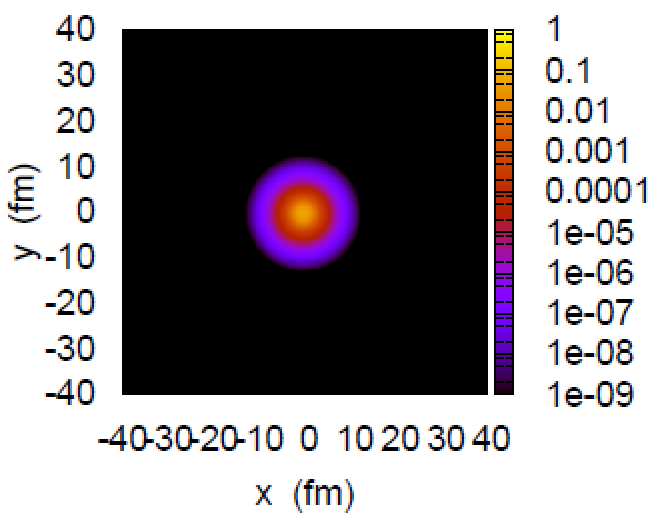
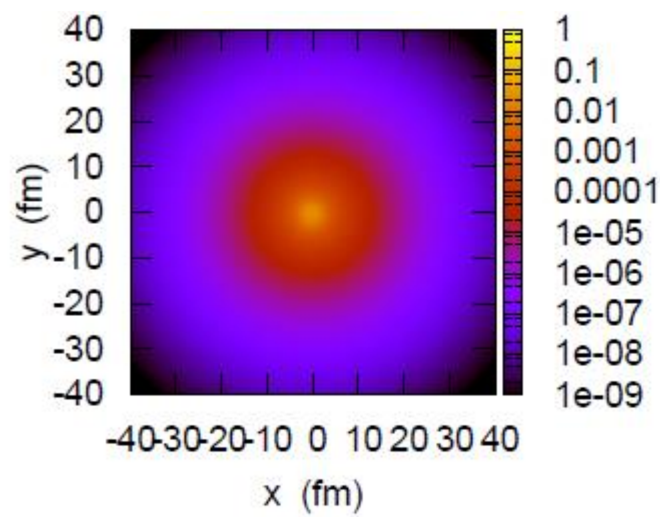
Properties of one-neutron halo nuclei

- bound states
- Effects of angular momentum
- Coulomb excitations
- Deformation

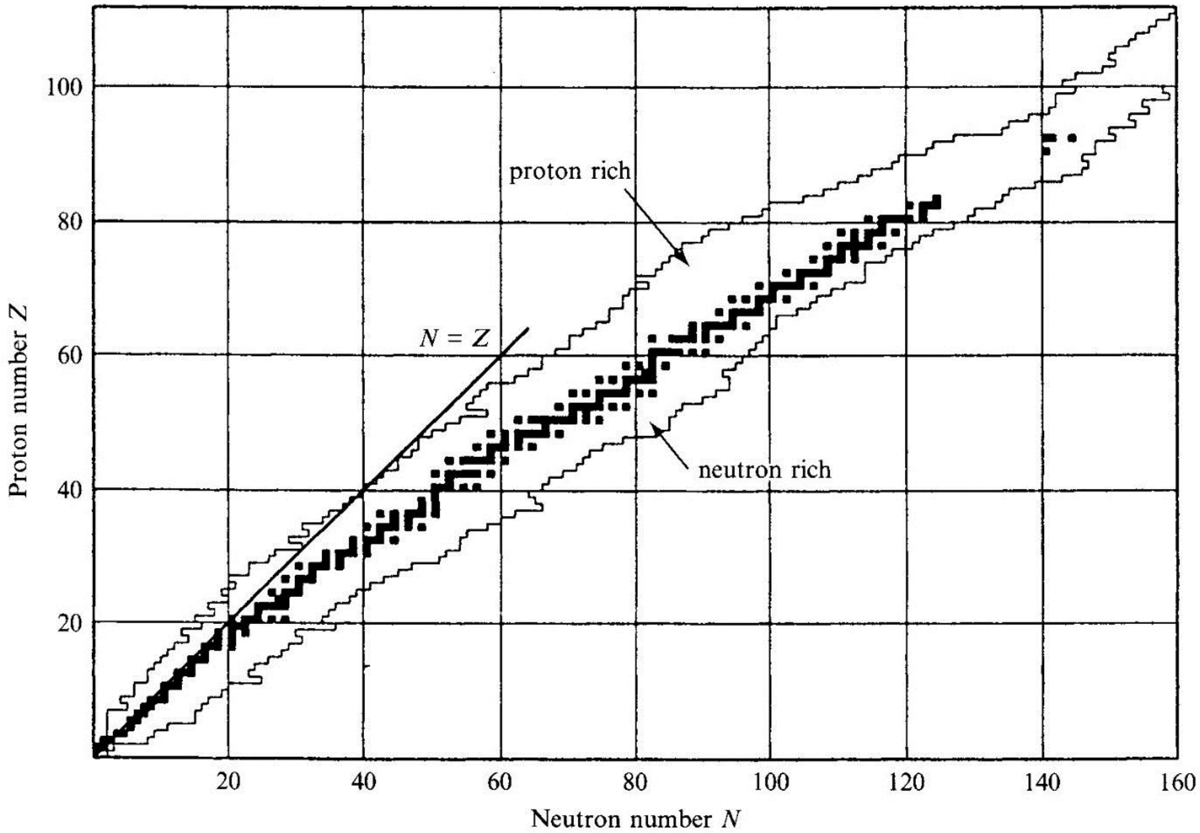


weakly bound



square well potential
(l=0 bound state)

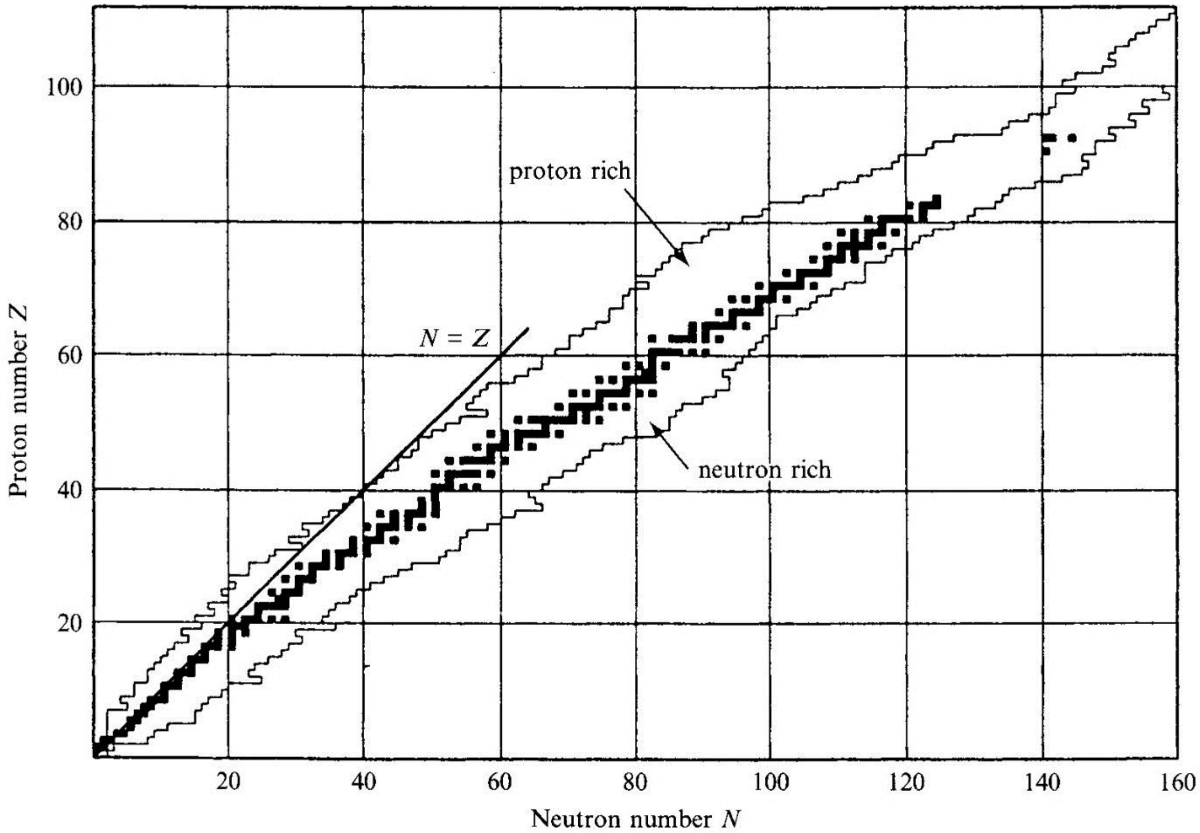
Nuclear Chart



Nuclear Physics: developed for stable nuclei (until mid 1980's)

saturation, radii, binding energy,
magic numbers and independent particle….

Nuclear Chart

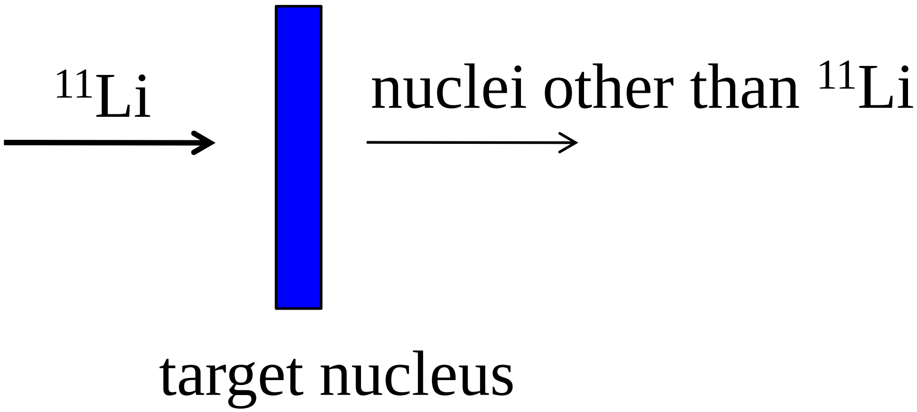


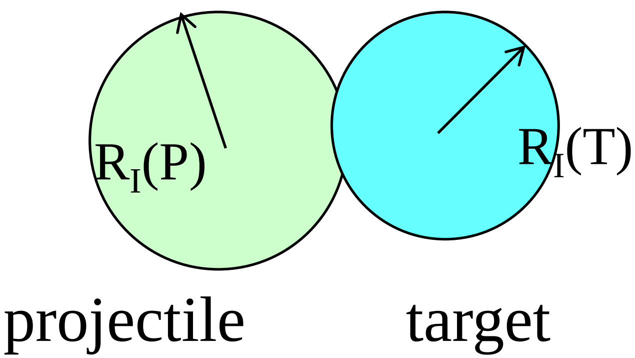
Nuclear Physics: developed for stable nuclei (until mid 1980's)

natural questions:

- how many neutrons can be put into a nucleus when the number of proton is fixed?
- what are the properties of nuclei far from the stability line?

Start of a research on unstable nuclei: interaction cross sections (1985)



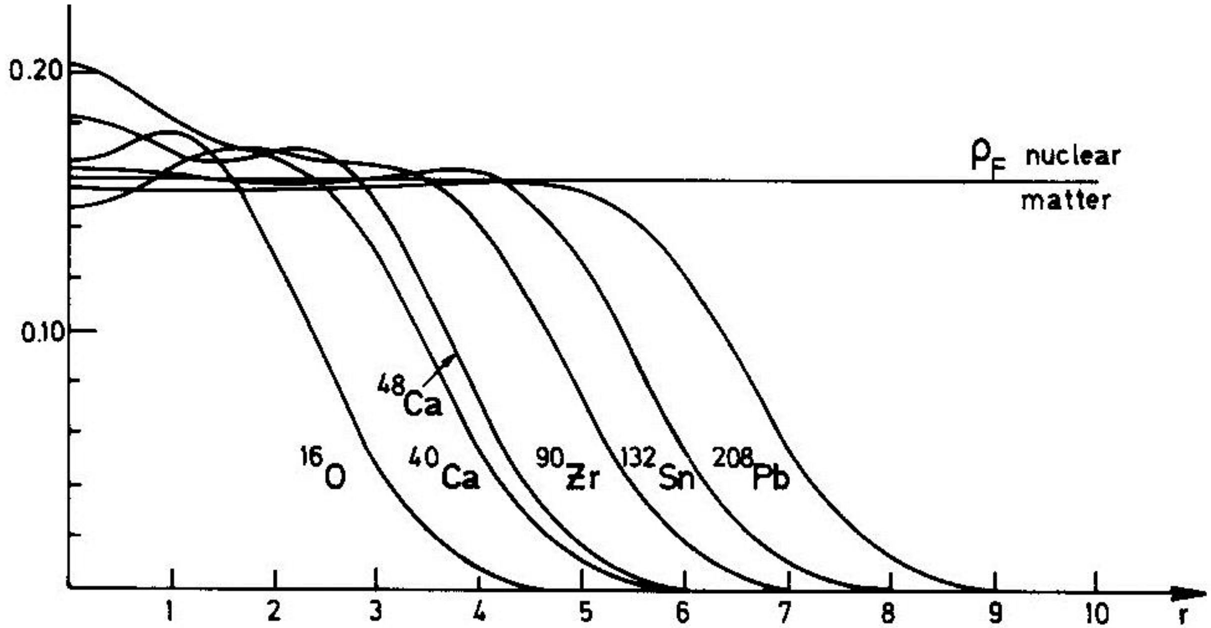


if reaction takes place when two nuclei overlap with each other:

$$\sigma_I \sim \pi[R_I(P) + R_I(T)]^2$$

$$\longrightarrow \; R_I(P)$$

stable nuclei



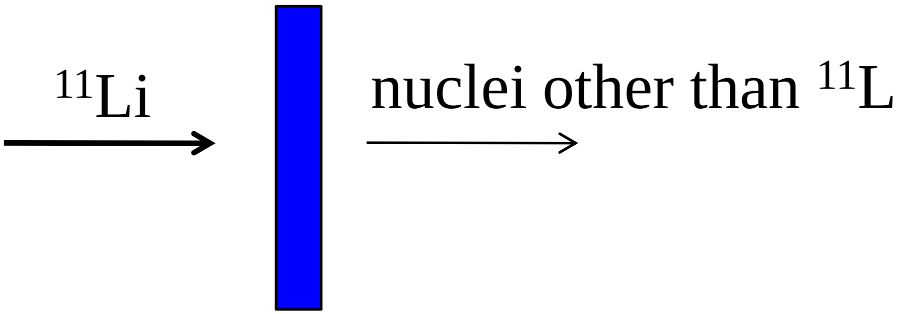
$$\rho(r) = \frac{\rho_0}{1 + \exp((r - R_0)/a)}$$

$$\rho_0 \sim 0.17 \ (\mathrm{fm}^{-3})$$

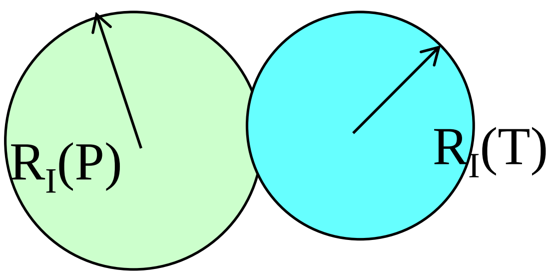
$$R_0 \sim 1.1 \times A^{1/3} \ (\mathrm{fm})$$

