Tetra-neutron system studied by (^{8}He,^{8}Be) reaction

- Motivation
  - Boundary of stability in nuclei
  - NN and NNN interaction/correlation and information on neutron matter → Neutron star
- 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

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Tetra-neutron

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

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

- Only upper limit of cross section was decided.

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

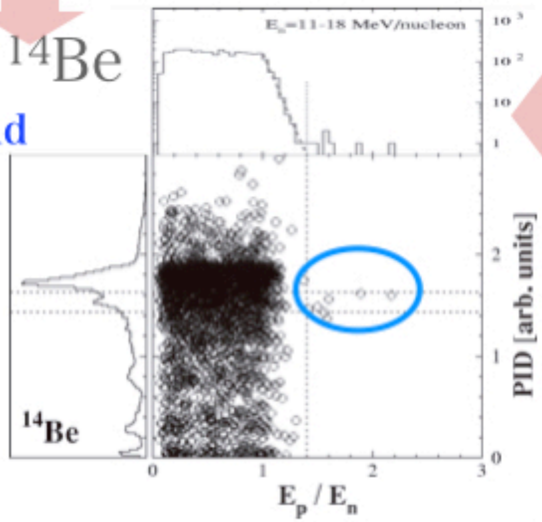
Bound state: No clear evidence.

2000s

Breakup of ^{14}Be

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

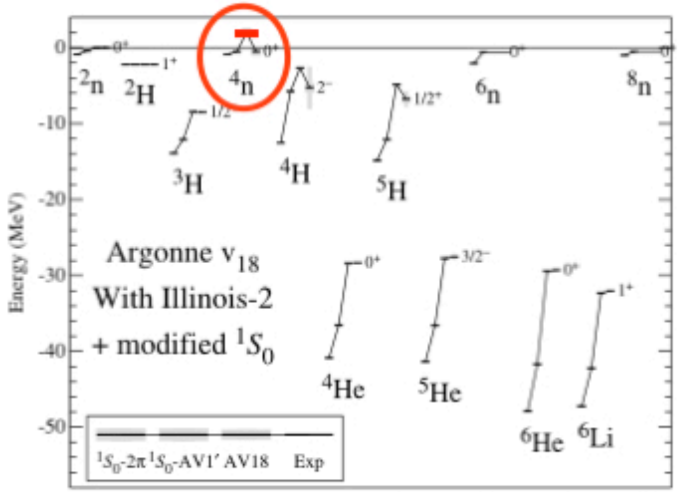
F. M. Marques, et al, Phys. Rev. C 65, 044006 (2002)



2000s

Theoretical work

- ab-initio calculation NN, NNN interaction

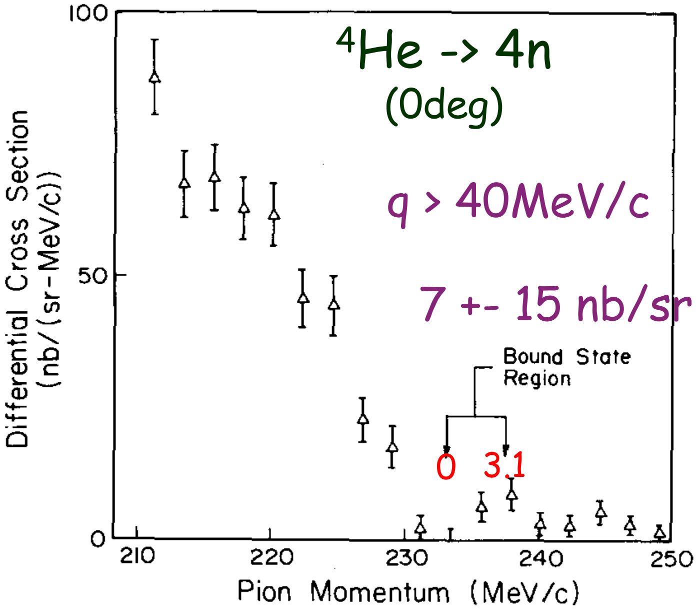


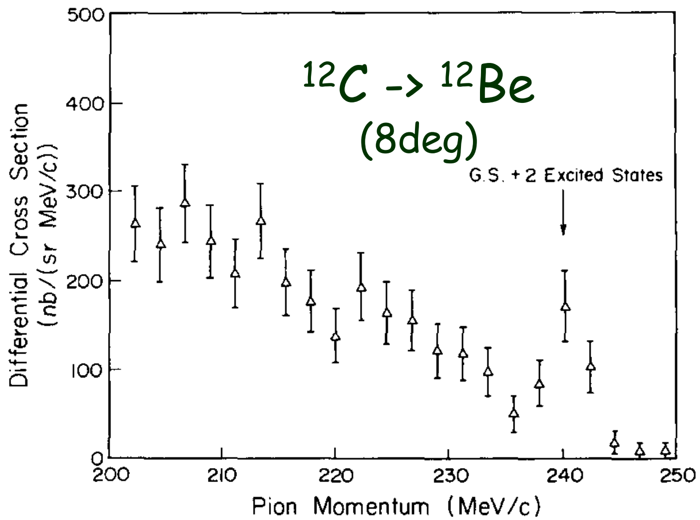
S. C. Piper, Phys. Rev. Lett. 90, 252501 (2003)

- **Bound ^{4}n 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

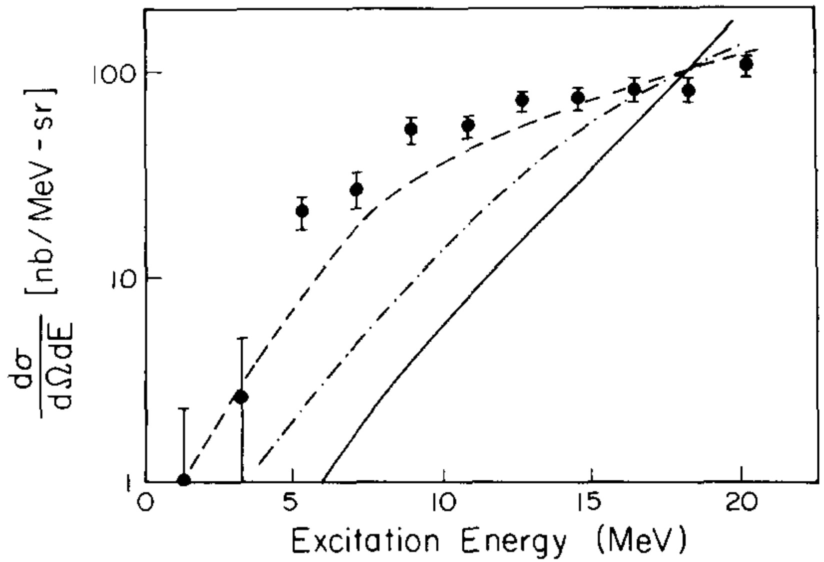
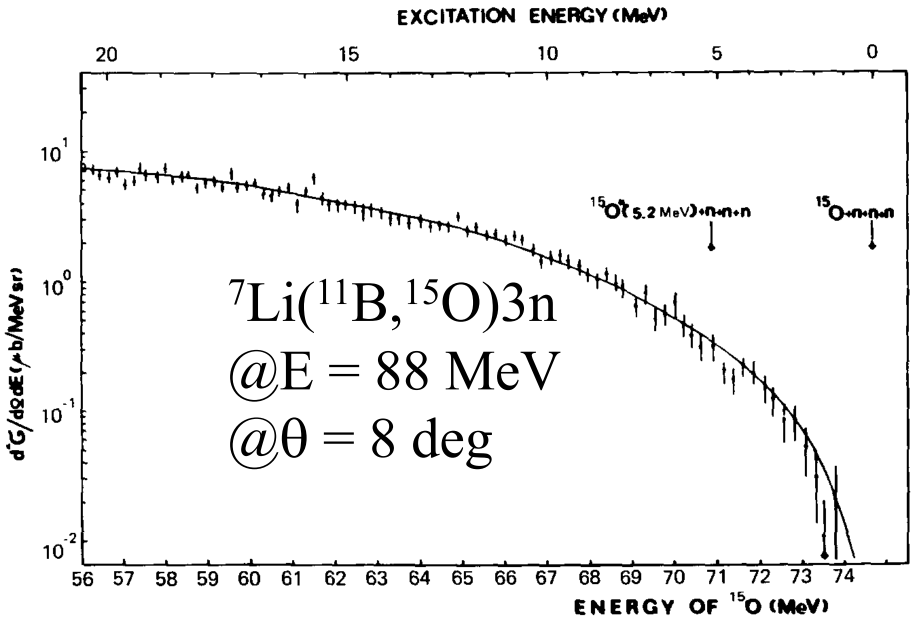


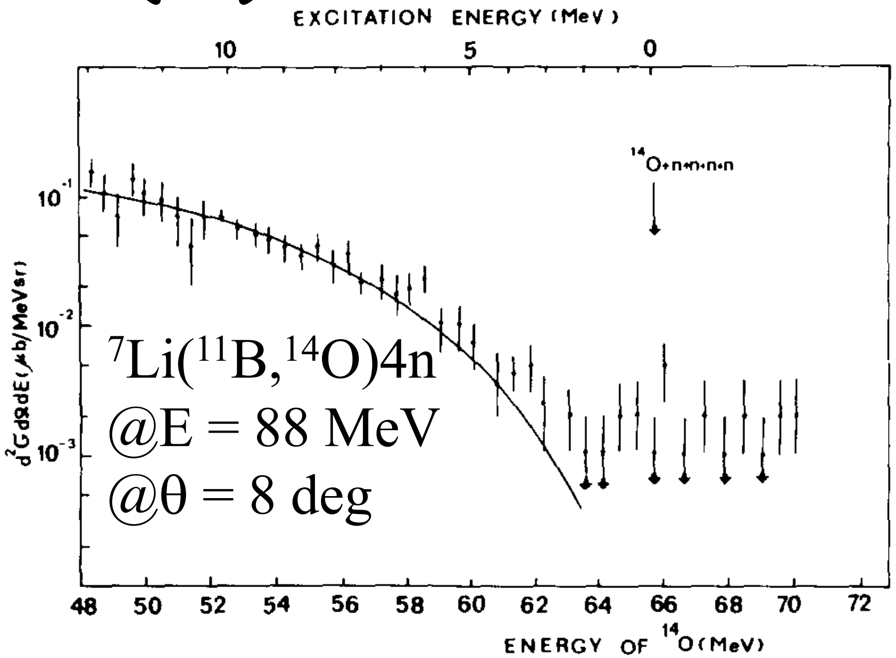
Fig. 3. The experimental results are plotted against the excitation of the final four-neutron state. The solid curve corresponds to the pure four-neutron phase space, while the dot-dashed and dashed curves are the four-neutron phase space curves with singlet state interactions in, respectively, one and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

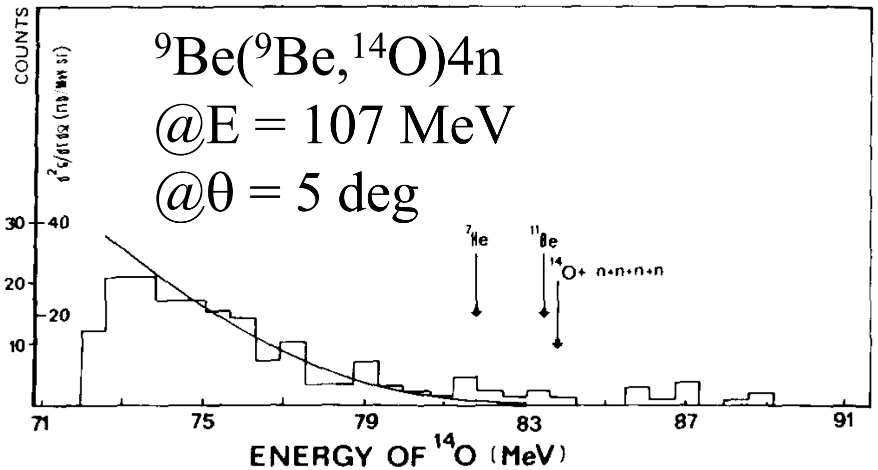
J.E. Ungar et al., PLB 144 (1987) 333

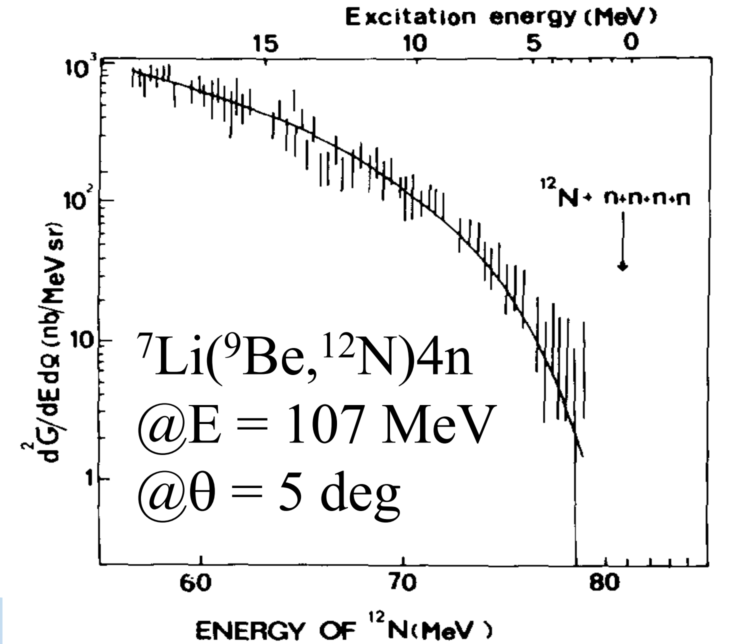
Historical review (2)

