Spectroscopy of Halo Nuclei by Breakup Reactions

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1 Coulomb Breakup of 1n-Halo Nucleus and Spectroscopic Factors

^{11}Be+Pb

T.Nakamura et al.,PLB331,296(1994)

N.Fukuda et al., in preparation (2004).

^{15}C+Pb, ^{19}C+Pb

T.Nakamura et al., in preparation (2004).

T.Nakamura et al. PRL 83, 1112 (1999).

2 Nuclear Breakup of 1n-Halo Nucleus

^{11}Be+C

N.Fukuda et al., in preparation (2004).

Angular Distributio

+

E_{rel} Spectrum

3 Breakup of 2n Halo Nuclei ^{11}Li, ^{14}Be, ^{17}B

A.M.Vinodkumar et al., in preparation (2004). ^{11}Li,

T.Sugimoto, M.Miura et al., in preparation (2004). ^{14}Be

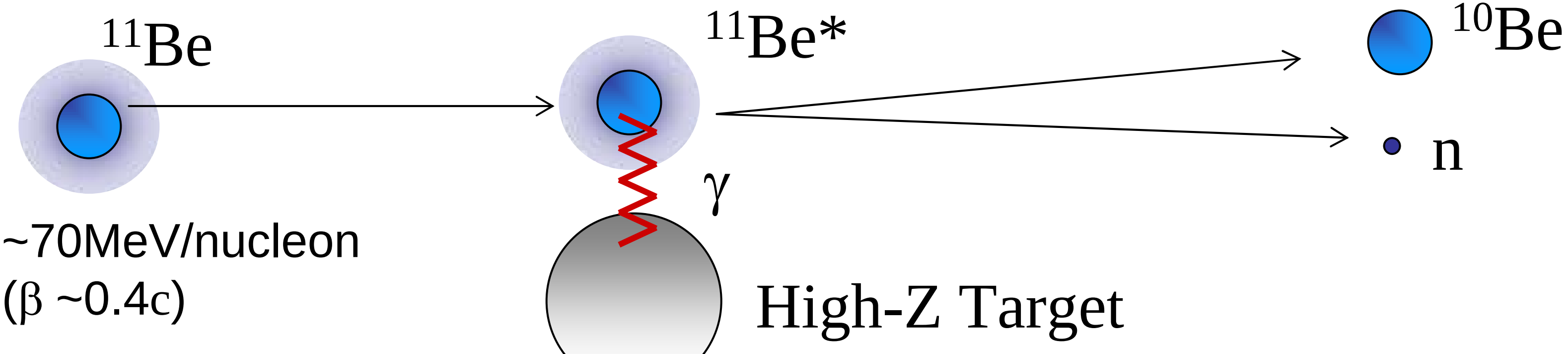
T.Sugimoto et al., in preparation (2004). ^{17}B

Introduction

Coulomb Dissociation

Invariant Mass

$$\vec{P}(n), \vec{P}(^{10}\mathrm{Be}) \Rightarrow E_x$$



^{11}Be

~70MeV/nucleon
(β ~0.4c)

^{11}Be*

γ

^{10}Be

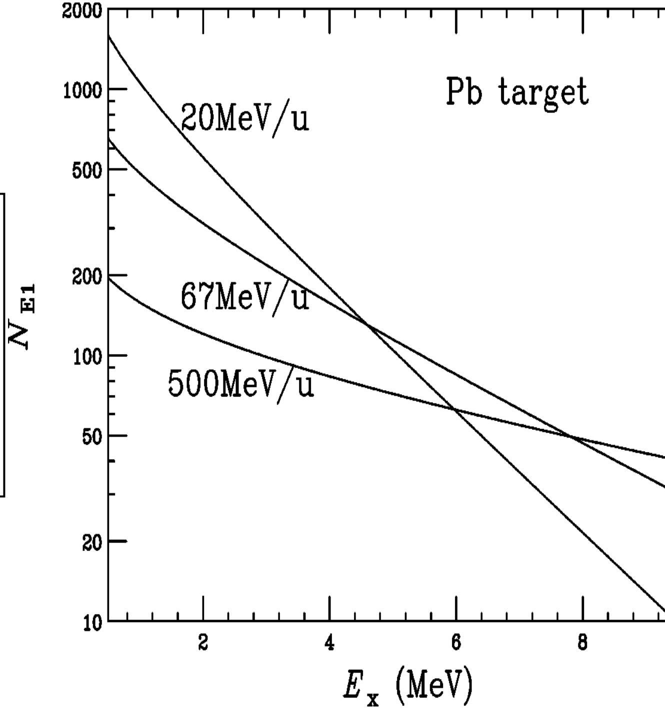
n

High-Z Target
(Pb)

Equivalent Photon Method

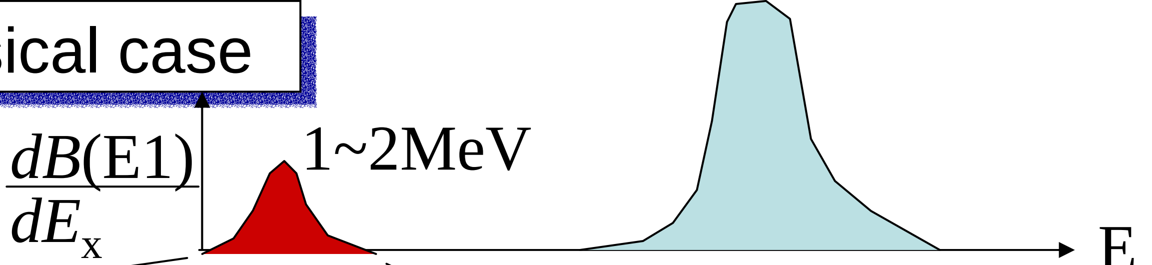
$$\frac{d\sigma_{CD}}{dE_x} = \frac{16\pi^3}{9\hbar c} N_{E1}(E_x)\frac{dB(E1)}{dE_x}$$

Cross section = (Photon Number)x(Transition Probability)

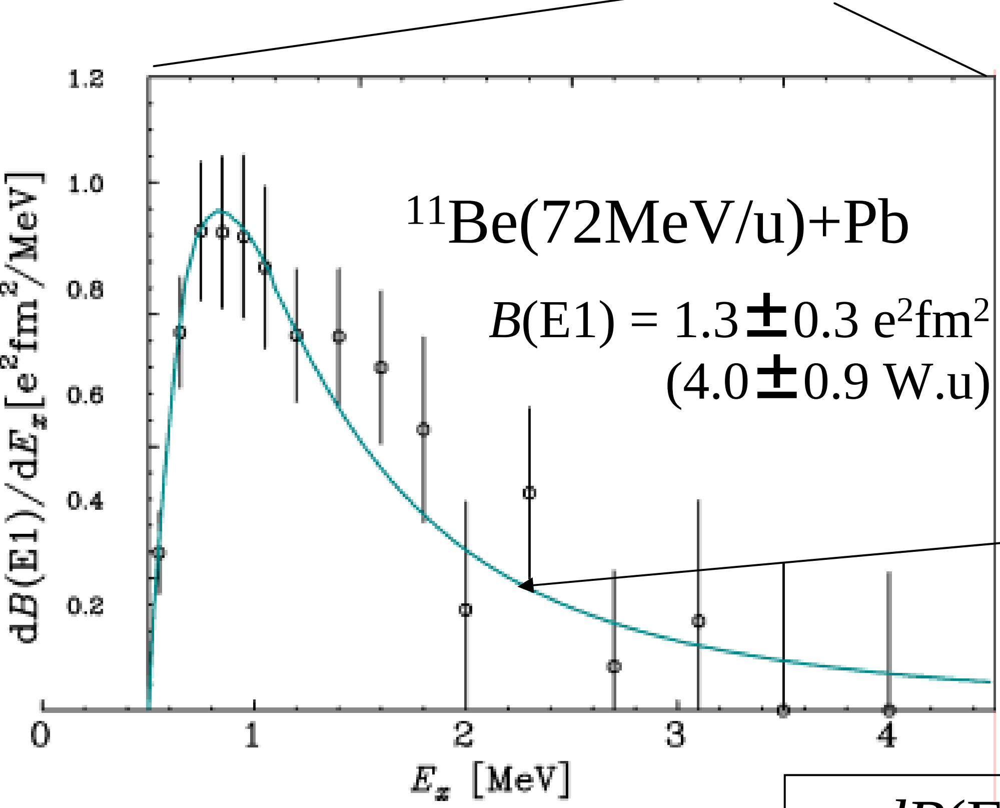


^{1}Be – The Classical case

S_n=504keV



10~20MeV



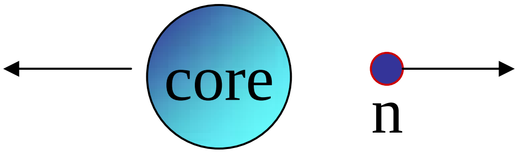
^{11}Be(72MeV/u)+Pb

B(E1) = 1.3±0.3 e^2fm^2
(4.0±0.9 W.u)

@RIKEN

T.Nakamura *et al.*,
PLB 331,296(1994)