$$a \sim 0.57 \ (\mathrm{fm})$$

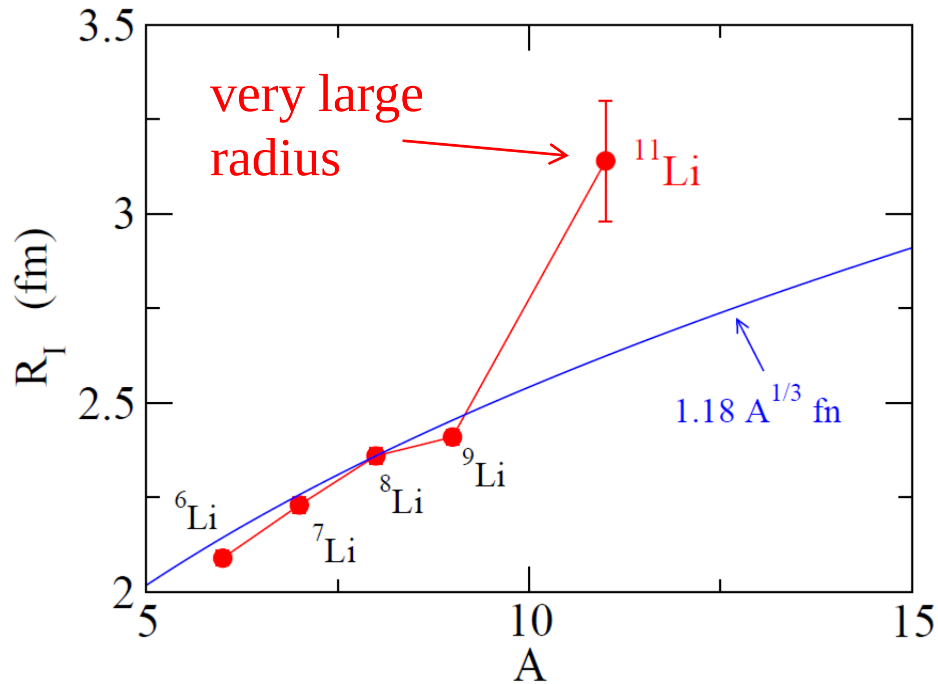
Start of a research on unstable nuclei: interaction cross sections (1985)



target nucleus



projectile target



I. Tanihata et al., PRL55('85)2676

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$$\sigma_I \sim \pi [R_I(P) + R_I(T)]^2$$

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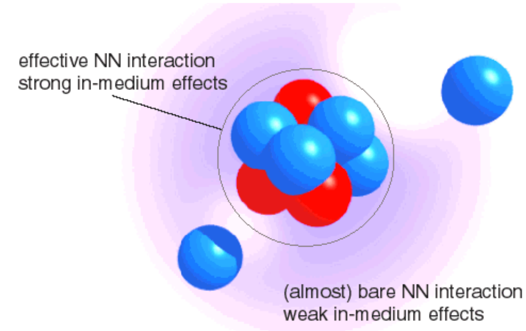
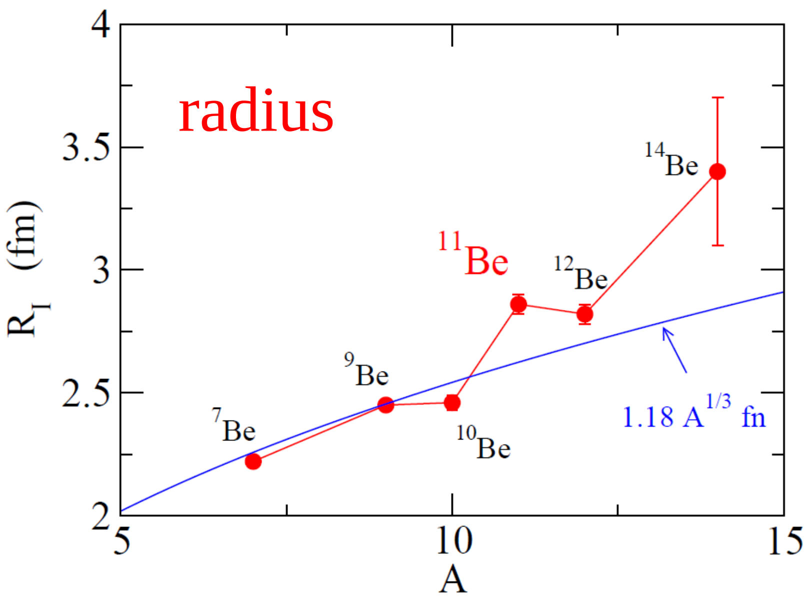


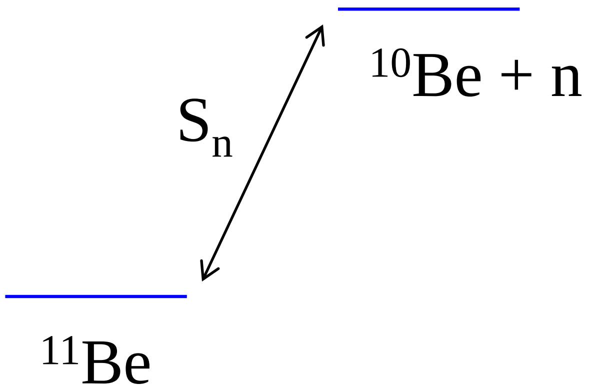
One neutron halo nuclei

A typical example: $^{11}_{4}\mathrm{Be}_{7}$



I. Tanihata et al.,
PRL55('85)2676; PLB206('88)592

One neutron separation energy



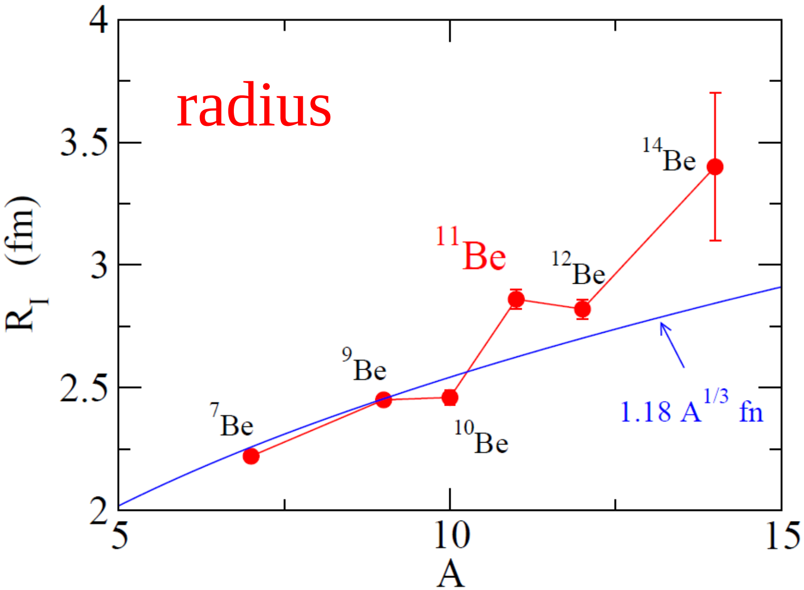
S_n = 504 +/- 6 keV

very small

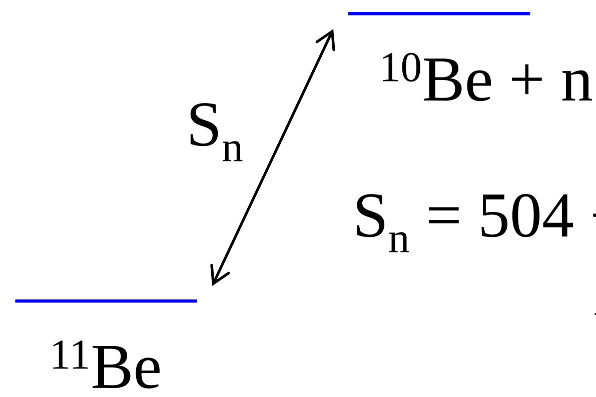
cf. S_n = 6.81 MeV
for ^{10}Be

One neutron halo nuclei

A typical example: ${}^{11}_{4}Be_7$



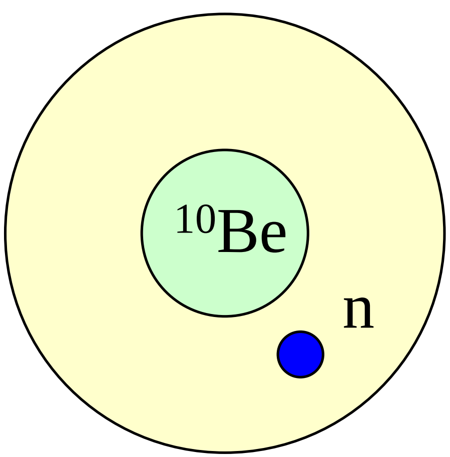
One neutron separation energy



S_n = 504 +/- 6 keV

very small

Interpretation : a weakly bound neutron surrounding ^{10}Be

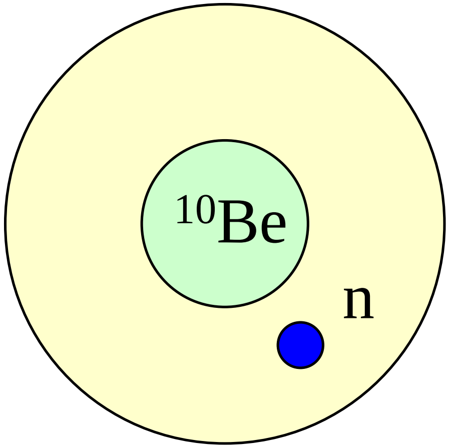


$$\psi(r) \sim \exp(-\kappa r) \qquad \kappa = \sqrt{2m|\epsilon|/\hbar^2}$$

weakly bound system

large spatial extension of density (halo structure)

Interpretation : a weakly bound neutron surrounding ^{10}Be



$$\psi(r) \sim \exp(-\kappa r) \qquad \kappa = \sqrt{2m|\epsilon|/\hbar^2}$$

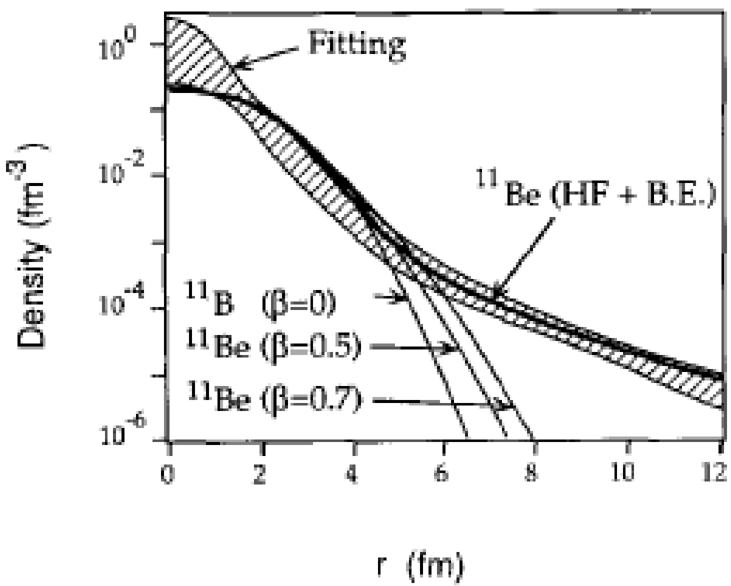
weakly bound system

⇓

large spatial extension of density (halo structure)

lunar halo
(a thin ring around moon)

Density distribution which explains
the experimental reaction cross section



M. Fukuda et al., PLB268('91)339

Momentum distribution

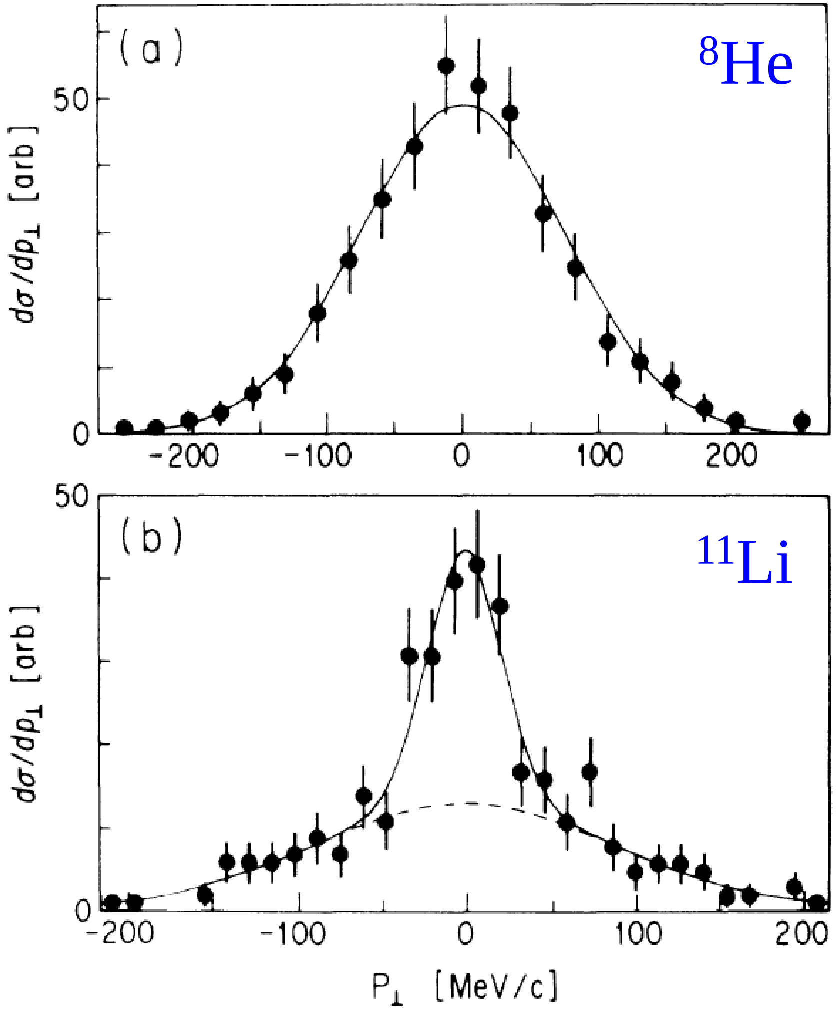


FIG. 1. Transverse-momentum distributions of (a) ^{6}He fragments from reaction ^{8}He+C and (b) ^{9}Li fragments from reaction ^{11}Li+C. The solid lines are fitted Gaussian distributions. The dotted line is a contribution of the wide component in the ^{9}Li distribution.

