Invariant mass spectroscopy of halo nuclei

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References

Topic 1 Coulomb Breakup of ^{11}Be
T.Nakamura et al. Phys. Lett. B 331, 296 (1994)
N.Fukuda et al., Phys. Rev. C 70, 054606 (2004)
R. Palit et al., Phys. Rev. C 68, 034318 (2003)

Coulomb Breakup of ^{19}C
T.Nakamura et al., Phys. Rev. Lett. 83, 1112 (1999)

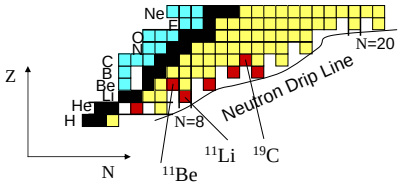
Coulomb Breakup Method, Equivalent Photon Method
J.D. Jackson, Classical Electrodynamics (Wiley, New York, 1975)
2nd Edition. (e.g. Section 13)
C.A. Bertulani and G.Baur, Phys. Rep. 163, 299 (1988)

Topic 2 Coulomb Breakup of ^{11}Li
T.Nakamura et al., Phys. Rev. Lett. 96, 252502 (2006).

Introduction-1

Neutron-halo Nuclei

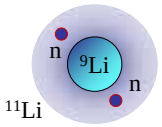
Neutron Halo Nuclei --- Nuclei at the limit



Stable Nuclei
β^+
β^-

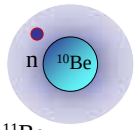
Neutron Halo

2n Halo Nucleus



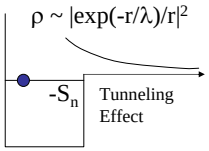
S_{2n}=300keV

1n Halo Nucleus



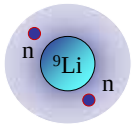
S_n=504keV

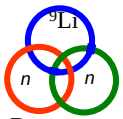
Weak Binding



Physic of Halo Nuclei -I

What is the binding Mechanism?





Borromean
(3-body system)

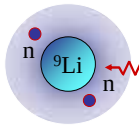
^{9}Li + n

n + n

^{9}Li+ n + n

How it is excited?

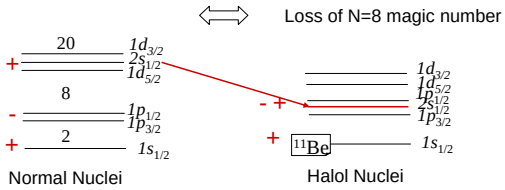
Neutron-matter, Two-fold structure



Photon (E1,E2,M1)
Alpha (E0)
(p,n) (Isospin)

Physic of Halo Nuclei -II

- Magic Number?



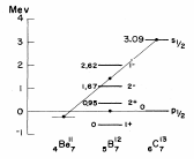


FIG. 1. Competition between $s_{\frac{1}{2}}$ and $p_{\frac{1}{2}}$ levels.

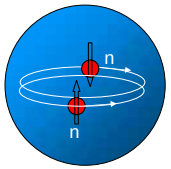
I. Talmi and I. Unna, PRL4, 469 (1960).
Residual interaction *(halo property not included)*

I. Hamamoto, S.Shimoura, J.Phys.G 34, 2715(2007)
Weakly bound neutron
in deformed potential

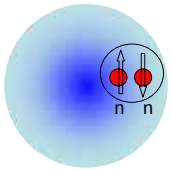
Di-neutron correlations

M.Matsuo, PRC73,044309(2006).
K.Hagino et al.,PRL 99, 022506(2007).

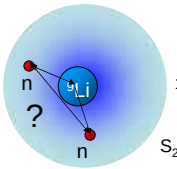
BCS-like pair correlation
(Long range)



BEC-like correlation (Dineutron)
(Short range)



Dineutron-like
Spatial Correlation
at ρ/ρ_0~10^{-4}-0.5



^{11}Li

S_{2n}=300 keV

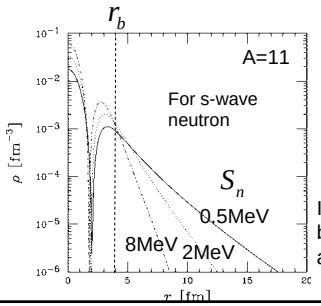
Note1: How halo is formed?--
Separation energy←→ Halo

Radial wave function for 3-D Shrodinger Equation

$$u(r) = rR(r)$$

$$-\frac{\hbar^2}{2m}\frac{d^2u}{dr} + \left[V(r) + \frac{l(l+1)\hbar^2}{2mr^2}\right]u = Eu$$

Centrifugal Barrier



$$V(r) = \frac{-V_0}{1+\exp[(r-R_0)/a]}$$

$$r_b: \quad V(r_b) = \frac{-V_0}{10}$$

In this lecture, we define r_b as boundary between inside and outside region of a nucleus

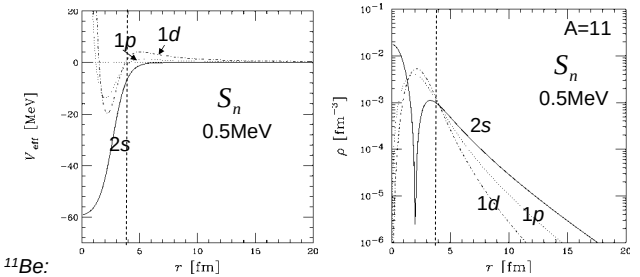
Note2: How halo is formed?--
Angular momentum of a single particle state←→ Halo

Radial wave function for 3-D Shrodinger Equation

$$u(r) = rR(r)$$

$$-\frac{\hbar^2}{2m}\frac{d^2u}{dr} + \left[V(r) + \frac{l(l+1)\hbar^2}{2mr^2}\right]u = Eu$$

Centrifugal Barrier

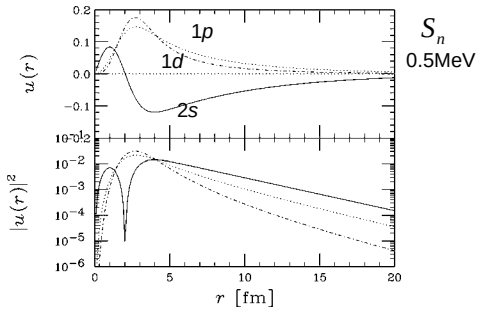


e.g. ^{11}Be:
valence neutron is either 2s,1p,1d

memo

$$u(r) = rR(r)$$

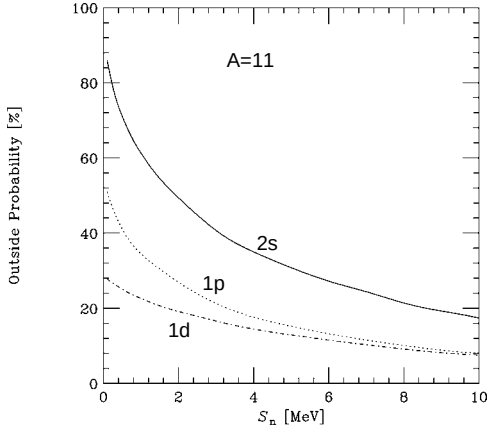
$$-\frac{\hbar^2}{2m}\frac{d^2u}{dr} + \left[V(r) + \frac{l(l+1)\hbar^2}{2mr^2}\right]u = Eu$$



S_n
0.5MeV

"Probability of being outside"

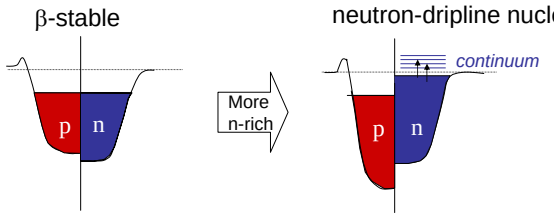
$$= \int_{R0+(\ln 9)a}^{\infty} |R(r)|^2 4\pi r^2 dr$$



Introduction-2

Experimental Method
-- Invariant mass spectroscopy

Excited states of neutron-drip line nuclei



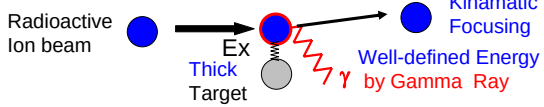
neutron drip-line nuclei
Fermi levels between n and p—Very Different
→Valence neutron – *Loosely-Bound*– Halo
→Excitation to the continuum– More significant

