# Tetra-neutron system populated by nuclear reactions using RI-beam

- Motivation
- Idea for populating 4n system at rest
  - Exothermic double-charge exchange ($^{8}He$,$^{8}Be$)
- Experimental result
- Analysis
  - Continuum spectrum with correlation
    - A simple picture of the reaction
- Remarks (my personal picture on reaction)

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# 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)

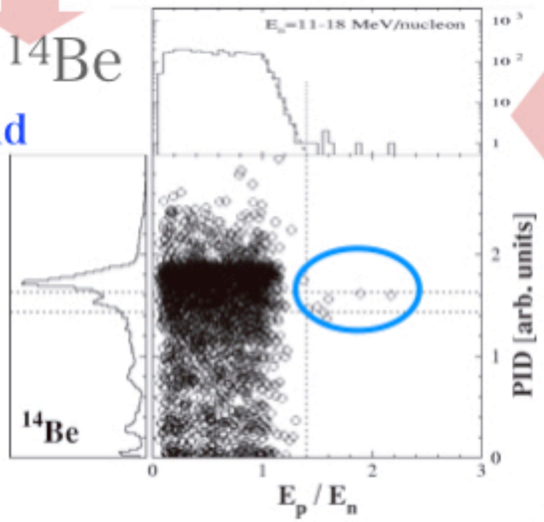
**Bound state: No clear evidence.**

2000s

### Breakup of $^{14}Be$

- Candidates of bound tetra-neutron were observed.

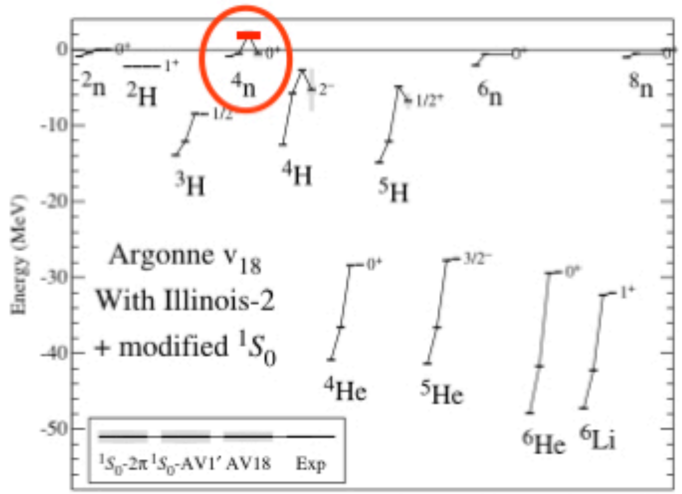
F. M. Marques, et al, Phys. Rev. C 65, 044006 (2002)




2000s

### Theoretical work

- ab-initio calculation
  NN, NNN interaction

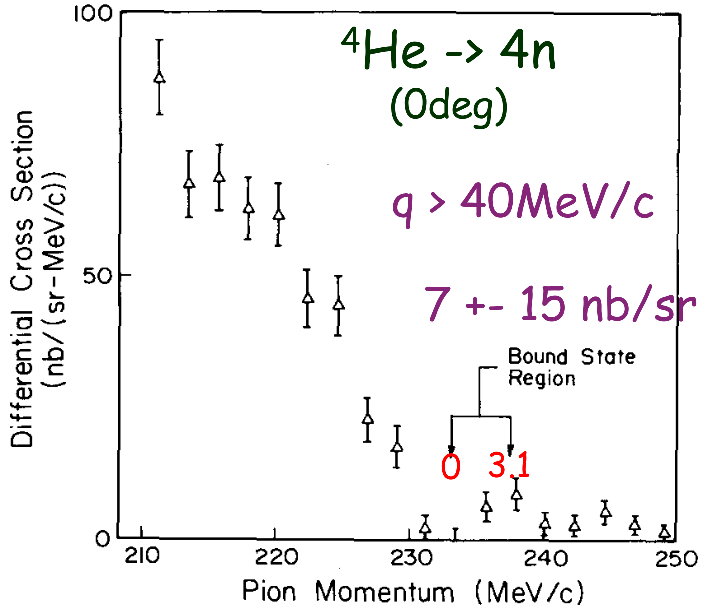


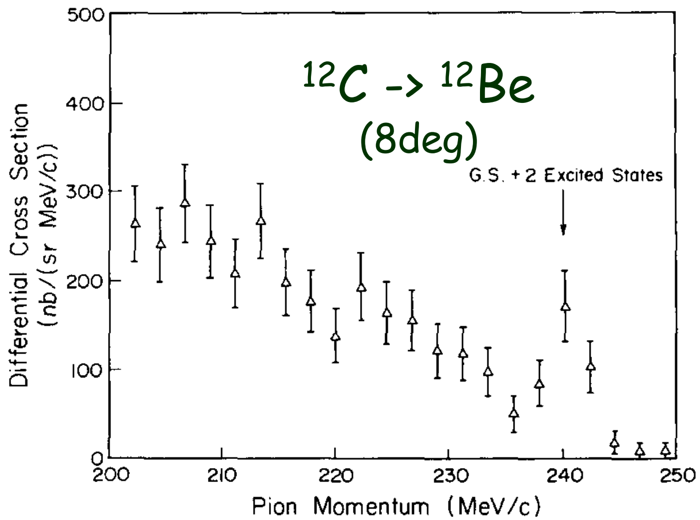

S. C. Piper, Phys. Rev. Lett. 90, 252501 (2003)

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

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

# $(\pi^-,\pi^+)$ 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 $\pi^+$ produced at 0° by 165 MeV $\pi^-$ on $^4$He. A $\Delta P/P$ = 1% beam of $10^6$ $\pi^-$ 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

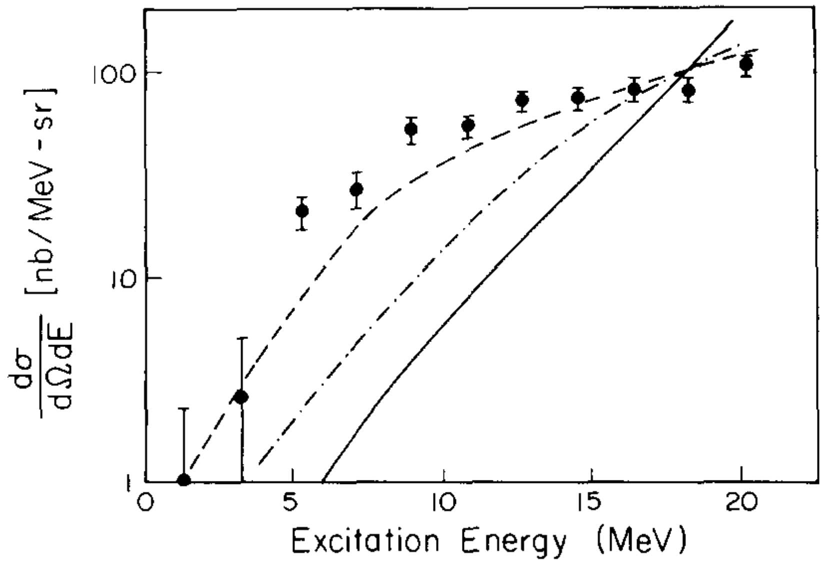
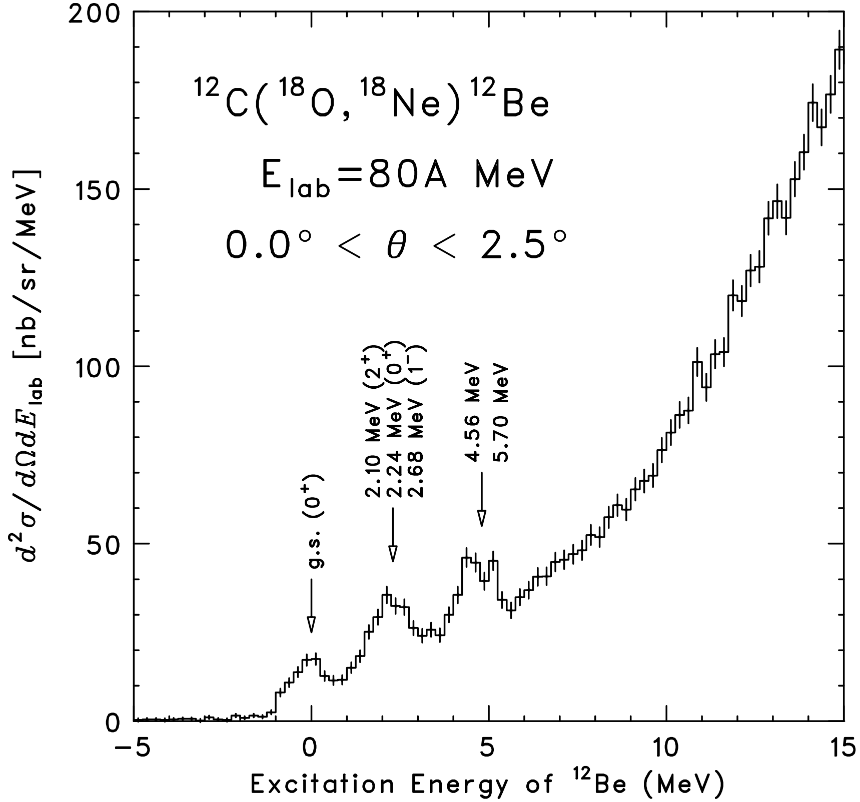



Fig. 3. The experimental results are plotted against the excitation of the final four-neutron state. The solid curve corresponds to the pure four-neutron phase space, while the dot–dashed and dashed curves are the four-neutron phase space curves with singlet state interactions in, respectively, one and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

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

# Double charge exchange (DCX) reaction of HI

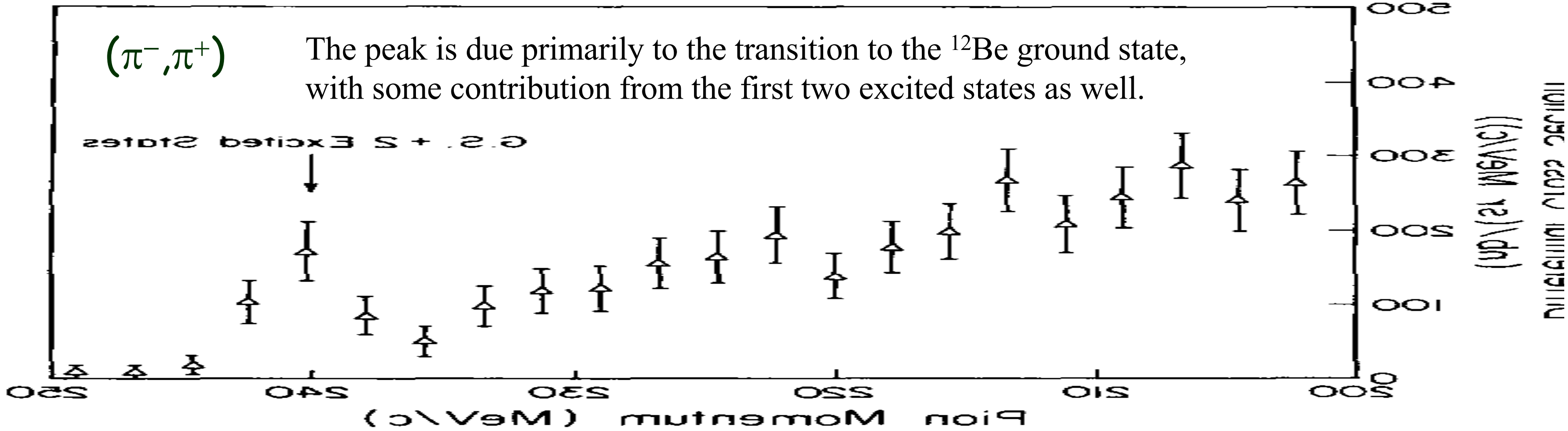



$^{12}C$ -> $^{12}Be$

Stable $^{18}O$ beam (80A MeV) (Takaki et al.)

