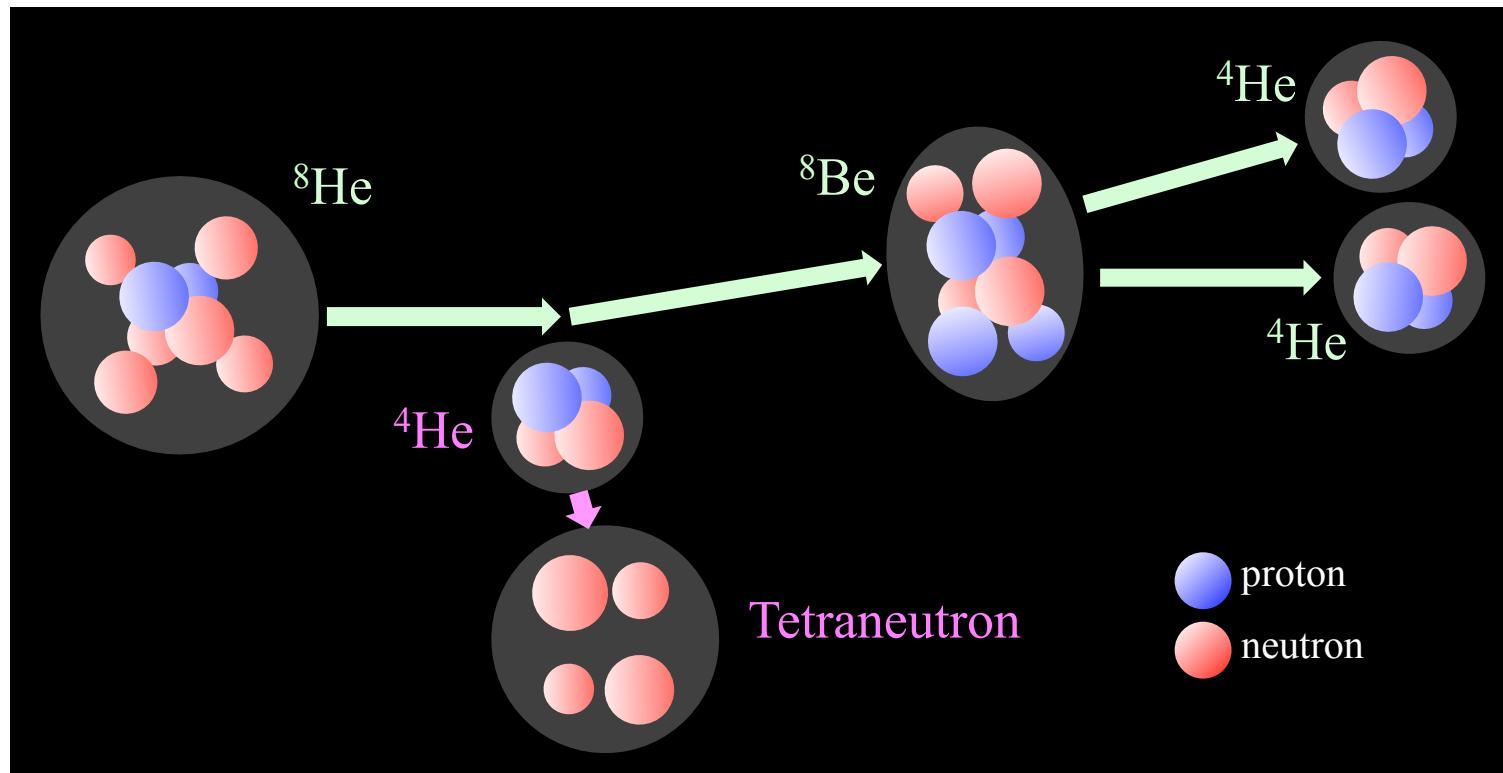


Tetra-neutron system populated by exothermic double-charge exchange reaction ${}^4\text{He}({}^8\text{He}, {}^8\text{Be})$ reaction at 190 MeV/u



No spin observable measured.
*Application using legacy knowledge of
 spin-isospin physics at low-energy*

S. Shimoura
 CNS, University of Tokyo



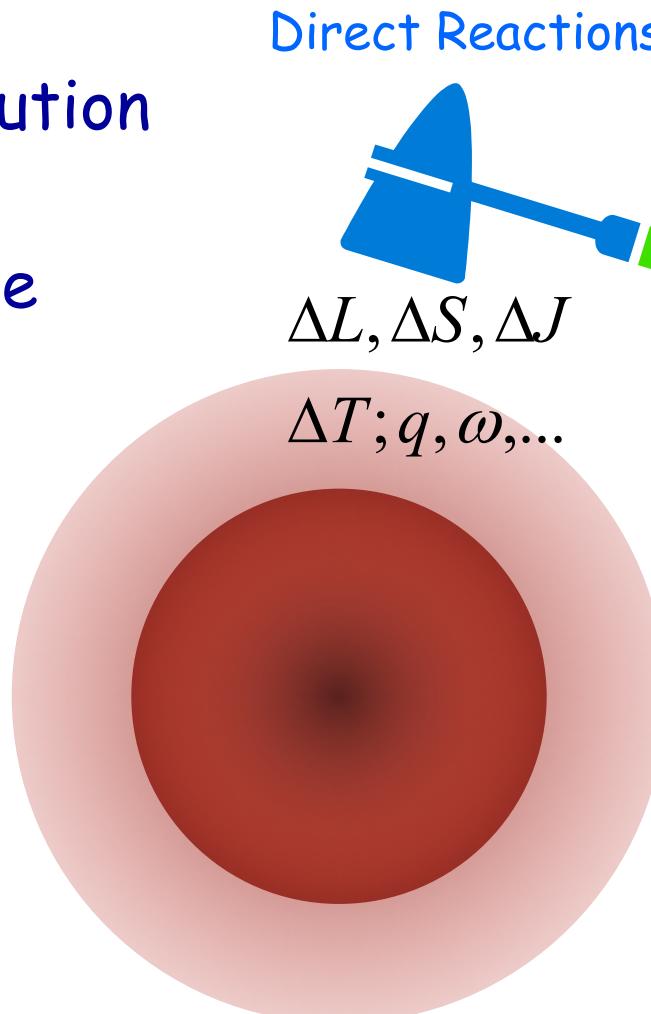
Tetra-neutron

- Multi-neutron System
 - Neutron cluster (?) in fragmentation of ^{14}Be
PRC65, 044006 (2002)
 - NN, NNN, NNNN interactions
 - NN in neutron matter
 - T=3/2 NNN force
 - 3-body force in neutron matter
 - Ab initio type calculations
 - Multi-body resonances
 - Correlations in multi-fermion scattering states
- Nuclear reaction populating 4n



Studies of Nuclei via Direct reactions

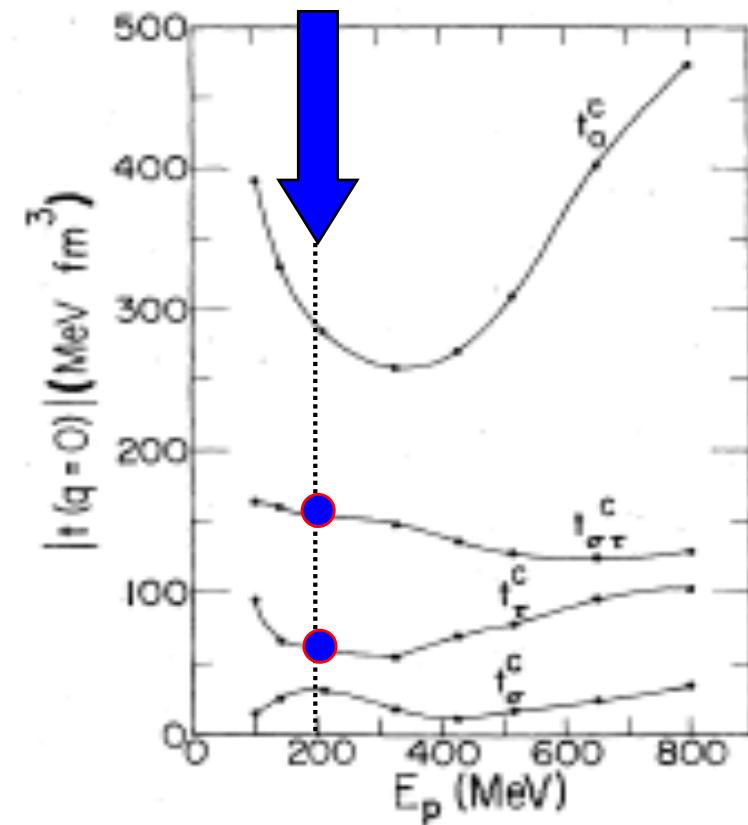
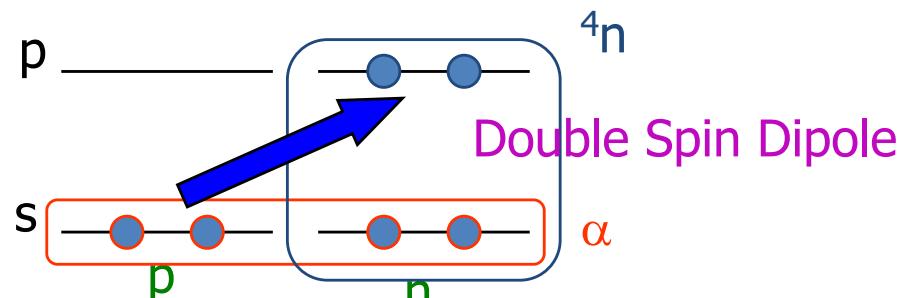
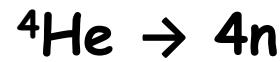
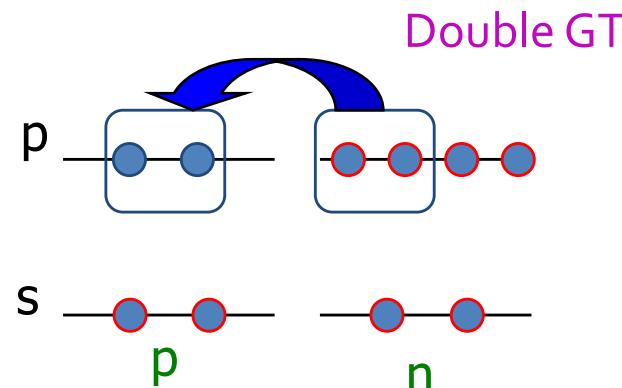
- Size/ p -distribution
 - Skin/Halo
- Shell Structure
 - New magic #
 - Isospin / Deformation
- New modes
 - IVE1
 - ISE0, ISE1
- etc.



- Size/ r -distribution
 - S_R , elastic scat.
- Shell Structure
 - Mass / S_n, S_{2n}
 - Inelastic scatt.
 - Low lying states
 - Knockout / Transfer
- New modes
 - Coulex
 - Inelastic scatt.
 - CEX
- etc.