Exited states-- mainly in the continuum above the n-decay threshold

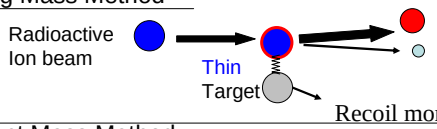
Invariant mass spectroscopy

Spectroscopic methods using fast-RIB

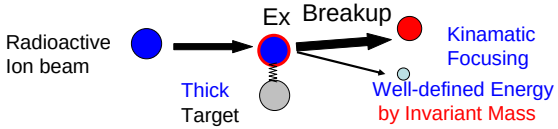
In-beam Gamma Ray Spectroscopy



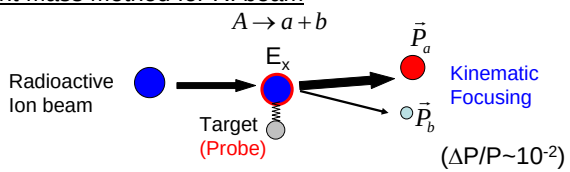
Missing Mass Method



Invariant Mass Method

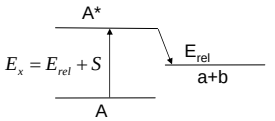


Invariant Mass Method for RI beam



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

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



$$E_x = E_{rel} + S$$

Advantages

Good Energy Resolution ~ a few hundred keV @E_{rel}=1MeV
Kinematic Focusing
Thick Target ~0.2g/cm² @70MeV/nucleon

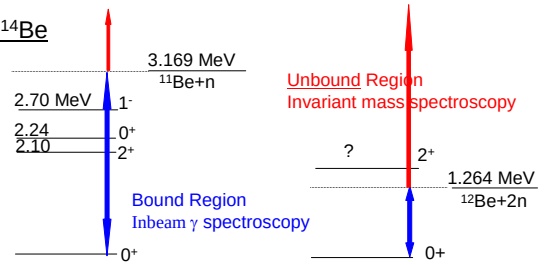
→ Good approach for nuclei at drip line

Disadvantages

Need to measure all the outgoing particles

Invariant Mass Method: Case of ^{14}Be

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



^{14}Be(^{12}C,^{12}C') @68MeV/nucleon

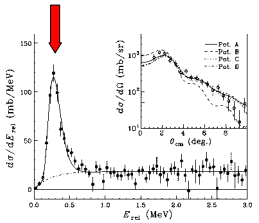
T.Sugimoto, T.N. et al.
Phys.Lett.B 654, 160 (2007).

^{14}Be(p,p') @69MeV/nucleon

Y.Kondo, T.N. et al.
Paper in preparation

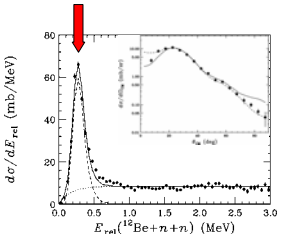
$$E_{\mathrm{rel}} = 0.27 \pm 0.01\,\mathrm{MeV}$$

$$E_{\mathrm{x}}(2_1^+) = S_{2n} + E_{\mathrm{rel}} = 1.54 \pm 0.13\,\mathrm{MeV}$$



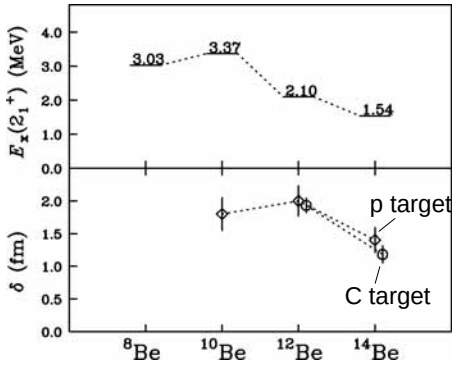
$\sigma(\mathrm{g.s.} \rightarrow 2^+) = 22.6 \pm 1.1(stat.) \pm 3.1(syst.)\,\mathrm{mb}$

$\delta = 1.18 \pm 0.13$ fm



$\sigma(\mathrm{g.s.} \rightarrow 2^+) = 12.5 \pm 0.2(stat.) \pm 1.6(syst.)\,\mathrm{mb}$

$\delta = 1.40 \pm 0.19$ fm



^{12}Be-^{14}Be: Different behavior from the Raman's systematics !

$$\beta = (466 \pm 41) E_{\mathrm{x}}^{-1/2} A^{-1}$$

S. Raman et al.: At. Data Nucl. Data Tables **78**, 1 (2001)

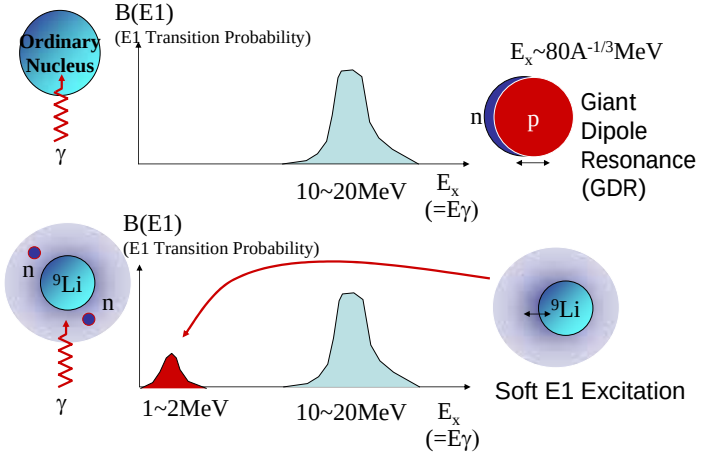
Small collectivity of ^{14}Be →smaller effective charges

Topics-1

^{11}Be,^{19}C,^{15}C

Coulomb Breakup of One-neutron Halo Nuclei,
and spectroscopic factor (single-particle property)

Photon Absorption of Nucleus



GDR(Giant Dipole Resonance)

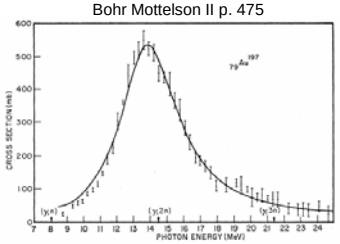
Note

S.C.Fultz et al., PR127,1273(1962).
Bohr Mottelson II p. 475

$E_x \sim 80A^{-1/3}$MeV

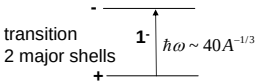
n p

Giant Dipole Resonance (GDR)



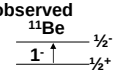
So far, it is believed that
E1 is exhausted almost purely by GDR

E1: transition
Bet. 2 major shells



The largest discrete-level transitions so far observed

T.Nakamura et al., PLB 394,11(1997).
S.S.Hanna et al., PRC3, 2198 (1971),
D.J.Millener et al., PRC28, 497(1983)



$B(E1) = 0.099(10)e^2\text{fm}^2 = 0.31(3)W.u.$

(1W.u for A=11, B(E1)=0.3188e²fm², where e as bare charge is used. See D.J.Millener et al.,PRC28,497(1983))

$B(E\lambda)$ Reduced Transition Probability $|I_i M_i\rangle \rightarrow |I_f M_f\rangle$

Note

$$B(E\lambda) = \sum_{M_i, M_f, m} \left|\langle I_f M_f | O(E\lambda\mu) | I_i M_i \rangle\right|^2 = \frac{1}{2I_i + 1} \left|\langle I_f \| O(E\lambda) \| I_i \rangle\right|^2$$

$$O(E\lambda\mu) = Ze\sum_{k=1}^{Z} r_k^\lambda Y_\mu^\lambda(\Omega)$$

Wigner Eckart's Theorem

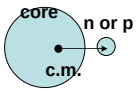
$$\langle I_f M_f | O(E\lambda\mu) | I_i M_i \rangle = \frac{1}{\sqrt{2I_f + 1}} \langle I_f \| O(E\lambda) \| I_i \rangle \langle I_i M_i \lambda m | I_f M_f \rangle$$

Reduced Matrix element — Clebsch-Gordan coefficient

Unit $e^2\, fm^{2l}$

e.g.

