Tetraneutron system populated by double-charge exchange 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
- Remarks on reaction to the continuum

- *No strangeness, but strange (?) phenomena*

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
    - 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

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

- Only upper limit of cross section was decided.

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

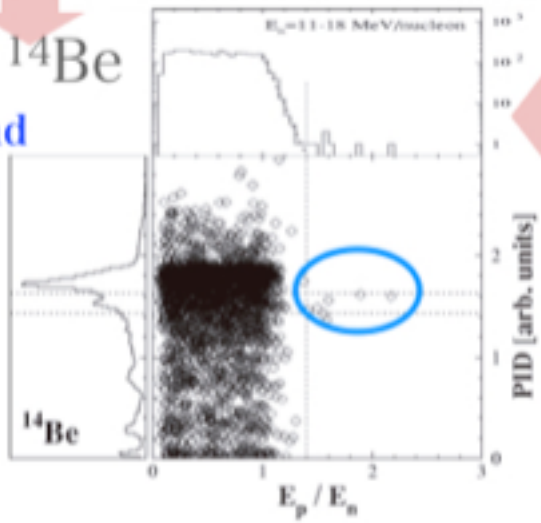
Bound state: No clear evidence.

2000s

Breakup of ^{14}Be

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

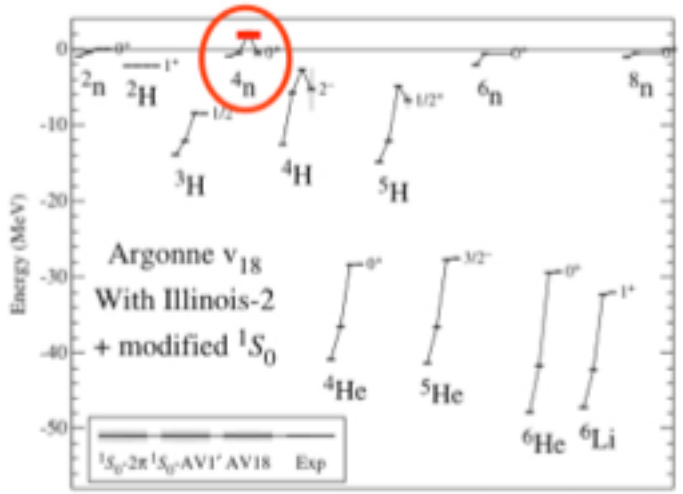
F. M. Marques, et al, Phys. Rev. C 65, 044006 (2002)



2000s

Theoretical work

- ab-initio calculation
  NN, NNN interaction

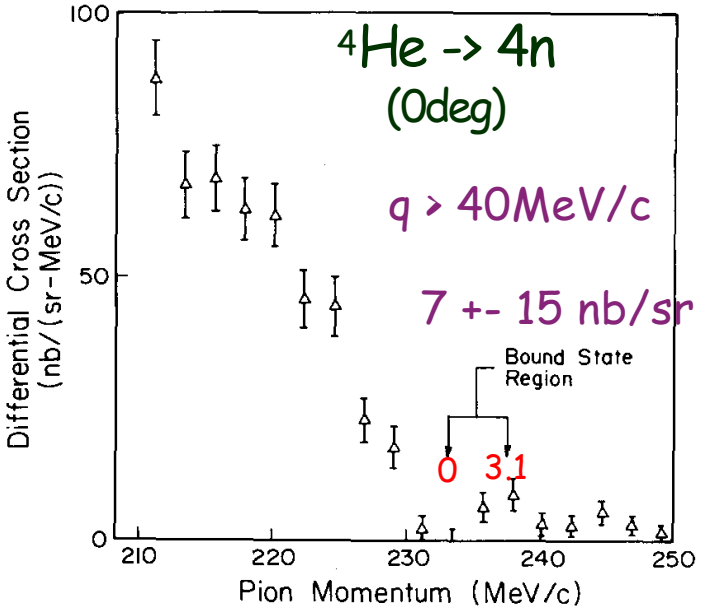


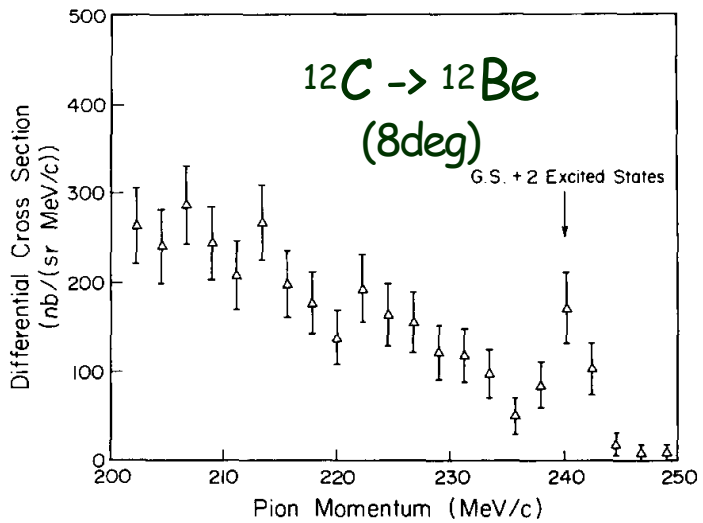
S. C. Piper, Phys. Rev. Lett. 90, 252501 (2003)