Direct Breakup



$$\frac{dB(\mathrm{E1})}{dE_x} \propto \left| \langle \boldsymbol{q} | \frac{Z}{A} r Y^1{}_m | \Phi_{gs} \rangle \right|^2$$

$$\Phi_{gs} \propto \frac{e^{-r/\lambda}}{r} \Rightarrow B(E1) \propto 1/S_n \quad E_x(peak) = \frac{8}{5} S_n$$

halo

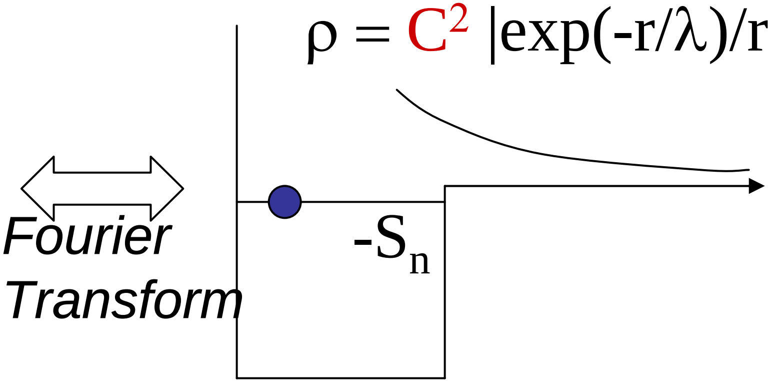
Spectroscopic Significance

Direct Breakup Mechanism

$$\frac{dB(E1)}{dE_x} \propto |\langle \exp(i\boldsymbol{qr})|\frac{Z}{A} rY^1{}_m|\Phi_{gs}\rangle|^2$$

$$\propto C^2|\langle \exp(i\boldsymbol{qr})|\frac{Z}{A} rY^1{}_m|\frac{\exp(-r/\lambda)}{r}\rangle|^2$$

Low-lying E1 Strength



$\rho = C^2\,|\exp(-r/\lambda)/r|^2$

Fourier Transform

$-S_n$

Halo State

ANC(C^2)->spectroscopic factor α^2

B(E1) @E~1MeV
Exclusively Sensitive to the Halo State

$$|\Phi_{gs}(1/2^+)\rangle = \underbrace{\alpha\,|{}^{10}\mathrm{Be}(0^+)\otimes 2s_{1/2}\rangle}_{\text{Halo State}} + \beta\,|{}^{10}\mathrm{Be}(2^+)\otimes 1d_{5/2}\rangle + ..$$

${}^{11}\mathrm{Be(g.s.)}$

α^2, β^2 : Spectroscopic factor

$\alpha^2 = 0.8 \pm 0.2$ (*1994 data*)

c.f. $\alpha^2 = 0.77$ ${}^{10}\mathrm{Be}(d,p){}^{11}\mathrm{Be}$

Remaining Issues on Coulomb Dissociation?

Direct Breakup
$$\frac{dB(E1)}{dE_x} \propto |\langle \boldsymbol{q} | \frac{Z}{A} rY^1{}_m | \Phi_{gs} \rangle|^2$$

Equivalent Photon Method---- 1st Order Perturbation

① Higher Order Effect

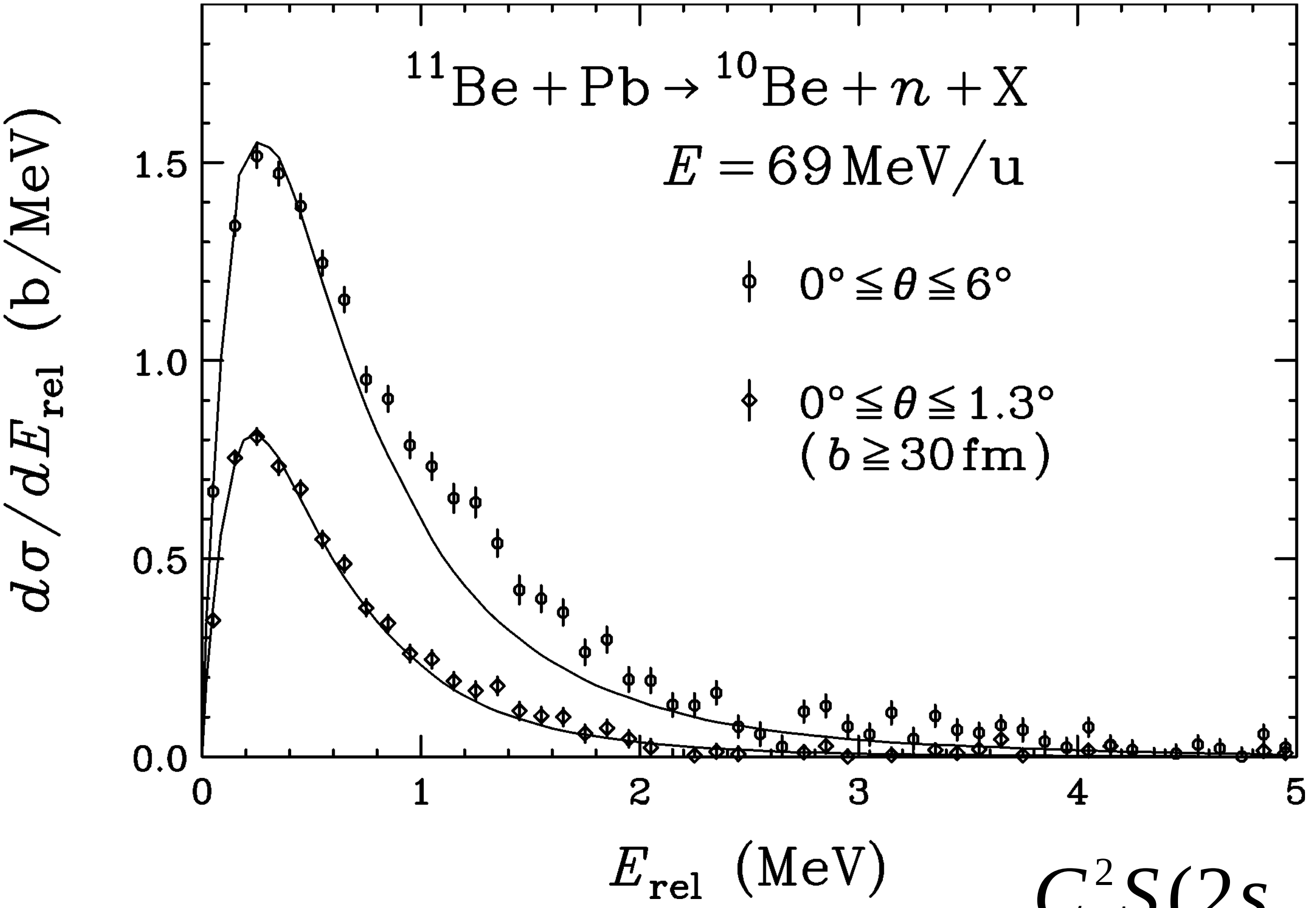
② Distorted Wave (Final State)

③ Nuclear Breakup Contribution

--*How To subtract the Nuclear Contribution?*

M.A. Nagarajan, C.H.Dasso, S.M.Lenzi,A.Vitturi PLB503,65(2001).
C.H. Dasso, S.M. Lenzi, and A.Vitturi PRC59,539(1999).
S. Typel and R.Shyam PRC64, 024605(2001).
G.Baur, C.A.Bertulani, D.M.Kalassa, NPA550, 527(1992)
H.Esbensen, G.F.Bertsch, C.A.Bertulani ,NPA581,107 (1995) .
J.Margueron, A. Bonaccorsso, and D.M.Brink, NPA720,337(2003); NPA703,105(2002).
I.J.Thompson and J.A. Tostevin NPA690,294c(2001).
S.Typel and G.Baur PRC64, 024601(2001).