"Hit and analyze the sound"

Reaction Mechanism



$$\left[(\vec{\tau}_p \cdot \vec{\tau}_t) (\vec{\sigma}_p \cdot \vec{\sigma}_t) r_t Y_1(\hat{r}_t) \right]^2$$



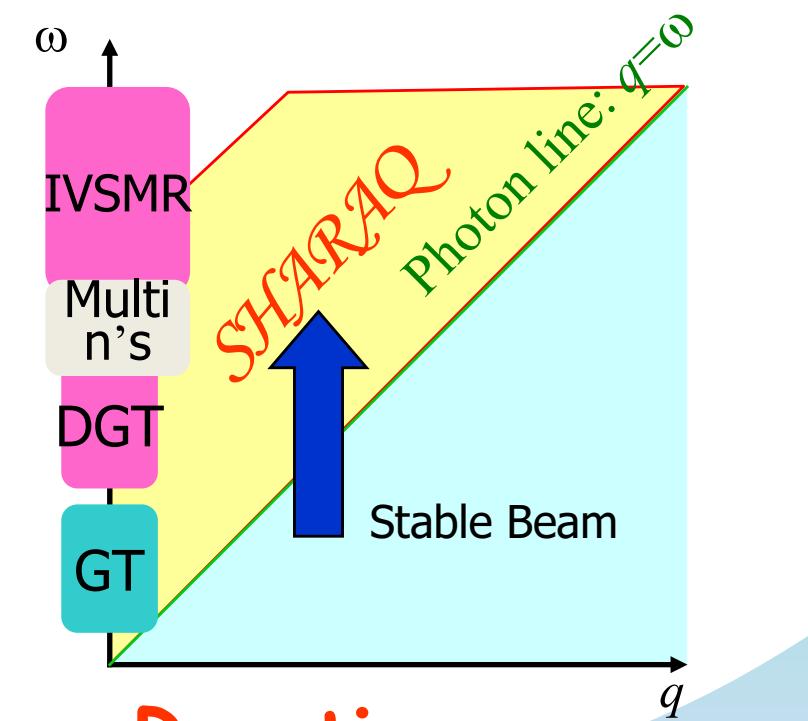
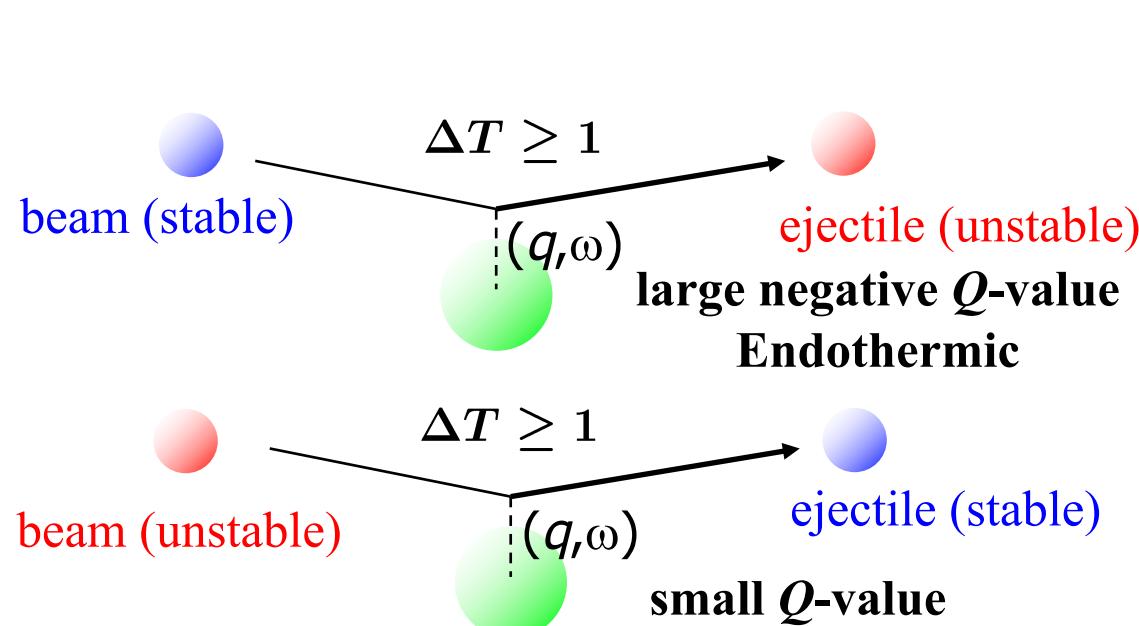
SHARAQ

Spectroscopy with High-resolution Analyzer of RadioActive Quantum beams



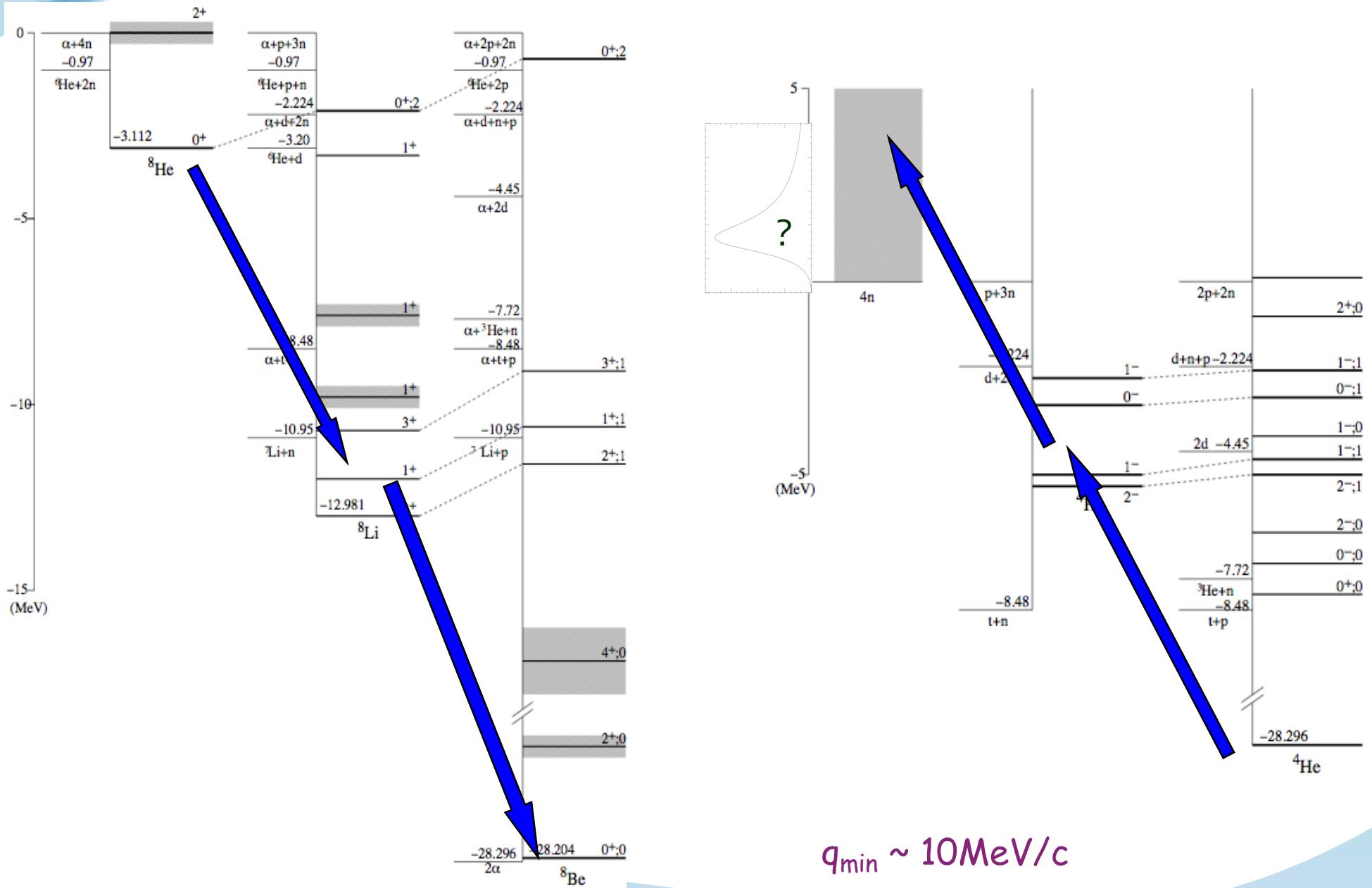
RI Beam ($E = 150 - 400$ MeV/A) as a new **PROBE**
to nuclear systems

- Large Isospin iso-tensor excitations
- Large internal energy (q,ω) inaccessible by stable beams



Exothermic Charge Exchange Reactions

Level diagrams





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

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

- Only upper limit of cross section was decided.

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

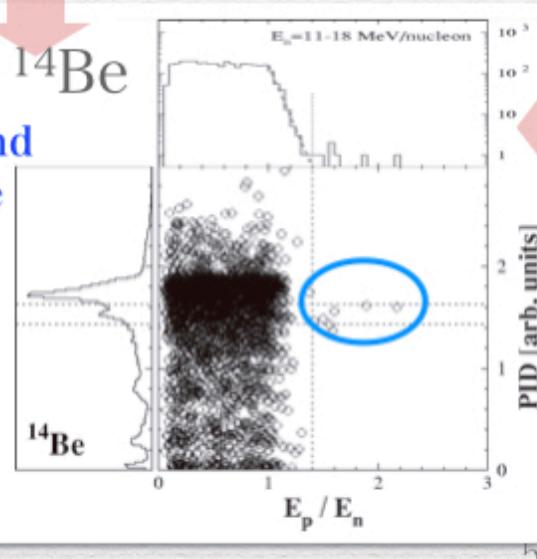
Bound state: No clear evidence.

2000s

❖ Breakup of ${}^{14}\text{Be}$

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

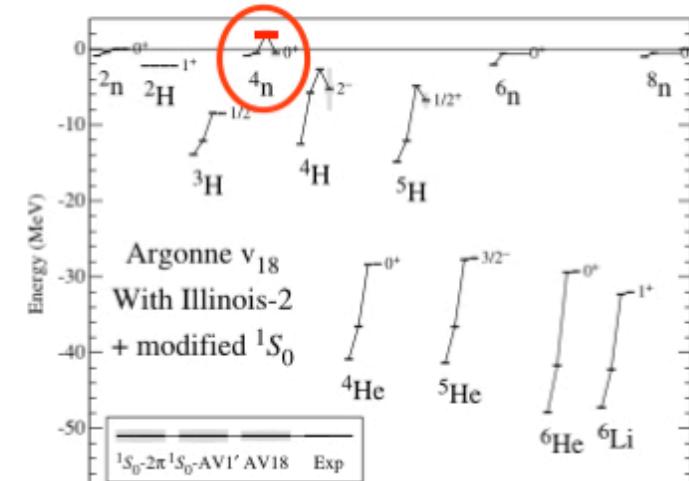
F. M. Marques, et al,
Phys. Rev. C 65,
044006 (2002)



2000s

❖ Theoretical work

- ab-initio calculation
NN, NNN interaction

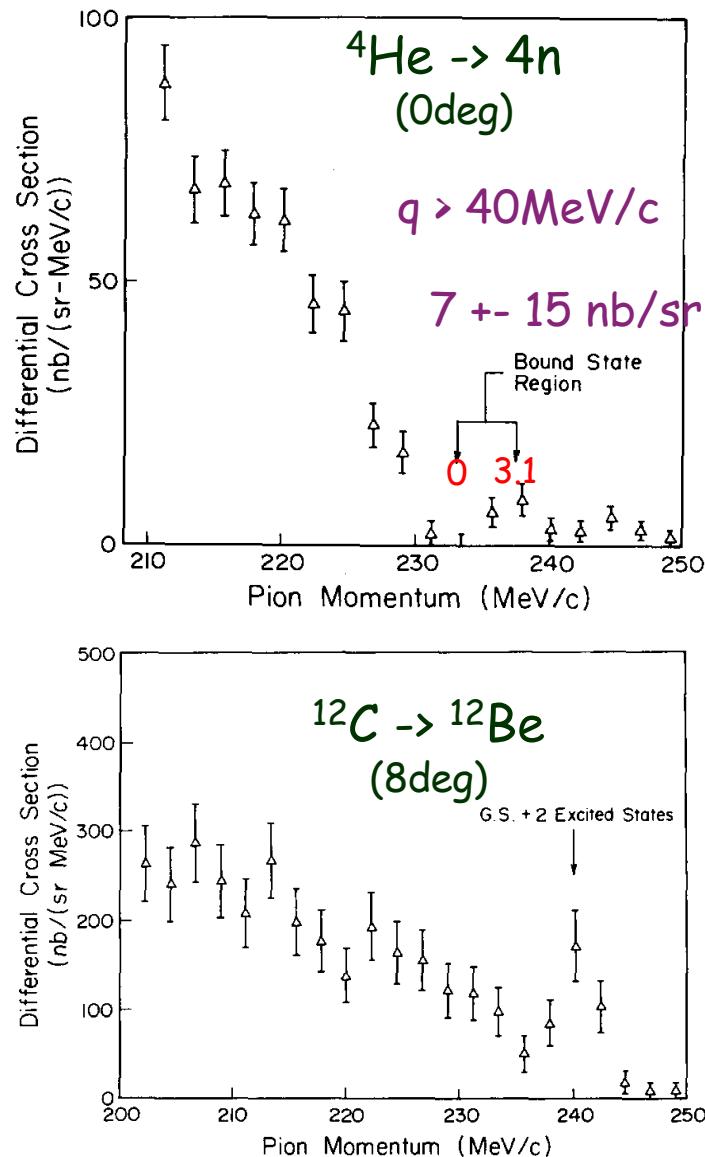


S. C. Piper, Phys. Rev. Lett. 90, 252501 (2003)

- **Bound ${}^4\text{n}$ cannot exist**
- **Possible resonance state ~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 ${}^{12}\text{Be}$ 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 ${}^4\text{He}$. A $\Delta P/P = 1\%$ beam of $10^6 \pi^-$ per second was provided by the P³ line of the Los Alamos Meson Physics Facility, and a cell of 910 mg/cm^2 liquid ${}^4\text{He}$ with windows of 18 mg/cm^2 Kapton served as the target [15]. An