$S_{2n} \sim 2.1$ MeV

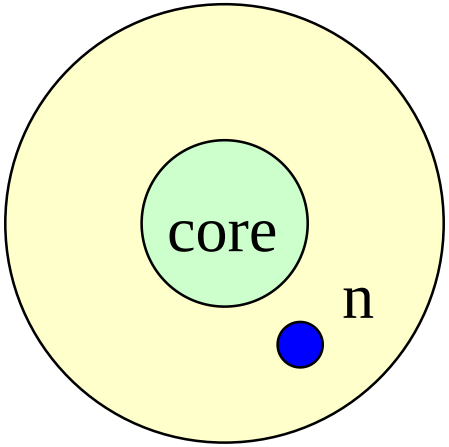
$S_{2n} \sim 300$ keV

a narrow mom. distribution when weakly bound and thus a large spatial extension

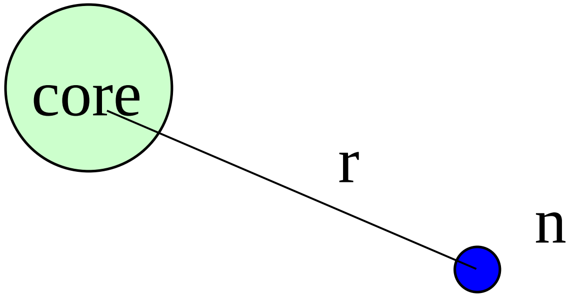
$\longleftrightarrow$ neutron halo

T. Kobayashi et al., PRL60 ('88) 2599

Properties of single-particle motion: bound state



assume a 2body system with a core nucleus and a valence neutron



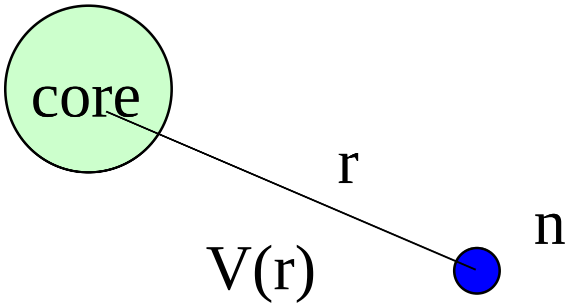
consider a spherical potential $V(r)$ as a function of r

cf. mean-field potential:

$$V(\boldsymbol{r}) \sim \int v(\boldsymbol{r}, \boldsymbol{r}')\rho(\boldsymbol{r}')d\boldsymbol{r}'$$

Hamiltonian for the relative motion

$$H = -\frac{\hbar^2}{2\mu}\nabla^2 + V(r)$$



Hamiltonian for the relative motion

$$H = -\frac{\hbar^2}{2\mu}\nabla^2 + V(r)$$

For simplicity, let us ignore the spin-orbit interaction
(the essence remains the same even if no spin-orbit interaction)

$$\boxed{\Psi_{lm}(\boldsymbol{r}) = \frac{u_l(r)}{r} Y_{lm}(\hat{\boldsymbol{r}})}$$

$$\boxed{\left[-\frac{\hbar^2}{2\mu}\frac{d^2}{dr^2} + \frac{l(l+1)\hbar^2}{2\mu r^2} + V(r) - \epsilon_l\right] u_l(r) = 0}$$

Boundary condition for bound states

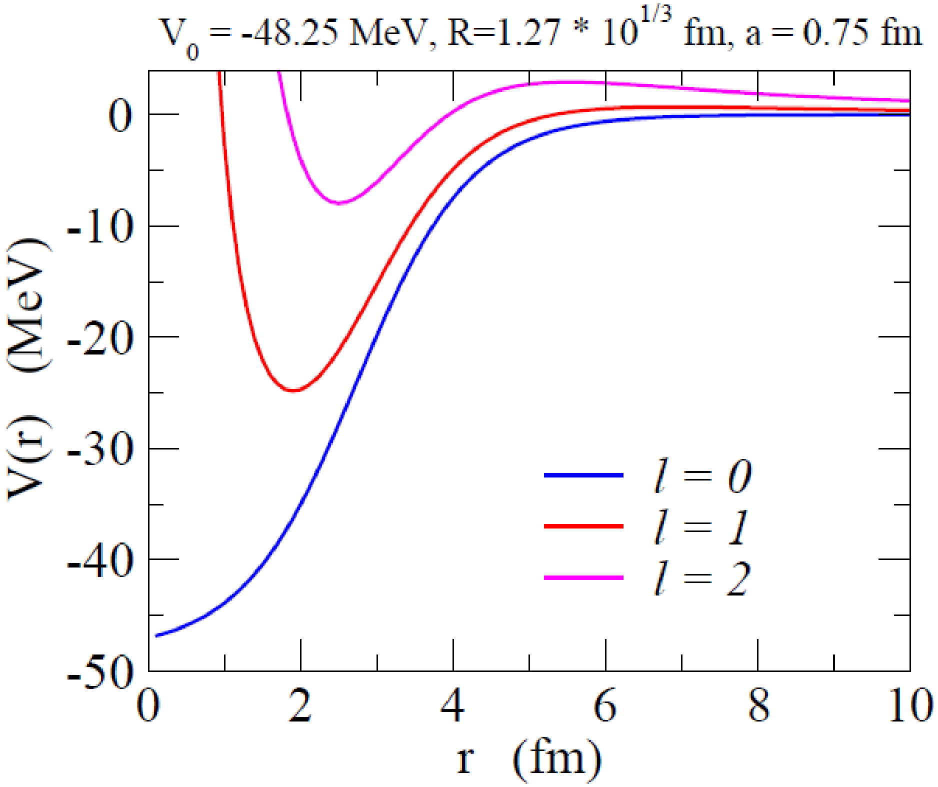
$$\begin{aligned} u_l(r) &\sim r^{l+1} \qquad (r \sim 0) \\ &\to e^{-\kappa r} \qquad (r \to \infty) \end{aligned}$$

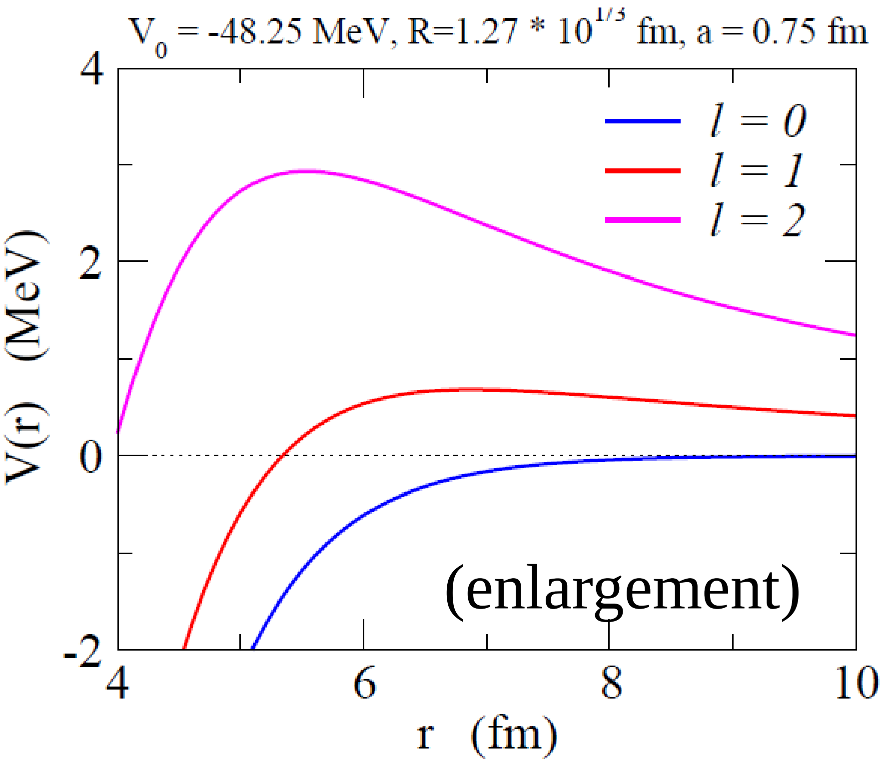
* For a more consistent treatment, a modified spherical Bessel function has to be used

Angular momentum and halo phenomenon

$$\left[-\frac{\hbar^2}{2\mu}\frac{d^2}{dr^2}+\frac{l(l+1)\hbar^2}{2\mu r^2}+V(r)-\epsilon_l\right]u_l(r)=0$$

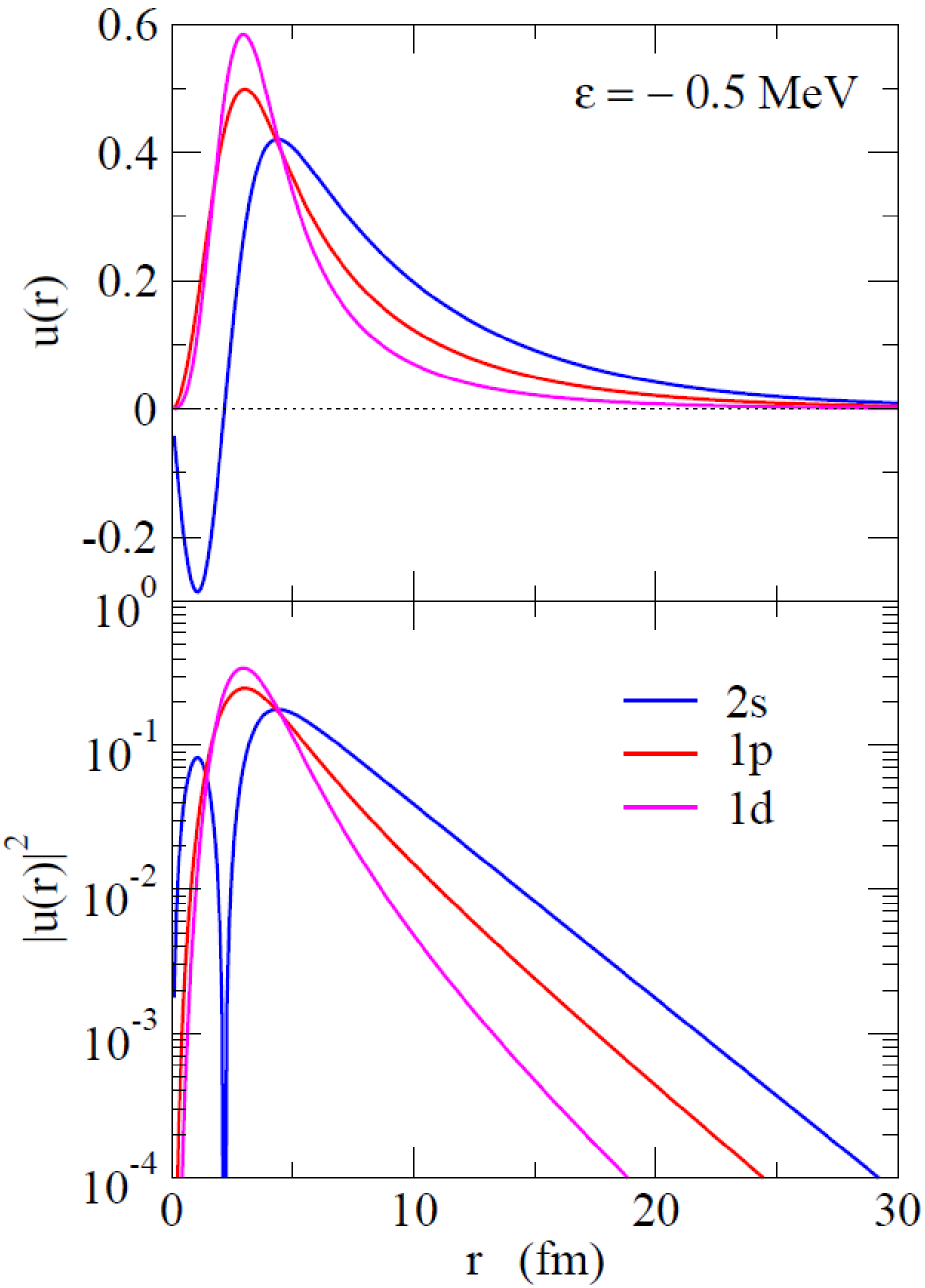
Centrifugal potential





Height of centrifugal barrier: 0 MeV (l = 0), 0.69 MeV (l = 1), 2.94 MeV (l = 2)

Wave function Change V_0 for each l so that ε = -0.5 MeV



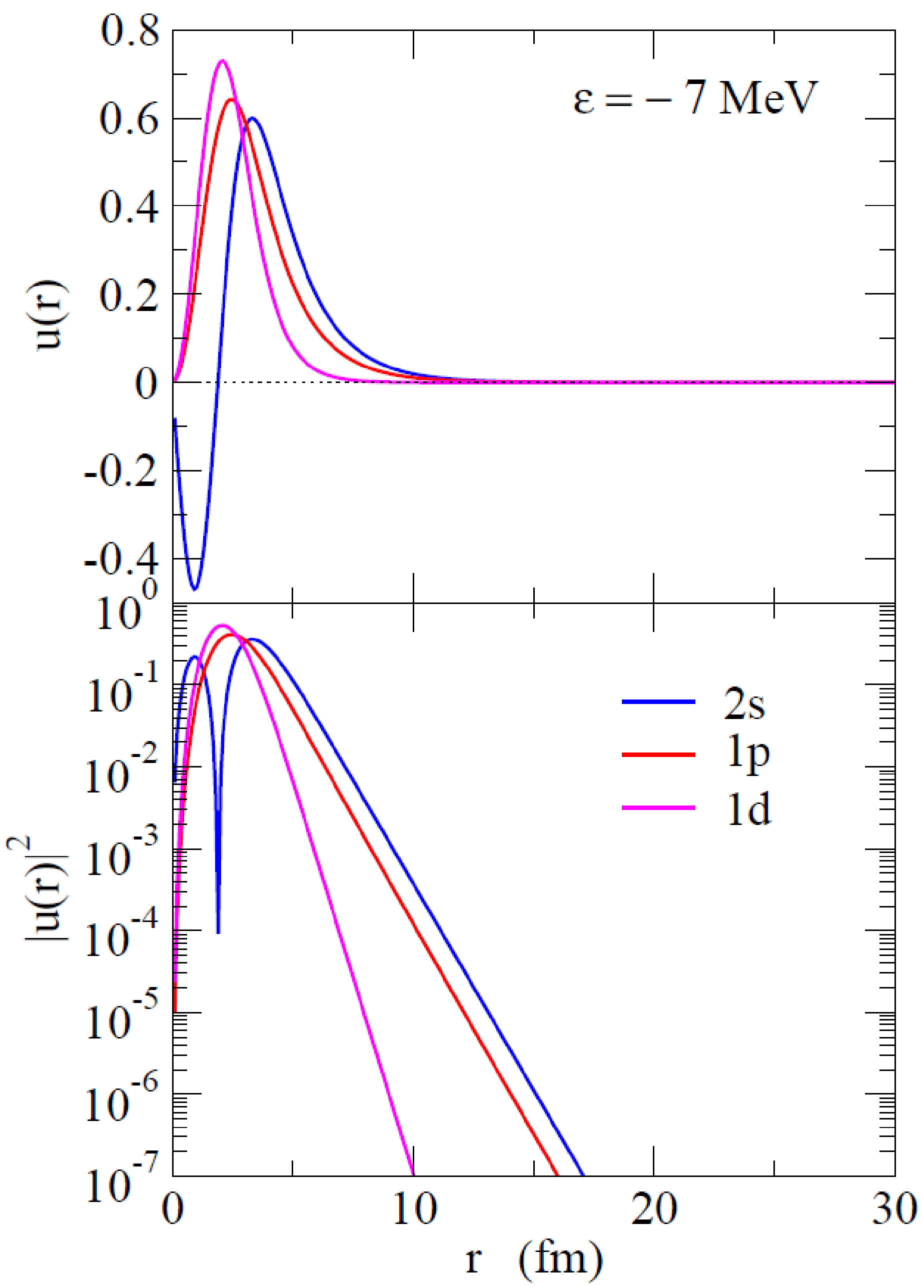
l = 0 : a long tail
l = 2 : localization
l = 1 : intermediate

root-mean-square radius

$$\sqrt{\langle r^2 \rangle} = \sqrt{\int_0^\infty dr\, r^2 u_l(r)^2}$$

7.17 fm (l = 0)
5.17 fm (l = 1)
4.15 fm (l = 2)

