Experiments on tetra-neutron "resonance"

- Introduction
  - Experiments before 2010
- Idea for populating 4n system at rest
  - Exothermic double-charge exchange (^{8}He,^{8}Be)
  - Knockout of alpha from light neutron-rich nuclei (p,pα)
  - Low-energy pickup reactions
- Analysis (assuming impulse process)
  - Continuum spectrum with correlation
    - A simple picture of the reaction
- Summary

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Tetra-neutron

- Multi-neutron System
  - Di neutron is unbound (a.k.a. virtual state*)
  - Can more neutrons be bound or meta-stable?
  - Multi-body `resonances'
    - What can be extended / different from the concepts of binary system?
    - Effect of phase-spaces ($E^{1/2}$, E^2, $E^{7/2}$) and Pauli blocking just above the threshold.
  - NN, NNN, NNNN interactions
    - T=3/2 NNN force
      -> 3-body force in neutron matter
    - Ab initio type calculations
  - Correlations in identical multi-fermion scattering states
    - NNN, NNNN correlation
    - "effective" many-body interactions

Slide by K. Kisamori

Historical Review

~ search for a bound state of 4n~

1960s

fission of Uranium

- No evidence for particle stable state of tetra-neutron

J. P. Shiffer Phys. Lett. 5, 4, 292 (1963)

1980s

$^4He(\pi^-, \pi^+)$ reaction

- Only upper limit of cross section was decided.

J. E. Unger, et al., Phys. Lett. B 144, 333 (1984)

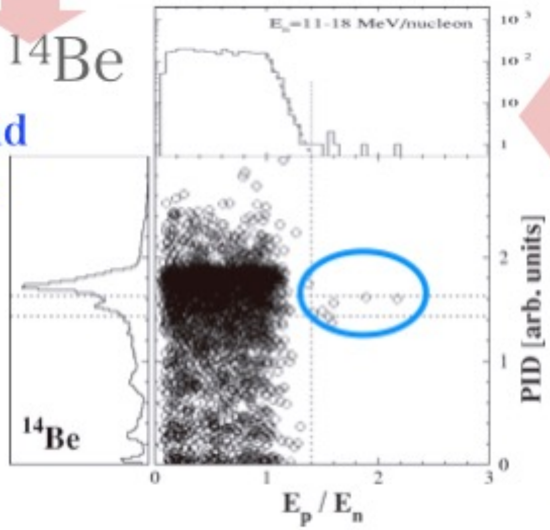
Bound state: No clear evidence.

2000s

Breakup of ^{14}Be

- Candidates of **bound tetra-neutron** were **observed.**

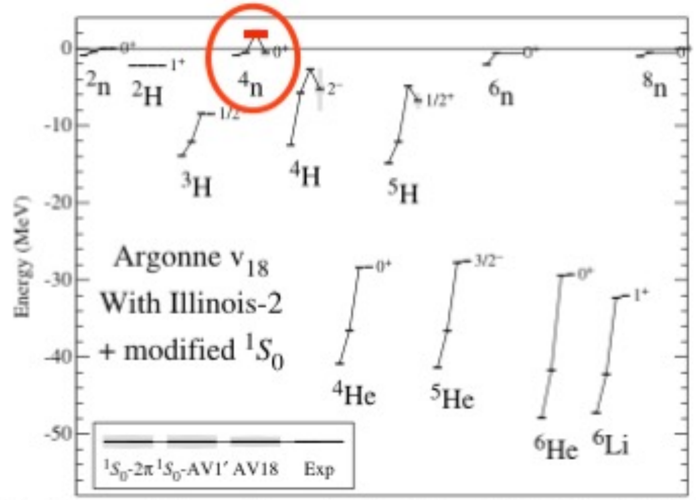
F. M. Marques, et al, Phys. Rev. C 65, 044006 (2002)



2000s

Theoretical work

- ab-initio calculation
  NN, NNN interaction

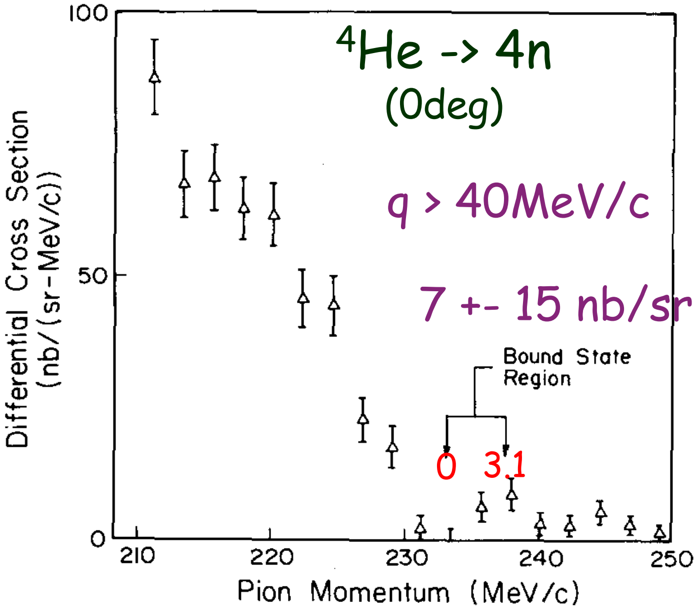


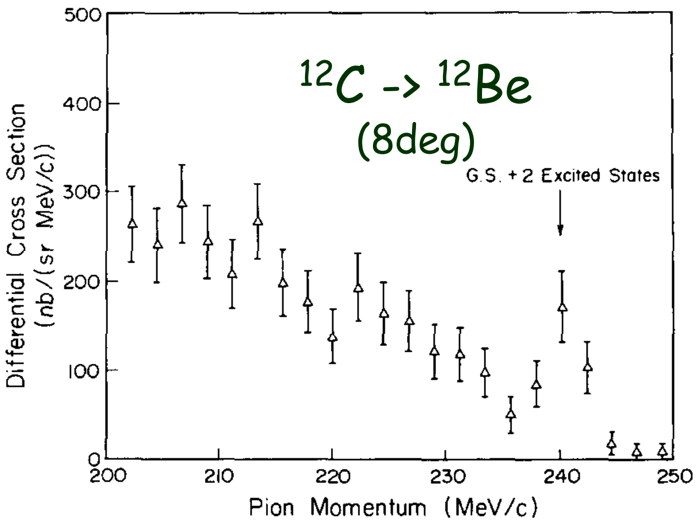
S. C. Piper, Phys. Rev. Lett. 90, 252501 (2003)

- **Bound ^4n cannot exist**
- **Possible resonance stete ~2 MeV**

Resonance state : Possibility of the state is still an open and fascinating question.

(π^-,π^+) reaction @ 165 MeV; $\theta_{\pi+}$ = 0 degree





The peak is due primarily to the transition to the ^{12}Be ground state, with some contribution from the first two excited states as well.

We have measured the momentum spectrum of π^+ produced at 0° by 165 MeV π^- on ^{4}He. A $\Delta P/P$ = 1% beam of 10^6 π^- per second was provided by the P^3 line of the Los Alamos Meson Physics Facility, and a cell of 910 mg/cm^2 liquid ^{4}He with windows of 18 mg/cm^2 Kapton served as the target [15]. An

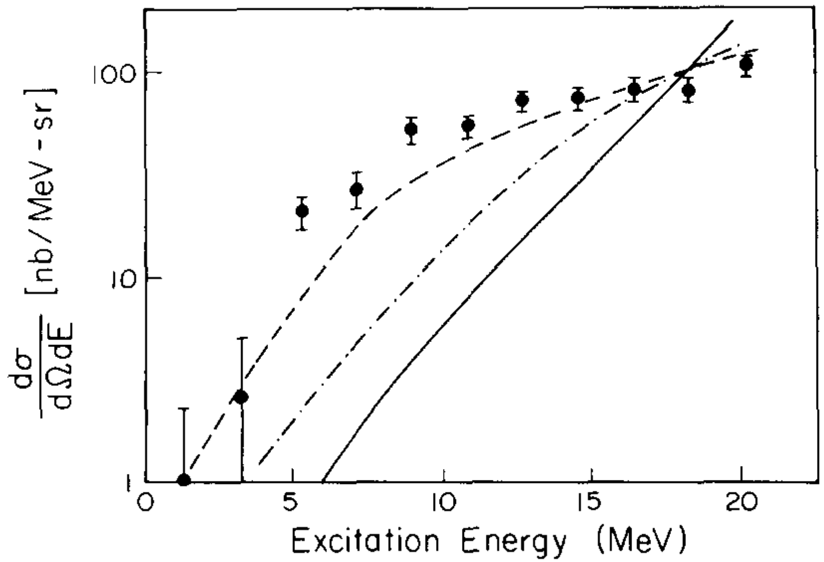
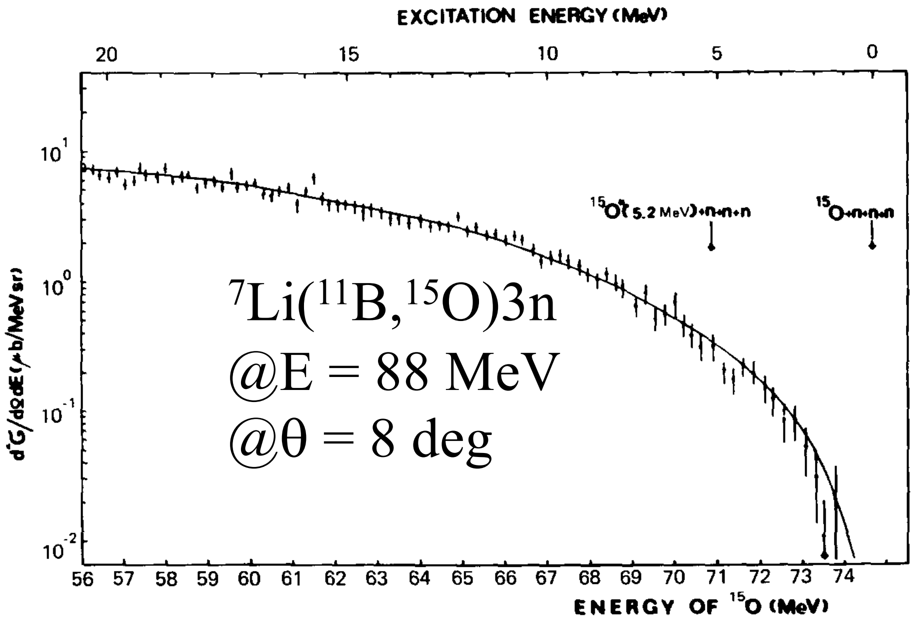


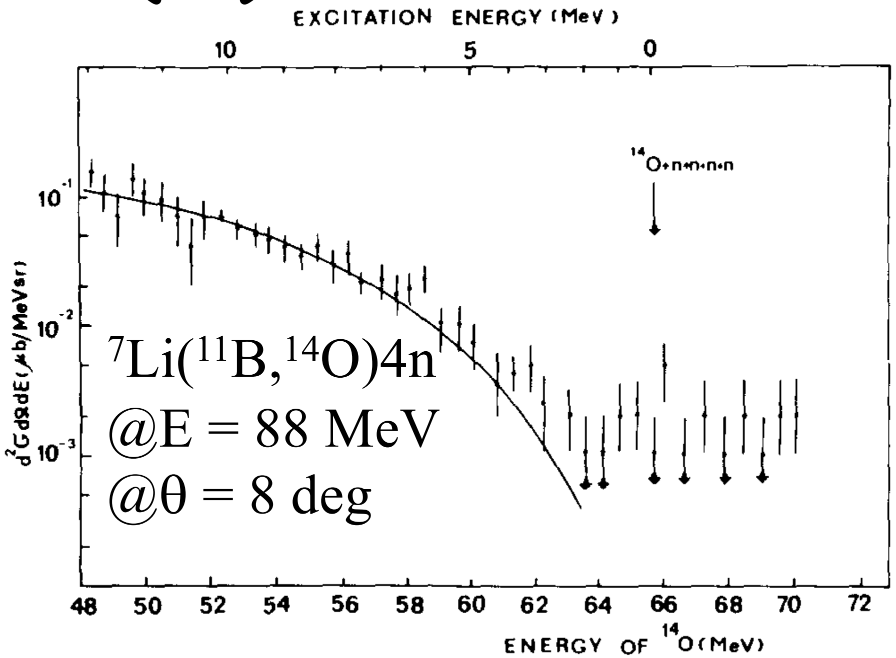
Fig. 3. The experimental results are plotted against the excitation of the final four-neutron state. The solid curve corresponds to the pure four-neutron phase space, while the dot–dashed and dashed curves are the four-neutron phase space curves with singlet state interactions in, respectively, one and both of the final state neutron pairs.

