Invariant Mass Spectroscopy and Exotic Structures of Halo Nuclei

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Tokyo Institute of Technology

Unbound Nuclei Workshop
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1 Inelastic scattering of ^{19,17}C on proton target

Y.Satou, TN et al., Phys. Lett. B660, 320 (2008).

2 Coulomb Breakup of ^{11}Li

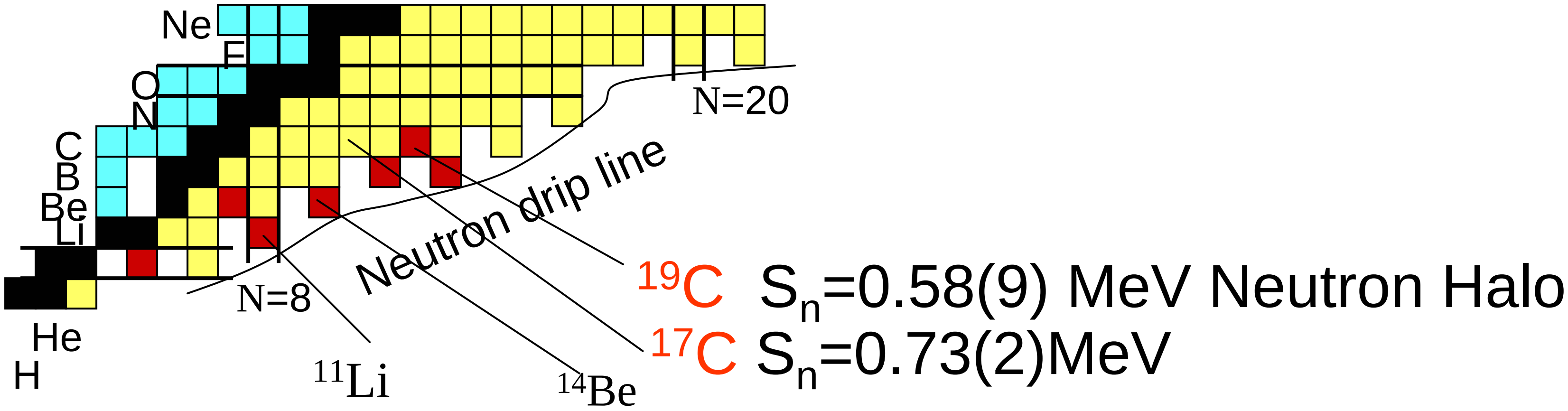
T. Nakamura, A.M.Vinodkumar et al., Phys. Rev. Lett. 96, 252502 (2006).

3 SAMURAI/NEBULA Project at RIKEN RIBF

1 Inelastic scattering of ^{19,17}C on proton target

Y.Satou, TN et al.,

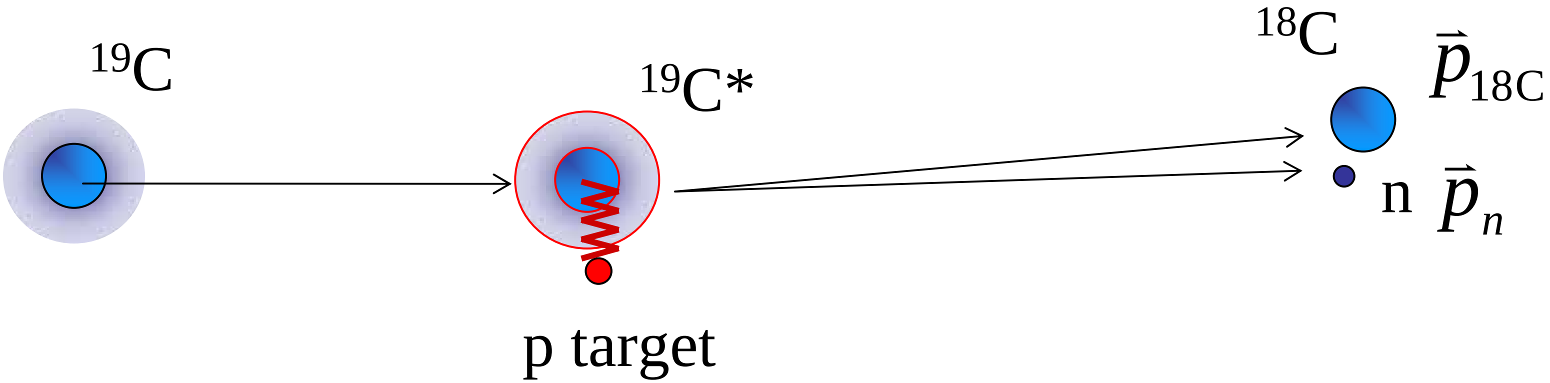
Phys. Lett. B 660, 320(2008).



^{19}C S_n=0.58(9) MeV Neutron Halo

^{17}C S_n=0.73(2)MeV

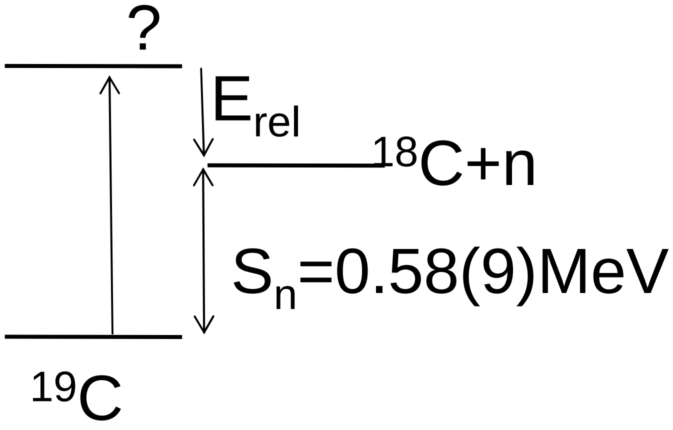
(p,p') inelastic scattering in the inverse kinematics *(Breakup channel)*



