Extremely neutron-rich nuclei probed by breakup reactions with rare-isotope beams

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Clusters & Hierarchies

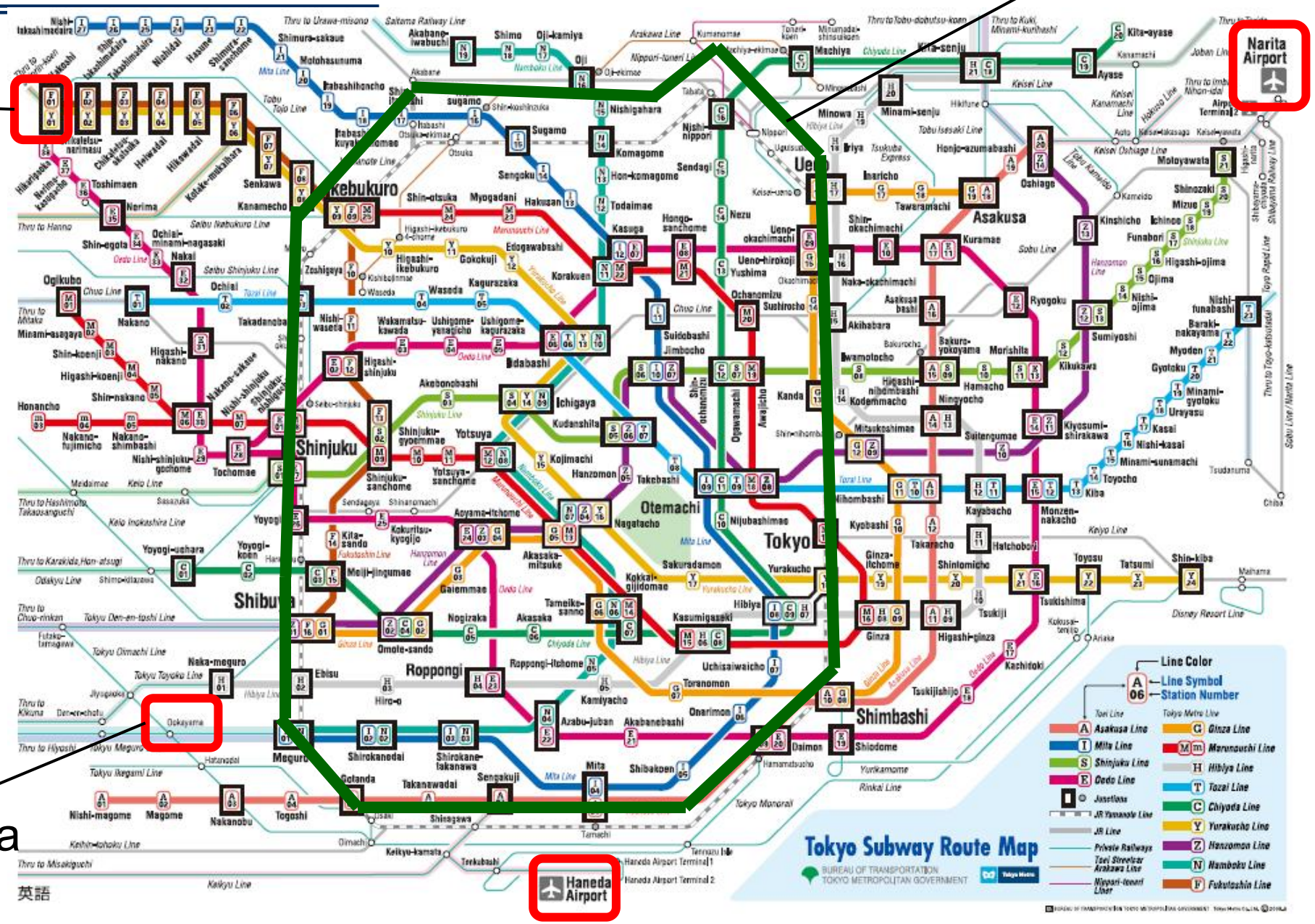
Nuclear Physics School for Young Scientists (NUSYS-2023) @ Fudan University, Shanghai, China, Aug 6-13, 2023

Where's Tokyo Institute of Technology?

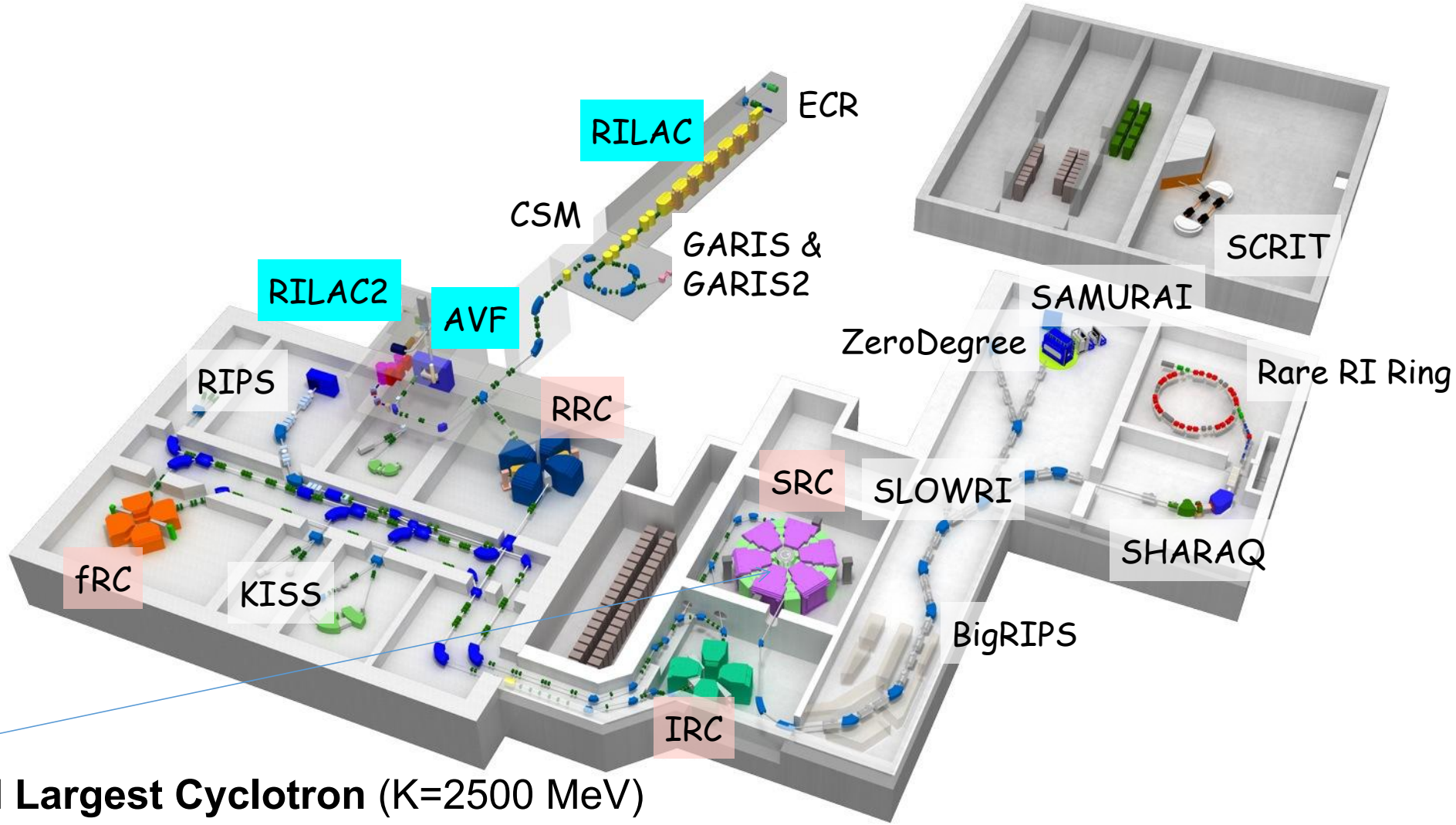
JR-Yamanote Line

RIKEN
@Wako-shi

Tokyo Tech
@O-Okayama



RIKEN-RIBF(RI-Beam Factory)



SRC: World Largest Cyclotron (K=2500 MeV)

High-Intense Heavy Ion Beams up to ^{238}U at 345MeV/u

eg. ^{48}Ca: ~700pnA (~4x10^{12}pps) *~10 times compared to 2008*

^{238}U: ~70pnA (~4x10^{11} pps) *~10^{3} times compared to 2007*

Contents

- Lecture-I: Clustering, Hierarchical Structure of Matter, and Nuclear Halo
  - Clusters and Hierarchies of Matter, Semi-hierarchy
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  - Three Signals of Neutron Halo
  - Anatomy of Neutron-halo nucleus
- Lecture-II: Coulomb breakup of Neutron Halo Nuclei and Soft E1 Excitation
  - Soft dipole resonance and Soft E1 excitation —Original Idea
  - Coulomb breakup
  - Coulomb breakup of one-neutron halo nuclei → ^{11}Be, ^{19}C,^{31}Ne
  - Coulomb breakup of two-neutron halo nuclei →^{11}Li,^{19}B,^{6}He
- Lecture-III: Multi-neutron states using quasi-free scattering
  - Tetra-neutron
  - ^{28}O: The last canonical doubly magic nucleus?
  - Perspectives: More multi-neutron nuclei

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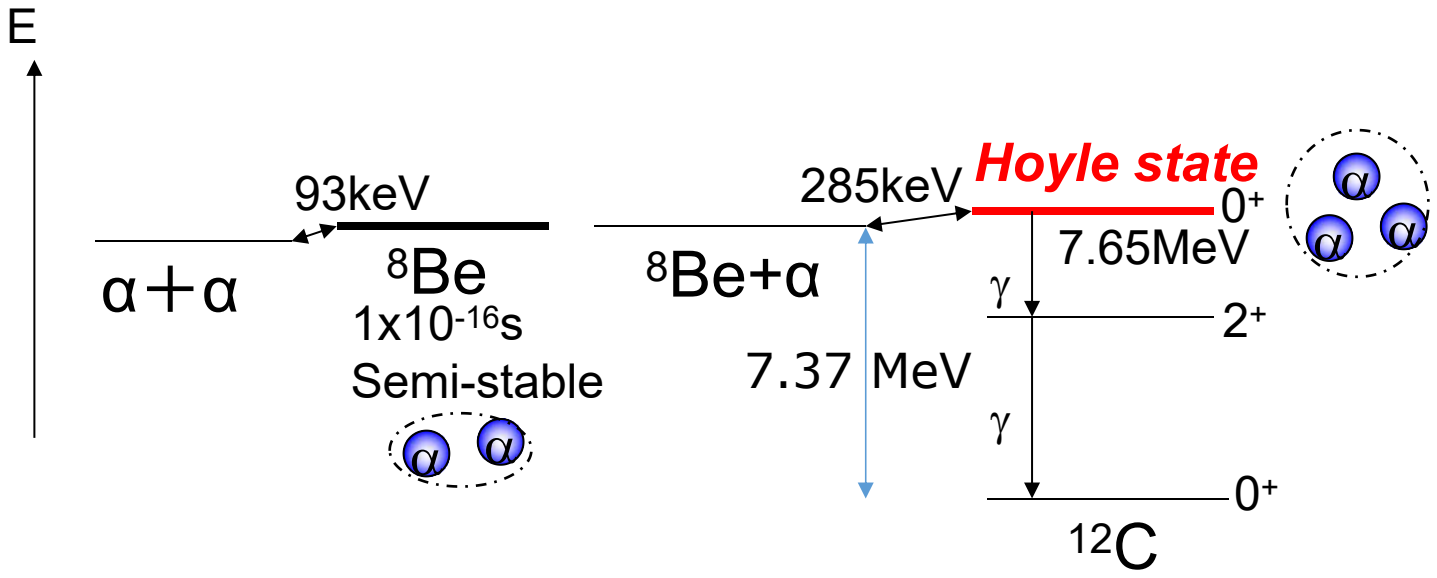
Our existence depends on a subtle balance of Nature

Triple α Reaction

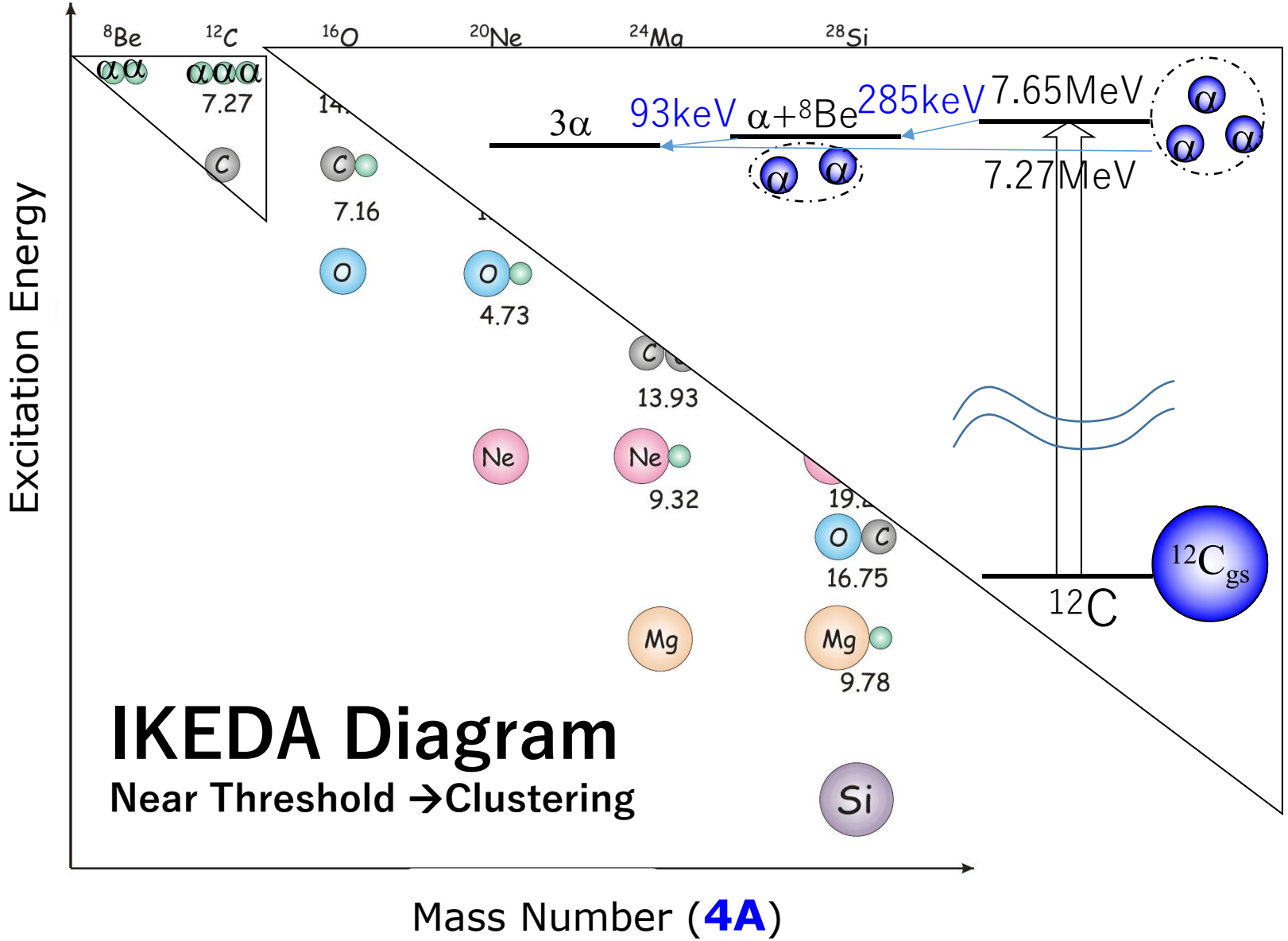
Detour for the synthesis of element ^{12}C

(C was not produced in the Big Bang due to the A=5,8 gaps)

