Coulomb and Nuclear Breakup of ^{11}Li

Takashi Nakamura

Tokyo Institute of Technology

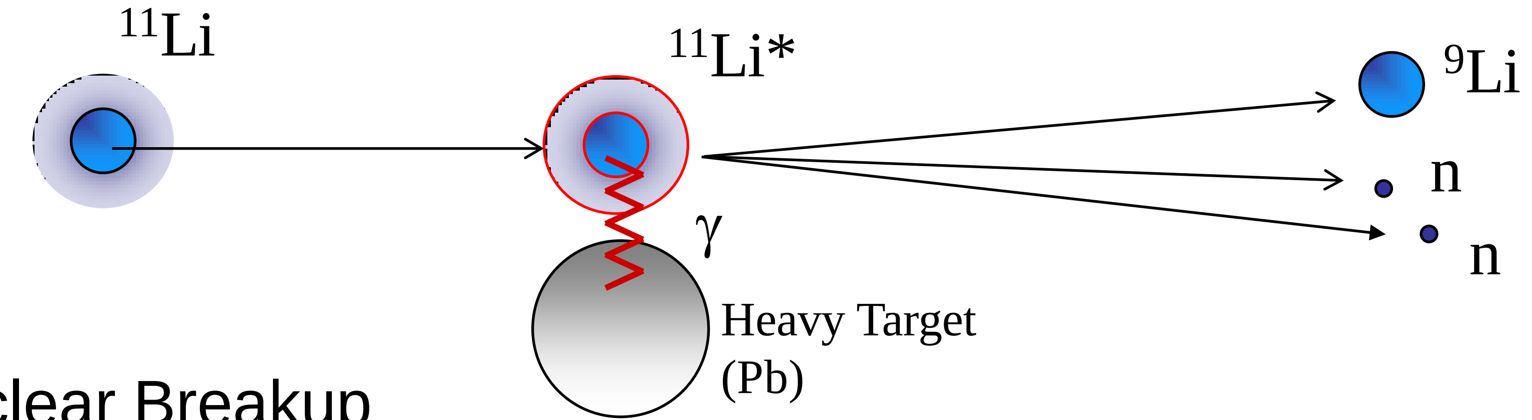
DREB2007, RIKEN

Collaborators

T.Nakamura, A.M. Vinodkumar,T.Sugimoto,
Y.Kondo , N.Fukuda, M.Miura,, N.Aoi, N.Imai,
T.Kubo, T.Kobayashi, T.Gomi, A.Saito, H.Sakurai,
S.Shimoura,D.Bazin, H.Hasegawa, H.Baba,
T. Motobayashi, T.Yakushiji, Y. Yanagisawa,
K.Yoneda, K. Watanabe, Y.X.Watanabe, M.Ishihara
M.Shinohara, Y.Hashimoto, T.Nakabayashi
Okumura

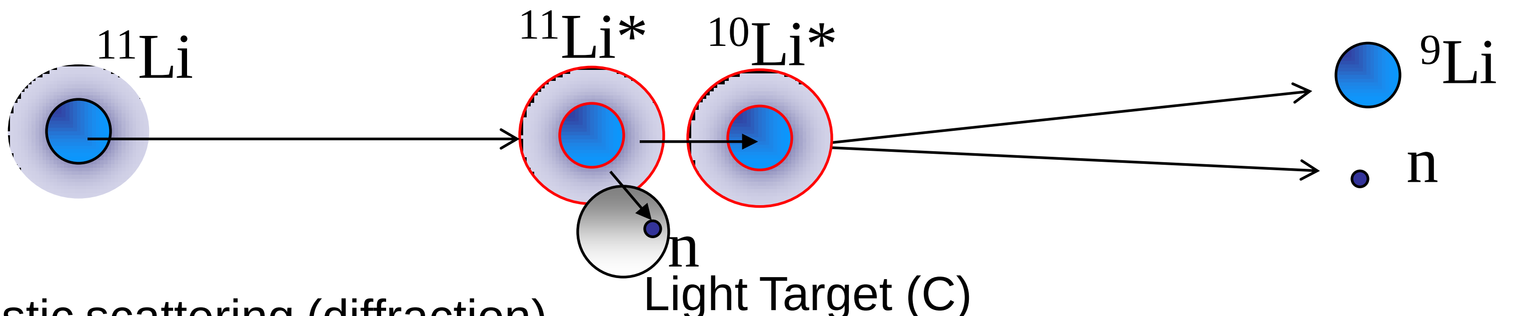
Breakup reactions of a two neutron halo nucleus

Coulomb Breakup

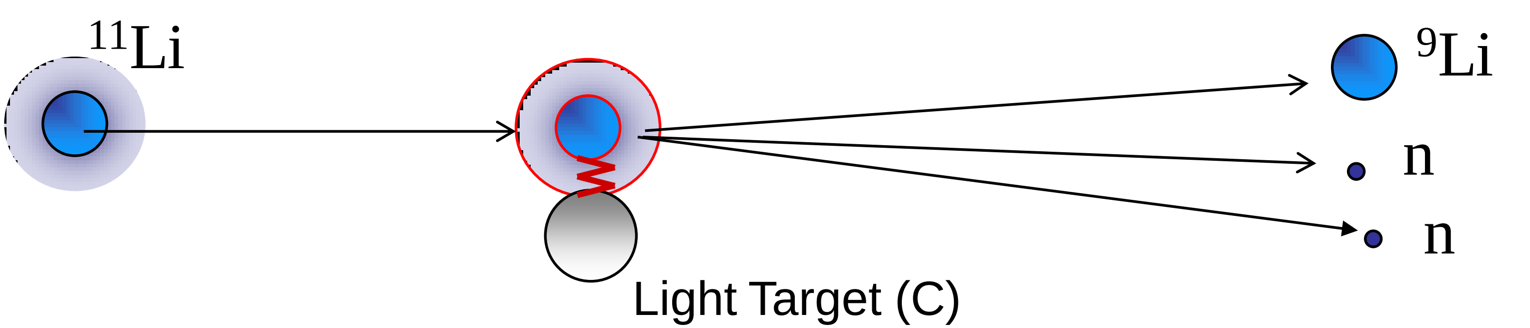


Nuclear Breakup

1n knockout reaction(stripping)



Inelastic scattering (diffraction)



In this talk…

Breakup of ^{11}Li on Pb @70MeV/nucleon

Coulomb Dominant

T. Nakamura, et al., PRL 96, 252502 (2006).

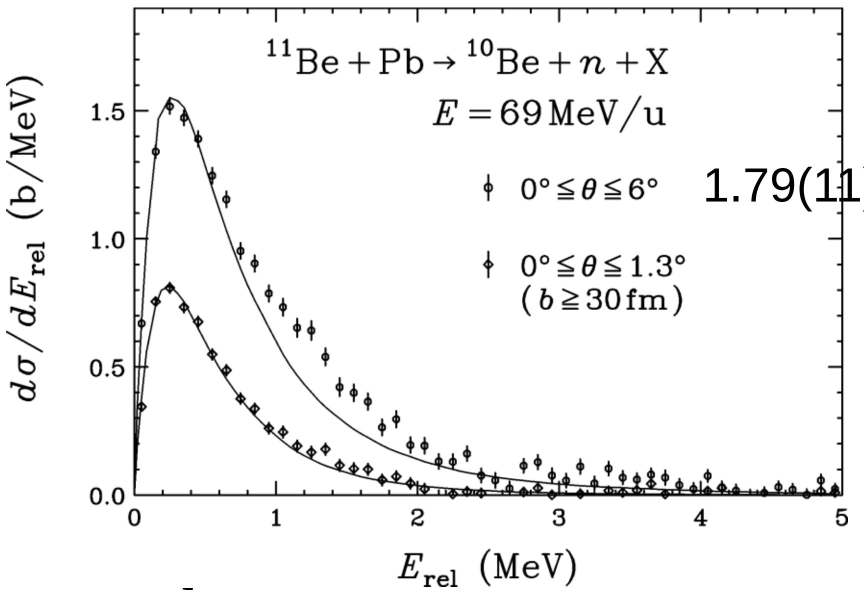
Breakup of ^{11}Li on C @69MeV/nucleon

Nuclear Dominant

Coulomb and Nuclear Breakup of One-neutron Halo nucleus ^{11}Be

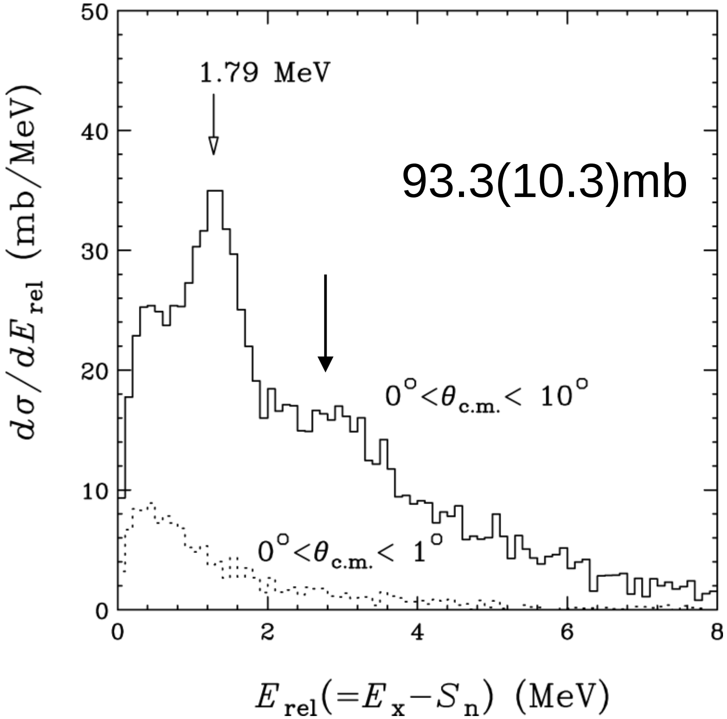
N.Fukuda, TN et al., PRCPRC 70, 054606 (2004)

