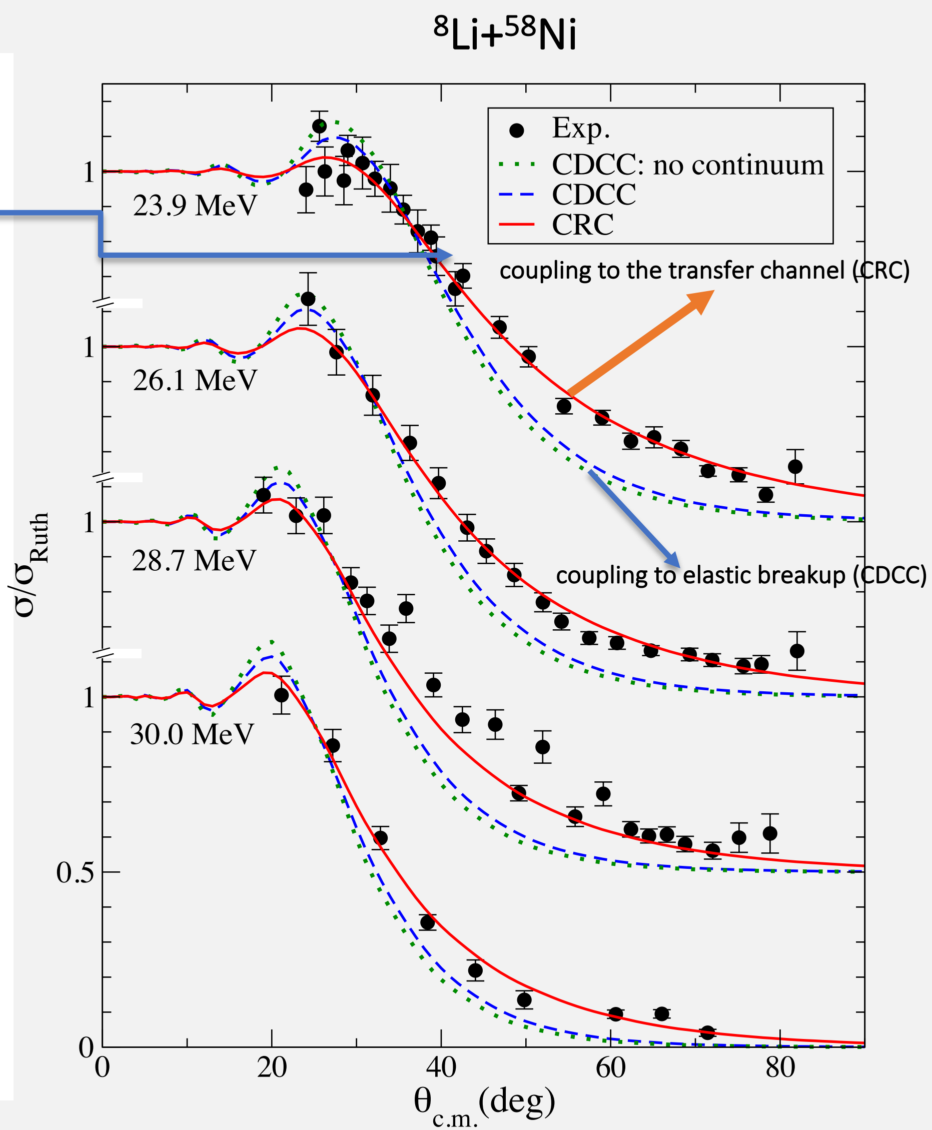
$^{8}Li+^{58}Ni$ elastic scattering





Physical Review C103,064601(2021)
Evidence of Strong stripping channels in the dynamics of the $^{8}Li+^{58}Ni$ reaction
O.C.B. SANTOS et al.

Calculations:

- Optical model for elastic scattering
- Continuum Discretized Coupled Channels (CDCC) for elastic scattering and elastic breakup
- Coupled Reaction Channels (CRC) for elastic scattering and transfer reactions
- Ichimura, Austern, Vincent (IAV) for transfer + breakup (NEB)

PHYSICAL REVIEW C VOLUME 32, NUMBER 2 AUGUST 1985

Equivalence of post and prior sum rules for inclusive breakup reactions

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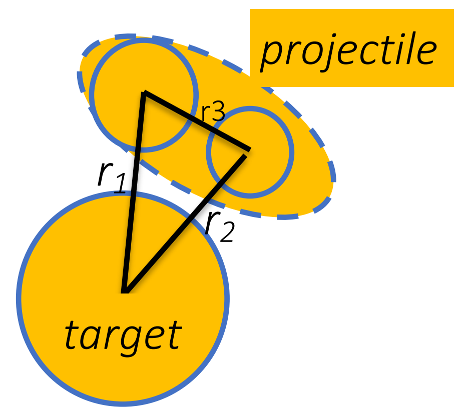
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260

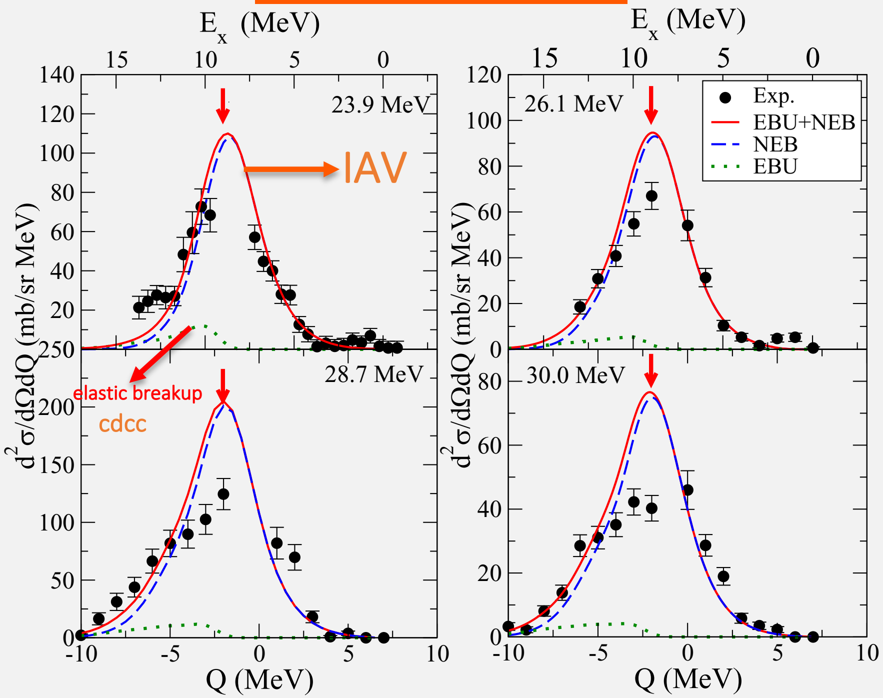


Ingredients: fragment-target optical potentials (V_1 ; V_2)
for CRC → representative excited states and spectroscopic factors
for IAV → the imaginary part of the optical potential between the transfered particle and the target.

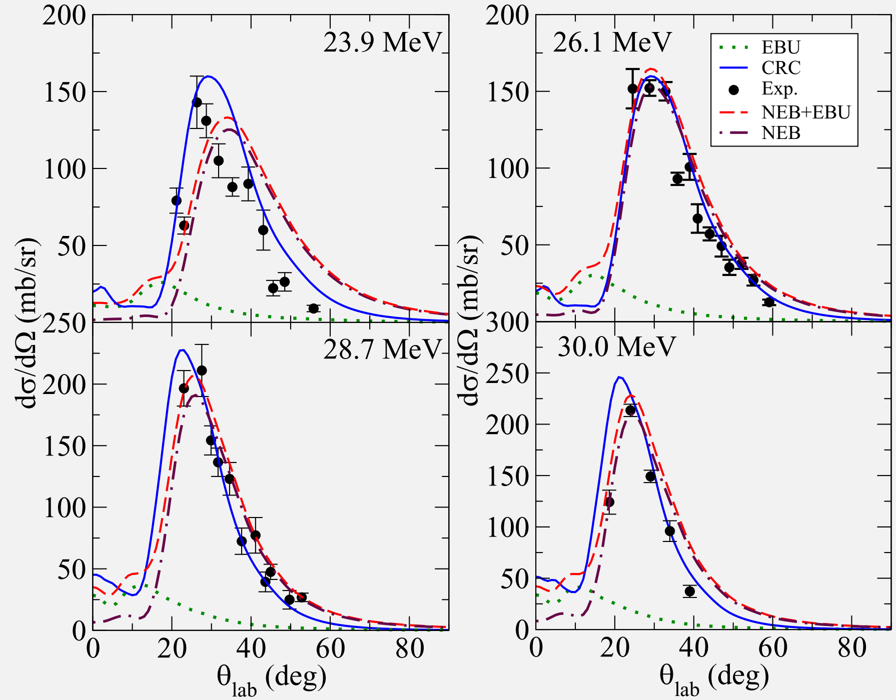
Energy and angular ^{7}Li distributions in the ^{8}Li+^{58}Ni reaction compared with Ichimura, Austern, Vincent (IAV) calculations.

^{58}Ni(^{8}Li,^{7}Li)X

^{7}Li Energy distributions



^{7}Li Angular distributions



No free parameters !