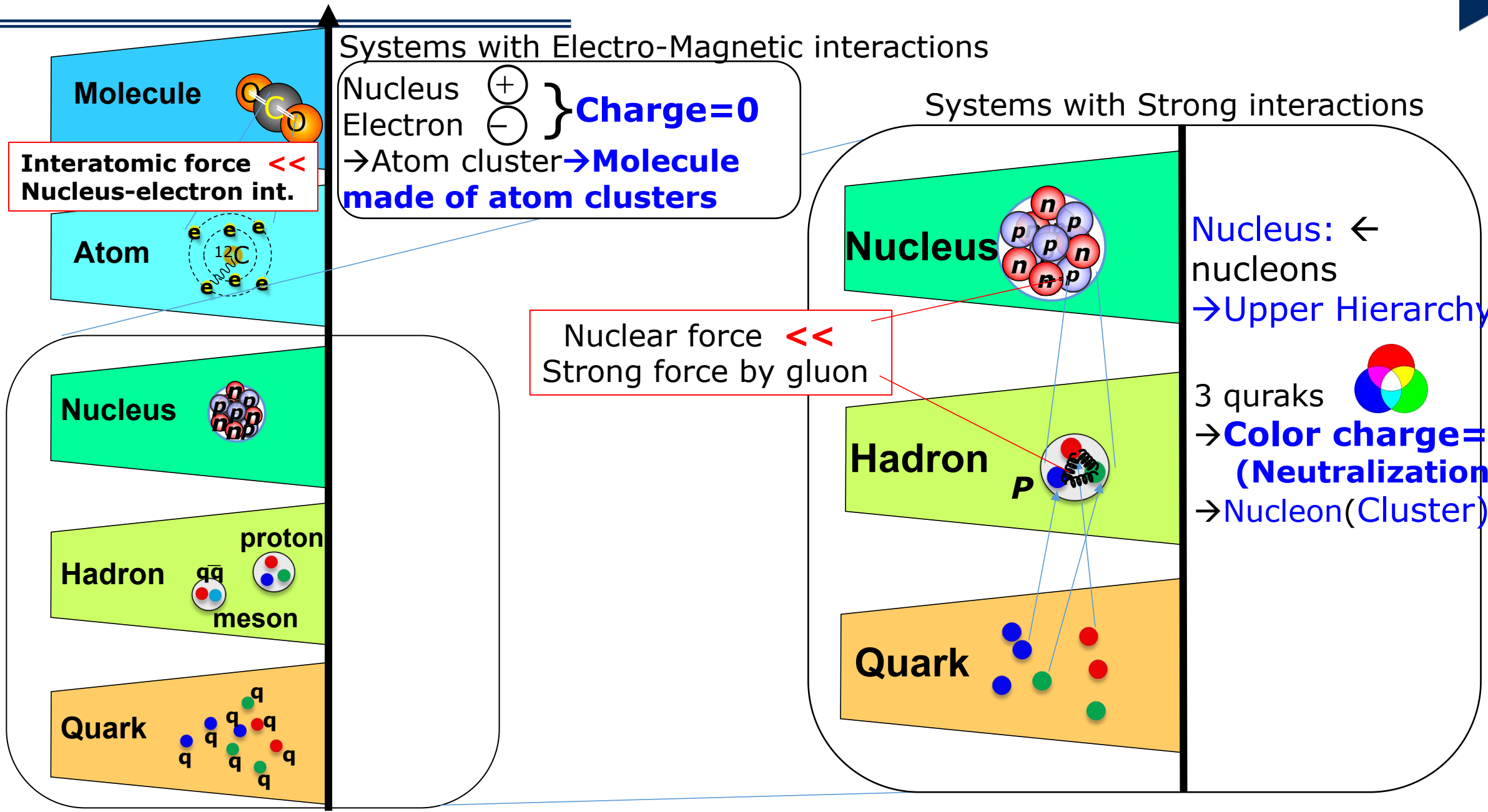


α-Cluster

K.Ikeda, N.Takigawa, H.Horiuchi,Prog.Theo.Phys.Suppl.464.(1968).
M.Freer, Rep. Prog. Phys. 70, 2149 (2007).

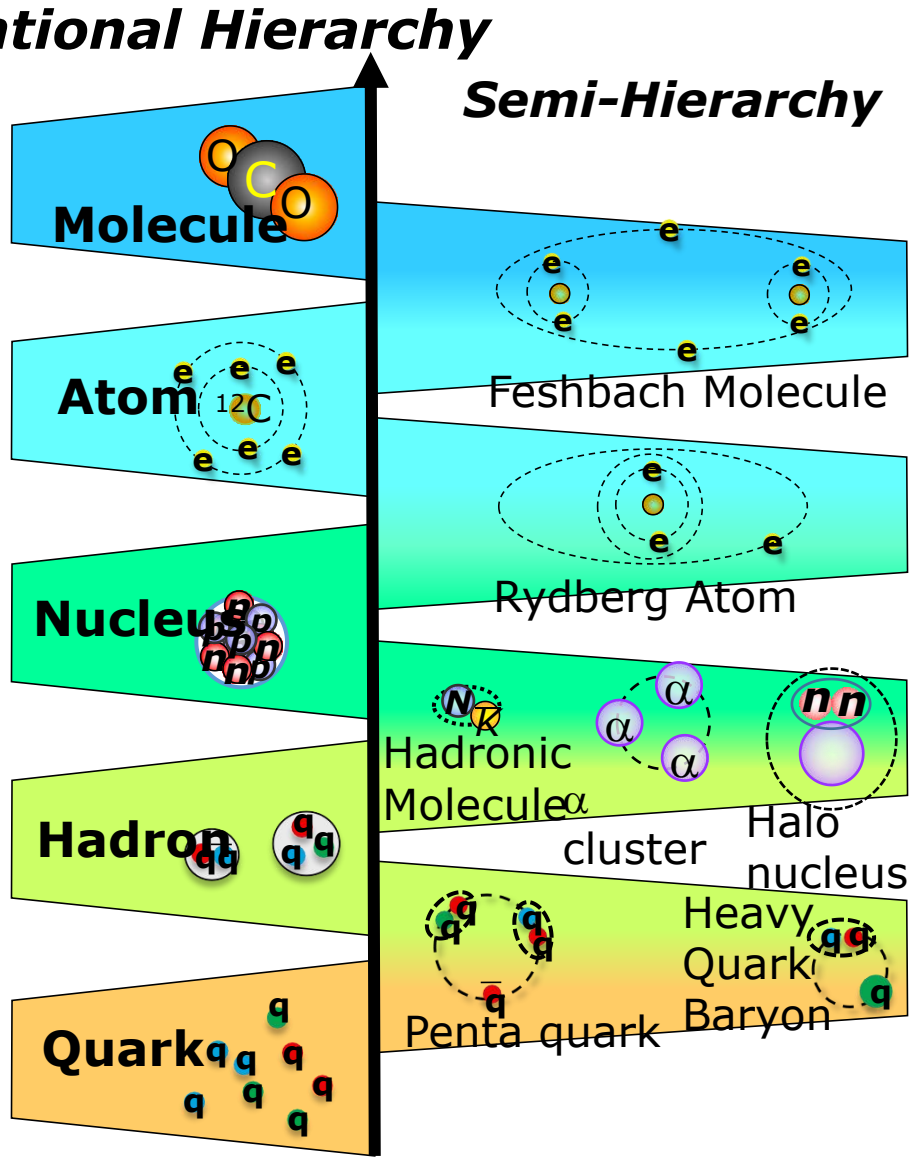


Clustering: Key to understand **hierarchy** in quantum world



Clusters and Semi-Hierarchy

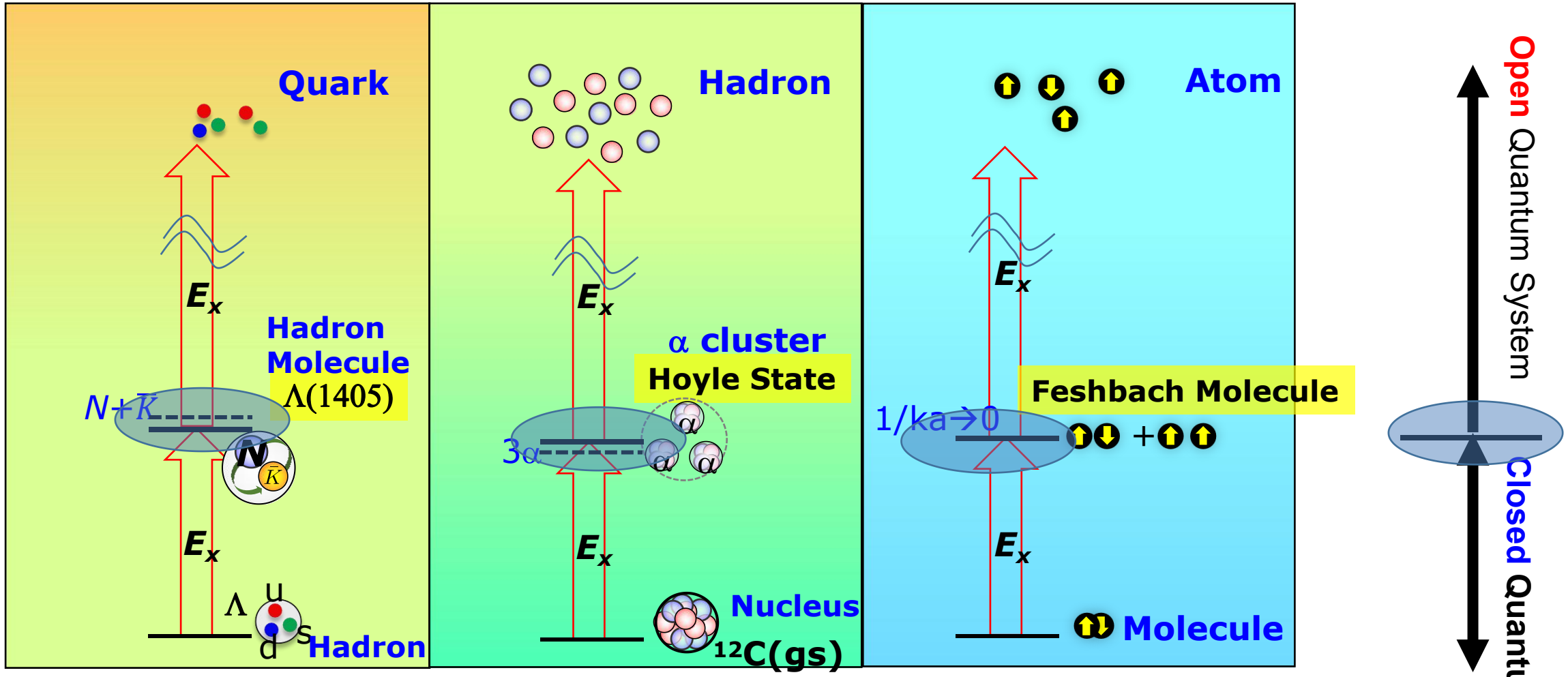
- ✓ Big Gap between Hierarchies
- ✓ **Strongly Bound**
- ✓ Simple constituents: Nucleus= "nucleonic" system



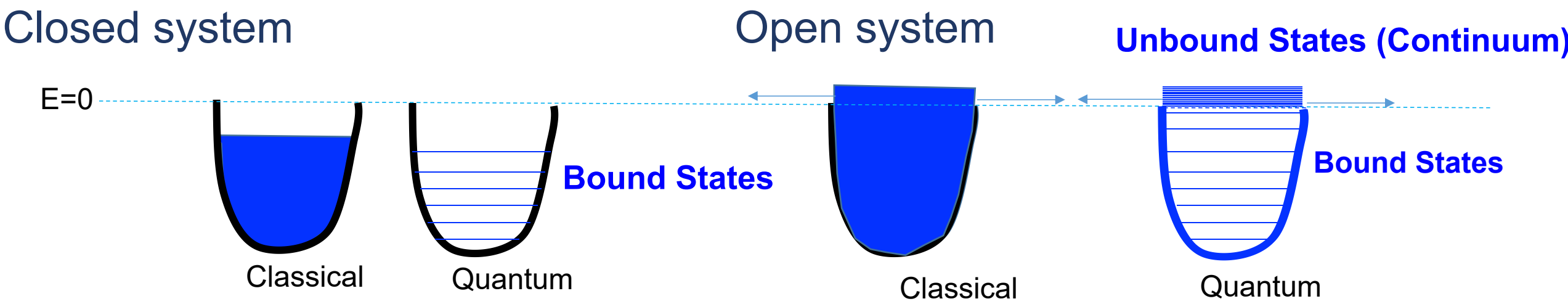
- ✓ Smaller Gap between Hierarchies
- ✓ **Weakly Bound (Unbound)**
- ✓ Mixed constituents: Halo Nucleus =*"nucleonic"+"dineutron" system*

Semi-Hierarchy: **Key Aspects to understand the hierarchical structure of matter**

Semi-Hierarchy: Clustering and Hierarchy of Matter



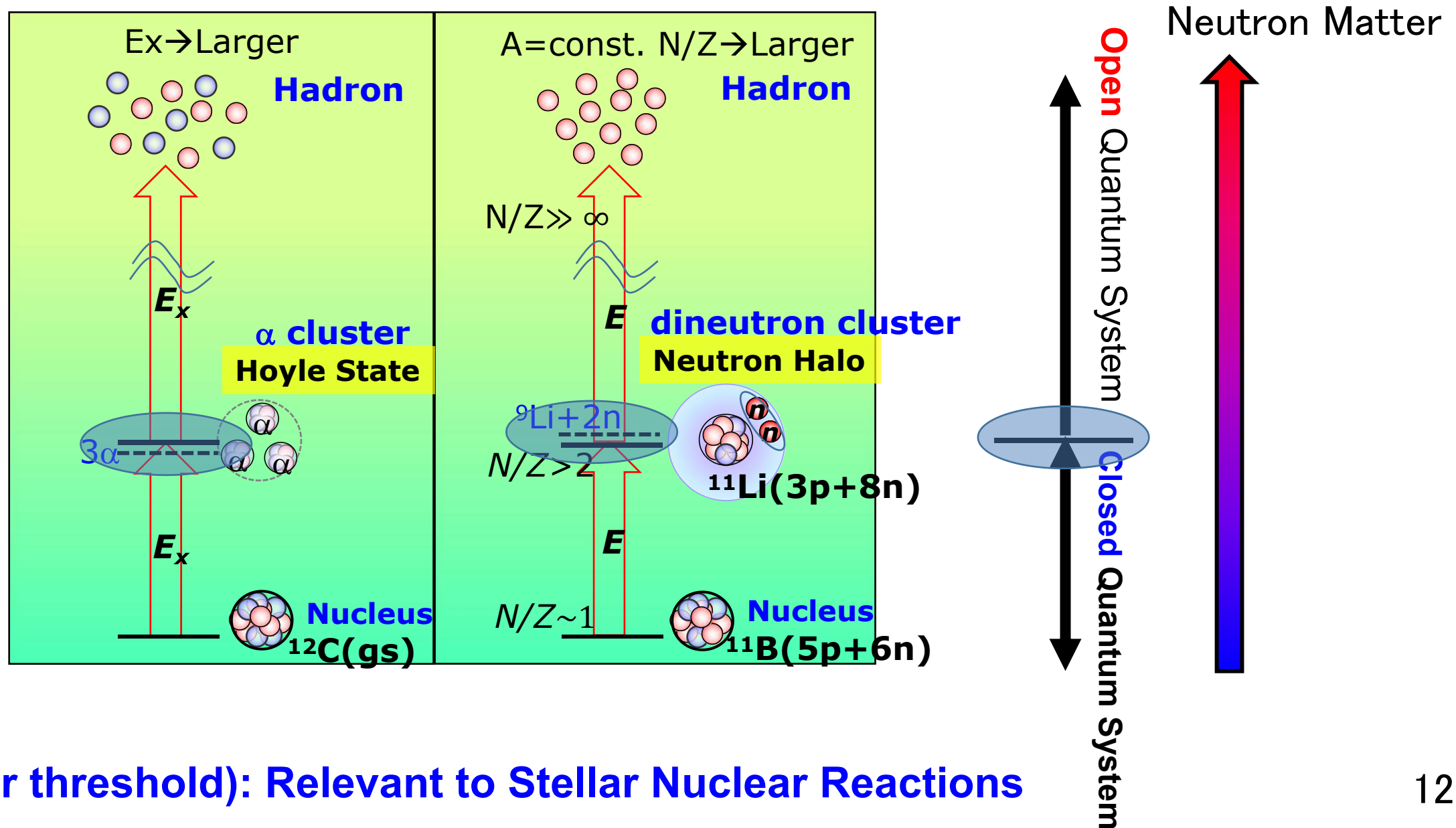
Closed or Open?