Wave function For ε = -7 MeV



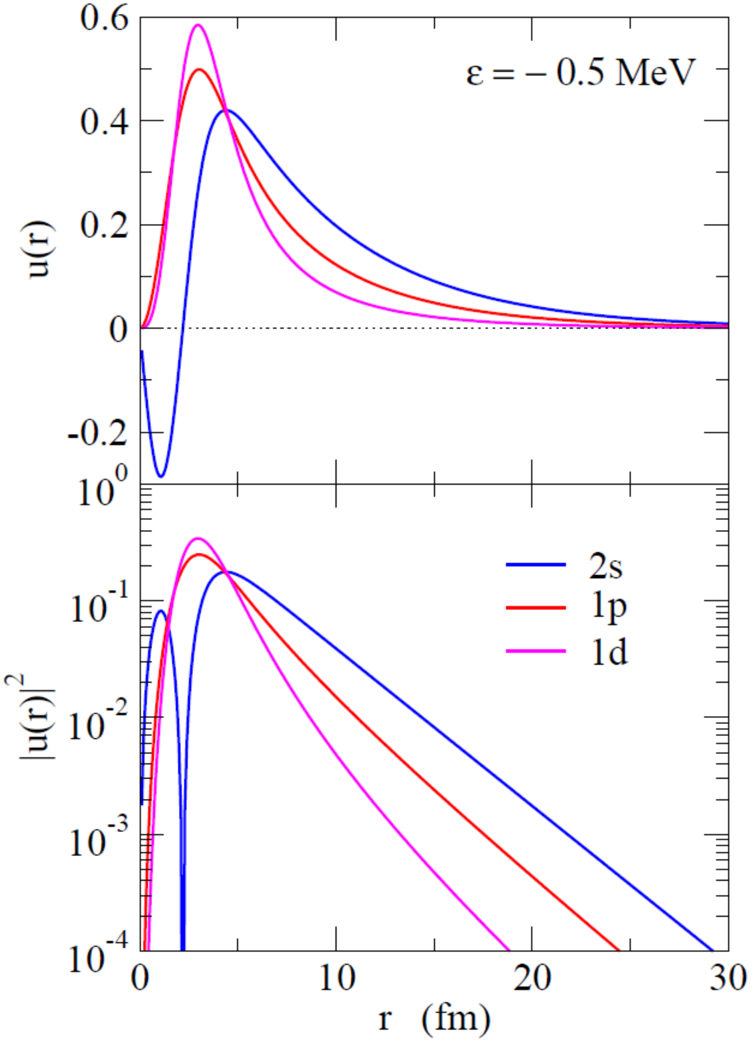
Wave function: localized for all *l*

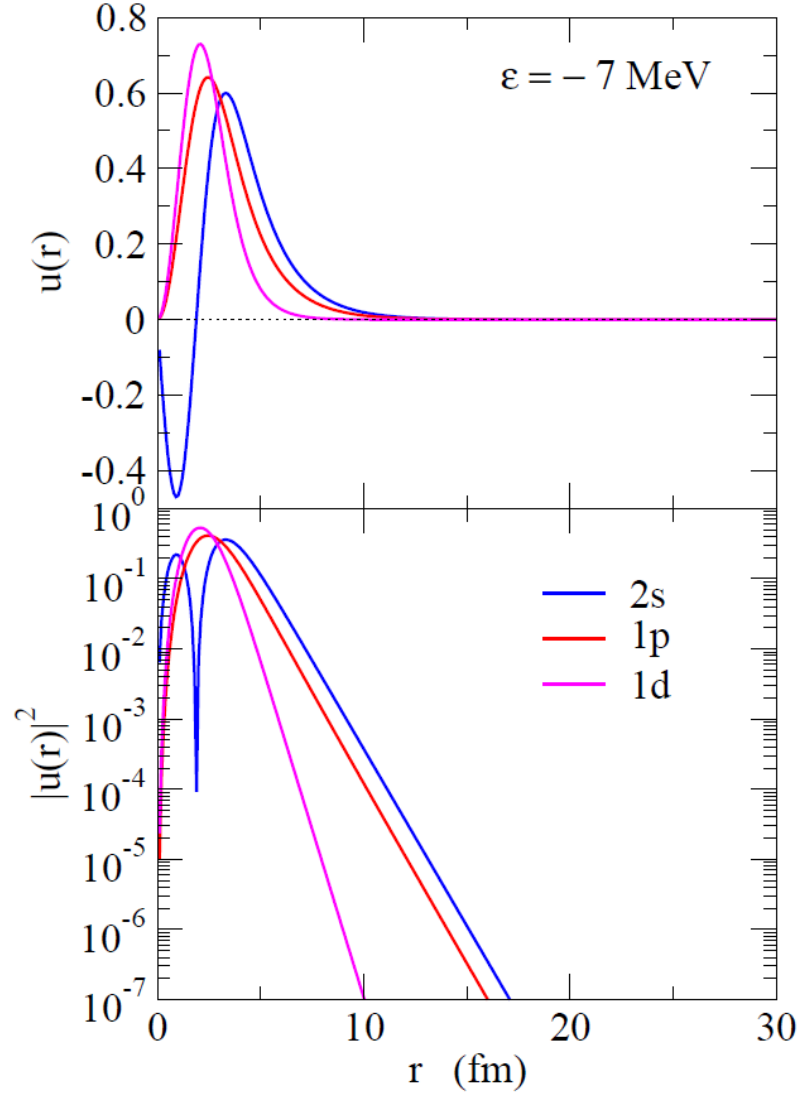
root-mean-square radius:

$$\sqrt{\langle r^2 \rangle} = \sqrt{\int_0^\infty dr\, r^2 u_l(r)^2}$$

3.58 fm (l = 0)
3.05 fm (l = 1)
3.14 fm (l = 2)

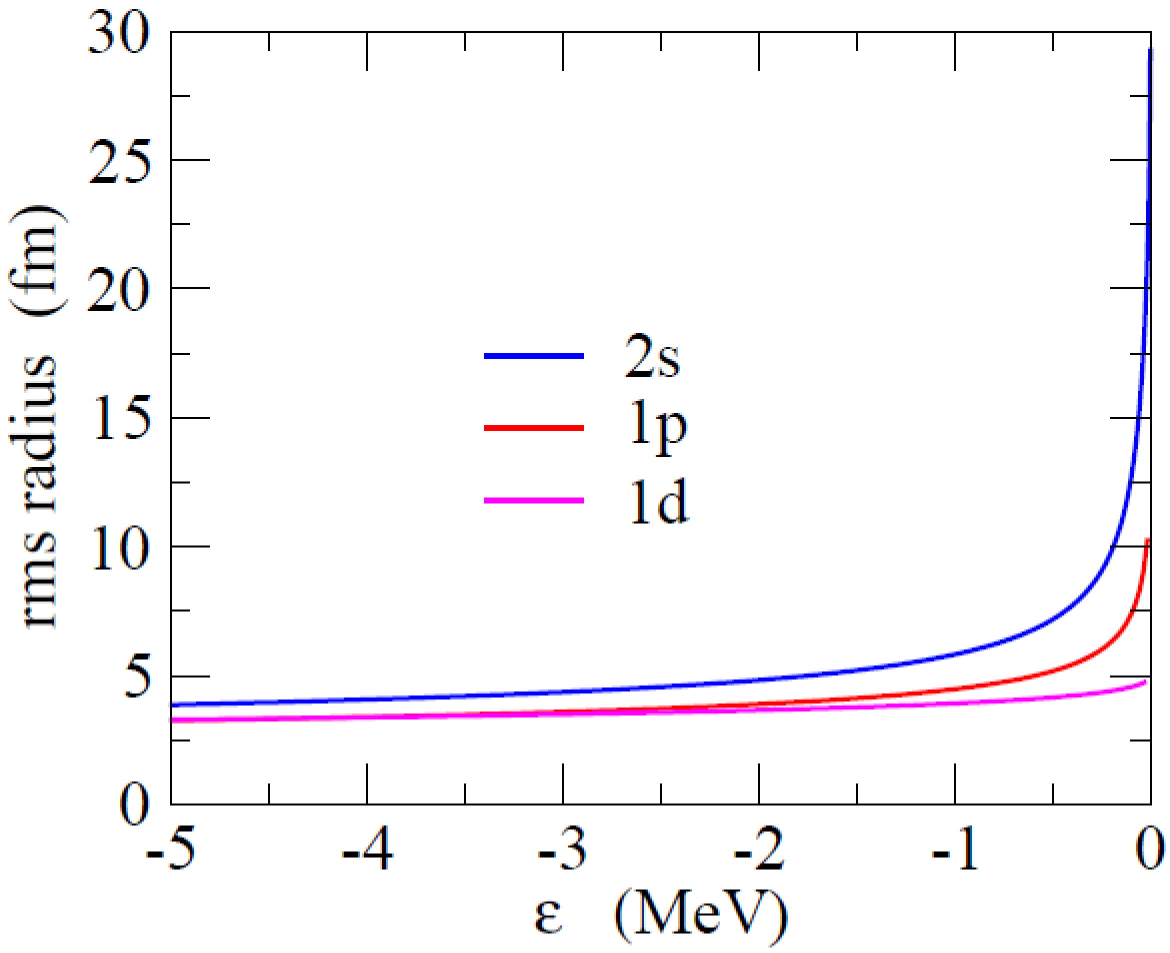
Wave functions





$$\langle r^2 \rangle \propto \begin{cases} 1/|\epsilon_0| & (l=0) \\ 1/\sqrt{|\epsilon_1|} & (l=1) \\ const. & (l=2) \end{cases}$$

$\Downarrow$



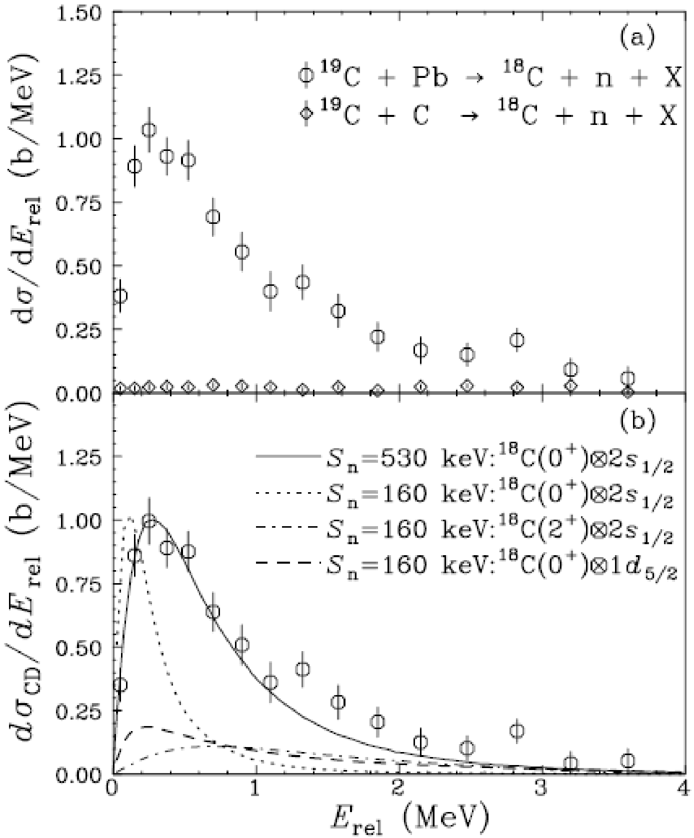
Radius: diverges for *l*=0 and 1 in the zero energy limit