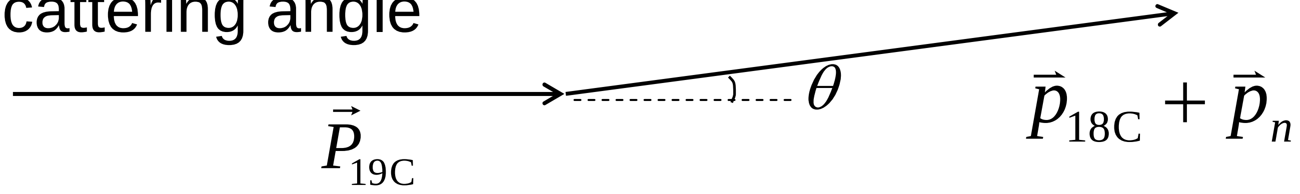
Invariant Mass Method

$$M = \sqrt{(E_{18C} + E_{n1})^2 - (\vec{P}_{18C} + \vec{P}_n)^2}$$

$$E_{rel} = M - m_{18\mathrm{C}} - m_n$$

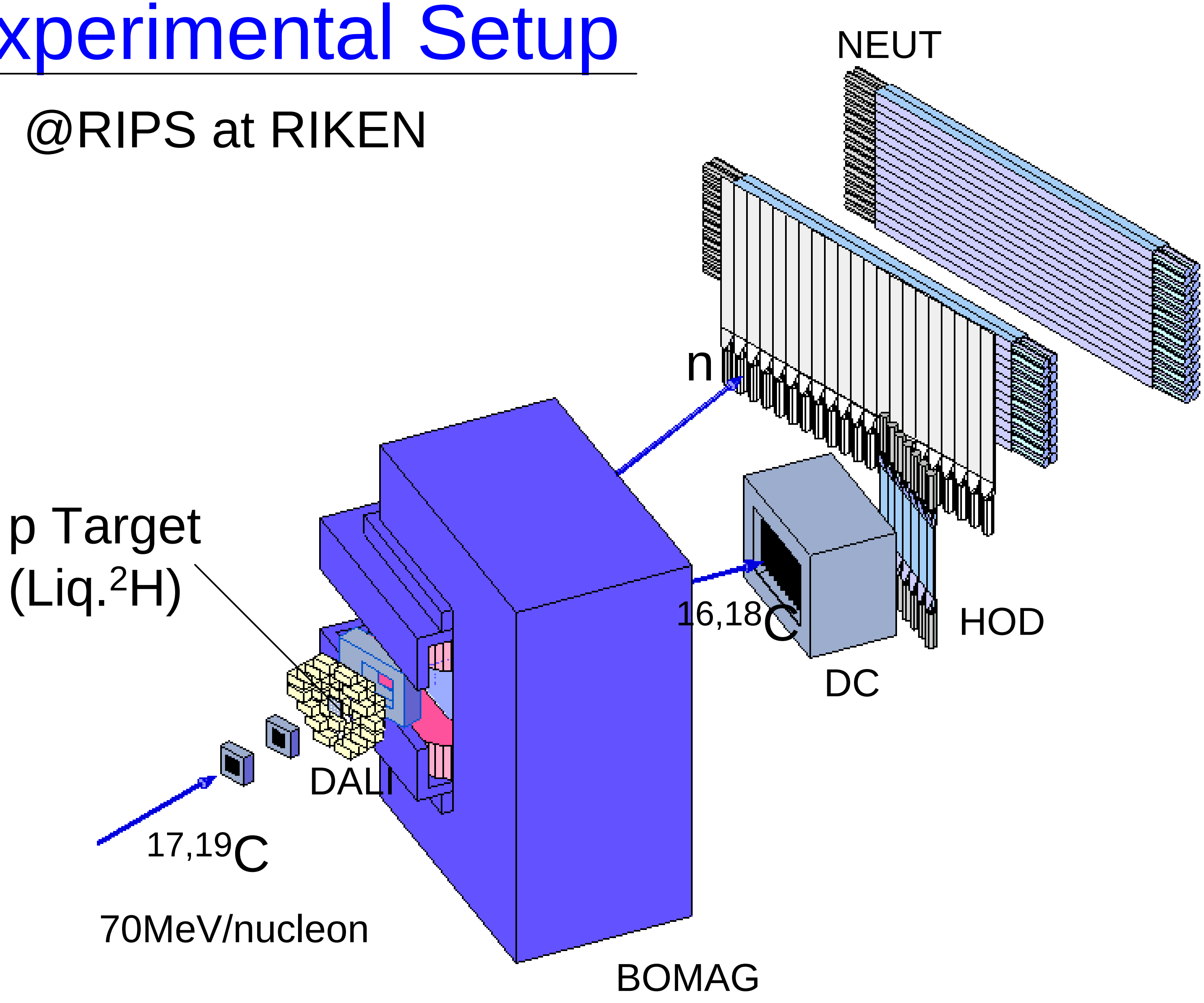


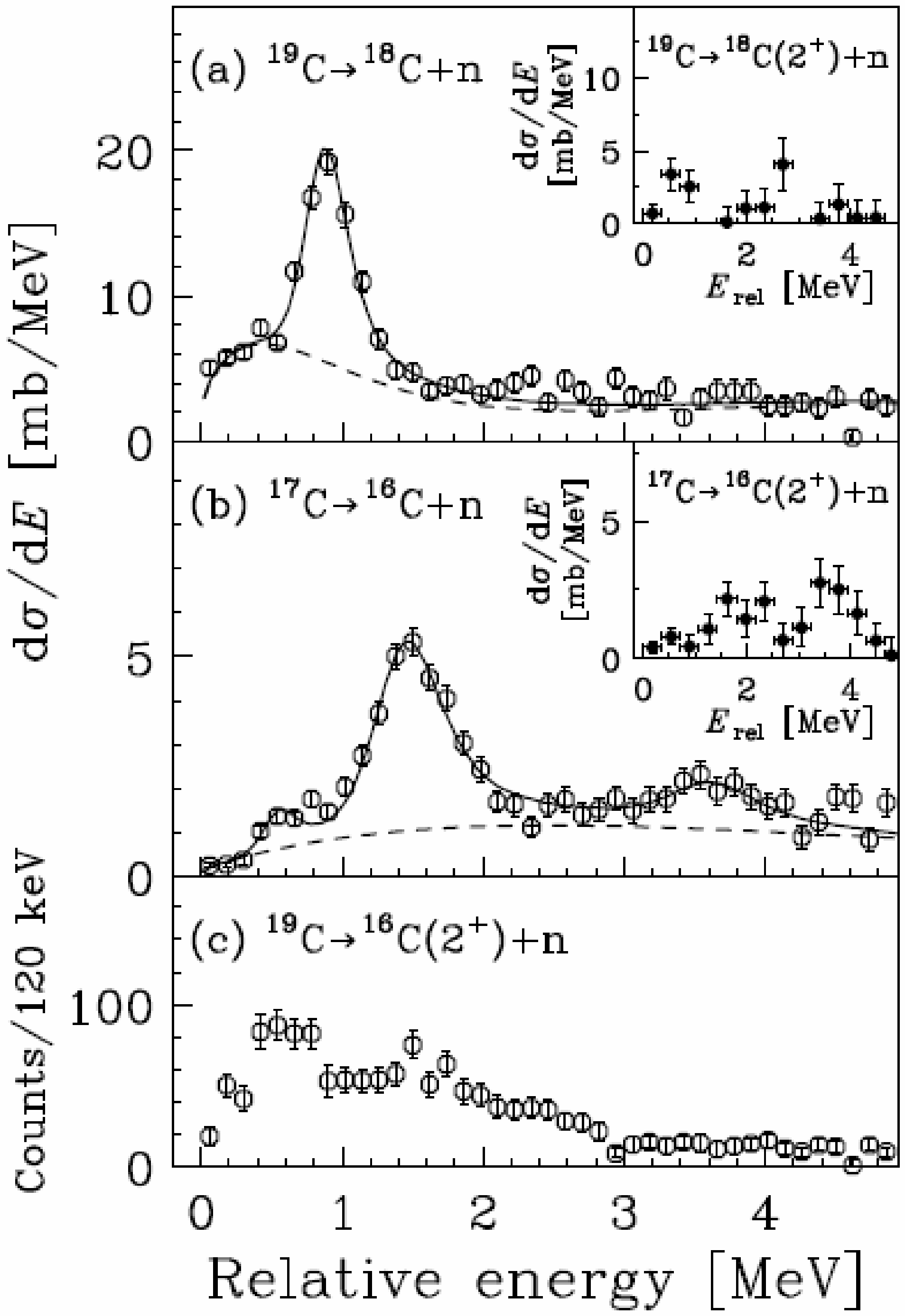
Scattering angle

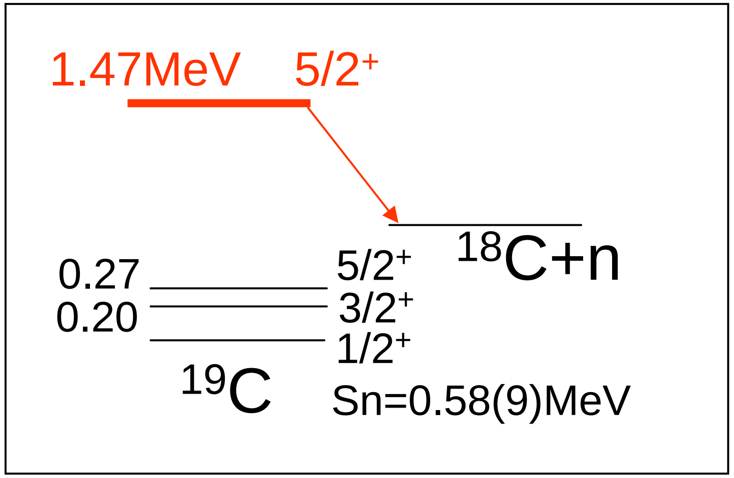


Experimental Setup

@RIPS at RIKEN







1.47MeV $5/2^+$

$^{18}C+n$

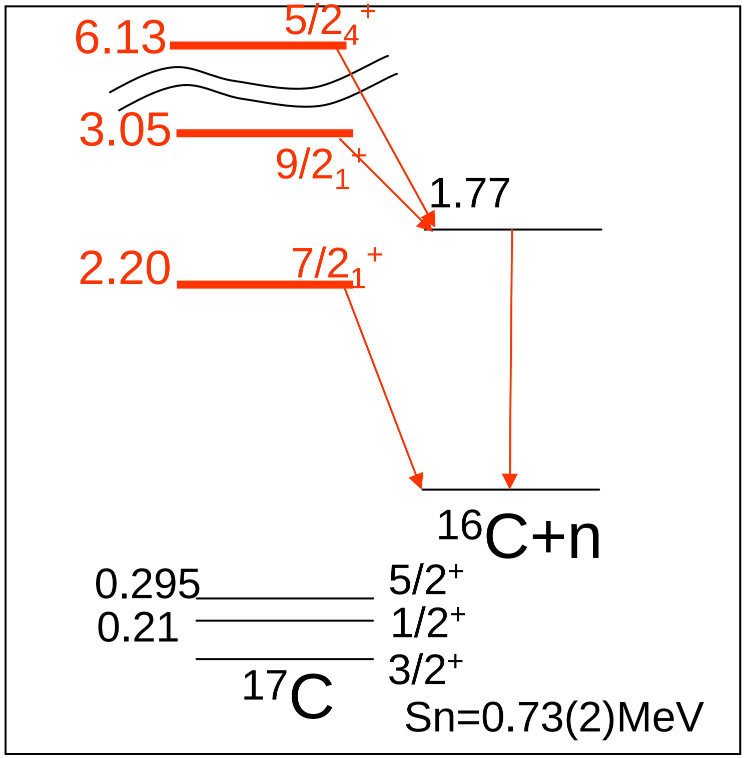
0.27 $5/2^+$

0.20 $3/2^+$

$1/2^+$

^{19}C

Sn=0.58(9)MeV



6.13 $5/2_4^+$

3.05 $9/2_1^+$

1.77

2.20 $7/2_1^+$

$^{16}C+n$

0.295 $5/2^+$

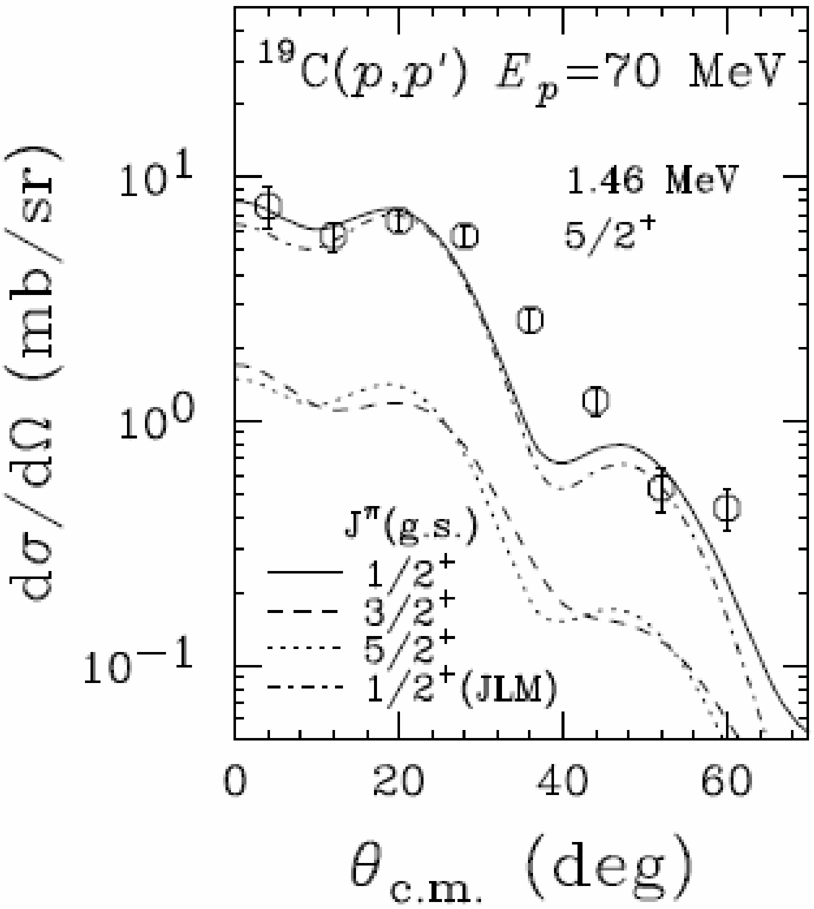
0.21 $1/2^+$

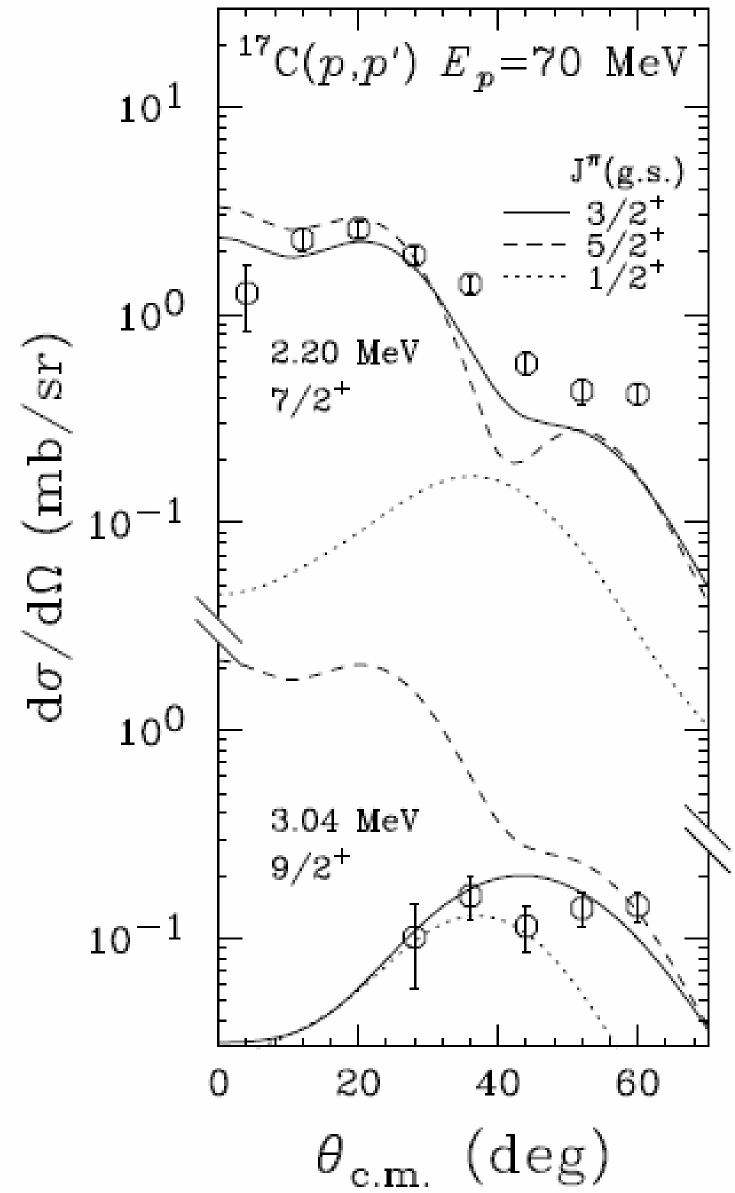
$3/2^+$

^{17}C

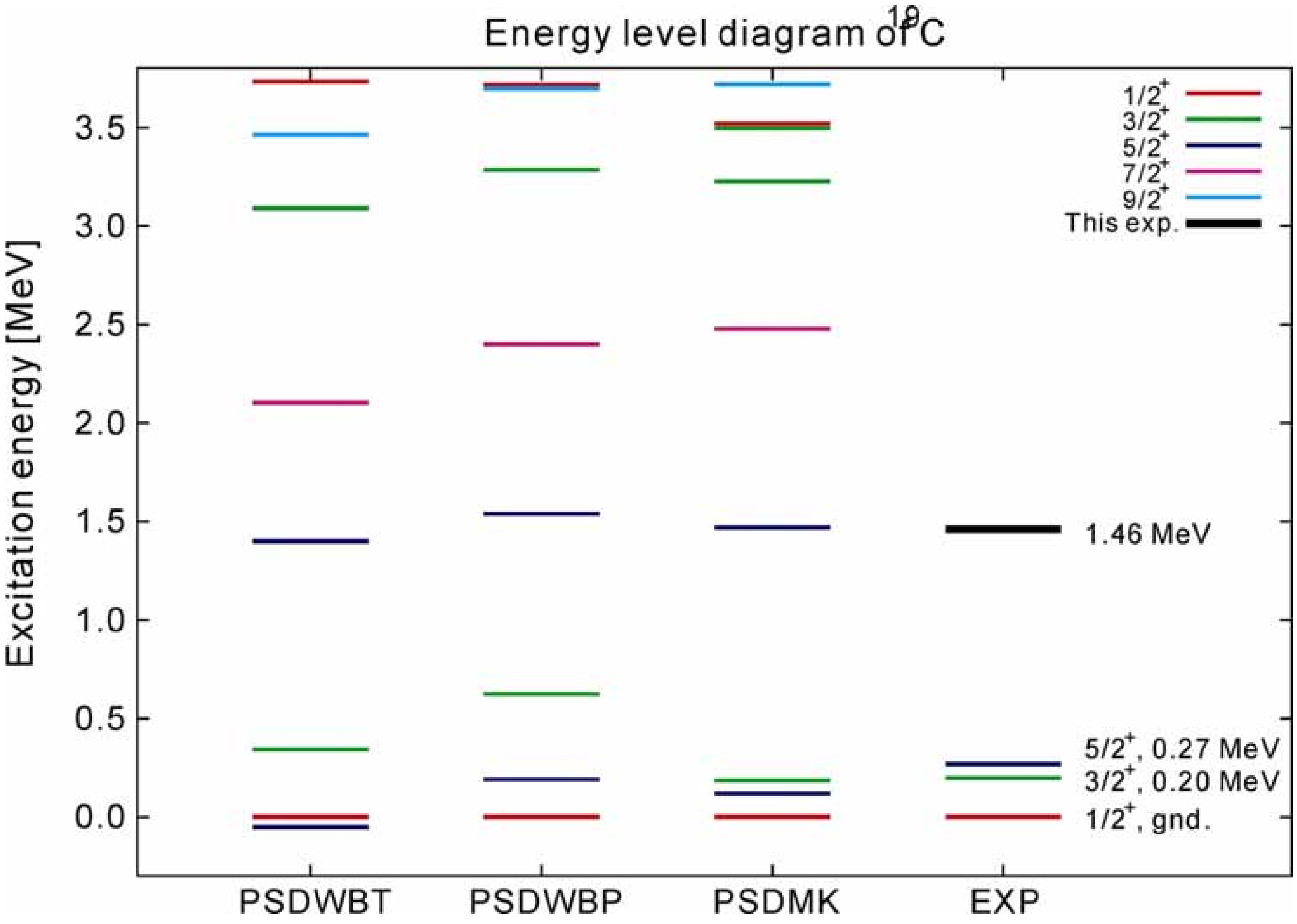
Sn=0.73(2)MeV

c.f. H.G.Bohlen et al., Eur. Phys. J. A31, 279 (2007).