- Normal particles: Bound and Isolated system→ Closed quantum system
- Particles at the edge: Highly excited states → (Near) Open quantum system

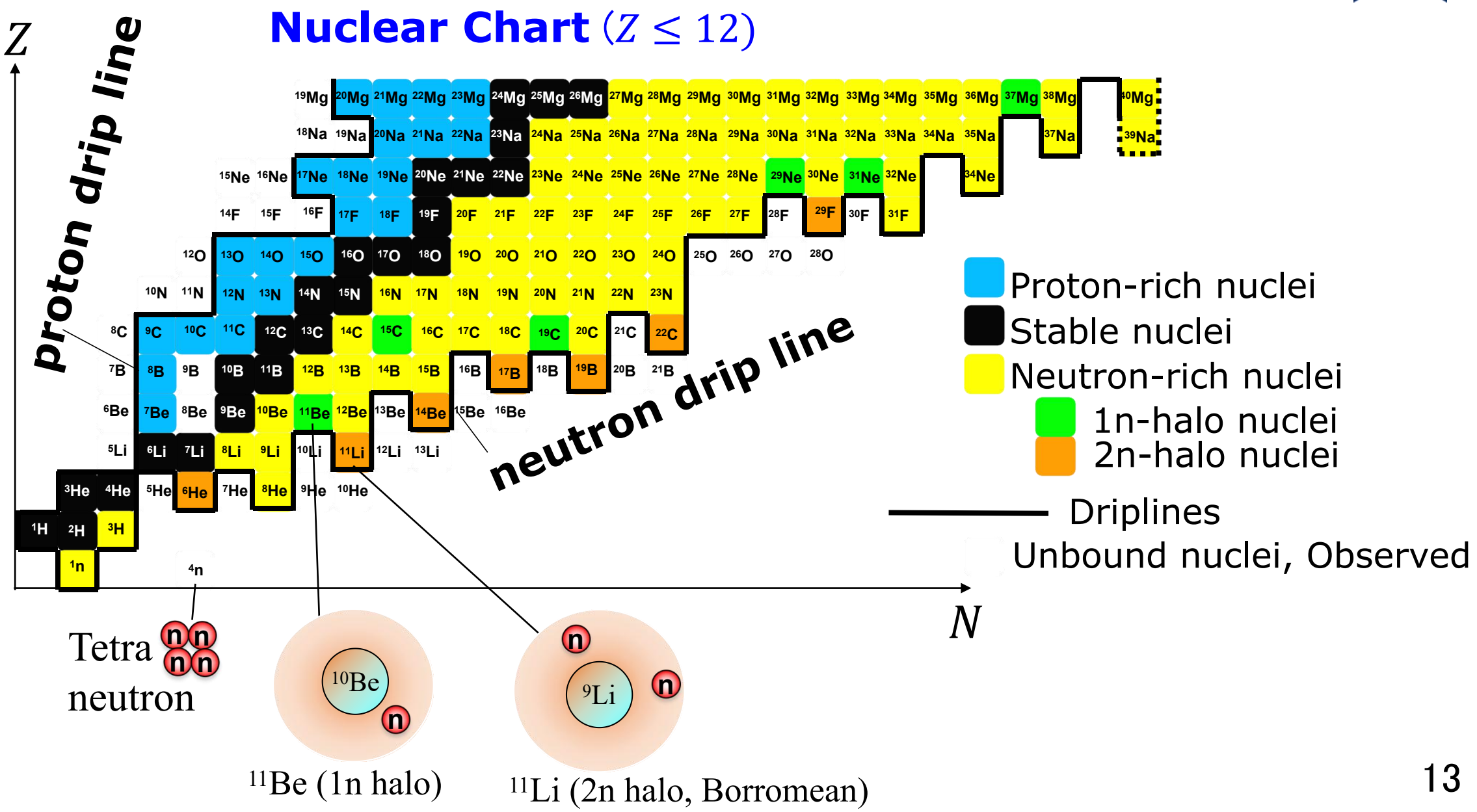
Boundary of Open-Closed regions: → Exotic phenomena?

Edges: Boundary of open/closed quantum systems

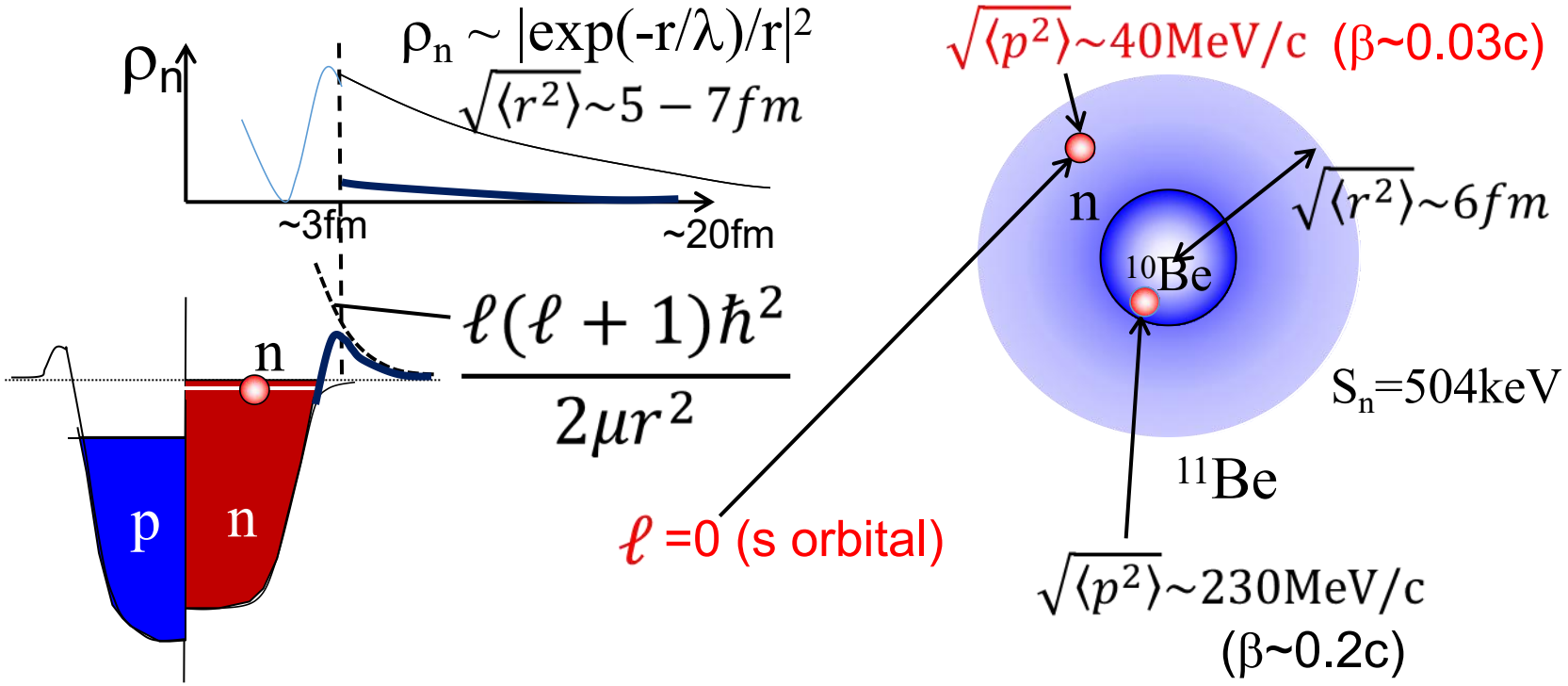


Edges (near threshold): Relevant to Stellar Nuclear Reactions

Nuclear Landscape at the limit



One-neutron halo nucleus



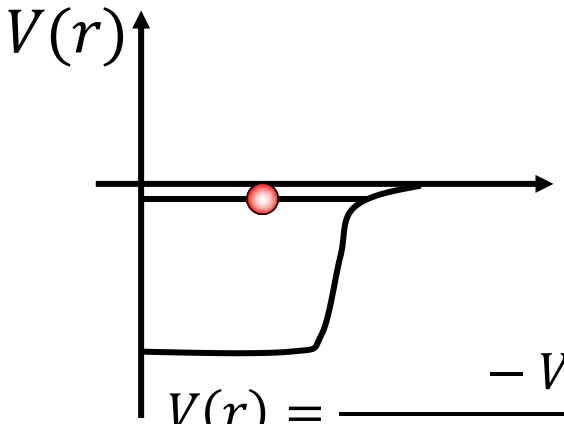
- Small $S_n < 1$ MeV ($\ll 8$ MeV)
- Extended ρ_n distribution beyond the range of nuclear force

  $\langle r \rangle \to \infty$ for $S_n \to 0$ $\quad (\sqrt{\langle r^2 \rangle} \sim 1/S_n)$ $\quad \sim 0.1nm\ at\ S_n = 1meV$
- Small Fermi Momentum → Small Kinetic Energy
- Small Orbital Angular Momentum $l = 0, 1$ (s, p) (Small Centrifugal Barrier)

⇨ Nuclear Stability At the Limit←→ Shell Evolution/Deformation
←→ Halo Structure

Note1: How halo is formed?—(Case of 1n halo)

Separation energy (S_n)←→ Halo

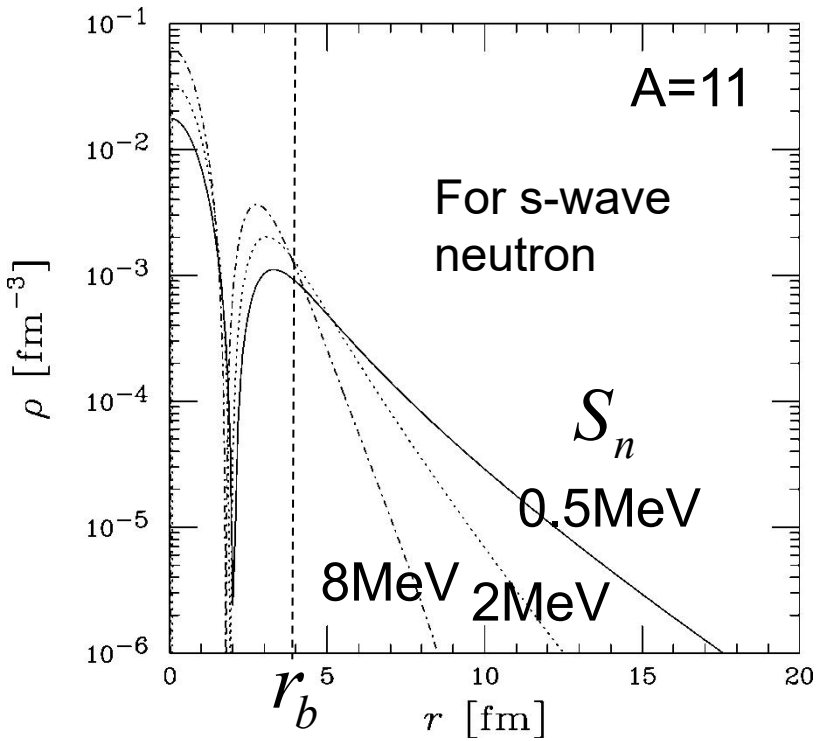


$$V(r) = \frac{-V_0}{1+\exp[(r-R_0)]}$$

Radial wave function for 3-D Shrodinger Equation

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

$$-\frac{\hbar^2}{2\mu}\frac{d^2u}{dr} + \left[V(r) + \underbrace{\frac{l(l+1)\hbar^2}{2\mu r^2}}_{\text{Centrifugal Barrier}}\right]u = Eu = -S_n u$$



$for\ l = 0$ (s-wave)

$$R(r) = Bh_0(ikr) \sim \frac{e^{-kr}}{kr} \qquad k = \sqrt{2\mu S_n}/\hbar$$

Yukawa-type wave function

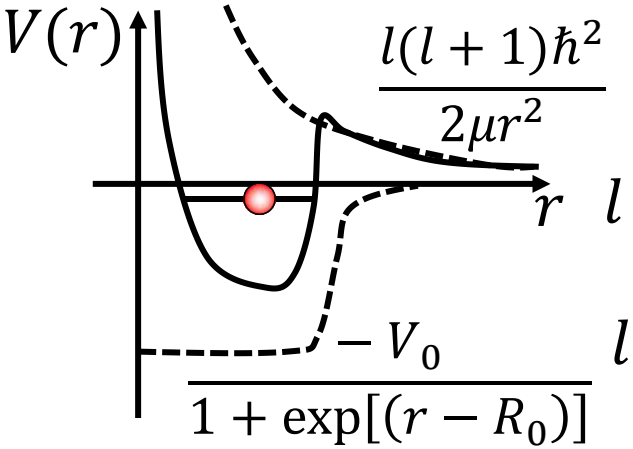
(Spherical Hankel's function)

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

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

Note2: How halo is formed?--

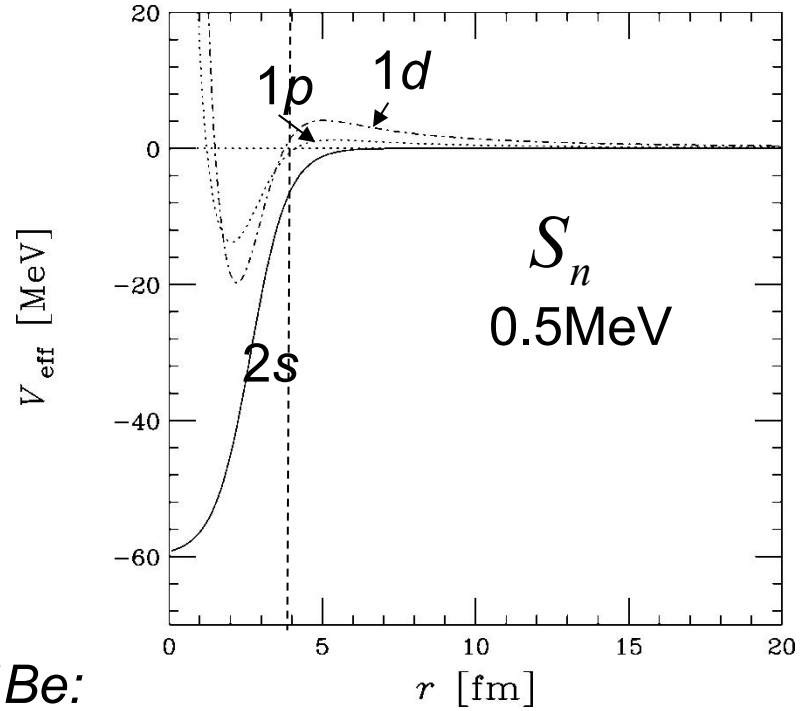
Angular momentum (l) of a single particle state←→ Halo

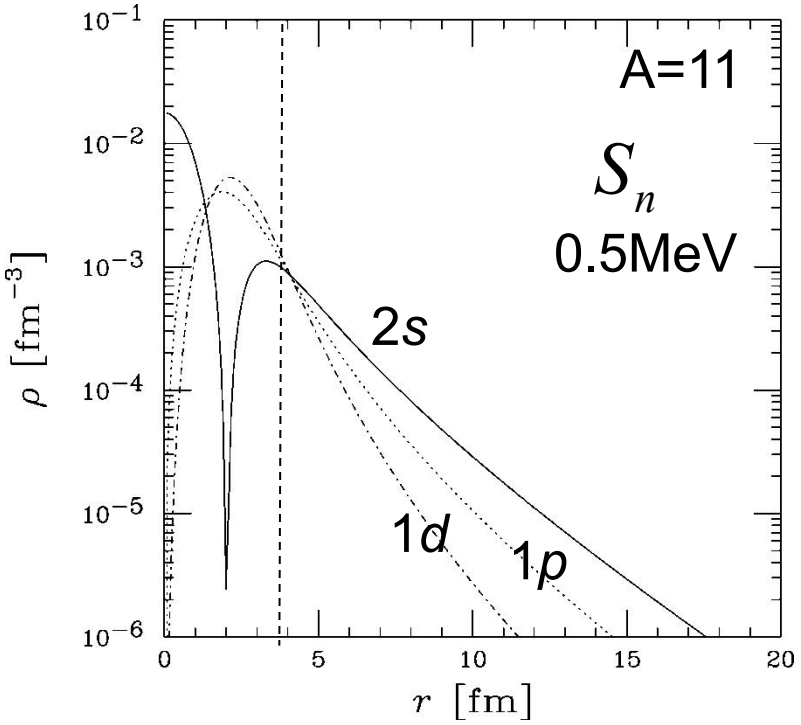


$$R(r) = Bh_l^{(1)}(ikr)$$

$l = 1$ (p-wave): $$R(r) = Bh_1^{(1)}(ikr) \sim \left[\frac{1}{kr} + \frac{1}{(kr)^2}\right] e^{-kr}$$

$l = 2$ (d-wave): $$R(r) = Bh_2^{(1)}(ikr) \sim \left[\frac{1}{kr} + \frac{3}{(kr)^2} + \frac{3}{(kr)^3}\right] e^{-kr}$$



