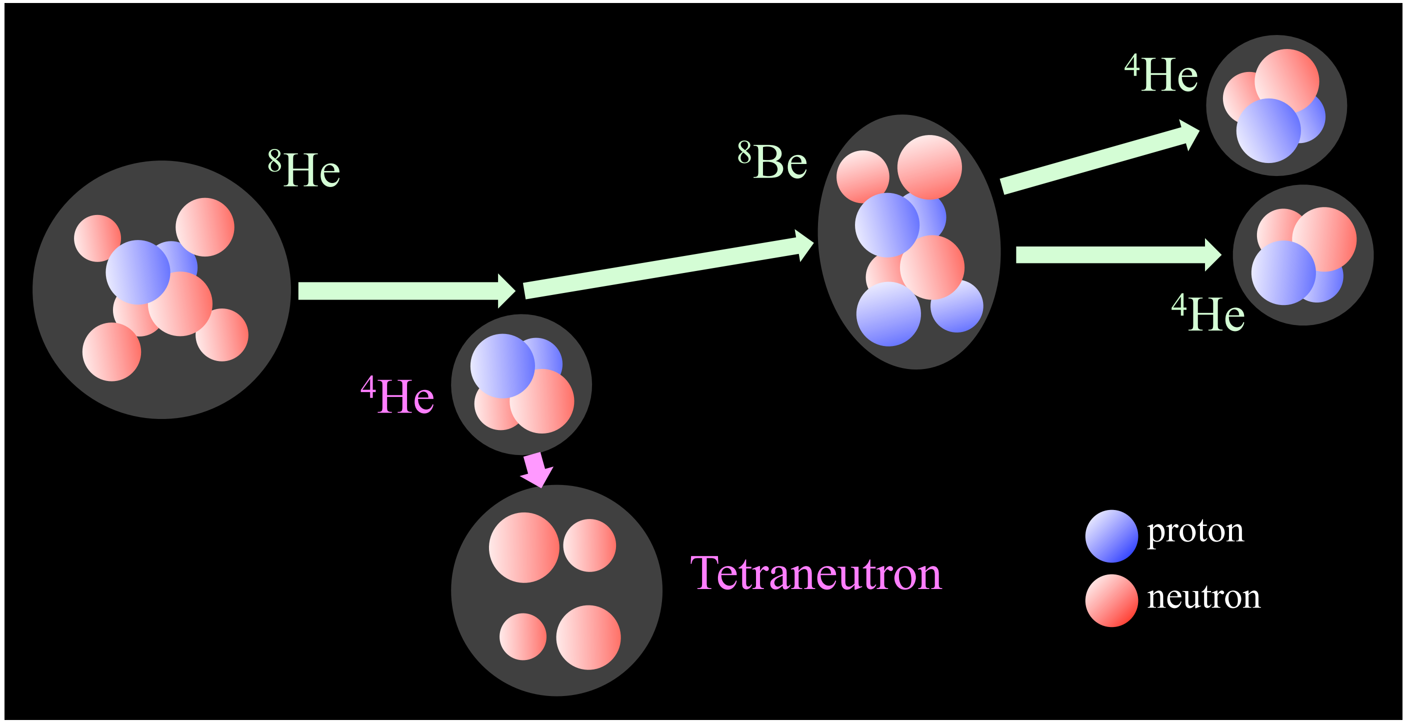
Tetra-neutron states populated by $^{4}He(^{8}He,^{8}Be)$ reaction

Exotic system populated by exotic reaction



S. Shimoura

CNS, University of Tokyo

K. Kisamori et al., Phys. Rev. Lett. 116, 052501

Tetra-neutron

- Multi-neutron System
  - Neutron cluster (?) in fragmentation of ^{14}Be
    PRC65, 044006 (2002)
  - NN, NNN, NNNN interactions
    - Neutron-Neutron interaction
    - T=3/2 NNN force
      -> 3-body force in neutron matter
    - Ab initio type calculations
  - Multi-body resonances
  - Correlations in multi-fermion scattering / resonant (?) states

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

^{4}He(π^-, π^+) reaction

- Only upper limit of cross section was decided.

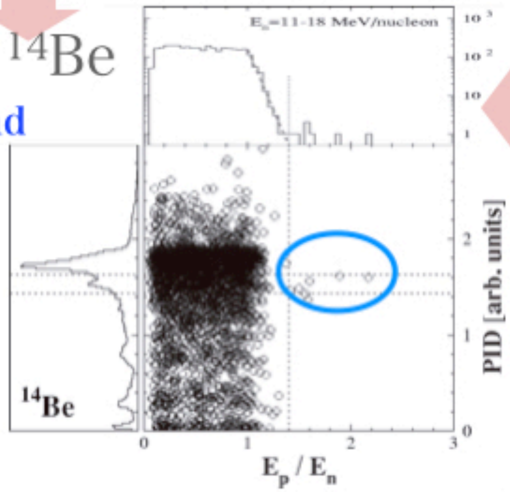
J. E. Unger, et al., Phys. Lett. B 144, 333 (1984)

Bound state: No clear evidence.