Nucl. Phys. A477 (1988) 131

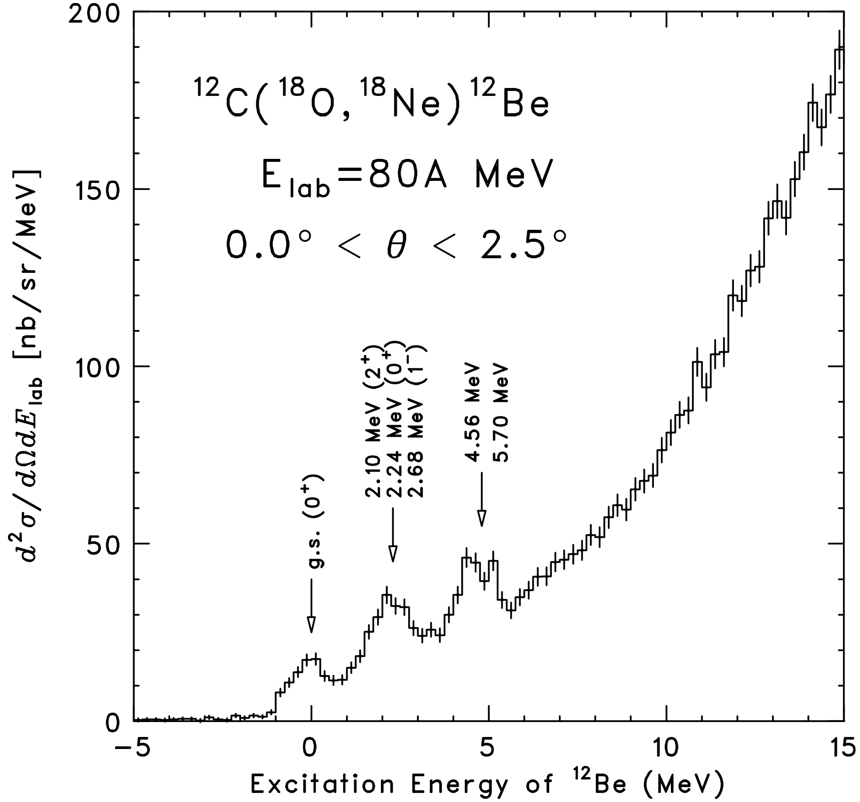








Double charge exchange (DCX) reaction of HI

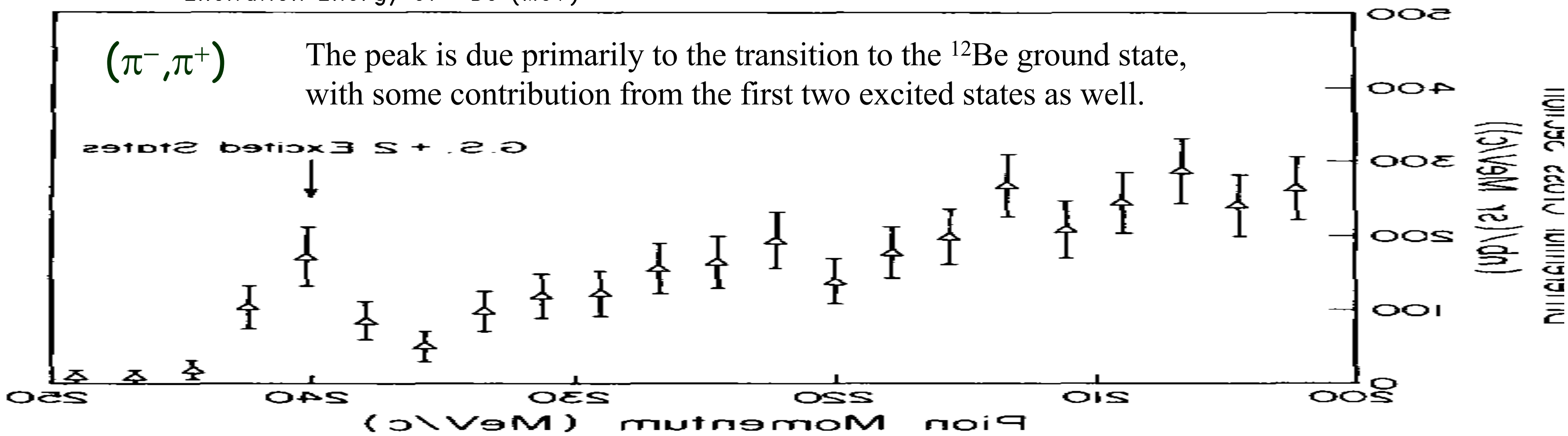


$^{12}C \rightarrow {}^{12}Be$

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

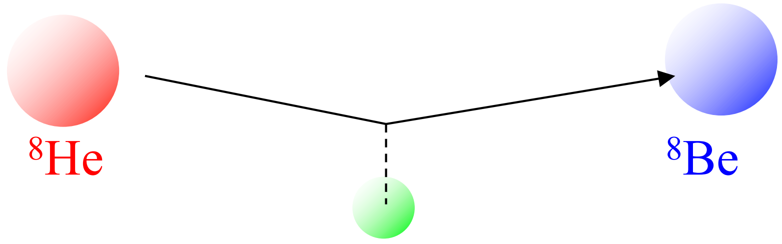
~70nb/sr (Gnd)
~200nb/sr (~2MeV)

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



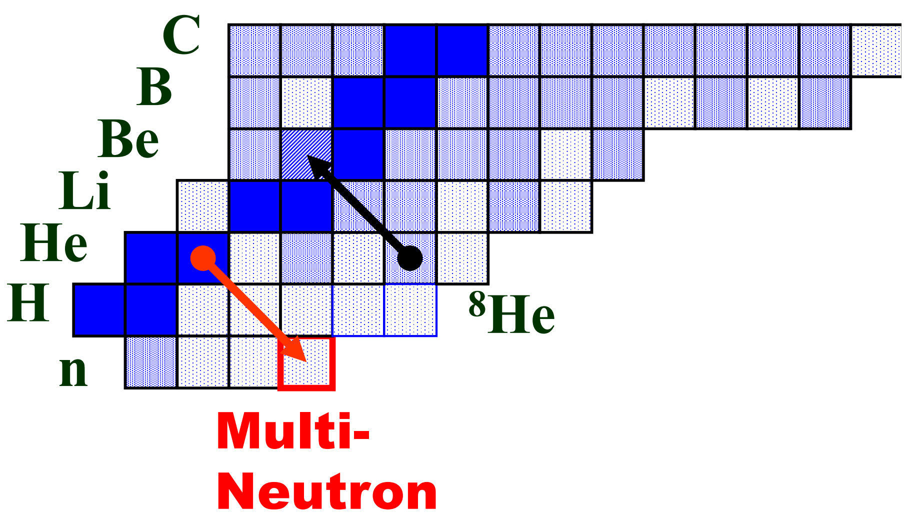
(π^-,π^+) The peak is due primarily to the transition to the ^{12}Be ground state, with some contribution from the first two excited states as well.

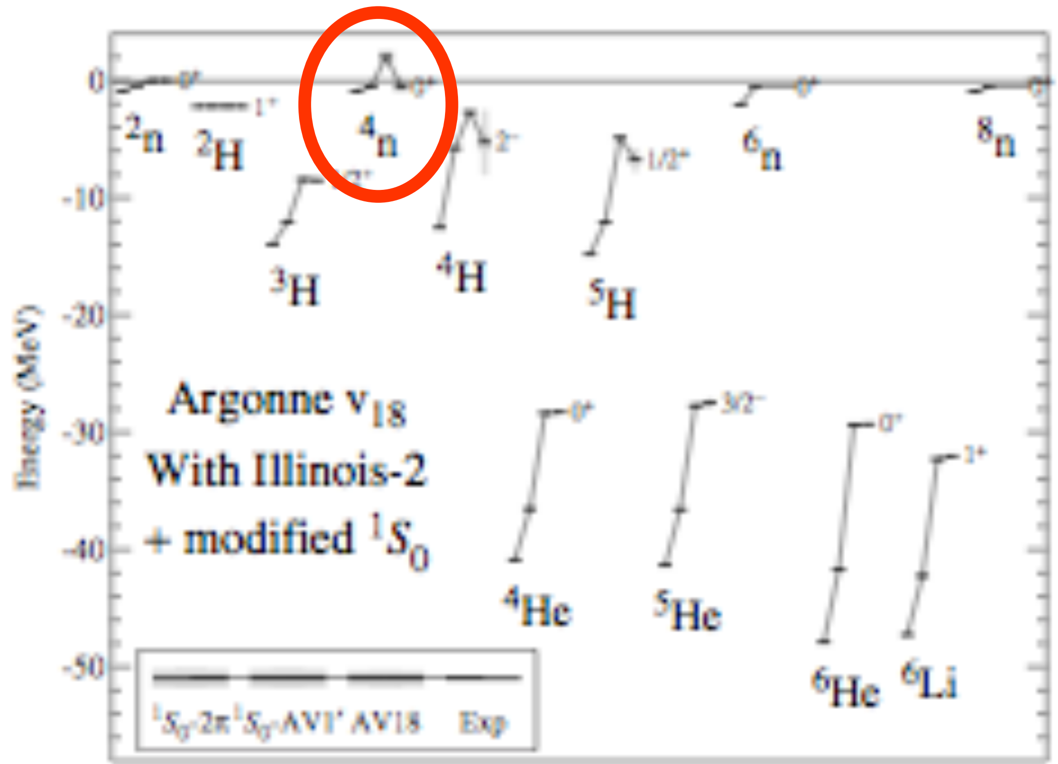
Tetra-neutron system produced by exothermic double-charge exchange reaction