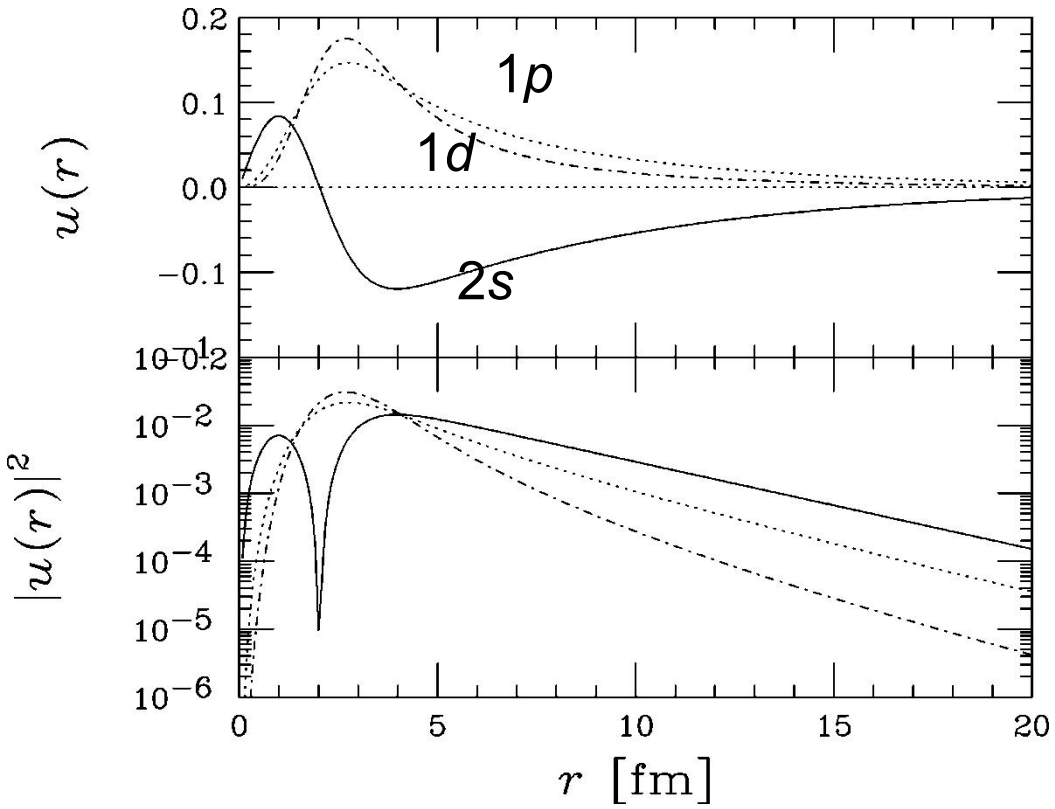


e.g. *^{11}Be:*
valence neutron is either 2s,1p,1d

memo

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

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

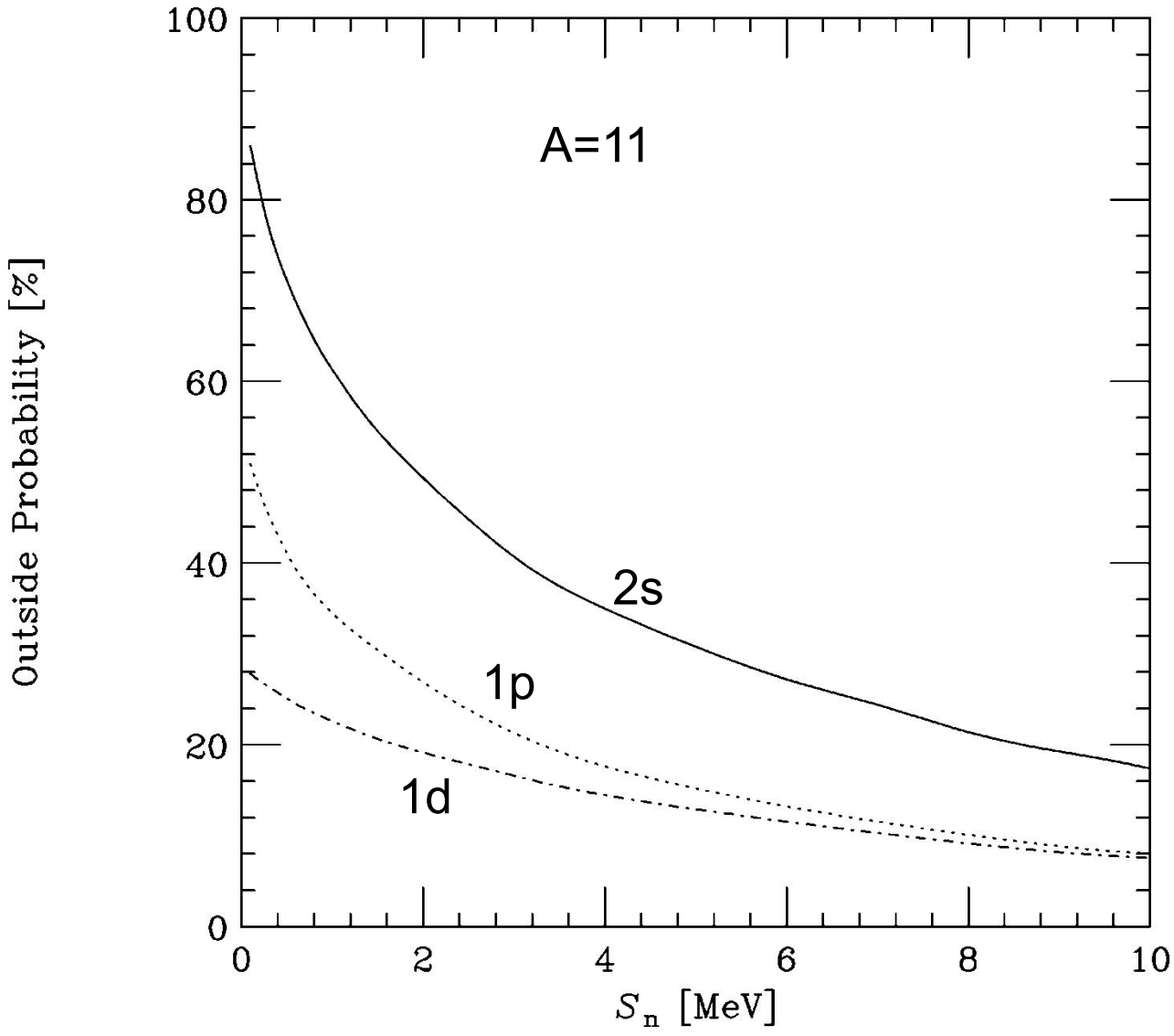


S_n
0.5MeV

HALO: How it is extended?

"Probability of being outside"

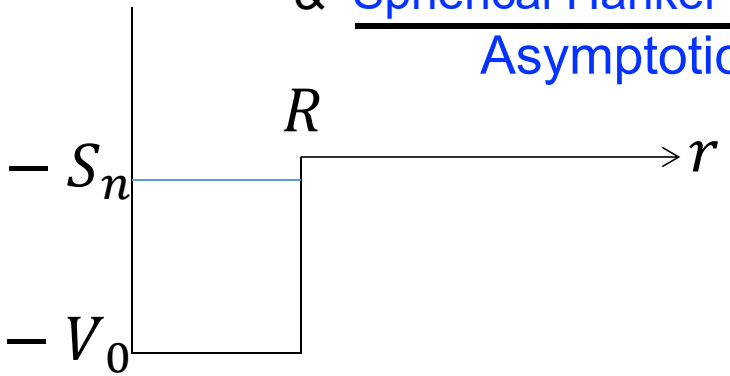
$$= \int_{R0+(\ln 9)a}^{\infty} |R(r)|^2 4\pi r^2 dr$$



memo

For Square-well Potential, Solutions for the Radial Wave Fn
R(r) (not u(r)) can be written by Spherical Bessel functions $j_l(kr)$(r<R)
& Spherical Hankel function of the 1st kind $h_l^{(1)}$(r>R)

Asymptotic w.f. for any short-range mean-field potential



$$\frac{d^2R}{d\rho}+\frac{2}{\rho}\frac{dR}{d\rho}+\left[1-\frac{l(l+1)}{\rho^2}\right]R=0$$

$$\rho=\kappa r \quad r\le R$$

$$\rho=ikr \quad r>R$$

Solutions

$$r<R \quad k=\sqrt{2\mu(V_0-S_n)}/\hbar$$

$$R(r)=Aj_l(ikr)$$

$$j_0(\kappa r)=\frac{\sin\kappa r}{\kappa r}$$

$$j_1(\kappa r)=\frac{\sin\kappa r}{(\kappa r)^2}-\frac{\cos\kappa r}{\kappa r}$$

$$j_2(\kappa r)=\left(\frac{3}{(\kappa r)^3}-\frac{1}{\kappa r}\right)\sin\kappa r-\frac{3}{(\kappa r)^2}\cos\kappa r$$

$$j_l(\kappa r)\to\frac{\rho^l}{(2l+1)!!}\quad(\rho\to 0)$$

$$r>R \quad k=\sqrt{2\mu S_n}/\hbar$$

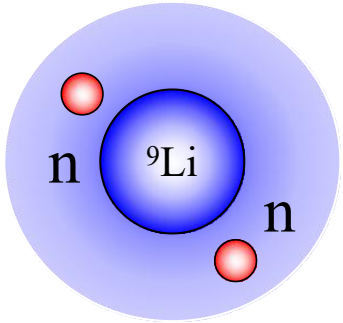
$$R(r)=Bh_l^{(1)}(ikr)$$

$$h_0^{(1)}(ikr)=-\frac{1}{kr}e^{-kr}$$

$$h_1^{(1)}(ikr)=i\left[\frac{1}{kr}+\frac{1}{(kr)^2}\right]e^{-kr}$$

$$h_2^{(1)}(ikr)=\left[\frac{1}{kr}+\frac{3}{(kr)^2}+\frac{3}{(kr)^3}\right]e^{-kr}$$

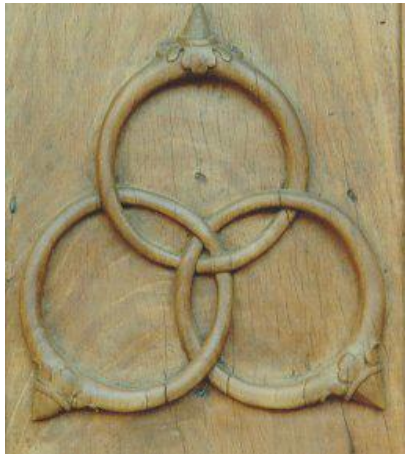
Two-neutron Halo nuclei



^{11}Li

(Z=3, N=8)

S_{2n}=0.37MeV



Borromean Ring

^{9}Li + n Barely Unbound

$a_s = -(13-23)$ fm PLB642, 449(2006).

n + n Barely Unbound

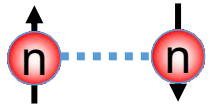
$a_s = -18.9(4)$ fm

^{9}Li + n+n Bound

S_{2n}=0.37MeV <<8MeV

- Small $S_{2n} < 1$ MeV ($\ll 8$ MeV)
- Extended ρ_n distribution beyond the range of nuclear force
- Small Fermi Momentum → Small Kinetic Energy
- Small Orbital Angular Momentum $l = 0, 1$ (s, p) (Small Centrifugal Barrier)
- Borromean
- Dineutron correlation (2n correlation, pair correlation)

Pairing correlation in Nuclei

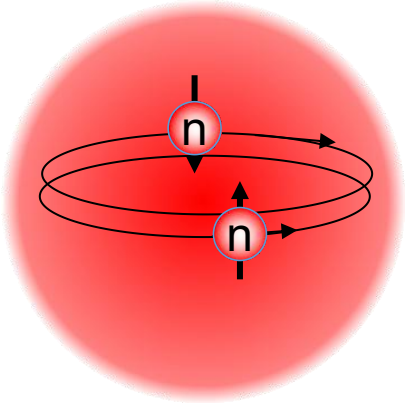


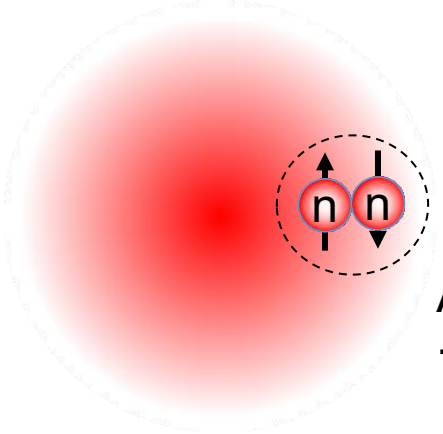
2n in Free space: S-wave Scattering Length: $a_s = -18.9(4) fm$

A.Gårdestig, J.Phys. G, Nucl. Part Phys. 36, 053001 (2009).

$|a_s| \gg r_e = 2.80(11) fm$

PRC36, 691 (1987)





A.B.Migdal, Sov.J.Nucl.Phys.**238**(1973).
→ Strong-correlated dineutron
(quasi-bound two neutrons)

BCS-like Pairing Correlation
(long range, weak coupling)

Known for (normal) nuclei for 60 years
*Bohr, Mottelson, Pines, Phys.Rev.**110**, 936(1958).*

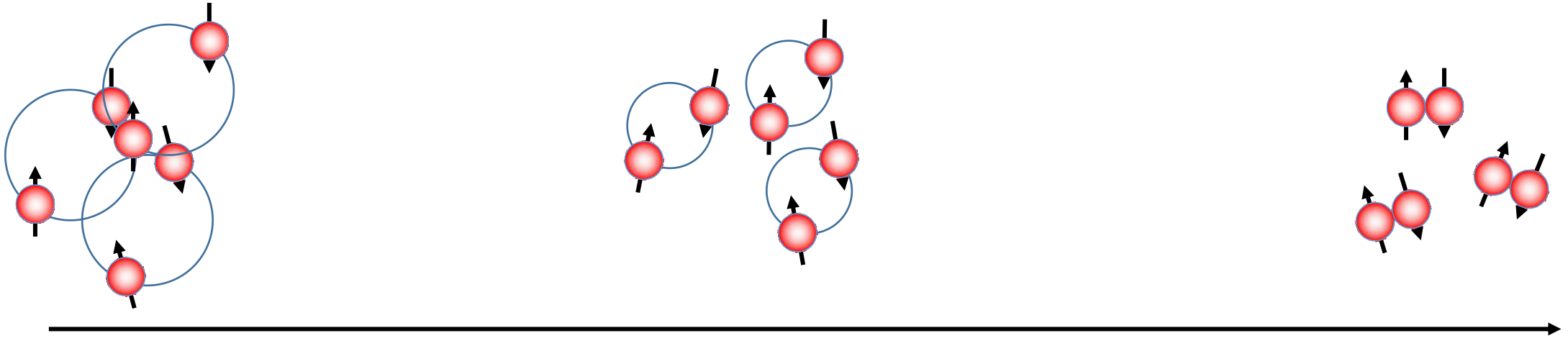
Dineutron correlation
（short-range, strong coupling)

Not yet established
(A Few examples suggested in Halo Nuclei)

Analogy in atomic systems

Ultra-cold atom experiments

Cooper pairs (BCS) Crossover Bose Gas (BEC)