Relative Energy Spectrum

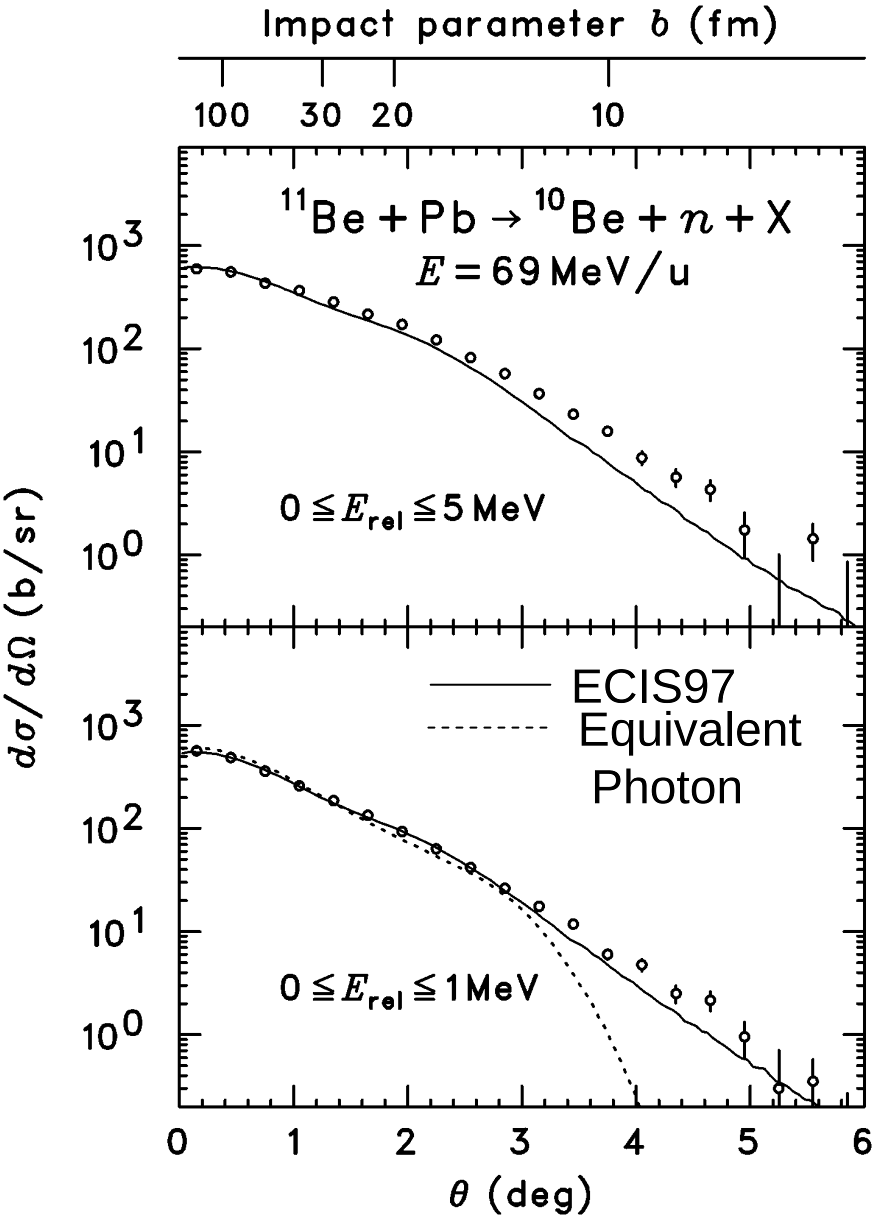


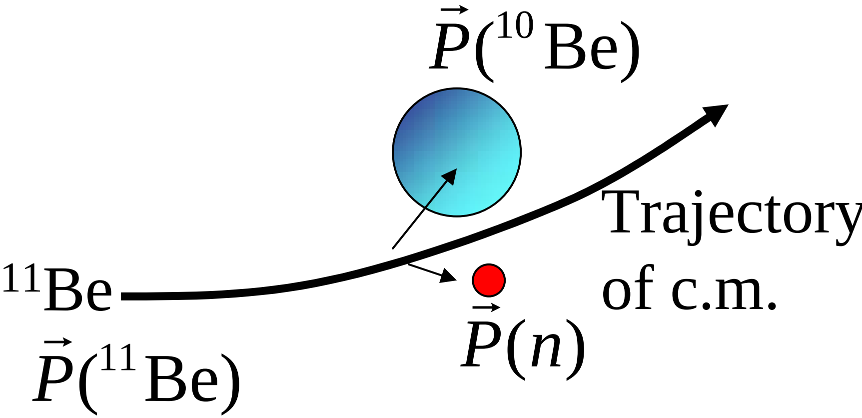
$$C^2S(2s_{1/2}) = 0.72 \pm 0.04$$

$$\sigma(\mathrm{Pb}) = 1.79 \pm 0.02\,(\mathrm{b})$$

$$\sigma(\mathrm{Pb};\mathrm{Coul}) = 1.51 \pm 0.02\,(\mathrm{b})$$

Angular Distribution of ^{10}Be+n c.m. System





$\vec{P}(^{10}\mathrm{Be})$

Trajectory of c.m.

^{11}Be

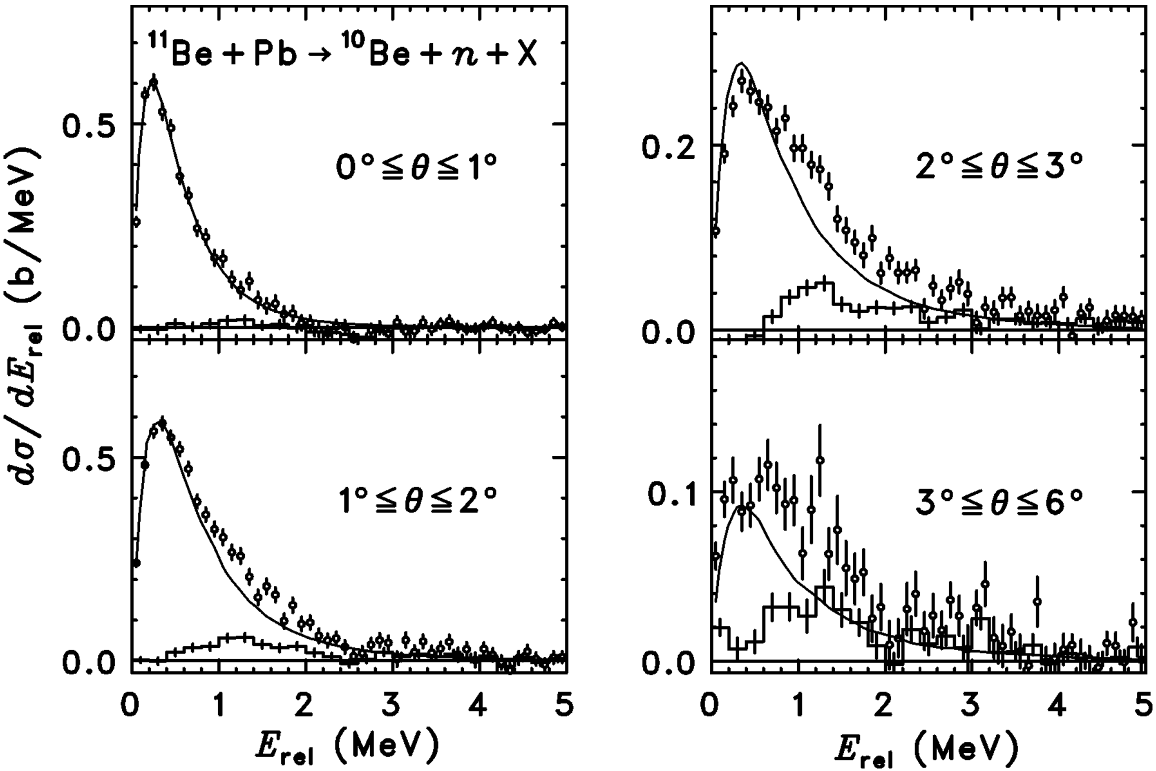
$\vec{P}(n)$

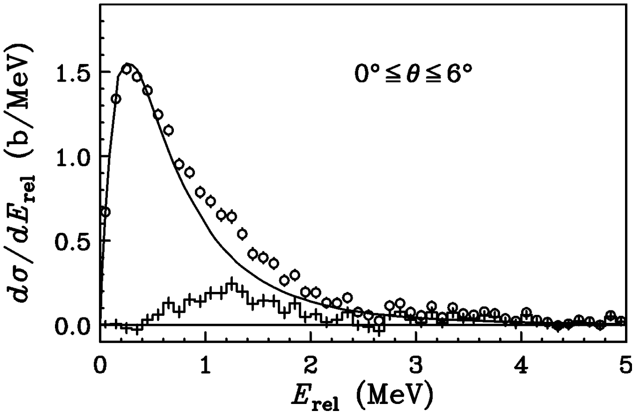
$\vec{P}(^{11}\mathrm{Be})$

$$b = a\cot(\theta/2)$$

Negligible Higher Order Effects and Nuclear Contribution for b >30 fm (θ<1.3deg)

Nuclear Contribution & Higher Order effect





Nuclear contribution and/or Higher order effects

$$\frac{280\,mb}{1.79\,\mathrm{b}} = 15.6\%$$

For the whole angular rang

$$\frac{\sigma(\mathrm{Pb;nucl})}{\sigma(\mathrm{C;nucl})} = \frac{280\ \mathrm{mb}}{81\ \mathrm{mb}} = 3.5 > 1.8\,(r_{sum}\ \ ratio)$$

Sum Rule

- Energy Weighted Sum Rule (TRK Sum Rule)

$$\int \sigma_\gamma(E_\gamma)dE_\gamma = \int \frac{16\pi^3}{9\hbar c} E_x \frac{dB(E1)}{dE_x} dE_x = 60\frac{NZ}{A}\,(\mathrm{MeV}\cdot\mathrm{mb})$$

153MeVmb for ^{11}Be

- Cluster sum rule Y.Alhassid, M.Gai, and G.F.Bertsch PRL49,1482(1982)

Sum= $60\frac{NZ}{A} - 60\frac{N_c Z_c}{A_c} = 8.73\,\mathrm{MeV}\cdot\mathrm{mb}$ For ^{11}Be

Experiment (E_x<4.5MeV)

$Sum = 5.69 \pm 0.45\,\mathrm{MeV}\cdot\mathrm{mb}$ = 3.7(2) % of TRK Sum =65(5) % of Cluster Sum

~ Spectroscopic Factor

- Non Energy Weighted Cluster Sum Rule H.Esbensen et al.,NPA542,310(1992)

