CENTRE FOR NUCLEAR & RADIATION PHYSICS

Exploring Nuclear Haloes by the Ratio Method

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Outline

1. Halo nuclei

   $^{11}Li = ^{9}Li + 2n$, $^{11}Be = ^{10}Be + n$, ……..

2. Recoil Excitation and Breakup Model (REB)

   Few-body model.

3. Dependence of Crosssections on Halo Structure.

   Halo form factors

4. Properties of crosssection ratios.

5. The Dynamical Eikonal approximation (DEA)

6. Conclusions

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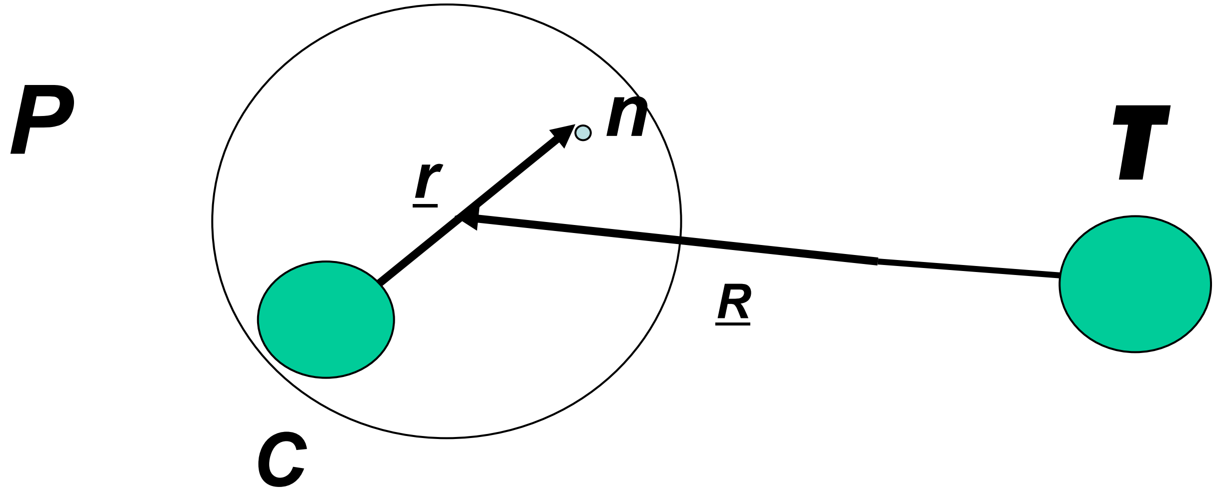
Few-body model



$$H = T_R + H_0 + V_{cT} + V_{nT}$$

$$H_0 = T_r + V_{nc}$$

$$(H_0 - \epsilon_0)\,\Phi_0(\vec{r}) = 0$$

$\Phi_0(\vec{r})$ =Ground state of P

Recoil Excitation and Breakup Model (REB).

Johnson, Al-Khalili and Tostevin,
PRL 79, 2771 (1997)

The model:

1. V_{nT} =0.
   (Validity to be discussed later in the talk)

2. Projectile excitation energy<< incident energy (Adiabatic approximation).

Complete solution of the three-body Schroedinger equation within the model.

Recoil Excitation and Breakup Model (REB). Elastic scattering

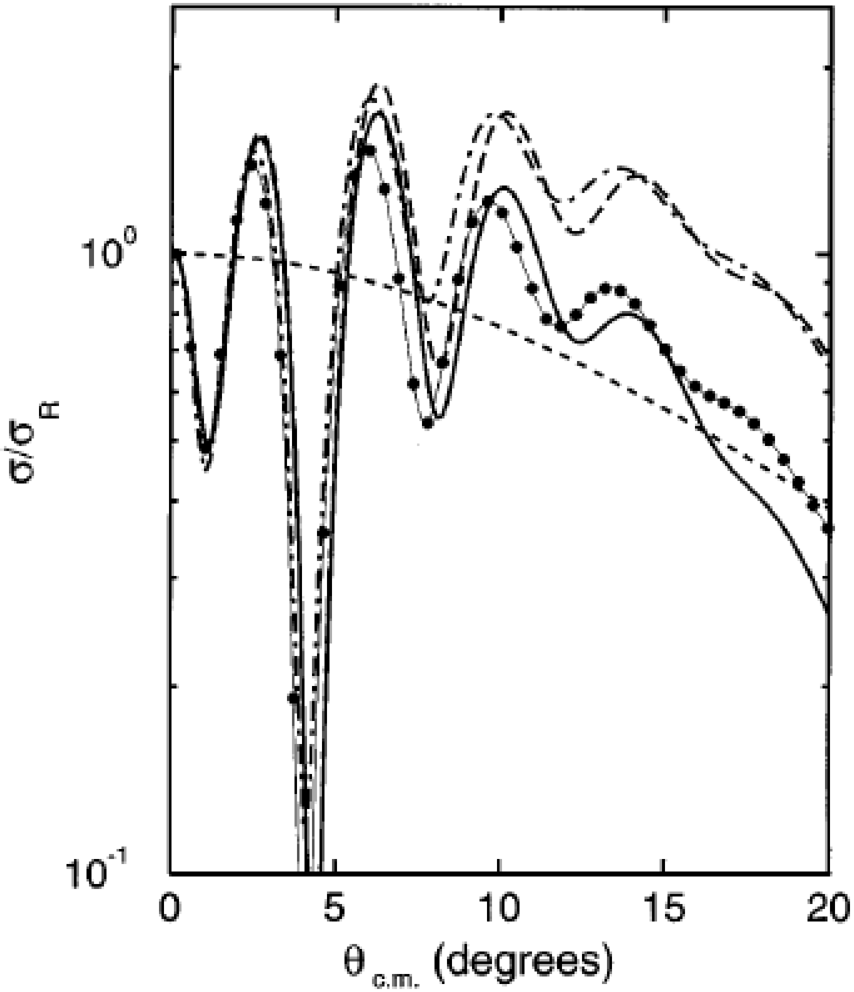
$$\frac{d\sigma_{\rm el}}{d\Omega} = \mid F_{0,0}(\vec{Q}) \mid^2 \times \frac{d\sigma_{\rm pt}}{d\Omega}$$

