Invariant mass spectroscopy of halo nuclei at Intermediate energies

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HALO'06 , @ECT Trento Italy*

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2 Coulomb Breakup of halo nuclei ^{11}Li

T. Nakamura, A.M.Vinodkumar et al.,

Phys. Rev. Lett. 96, 252502 (2006)

3 Inelastic scattering of ^{14}Be

T. Sugimoto et al., in preparation (2006).

Collaborators

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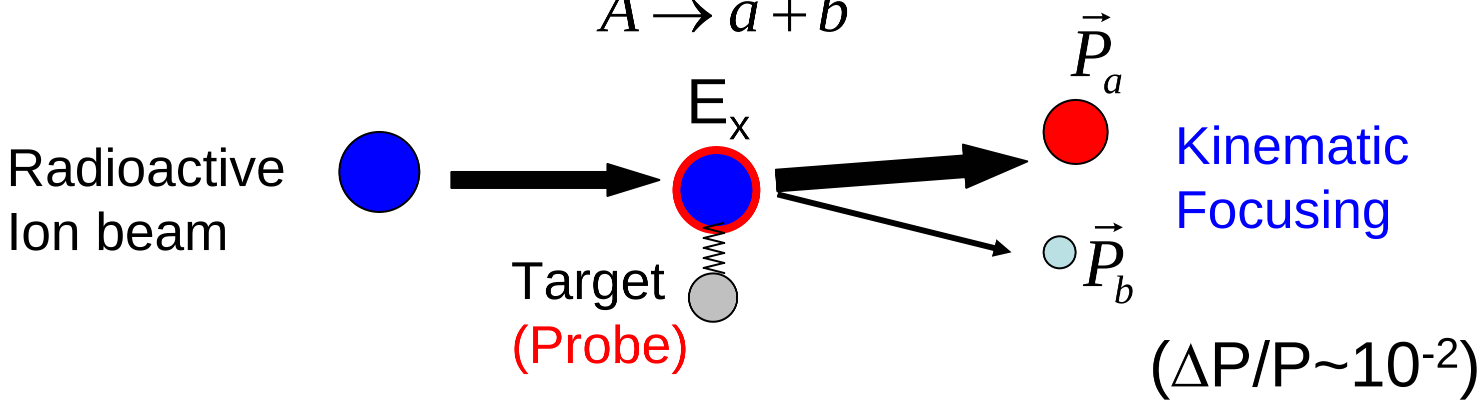
M.Shinohara, Y.Hashimoto, T.Nakabayashi
Okumura

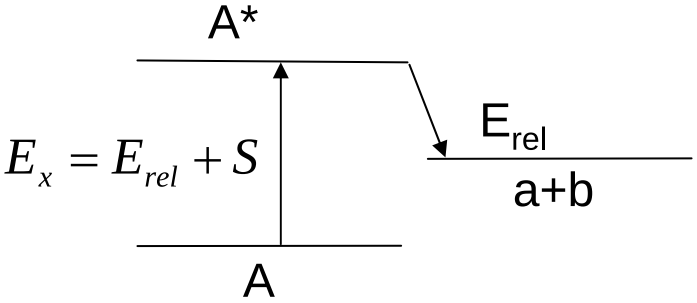
☐ Invariant Mass Method for RI beam

$$A \rightarrow a + b$$



$$M = \sqrt{(E_a + E_b)^2 - (\vec{P}_a + \vec{P}_b)^2}$$

$$E_{\mathrm{rel}} = M - (M_a + M_b)$$



Advantages

Good Energy Resolution ~ a few hundred keV @E_{rel}=1MeV
Kinematic Focusing
Thick Target ~0.2g/cm^2 @70MeV/nucleon

→ Good approach for nuclei at drip line

Disadvantages

Need to measure all the outgoing particles

2 Coulomb Breakup of halo nuclei ^{11}Li

T. Nakamura, A.M.Vinodkumar et al.,

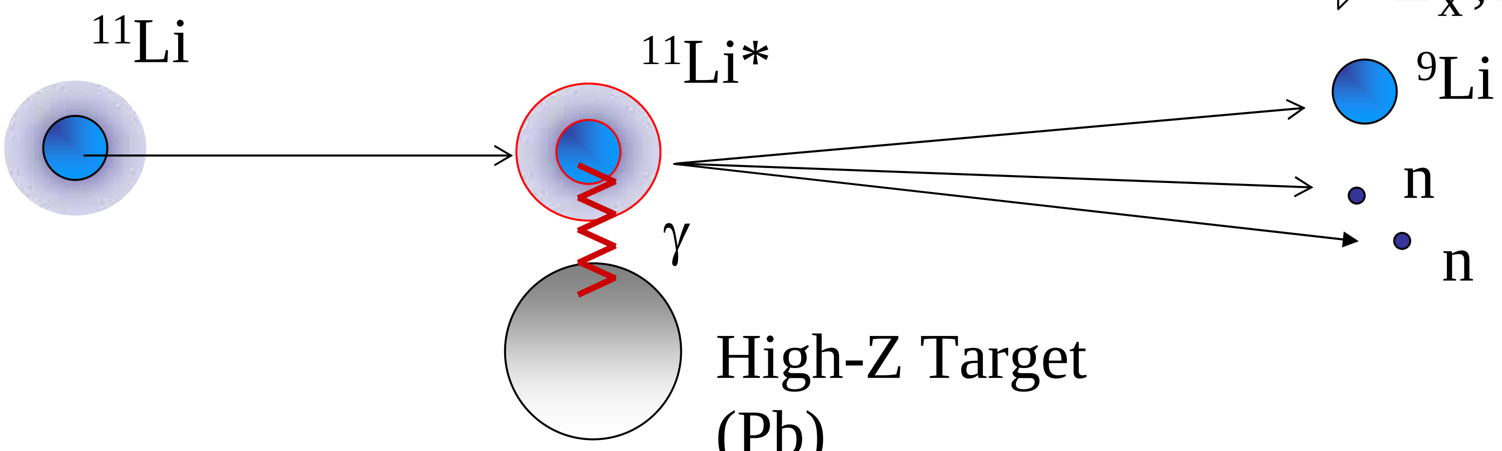
Phys. Rev. Lett. 96, 252502 (2006).

Coulomb Breakup

$\vec{P}(n), \vec{P}(n), \vec{P}(^{9}\mathrm{Li})$

Invariant Mass

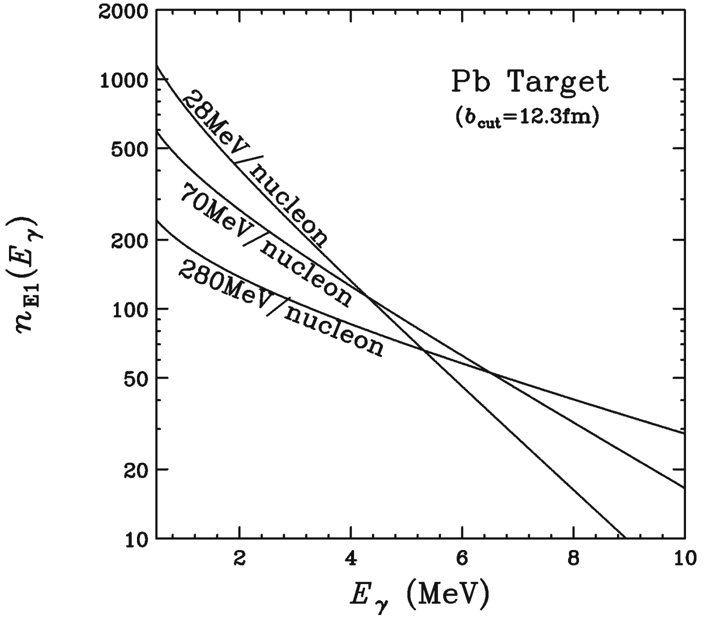
$\Rightarrow E_x, E_{rel}$



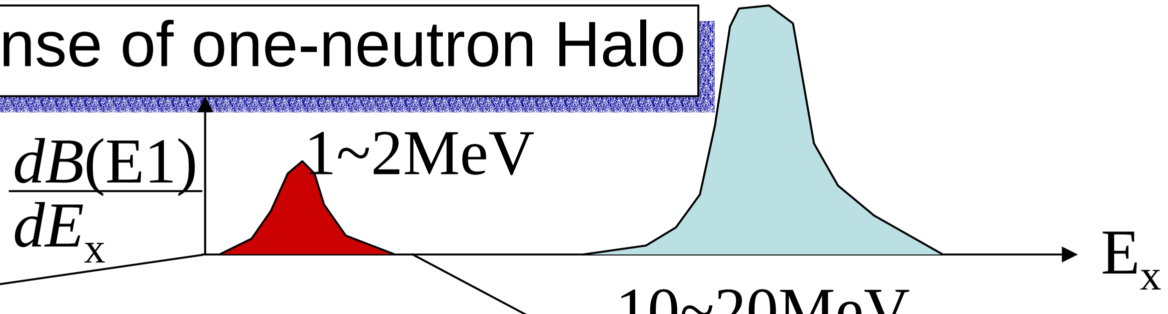
Equivalent Photon Method

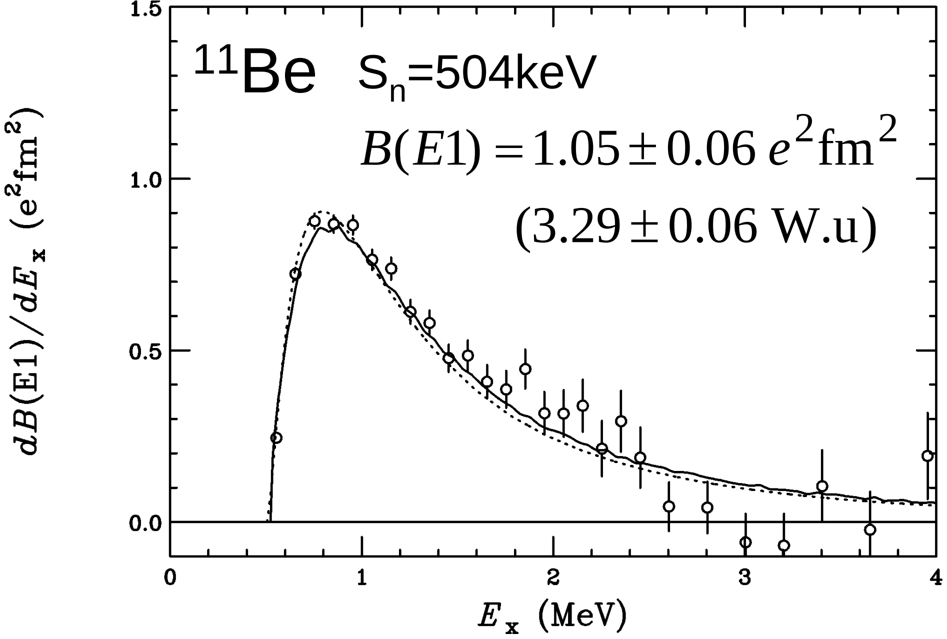
$$\frac{d\sigma_{CD}}{dE_x} = \frac{16\pi^3}{9\hbar c} N_{E1}(E_x)\frac{dB(E1)}{dE_x}$$