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

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

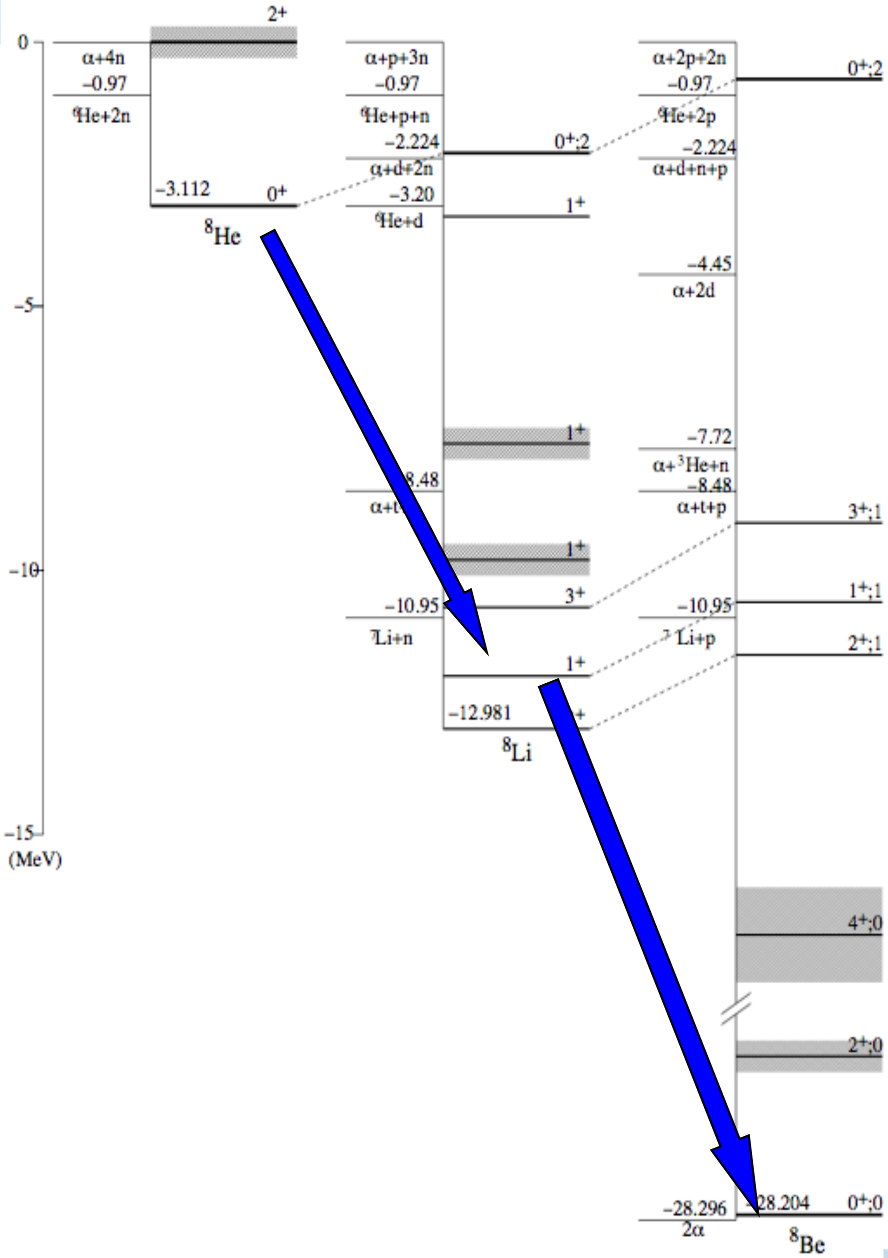


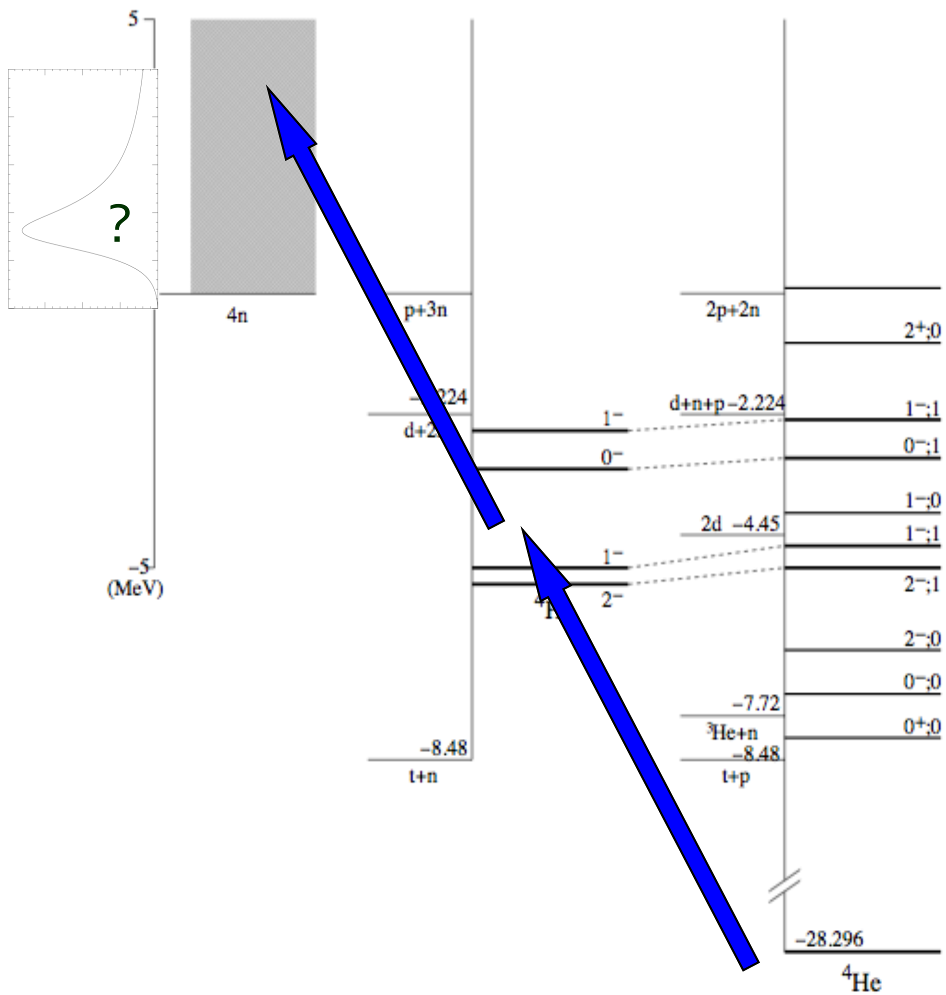


S.C. Pieper et al., PRL 90, 252501 (2003)