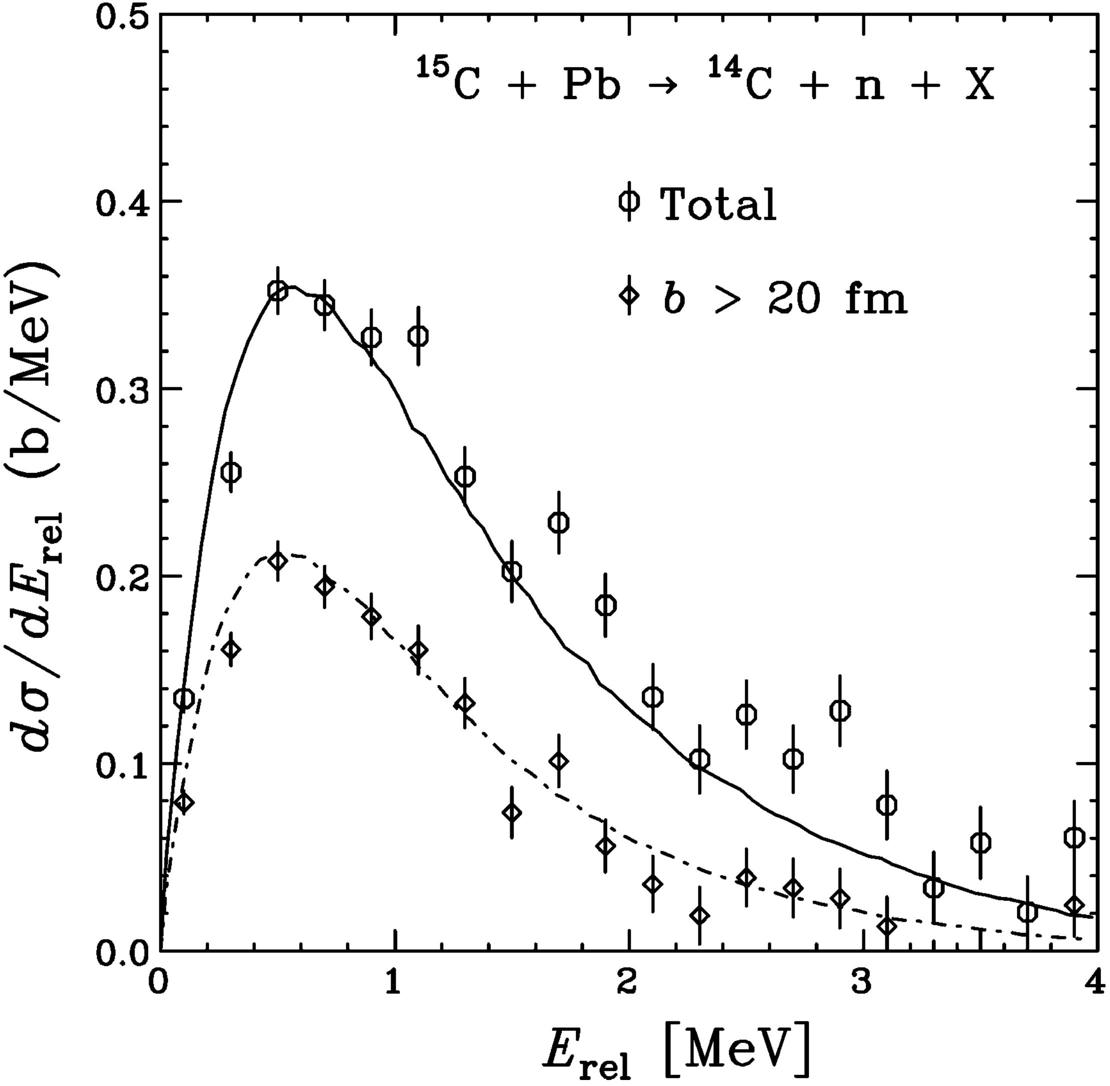
$$B(E1) = \int_0^\infty \frac{dB(E1)}{dE_x} dE_x = \frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2 \langle r^2 \rangle$$

Experiment: $B(E1) = 1.10 \pm 0.08\, e^2\mathrm{fm}^2 \Longrightarrow \sqrt{\langle r^2 \rangle} = 5.37 \pm 0.20\mathrm{fm}$

Application: Coulomb Dissociations of ^{15}C

S_n=1.218MeV

$^{15}\mathrm{C(g.s)} = \alpha|\,^{14}\mathrm{C}(0^+)\otimes 2s_{1/2}\rangle + \beta|\,^{14}\mathrm{C}(2^+)\otimes 1d_{5/2}\rangle$



^{15}C+Pb@68MeV/u

α^2=0.74(4)

r_0=1.25 fm
a=0.65 fm

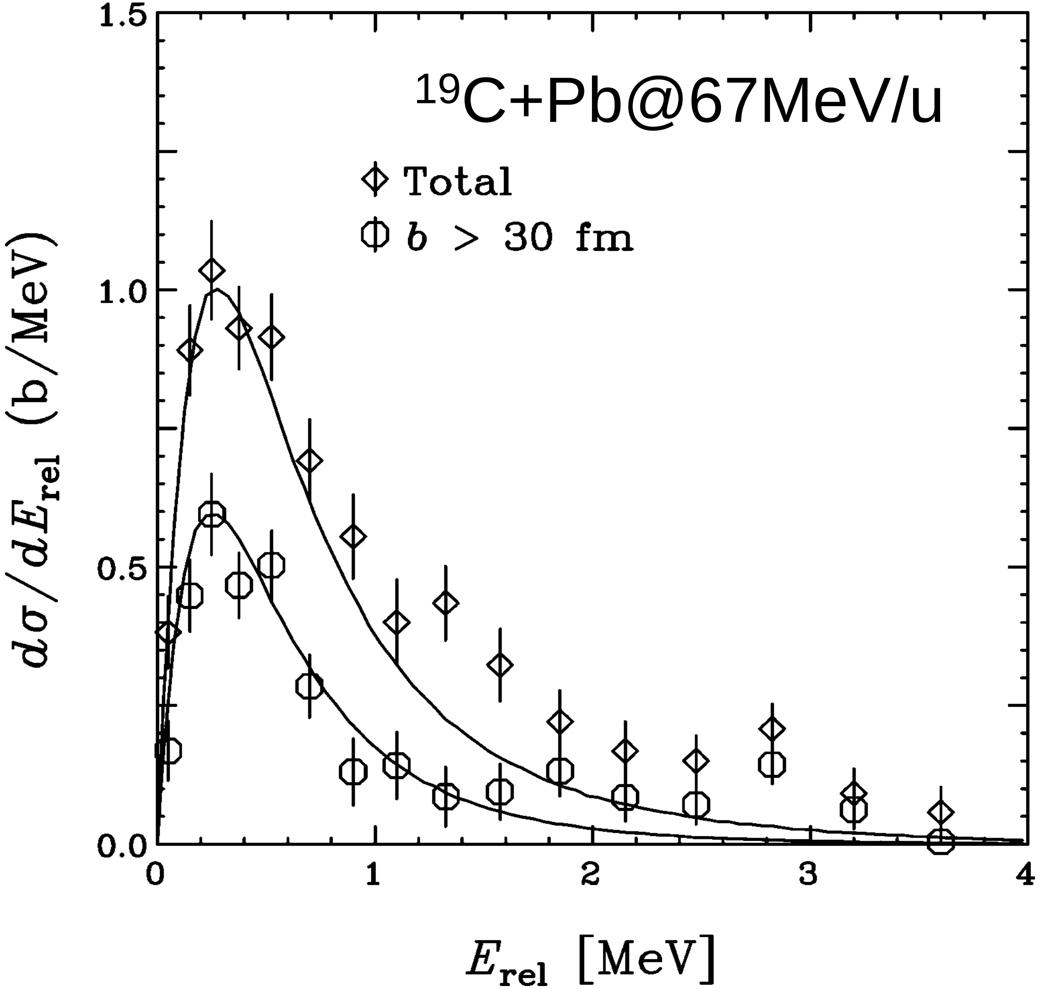
Consistent with GSI data(0.73)
(D.Pramanik et alPLB551,63
(2003))
But not with MSU data
A.Horvath et al., APJ (2001)
Beer et al. ApJ 387, 258(1992)

Coulomb Dissociations of ^{19}C

^{19}C S_n=0.53MeV

T.Nakamura *et al.*,
PRL. 83, 1112 (199

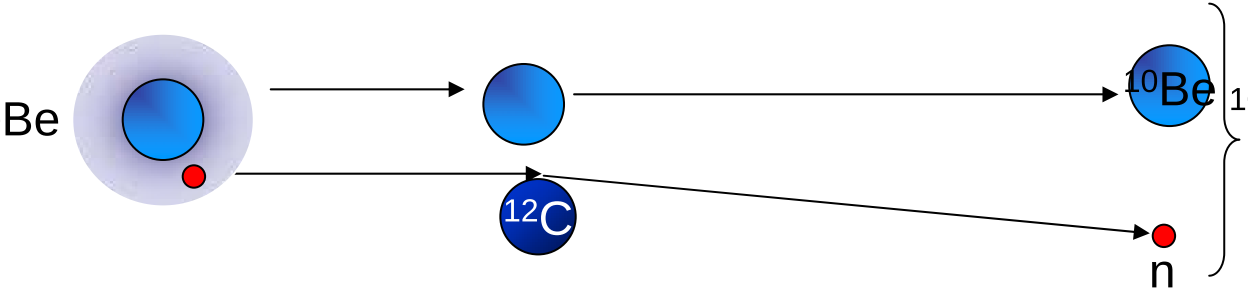
$$^{19}\mathrm{C(g.s)} = \underline{\alpha |\, ^{18}\mathrm{C}(0^+) \otimes 2s_{1/2} \rangle} + \beta |\, ^{18}\mathrm{C}(2^+) \otimes 1d_{5/2} \rangle$$