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



^{11}Be : E1 Response of one-neutron Halo



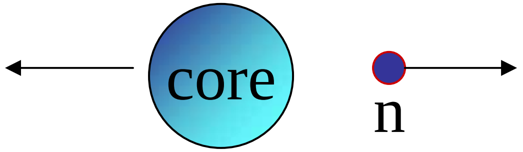


70MeV/nucleon @RIKEN

N.Fukuda, TN et al., PRC70, 054606 (2004)

TN *et al.*,PLB 331,296(1994)

Direct Breakup Mechanism

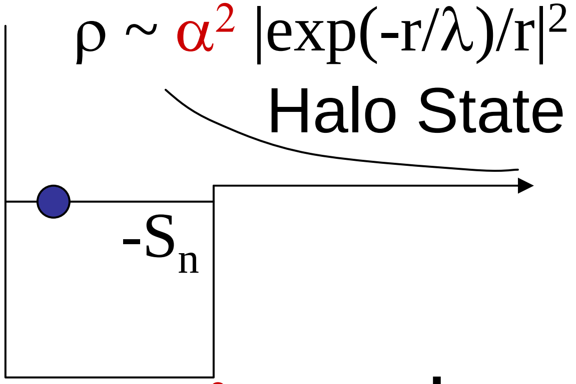


Low-lying E1 Strength

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

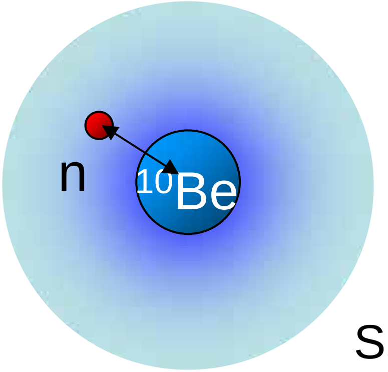
$$\propto \alpha^2 |\langle \exp(i\boldsymbol{qr})|\frac{Z}{A} rY^1{}_m|s_{1/2}\rangle|^2$$

⇔ *Fourier Transform*



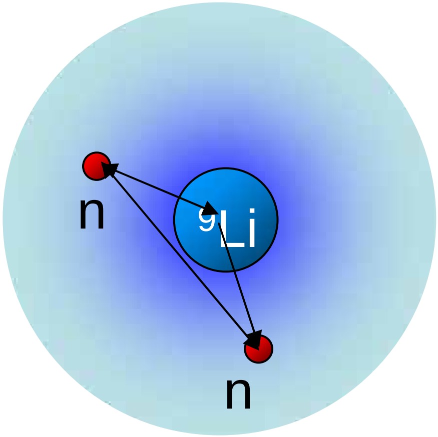
$\alpha^2 = 0.72 \pm 0.04$

One neutron halo nucleus vs. Two neutron halo nucleus



S_n=504 keV

Motion between
core and 1 valence neutron

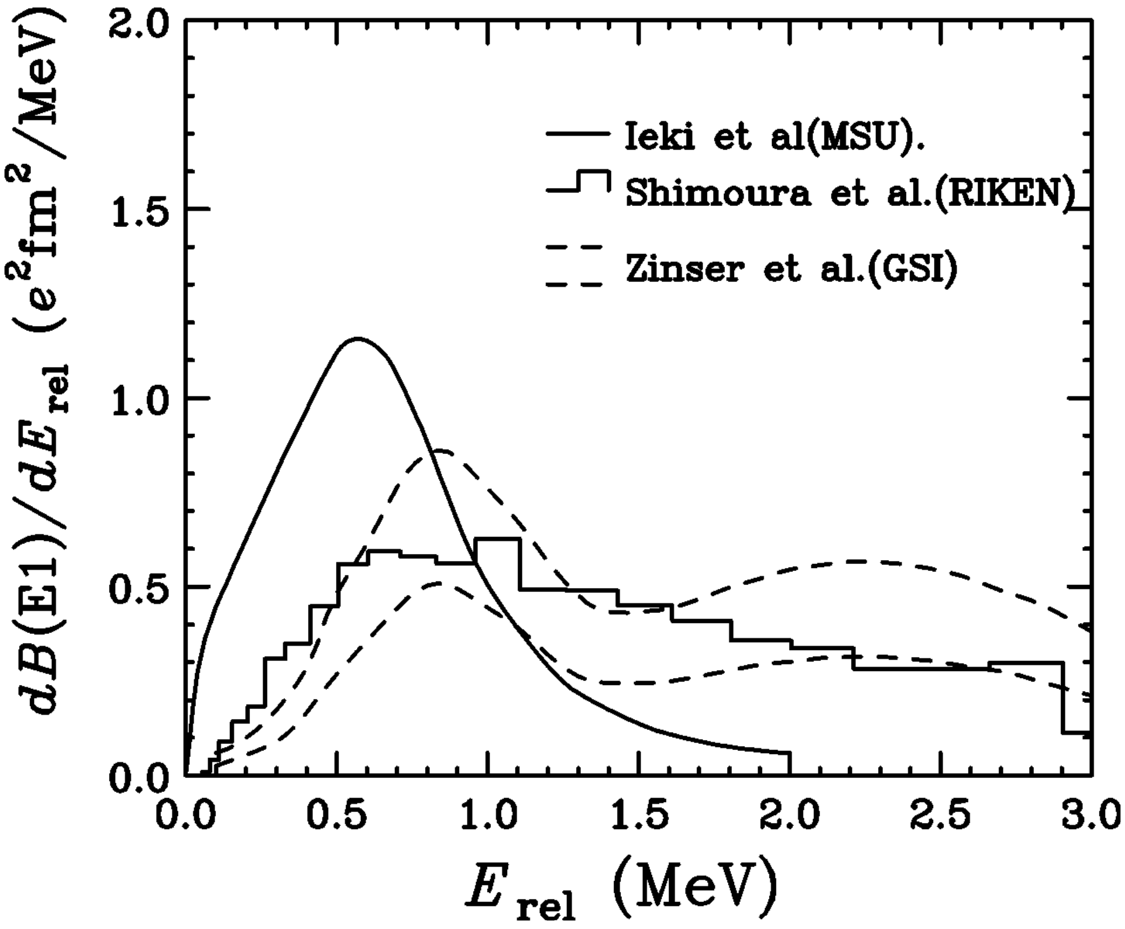


S_{2n}=300 keV

Motion between

1. Core and neutron
2. Core and neutron
3. Two valence neutrons
   (neutron-neutron correlations)

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



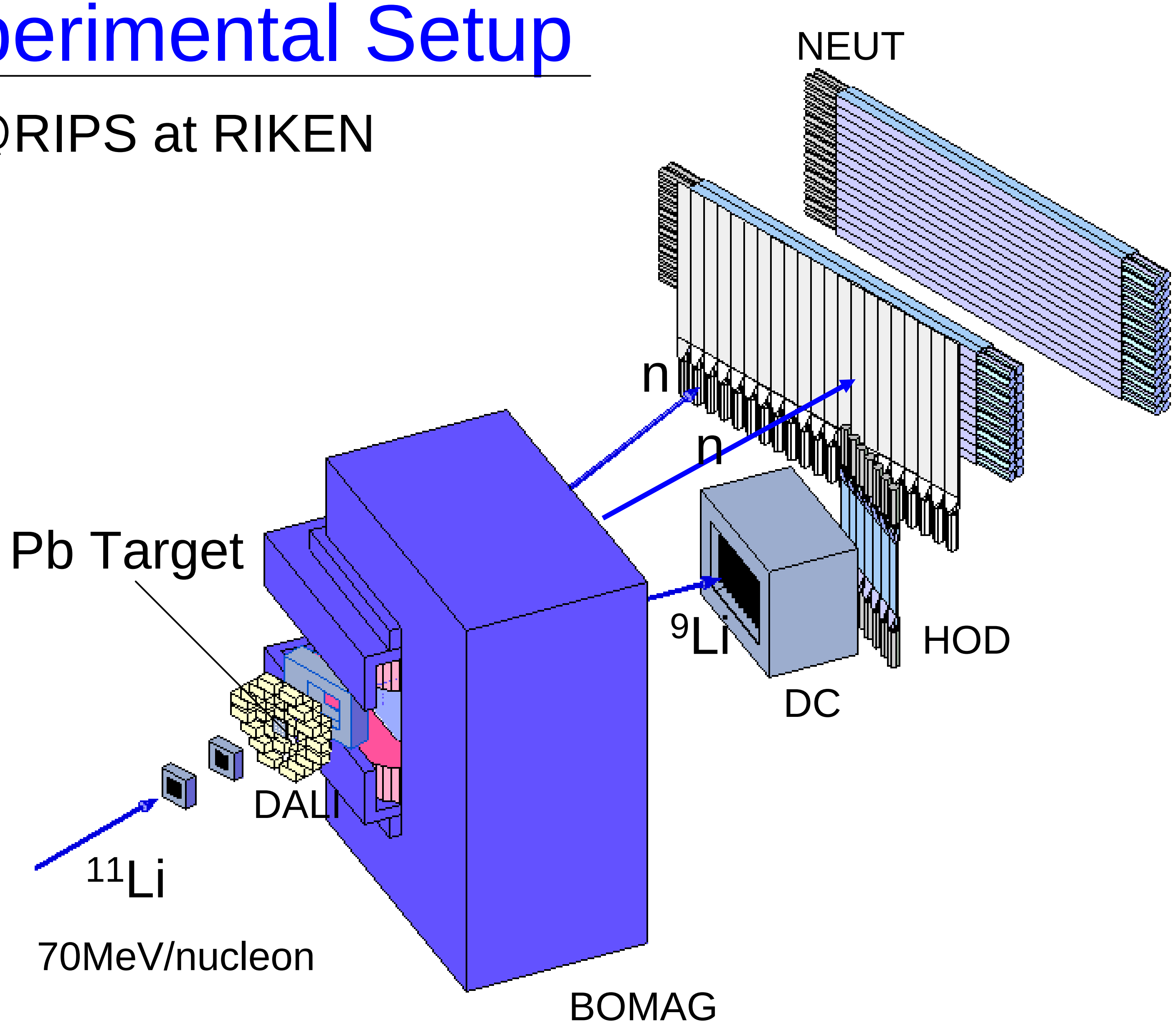
MSU@ 28MeV/nucleon
PRL 70 (1993) 730.
PRC 48(1993) 118.