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

Level diagrams

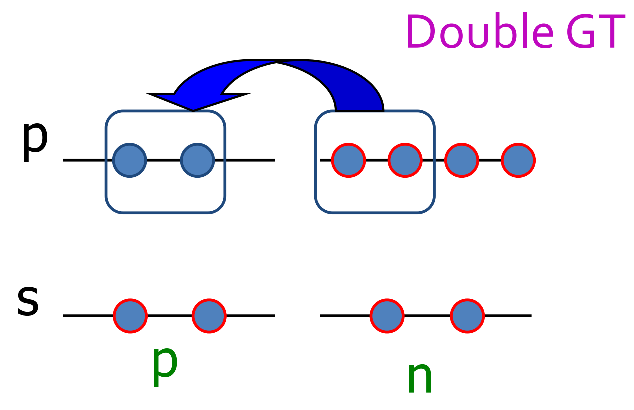




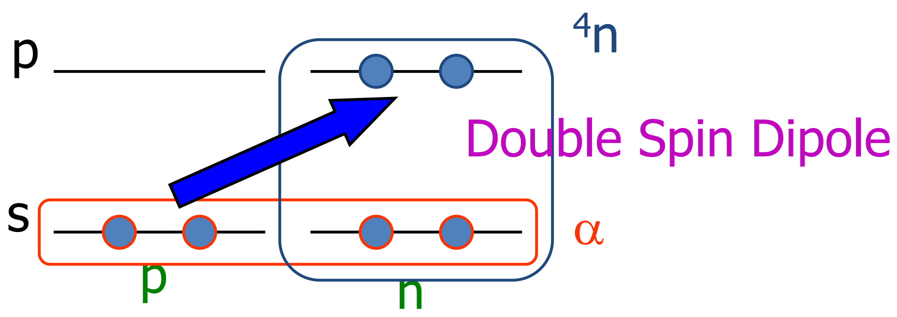
$q_{min} \sim 10 MeV/c$

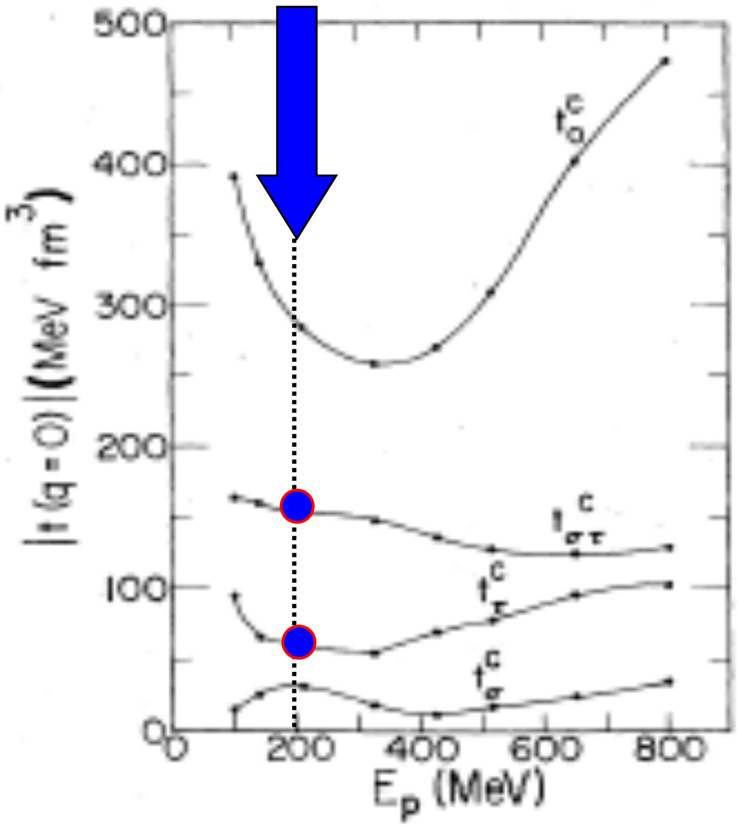
Reaction Mechanism

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



$^{4}He \rightarrow 4n$

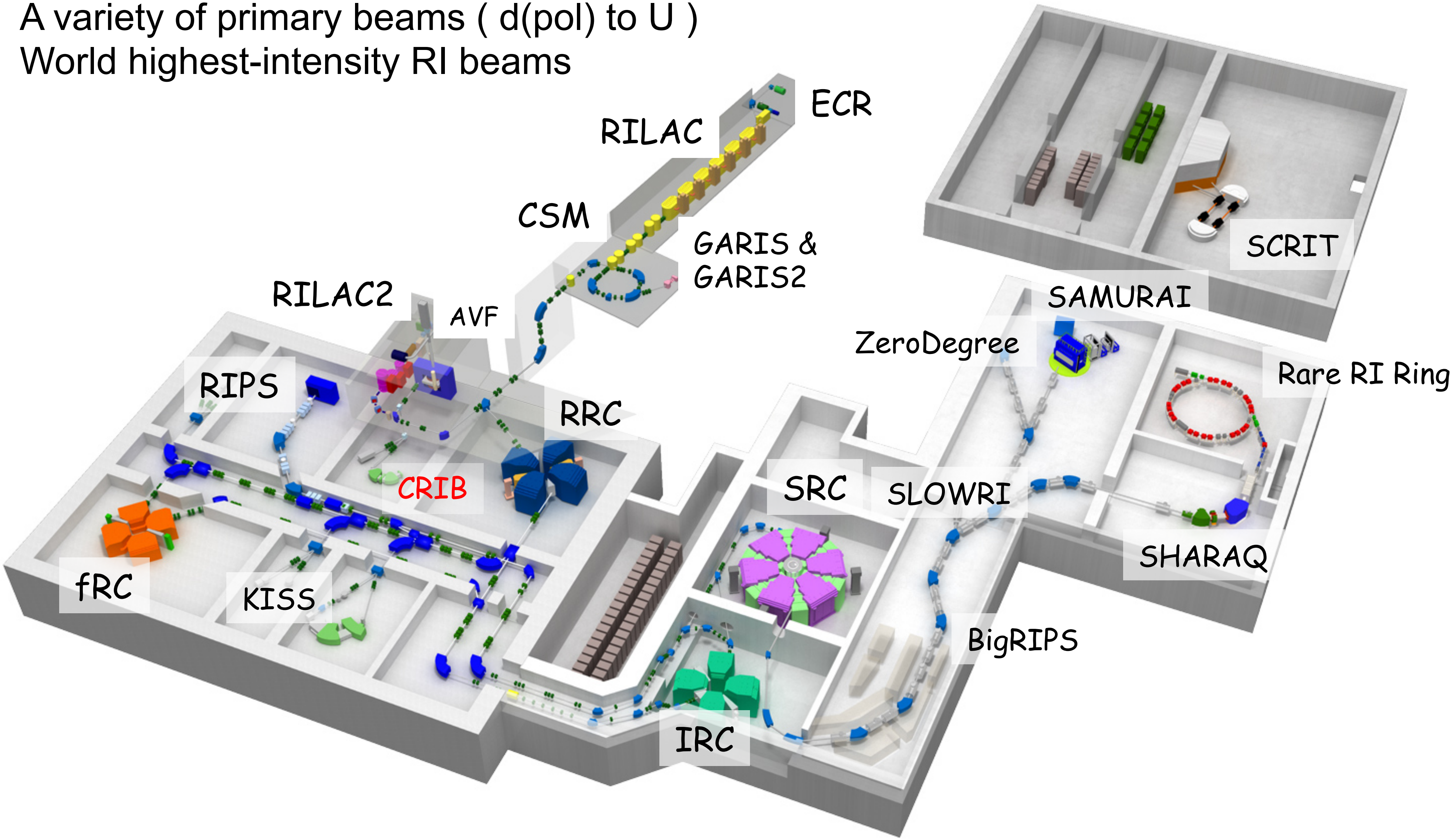




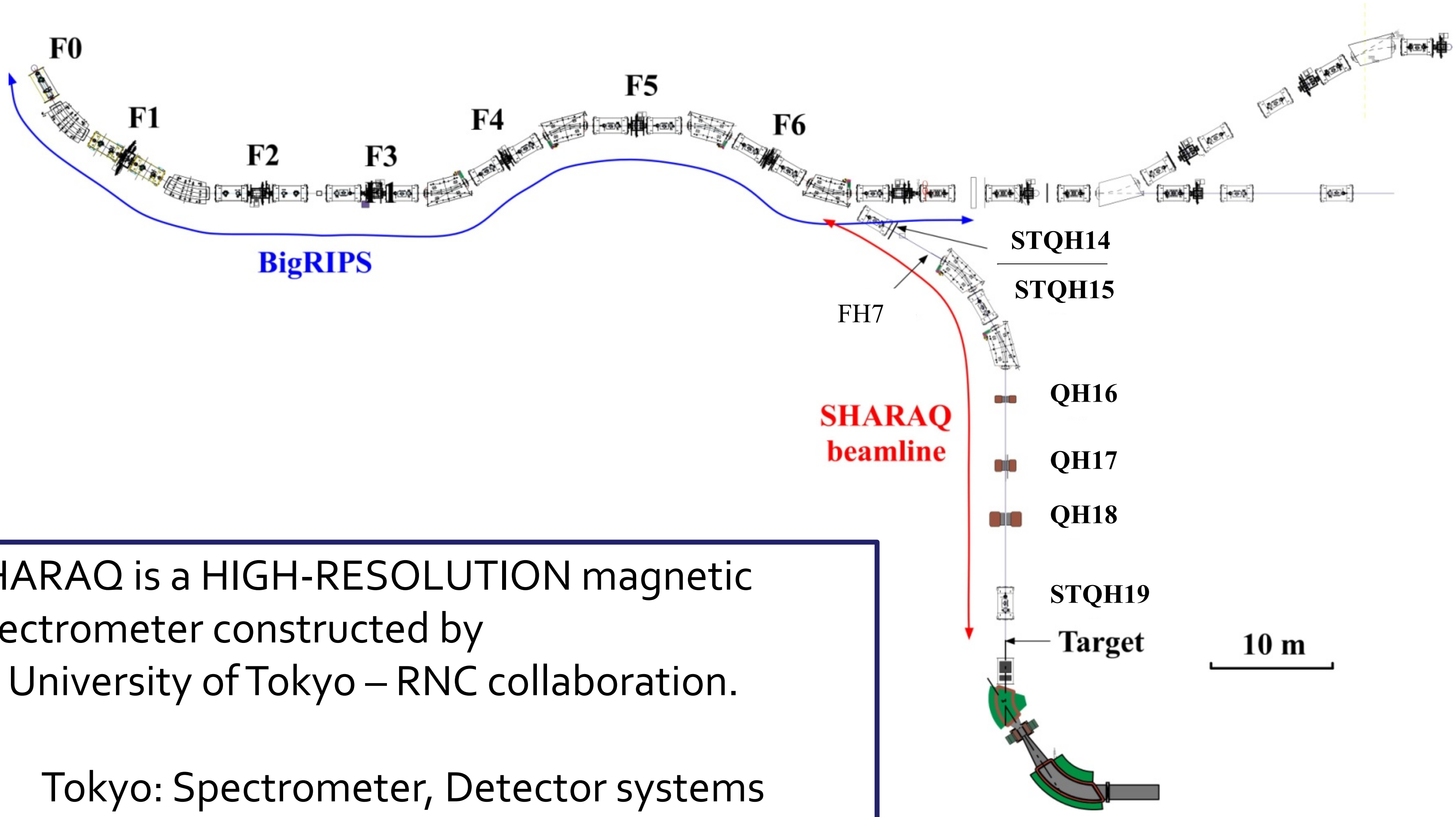
$$\left[\left(\vec{\tau}_{p}\cdot\vec{\tau}_{t}\right)\left(\vec{\sigma}_{p}\cdot\vec{\sigma}_{t}\right)r_{t}Y_{1}\left(\hat{r}_{t}\right)\right]^{2}$$

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 @ RI beam factory

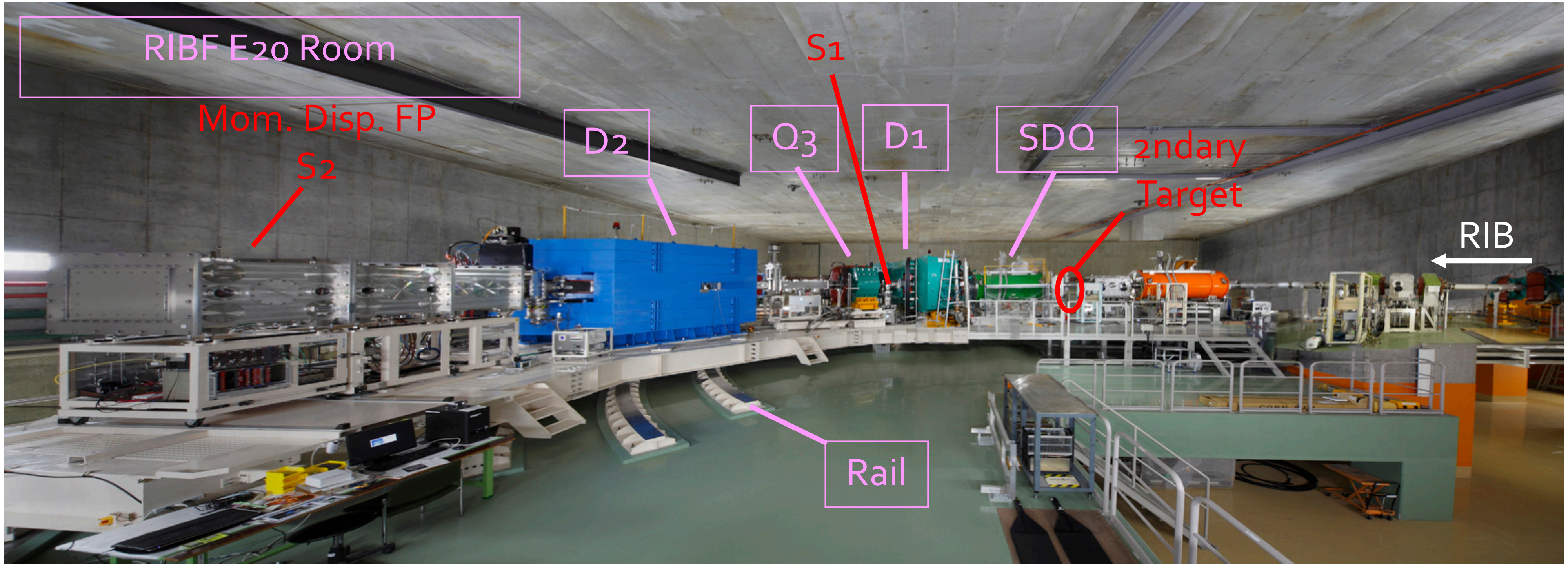


SHARAQ is a HIGH-RESOLUTION magnetic spectrometer constructed by
University of Tokyo – RNC collaboration.

Tokyo: Spectrometer, Detector systems
RNC: Beam-line, Infrastructure

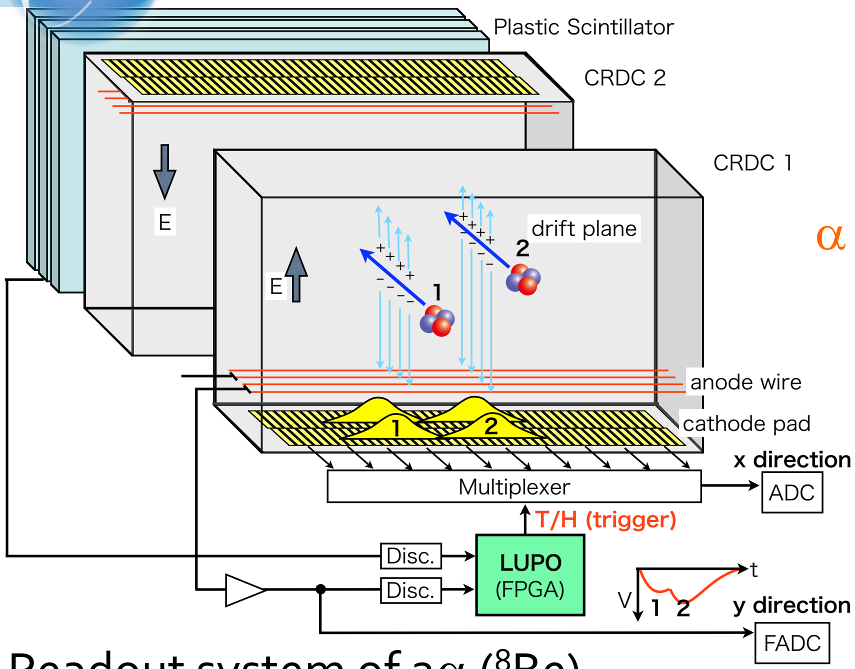
SHARAQ spectrometer

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**

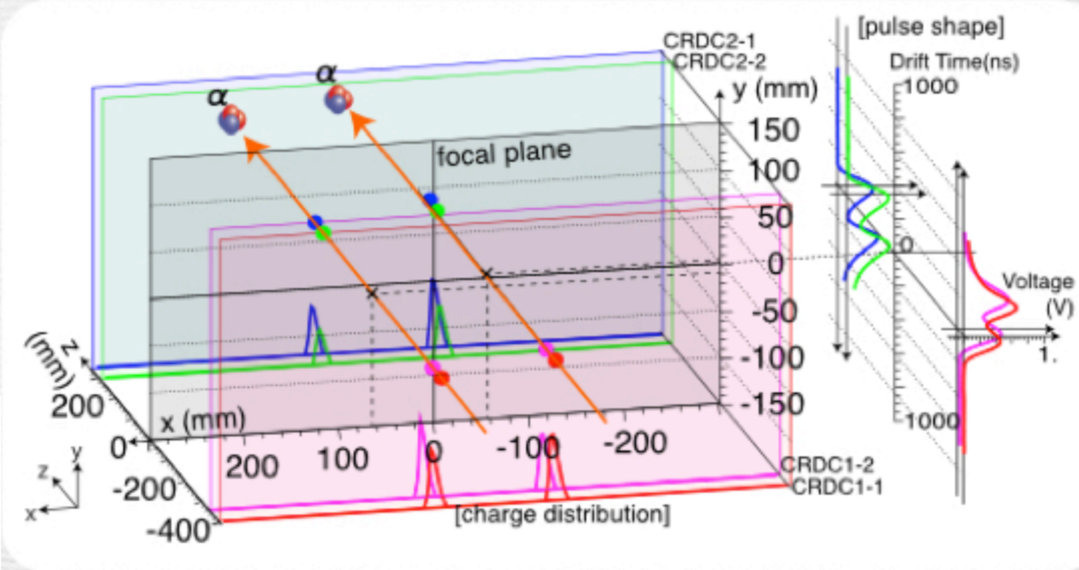
銀杏 ICHOR



Readout system of 2α (^{8}Be)