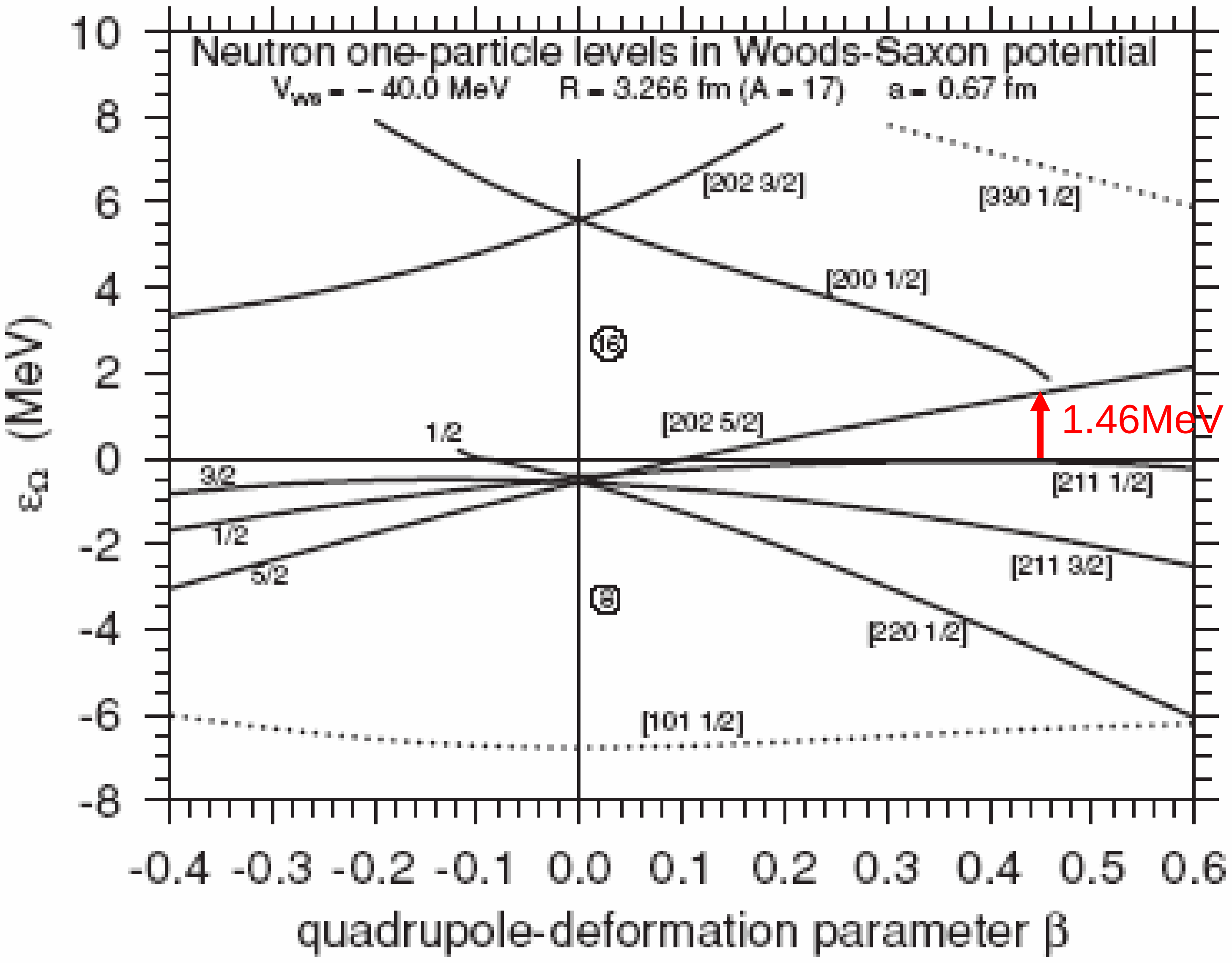




Optical Potential KD02,JLM(dotdash)
Interaction(projectile-p) M3Y
Shell model: WBT


Energy level diagram of ^{19}C
Excitation energy [MeV]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
PSDWBT
PSDWBP
PSDMK
EXP
$1/2^+$
$3/2^+$
$5/2^+$
$7/2^+$
$9/2^+$
This exp.
1.46 MeV
$5/2^+$, 0.27 MeV
$3/2^+$, 0.20 MeV
$1/2^+$, gnd.

^{19}C 1/2^{+}→ 5/2$_{2}^{+}$(1.46MeV)



Nilsson diagram is
from I.Hamamoto PRC,2007.

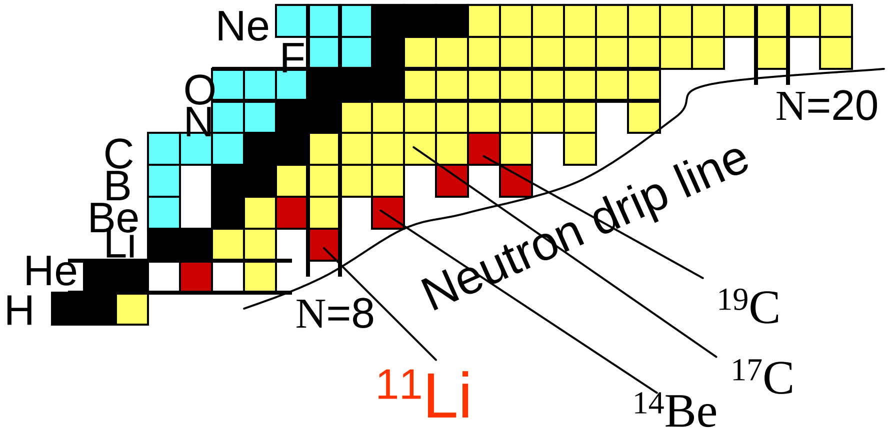
[211 1/2]→[202 5/2]?

2

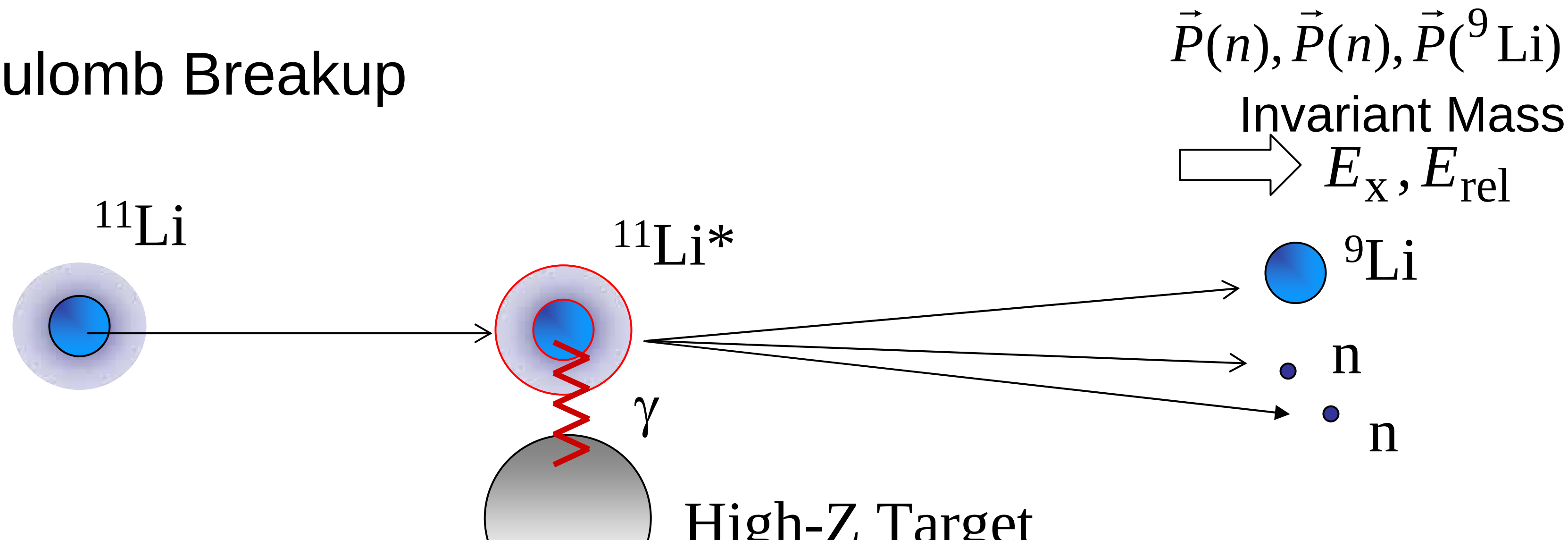
Coulomb Breakup of ^{11}Li and two-neutron correlation

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

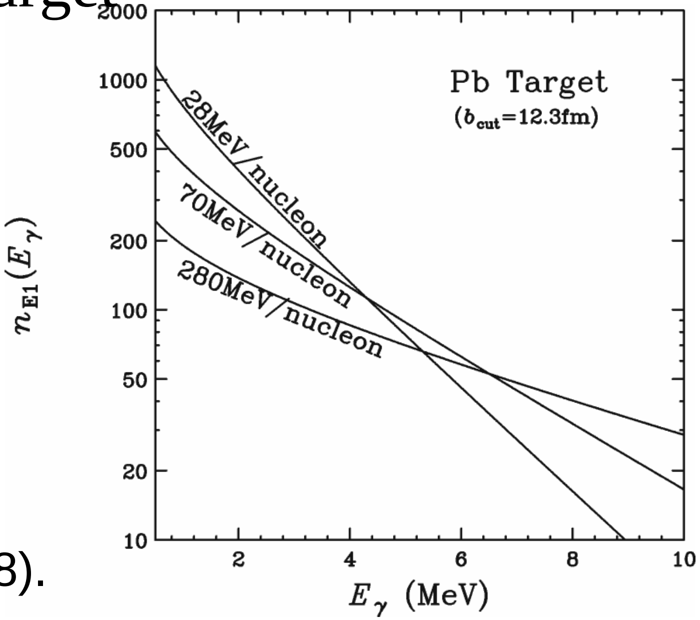
Phys. Rev. Lett. 96, 252502 (2006).