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

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

Experimental Setup

@RIPS at RIKEN

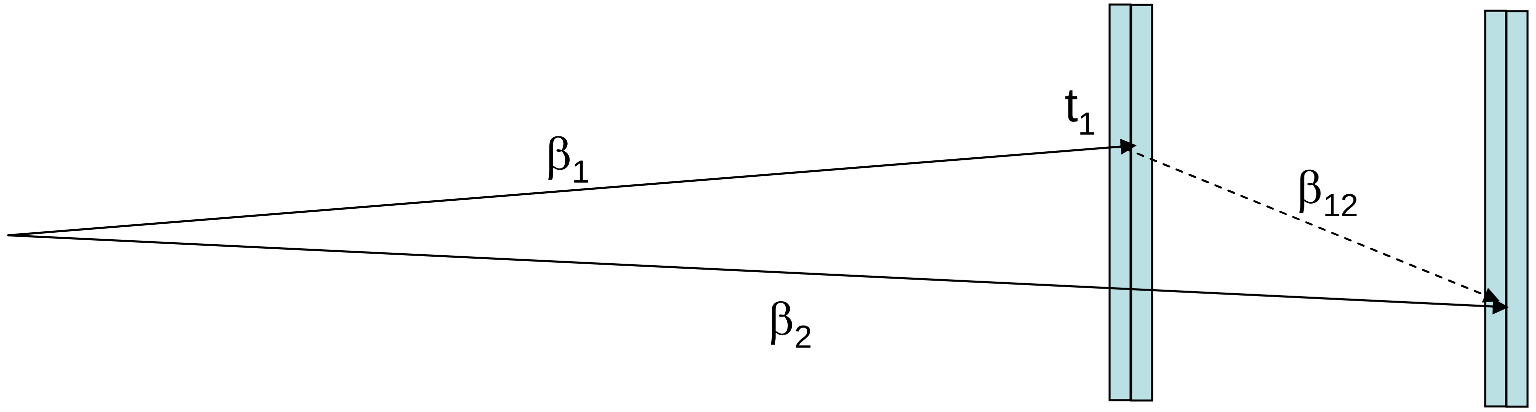


Elimination of Cross-Talk events

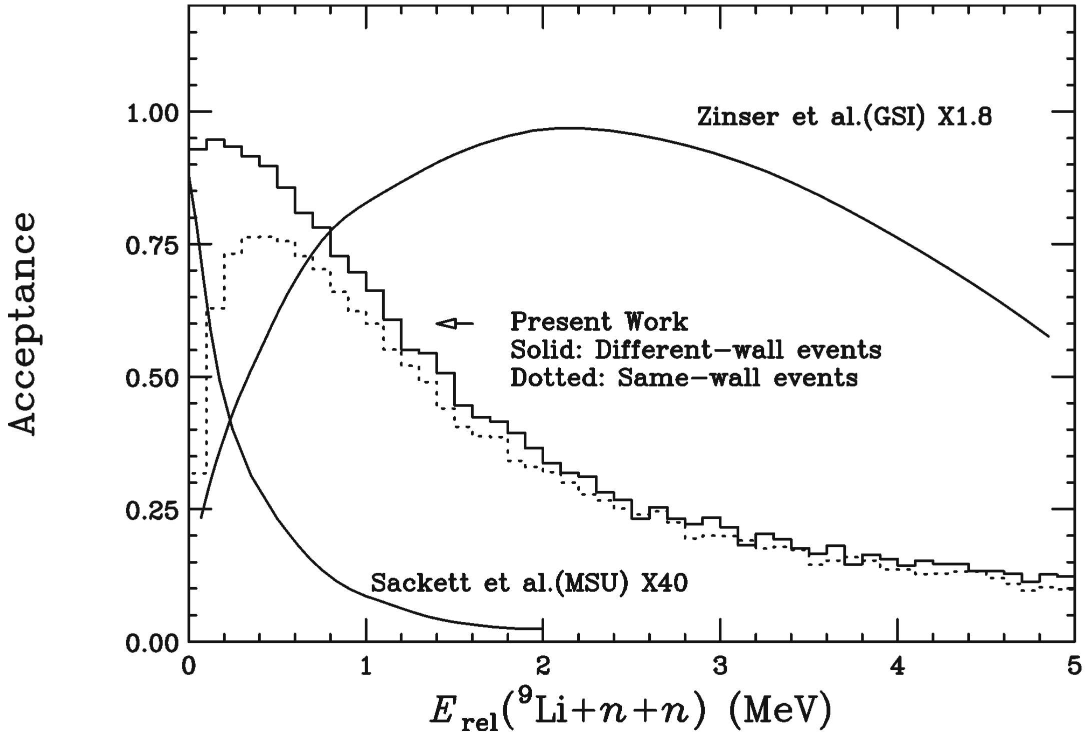
Examine Different Wall Events

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

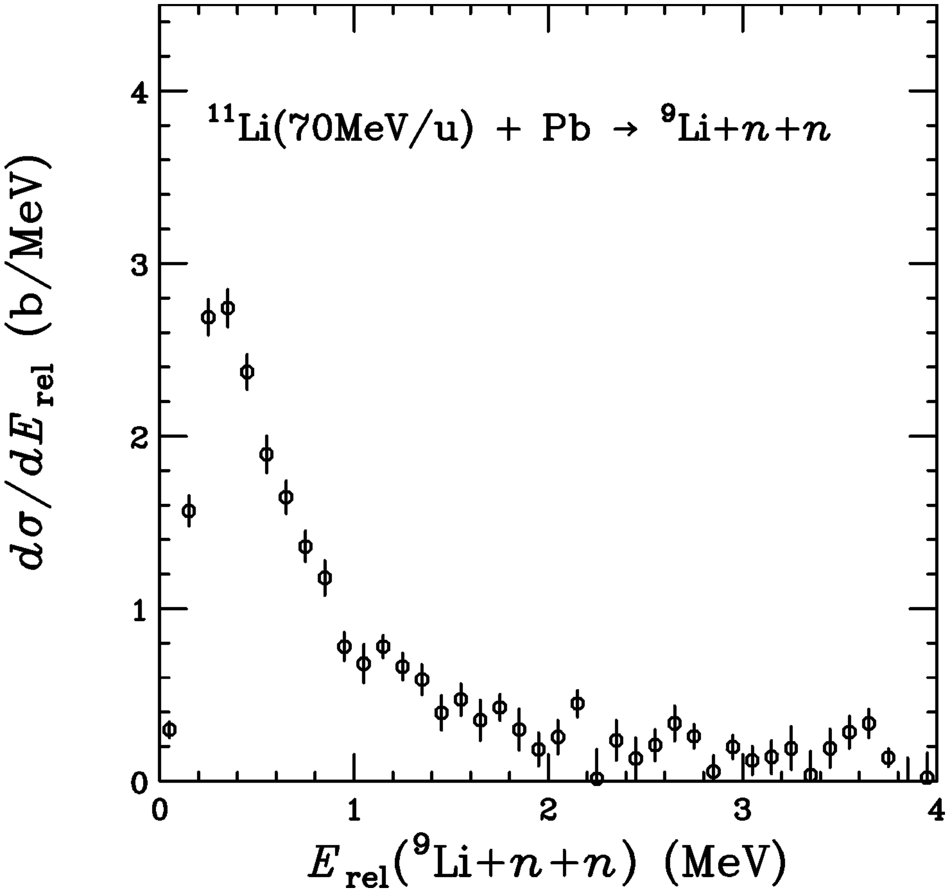
Almost no bias



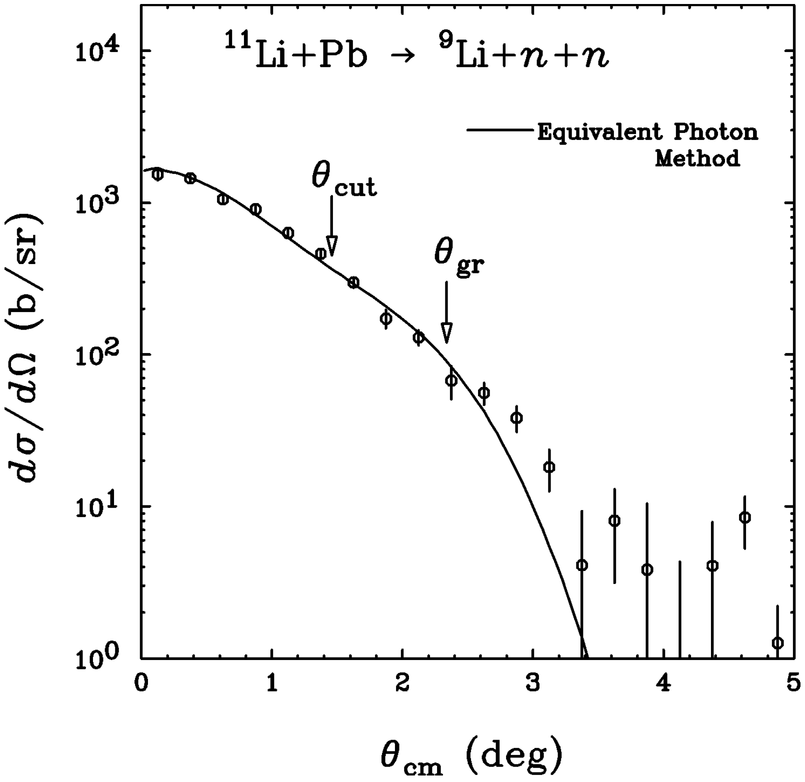
E_{th}=6MeVee to avoid any gamma related events