- Weisskopf unit: $B(E\lambda)$ for a single-particle excitation



$$B(E\lambda) = \frac{(1.2)^{2\lambda}}{4\pi}\left(\frac{3}{\lambda+3}\right)^2 A^{2\lambda/3} e^2 (fm)^{2\lambda}$$

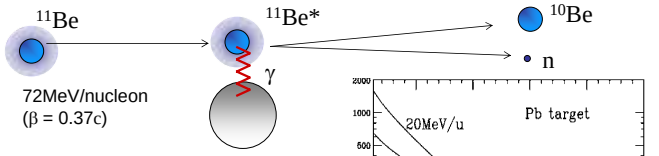
E1: e→e_{eff}

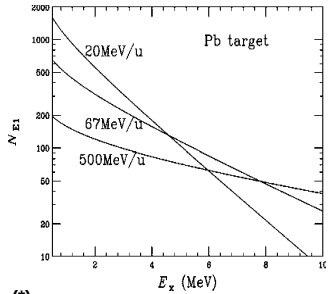
$$e_{eff} = \begin{cases} eN/A & \text{for p} \\ -eZ/A & \text{for n} \end{cases}$$

- Gamma decay probability

$$T = \frac{1}{\tau} = \frac{8\pi(\lambda+1)}{\lambda[(2\lambda+1)!!]^2\hbar}\left(\frac{E_\gamma}{\hbar c}\right)^{2\lambda+1} B(E\lambda)$$

Coulomb Breakup





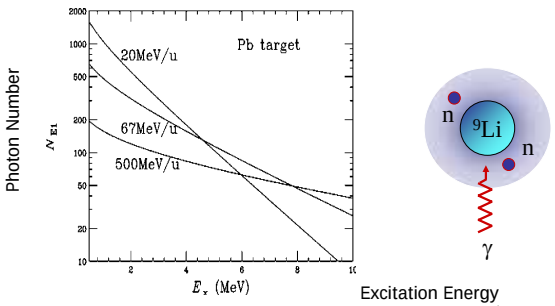
- Excitation by a Virtual Photon

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

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

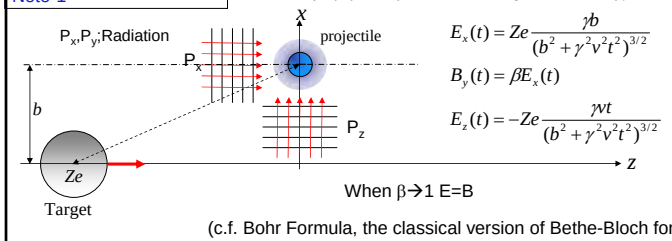
Excitation Energy (=Photon Energy)

- Invariant Mass Spectroscopy



Equivalent Photon Method Note-1

In the projectile-rest frame: Target (E-field) is approaching with Velocity −β (It is equivalent in the fig below with +β)



$$E_x(t) = Ze\frac{\gamma b}{(b^2+\gamma^2v^2t^2)^{3/2}}$$

$$B_y(t) = \beta E_x(t)$$

$$E_z(t) = -Ze\frac{\gamma vt}{(b^2+\gamma^2v^2t^2)^{3/2}}$$

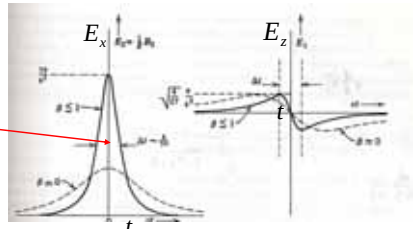
When β→1 E=B

(c.f. Bohr Formula, the classical version of Bethe-Bloch formula)

A sharp pulse of E

$$\Delta t = b/\gamma v$$

v→larger
Δt→smaller



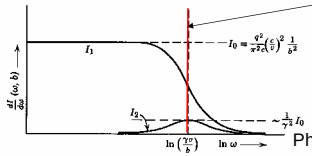
Sec.15, J.D.Jackson Classical Electrodynamics

Equivalent Photon Method Note 2

•Amplitude of E-field: dI/dE_x can be seen as a photon spectrum
:Weizsacker-Williams Method of Virtual Quanta (Equivalent Photon Method)

$$\frac{dI(E_x,b)}{dE_x}dE_x = N(E_x,b)dE_x$$

•Amplitude Spectrum (=Virtual Photon Spectrum) :
Shorter pulse (uncertainty of T is small) →E_x *is broader* (Uncertainty Principle)



Adiabatic cutoff

$$\frac{E_x b}{\hbar c\beta\gamma} \le 1$$

Photon energy

Fig. 15.7 Frequency spectra of the two equivalent pulses of radiation.

This is nothing but the Fourier Transform of dI/dt

Quiz: Find energies corresponding to the adiabatic cutoff for *b*=10fm with β=0.3,0.6,0.9, respectively.

Equivalent Photon Method Note-3

C.A.Bertulani and G.Baur, Phys. Rep. 163, 299, (1988)

$$P(b) = \int N(E_x,b)\sigma_\gamma(E_x)\frac{dE_x}{E_x}$$

Photo-absorption Probability at b = Virtual photon number x Photo-absorption cross section

Photo-absorption Cross Section : Probability to absorb one photon with Ex at b

$$\sigma = \int_R^\infty P(b)2\pi b db = \int n(E_x)\sigma_\gamma(E_x)\frac{dE_x}{E_x}$$

Coulomb Excitation(Breakup) Cross Section

$$n(E_x) = \int_R^\infty N(E_x,b)2\pi b db$$

R: Minimum Impact parameter (~sum of projectile and target radii)

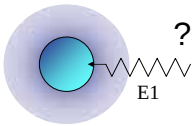
$\pi : E$ or M, λ :1,2,...

$$\sigma_\gamma^{\pi\lambda} = \frac{(2\pi)^3(\lambda+1)}{\lambda[(2\lambda+1)!!]^2}\left(\frac{E_x}{\hbar c}\right)^{2\lambda-1}\frac{dB(\pi\lambda)}{dE_x}$$

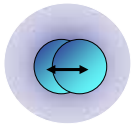
$\frac{d\sigma}{dE_x db}$, $\frac{d\sigma}{dE_x d\Omega}$ Can be dscribed by this formalism as well. θ~1/b

Quiz: Derive the formula (*) in page 24 (4pages above)
Quiz: Explain qualitatively the photon spectra for three incident energies in the same page

Reaction Mechanism of Soft Excitation?



- Soft Dipole Resonance



Slow Vibration
of core against halo

- Direct Coulomb Breakup



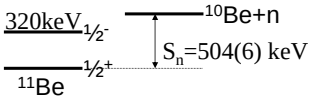
$$\frac{dB(E1)}{dE_x} \propto |\langle \exp(i\boldsymbol{qr})|\frac{Z}{A}rY^1_m|\Phi_{gs}\rangle|^2$$

$$\propto \frac{\sqrt{S_n}(E_x - S_n)^{3/2}}{E_x^4}$$

$E_x(\text{Peak}) \propto \frac{8}{5}S_n \quad B(E1) \propto 1/S_n$

^{11}Be Nucleus → Basic Understandings

- Well-Known Structure

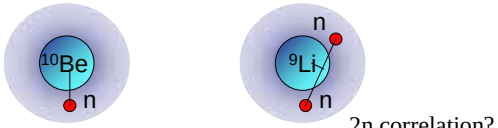


$^{11}\text{Be(g.s)}=\alpha|^{10}\text{Be}(0^+)\otimes(2s_{1/2})_\nu\rangle + \beta|^{10}\text{Be}(0^+)\otimes(1d_{5/2})_\nu\rangle$

$\alpha^2=0.77$ ^{10}Be(d,p)^{11}Be B.Zwieglinski et al. NPA315,124(1979).

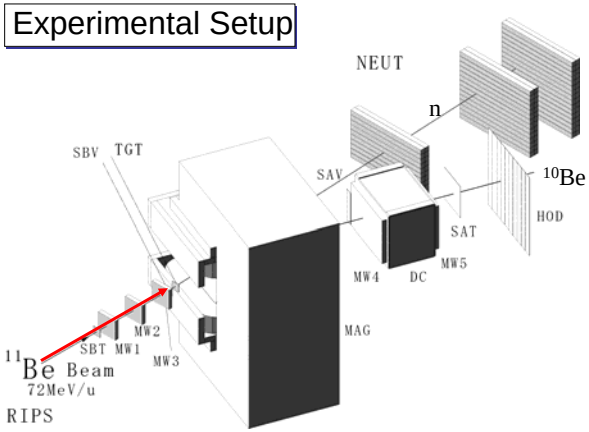
$\alpha^2=0.74$ ^{9}Be(^{11}Be, ^{10}Beγ) X T.Aumann et al. PRL84,35(2000).

- Simple One-neutron Halo Nucleus

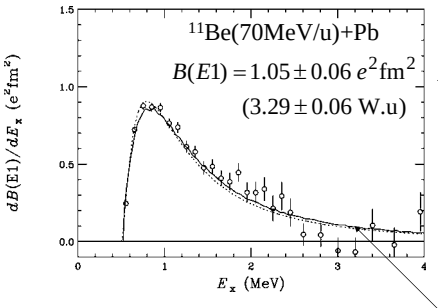


^{11}Be ^{11}Li 2n correlation?

Experimental Setup



B(E1) Observed for Neutron-halo ^{11}Be nucleus



Huge E1 Probability
(usually B(E1) < 10^{-3})

T.Nakamura *et al.*,
PLB 331,296(1994)
N.Fukuda et al.,
PRC70, 054606 (2004)

No Resonance
But Huge Peak

Direct Breakup Model

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

$$\propto \frac{\sqrt{S_n}(E_x - S_n)^{3/2}}{E_x^4}$$



Low-energy B(E1)---Very Sensitive to Halo Wave Function !