2000s

Breakup of ^{14}Be

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

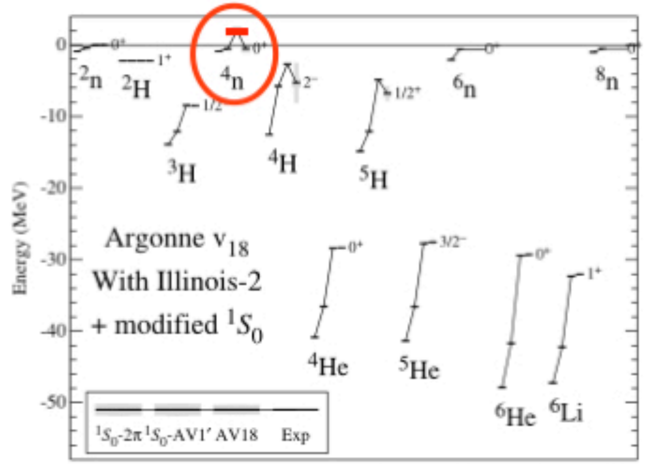


F. M. Marques, et al, Phys. Rev. C 65, 044006 (2002)

2000s

Theoretical work

- ab-initio calculation
  NN, NNN interaction

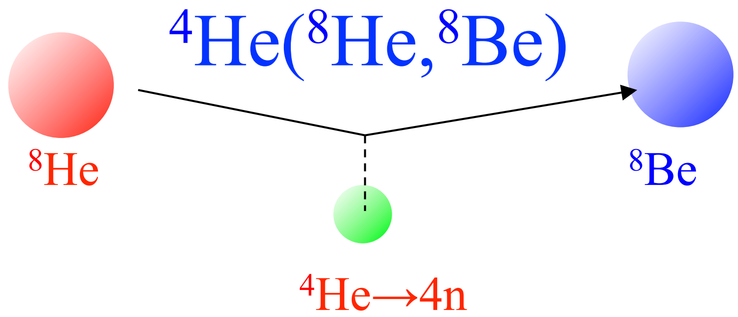


S. C. Piper, Phys. Rev. Lett. 90, 252501 (2003)

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

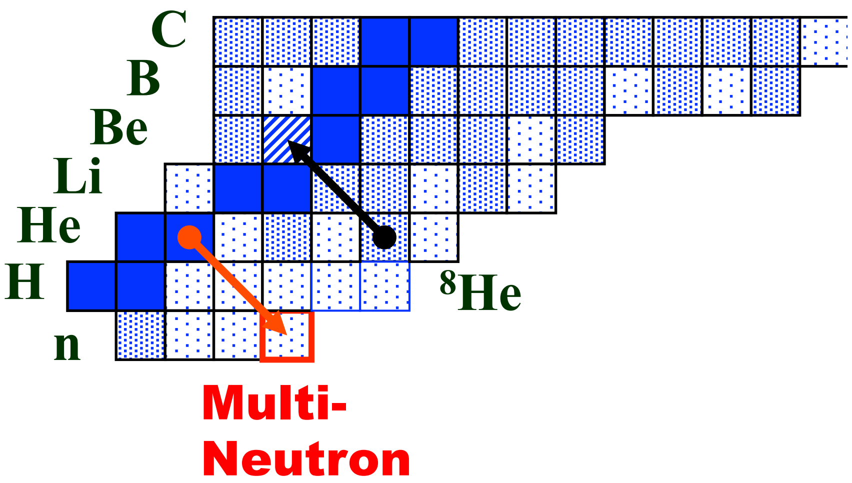
Resonance state : Possibility of the state is still an open and fascinating question.

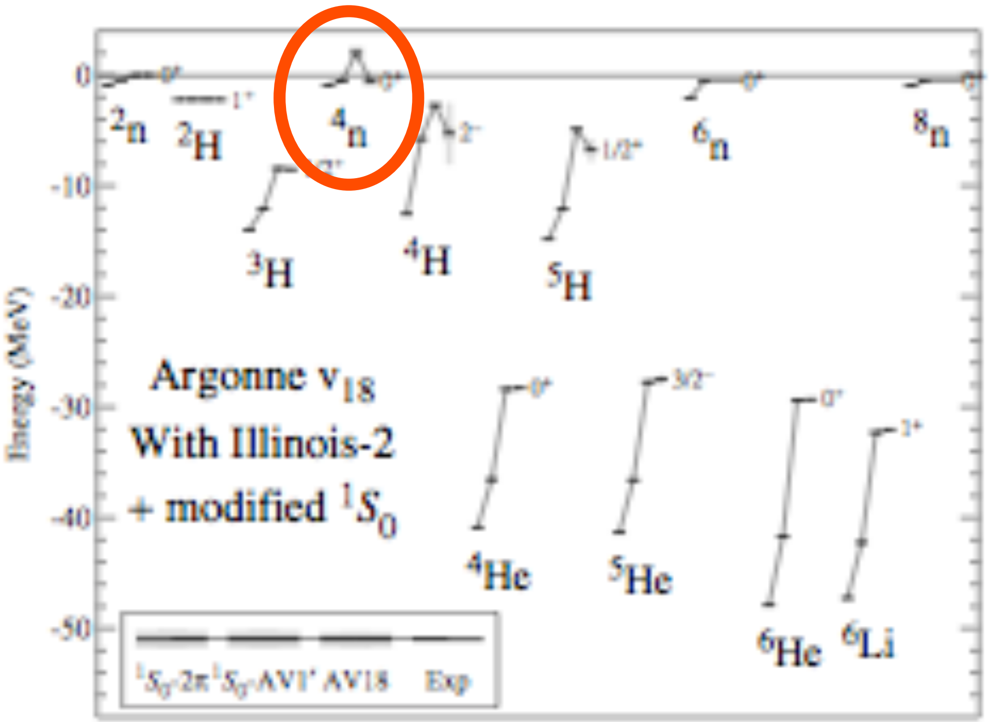
Tetra-neutron system produced by exothermic double-charge exchange reaction



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

Recoil-less 4n system via DCX using internal energy of ^8He



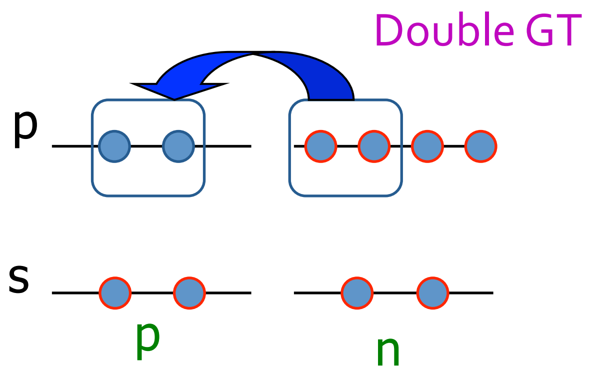


S.C. Pieper et al., PRL 90, 252501 (2003)

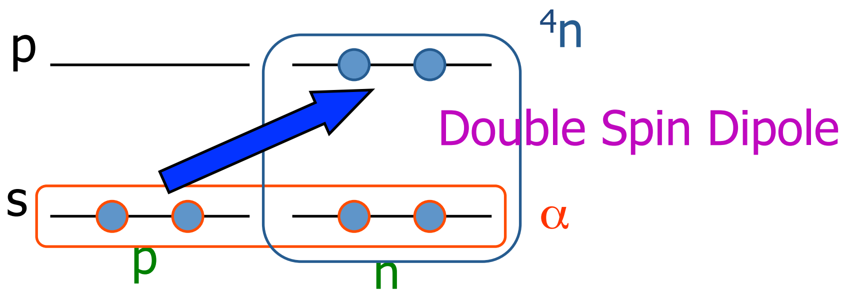
4n in breakup of ^{14}Be : Marques et al. PRC 65 (2002) 044006

