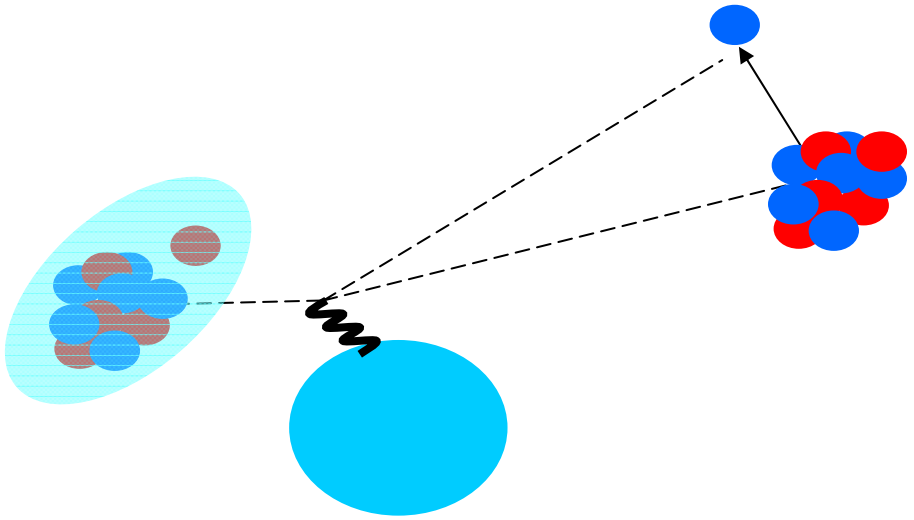
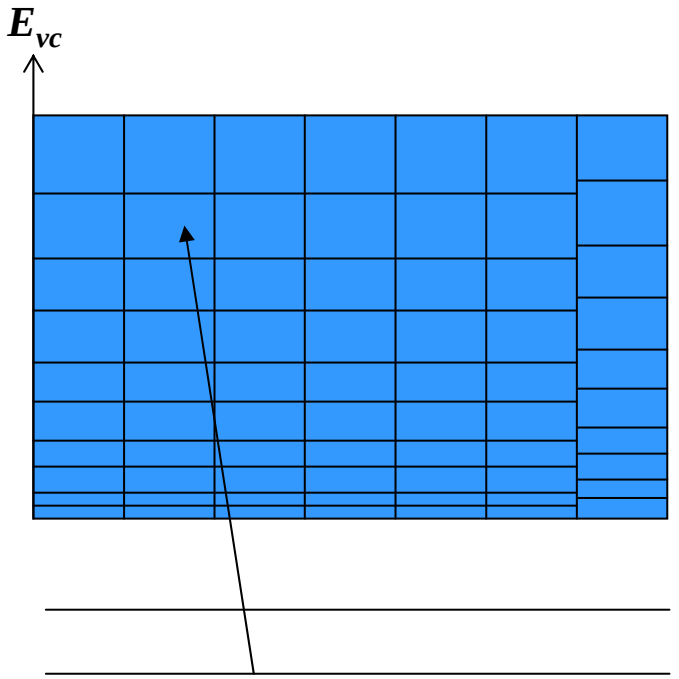
Breakup reactions with the Continuum discretized coupled channel method

Filomena Nunes

standard 3-body CDCC in one slide





- three-body Hamiltonian for reaction
- three-body wavefunction expanded in term of projectile states
- projectile described in terms of single particle states
- optical potentials from elastic scattering

How to do a breakup calculation with fresco?

cdc < short.in >fresco.in

```
8B+208Pb ; N+C breakup with q=0,1,2
CDCC
 &CDCC
   hcm=0.01  rmatch=-60 rasym=1000 accrcy=0.001 absend=-50
   elab=656
   jbord=  0  200 300 1000 9000
   jump =  1   10  50  200
   thmax=20 thinc=0.05 cutr=-20 smats=2 xstabl=1
   ncoul=0 reor=0 q=2
   /
 &NUCLEUS part='Proj' name='8B' charge=5 mass=8
                              spin=1.5 parity=-1 be = 0.137 n=1 l=1 j=1.5 /
 &NUCLEUS part='Core' name='7Be' charge=4 mass=7 /
 &NUCLEUS part='Valence' name='proton' charge=1 mass=1 spin=0.5/
 &NUCLEUS part='Target' name='208Pb' charge=82 mass=208 spin=0 /

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 &BIN /

 &POTENTIAL part='Proj' a1=1 rc=2.65 /
 &POTENTIAL part='Core'      a1=208 rc=1.3 v=114.2 vr0=1.286 a=0.853 w=9.44 wr0=1.739 aw=0.809 /
 &POTENTIAL part='Valence' a1=208 rc=1.3 v=34.819 vr0=1.17 a=0.75 w=15.340 wr0=1.32 aw=0.601/
 &POTENTIAL part='Gs' a1=1 rc=2.391 v=44.675 vr0=2.391 a=.48 vso=4.898 rso0=2.391 aso=0.48 /
```

Box B.4 FRESCO input for the breakup of ^{8}B on ^{208}Pb at 82 MeV per nucleon (short version)

How to do a breakup calculation with fresco?

```
8B+208Pb ; N+C breakup with q=0,1,2
CDCC
 &CDCC
   hcm=0.01  rmatch=-60 rasym=1000 accrcy=0.001 absend=-50
   elab=656
   jbord=  0  200 300 1000 9000
   jump =  1   10  50  200
   thmax=20 thinc=0.05 cutr=-20 smats=2 xstabl=1
   ncoul=0 reor=0 q=2
   /
```

CDCC namelist: contains all the relevant parameters for the fresco namelist

- rmatch<0 and rasym (couplings have long range so match to coupled channel Coulomb function all the way to rasym)
- Jmax=9000! Need many partial waves for this high energy. But jumping...(all j's up to 200, then in 10's up to 300, then in 50's up to 1000, then in 200's up to 9000)
- Theta grid: angular distribution very forward focused – high energy
- cutr – avoids integration at small r due to the strong repulsive potentials (cutr=-20fm put the integration starting point 20 fm inside the coulomb turning radius)

How to do a breakup calculation with fresco?

```
8B+208Pb ; N+C breakup with q=0,1,2
CDCC
 &CDCC
   hcm=0.01  rmatch=-60 rasym=1000 accrcy=0.001 absend=-50
   elab=656
   jbord=  0  200 300 1000 9000
   jump =  1   10  50  200
   thmax=20 thinc=0.05 cutr=-20 smats=2 xstabl=1
   ncoul=0 reor=0 q=2
   /
```

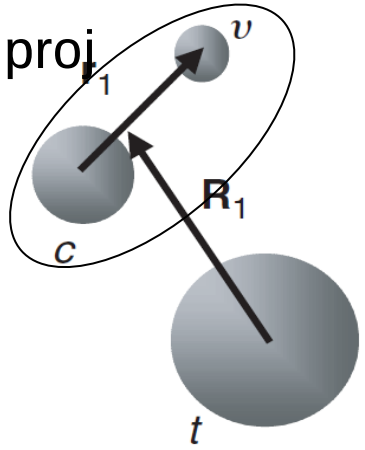
some key additional parameters:

- ncoul (0=nucl+Coul; 1=nucl only, 2=Coul only)
- reor (different choices for the <phi_i |V|phi_i> couplings)
- q (multipoles to include: all multipoles up to 2)

How to do a breakup calculation with fresco?

```
&NUCLEUS part='Proj' name='8B' charge=5 mass=8
                              spin=1.5 parity=-1 be = 0.137 n=1 l=1 j=1.5 /
&NUCLEUS part='Core' name='7Be' charge=4 mass=7 /
&NUCLEUS part='Valence' name='proton' charge=1 mass=1 spin=0.5/
&NUCLEUS part='Target' name='208Pb' charge=82 mass=208 spin=0 /

&BIN spin=0.5 parity=+1 start=0.001 step=0.50 end=10. energy=F l=0 j=0.5/
&BIN /
```



NUCLEUS namelist contains info for partition, overlap and states

•part=(the particle we wish to define including charge, mass, spin and parity, binding energy and the quantum numbers for the state)

BIN namelist contains info for overlap part

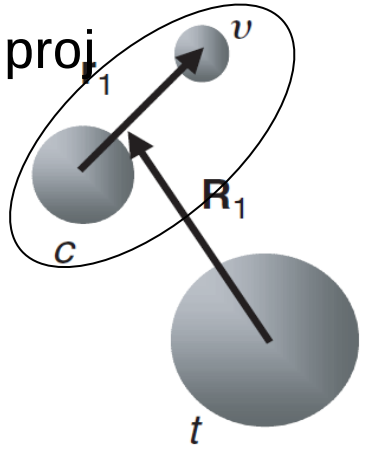
•energy=F (grid in momentum) or T (grid in energy)

•start, step and end define the details of the grid

•spin, parity are the total spin and parity of the projectile bin with quantum numbers l,j

How to do a breakup calculation with fresco?

```
&POTENTIAL part='Proj' a1=1 rc=2.65 /
&POTENTIAL part='Core'      a1=208 rc=1.3 v=114.2 vr0=1.286 a=0.853 w=9.44 wr0=1.739 aw=0.809
&POTENTIAL part='Valence' a1=208 rc=1.3 v=34.819 vr0=1.17 a=0.75 w=15.340 wr0=1.32 aw=0.601/
&POTENTIAL part='Gs' a1=1 rc=2.391 v=44.675 vr0=2.391 a=.48 vso=4.898 rso0=2.391 aso=0.48 /
```