Coulomb Breakup



High-Z Target
(Pb)



Equivalent Photon Method

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

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

e.g. C.A.Bertulani, G.Baur, Phys.Rep.163.299(1988).

Strong Low-energy E1 transitions (Soft E1 excitation)

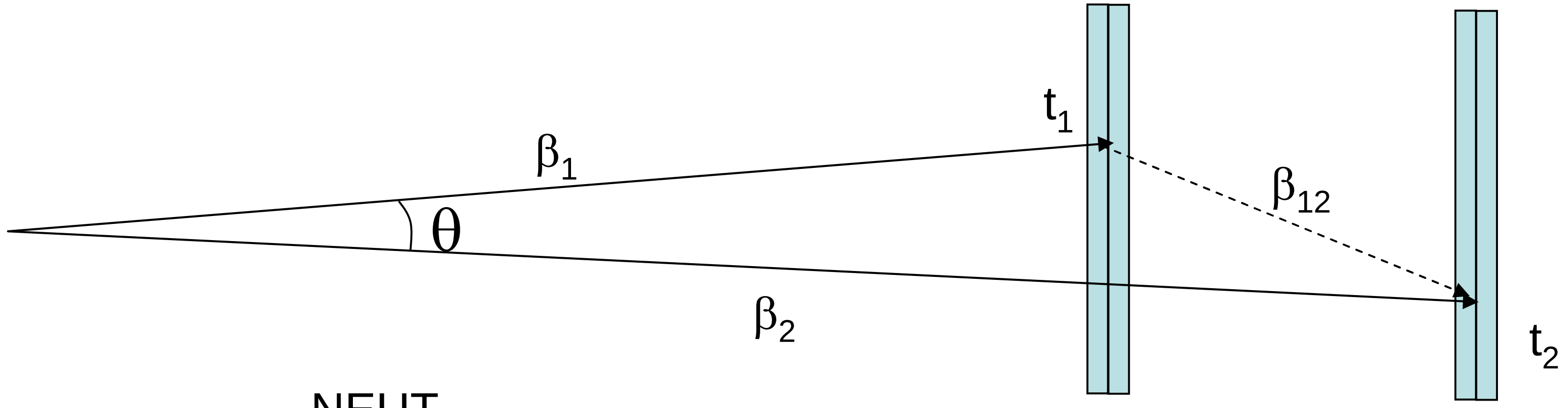
--------------Unique property of Halo Nuclei

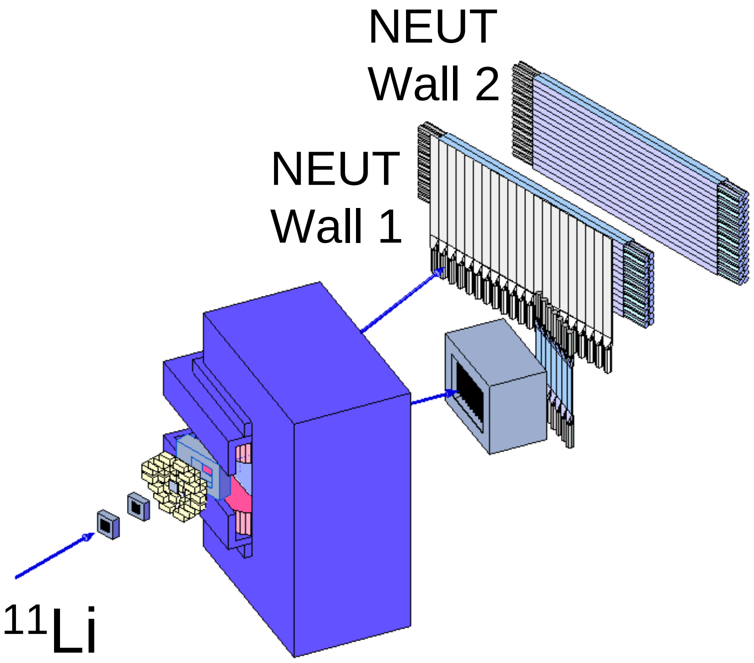
Elimination of Cross-Talk events

Examine Different Wall Events

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

Almost no bias



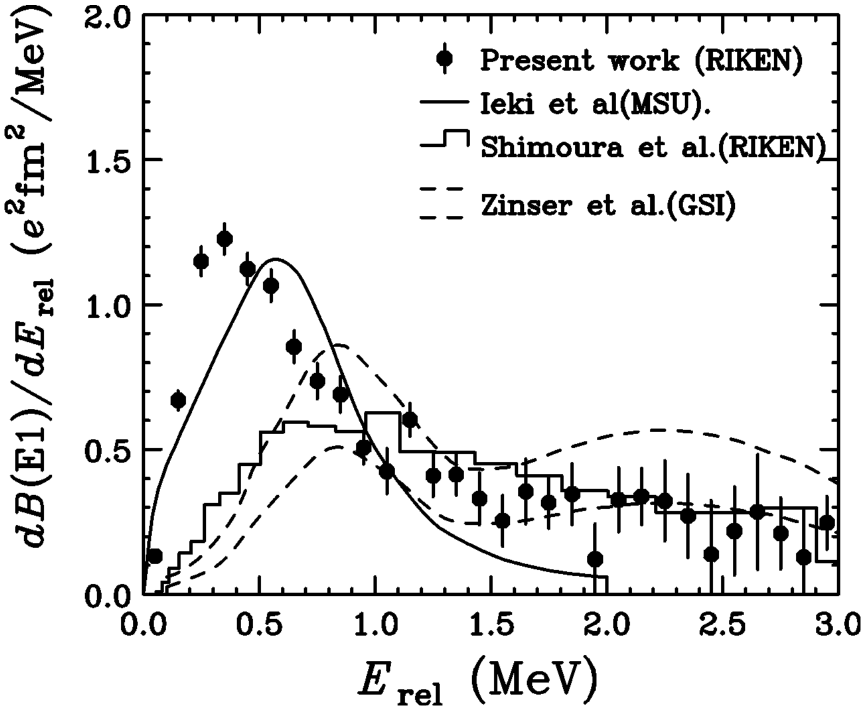


High detection sensitivity even at E_{rel}~0MeV (θ~0)

⇨ Precise measurement of B(E1) distribution of ^{11}Li

Experimental Results

TN et al. PRL96,252502(2006).



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

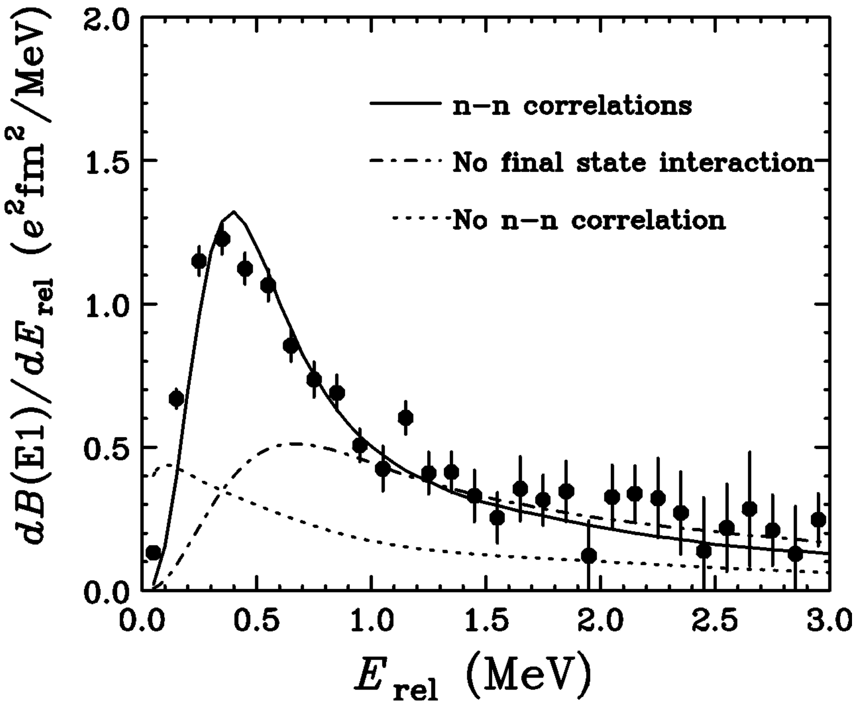
S_{2n}=300(19)keV →378(5)keV

C.Bachelet et al.,PRL100,182501(2008).

→Smaller N(E1)

→ 6% larger B(E1) strength

Comparison with 3-body Theory-1



Calculation

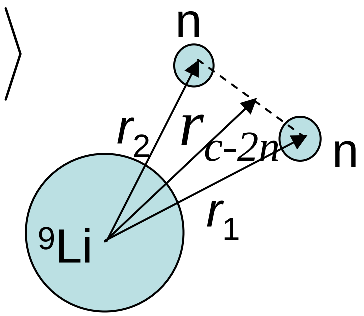
H.Esbensen and G.F. Bertsch
NPA542,310 (1992).

H.Esbensen et al.,
PRC76, 024302 (2007)

Can “Soft E1 of ^{11}Li” be a signature of “dineutron”? Can one determine “Borromean Halo Geometry” from “Soft E1” ?

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

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



$\langle r_{c-2n} \rangle$: directly from B(E1)

$\langle r_1 \cdot r_2 \rangle$: $\langle r_{c-2n} \rangle$ & Non-correlated B(E1) value

i.e. B(E1) value for $\langle r_1 \cdot r_2 \rangle = 0$

Theoretical. H.Esbensen and G.F. Bertsch, NPA542,310 (1992).

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

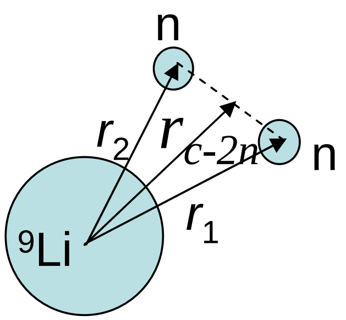
$$\rightarrow 1.78(22)\, e^2\, fm^2$$

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

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

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

^{11}Li Borromean Geometry



- H.Esbensen et al.,
  PRC76, 024302 (2007)

  B(E1) or Charge Radius → $r_{c\text{-}2n}$

  $\langle r_{c\text{-}2n} \rangle$ from charge radius is larger by 10-20%

  → Core excitation?