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

$$\propto \alpha^2 \frac{\sqrt{S_n}(E_x - S_n)^{3/2}}{E_x^4}$$

Low-energy B(E1)

$\Leftrightarrow$ Fourier Transform

$\rho \sim \alpha^2 |\exp(-r/\lambda)/r|^2$

$-S_n$ Halo State

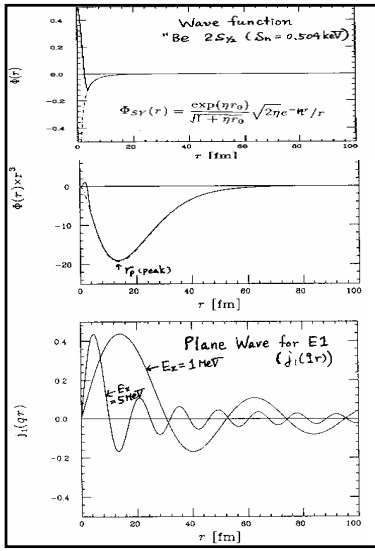
^{11}Be ground state

Halo State Non-Halo State

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

α^2, β^2 : Spectroscopic factor

$\alpha^2 = 0.72 \pm 0.04$



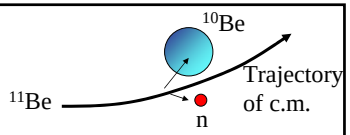
B(E1)
SENSITIVE to Halo

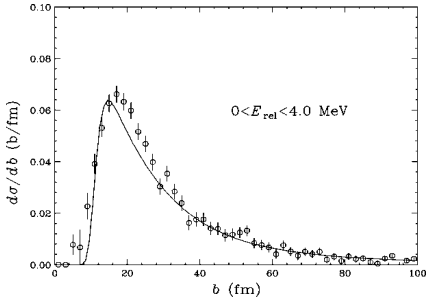
$$B(E1) \propto \left|\left\langle e^{iqr}\left|rY^1_m\right|\Phi(r)\right\rangle\right|^2$$

$$\left\langle e^{iqr}\left|rY^1_m\right|\Phi(r)\right\rangle \propto \int e^{iqr} r^3 \Phi(r) dr$$

T. Otsuka, M. Ishihara, N. Fukunishi, T. Nakamura, and M. Yokoyama
Phys. Rev. C 49 (1994) R2289-R2292.

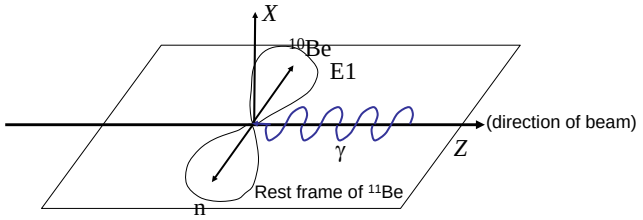
Impact Parameter Dependence

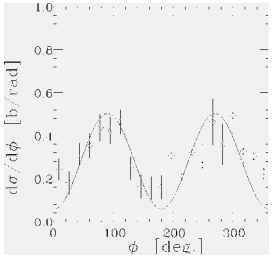




$$b = a\cot(\theta/2)$$

Angular Correlation: Signal of E1 multipolarity





Consistent with E1 multipolarity

Compare with 1st order perturbation theory for E1 excitation

G.Baur, C.A. Bertulani, and D.M. Kalassa, Nucl. Phys. A550,527(1992).

B(E1) and Sum Rule

- Energy Weighted Sum Rule (TRK Sum Rule)

$$\int \sigma_\gamma(E_\gamma)dE_\gamma = \int \frac{16\pi^3}{9\hbar c}E_x \frac{dB(E1)}{dE_x}dE_x = \frac{9}{4\pi}\frac{\hbar^2 e^2}{2m}\frac{NZ}{A}$$

38.1 e^2fm^{2}MeV for ^{11}Be

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

$$\text{Sum}=60\frac{NZ}{A}-60\frac{N_c Z_c}{A_c}=2.18\,e^2\text{fm}^2\text{MeV}$$ For ^{11}Be

Experiment (E_x<4 MeV)

$Sum = 1.52 \pm 0.22\ e^2\text{fm}^2\text{MeV}$= 4.0(5) % of TRK Sum =70(10) % of Cluster Sum

~ Spectroscopic Factor

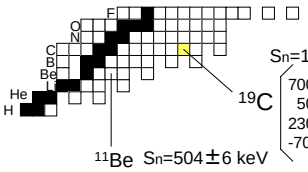
- Non Energy Weighted Cluster Sum Rule H.Esbensen et al.,NPA542,310(1992)

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

Experiment: $B(E1)=1.05\pm0.06\ e^2\text{fm}^2 \Rightarrow \sqrt{\langle r^2\rangle}=5.77\pm0.16\text{fm}$

Coulomb Breakup of ^{19}C

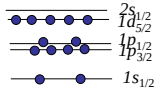
Halo Nucleus Candidate ^{19}C



S_n=160 ±110 keV (1993 Mass evalulation)

700±240 keV (Vieira et al. PRL57,3253(1986).
50 ±420 keV (Gillbert et al. PLB192,39(1988).
230 ±120 keV (Wouters et al. ZPA331,229(1988).
-70 ± 240 keV (Orr et al. PLB258,29(1991).

S_n=504±6 keV



Neutron orbital

- Spin-Partiry, Configuration of Single Particle State?

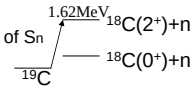
○ $J^\pi = 1/2^+$ $\alpha|\,^{18}\text{C}(0^+)\otimes 2s_{1/2}\rangle + \beta|\,^{18}\text{C}(2^+)\otimes 1d_{5/2}\rangle$

Halo State

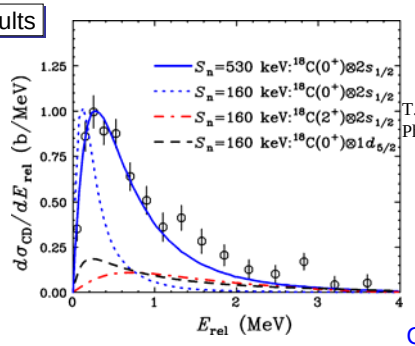
○ $J^\pi = 5/2^+$ $\gamma|\,^{18}\text{C}(2^+)\otimes 2s_{1/2}\rangle + \delta|\,^{18}\text{C}(0^+)\otimes 1d_{5/2}\rangle$

Centrifugal Barrier

Deepening of Sn



Results



T.Nakamura *et al.*,
Phys. Rev. Lett. 83, 1112 (1999).

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

$$|\Phi_{gs}\rangle = \begin{matrix}J^\pi\\ 1/2^+\\ 5/2^+\end{matrix}\begin{matrix}\alpha|\,^{18}\text{C}(0^+)\otimes 2s_{1/2}\rangle+\beta|\,^{18}\text{C}(2^+)\otimes 1d_{5/2}\rangle\\ \gamma|\,^{18}\text{C}(2^+)\otimes 2s_{1/2}\rangle+\delta|\,^{18}\text{C}(0^+)\otimes 1d_{5/2}\rangle\end{matrix}$$

Conclusion for ^{19}C(g.s)

$J^\pi = 1/2^+$

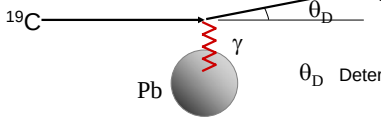
S_n should be larger!

α^2=0.67 for S_n=530keV

B(E1)=0.71(7) e^2fm^2

Determination of S_n (Mass)

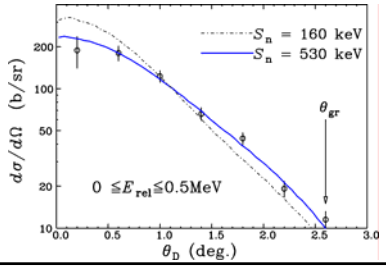
Rutherford Trajectory
(^{18}C+n) system



θ_D Determined event by event

$$\frac{d\sigma(\theta_D,E_x)}{d\Omega} \propto \frac{dN_{E1}(\theta_D,E_x)}{d\Omega} B(E1;E_x)$$

$E_x = E_{rel} + S_n \longrightarrow S_n$



$S_n = 530 \pm 130$keV

Why $dN/d\Omega$ has Ex dependence?

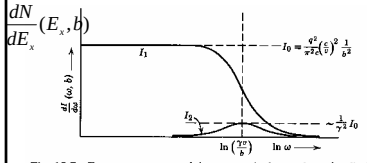
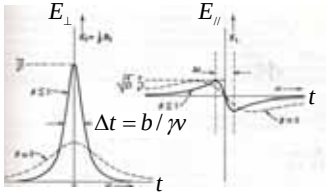


Fig. 15.7 Frequency spectra of the two equivalent pulses of radiation.

