Coulomb Breakup of Neutron Drip-line Nuclei at SAMURAI

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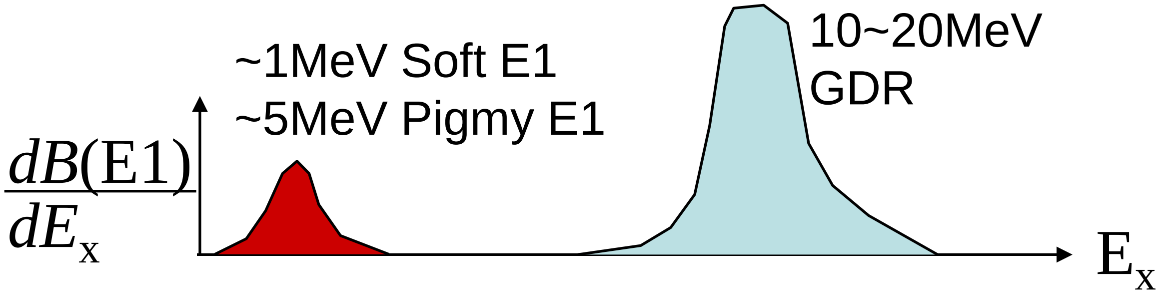
SAMURAI Workshop, Mar.2011

Introduction

Enhancement of E1 Strength at Low Excitation Energies



Unique properties
for Neutron Halo/Skin Nuclei

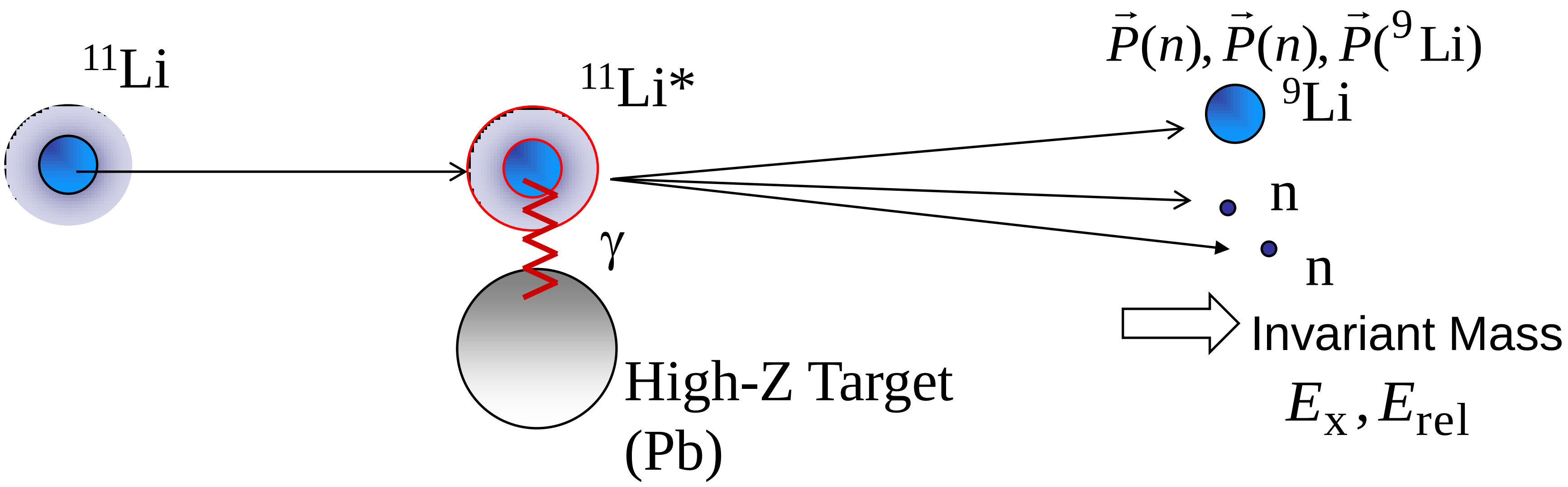
- **Soft Dipole Excitation**

  —Strong E1 transitions due to Halo Structure

- Pigmy Dipole Resonance

  —Collective Motion in Neutron Skin Nuclei→T.Kobayashi

Coulomb Breakup



^{11}Li

^{11}Li*

γ

High-Z Target (Pb)