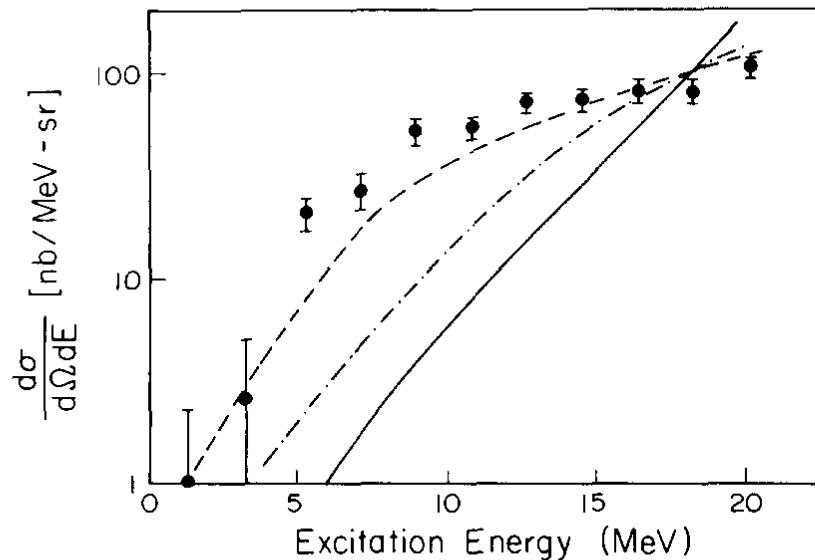
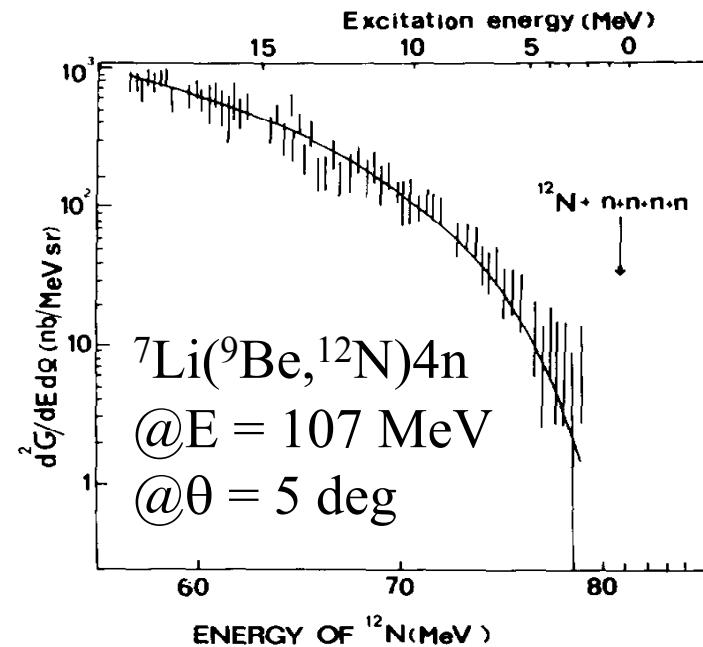
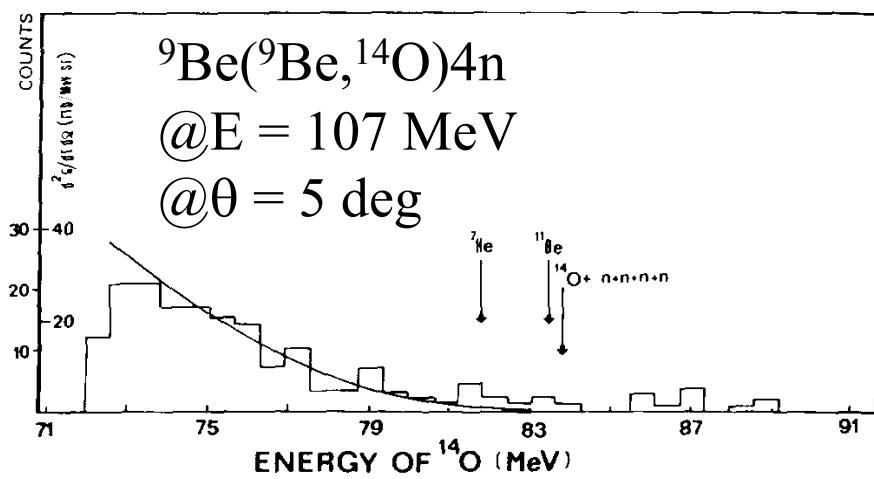
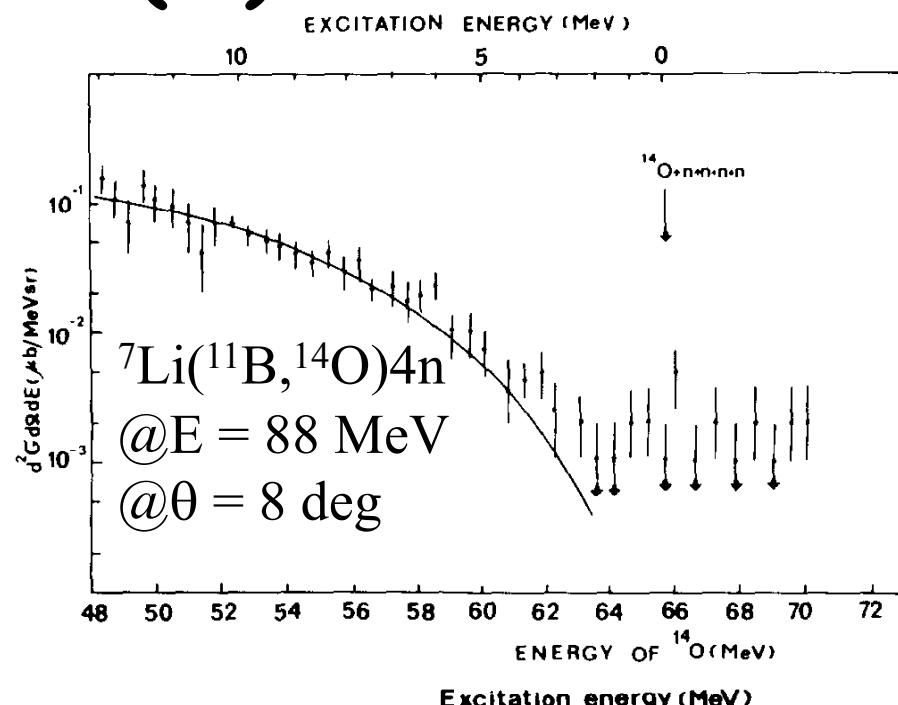
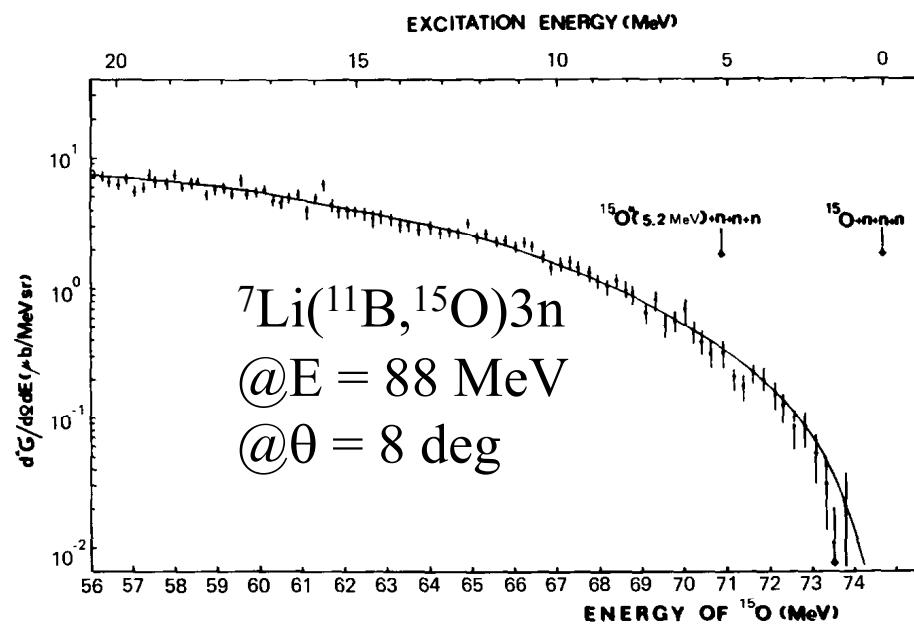


Fig. 3. The experimental results are plotted against the excitation of the final four-neutron state. The solid curve corresponds to the pure four-neutron phase space, while the dot-dashed and dashed curves are the four-neutron phase space curves with singlet state interactions in, respectively, one and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

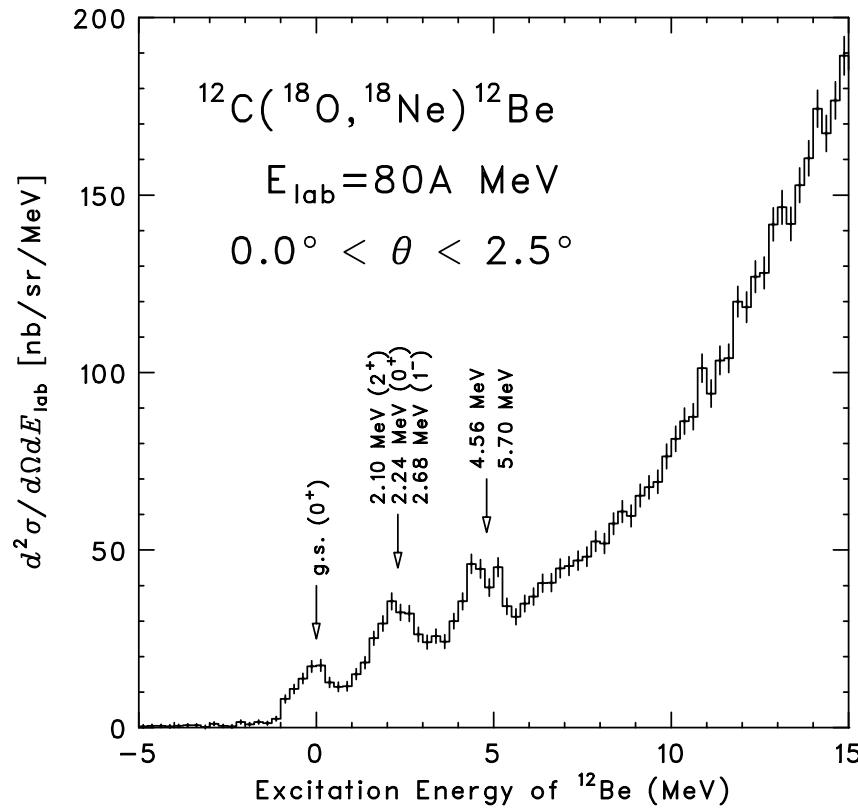
Historical review (2)

