Understanding low energy reactions with exotic nuclei

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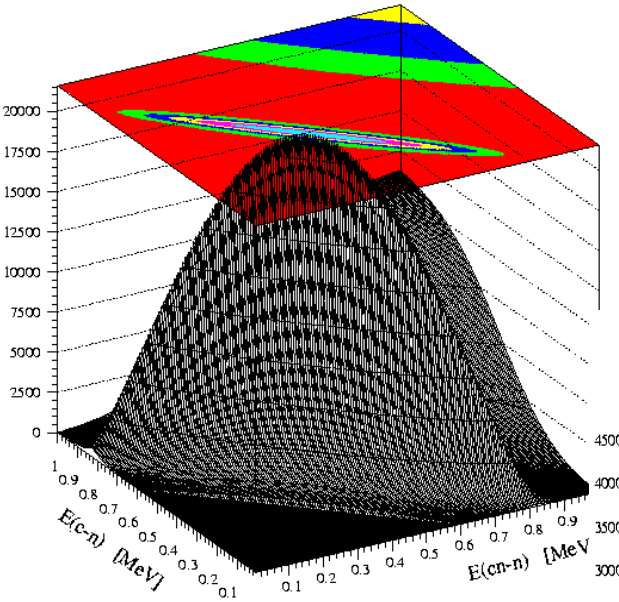
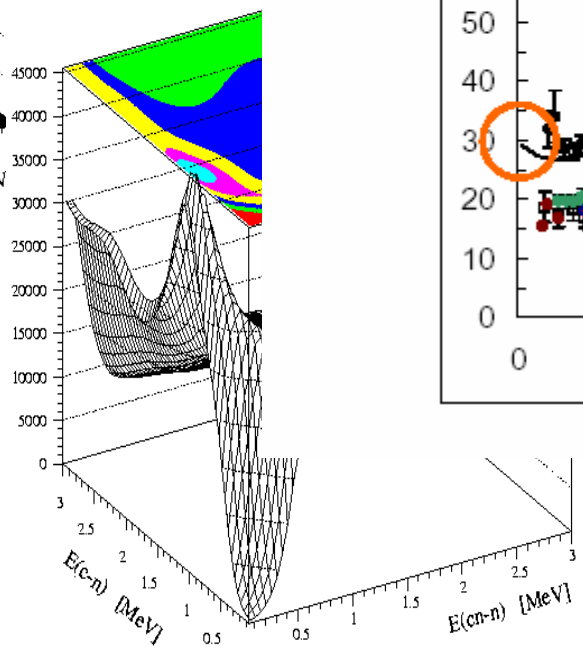
Motivation for Reactions at low energy



^{6}He 2$^+$ resonance

Structure

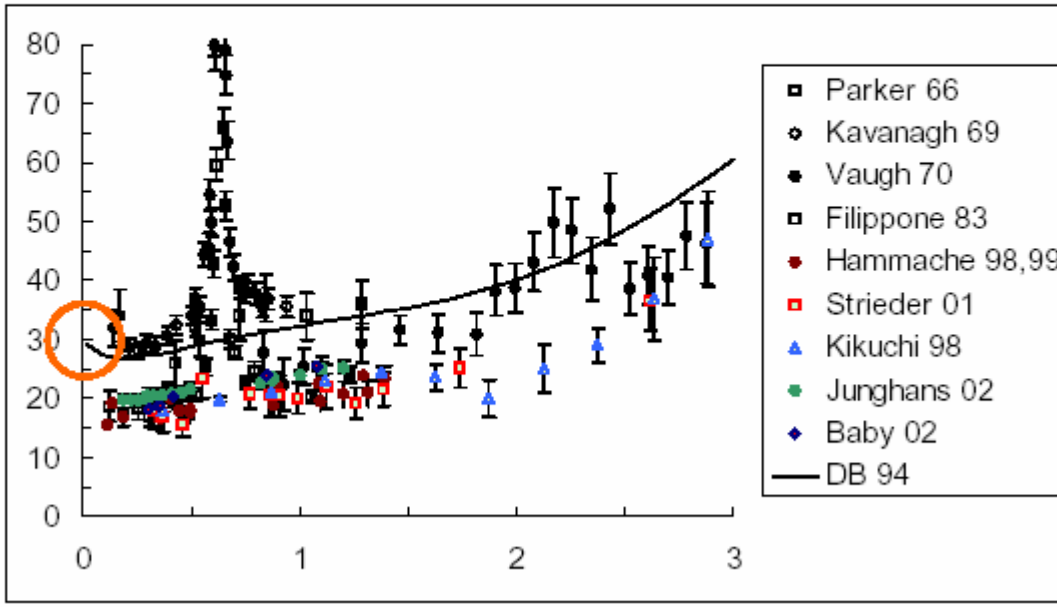
[I.J. Thompson, NSCL 2004]



^{6}He no 1$^-$ resonance

Astrophysics

^{7}Be(p,γ)^{8}B reaction



[D. Baye, Trento 2004]

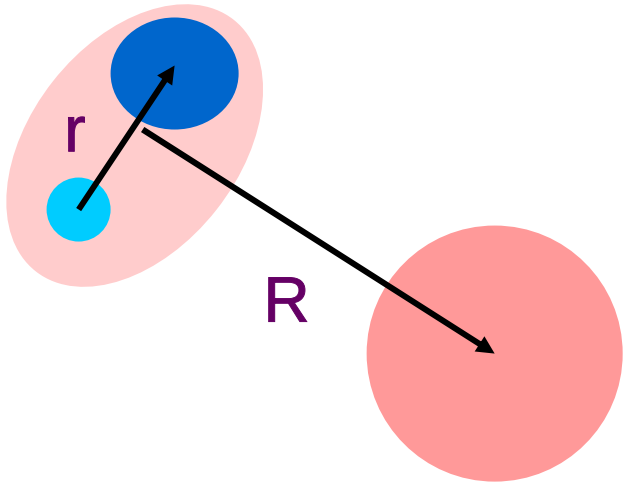
Continuum Discretized Coupled Channels (CDCC)

The Hamiltonian for the reaction of a projectile on a target

$$\mathbf{H} = \mathbf{h}_{\mathbf{proj}} + \mathbf{h}_{\mathbf{t}\arg} + \mathbf{T}_{\alpha} + \mathbf{V}_{\alpha}$$

$$\Rightarrow \mathbf{h}_{\mathbf{proj}} = \mathbf{h}_{\mathbf{core}} + \mathbf{h}_{\mathbf{frag}} + \mathbf{T}_{\mathbf{cf}} + \mathbf{V}_{\mathbf{cf}}$$

$$\Rightarrow \mathbf{V}_{\alpha} = \mathbf{V}_{\mathbf{core}-\mathbf{t}\arg} + \mathbf{V}_{\mathbf{frag}-\mathbf{t}\arg}$$



$$\psi_{\mathbf{JM}}^{\mathbf{CDCC}}(\mathbf{r},\mathbf{R}) = [\phi_0(\mathbf{r}) \otimes \mathbf{Y}_{\mathbf{L}}(\hat{\mathbf{R}})]_{\mathbf{JM}}\, \chi_{0,\mathbf{L}}^{\mathbf{J}}(\mathbf{R}) + \sum_{\mathbf{l}=0}^{\mathbf{l}\max}\sum_{\mathbf{L}}\sum_{\mathbf{i}=1}^{\mathbf{N}} [\phi_{\mathbf{i},\mathbf{l}}(\mathbf{r}) \otimes \mathbf{Y}_{\mathbf{L}}(\hat{\mathbf{R}})]_{\mathbf{JM}}\, \chi_{\mathbf{i},\mathbf{l},\mathbf{L}}^{\mathbf{J}}(\mathbf{R})$$

(neglect the internal structure of the target)

CDCC (cont.)

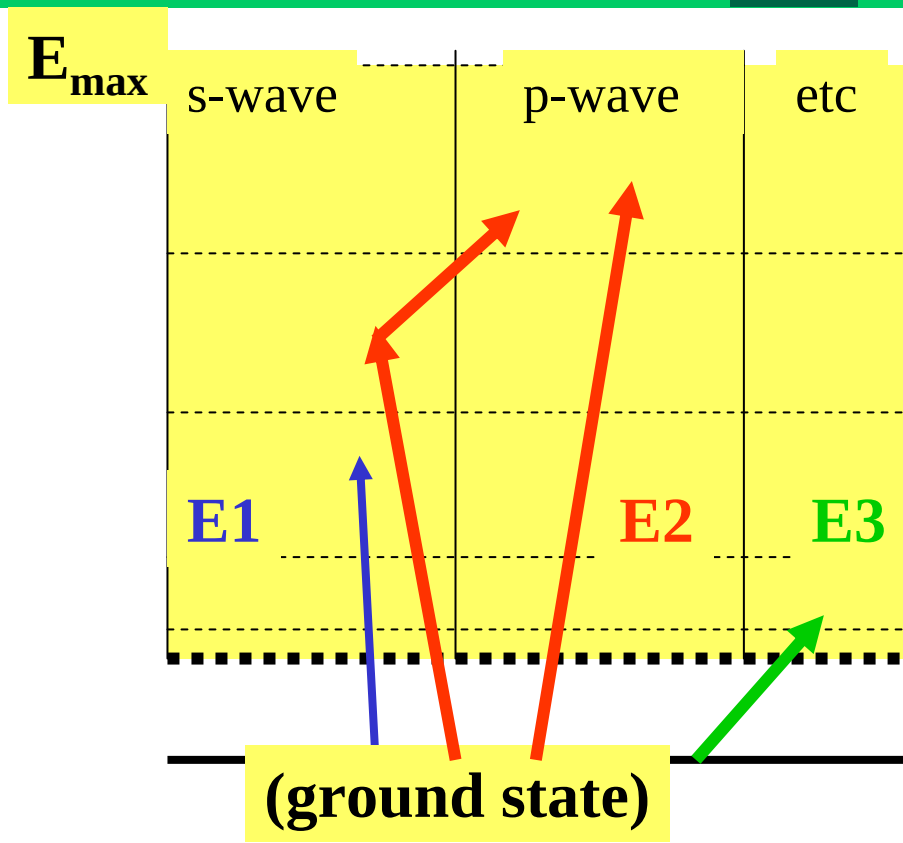
The CDCC basis consists of scattering wavefunctions averaged over an energy interval

$$\mathbf{h}_{\mathbf{proj}}\phi_{\mathbf{k}} = \varepsilon_{\mathbf{k}}\phi_{\mathbf{k}}$$

$$\phi_{\mathbf{i,l}} = \sqrt{\frac{2}{\pi \mathbf{N}_{\mathbf{i}}}} \int_{\mathbf{k}_{\mathbf{i-1}}}^{\mathbf{k}_{\mathbf{i}}} \mathbf{w}_{\mathbf{i}}(\mathbf{k})\phi_{\mathbf{lm}}(\mathbf{k},\mathbf{r})\mathbf{dk}$$

$$\mathbf{N}_{\mathbf{i}} = \int_{\mathbf{k}_{\mathbf{i-1}}}^{\mathbf{k}_{\mathbf{i}}} |\mathbf{w}_{\mathbf{i}}(\mathbf{k})|^2 \, \mathbf{dk}$$

$$\mathbf{N}_{\mathbf{bins}} = \frac{\mathbf{k}_{\max}}{\Delta \mathbf{k}}$$



Coupling potentials

$$V^{CDCC}_{il,i'l'}(R) = \langle \phi_{il}(r) | V_{\alpha}(r,R) | \phi_{i'l'}(r) \rangle$$