Total BU cross sections →

Energy (MeV)	σ_{reac}^{CRC} (mb)	$\sigma_{reac}^{OM\text{-}fit}$ (mb)	σ_{bu}^{CRC} (mb)	$\sigma_{bu}^{NEB+EBU}$ (mb)	σ_{bu}^{NEB} (mb)
23.9	1354	1194	244	291	262
26.1	1484	1322	242	290	261
28.7	1606	1446	236	284	255
30.0	1657	1500	233	281	252

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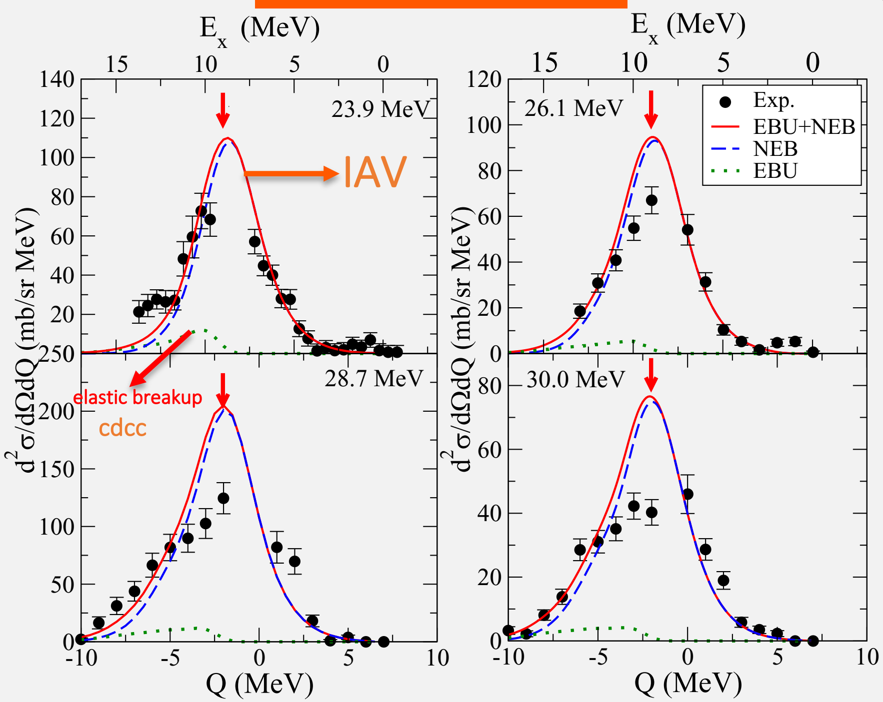

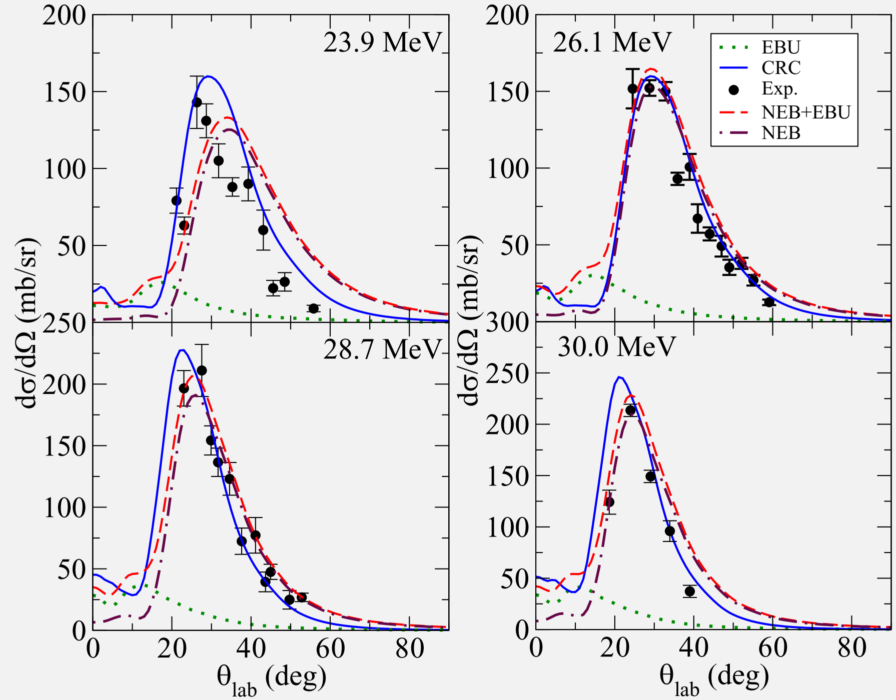

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Light target ^8Li + ^9Be: $\underline{^9Be}(^8Li,^7Li)^{10}Be$

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THE EUROPEAN PHYSICAL JOURNAL A
Regular Article - Experimental Physics

One-neutron stripping from ^8Li projectiles to ^9Be target nuclei

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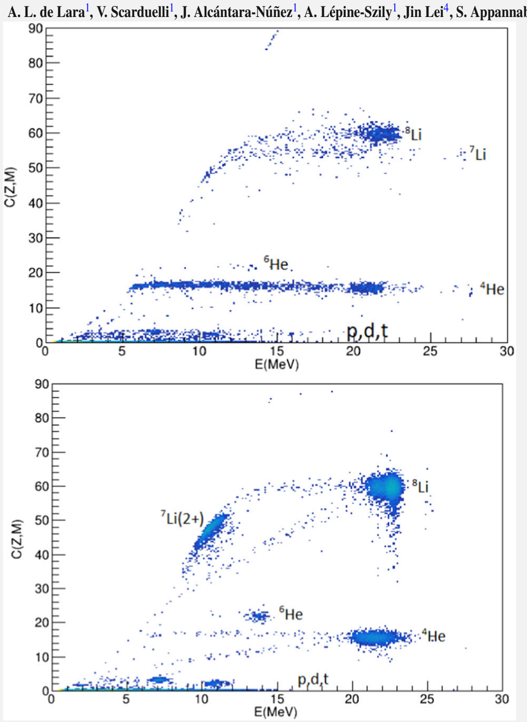
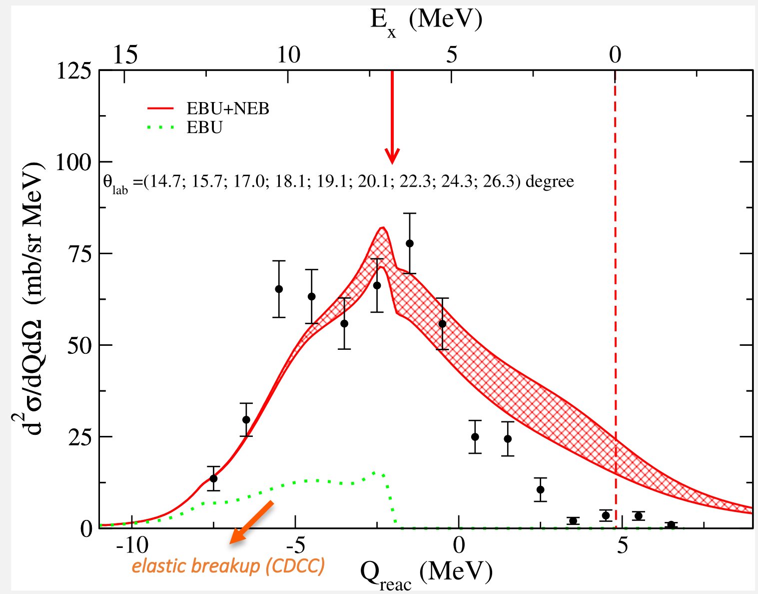
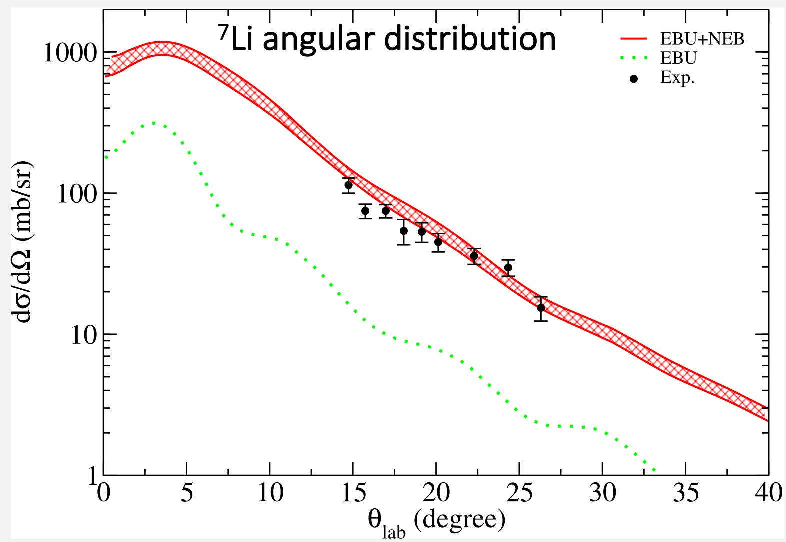


TRCS=1440 mb
Total-Bu-cs=130 mb

Elastic breakup gives small contribution

^7Li energy distribution





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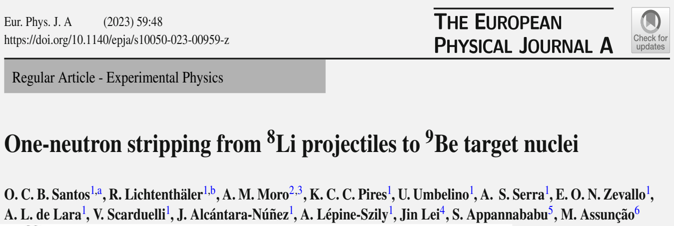
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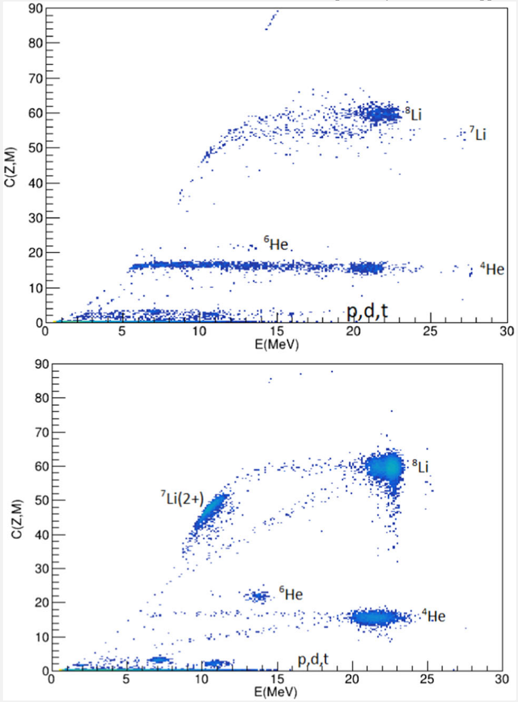