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

^{9}Li

n

n

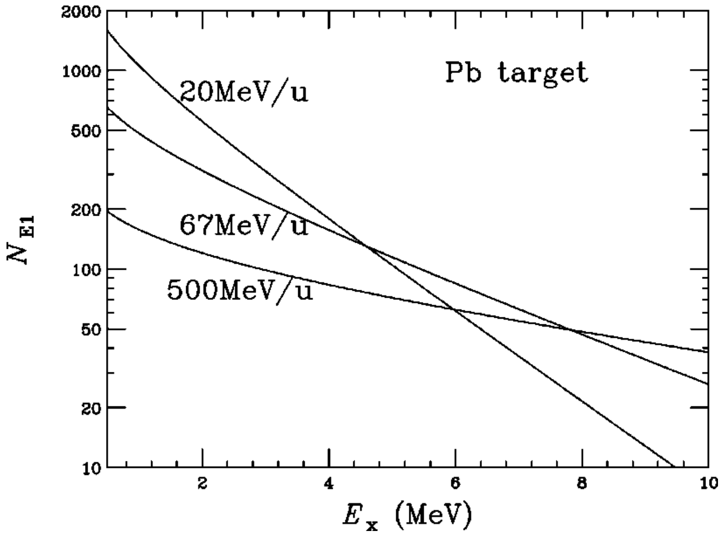
⇨ Invariant Mass

E_x, E_{rel}

Equivalent Photon Method

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

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

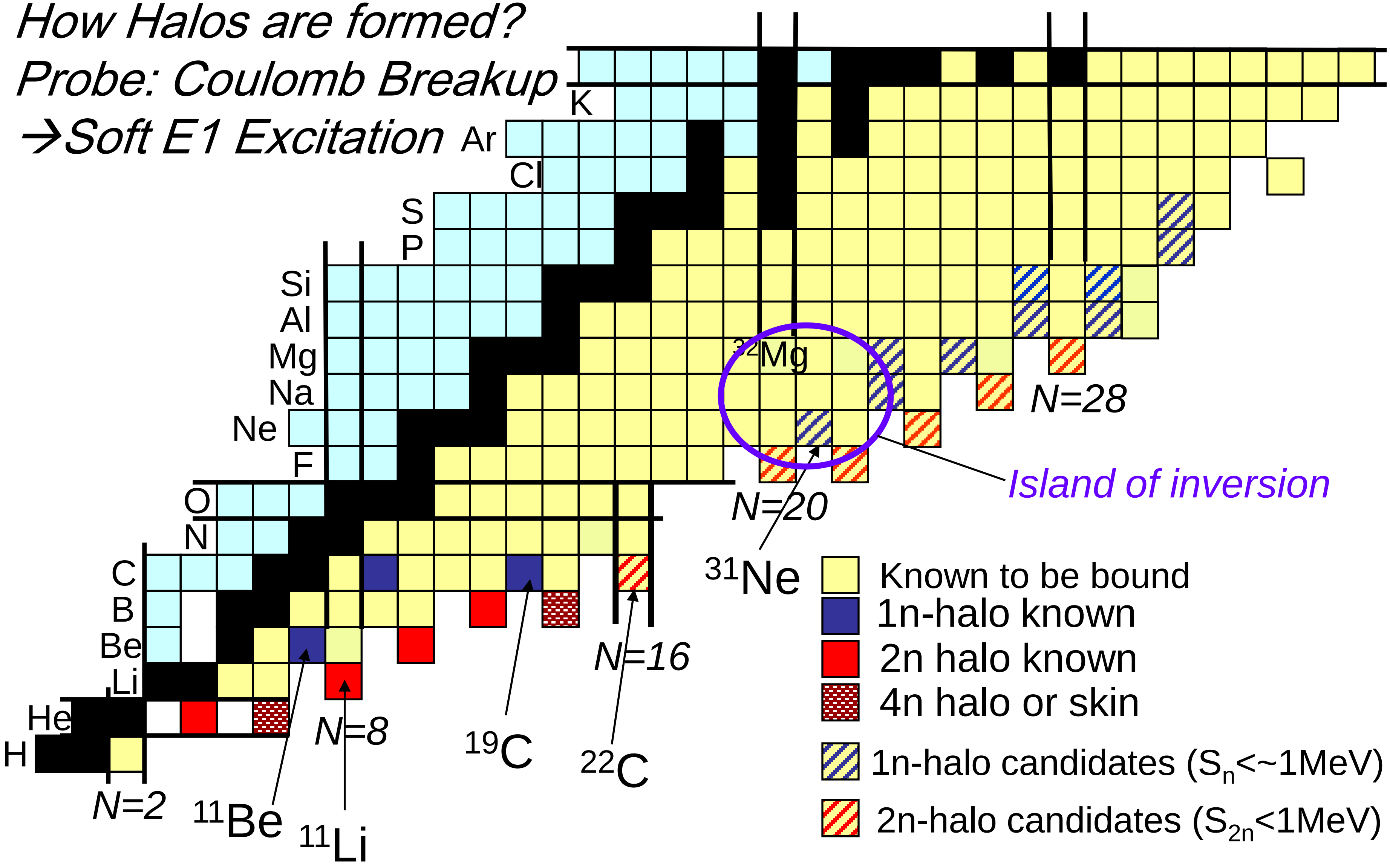


How neutron-drip line looks like towards heavier nuclei?

How Halos are formed?

Probe: Coulomb Breakup

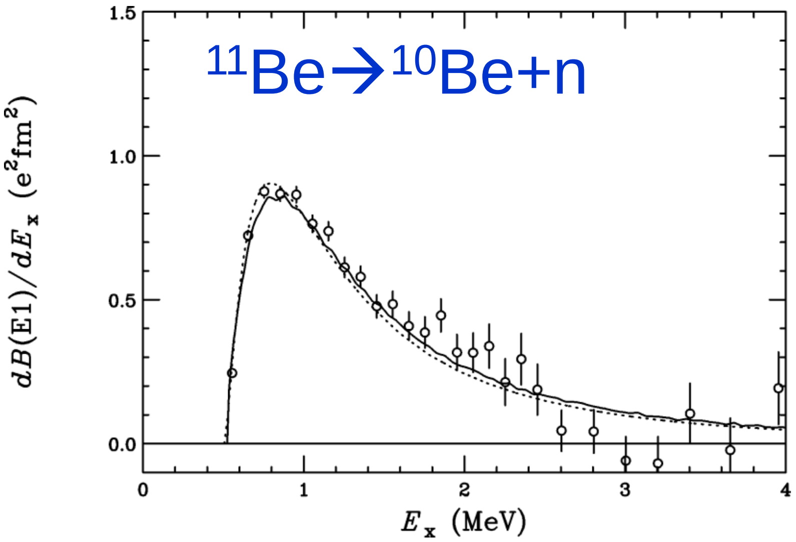
→Soft E1 Excitation



- 🟨 Known to be bound
- 🟦 1n-halo known
- 🟥 2n halo known
- ▦ 4n halo or skin
- ▨ 1n-halo candidates (S_n<~1MeV)
- ▨ 2n-halo candidates (S_{2n}<1MeV)

N.B. S_n,S_{2n}: Estimated value by Audi & Wapstra (Jurado et al.(PLB649,43(2007)), incorporated)

Soft E1 Excitation—1n Halo Nucleus

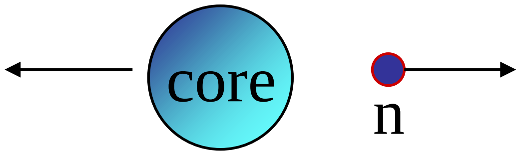


Huge Cross Section & B(E1)

B(E1)=1.05(6) e^2fm^2 = 3.29(19) W.u. (Erel<4MeV)
σ=1.51(9) barn (Erel<5MeV) @72MeV/nucleon

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

Direct Breakup Mechanism



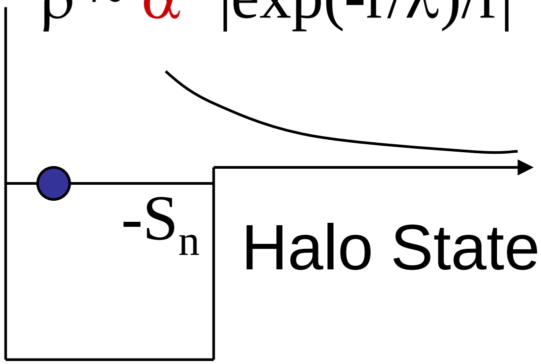
E1 Strength

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

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

Fourier Transform

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

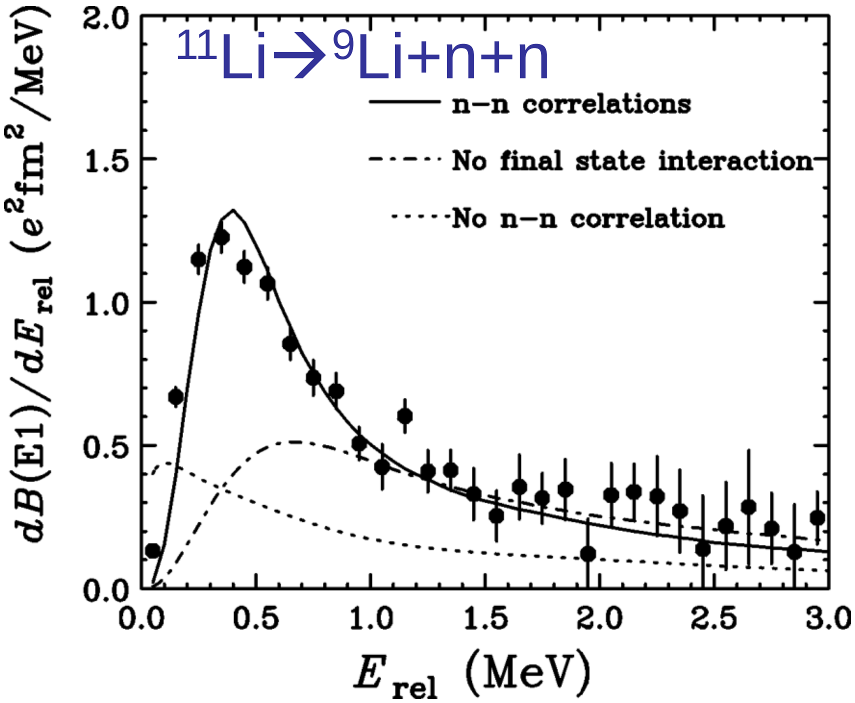


Halo State

→Spectroscopic Factor & Angular Momentum of Valence Neutron

c.f. ^{19}C, T.N *et al*., PRL 83, 1112 (1999).