- **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

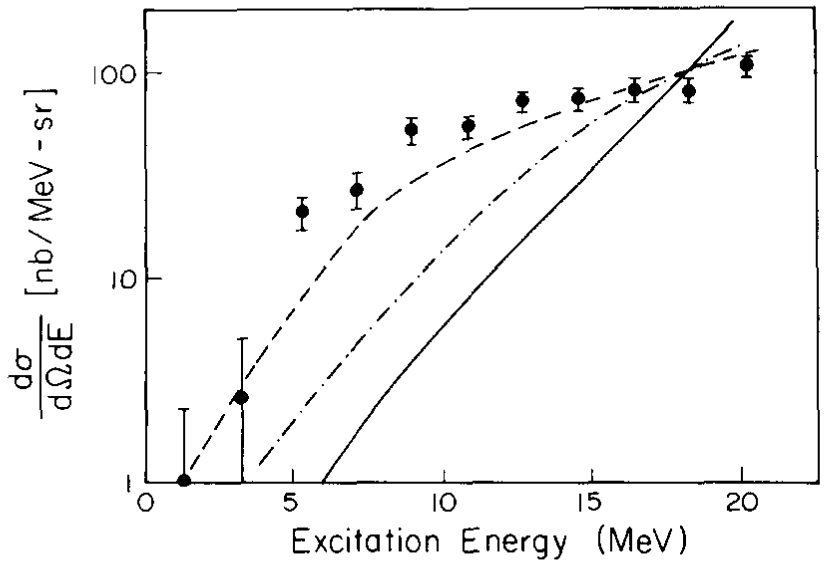
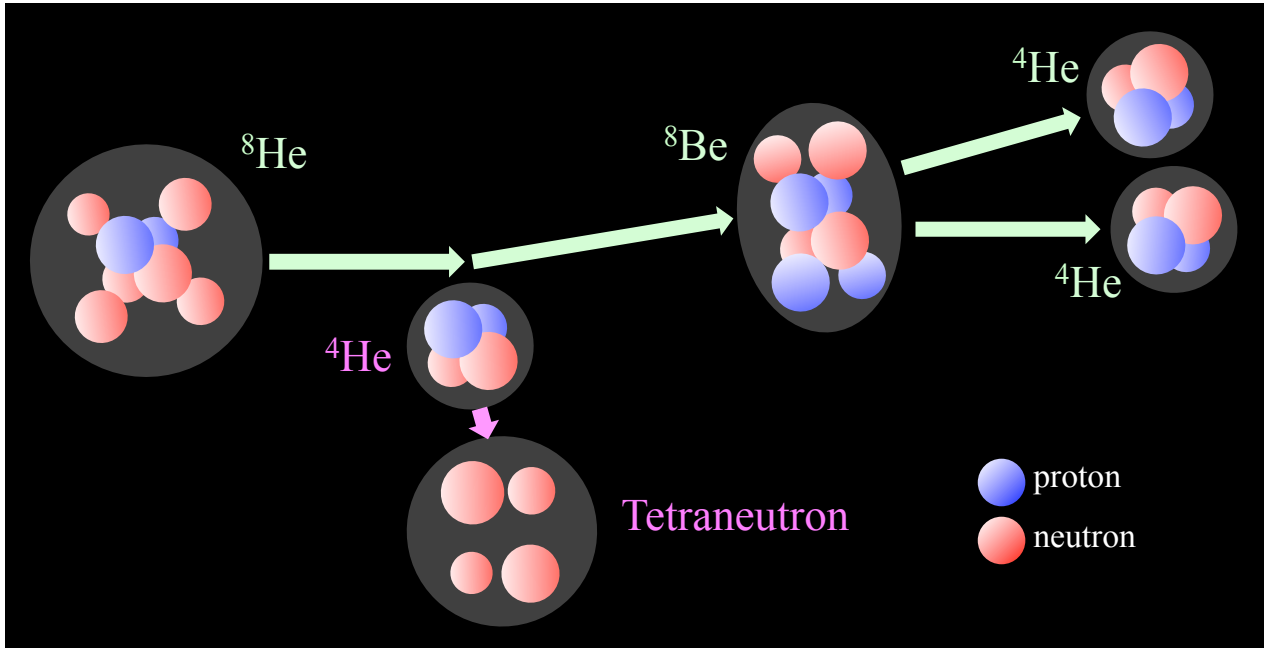


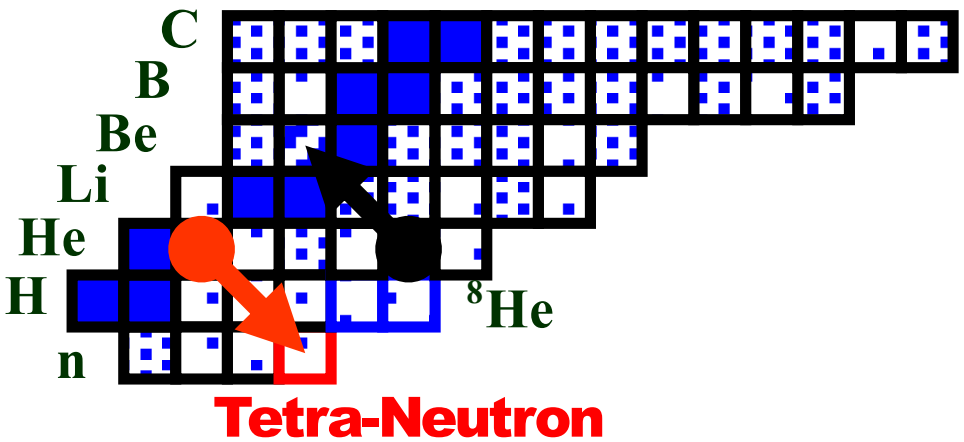
Fig. 3. The experimental results are plotted against the excitation of the final four-neutron state. The solid curve corresponds to the pure four-neutron phase space, while the dot–dashed and dashed curves are the four-neutron phase space curves with singlet state interactions in, respectively, one and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