$$F_{0,0}(\vec{Q}) = \int d\vec{r}\Phi_0^*(\vec{r})\Phi_0(\vec{r})\exp(\imath\vec{Q}.\vec{r})$$

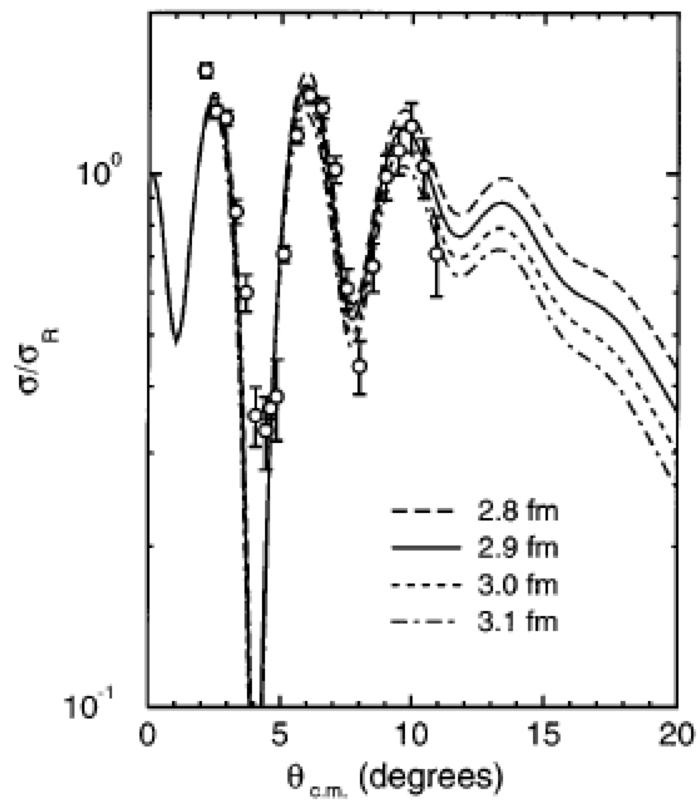
$$\vec{Q} = \frac{m_n}{m_P}(\vec{K} - \vec{K}'), \quad Q = \frac{m_n}{m_P}2K\sin\theta/2$$

$\frac{d\sigma_{\rm pt}}{d\Omega}$ = point elastic crosssection for P particle by V_{cT}.

REB Model for elastic scattering



Johnson, Al-Khalili and Tostevin, PRL79,2771(1997)



Elastic Scattering; $^{11}Be+^{12}C$ at 43.9MeV/A. GANIL expt. data.

Recoil Excitation and Breakup Model (REB). Breakup Crosssections

$$\frac{d\sigma_{\rm bu}}{dE\, d\Omega} = \mid F_{E,0}(\vec{Q}) \mid^2 \times \frac{d\sigma_{\rm pt}}{d\Omega}$$

$$\mid F_{E,0}(\vec{Q}) \mid^2 = \sum_{ljm} \mid \int d\vec{r}\,\Phi^*_{Eljm}(\vec{r})\Phi_0(\vec{r}) \exp(\imath\vec{Q}.\vec{r}) \mid^2$$

Ω = direction of centre-of-mass of n-c pair.

E = relative energy of $n - c$ pair in the break-up continuum.

l, j, m = relative angular momentum of $n - c$ pair.

REB ratios

$$\frac{d\sigma_{\rm bu}/dE\, d\Omega}{d\sigma_{\rm el}/d\Omega} = \frac{|\ F_{E,0}(\vec{Q})\ |^2}{|\ F_{0,0}(\vec{Q})\ |^2}$$

1.Independent of reaction dynamics. Not affected by the c-T optical potential V_{cT}

2.Depends only on internal dynamics of projectile P.

3.Independent of target for a fixed momentum transfer .

4.Independent of absolute normalization of experimental crosssections.