POTENTIAL namelist is identical to POT namelist is standard input

- part=proj (projectile-target interaction) =core (core-target interaction)
- part=valence (valence-target interaction)
- part=gs/bin (core-valence interaction in g.s. or continuum)

How to do a breakup calculation with fresco?

```
CDCC 8B+208Pb ; nuclear and coulomb s-wave breakup
NAMELIST
 &FRESCO  hcm= 0.01 rmatch= -60.000 rintp=0.15 rsp=   0.0 rasym=  1000.00 accrcy= 0.001
    jtmin=   0.0 jtmax=   9000.0 absend=  -50.0000
    jump =       1      10      50     200
    jbord=     0.0   200.0   300.0  1000.0  9000.0
    thmin=  0.00 thmax=  20.00 thinc=  0.05  cutr=-20.00
    ips= 0.0000  it0= 0 iter=  0 iblock= 21 nnu= 24 smallchan= 1.00E-12  smallcoup= 1.00E-12
    elab=   656.0000    pel=1 exl=1 lab=1 lin=1 lex=1 chans= 1 smats= 2 xstabl= 1 cdcc= 1/
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 &States jp= 0.5 ptyp= 1 ep=  7.8253  cpot=  1 copyt= 1/
 &States jp= 0.5 ptyp= 1 ep=  8.7173  cpot=  1 copyt= 1/
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 &Partition namep='7Be' massp=  7. zp=  4 nex=-1 pwf=T namet='209Pb' masst=209.0000 zt=83 qval=  0./
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 &Partition /
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 &Pot kp= 2 type= 0 shape= 0 p(1:3)=  208.0000   0.0000   1.3000 /
 &Pot kp= 2 type= 1 shape= 0 p(1:6)=  114.2000   1.2860   0.8530   9.4400   1.7390   0.8090 /
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 &Pot kp= 3 type= 1 shape= 0 p(1:6)=   34.8190   1.1700   0.7500  15.3400   1.3200   0.6010  /
 &Pot kp= 4 type= 0 shape= 0 p(1:3)=    1.0000   0.0000   2.3910 /
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 &Pot kp= 4 type= 3 shape= 0 p(1:3)=    4.8980   2.3910   0.4800 /
 &Pot /
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 &Overlap kn1=  2 ic1=1 ic2=2 in= 1 kind=0 l=0 sn=0.5 j= 0.5 nam=1 ampl=  1.00 kbpot= 4 be= -0.0182 isc=12 ipc=2 nk=  20 er= -0.0344 /
 &Overlap kn1=  3 ic1=1 ic2=2 in= 1 kind=0 l=0 sn=0.5 j= 0.5 nam=1 ampl=  1.00 kbpot= 4 be= -0.0771 isc=12 ipc=2 nk=  20 er= -0.0834 /
 &Overlap kn1=  4 ic1=1 ic2=2 in= 1 kind=0 l=0 sn=0.5 j= 0.5 nam=1 ampl=  1.00 kbpot= 4 be= -0.1850 isc=12 ipc=2 nk=  20 er= -0.1324 /
 &Overlap kn1=  5 ic1=1 ic2=2 in= 1 kind=0 l=0 sn=0.5 j= 0.5 nam=1 ampl=  1.00 kbpot= 4 be= -0.3419 isc=12 ipc=2 nk=  20 er= -0.1814 /
 &Overlap kn1=  6 ic1=1 ic2=2 in= 1 kind=0 l=0 sn=0.5 j= 0.5 nam=1 ampl=  1.00 kbpot= 4 be= -0.5479 isc=12 ipc=2 nk=  20 er= -0.2304 /
 &Overlap kn1=  7 ic1=1 ic2=2 in= 1 kind=0 l=0 sn=0.5 j= 0.5 nam=1 ampl=  1.00 kbpot= 4 be= -0.8028 isc=12 ipc=2 nk=  20 er= -0.2794 /
 &Overlap kn1=  8 ic1=1 ic2=2 in= 1 kind=0 l=0 sn=0.5 j= 0.5 nam=1 ampl=  1.00 kbpot= 4 be= -1.1067 isc=12 ipc=2 nk=  20 er= -0.3284 /
 &Overlap kn1=  9 ic1=1 ic2=2 in= 1 kind=0 l=0 sn=0.5 j= 0.5 nam=1 ampl=  1.00 kbpot= 4 be= -1.4596 isc=12 ipc=2 nk=  20 er= -0.3774 /
 &Overlap kn1= 10 ic1=1 ic2=2 in= 1 kind=0 l=0 sn=0.5 j= 0.5 nam=1 ampl=  1.00 kbpot= 4 be= -1.8616 isc=12 ipc=2 nk=  20 er= -0.4264 /
 &Overlap kn1= 11 ic1=1 ic2=2 in= 1 kind=0 l=0 sn=0.5 j= 0.5 nam=1 ampl=  1.00 kbpot= 4 be= -2.3125 isc=12 ipc=2 nk=  20 er= -0.4754 /
 &Overlap kn1= 12 ic1=1 ic2=2 in= 1 kind=0 l=0 sn=0.5 j= 0.5 nam=1 ampl=  1.00 kbpot= 4 be= -2.8125 isc=12 ipc=2 nk=  20 er= -0.5245 /
 &Overlap kn1= 13 ic1=1 ic2=2 in= 1 kind=0 l=0 sn=0.5 j= 0.5 nam=1 ampl=  1.00 kbpot= 4 be= -3.3614 isc=12 ipc=2 nk=  20 er= -0.5735 /
 &Overlap kn1= 14 ic1=1 ic2=2 in= 1 kind=0 l=0 sn=0.5 j= 0.5 nam=1 ampl=  1.00 kbpot= 4 be= -3.9594 isc=12 ipc=2 nk=  20 er= -0.6225 /
 &Overlap kn1= 15 ic1=1 ic2=2 in= 1 kind=0 l=0 sn=0.5 j= 0.5 nam=1 ampl=  1.00 kbpot= 4 be= -4.6064 isc=12 ipc=2 nk=  20 er= -0.6715 /
 &Overlap kn1= 16 ic1=1 ic2=2 in= 1 kind=0 l=0 sn=0.5 j= 0.5 nam=1 ampl=  1.00 kbpot= 4 be= -5.3023 isc=12 ipc=2 nk=  20 er= -0.7205 /
 &Overlap kn1= 17 ic1=1 ic2=2 in= 1 kind=0 l=0 sn=0.5 j= 0.5 nam=1 ampl=  1.00 kbpot= 4 be= -6.0473 isc=12 ipc=2 nk=  20 er= -0.7695 /
 &Overlap kn1= 18 ic1=1 ic2=2 in= 1 kind=0 l=0 sn=0.5 j= 0.5 nam=1 ampl=  1.00 kbpot= 4 be= -6.8413 isc=12 ipc=2 nk=  20 er= -0.8185 /
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 &Overlap kn1= 20 ic1=1 ic2=2 in= 1 kind=0 l=0 sn=0.5 j= 0.5 nam=1 ampl=  1.00 kbpot= 4 be= -8.5763 isc=12 ipc=2 nk=  20 er= -0.9165 /
 &Overlap kn1= 21 ic1=1 ic2=2 in= 1 kind=0 l=0 sn=0.5 j= 0.5 nam=1 ampl=  1.00 kbpot= 4 be= -9.5173 isc=12 ipc=2 nk=  20 er= -0.9655 /
 &Overlap /   !
 &Coupling icto= 1 icfrom= 2 kind=3 ip1= 2 ip2= 0 ip3= 0 p1=    3.0000 p2=  2.0000 /
 &Coupling /
```

cdc < short.in >fresco.in

This command produce the standard fresco input where all states/overlaps are explicitly defined

isc=12 standard normalization for momentum bins

kind=3 projectile single-particle coupling

How to do a breakup calculation with fresco?