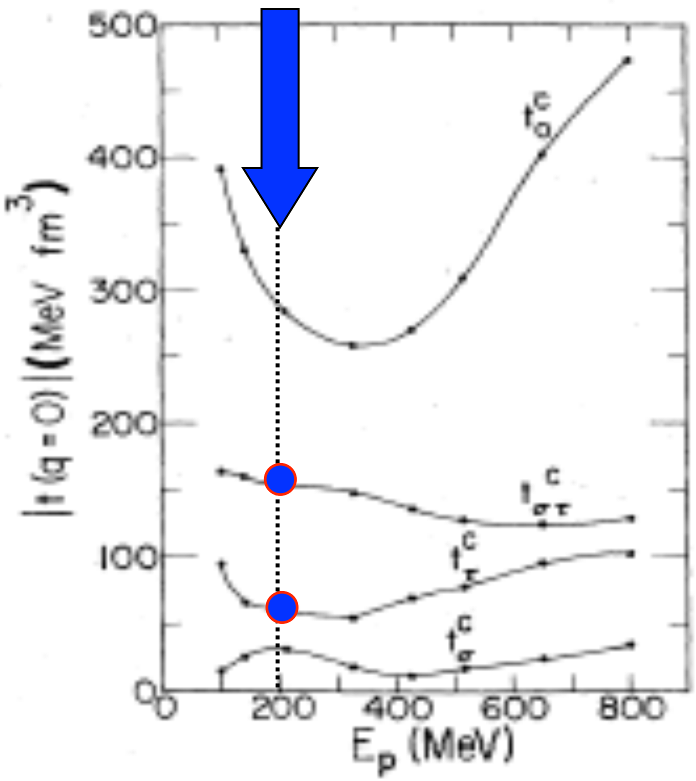
Reaction Mechanism

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



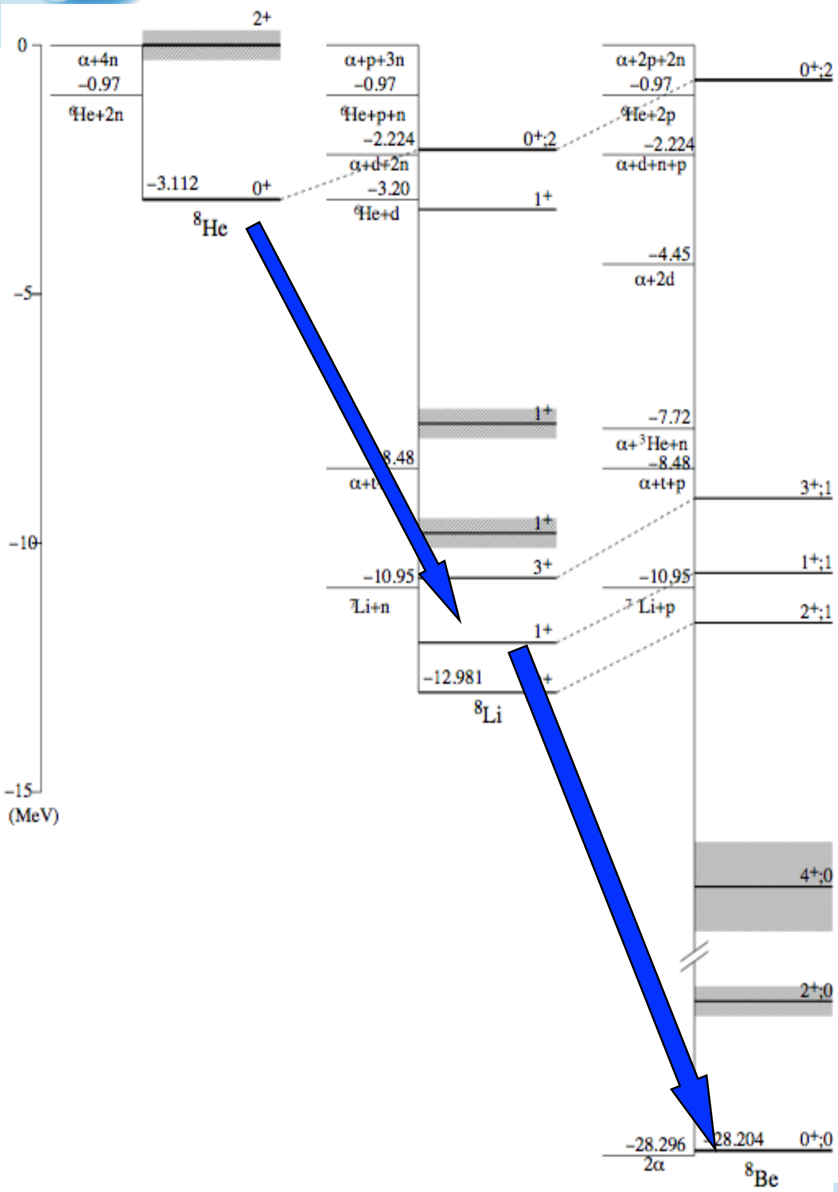
$^{4}He \rightarrow 4n$

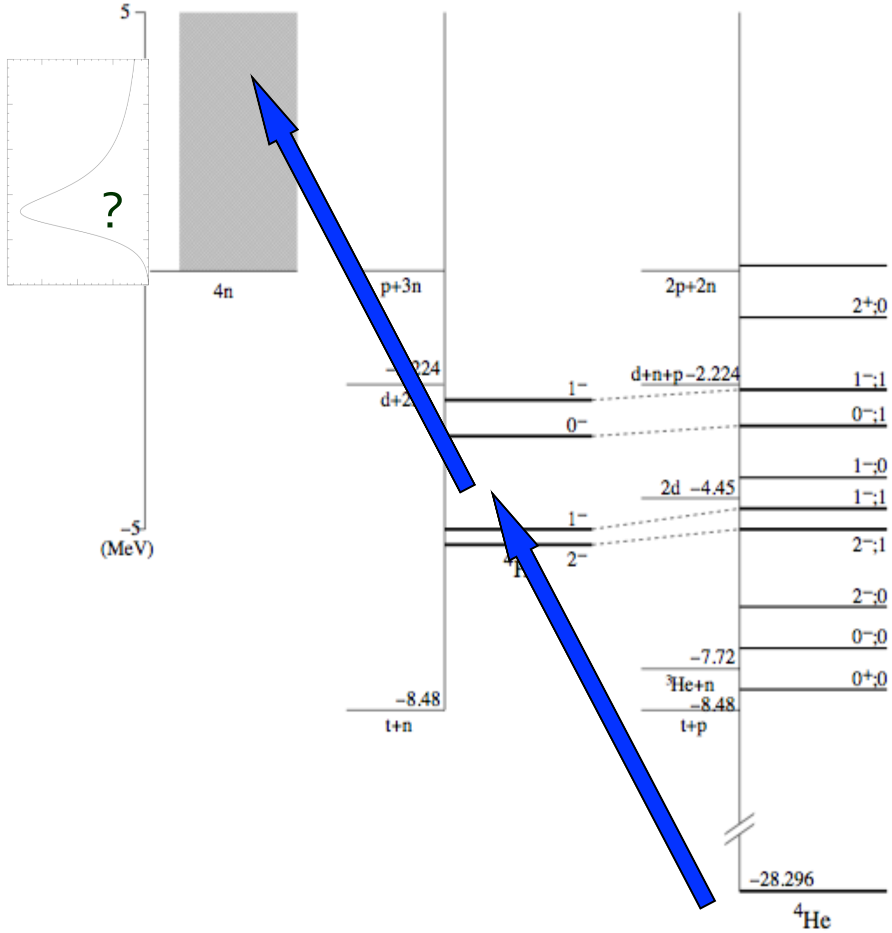




$$\left[\left(\vec{\tau}_{\mathrm{p}}\cdot\vec{\tau}_{\mathrm{t}}\right)\left(\vec{\sigma}_{\mathrm{p}}\cdot\vec{\sigma}_{\mathrm{t}}\right)r_{\mathrm{t}}Y_{1}\left(\hat{r}_{\mathrm{t}}\right)\right]^{2}$$