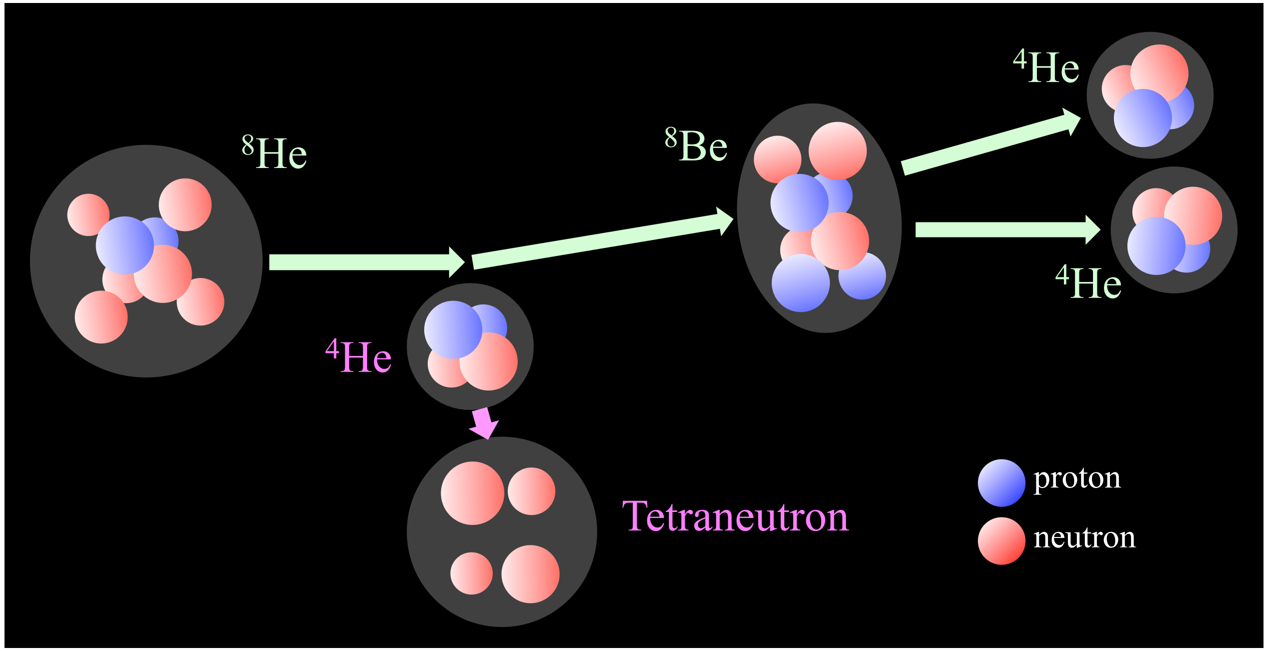
~70nb/sr (Gnd)
~200nb/sr (~2MeV)

HI DCX reaction can be used for spectroscopy for exotic nuclei (q is not so small >80 MeV/c)

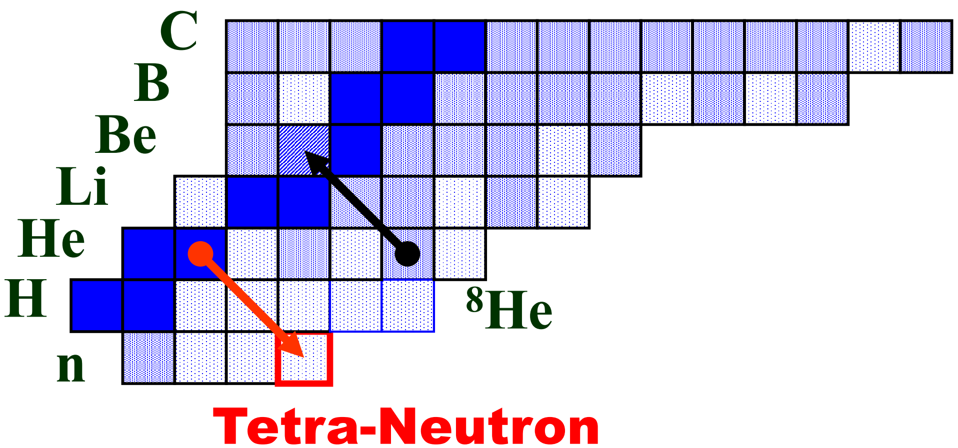


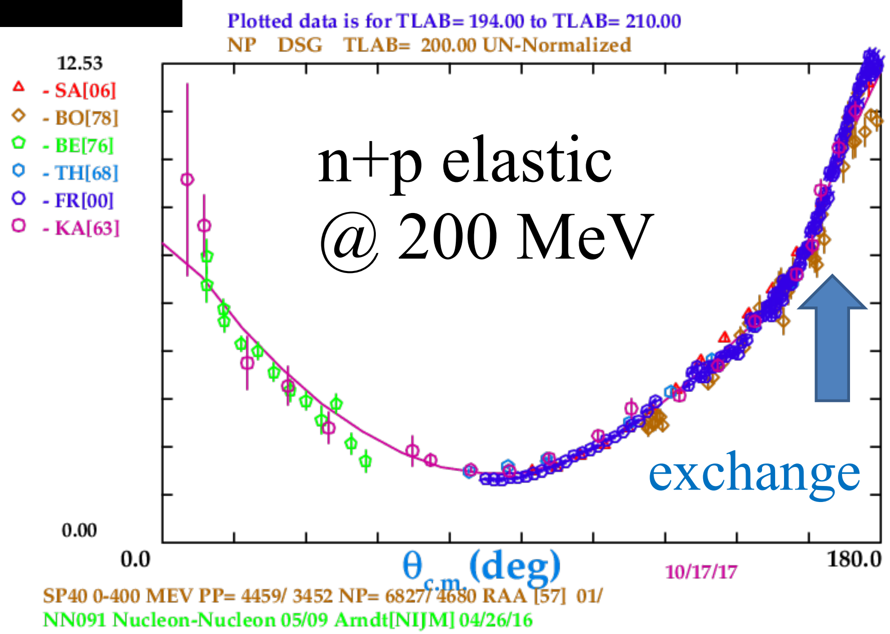

($\pi^-$,$\pi^+$) The peak is due primarily to the transition to the $^{12}$Be ground state, with some contribution from the first two excited states as well.

# Tetra-neutron system produced by exothermic double-charge exchange reaction

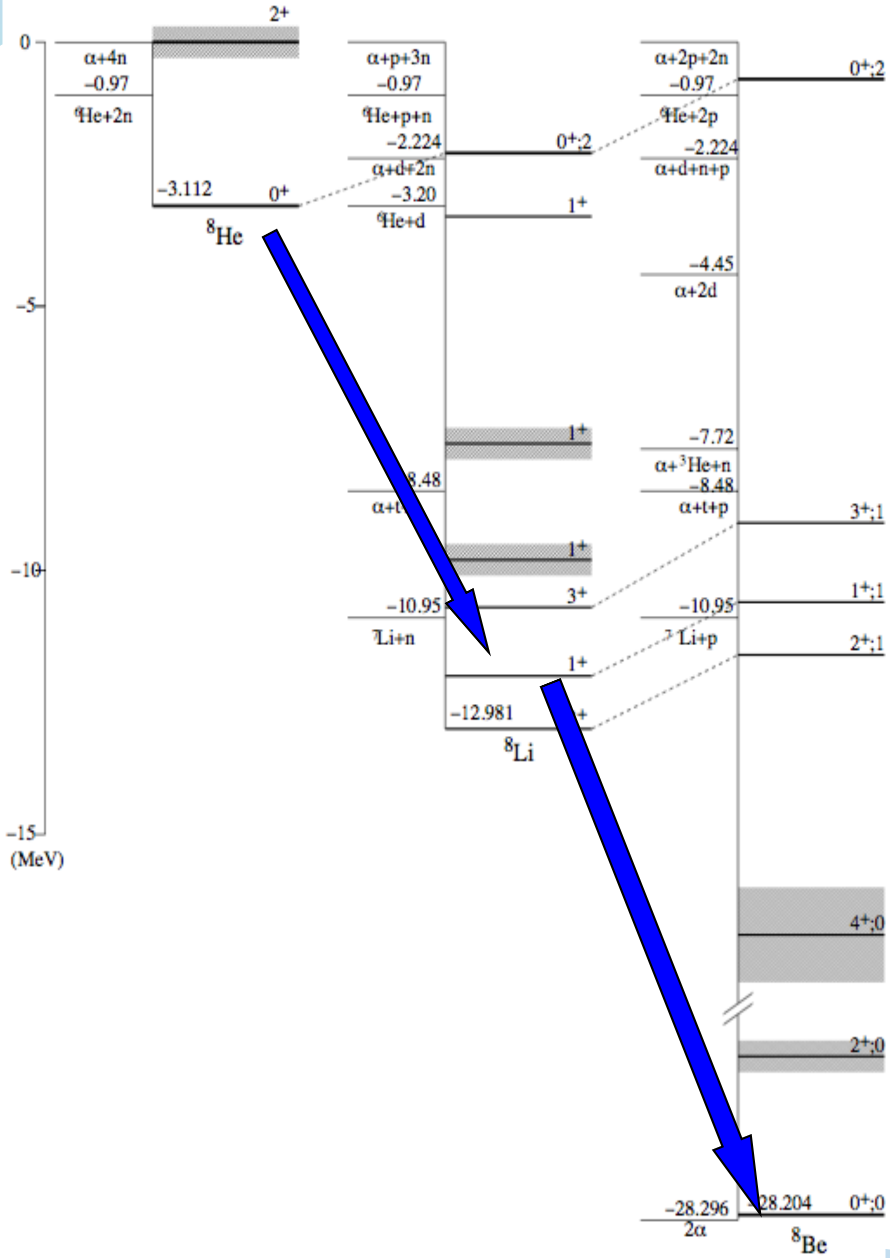


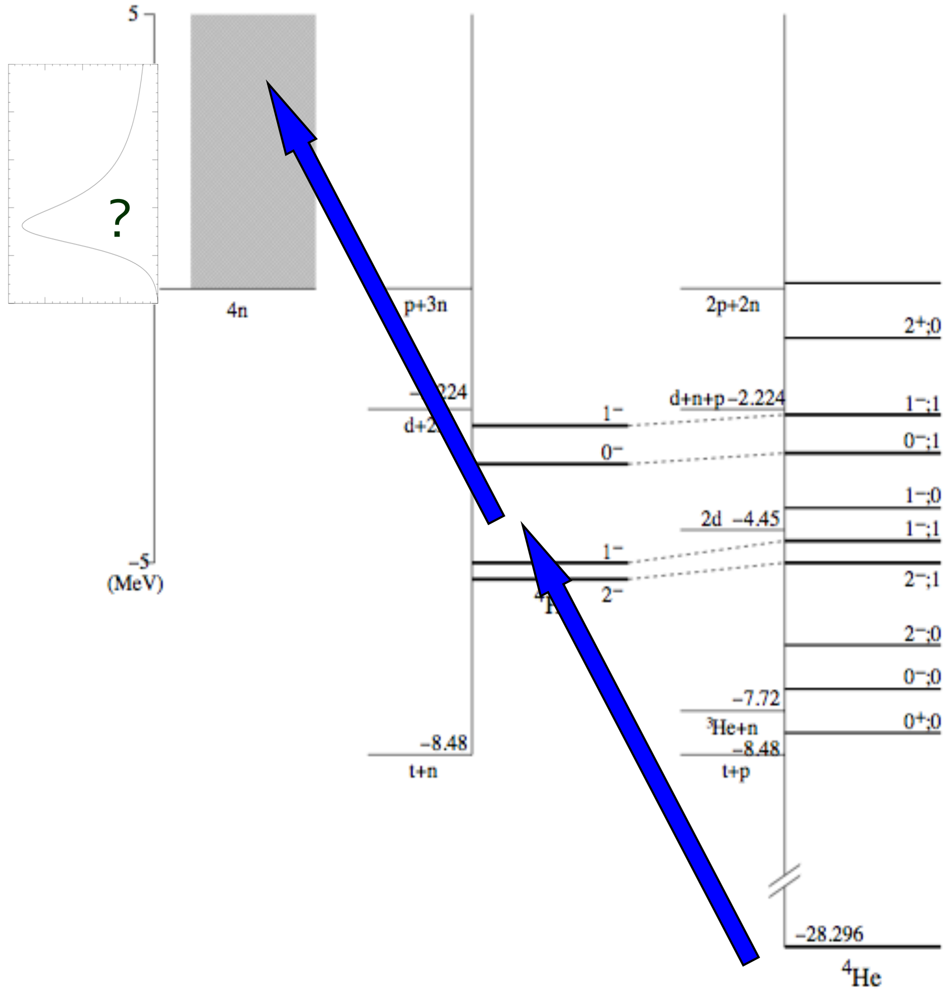

Almost recoil-less condition with $^4$He($^8$He,$^8$Be)4n reaction at 200 A MeV (0.63 c)