Breakup: continuum couplings

CDCC $^{8}B + ^{58}Ni \rightarrow ^{7}Be + p + ^{58}Ni$ (E_{beam}=26 MeV)

Continuum continuum Coupling potentials

$$V_{il,i'l'}^{CDCC}(R) = \langle \phi_{il}(r) | V_{cT}(r,R) + V_{xT}(r,R) | \phi_{i'l'}(r) \rangle$$

Asymptotic behaviour of the couplings

The long range behaviour of the cont-cont coupling is determined by the core-target Coulomb force

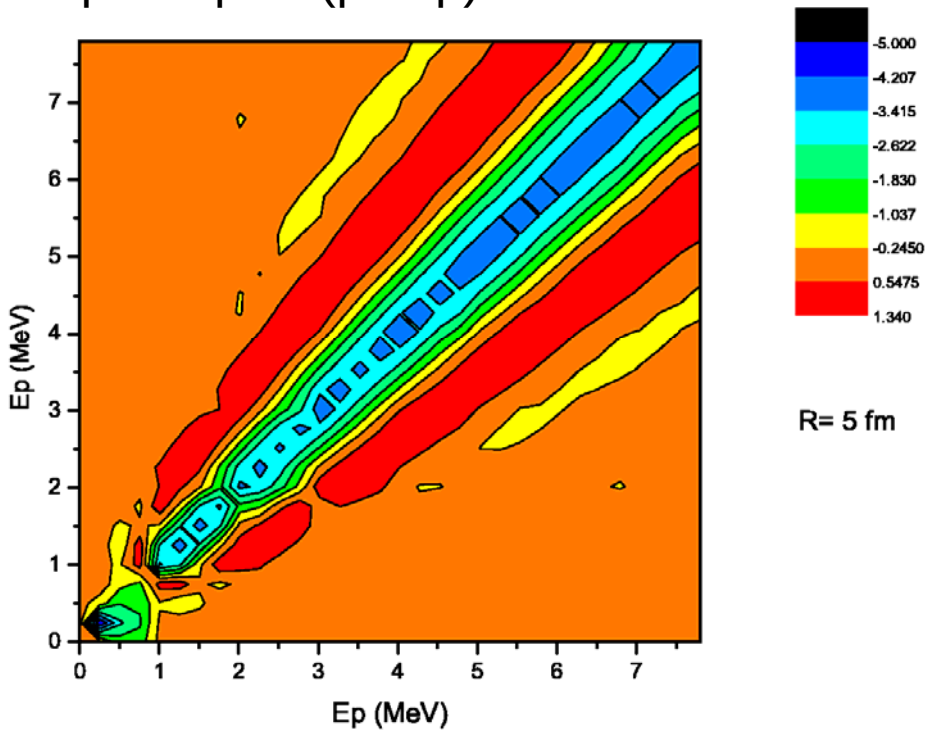
When using CC bins

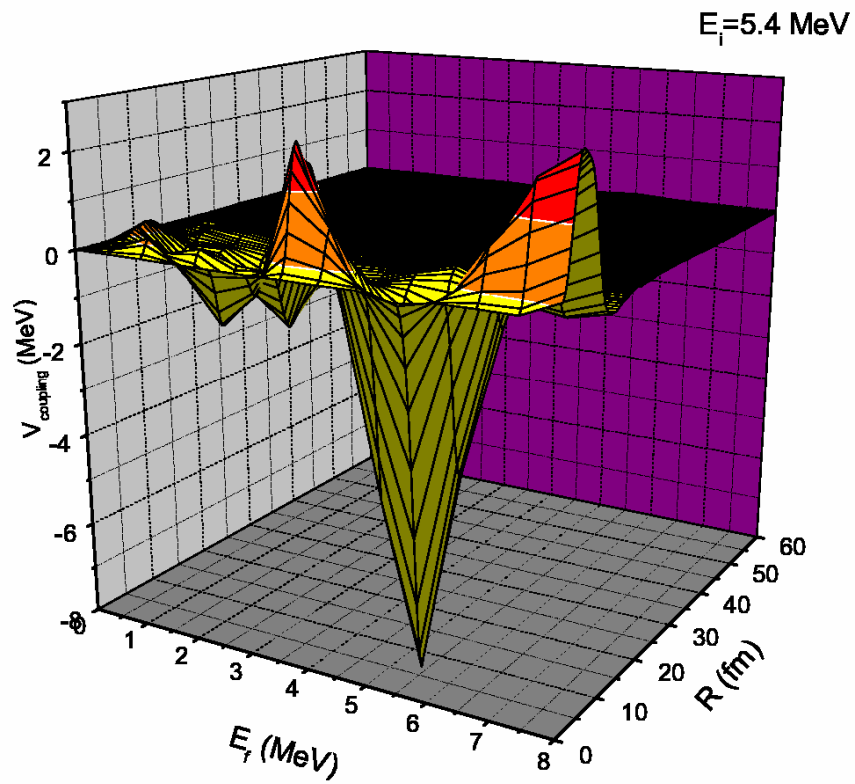
- Dipole couplings go as ~ $1/R^2$
- All higher multipoles go as ~ $1/R^3$

[Nunes et al., NPA 736(2004)255]

Breakup: continuum couplings

quadrupole (p to p)



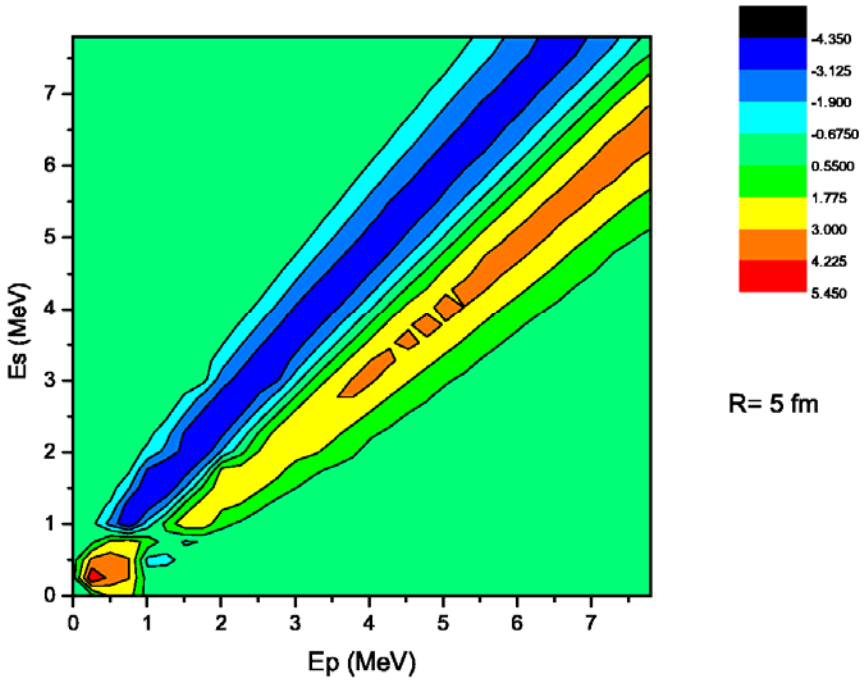


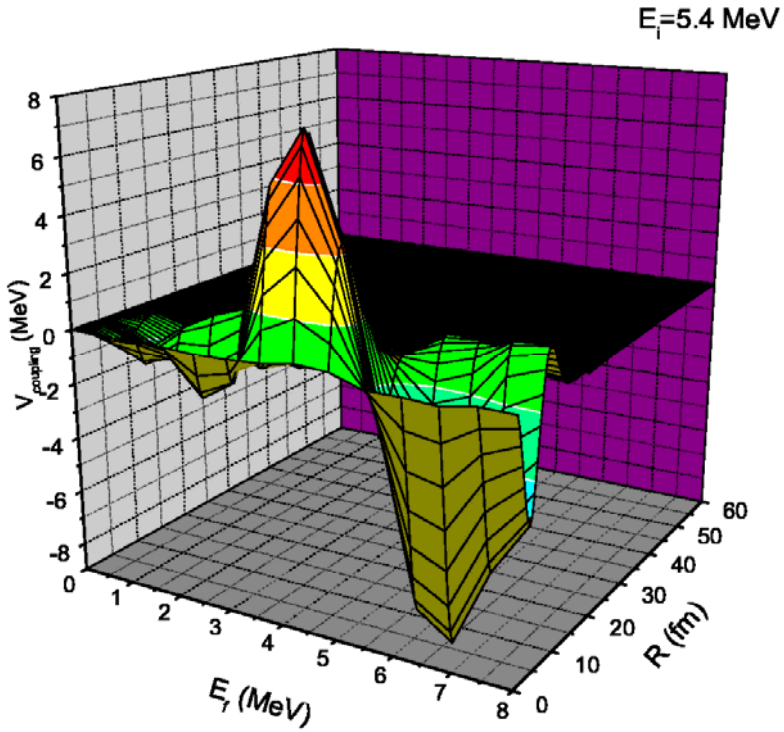
CDCC $^{8}B + ^{58}Ni \rightarrow ^{7}Be + p + ^{58}Ni$

[Nunes et al., NPA 736(2004)255]

Breakup: continuum couplings

dipole (p to s)