5.Validity of REB can be tested by using a more complete theory.

Alternative Ratio

$$\frac{d\sigma_{\mathrm{sum}}}{d\Omega} = \frac{d\sigma_{\mathrm{el}}}{d\Omega} + \frac{d\sigma_{\mathrm{inel}}}{d\Omega} + \int \frac{d\sigma_{\mathrm{bu}}}{dE d\Omega} dE.$$

$$\frac{d\sigma_{\mathrm{bu}}/dEd\Omega}{d\sigma_{\mathrm{sum}}/d\Omega} = |F_{E,0}(\boldsymbol{Q})|^2.$$

$$| F_{E,0}(\vec{Q}) |^2 = \sum_{ljm} | \int d\vec{r} \Phi^*_{Eljm}(\vec{r}) \Phi_0(\vec{r}) \exp(\imath \vec{Q}.\vec{r}) |^2$$

^{11}Be halo structure

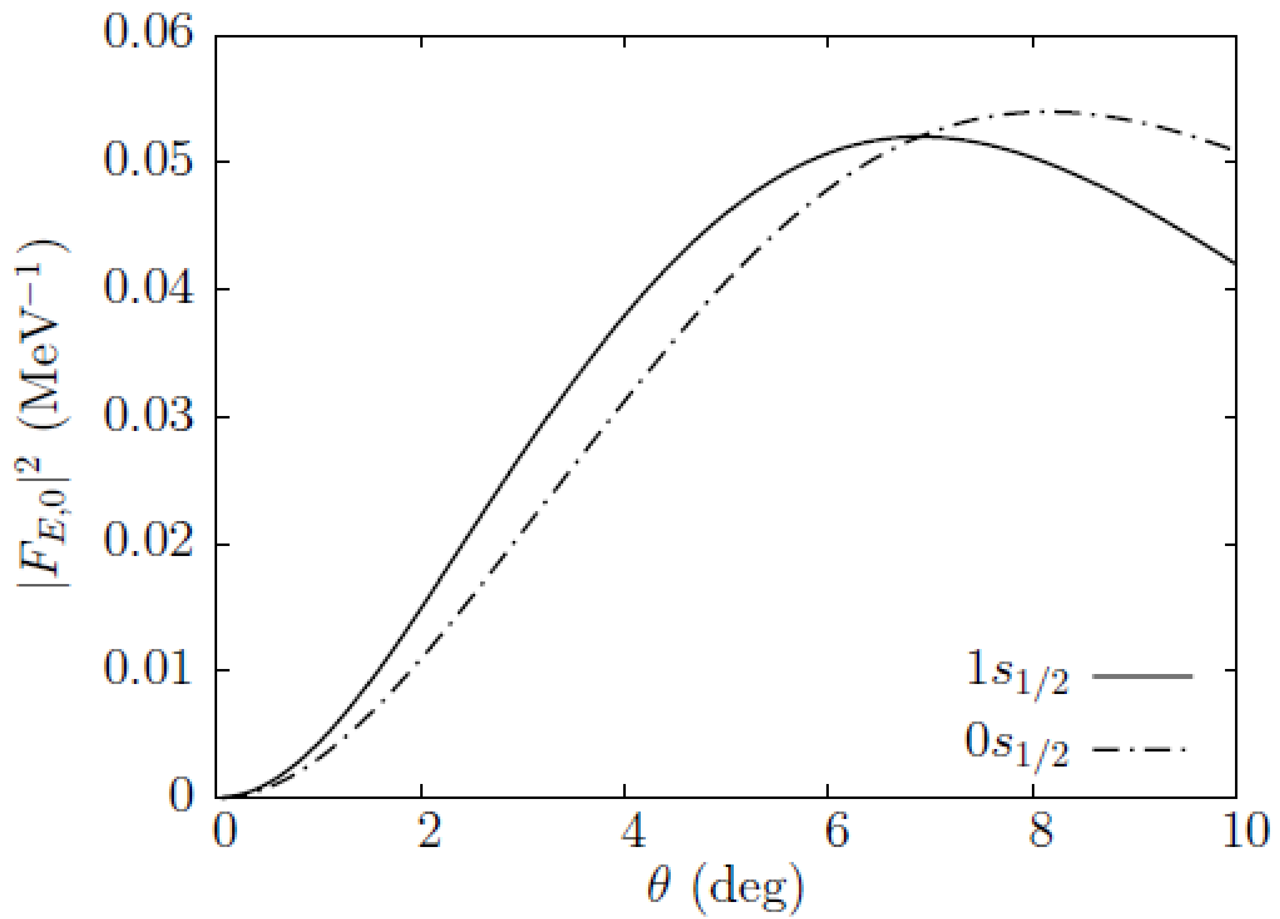
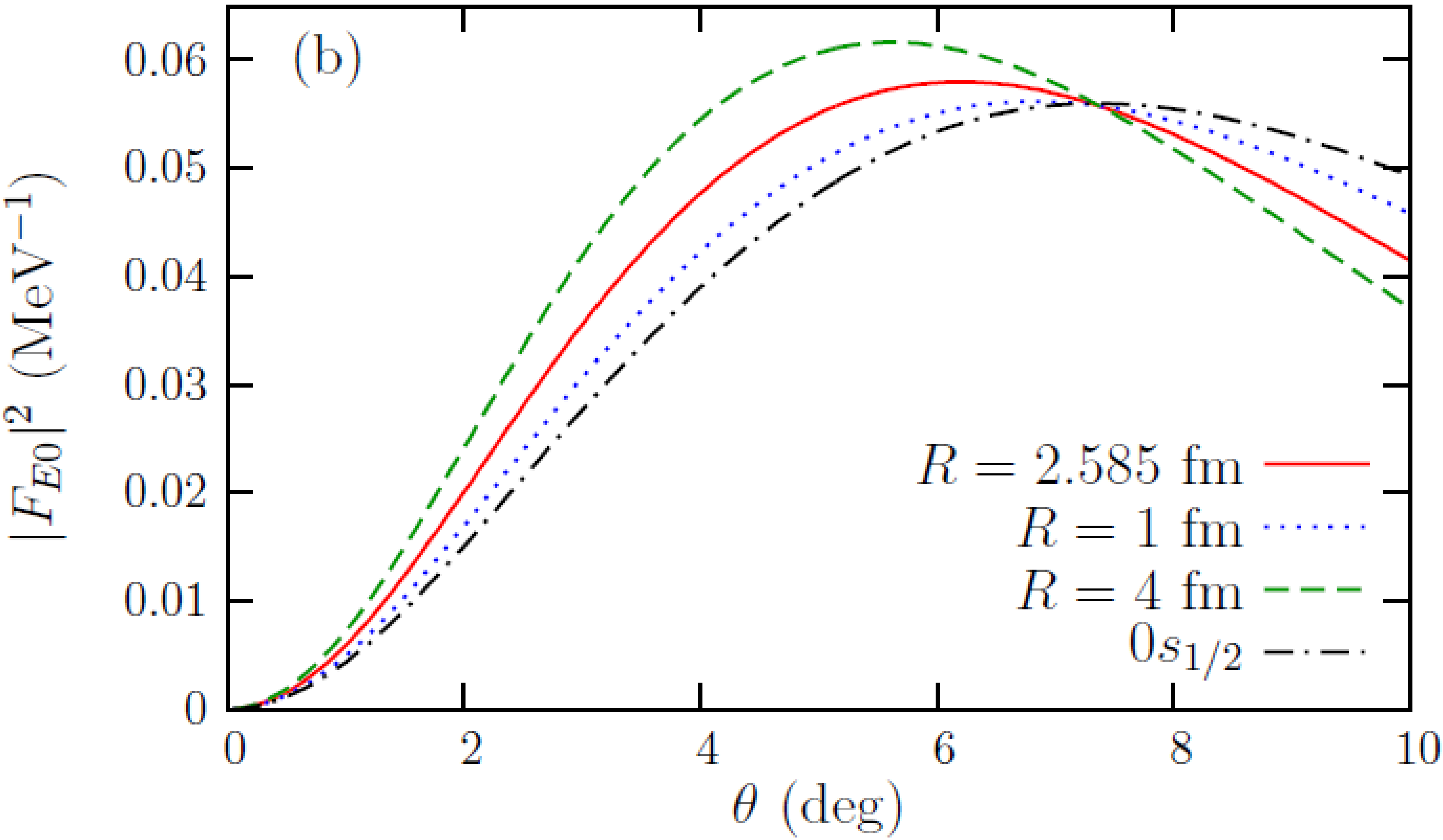