Nucl. Phys. A477 (1988) 131





Double charge exchange (DCX) reaction of HI

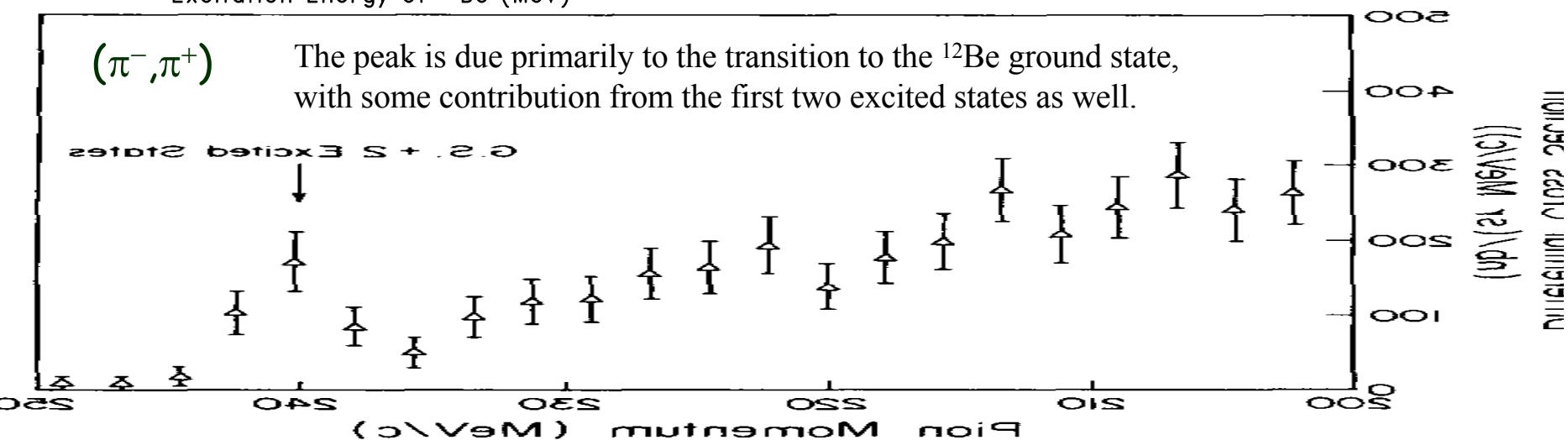


Stable ^{18}O beam (80A MeV) (Takaki et al.)

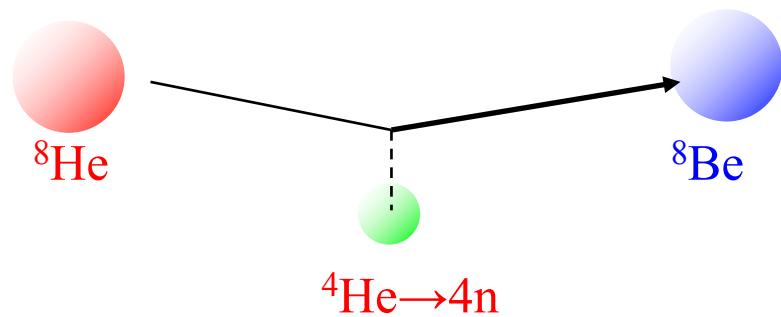
$\sim 70\text{nb/sr}$ (Gnd)

$\sim 200\text{nb/sr}$ ($\sim 2\text{MeV}$)

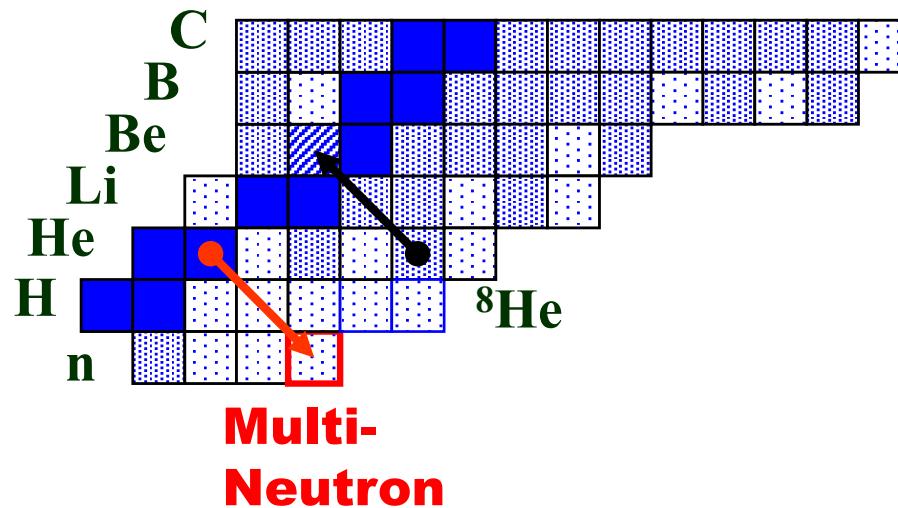
HI DCX reaction can be used for spectroscopy for exotic nuclei
(q is not so small $> 80\text{ MeV/c}$)



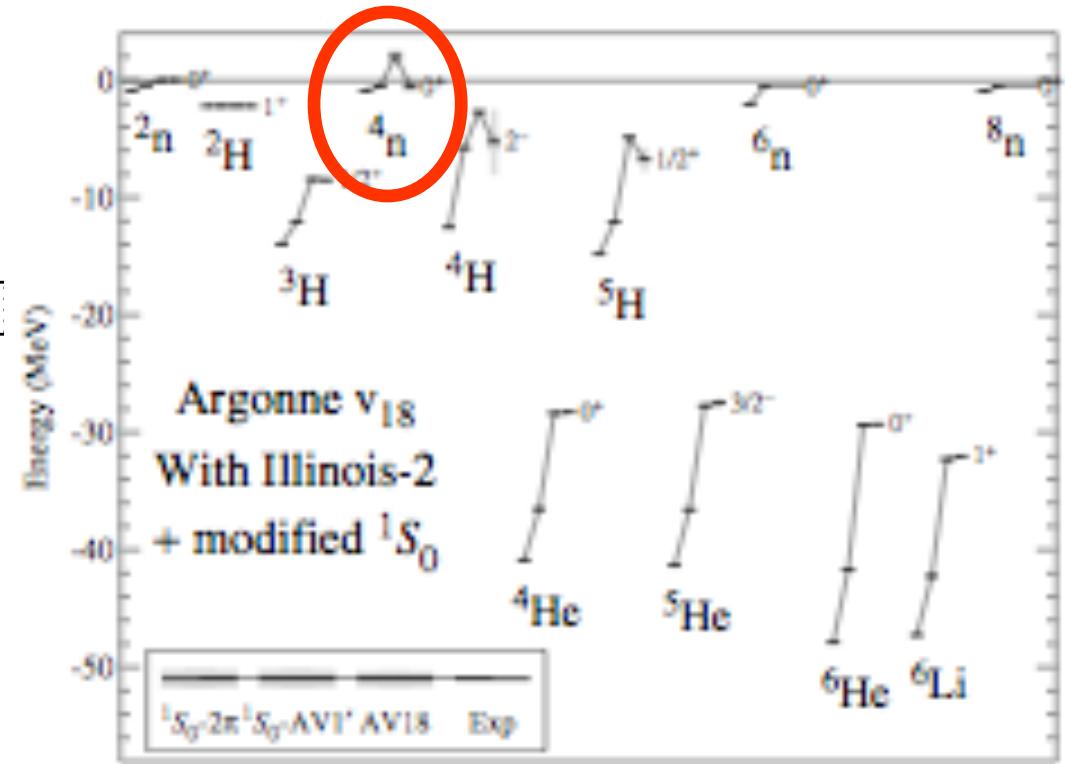
Tetra-neutron system produced by exothermic double-charge exchange reaction