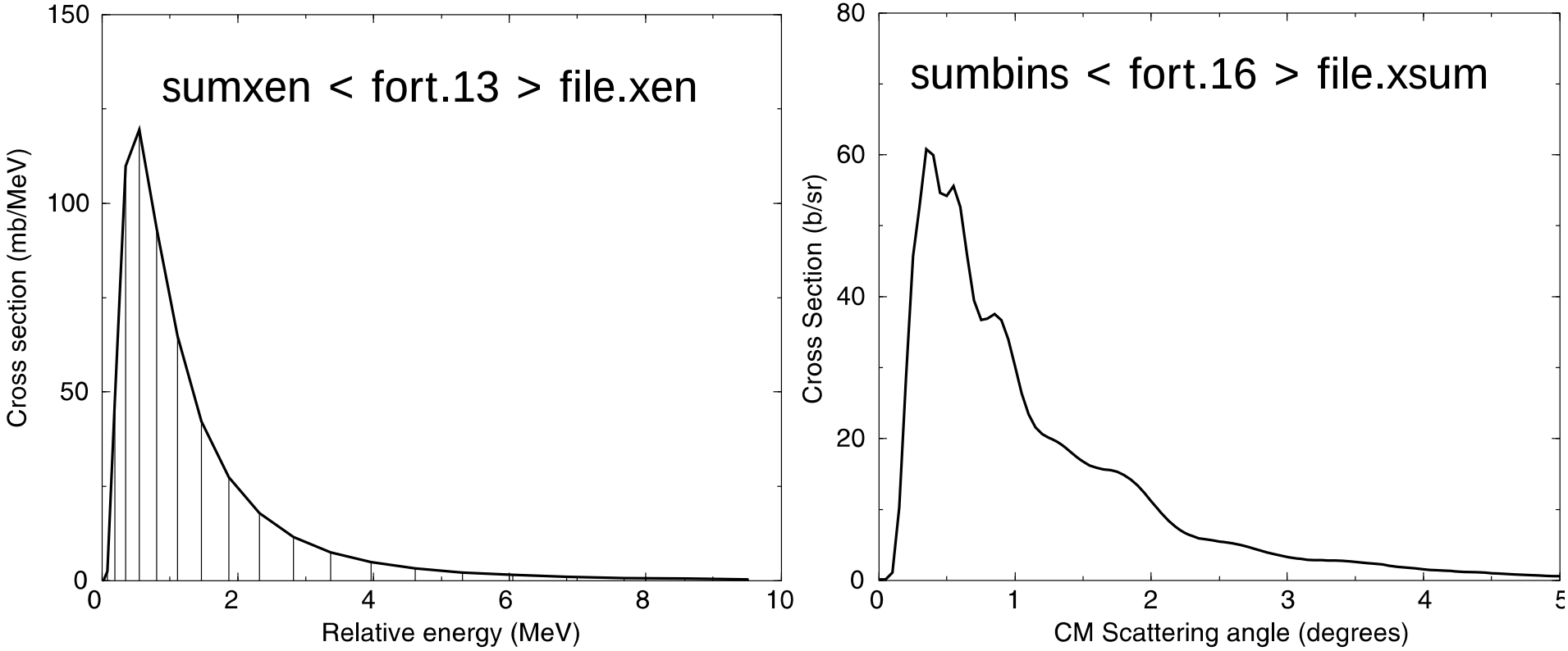
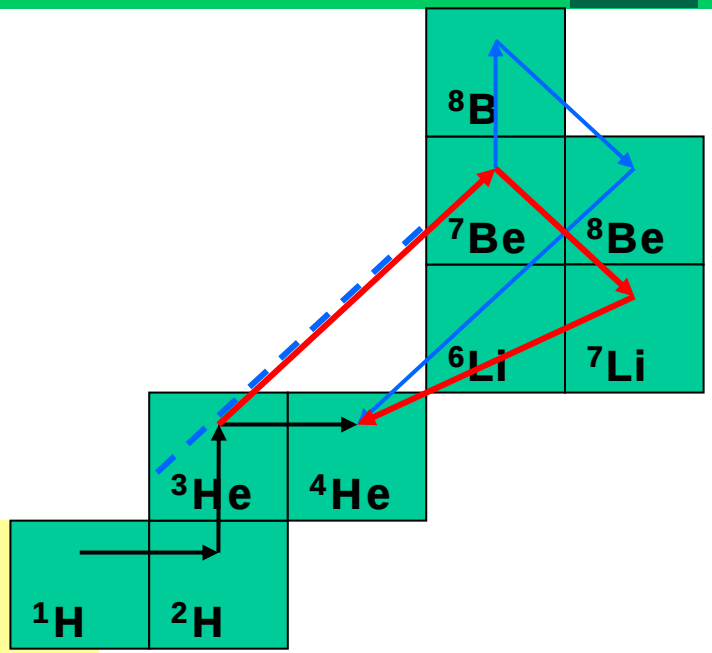


Fig. B.3. Breakup of ^{8}B on ^{208}Pb at 82 MeV/u. Left: p$-^{7}$Be relative energy distribution. Right: center-of-mass angular distribution. Both are obtained with the input of Box B.3.

Breakup with CDCC: one case in detail

Capture rate $^3He(\alpha,\gamma)^7Be$

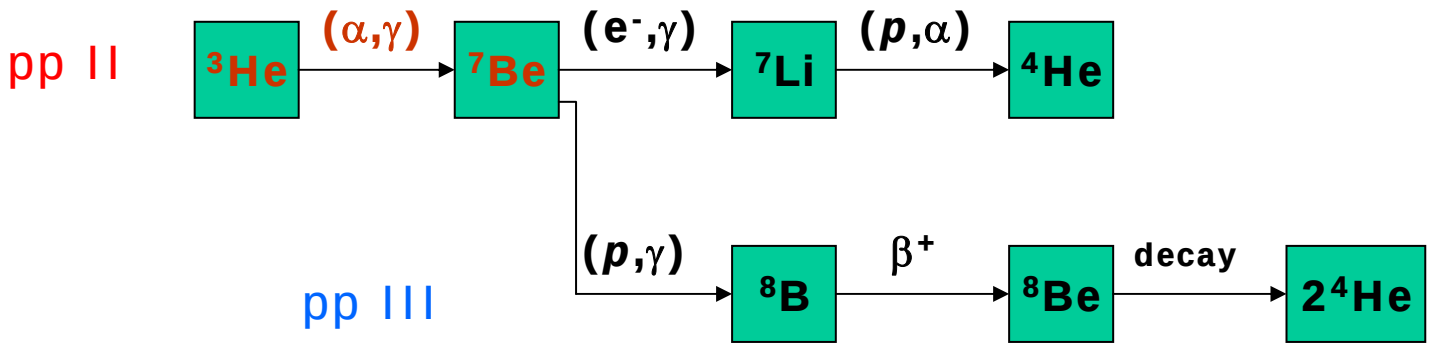
Capture rates at astrophysical energies are hard to measure and thus rely on extrapolations to low energies



Motivates alternative methods using inverse reaction $^7Be + \gamma \rightarrow \alpha + {}^3He$

(i) Coulomb Dissociation method

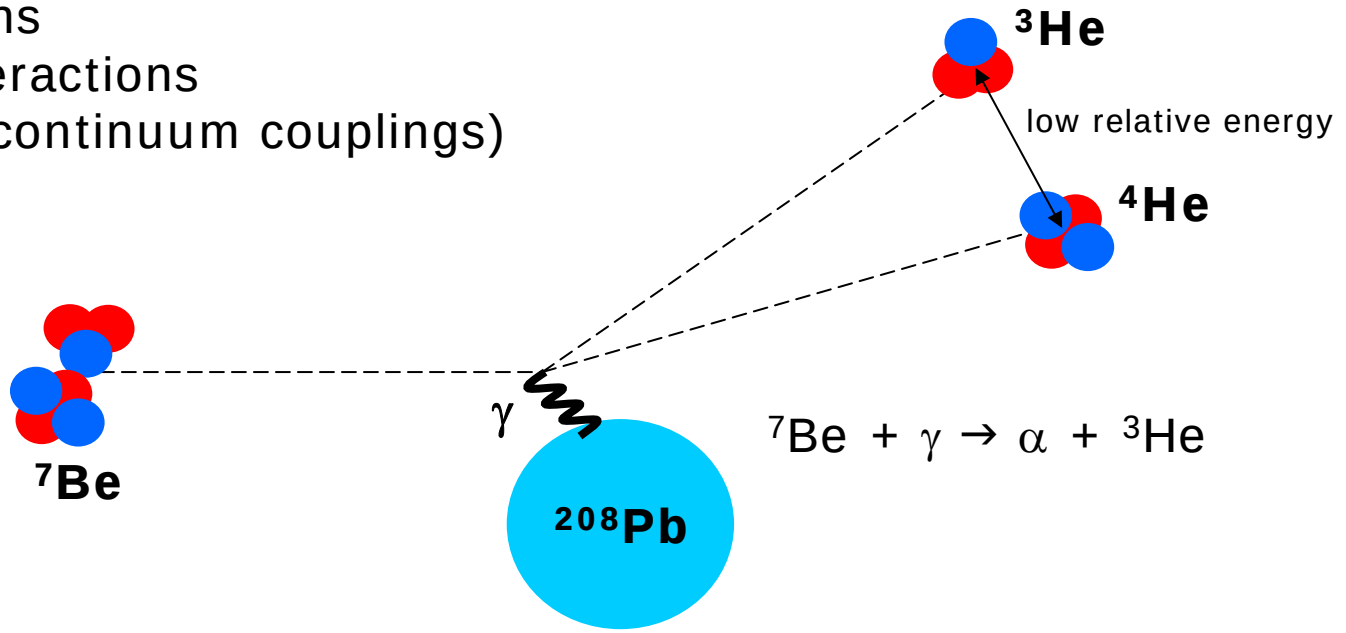
(ii) Asymptotic Normalization Coefficient (ANC) method



Coulomb Dissociation method

Cross sections larger for inverse breakup reaction
Can relate breakup cross section to capture rate using semi-classical reaction theory

complications
- **Nuclear breakup**
- E2 contributions
- Final state interactions
  (continuum-continuum couplings)



Motivated experiment at NSCL : ^{7}Be + ^{208}Pb @ 100 MeV/nucleon

ANC method (nuclear breakup)

$$\left(\frac{d\sigma}{d\Omega}\right)_{\exp} = \frac{C_{lj}^{\ 2}}{b_{nlj}^{\ 2}}\left(\frac{d\sigma}{d\Omega}\right)_{theory}^{nlj}$$