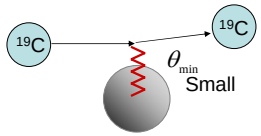
J.D.Jackson Classical Electrodynamics



For a given E_{rel}

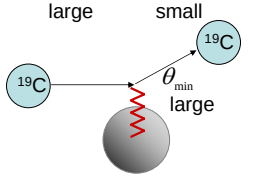
E_x ⇨ $b_{max} = \gamma v / E_x$

small ⇨ large



E_x ⇨ $b_{max} = \gamma v / E_x$

large ⇨ small



Angular distribution -----Independent of the Structure

Coulomb Breakup of ^{15}C

——— Application to Astrophysics

Neutron Capture Reaction ←→ Coulomb Dissociation

^{14}C(n,γ)^{15}C ^{15}C(γ,n)^{14}C

- Burning zone in Low mass Asymptotic Giant Branch(AGB) stars
  Neutrons from ^{13}C(α,n) reaction
  ^{14}C(n,γ)^{15}C(β⁻)^{15}N(n,γ)^{16}N(β⁻)^{16}O(n,γ)^{17}O(n,α)^{14}C *M.Wiescher et al.*, ApJ, 363,340
- Inhomogeneous Big Bang Model
- r-process model Terasawa,Sumiyoshi,Kajino, ApJ562,470(2001).

Previous Experiments

^{14}C(n,γ)^{15}C:

Beer et al.(Karlsruhe), 1/5 of Direct Capture, *APJ387,258 (1992)*

R.Reifarth et al.(Karlsruhe), Consitent with Direct Capture *PRC77,015804(2008)*

^{15}C(γ,n)^{14}C: Coulomb breakup

Horvath et al.(MSU), Inconsistent with Direct breakup *APJ570, 926(1992)*

D. Pramanik et al.(GSI), Consistent with Direct breakup *PLB551,63(2003)*

Neutron Capture Reaction vs. Coulomb Dissociation

$^{14}C(n,\gamma)^{15}C$ $^{15}C(\gamma,n)^{14}C$

Neutron Capture ⇔ Coulomb Dissociation

$$\sigma_{n,\gamma}(E_{rel}) = \frac{(2I_A+1)}{(2I_{A-1}+1)} \frac{E_\gamma^{\,2}}{2\mu c^2 E_{rel}} \sigma_{\gamma,n}(E_\gamma)$$

The principle of detailed balance

Advantages of Coulomb Dissociation

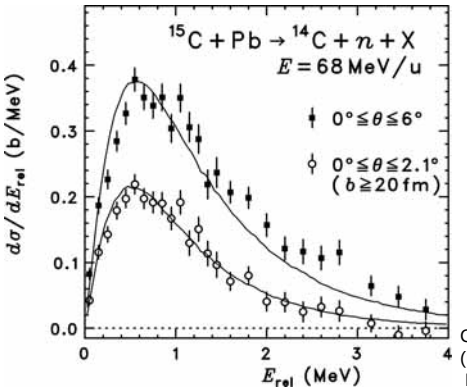
Phase Factor ~100, Photon Number ~500

Target(Thick, Stable), Kinematical Focusing

Results: Coulomb Breakup of ^{15}C

^{15}C: moderate neutron-halo $1/2^+$ gs, S_n=1.27MeV

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



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

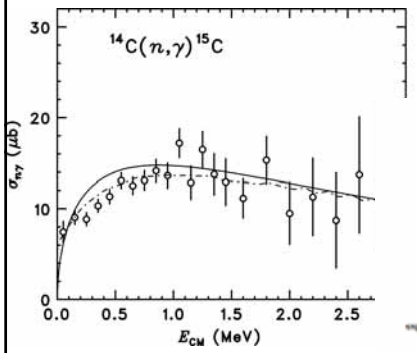
α^2=0.75(4)

r_0=1.25 fm
a=0.65 fm

Consistent with GSI (α^2=0.73) (D.Pramanik et al) Data
But not with MSU data

Neutron Capture Cross Section

From the data with b>20fm



$$\sigma_{n,\gamma}(E_{rel}) = \frac{E_\gamma^{\,2}}{\mu c^2 E_{rel}} \sigma_{\gamma,n}(E_\gamma)$$

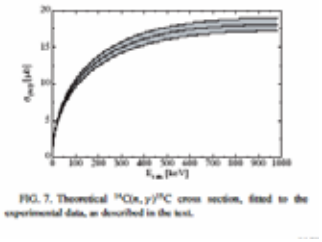


FIG. 7. Theoretical $^{14}C(n,\gamma)^{15}C$ cross section, fitted to the experimental data, as described in the text.

Consistent with Direct Capture Measurement $^{14}C(n,\gamma)^{15}C$
By R.Reifarth et al., PRC77,015804(2008)

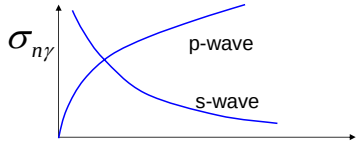
s-wave capture vs. p-wave capture

A(n,γ)B(Normal)

S-wave capture dominant $\sigma_{n\gamma} \propto 1/v \propto 1/\sqrt{E_{rel}}$

A(n,γ)B(Halo)

p-wave capture dominant $\sigma_{n\gamma} \propto \sqrt{E_{rel}}$



$^{18}C(n,\gamma)^{19}C$ Case

Experimental Input
Coulomb Breakup of ^{19}C
T.Nakamura et al.,PRL83,1112(1999).

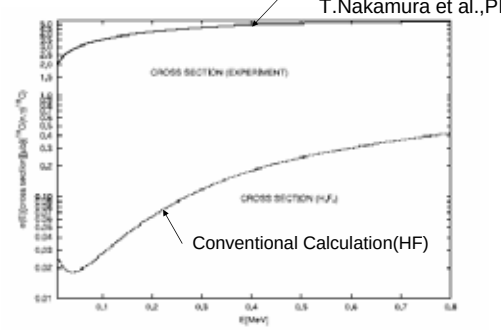


FIG. 9.—Comparison of the experimentally determined $^{18}C(n,\gamma)^{19}C$ cross section (*solid line*) of Nakamura et al. (1999) with Hauser-Feshbach estimates (*dotted line*).

Theoretical Results: T.Sasaqui, T.Kajino, G.J.Mathews, K.Otsuki, T.Nakamura, Astrophys.J. 634, 1173 (2005).

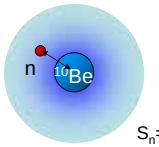
Summary of
Topics 1 :
Coulomb breakup of one-neutron halo nucleus

- Huge B(E1) at low excitation energy (not like ordinary nuclei !)
- Direct Breakup Mechanism
- Spectroscopic Tool for Halo structure
- Application to Astrophysical Reaction rate

TOPICS-2

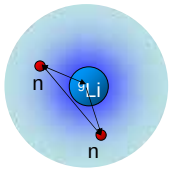
Coulomb Breakup of Two-neutron Halo Nuclei, and neutron-neutron correlation

One neutron halo nucleus vs. Two neutron halo nucleus



S_n=504 keV

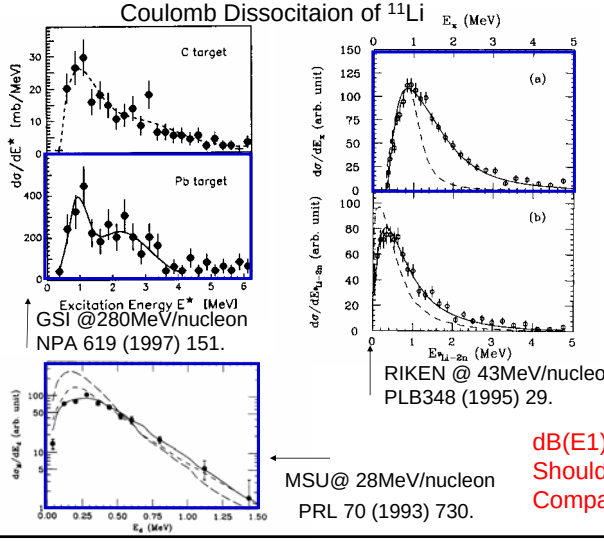
Motion between
core and 1 valence neutron



S_{2n}=300 keV

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

Coulomb Dissocitaion of ^{11}Li



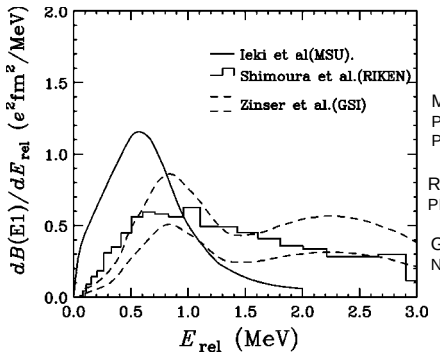
GSI @280MeV/nucleon
NPA 619 (1997) 151.