^{11}Be+Pb



1.79(11)b

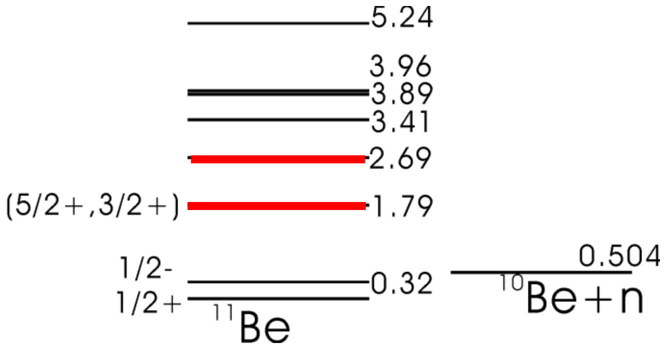
^{11}Be+C



93.3(10.3)mb

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

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

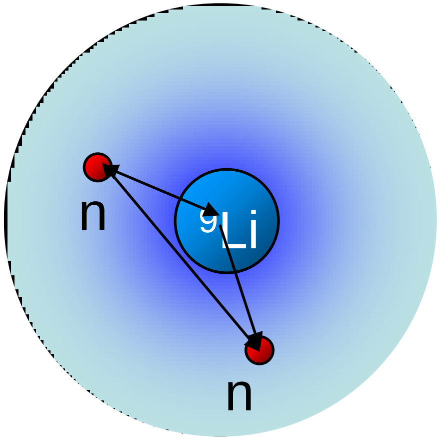


Direct Breakup Mechanism

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

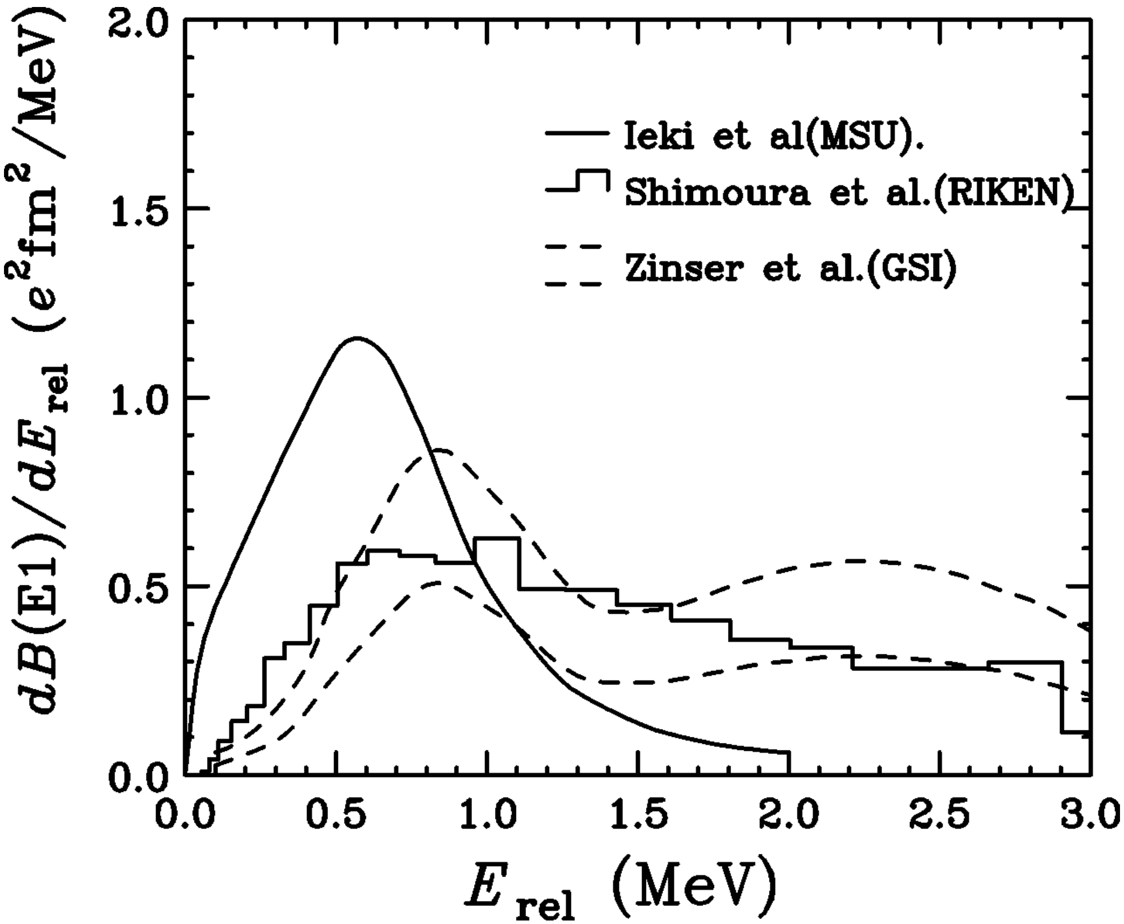
$$\propto \alpha^2 |\langle \exp(i\boldsymbol{qr})|\frac{Z}{A} rY^1{}_m|s_{1/2}\rangle|^2$$

Breakup of ^{11}Li on Pb



S_{2n}=300 keV

Coulomb Breakup of ^{11}Li
(Summary of Previous Results)



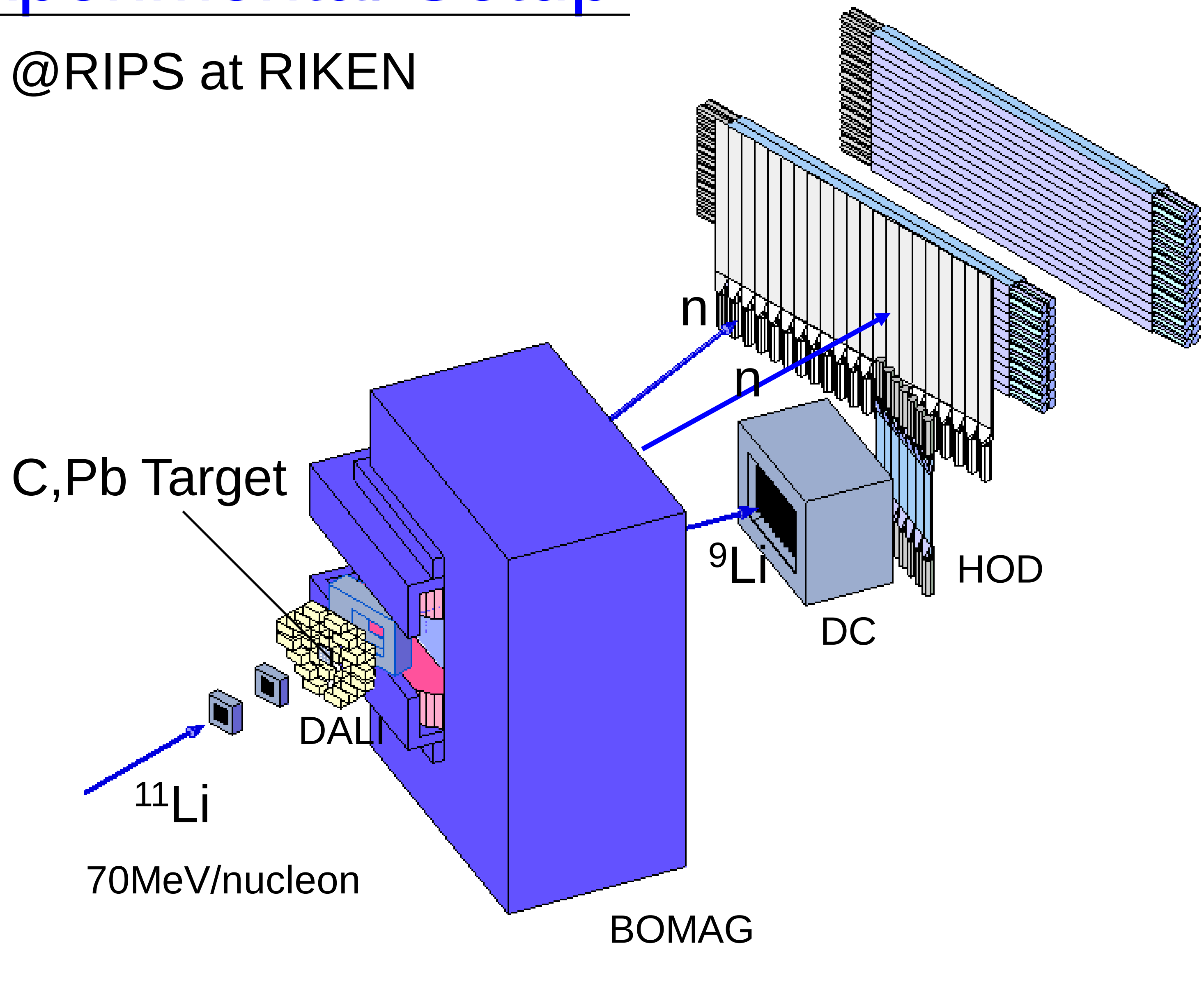
MSU@ 28MeV/nucleon
PRL 70 (1993) 730.
PRC 48(1993) 118.

RIKEN @ 43MeV/nucleon
PLB348 (1995) 29.

GSI @280MeV/nucleon
NPA 619 (1997) 151.