Outside range of nuclear force, in asymptotic region

$$I_{cvlj}^{P}(r) \rightarrow S_{nlj}^{1/2}\phi_{nlj}(r) \rightarrow C_{cvlj}^{P}\frac{W_{-\eta,l+\frac{1}{2}}(2kr)}{r}$$

$$C_{cvlj}^{P} = S_{nlj}^{1/2} b_{nlj}$$

overlap integral

c = core ^{4}He

v = valence ^{3}He

P = projectile ^{7}Be

Spectroscopic factor

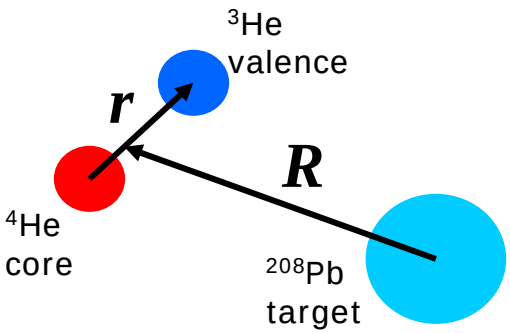
g.s. single particle wavefunction

ANC

Whittaker function

Motivated experiment at Texas A&M : ^{7}Be + ^{12}C @ 25 MeV/nucleon

Breakup of ^{7}Be: one application in detail



- ^{7}Be treated as 2-body projectile
- 3-body Hamiltonian for reaction

$$H = T_R + U_{cT} + U_{vT} + h_{vc}$$

$$h_{vc} = T_r + V_{vc}$$

fix V_{cT} and V_{vT} from elastic scattering

ϕ is ^{7}Be (α+^{3}He) cluster wavefunction defined by potential V_{vc}

$$h_{vc}\phi_n(r) = \varepsilon_n\phi_n(r) \qquad \varepsilon_n < 0$$

$$h_{vc}\phi_{lj}(k,r) = \varepsilon_k\phi_{lj}(k,r) \qquad \varepsilon_k > 0$$

fixed by
binding energy for bound states

resonances and scattering phase shifts for continuum

l = core-valence relative angular momentum
j = projectile total angular momentum

Breakup of ^{7}Be: continuum discretization

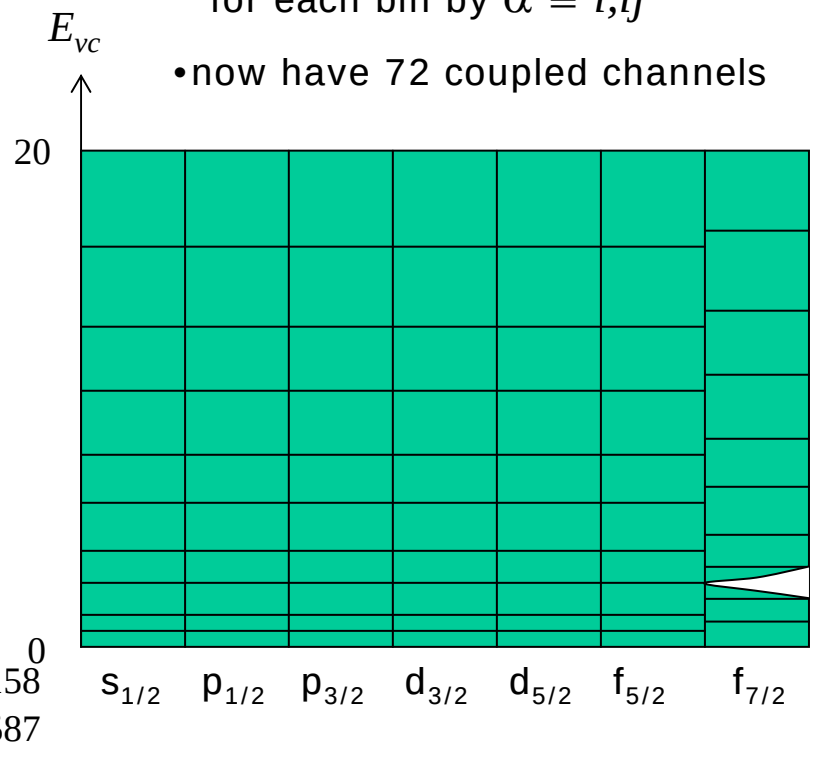
- Discretize continuum into bins
- average wavefuntion over a bin with weight $w_i(k)$

$$\phi_{i,lj}(r) = \sqrt{\frac{2}{\pi N_i}} \int_{k_{i-1}}^{k_i} w_i(k)\phi_{lj}(k,r)dk$$

$w_i(k)$ chosen so that the bin wavefunctions are real and normalized correctly using

$$N_i = \int_{k_{i-1}}^{k_i} |\, w_i(k)\,|^2 \, dk$$

- label the quantum numbers for each bin by $\alpha \equiv i,lj$
- now have 72 coupled channels



Breakup of ^{7}Be: CDCC equations

- We have 72 coupled channels, each labeled by the set of quantum numbers

$$\alpha \equiv (i\ l\ \ j\ L)$$

- Solve set of radial coupled equations

$$\left[T_R^L + V_{\alpha\alpha}^J(R) - E_\alpha\right] u_\alpha^J(R) = -\sum_{\alpha' \neq \alpha} V_{\alpha\alpha'}^J(R)\, u_{\alpha'}^J(R) \qquad (1)$$

- Where the coupling potential from state α to state α' is

$$V_{\alpha\alpha'}^J(R) = \left\langle \left[\phi_{\alpha'}(\vec{r}) \otimes Y_{L'}(\hat{R})\right]_{JM} \middle| V(\vec{r},\vec{R}) \middle| \left[\phi_\alpha(\vec{r}) \otimes Y_L(\hat{R})\right]_{JM} \right\rangle$$

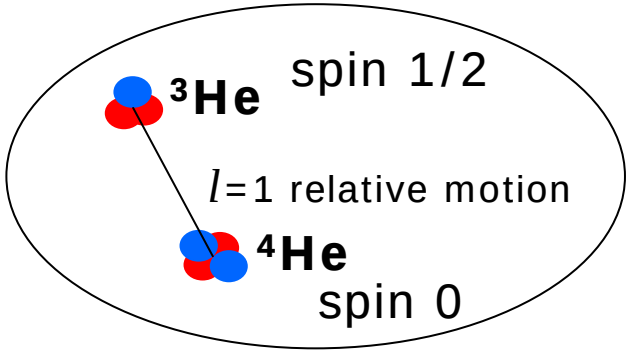
$$V(\vec{r},\vec{R}) = U_{cT}(\vec{R}_{cT}) + U_{vT}(\vec{R}_{vT})$$

and the cluster target potentials include both Coulomb and Nuclear parts

Coulomb breakup ≡ neglect Nuclear in coupling potentials on rhs of Eq. (1)
Nuclear breakup ≡ neglect Coulomb in coupling potentials on rhs of Eq. (1)

Breakup of ^{7}Be: inputs

^{7}Be modeled as 2-body projectile

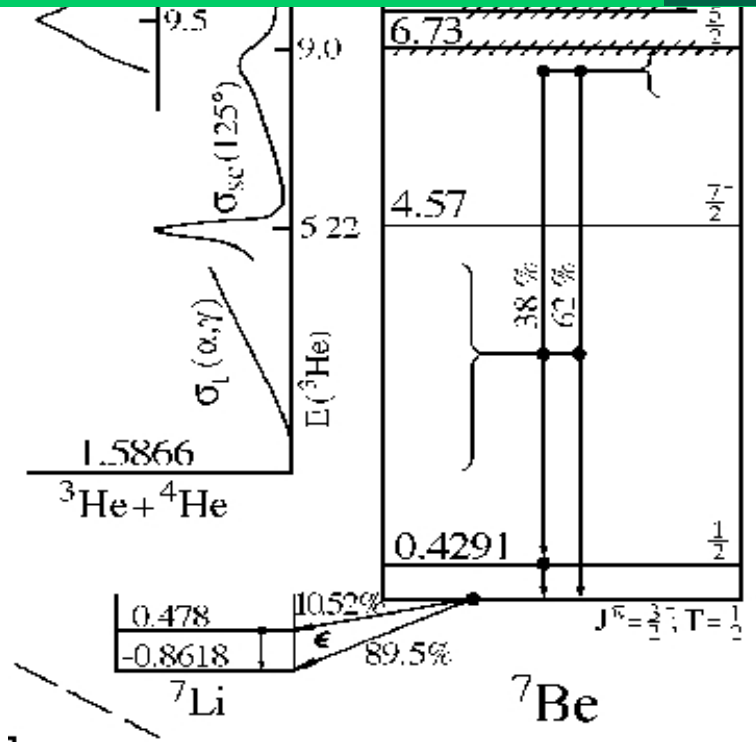


Buck *et al.*

potential fitted to :
- ground and excited state energies
- 7/2- and 5/2- resonances
- scattering phase shifts
- charge radius, quadrupole and octupole moments and B(E2) for ^{7}Li