Level diagrams

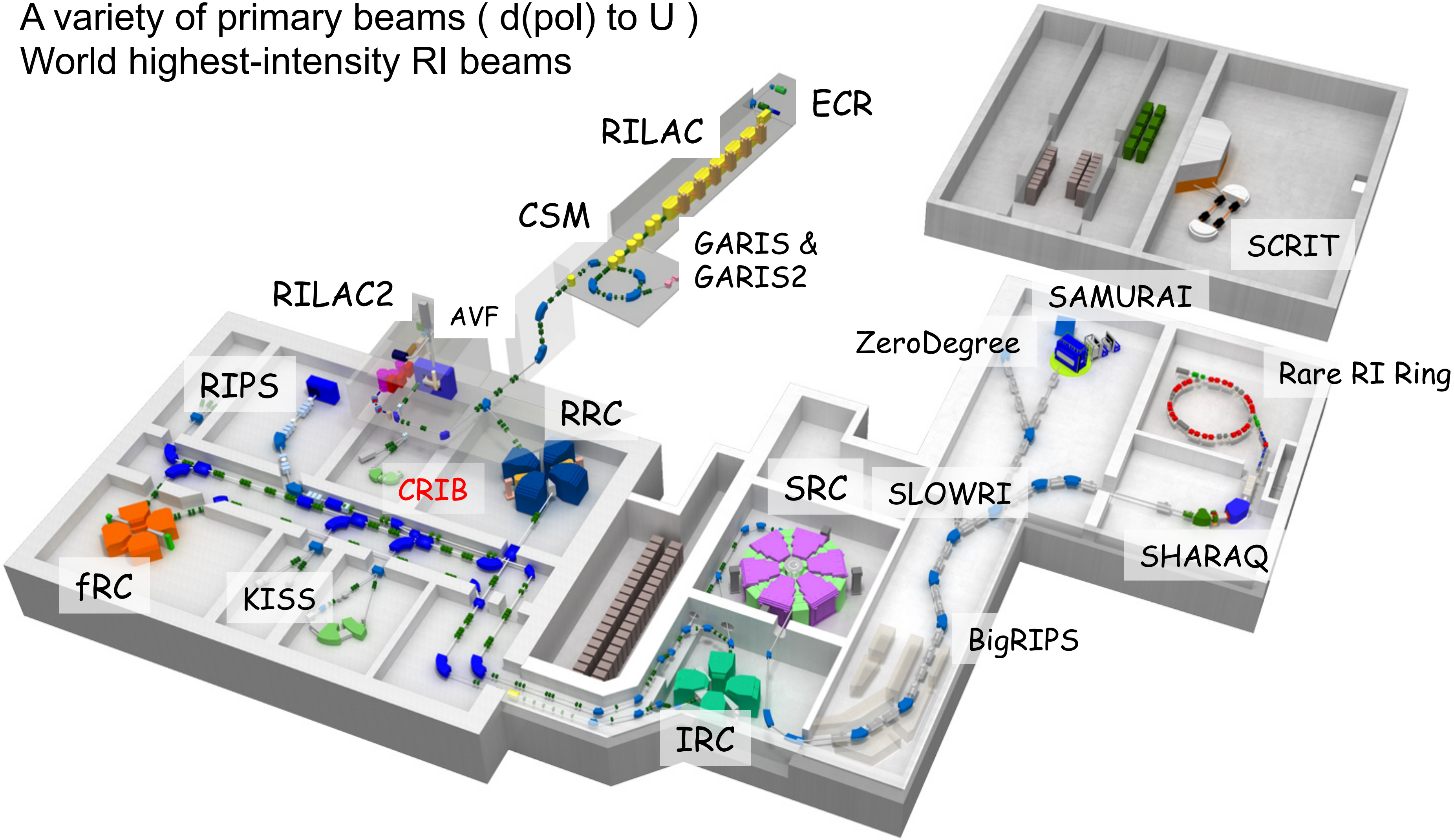




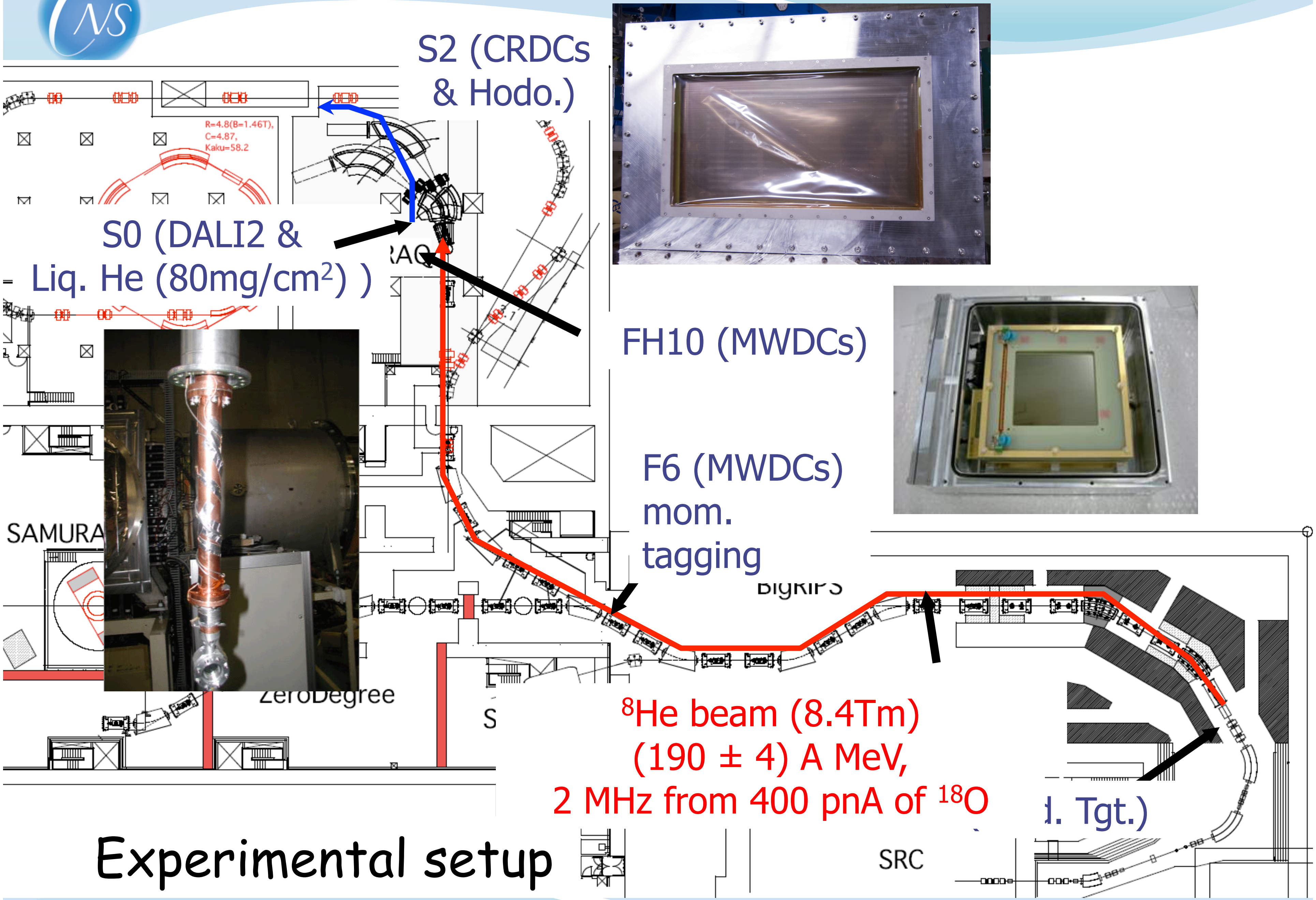
q_{min} ~ 10MeV/c

RI Beam Factory at RIKEN