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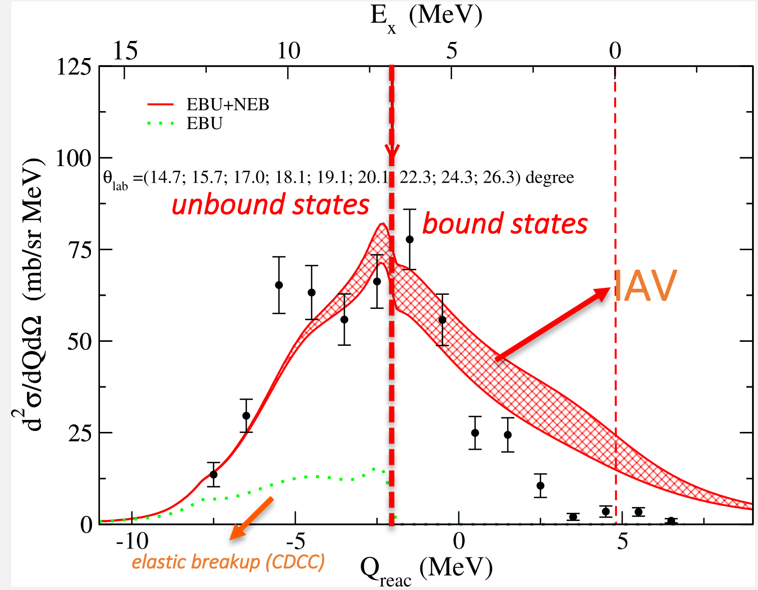
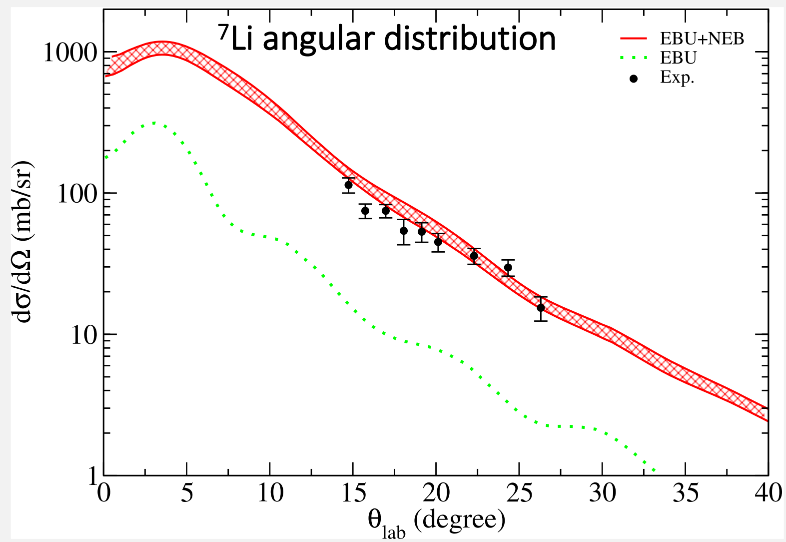
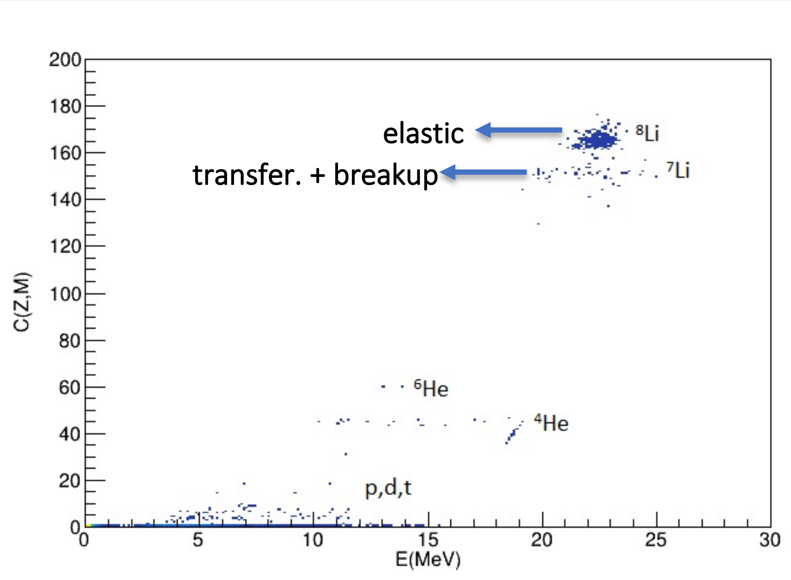
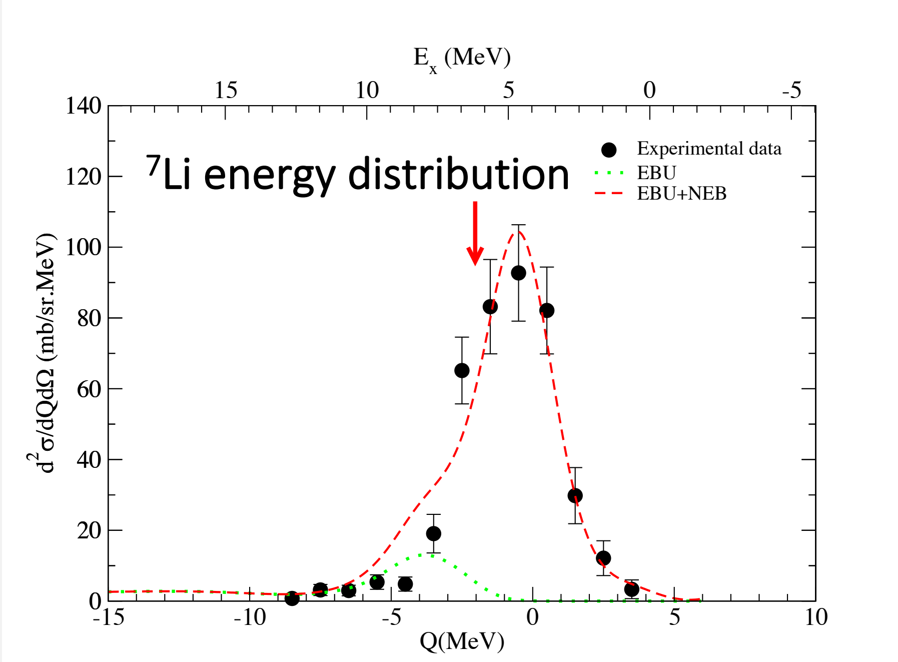




^{8}Li on a heavy target: ^{120}Sn(^{8}Li,^{7}Li)^{121}Sn





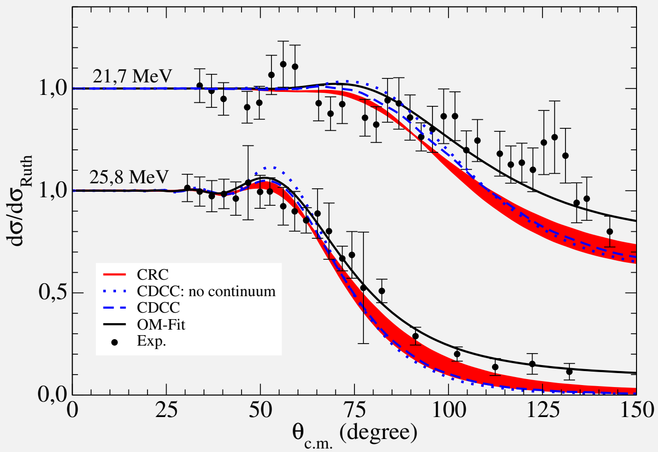
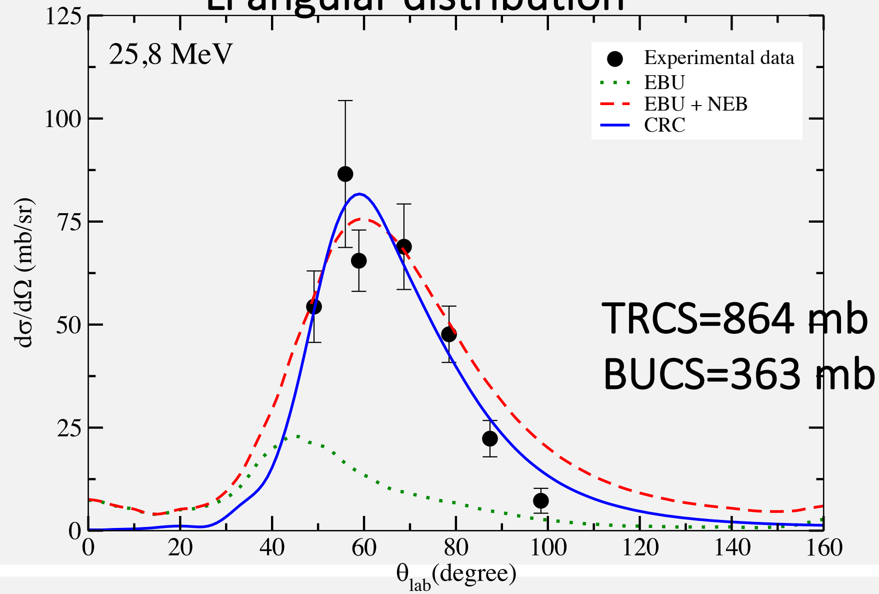


FIG. 2. ^{8}Li + ^{120}Sn experimental elastic scattering angular distributions compared with the CDCC no-continuum (dotted blue line), full CDCC (dashed blue line), CRC (solid red line), and OM-Fit (solid black line).