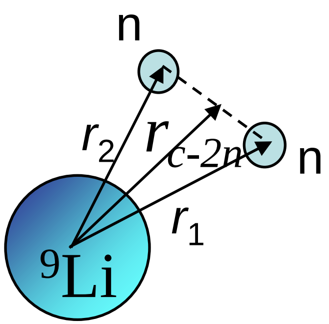
Soft E1 Excitation—2n Halo Nucleus



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

Even Larger Cross Section & B(E1)

B(E1)=1.42(18) e^2fm^2 = 4.5(6) W.u. (Erel<3MeV)
σ=2.34(28) barn @70MeV/nucleon



Non-energy Cluster Sum Rule H.Esbensen and G.F.Bertsch, NPA542, 310 (1992)

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

$$\left\langle\theta_{12}\right\rangle=48^{+14}_{-18}\,\mathrm{deg}$$ **<90deg**

→Neutron-Neutron Spatial Correlation

1n halo nuclei

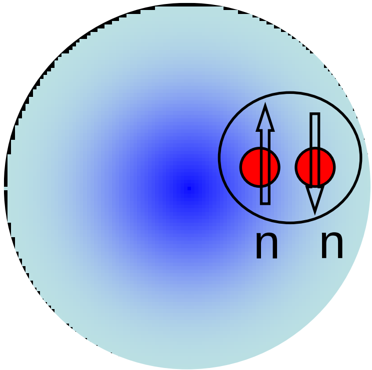
- Low S_n value (<~1MeV)
- Dominance of s or p orbital for the valence neutron

For 20<N<28→ valence neutron: $f_{7/2}$
Conventional Shell order forbids the formation of halo

Shell-melting, Deformation →Halo formation?

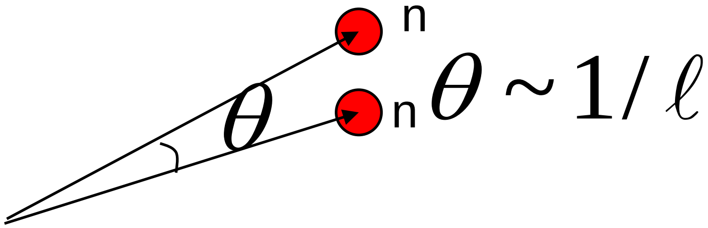
2n halo nuclei

In addition to low S_n and low L,
Dineutron-like correlation--- (mixing of L)



Di-neutron correlation
(short-range)
@Weak-binding
Low-density

A.B.Migdal
Sov.J.Nucl.Phys.238(1973).
M.Matsuo, PRC73,044309(2006).



$\theta \sim 1/\ell$

^{11}Li p & s mixing
^{22}C s & d and more?

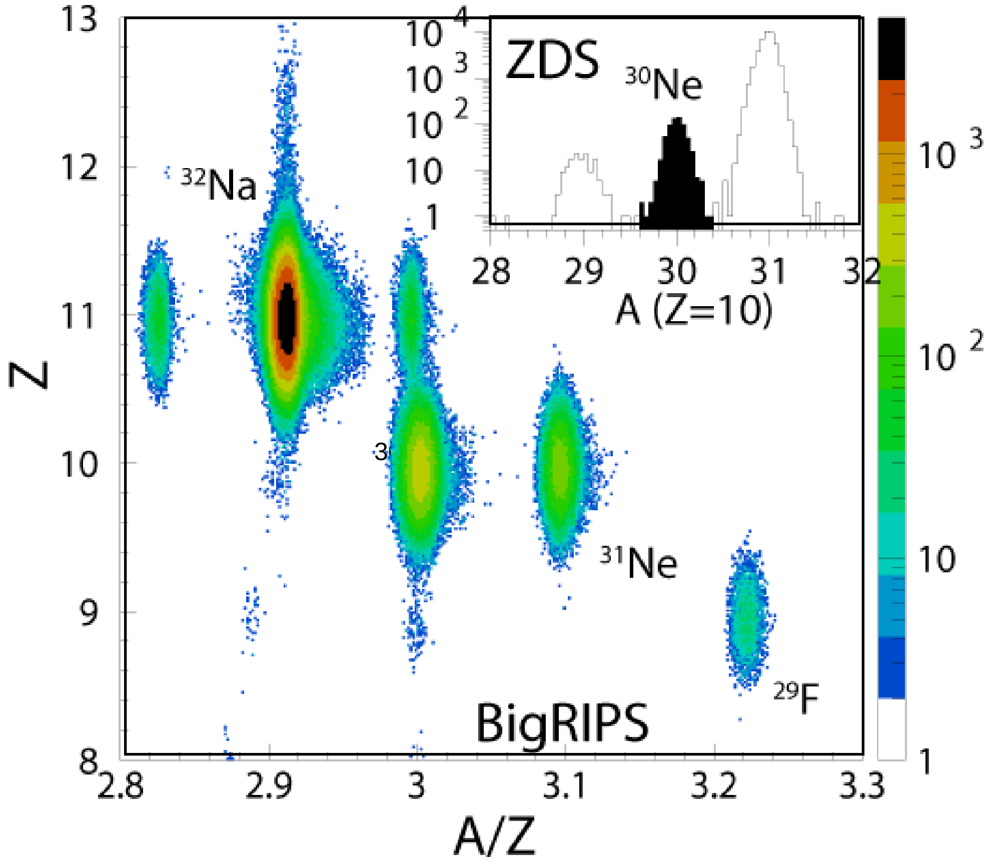
Dineutron correlation is enhanced?

“Inclusive” Coulomb Breakup (Day1Dec.2008)

^{31}Ne+Pb→^{30}Ne+X @230MeV/nucleon PRL

^{22}C+Pb→^{20}C+X @240MeV/nucleon

^{29}Ne,^{33,35,37}Mg,^{39,41}Si (Nov.2010)