Coulomb Dissociation Spectrum of ^{11}Li



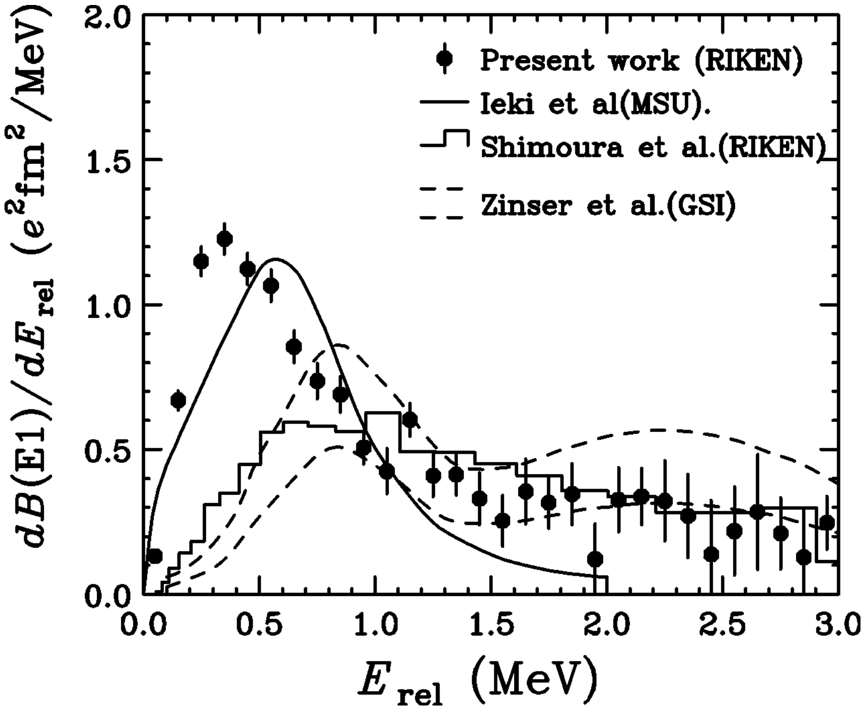
Angular Distribution



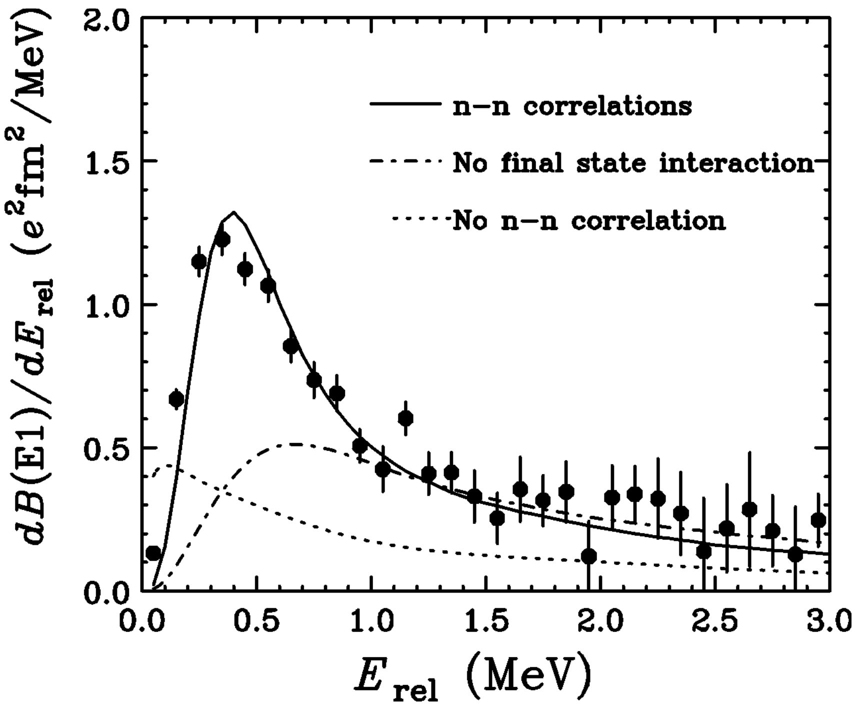
$$\sigma = 2.34 \pm 0.05(stat.) \pm 0.28(syst.)\ \mathrm{b}$$

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

Comparison with Previous results



Comparison with a 3-body theory



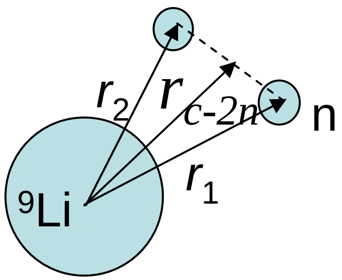
Calculation

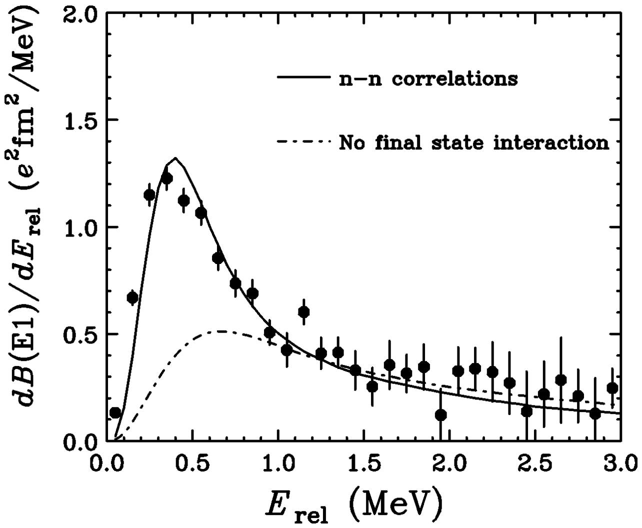
H.Esbensen and G.F. Bertsch
NPA542(1992)310.
“Soft dipole excitations in ^{11}Li”

Non-energy weighted
E1 Cluster Sum Rule

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

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





$$\underline{B(E1)=1.42\pm0.18\,e^2\,fm^2\,(E_{\mathrm{rel}}\leq 3\mathrm{MeV})}$$

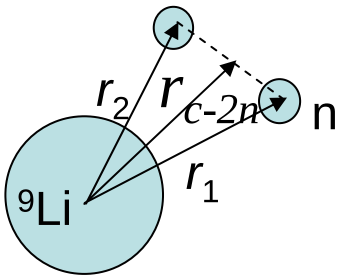
$\rightarrow 1.78(22)\,e^2\,fm^2$(Extrapolated value)

$$\rightarrow\sqrt{\left\langle r_{c-2n}\right\rangle^2}=5.01\pm0.32\ \mathrm{fm}$$

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

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

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).

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

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

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

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

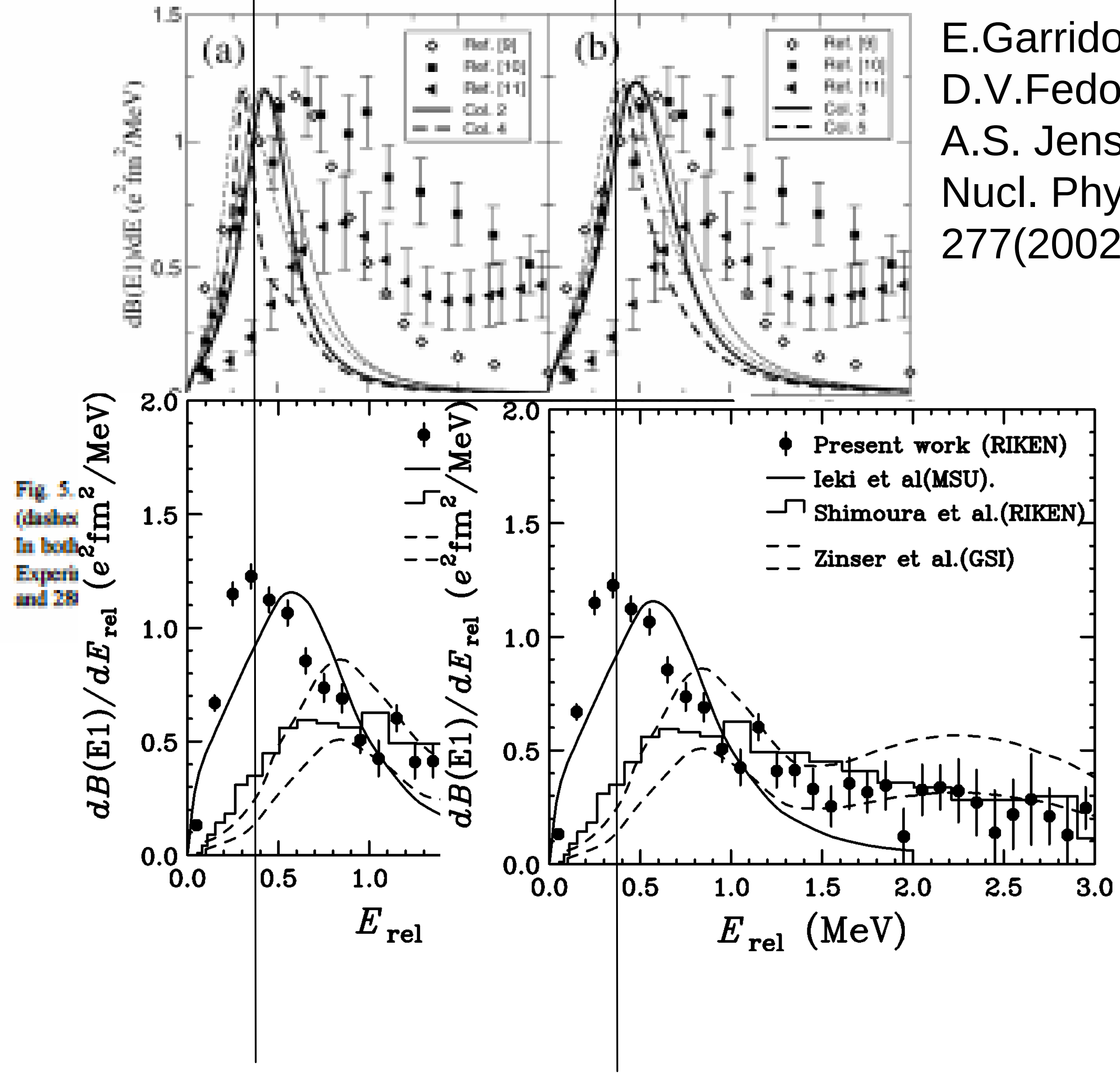
If 50% overlap integral ⟹ $\left\langle\cos\theta_{12}\right\rangle = 1/(2\sqrt{3}), \quad \left\langle\theta_{12}\right\rangle = 73^\circ$

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

Mixture of different parity states is essential !