CDCC $^{8}B + ^{58}Ni \rightarrow ^{7}Be + p + ^{58}Ni$

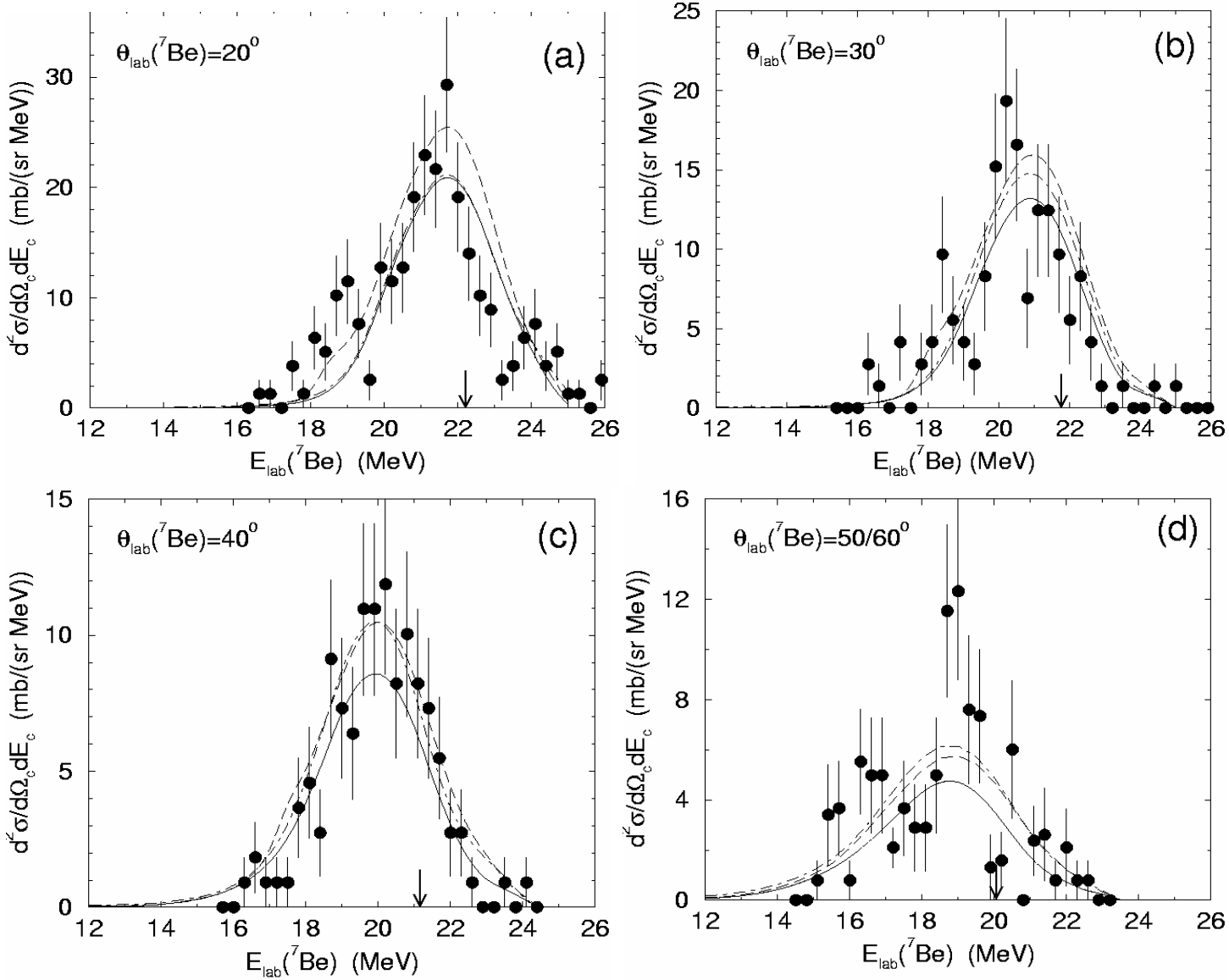
[Nunes et al., NPA 736(2004)255]

Breakup: energy distributions (CDCC versus data)

^{8}B breakup on ^{58}Ni (E_{beam}=26 MeV)

Results of CDCC calculations assuming a single particle structure for ^{8}B=^{7}Be+p

Disagreement for large angles due to transfer.



[Tostevin, Nunes and Thompson, PRC (2001) 024617]

Breakup: MSU versus ND

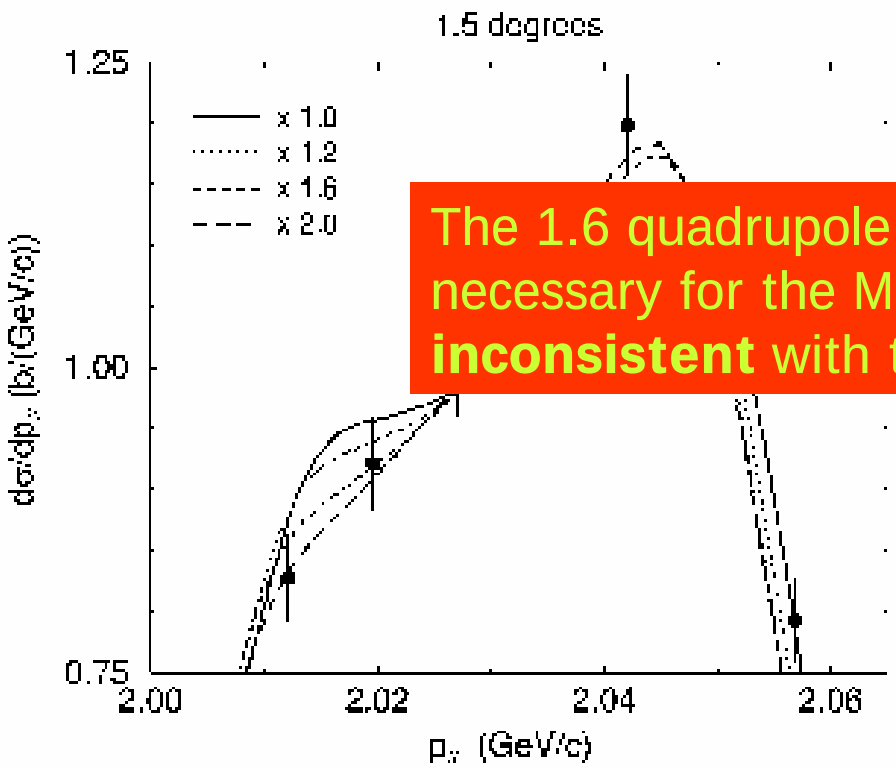
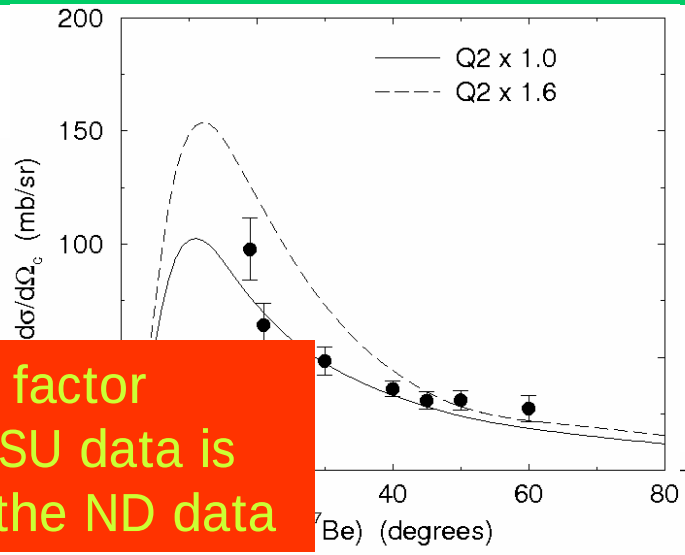
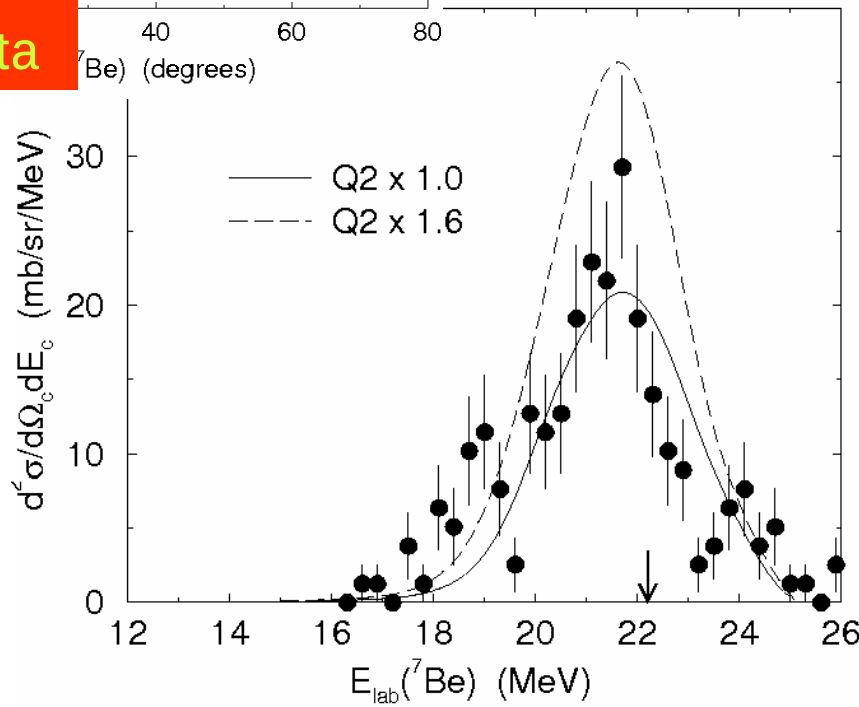


FIG. 4. Parallel momentum distribution of ^{7}Be from the breakup of ^{8}B on Pb at 44 MeV/nucleon with $\theta_{max} = 1.5°$. The curves are results of CDCC calculations with the $\lambda = 2$ multipole amplitudes scaled by the factors indicated.



The 1.6 quadrupole factor necessary for the MSU data is **inconsistent** with the ND data