# Level diagrams

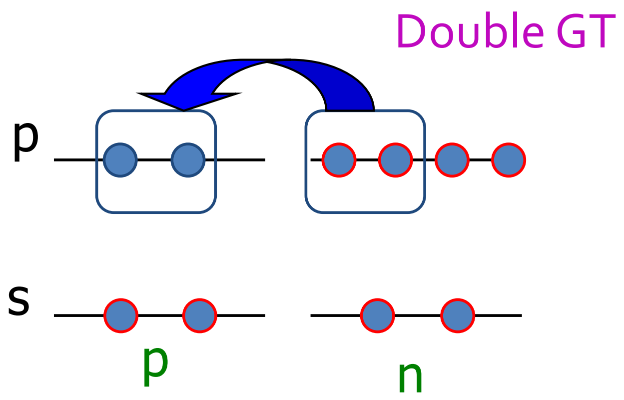


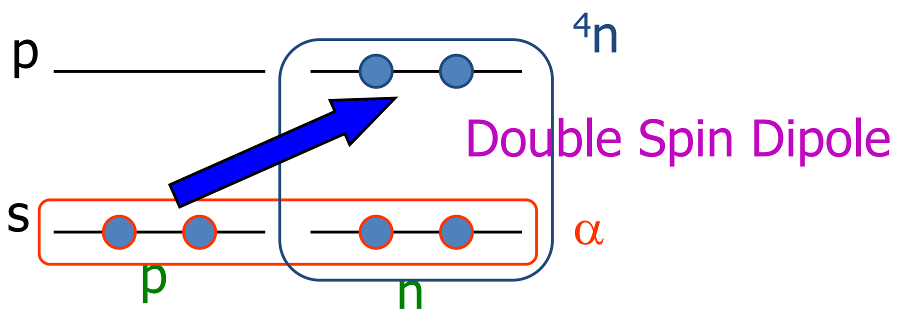

$q_{min} \sim 10 MeV/c$

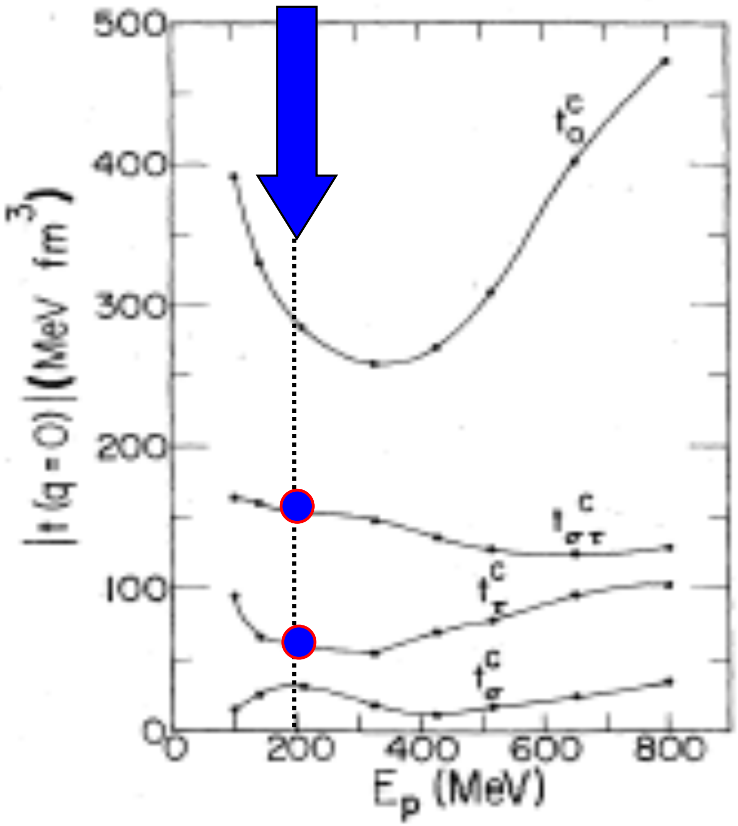
# Reaction Mechanism

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




$^{4}He \rightarrow 4n$

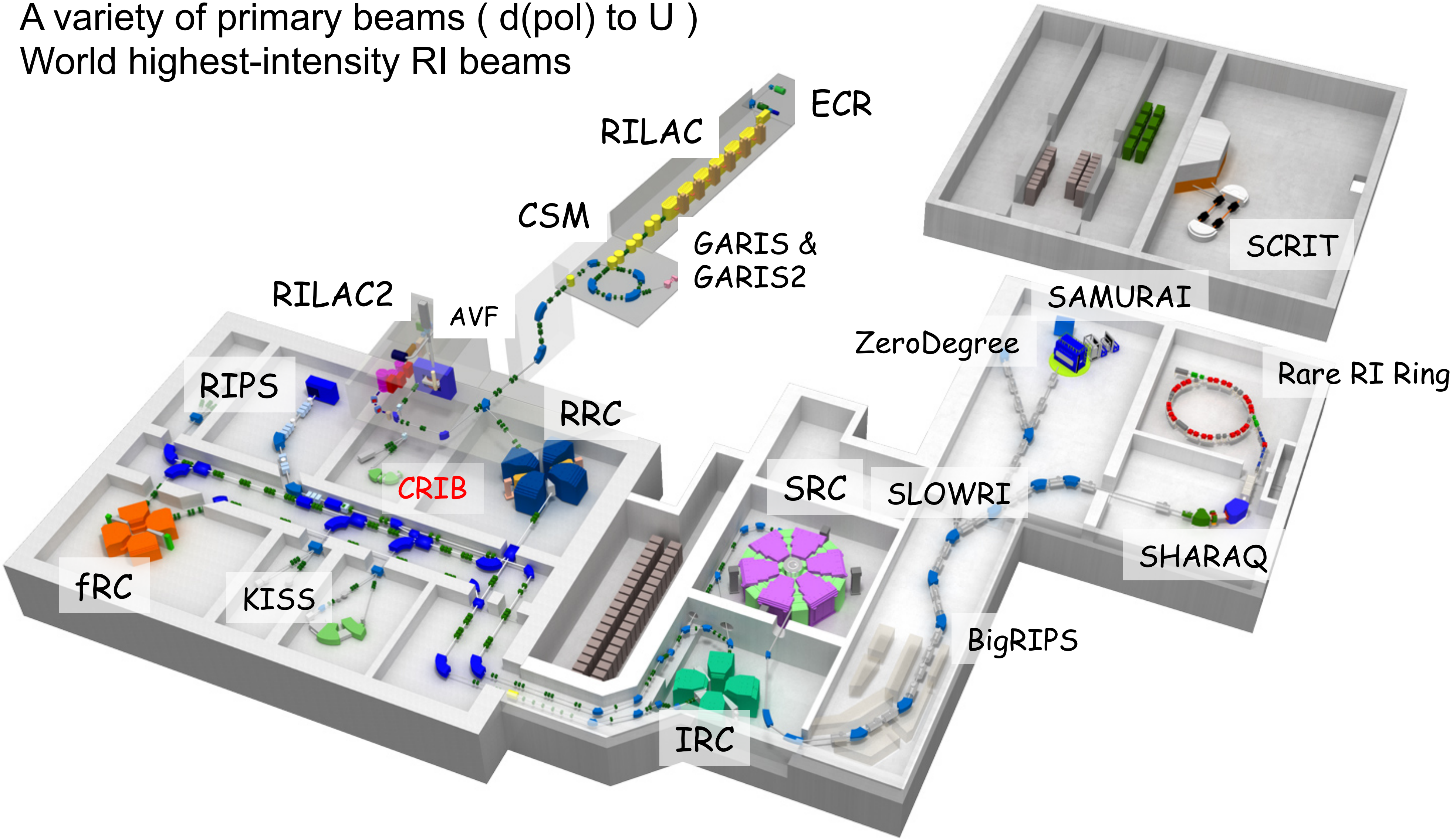



$$\left[\left(\vec{\tau}_{\mathrm{p}}\cdot\vec{\tau}_{\mathrm{t}}\right)\left(\vec{\sigma}_{\mathrm{p}}\cdot\vec{\sigma}_{\mathrm{t}}\right)r_{\mathrm{t}}Y_{1}\left(\hat{r}_{\mathrm{t}}\right)\right]^{2}$$

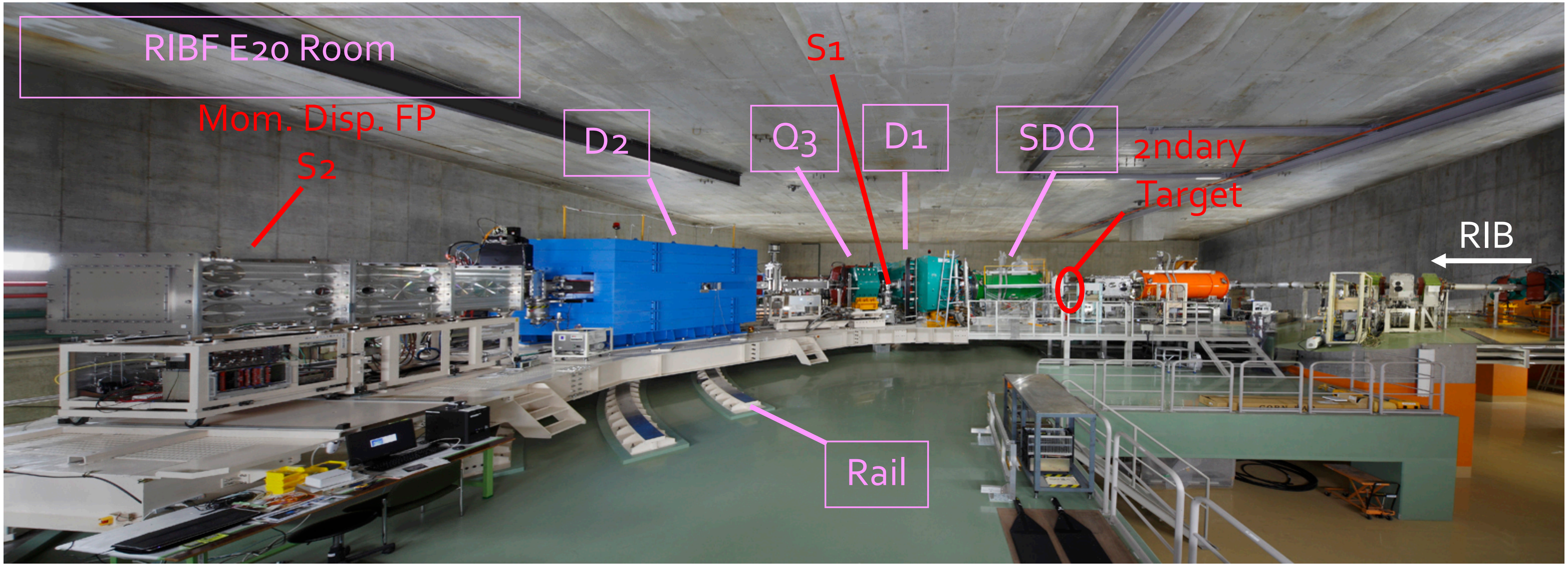
# RI Beam Factory at RIKEN

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



# SHARAQ spectrometer

T. Uesaka et al.,
NIMB B **266** (2008) 4218.
PTEP 2012, 03C007 (2012)




| | |
|---|---|
| **Maximum rigidity** | **6.8 Tm** |
| **Momentum resolution** | **d*p*/*p* = 1/14700** |
| **Angular resolution** | **~ 1 mrad** |
| **Momentum acceptance** | **± 1%** |
| **Angular acceptance** | **~ 5 msr** |