wavefunction has node due to Pauli blocking

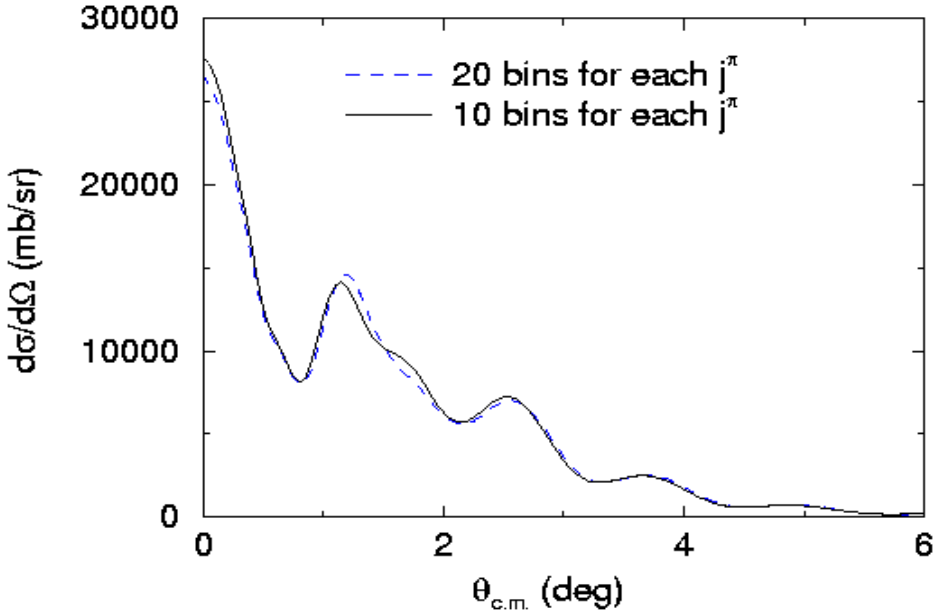
parity dependent potential



cluster-target potentials from elastic scattering

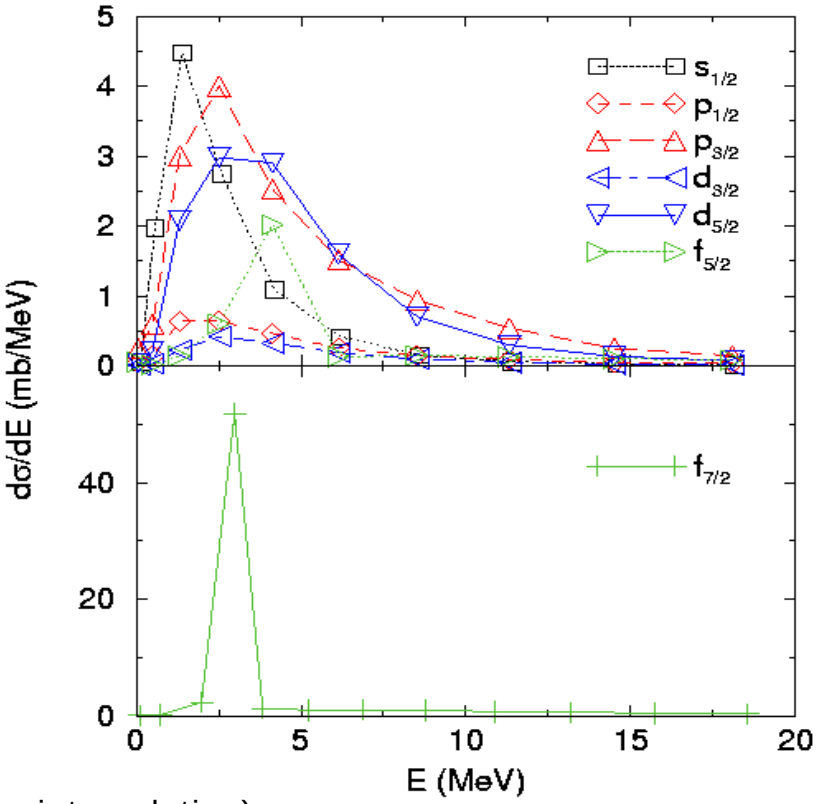
^{3}He + ^{208}Pb @ 300 MeV	NSCL
^{4}He + ^{208}Pb @ 400 MeV	
^{3}He + ^{12}C @ 75 MeV	Texas
^{4}He + ^{12}C @ 100 MeV	A & M

Breakup of ^{7}Be: convergence



^{7}Be + ^{208}Pb → ^{3}He + ^{4}He + ^{208}Pb

E_{lab} = 100 MeV/nucleon

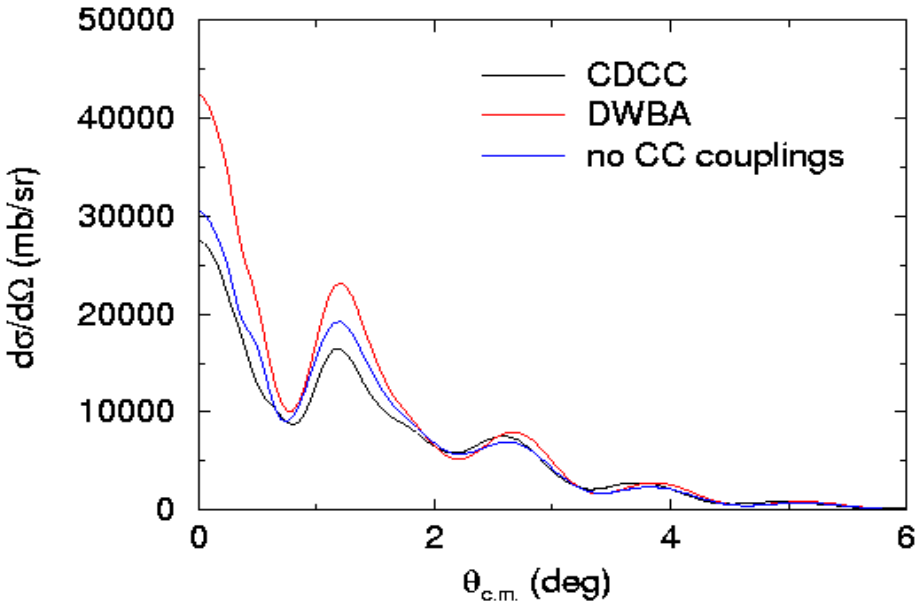


Convergence checked for many variables, such as:

- Potential multipoles ($Q \leq 2$)
- Max radius for coupled equations (R_{max}=1000fm)
- Maximum relative energy (E_{max}=20 MeV)
- Number of partial waves in coupled equations (L_{max}=10000,2000 using interpolation)
- Bin radius and step length for coupling integrals (r_{bin}=50fm, h=0.04fm)
- Number of partial waves for breakup states ($l \leq 3$)
- Iterative solution of coupled equations versus solving set of equations exactly

[PRC 70 (2004) 011602]

Breakup of ^{7}Be: higher order couplings

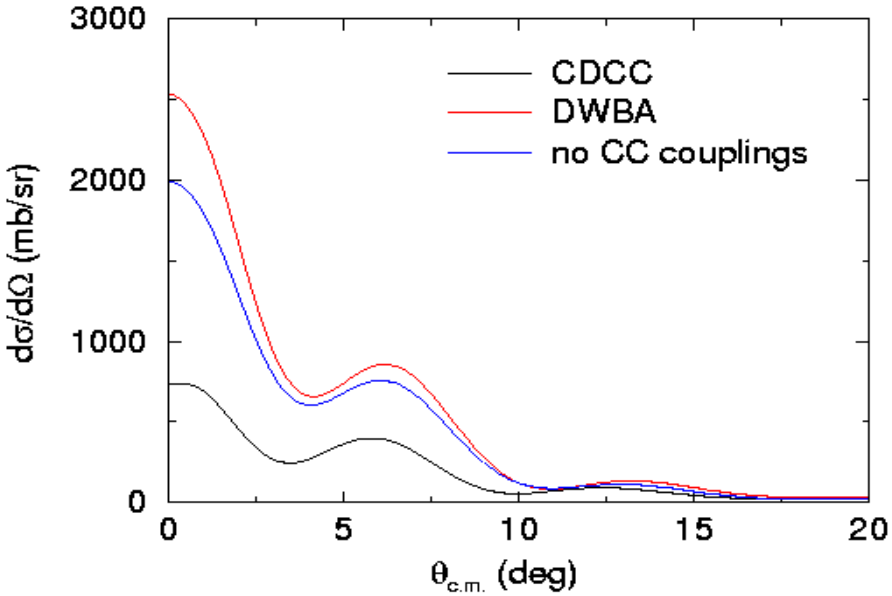


^{7}Be + ^{208}Pb → ^{3}He + ^{4}He + ^{208}Pb

E_{lab} = 100 MeV/nucleon

^{7}Be + ^{12}C → ^{3}He + ^{4}He + ^{12}C

E_{lab} = 25 MeV/nucleon



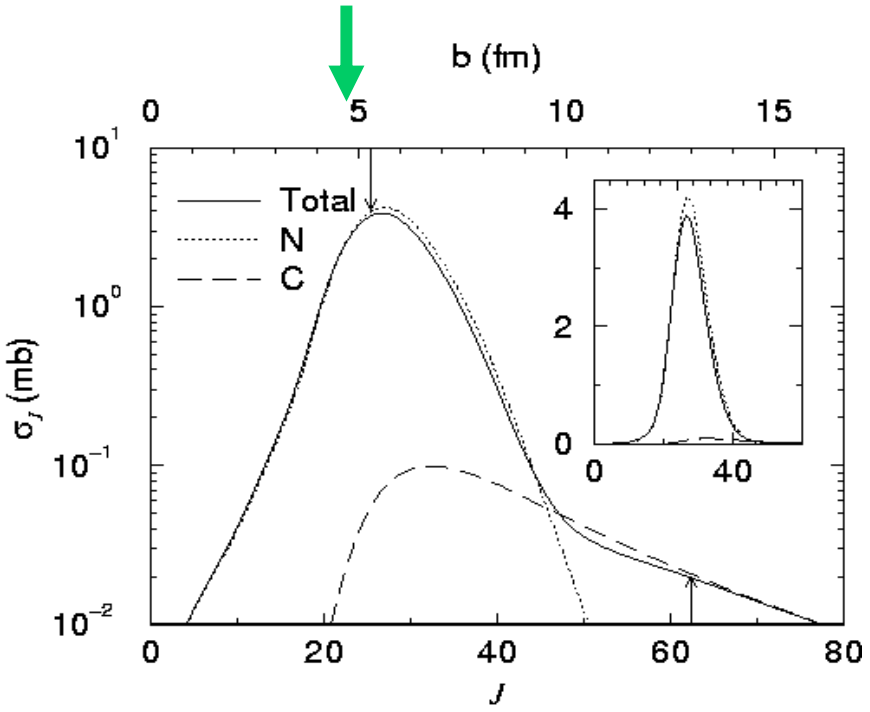
[PRC 70 (2004) 011602]