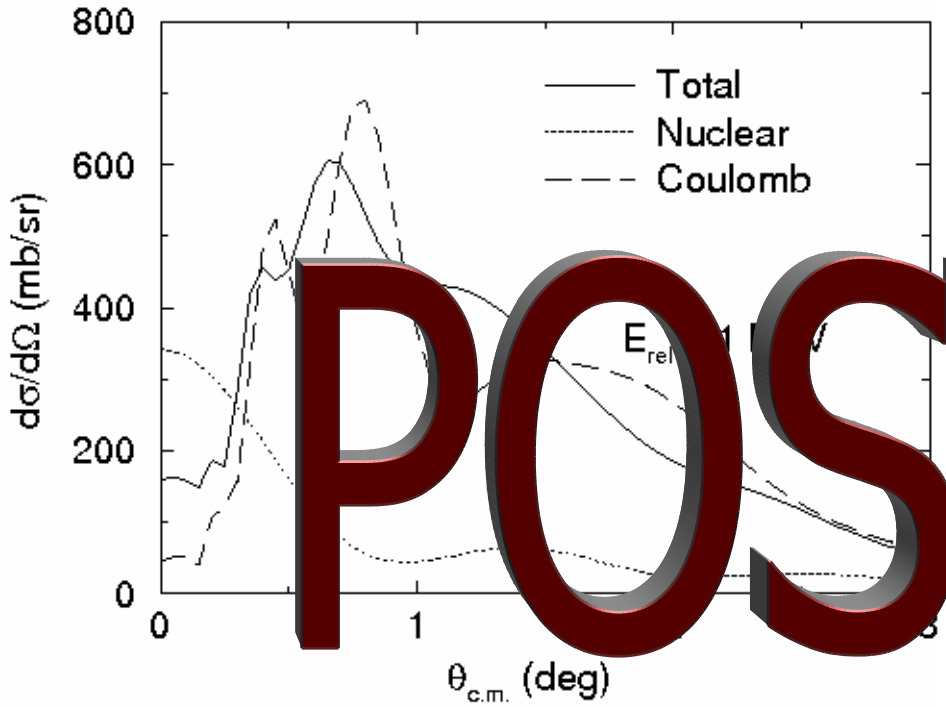


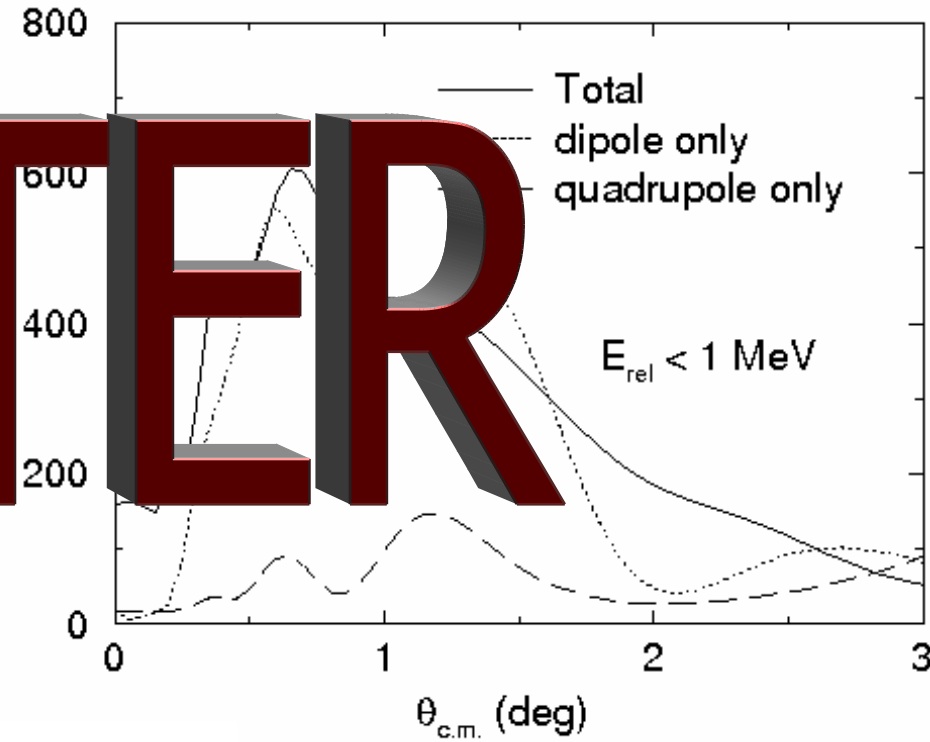
[Mortimer et al, PRC65, 064619]

[Summers and Nunes, PRC to be submitted]

Breakup of ^{7}Be on light and heavy targets

CDCC $^{7}Be + ^{208}Pb \rightarrow ^{4}He + ^{3}He + ^{208}Pb$ (E_{beam}~700 MeV) for MSU





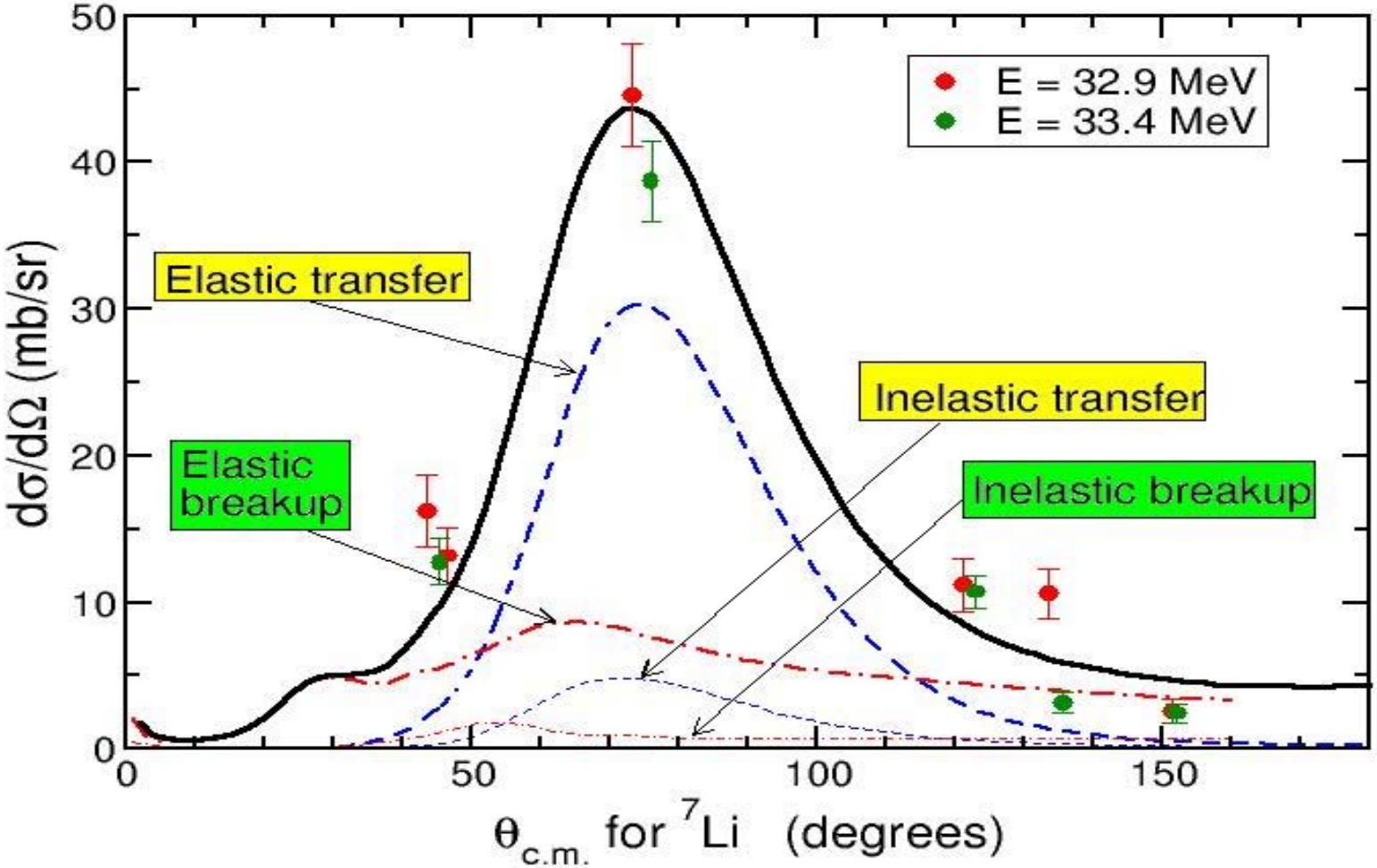
POSTER

also $^{7}Be + ^{12}C \rightarrow ^{4}He + ^{3}He + ^{12}C$ (E_{beam}~175 MeV) for Texas

[Summers and Nunes, PRC 70 (2004) 011602]

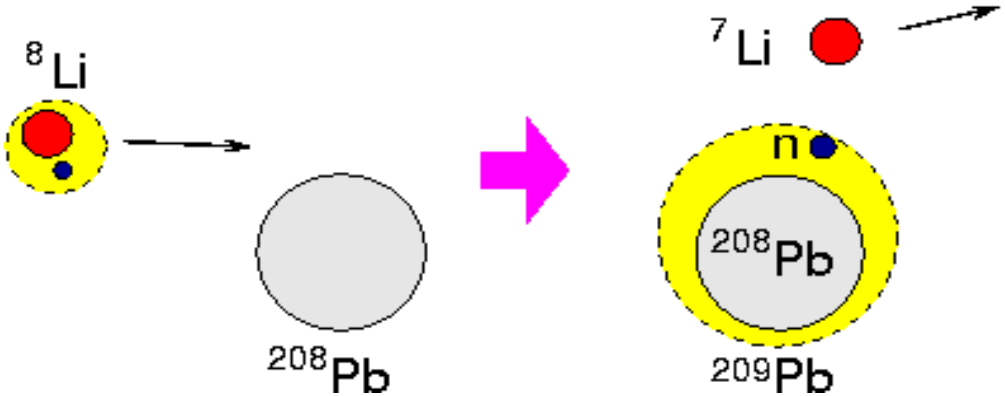
Transfer for ^{8}Li on ^{208}Pb including continuum of the target

CCBA+CDCC $^{8}Li + ^{208}Pb \rightarrow ^{7}Li + X$ (E_{beam}~33 MeV)

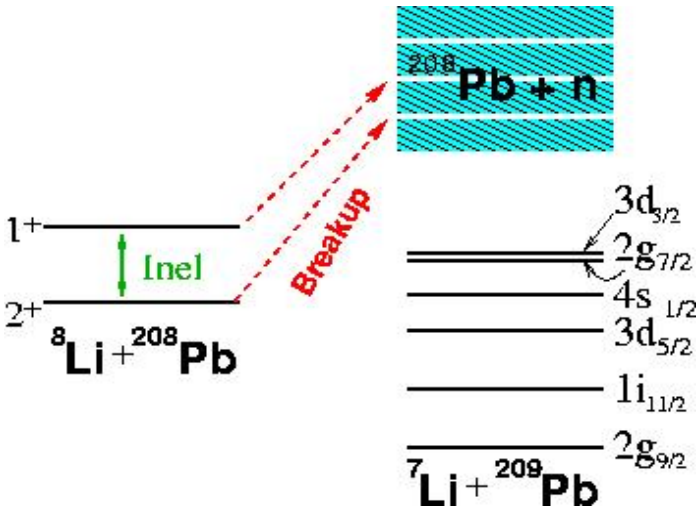


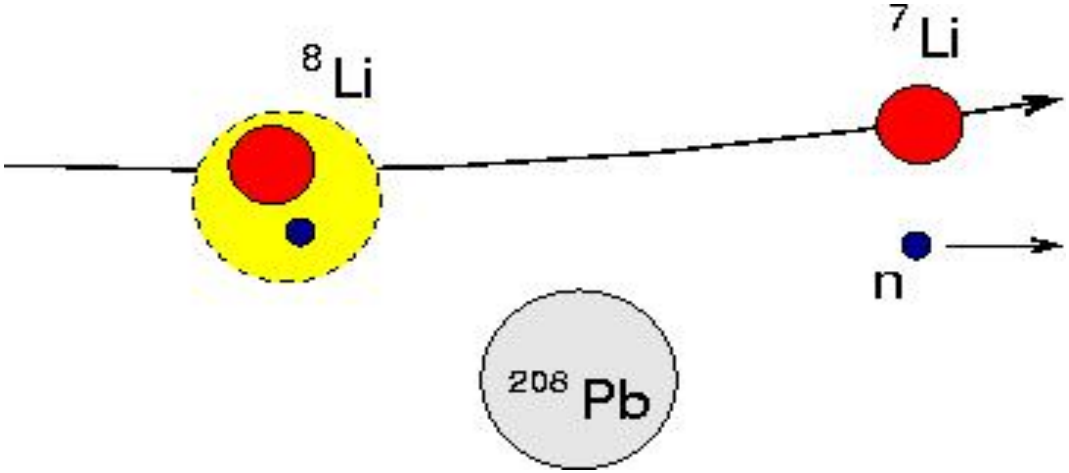
[Moro et al, PRC 68 (2003) 034614]

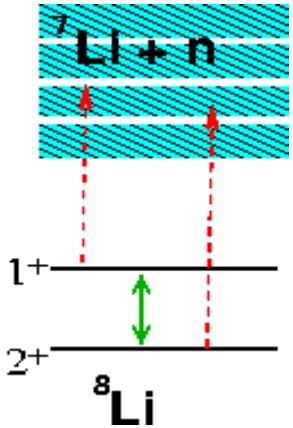
Breakup or transfer to the continuum?