T. Nakamura, N.Kobayashi, Y.Kondo,
Phys.Rev.Lett.103,262501(2009).

RI beam Intensity @RIBF

~10^{3}-10^{4} times/RIPS

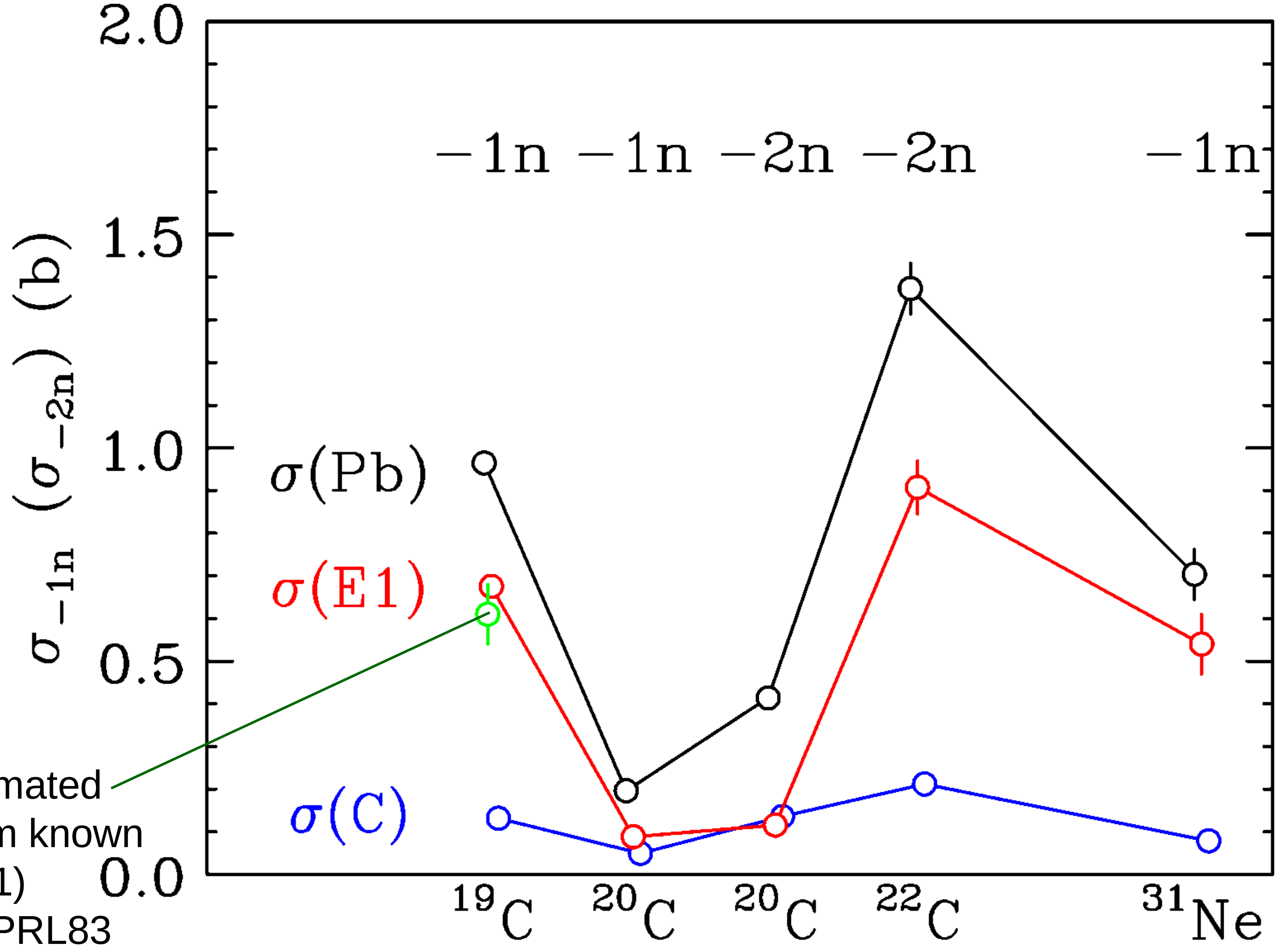
^{31}Ne ~5 counts/s
^{22}C ~ 6 counts/s
From ^{48}Ca @345MeV (60-80pnA)
→ ~200pnA (2010)

c.f. *About 10years ago…*
^{31}Ne -- 4 counts/day @RIPS

H.Sakurai et al.,
PRC54,2802R(1996).

1n(or 2n) removal cross section

→Coulomb breakup cross section



Estimated
From known
B(E1)
TN.PRL83
1112(1999).

S_n(MeV)=0.58(9) 2.93(28) S_n=0.29(1.64)

S_{2n}(MeV)=3.51(24) 0.41(93)

Evidence for

2n Halo in ^{22}C

1n Halo in ^{31}Ne

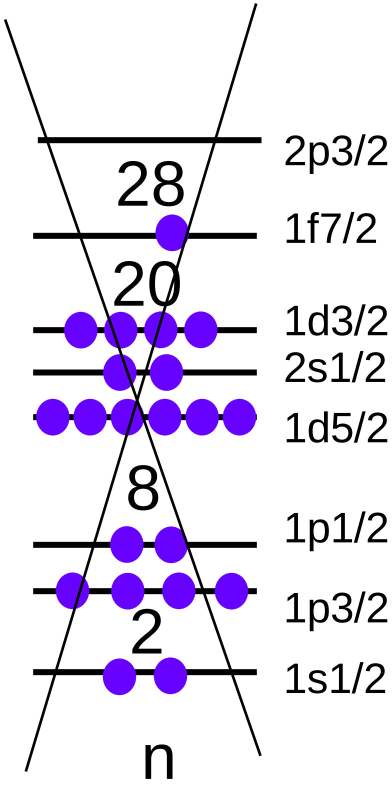
c.f.

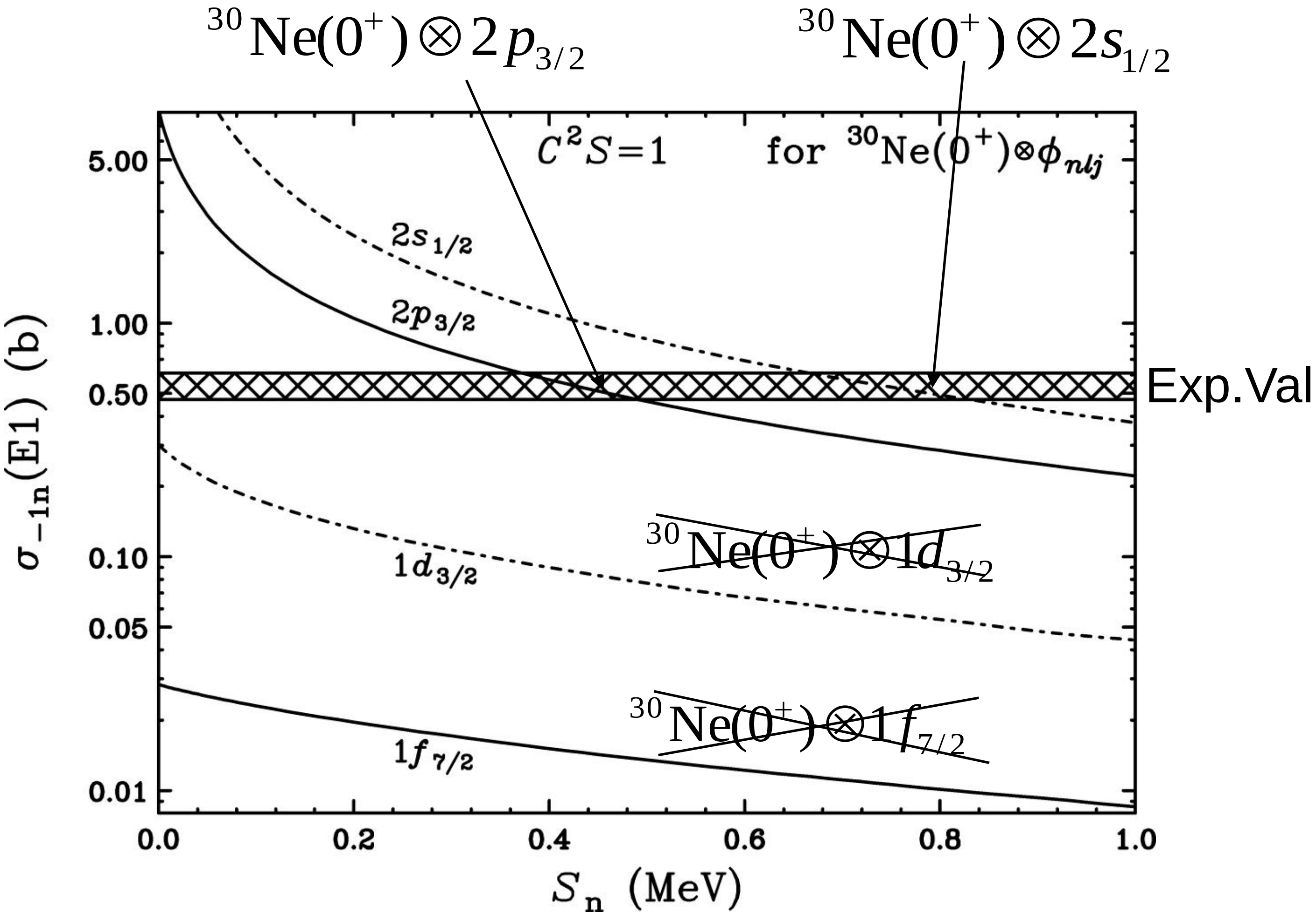
^{19}C (known halo)

$$\sigma(E1) = \sigma(Pb) - \Gamma\sigma(C)$$

$$\Gamma = \sim 1.7 - 2.6$$

^{31}Ne (N=21)