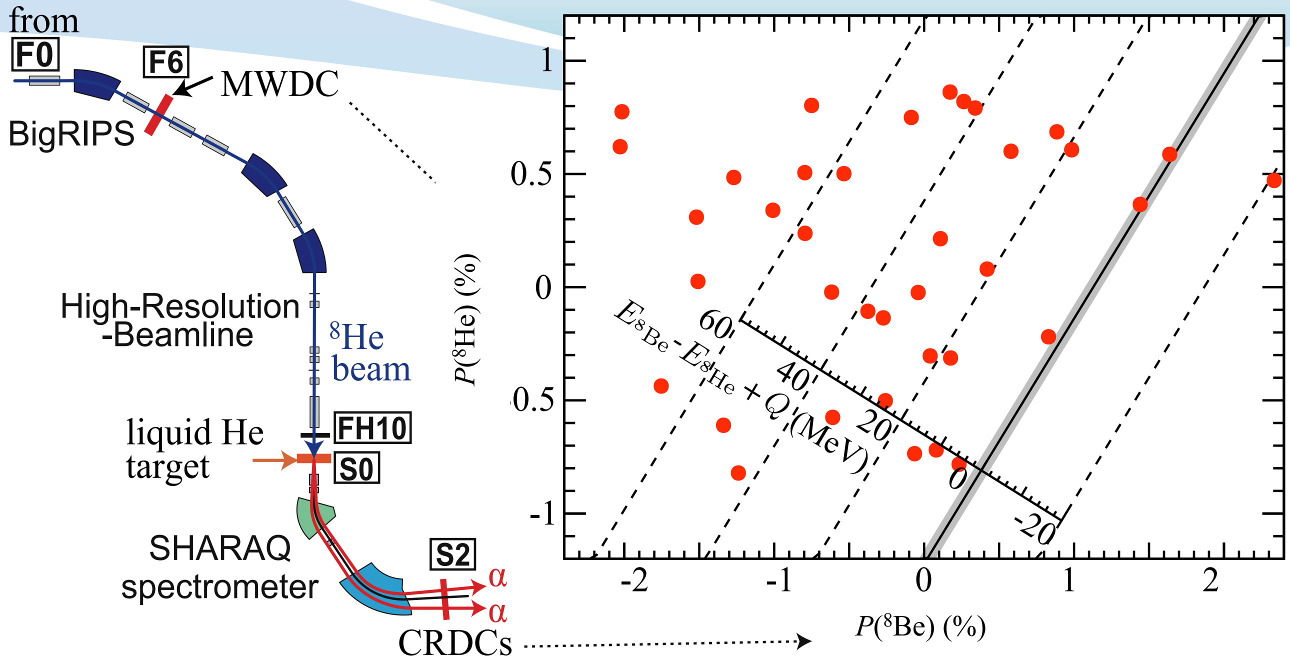
3 injectors + cascade of 4 cyclotrons
⇒ several to 345 MeV/nucleon
A variety of primary beams (d(pol) to U)
World highest-intensity RI beams