$\Downarrow$

Halo (a very large radius) happens only for *l*= 0 or 1

Other candidates for 1n halo nuclei

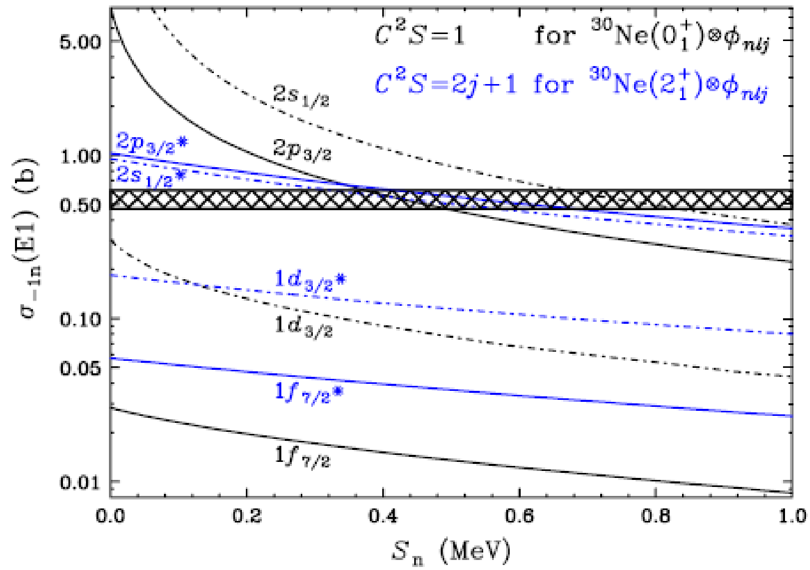
^{19}C: S_n = 0.58(9) MeV



Coulomb breakup of ^{19}C

T. Nakamura et al., PRL83('99)1112

^{31}Ne: S_n = 0.29 +/- 1.64 MeV

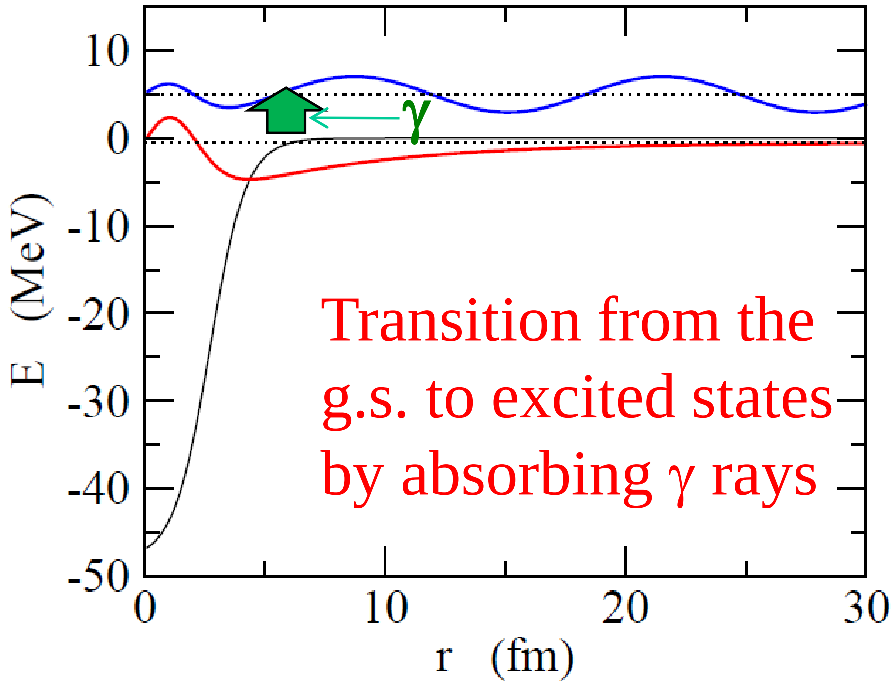


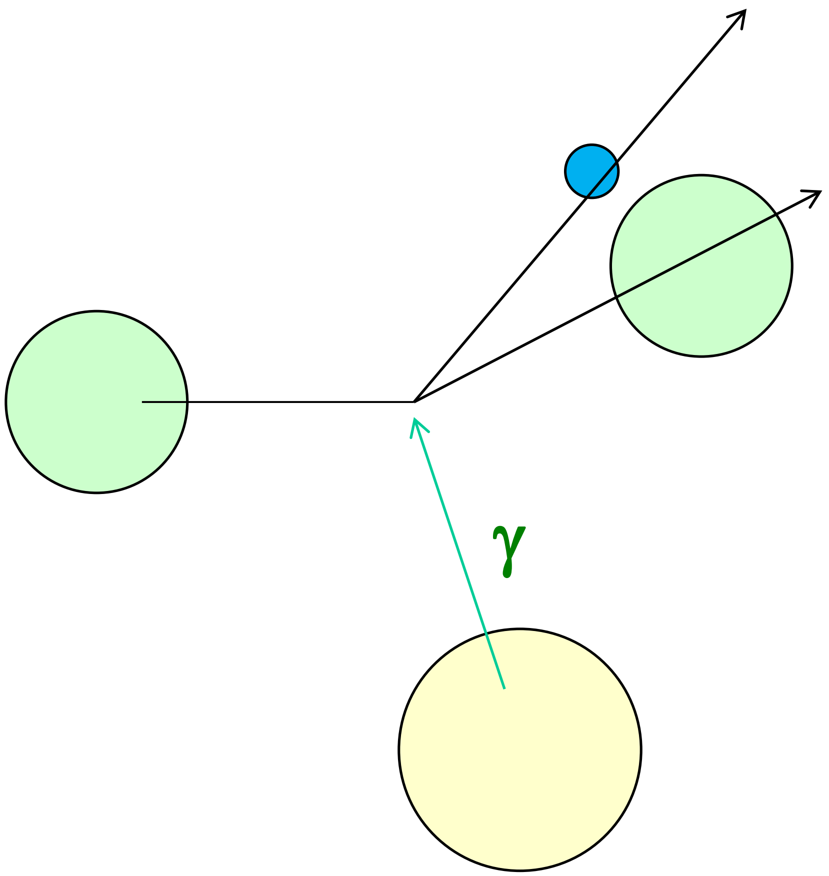
Large Coulomb breakup cross sections

T. Nakamura et al., PRL103('09)262501

Coulomb breakup of 1n halo nuclei

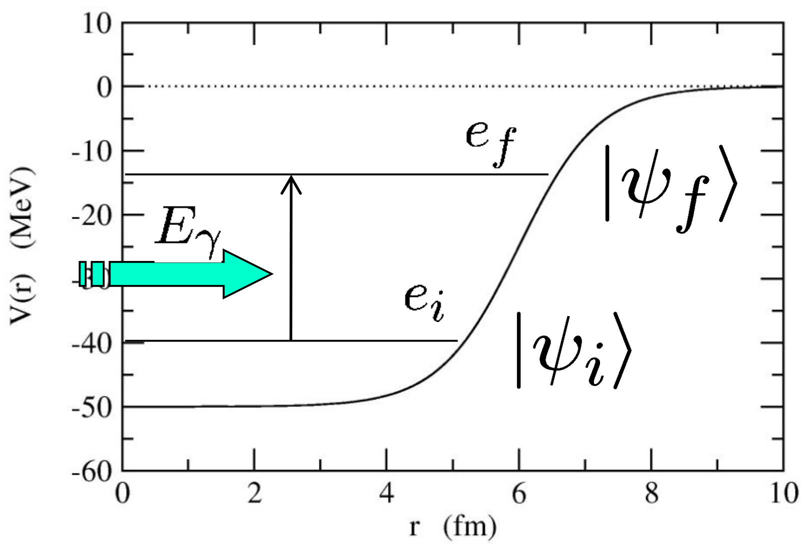
$^{A}Z \rightarrow {}^{A}Z^{*} \rightarrow {}^{A-1}Z + n$



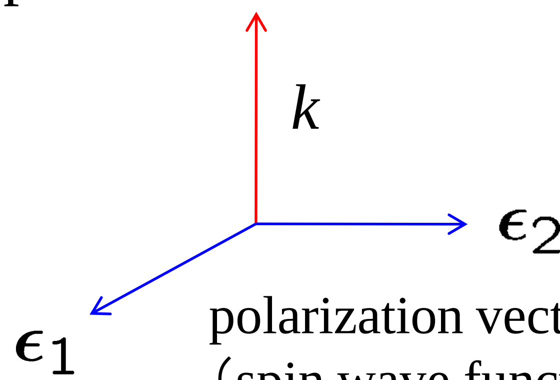


breakup if excited to continuum states ← excitations due to the Coulomb field from the target nucleus

Electromagnetic transitions



photon



polarization vector
(spin wave function of photon)

initial state: $|\psi_i\rangle |n_{k\alpha} = 1\rangle$

State of nucleus: Ψ_i,
+ one photon with
momentum k, and
polarization α
(α = 1 or 2)

transition

H_{int}
(interaction between
a nucleus and EM field)

final state: $|\psi_f\rangle |n_{k\alpha} = 0\rangle$

(note) time-dependent perturbation theory

$$\boxed{H_{\rm int} = \frac{1}{Am} \cdot \frac{Ze}{c} \boldsymbol{A} \cdot \boldsymbol{p}}$$

$$\boxed{\boldsymbol{A}(\boldsymbol{r},t) \;=\; \sum_{\alpha} \int \frac{d\boldsymbol{k}}{2\pi} \frac{\hbar c}{\sqrt{\hbar\omega}} \left[a_{\boldsymbol{k}\alpha}\epsilon_\alpha e^{-i\omega t} + a^\dagger_{\boldsymbol{k}\alpha}\epsilon_\alpha e^{i\omega t}\right] = \boldsymbol{A}(t)}$$

(dipole approximation)

transition probability per unit time due to: $V(\boldsymbol{r},t) = F(\boldsymbol{r})e^{\pm i\omega t}$

(for a transition to a single state)

$$\boxed{\Gamma_{i\to f} = \frac{2\pi}{\hbar} |\langle f|F|i\rangle|^2 \, \delta(e_f - e_i \pm \hbar\omega)}$$

Fermi's Golden Rule

application to the present problem:

$$\boxed{\Gamma_{i\to f} = \frac{1}{2\pi\hbar}\left(\frac{Ze}{A+1}\right)^2 (e_f - e_i) \left|\langle\psi_f|z|\psi_i\rangle\right|^2 \delta(e_f - e_i - \hbar\omega)}$$

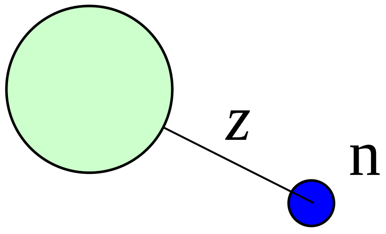
(note) photo-absorption cross section if Γ is devided by the photon flux $c/(2\pi)^3$:

$$\sigma_\gamma = \frac{4\pi^2}{\hbar c}\left(\frac{Ze}{A+1}\right)^2 (e_f - e_i) \left|\langle\psi_f|z|\psi_i\rangle\right|^2 \delta(e_f - e_i - \hbar\omega)$$

Application to the present problem:

$$\Gamma_{i\to f} = \frac{1}{2\pi\hbar}\left(\frac{Ze}{A+1}\right)^2 (e_f - e_i)\left|\langle\psi_f|z|\psi_i\rangle\right|^2 \delta(e_f - e_i - \hbar\omega)$$

$$\boxed{P_{i\to f} \sim \left|\langle\psi_f|z|\psi_i\rangle\right|^2}$$

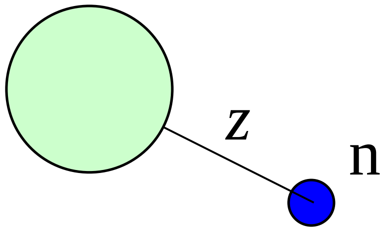


$$\sum_f P_{i\to f} =$$

Application to the present problem:

$$\Gamma_{i\to f} = \frac{1}{2\pi\hbar}\left(\frac{Ze}{A+1}\right)^2 (e_f - e_i)\left|\langle\psi_f|z|\psi_i\rangle\right|^2 \delta(e_f - e_i - \hbar\omega)$$

$$\boxed{P_{i\to f} \sim \left|\langle\psi_f|z|\psi_i\rangle\right|^2}$$



$$\sum_f P_{i\to f} = \sum_f \langle\psi_i|z|\psi_f\rangle\langle\psi_f|z|\psi_i\rangle$$

$$= \langle\psi_i|z^2|\psi_i\rangle$$

large transition probability if the spatial extention in *z* is large

Wigner-Eckart theorem and reduced transition probability

$$\boxed{\sigma_\gamma = \frac{16\pi^3}{3\hbar c}\left(\frac{Ze}{A+1}\right)^2 E_\gamma \left|\langle\psi_f|rY_{10}|\psi_i\rangle\right|^2 \delta(e_f - e_i - E_\gamma)}$$

$$E_\gamma = e_f - e_i = \hbar\omega$$

$$\begin{aligned}\left|\langle\psi_f|rY_{10}|\psi_i\rangle\right|^2 \;\rightarrow\;& \frac{1}{2l+1}\sum_{m,m'}|\langle\psi_{l'm'}|rY_{10}|\psi_{lm}\rangle|^2 \\ =\;& \frac{1}{3}\cdot\frac{1}{2l+1}|\langle\psi_{l'}||rY_1||\psi_l\rangle|^2\end{aligned}$$

$$\boxed{\begin{aligned}\sigma_\gamma &= \frac{16\pi^3}{9\hbar c}E_\gamma\cdot\frac{1}{2l+1}\left|\langle\psi_f||e_{\mathrm{E1}}rY_1||\psi_i\rangle\right|^2\delta(e_f - e_i - E_\gamma) \\ &= \frac{16\pi^3}{9\hbar c}E_\gamma\cdot\frac{dB(E1)}{dE_\gamma}\end{aligned}}$$

Reduced transition probability

$$\boxed{\frac{dB(E1)}{dE_\gamma} = \frac{1}{2l+1}\left|\langle\psi_f||e_{\mathrm{E1}}rY_1||\psi_i\rangle\right|^2\delta(e_f - e_i - E_\gamma)}$$

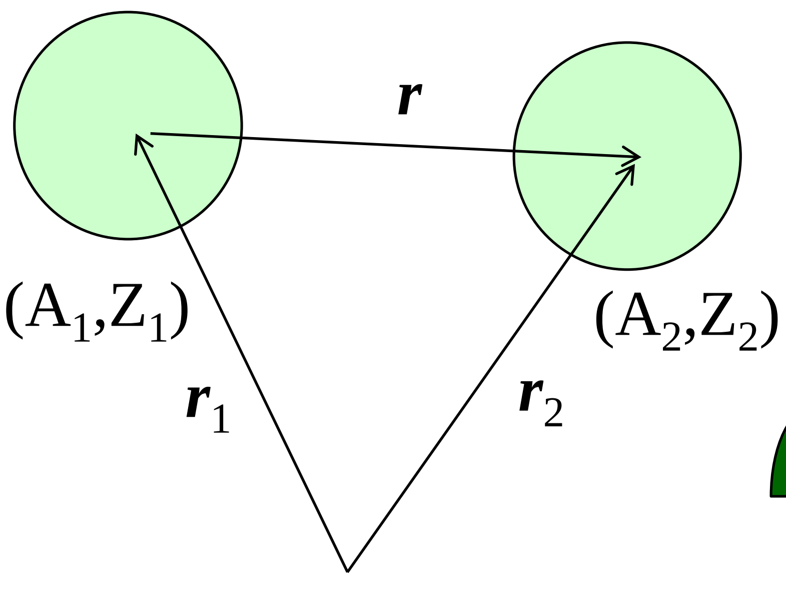
E1 effective charge

$$\sigma_\gamma = \frac{16\pi^3}{3\hbar c}\left(\frac{Ze}{A+1}\right)^2 (e_f - e_i)\left|\langle\psi_f|rY_{10}|\psi_i\rangle\right|^2 \delta(e_f - e_i - \hbar\omega)$$

dipole operator: $$\hat{D}_\mu = e_{\rm E1}\cdot rY_{1\mu}(\theta,\phi)$$

$$e_{\rm E1} = \frac{Z}{A+1}e$$

Distribution of charges measured from the center of mass



$$Z_1(\boldsymbol{r}_1 - \boldsymbol{R}) + Z_2(\boldsymbol{r}_2 - \boldsymbol{R})$$

$$\boldsymbol{R} = \frac{A_1\boldsymbol{r}_1 + A_2\boldsymbol{r}_2}{A_1 + A_2}$$

$$= \cdots$$

$$= \frac{Z_1A_2 - Z_2A_1}{A_1 + A_2}(\boldsymbol{r}_1 - \boldsymbol{r}_2)$$

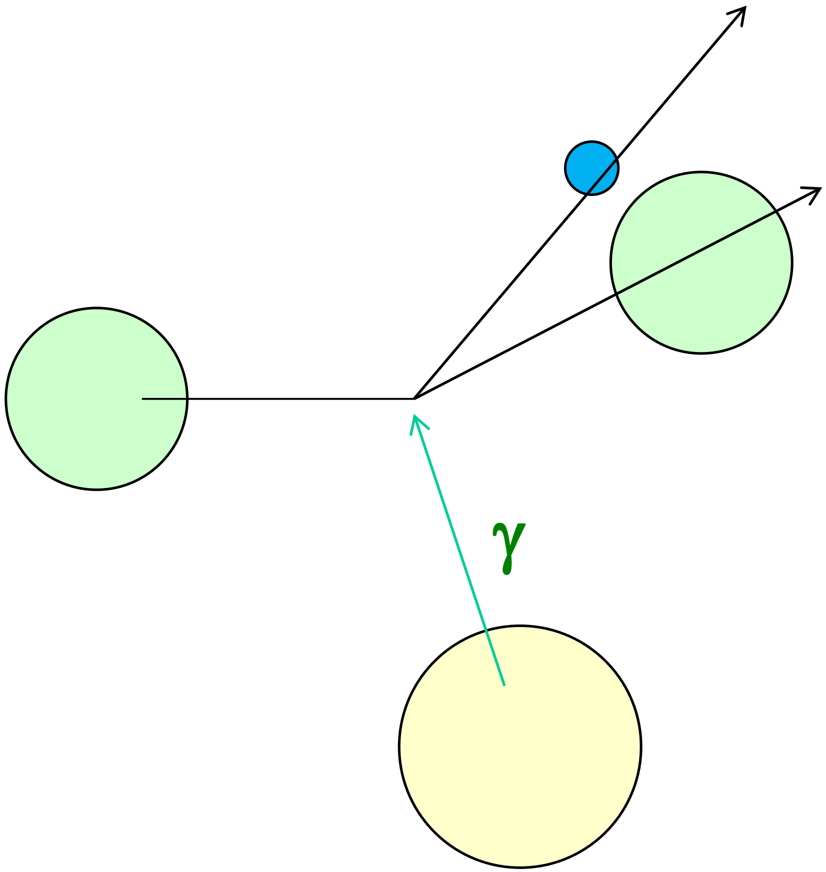
$$= \frac{Z_1A_2 - Z_2A_1}{A_1 + A_2}\boldsymbol{r}$$

$$e_{\rm E1} = \frac{Z_1A_2 - Z_2A_1}{A_1 + A_2}e$$

(a general formula for 2-body)