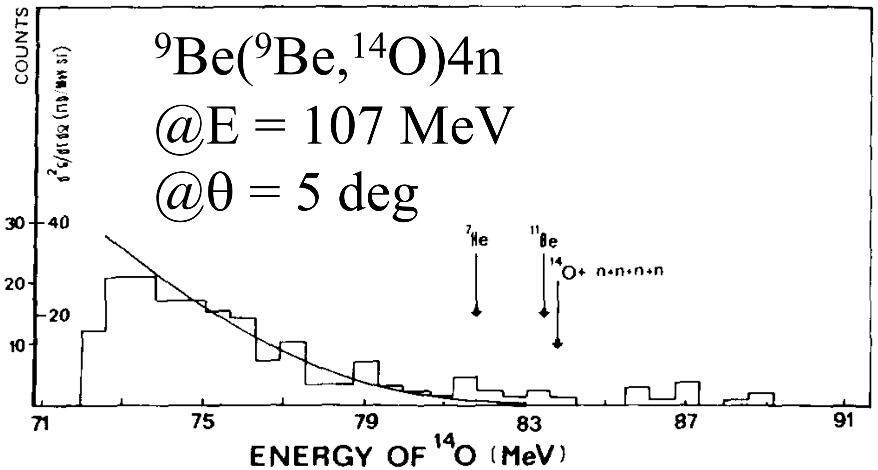
J.E. Ungar et al., PLB 144 (1987) 333

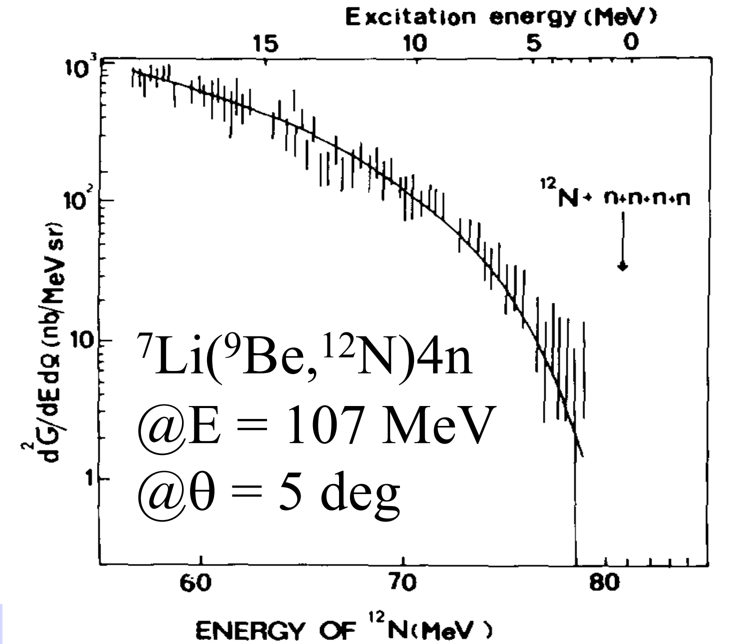
Historical review (2)

Nucl. Phys. A477 (1988) 131

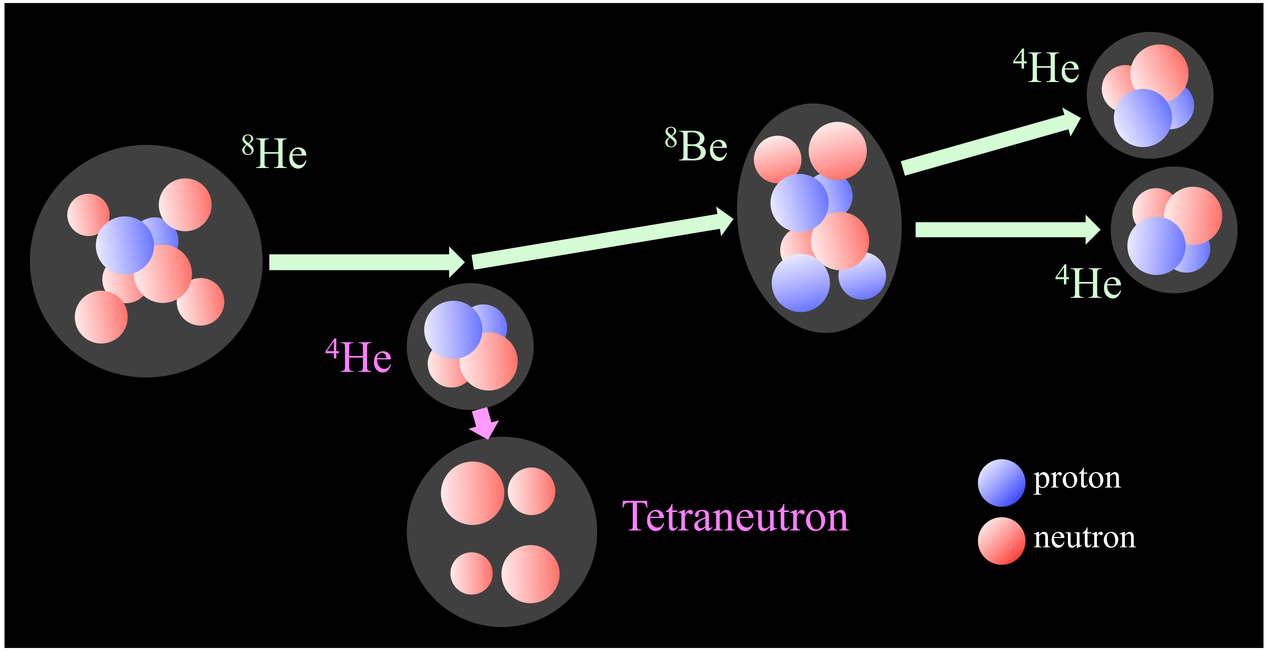






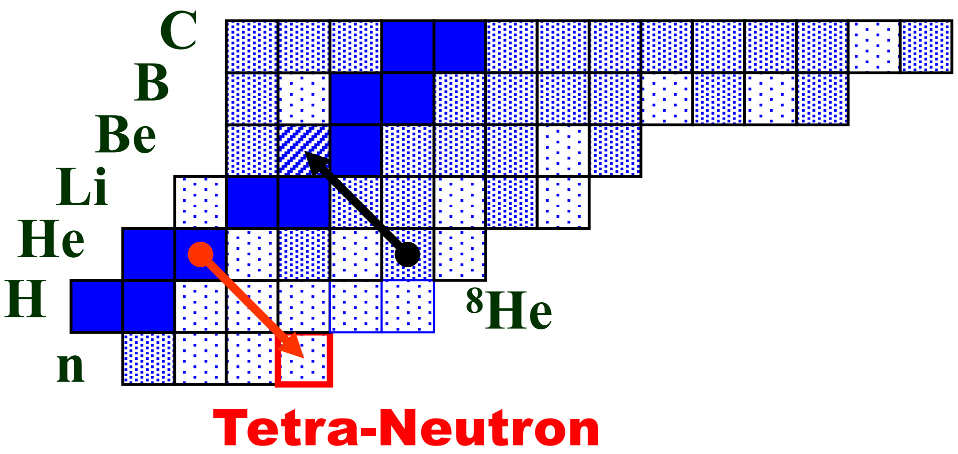


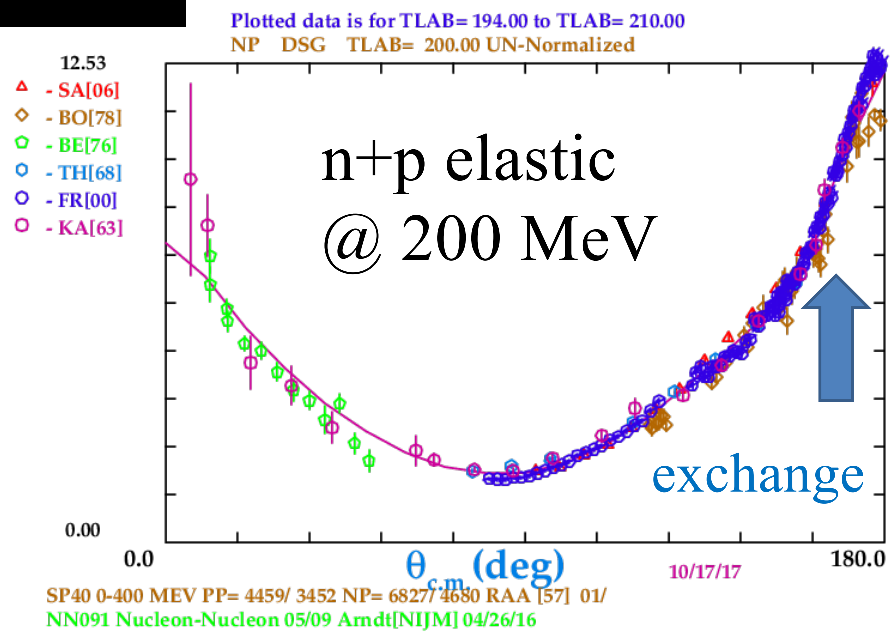
Exothermic double-charge exchange reaction



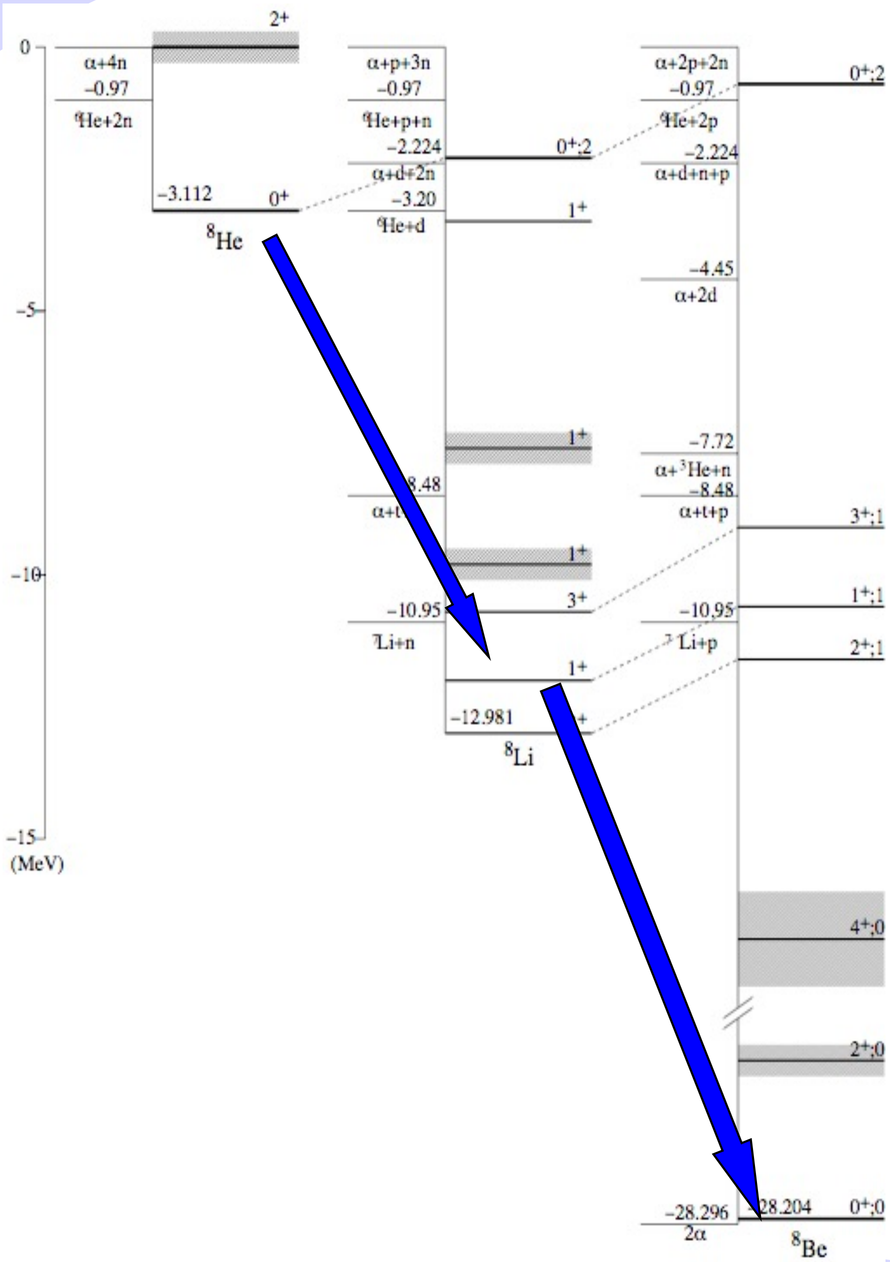
K. Kisamori et al.,
Phys. Rev. Lett. 116, 052501 (2016)