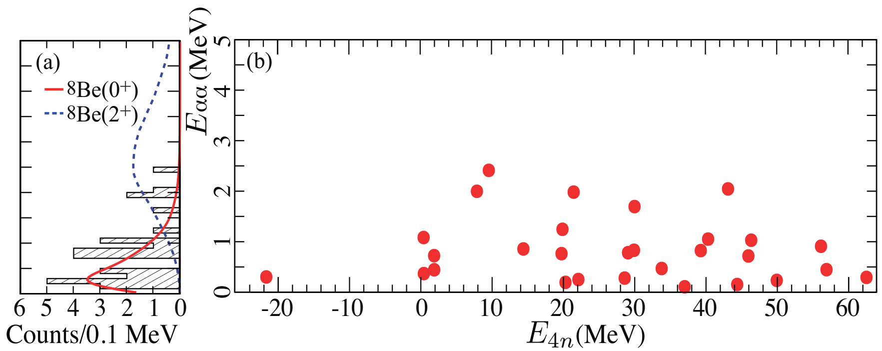


Experimental setup

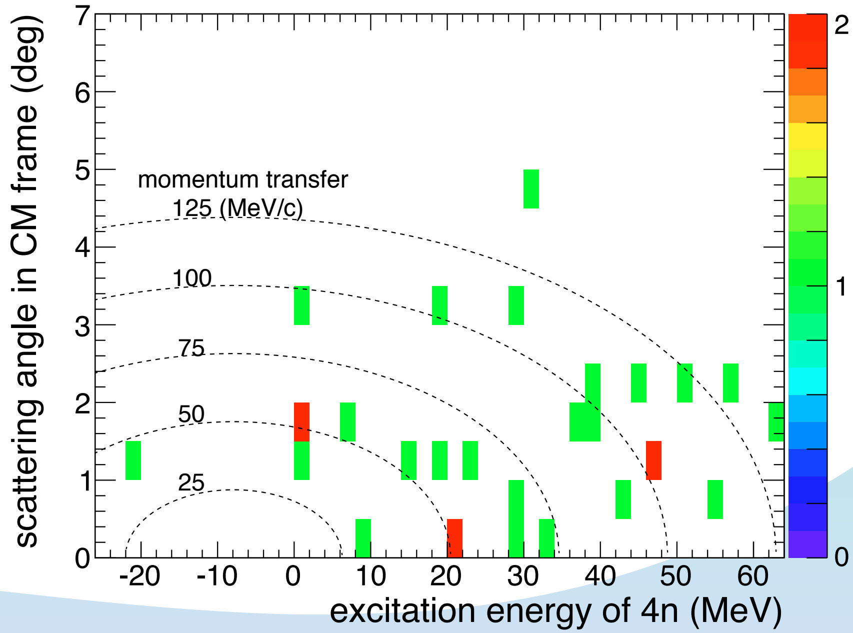


Experimental Results

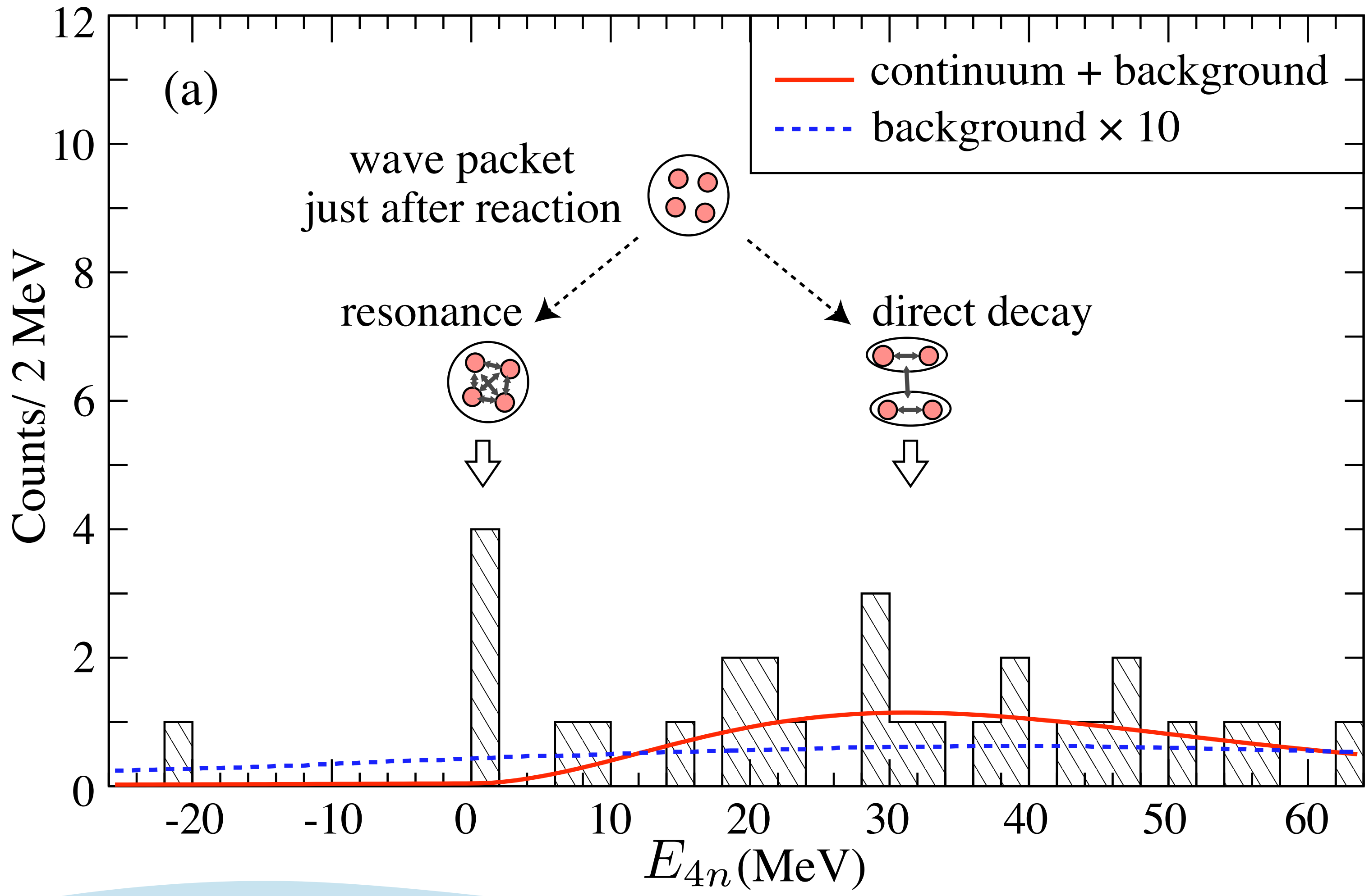




Acceptance for ^{8}Be(2+) was 13 % of that for ^{8}Be(0+)
A few events could be from ^{8}Be(2+).



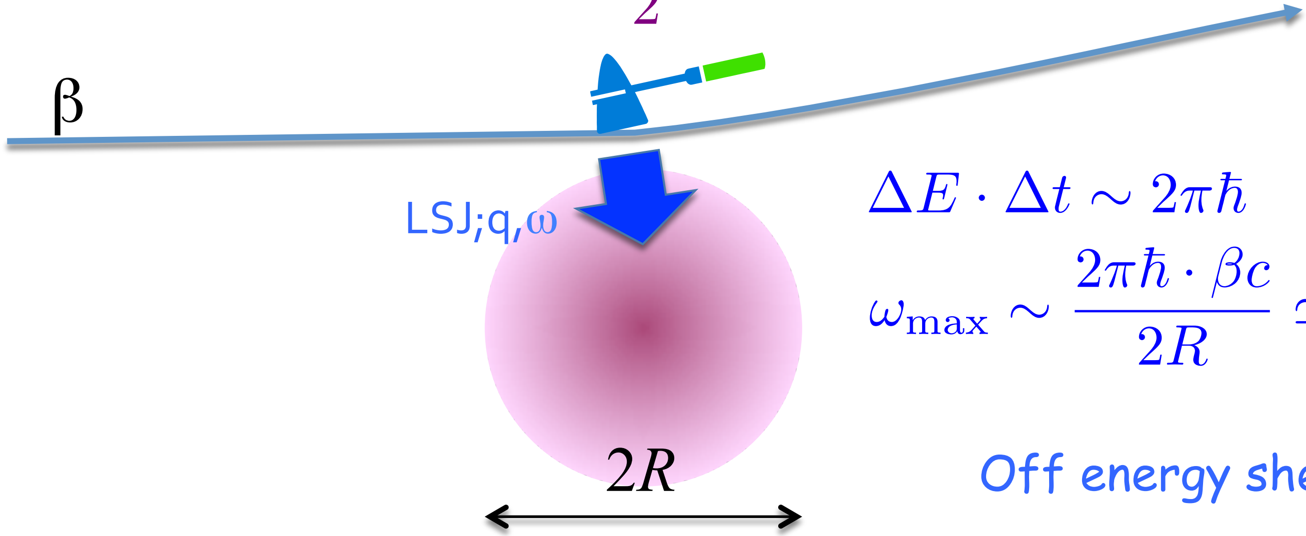
Experimental Results



Reaction time & excitation energy

for intermediate-energy "inelastic-type scattering"

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



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

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

Off energy shell

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

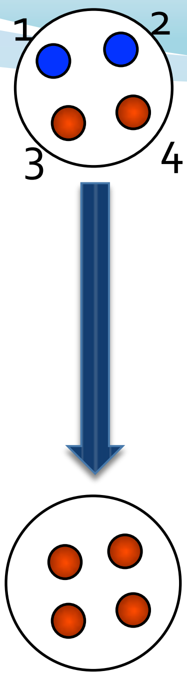
$$O(lsj\tau;\xi)\left|E_i J_i \pi_i T_i;\xi_i\right\rangle = \sum_f\!\!\!\!\!\!\int M_{if}(E_f)\left|E_f J_f \pi_f T_f;\xi_f\right\rangle \quad \text{Response}$$

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

Direct Part

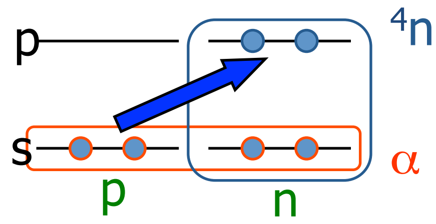
c.f. Continuum spectrum with n-n FSI

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



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

DCX



$$\mathcal{A}\Phi_0(\boldsymbol{r}_{12}, \boldsymbol{r}_{34}, \boldsymbol{r}_\alpha) \sim$$