Experimental Setup

@RIPS at RIKEN

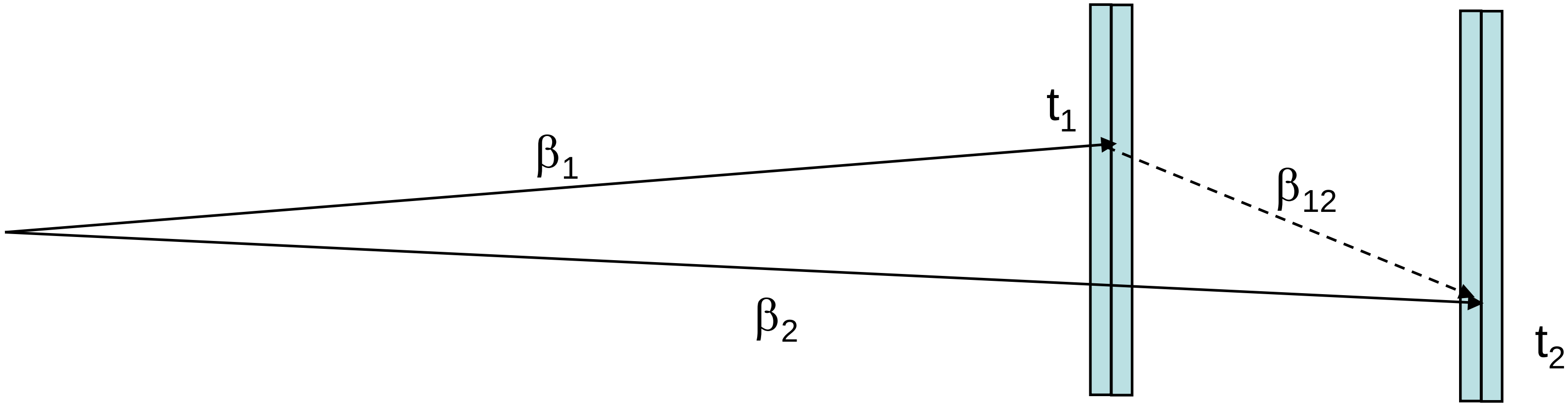


Elimination of Cross-Talk events for $2n+{}^{9}Li$ coincidence events

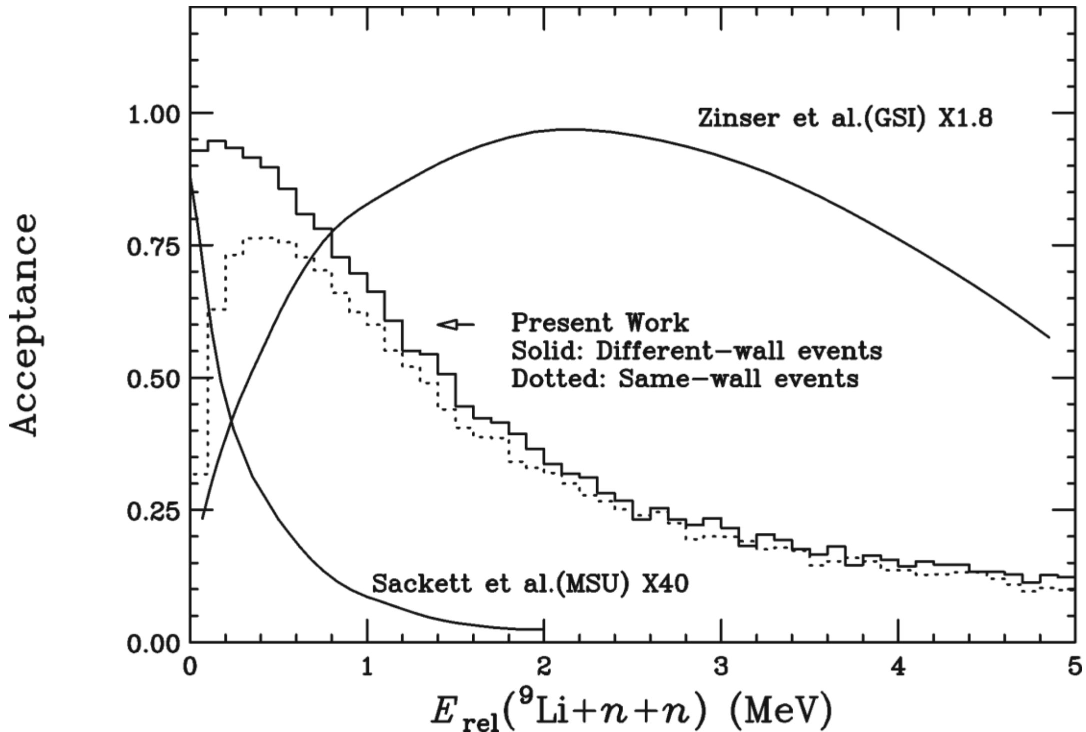
Examine Different Wall Events

Condition: $\beta_1 \leq \beta_{12}$

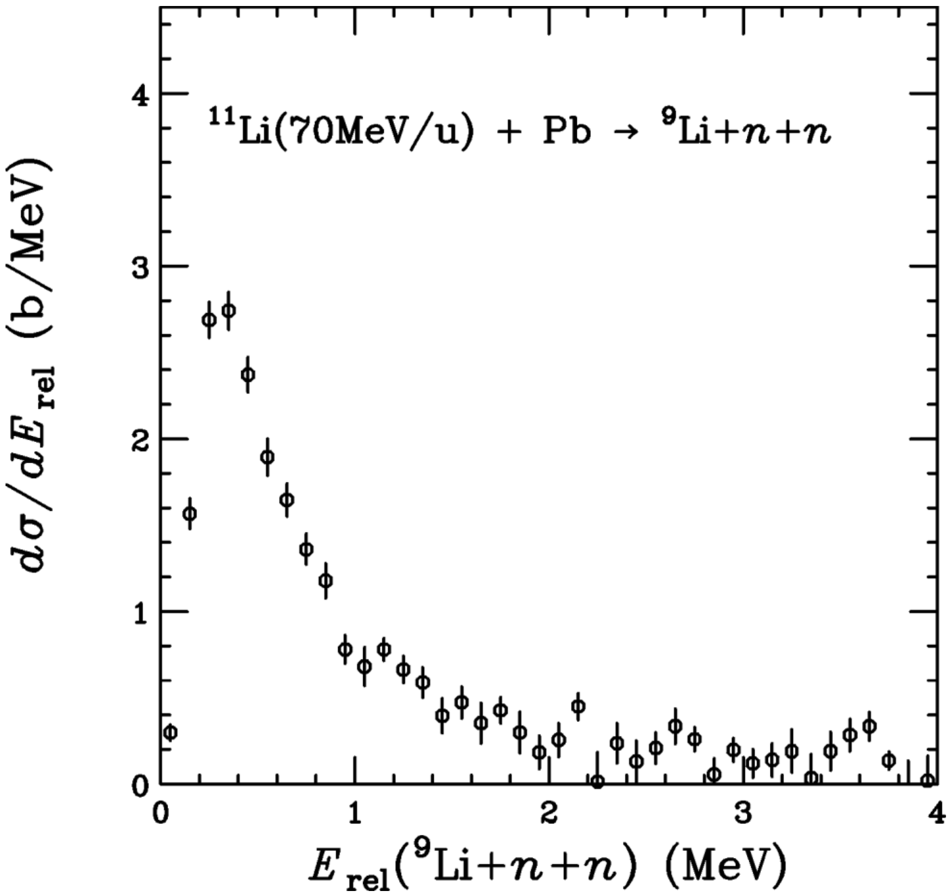
Almost no bias



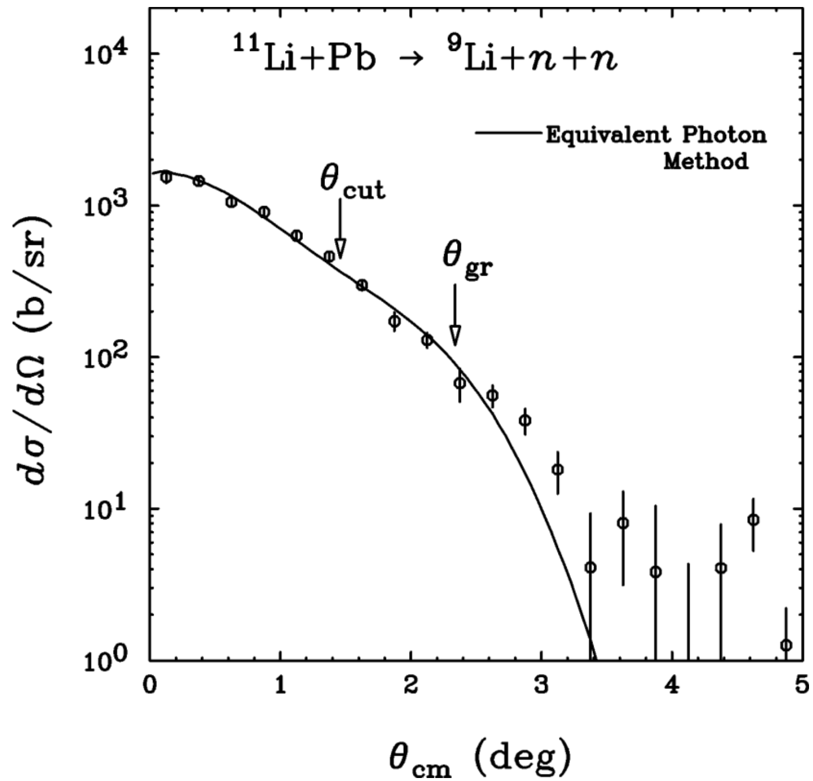
E_{th}=6MeVee to avoid any gamma related events