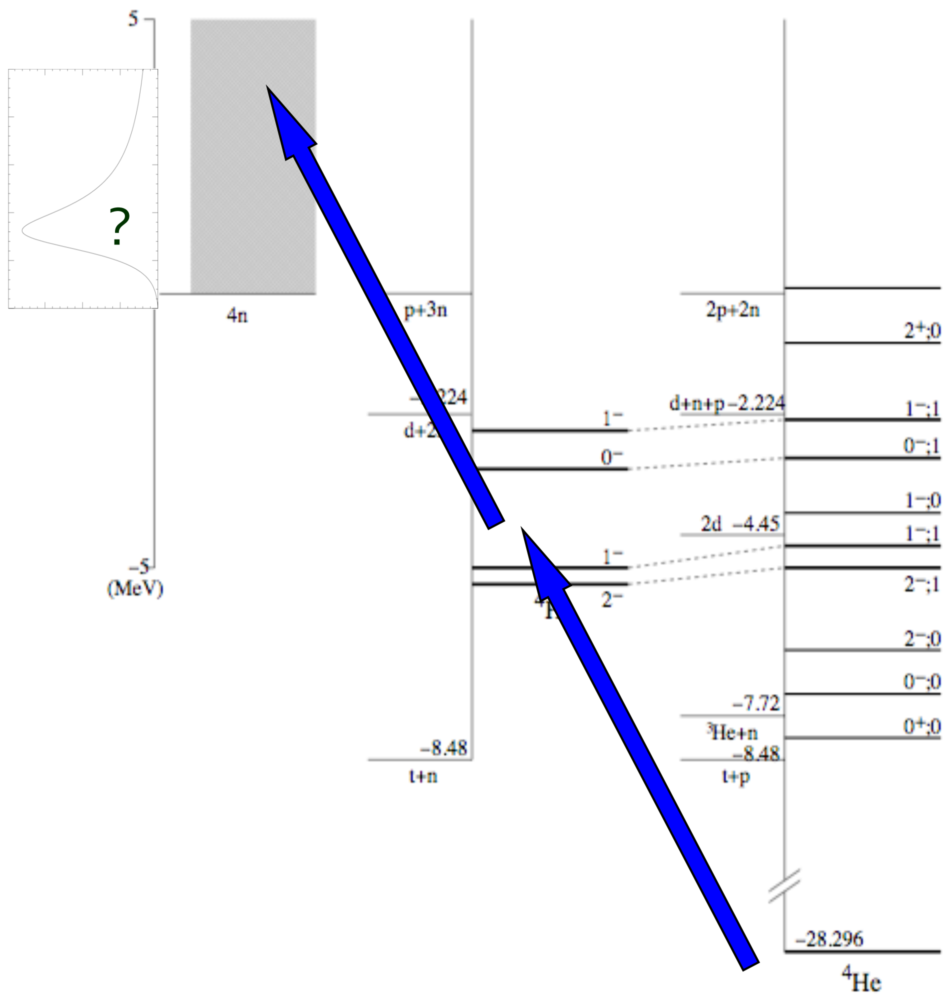
Almost recoil-less condition with ^{4}He(^{8}He,^{8}Be)4n reaction at 200 A MeV (0.63 c)





Level diagrams

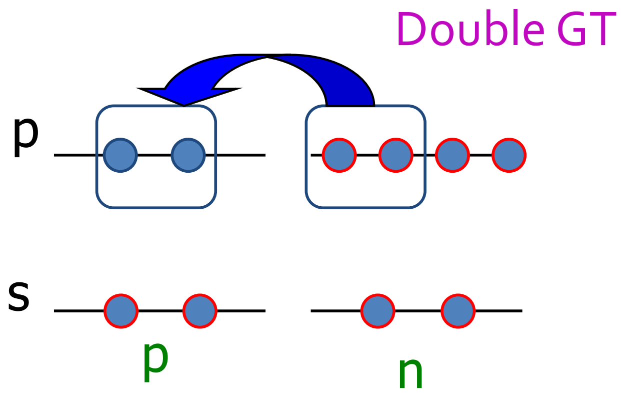




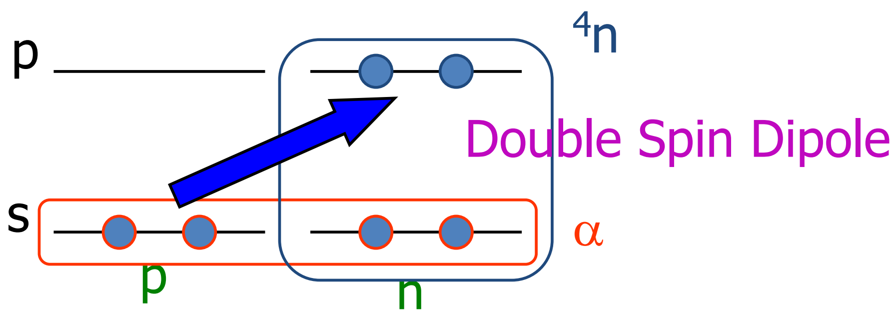
q_{min} ~ 10MeV/c

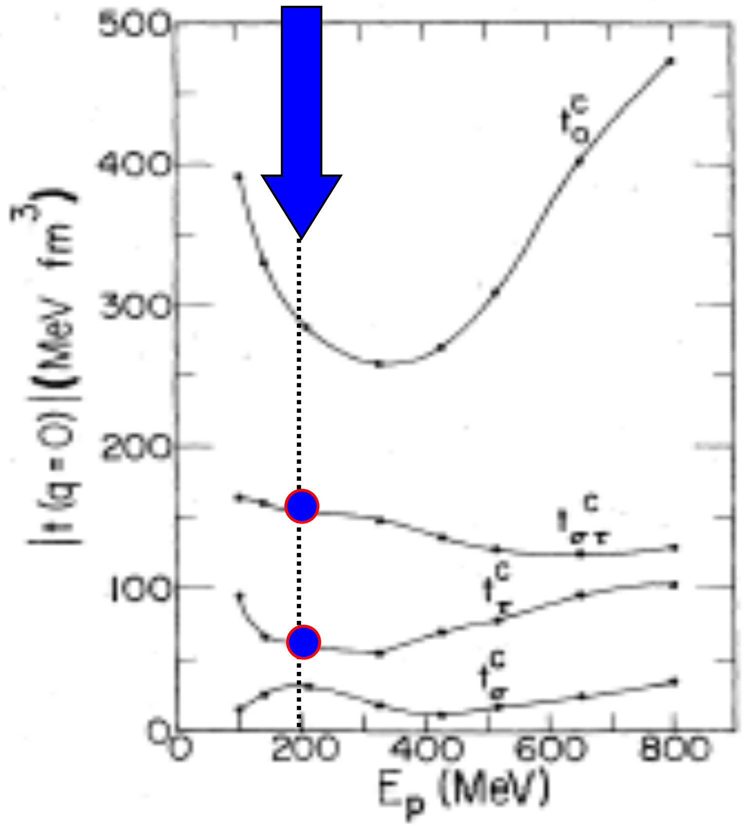
Reaction Mechanism

$^{8}He \rightarrow {}^{8}Be$



$^{4}He \rightarrow 4n$

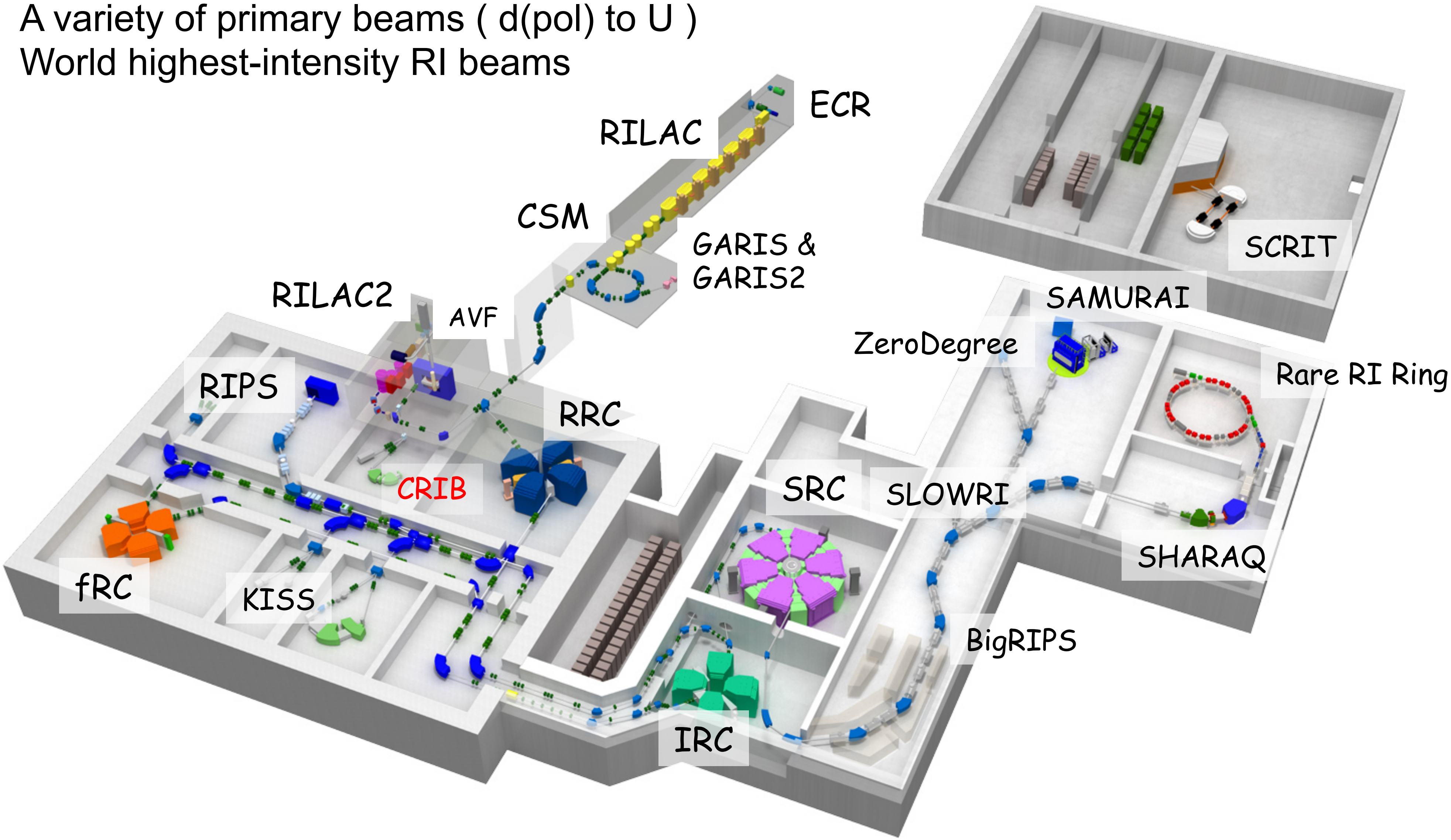




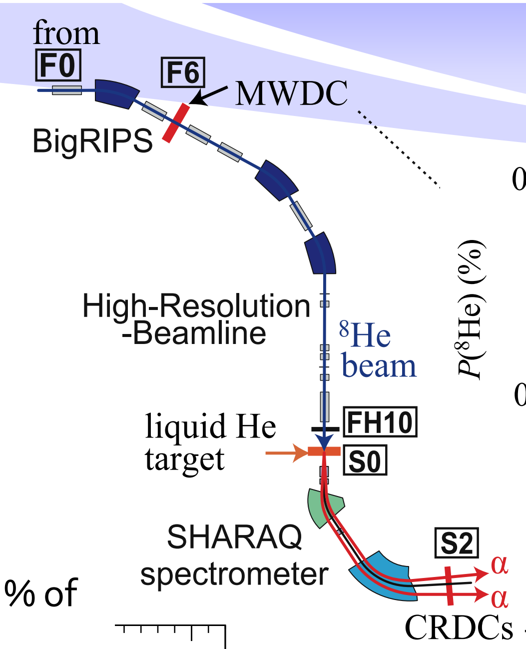
$$\left[\left(\vec{\tau}_{\mathrm{p}}\cdot\vec{\tau}_{\mathrm{t}}\right)\left(\vec{\sigma}_{\mathrm{p}}\cdot\vec{\sigma}_{\mathrm{t}}\right)r_{\mathrm{t}}Y_{1}\left(\hat{r}_{\mathrm{t}}\right)\right]^{2}$$