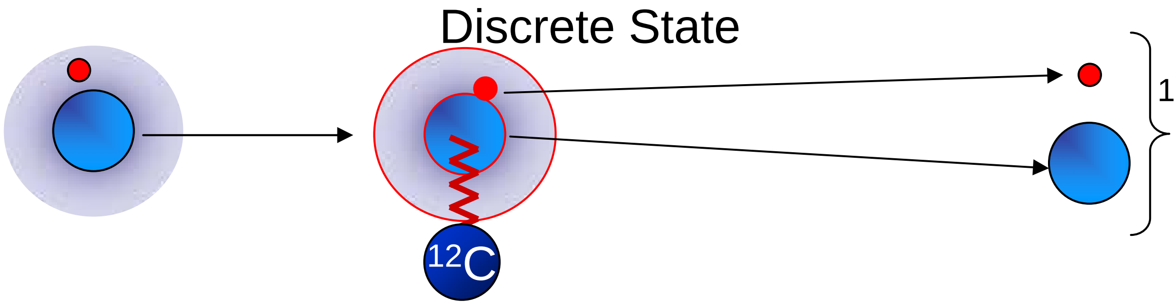
α^2=0.67

2 Nuclear Breakup of ^{11}Be

Diffractive Breakup (Elastic Breakup)