Coulomb breakup cross sections

$$\sigma_\gamma = \frac{16\pi^3}{9\hbar c} E_\gamma \cdot \frac{dB(E1)}{dE_\gamma} \qquad \frac{d\sigma_\gamma}{dE_\gamma} \sim \frac{16\pi^3}{9\hbar c} \cdot \frac{dB(E1)}{dE_\gamma}$$



In actual nuclear reactions, absorption of virtual photons rather than real photons

$$\frac{d\sigma}{dE_{\rm ex}} \sim \frac{16\pi^3}{9\hbar c} \cdot N_{\rm E1}(E_{\rm ex}) \cdot \frac{dB(E1)}{dE_{\rm ex}}$$

# of virtual photon

See: C.A. Bertulani and P. Danielwicz,
"Introduction to Nuclear Reactions"
for more details

Simple estimate of E1 strength distribution (analytic model)

Transition from an l = 0 to an l = 1 states:

WF for the initial state: $\Psi_i(\boldsymbol{r}) = \sqrt{2\kappa}\,\frac{e^{-\kappa r}}{r} Y_{00}(\hat{\boldsymbol{r}})$ $\qquad \kappa = \sqrt{\frac{2\mu|E_b|}{\hbar^2}}$

WF for the final state: $\Psi_f(\boldsymbol{r}) = \sqrt{\frac{2\mu k}{\pi\hbar^2}}\, j_1(kr) Y_{1m}(\hat{\boldsymbol{r}})$ $\qquad j_1(kr)$: spherical Bessel function

$$k = \sqrt{\frac{2\mu E_c}{\hbar^2}}$$

$$\frac{dB(E1)}{dE} = \frac{3}{4\pi} e_{\mathrm{E1}}^2 \left| \int_0^\infty r^2 dr\, r \cdot \frac{\sqrt{2\kappa} e^{-\kappa r}}{r} \cdot \sqrt{\frac{2\mu k}{\pi\hbar^2}}\, j_1(kr) \right|^2$$

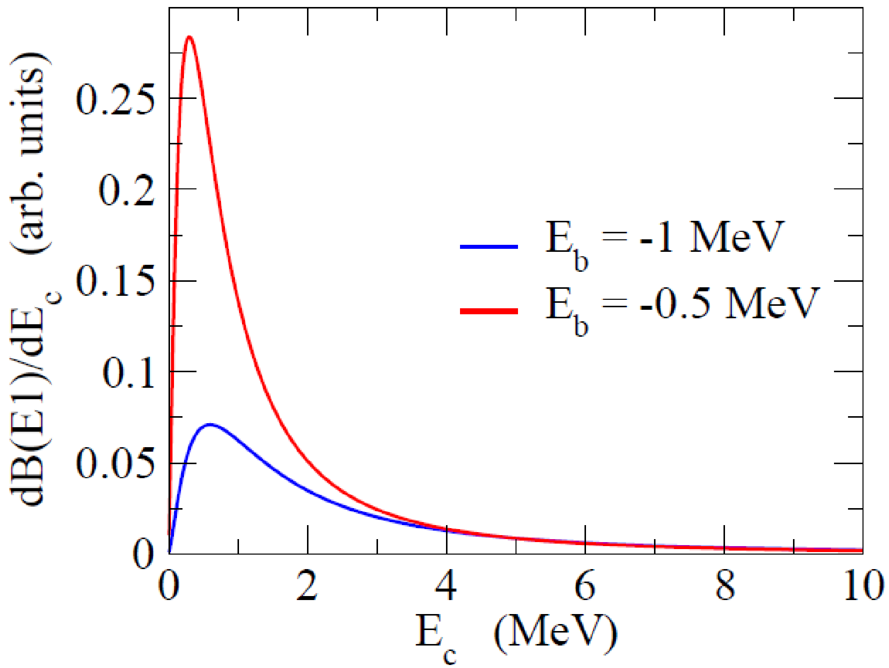
The integral can be performed analytically

$$\boxed{\frac{dB(E1)}{dE} = \frac{3\hbar^2}{\pi^2\mu} e_{\mathrm{E1}}^2 \frac{\sqrt{|E_b|}\, E_c^{3/2}}{(|E_b| + E_c)^4}}$$

Refs. (for more general l_i and l_f)

- M.A. Nagarajan, S.M. Lenzi, A. Vitturi, Eur. Phys. J. A24('05)63
- S. Typel and G. Baur, NPA759('05)247

$$\boxed{\frac{dB(E1)}{dE} = \frac{3\hbar^2}{\pi^2\mu} e_{E1}^2 \frac{\sqrt{|E_b|}\, E_c^{3/2}}{(|E_b| + E_c)^4}}$$



peak position: $E_c = \frac{3}{5}|E_b|$

$\left(E_x = E_c - E_b = \frac{8}{5}|E_b|\right)$

peak height: $\propto 1/|E_b|^2$

Total transition probability:

$$B(E1) = S_0 = \frac{3\hbar^2 e_{E1}^2}{16\pi^2\mu|E_b|}$$

- a high and sharp peak as the bound state energy, $|E_b|$, becomes small
- As the bound state energy, $|E_b|$, gets small, the peak appears at a low energy

E_{peak} = 0.28 MeV (E_b=-0.5 MeV)

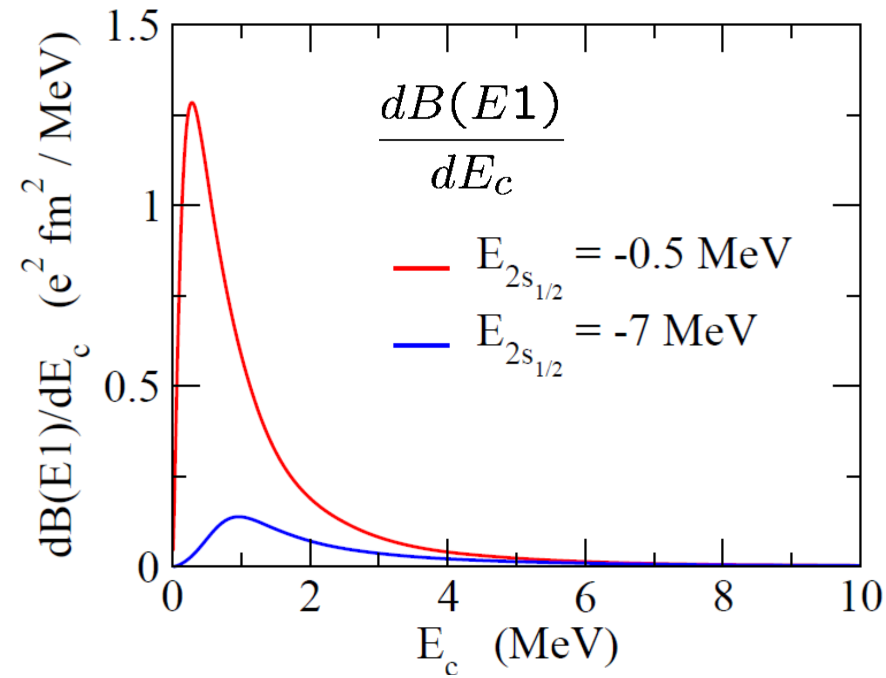
cf. $\frac{3}{5}|E_b| = 0.3$ MeV

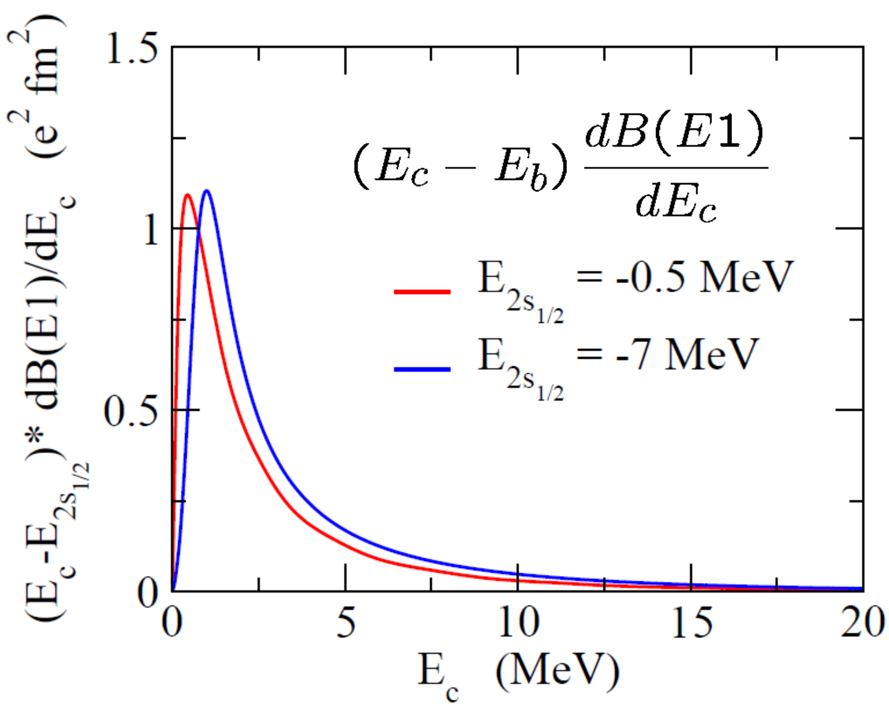
Actual numerical calculations with a *Woods-Saxon* potential

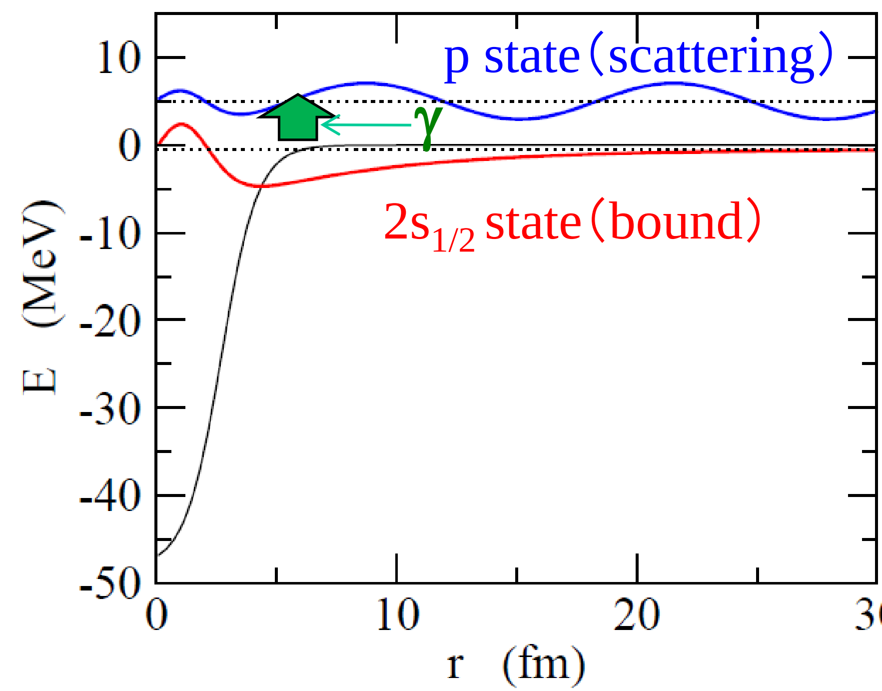
^{11}Be = ^{10}Be + n

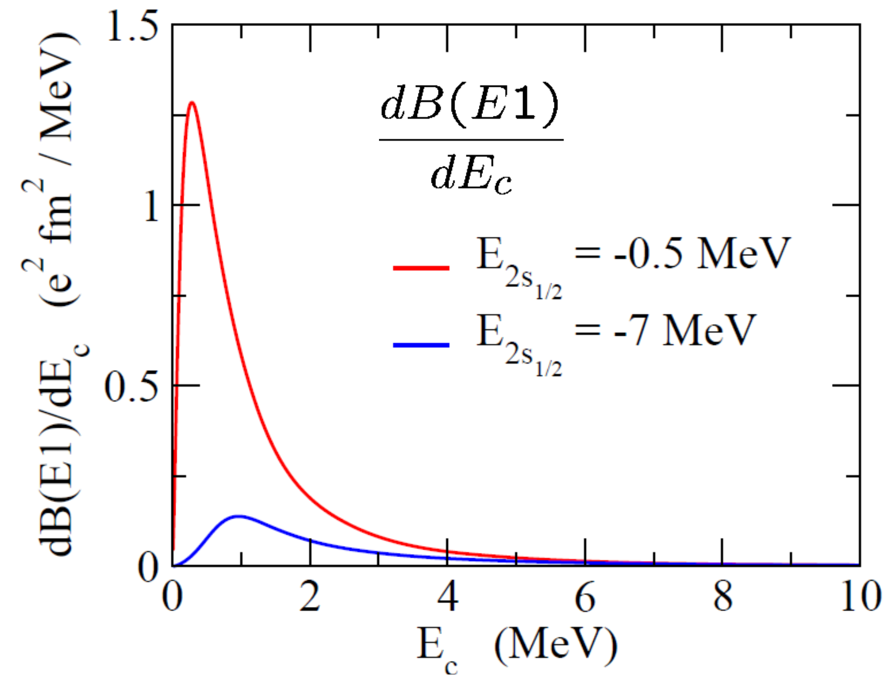
transition from the $2s_{1/2}$ state (bound) to the p-wave (l = 1) state