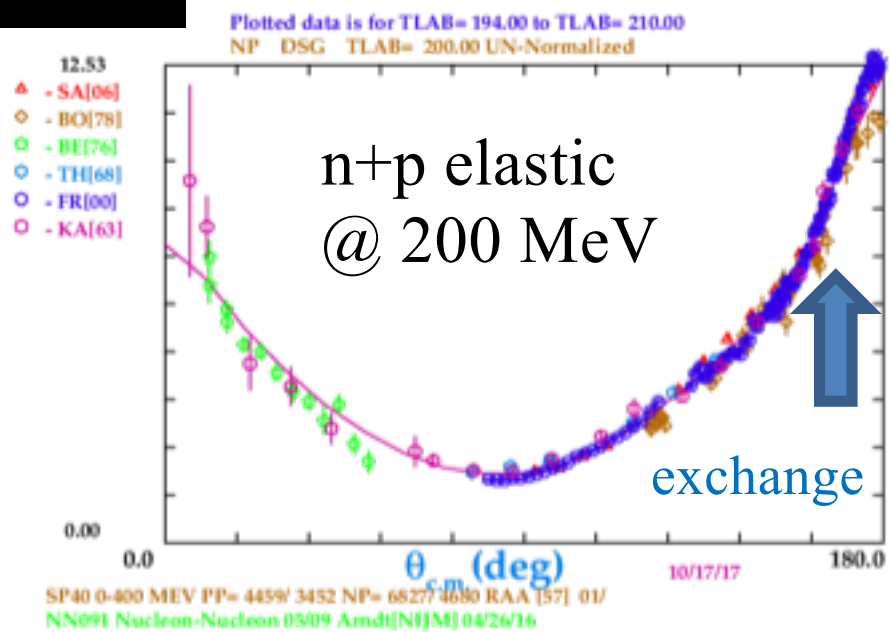
J.E. Ungar et al., PLB 144 (1987) 333

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

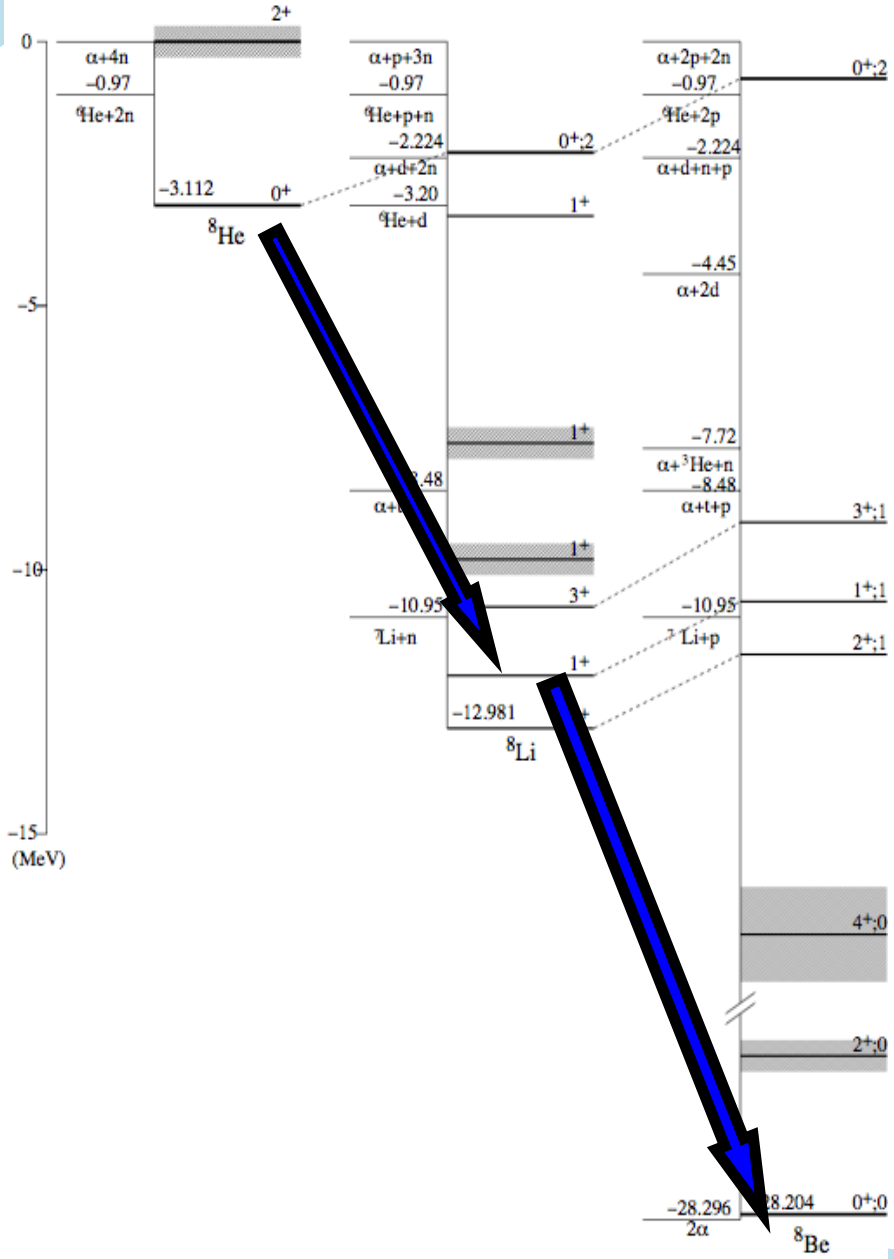


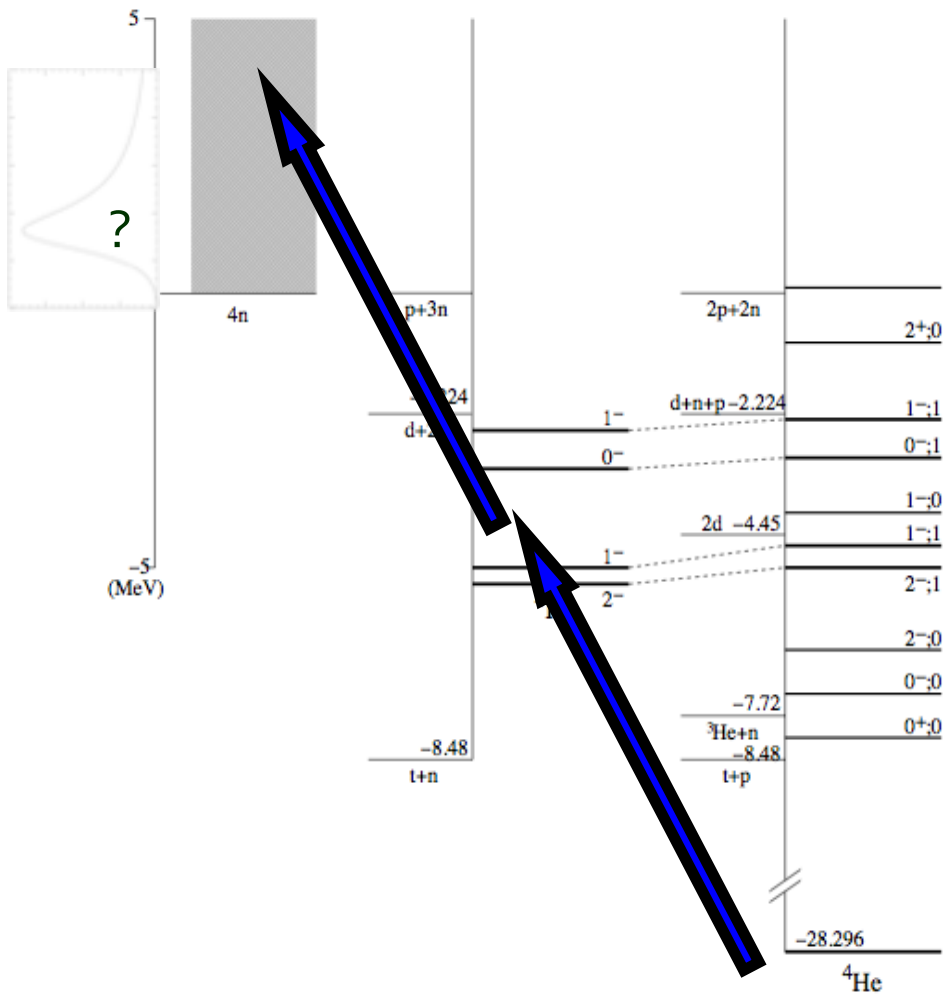
Almost recoil-less condition with ^{4}He(^{8}He,^{8}Be)4n reaction at 200 A MeV (0.63 c)