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



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



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

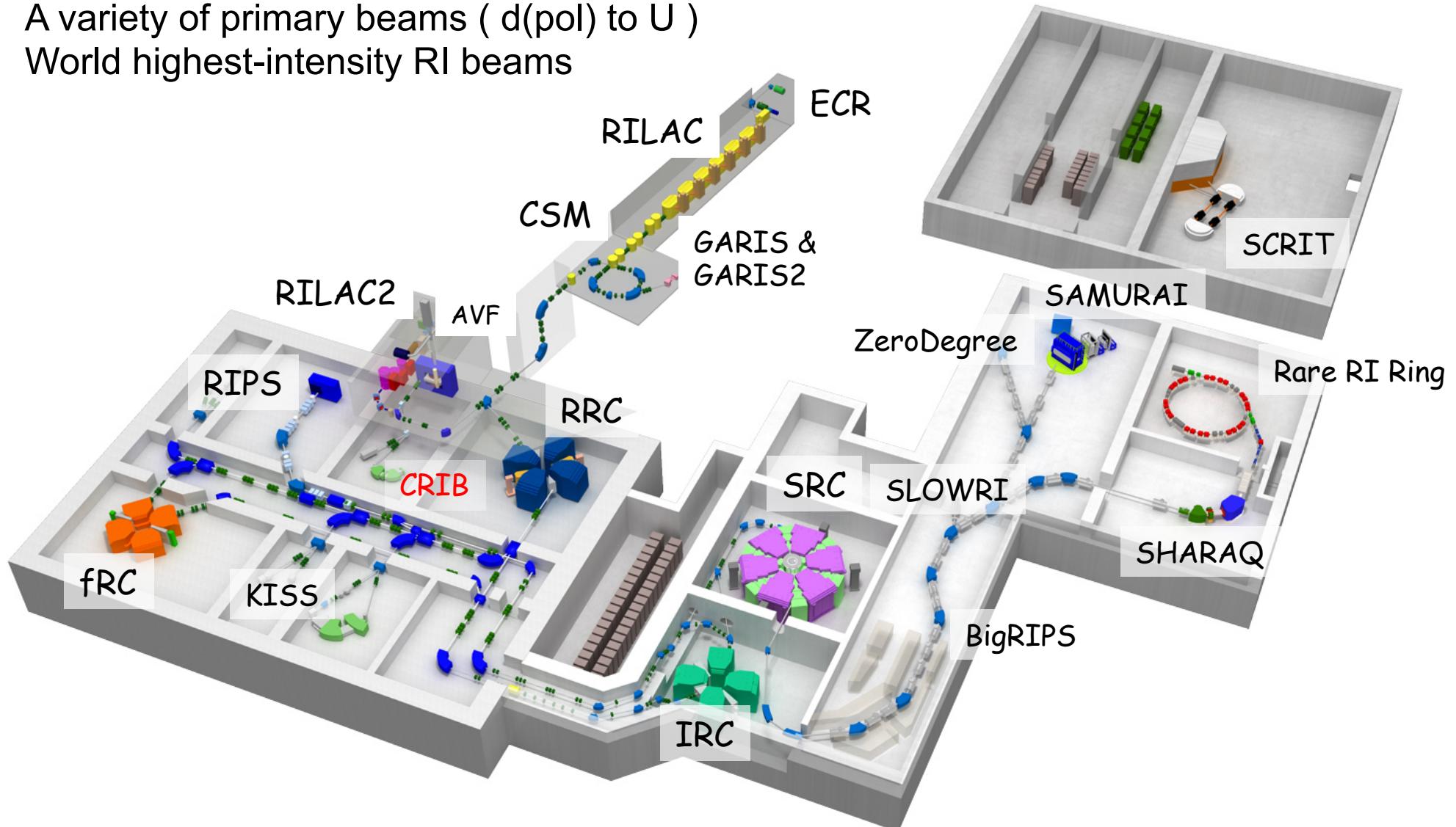
RI Beam Factory at RIKEN

3 injectors + cascade of 4 cyclotrons

⇒ several to 345 MeV/nucleon

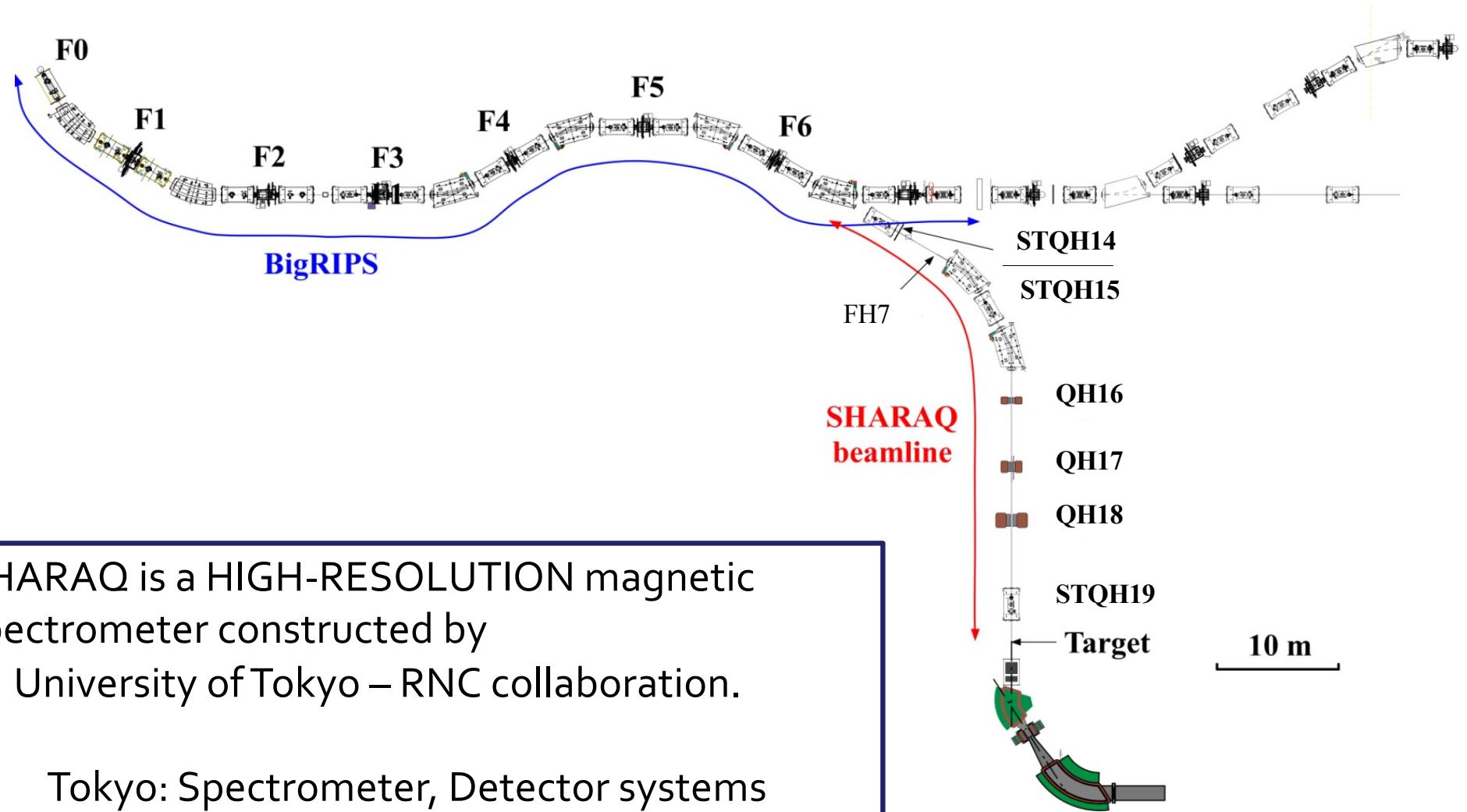
A variety of primary beams (d(pol) to U)

World highest-intensity RI beams



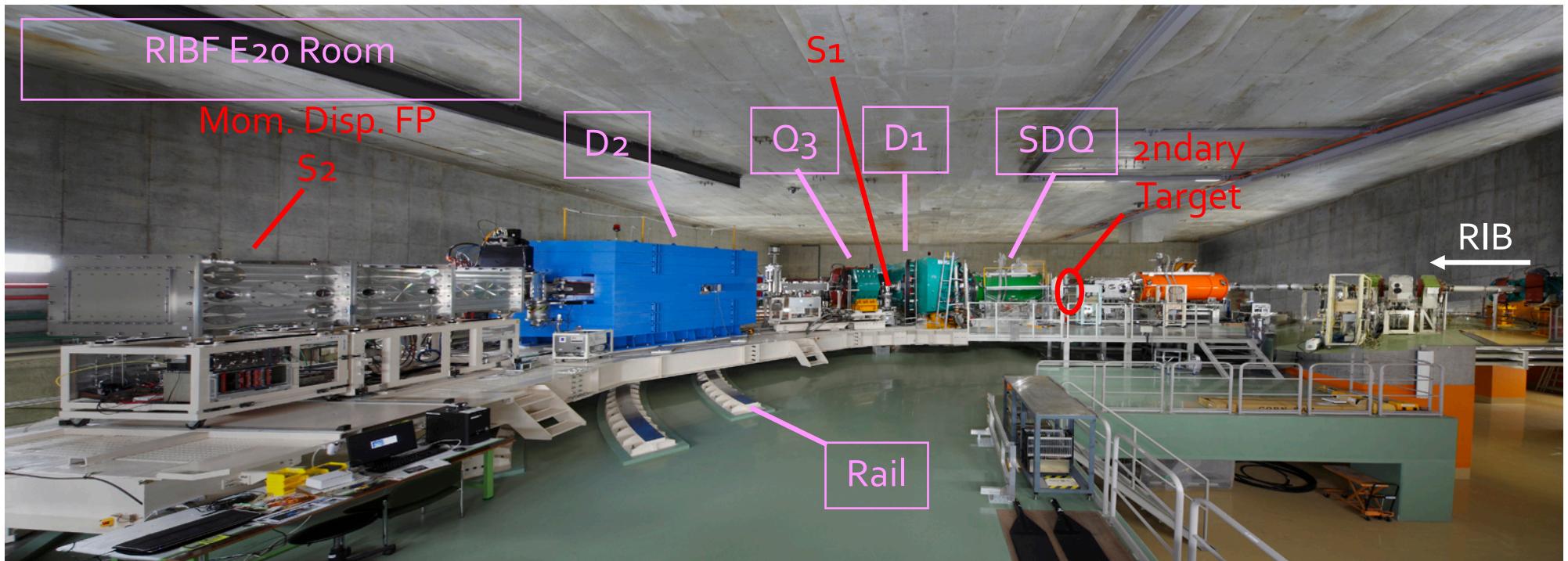


SHARAQ @ RI beam factory



SHARAQ spectrometer

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



Maximum rigidity

6.8 Tm

Momentum resolution

$dp/p = 1/14700$

Angular resolution

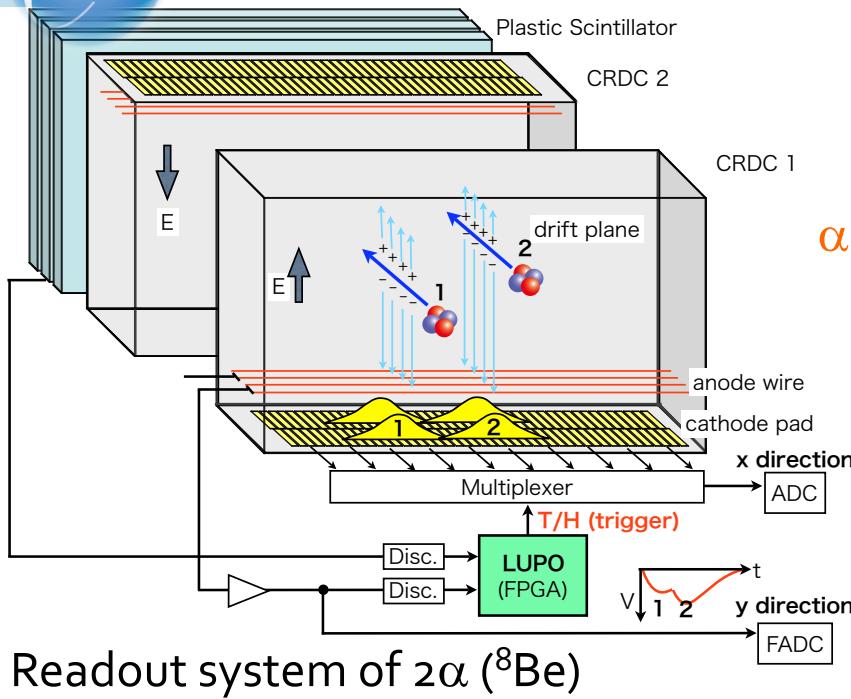
~ 1 mrad

Momentum acceptance

$\pm 1\%$

Angular acceptance

~ 5 msr





Analysis

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

Background process:

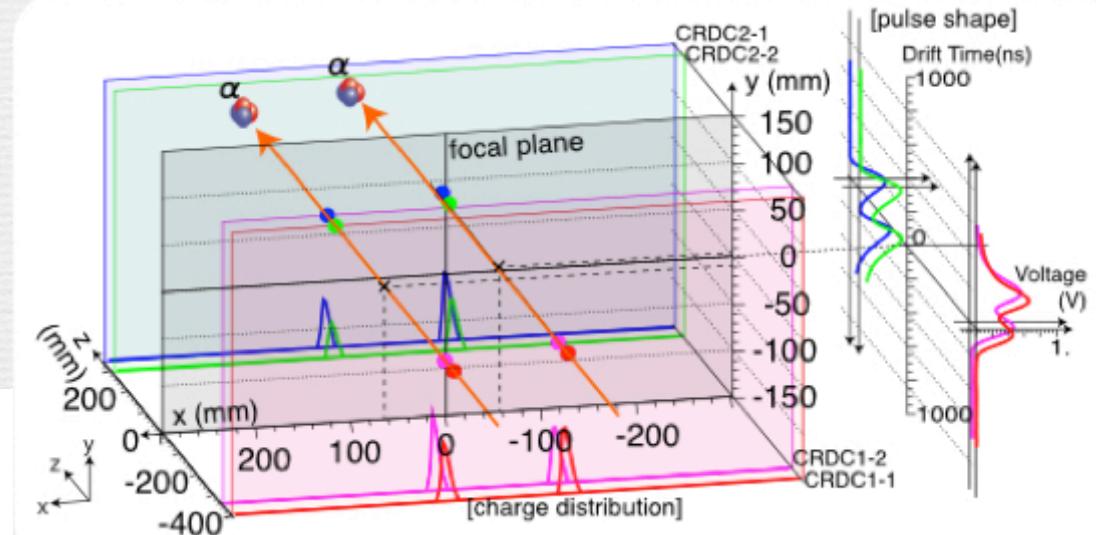
Breakup of two ${}^8\text{He}$ in the same beam bunch to two alpha particle

Identified by multi-hit in F6-MWDC

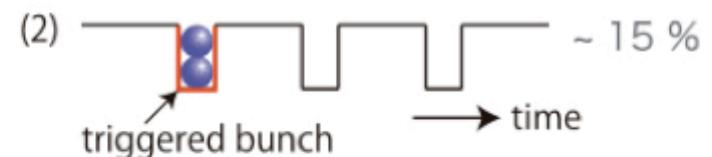
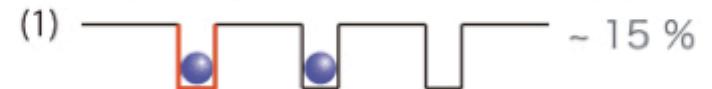
- Background Estimation

- Shape in spectrum: random 2 α
- 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