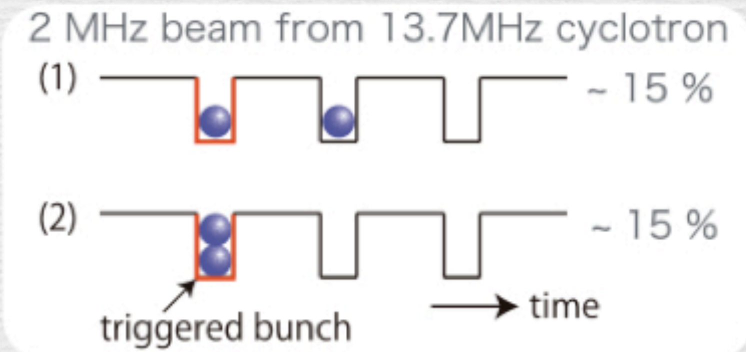
Analysis

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



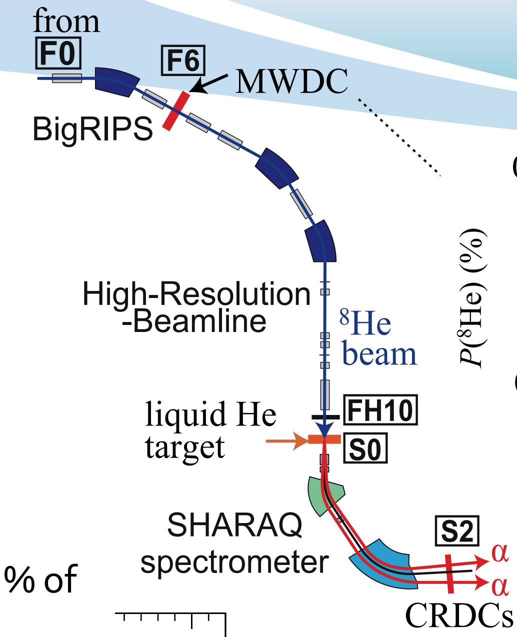
Background process:
Breakup of two ^{8}He in the same beam bunch to two alpha particle
Identified by multi-hit in F6-MWDC

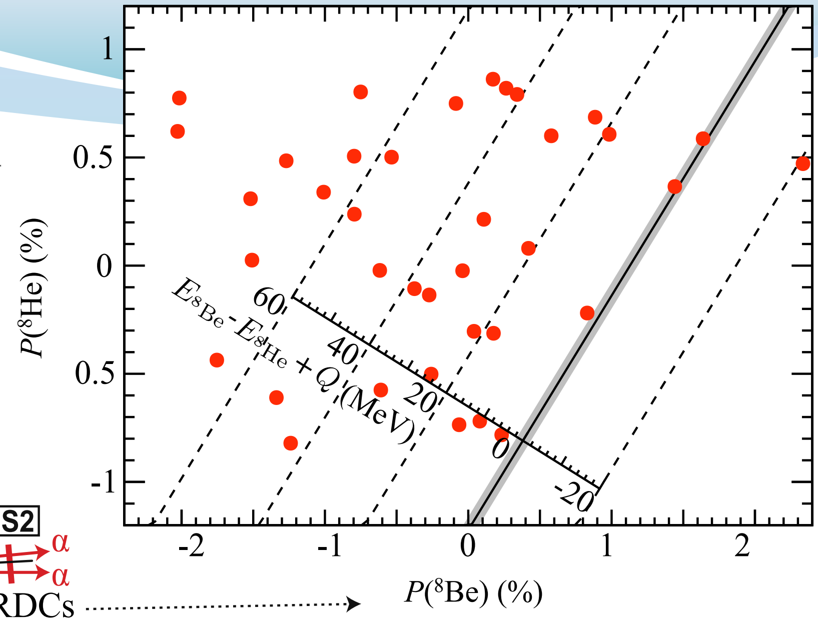
- Background Estimation
  - Shape in spectrum: random 2α
  - Number of events:
    - failure of the multi-particle rejection at MWDC
    - multi-particle in one cell of MWDC



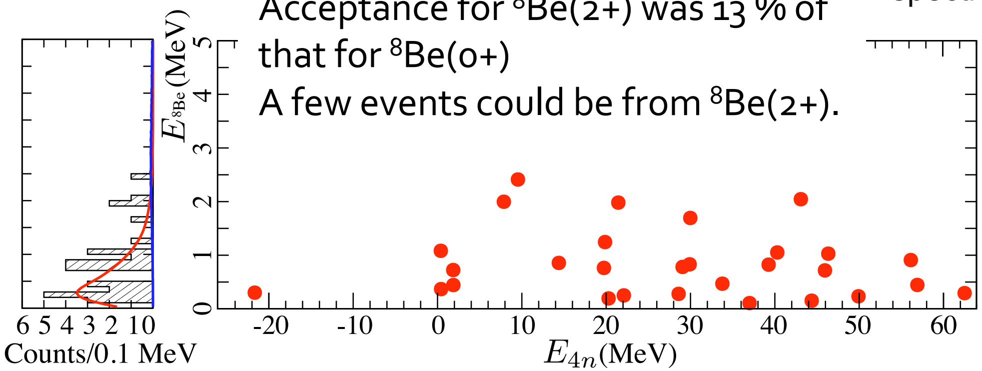
Backgrounds after analysis:
Finite efficiency of multi-hit events at F6-MWDC

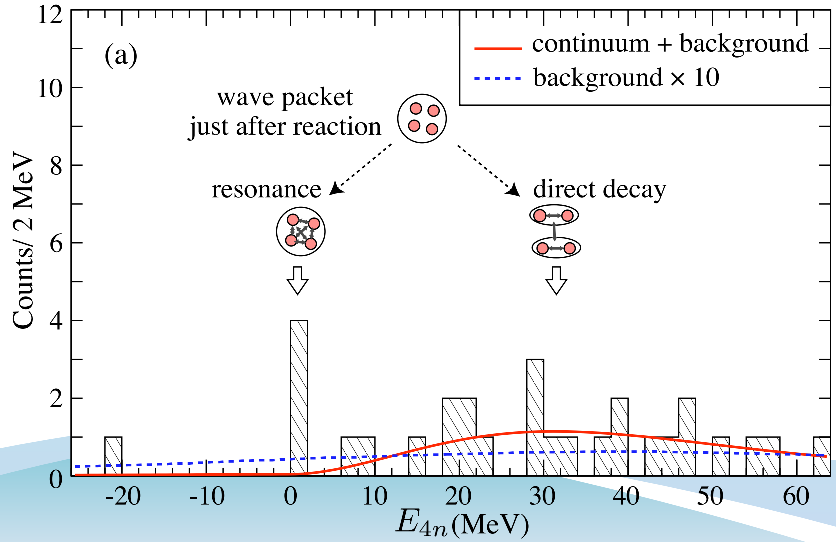
Experimental Results

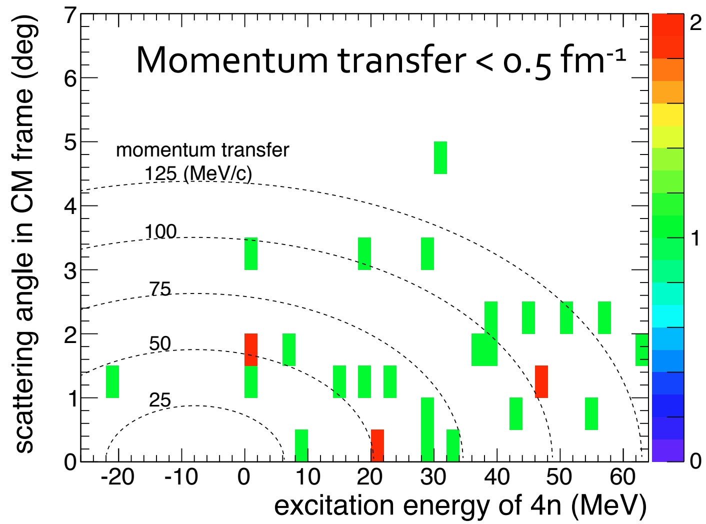




Acceptance for ^{8}Be(2+) was 13 % of that for ^{8}Be(0+)
A few events could be from ^{8}Be(2+).