Level diagrams

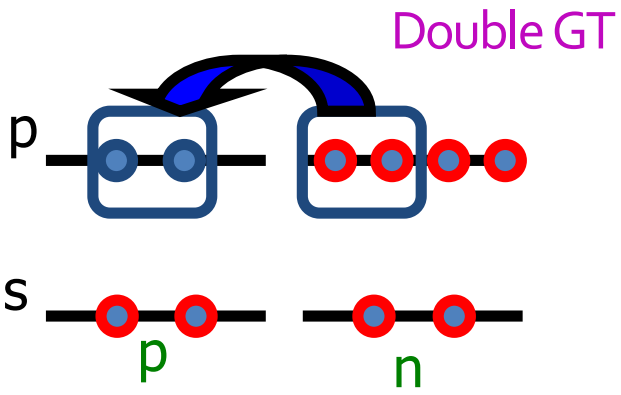




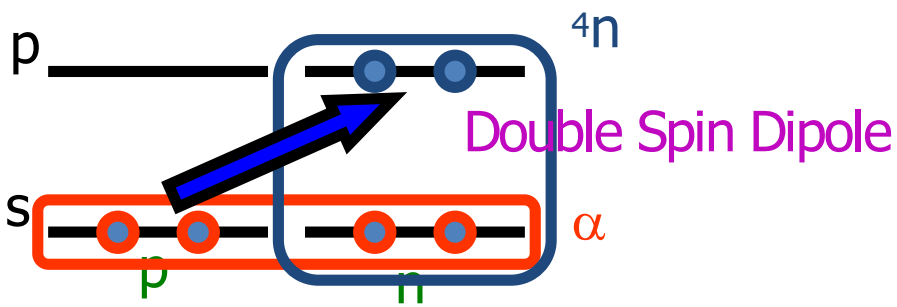
$q_{min} \sim 10 MeV/c$

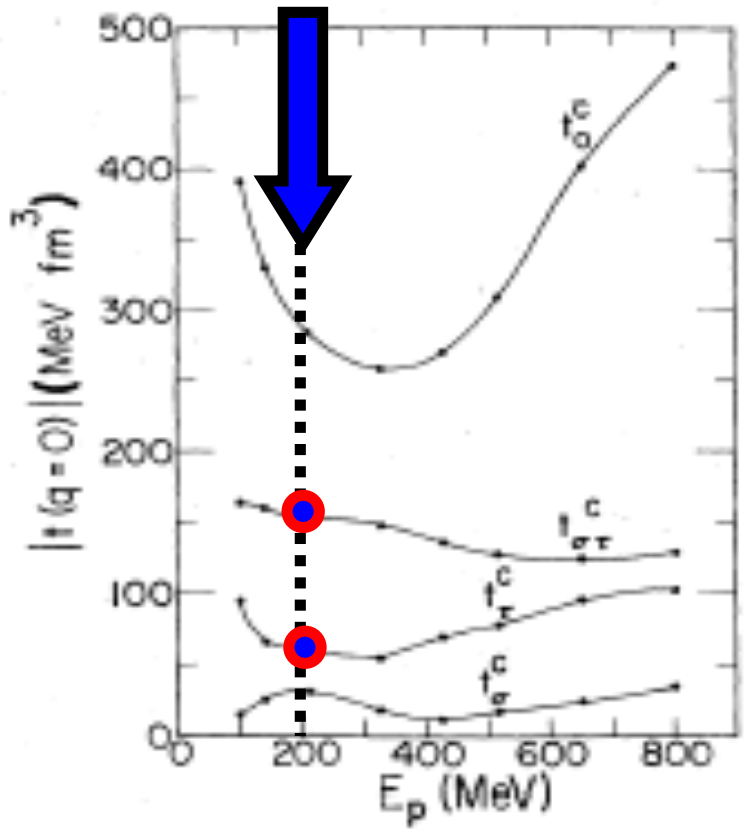
Reaction Mechanism

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