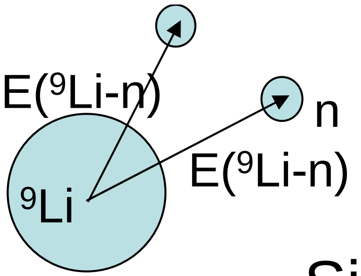
Mixture of higher L orbitals→ More correlated

3body Resonance?

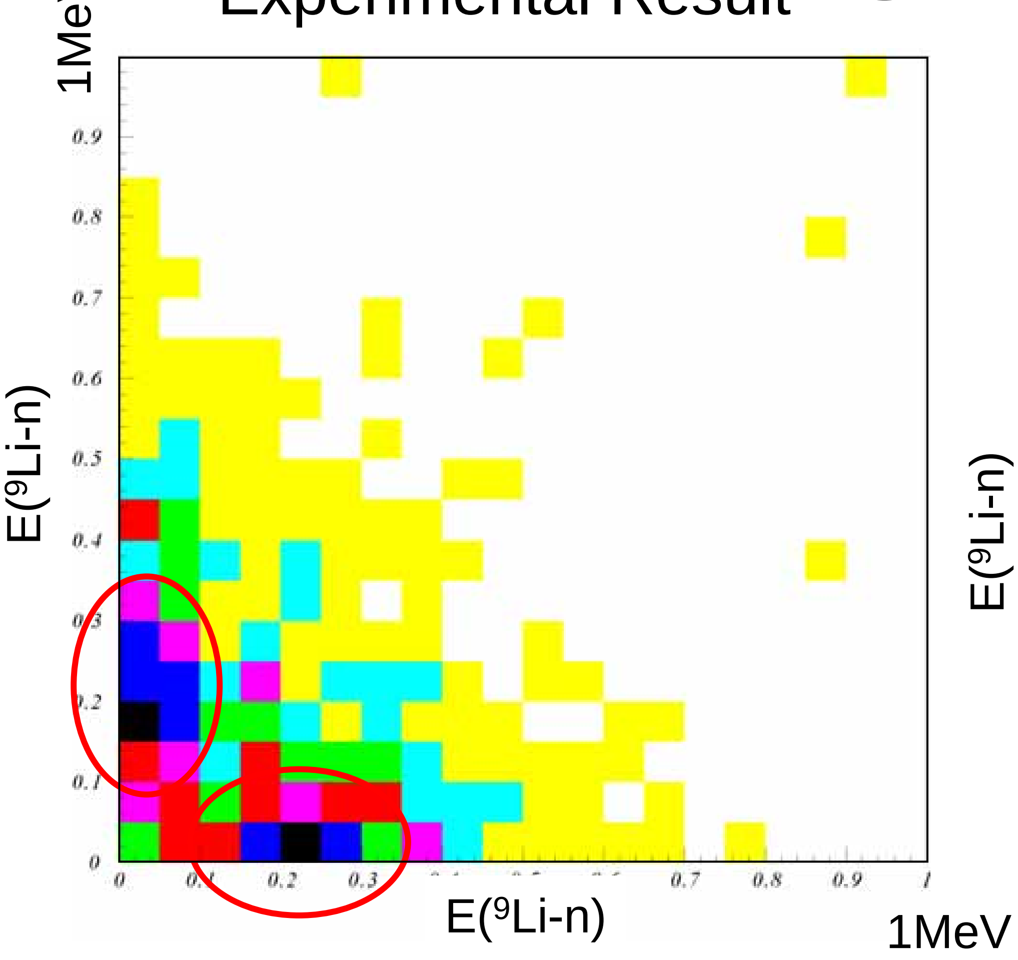


E.Garrido,
D.V.Fedorov,
A.S. Jensen
Nucl. Phys. A 708,
277(2002).

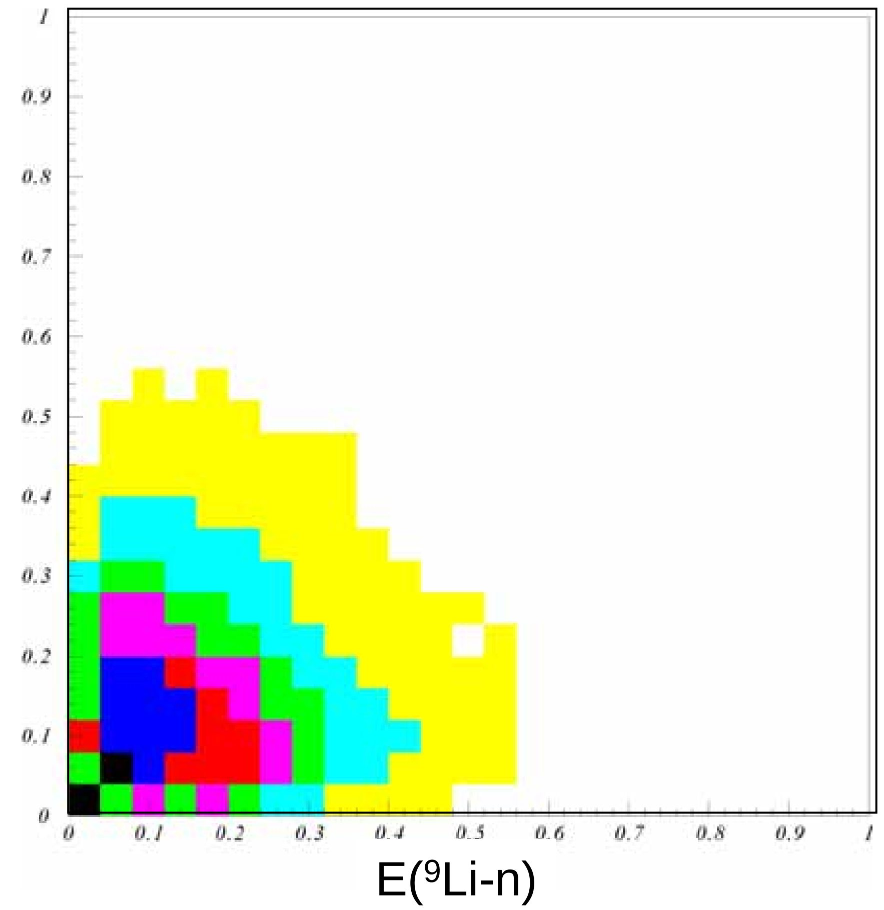
Further Correlation?



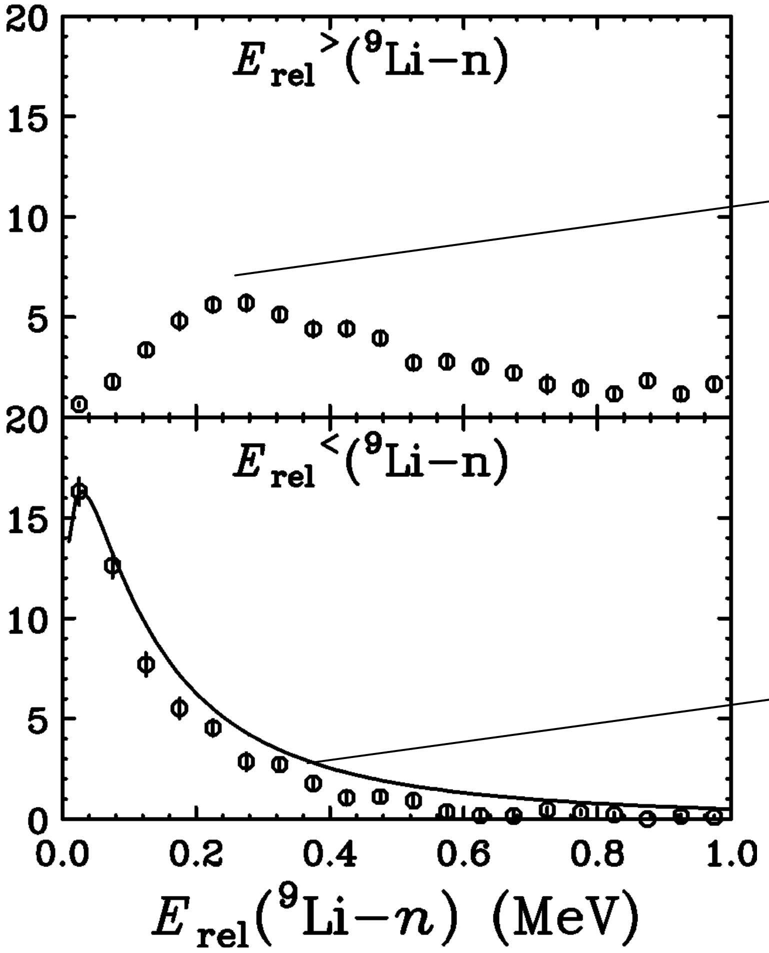
Experimental Result



Simulation (Phase Space)



preliminary



p-wave?