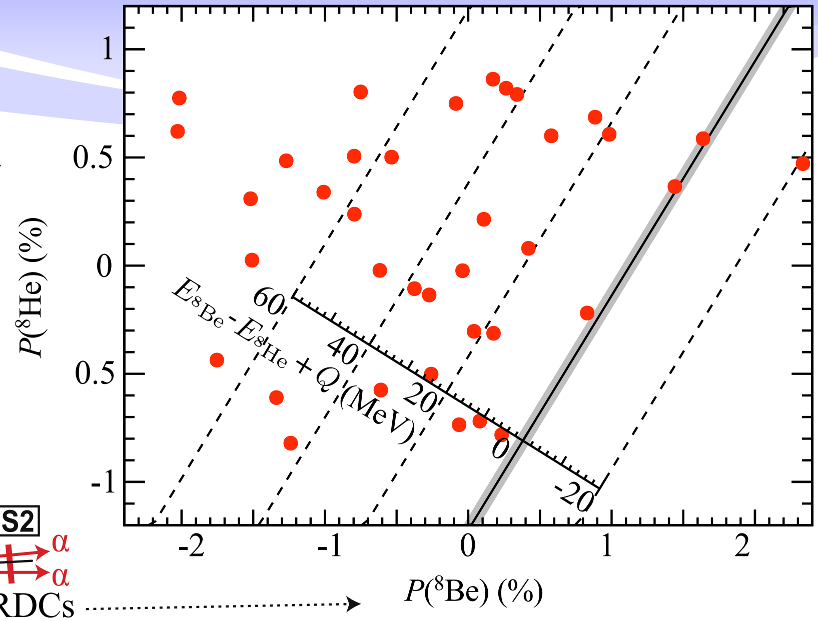
RI Beam Factory at RIKEN

3 injectors + cascade of 4 cyclotrons
⇒ several to 345 MeV/nucleon
A variety of primary beams (d(pol) to U)
World highest-intensity RI beams

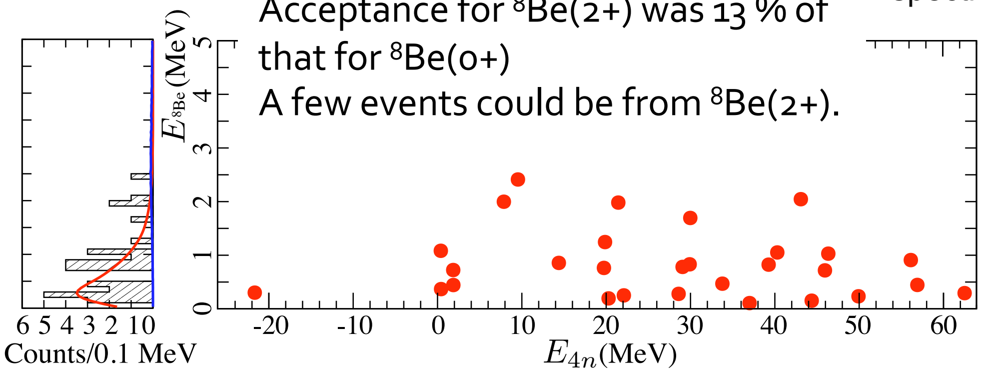


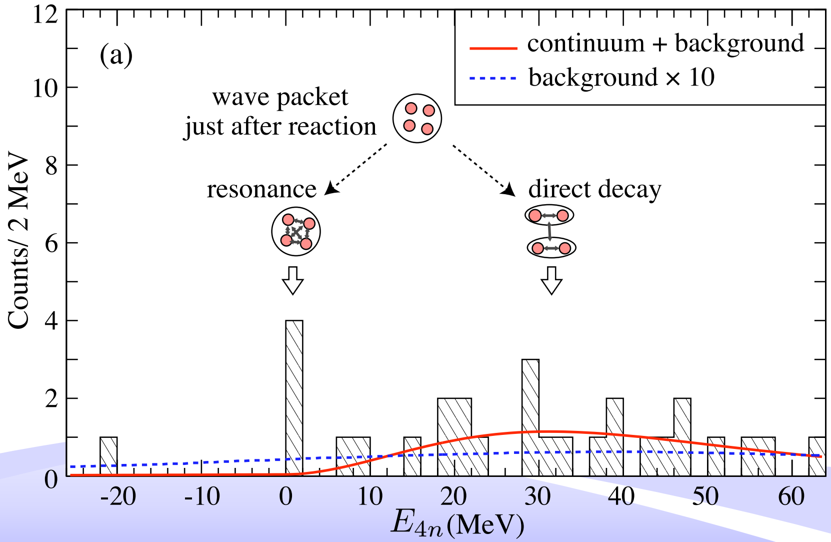
Experimental Results

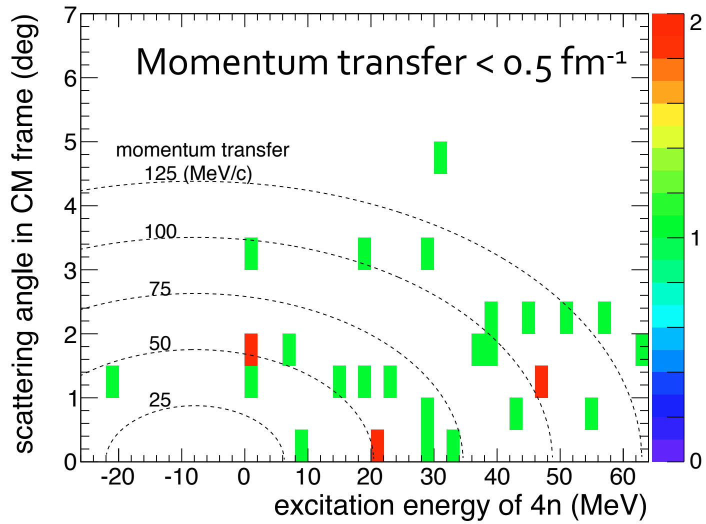




Acceptance for ^{8}Be(2+) was 13 % of that for ^{8}Be(0+)
A few events could be from ^{8}Be(2+).

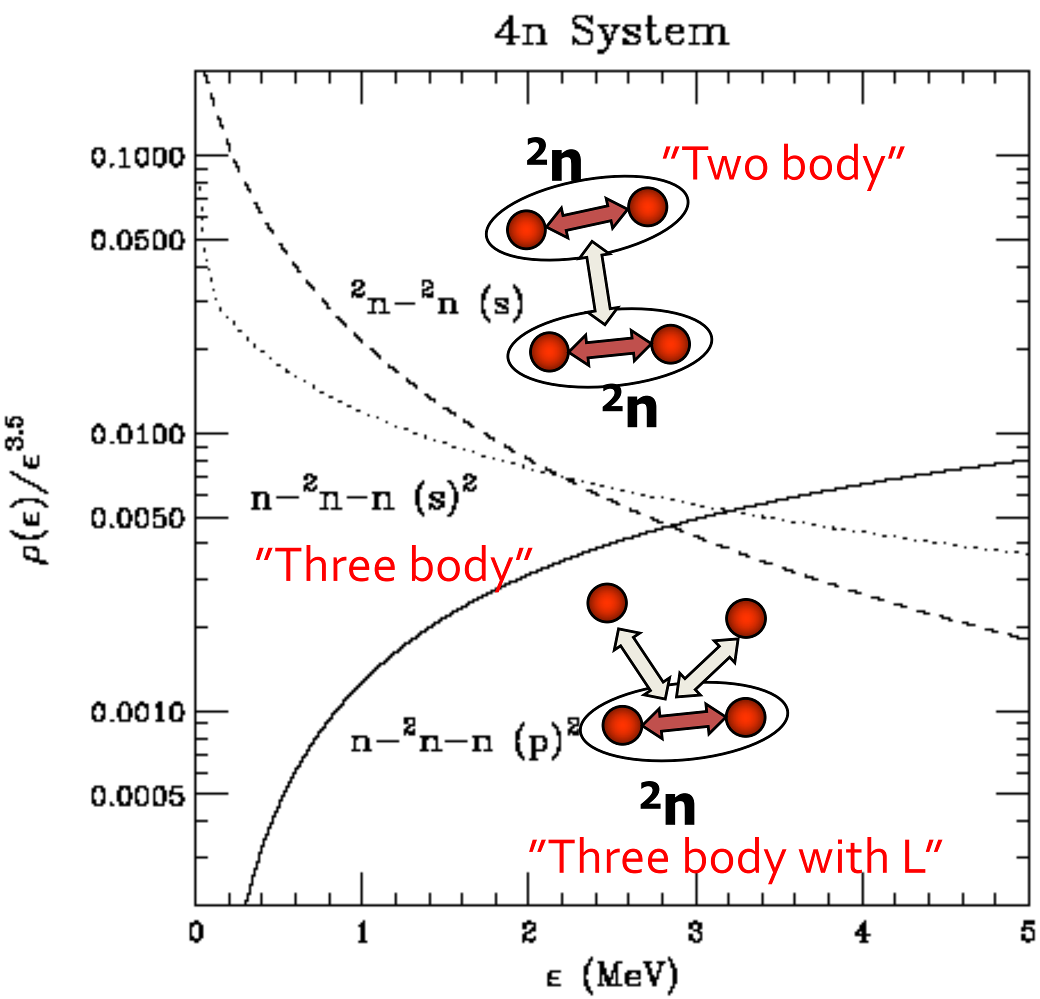






Look like having two components:
Continuum + Peak (?)
? The 4 counts just above threshold can be explained by the fluctuation of continuum or not?

Phase space in multi-body continuum



Phase Space

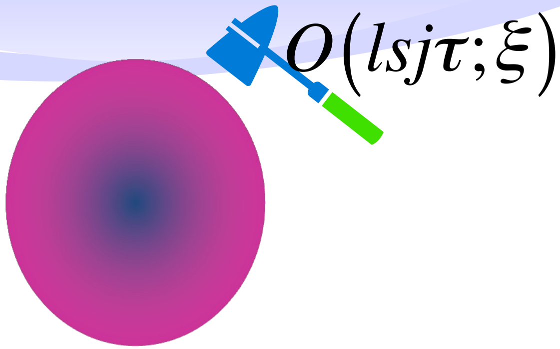
$\rho(E) \propto E^{1/2}$ (2 body)

$\propto E^{2}$ (3 body)

$\propto E^{7/2}$ (4 body)

Deviation from four-body phase space informs us the final state interaction(s) of sub-system

Transition Probabilities



$$M_{if} = \left\langle E_f J_f \pi_f T_f;\xi_f \left\| O(lsj\tau;\xi) \right\| E_i J_i \pi_i T_i;\xi_i \right\rangle$$

if distortion is insensitive to ω

$$\text{Cross Section} \propto \left|M_{if}\right|^2 \quad ; \quad \text{Lifetime} \propto 1/\left|M_{if}\right|^2$$

$O(lsj\tau;\xi)$: Propety of Reaction / Aciton / Decay Processes

sum of
one-body operator

e.g.

$$O(lsj\tau;\vec{r}) = \sum_i f(r_i)\,T(\tau_i)\left[S(\sigma_i)\otimes Y_l(\hat{r}_i)\right]_j$$

$\left|E_i J_i \pi_i T_i;\xi_i\right\rangle$ and/or $\left|E_f J_f \pi_f T_f;\xi_f\right\rangle$ energy eigen functions

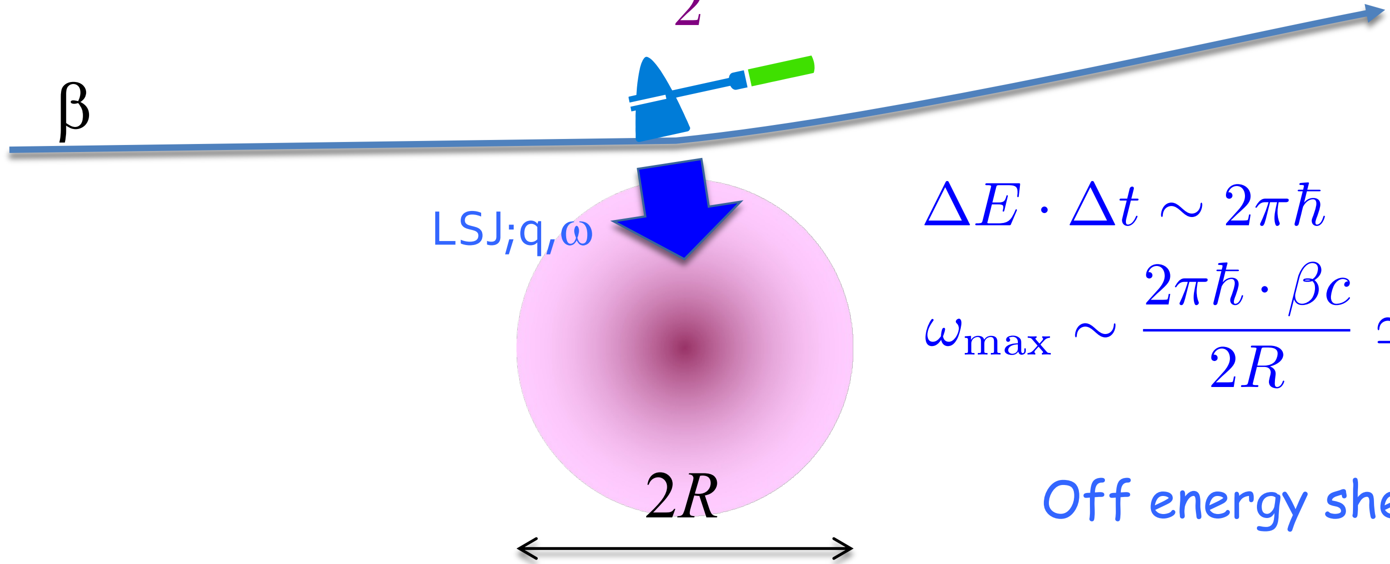
$$O(lsj\tau;\xi)\left|E_i J_i \pi_i T_i;\xi_i\right\rangle = \sum_f\!\!\!\!\!\!\int M_{if}(E_f)\left|E_f J_f \pi_f T_f;\xi_f\right\rangle \quad \text{Response}$$

$$\left|M_{if}(E_f)\right|^2 \; : \text{Energy Spectrum}$$

coherent sum of wave packets made by one-body action
"Collective wave packet" (not always energy eigen state),
e.g. coherent sum of 1p-1h for inelastic-type excitation