Comparison between a weakly-bound case and a strongly-bound case









$^{11}Be = {}^{10}Be + n$ $2s_{1/2} \longrightarrow$ p state

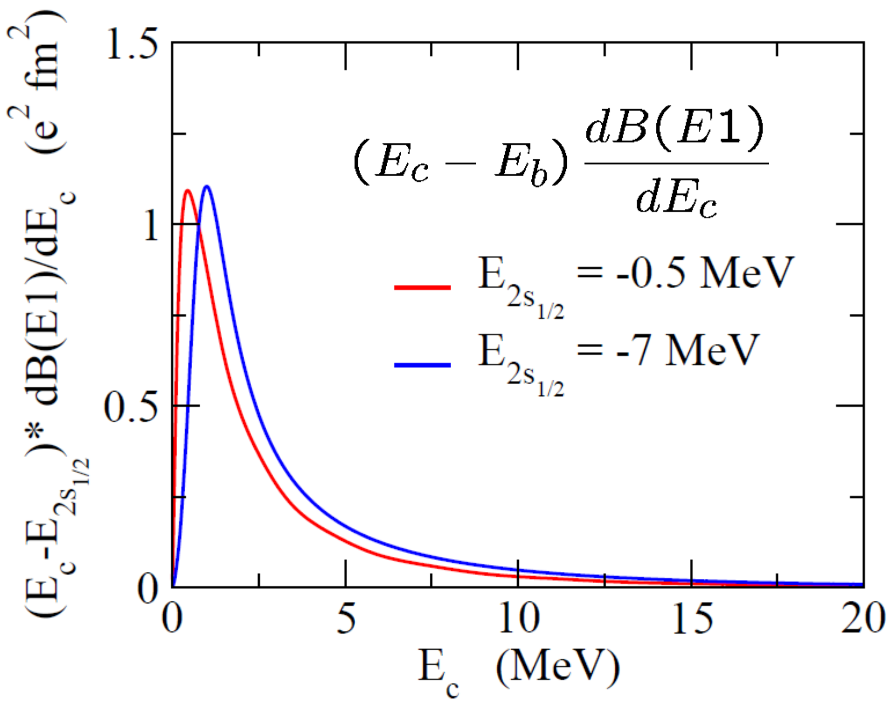
- a high and sharp peak as the bound state energy, $|E_b|$, becomes small

$$S_0 = \int_0^\infty dE_c \frac{dB(E1)}{dE_c}$$

$=1.53\ e^2fm^2$ (E_b = -0.5 MeV)
$0.32\ e^2fm^2$ (E_b = -7 MeV)

- As the bound state energy, $|E_b|$, gets small, the peak appears at a low energy

E_{peak} = 0.28 MeV (E_b=-0.5 MeV)
0.96 MeV (E_b = -7MeV)



- Weak E_b dependence when the transition strength is multiplied by $(E_c - E_b)$

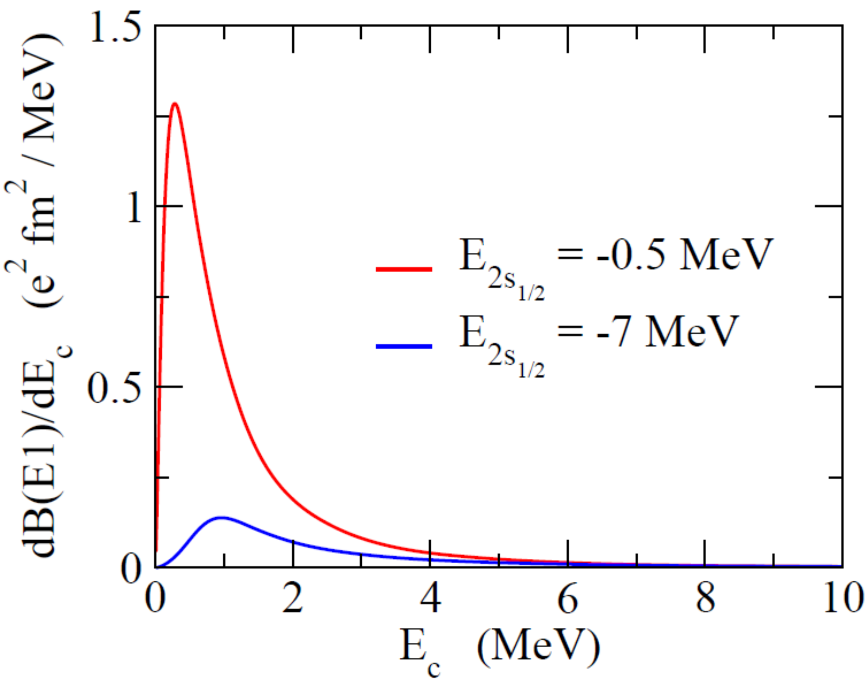
$$S_1 = \int_0^\infty dE_c (E_c - E_b) \frac{dB(E1)}{dE_c}$$

$=2.79\ e^2fm^2$ MeV (E_b = -0.5 MeV)
$3.18\ e^2fm^2$ MeV (E_b = -7 MeV)

Sum Rule

$$S_0 = \int_0^\infty dE_c \frac{dB(E1)}{dE_c} = \frac{3}{4\pi} e_{E1}^2 \langle r^2 \rangle_i$$

Total E1 transition probability: proportional to the g.s. expectation value of r^2



$$S_0 = \int_0^\infty dE_c \frac{dB(E1)}{dE_c}$$

=1.53 $e^2 fm^2$ (E_b = -0.5 MeV)
0.32 $e^2 fm^2$ (E_b = -7 MeV)

$$\frac{3}{4\pi} e_{E1}^2 \langle r^2 \rangle_i$$

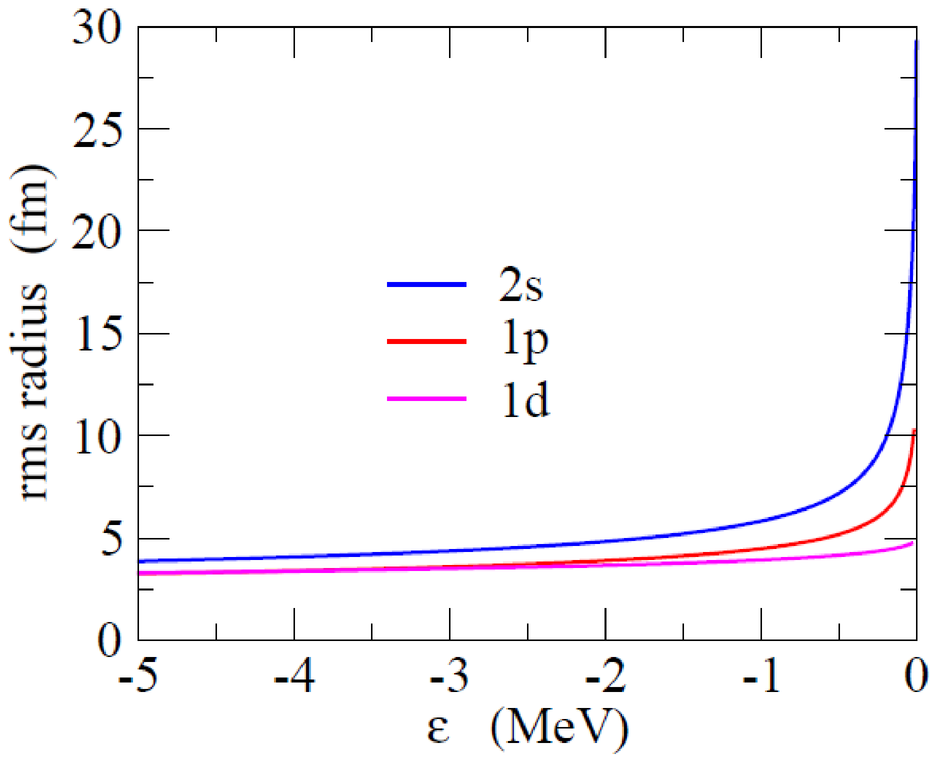
=1.62 $e^2 fm^2$ (E_b = -0.5 MeV)
0.41 $e^2 fm^2$ (E_b = -7 MeV)

* almost coincide with each other. Small difference due to Pauli forbidden transitons (the transition from 2s to 1p)

Sum Rule

$$S_0 = \int_0^\infty dE_c \frac{dB(E1)}{dE_c} = \frac{3}{4\pi} e_{E1}^2 \langle r^2 \rangle_i$$

Total E1 transition probability: proportional to the g.s. expectation value of r^2



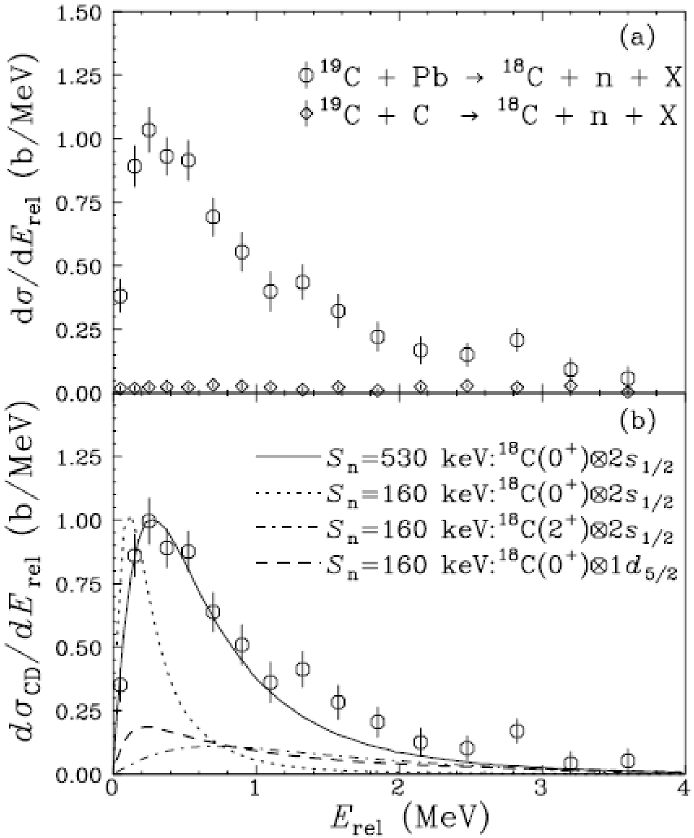
If the initial state is l=0 or l=1, the radius increases forweakly bound

Enhancement of total E1 prob.

Inversely, if a large E1 prob. (or a large Coul. b.u. cross sections) are observed, this indicates l=0 or l=1 $\longrightarrow$ halo structure

Other candidates for 1n halo nuclei

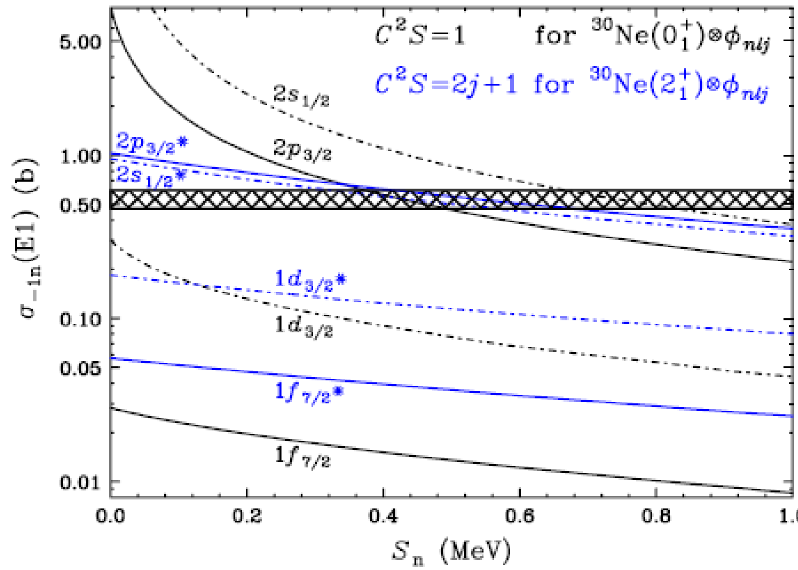
^{19}C: S_n = 0.58(9) MeV



Coulomb breakup of ^{19}C

T. Nakamura et al., PRL83(‘99)1112

^{31}Ne: S_n = 0.29 +/- 1.64 MeV

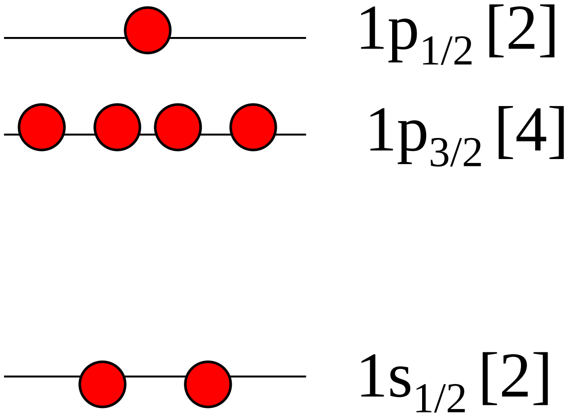


Large Coulomb breakup cross sections

T. Nakamura et al., PRL103(‘09)262501

Nuclear deformation

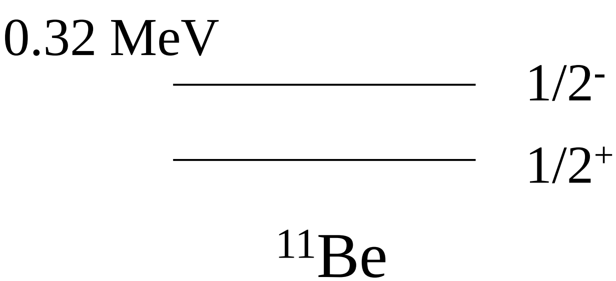
With a spherical potential :



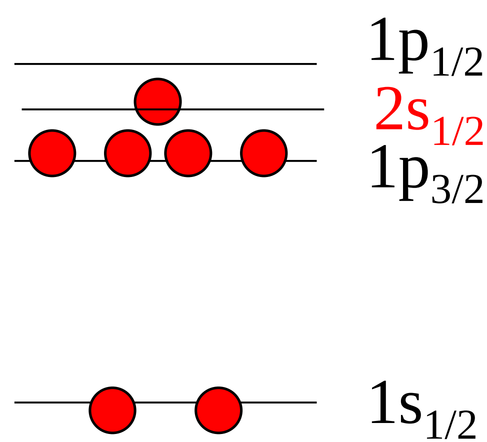
The g.s. of ^{11}Be : $I^{\pi} = 1/2^{-}$

very artificial

In reality…..



?