Breakup of ^{7}Be on C: peripherality

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

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

E_{lab} = 25 MeV/nucleon



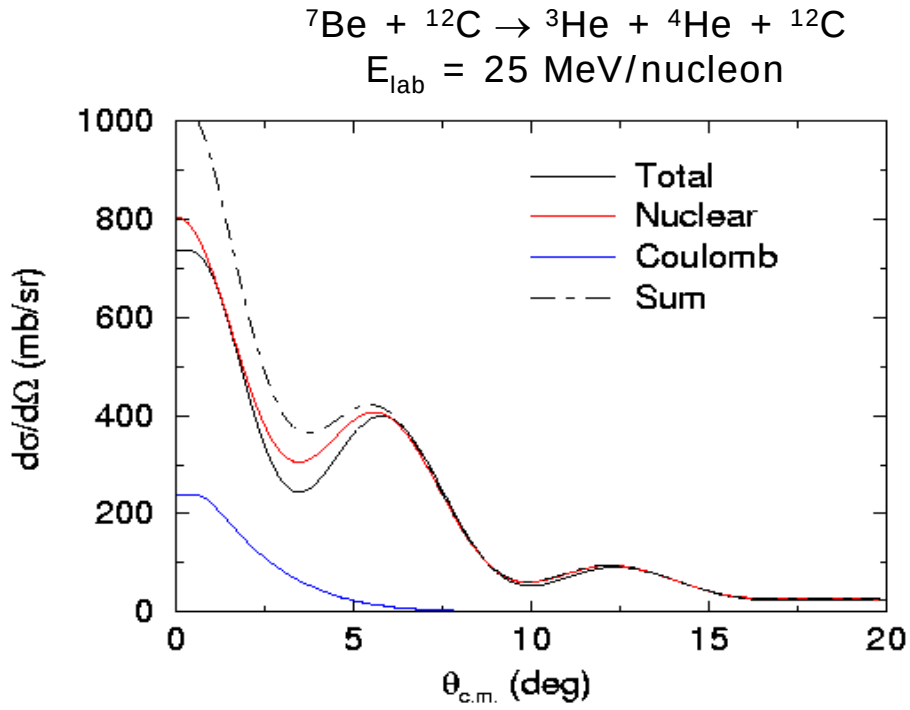
approx 28% of breakup
cross section comes from
impact parameters
less than sum of radii

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

[PRC 70 (2004) 011602]

Breakup of ^{7}Be on C: Coulomb free?

Note that Coulomb is not negligible

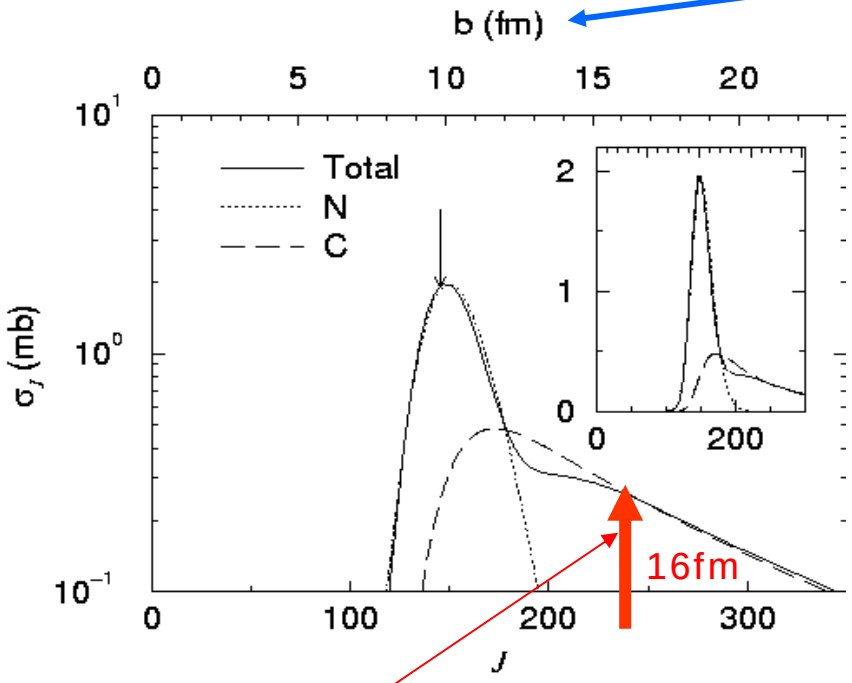


[PRC 70 (2004) 011602]

Breakup of ^{7}Be: nuclear free?

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

E_{lab} = 100 MeV/nucleon



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

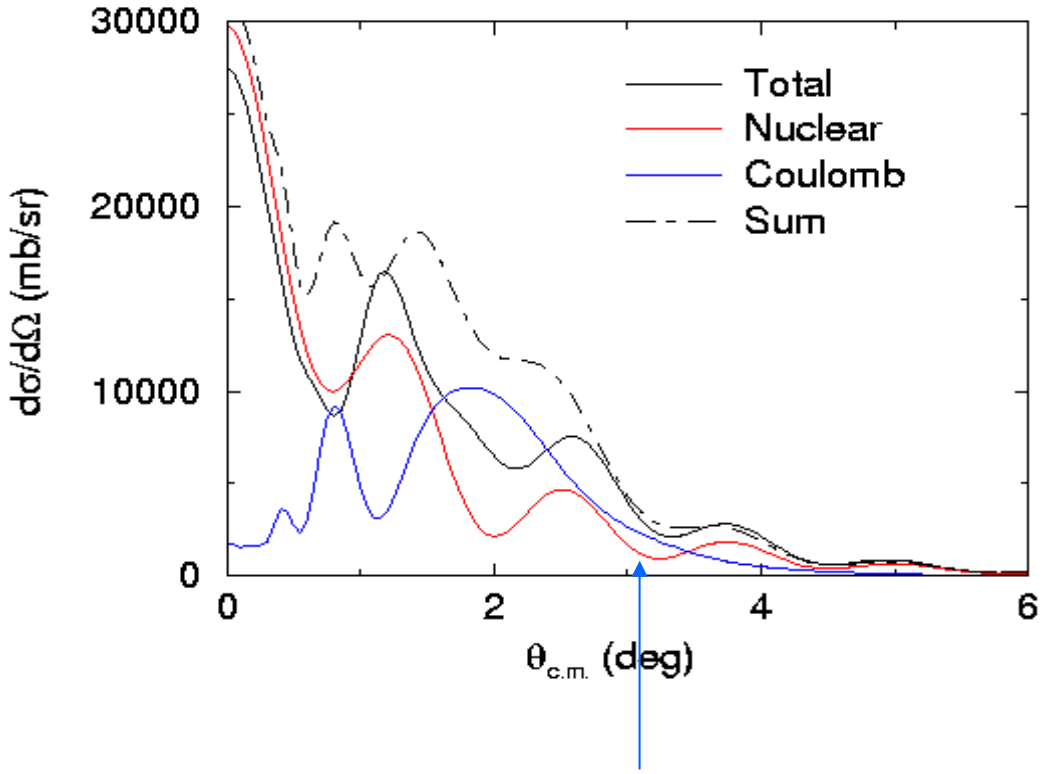
Coulomb dissociation method requires that the reaction is Coulomb dominated, outside the range of the nuclear force

maximum range of nuclear force

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

[PRC 70 (2004) 011602]

Breakup of ^{7}Be: nuclear component



^{7}Be + ^{208}Pb → ^{3}He + ^{4}He + ^{208}Pb

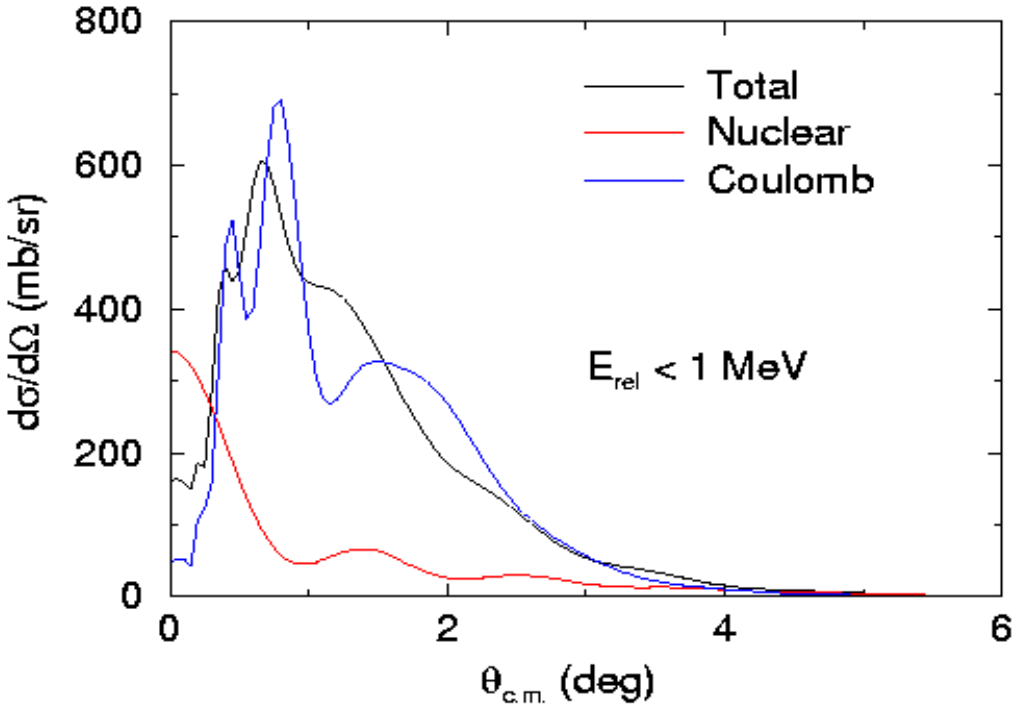
E_{lab} = 100 MeV/nucleon

Cut-off angle from Rutherford orbit = 2.5°

cross section dominated by nuclear breakup even for small scattering angles below the cut-off angle