Energy Spectrum of ^{11}Li on Pb

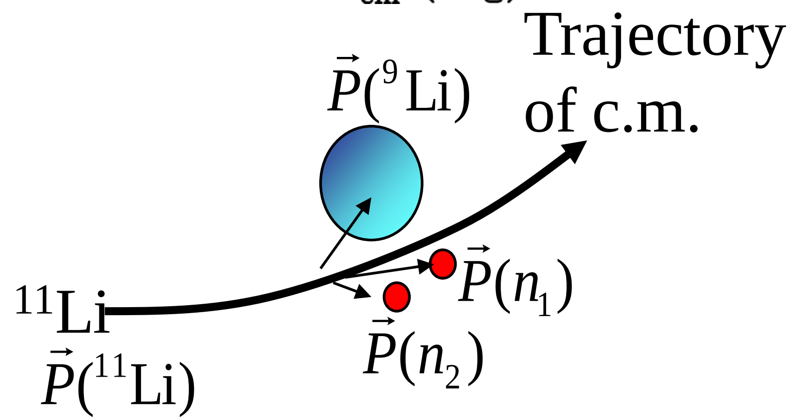


Angular Distribution



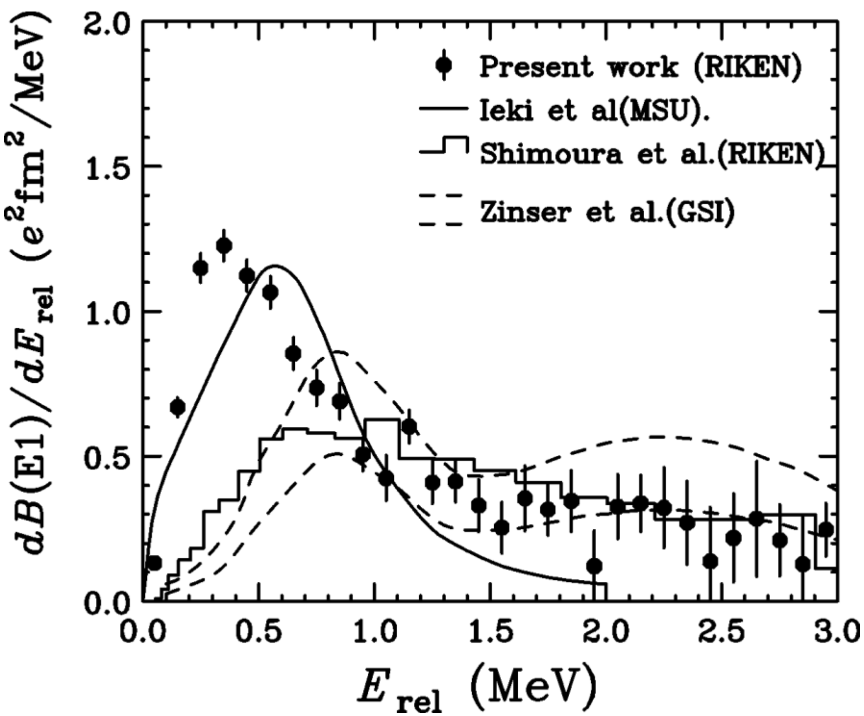
$$\sigma = 2.34 \pm 0.05(stat.) \pm 0.28(syst.)\ \mathrm{b}$$

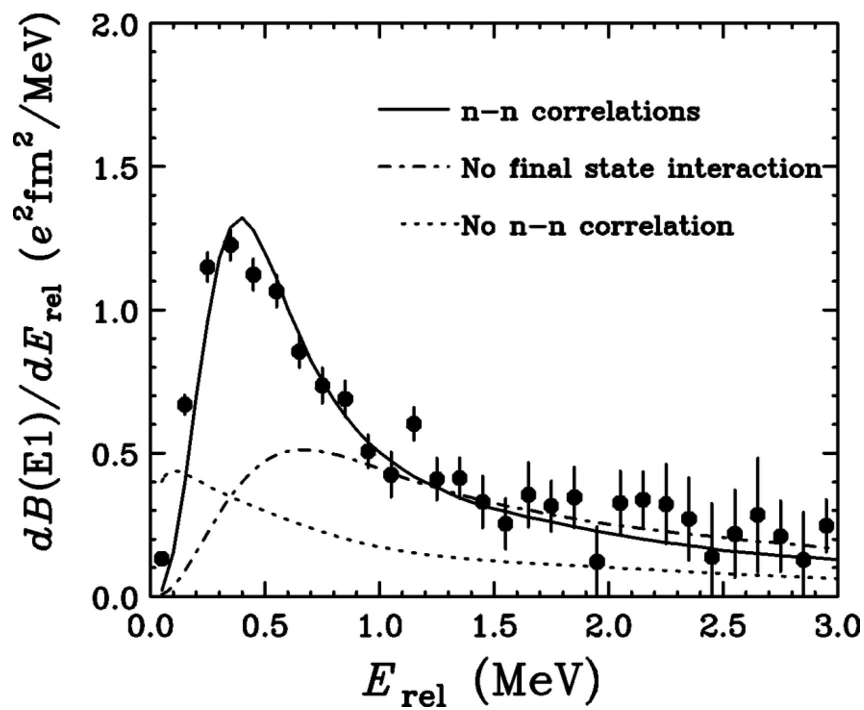
for $E_{\mathrm{rel}} \leq 3\,\mathrm{MeV}$



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

Comparison with a 3-body theory





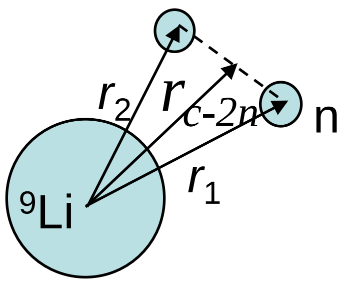
Calculation

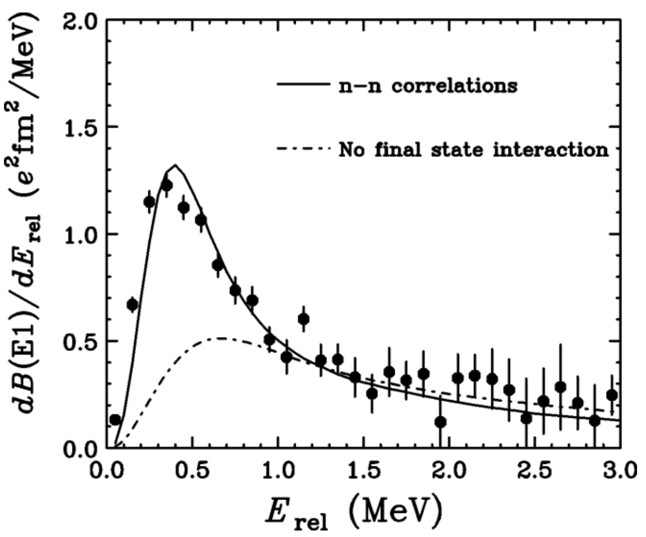
H.Esbensen and G.F. Bertsch NPA542(1992)310.
"Soft dipole excitations in ^{11}Li"

Non-energy weighted E1 Cluster Sum Rule

$$B(E1) = \int_0^\infty \frac{dB(E1)}{dE_x} dE_x = \frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2 \left\langle r_1^{\ 2} + r_2^{\ 2} + 2(\vec{r}_1 \cdot \vec{r}_2) \right\rangle$$

$$= \frac{3}{\pi}\left(\frac{Ze}{A}\right)^2 \left\langle r_{c-2n}^{\ \ 2} \right\rangle$$





$$B(E1) = 1.42 \pm 0.18\, e^2\, fm^2 (E_{\mathrm{rel}} \leq 3\mathrm{MeV})$$

$\rightarrow 1.78(22)\, e^2\, fm^2$ (Extrapolated value)

$$\rightarrow \sqrt{\left\langle r_{c-2n} \right\rangle^2} = 5.01 \pm 0.32\ \mathrm{fm}$$

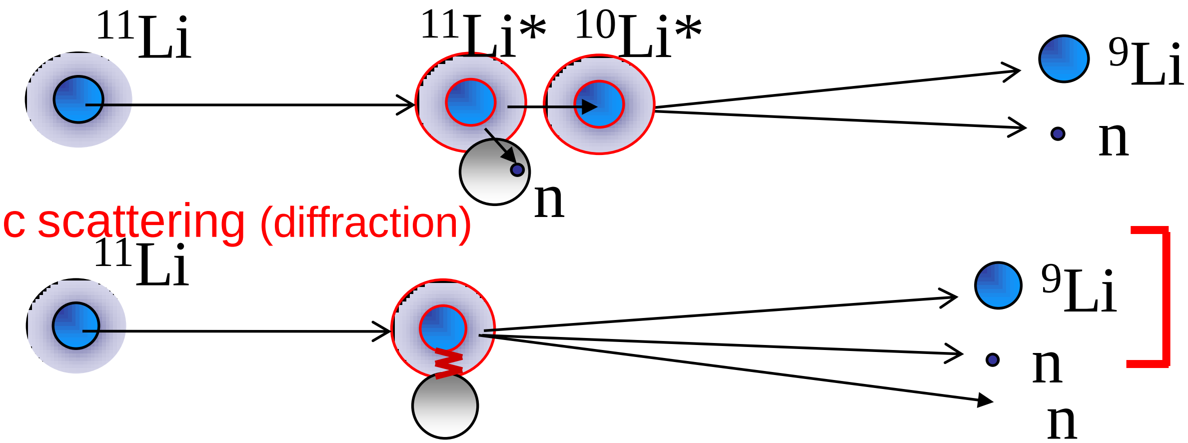
~70% larger than non-correlated strength $\left(\vec{r}_1 \cdot \vec{r}_2 = 0\right)$