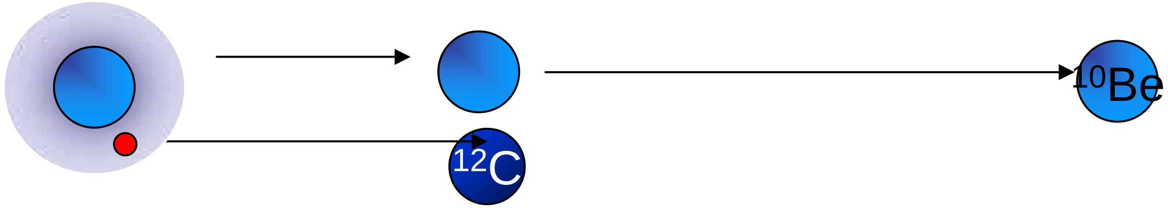


^{10}Be+n detected
@forward detectors



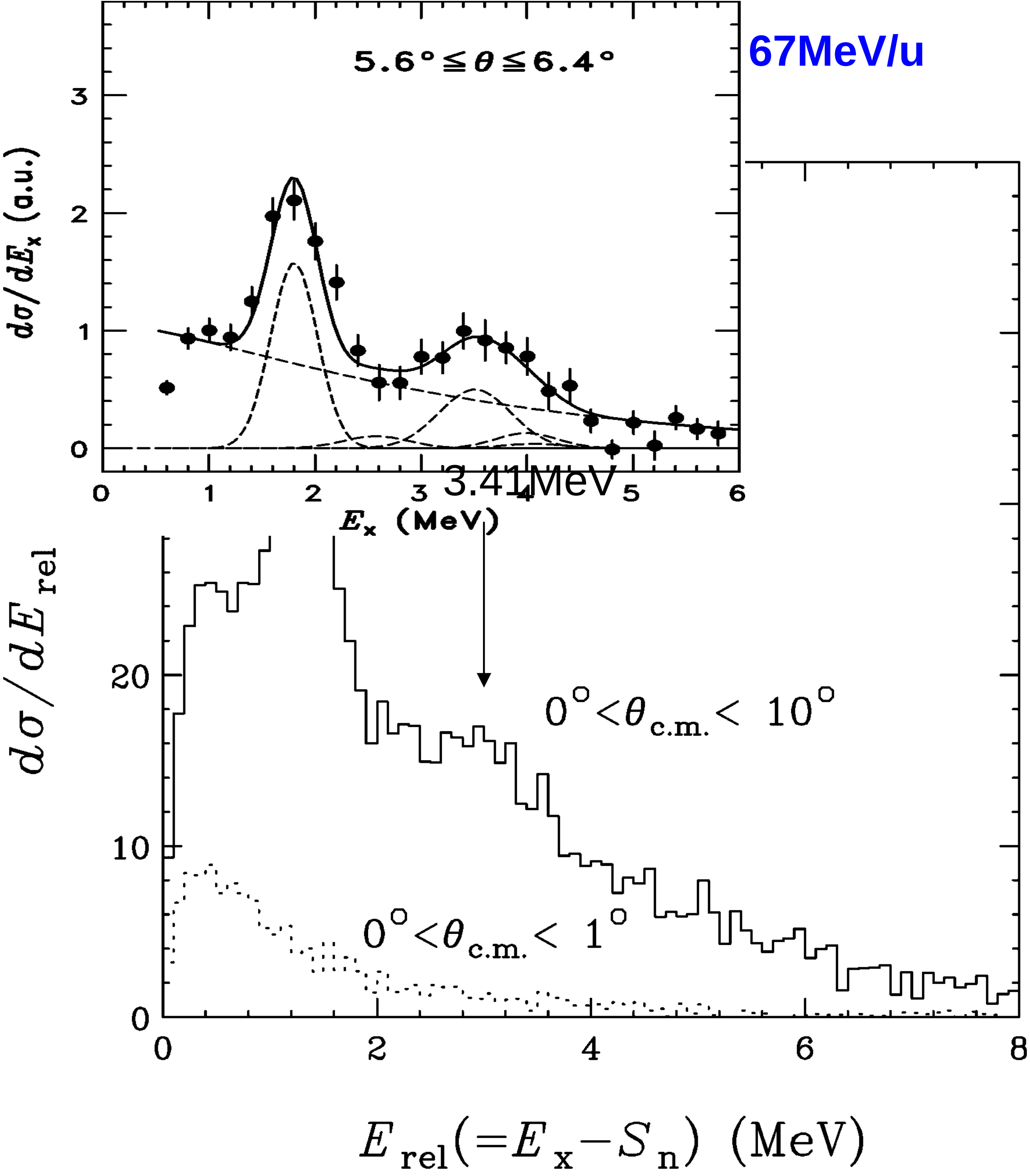
^{10}Be+n detected
@forward detectors

1n-stripping (knockout) reaction

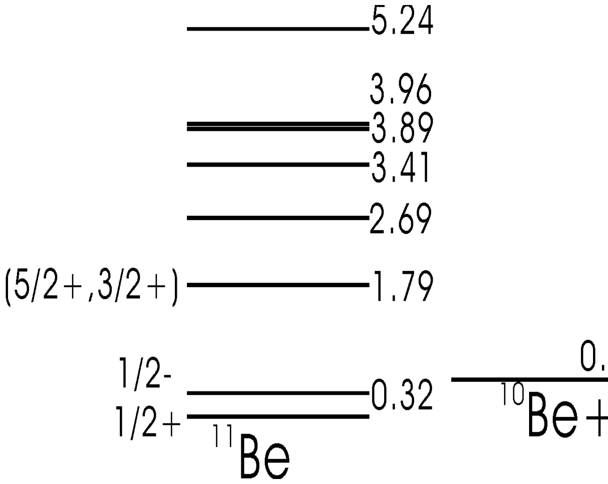


Only ^{10}Be detected
@forward detectors

67MeV/u



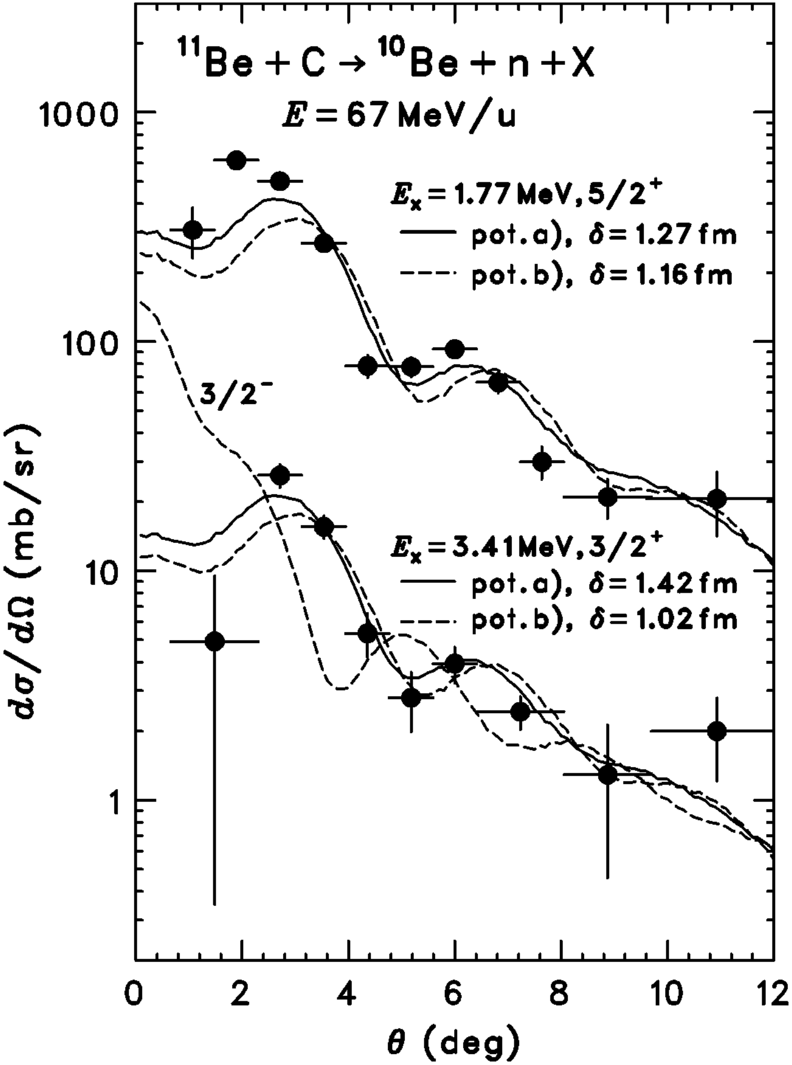
3.41MeV



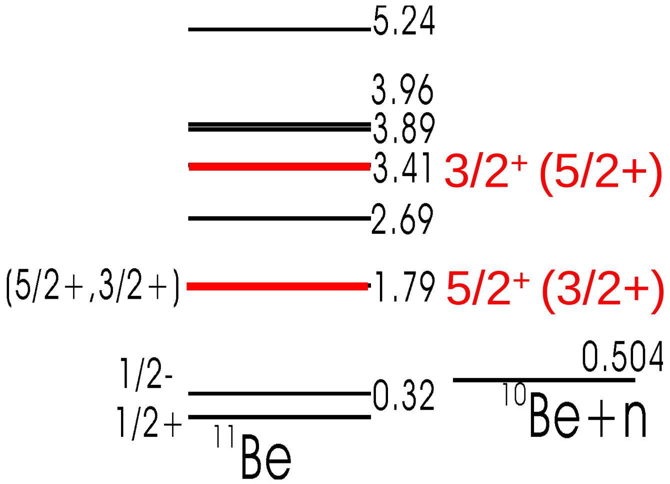
Known Levels

^{11}Be+C - Angular Distribution

^{11}Be+C @ 67MeV/u

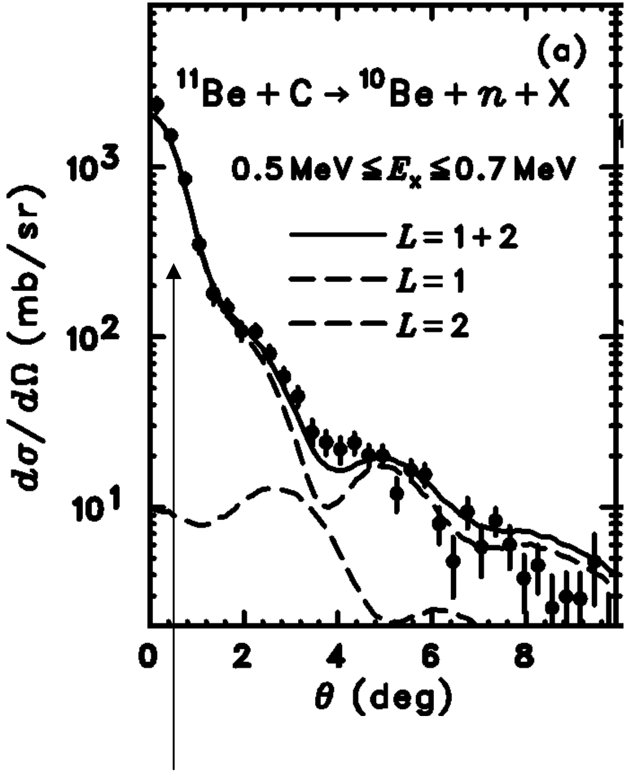


ΔL=2 Transition @ Ex=1.79MeV
@ Ex=3.41MeV

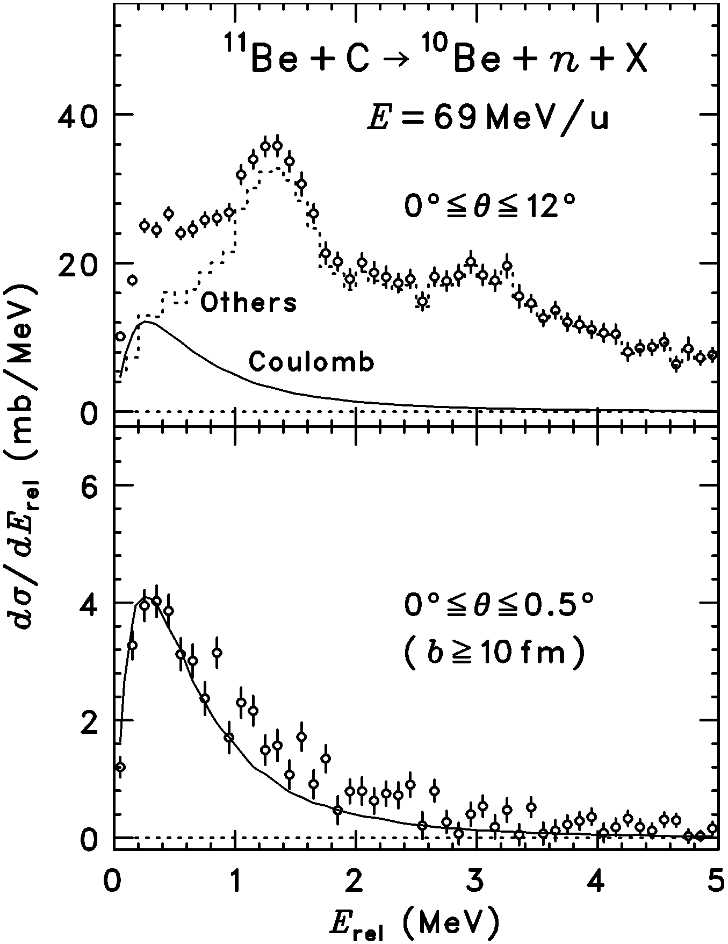


Potential a) ^{11}Be+^{12}C @48MeV/u
b) ^{12}C+^{12}C @84MeV/u

Coulomb Contribution in C target data



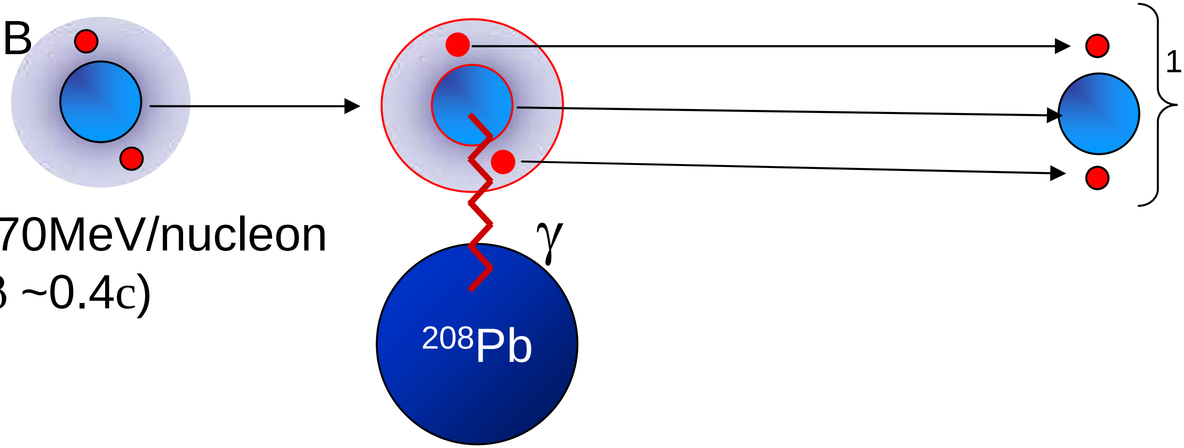
Strong Coulomb Contribution (Absolute value is consistent with Coulomb contribution at Pb target)



Direct Coulomb Breakup even for C target

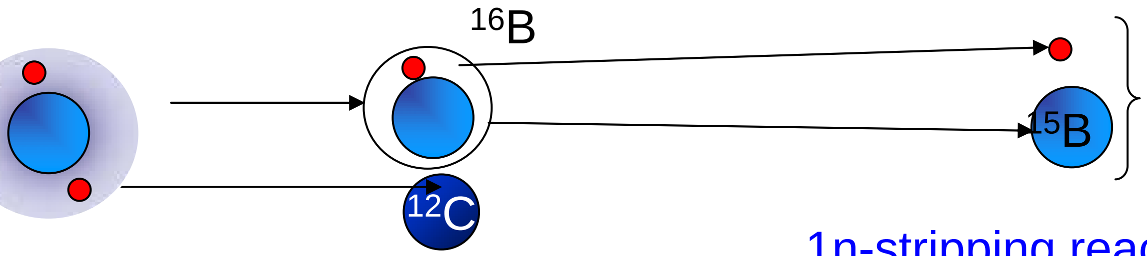
3 Breakup of 2-n Halo Nuclei ^{11}Li, ^{14}Be, ^{17}B