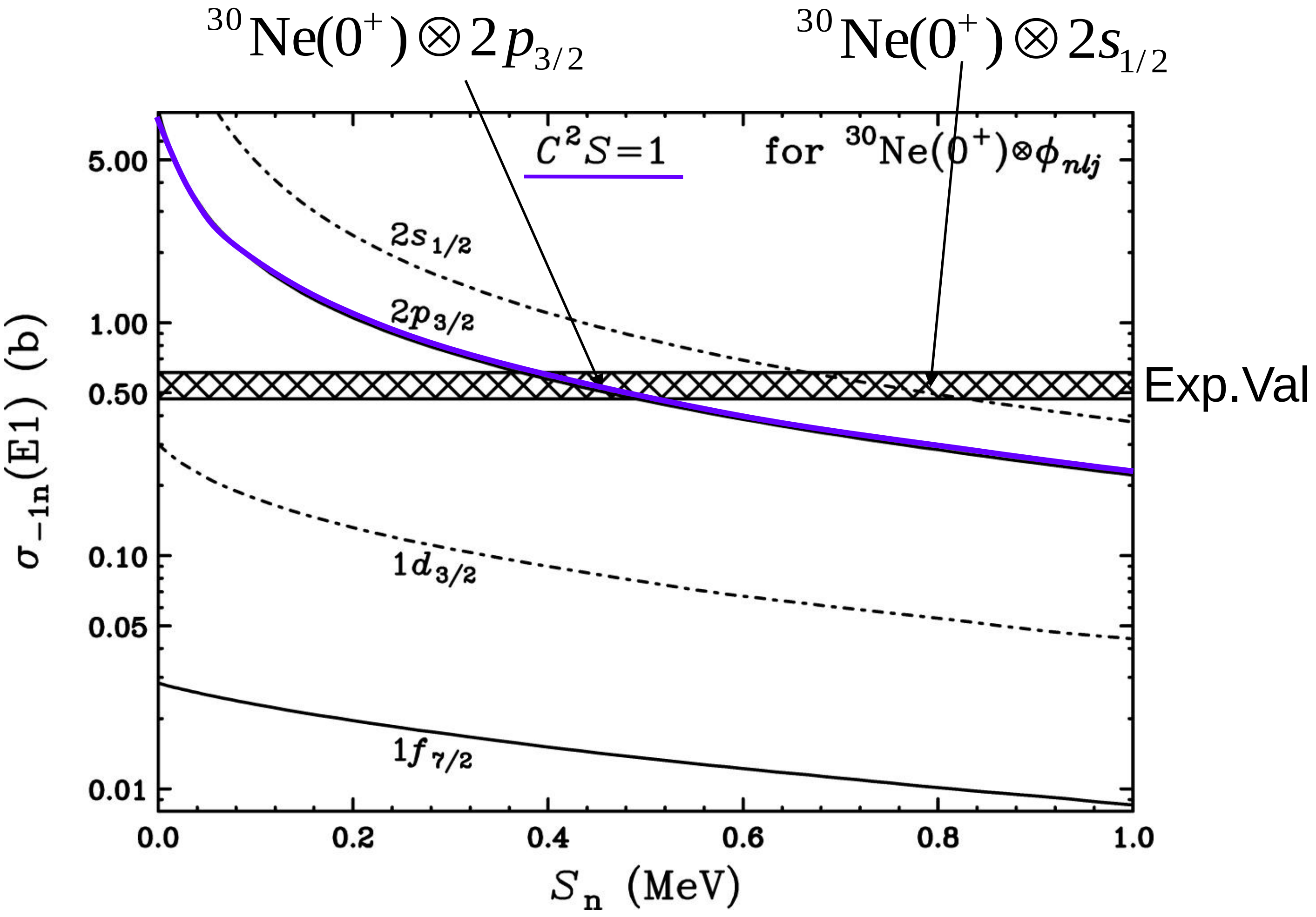




$2p_{3/2}$ or $2s_{1/2}$ Low-L orbits dominant 1n-halo structure of ^{31}Ne

^{30}Ne(0$^+$)X1$f_{7/2}$ dominance excluded →Shell gaps(20,28) vanish

This is not the end of the story…



Deformation---Strong Configuration Mixing $C^2S<1$

S_n– Basically Not Known! (Sn<0.4MeV for p config.)

Particle Rotor? (I.Hamamoto, Hagino, Private Comm.)

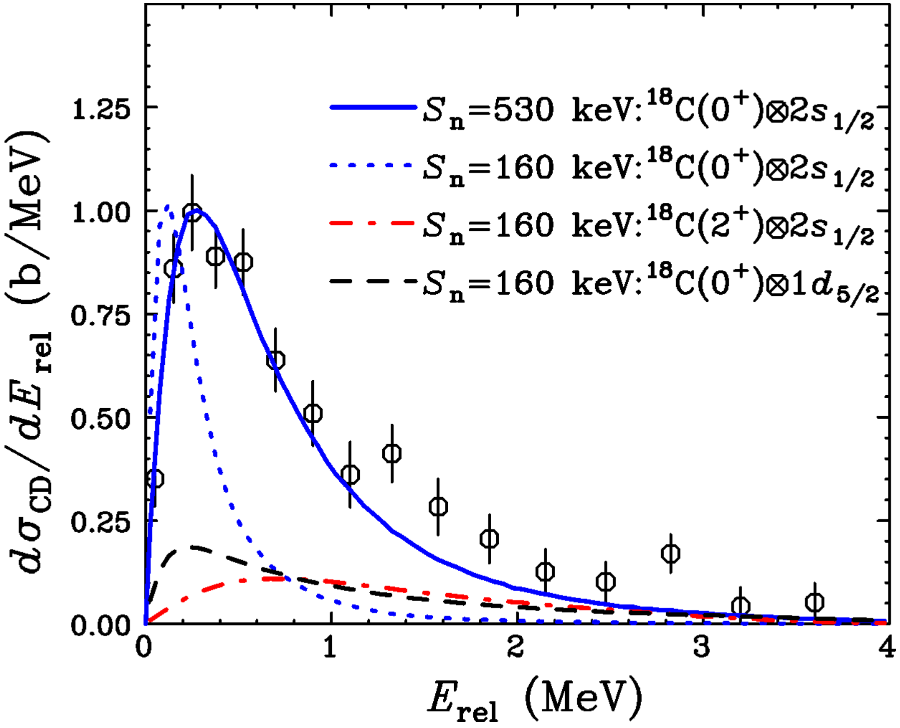
Coulomb Breakup of (1n+core)-system

Shape & Strength of B(E1) spectrum

⇒ S_n, ℓ , Spectroscopic factor

s, p → Halo, peak at low E_{rel}

^{19}C Coulomb breakup



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

^{19}C(g.s)