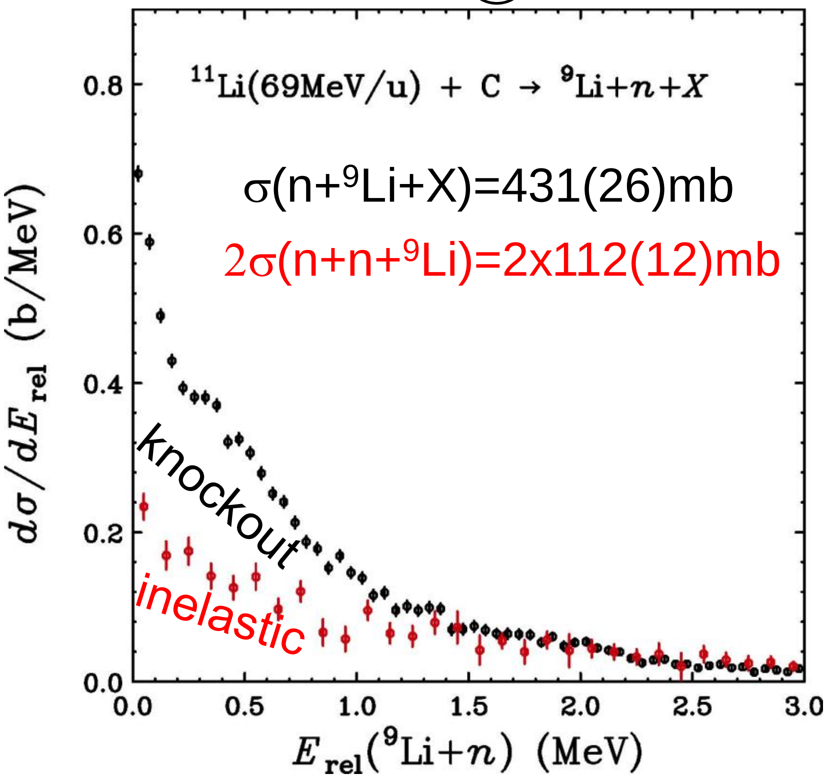
$$\longrightarrow \left\langle \theta_{12} \right\rangle = 48^{+14}_{-18}\ \mathrm{deg}$$

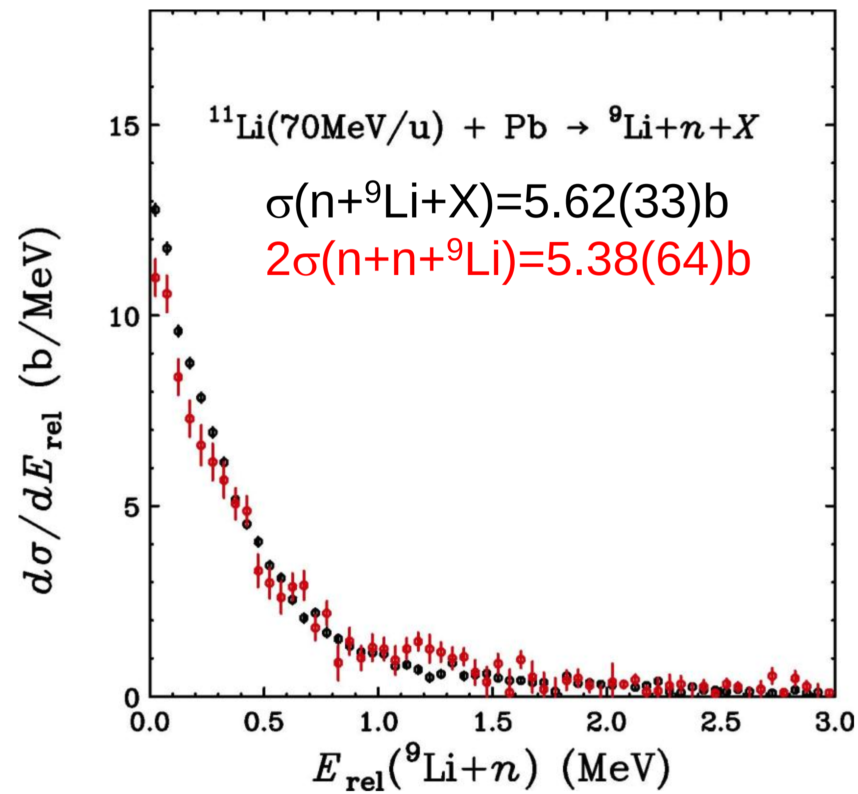
Breakup of ^{11}Li on C

1n + ^{9}Li spectrum

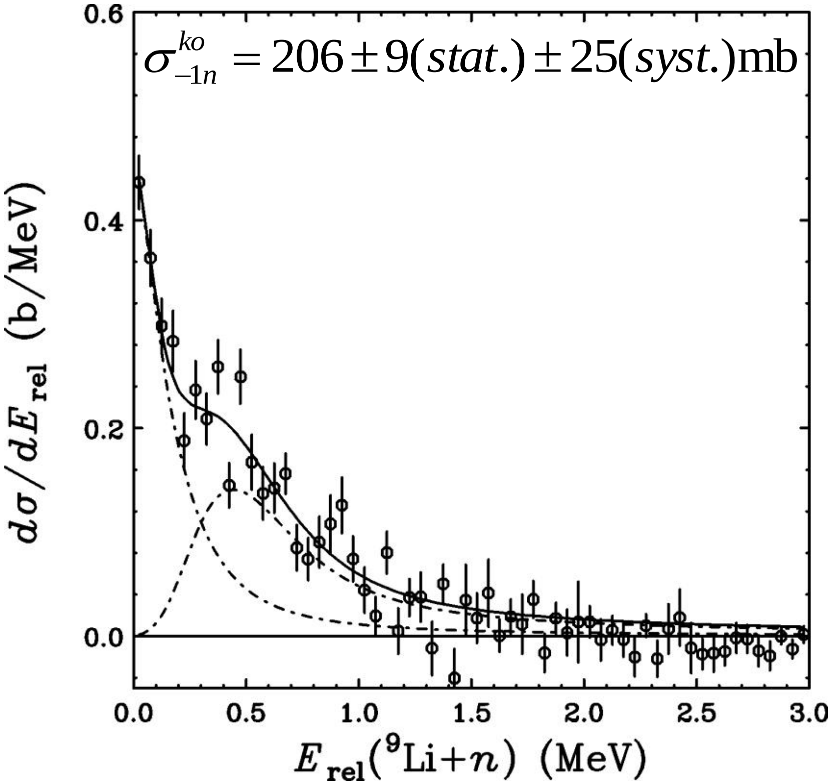
1n knockout reaction







^{10}Li spectrum (1n Knockout component)



s-wave scattering state (virtual state)

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

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

Initial: ^{11}Li $\quad \Psi_0(r) \propto \frac{\exp(-\alpha r)}{r}$

Final: s-wave

$$\psi_k(r) \propto \frac{\sin(kr+\delta)}{kr} \qquad k\cot\delta = -\frac{1}{a} + \frac{1}{2} r_e k^2$$

p-wave resonance

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

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

s-component

$a = -12(13)\text{fm}$

$\alpha = 11.1(4.3)\text{MeV}$

$(S_n = 73(56)\text{keV})$

p-component

$E_R = 0.470(27)\,\text{MeV}$

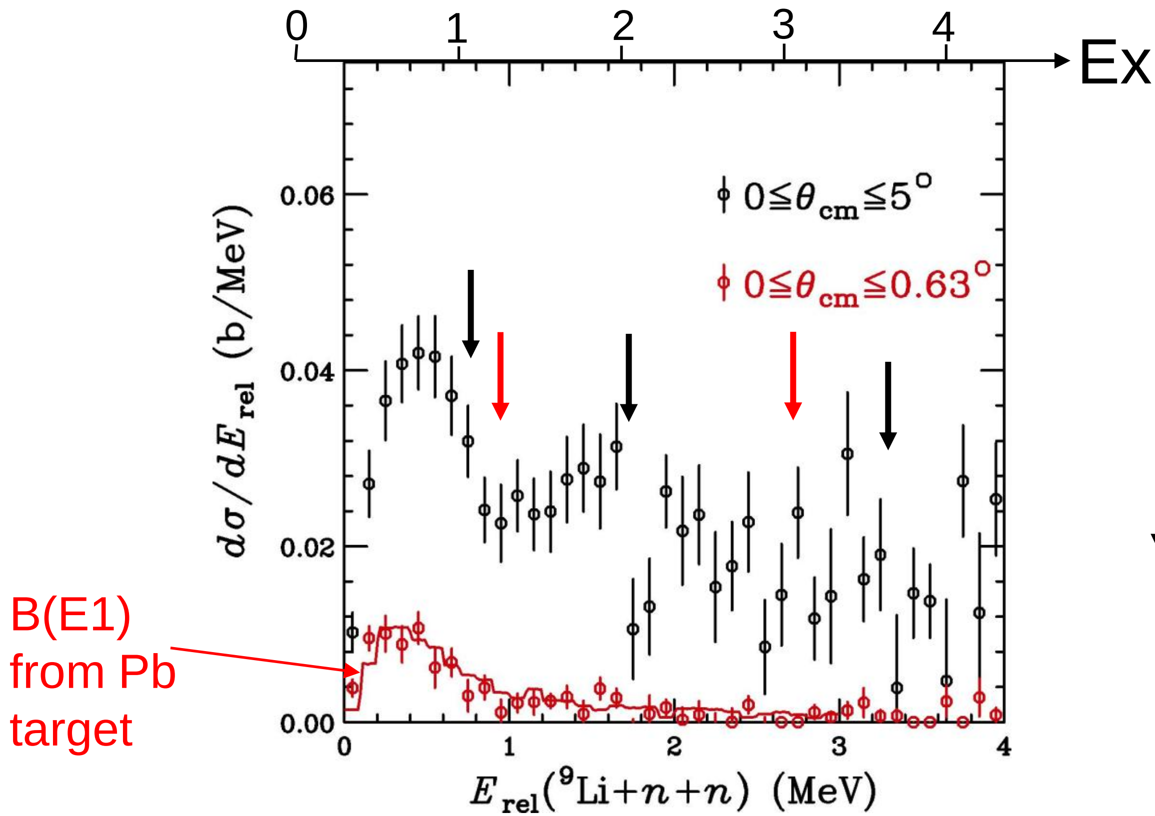
$\gamma^2 = 1.70(24)\,\text{MeV}$

$(\Gamma = 0.37\ \text{MeV})$

c.f. $a < -20$ fm L.Chen et al.,PLB505,21(2001).