Coulomb Breakup of two-neutron halo nuclei



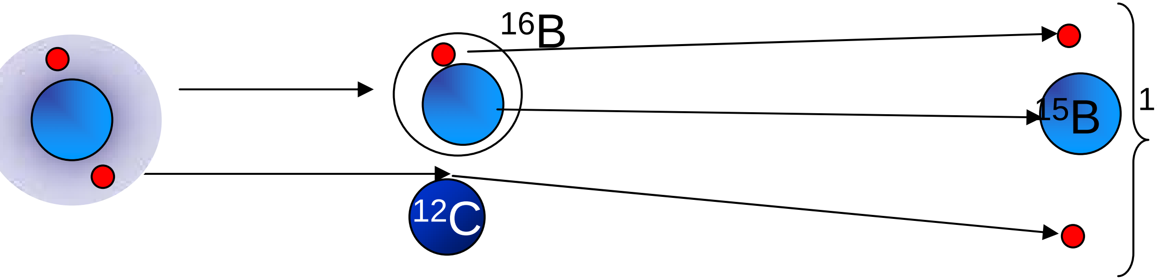
^{15}B+n+n detected
@forward detectors

luclear Breakup of two-neutron halo nuclei



^{15}B+n detected
@forward detectors

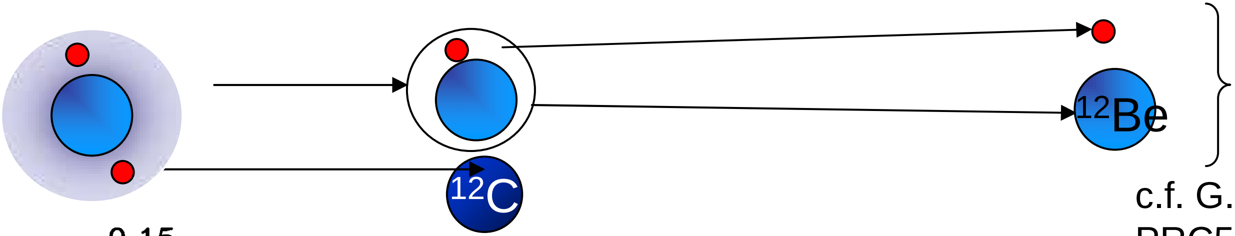
1n-stripping reaction



^{15}B+n+n detected
@forward detectors

Diffractive Breakup (Elastic Breakup)

^{12}Be+n (^{13}Be) Relative Energy Spectrum



S-wave scattering state

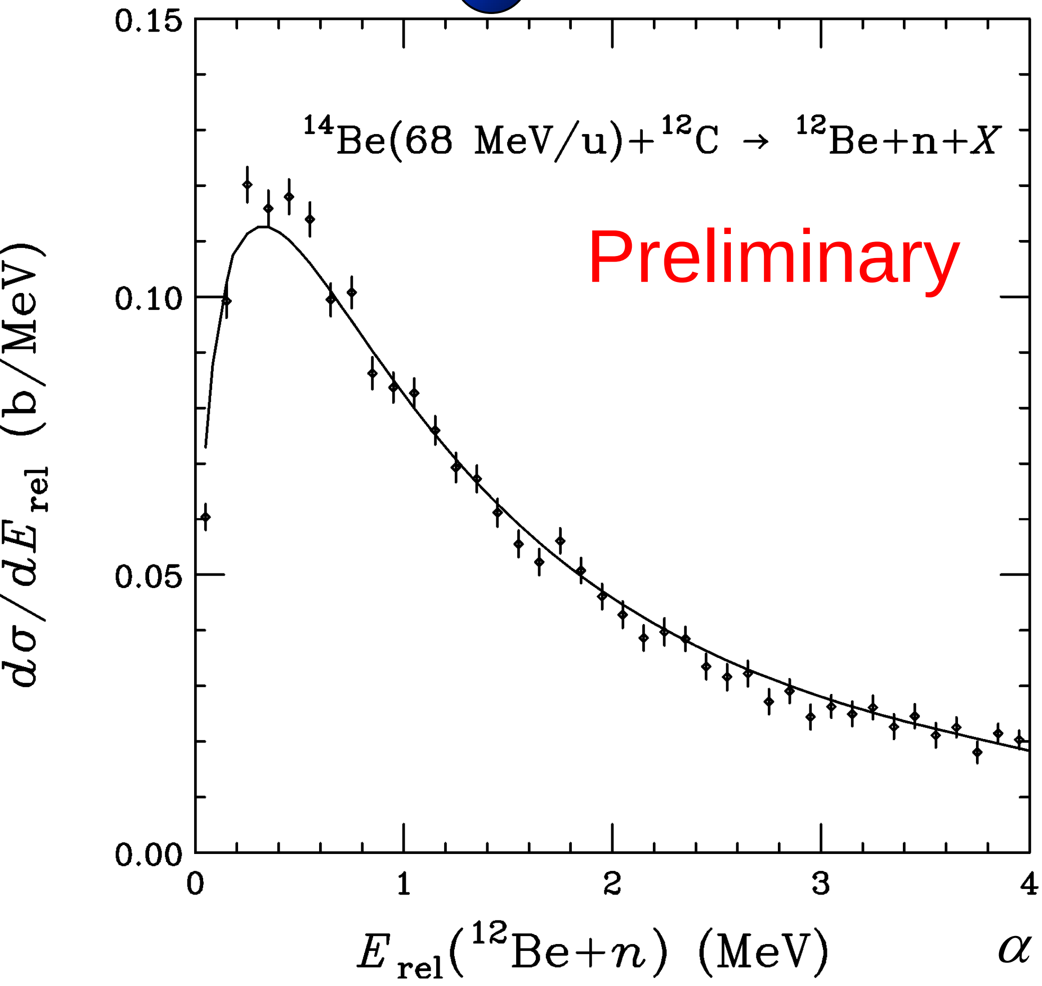
c.f. G.F. Bertsch, K. Hencken, H.Esbense
PRC57, 1366(1998)

$$\frac{d\sigma}{dE_{rel}} \propto \left|\int d^3r\,\psi_k^*(r)\Psi_0(r)\right|^2 k$$

Initial: ^{14}Be $\Psi_0(r) \propto \frac{\exp(-\alpha r)}{r}$

Final: s-wave $\psi_k(r) \propto \frac{\sin(kr+\delta}{kr}$

$$k\cot\delta = -\frac{1}{a} + \frac{1}{2}r_e k^2$$

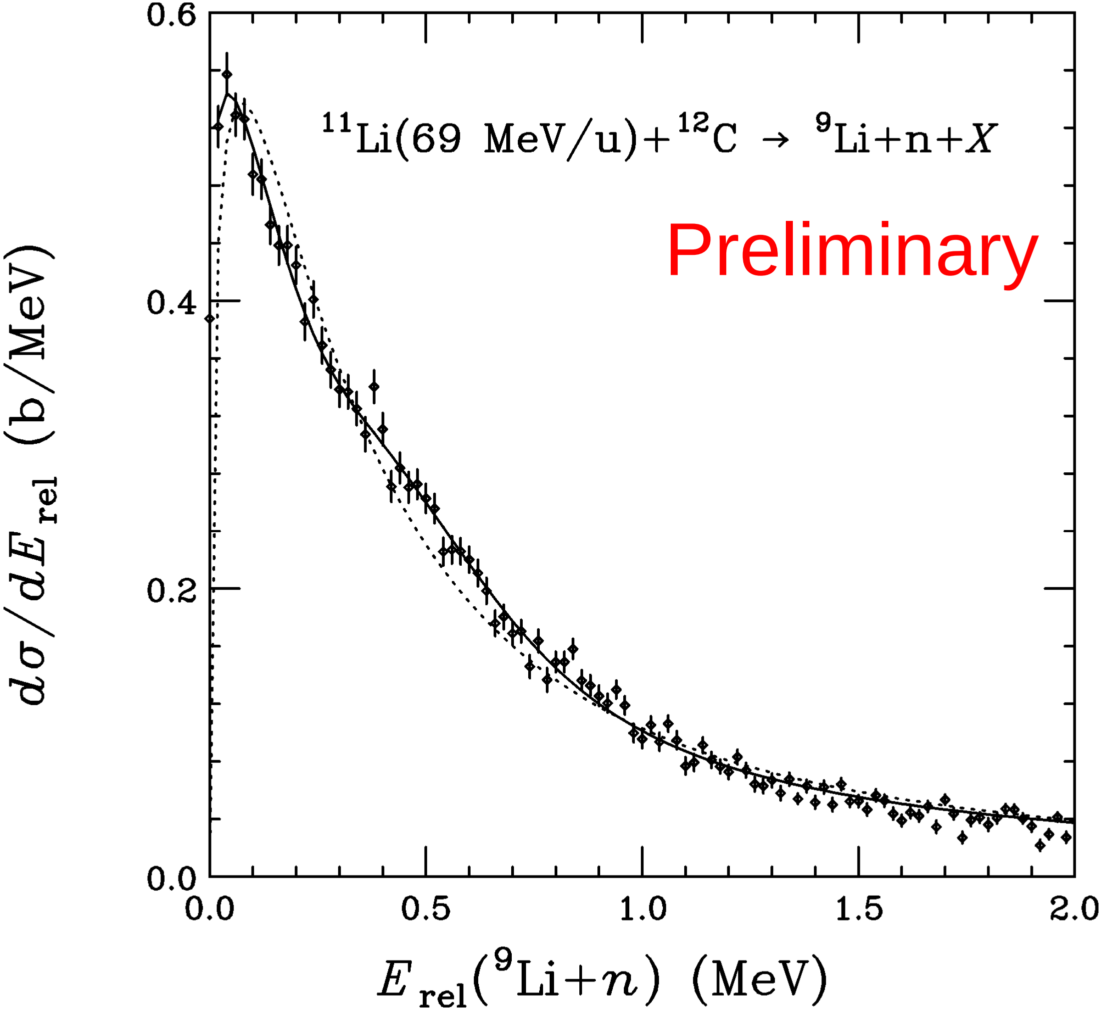


$$\begin{cases} a = -3.5(5)\ fm \\ \alpha = 0.26(2)\ fm^{-1} \\ r_e = 0.8(3)\ fm \end{cases}$$