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

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

dB(E1)/dEx
Should be
Compared !

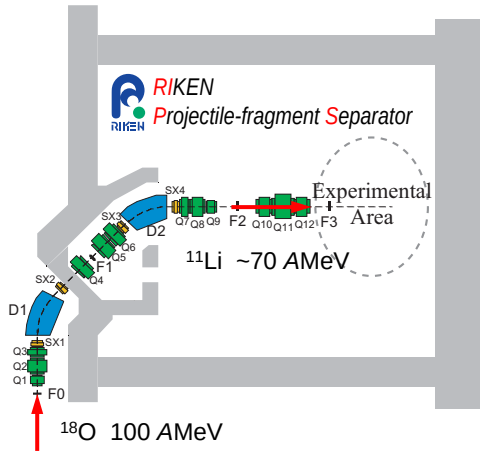
Coulomb Breakup of ^{11}Li
(Summary of Previous Results)



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

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

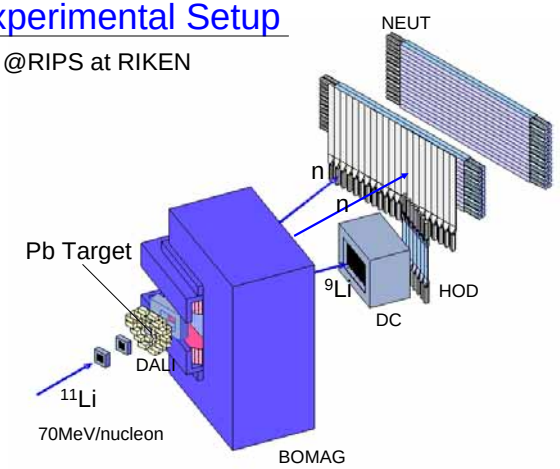
GSI @280MeV/nucleon
NPA 619 (1997) 151.



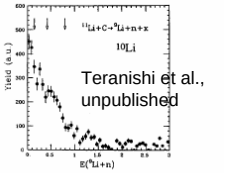
- RIPS@RIKEN
- Primary Beam
  ^{18}O 100 *A*MeV
- Projectile Fragmentation
- Secondary Beam
  ^{11}Li ~70 *A*MeV
  ~20 kcps

Experimental Setup

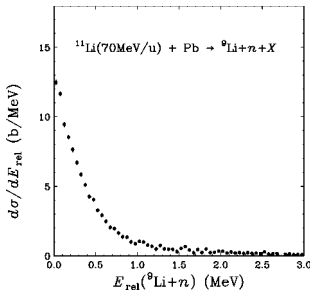
@RIPS at RIKEN



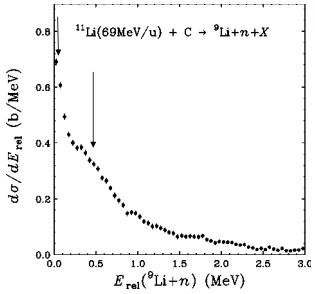
^{9}Li+n (^{10}Li)
Relative Energy Spectrum



Pb target

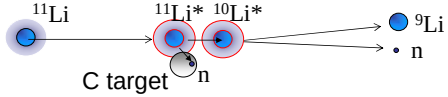


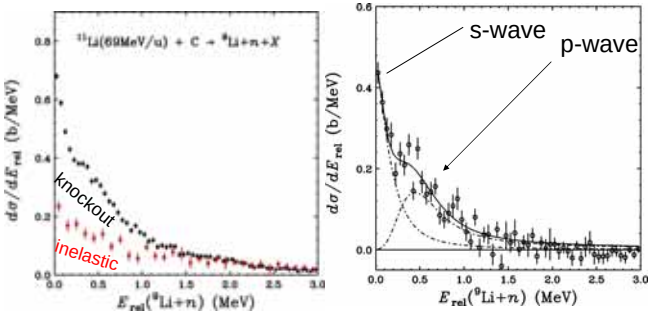
C target



^{10}Li Invariant mass method

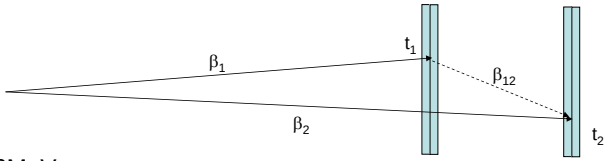
1n knockout reaction



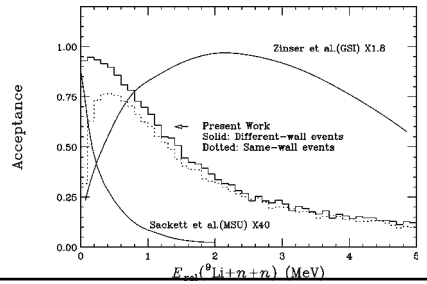


Elimination of Cross-Talk events for 2n+^{9}Li coincidence events

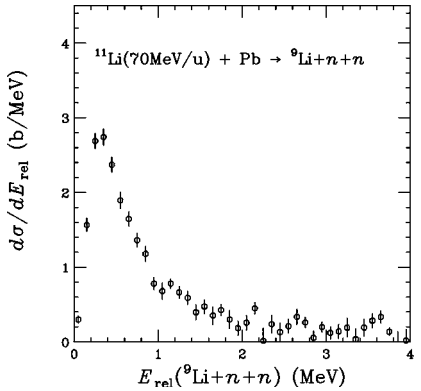
Examine Different Wall Events Condition: $\beta_1 \le \beta_{12}$ Almost no bias

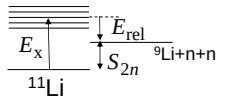


E_{th}=6MeVee to avoid any gamma related events



Coulomb Dissociation Spectrum of ^{11}Li

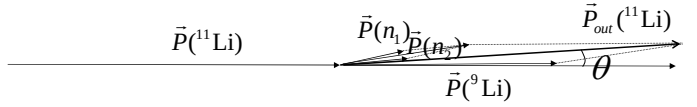


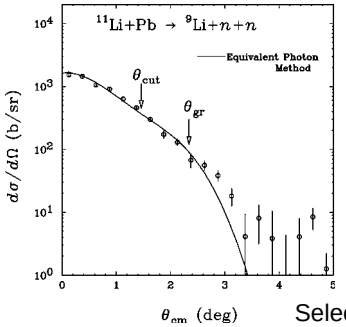


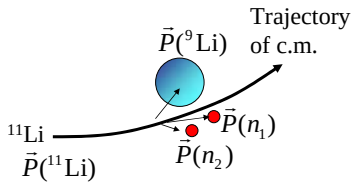
$\sigma = 2.34 \pm 0.05(stat.) \pm 0.28(syst.)$ b

for $E_{rel} \le 3$MeV

Angular Distribution



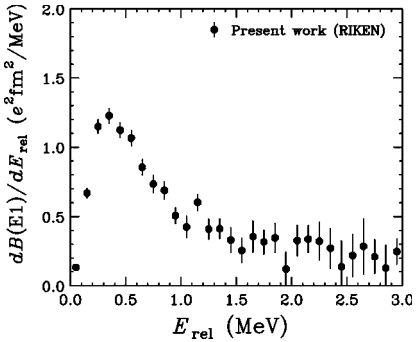




$$b = a\cot(\theta/2)$$

Selection of forward angles
--- Selection of large impact parameter

E1 Strength Distribution (Soft E1 Excitation of ^{11}Li)



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

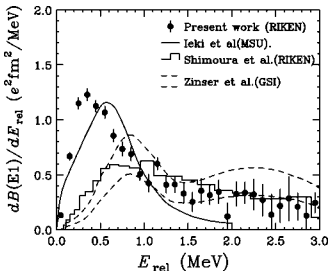
$$B(E1) = 1.42 \pm 0.18\ e^2\ fm^2$$

$E_{rel} \le 3$ MeV 4.5(6) W.u

$S_{2n} = 300 \pm 19$ keV

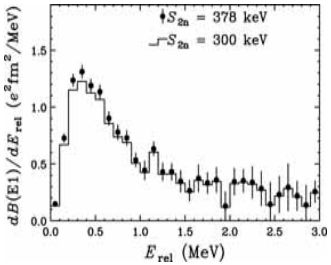
Experimental Results

TN et al. PRL96,252502(2006)



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

S_{2n}=300(19)keV →378(5)keV
C.Bachelet et al.,PRL100,182501(2008).
→E_x higher
→Smaller N(E1)
→ 6% larger B(E1) strength