$^4He \rightarrow 4n$

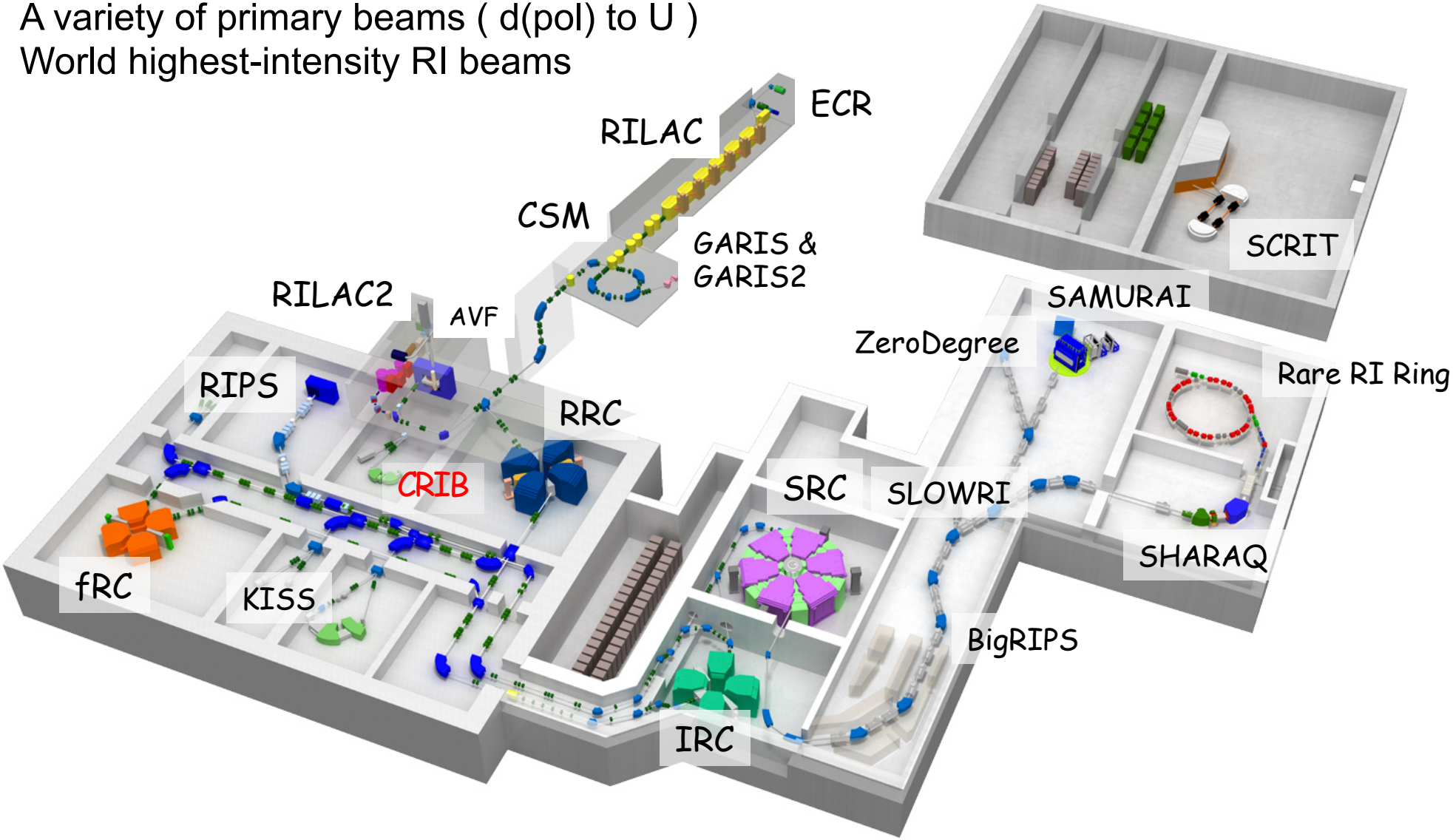




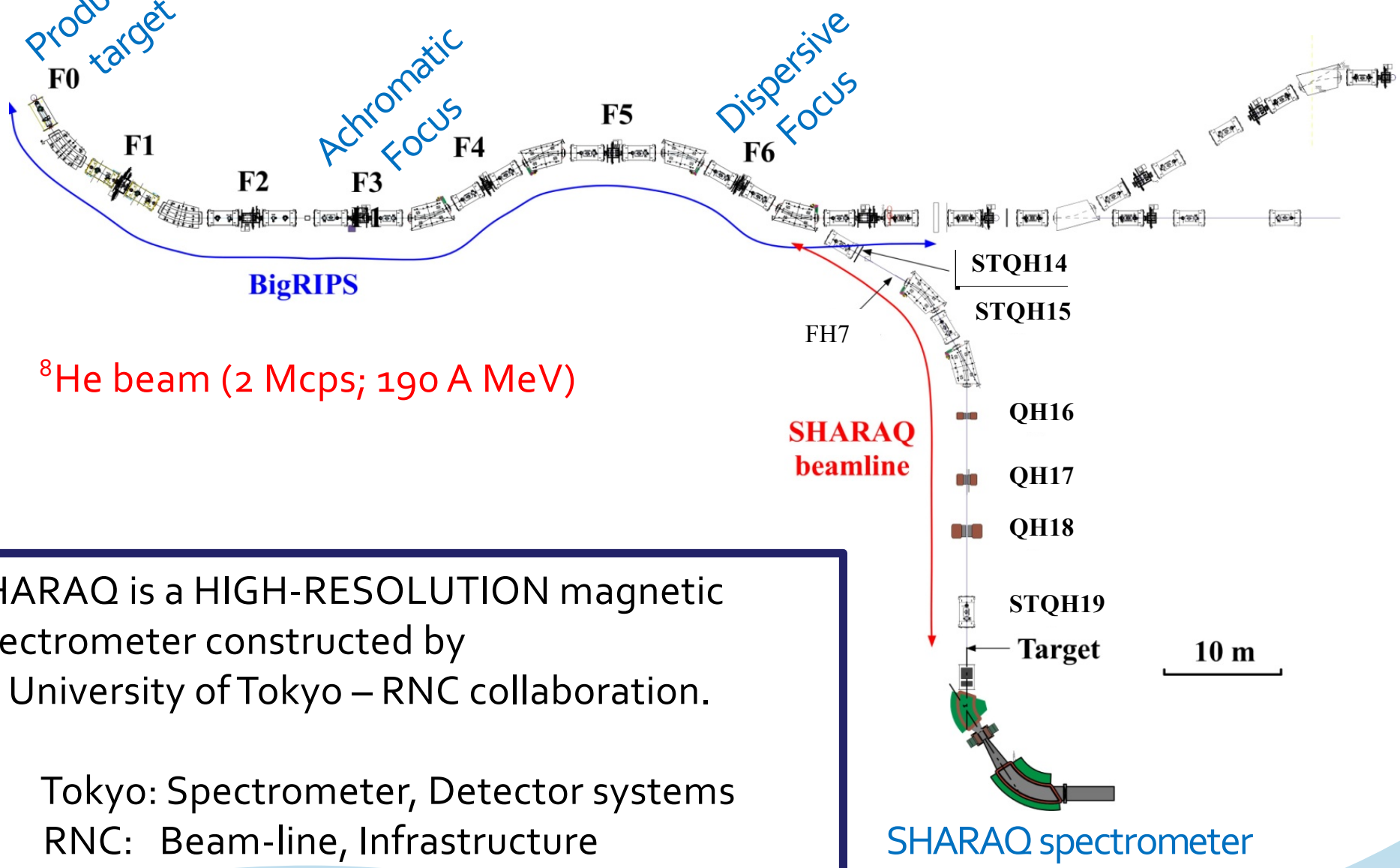
$$\left[\left(\vec{\tau}_p \cdot \vec{\tau}_t\right)\left(\vec{\sigma}_p \cdot \vec{\sigma}_t\right) r_t Y_1\left(\hat{r}_t\right)\right]^2$$