[PRC 70 (2004) 011602]

Breakup of ^{7}Be: small relative energies



Angular cross section summed for only first 2 bins in each j^{π} set

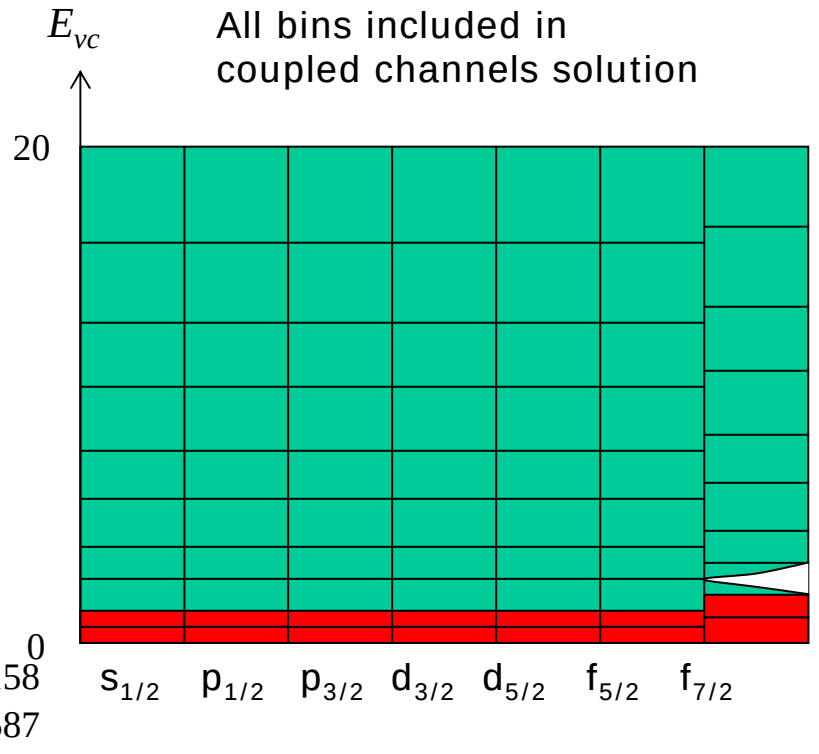
This dramatically reduces the amount of nuclear breakup in the forward angles

^{7}Be + ^{208}Pb → ^{3}He + ^{4}He + ^{208}Pb

E_{lab} = 100 MeV/nucleon

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

All bins included in coupled channels solution

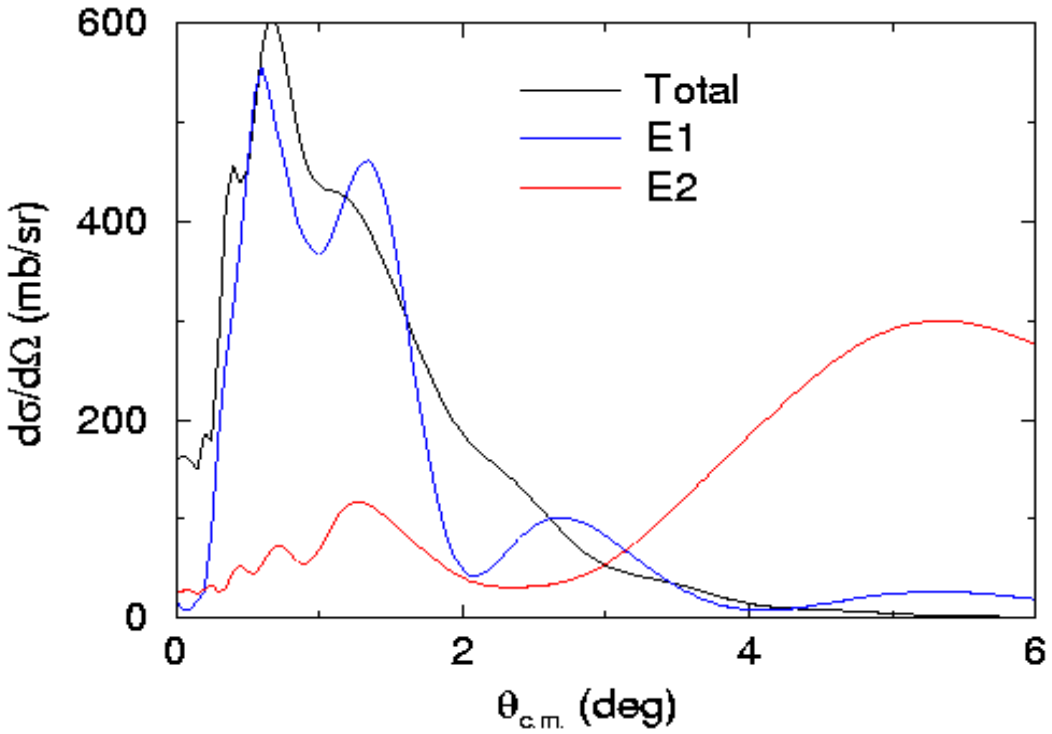


[PRC 70 (2004) 011602]

Breakup of ^{7}Be: E1 versus E2

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

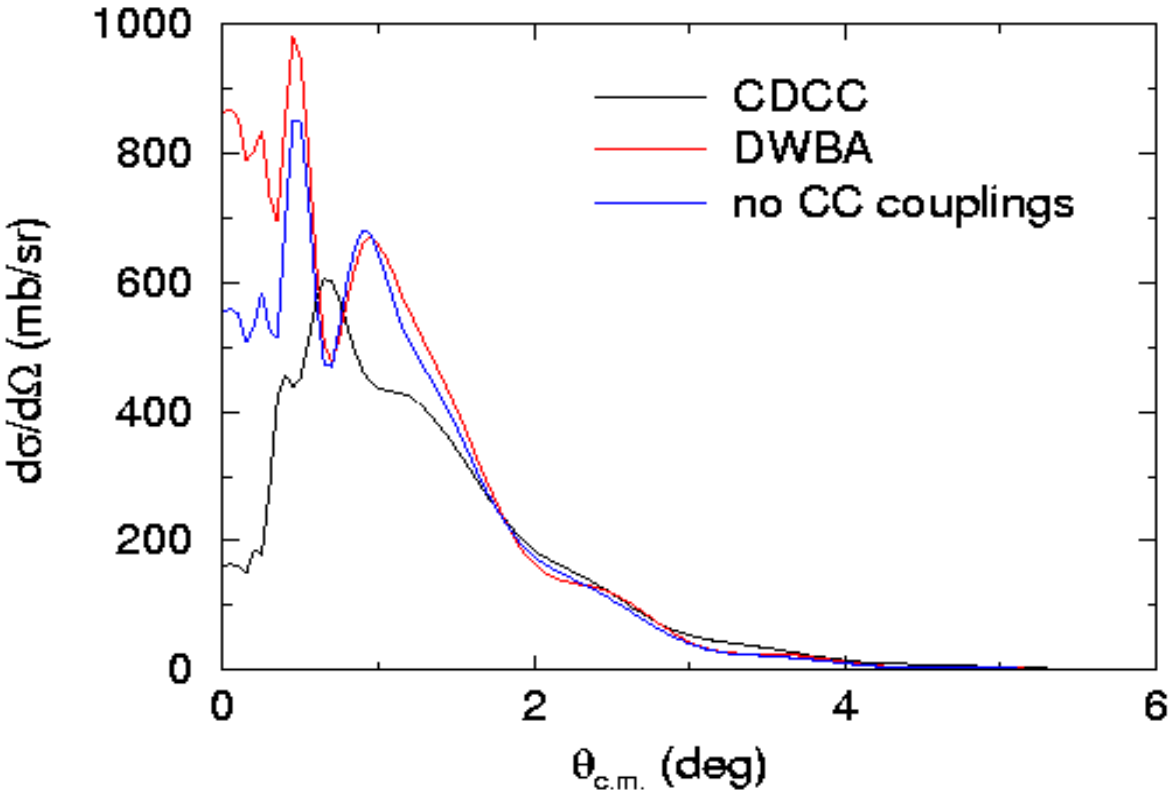
E_{lab} = 100 MeV/nucleon



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

[PRC 70 (2004) 011602]