FIG. 1: Form factor $|F_{E,0}|^2$ for ^{11}Be impinging on Pb at 69 MeV/nucleon. Differences are observed between (realistic) $1s_{1/2}$ and $0s_{1/2}$ ground states.

Sensitivity to n-^{10}Be interaction



^{11}Be, $E = 0.1$MeV, $Q(\theta) \Longrightarrow 69$ Mev/A on Pb.

Dynamic Eikonal Approximation (DEA)

Goldstein, Baye and Capel, PRC 73, 024602(2006)

1. V_{nT} included.
2. Adiabatic approximation not used.
3. Gives a good account of break-up crossections.

$$(T_R + H_0 + V_{cT} + V_{nT} - E)\Psi(\vec{R},\vec{r}) = 0$$

$$\Psi(\vec{R},\vec{r}) = \exp(\imath KZ)\hat{\Psi}(\vec{R},\vec{r})$$

$$-T_R\hat{\Psi} + \imath\hbar\, v\frac{\partial\hat{\Psi}}{\partial Z} = (H_0 + V_{cT} + V_{nT} - \epsilon_0)\hat{\Psi}$$

Comparison of REB and DEA predictions

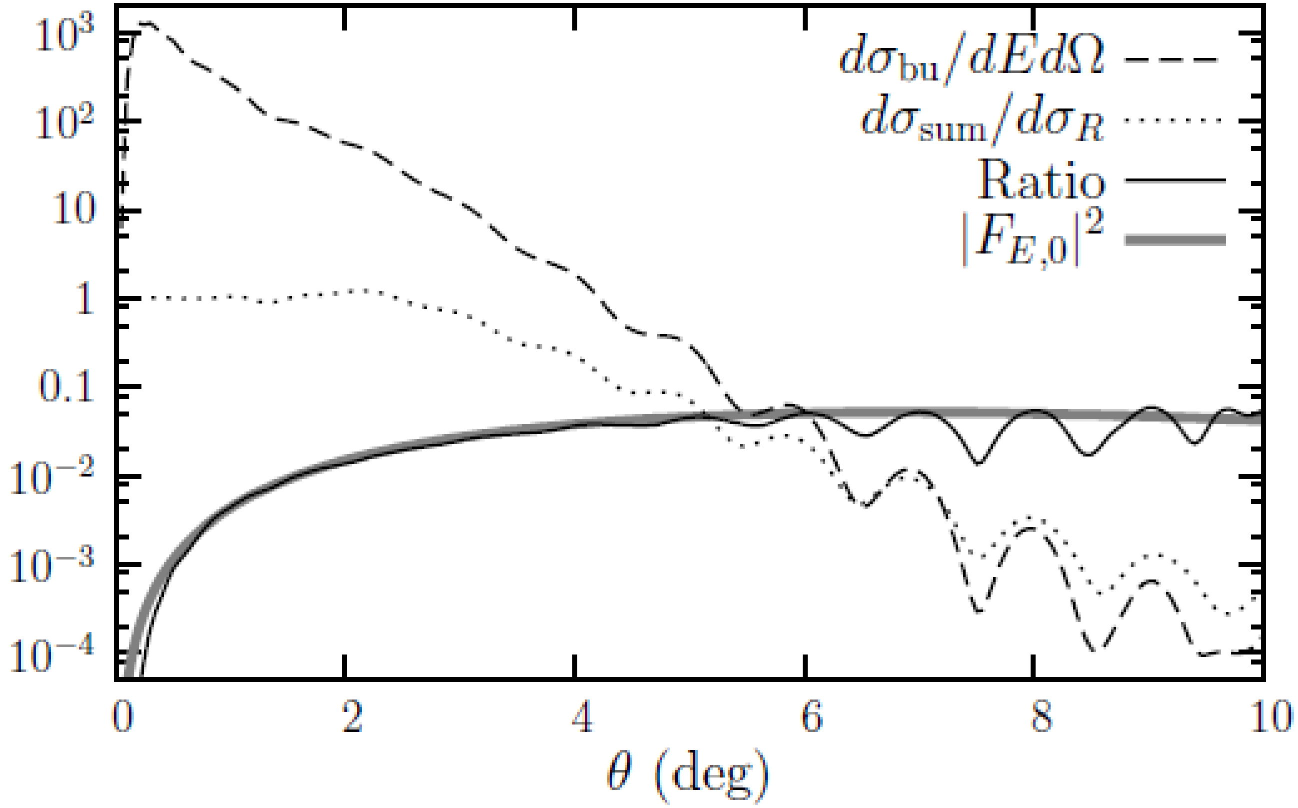


FIG. 2: Ratio of the breakup and summed angular distributions for ^{11}Be on Pb at 69 MeV/nucleon. DEA calculation is compared to its REB estimation $|F_{E,0}|^2$.