^{10}Li s-wave
Virtual state
Obataind from
$^{11}\mathrm{Li}+\mathrm{C} \rightarrow {}^{9}\mathrm{Li}+\mathrm{n}$
spectrum

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

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

Summary of
Coulomb breakup of two-neutron halo nucleus ^{11}Li

- 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 & ^{9}Li-n correlation in ^{11}Li
(E1 Non-energy weighted sum rule)

- E(^{9}Li-n) - E(^{9}Li-n) 2-dim Plot (Dalitz Plot)

→ Strong Correlations
Peaks at E(^{10}LI)= ~0MeV, and 0.25MeV

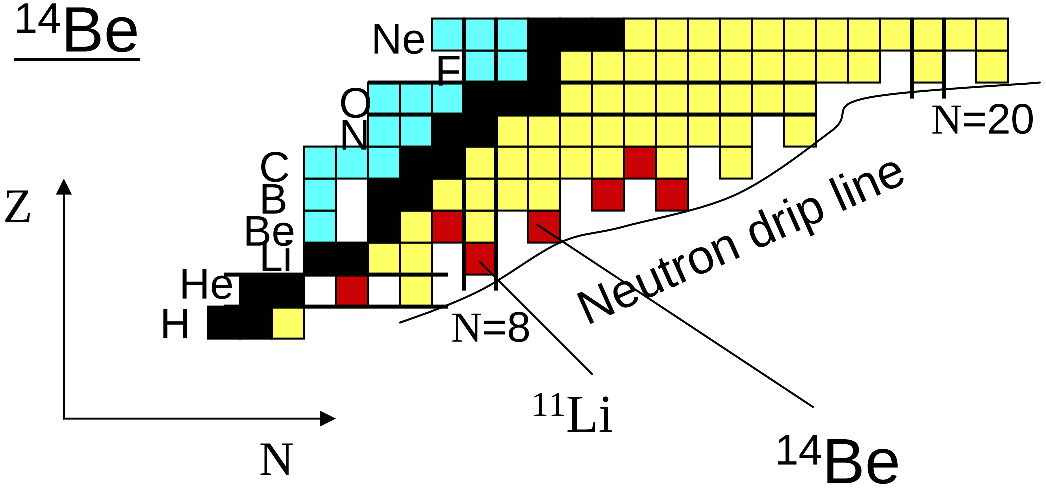
- E(^{9}Li-nn) – E(n-n) 2-dim Plot <E(n-n)> is slightly smaller than <E(9Li-nn) >

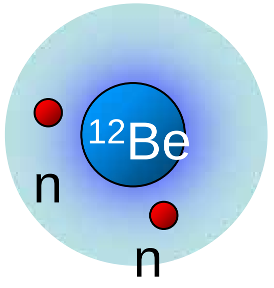
Further Theoretical Studies are called for!

Resonance or not?
2body Correlations? (Final State Interactions?)
What kind of 3-body models?
2n correlations (Why s and p mixed? Higher L orbitals?)
Efimov States?

3 Inelastic scattering of ^{14}Be

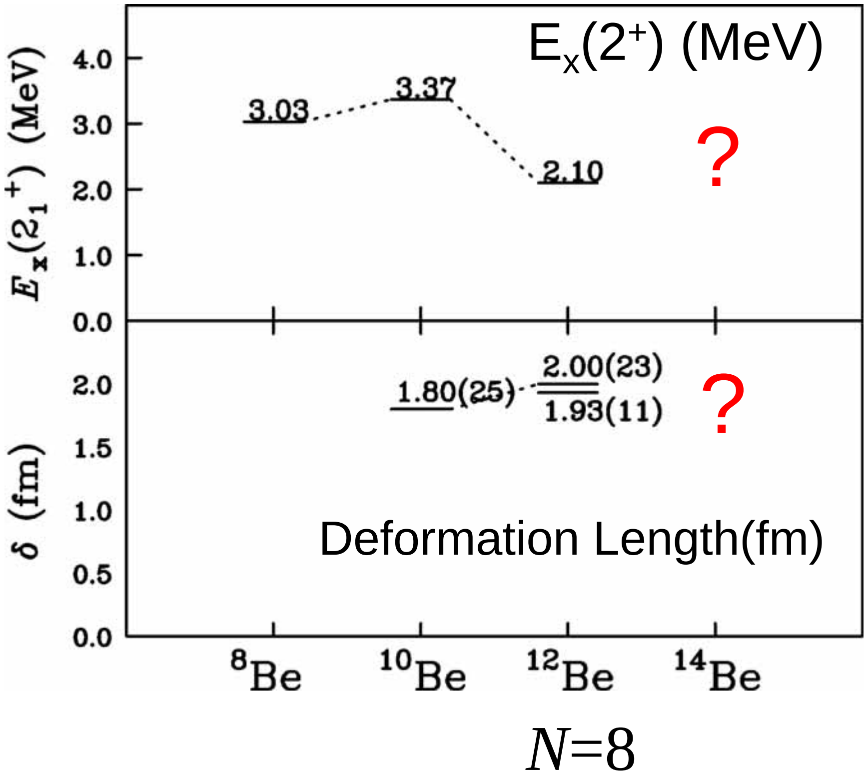
^{14}Be





Neutron Halo

S_{2n}=1.26(13) MeV



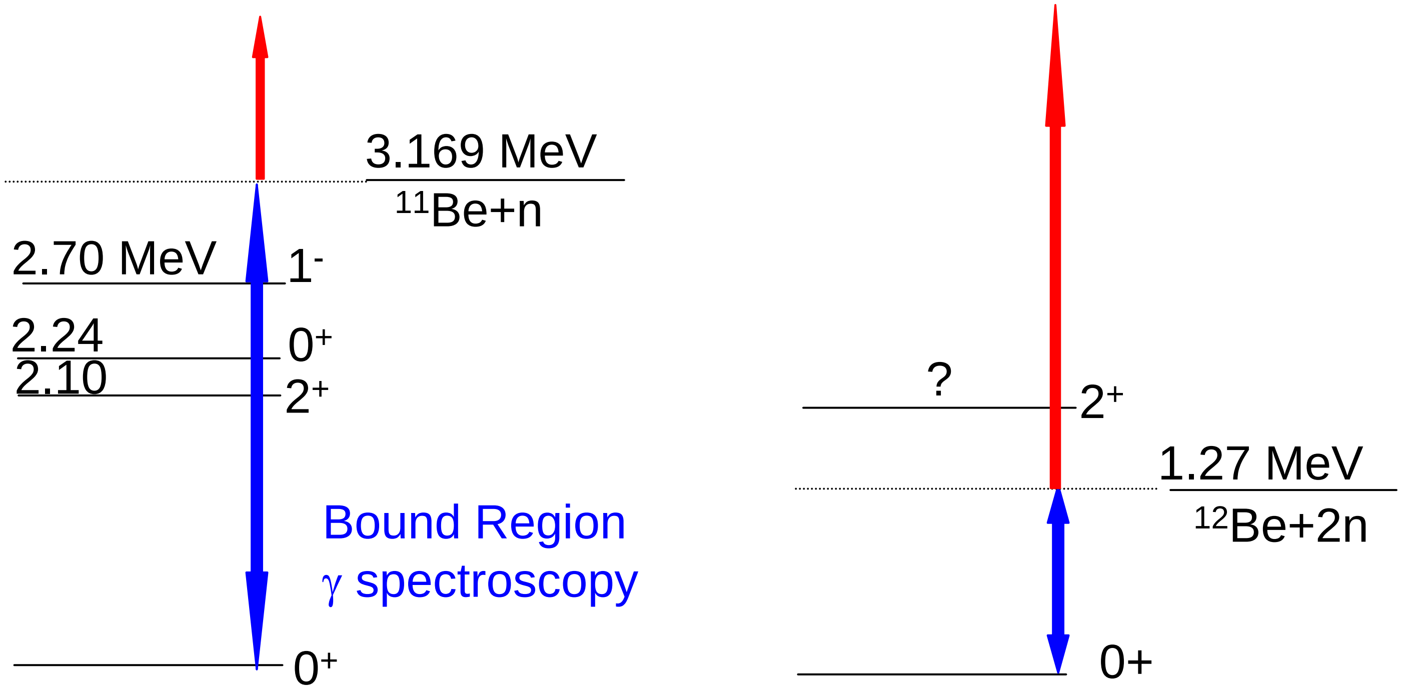
Exotic ^{12}Be core or?

2^+_1 state (& transition)

→ shell stability & collectivity

^{12}Be vs. ^{14}Be

Unbound Region
Invariant mass spectroscopy



^{12}Be N=8

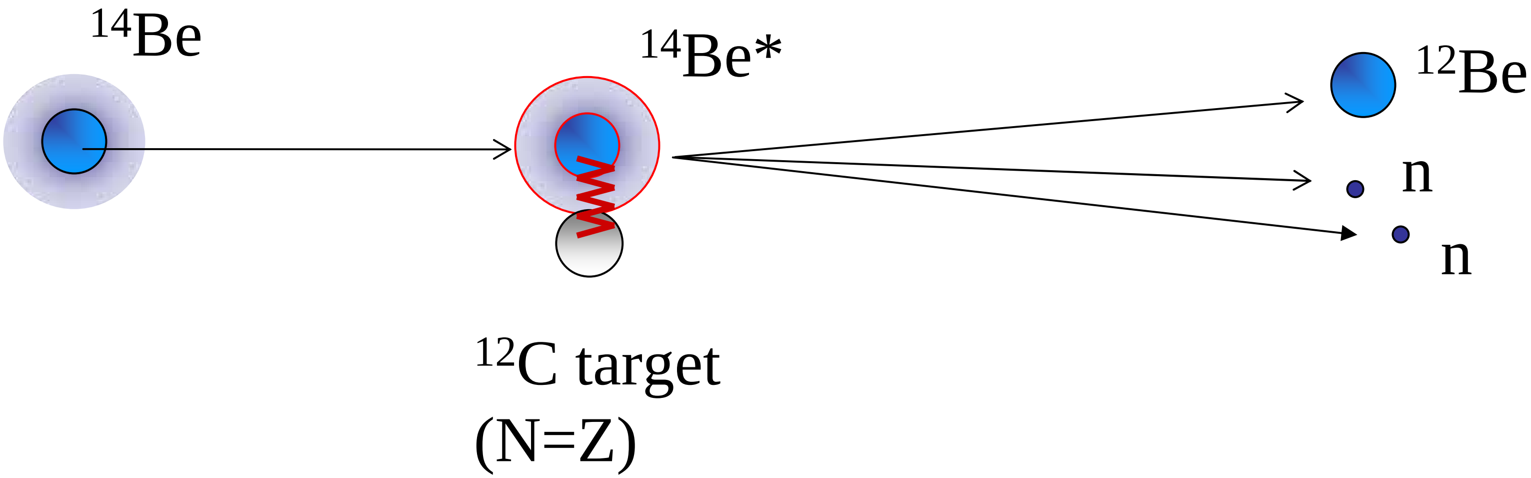
^{14}Be N=10
Drip line

Large Deformation in spite of N=8

H.Iwasaki et al.,PLB491, 8 (2000).
H.Iwasaki et al.,PLB481, 7 (2000).
S.Shimoura et al., PLB560, 31(2003).