- C.A. Bertulani and M.S.Hussein
  PRC76, 051602(R) (2007).

  B(E1) or Charge Radius → $r_{c\text{-}2n}$

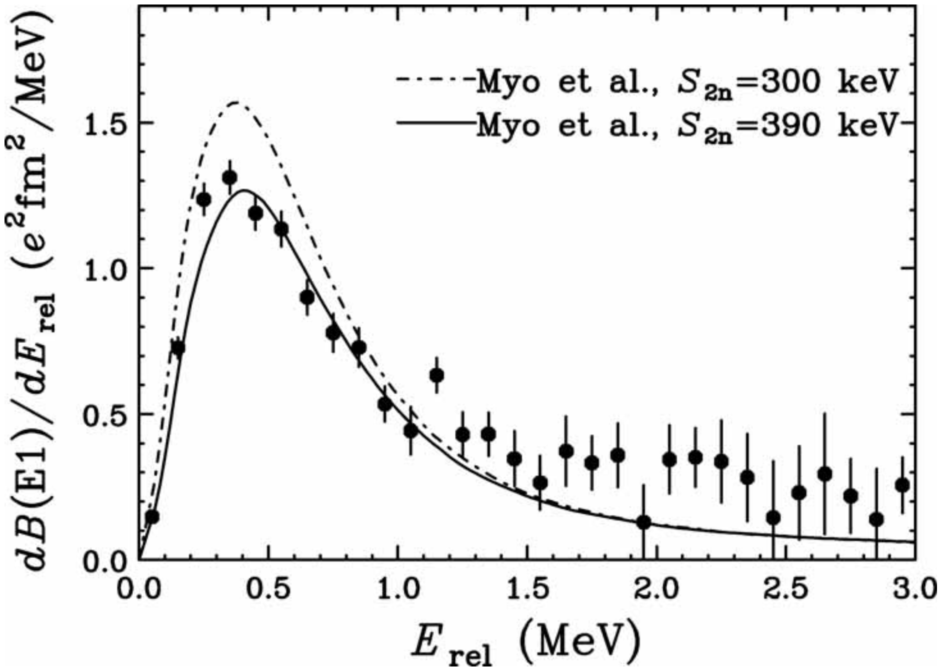
  Correlation function→r_{nn}

$$C(\mathbf{p}_1, \mathbf{p}_2) = \frac{P_2(\mathbf{p}_1, \mathbf{p}_2)}{P_1(\mathbf{p}_1)P_1(\mathbf{p}_2)},$$

r_{nn} of continuum, not g.s.

Marques et al.,PRC64, 061301(R) (2001).

Comparison with 3-body theory-2



Myo et al.,PRC76,024305 (2007).

Core polarization

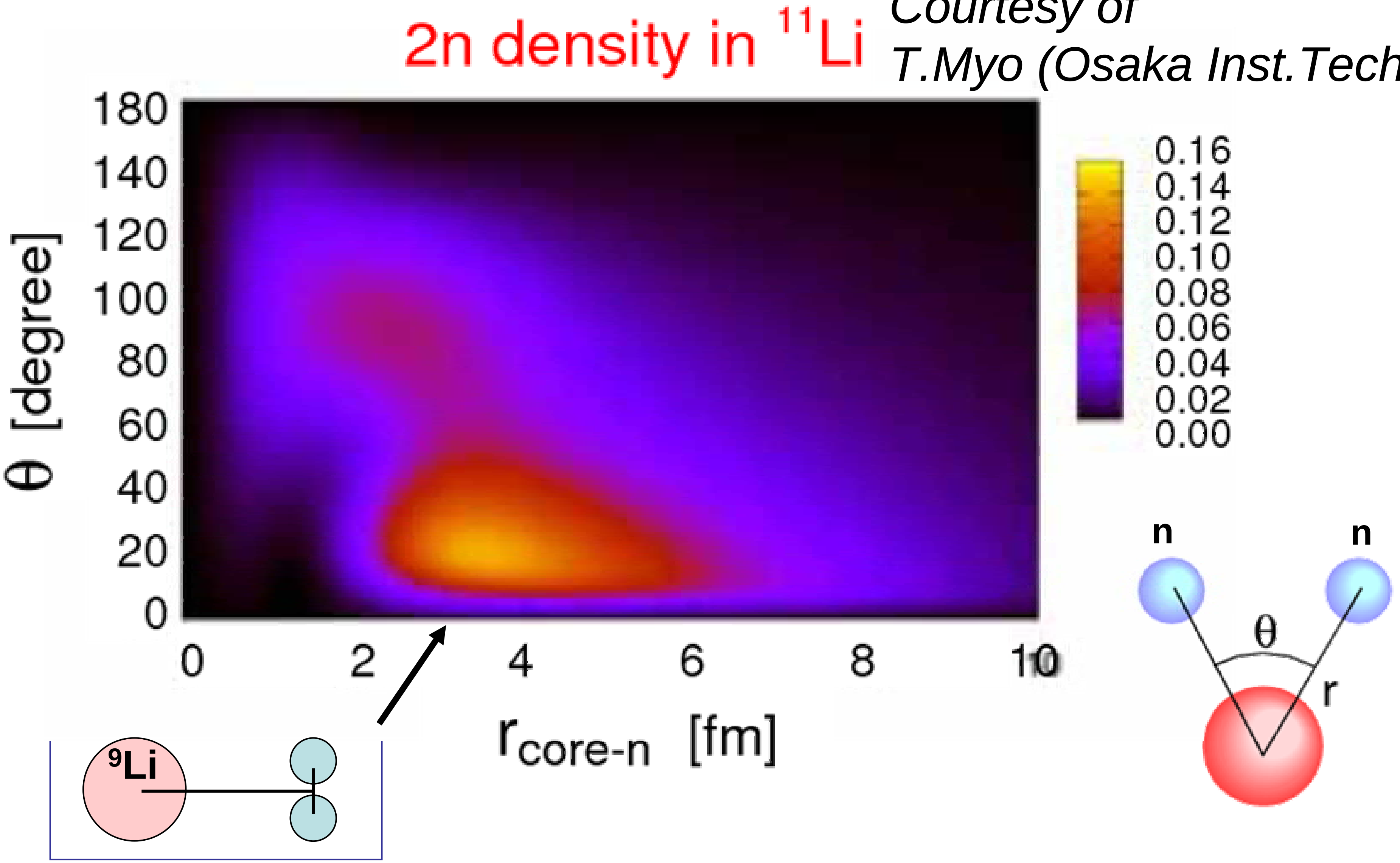
(Tensor correlation+Pauli Principle)

P(S^2)~ 40% $\sqrt{\langle r_{c-2n}\rangle^2} = 5.38\ \mathrm{fm}$ $\langle \theta_{12} \rangle = 65\,\mathrm{deg}$

Both Charge distribution & B(E1) are reproduced.

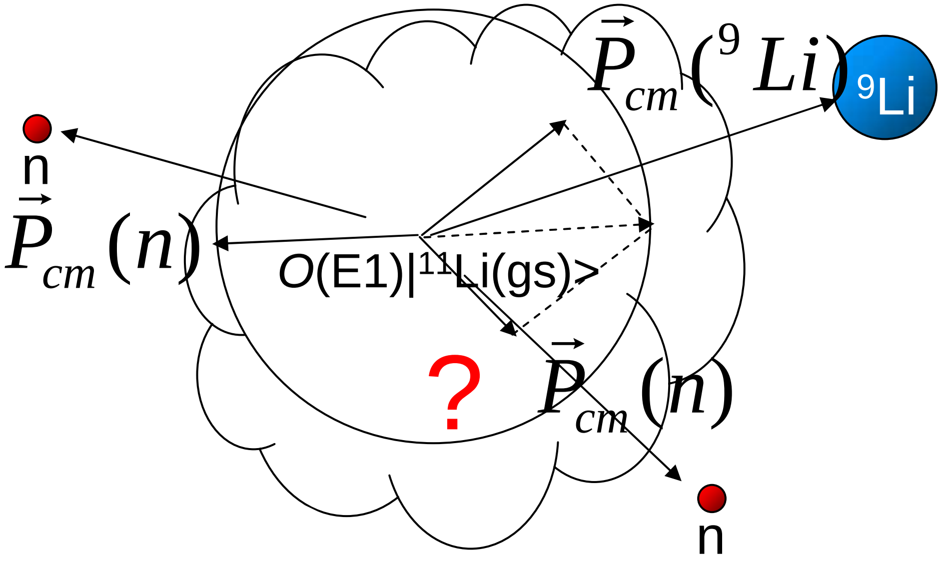
2n correlation density in ^{11}Li

Courtesy of
T.Myo (Osaka Inst.Tech)



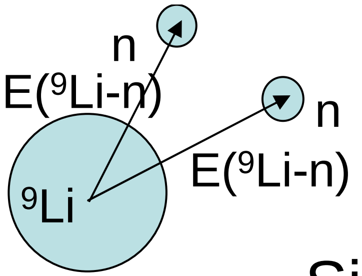
Cf. H.Esbensen and G.F.Bertsch, NPA542(1992)310

2n Correlations can be studied by 3-body decay of ^{11}Li*?