Dependence on Target: Pb and C

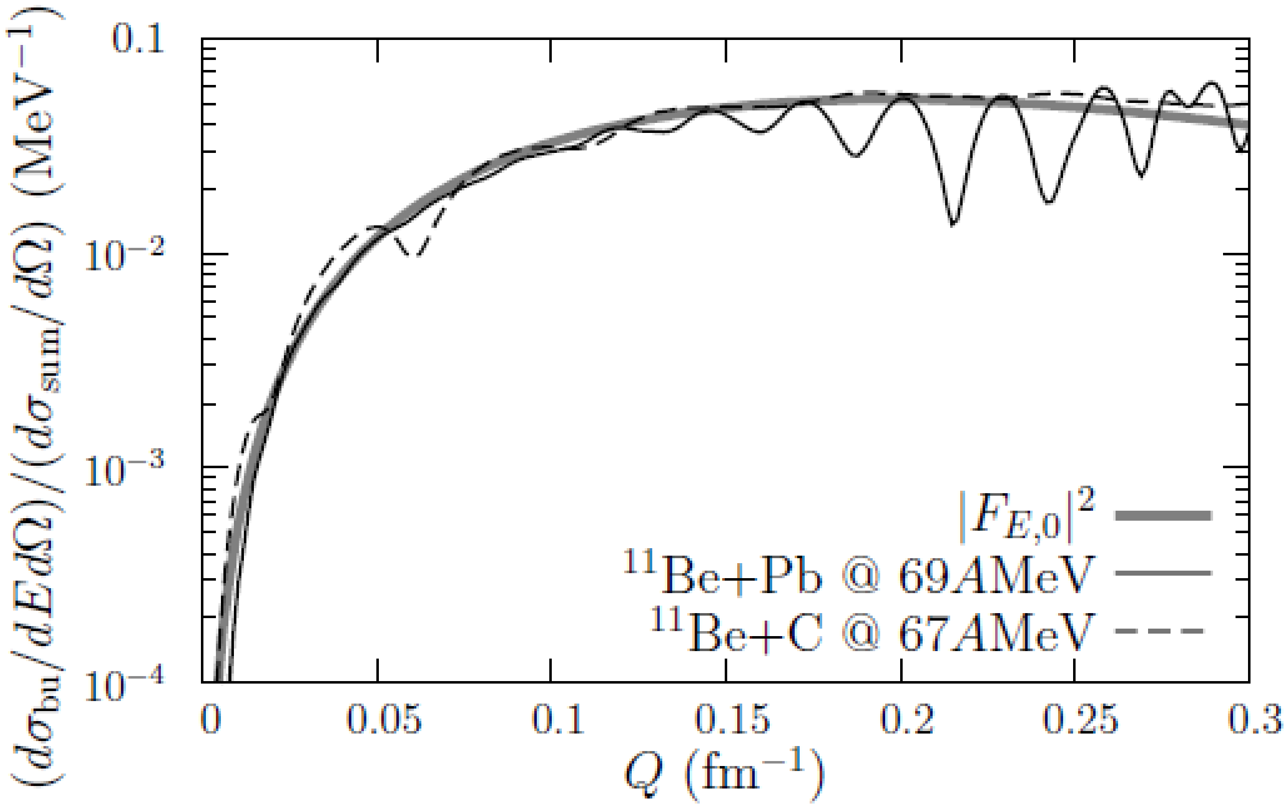
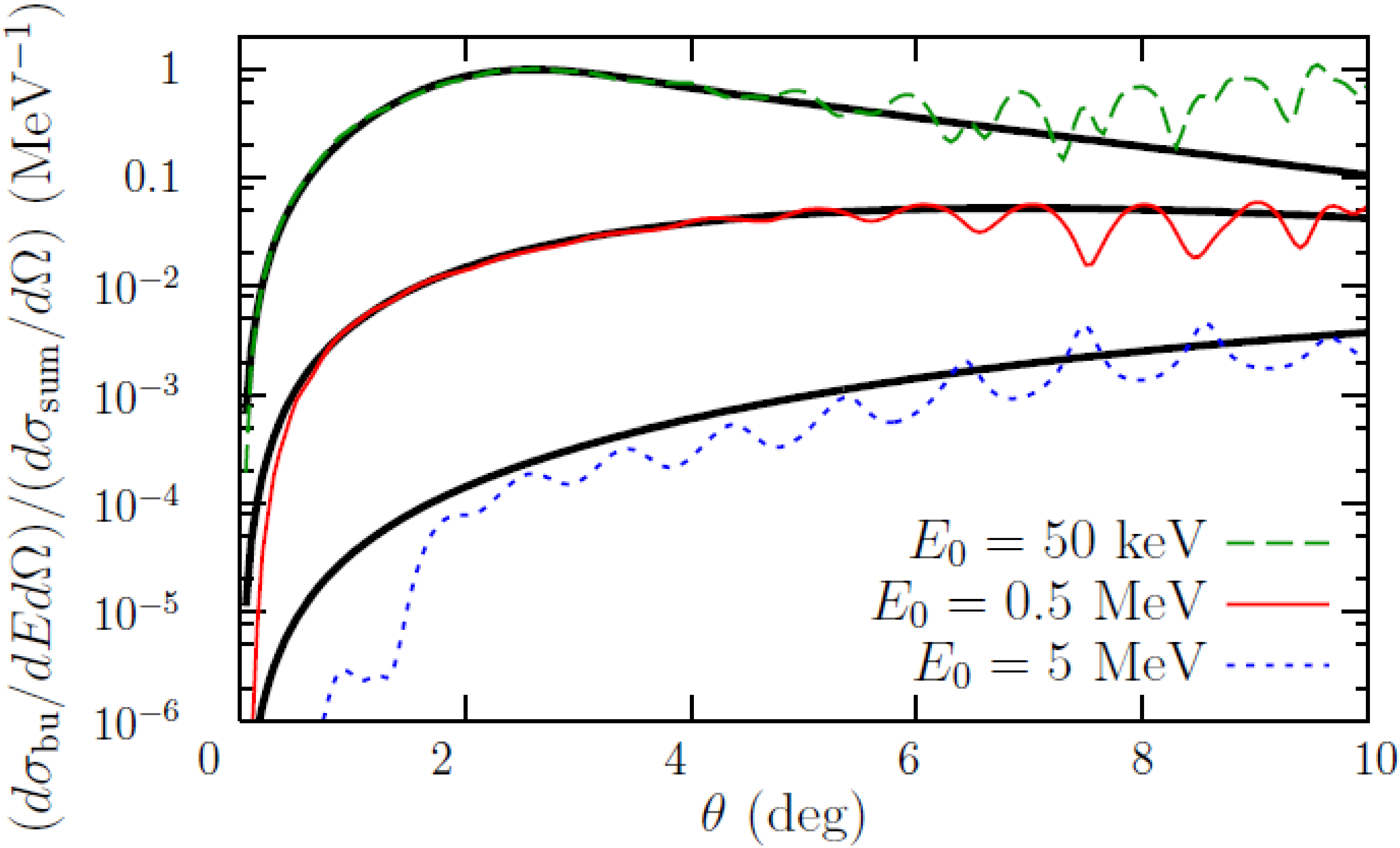