^{7}Li angular distribution



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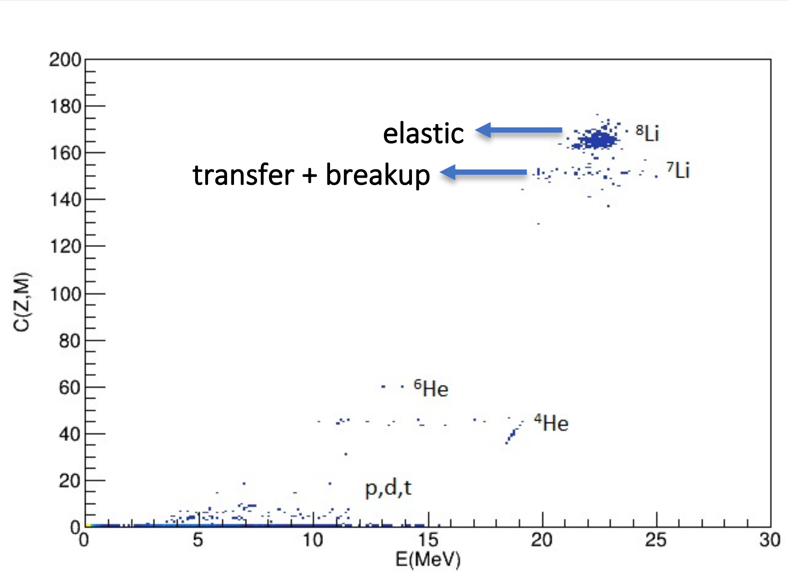

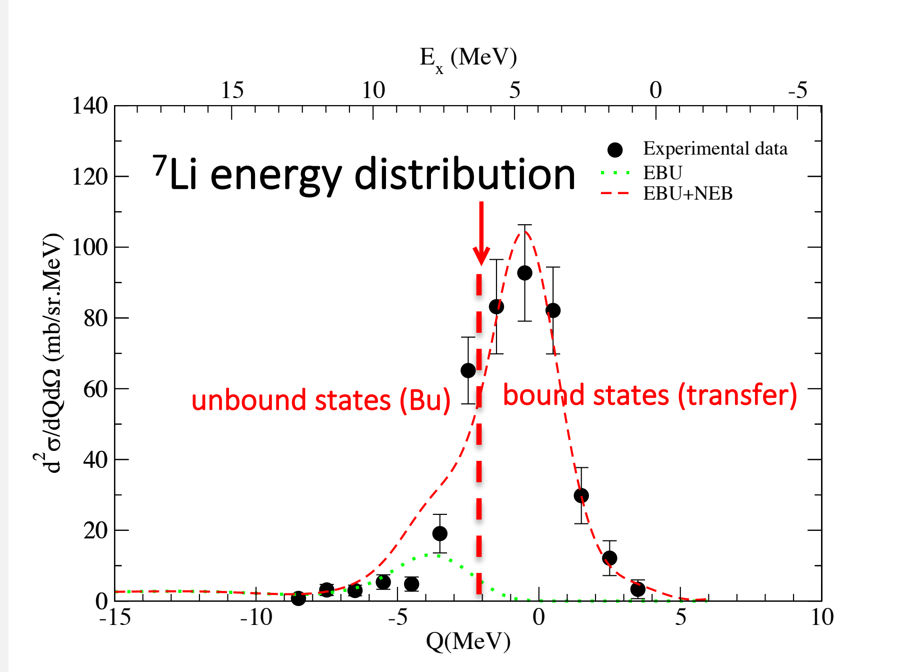

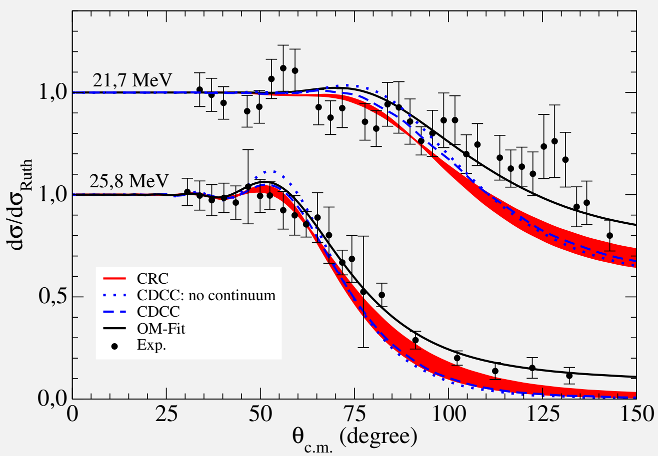

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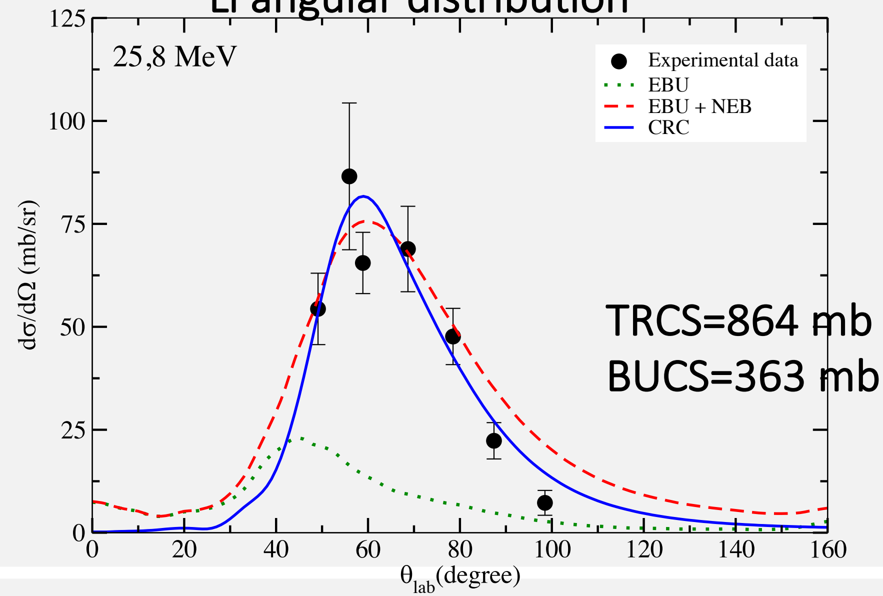


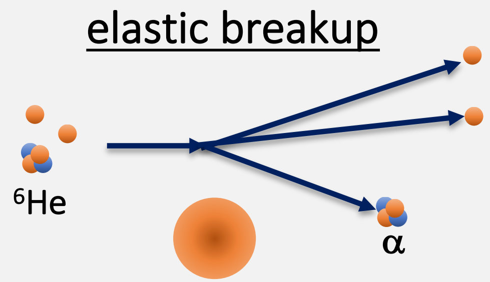
Numerical results for ^{8}Li + ^{9}Be ; ^{58}Ni and ^{120}Sn targets

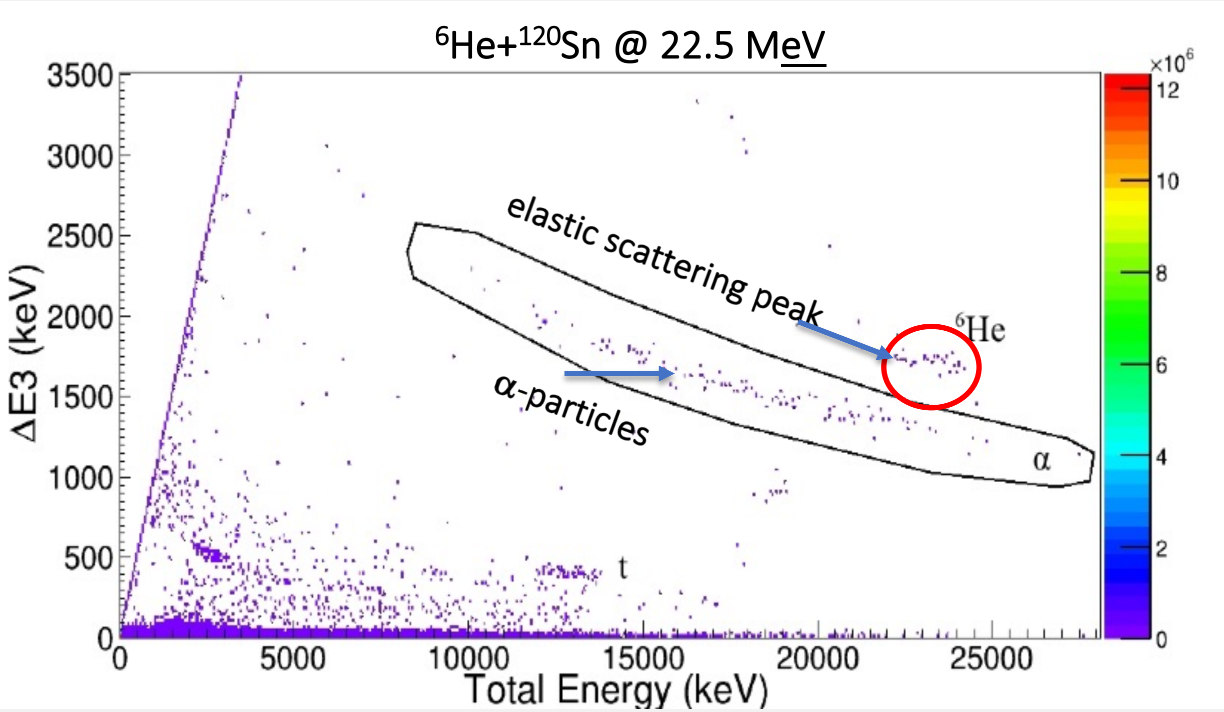
TABLE III. Total (angle integrated) breakup cross sections (σ_{bu}) and total reaction cross section for ^{8}Li on ^{9}Be [1], ^{58}Ni [2], and ^{120}Sn targets.