Reaction time & excitation energy
for intermediate-energy "inelastic-type scattering"

$$\omega \ll \mu c^2(\gamma - 1) \simeq \frac{1}{2}\mu c^2 \beta^2$$

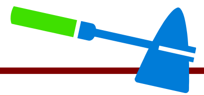


$$\Delta E \cdot \Delta t \sim 2\pi\hbar$$

$$\omega_{\max} \sim \frac{2\pi\hbar \cdot \beta c}{2R} \simeq 100\beta \quad \text{MeV}$$

Off energy shell

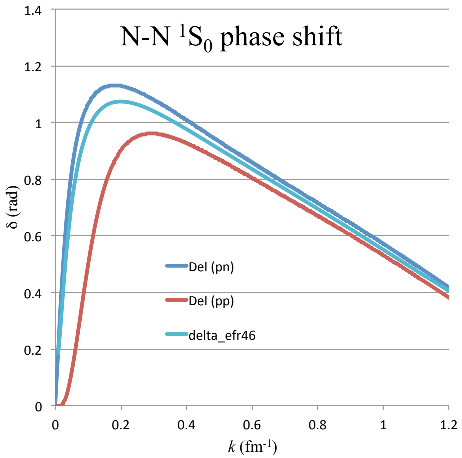
E/A ~ 200 MeV : β ~ 0.6 : ω_{max} ~ 60 MeV

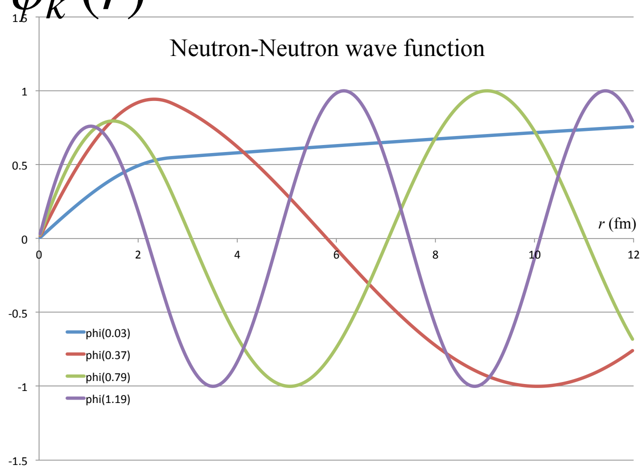


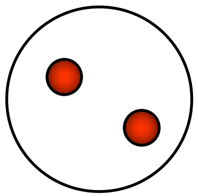
$$O(lsj\tau;\xi)\left|E_i J_i \pi_i T_i;\xi_i\right\rangle = \sum\!\!\!\!\!\!\int M_{if}(E_f)\left|E_f J_f \pi_f T_f;\xi_f\right\rangle$$ Response

$\left|M_{if}(E_f)\right|^2$: Energy Spectrum

NN case with FSI

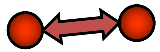






2n wave packet just after a certain reaction
ϕ_0~ **Gaussian**

^{2}n

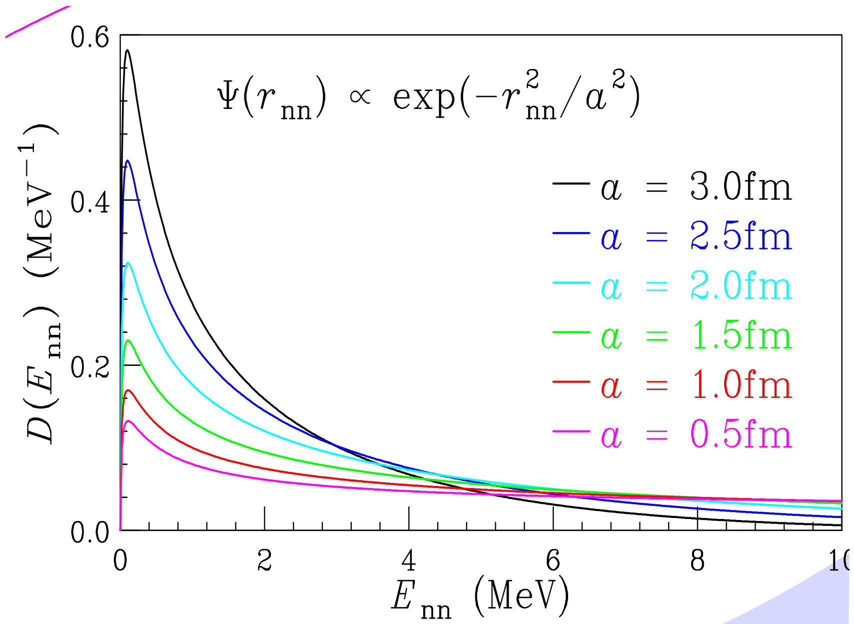


Scattering state of correlated neutron pair

Density of State

$$D\left(E_{\rm nn}\right) = \frac{\left|A\left(k\right)\right|^2}{k} \; ; \; E_{\rm nn} = \frac{\hbar^2 k^2}{m_{\rm N}}$$

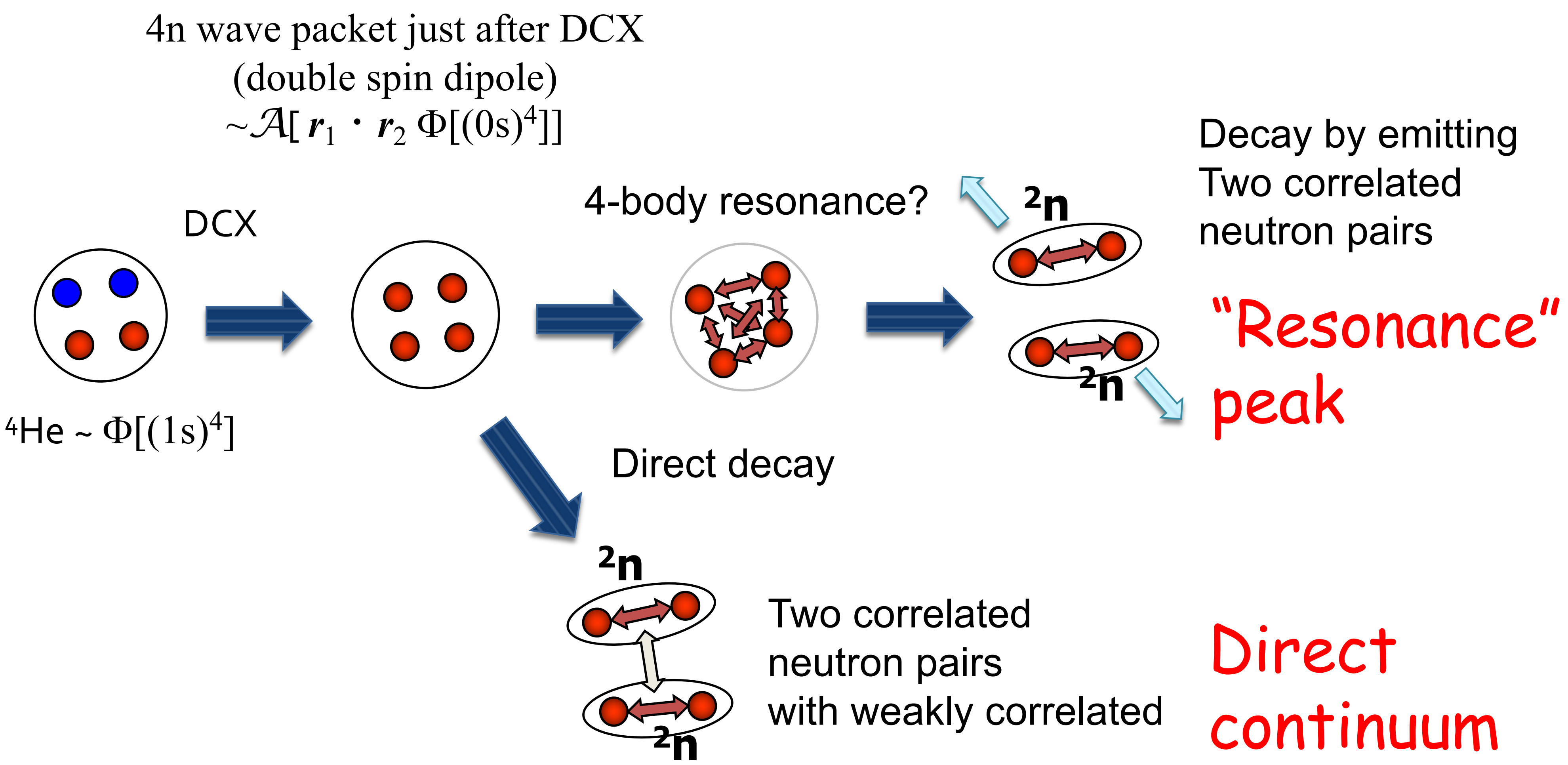
$$A\left(k\right) = \int dr r \Psi\left(r\right) \phi_k\left(r\right)$$



Expand Ψ_0 with correlated n-n scattering wave $\phi_k(r)$
$A(k)$'s are used instead of Fourier component

Effective Range Theory :
$\phi_k(r) \sim \sin \delta(k) \times f(r)$ for small r
$D \sim (\sin \delta)^2/k$ (Watson-Migdal approx.)

Picture of ^{4}He DCX reaction @ 200 A MeV



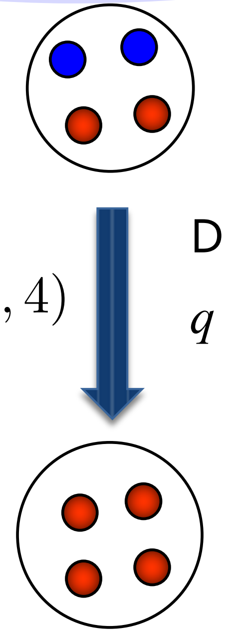
Direct Part

$$\Phi_0 \propto \mathcal{A}\left[\left(r_\alpha^2 - r_{12}^2\right)\exp\left(-\frac{r_\alpha^2}{a^2} - \frac{r_{12}^2}{2a^2} - \frac{r_{34}^2}{2a^2}\right)\chi(1,2)\,\chi(3,4)\right]$$

$$\propto \left(\frac{4r_\alpha^2}{a^2} - \frac{r_{12}^2}{a^2} - \frac{r_{34}^2}{a^2}\right)\exp\left[-\frac{r_\alpha^2}{a^2} - \frac{r_{12}^2}{2a^2} - \frac{r_{34}^2}{2a^2}\right]\chi(1,2)\,\chi(3,4)$$

$$+\frac{4\vec{r}_{12}\cdot\vec{r}_{34}}{a^2}\exp\left[-\frac{r_\alpha^2}{a^2} - \frac{r_{12}^2}{2a^2} - \frac{r_{34}^2}{2a^2}\right]\vec{X}(1,2)\cdot\vec{X}(3,4)$$

^{4}He ~ $\Phi[(0\mathrm{s})^4]$



DCX

$q << 200$ MeV/c

4n wave packet just after DCX
$\Phi_0 \sim \boldsymbol{r}_1 \cdot \boldsymbol{r}_2\, \Phi[(0\mathrm{s})^4]$

$$\vec{r}_\alpha = \frac{\vec{r}_1 + \vec{r}_2}{2} - \frac{\vec{r}_3 + \vec{r}_4}{2}$$

$$\chi(i,j) = \frac{1}{\sqrt{2}}\left(\uparrow(i)\downarrow(j) - \downarrow(i)\uparrow(j)\right)$$

$$\vec{X}(i,j) = \begin{pmatrix} \uparrow(i)\uparrow(j) \\ \frac{1}{\sqrt{2}}\left(\uparrow(i)\downarrow(j) + \downarrow(i)\uparrow(j)\right) \\ \downarrow(i)\downarrow(j) \end{pmatrix}$$