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

2$s_{1/2}$ dominant

$C^2S(s_{1/2})$=0.67

S_n=530keV

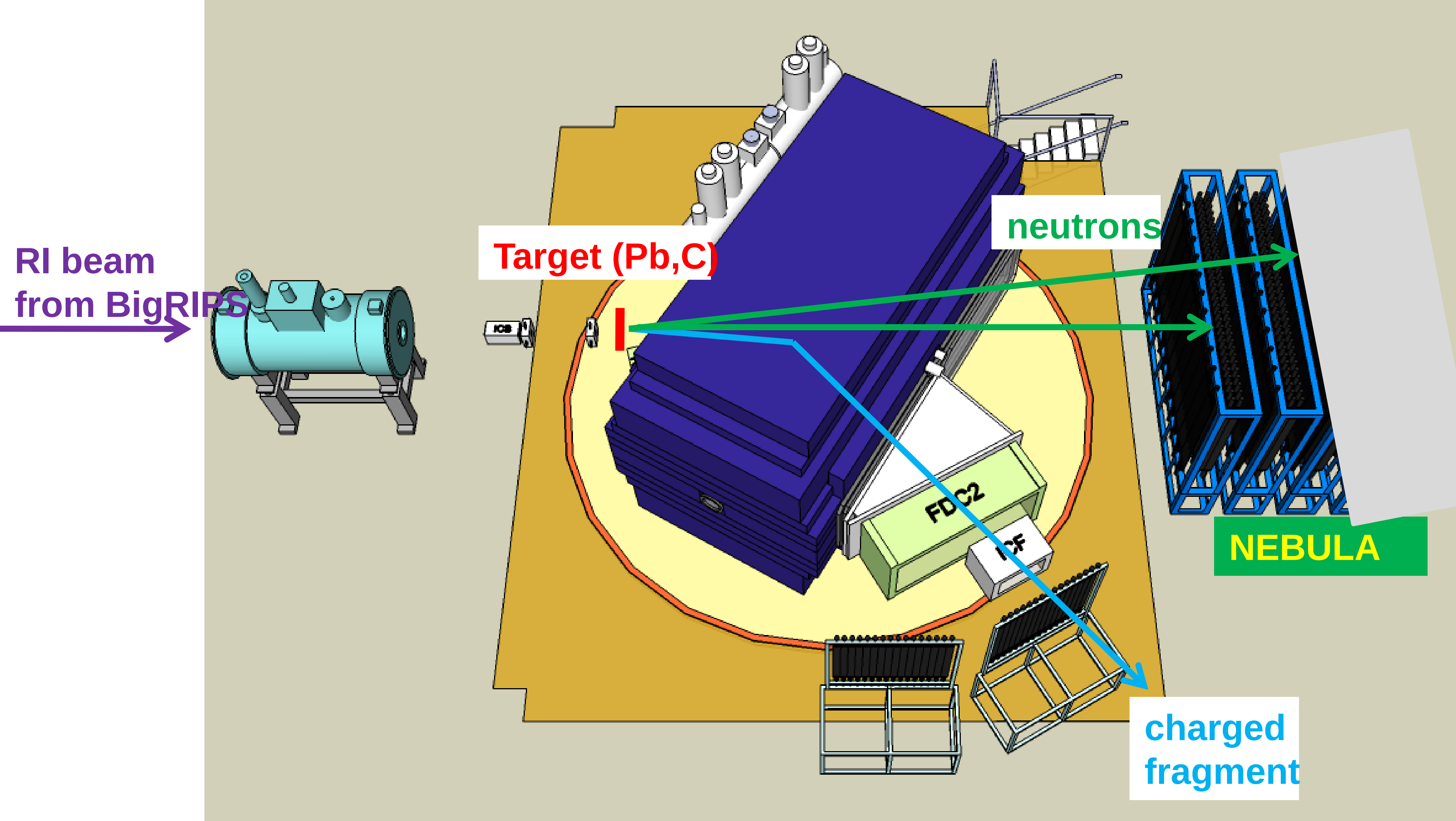
Exclusive Coulomb Breakup of ^{19}B, ^{22}C and ^{31}Ne (if possible other neutron drip line nuclei ^{35,37}Mg,^{41}Si). as a Day-1 experiment of SAMURAI/NEBULA

•Could be symbolic experiments for "Heavy Halo"
^{31}Ne, ^{22}C: Inclusive measurements done
Halo Structures have been suggested (but microscopically not at all known so far)
→ Physics results have impacts!

•Suitable for check the SAMURAI system(except for heavy frag.)
Neutron detectors for 1n decay channel (^{31}Ne,^{35,37}Mg,^{41}Si)
and for 2n decay channel (^{19}B,^{22}C)
\+ Basic functions of beam and fragment detectors.

Important at the early stage of SAMURAI/NEBULA!

Setup



RI beam
from BigRIPS

Target (Pb,C)

neutrons

NEBULA

charged
fragment

Yield Estimation

	Intensity(cps)	E/A	Channel	Yield C(cph)	Yield Pb(cph)
^{19}B	20	240.	^{17}B+2n	80	68
^{22}C	20	240.	^{20}C+2n	160	93
^{31}Ne	20	240.	^{30}Ne+n	200	160

200pnA ^{48}Ca beam at 345MeV/nuc
2ndary Targets: C(2g/cm^2),Pb(3g/cm^2)
σ(^{22}C+C)=210mb, σ(^{22}C+Pb)=1.4b (measured)
σ(^{31}Ne+C)=80mb, σ(^{31}Ne+Pb)=0.7b (measured)
σ(^{19}B+C)= 100mb, σ(^{19}B+Pb)=1b (assumed)

	Channel	C(days)	Pb(days)	Emp(days)	Total (days)
^{19}B	^{17}B+2n	2.6	3.1	0.8	6.5
^{22}C	^{20}C+2n	1.3	2.3	0.4	4.0
^{31}Ne	^{30}Ne+n	1.0	1.3	0.3	2.6
Calibration/Tuning					1.9
					15.0 days

5000 events/one setting

We would like to submit
a proposal to RIBF PAC in
summer 2011.

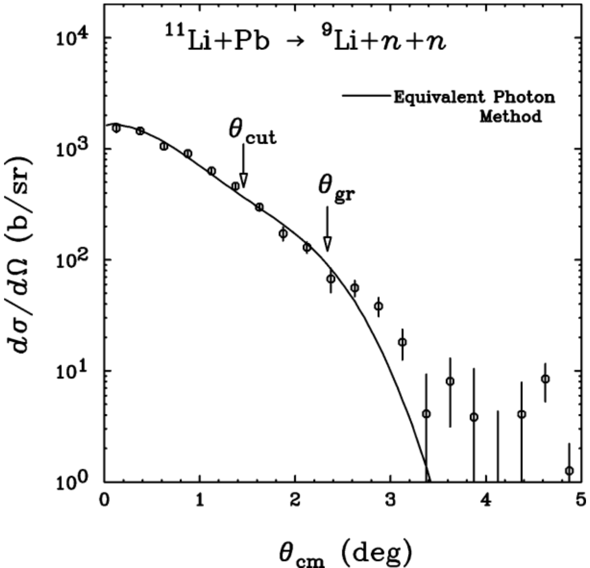
How to extract physics observables (B(E1) spectrum)

- **Method 1: Subtract nuclear contribution estimated from the breakup with C taget**

$$\frac{d\sigma(E1)}{dE_x} = \frac{d\sigma(Pb)}{dE_x} - \Gamma \frac{d\sigma(C)}{dE_x} \qquad \Gamma = \sim 1.7 - 2.6$$

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

- **Method 2:Use of Angular distribution**

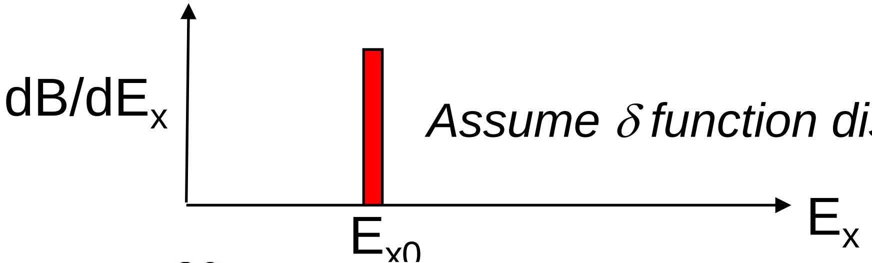


Angular resolution sufficient?