$E_R = 0.538(62)$ MeV, $\Gamma = 0.358(23)$ MeV B.M.Young et al.,PRC49,279(1994).

^{11}Li+C→^{9}Li+n+n



^{11}Li(p,p') Korsheninnikov et al.,PRC53, R537(1996); PRL78,2317(1997). (Ex=1.25(15),3.0(2))

^{14}C(π^-,pd)^{11}Li M.G. Gornov et al., PRL81,4325(1998). (Ex=1.02(7), 2.07(12), 3.63(13))

$$\sigma = 108 \pm 4(stat.) \pm 13(syst.)\text{mb}$$

$$\theta_{cm} \leq 5^\circ$$

Summary

Breakup of ^{11}Li on Pb

- Strong B(E1) at very low excitation energy

$$B(E1) = 1.42 \pm 0.18 e^2 fm^2$$

c.f. B(E1)=1.05(6) e^2fm^2 ^{11}Be

- B(E1) Strength Distribution ⇒ nn correlation in ^{11}Li
(E1 Non-energy weighted sum rule)

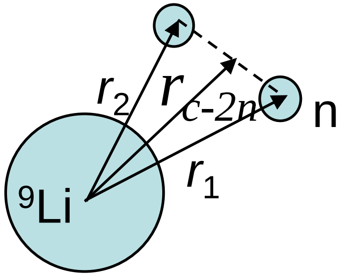
Correlation in Decay Spectrum (Dalitz plots) → INPC

Breakup of ^{11}Li on C

- 1n-knockout component is seen
s-wave component + p-wave component
Scattering length a=-12(13)fm Er=0.47(3) MeV

- ^{9}Li+2n invariant mass spectrum
Coulomb component is observed
Structures→further studies are necessary

Implication of the Narrow Opening Angle



Simple two-neutron shell model

$$\left|\Psi(^{11}\mathrm{Li})\right\rangle = Core \otimes \left[\alpha\left|(1s)^2\right\rangle + \beta\left|(0p)^2\right\rangle\right]$$

Melting of s(+ parity) and p(-parity) orbitals

H.Simon et al. PRL83,496(1999).
N. Aoi et al. NPA616,181c(1997).

$$\langle\cos\theta_{12}\rangle = \alpha^2\left\langle(1s)^2\right|\cos\theta_{12}\left|(1s)^2\right\rangle + \beta^2\left\langle(0p)^2\right|\cos\theta_{12}\left|(0p)^2\right\rangle + 2\alpha\beta\left\langle(0p)^2\right|\cos\theta_{12}\left|(1s)^2\right\rangle$$

$$= 2\alpha\beta\left\langle(0p)^2\right|\cos\theta_{12}\left|(1s)^2\right\rangle$$

If only $(1s)^2$ or $(0p)^2$ ⇨ $\langle\cos\theta_{12}\rangle = 0,\quad \langle\theta_{12}\rangle = 90^\circ$

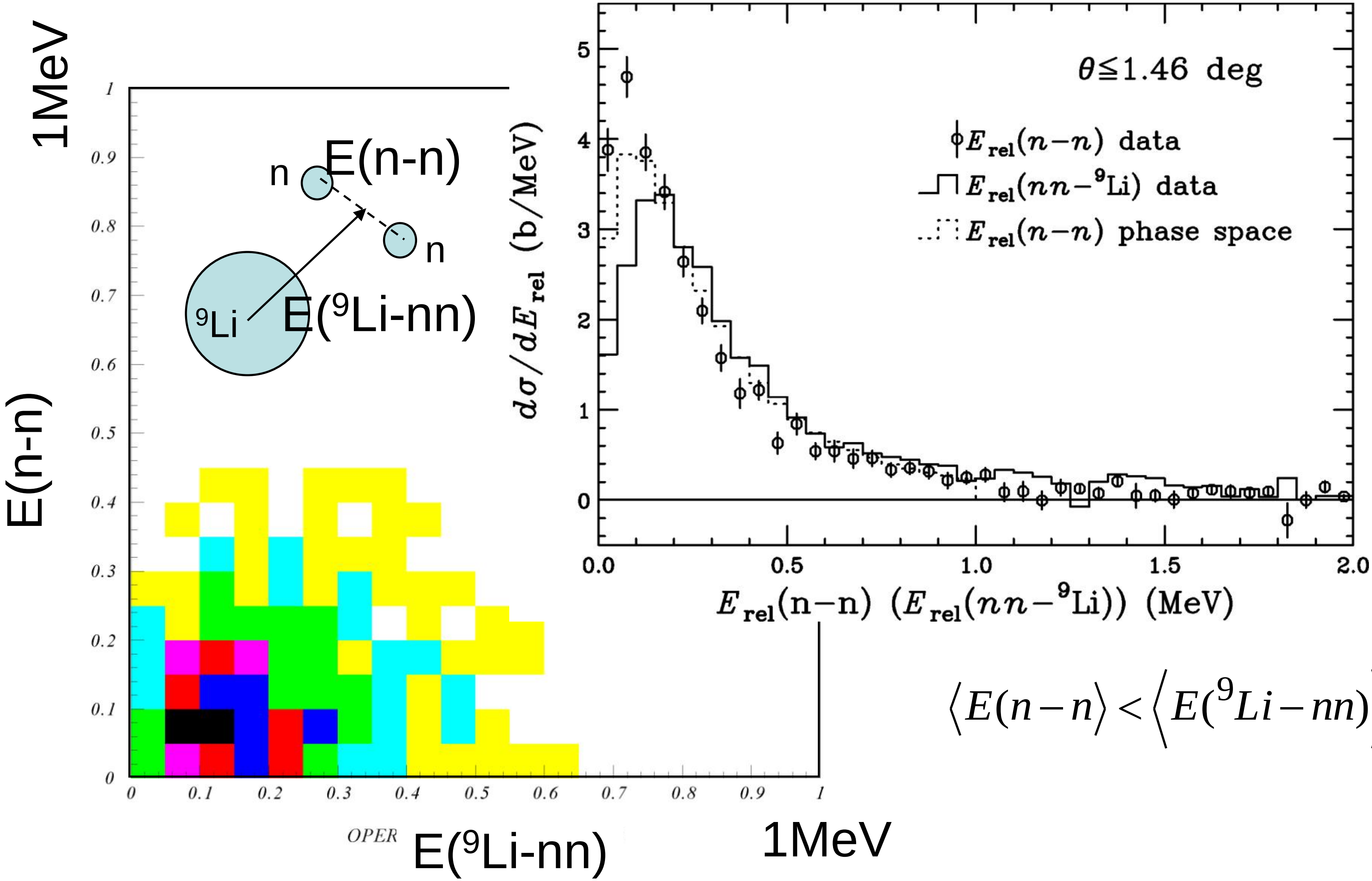
If full overlap $(1s)^2$ & $(0p)^2$ ⇨ $\langle\cos\theta_{12}\rangle = 1/\sqrt{3},\quad \langle\theta_{12}\rangle = 55^\circ$

If 50% overlap integral ⇨ $\langle\cos\theta_{12}\rangle = 1/(2\sqrt{3}),\quad \langle\theta_{12}\rangle = 73^\circ$

$$\langle\theta_{12}\rangle = 48^{+14}_{-18}\ \mathrm{deg}$$

Mixture of different parity states is essential !

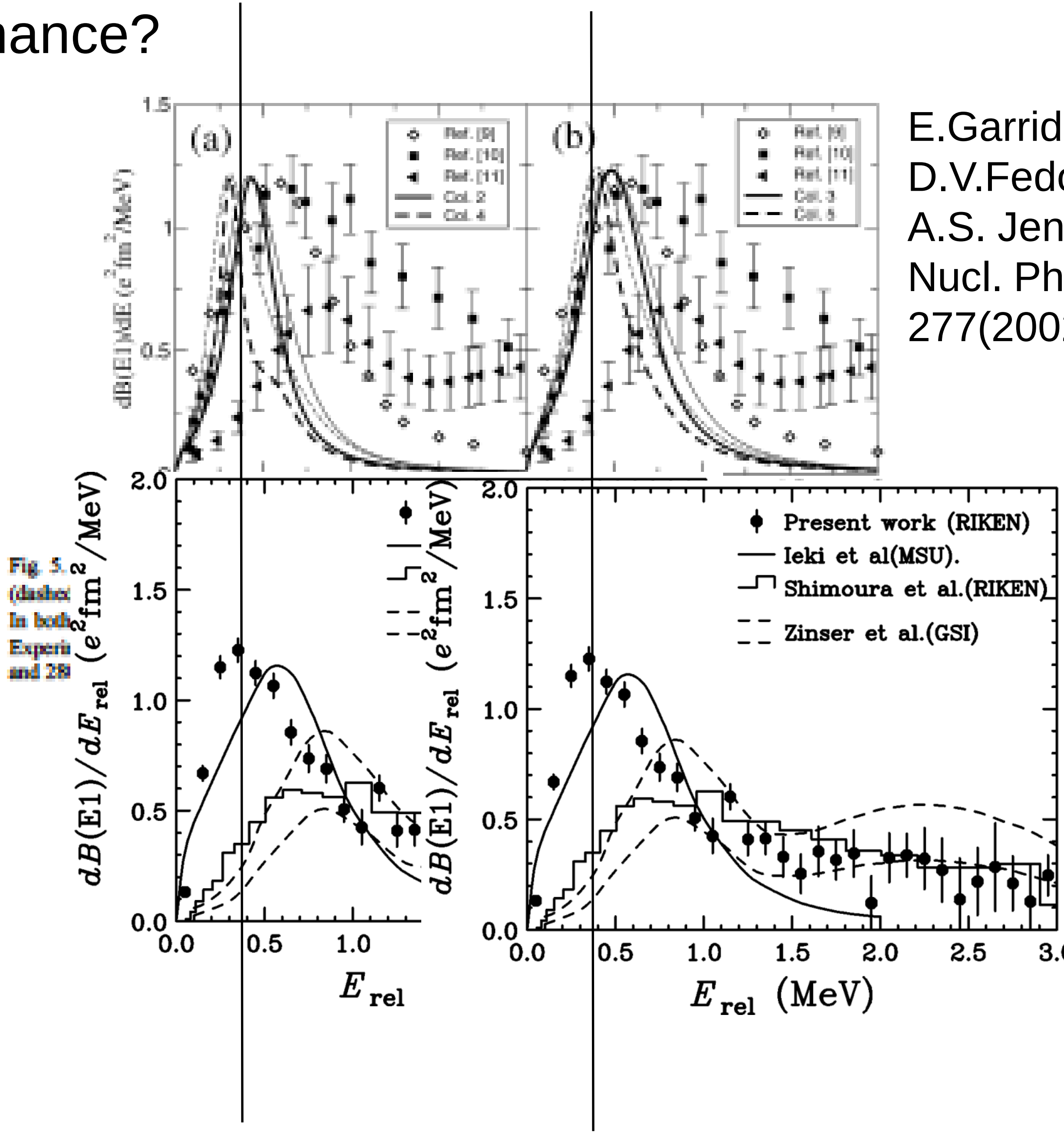
Mixture of higher L orbitals→ More correlated