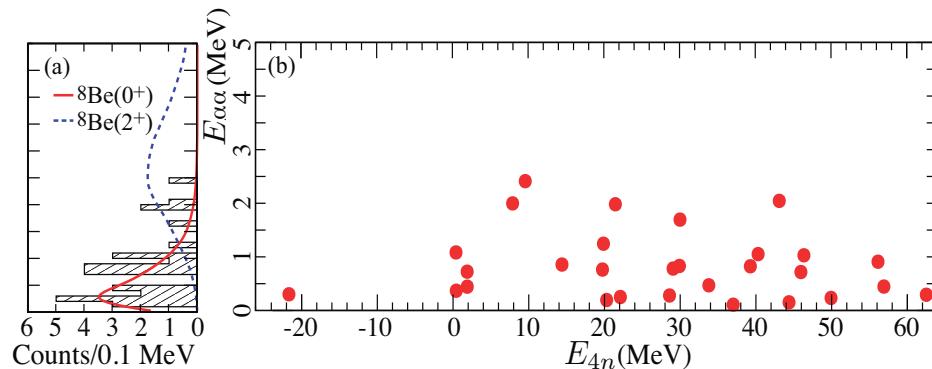
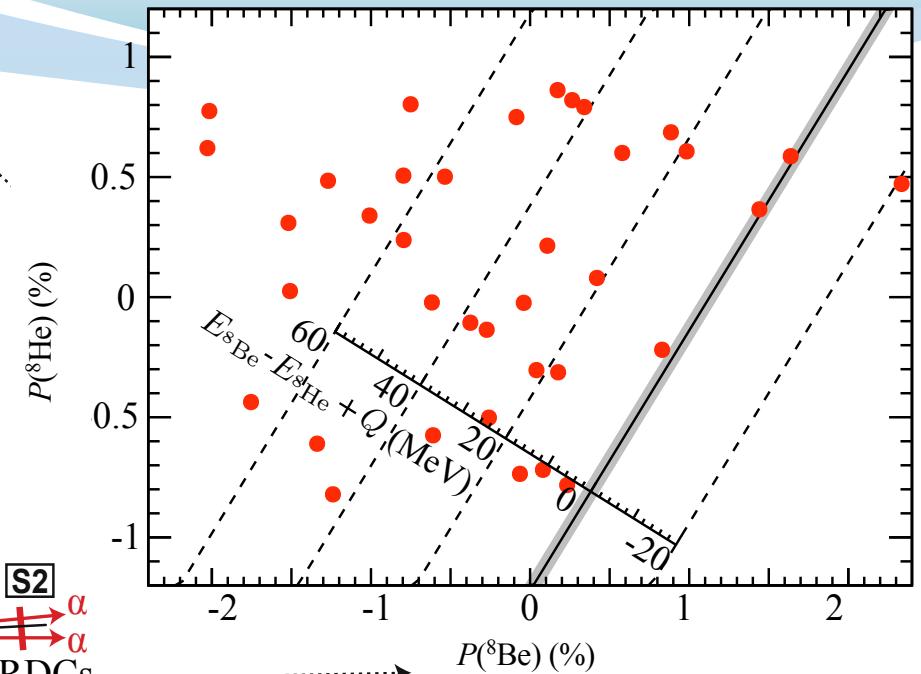
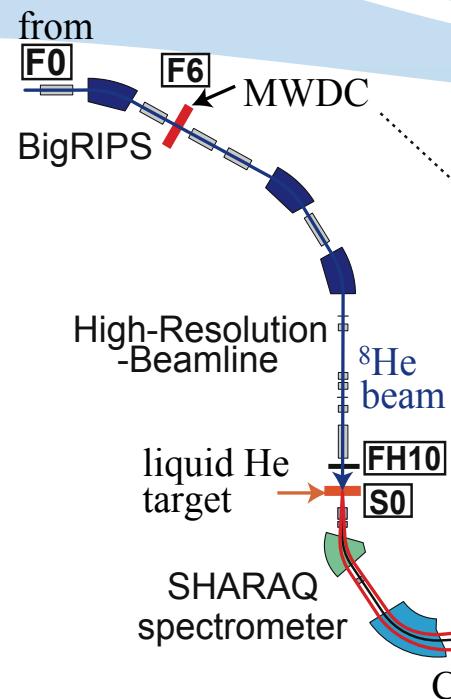


2 MHz beam from 13.7MHz cyclotron

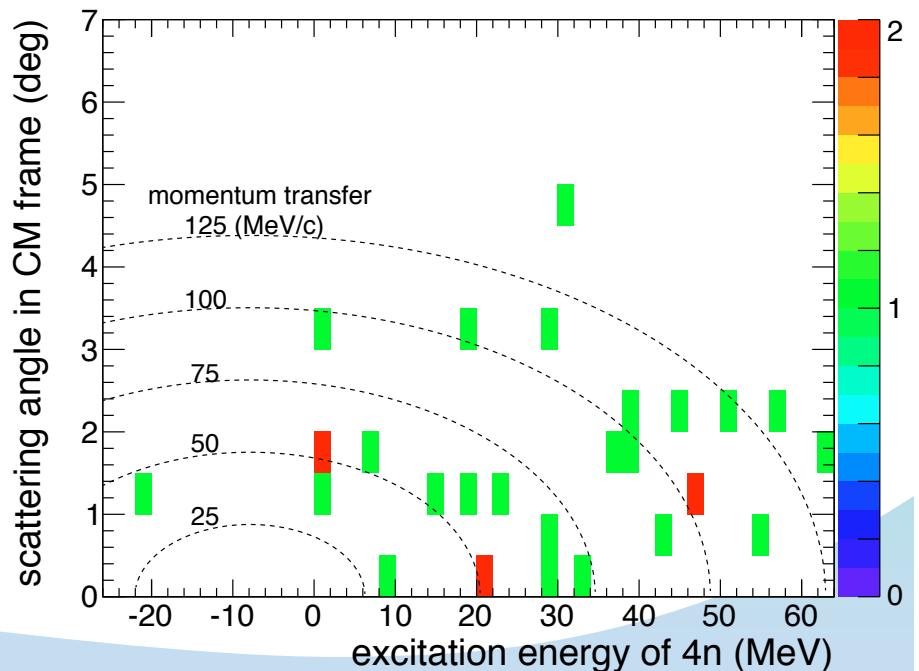


time

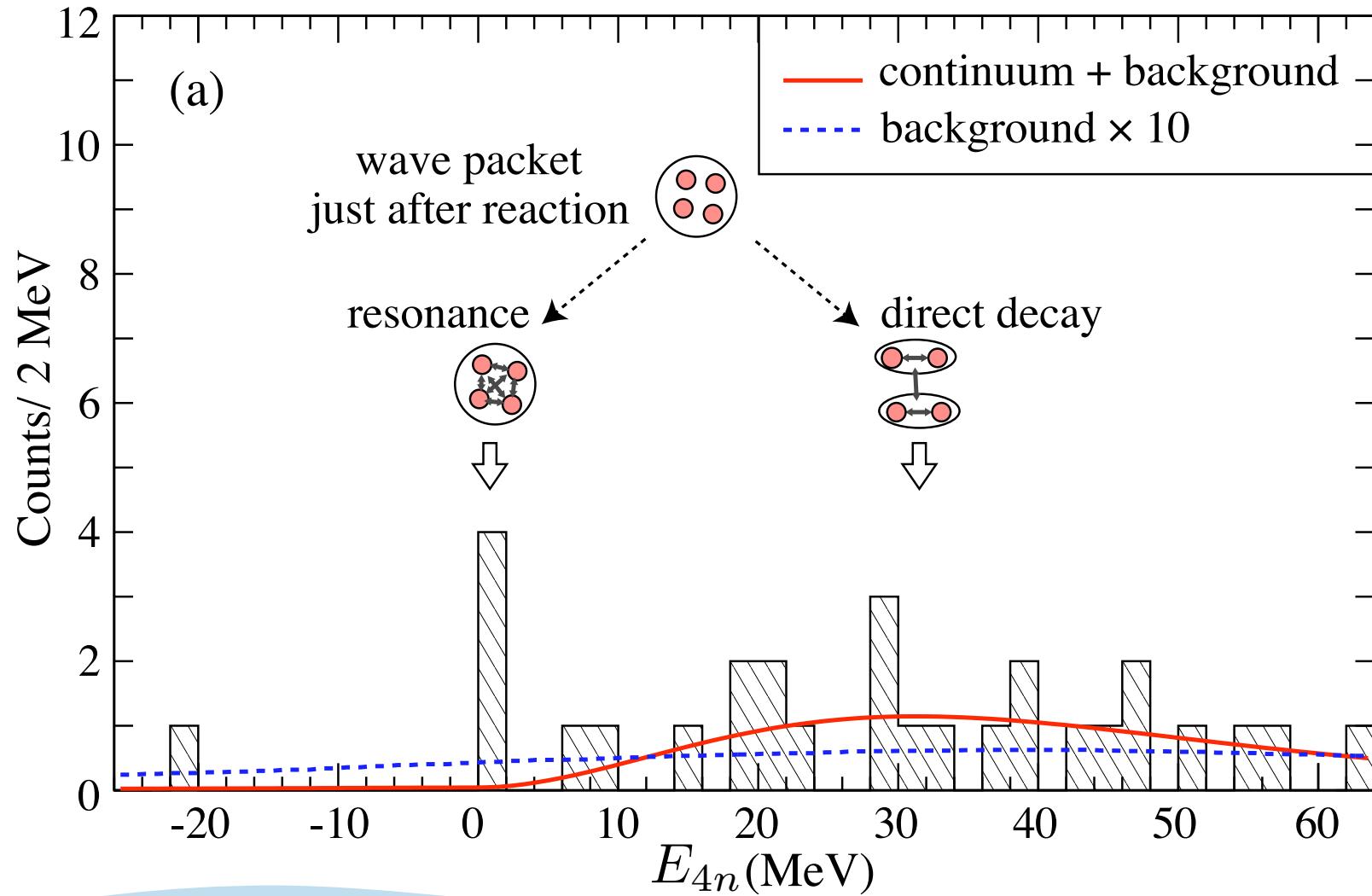
Experimental Results



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



Experimental Results





Transition Probabilities

$O(lsj\tau; \xi)$

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

if distortion is insensitive to ω

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

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

sum of
one-body operator

e.g.