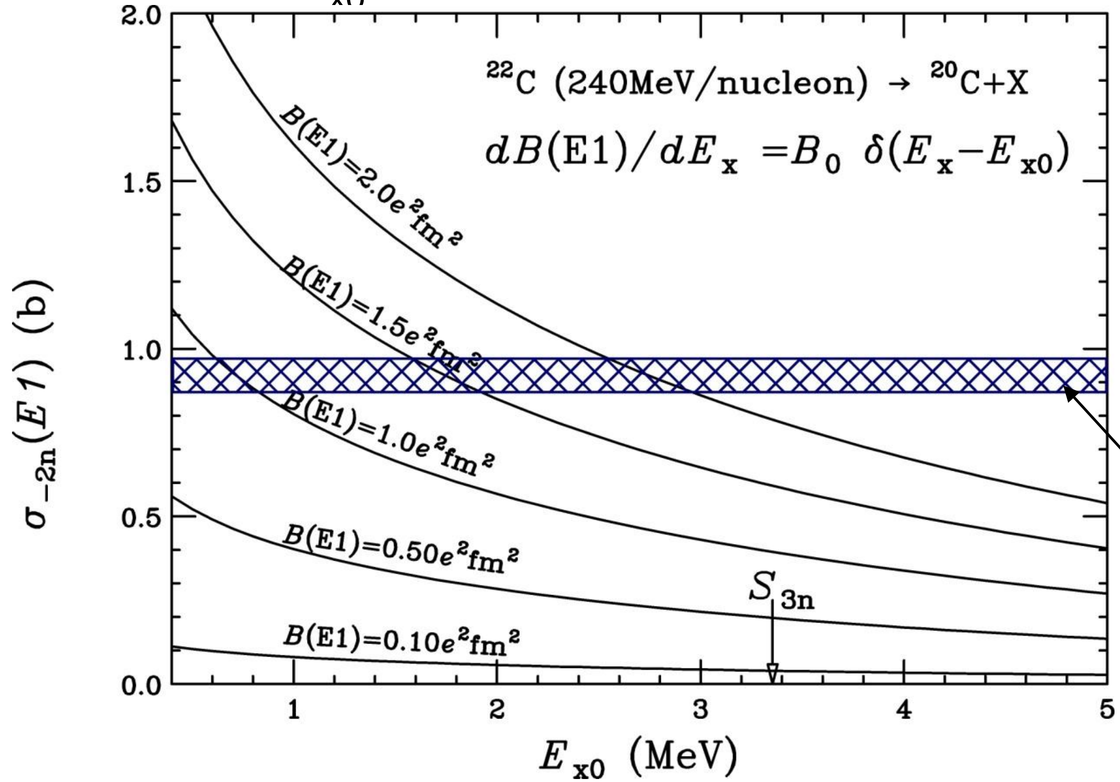
θ_{gr}=0.84 deg (^{22}C+Pb, 240MeV/n)
($\Delta\theta$(mul)=0.34 deg)
θ_{gr}=0.99 deg (^{31}Ne+Pb, 240MeV/n)
($\Delta\theta$(mul)=0.40 deg)

Inclusive Coulomb Breakup of ^{22}C and B(E1)

-*Possible Prominent 2n-Halo above ^{11}Li (c.f. K.Tanaka et al., PRL 104, 062701(2010))*



Assume δ function distribution for B(E1)



B(E1)~ 1-2e^{2}fm^2

σ(E1)=0.92(5) barn

→Strong Soft E1 Excitation as in ^{11}Li … But

This is not final since this is based on "inclusive" measurement.

Estimation of required duration of empty-target runs

- α : Yield(beam) for empty run/ that for in-target run

$$\alpha = \frac{N_{beam}(Empty)}{N_{beam}(Target)} \approx \frac{T_{beam}(Empty)}{T_{beam}(Target)}$$

Yield of events and
its statistical uncertainty

$$N_{sg} - \frac{N_{bg}}{\alpha} \pm \sqrt{N_{sg} + \frac{N_{bg}}{\alpha^2}}$$

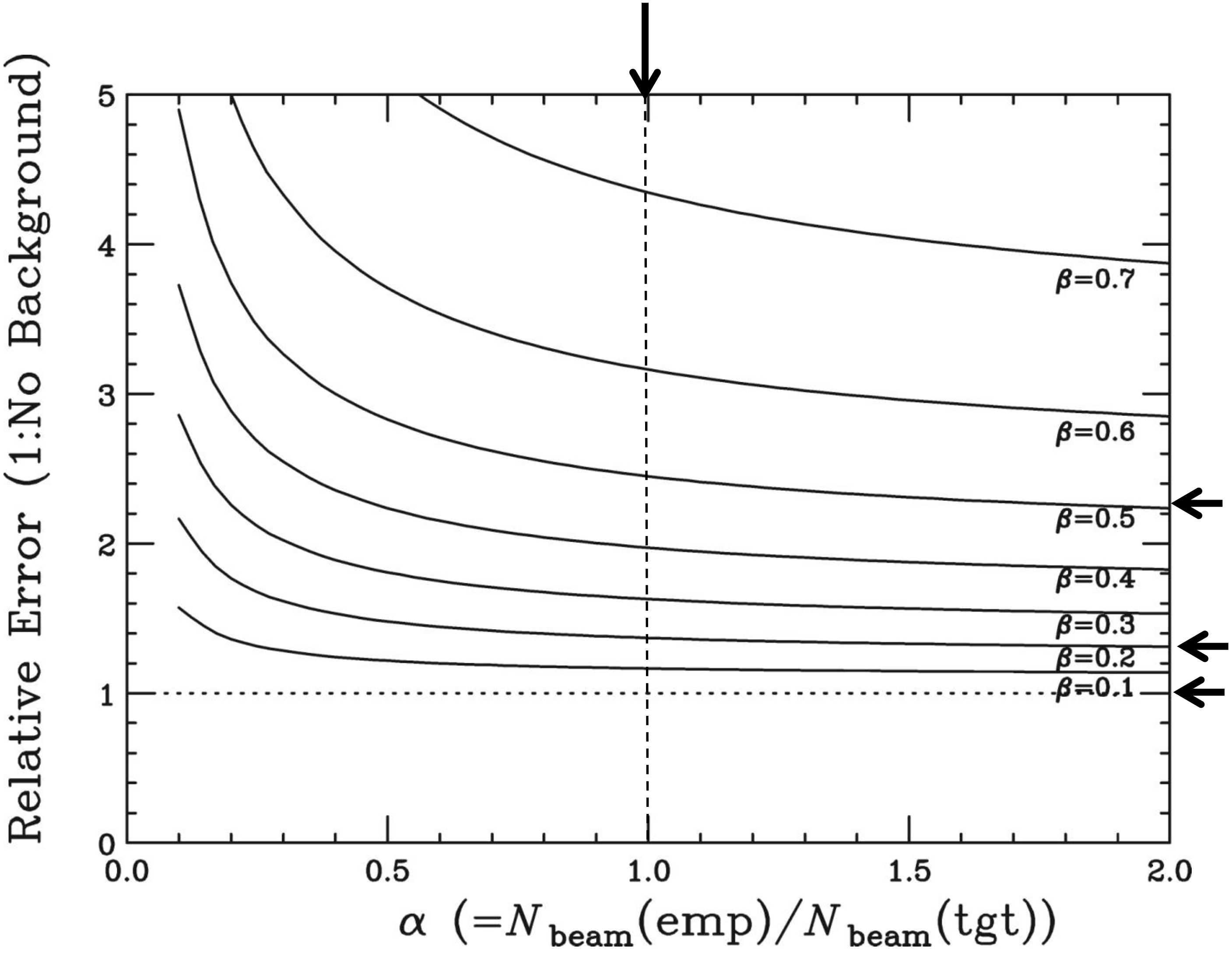
- β :inverse of S/N ratio

$$\left(\frac{N_{bg}}{\alpha}\right) = N_{bg}(for\ \ N_{beam}(target)) = \beta N_{sg}$$