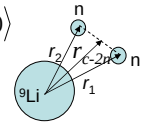


$B(E1) = 1.50 \pm 0.19\ e^2\ fm^2\ (E_{rel} \le 3\mathrm{MeV})$

Non-energy weighted E1 Cluster Sum Rule

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

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



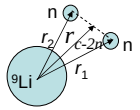
Assumption:
1. c.m. of ^{9}Li === c.m. of charge distribution
OK for 3body model with no E1-like core excitation
2. Closure relationship is met: Final states of E1 excitation are all allowed
------ There are some contributions to forbidden states

$B(E1) = 1.42 \pm 0.18\ e^2\ fm^2\ (E_{rel} \le 3\mathrm{MeV})$
→ $1.78(22)\ e^2\ fm^2$ (Extrapolated value)
→ $\sqrt{\langle r_{c-2n}\rangle^2} = 5.01 \pm 0.32$ fm

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

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

Comparison with 3-body theories-1

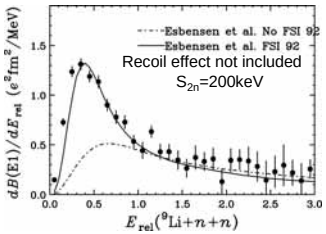


$$H(\vec{r}_1,\vec{r}_2) = T_1 + T_2 + V_{cn1}(r_1) + V_{cn2}(r_2) + v(\vec{r}_1,\vec{r}_2)$$

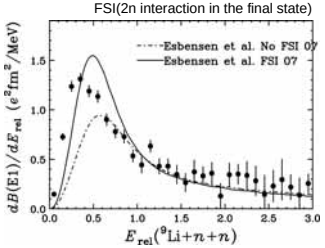
Model: S23 model(23%S)
Recoil efffect included
S_{2n}=295keV

$$H(\vec{r}_1,\vec{r}_2) = \frac{p_1^2}{2\mu_{cn}} + \frac{p_2^2}{2\mu_{cn}} + \frac{\vec{p}_1\cdot\vec{p}_2}{A_c m} + V_{cn1}(r_1) + V_{cn2}(r_2) + v(\vec{r}_1,\vec{r}_2)$$

FSI(2n interaction in the final state)



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



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

c.f. Cluster sum rule $\sqrt{\langle r_{c-2n}\rangle^2} = 5.01 \pm 0.32$ fm

$\sqrt{\langle r_{c-2n}\rangle^2} = 5.22$ fm

Note:

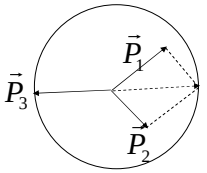
3body Hamiltonian in general

$$H(\vec{r}_1,\vec{r}_2) = T_1 + T_2 + T_3 + V_{12}(r_{12}) + V_{13}(r_{13}) + V_{23}(r_{23})$$

$$T_1 + T_2 + T_3 = \frac{p_1^2}{2m_1} + \frac{p_2^2}{2m_2} + \frac{p_3^2}{2m_3}$$

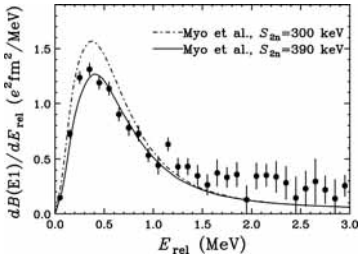
$$= \frac{p_1^2}{2m_1} + \frac{p_2^2}{2m_2} + \frac{(\vec{p}_1+\vec{p}_2)^2}{2m_3}$$

$$= \frac{p_1^2}{2\mu_{13}} + \frac{p_2^2}{2\mu_{23}} + \frac{\vec{p}_1\cdot\vec{p}_2}{m_3}$$



Momenta in the rest frame of the 3-body c.m.

Comparison with theories-2



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

Core polarization
(Tensor correlation+
Pauli Principle)

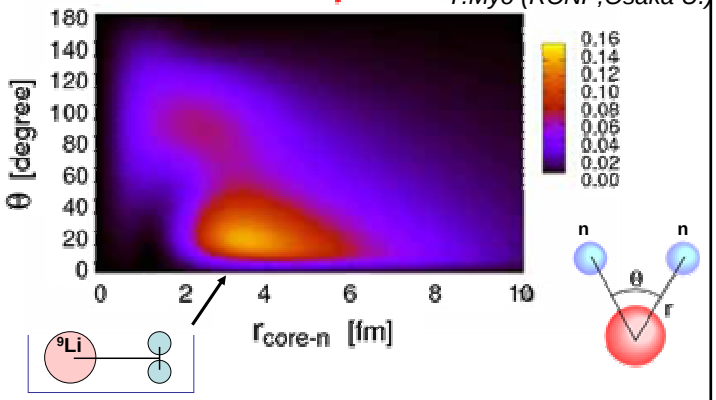
P(S^2)~ 40%

$\sqrt{\langle r_{c-2n}\rangle^2} = 5.69$ fm

2n correlation density in ^{11}Li

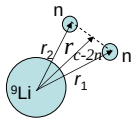
2n density in ^{11}Li

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



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

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).

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

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

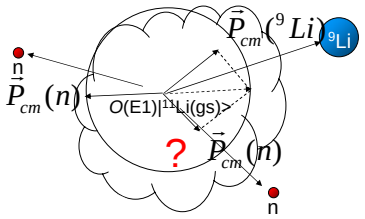
If full overlap $(1s)^2$ & $(0p)^2$ $\Rightarrow$ $\left\langle\cos\theta_{12}\right\rangle = 1/\sqrt{3}, \quad \left\langle\theta_{12}\right\rangle = 55^\circ$

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

$\left\langle\theta_{12}\right\rangle = 48^{+14}_{-18}$ deg Mixture of different parity states is essential !

Mixture of higher L orbitals→ More correlated

Details of Three body decay

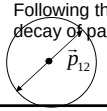


In the rest frame of ^{11}Li, it decays in a specific plane, keeping the following relation;

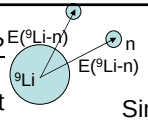
$$E_{rel}(3body) \equiv \varepsilon = \frac{P_1^2}{2m_1} + \frac{P_2^2}{2m_2} + \frac{P_3^2}{2m_3} = \varepsilon_{12-3} + \varepsilon_{12}$$

$$\varepsilon_{12-3} = \frac{P_3^2}{2\mu_{12-3}}, \quad \varepsilon_{12} = \frac{p_{12}^2}{2\mu_{12}}$$

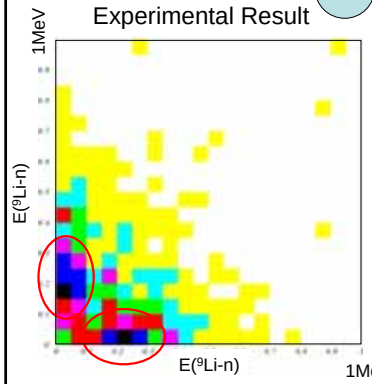
Following the decay of particle 3



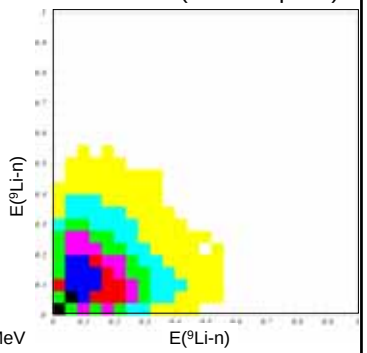
Further Correlation?



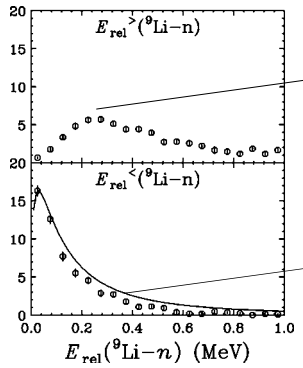
Experimental Result



Simulation (Phase Space)



preliminary

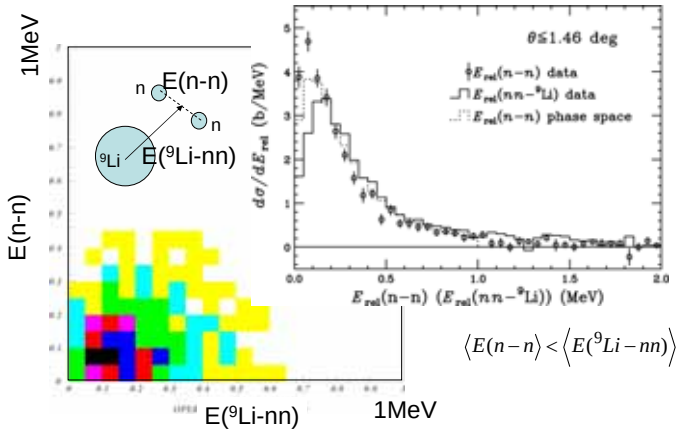


p-wave?