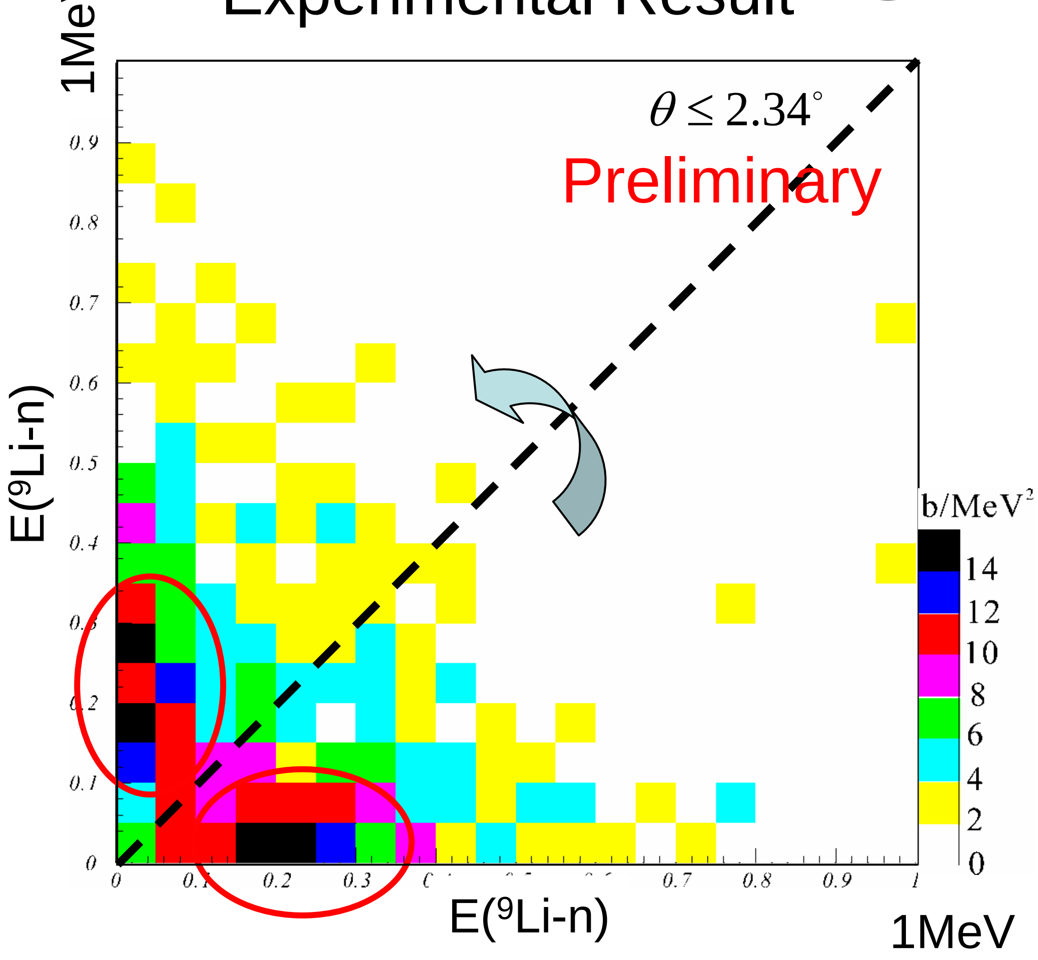


--Kinematically complete measurement

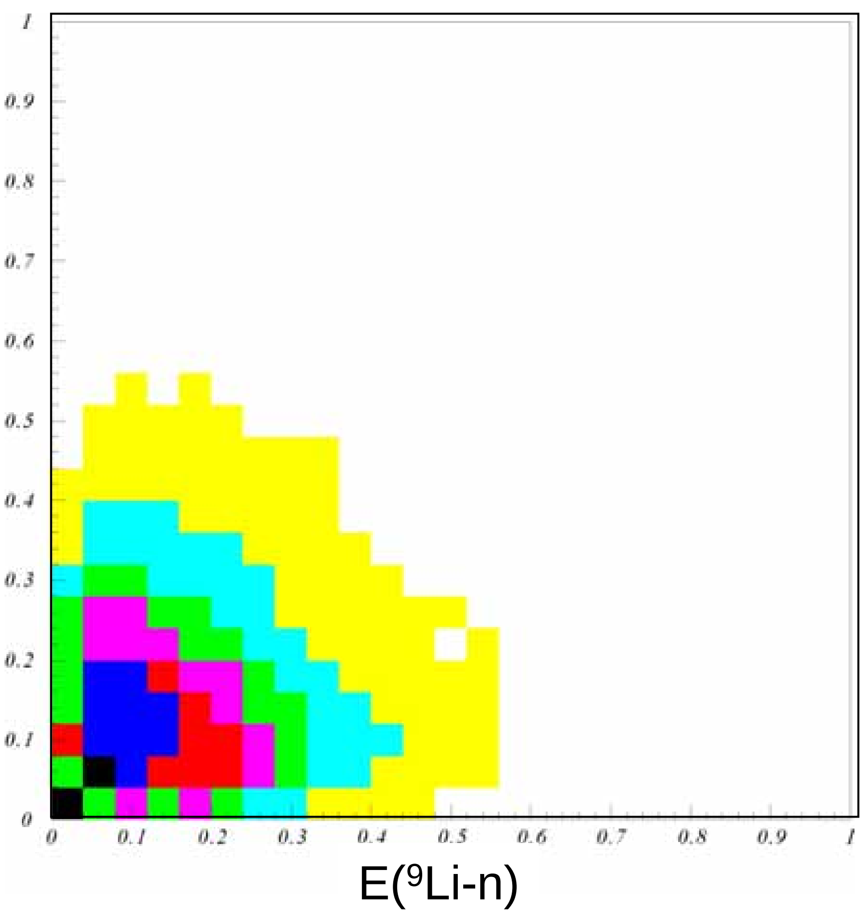
Further Correlation?

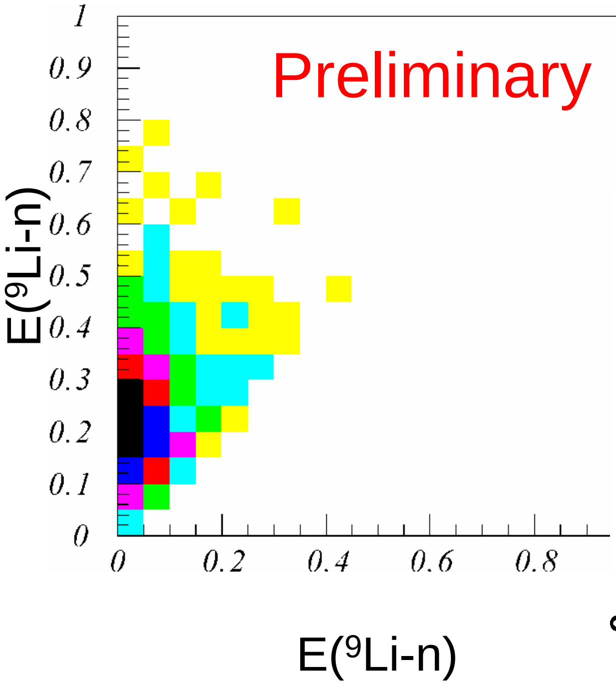


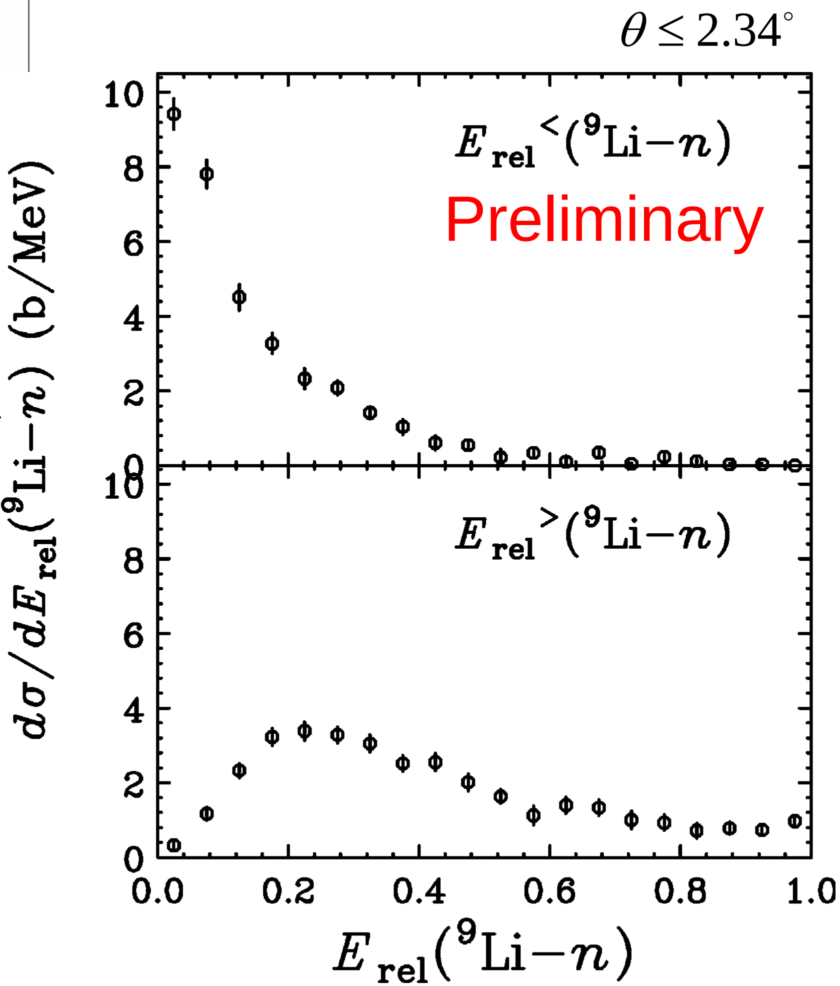
Experimental Result



Simulation (Phase Space)





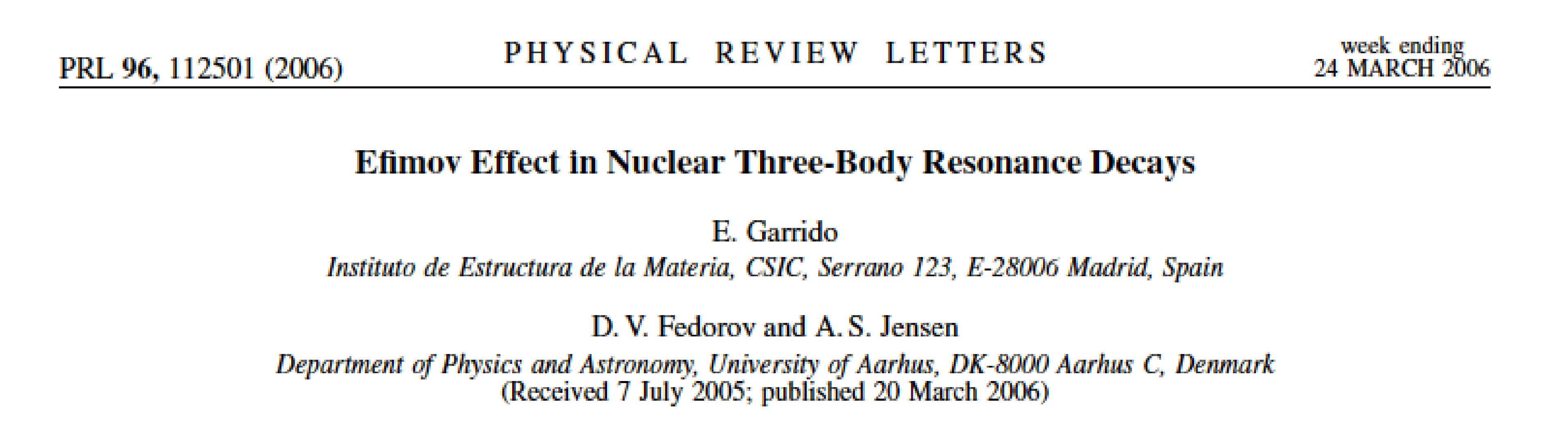


^{10}Li s-wave
Virtual state

p-wave?

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

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



PRL 96, 112501 (2006) PHYSICAL REVIEW LETTERS week ending 24 MARCH 2006

Efimov Effect in Nuclear Three-Body Resonance Decays

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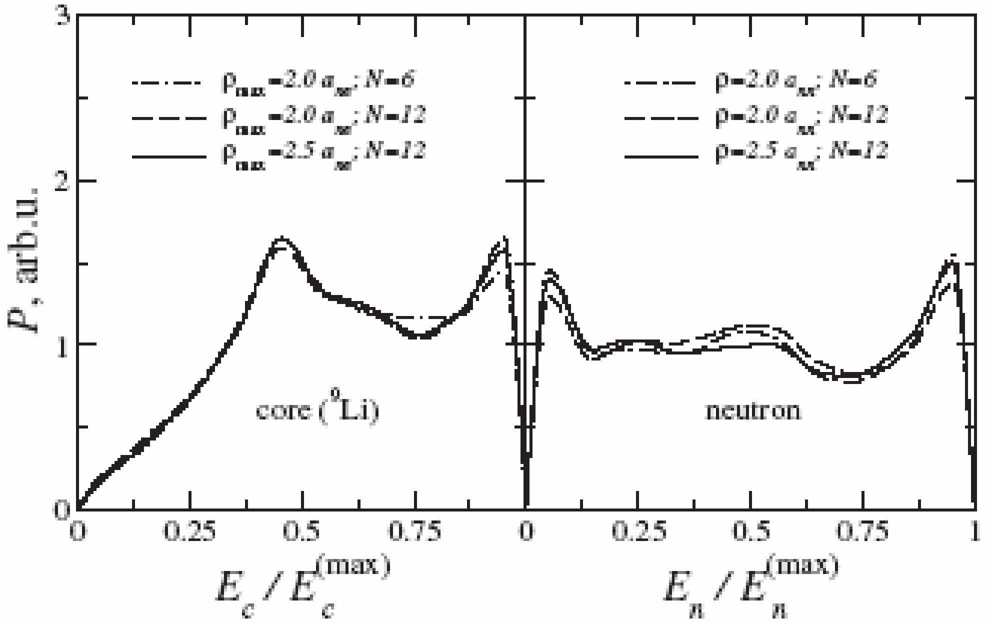
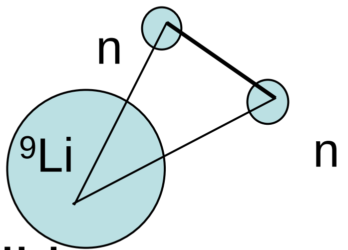
(Received 7 July 2005; published 20 March 2006)