Transfer to the continuum



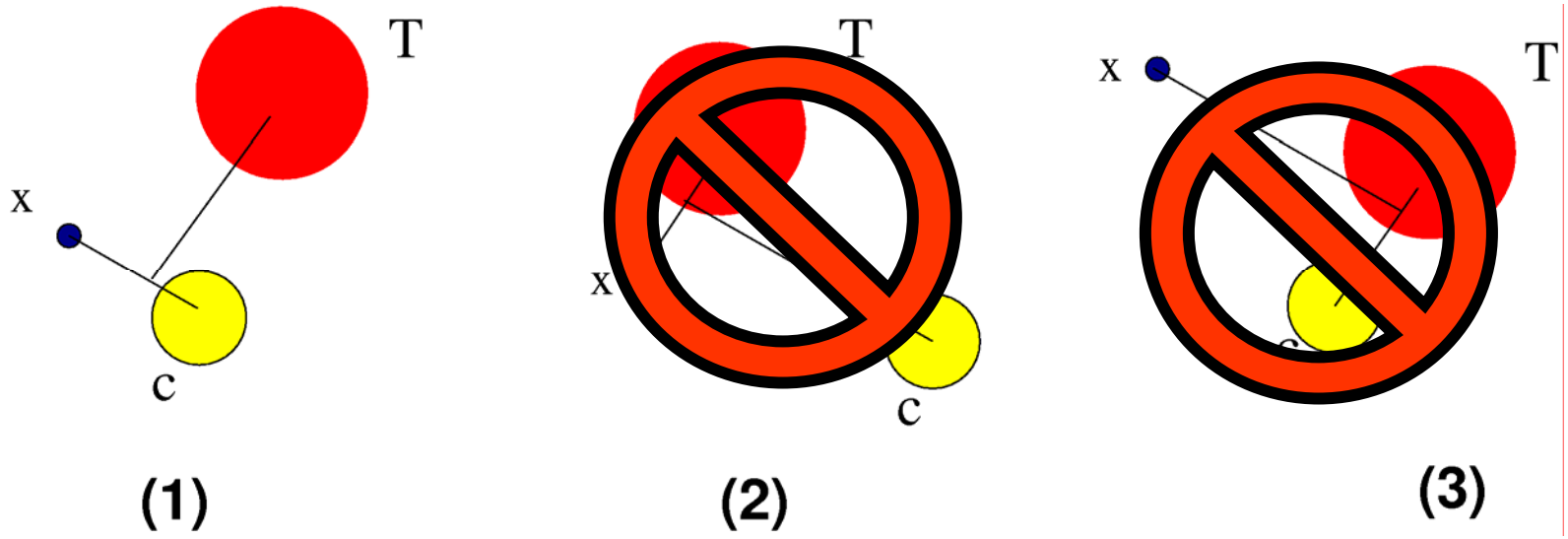




Breakup

Equivalence of TR* or BU?

A two body projectile and a target forms a 3-body system.
Exact treatment: Faddeev Equations!!

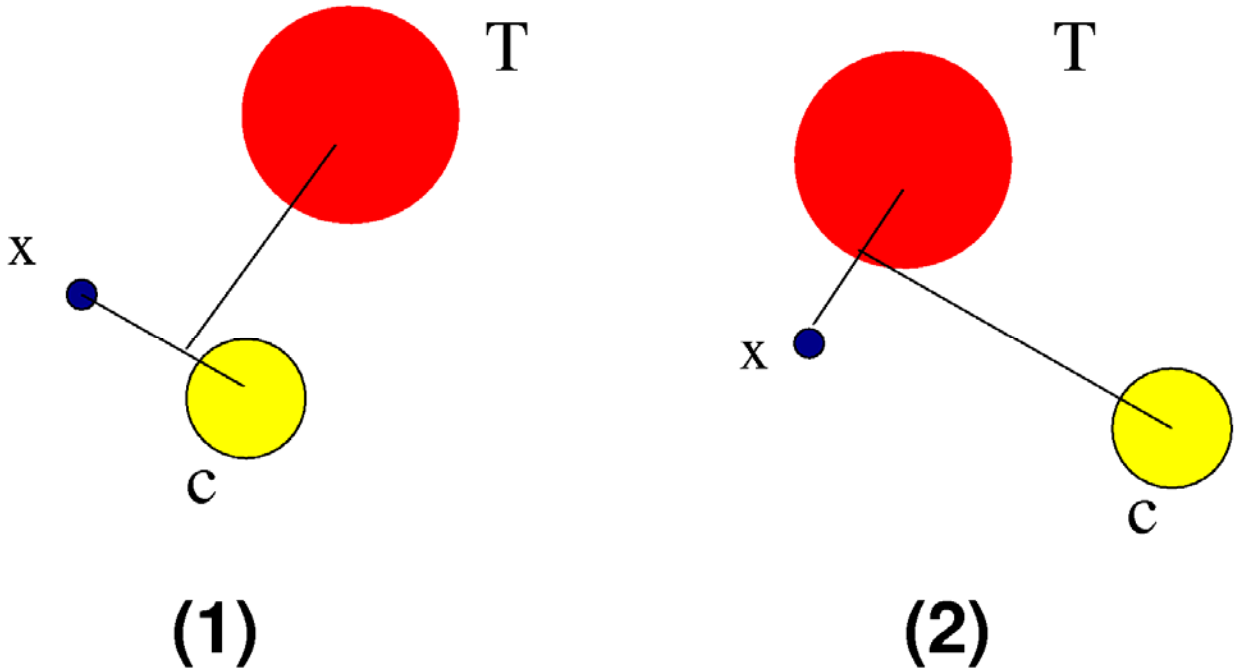


- Faddeev Equations in the continuum not easy
- In principle three components should be included
- CDCC reduces the space such that only one component is necessary

[Austern et al, PRC 53 (1996) 314]

Equivalence of TR* or BU?

Comparison of two CDCC expansions



How to decide which is best: TR* or BU?

The best option is the one that requires a smaller subspace!

- L-distribution of cross section: $\langle L_{rel} \rangle$ should be small
- If BU is a good option: $\langle E_{xc} \rangle$ should be small compared to E_{cm}
- If TR* is a good option: $\langle E_{xT} \rangle$ should be small compared to E_{cm}

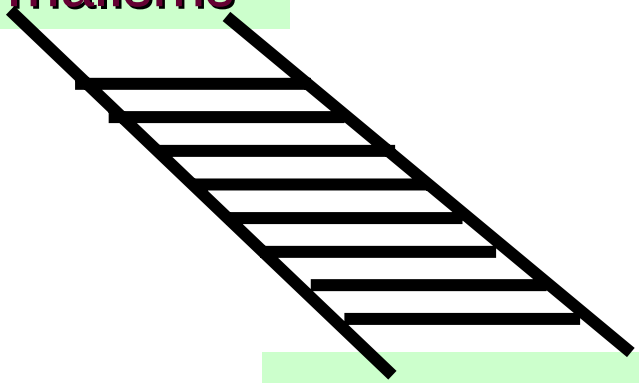
For the ^{8}B case: $\langle E_{xc} \rangle / E_{cm} = 0.08$
For the ^{8}Li case $\langle E_{xT} \rangle / E_{cm} = 0.05$!

[Moro and Nunes,in re-preparation]

Theoretical challenges

Structure:

build the bridge between
many-body formalisms



Reactions:

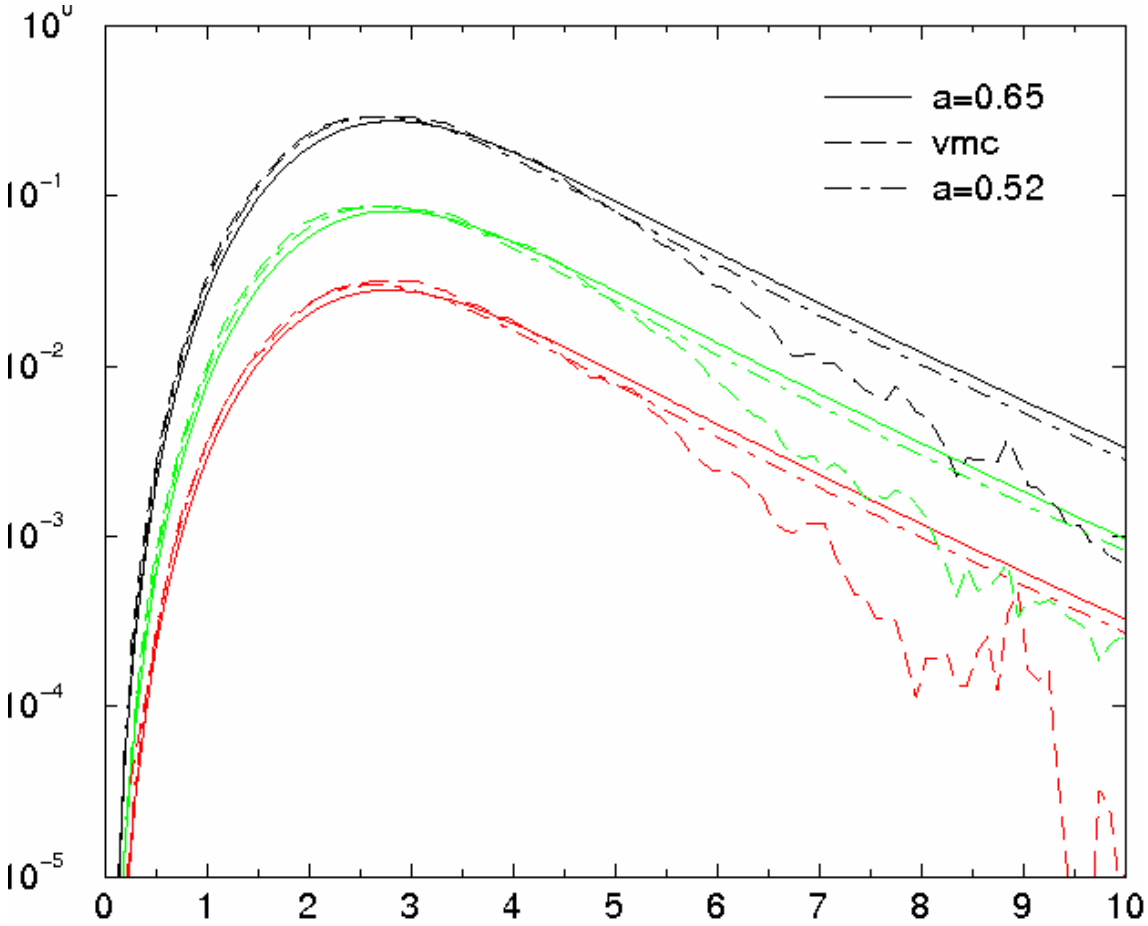
few-body models

high energy: life is easy
straight-line; adiabatic; perturbative

low energy: new generation ISOL facilities
- couplings are generally more important
- no adiabatic or eikonal approximations
- not easy to isolate nuclear from Coulomb