Weak Pairing Interaction Strong

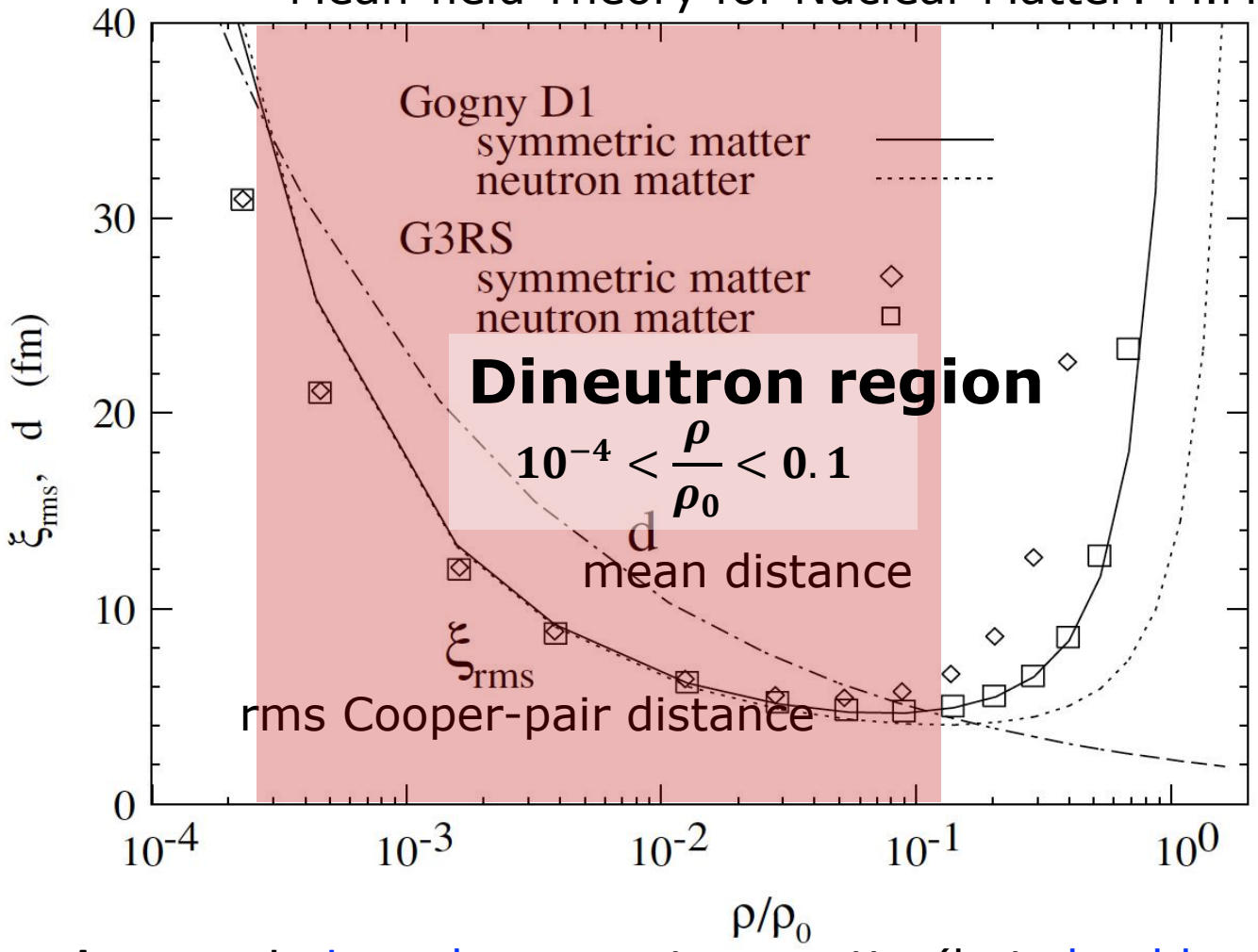
$(k_F a_s)^{-1}$

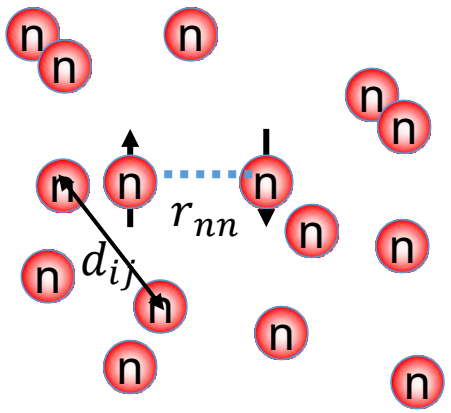
Density dependence of nn correlation

Mean-field Theory for Nuclear Matter: M.Matsuo Phys. Rev. C73, 044309 (2006).

$$\xi_{rms} = \sqrt{\langle r_{nn}{}^2 \rangle} = \int d\vec{r}\, r^2 |\psi_{pair}(r)|^2$$

rms distance of the cooper pair





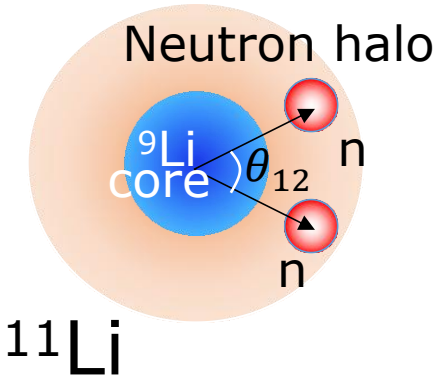
Neutron matter

Dineutron Appears in Low-dense neutron matter(but should not be too low) !

→ Dineutron appears near the surface of ^{9}Li core in ^{11}Li: ^{11}Li(p,pn) experiment

Y. Kubota et al., PRL **125**, 252501 (2020).

Dineutron: Mixture of Opposite-parity orbitals-- Essential



F. Catara, A. Insolia, E. Maglione, A.Vitturi, PRC29, 1091 (1984).

$$\Psi(^{11}\mathrm{Li}) = \phi(^{9}\mathrm{Li}) \otimes \left[\alpha\left(1p_{1/2}\right)^2 + \beta\left(2s_{1/2}\right)^2\right]$$

Core Two halo neutrons

$$\langle\cos\theta_{12}\rangle = \cancel{\alpha^2\left\langle\left(1p_{1/2}\right)^2|\cos\theta_{12}|\left(1p_{1/2}\right)^2\right\rangle} + \cancel{\beta^2\left\langle\left(2s_{1/2}\right)^2|\cos\theta_{12}|\left(2s_{1/2}\right)^2\right\rangle} + 2\alpha\beta\left\langle\left(2s_{1/2}\right)^2|\cos\theta_{12}|\left(1p_{1/2}\right)^2\right\rangle$$

If $\beta = 0$ $\quad \langle\cos\theta_{12}\rangle = \alpha^2\left\langle\left(1p_{1/2}\right)^2|\cos\theta_{12}|\left(1p_{1/2}\right)^2\right\rangle = 0$

If $\alpha = 0$ $\quad \langle\cos\theta_{12}\rangle = \beta^2\left\langle\left(2s_{1/2}\right)^2|\cos\theta_{12}|\left(2s_{1/2}\right)^2\right\rangle = 0$

$$\langle\theta_{12}\rangle = 90°$$

If $\alpha \neq 0$ *and* $\beta \neq 0$

$$\langle\cos\theta_{12}\rangle = 2\alpha\beta\left\langle\left(2s_{1/2}\right)^2|\cos\theta_{12}|\left(1p_{1/2}\right)^2\right\rangle \neq 0$$

$\langle\theta_{12}\rangle < 90°$ (attractive)

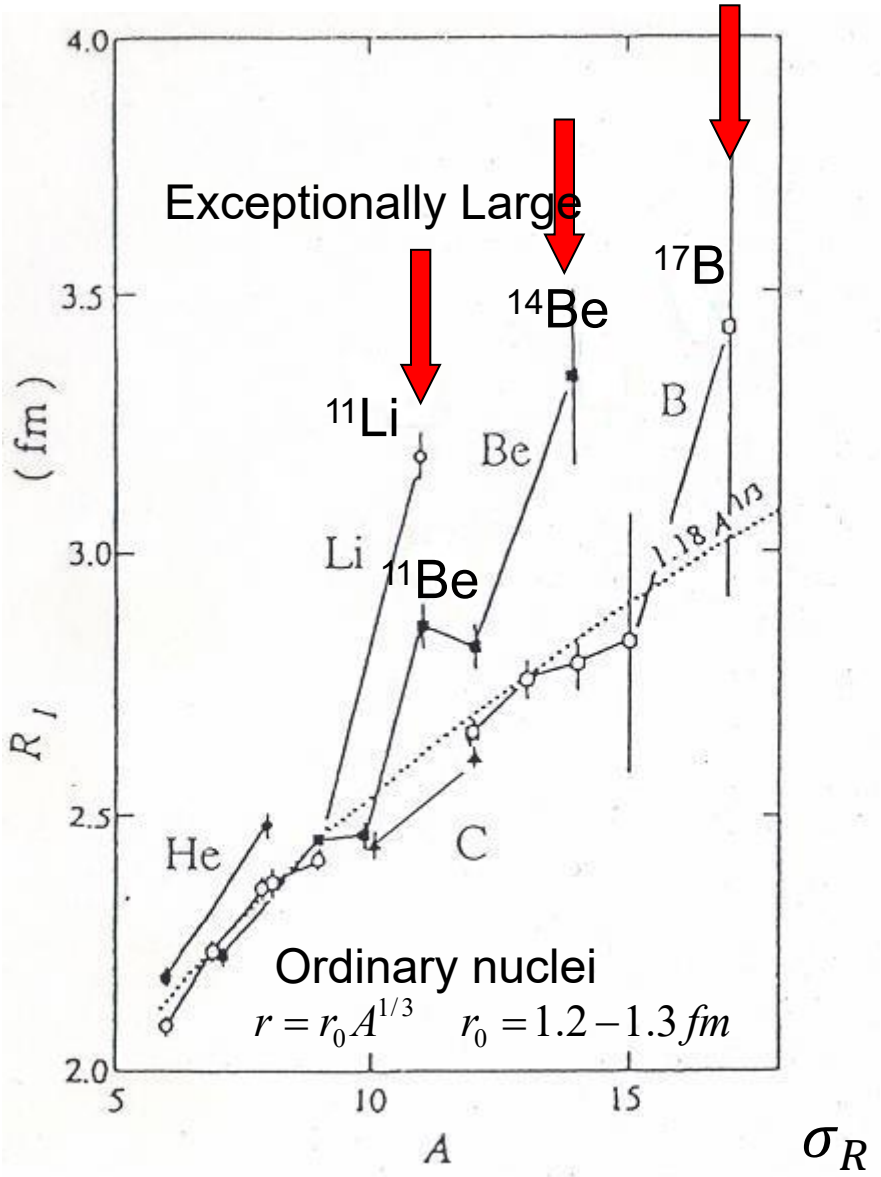
$\langle\theta_{12}\rangle > 90°$ (repulsive)

$(1p_{1/2})^2$: 35(4)%, $(2s_{1/2})^2$: 59(1)%, $(1d_{5/2})^2$: 6(14)%, ^{11}Li(p,pn) Kubota, PRL2020

Three Signals of Halo

- Large Reaction (Interaction) Cross Section
- Narrow Momentum Distribution of Halo Neutrons
- Soft E1 Excitation: Enhanced Electric-dipole Strength at Low excitation energies → Lecture II

Reaction (Interaction) Cross Section→Radius

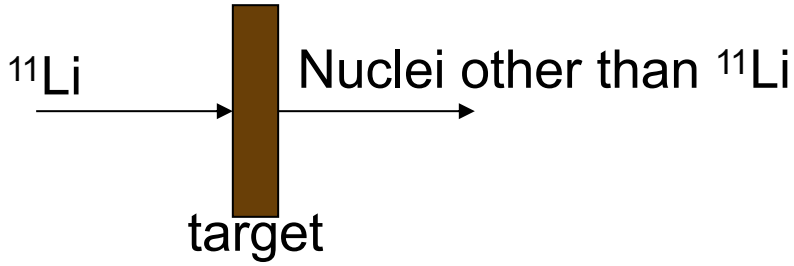


I.Tanihata et al., PRL**55**,2676(1985).

Interaction Cross Section σ_I

$$I = I_0 \exp(-n\sigma_I t)$$

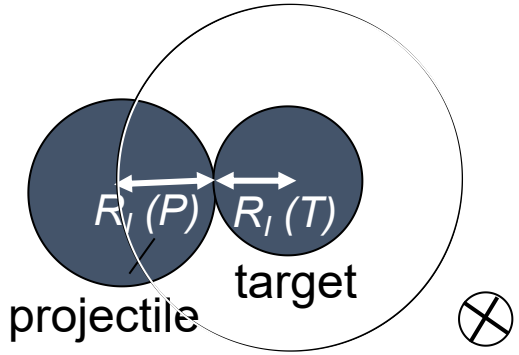
(Density)x(crosssection)x(thickness)



$$\sigma_I = \pi\left[R_I(P) + R_I(T)\right]^2$$

R of Projectile

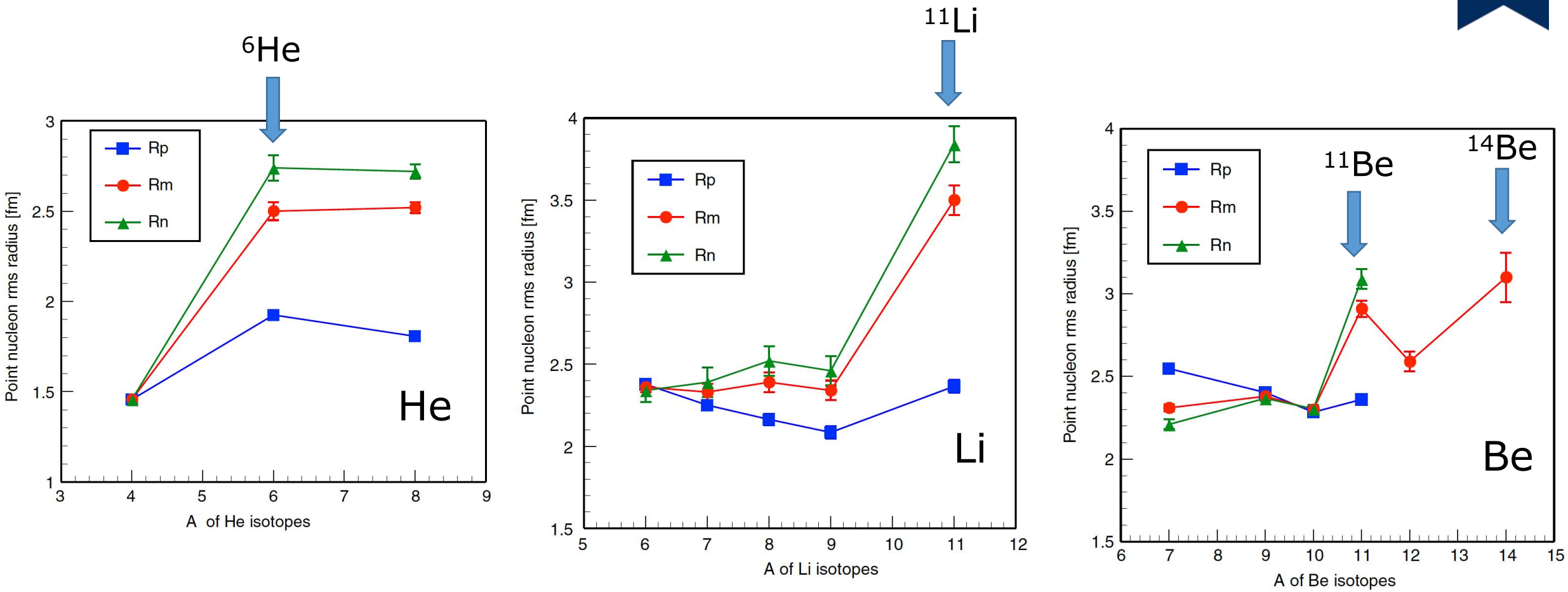
R of Target



$\otimes$

$\sigma_R = \sigma_I + \sigma_{inel}$ →Glauber Theory→R_m

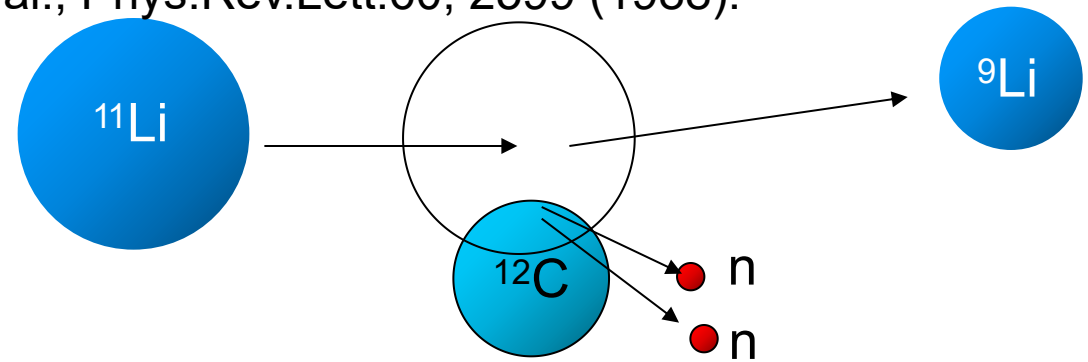
Summary of rms Radii for He, Li, and Be

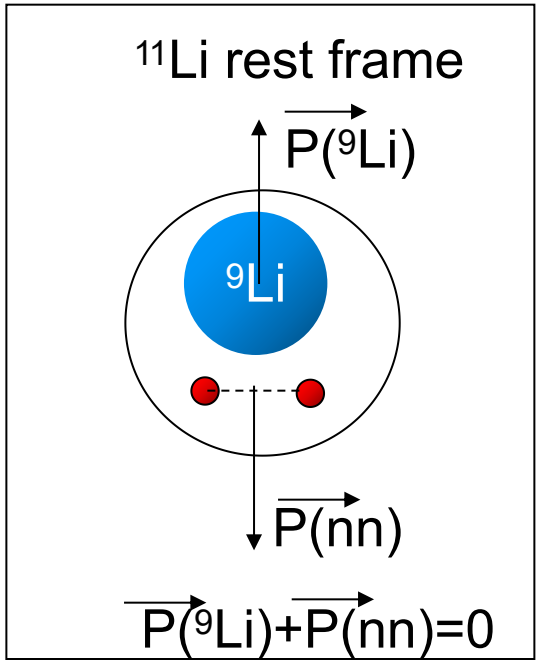


I. Tanihata et al., PPNP68, 215 (2013).

Momentum distribution of halo neutron(s)

T.Kobayashi et al., Phys.Rev.Lett.60, 2599 (1988).