Bohlen et al., NPA583,775(1995)
Ex=1.59(13) no firm J^π assignment
Korsheninnikov et al.NPA616,189c(1995)
M.Labiche et al., PRL86,600(2001) **No peak**
B.Jonson et al., Phys. Rep.389,1.(2004)

Reaction :   Inelastic scattering on ^{12}C

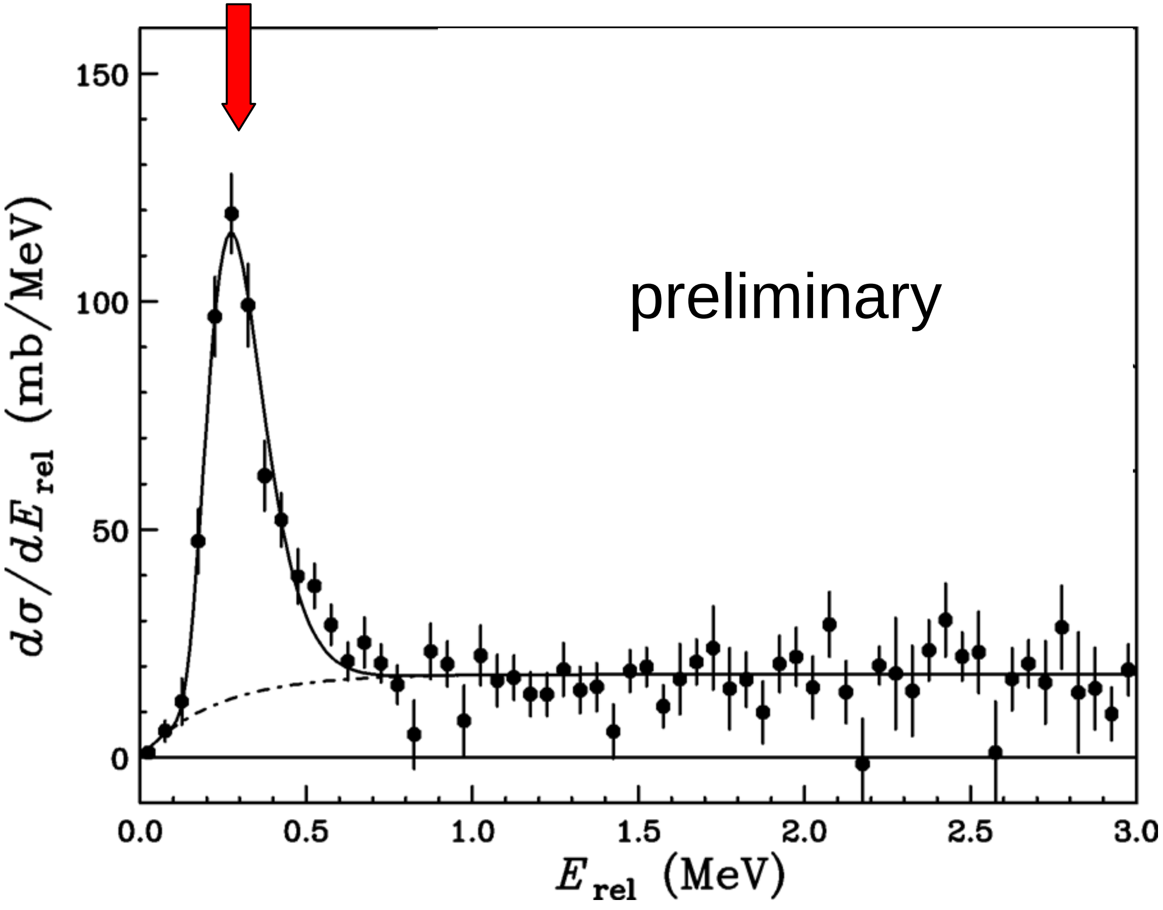


Reaction :   Inelastic scattering on   p

Relative-Energy Spectrum

$^{14}\mathrm{Be}(^{12}\mathrm{C},^{12}\mathrm{C}')$

$$E_{\mathrm{rel}} = 0.27 \pm 0.01\,\mathrm{MeV} \quad E_{\mathrm{x}} = S_{2n} + E_{\mathrm{rel}} = 1.54 \pm 0.13\,\mathrm{MeV}$$