More structure in reaction models

VMC overlap functions: very accurate for spec. fac. (interior) but very noisy in the asymptotic region



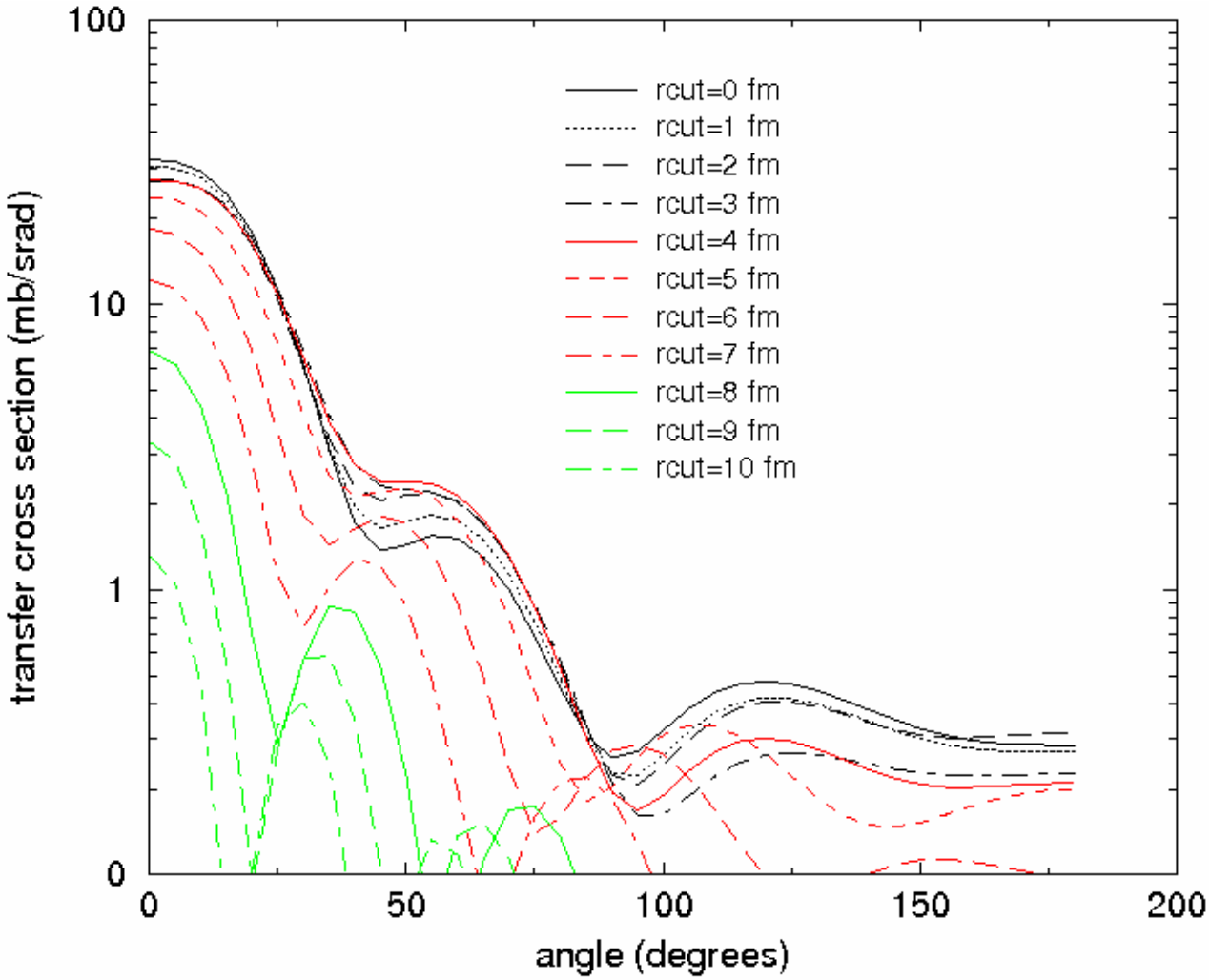
$<^{8}Li\ |^{7}Li>$

Provided by B. Wiringa

averaged to reduce the noise

[Wiringa and Nunes]

More structure in reaction models



^{7}Li **(d,p)** ^{8}Li **@12 MeV**

Sensitivity
to surface

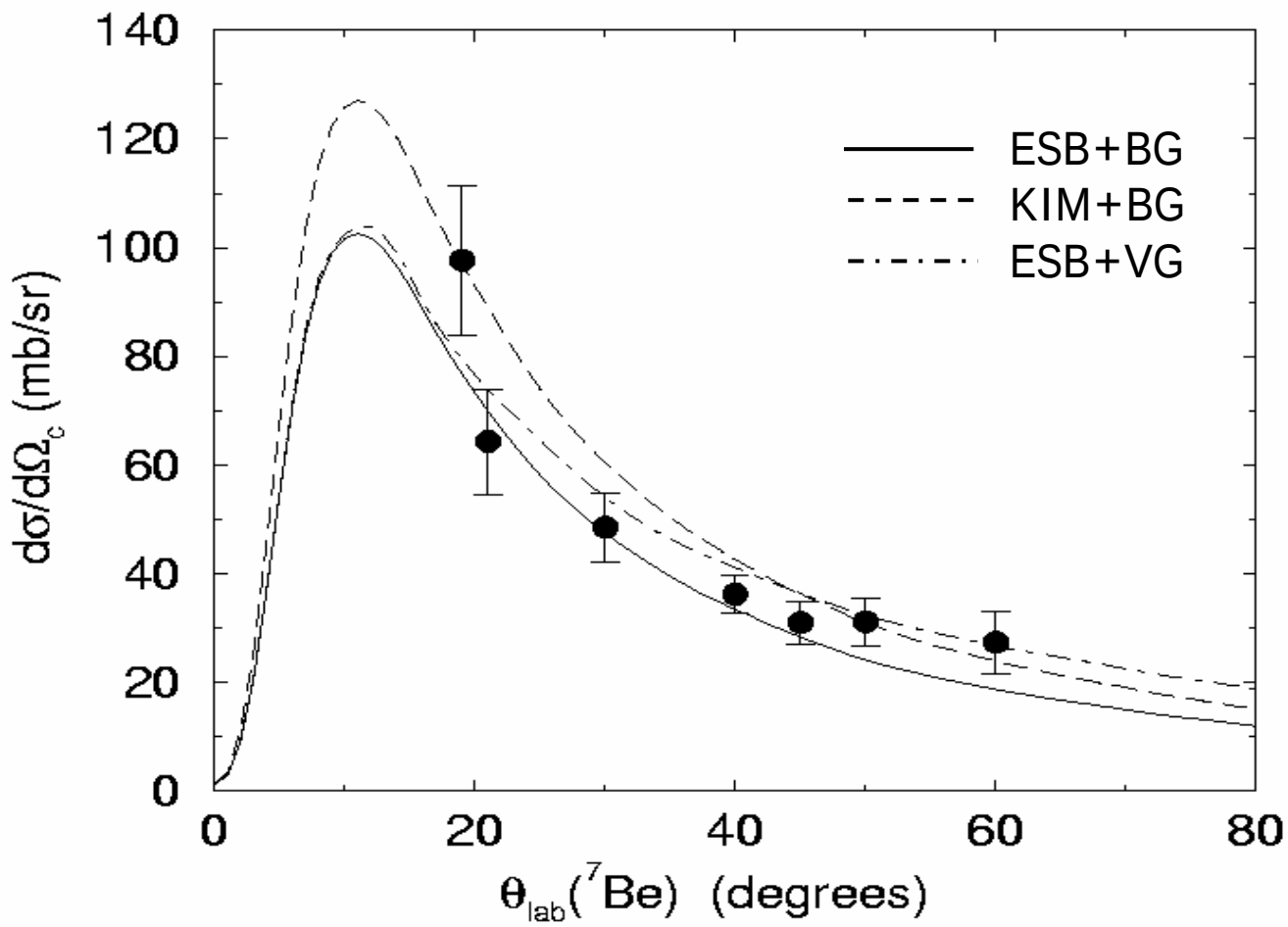
[Wiringa and Nunes]

Breakup: theory versus data

^{8}B breakup on ^{58}Ni
(E_{beam}=26 MeV)

3-body observables

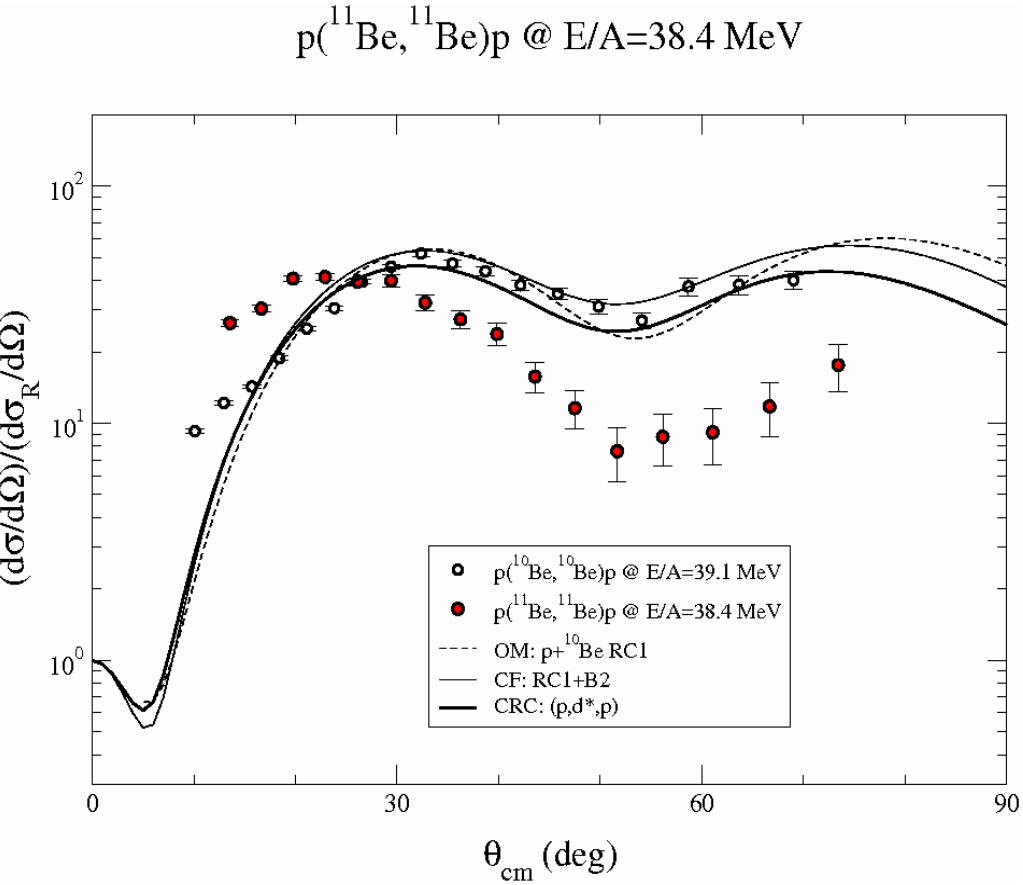
- sensitivity to ^{8}B structure: overall normalisation
- sensitivity to p-target optical potential at larger angles