Breakup of ^{7}Be: cont-cont couplings



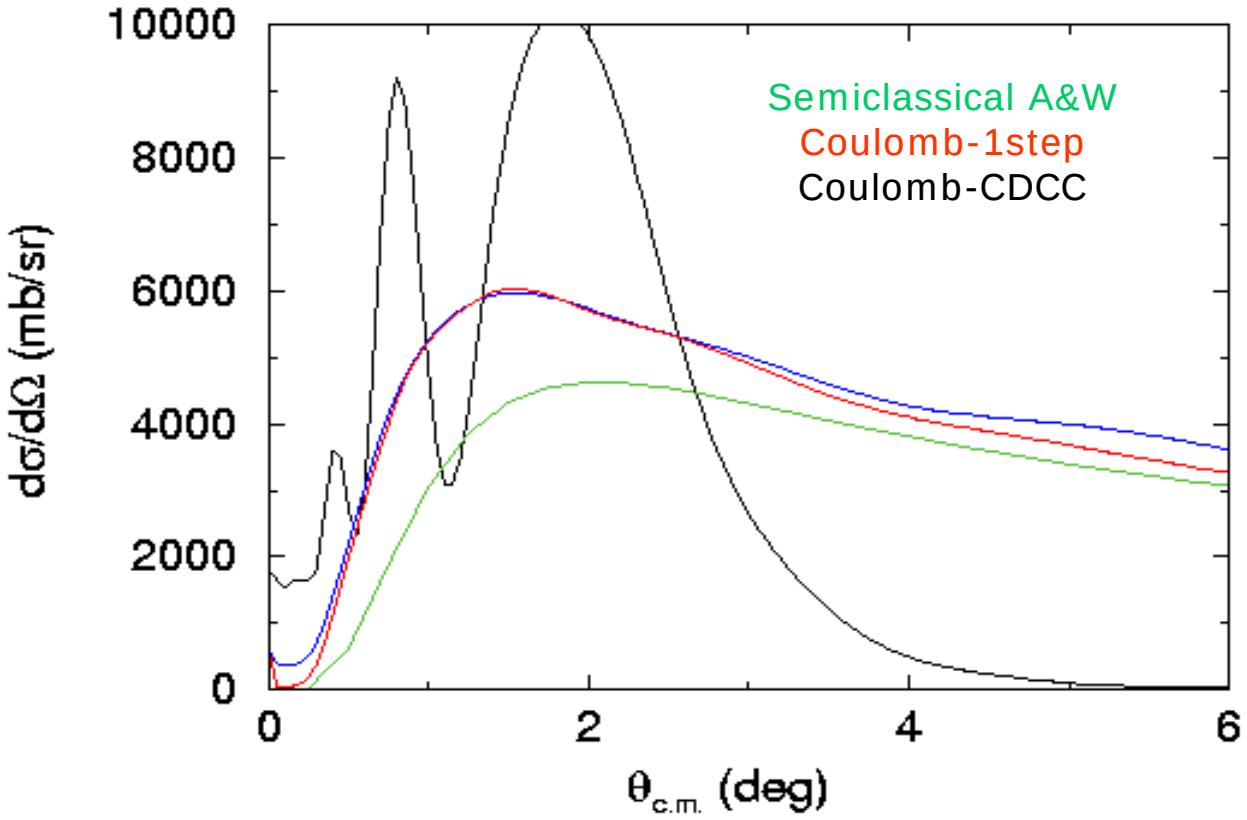
restricted maximum relative energy between ^{3}He and ^{4}He fragments in final state

DWBA → first order

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

[PRC 70 (2004) 011602]

Breakup of ^{7}Be: comparison with other models



^{7}Be + ^{208}Pb → ^{3}He + ^{4}He + ^{208}Pb

E_{lab} = 100 MeV/nucleon

[PRC 70 (2004) 011602]

CDCC cross sections

1) Calculate:
   - projectile wfns: bound and scattering states
   - bins wfns
   - coupling potentials
2) Solve coupled channel equations and match to obtain S-matrix
3) Construct observables.

Scattering amplitude

$$\tilde{\mathcal{F}}_{M'M}(\mathbf{K}_{p'}) = \frac{4\pi}{K_0}\sqrt{\frac{K_{p'}}{K_0}}\sum_{LL'J}\langle L0, I_p M\,|JM\rangle\,\langle L'M-M', I_{p'}M'|JM\rangle$$

$$\times\,\exp(\mathrm{i}[\sigma_L+\sigma_{L'}])\,\frac{1}{2\mathrm{i}}\,\mathbf{S}^J_{\alpha'\alpha}(p')\,Y^0_L(\hat{\mathbf{K}}_0)\,Y^{M-M'}_{L'}(\hat{\mathbf{K}}_{p'}).$$

$$\frac{d\sigma(p')}{d\Omega_K} = \frac{1}{2I_p+1}\sum_{MM'}\left|\tilde{\mathcal{F}}_{M'M}(\mathbf{K}_{p'})\right|^2$$

Three-body observables: T-matrix

T matrix can be constructed from the CDCC solution

$$\mathbf{T}_{\mu\sigma:M}(\mathbf{k},\mathbf{K}) = \langle \phi^{(-)}_{\mathbf{k}\mu\sigma}(\mathbf{r})\, \mathrm{e}^{\mathrm{i}\mathbf{K}\cdot\mathbf{R}} | U(\mathbf{r},\mathbf{R}) | \Psi^{\mathrm{CDCC}}_{\mathbf{K}_0 M}(\mathbf{r},\mathbf{R}) \rangle$$

$$\mathbf{T}_{\mu\sigma:M}(\mathbf{k},\mathbf{K}) = \sum_{p,M'} \langle \phi^{(-)}_{\mathbf{k}\mu\sigma} | \tilde{\phi}^{M'}_{p} \rangle \langle \tilde{\phi}^{M'}_{p}\, \mathrm{e}^{\mathrm{i}\mathbf{K}\cdot\mathbf{R}} | U(\mathbf{r},\mathbf{R}) | \Psi_M(\mathbf{r},\mathbf{R}) \rangle$$

$$\langle \hat{\phi}^{(-)}_{\mathbf{k}\mu\sigma} | \phi^{M'}_{p} \rangle = \frac{(2\pi)^{3/2}}{k\sqrt{N_\alpha}} \sum_{\nu} (-\mathrm{i})^{\ell}\, \langle \ell\nu, s\sigma | jm \rangle \langle jm, I_c\mu | I'_p M' \rangle \mathrm{e}^{\mathrm{i}\bar{\delta}_p(k)}\, \tilde{u}_p(k) Y_{\ell\nu}(\hat{\mathbf{k}}).$$

$$\widehat{\mathcal{T}}^{p}_{M'M}(\mathbf{K}_p) = \langle \hat{\phi}^{M'}_{p}\, \mathrm{e}^{\mathrm{i}\mathbf{K}_p\cdot\mathbf{R}} | U(\mathbf{r},\mathbf{R}) | \Psi^{\mathrm{CDCC}}_{\mathbf{K}_0 M}(\mathbf{r},\mathbf{R}) \rangle = -\frac{2\pi\hbar^2}{\mu_{(vc)t}} \sqrt{\frac{K_0}{K_p}}\, \tilde{\mathcal{F}}_{M'M}(\mathbf{K}_p)$$

CDCC three-body observables

Let's say we measure the energy of one fragment c and the angles of both:

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}\Omega_c \mathrm{d}\Omega_v \mathrm{d}E_c} = \frac{2\pi\,\mu_{(vc)t}}{\hbar^2 K_0}\,\frac{1}{(2I_p+1)}\sum_{\mu\sigma M}\left|\mathbf{T}_{\mu\sigma:M}(\mathbf{k},\mathbf{K})\right|^2\,\rho_{\mathrm{ps}}(E_c,\Omega_c,\Omega_v),$$

Phase space factor

$$\rho_{\mathrm{ps}}(E_c,\Omega_c,\Omega_v)\mathrm{d}E_c\mathrm{d}\Omega_c\mathrm{d}\Omega_v =$$

$$\int \mathrm{d}^3\mathbf{k}_c\mathrm{d}^3\mathbf{k}_v\mathrm{d}^3\mathbf{k}_t\;\delta(\mathbf{P}-\hbar\mathbf{k}_c-\hbar\mathbf{k}_v-\hbar\mathbf{k}_t)\;\delta(E-E_c-E_v-E_t),$$

CDCC three-body observables

Let's say we only measure fragment c both energy and angles, with a certain solid angle and an efficiency dependent on angle:

$$\left\langle \frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega_c \mathrm{d}E_c} \right\rangle = \frac{1}{\Delta\Omega_c} \int_{\Delta\Omega_c} \mathrm{d}\Omega_c \left\{ e(\Omega_c) \int \mathrm{d}\Omega_v \frac{\mathrm{d}^3\sigma}{\mathrm{d}\Omega_c \mathrm{d}\Omega_v \mathrm{d}E_c} \right\}$$

Other typical observables:
momentum distributions

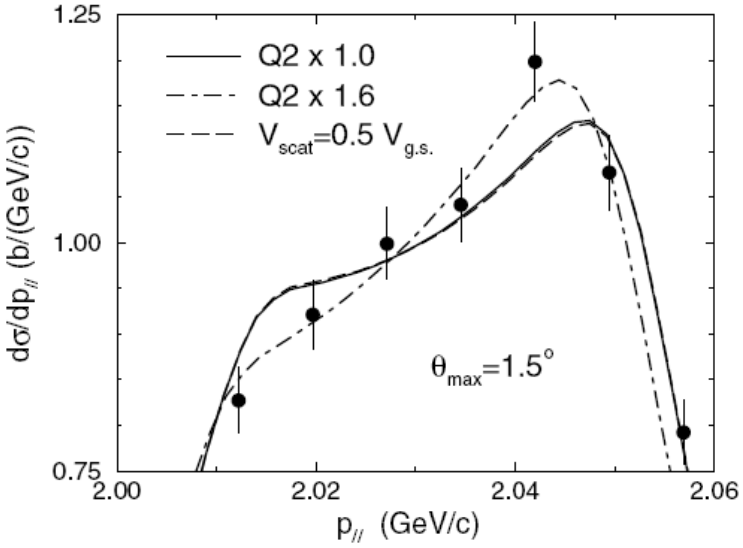


FIG. 4: Momentum distribution of ^{7}Be following the breakup of 44 MeV/A ^{8}B on a ^{208}Pb target integrated up to $\theta_{max} = 1.5°$: the previous results [8] with no renormalisation of the quadrupole excitation (solid line) and with a 1.6 renormalization (dot-dashed line) and the result using 0.5*V(p-Be) for the final state (dashed line).