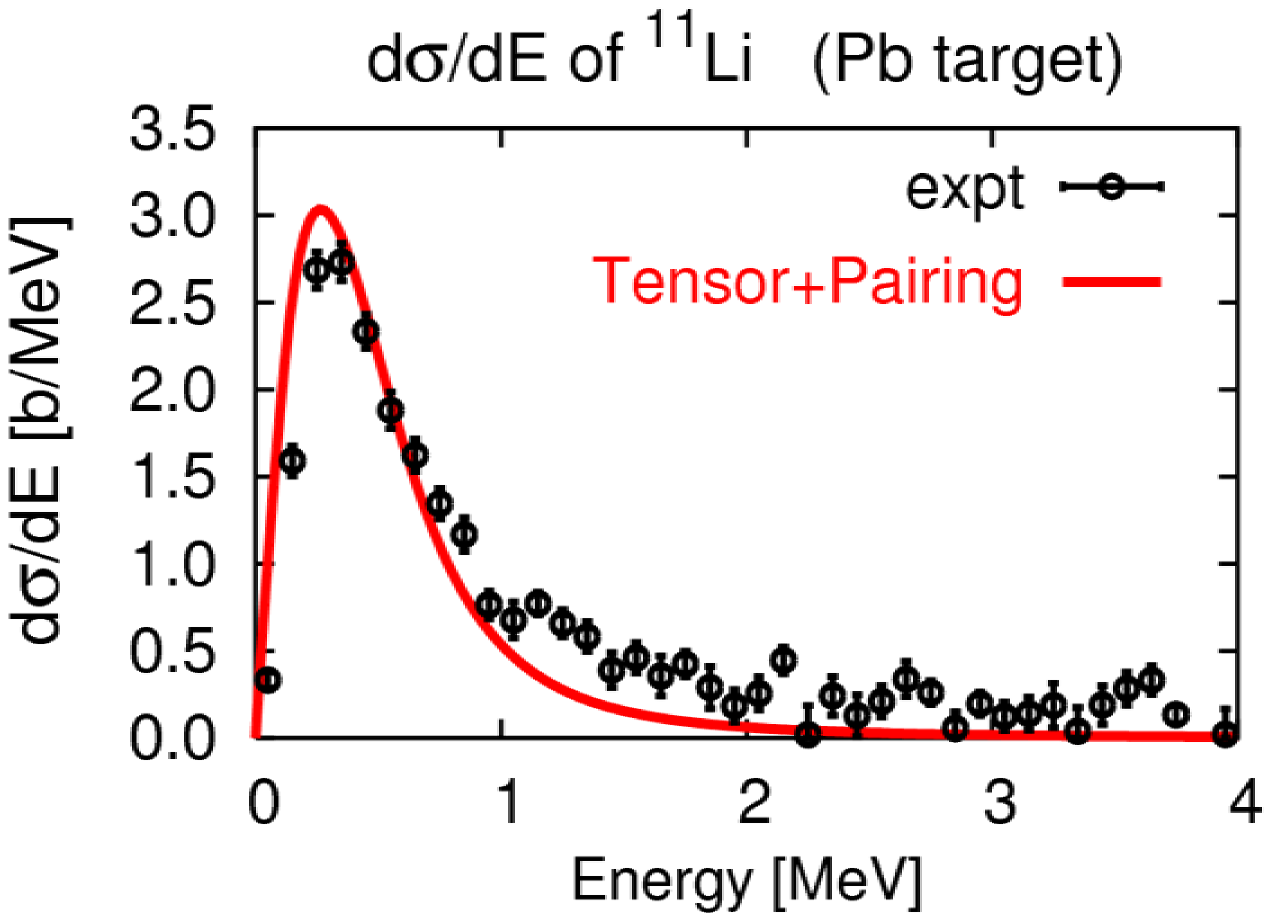
$$\left\langle E(n-n)\right\rangle < \left\langle E(^9Li-nn)\right\rangle$$

preliminary

3body Resonance?



E.Garrido, D.V.Fedorov, A.S. Jensen Nucl. Phys. A 708, 277(2002).



E1 strength by using the Green's function method

+Complex scaling method

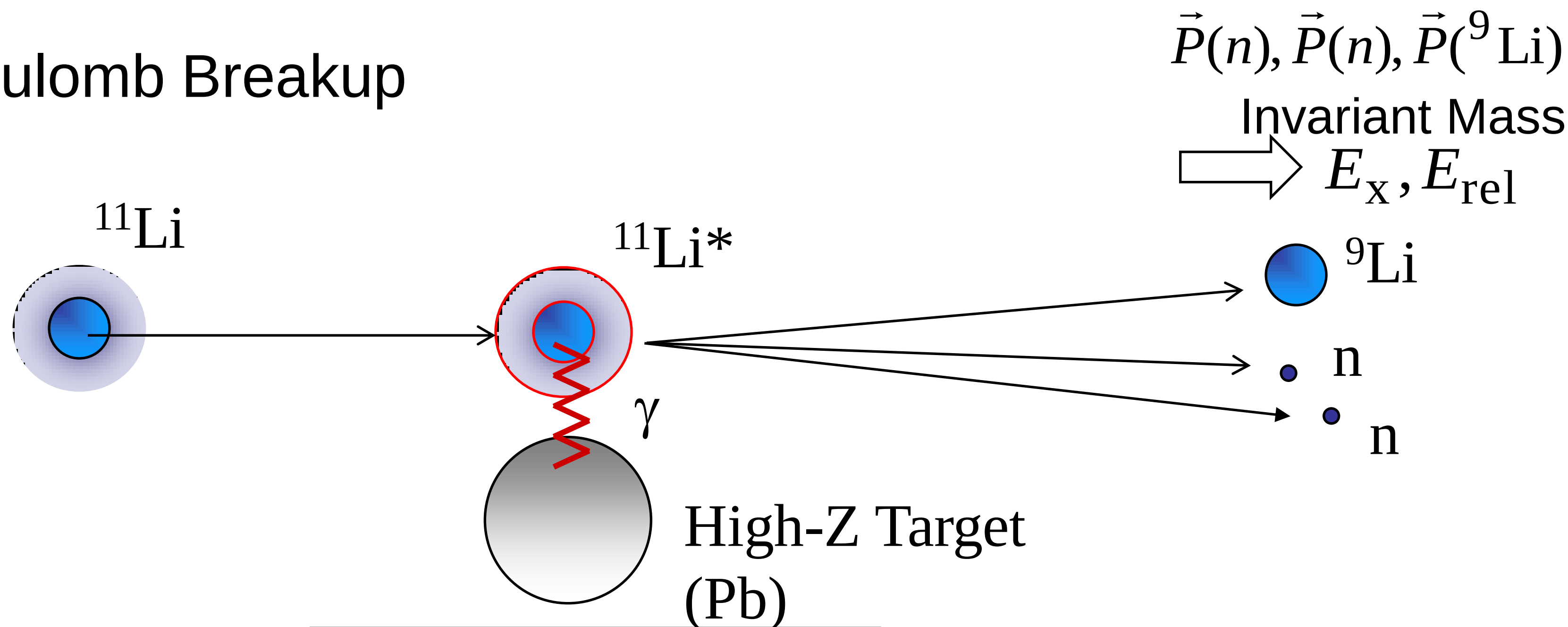
+Equivalent photon method

(**T.Myo et al., PRC63(2001)**)

Expt: T. Nakamura et al. , PRL96,252502(2006)

Courtesy of T.Myo (RCNP,Osaka U.)