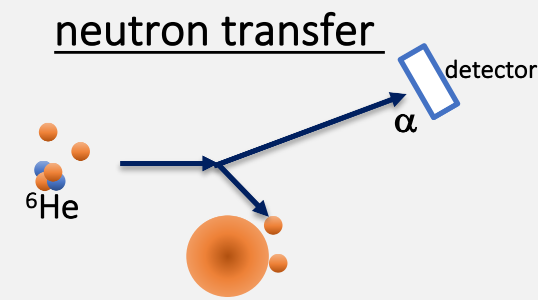
System	E_{Lab} (MeV)	σ_{bu}^{CRC} (mb)	$\sigma_{bu}^{IAV+CDCC}$ (mb)	$\sigma_{reac.}^{OM}$ (mb)	$\sigma_{reac.}^{CRC}$ (mb)	$\sigma_{bu}/\sigma_{reac}$	E/Vb
^{8}Li+^{9}Be	23.8	-	124(5)	1440	-	0.0861(35)	**6.76**
^{8}Li+^{58}Ni	23.9	244	291	1194	1354	0.210(23)	**1.76**
^{8}Li+^{58}Ni	26.1	242	290	1322	1484	0.190(20)	**1.93**
^{8}Li+^{58}Ni	28.7	236	284	1446	1606	0.170(18)	**2.112**
^{8}Li+^{58}Ni	30.0	233	281	1500	1657	0.163(17)	**2.21**
^{8}Li+^{120}Sn	21.7	267(6)	271	316	565(11)	0.842(16)	**1.06**
^{8}Li+^{120}Sn	25.8	291(4)	325	816	1077(25)	0.375(26)	**1.26**

Alpha particle production in ^{6}He induced reactions

Large alpha particle yield observed in ^{6}He +^{120}Sn collision
- breakup or neutron transfer reactions?







Possible processes:

X=n+n+^{120}Sn; elastic breakup

X=n+^{121}Sn*; 1 nêutron transfer

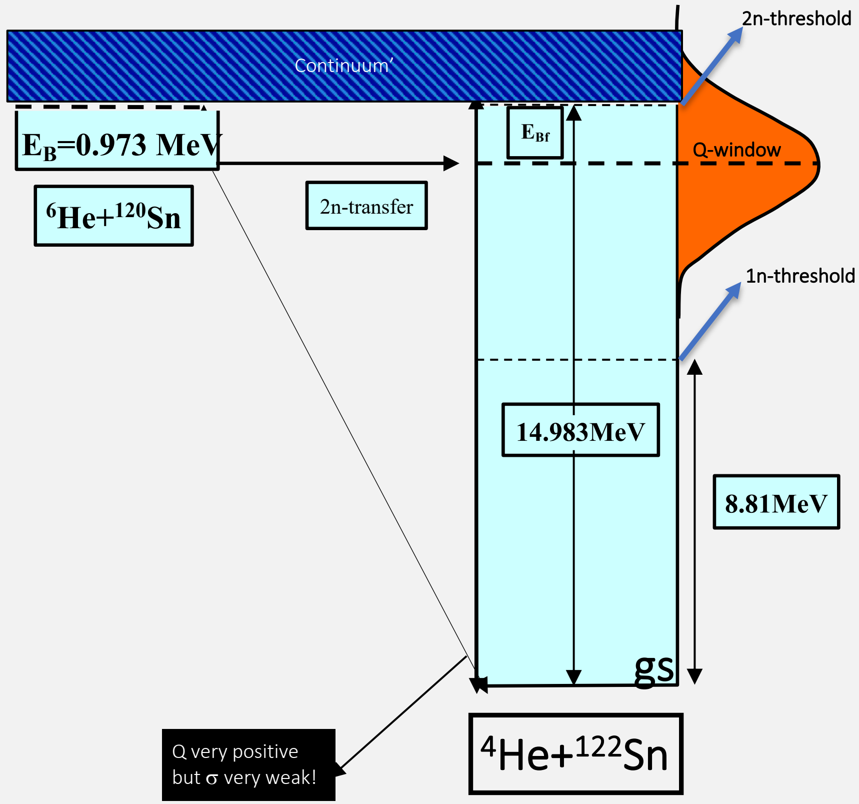
X=^{122}Sn* ; 2 nêutron transfer

X=^{126}Te* → α complete fusion
n
p
.
.

Is it possible to distinguish between different processes just by detecting the alpha-particle distributions?

$^{120}Sn(^{6}He,\alpha)X$ breakup or transfer?

The transfer process is very selective in terms of the excitation energies in the final nucleus. It will favour transfer to states around the optimum-Q_{value} which is determined by momentum matching condidtions (*Brink, 1972*). In particular, for nêutron transfers, the optimum Q-value Is located **around Q~0.**



Two-neutron transfer in the ^{6}He + ^{120}Sn reaction

S. Appannababu,[1,*] R. Lichtenthäler,[1] M. A. G. Alvarez,[2] M. Rodríguez-Gallardo,[2] A. Lépine-Szily,[1] K. C. C. Pires,[1]

PHYSICAL REVIEW C **99**, 014601 (2019)

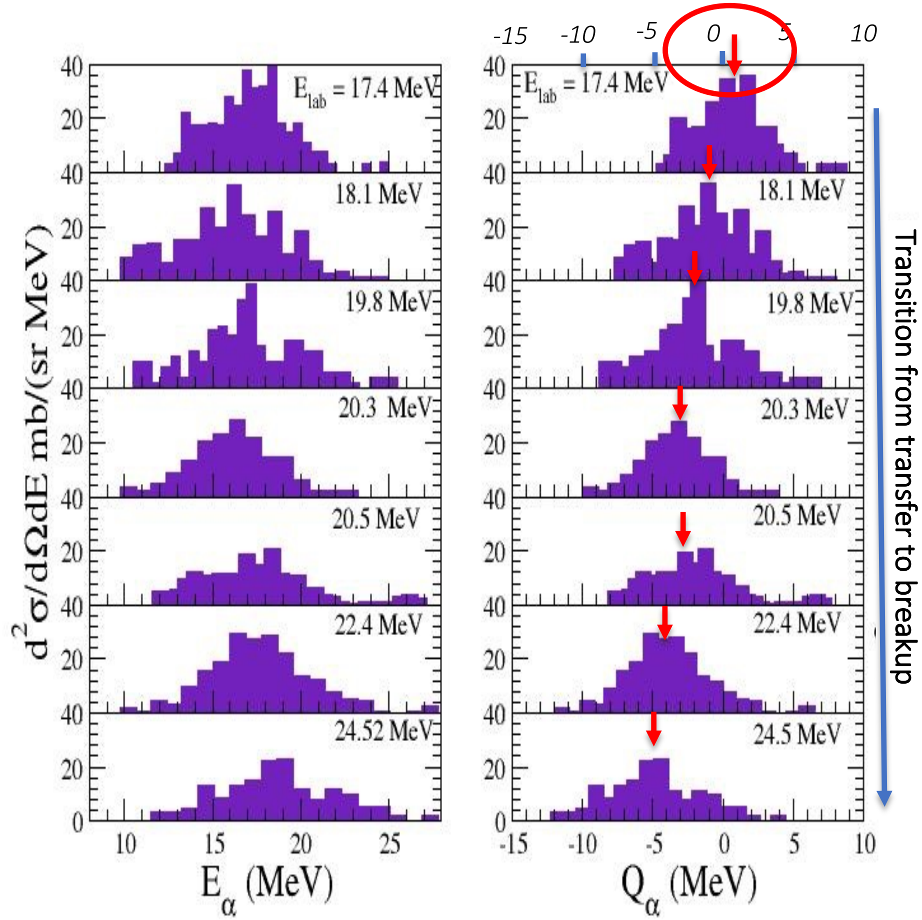
Q-optimum considerations
linear and angular momentum matching conditions