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



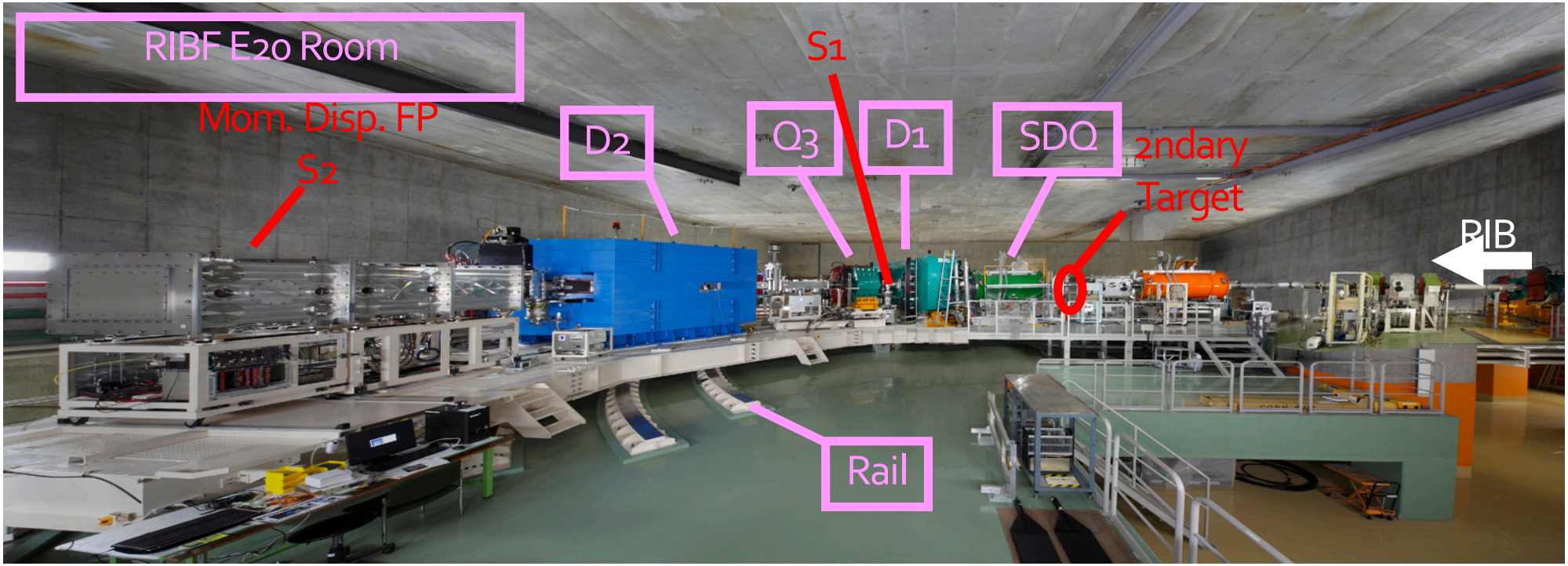
^{8}He beam (2 Mcps; 190 A MeV)

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

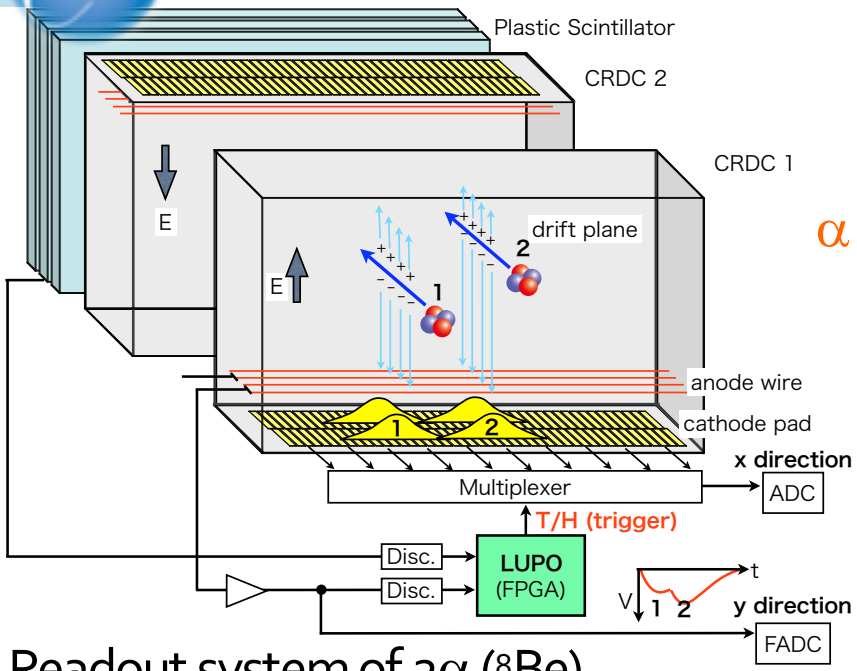
Tokyo: Spectrometer, Detector systems
RNC: Beam-line, Infrastructure

SHARAQ spectrometer

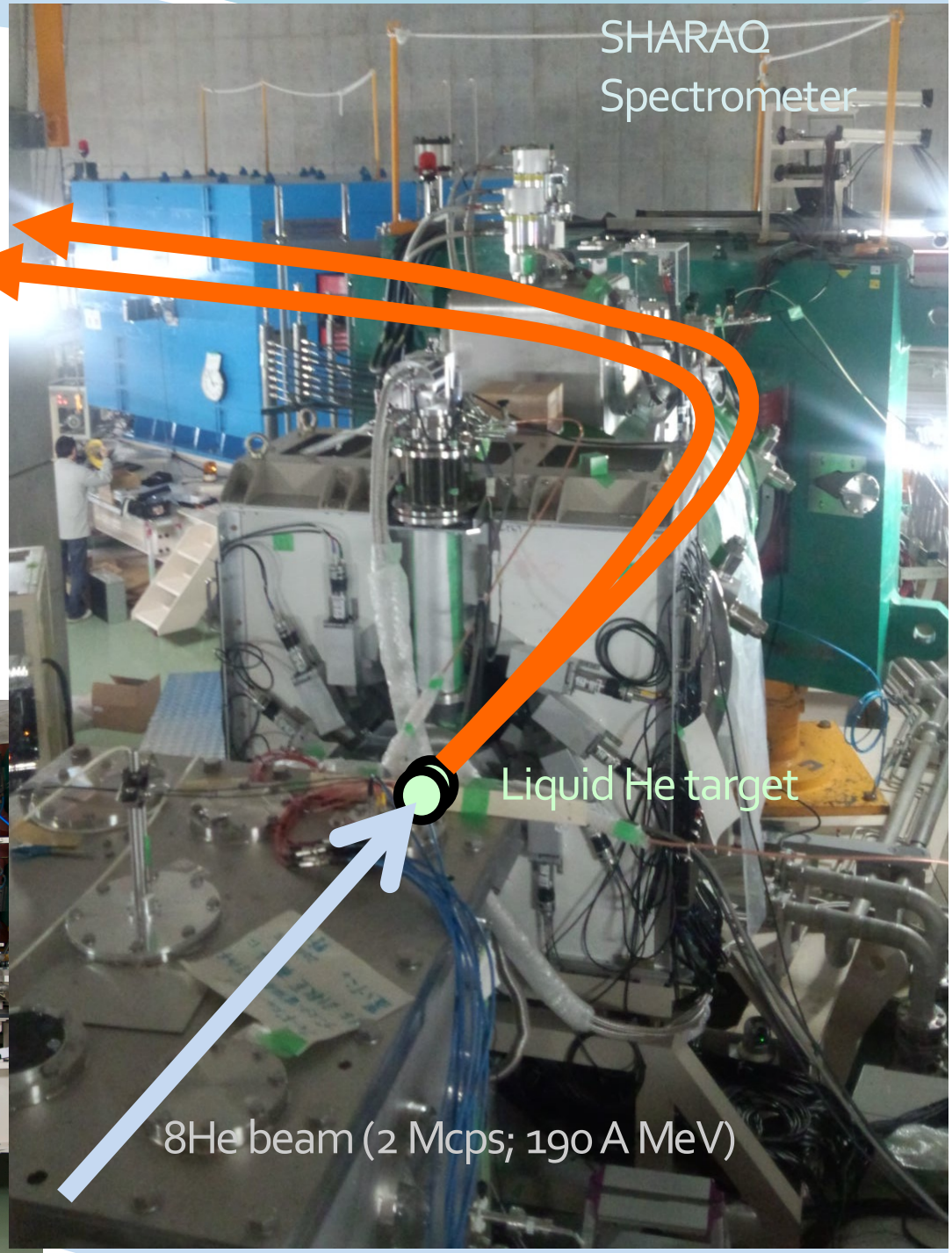
T. Uesaka et al.,
NIMB B **266** (2008) 4218.
PTEP 2012, 03C007 (2012)