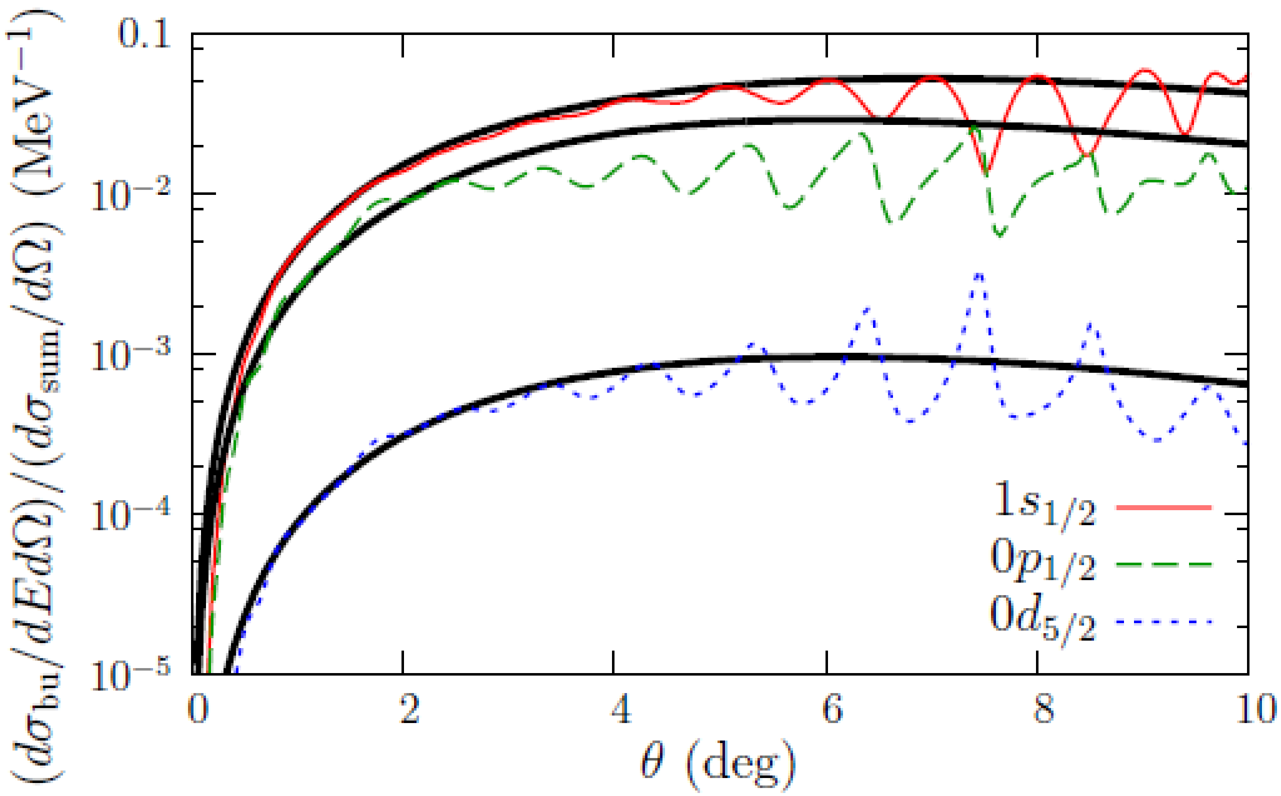
FIG. 3: Sensitivity of ratio (6) to the reaction mechanism. DEA calculations on different targets are compared to $|F_{E,0}|^2$.

Sensitivity to Binding Energy



^{11}Be, $E = 0.1$MeV, $Q(\theta) \Longrightarrow$ 69 Mev/A on Pb.

Sensitivity to binding orbital



^{11}Be, $E = 0.1$MeV, $Q(\theta) \Longrightarrow$ 69 Mev/A on Pb.

Conclusions

1. Elastic-scattering and breakup angular distributions exhibit similar features as if projectile is scattered in the same way in a bound or broken up state.