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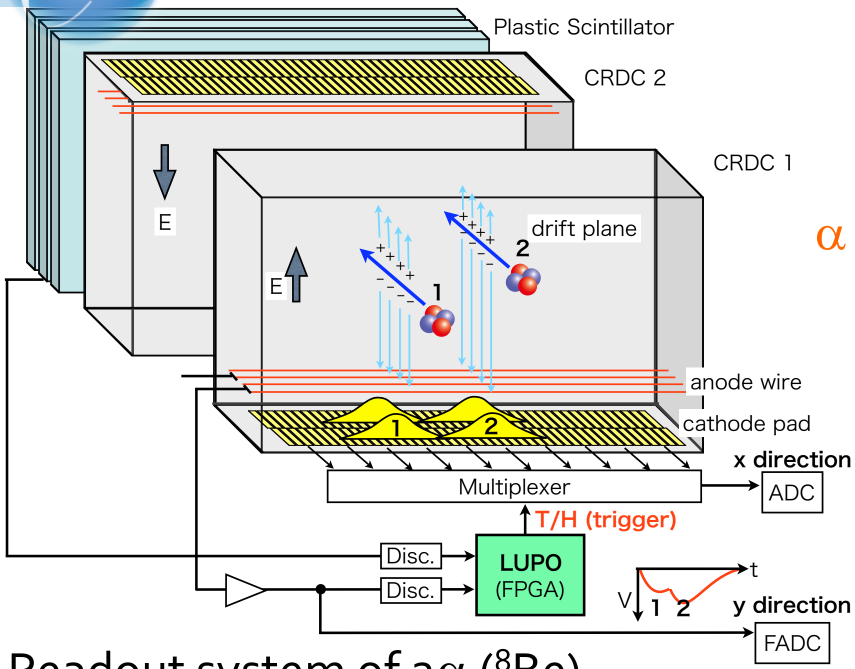
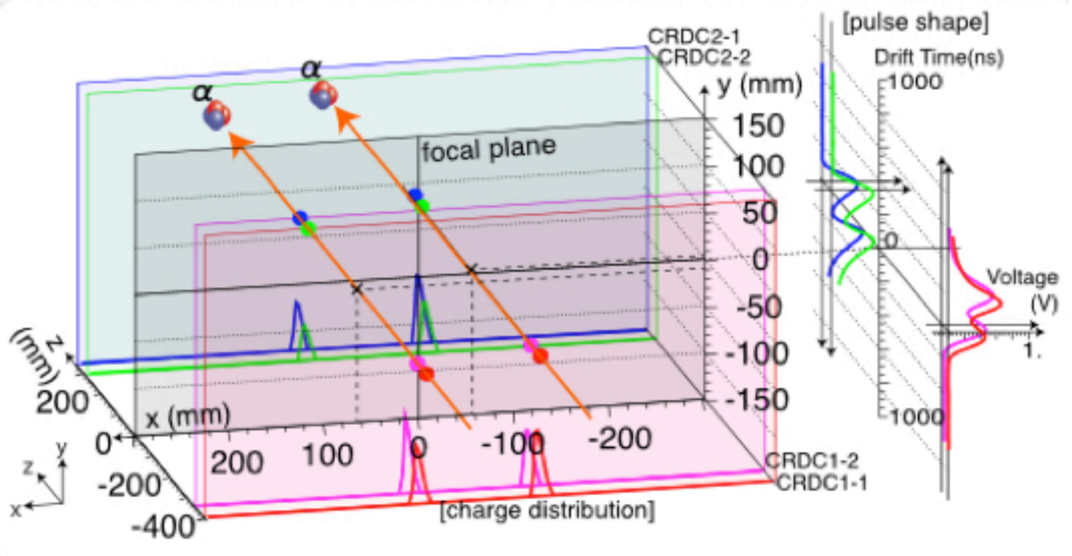



Readout system of 2α ($^8$Be)

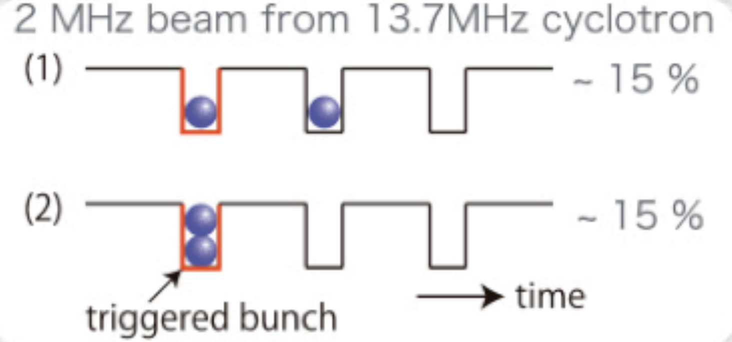

# Analysis

- Selection of 4n Events
  - Extracting 2$\alpha$ events @SHARAQ
  - Multi-particle in high-intensity beam



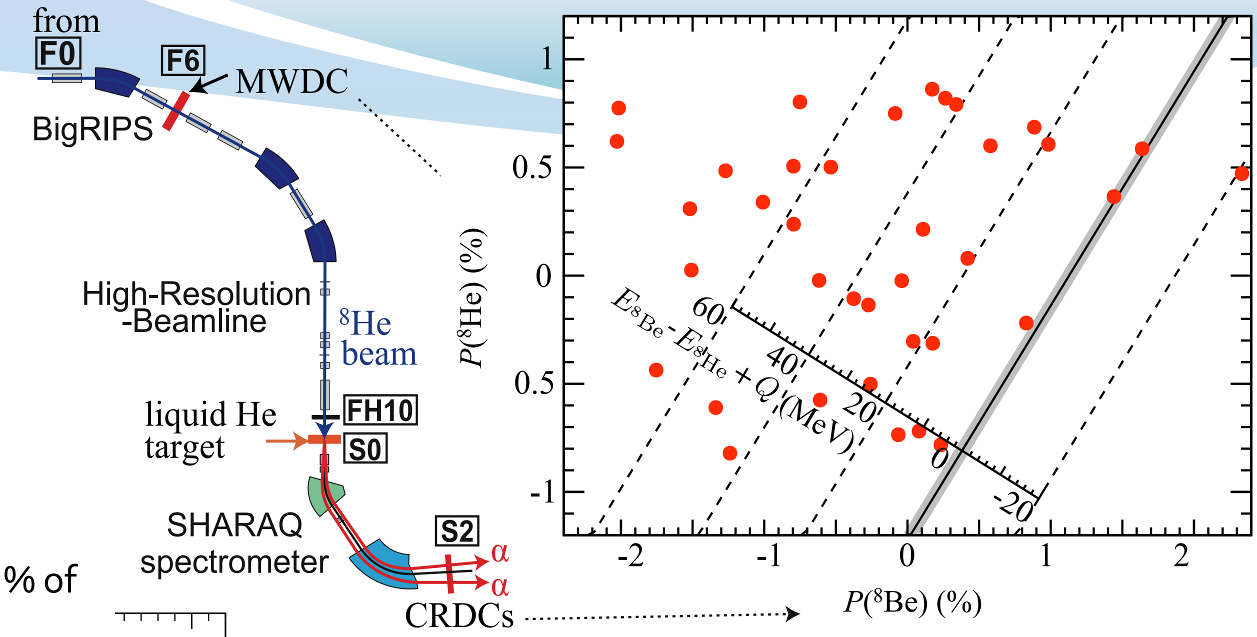

Background process:
Breakup of two $^8$He in the same beam bunch to two alpha particle
Identified by multi-hit in F6-MWDC

- Background Estimation
  - Shape in spectrum: random 2$\alpha$
  - Number of events:
    - failure of the multi-particle rejection at MWDC
    - multi-particle in one cell of MWDC



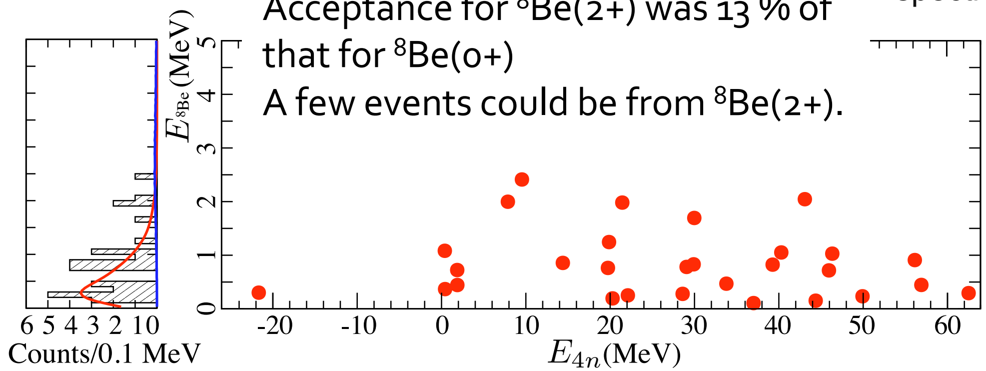

Backgrounds after analysis:
Finite efficiency of multi-hit events at F6-MWDC

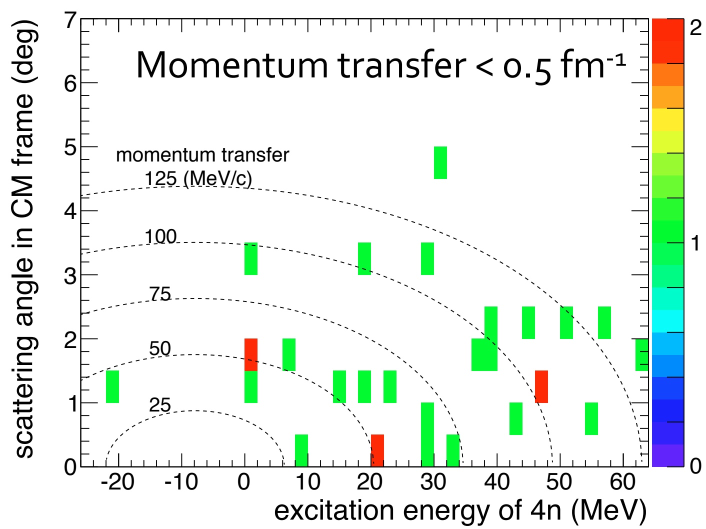
# Experimental Results

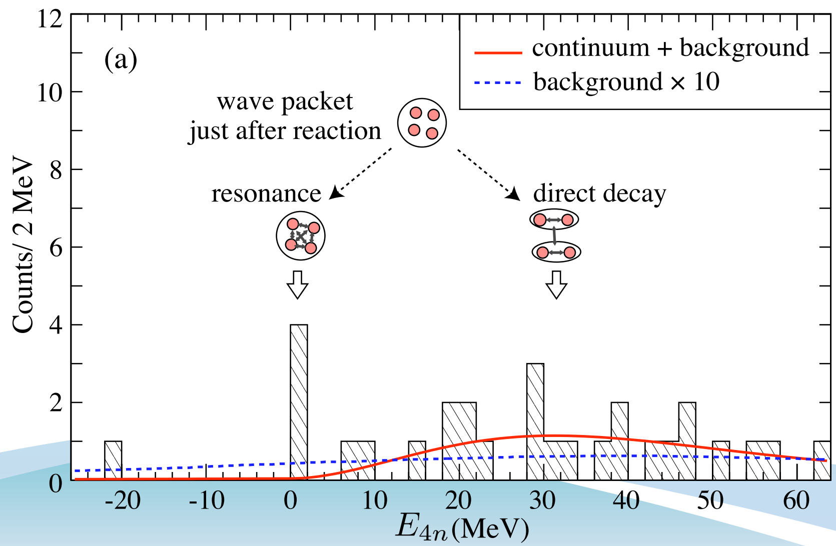



Acceptance for $^8$Be(2+) was 13 % of that for $^8$Be(0+)

A few events could be from $^8$Be(2+).