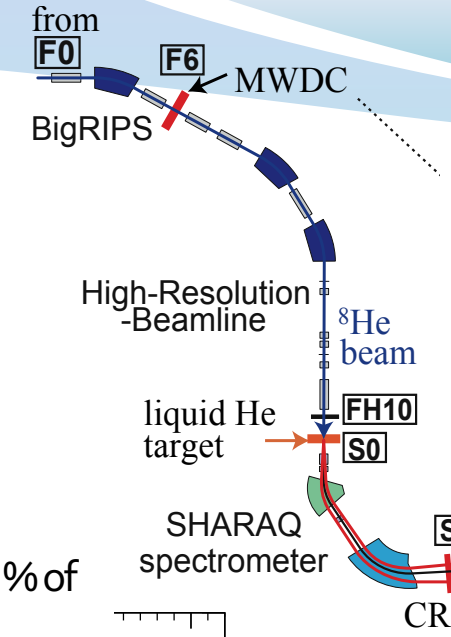
Maximum rigidity	**6.8 Tm**
Momentum resolution	**d*p*/*p* = 1/14700**
Angular resolution	**~ 1 mrad**
Momentum acceptance	**± 1%**
Angular acceptance	**~ 5 msr**

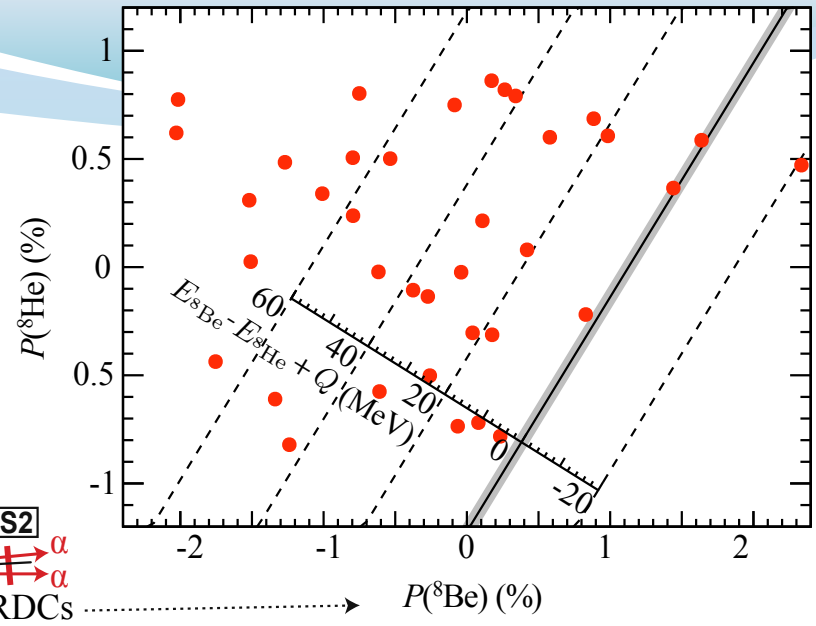


Readout system of 2α (^{8}Be)