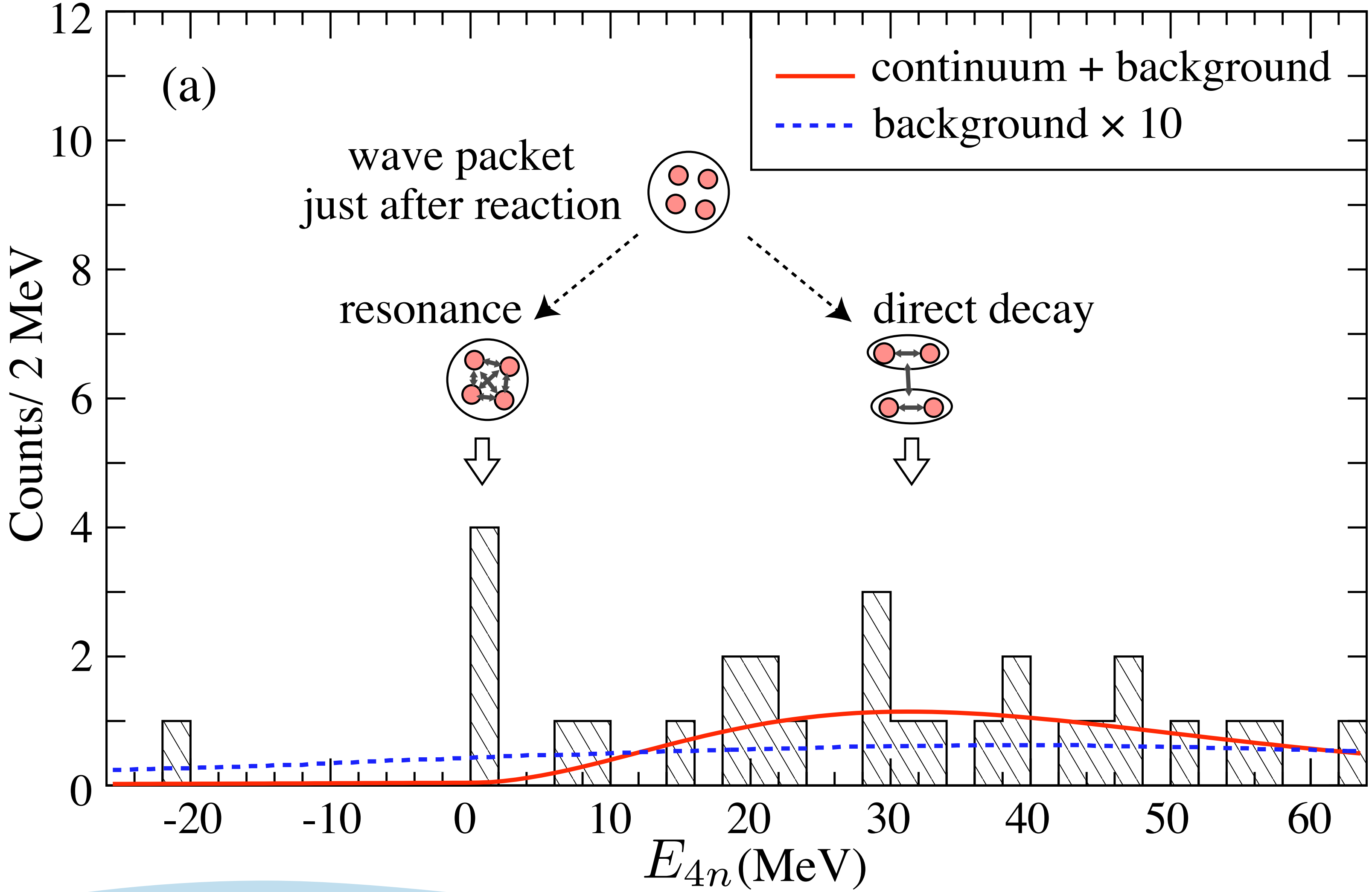




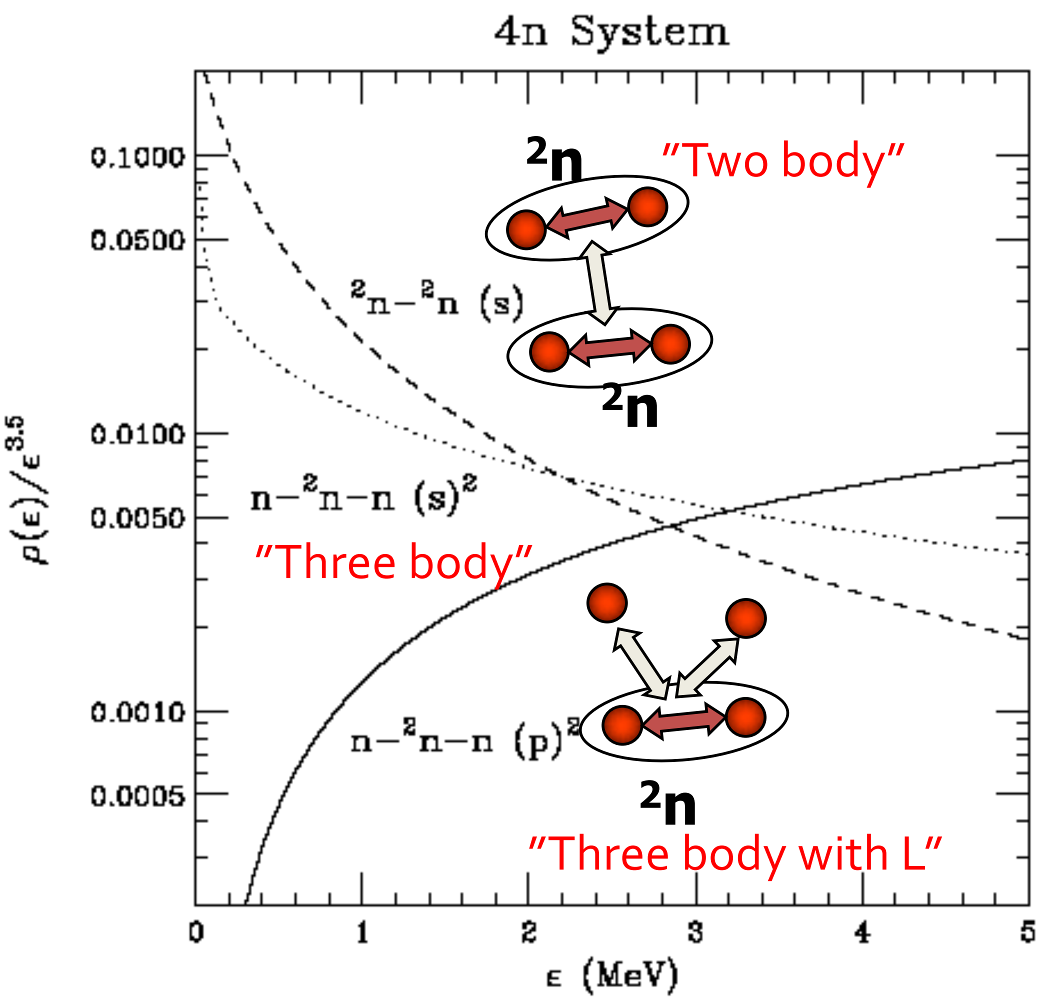


Look like having two components:
Continuum + Peak (?)
? The 4 counts just above threshold can be explained by the fluctuation of continuum or not?

Experimental Results



Phase space in multi-body continuum

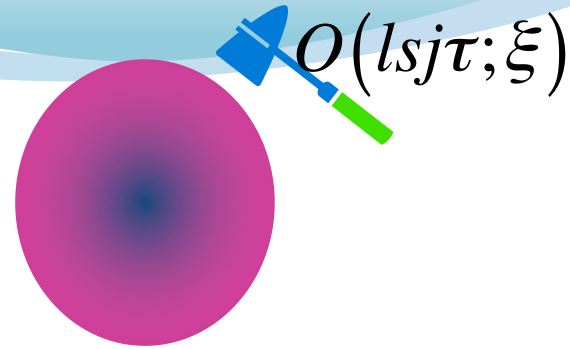


Phase Space

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

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

Transition Probabilities



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

if distortion is insensitive to ω

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

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

sum of
one-body operator

e.g.

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

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

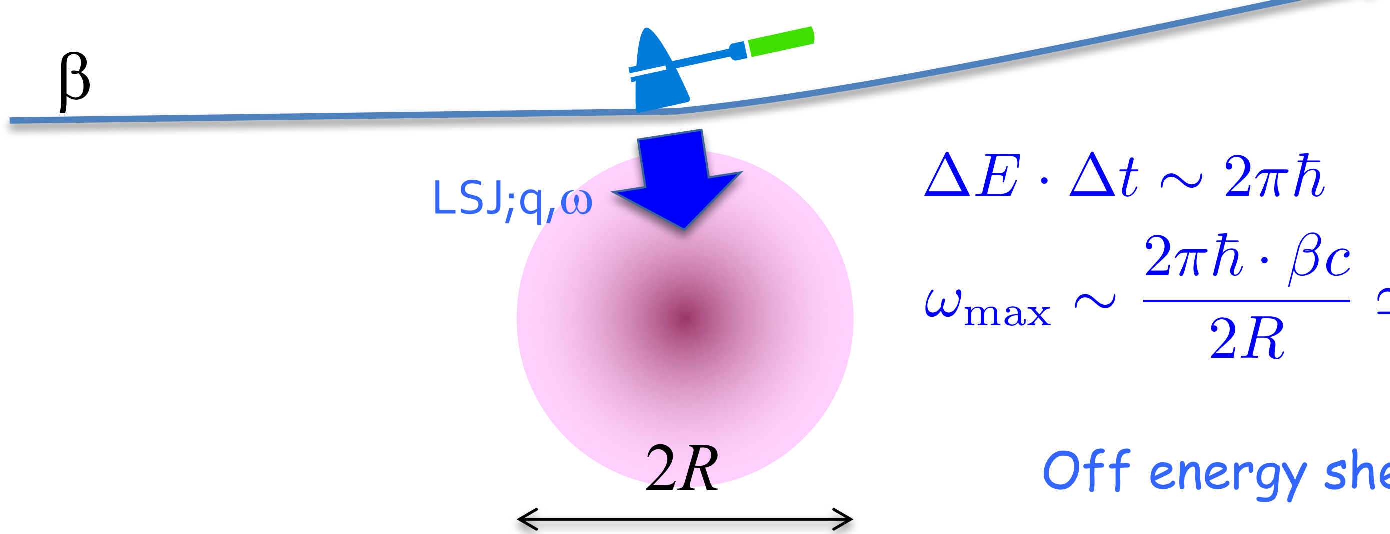
$$O(lsj\tau;\xi) |E_i J_i \pi_i T_i ; \xi_i\rangle = \sum_f\!\!\!\!\!\!\int M_{if}(E_f) |E_f J_f \pi_f T_f ; \xi_f\rangle$$ Response

$|M_{if}(E_f)|^2$: 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"

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



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

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

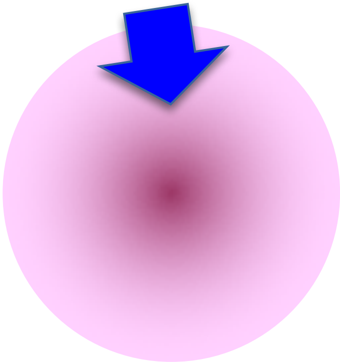
Off energy shell

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

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

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

"Transition" as time-dependent action



$$i\hbar\frac{\partial}{\partial t}\Psi(t) = (H + V_R(t))\,\Psi(t)$$

$$\Psi(t) = \sum_i a_i(t)\,\psi_i \exp(-iE_i t/\hbar)$$

$$H\psi_i = E_i\psi_i$$

$$a_0(-\infty) = 1 \quad ; \quad a_i(-\infty) = 0 \quad \text{for } i > 0$$

$$|a_i(+\infty)|^2 : \text{Energy spectrum after reaction}$$

$$\sum_i i\hbar\,\dot{a}_i(t)\,\psi_i \exp(-iE_i t/\hbar) = \sum_i a_i(t)\,V_R(t)\,\psi_i \exp(-iE_i t/\hbar)$$

$$i\hbar\,\dot{a}_k(t) = \frac{1}{\sqrt{2\pi}}\exp\left(-\frac{t^2}{2\Delta T^2}\right) \times \sum_i a_i(t)\,\langle\psi_k|\mathcal{O}|\psi_i\rangle \exp\left(-\frac{i(E_i - E_k)t}{\hbar}\right)$$

$$V_R(t) = \frac{\mathcal{O}}{\sqrt{2\pi}}\exp\left(-\frac{t^2}{2\Delta T^2}\right)$$

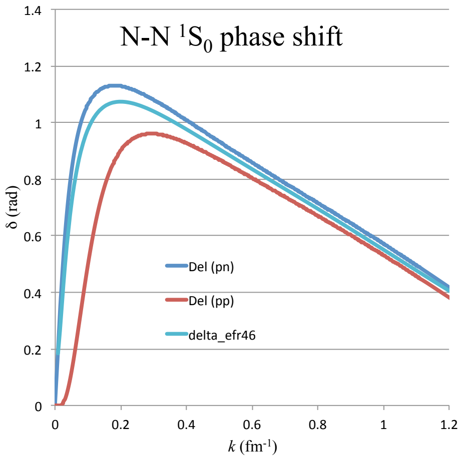
Perturbation

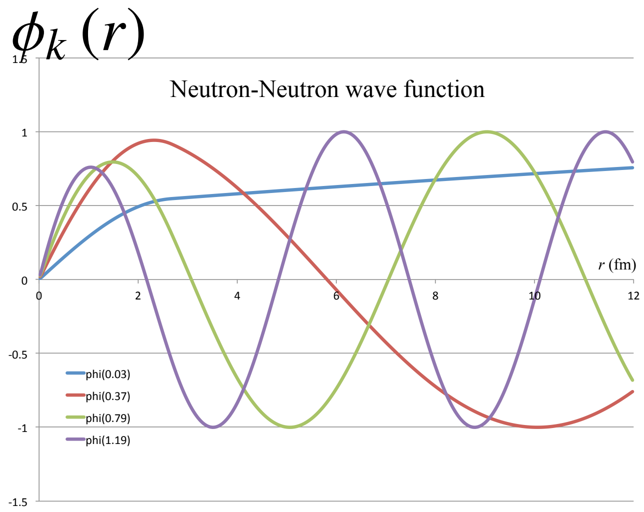
$$a_i(-\infty) \ll 1 \quad \text{for } i > 0$$

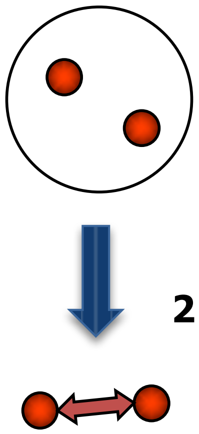
$$a_0(+\infty) - a_0(-\infty) \simeq -i\frac{\Delta T}{\hbar}\langle\psi_0|\mathcal{O}|\psi_0\rangle$$

$$a_k(+\infty) \simeq -i\frac{\Delta T}{\hbar}\langle\psi_k|\mathcal{O}|\psi_0\rangle \exp\left(-\frac{(E_{i0}\Delta T)^2}{2\hbar^2}\right)$$

NN case with FSI







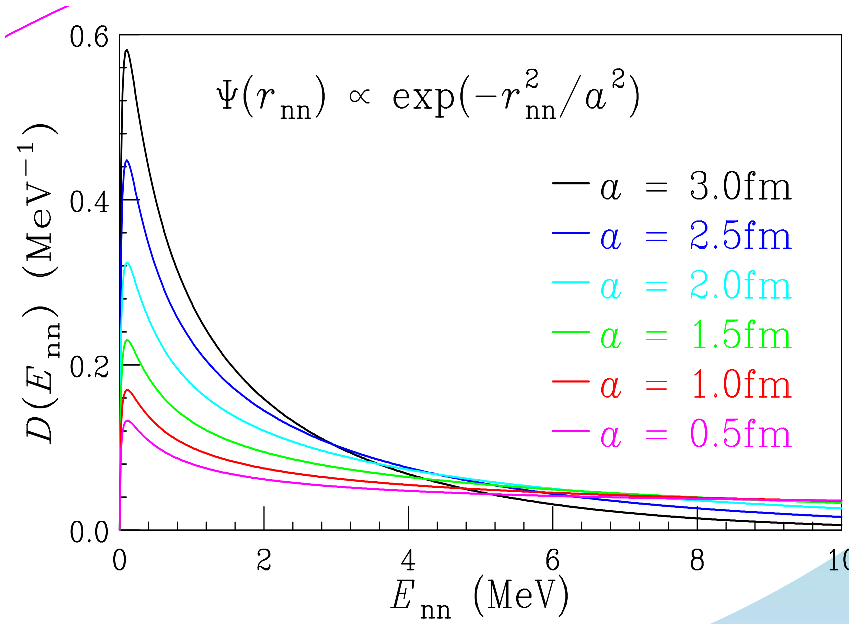
2n wave packet just after a certain reaction ϕ_0~ **Gaussian**