Qopt≈0 for neutron transfer

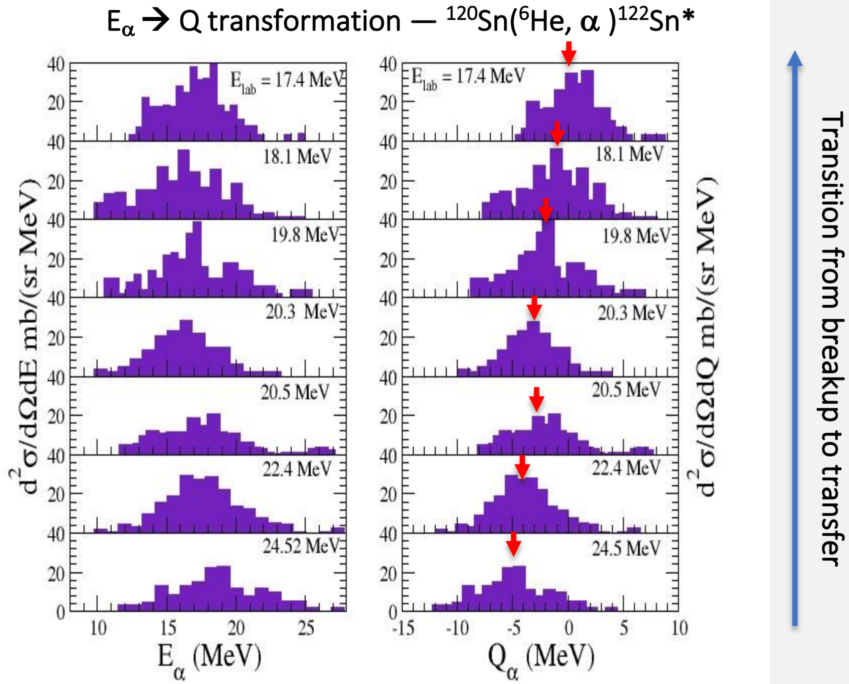
D. M. Brink, PLB v.40, pg 37 (1972)

Alpha-particle energy distributions @ 60 deg

$E_\alpha \rightarrow$ Q transformation — $^{120}Sn(^{6}He,\alpha)^{122}Sn^*$



Alpha-particle energy distributions @ 60 deg



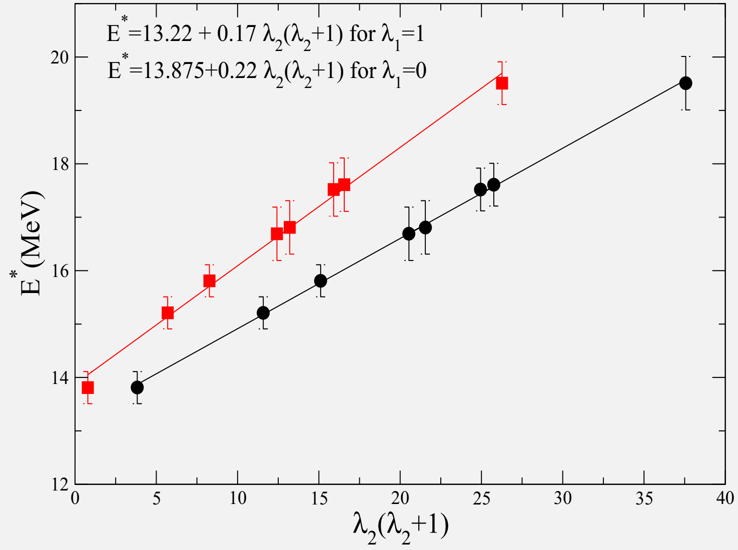
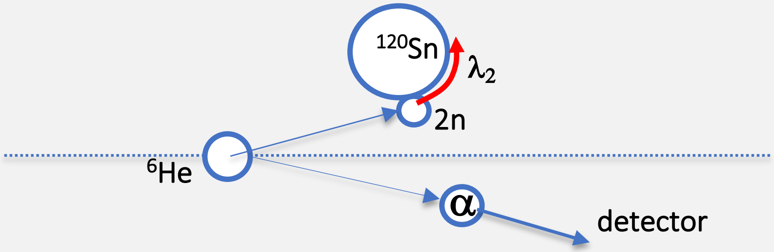


FIG. 7. Excitation energy of the final nucleus as a function of the square of the angular momentum in the final nucleus for $\lambda_1 = 1$ (dots) and $\lambda_1 = 0$ (squares). The solid line is a linear fit (see text).



The present results show, for $\lambda_1 = 1$ (dots), a linear relation between the excitation energy of the recoil nuclei and its angular momentum square $\lambda_2(\lambda_2 + 1)$. This seems to behave as a typical rotational band with $K = 13.22$ MeV and a slope $\hbar^2/(2I) = 0.17$ MeV which is very close to that expected for a rotating $2n$-^{120}Sn system with a moment of inertia $I = \mu R^2$ where μ is the reduced mass of the ^{120}Sn-$2n$ dinuclear system and $R = 1.2(120^{1/3} + 2^{1/3})$ fm.

The present results indicate that the experimental α-energy distributions are consistent with the formation of composite $2n$-^{120}Sn rotating system driven by the momentum of the transferred particle ($2n$).

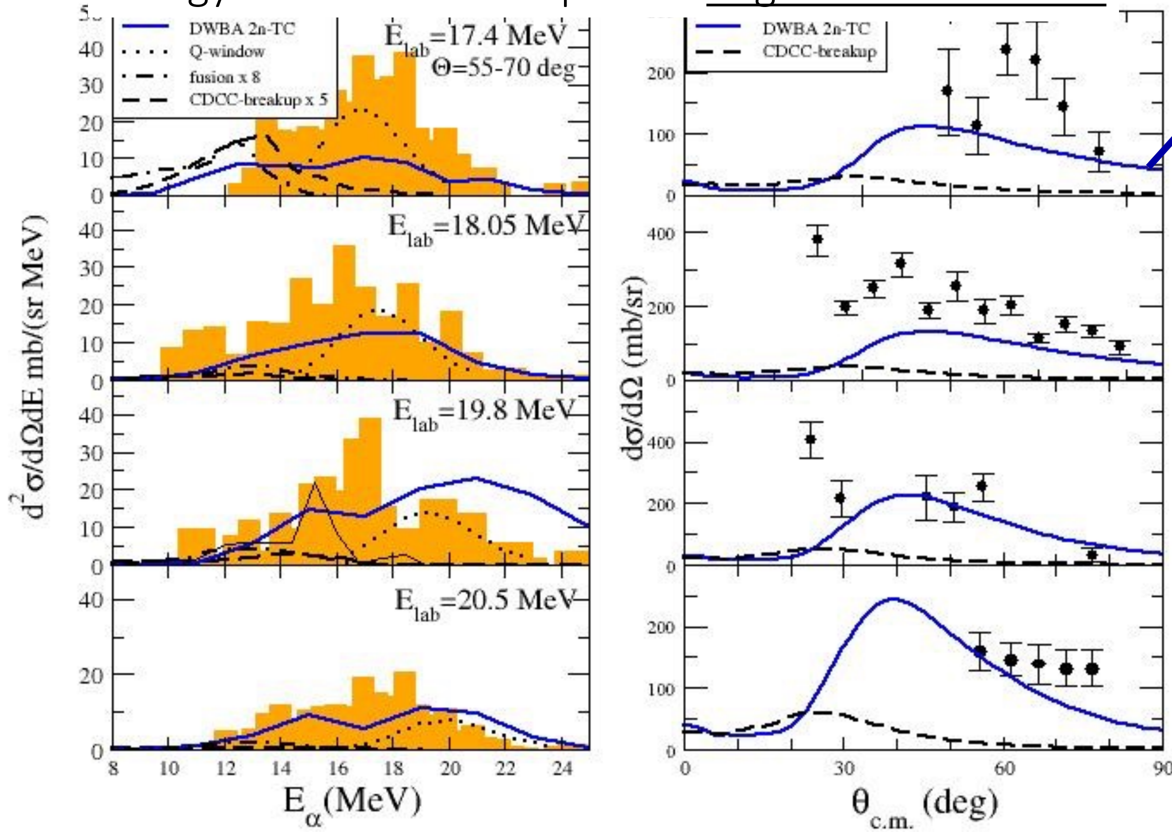
Two-neutron transfer in the ^{6}He + ^{120}Sn reaction

S. Appannababu,[1,*] R. Lichtenthäler,[1] M. A. G. Alvarez,[2] M. Rodríguez-Gallardo,[2] A. Lépine-Szily,[1] K. C. C. Pires,[1]

PHYSICAL REVIEW C **99**, 014601 (2019)

Alpha particles from the $^{6}He+^{120}Sn$ collision: DWBA for the angular distributions

energy distribution of alphas angular distributions



- *P. N. de Faria et. al, Phys. Rev. C 82, 034602 (2010)*

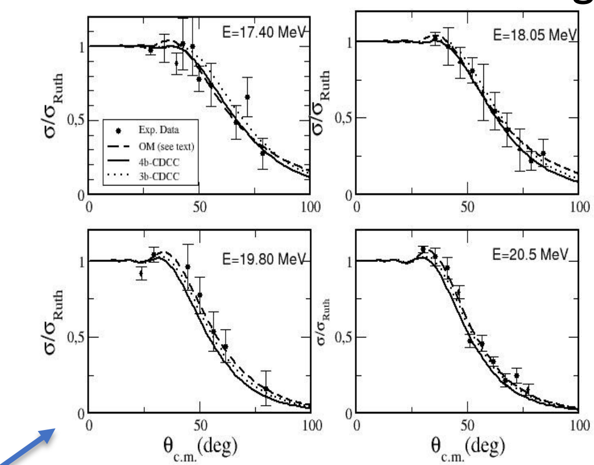
total alpha-cross section

650 mb

Total reaction cross section: 1300-1500 mb

DWBA 2n-transfer to continuum and bound states (calculations by A. Moro)