Investigate 1^- state in ^{11}Li



Energy distribution of core(^{9}Li) and *n* in the decay of E1 state of ^{11}Li

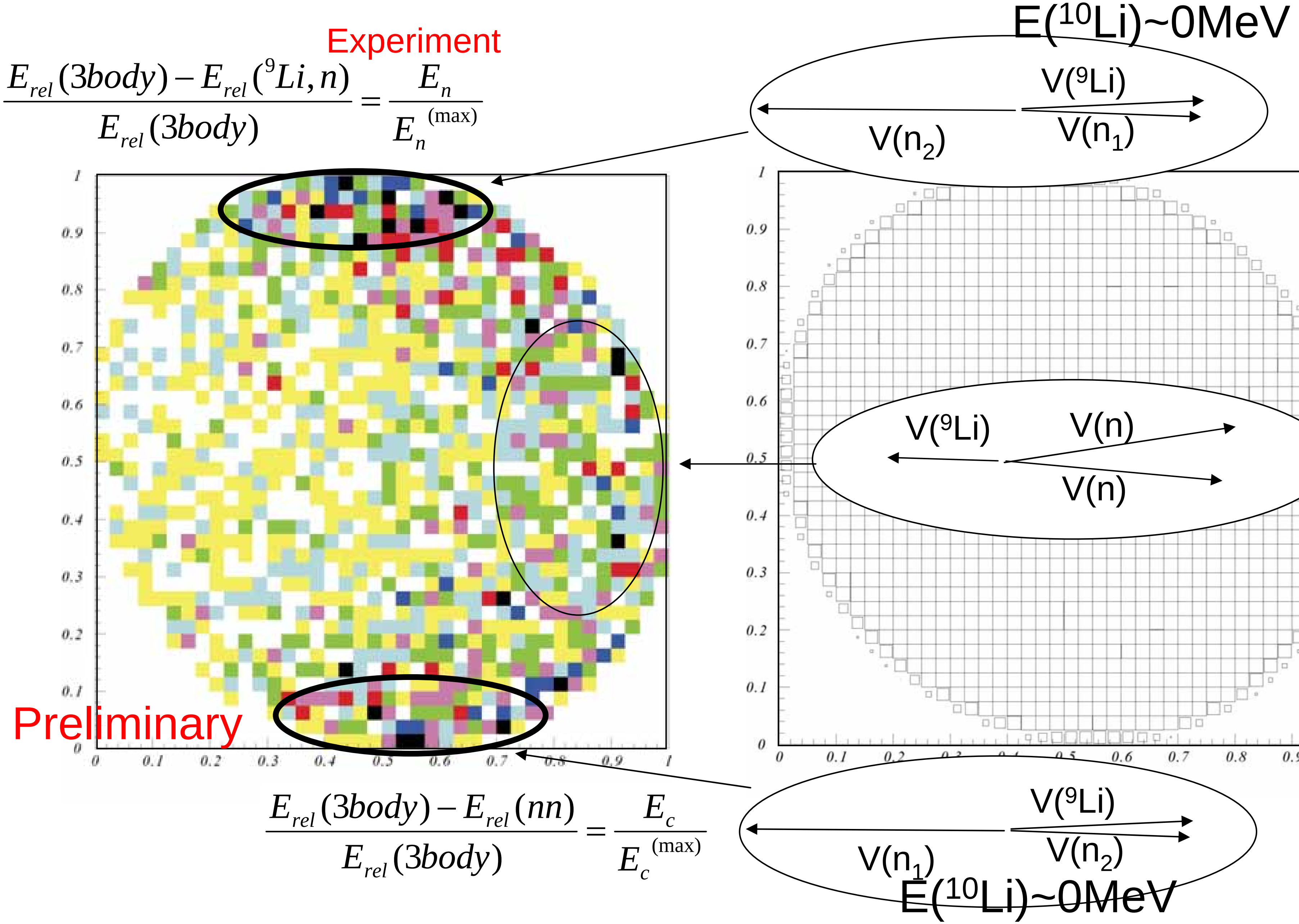


Efimov Condition:
At least 2-out-of-3 two-body scattering lengths are large

$$a(^9\mathrm{Li}\, n) \sim a(nn) \sim 20\ \mathrm{fm}$$

Experiment

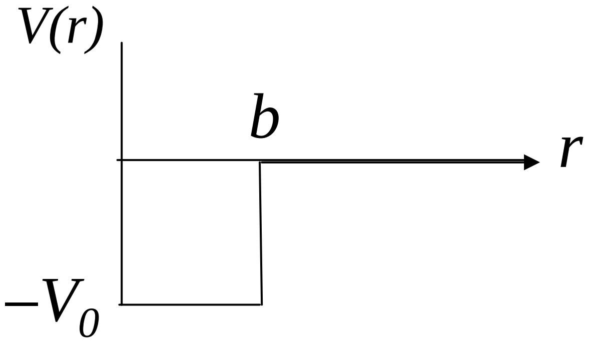
$$\frac{E_{rel}(3body) - E_{rel}({}^{9}Li, n)}{E_{rel}(3body)} = \frac{E_n}{E_n^{(\max)}}$$



$$\frac{E_{rel}(3body) - E_{rel}(nn)}{E_{rel}(3body)} = \frac{E_c}{E_c^{(\max)}}$$

memo Scattering length

$V(r)$—Potential between n and A
(A can be ${}^9Li$ or n or whatever)

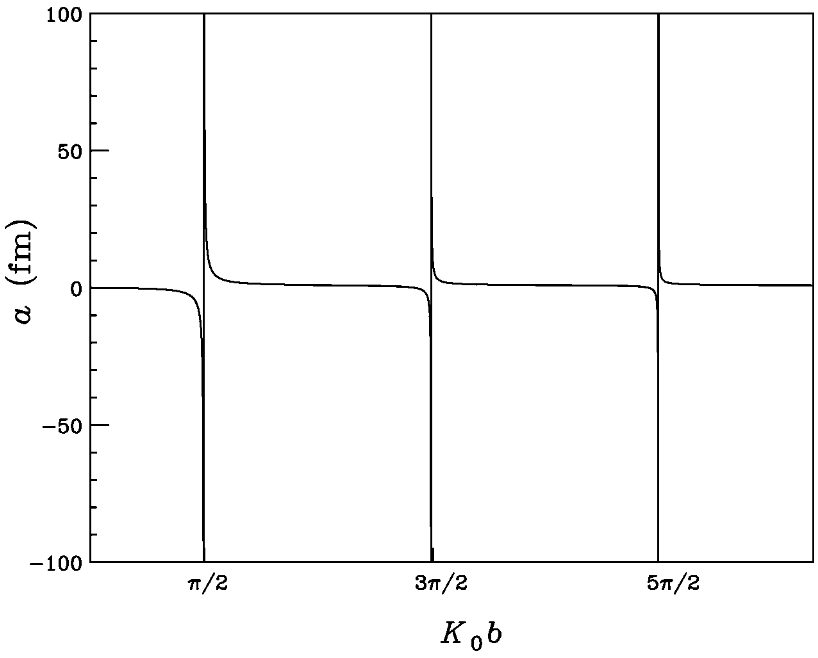


For a square well potential,

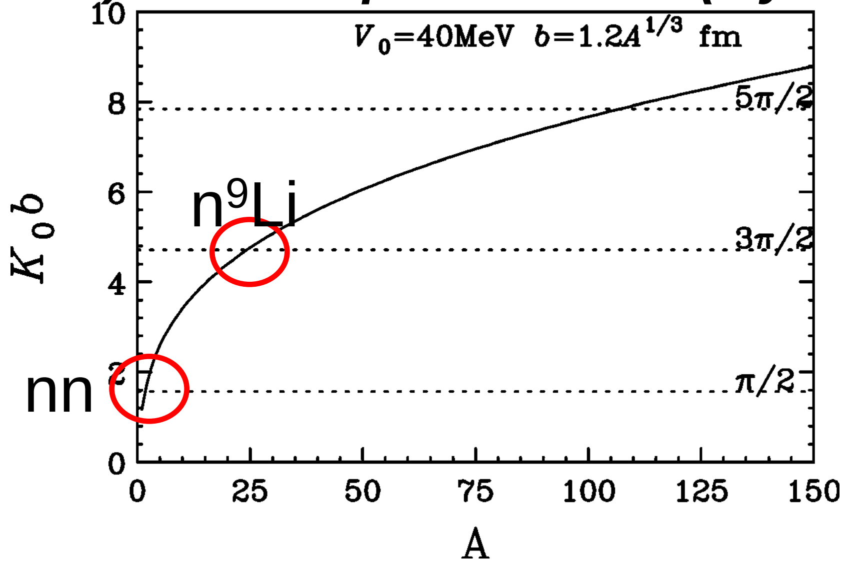
$$a = b\left[1-\frac{\tan K_0 b}{K_0 b}\right], \quad K_0 = \frac{\sqrt{2\mu V_0}}{\hbar}$$

$$\lim_{k\to 0}\sigma = 4\pi a^2, \quad k\cot\delta = -\frac{1}{a}+\frac{1}{2}k^2 r_0$$

a can be “negatively very large” only when there is an unbound state under a specific potential condition



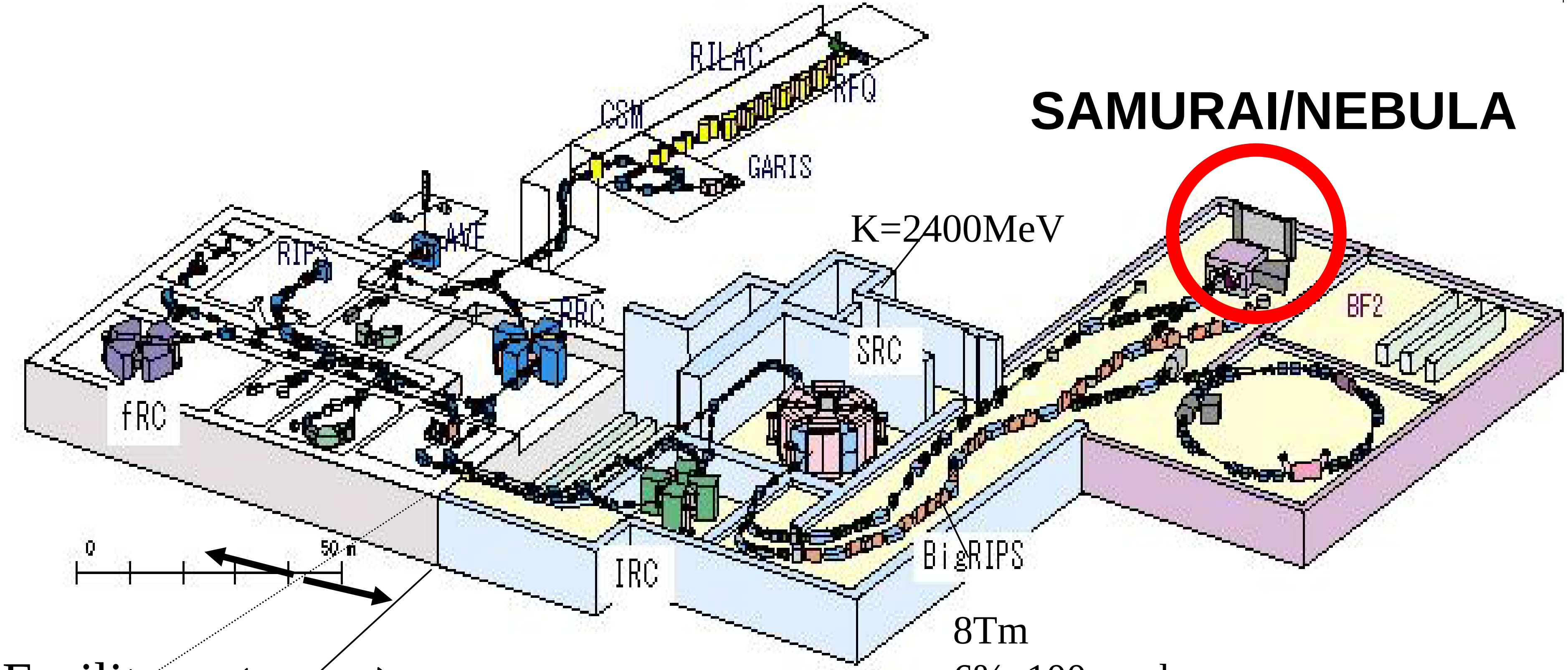
V(n-9Li) is as deep as ~65MeV (Myo et al.)