Fourier Transform: $(\boldsymbol{r}_{12}, \boldsymbol{r}_{34}, \boldsymbol{r}_\alpha) \rightarrow (\boldsymbol{k}_{12}, \boldsymbol{k}_{34}, \boldsymbol{k})$

$$\int \left|\mathcal{A}\tilde{\Phi}_0\right|^2 d^3k\, d^3k_{12}\, d^3k_{34}\, \delta(E - \epsilon - \epsilon_{12} - \epsilon_{34}) \propto X^{11/2}\exp(-X)$$

Peak at $X = 11/2$; $E \sim 60$ MeV

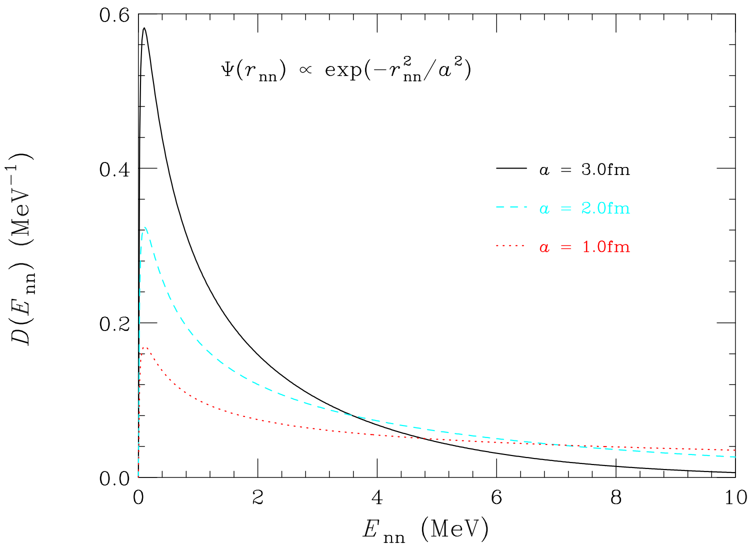
$$X = E/\epsilon_a \qquad \epsilon_a = \frac{\hbar^2}{m_N a^2} = 11\mathrm{MeV}$$

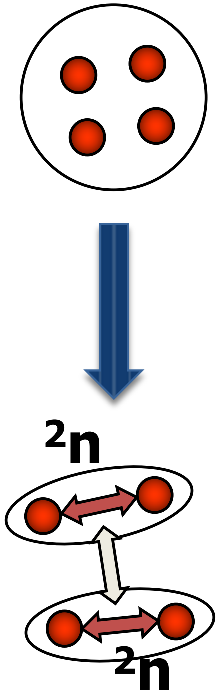
NN FSI

c.f. Continuum spectrum with n-n FSI

L.V. Grigorenko, N.K. Timofeyuk, M.V. Zhukov, Eur. Phys. J. A 19, 187 (2004)

Density of State





4n wave packet just after DCX
$\Phi_0 \sim \boldsymbol{r}_1 \cdot \boldsymbol{r}_2\, \Phi[(0s)^4]$

Two correlated neutron pairs with weakly correlated

$$D_{ns}(\epsilon_{nn}) = \frac{\left|\hat{A}_{ns}(k)\right|^2}{k} \quad (\text{for } n = 1, 2) \quad ; \quad \epsilon_{nn} = \frac{\hbar^2 k^2}{m_N}$$

$$\hat{A}_{1s}(k) = \int_0^\infty dr\, r\, \psi_{1s}(r)\, \phi_k(r) = 2\left(\frac{1}{\sqrt{\pi}a^3}\right)^{1/2} k\, A_{1s}(k)$$

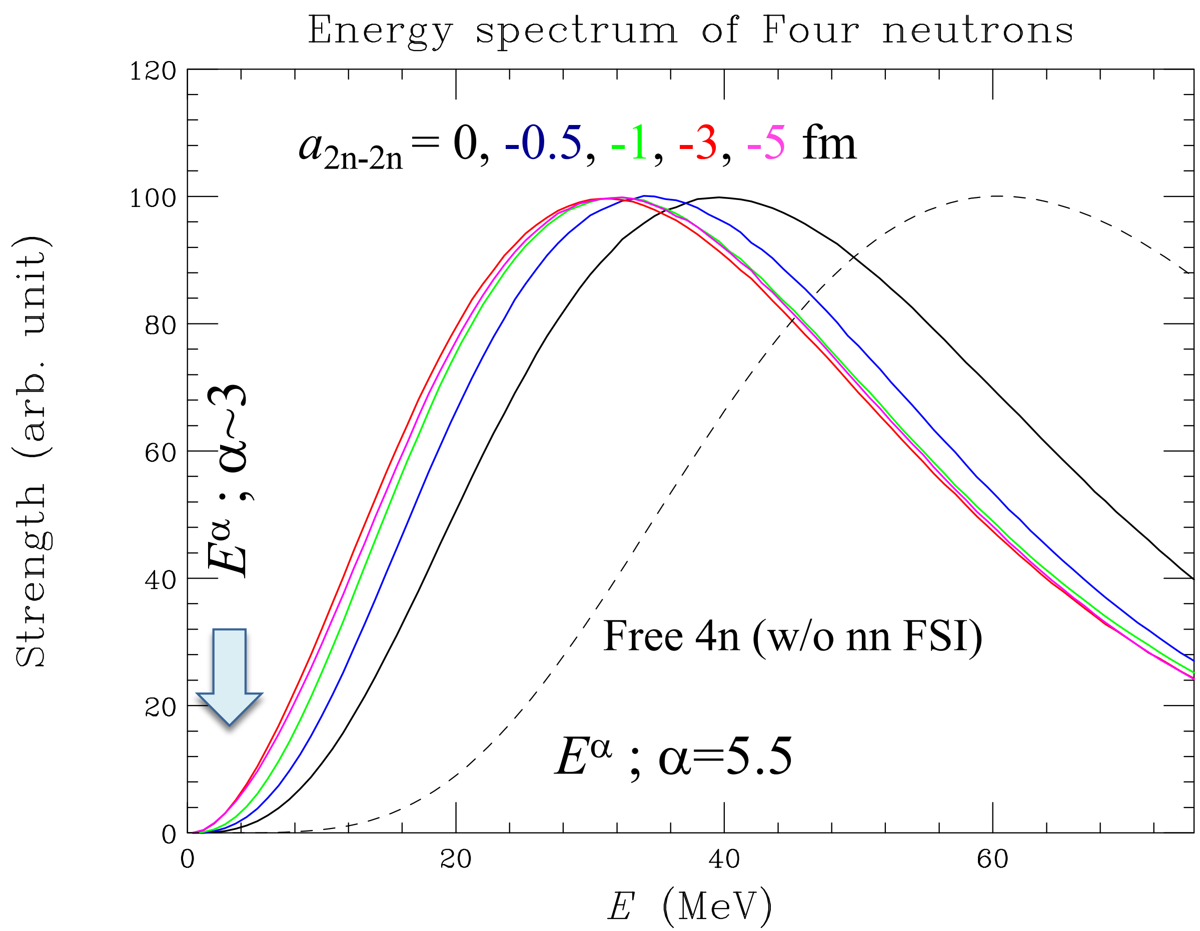
$$\hat{A}_{2s}(k) = \int_0^\infty dr\, r\, \psi_{2s}(r)\, \phi_k(r) = 2\sqrt{\frac{2}{3}}\left(\frac{1}{\sqrt{\pi}a^3}\right)^{1/2} k\, A_{2s}(k)$$

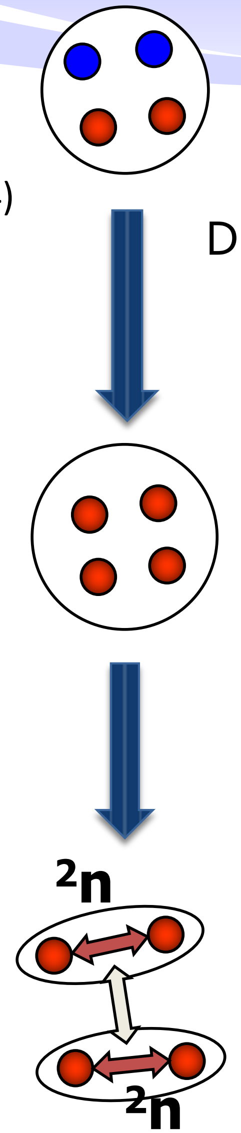
Expand $\mathcal{A}\Phi_0$ with correlated n-n scattering wave $\phi_k(r)$
$A(k)$'s are used instead of Fourier component

Direct Part

Continuum spectrum with n-n FSI

c.f.
L.V. Grigorenko, N.K. Timofeyuk, M.V. Zhukov, Eur. Phys. J. A 19, 187 (2004)





^{4}He ~ $\Phi[(0s)^4]$

DCX

$q << 200$ MeV/c

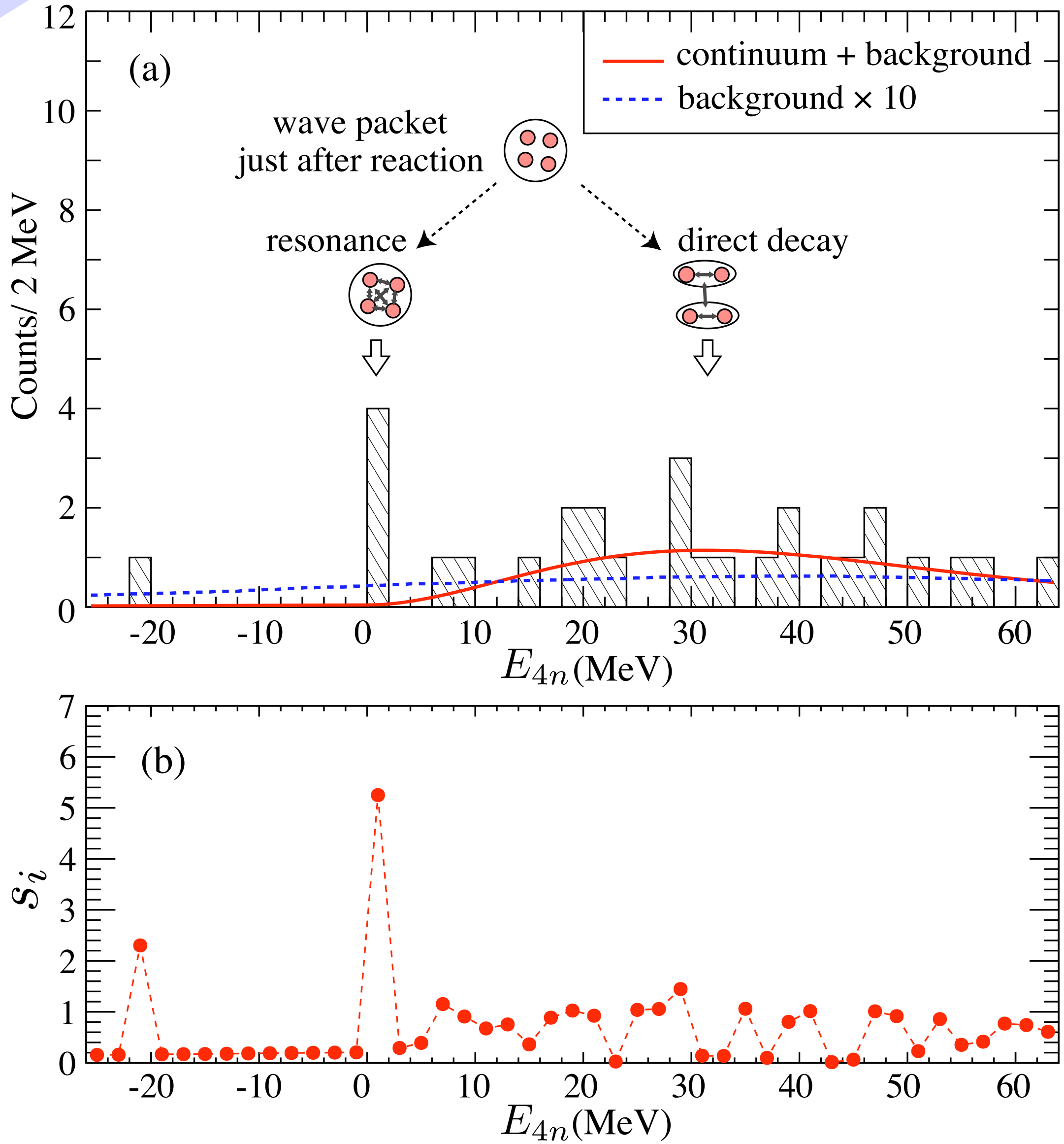
4n wave packet just after DCX
$\Phi_0 \sim \boldsymbol{r}_1 \cdot \boldsymbol{r}_2\, \Phi[(0s)^4]$

Two correlated neutron pairs with weakly correlated

Correlation is taking into account for 2n-2n relative motion by using scattering length

$$E^{\alpha} \exp(-E/\epsilon)$$

Fit with direct component & BG



Energy spectrum is expressed by the continuum from the direct decay and (small) experimental background except for four events at $0<E_{4n}<2$ MeV