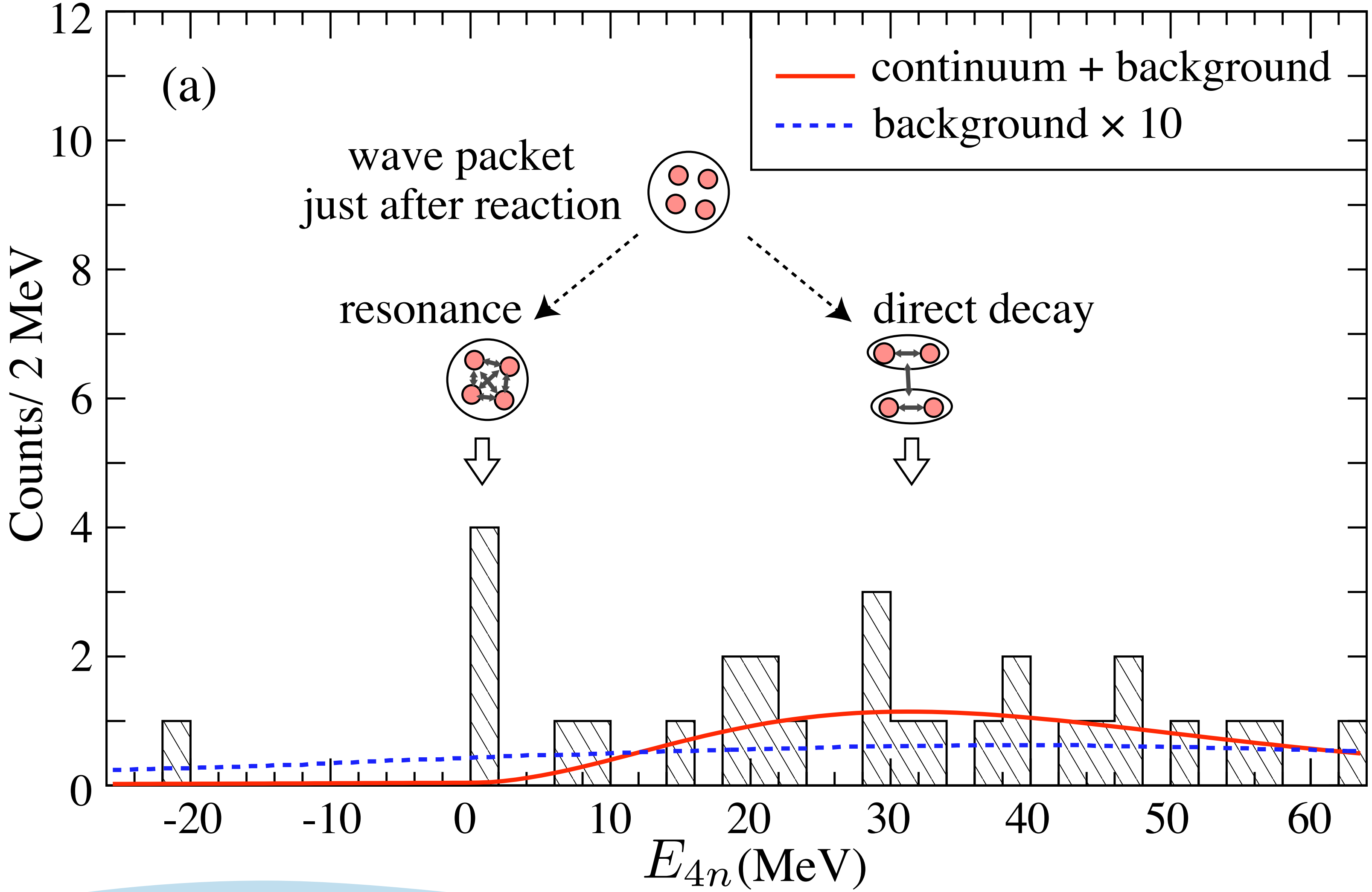




Look like having two components:

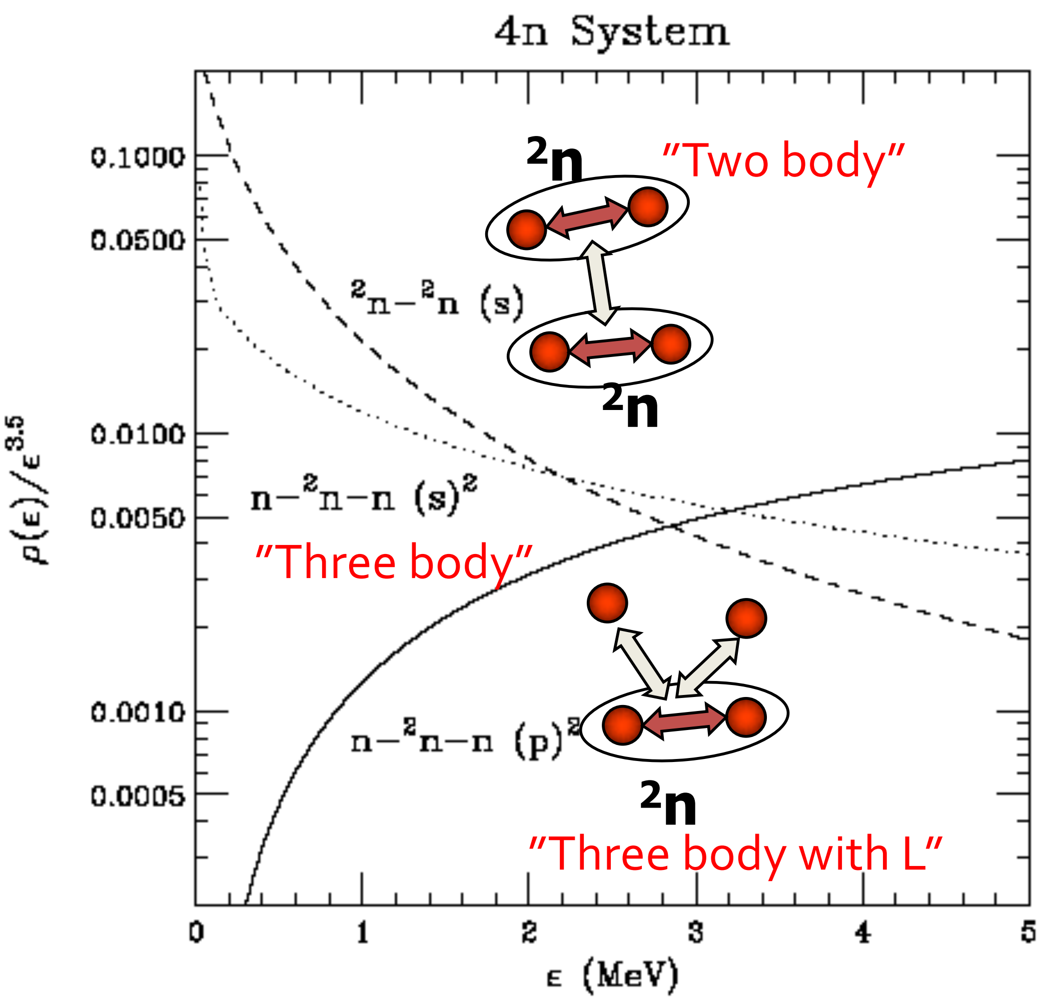
Continuum + Peak (?)

? The 4 counts just above threshold can be explained by the fluctuation of continuum or not?

# Experimental Results



# Phase space in multi-body continuum

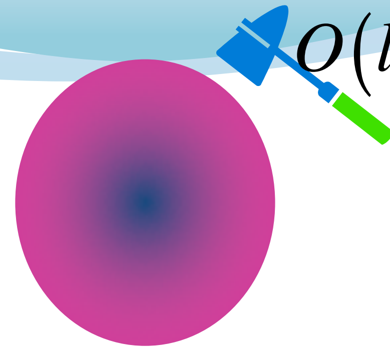



Phase Space

$$\rho(E) \propto E^{1/2} \quad \text{(2 body)}$$
$$\propto E^{2} \quad \text{(3 body)}$$
$$\propto E^{7/2} \quad \text{(4 body)}$$

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

# Transition Probabilities



$O(lsj\tau;\xi)$

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

if distortion is insensitive to ω

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

$O(lsj\tau;\xi)$ : 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

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

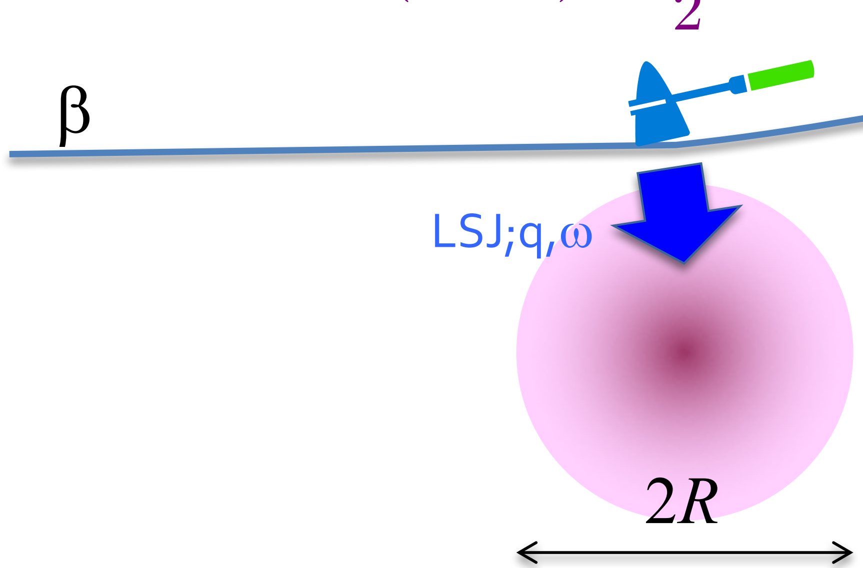
$\left|M_{if}(E_f)\right|^2$ : Energy Spectrum

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"

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




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

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

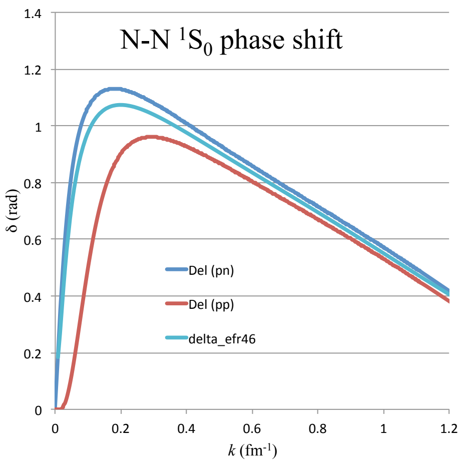
Off energy shell

E/A ~ 200 MeV : β ~ 0.6 : $\omega_{max}$ ~ 60 MeV

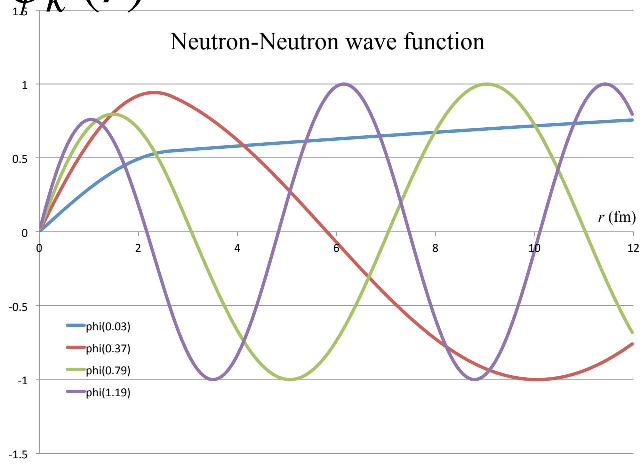
$$\boxed{O(lsj\tau;\xi)\left|E_i J_i \pi_i T_i;\xi_i\right\rangle} = \sum\!\!\!\!\!\!\int_f M_{if}(E_f)\left|E_f J_f \pi_f T_f;\xi_f\right\rangle$$ Response

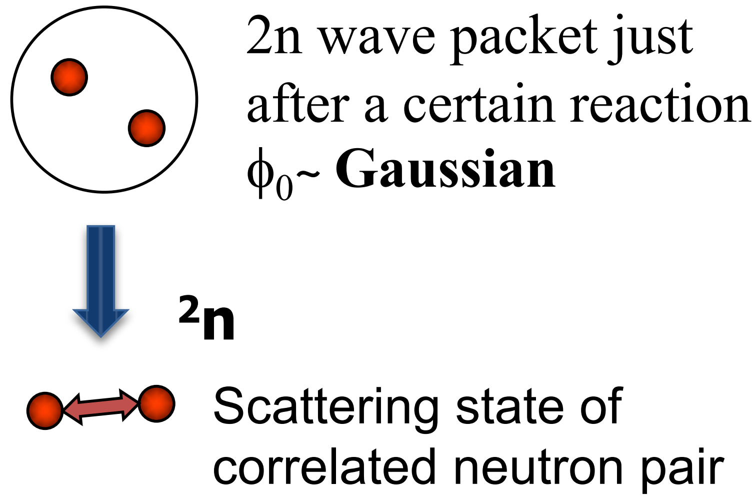
$\left|M_{if}(E_f)\right|^2$ : Energy Spectrum