$$a(nn) = -18.5\,\text{fm},\ a({}^9\text{Li}, n) = -10 \sim -25\,\text{fm}$$

3 SAMURAI / NEBULA PROJECT @ RIKEN RI BEAM FACTORY

RIBF
(RIKEN RI Beam Factory)



SAMURAI/NEBULA

K=2400MeV

8Tm
6%, 100mrad

Facility
before 2007
100MeV/nucleon

New
Facility

Completed in 2007
World Largest RI-beam facility

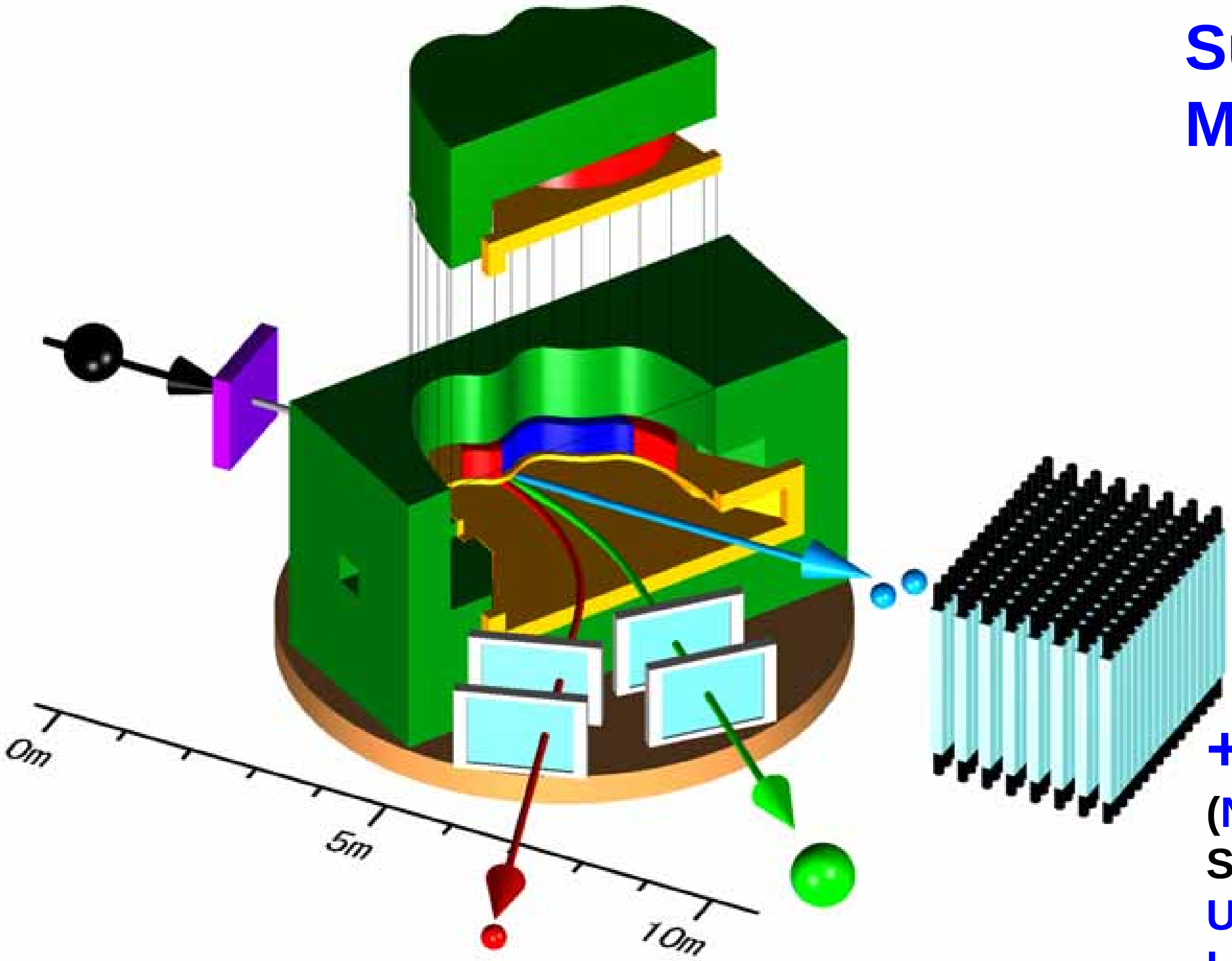
350MeV/nucleon, ~1pμA
Heavy ions up to U beam

SAMURAI

Superconducting Analyser for MUlti-particles from RAdio-Isotope Beam

Funded! 2008-2011 *1.5GJPY~15MUSD~12MEuro*

(10MEuro 1Month Ago)



Superconducting Magnet

To let neutron(s) pass through the gap

Sweep Beam and Charged Fragments

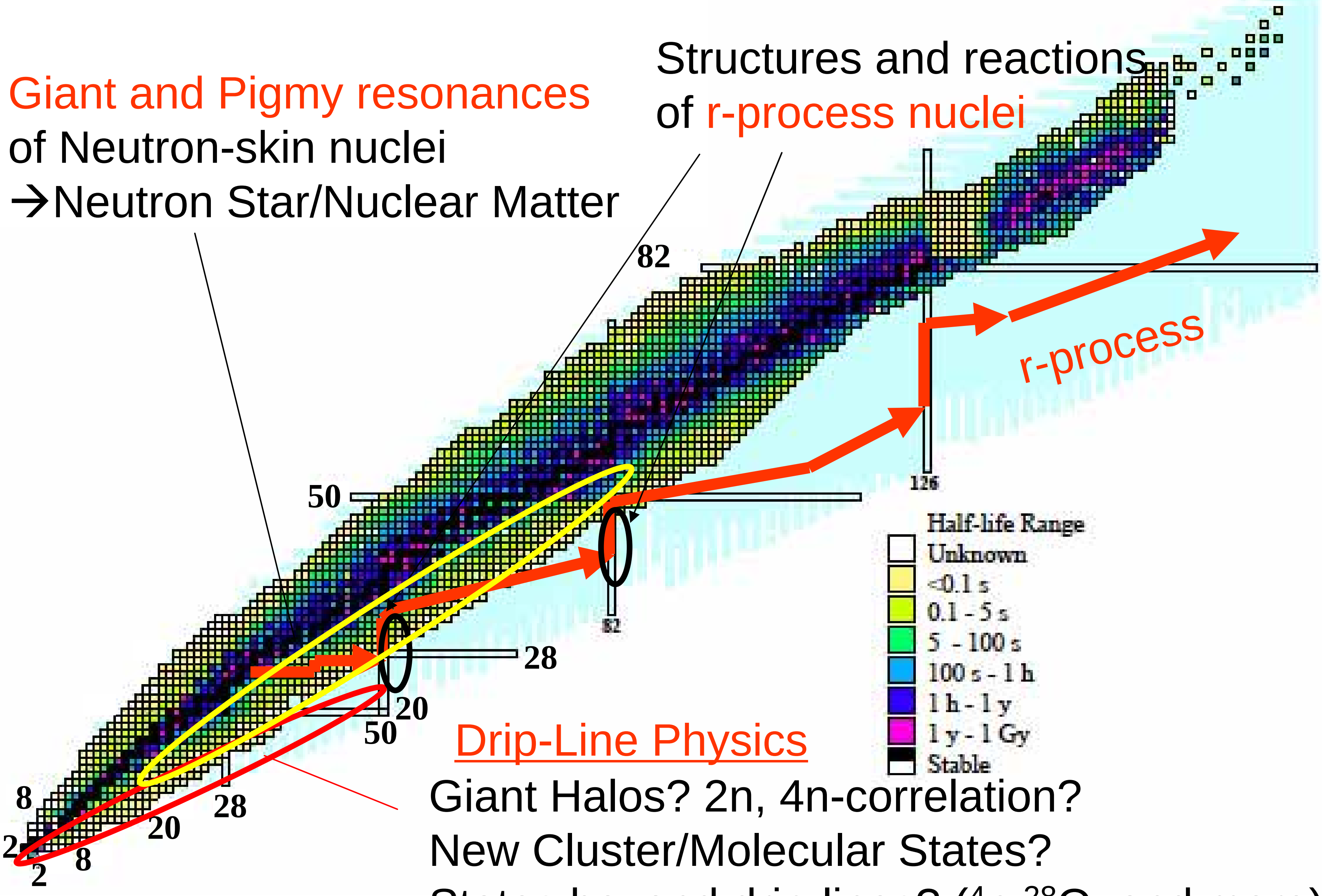
Good Mass Resolution for PID @ A~100

+NEBULA

(NEutron Detection System for Breakup of Unstable Nuclei with Large Acceptance)

Bending Power
BL=7Tm (B=3Tesla, 60deg bending)

Physics of Neutron-rich Nuclei via Breakup Reactions (@SAMURAI/NEBULA)



Giant and Pigmy resonances
of Neutron-skin nuclei
→Neutron Star/Nuclear Matter

Structures and reactions
of r-process nuclei

Drip-Line Physics

Giant Halos? 2n, 4n-correlation?
New Cluster/Molecular States?
States beyond drip-lines? (^{4}n,^{28}O, and more)

Summary

1 Inelastic scattering of ^{19,17}C on proton target

Y.Satou, TN et al., Phys. Lett. B 96, 252502 (2008).

- (p,p’) with DWBA: useful tool
- ^{19}C: $1/2^{+} \rightarrow 5/2_{2}^{+}$ at 1.47MeV (new state) ; ^{17}C: 3 transitions

2 Coulomb Breakup of ^{11}Li and two-neutron correlation

T. Nakamura, A.M.Vinodkumar et al., Phys. Rev. Lett. 96, 252502 (2006).

- Strong B(E1) at very low excitation energy

$$B(E1) = 1.42 \pm 0.18 e^{2}\, fm^{2} (S_{2n} = 300\mathrm{keV})$$

$$B(E1) = 1.50 \pm 0.19\, e^{2}\, fm^{2} (S_{2n} = 378\mathrm{keV})$$

- neutron-neutron spatial correlation from E1 sum rule θ_{nn}~50-60deg
- 3-body decay of Dipole state of ^{11}Li----Signature of strong virtual state in ^{10}Li and nn

→Efimov?

3 SAMURAI/NEBULA Project

Collaborators

T.Nakamura, Y.Satou(^{19}C), T.Sugimoto, Y.Kondo, A.M.Vinodkuar(^{11}Li), N. Aoi, H. Baba, D. Bazin, N.Endo, N. Fukuda**,** T. Gomi, H. Hasegawa, Y. Hashimoto, N. Imai, M. Ishihara, S.Kawai, M.Kitayama, T.Kobayashi, T. Kubo, Y.Matsuda, N.Matsui, M. Miura**,** T. Motobayashi, T. Nakabayashi, T.Okumura, H. Otsu, H.J.Ong, T.K. Onishi, A.Saito, H.Sakurai, S. Shimoura, M. Shinohara, S.Takeuchi, M.Tamaki, Y.Togano, K. Watanabe, Y.X. Watanabe, T. Yakushiji, Y. Yanagisawa, K. Yoneda