The Four events suggest a possible resonance at
0.83 ± 0.65(stat.) ± 1.25(sys.) MeV
with width narrower than 2.6 MeV (FWHM). [4.9σ significance]

Integ. cross section $\theta_{cm}< 5.4$deg:
$3.8^{+2.9}_{-1.8}$ nb

- likelihood ratio test

$$\chi^2_\lambda = -2\ln\left[L(\boldsymbol{y};\boldsymbol{n})/L(\boldsymbol{n};\boldsymbol{n})\right]$$

  - Significance:

$$s_i = \sqrt{2[y_i - n_i + n_i \ln(n_i/y_i)]}$$

n_i : num. of events in the i-th bin
y_i : trial function in the i-th bin

- Look Elsewhere Effect

$$\mu^n e^{-\mu}/n! \simeq 10^{-6} \quad \text{for} \quad \mu = 0.07,\ n = 4$$

Other experimental approaches

E/A>150 MeV

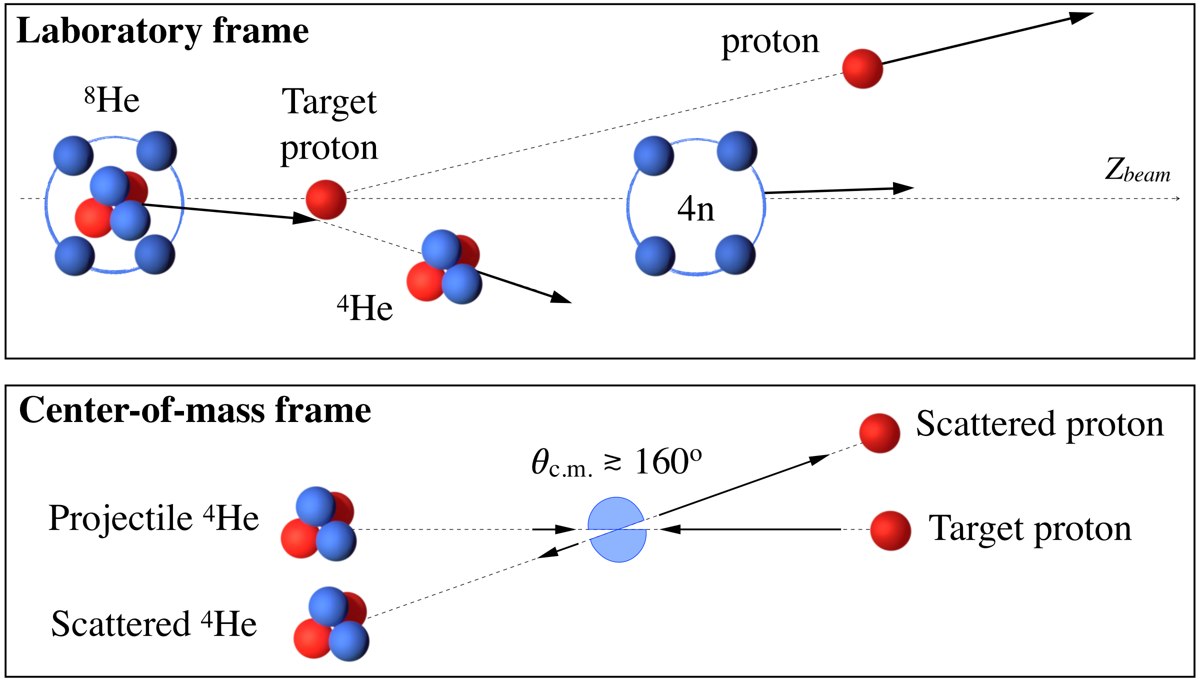
- $^{4}He(^{8}He,^{8}Be)4n$ again for more statistics & for $^{1}H(t,^{3}He)n$ for calibration
- ^{8}He (knockout α by proton) -> 4n
- ^{8}He (knockout proton by proton) -> ^{7}H -> 4n+t
- $^{1,2,3}H(^{3}H,^{3}He)1,2,3n$ for basic understanding

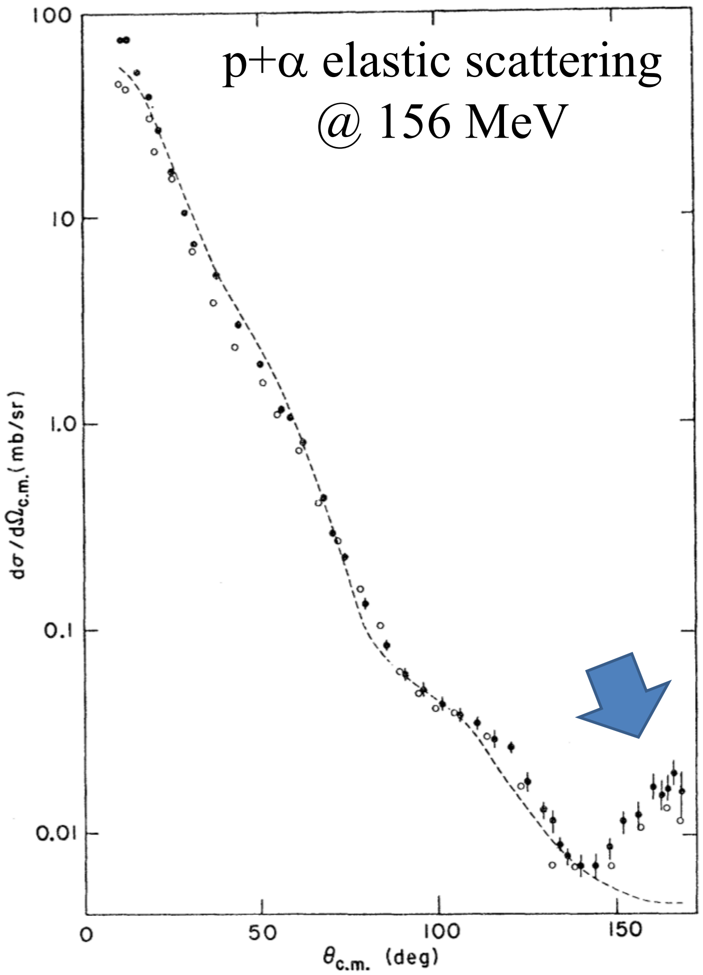
Low energy 3p pickup reaction

- $^{7}Li(^{7}Li,^{10}C(*))4n$ @ 46 MeV PLB 824 (2022) 136799

M. Duer et al., Nature **606**, 678 (2022)

Inverse kinematics of ^{8}He(p,pα)4n @156 *A* MeV @ SAMURAI



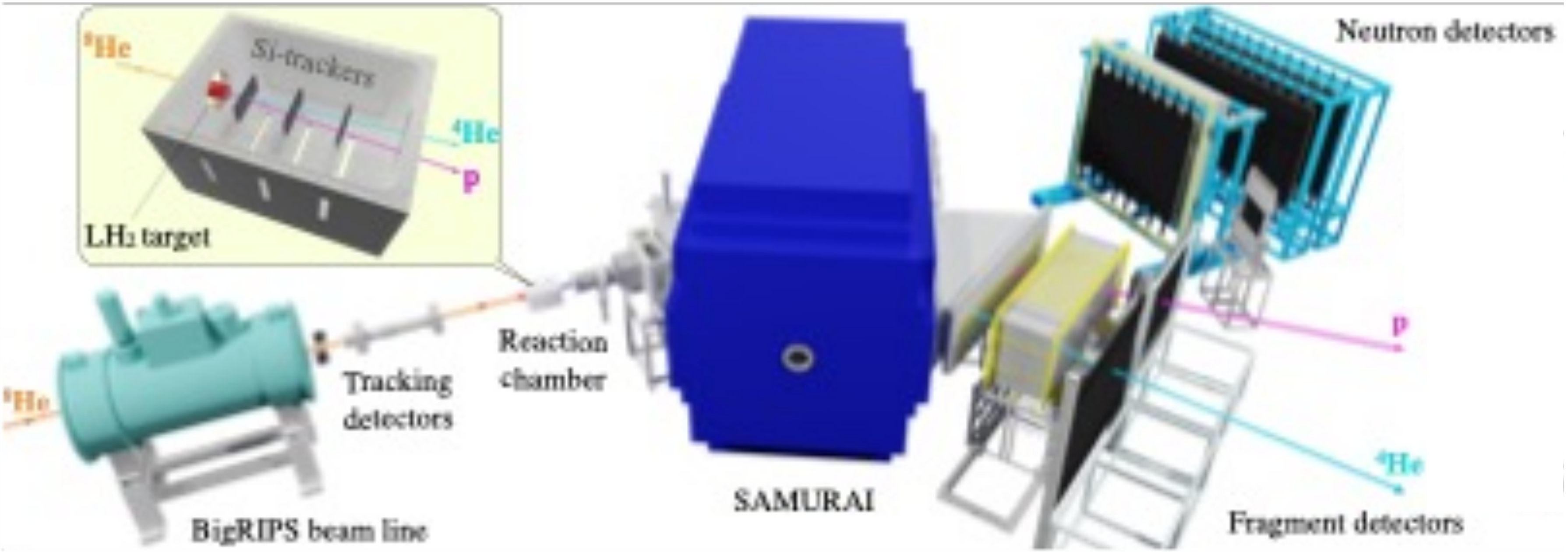


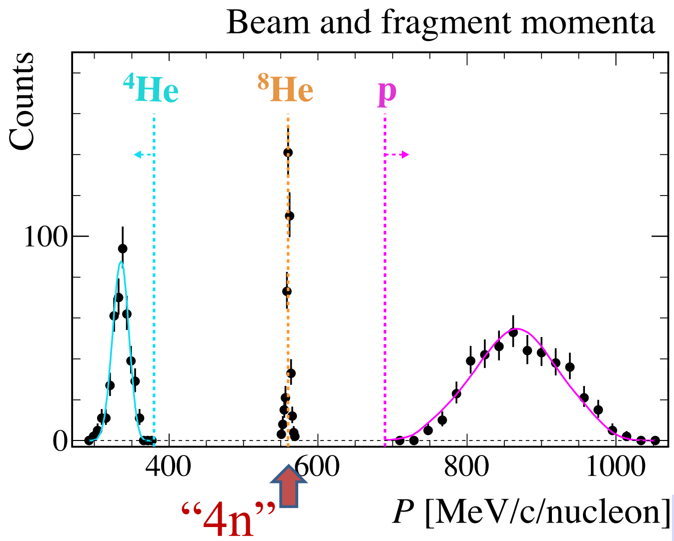
Quasi-free head-on alpha-proton scattering:

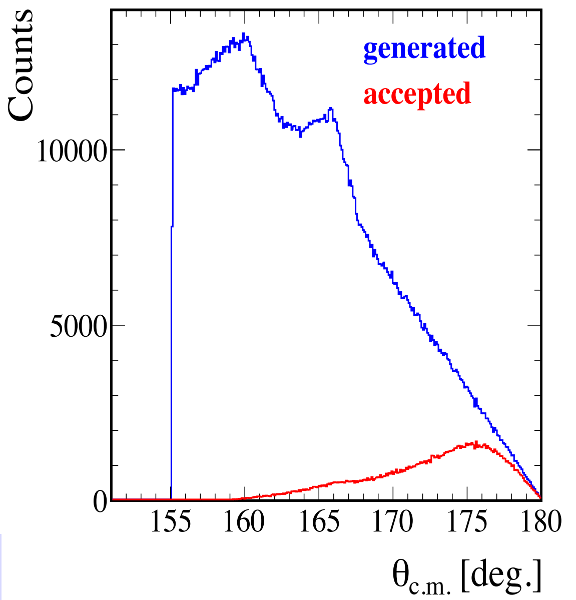
^{8}He(p,pα)4n

^{6}He(p,pα)2n (control)

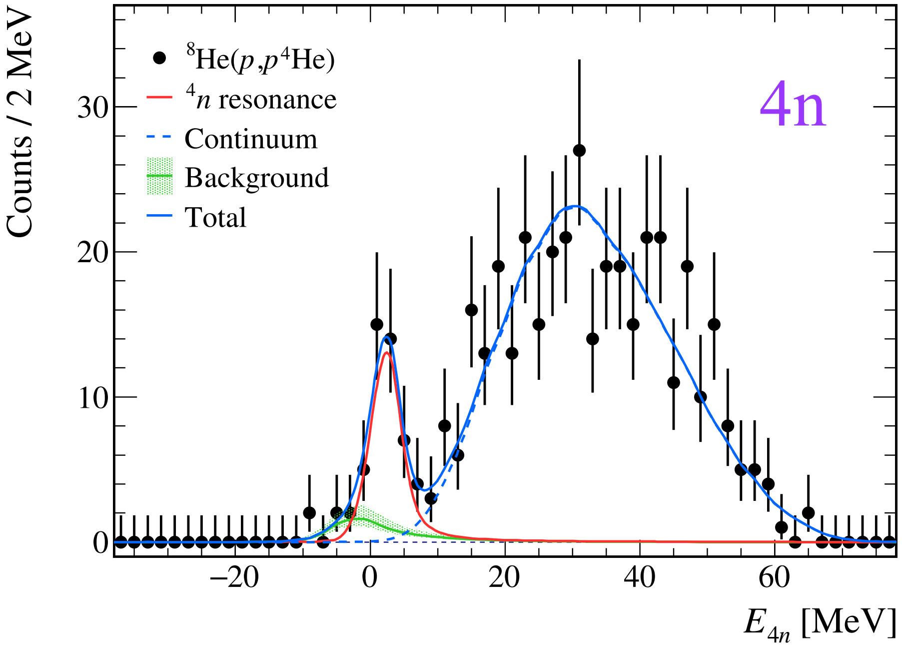
Inverse kinematics of ^{8}He(p,pα)4n @156 *A* MeV