# NN case with FSI




$\phi_k(r)$

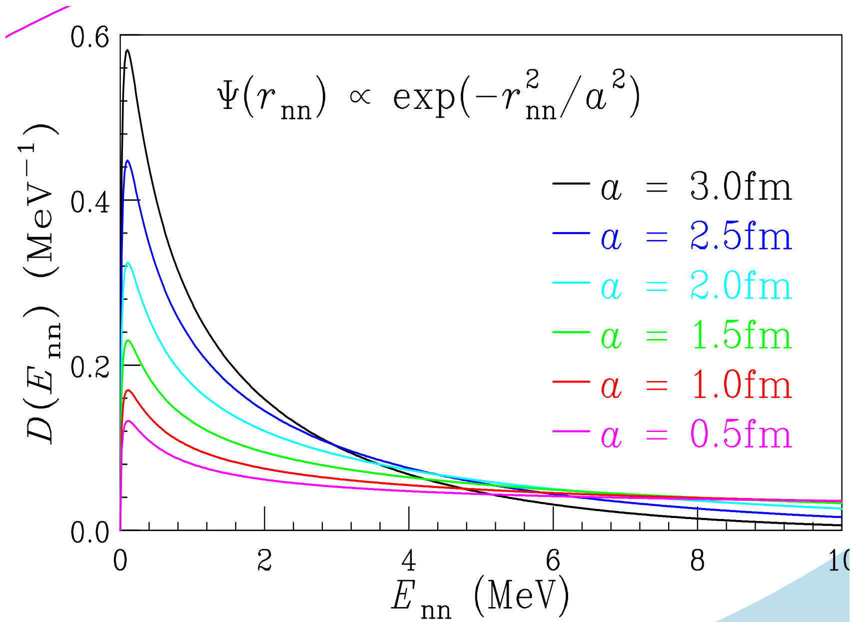



Density of State

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

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



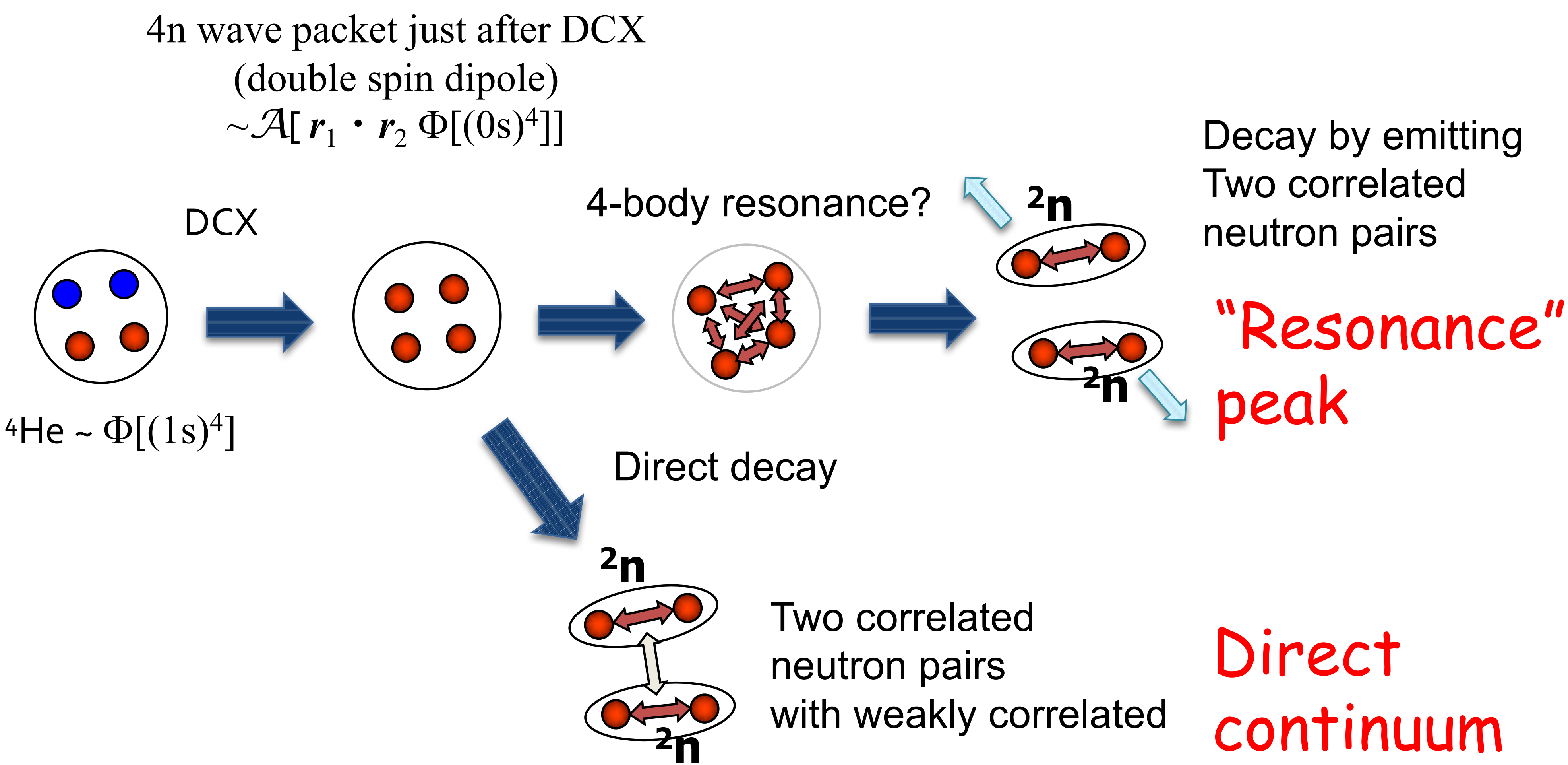

Expand $\Psi_0$ with correlated n-n scattering wave $\phi_k(r)$
$A(k)$'s are used instead of Fourier component

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

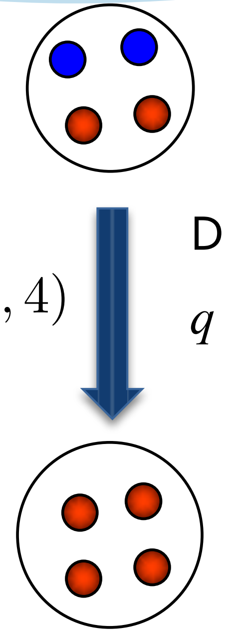


# Direct Part

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

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

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



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

DCX

$q << 200$ MeV/$c$

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

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

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

4n wave packet just after DCX

$\Phi_0$~ $\boldsymbol{r}_1 \cdot \boldsymbol{r}_2\, \Phi[(0s)^4]$

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

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

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

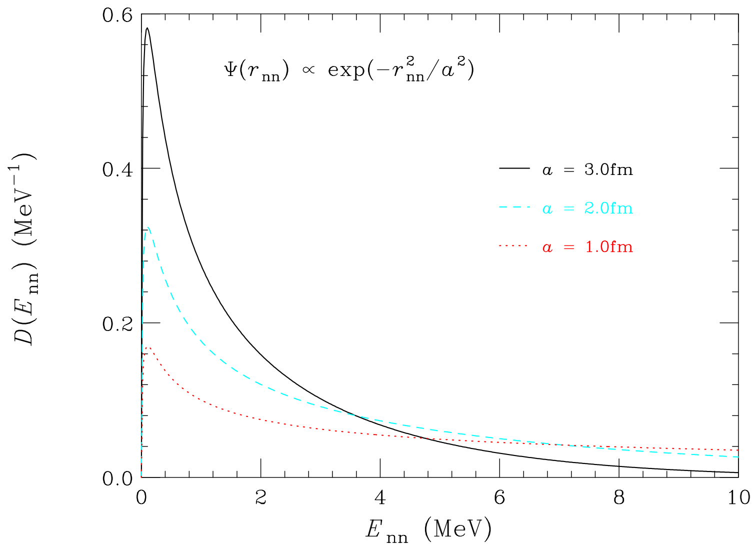
$$X = E/\epsilon_a \qquad \epsilon_a = \frac{\hbar^2}{m_N a^2} = 11\,\text{MeV}$$

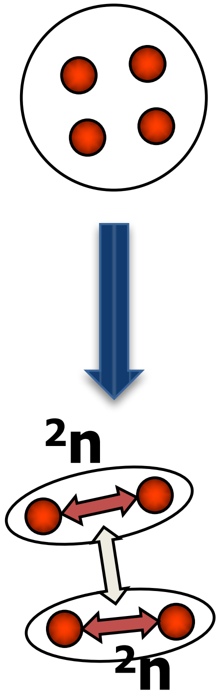
# NN FSI

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

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

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

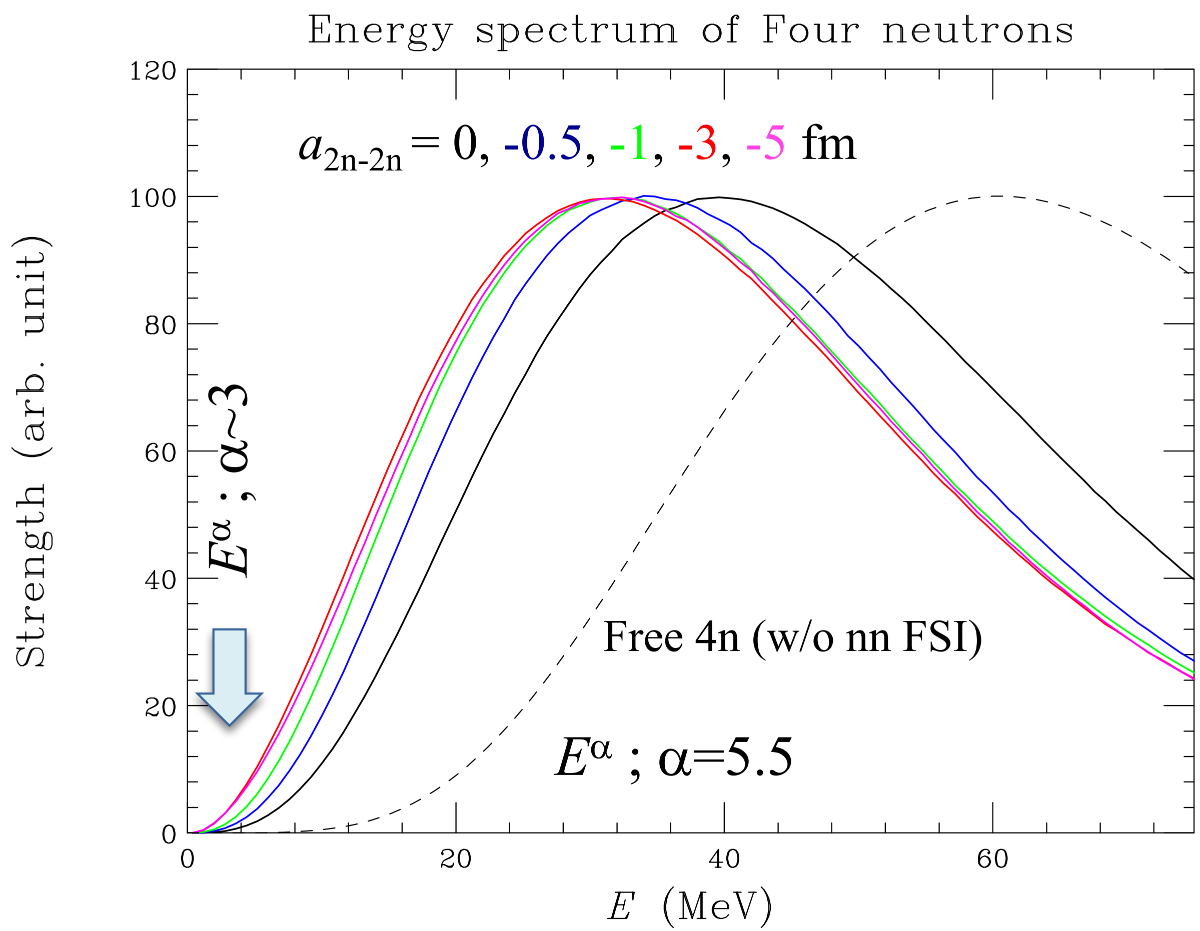
$$\hat{A}_{2s}(k) = \int_0^\infty dr\, r\, \psi_{2s}(r)\, \phi_k(r) = 2\sqrt{\frac{2}{3}}\left(\frac{1}{\sqrt{\pi}a^3}\right)^{1/2} k\, A_{2s}(k)$$