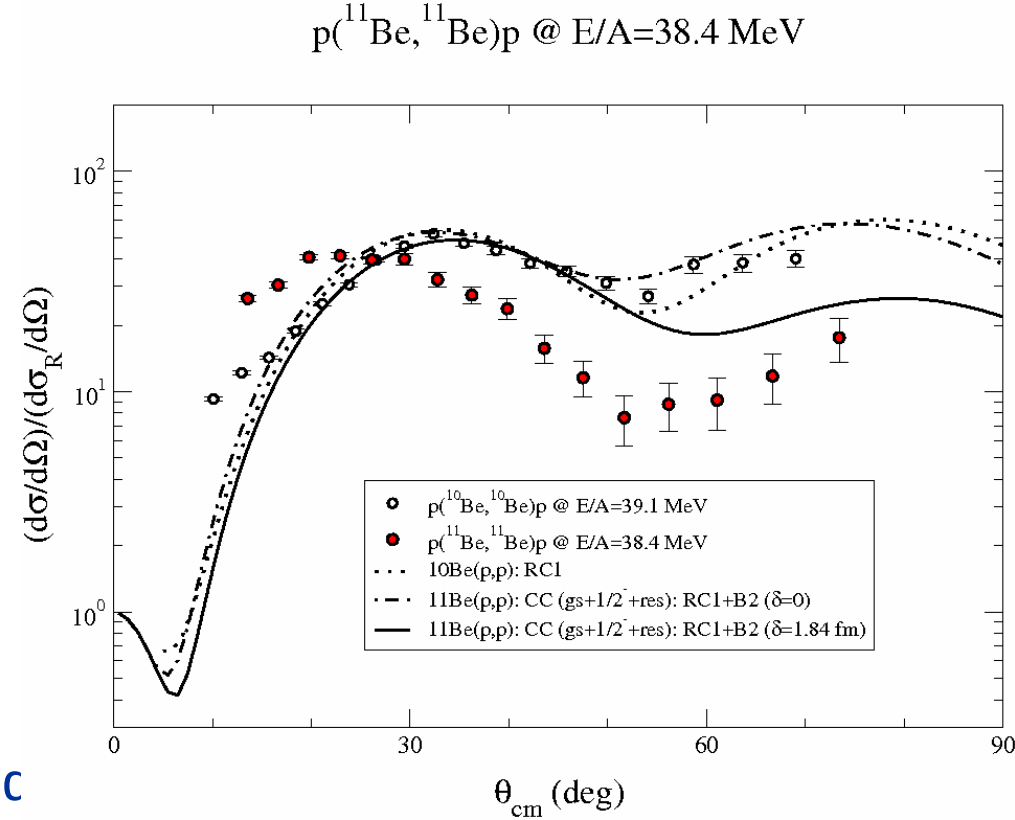


[Tostevin, Nunes and Thompson, PRC (2001) 024617]

Open problems: ^{11}Be elastic and inelastic

^{11}Be(p,p) @GANIL

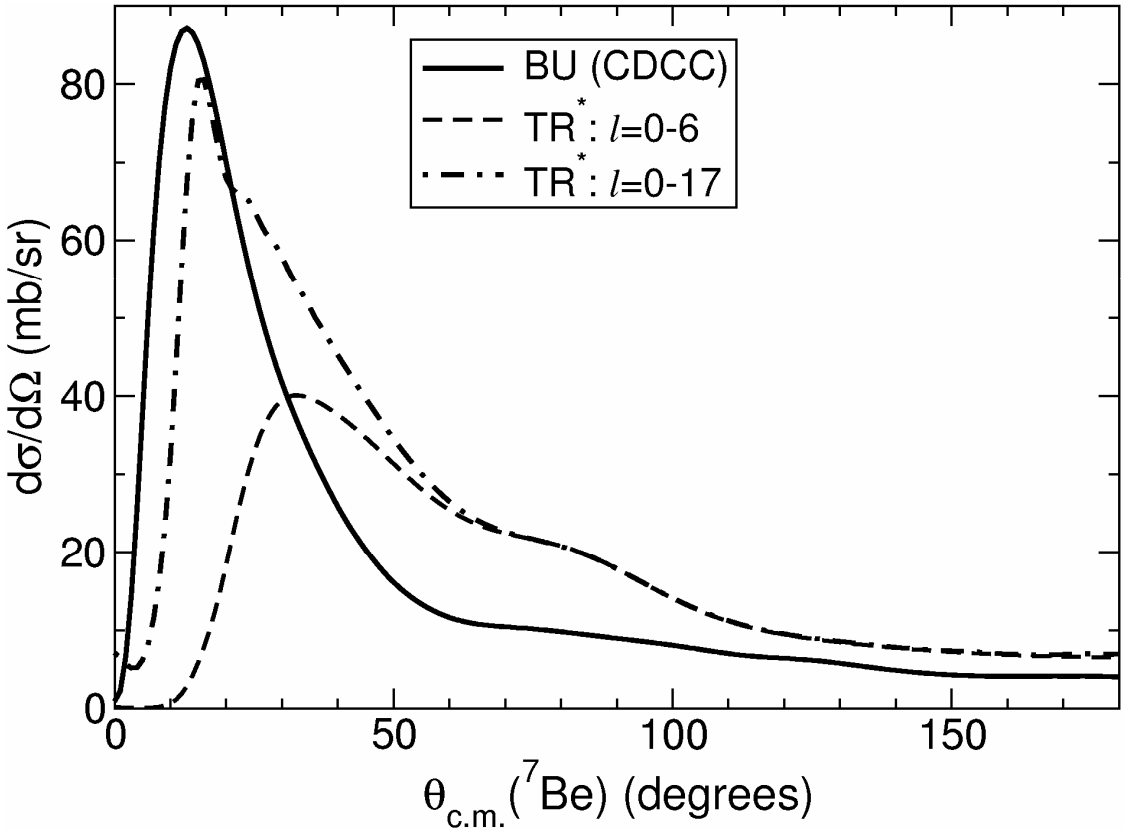




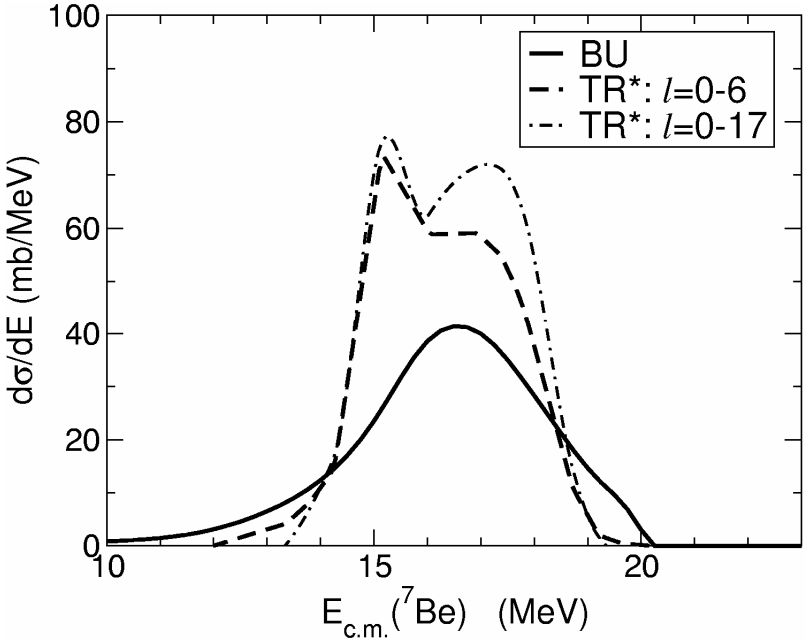
In the usual CDCC approach, a fit to the ^{10}Be data is inconsistent with the ^{11}Be c

[Moro and Nunes]

Comparing TR* and BR: ^{8}B case



^{8}B + ^{58}Ni
@E_{beam} = 26 MeV



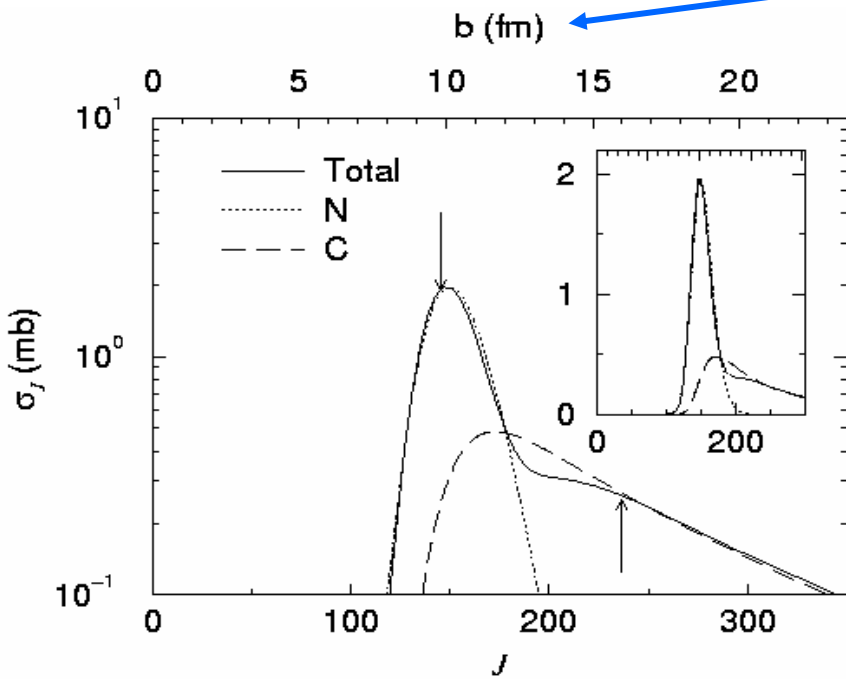
BU convergence achieved for
E_{rel}(max)=8 MeV, l=0,1,2,3, Q=3