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

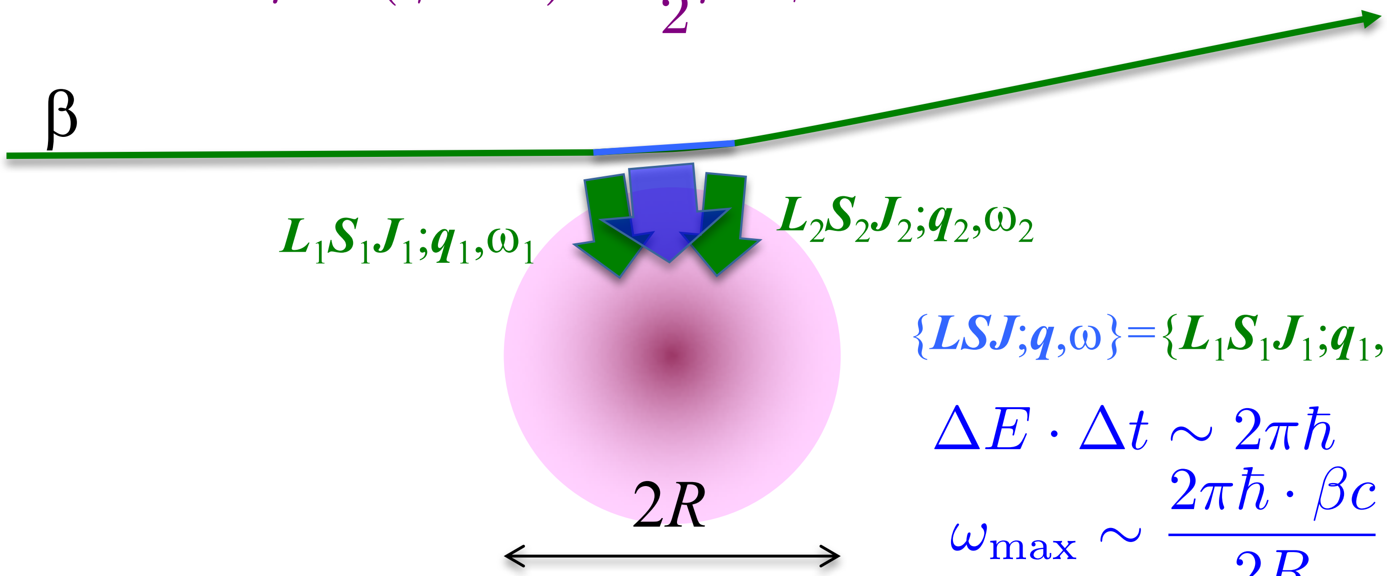
Effective Range Theory :

$\phi_k(r) \sim \sin\delta(k) \times f(r)$ for small r

$D \sim (\sin\delta)^2/k$ (Watson-Migdal approx.)

Two step

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



$\{LSJ;q,\omega\} = \{L_1S_1J_1;q_1,\omega_1\} \oplus \{L_2S_2J_2;q_2,\omega_2\}$

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

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

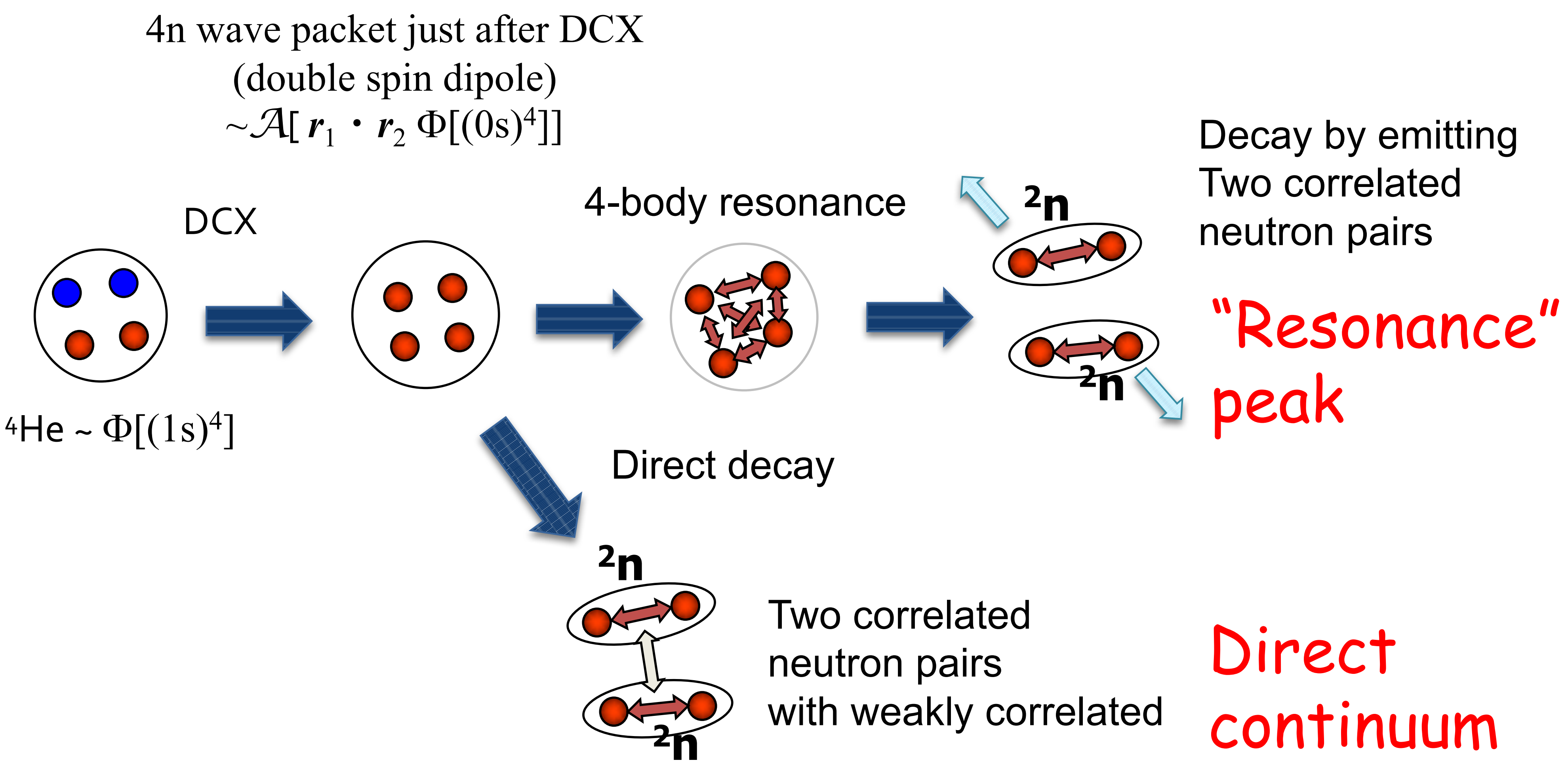
$$\Delta t = \Delta t_1 + \Delta t_2$$

"Intermediate state": Not energy eigen state

~ wave packet consists of "eigen states" over 200β MeV

~ closure approximation ~ almost one-step

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

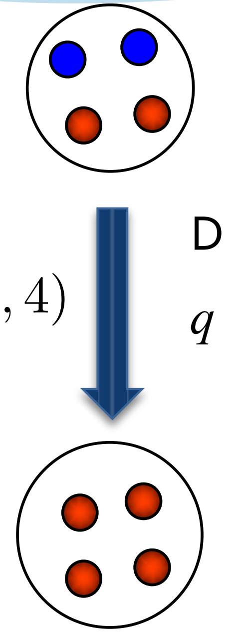


Direct Part

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

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

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



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

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

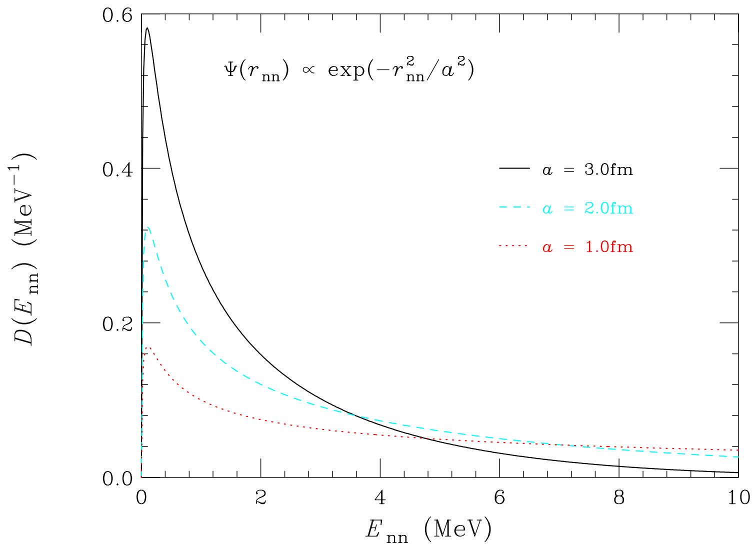
$$X = E/\epsilon_a \qquad \epsilon_a = \frac{\hbar^2}{m_N a^2} = 11\text{MeV}$$

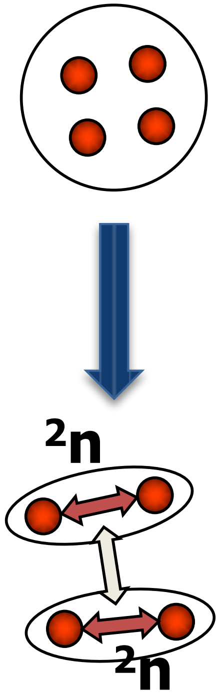
NN FSI

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

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

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

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

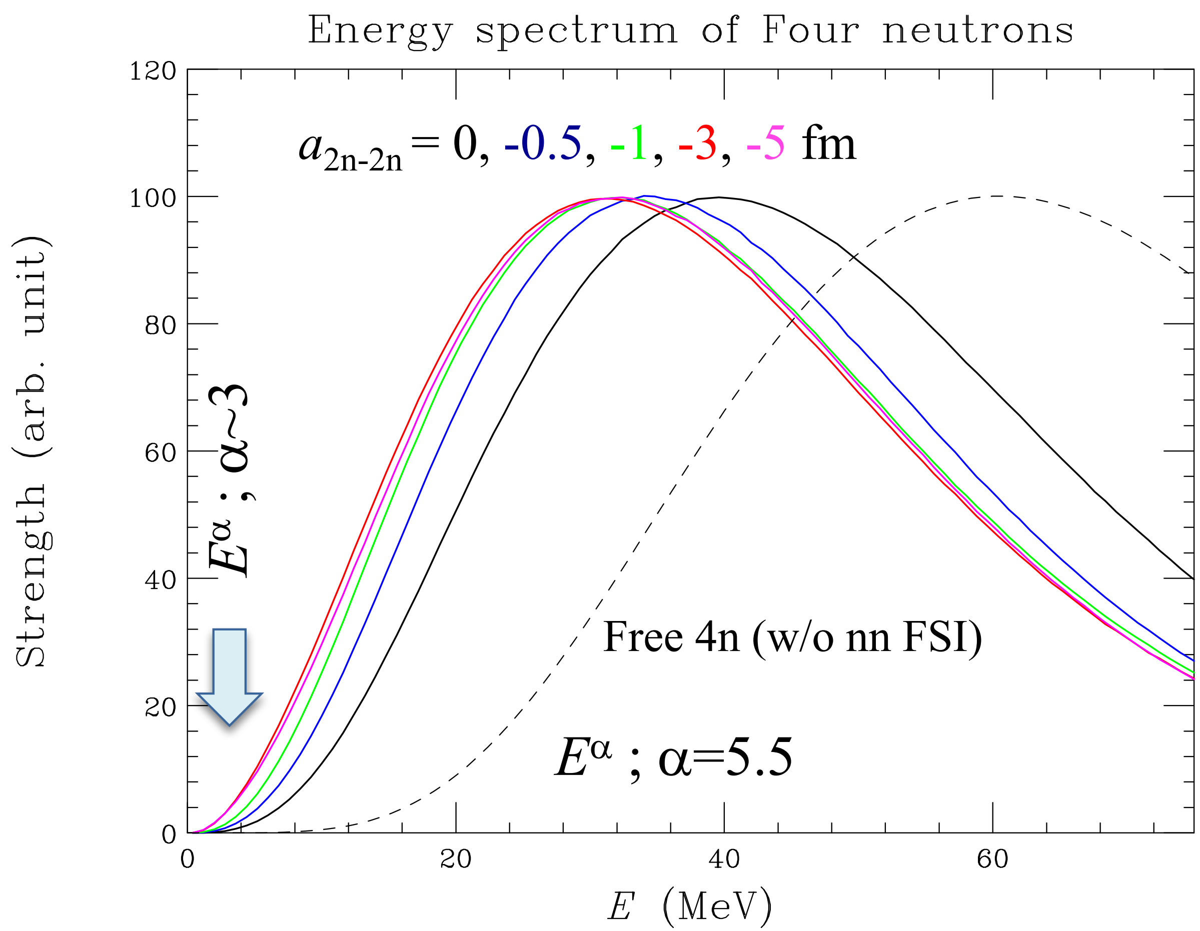
Expand $\mathcal{A}\Phi_0$ with correlated n-n scattering wave $\phi_k(r)$