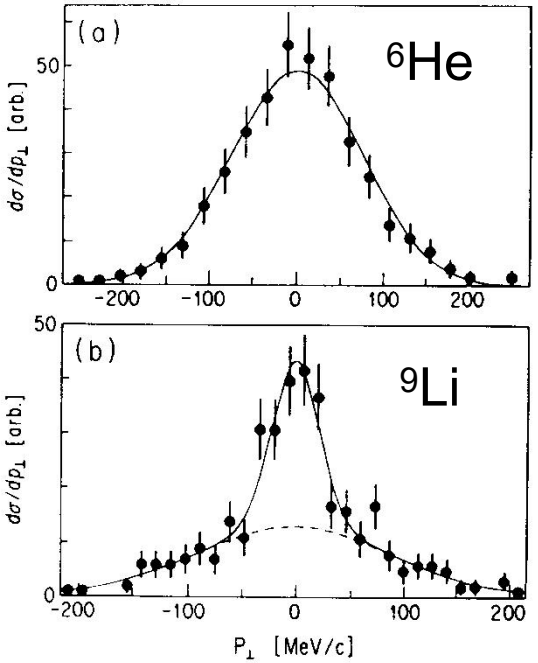


FIG. 1. Transverse-momentum distributions of (a) ^{6}He fragments from reaction ^{8}He+C and (b) ^{9}Li fragments from reaction ^{11}Li+C. The solid lines are fitted Gaussian distributions. The dotted line is a contribution of the wide component in the ^{9}Li distribution.

^{8}He+C→^{6}He

$$\sigma_0 = 60\,\mathrm{MeV/c}$$

^{11}Li +C→^{9}Li

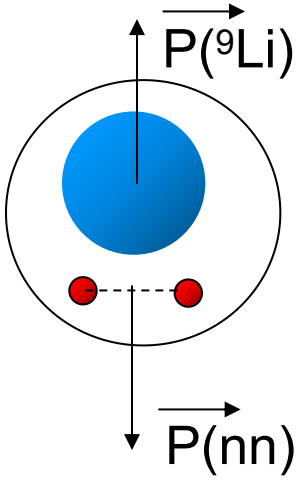
$$\sigma_0 = 17 \pm 4\,\mathrm{MeV}/c$$

Stable Nuclei

$$\Delta = \sigma_0 \sqrt{\frac{F(A-F)}{A-1}}$$

$$\sigma_0 \cong 90\,\mathrm{MeV/c}$$

^{11}Li Rest Frame

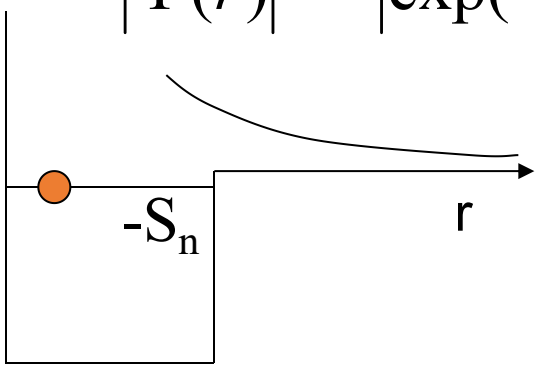


$\vec{P}(^9\mathrm{Li}) + \vec{P}(\mathrm{nn}) = 0$

$P(^9\mathrm{Li}) \sim P(\mathrm{nn})$

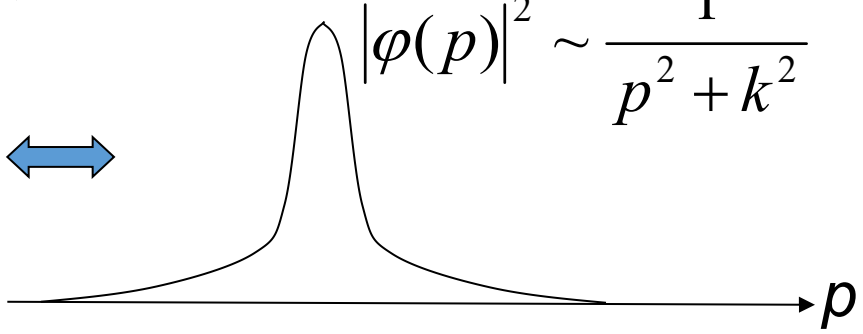
P(nn): **Narrow** distribution
→ Spatial(**r**) distribution for 2n
Wide（Uncertainty Principle）

$$|\Psi(r)|^2 \sim |\exp(-kr)/r|^2$$



$$k = \sqrt{2\mu S_n}/\hbar$$

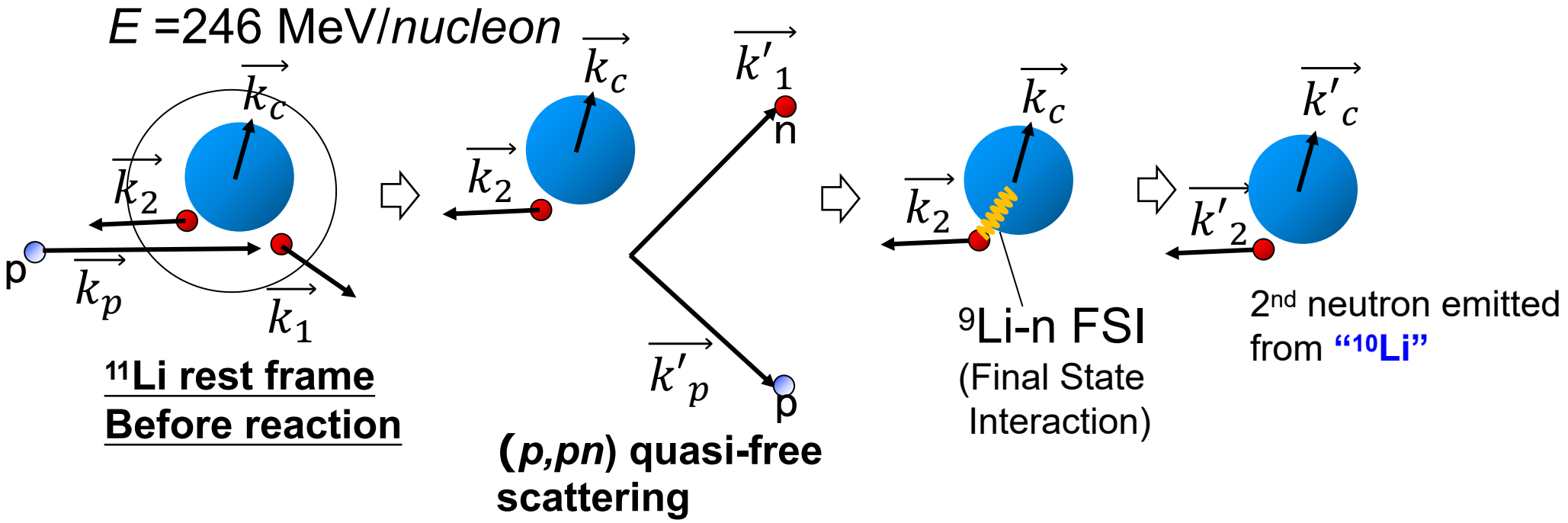
$$|\varphi(p)|^2 \sim \frac{1}{p^2 + k^2}$$

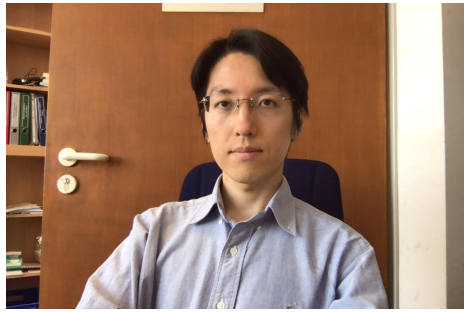


Proton quasi-free scattering (p,pn) on ^{11}Li

-- **Nuclear Anatomy**: Y. Kubota, A. Corsi, et al.

Phys. Rev. Lett. 125, 252501 (2020).





- ✓ Momentum of a halo neutron inside ^{11}Li ($\vec{k_1}$) : directly measured

$$\vec{k_1} = \vec{k'_1} + \vec{k'_p} - \vec{k_p}$$

- ✓ Momentum of another halo neutron inside ^{10}Li : Relative momentum $\vec{K}$

$$\vec{K} = \vec{k'_2} - \vec{k'_c} \approx \vec{k_2} - \vec{k_c}$$

Proton quasi-free scattering (p,pn) of ^{11}Li

Y.Kubota et al., Phys. Rev. Lett. 125, 252501 (2020).

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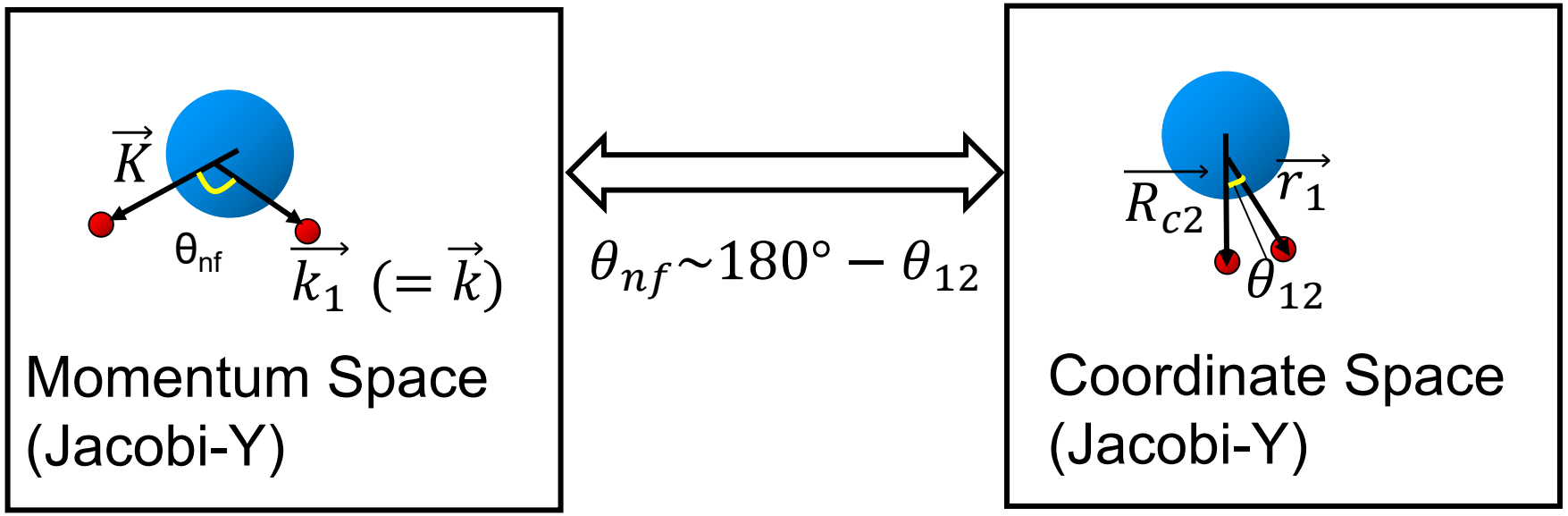


Proton quasi-free scattering (p,pn) of ^{11}Li

Y. Kubota, A. Corsi et al.

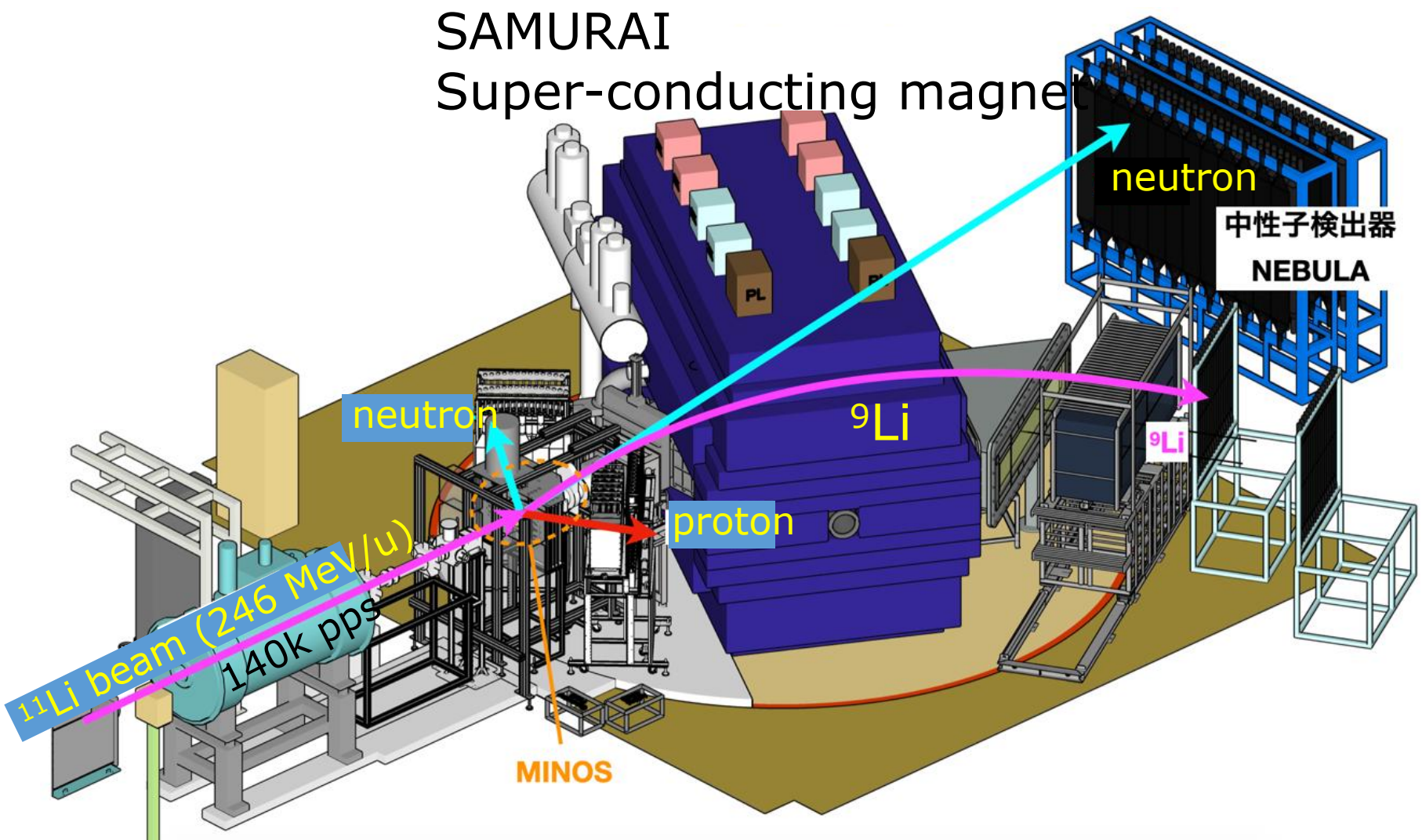
Phys. Rev. Lett. 125, 252501 (2020).