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

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

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

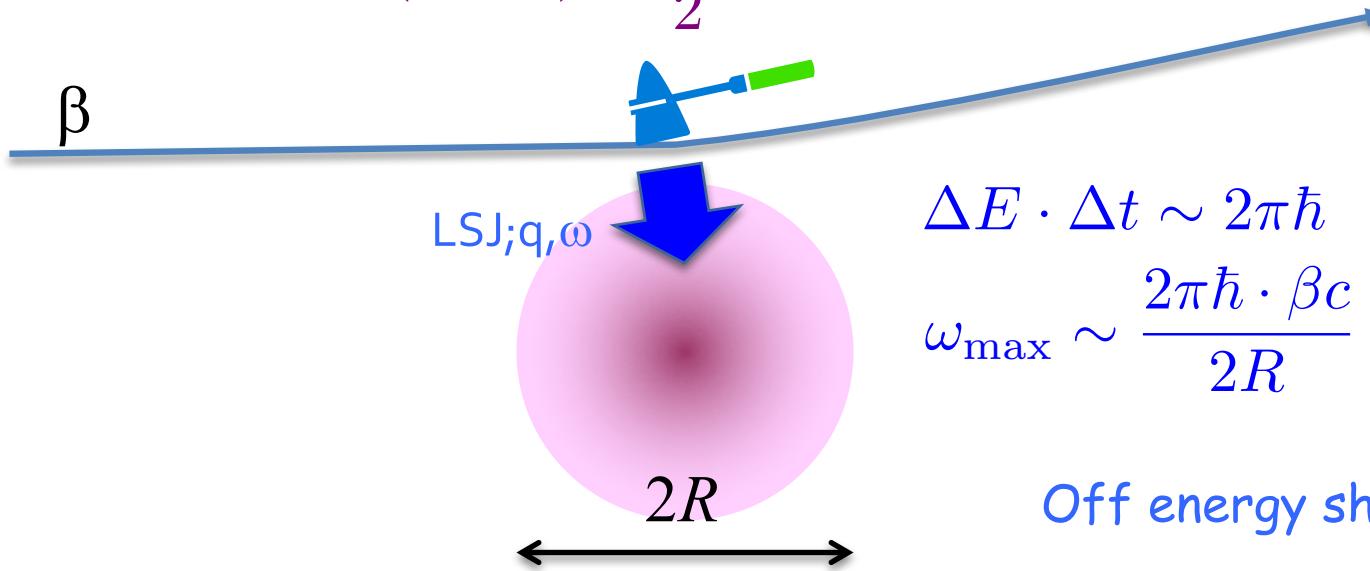
$|M_{if}(E_f)|^2$: Energy Spectrum

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

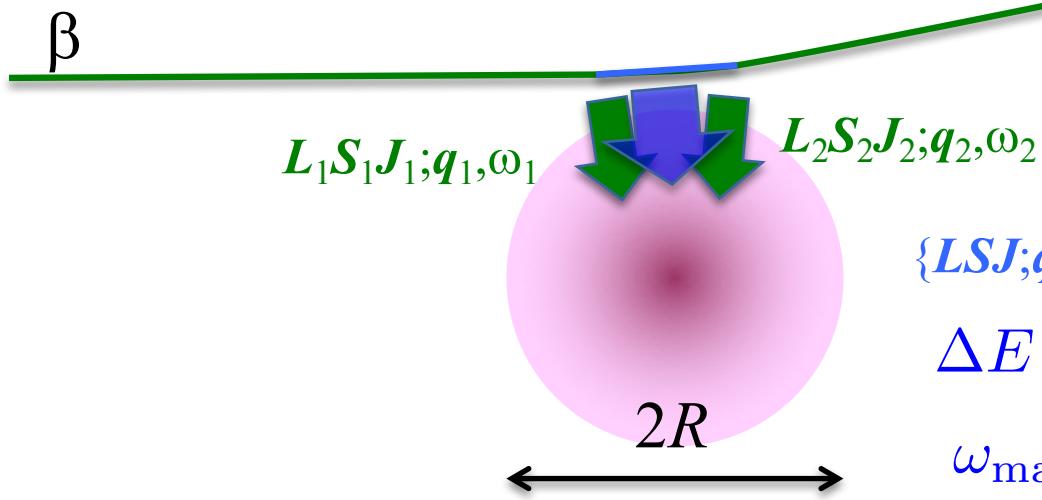
$$E/A \sim 200 \text{ MeV} : \beta \sim 0.6 : \omega_{\max} \sim 60 \text{ MeV}$$

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

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

Two step?

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



$$\{LSJ; q, \omega\} = \{L_1 S_1 J_1; q_1, \omega_1\} \oplus \{L_2 S_2 J_2; q_2, \omega_2\}$$

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

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

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

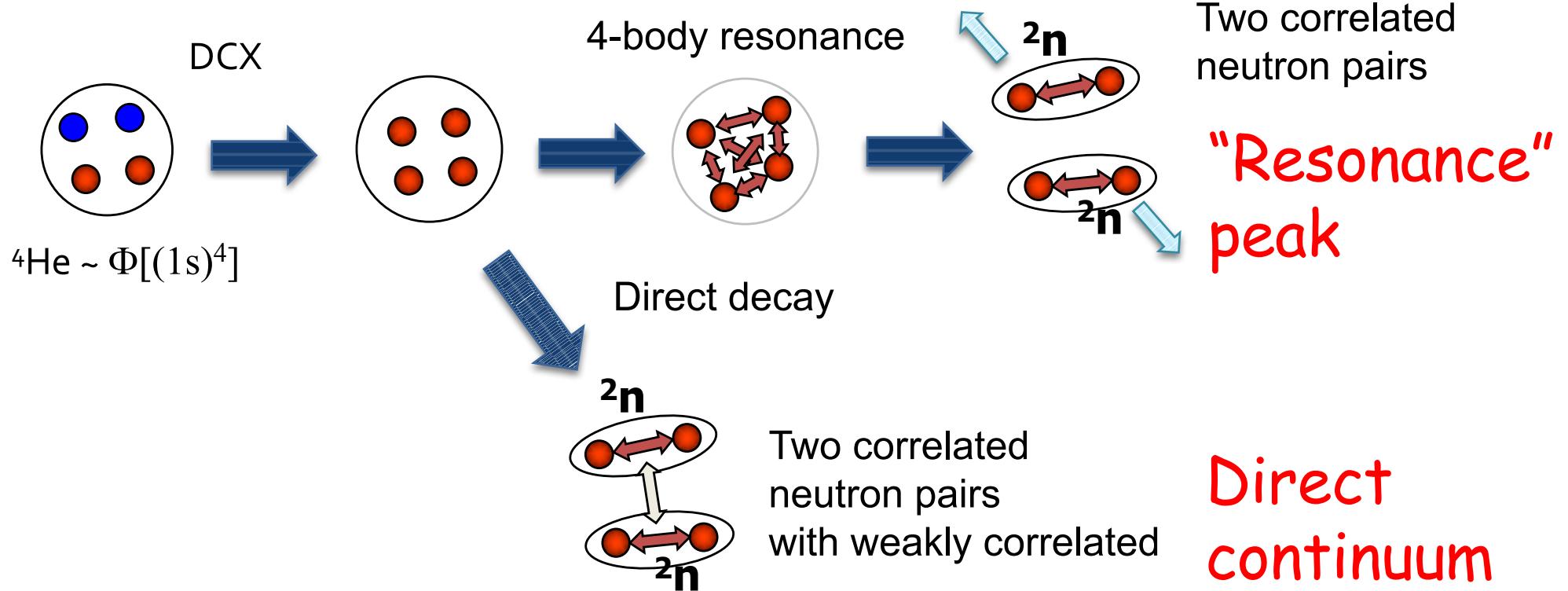
“Intermediate state”: Not energy eigen state

~ wave packet consists of “eigen states” over 200 β MeV

~ closure approximation ~ almost one-step

Picture of ^4He DCX reaction @ 200 A MeV

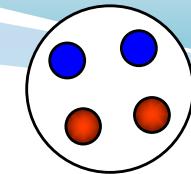
$4n$ wave packet just after DCX
 (double spin dipole)
 $\sim \mathcal{A}[\mathbf{r}_1 \cdot \mathbf{r}_2 \Phi[(0s)^4]]$





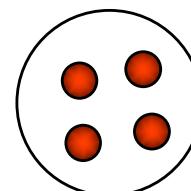
Direct Part

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



DCX

$q \ll 200 \text{ MeV}/c$



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

$$\begin{aligned} \mathcal{A}\Phi_0(\mathbf{r}_{12}, \mathbf{r}_{34}, \mathbf{r}_\alpha) \sim & \left[\left(\frac{r_{12}^2}{a^2} - \frac{3}{2} \right) - \left(\frac{r_\alpha^2}{a^2} - \frac{3}{4} \right) \right] \exp \left[-\frac{r_\alpha^2}{a^2} - \frac{r_{12}^2}{2a^2} - \frac{r_{34}^2}{2a^2} \right] \chi(1, 2) \chi(3, 4) \\ & \left[\left(\frac{r_\alpha^2}{(a/\sqrt{2})^2} - \frac{3}{2} \right) - \frac{2\vec{r}_{12} \cdot \vec{r}_{34}}{a^2} \right] \exp \left[-\frac{r_\alpha^2}{a^2} - \frac{r_{12}^2}{2a^2} - \frac{r_{34}^2}{2a^2} \right] \chi(1, 3) \chi(4, 2) \\ & \left[\left(\frac{r_\alpha^2}{(a/\sqrt{2})^2} - \frac{3}{2} \right) + \frac{2\vec{r}_{12} \cdot \vec{r}_{34}}{a^2} \right] \exp \left[-\frac{r_\alpha^2}{a^2} - \frac{r_{12}^2}{2a^2} - \frac{r_{34}^2}{2a^2} \right] \chi(1, 4) \chi(2, 3) \end{aligned}$$

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



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

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

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

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



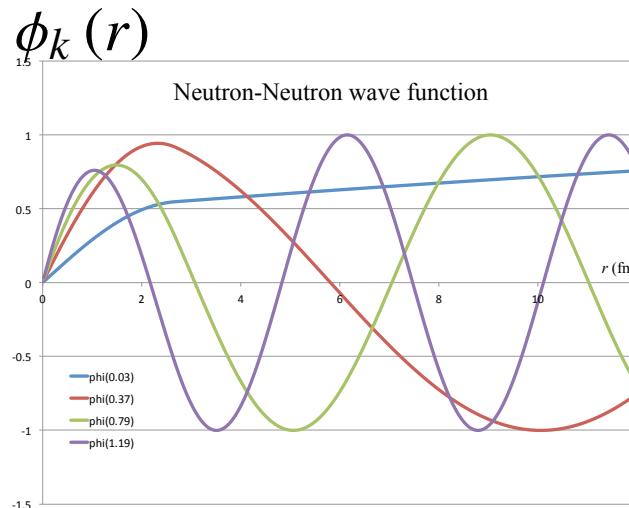
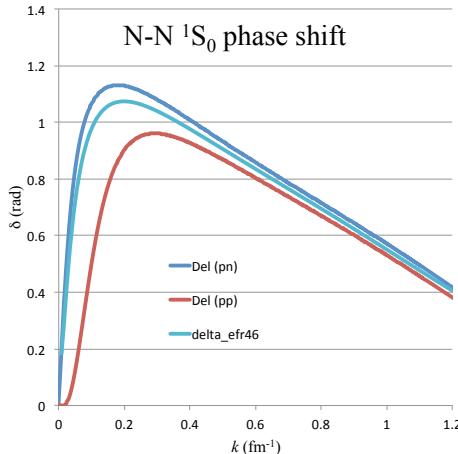
NN FSI

c.f.

Continuum spectrum with n-n FSI

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

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



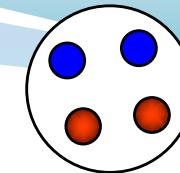
Density of State

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

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

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

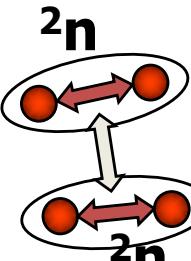
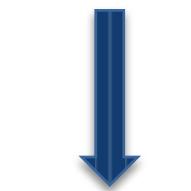
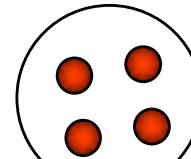
Expand $\mathcal{A}\Phi_0$ with correlated n-n scattering wave $\phi_k(r)$
 $A(k)$'s are used instead of Fourier component