$$\Rightarrow \delta = 1.29 \pm 0.12\ \mathrm{fm}$$

ECIS:rotational model

Optical model parameters

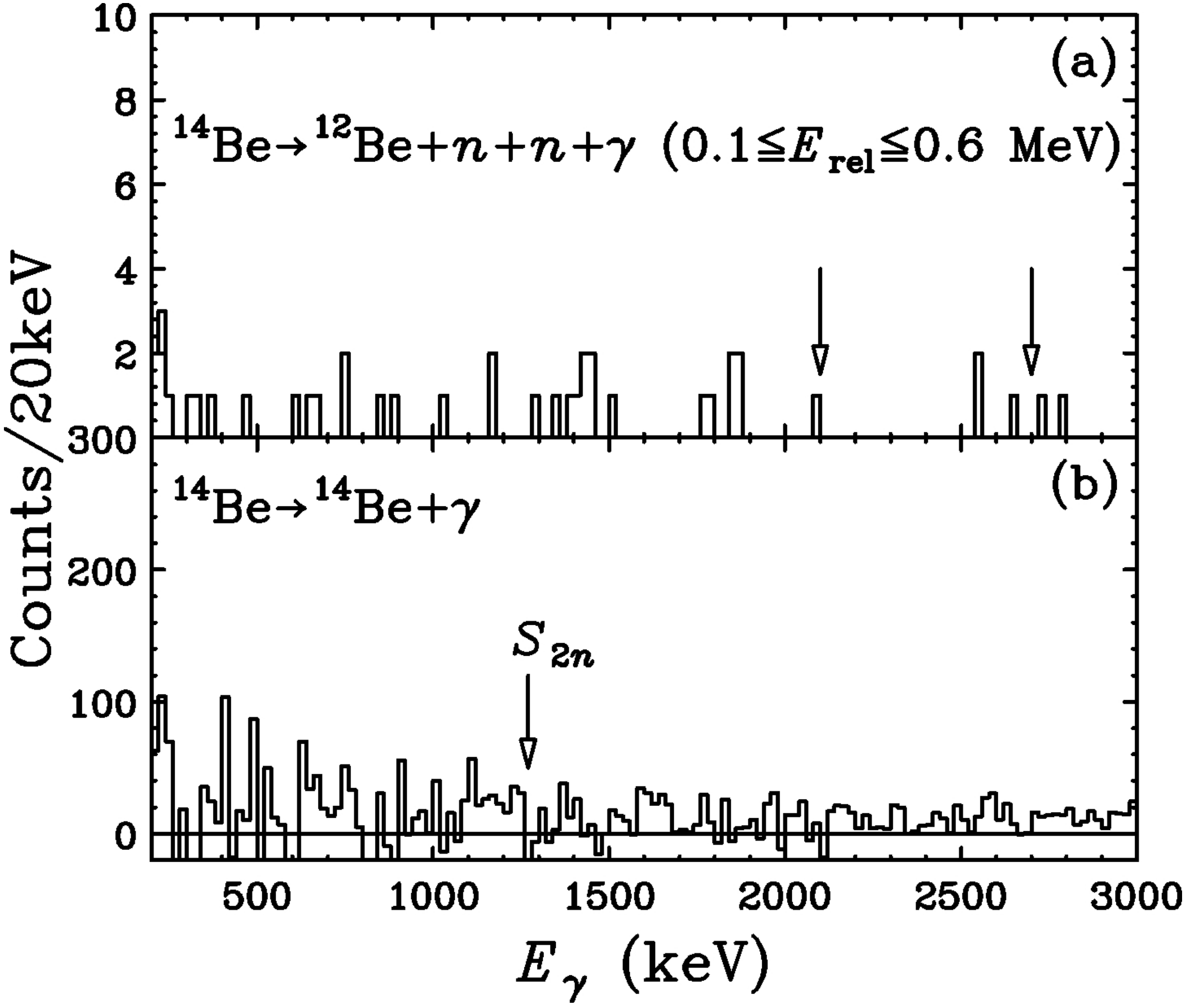
^{11}Be+^{12}C @49.3MeV/u

P.Russel-Chomaz et al.,

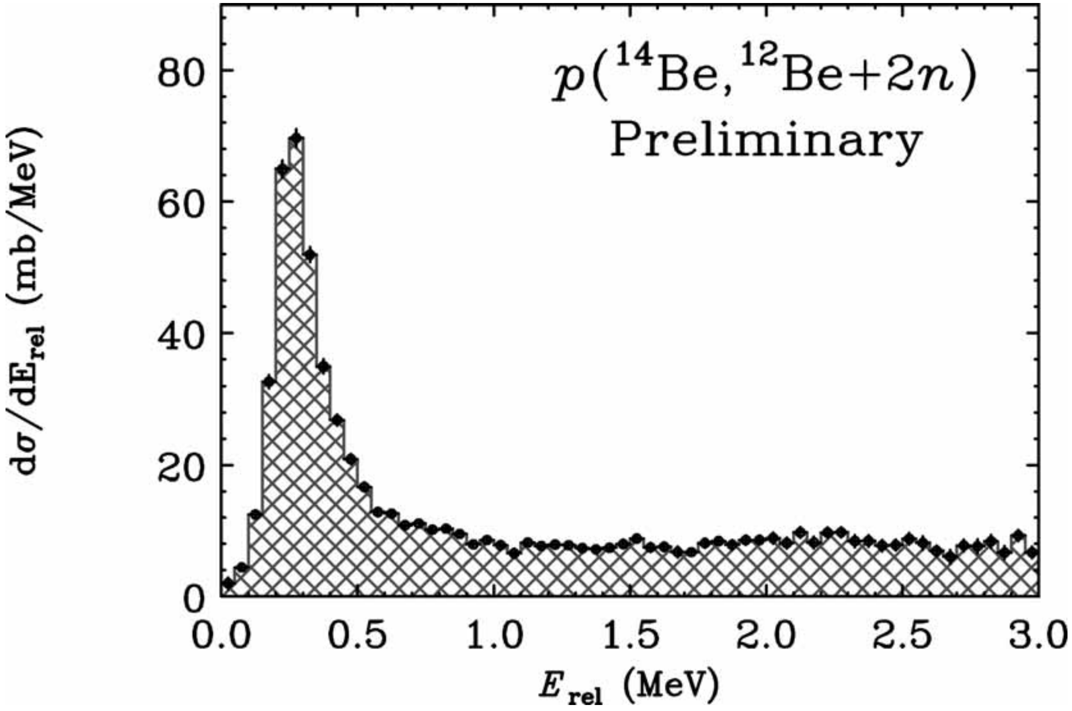
Takashina

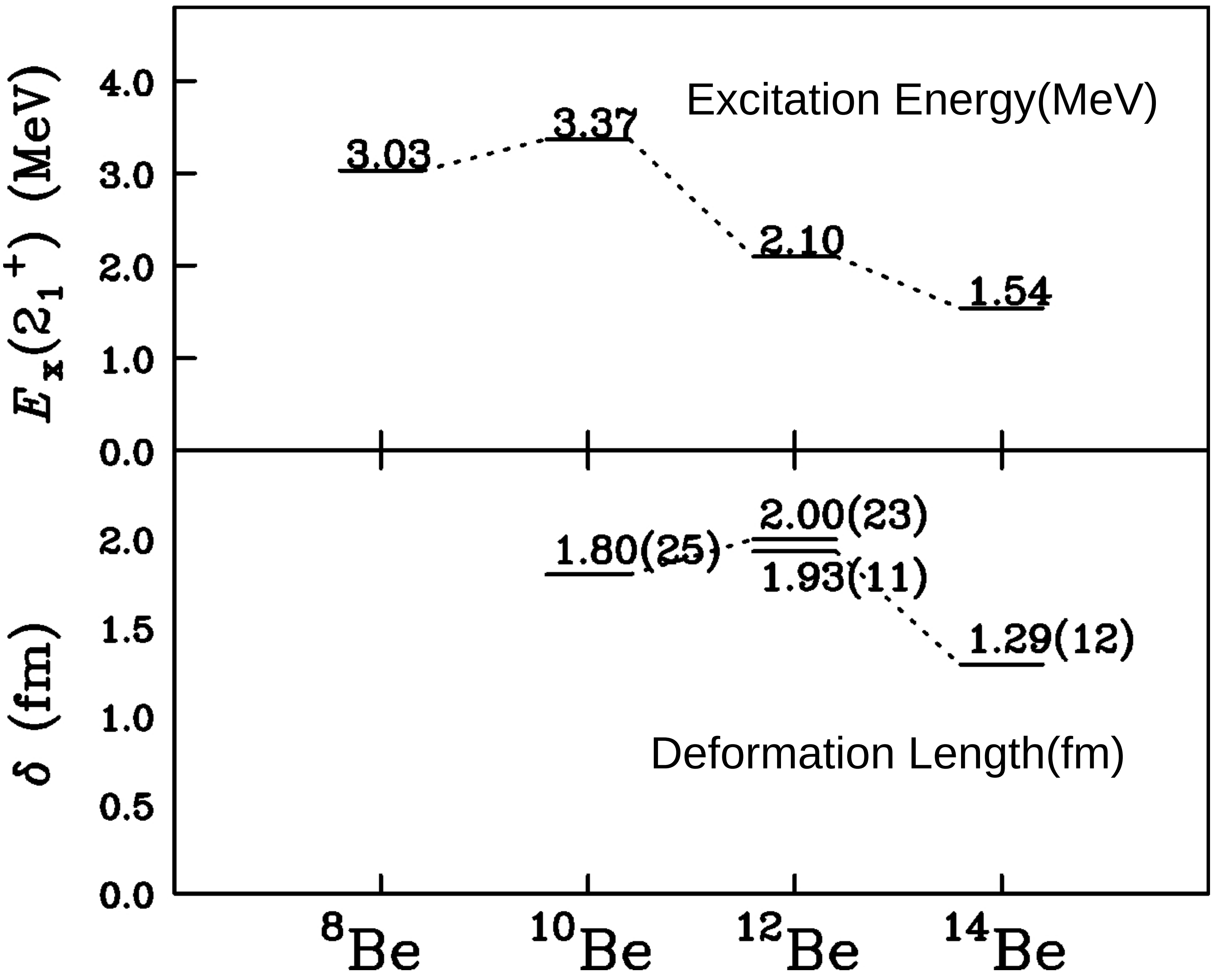
$$\sigma(\mathrm{g.s.} \rightarrow 2^{+}) = 22.6 \pm 1.1(stat.) \pm 3.1(syst.)\,\mathrm{mb}$$

Gamma ray spectra → No γ for 2^+ peak

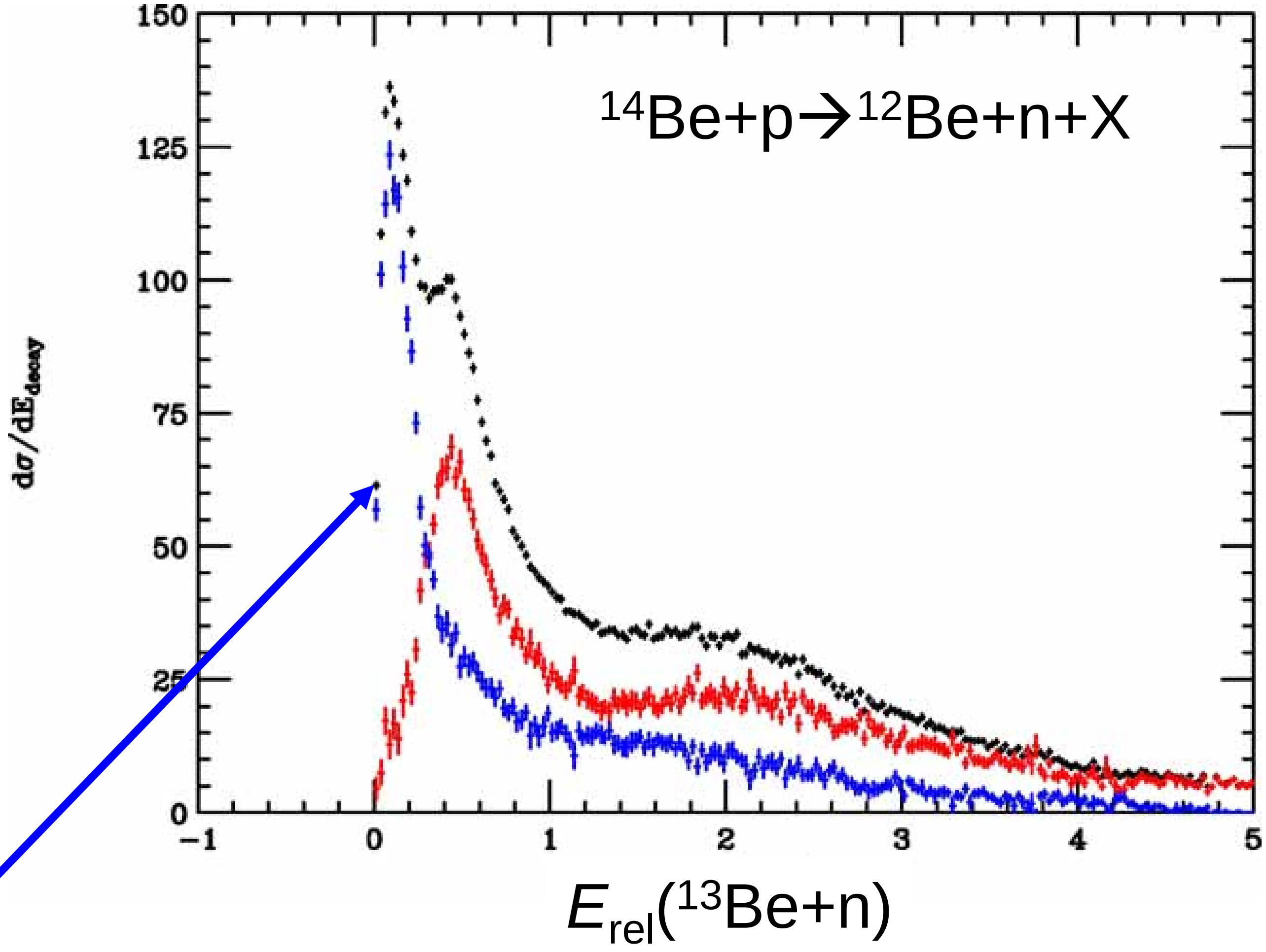


Confirmed by proton scattering data
Y.Kondo, T.N. et al.,




Excitation Energy(MeV)
$E_x(2_1^+)$ (MeV)
4.0
3.0
2.0
1.0
0.0
3.03
3.37
2.10
1.54
Deformation Length(fm)
δ (fm)
2.0
1.5
1.0
0.5
0.0
1.80(25)
2.00(23)
1.93(11)
1.29(12)
^{8}Be
^{10}Be
^{12}Be
^{14}Be

Spectrum of ^{13}Be by proton knockout from ^{14}Be



Decay from ^{14}Be(2^+)

Summary of Inelastic Scattering of ^{14}Be

^{14}Be+^{12}C

- Observation of the first 2^{+} state at E_x=1.54 MeV

  <2.1 MeV for ^{12}Be

- Smaller deformation δ=1.29(12) fm for ^{14}Be

  cf. ^{12}Be: δ~2.0fm

- What is the core of ^{14}Be?

^{14}Be+p

- Same peak as in ^{14}Be+^{12}C
- ^{13}Be spectrum observed in knockout channel