Characteristic Features

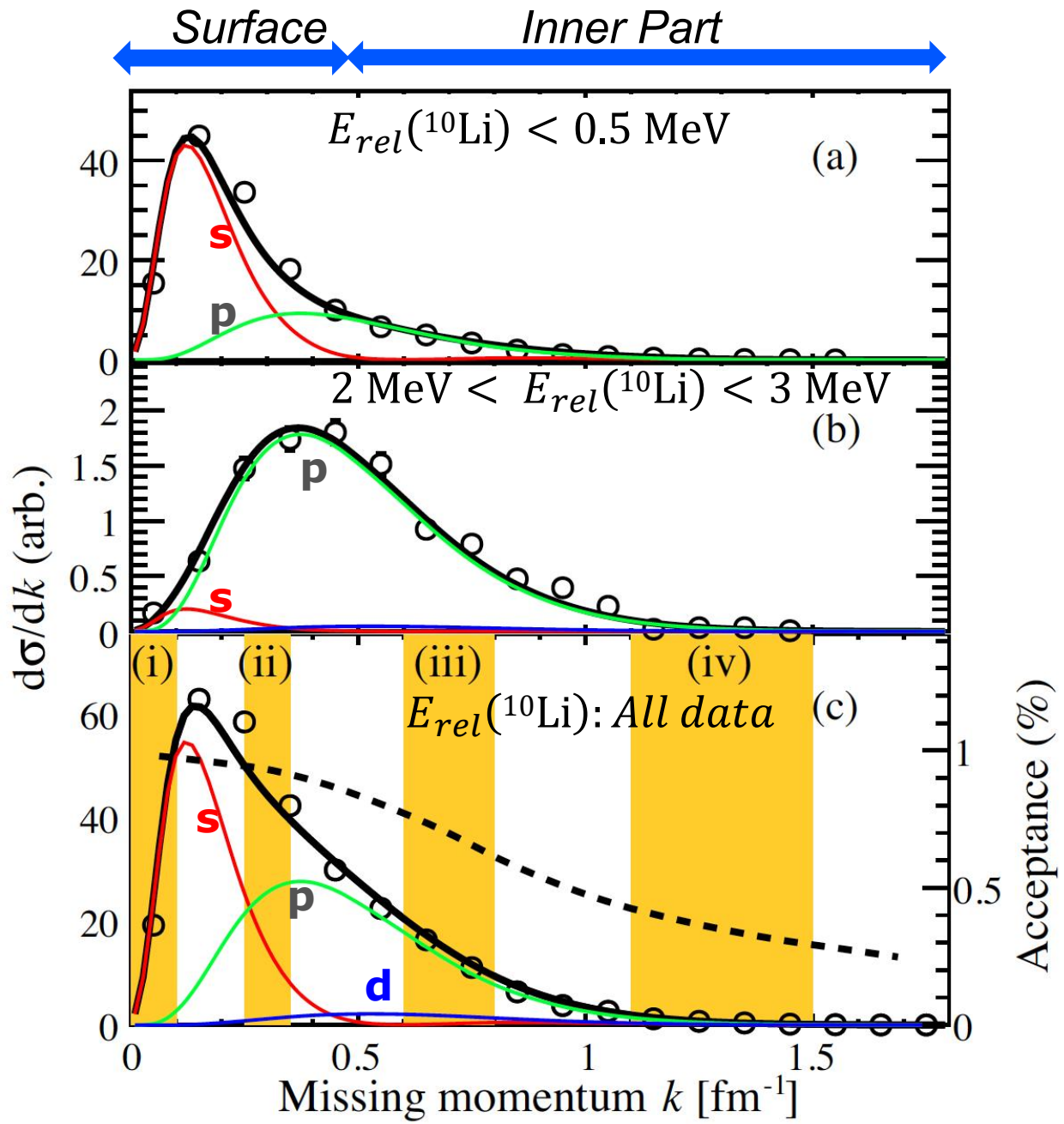
- ✓ **Momentum of a neutron (k_1) inside ^{11}Li can be directly Measured:**
- ✓ **Neutron configuration can be estimated from the remaining ^{10}Li**
  ($\vec{K} = \vec{k'}_2 - \vec{k'}_c \approx \vec{k}_2 - \vec{k}_c$)
- ✓ Simple Reaction Mechanism
- ✓ Effect of FSI: Minimized (2-body FSI: can be controlled)
- ✓ Transparent Probe (p can enter deep inside ^{11}Li)
- ✓ Kinematically Complete Measurement

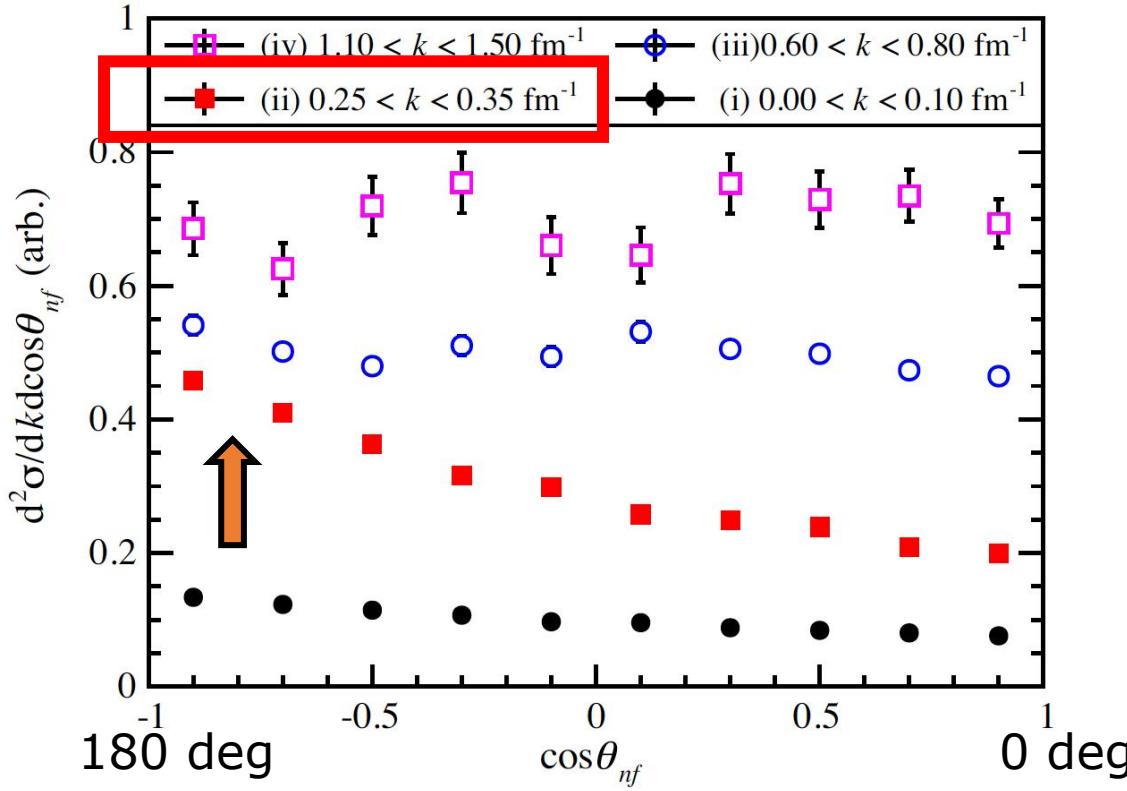
Reaction Theory
Y. Kikuchi *et al.*, Prog. Theor. Exp. Phys. **2016** 103D03 (2016).

Experimental setup
for proton quasi-free scattering of ^{11}Li at SAMURAI

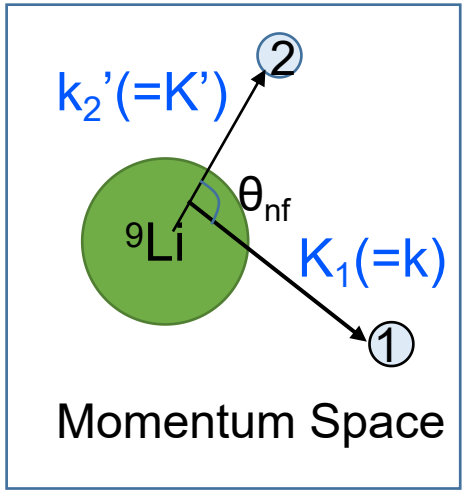


Results: Missing Momentum Spectra

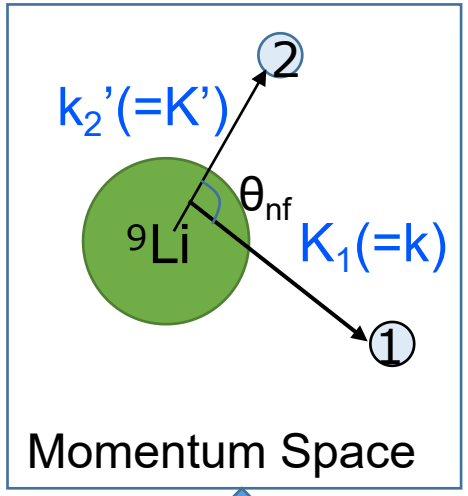




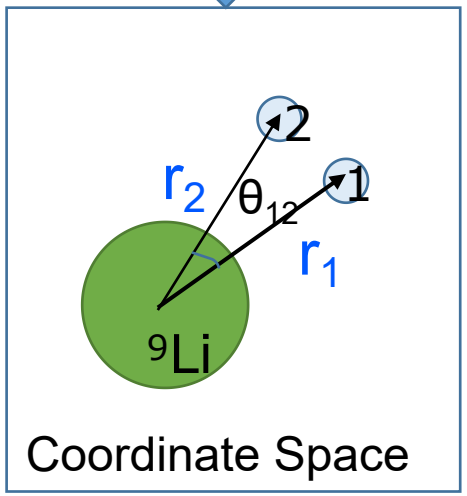
^{10}Li Energy spectrum→
2n configuration of ^{11}Li
$(2s)^2$: 35(4)%
$(1p)^2$: 59(1)%
$(1d)^2$: 6(4)%

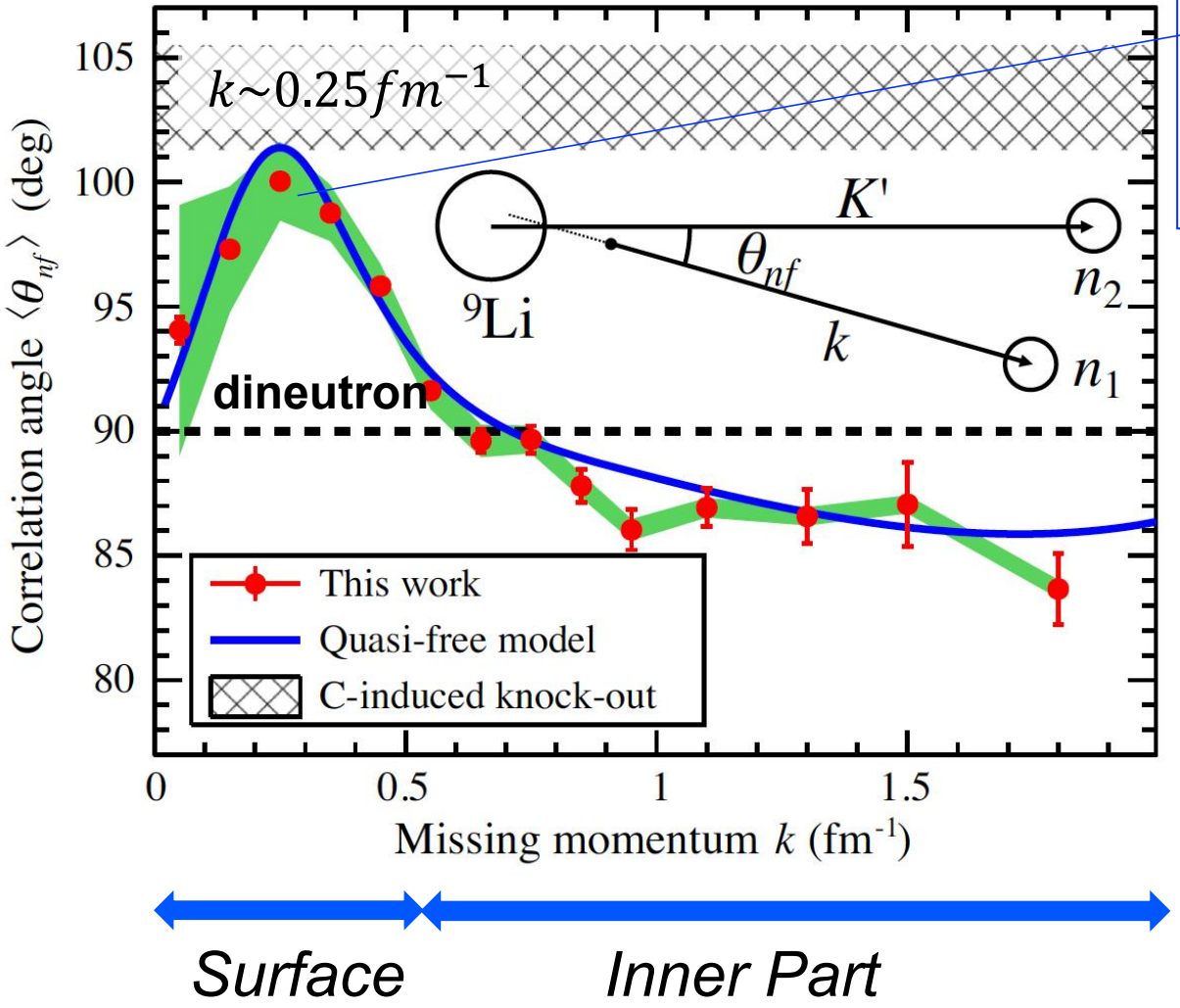


Dineutron correlation in ^{11}Li



$\theta_{nf} \sim 180° - \theta_{12}$

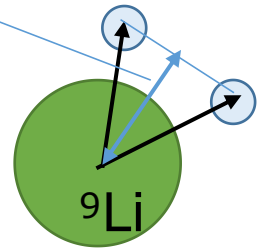




Dineutron is localized on the surface of ^{9}Li core

$$10^{-3} < \frac{\rho}{\rho_0} < 10^{-2}$$

$r_{c-2n} \sim 3.6fm$



$r_{rms}(^{9}\mathrm{Li}) = 2.43(2)\mathrm{fm}$

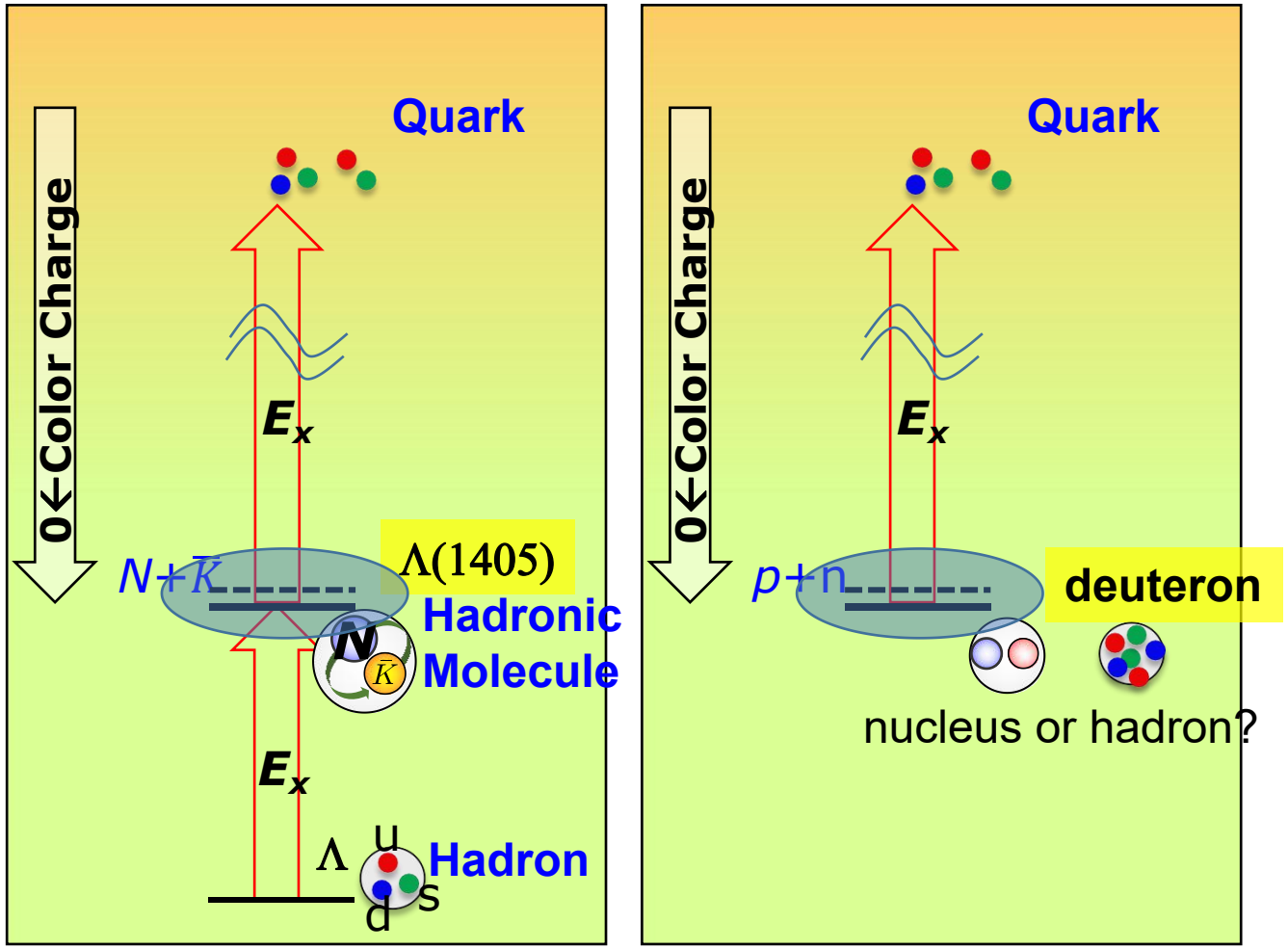
Summary of Lecture-I

Take-home messages

- ✓ Clusters and Hierarchies of Matter, Semi-hierarchy
  - ✓ Cluster formation==Hierarchy
  - ✓ Semi Hierarchy: Hierarchy in the boundary→ Exotic Particles
- ✓ Clusters near the neutron drip line
  - ✓ Neutron drip line nuclei : semi hierarchy: boundary between the closed (bound) and open (unbound) nuclei
  - ✓ Boundary: Drip-line
- ✓ Neutron Halo nuclei—Basics
  - ✓ One-neutron halo nuclei : Low S_n, Low l
  - ✓ Two-neutron halo nuclei : Low S_{2n}, Low l, Borromean, dineutron
- ✓ Three Signals of Neutron Halo
  - ✓ Large Interaction Cross section – Large Radius
  - ✓ Narrow Momentum Distribution – Fourier Transform of halo neutron(s)
  - ✓ Soft E1 Excitation: Enhanced electric-dipole strength at low Ex
- ✓ Anatomy of Neutron-halo nucleus
  - ✓ Momenta of two halo neutrons → Visualize Dineutron correlation

Backup

What is the Role of "Threshold" in the formation of clusters and semi-hierarchy?