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

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

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

$q << 200$ MeV/c

4n wave packet just after DCX

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

$$\vec{r}_\alpha = \frac{\vec{r}_1 + \vec{r}_2}{2} - \frac{\vec{r}_3 + \vec{r}_4}{2} \qquad \chi(i,j) = \frac{1}{\sqrt{2}}(\uparrow(i)\downarrow(j) - \downarrow(i)\uparrow(j))$$

Fourier Transform: $\mathcal{A}\Phi_0(\boldsymbol{r}_{12}, \boldsymbol{r}_{34}, \boldsymbol{r}_\alpha) \rightarrow \mathcal{A}\tilde{\Phi}_0(\boldsymbol{k}_{12}, \boldsymbol{k}_{34}, \boldsymbol{k})$

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

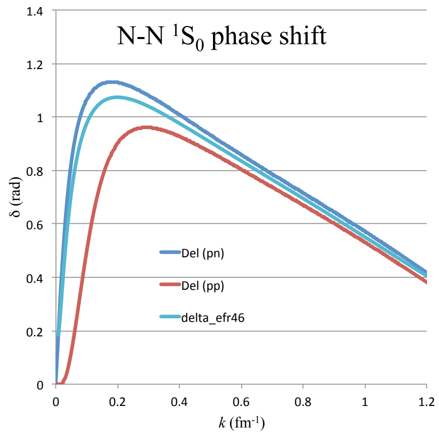
Peak at $X = 11/2$; $E \sim 60$ MeV

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

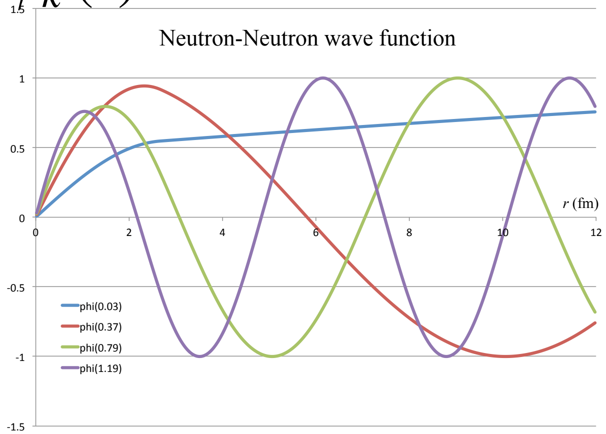
Fourier Transform is expansion with plane waves => correlated scattering waves for FSI

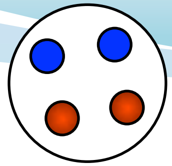
NN FSI

Continuum spectrum with n-n FSI



$\phi_k(r)$

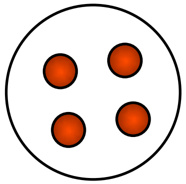




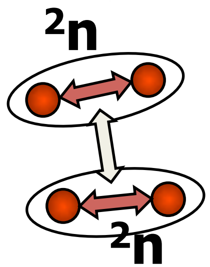
^{4}He ~ $\Phi[(0s)^4]$

DCX

$q > 15$ 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

Density of State

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

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

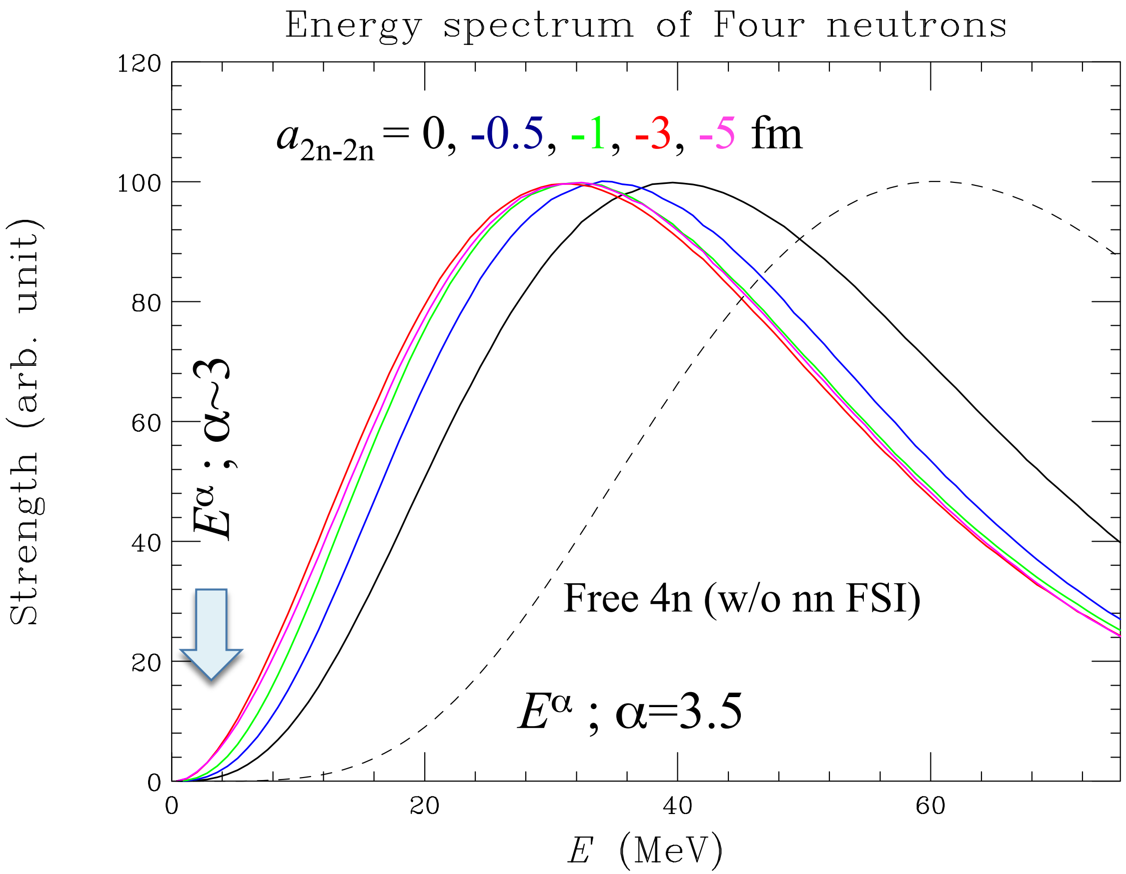
$$\hat{A}_{2s}(k) = \int_0^\infty dr\, r\, \psi_{2s}(r)\, \phi_k(r) = 2\sqrt{\frac{2}{3}}\left(\frac{1}{\sqrt{\pi}a^3}\right)^{1/2} k\, A_{2s}(k)$$