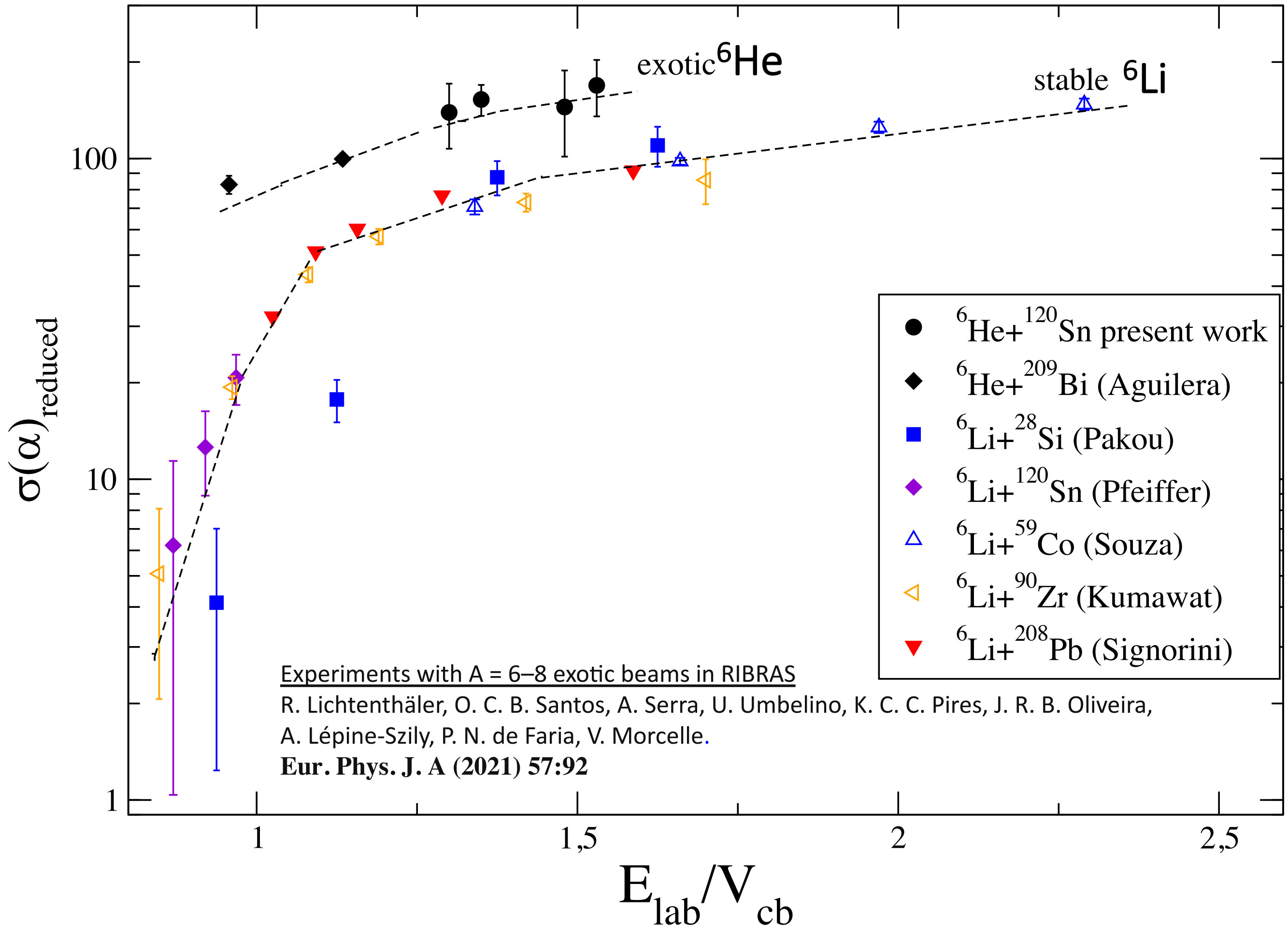
$^{6}He+^{120}Sn$ elastic scattering



CDCC is reproduces very well the $^{6}He+^{120}Sn$ angular distributions (elastic scattering) but not the large alpha particle yields observed in the $^{120}Sn(^{6}He,\alpha)X$ reaction.
CDCC description does not provide a complete description of the problem.

Comparison between alpha-particles production induced by ^{6}He and ^{6}Li reactions.

Alpha particle production cross section in ^{6}He and ^{6}Li induced reactions



Breakup for More exotic projectiles $^{11}Li + ^{208}Pb$

PRL **110,** 142701 (2013) PHYSICAL REVIEW LETTERS week ending 5 APRIL 2013

^{11}Li Breakup on ^{208}Pb at Energies Around the Coulomb Barrier

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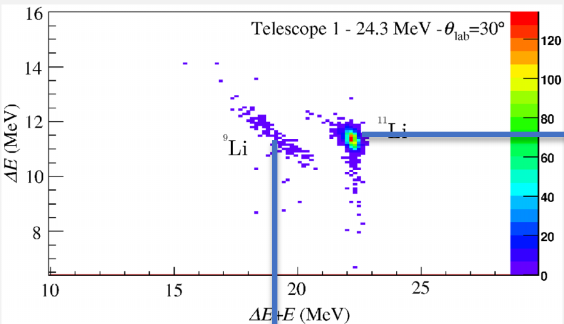
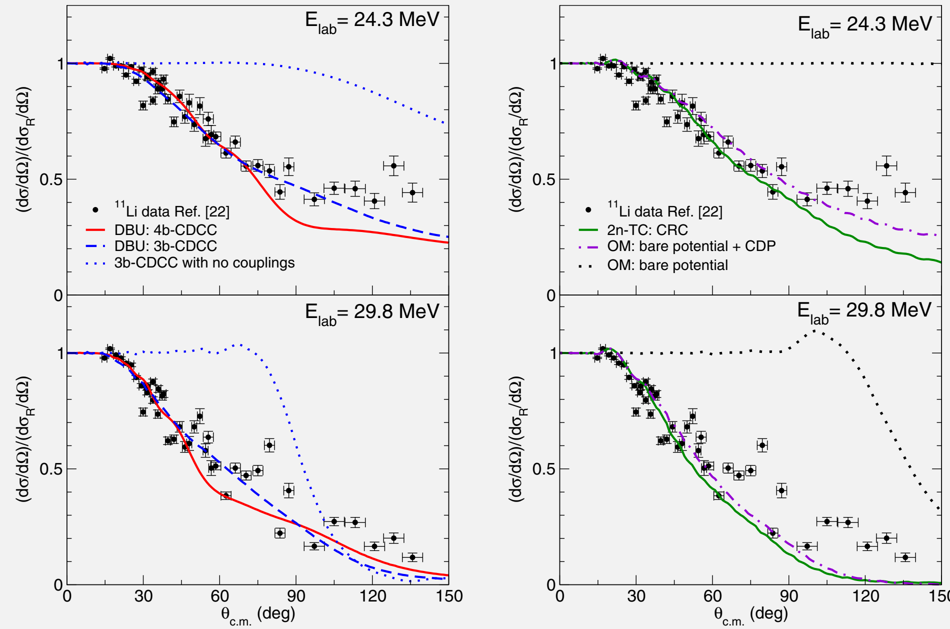




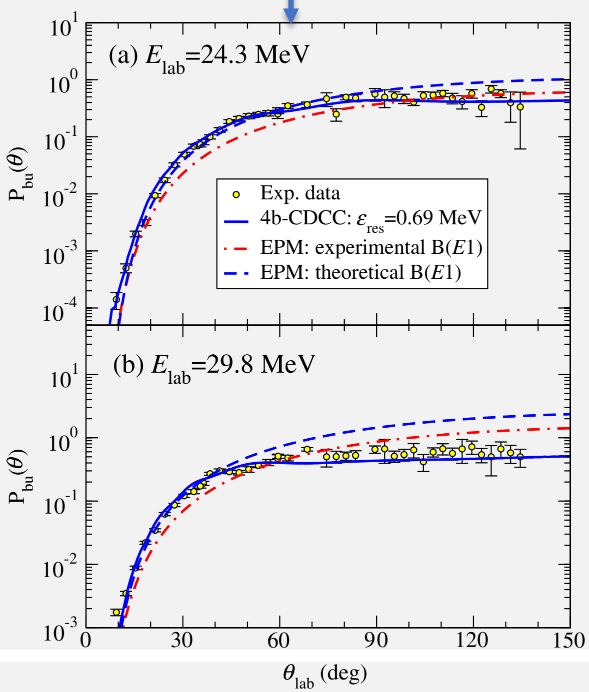


TABLE II. Comparison of the experimental total reaction cross section (σ_{reac}) and breakup cross section (σ_{BU}) with the DBU, 2n-TC and 1n-TC mechanisms. The experimental reaction cross sections are obtained from the optical model fit to the elastic differential cross sections (see text for details).