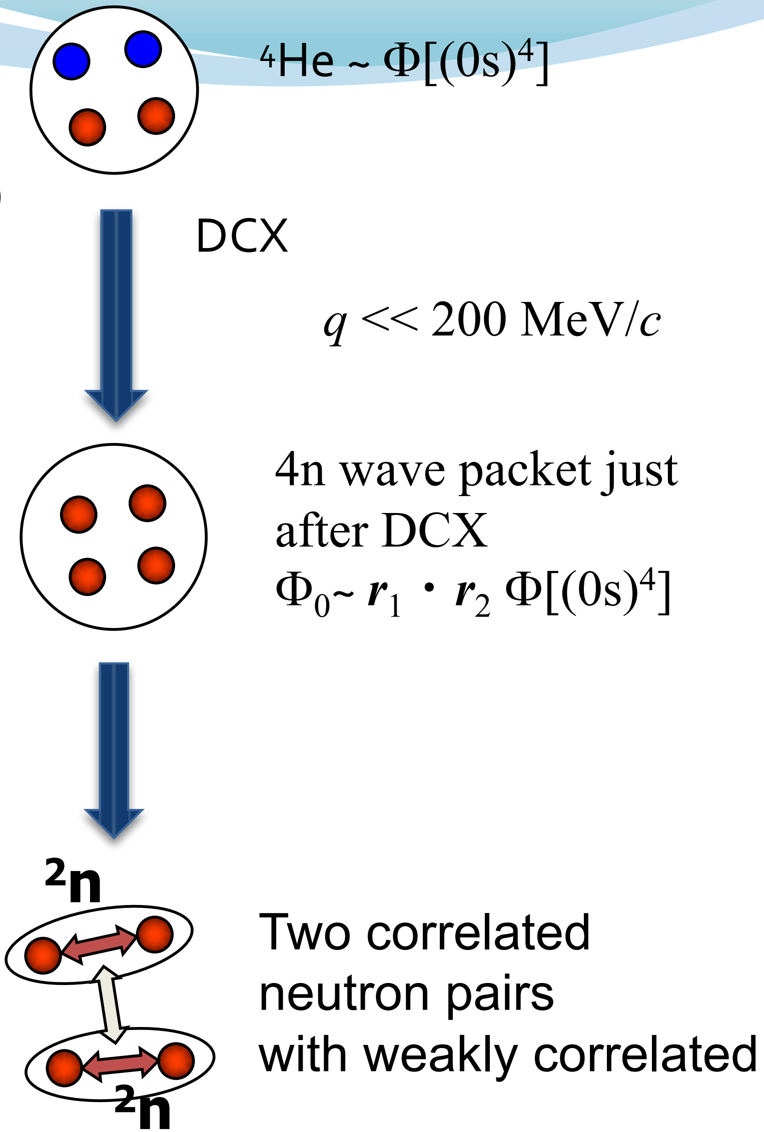
$A(k)$'s are used instead of Fourier component

Direct Part

Continuum spectrum with n-n FSI

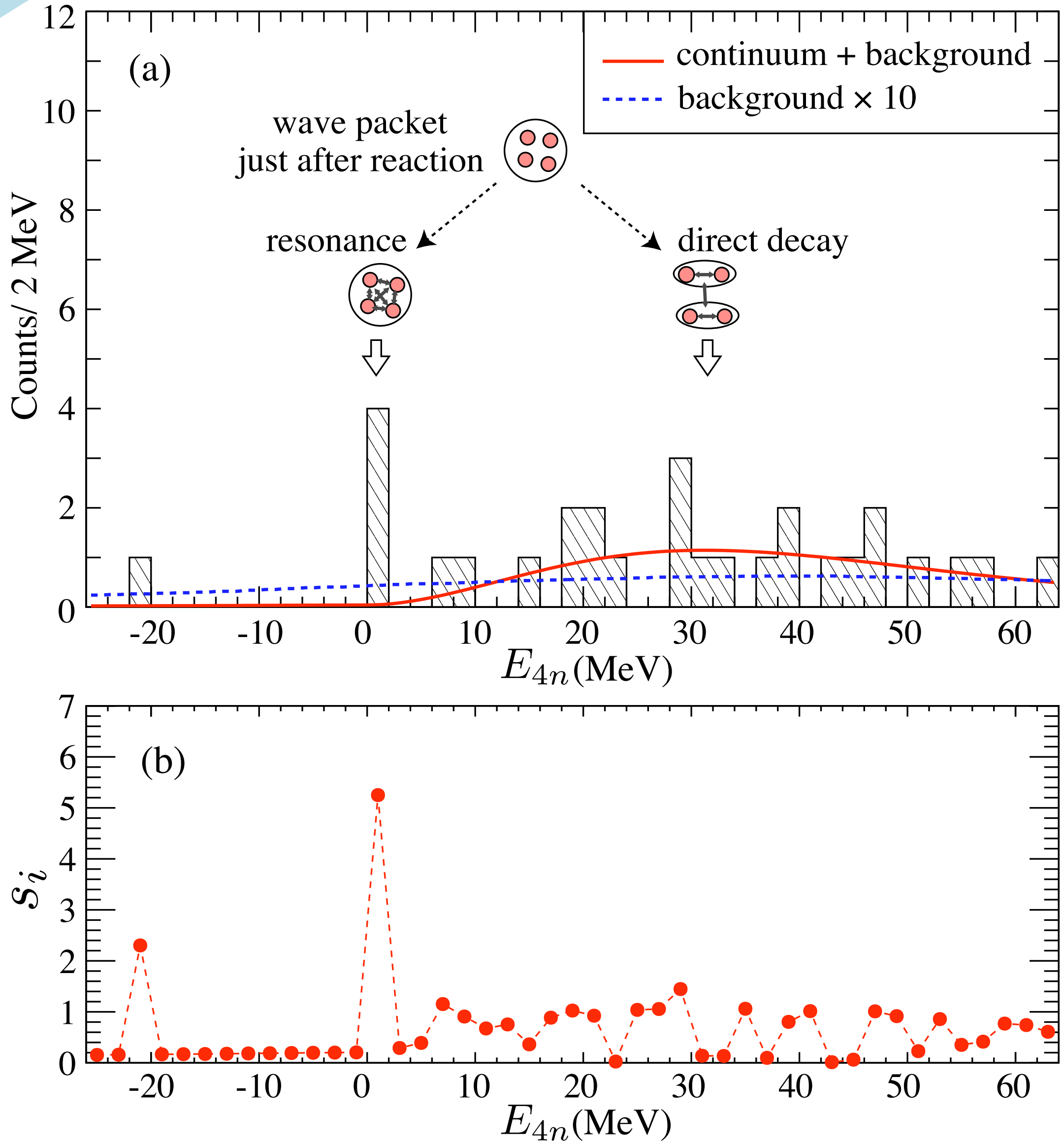
c.f.
L.V. Grigorenko, N.K. Timofeyuk, M.V. Zhukov, Eur. Phys. J. A 19, 187 (2004)





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
$0.83 \pm 0.65(\text{stat.}) \pm 1.25(\text{sys.})$ 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

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

Further experimental approarch

- ^{29}F (knockout 1p) -> ^{28}O -> ^{24}O + 4n
- ^{8}He (knockout a by proton) -> 4n
- $^{4}He(^{8}He,^{8}Be)4n$ again with 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

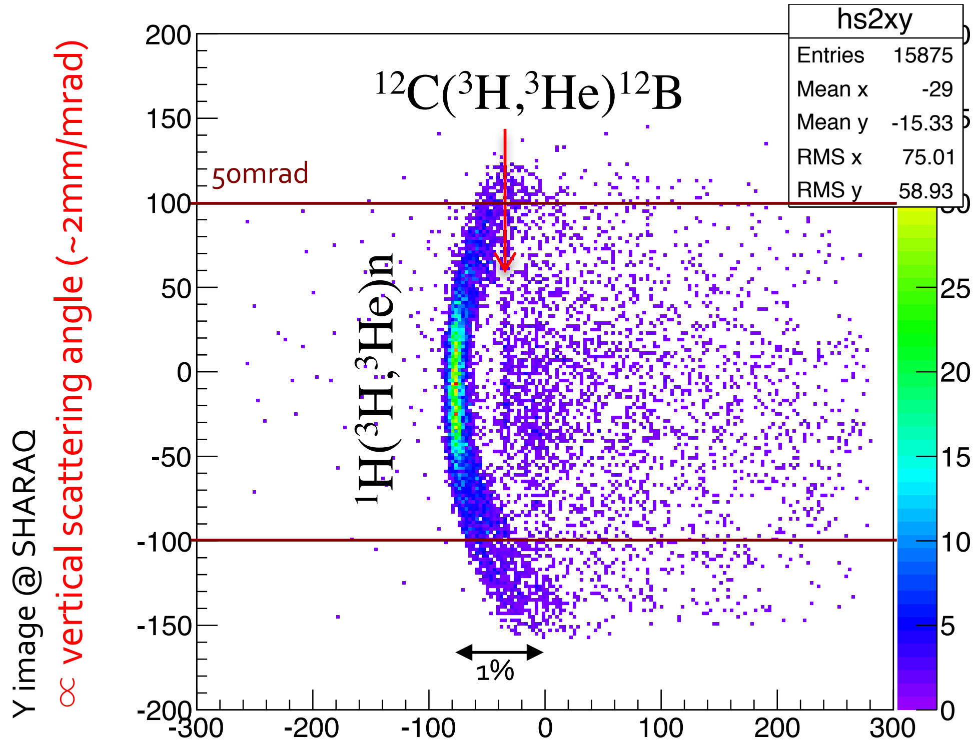
Improve efficiencies (redundancy)

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

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

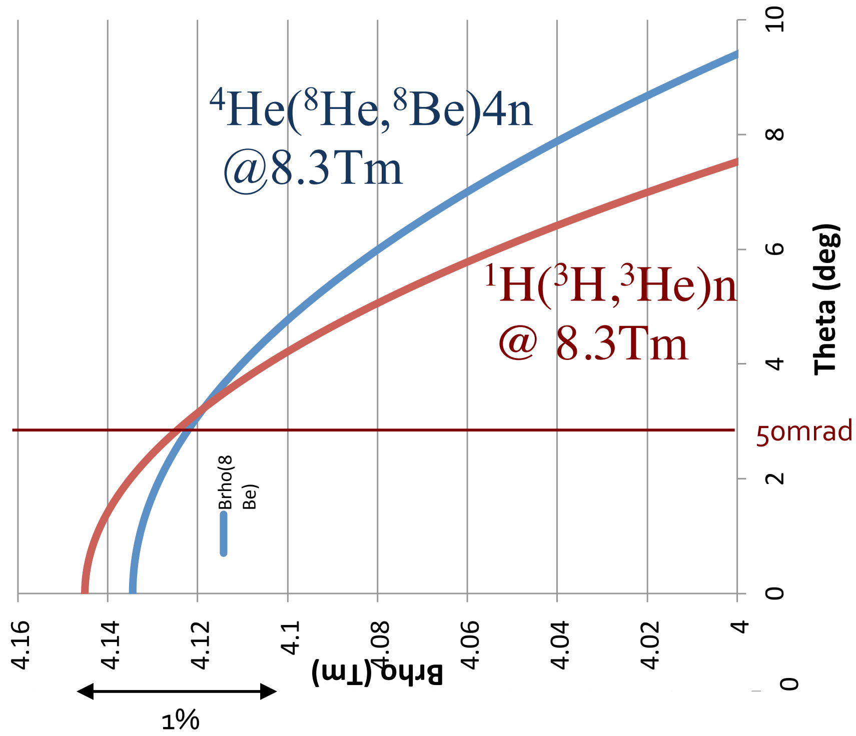
Calibration using ^{1}H(^{3}H,^{3}He)n with same rigidity ^{3}H beam (310 MeV/u) as ^{8}He

preliminary achievement : < 100 keV



On-line X image @ SHARAQ corrected by beam momentum

∝ momentum (~60mm/%)



Resolution & Statistics are consistent with expected

Summary

- ^{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 (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 T=3/2 three-body force