$\alpha = \sqrt{2\mu S_{eff}}/\hbar$ Small effective rang

$S_{eff} = 1.5\,\mathrm{MeV}$

^{9}Li+n (^{10}Li) Relative Energy Spectrum



S-wave scattering state
+ p-wave resonance

S-wave

$$\begin{cases} a = -26.2(1.4)\ fm \\ \alpha = 0.16(1)\ fm^{-1} \\ r_e = 5.6(4)\ fm \end{cases}$$

$$\alpha = \sqrt{2\mu S_{eff}}\,/\,\hbar$$

$$S_{eff} = 0.6\,\mathrm{MeV}$$

p-wave

$$\frac{d\sigma}{dE_{rel}} \propto \frac{\Gamma}{(E - E_R)^2 + \Gamma^2/4}$$

$$\Gamma = 2P_l\gamma^2 \quad P_{l=1}(kr) = \frac{(kr)^3}{1+(kr)^2}$$

$$E_R = 0.52(2)\ \mathrm{MeV}$$

$$\gamma^2 = 0.36(7)\ \mathrm{MeV}$$

c.f. p-wave resonance:
B.Young et al. 0.54(6)MeV

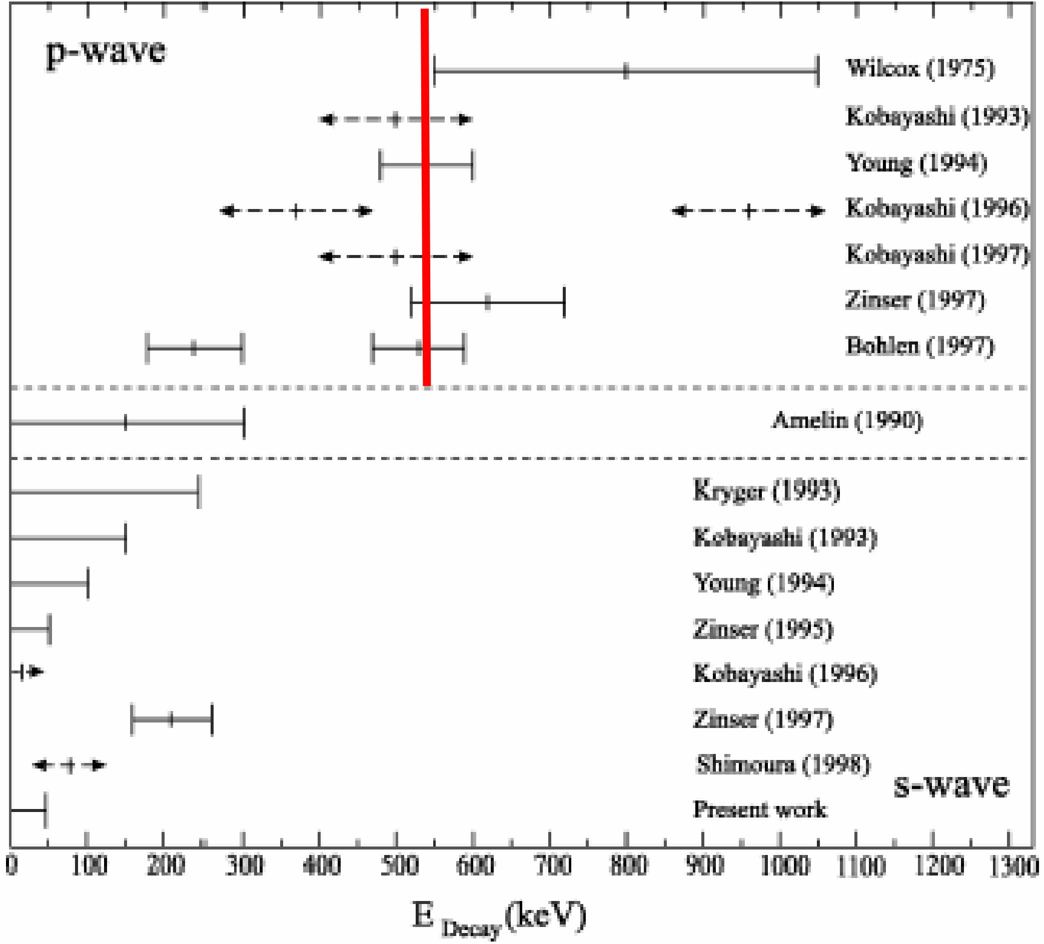
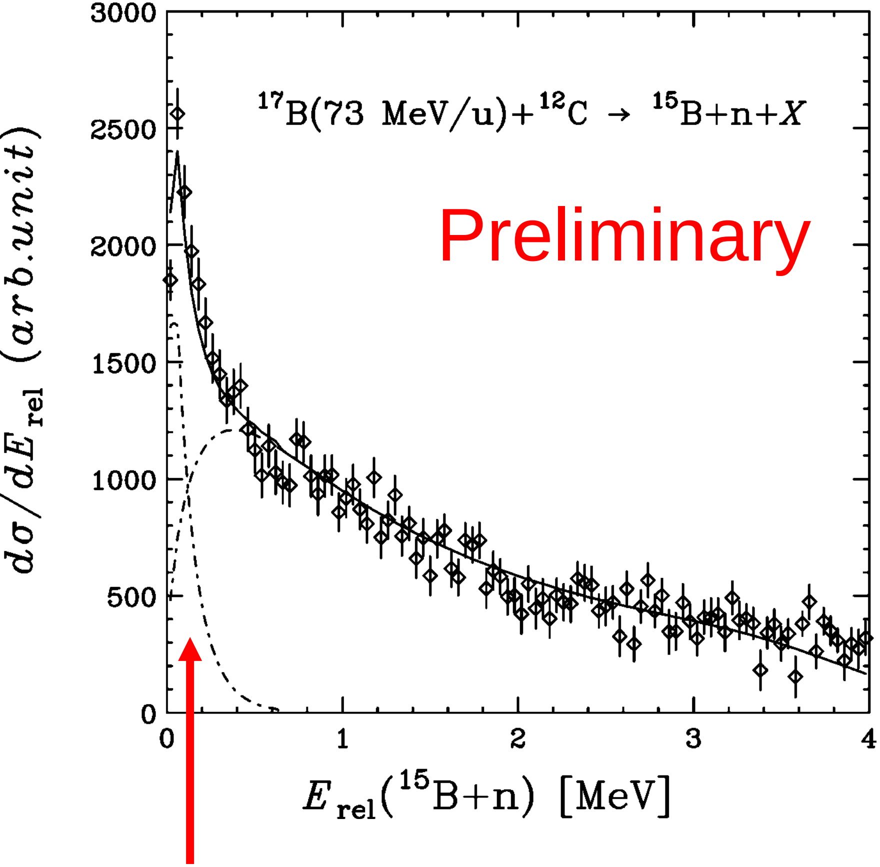


FIG. 9. Comparison of experimental results for *p*- and *s*-wave states. The *s*-wave states are presented in terms of apparent peak energies.

Phys. Rev. C 59, 111–117 (1999).
M.Thoennessen

^{16}B (^{15}B+n)

(S.Sugimoto’s analysis)



$$E_R = 60\ \mathrm{keV}$$

$$\gamma^2 = 91(9)\ \mathrm{keV}$$

c.f.

Eur.phys. J. A7, 451 (2000) E =40keV?

Assumed

s-wave scattering state

$$a = -0.0025 \pm 0.17\ fm$$

$$\alpha = 0.206 \pm 0.002\ fm^{-1}$$

$$r_e = 4.2 \pm 6.6\ fm$$

\+

d-wave resonance

$$\frac{d\sigma}{dE_{rel}} \propto \frac{\Gamma}{(E - E_R)^2 + \Gamma^2/4}$$

$$\Gamma = 2P_l\gamma^2$$

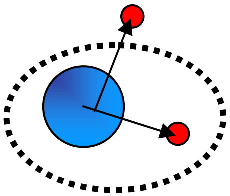
$$P_{l=2}(kr) = \frac{(kr)^5}{9 + 3(kr)^2 + (kr)^4}$$

$$E_R = 60\ \mathrm{keV}$$

$$\gamma^2 = 91(9)\ \mathrm{keV}$$

S-wave scattering analysis

$$\frac{d\sigma}{dE_{rel}} \propto \left|\int d^3r\,\psi_k^*(r)\Psi_0(r)\right|^2 k$$



Initial: ^{14}Be $\Psi_0(r) \propto \frac{\exp(-\alpha r)}{r}$

Final: s-wave $\psi_k(r) \propto \frac{\sin(kr+\delta)}{kr}$

Things to be investigated:

- Amplitude should be related to the Spectroscopic factor?
- Can this be used to study the phase shift of halo nuclei?
- $\overrightarrow{P(^{13}\mathrm{Be})}$ should have information of the Spectroscopic factor

Summary

1 Coulomb Dissociation (Coulomb Breakup)-----

Low-lying B(E1) Strength ----Sensitive to Halo

s-wave neutron ⊗ Core(0^+)

→ Powerful Spectroscopic Tool

Higher order effects and Nuclear Contribution

Impact Parameter analysis

------ Small and Can be estimate

2 ^{11}Be+C ------ Coulomb at Very forward angles

1.79MeV,3.41MeV states: L=2 angular distribution

→ Understand the Nuclear Breakup Mechanism

→ Can be used as a test for reaction theories

3 ^{13}Be, ^{16}B, ^{10}Li mass spectra from 2n-halo Breakup

^{11}Li E1 spectrum (Very Very Preliminary)

1 2

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