24.3 MeV	Exp. (mb)	DBU(4b-CDCC) (mb)	2n-TC (CRC) (mb)	1n-TC (CRC) (mb)
σ_{reac}	5400	6500	5500	5600
σ_{BU}	5100	4200	780	940
29.8 MeV	Exp. (mb)	DBU(4b-CDCC) (mb)	2n-TC (CRC) (mb)	1n-TC (CRC) (mb)
σ_{reac}	7800	8400	7100	7900
σ_{BU}	6500	5400	1100	1000

$^{11}Be + ^{208}Pb$ breakup @ 140 MeV

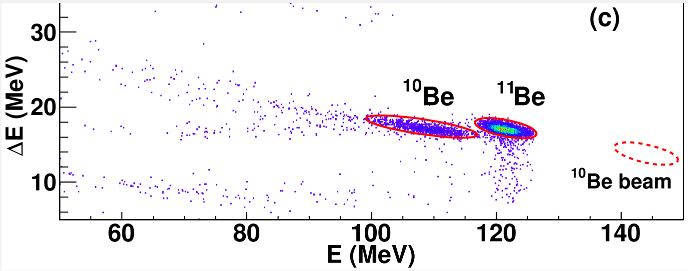
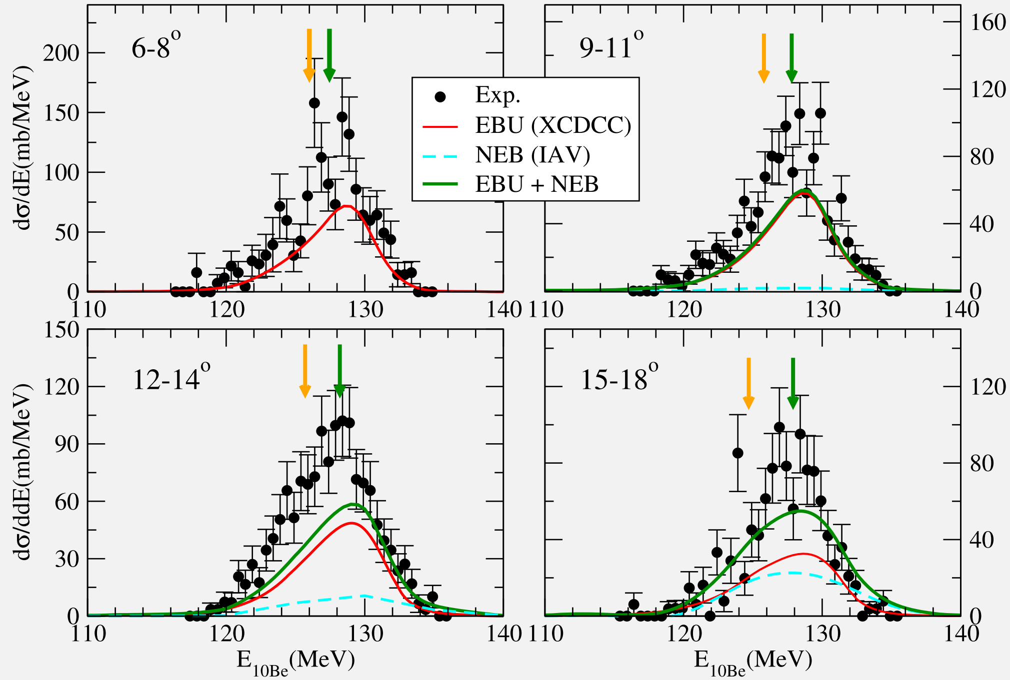
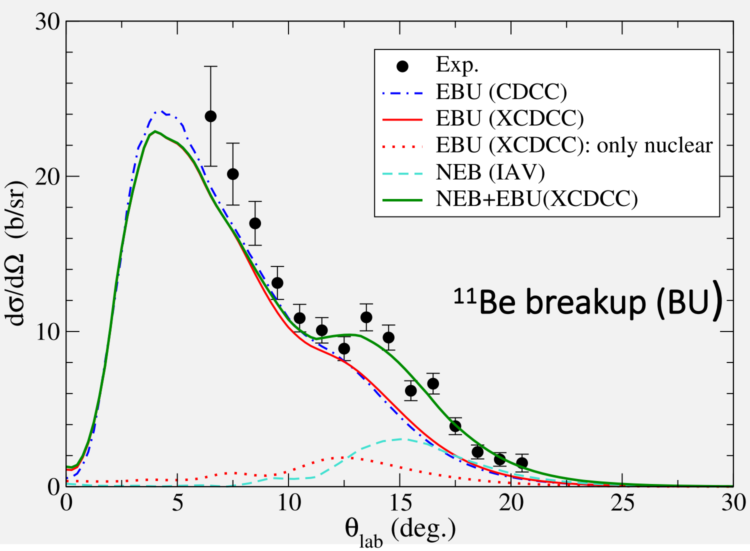


Fig. 2. The two-dimensional $\Delta E - E$ particle identification spectra for the (a) ^{9}Be, (b) ^{10}Be and (c) ^{11}Be beams within all the angles covered by the current measurement. In (c), the expected loci of ^{10}Be beam contamination are indicated and it is well separated from the group of ^{10}Be breakup fragment particles.

^{10}Be energy distribution



^{10}Be angular distribution



Physics Letters B 811 (2020) 135942

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Scattering of the halo nucleus ^{11}Be from a lead target at 3.5 times the Coulomb barrier energy

RIBLL Collaboration

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Total Bu cross –section ~ 3632 mb

Total reaction cross sections is 7798 mb ^{11}Be.

$^{8}B + ^{208}Pb$ breakup @ 238 MeV

PHYSICAL REVIEW C **103**, 024606 (2021)

Elastic scattering and breakup reactions of the proton drip-line nucleus ^{8}B on ^{208}Pb at 238 MeV

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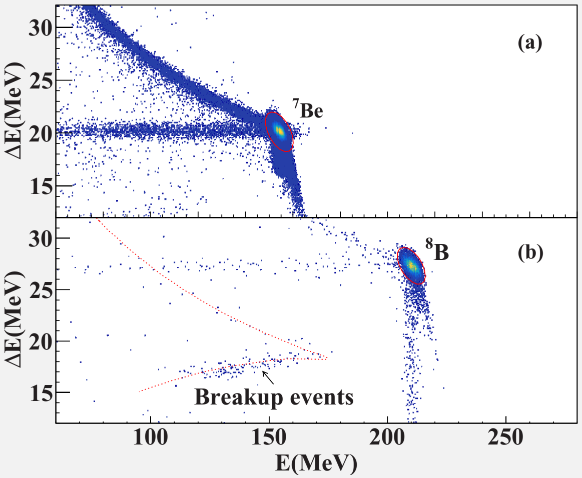
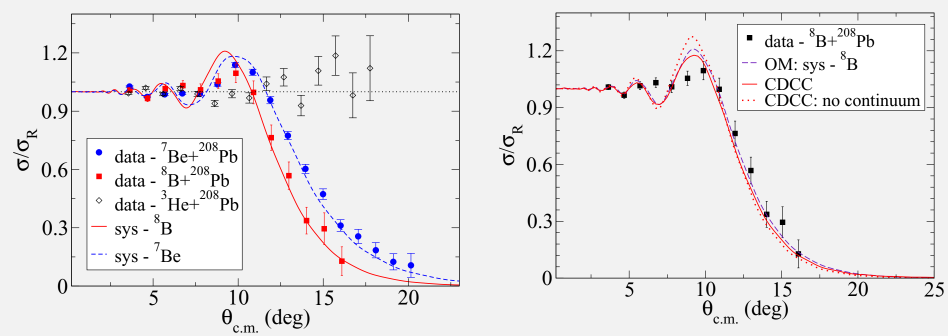
(RIBLL Collaboration)





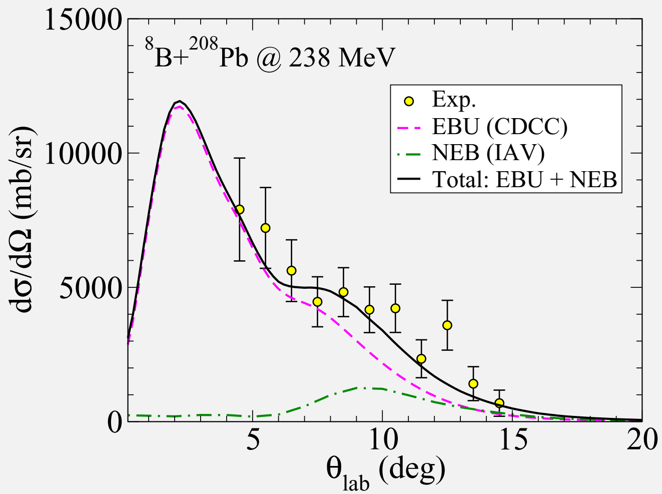


FIG. 5. Experimental ^{7}Be angular distributions from the $^{8}B + ^{208}Pb$ reaction at $E_{lab} =$ 238 MeV (yellow circle) and comparisons with calculations. Error bars are statistical only.

<u>dominance of EBU @ 238 MeV</u>

779 mb BU cross-section

Total reaction CS = 3423 mb

Conclusions:

- The fragments energy and angular distributions in ^{8}Li reactions indicate that the dominant process at low energies is the nêutron transfer/non-elastic breakup (NEB) rather than elastic breakup. Elastic breakup seems to give a minor contribution at low energies.

- The transfered particle (nêutron) interacts strongly with the target, exciting the recoil system over a wide excitation energy range from bound to unbound states with a maximum cross-section below the nêutron threshold. The fragments energy distributions are well described by IAV calculations and momentum matching conditions as predicted by Q-optimum calculations.

- The coupling between the transfer and the elastic channels explain the backward rise observed in the ^{8}Li+target elastic scattering angular distributions.

- For ^{6}He projectiles, it seems that there is a transition from transfer (or NEB) to elastic breakup as the beam energy increases.

- The total breakup cross section increases relatively to the total reaction cross section for lower energies, in some cases, reaching almost 100% of the total reaction cross section.

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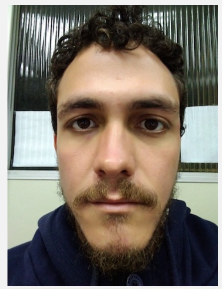



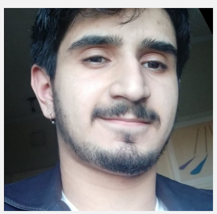




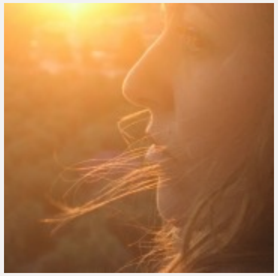

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and José Roberto Brandão de Oliveira from IFUSP

Thank you!