[Moro and Nunes,in re-preparation]

$^{7}Be + {}^{208}Pb \rightarrow {}^{3}He + {}^{4}He + {}^{208}Pb$

E_{lab} = 100 MeV/nucleon

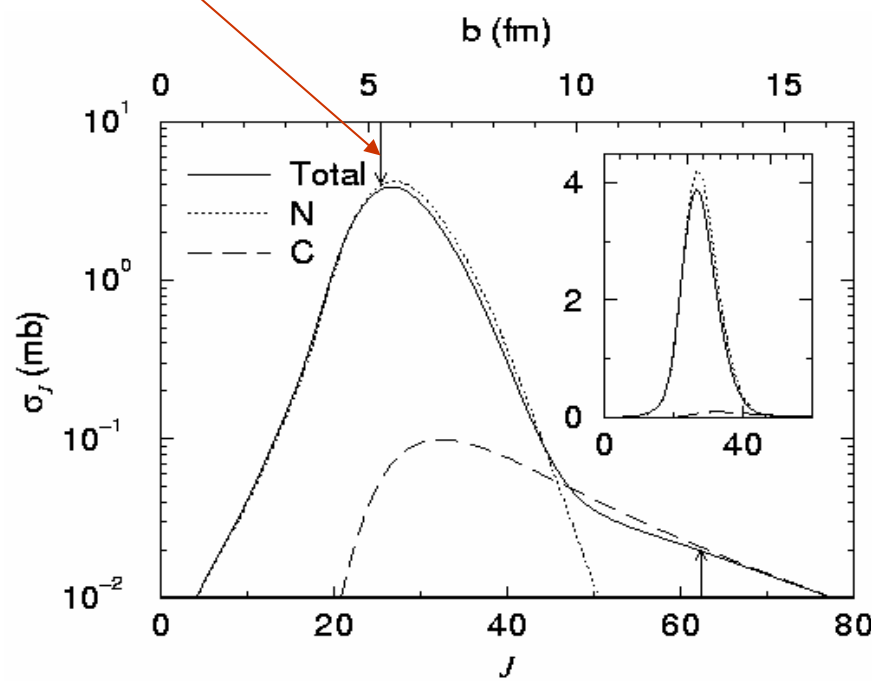
impact parameter from semi-classical relation $J=Kb$



(16%)

approx 28% of breakup cross section comes from impact parameters less than sum of radii

sum of radii



$^{7}Be + {}^{12}C \rightarrow {}^{3}He + {}^{4}He + {}^{12}C$

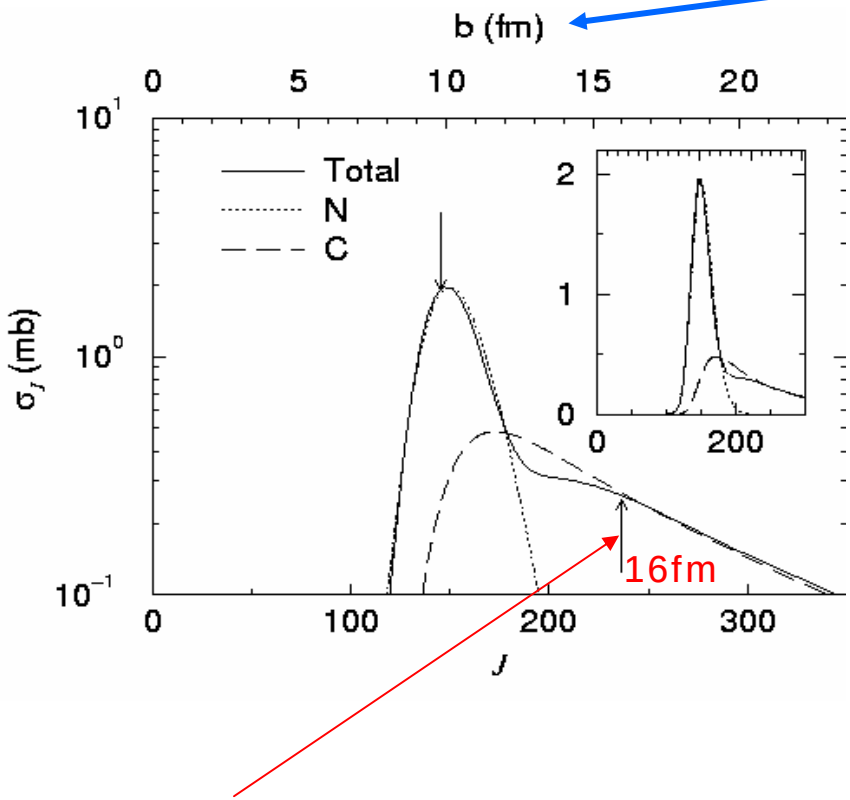
E_{lab} = 25 MeV/nucleon

ANC method requires that reaction is peripheral and therefore only probes the tail of the wavefunction

$^{7}Be + {}^{208}Pb \rightarrow {}^{3}He + {}^{4}He + {}^{208}Pb$

E_{lab} = 100 MeV/nucleon

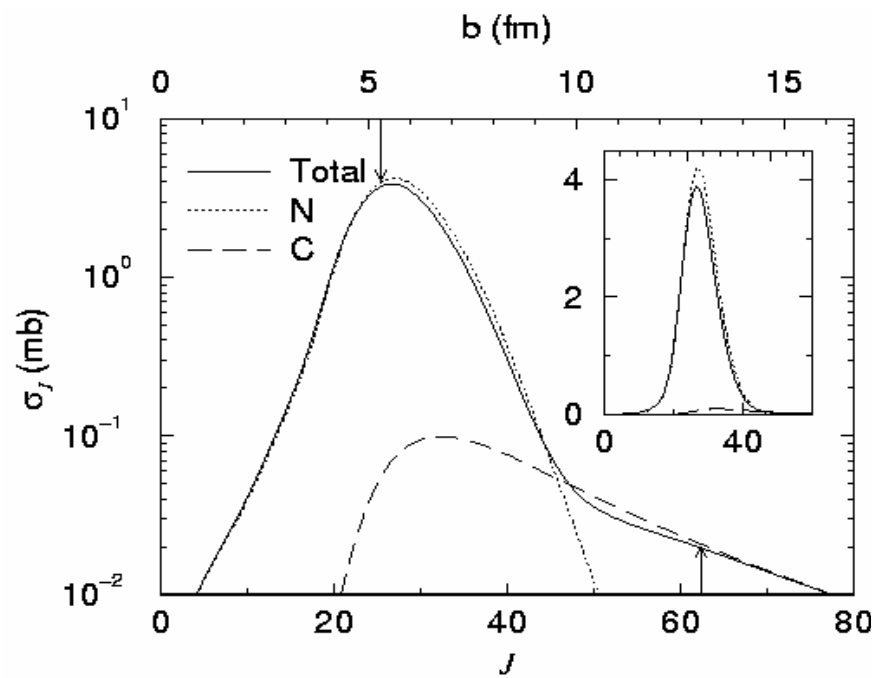
impact parameter from semi-classical relation $J=Kb$



Coulomb dissociation method requires that the reaction is Coulomb dominated, outside the range of the nuclear force

maximum range of nuclear force

assuming Rutherford trajectories this impact parameter relates to a scattering angle of 2.5°

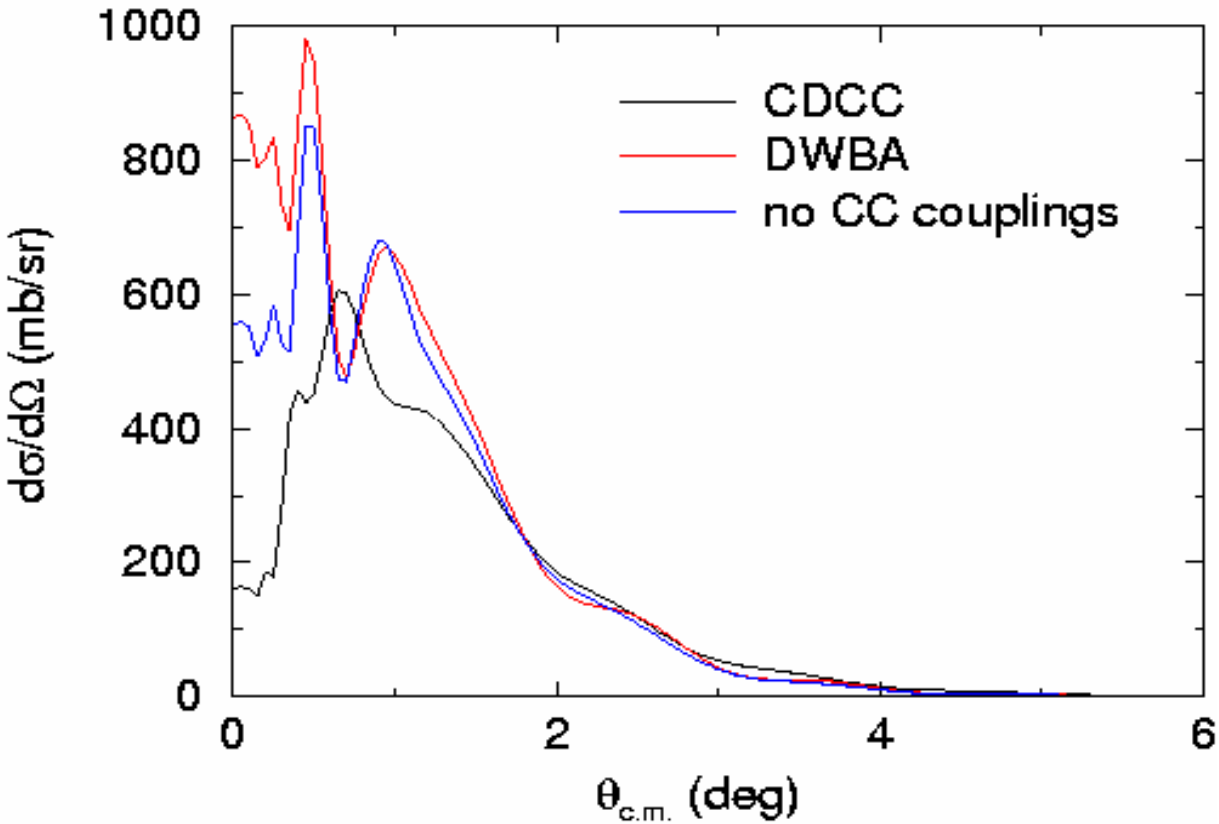


$^{7}Be + {}^{12}C \rightarrow {}^{3}He + {}^{4}He + {}^{12}C$

E_{lab} = 25 MeV/nucleon

CC Couplings

restricted maximum relative energy between ^{3}He and ^{4}He fragments in final state



DWBA → first order

No CC couplings includes couplings to all orders to/from ground state only