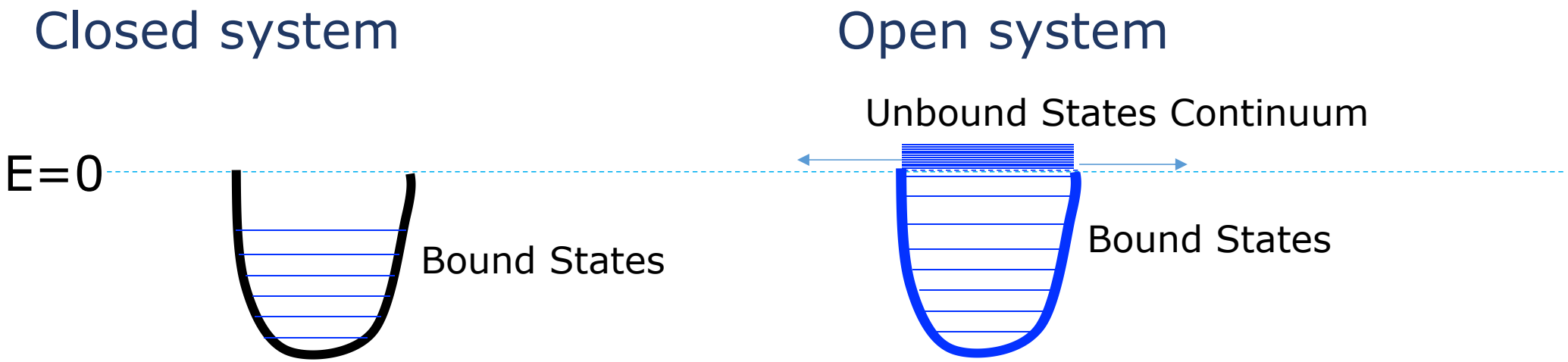
deuteron :

a nucleus (two-nucleon system, cluster)

or

a hadron (6q system)?

Edges of nuclei (driplines) : Closed or Open?



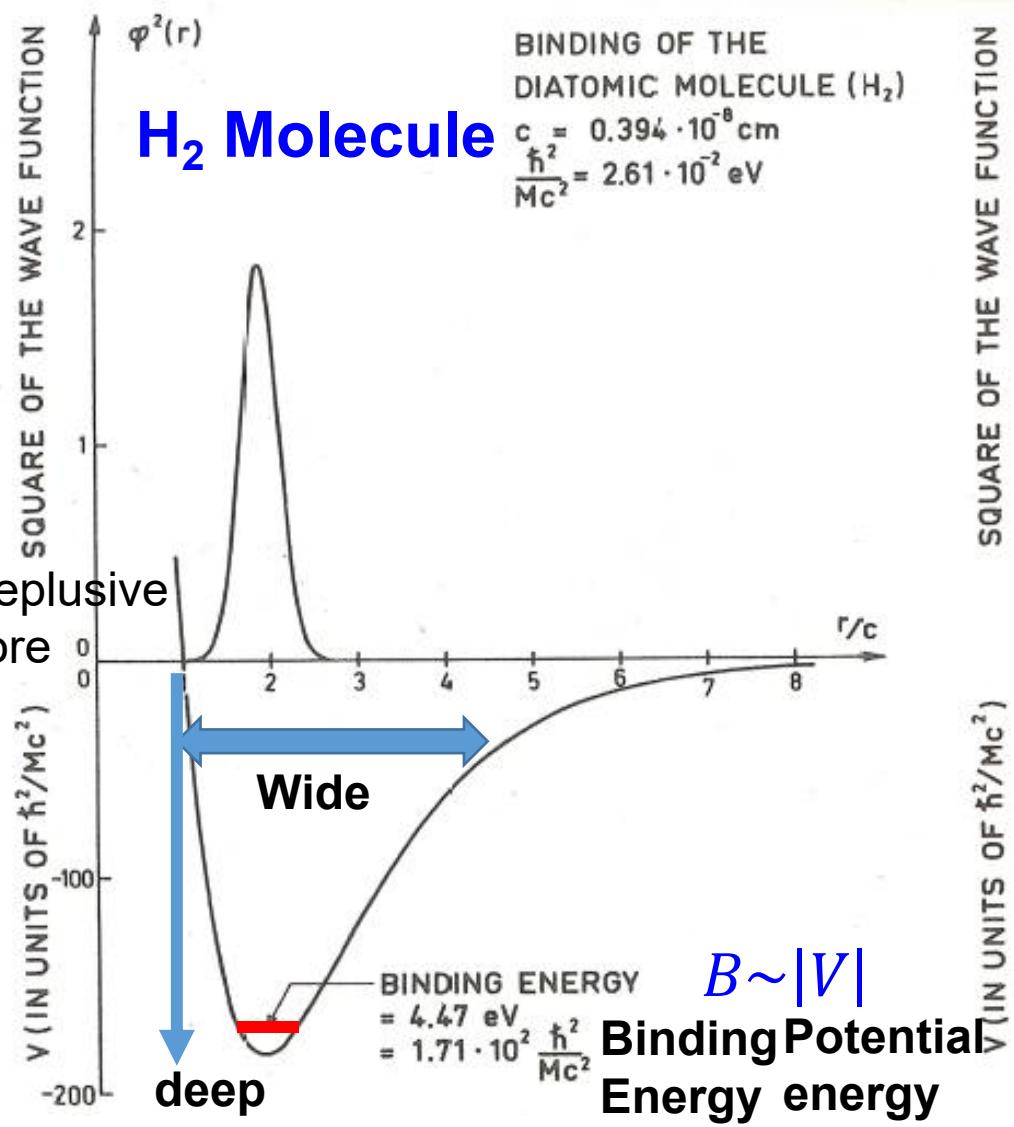
- Normal Nuclei: Bound and Isolated system→ Closed quantum system
- Nuclei beyond driplines, Highly excited states → Open quantum system

Boundary between “Closed” and “Open”
→ Novel phenomena and features in Nuclear Structures and Reactions

Deuteron in the text book

Nuclear Structure, Bohr & Mottelson p269, Vol.1

Nobel prize 1975



H_2 Molecule

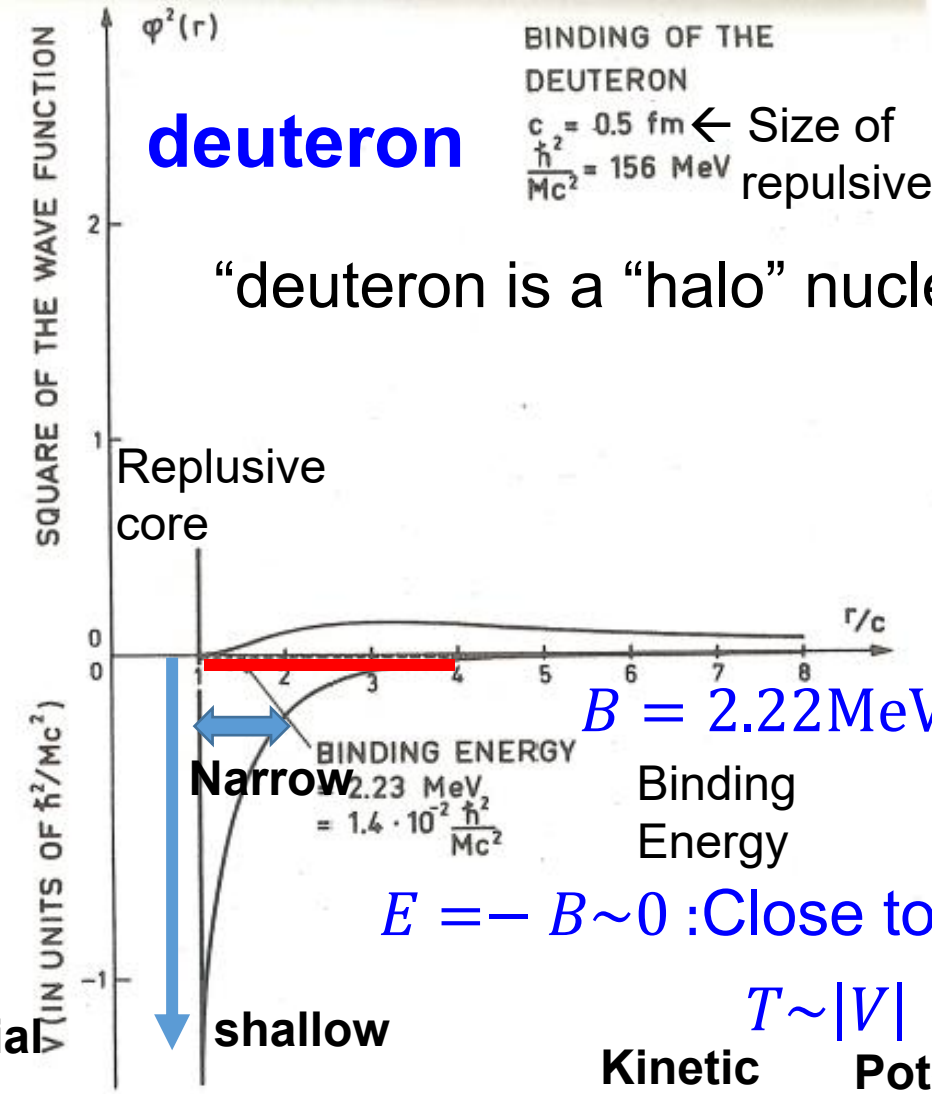
Replusive core

Wide

deep

$B \sim |V|$

Binding Energy **Potential energy**



deuteron

← Size of repulsive core

"deuteron is a "halo" nucleus"

Replusive core

Narrow

shallow

$B = 2.22\text{MeV} \sim 0 \ll |V|$

Binding Energy

$E = -B \sim 0$:Close to pn threshold

$T \sim |V|$

Kinetic energy **Potential energy**

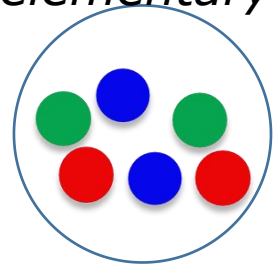
deuteron :

a nucleus (two-nucleon system, cluster) or a hadron (6q system)?

S. Weinberg, PR 137, 672 (1965)
T. Hyodo, IJMPA 28, 1330045 (2013)

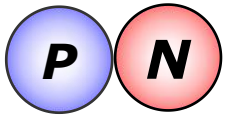
Compositeness : Z

deuteron (hadron)
: *elementary*



Z~1

Deuteron (nucleus)
: *composite (cluster)*



Z~0

$$|bound\ state\rangle = \sqrt{Z}|elementary\rangle + \sqrt{1-Z}|composite\rangle$$

S-wave scattering length $a = \frac{2(1-Z)}{2-Z}R + \mathcal{O}(m_\pi^{-1})$

Effective range $r_e = -\frac{Z}{1-Z}R + \mathcal{O}(m_\pi^{-1})$

Deuteron: Weakly bound:
(B=2.22 MeV, $a = 5.42$fm, $r_e = 1.74$fm)

➡ **Z~0**

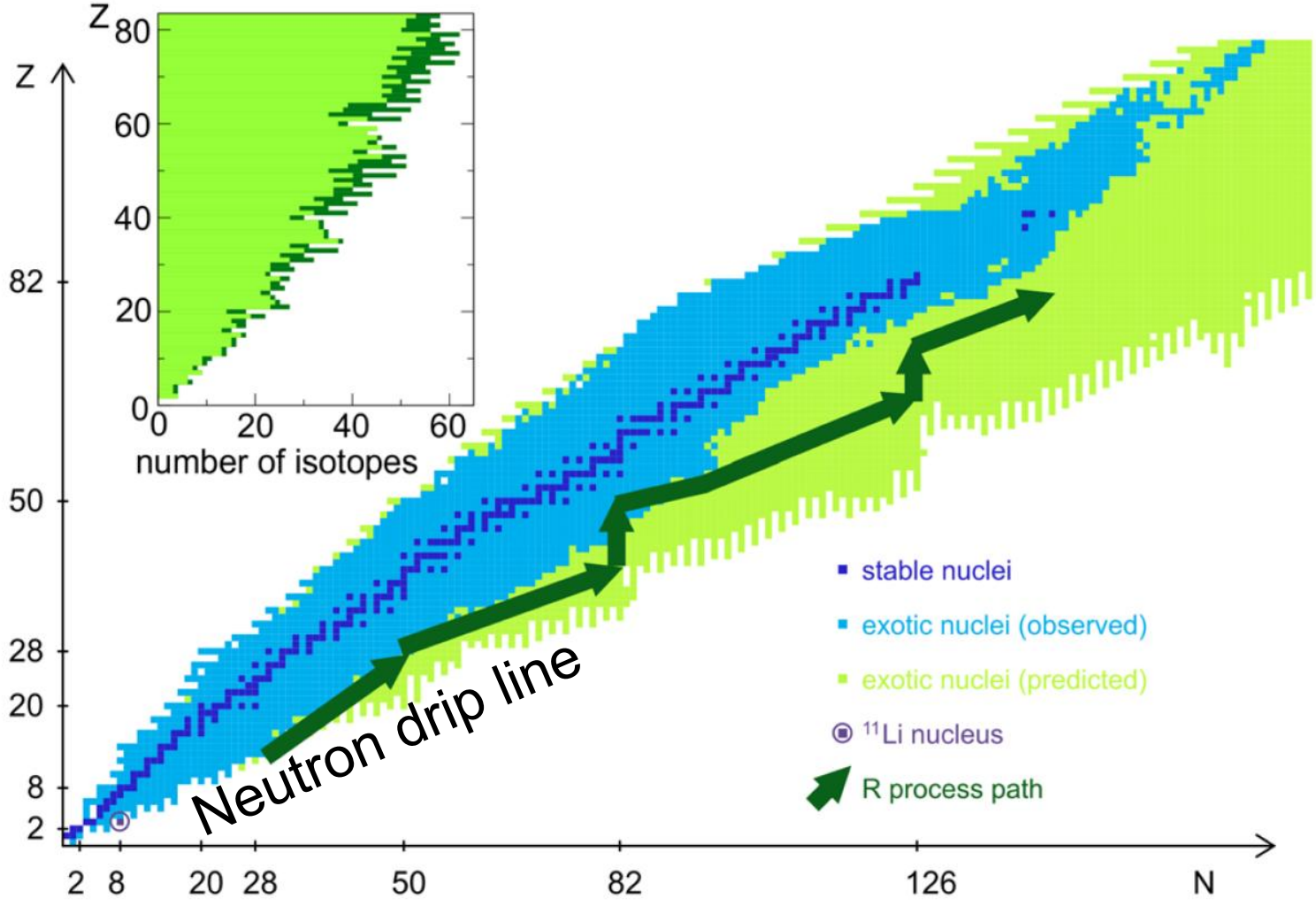
Cluster formation (2-body)
is dictated by **scattering length**
or equivalently **closeness to threshold**

Note: Weak bound limit:

Binding energy $B = \frac{\hbar}{ma^2}$ $\quad \sqrt{\langle R^2\rangle} = \frac{\hbar}{\sqrt{2\mu B}} = 4.31\ fm$ $\quad a \sim R$

Nuclear Landscape

T.Otsuka et al., Rev. Mod. Phys. 92, 015002 (2020).



What happens if neutron(s) are weakly bound or no longer bound to nuclei?