DCX

$$q > 15 \text{ MeV}/c$$

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



Two correlated
neutron pairs
with weakly correlated

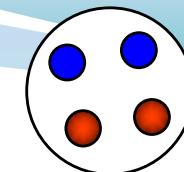
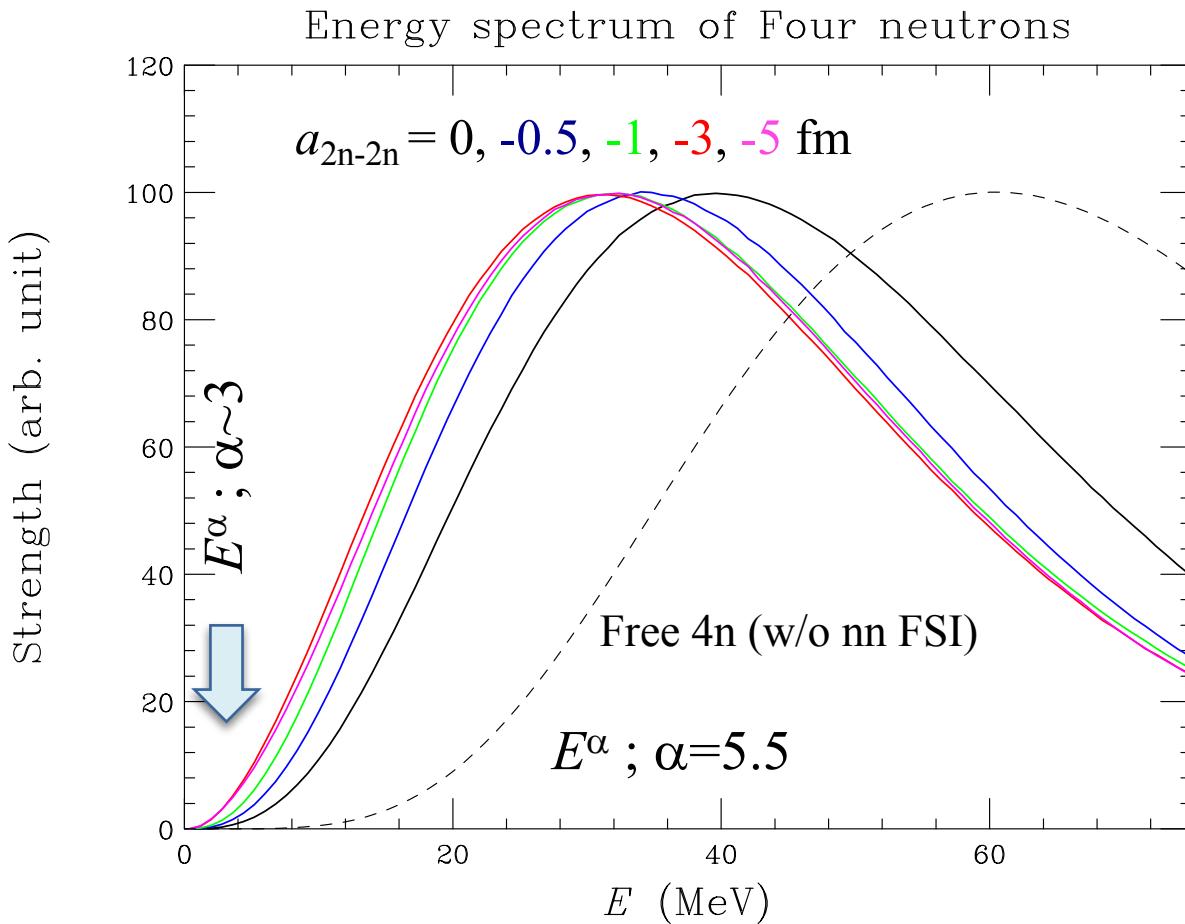


Direct Part

c.f.

Continuum spectrum with n-n FSI

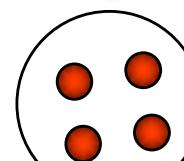
L.V. Grigorenko, N.K. Timofeyuk, M.V. Zhukov, Eur. Phys. J. A 19, 187 (2004)



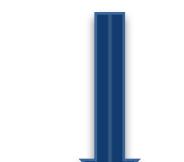
$${}^4\text{He} \sim \Phi[(0s)^4]$$

DCX

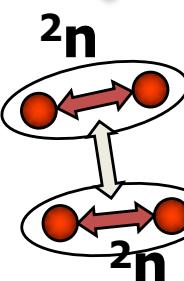
$$q \ll 200 \text{ MeV}/c$$



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

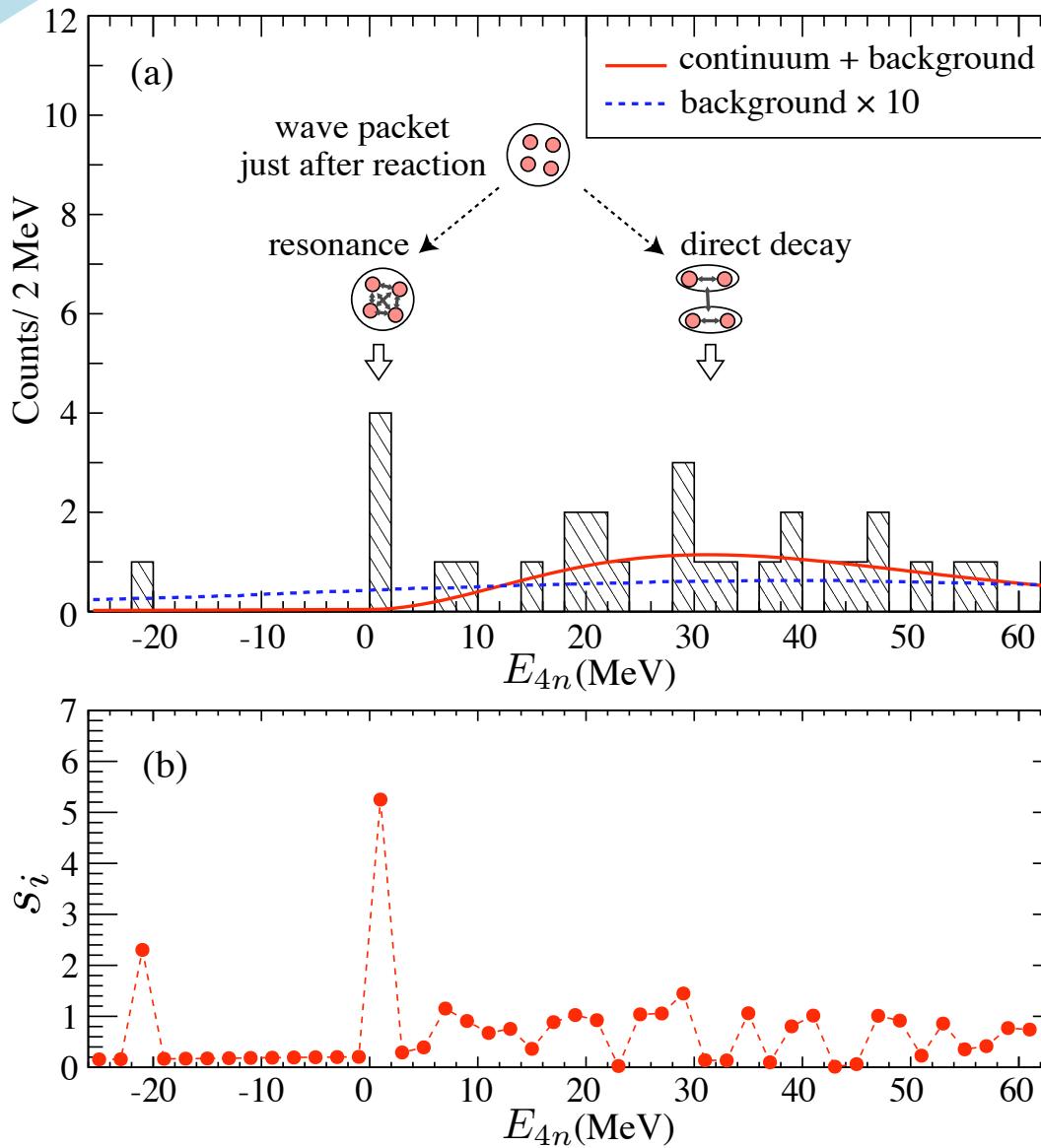


Two correlated
neutron pairs
with weakly correlated



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

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). [4.9 σ significance]

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

- likelihood ratio test

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

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



Experiment for confirmation (2016.6.16-25)

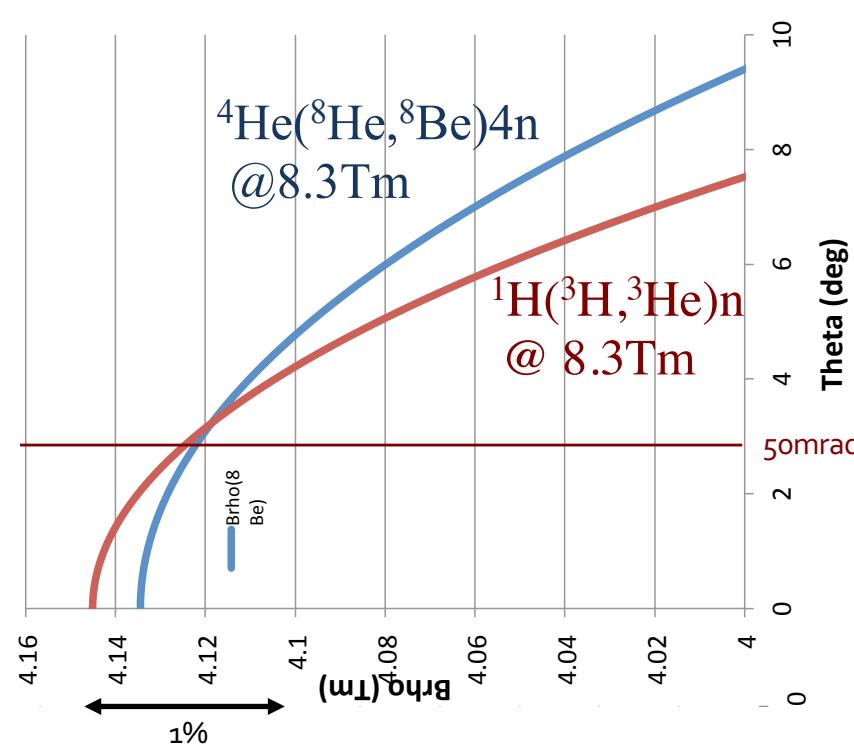
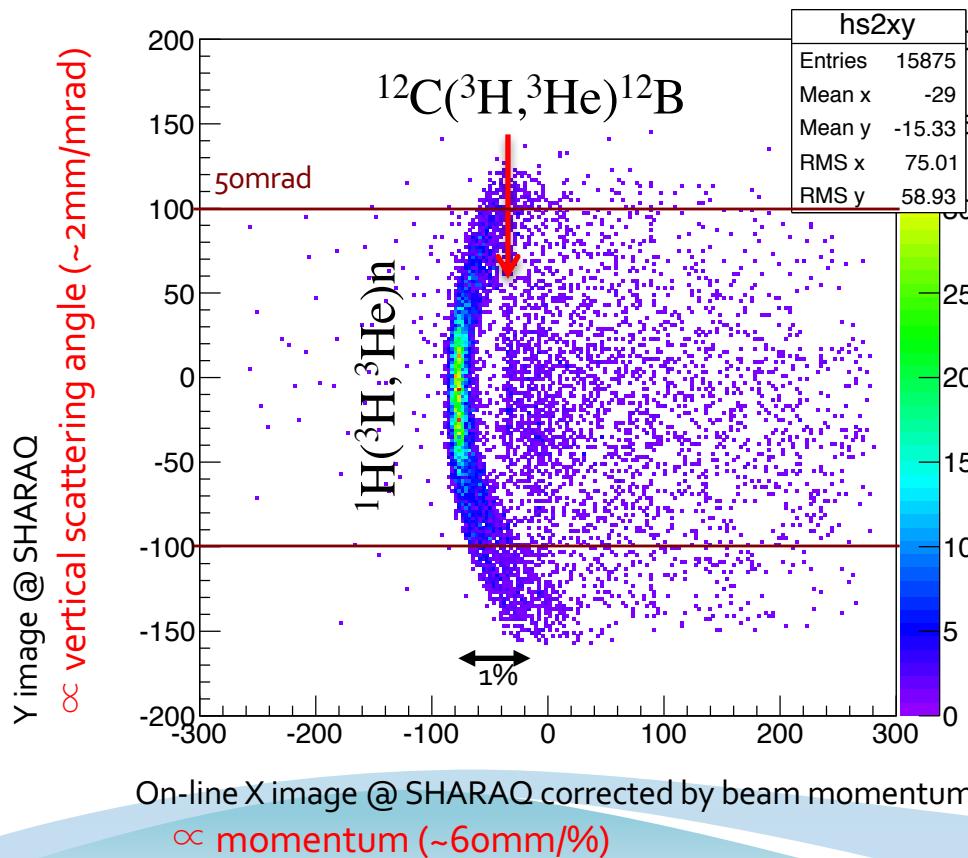
Better statistics and accuracy of energy than previous experiment (${}^4\text{He}({}^8\text{He}, {}^8\text{Be})$ @ 186 MeV/u)

4 events → **5 times or more**: Improve efficiencies (redundancy)

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

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

Calibration using ${}^1\text{H}({}^3\text{H}, {}^3\text{He})\text{n}$ ($(\text{CH}_2)_n$ target)
with same rigidity ${}^3\text{H}$ beam (310 MeV/u) as ${}^8\text{He}$



Resolution & Statistics are consistent with expected



Summary

- $^4\text{He}(^8\text{He}, ^8\text{Be})4\text{n}$ 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 (4.9σ 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 nuclear forces



Thank you for your attention