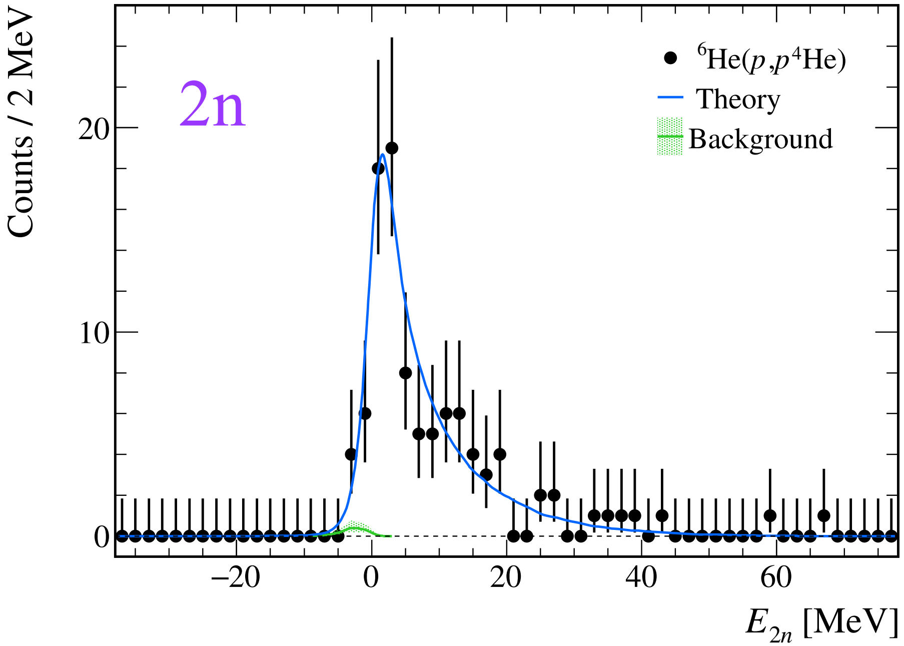






Inverse kinematics of ^{8}He(p,pα)4n @156 *A* MeV





Sharp peak just above threshold + Continuum

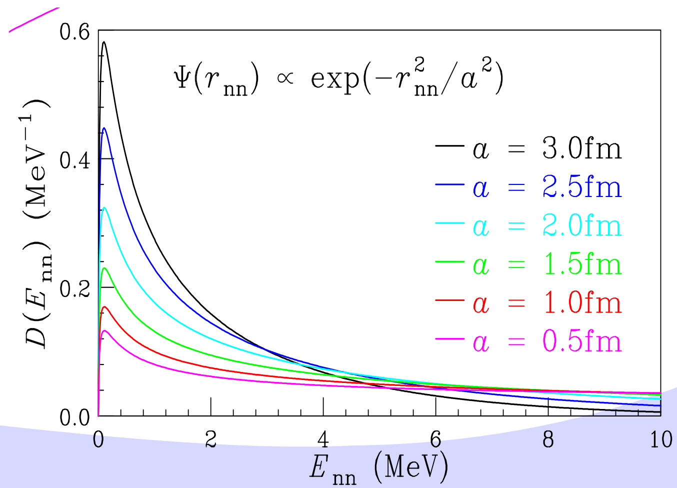
Well-known n-n FSI peak

Conventional B-W fitting:

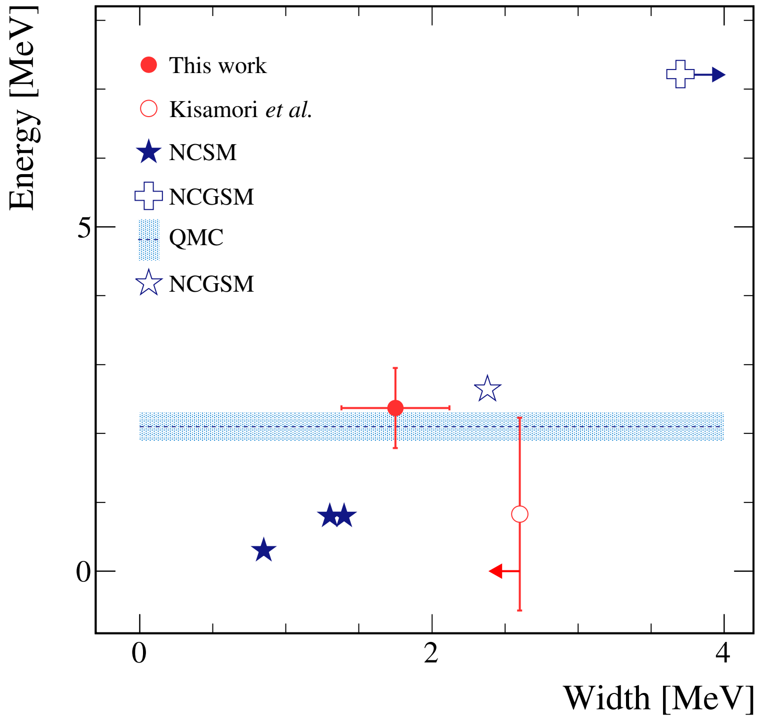
$$E_{\rm r} = 2.37 \pm 0.38({\rm stat.}) \pm 0.44({\rm sys.})\ {\rm MeV},$$
$$\Gamma = 1.75 \pm 0.22({\rm stat.}) \pm 0.30({\rm sys.})\ {\rm MeV}.$$

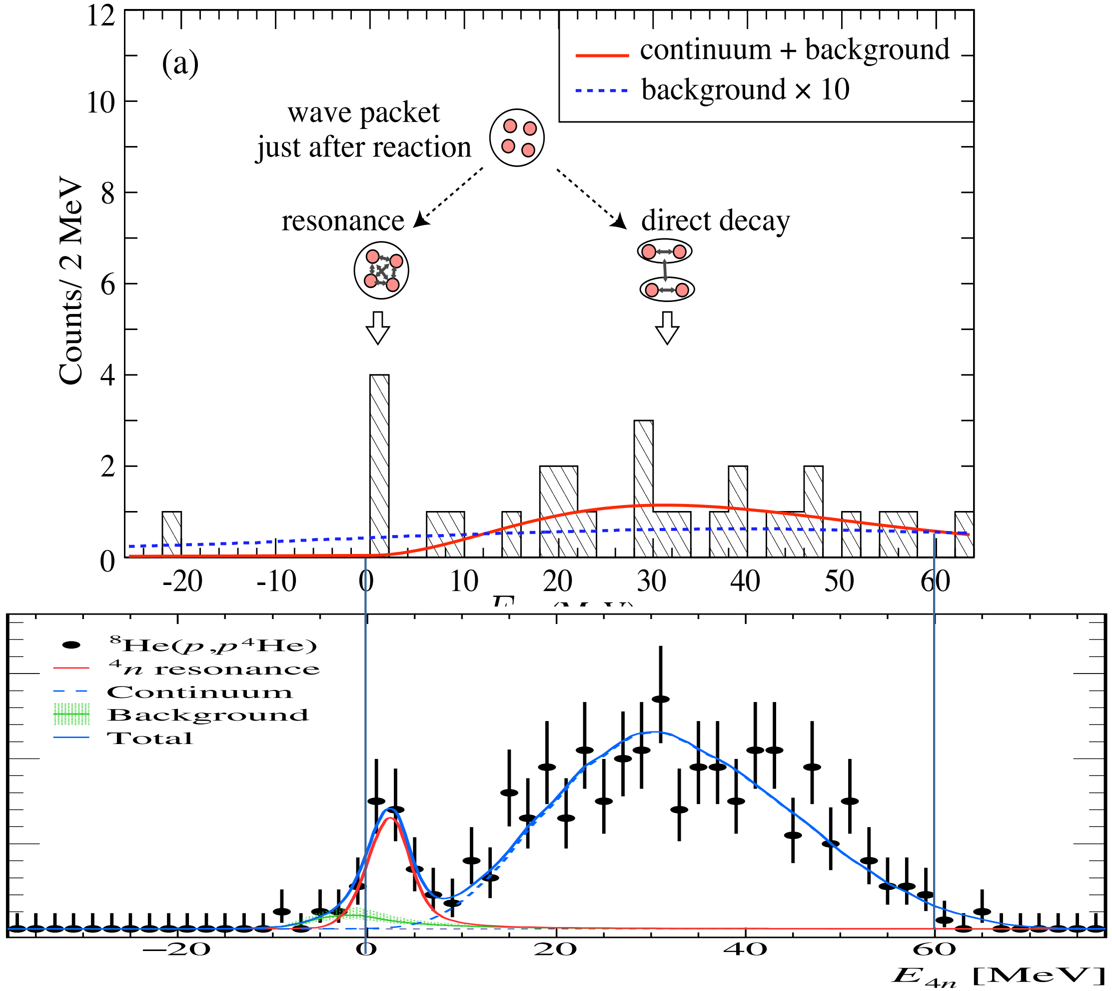
Continuum

$$f_{\rm cont}(E_{4n}) = E_{4n}^{\alpha} \cdot \exp(-E_{4n}/\epsilon_a),$$



Comparison between DCX and Knock-out spectra





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Low-energy 3p pickup reaction

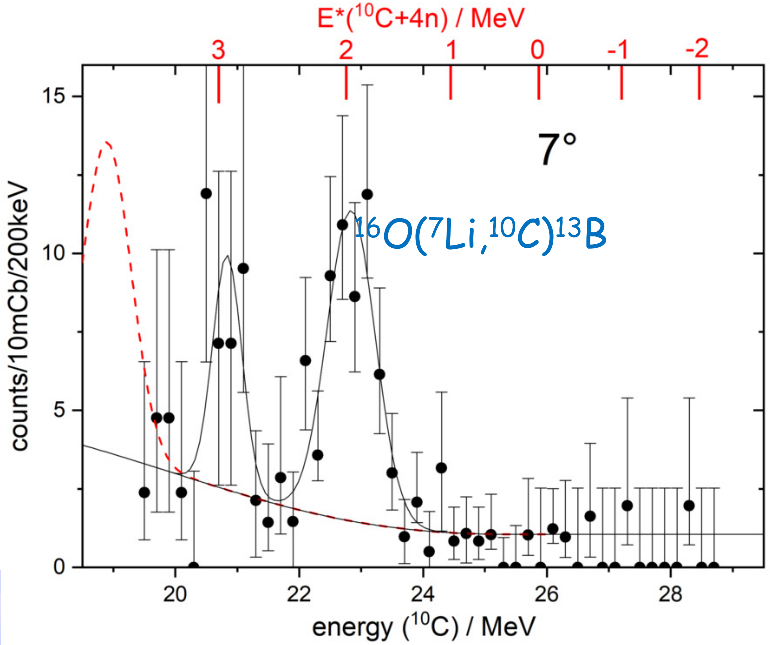
Pickup reaction with a larger negative Q-value can be recoil-less condition

- (d,^{3}He) for pionic atom at ~200 MeV
- ^{7}Li(^{7}Li,^{10}C(*))4n @ 46 MeV Q_{gg} = -18.2 MeV :

  small q at very forward angle < 1 deg

Indications for a bound tetraneutron

Thomas Faestermann [a,*], Andreas Bergmaier [b], Roman Gernhäuser [a], Dominik Koll [a,1], Mahmoud Mahgoub [c,d]



Sharp peak at E*=2.9 may be ^{10}C*(2^{+})+4n(bound)

? Significance (< 2σ ?)

q at 7 deg ~ 150 MeV/c

Summary

- $^{4}He(^{8}He,^{8}Be)4n$ has been measured at 190 A MeV at RIBF-SHARAQ
  - Continuum is estimated with n-n FSI
  - Four events just above 4n threshold is statistically beyond prediction of continuum + background (4.9 σ significance)

    → candidate of 4n resonance
- Alpha knockout reaction from ^{8}He was measured at 156 A MeV at RIBF-SAMURAI
  - Sharp peak + broad continuum spectrum with higher statistics
- Low-energy 3p pickup reaction from ^{7}Li was reported
  - Observed peak may be indication of bound 4n?