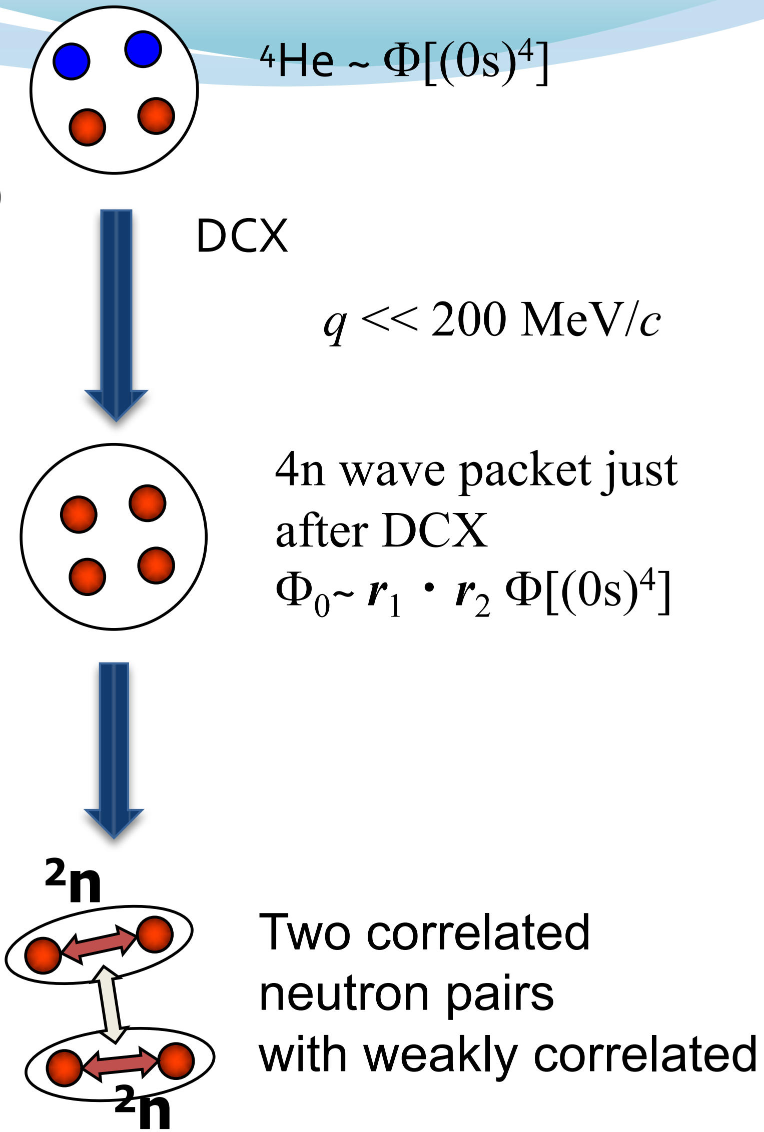
Expand $\mathcal{A}\Phi_0$ with correlated n-n scattering wave $\phi_k(r)$
$A(k)$'s are used instead of Fourier component

# Direct Part

Continuum spectrum with n-n FSI

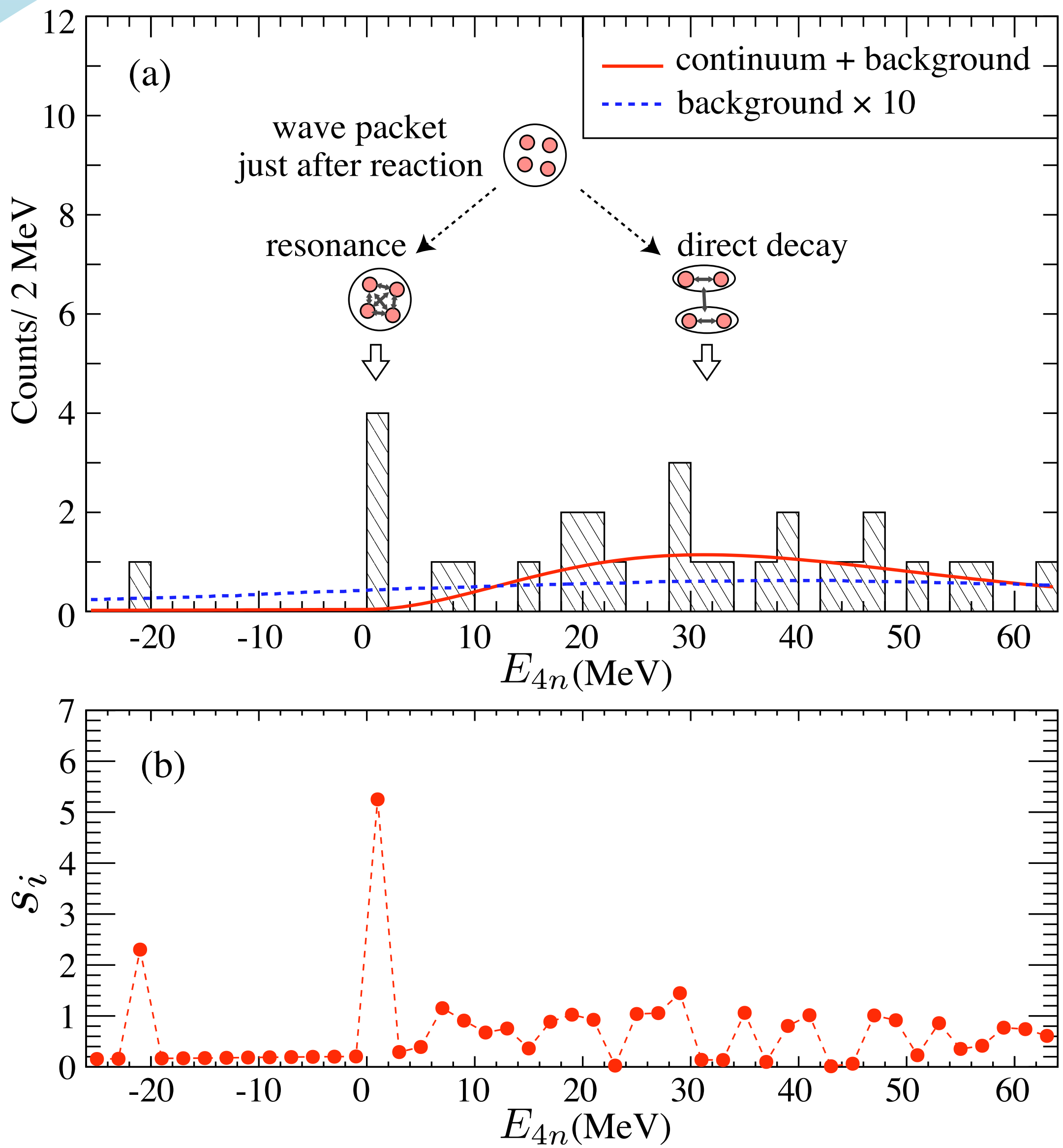
c.f.
L.V. Grigorenko, N.K. Timofeyuk, M.V. Zhukov, Eur. Phys. J. A 19, 187 (2004)




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

# 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

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

- 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

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

# Further experimental approach

- $^{29}F$ (knockout 1p) -> $^{28}O$ -> $^{24}O$ + 4n
- $^{8}He$ (knockout $\alpha$ by proton) -> 4n
- $^{8}He$ (knockout proton by proton) -> $^{7}H$ -> 4n+t
- $^{4}He(^{8}He,^{8}Be)4n$ again for more statistics

All of three can produce recoil-less condition

Three approaches produce different initial wave packets of 4n

- resonance/continuum will be different

# Experiment for confirmation (2016.6.16-25)

Better statistics and Better accuracy of energy than previous experiment ($^4$He($^8$He,$^8$Be)4n @ 186 MeV/u)

4 events

→ 5 times or more

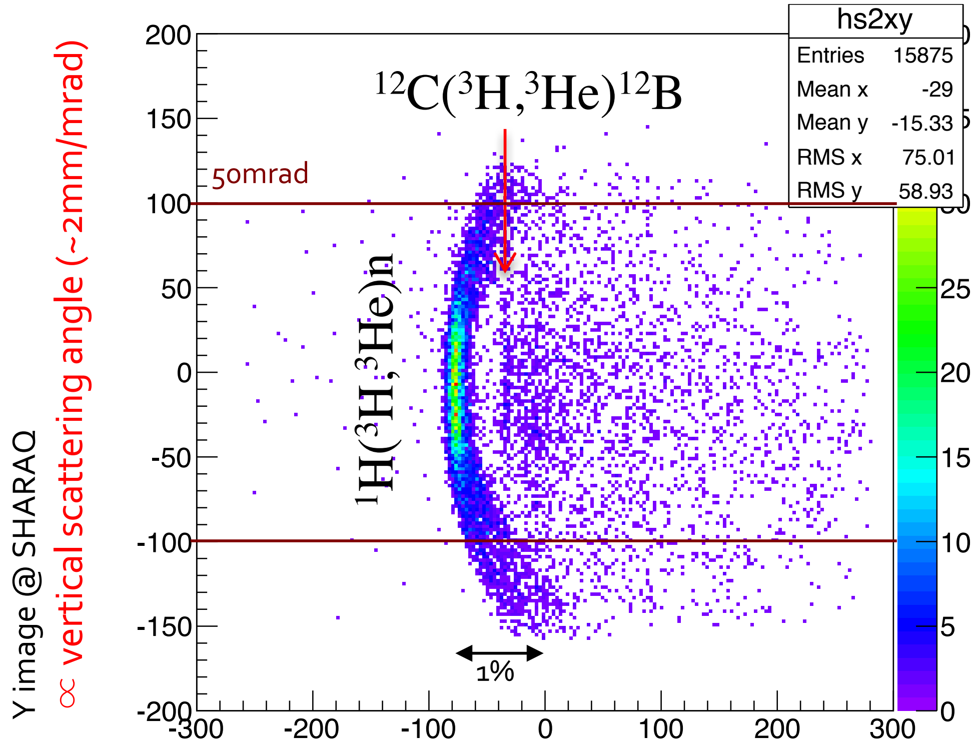
Improve efficiencies (redundancy)

$E_{4n} = 0.83 \pm 0.65(\text{stat.}) \pm 1.25(\text{sys.})$ MeV

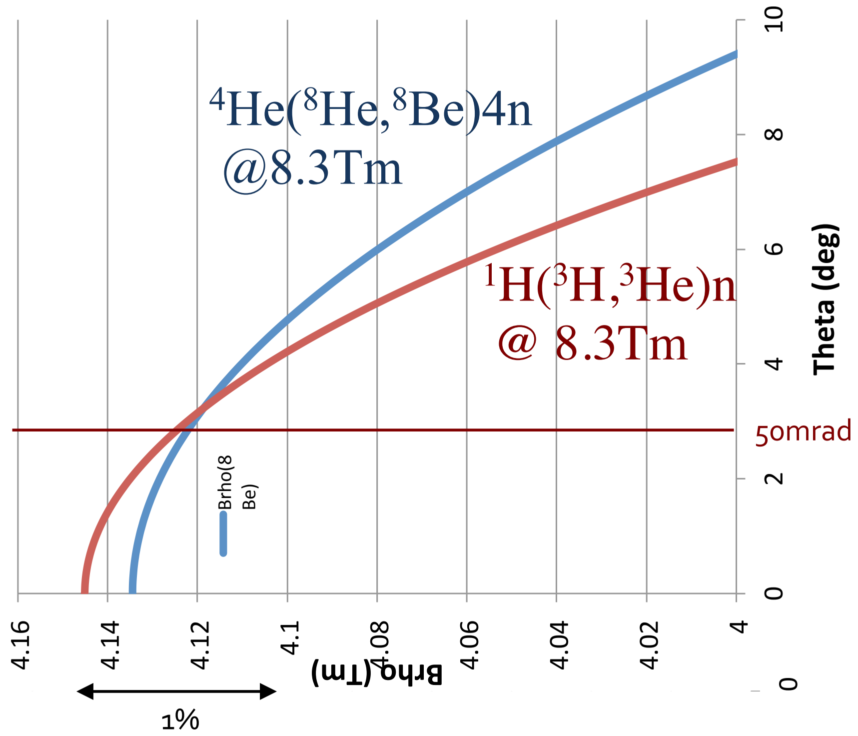
→ better than 0.3 MeV both for stat. and syst.