   Capel, Hussein and Baye PLB 693, 448 (2010)

2. REB model explains this similarity and suggests that the

   RATIOS OF CROSSSECTIONS

   will provide useful information about halo structure

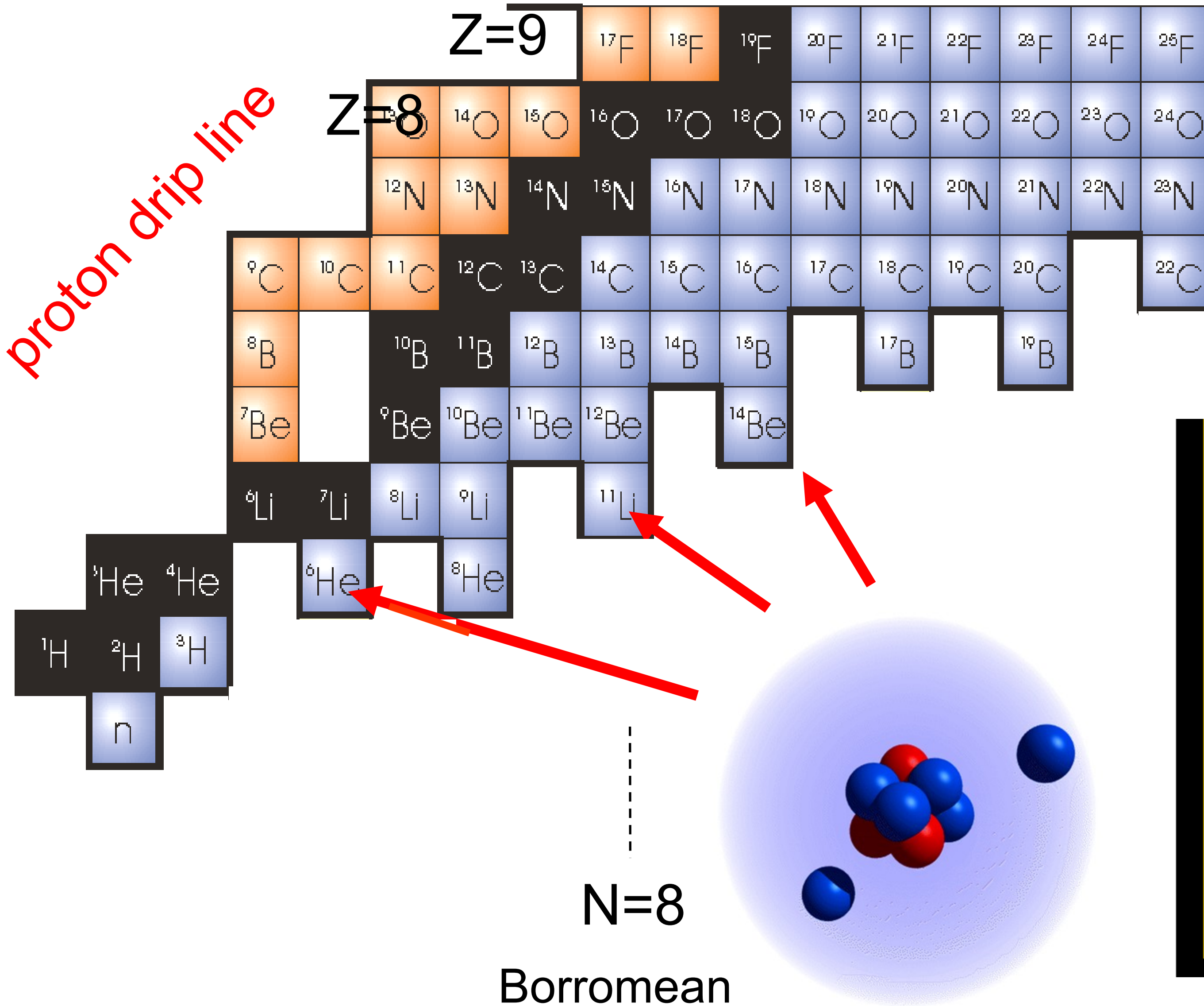
3. DEA calculations support this idea.

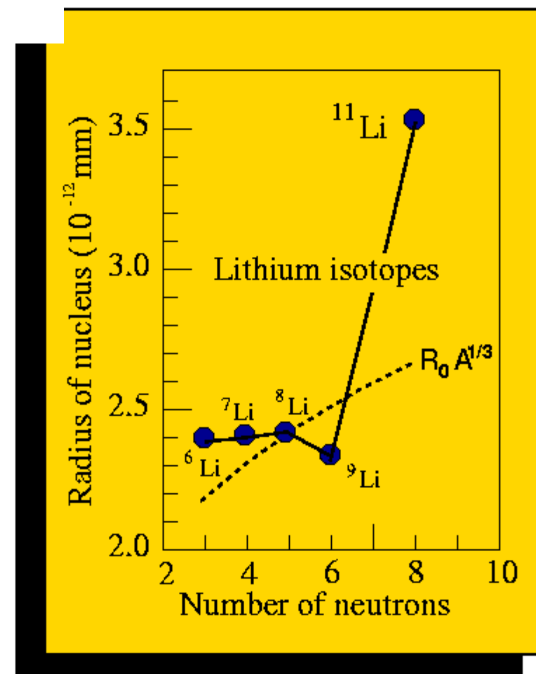
4. Properties of ratio:

- weak dependence on c-T optical potential and dynamics.
- weak dependence on target
- sensitive to halo binding energy, angular momentum and details of radial wave function.

4. Ratio provides an ideal tool to study exotic nuclei.

Part of the N-Z plane





Borromean

halo nuclei