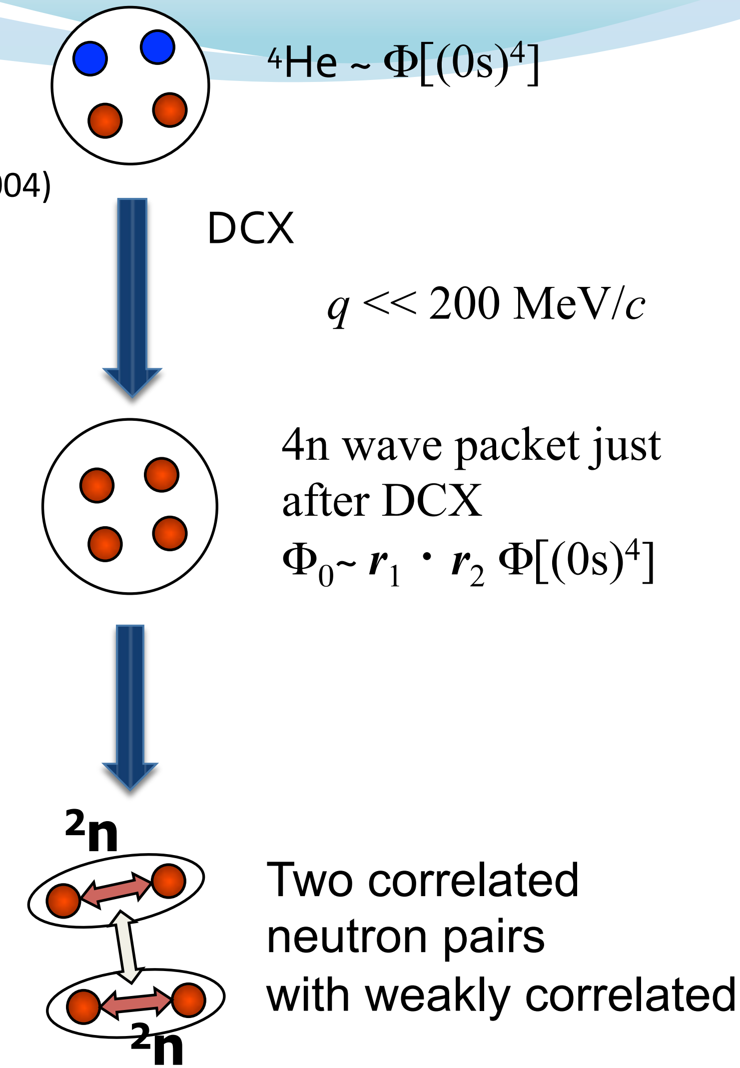
Expand $\mathcal{A}\Phi_0$ with correlated n-n scattering wave $\phi_k(r)$
$A(k)$'s are used instead of Fourier component

Direct Part

Continuum spectrum with n-n FSI

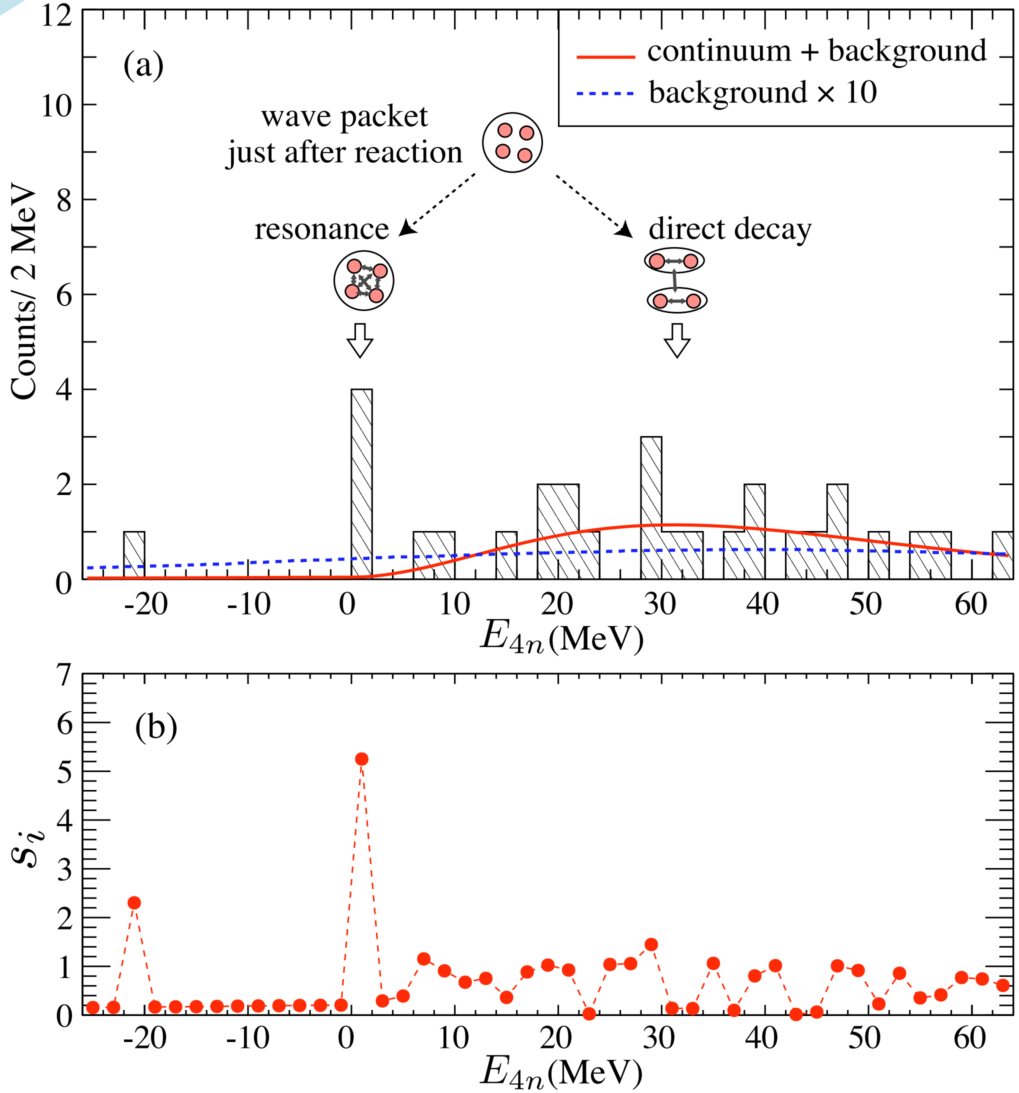
c.f.
L.V. Grigorenko, N.K. Timofeyuk, M.V. Zhukov, Eur. Phys. J. A 19, 187 (2004)





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 θ_{cm}< 5.4deg:
$3.8^{+2.9}_{-1.8}$ 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

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

Summary

- $^4He(^8He,^8Be)4n$ has been measured at 190 A MeV at RIBF-SHARAQ
- Missing mass spectrum with very few background
- Although statistics is low (27 evs), 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 σ significance)

  → candidate of 4n resonance

  at $0.83 \pm 0.65(\text{stat.}) \pm 1.25(\text{sys.})$ MeV; $\Gamma < 2.6$ MeV
- Constraint to nucleon forces : n-n two body; T=3/2 three-body force; non-central; off-energy shell ...