- Relative statistical uncertainty:

$$\frac{\sqrt{N_{sg} + \frac{N_{bg}}{\alpha^2}}}{N_{sg} - \frac{N_{bg}}{\alpha}} = \frac{\sqrt{N_{sg}}}{N_{sg}} \frac{\sqrt{1 + \frac{\beta}{\alpha}}}{(1-\beta)}$$

$N_{beam}(emp)=N_{beam}(tgt)$



N/S=50%

N/S=20%

N/S=0%

$$dB(E1; i \to f)/dE_{rel} \propto \left|\langle f|r|i\rangle\right|^2$$

Plane wave approximation

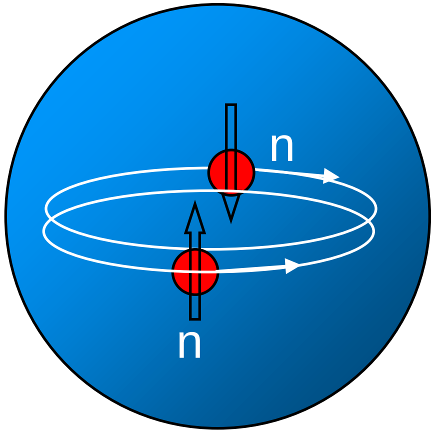
$\ell_i \to \ell_f$	$dB(E1)/dE \propto E_{rel}^{\ell_c+1/2} (E_{rel} \sim 0)$	$dB(E1)/dE\_\max at$
$s \to p$	$\propto E_{rel}^{3/2}$	$E_{rel} = 3/5(S_n)$
$p \to s$	$\propto E_{rel}^{1/2}$	$E_{rel} \approx 0.18 S_n$
$p \to d$	$\propto E_{rel}^{5/2}$	$E_{rel} = 5/3(S_n)$
$d \to p$	$\propto E_{rel}^{3/2}$	$E_{rel} = 5/3(S_n)$

c.f. Lecture at Tokyo Tech by I.Hamamoto
Mar.2009

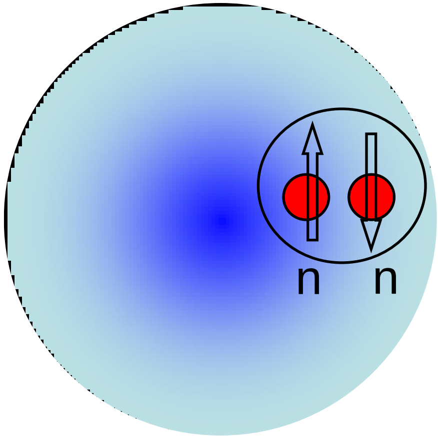
Exclusive Measurement is essential
to understand microscopically halo structure !

Dineutron in Halo?

A.B.Migdal predict strong-correlated dineutron system   Sov.J.Nucl.Phys.238(1973).

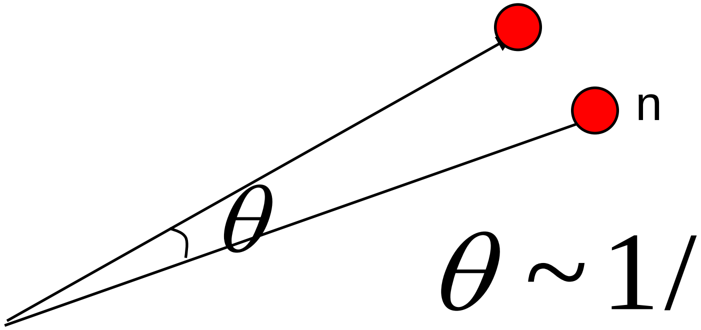


BCS-like Pairing
Correlation
(long range)



Di-neutron correlation
（short-range)
@Weak-binding
Low-density

M.Matsuo
PRC73,044309(2006).



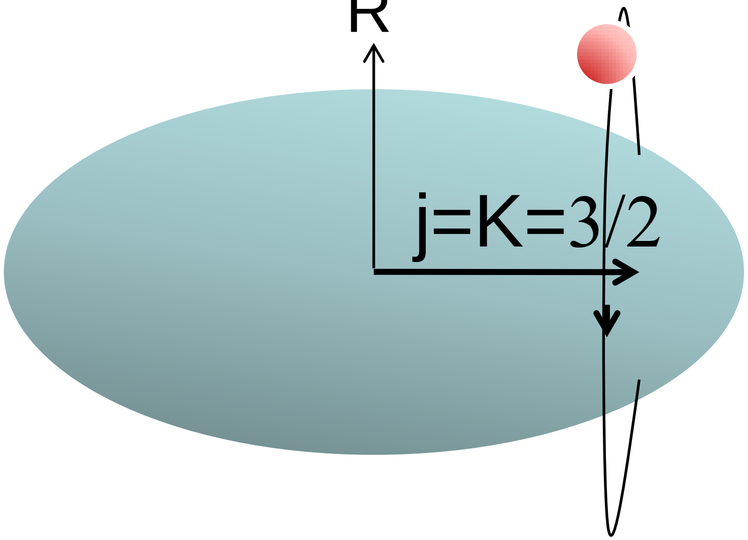
$$\theta \sim 1/\ell$$

Mixing of Angular Momentum : Essential for dineutron correlation

^{11}Li   p & s mixing

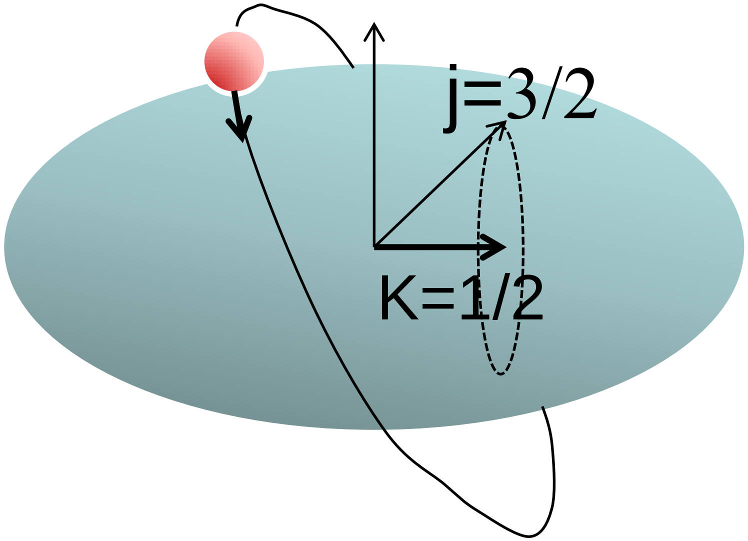
^{22}C   s & d and more?

(^{22}C could be easier in theory since core ^{20}C(gs) is 0+)



$[321]3/2^-$

$p_{3/2}$



$[330]1/2^-$

$p_{3/2}$