Calibration using $^1$H($^3$H,$^3$He)n with same rigidity $^3$H beam (310 MeV/u) as $^8$He

preliminary achievement : < 100 keV




On-line X image @ SHARAQ corrected by beam momentum
∝ momentum (~60mm/%)




Resolution & Statistics are consistent with expected

# Summary (exp.)

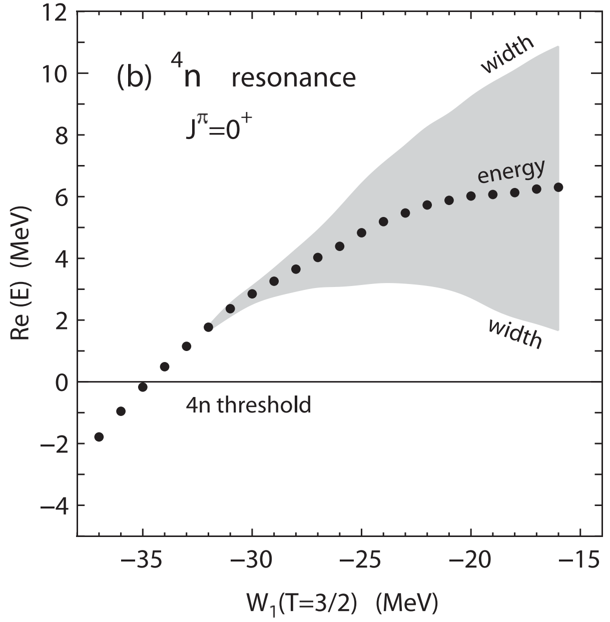
- $^{4}He(^{8}He,^{8}Be)4n$ has been measured at 190 A MeV at RIBF-SHARAQ
- Missing mass spectrum with very few background
- Although statistics is low, spectrum looks two components (continuum + peak)
- Continuum is consistent with direct breakup process from $(0s)^2(0p)^2$ wave packet
- Four events just above 4n threshold is statistically beyond prediction of continuum + background (4.9 $\sigma$ significance)

  → candidate of 4n resonance

  at $0.83 \pm 0.65(\mathrm{stat.}) \pm 1.25(\mathrm{sys.})$ MeV; $\Gamma < 2.6$ MeV
- Preliminary result of the new experiment looks consistent with the published result.

# Recent theoretical works

E. Hiyama et al., PRC 93, 044004 (2016)




$$V_{ijk}^{3N} = \sum_{T=1/2}^{3/2} \sum_{n=1}^{2} W_n(T) e^{-(r_{ij}^2+r_{jk}^2+r_{ki}^2)/b_n^2} \mathcal{P}_{ijk}(T),$$

Too strong attraction is necessary for 4n resonance, which makes 4H bound!

A.M. Shirokov et al., PRL 117, 182502 (2016)

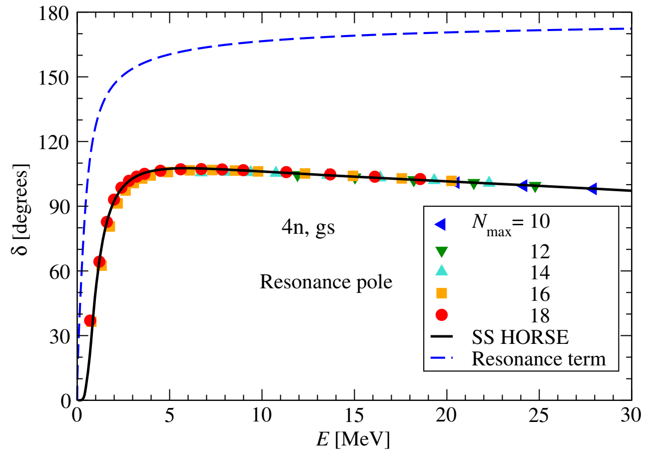



FIG. 2. The 4 → 4 scattering phase shifts: parametrization with a single resonance pole (solid line) and obtained directly from the selected NCSM results using Eq. (2) (symbols). The dashed line shows the contribution of the resonance term.

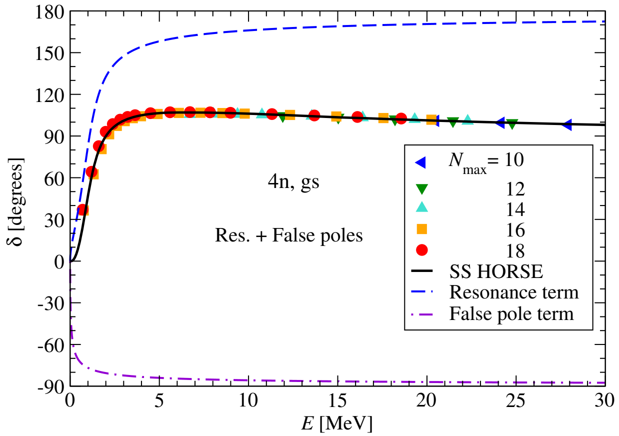



FIG. 3. The same as Fig. 2 but for the parametrization with resonance and false state poles. The dashed-dotted line shows the contribution of the false state pole term.

NCSM calculation w/ DISP16 interaction: No NNN, Non-local

4-body phase shift (HH coordinate) shows resonance around 0.8 MeV.

# Old theoretical work on α–α interaction

J. Hiura & R. Tamagaki, PTP Suppl. 52, 25 (1972)

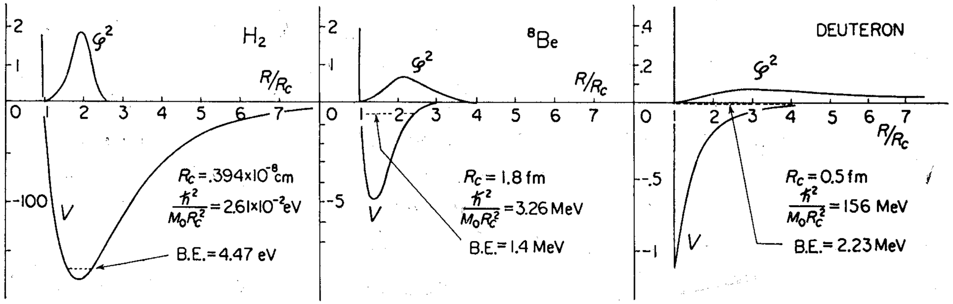
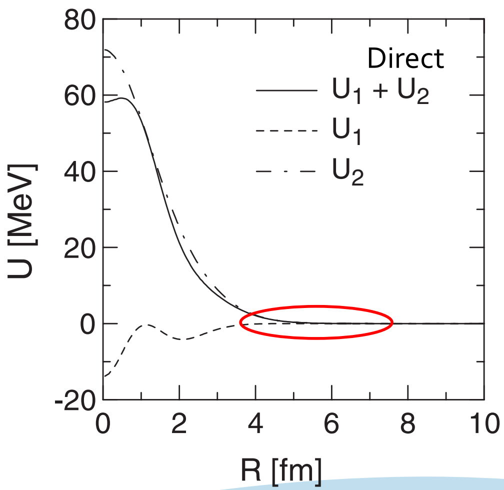
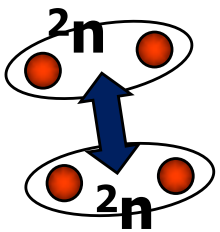



Fig. 3. Comparison of three binding forces; the binding potential for the ground state ($^1\Sigma_g$) of $H_2$-molecule, the $\alpha$-$\alpha$ potential (nuclear only) for the $^8$Be ground state and the two-nucleon potential (effective central) for the deuteron. Relative distance is given in units of the extent of short-range repulsion ($R_c$) and the energy unit is taken as $\hbar^2/M_0R_c^2$, where $M_0$ is the mass of subunits. For $H_2$ and the deuteron, Fig. 2-36 in Ref. 8) should be referred to. For $^8$Be, we show the $S$-state potential of Endo et al. shown in Fig. 2. $\varphi^2$ are the resulting probability densities. These figures indicate the intermediate character of the two-$\alpha$ "molecular" states in $^8$Be, in comparison with the other two cases.

C.A. Bertulani & V. Zelevinsky, JPG 29, 2431 (2003)




Effective core due to Pauli principle (local?)

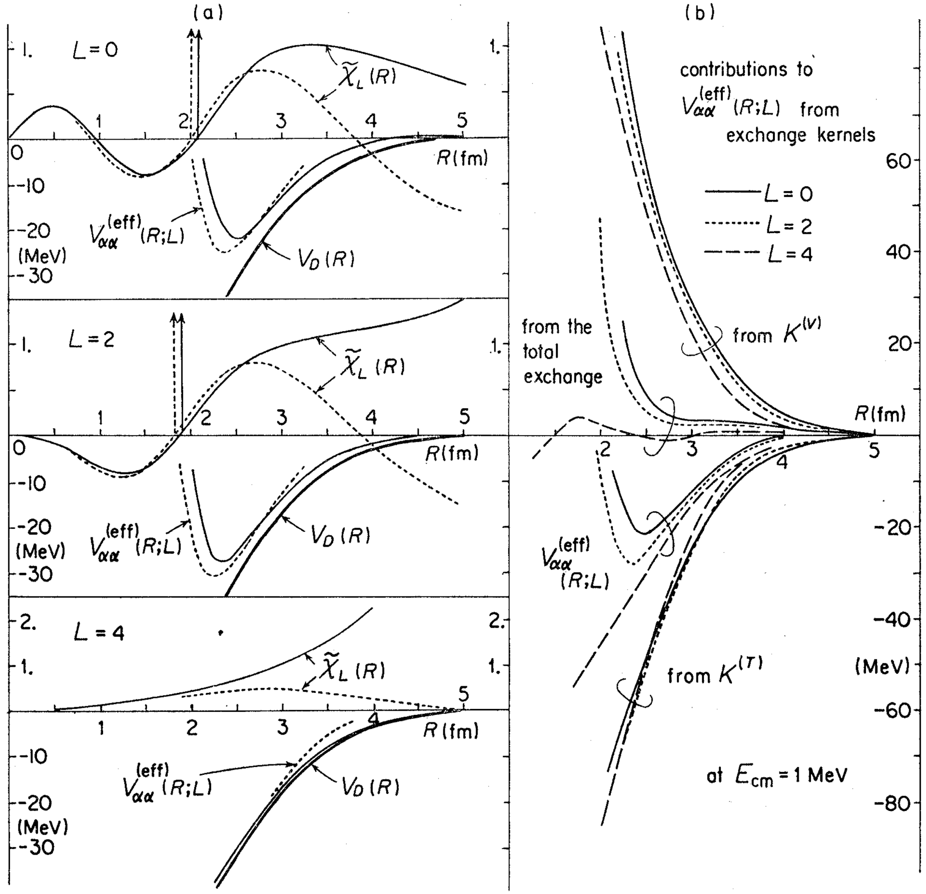



Fig. 8. Energy dependence of the relative wave functions $\tilde{\chi}_L(R)$ and angular momentum and energy dependence of the effective $\alpha$-$\alpha$ potential $V_{\alpha\alpha}^{(\text{eff})}$. $\tilde{\chi}_L(R)$ and $V_{\alpha\alpha}^{(\text{eff})}(R;L)$ calculated at the two energies (—; $E_{\text{cm}}=1$ MeV and $\cdots$; $E_{\text{cm}}=14.45$ MeV) are normalized at $R=1.5$fm in part (a). The arrows at $R\sim2$ fm indicate the equivalent core radius for $L=0$ and 2. Part (b) shows the $L$-dependences of the contributions to $V_{\alpha\alpha}^{(\text{eff})}(R;L)$ from the kinetic, potential and total exchange terms.

Effective repulsive core due to Pauli blocking

Direct potential is deeply attractive
W.f. has nodes in the core region orthogonal to the Pauli-forbidden state
   simple Effective Range treatment may not be adequate