"parity inversion"

What happens if ^{11}Be is deformed?

s.p. motion in a deformed potential

halo : only for l = 0 or 1

⇒ however, a possibility is enlarged for a deformed nucleus

deformed potential $V(r,\theta)$ ⟶ mixture of angular momenta

e.g.,

$$|d_{5/2}\rangle \to |d_{5/2}\rangle + |s_{1/2}\rangle + |g_{7/2}\rangle + \cdots$$

$$|f_{7/2}\rangle \to |f_{7/2}\rangle + |p_{3/2}\rangle + |p_{1/2}\rangle + \cdots$$

(note) $s_{1/2}$: $\Omega^\pi = 1/2^+$ only
$p_{1/2}$: $\Omega^\pi = 1/2^-$ only
$p_{3/2}$: $\Omega^\pi = 3/2^-$ and $1/2^-$ only

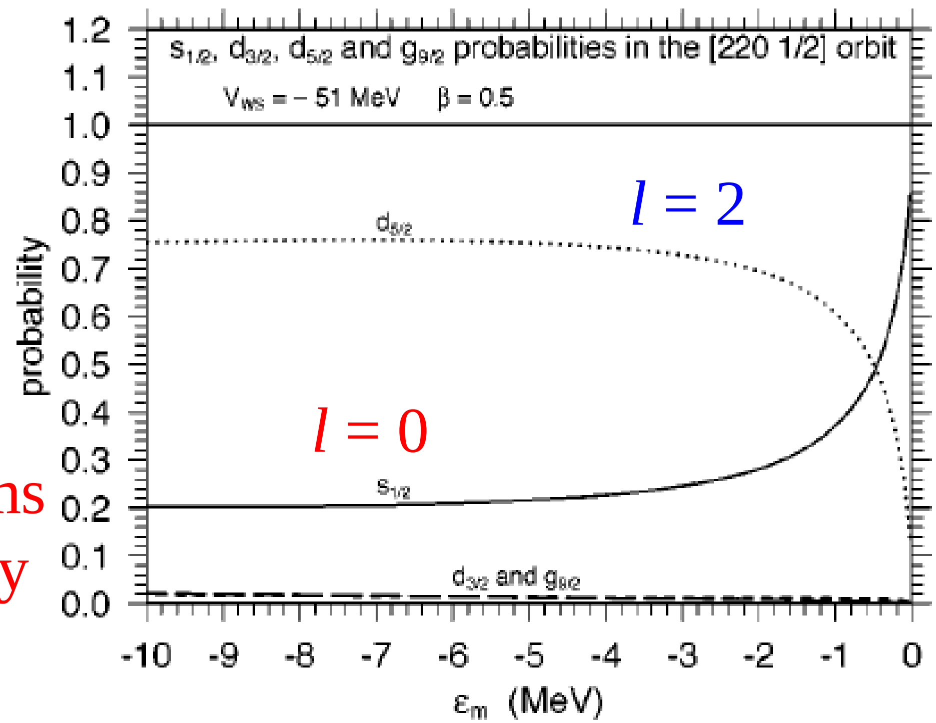
⟶ possibility of halo only for s.p. states with $\Omega^\pi = 1/2^+, 1/2^-, 3/2^-$

s.p. motion in a deformed potential

$$|d_{5/2}\rangle \;\rightarrow\; |d_{5/2}\rangle + |s_{1/2}\rangle + |g_{7/2}\rangle + \cdots$$

$$\rightarrow\; |s_{1/2}\rangle \qquad (|\epsilon| \rightarrow 0)$$

T. Misu, W. Nazarewicz, and S. Aberg, NPA614('97)44 (deformed square well)

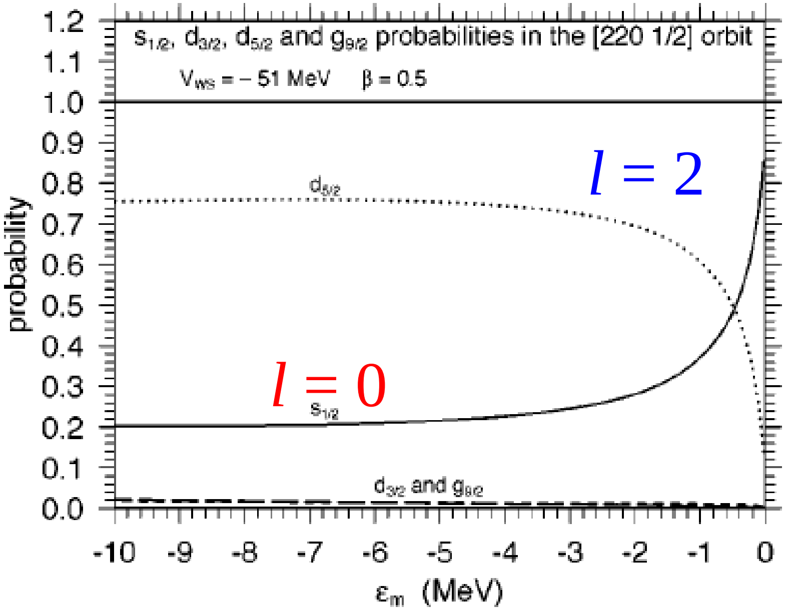


When weakly bound, the l=0 terms becomes dominant even for a very small deformation

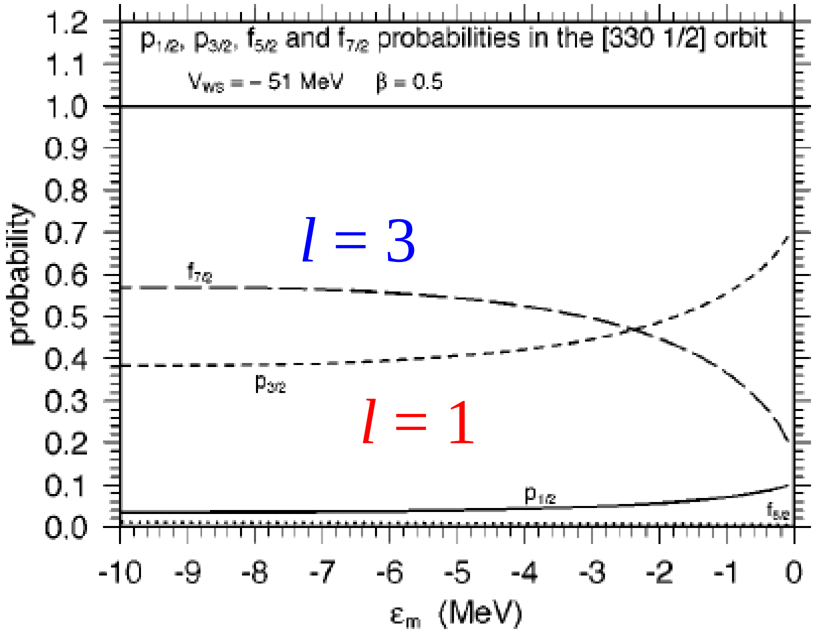
(in the zero binding limit, 100% of l=0 component)

I. Hamamoto, PRC69('04)041306(R) (deformed Woods-Saxon)

s-wave dominance phenomenon



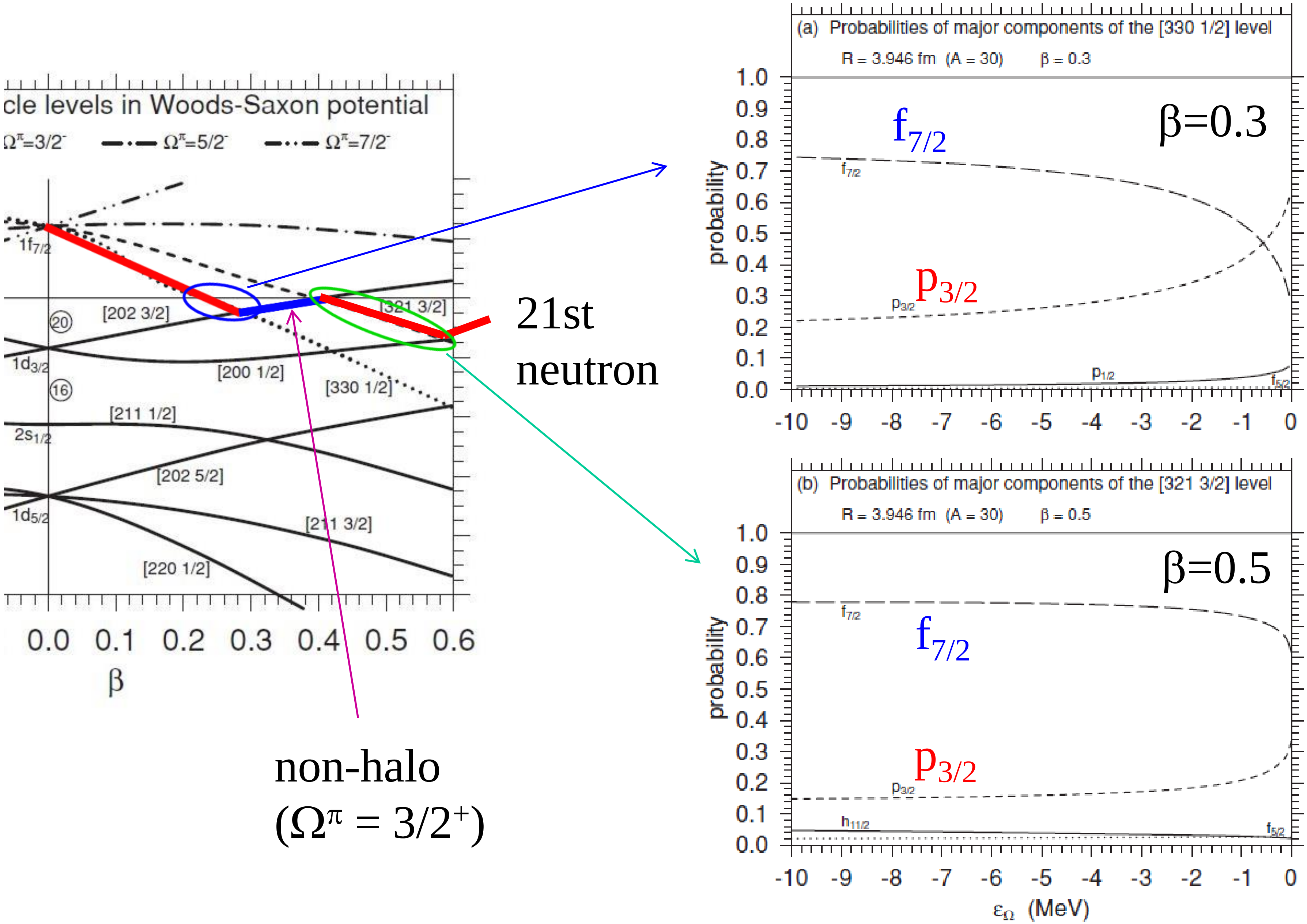
I. Hamamoto, PRC69('04)041306(R)



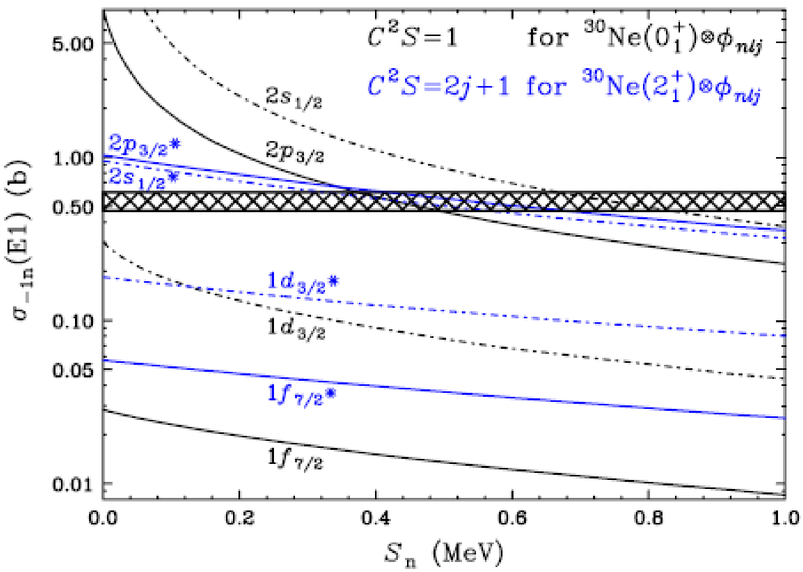
$l = 1$ component is also enhanced when weakly bound (but, always less than 100%)

a possibility of deformed halo nucleus: ^{31}Ne

Nilsson model analysis [I. Hamamoto, PRC81('10)021304(R)]

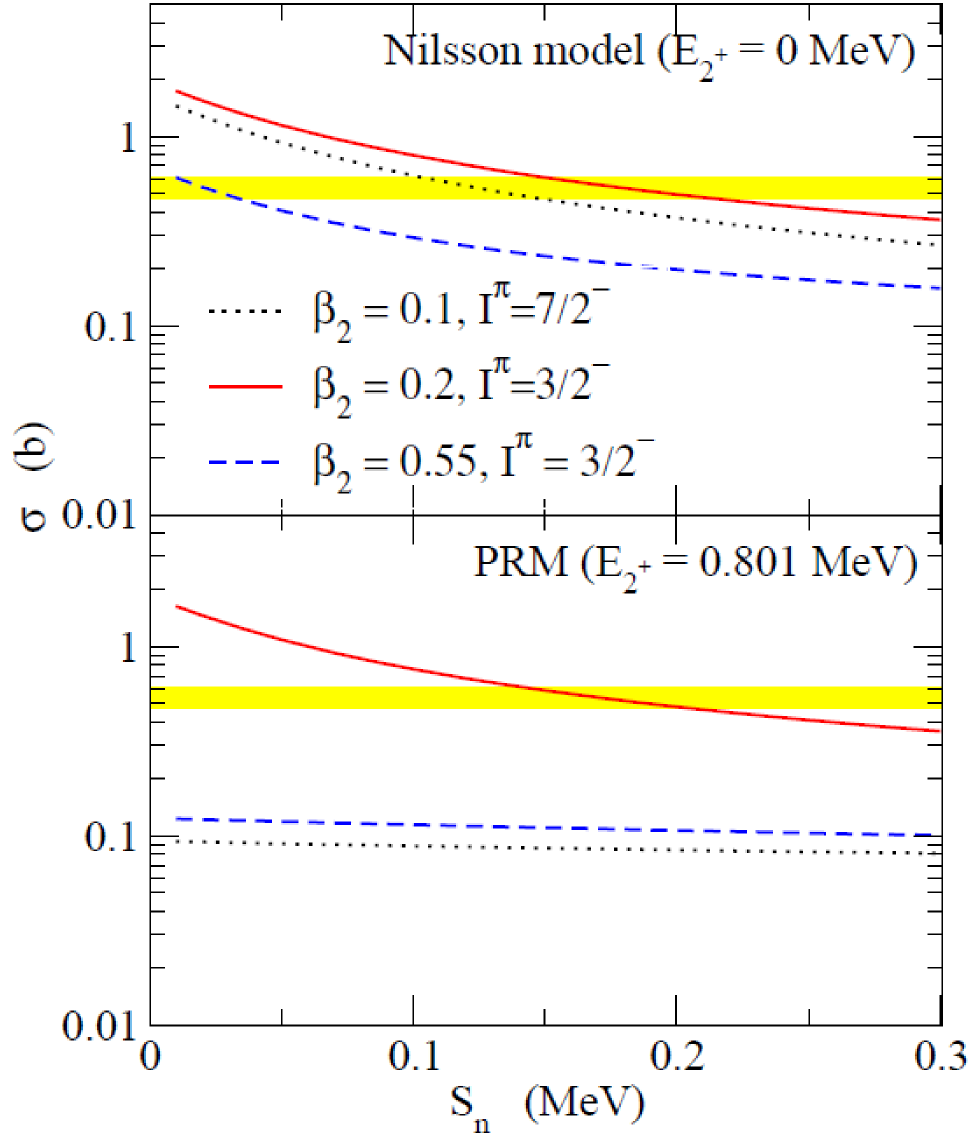


^{31}Ne



Large Coulomb breakup cross section

T. Nakamura et al., PRL103('09)262501



Y. Urata, K.Hagino, and H. Sagawa, PRC83('11)041303(R)

Another example: ^{37}Mg

PRL 112, 242501 (2014) PHYSICAL REVIEW LETTERS week ending 20 JUNE 2014

Observation of a *p*-Wave One-Neutron Halo Configuration in ^{37}Mg

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