Coulomb Breakup

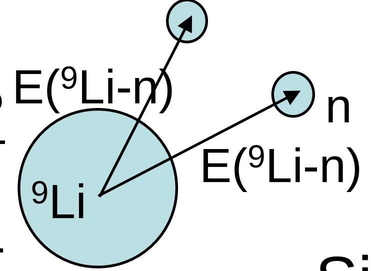


Equivalent Photon Method

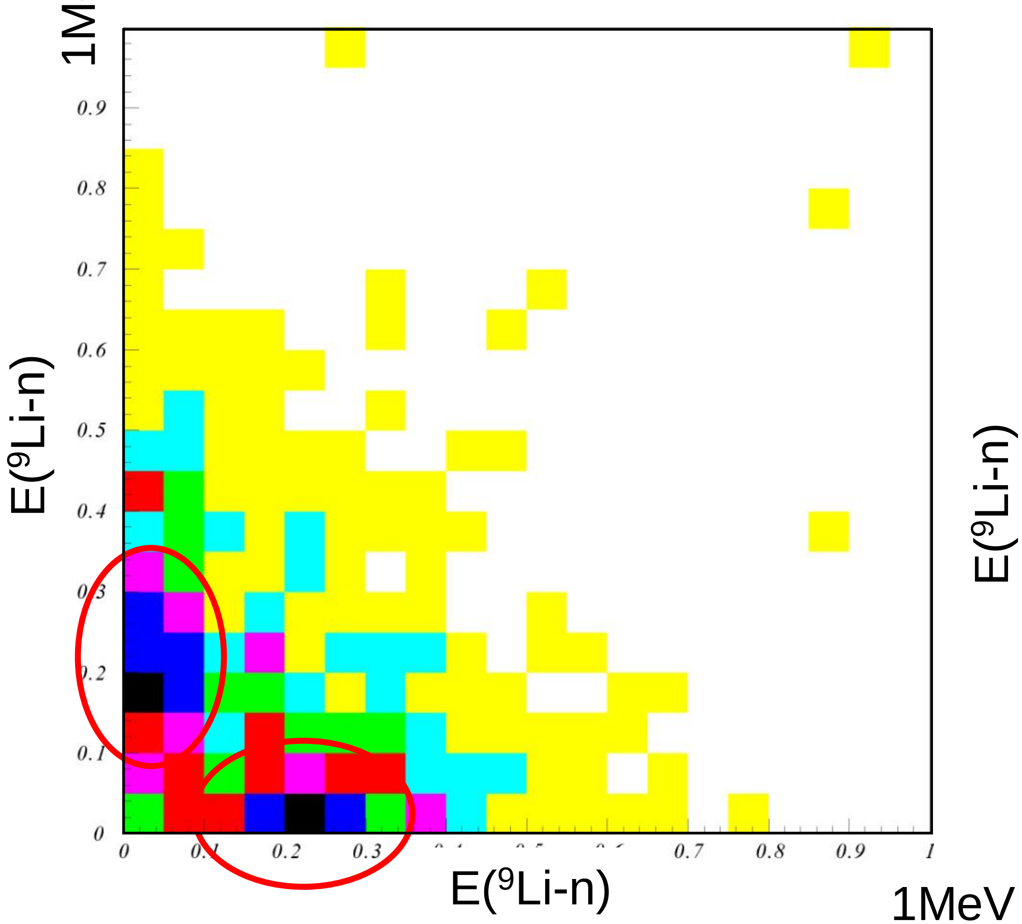
$$\frac{d\sigma_{CD}}{dE_x} = \frac{16\pi^3}{9\hbar c} N_{E1}(E_x) \frac{dB(E1)}{dE_x}$$

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

Further Correlation?

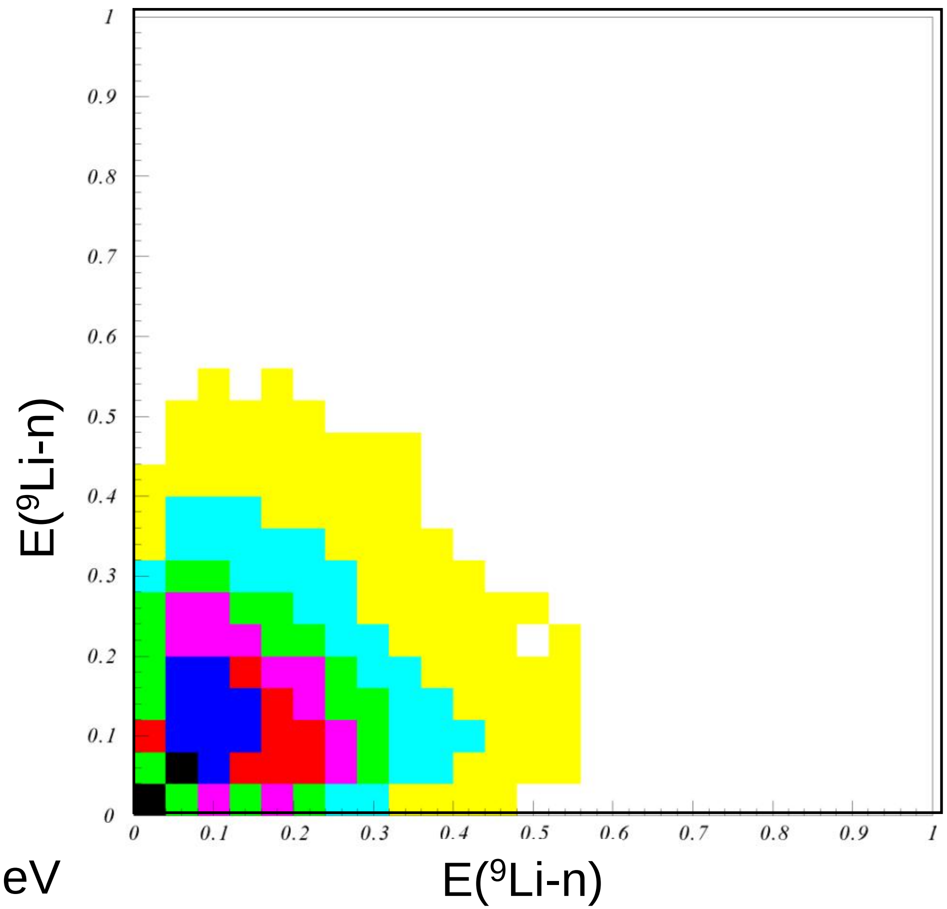


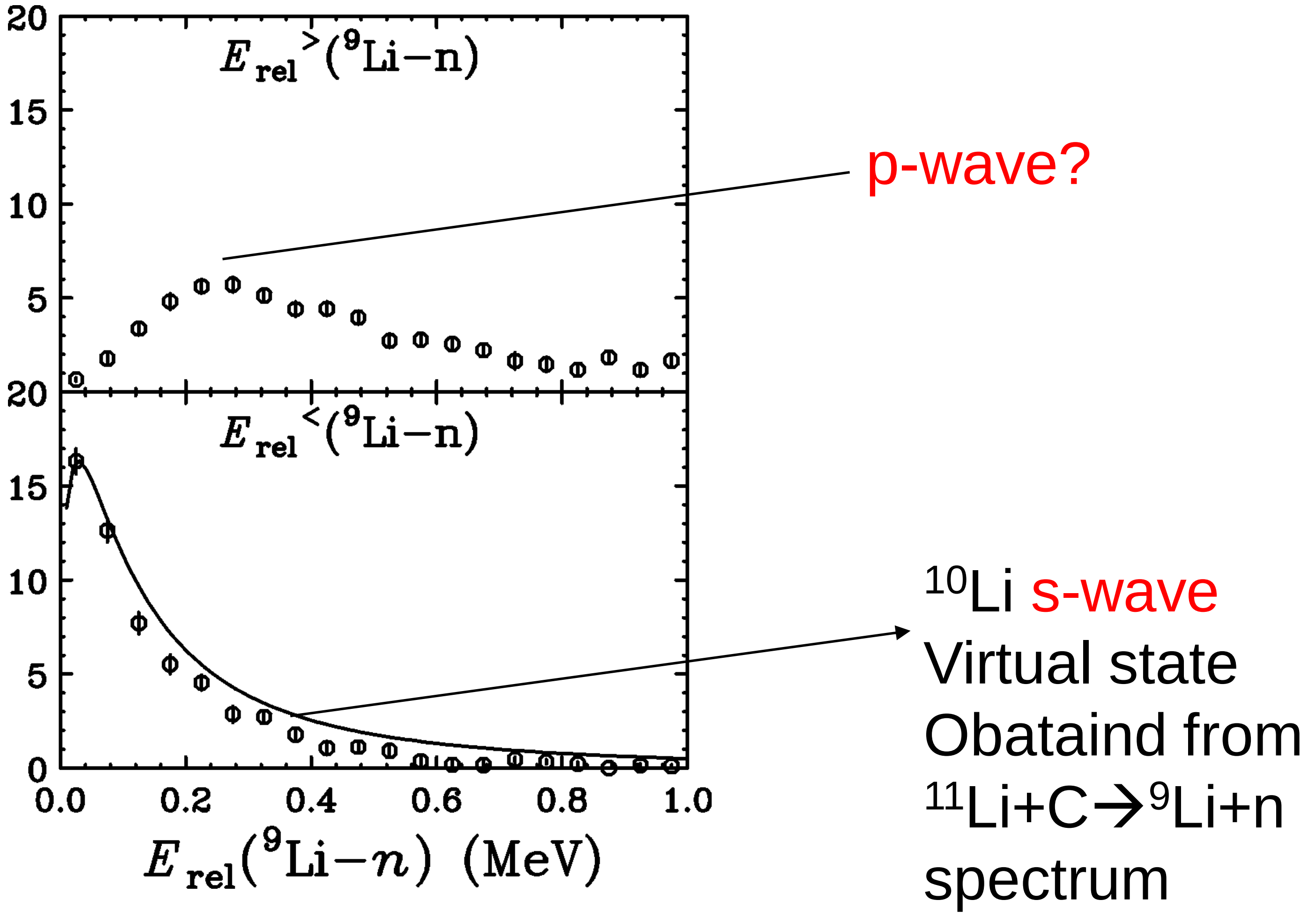
Experimental Result



preliminary

Simulation (Phase Space)





$$\left|\Phi(^{11}\mathrm{Li}_{gs})\right\rangle = \alpha\left|\Phi(^{9}\mathrm{Li}_{gs})\otimes(s_{1/2})^2\right\rangle + \beta\left|\Phi(^{9}\mathrm{Li}_{gs})\otimes(p_{1/2})^2\right\rangle + \ldots$$

$$\left|O(E1)\,|\,\Phi(^{11}\mathrm{Li}_{gs})\right\rangle = \gamma\left|\Phi(^{9}\mathrm{Li}_{gs})\otimes(s_{1/2})^1(p_{1/2})^1\right\rangle + \ldots$$