^{10}Li s-wave Virtual state Obataind from ^{11}Li+C→^{9}Li+n spectrum

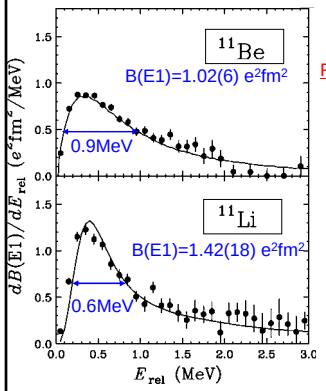
$$\left|\Phi(^{11}\mathrm{Li}_{gs})\right\rangle = \alpha\left|\Phi(^9\mathrm{Li}_{gs})\otimes(s_{1/2})^2\right\rangle + \beta\left|\Phi(^9\mathrm{Li}_{gs})\otimes(p_{1/2})^2\right\rangle + \ldots$$

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



preliminary

Soft E1 Excitation : ^{11}Be vs. ^{11}Li



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

For ^{11}Be

$$\frac{9}{4\pi}\frac{\hbar^2 e^2}{2m}\left(\frac{NZ}{A}-\frac{N_c Z_c}{A_c}\right)=2.18\ e^2\mathrm{fm}^2\mathrm{MeV}$$

Experiment (E_{rel}<3 MeV) $1.39 \pm 0.18\ e^2\mathrm{fm}^2\mathrm{MeV}$ 64(10) %

For ^{11}Li

$$\frac{9}{4\pi}\frac{\hbar^2 e^2}{2m}\left(\frac{NZ}{A}-\frac{N_c Z_c}{A_c}\right)=2.72\ e^2\mathrm{fm}^2\mathrm{MeV}$$

Experiment (E_{rel}<3MeV) $1.95 \pm 0.27\ e^2\mathrm{fm}^2\mathrm{MeV}$ 72(12) %

Summary of Topics 2 : Coulomb breakup of two-neutron halo nucleus

- 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) e²fm² ^{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 dimensional Plot
  → Strong Correlations
  Peaks at E(^{10}LI)= ~0MeV, and 0.25MeV

Recent Experimental Achievements for ^{11}Li

- New Coulomb breakup Measurement (Precise E1 Strength)
  T.Nakamura et al.,PRL96,252502(2006).
- Charge Radius
  R.Sanchez et al., PRL96,033002 (2006).
- Precise Mass Measurement
  C. Bachelet et al., PRL100, 182501 (2008).
- ^{1}H(^{11}Li,^{9}Li)^{3}H
  I. Tanihata et al., PRL100, 192502 (2008).

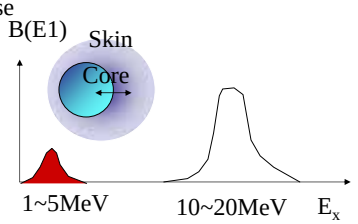
We can now discuss the 3-body structure of ^{11}Li: But not yet satisfactory!

^{6}He Puzzle

Perspectives
-- Invariant mass spectroscopy
at RIKEN RI-beam factory (RIBF)

Coulomb breakup of Neutron-Skin/halo Nuclei

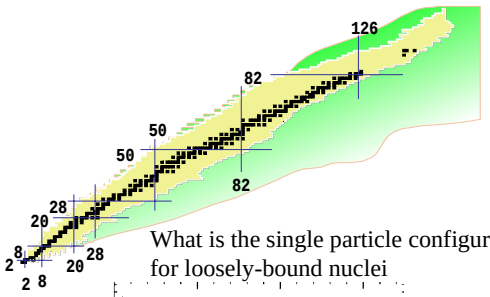
E1 Response



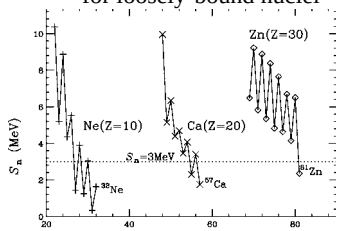
Pigmy/Soft Resonance in Neutron skin/Halo

Continuum spectrum— ground state nature
(single particle, neutron-neutron correlation)

Dineutron correlation in dilute system



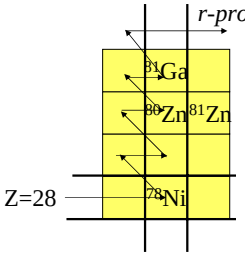
What is the single particle configuration
for loosely-bound nuclei



Single Particle State

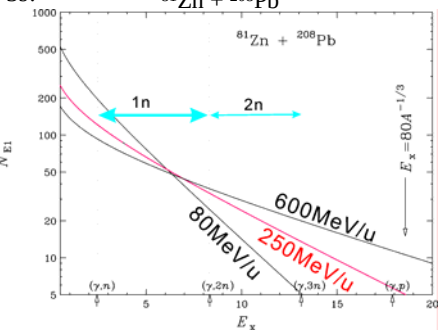
c.f.
Coulomb Dissociation of ^{19}C
T.Nakamura et al., PRL**83**,1112(1999).

r-process?

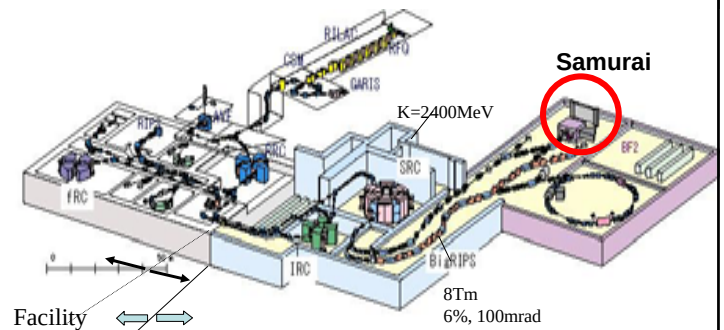


3s?

Non-resonant Soft Excitation
Spin-parity, Spectroscopic factor for g.s.
~100ions/second
^{81}Zn + ^{208}Pb



RIBF
(RIKEN RI Beam Factory)

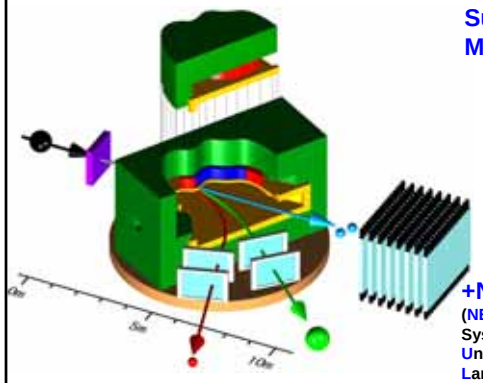


Completed in 2007
World Largest RI-beam facility

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~10MEuro*



Superconducting Magnet

To let neutron(s) pass through the gap

Sweep Beam and Charged Fragments

Good Mass Resolution for PID @ A~100

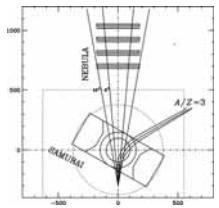
+NEBULA
(NEutron Detection System for Breakup of Unstable Nuclei with Large Acceptance)

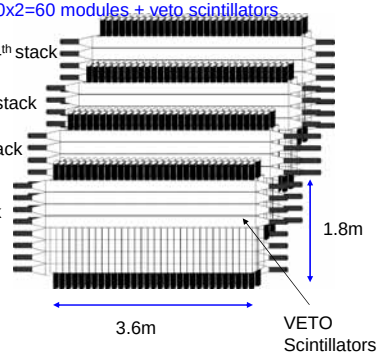
Bending Power
BL=7Tm (B=3Tesla, 60deg bending)

NEBULA

NEutron-detection system for **B**reakup of **U**nstable-Nuclei with **L**arge **A**cceptance

Typical Setup 1module: 12cm(H)x180cm(H)x12cm(D) plastic scintillator coupled to 2 PMT's
1stack: 30x2=60 modules + veto scintillators





Features of NEBULA

- Large acceptance
- Good energy resolution
- Multi-neutron detection
- Flexibility of setup configuration

Summary of the Lecture

Takashi Nakamura

- Invariant mass spectroscopy :
  Useful and Powerful tool to explore HALO structures

- Coulomb Breakup: Huge strength of Soft E1 Excitation
  Spectrum→ Single-particle nature for one-neutron halo
  nn correlation, 3body nature for two-neutron halo

- Invariant Mass Spectroscopy is a "MUST
  for RIBF and other future facilities
  → SAMURAI+NEBULA at RIBF

Drip-line nulcei, Loosely-Bound nulcei
-----Single particle states, Collective States, pairing, dineutron correlation

R301n Collaborators: (Coulomb Breakup of ^{11}Li)

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