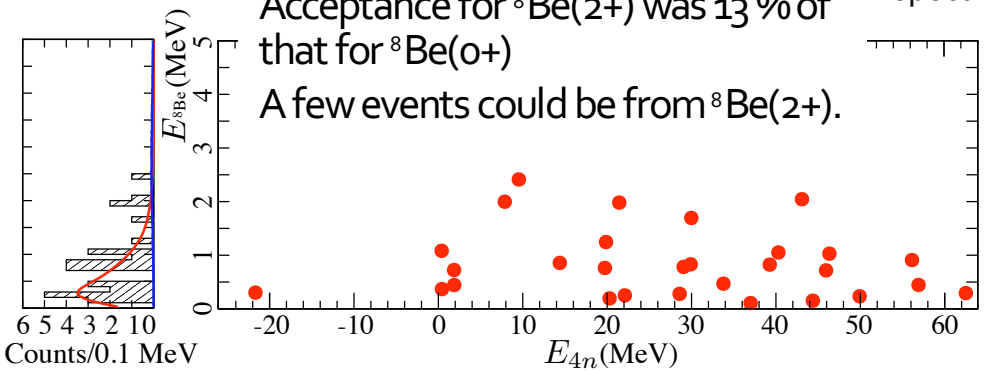
Experimental Results

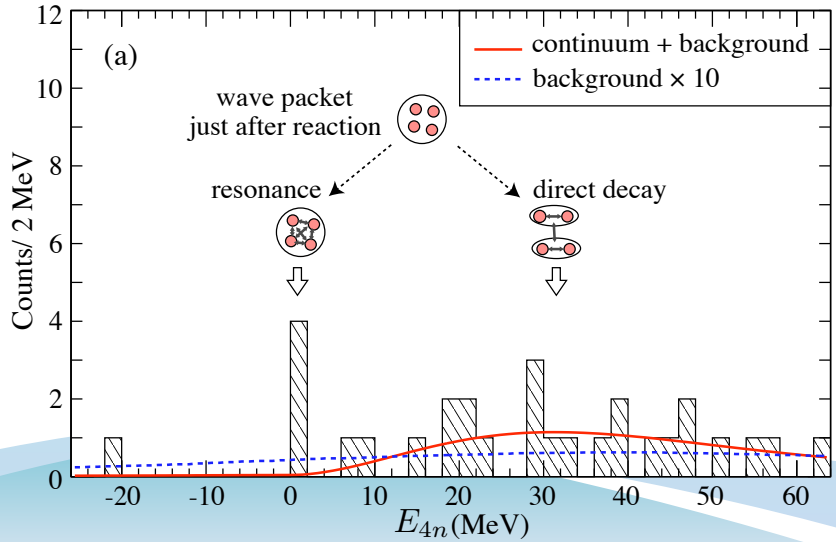


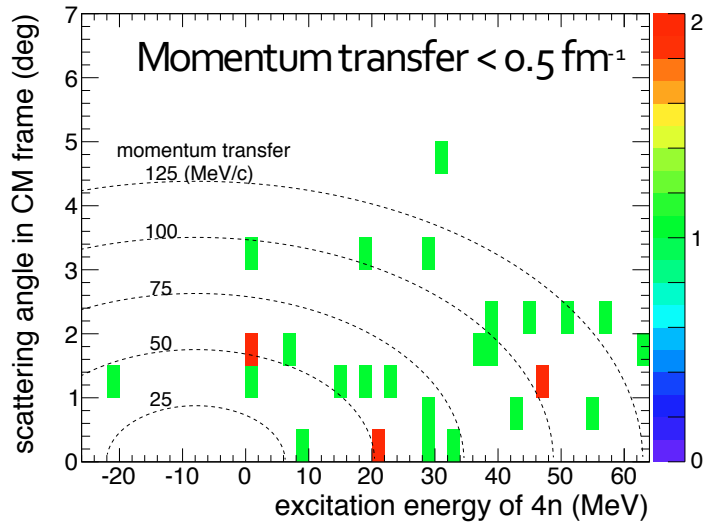


Acceptance for ^{8}Be(2+) was 13 % of that for ^{8}Be(0+)

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



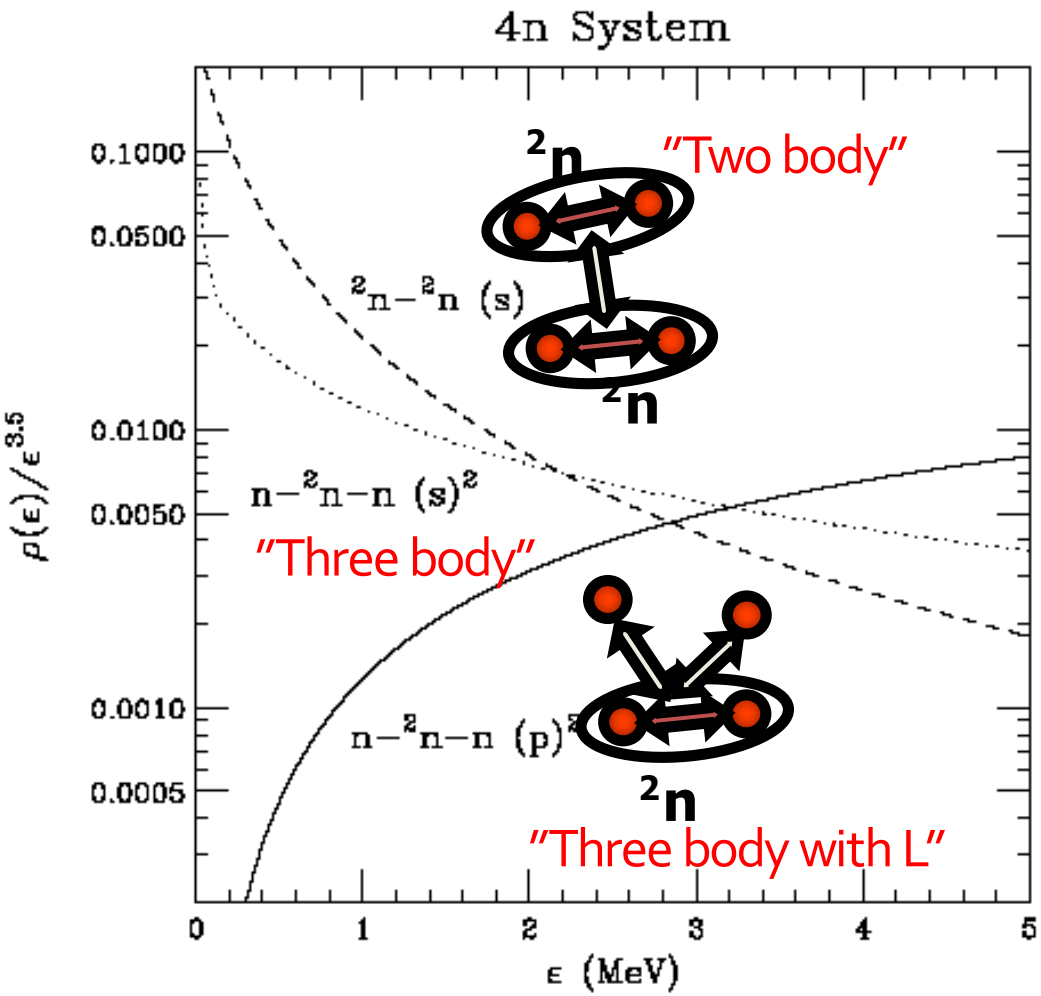




Look like having two components:
Continuum + Peak (?)

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

Phase space in multi-body continuum

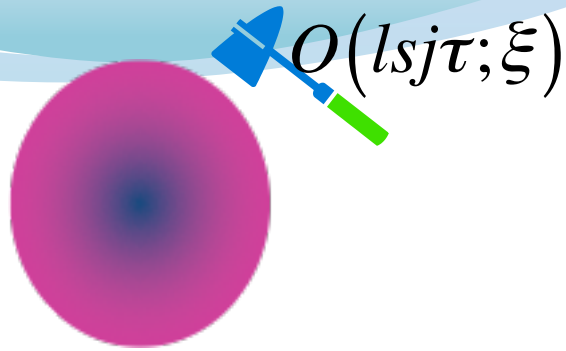


Phase Space

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

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

Transition Probabilities



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

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.

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

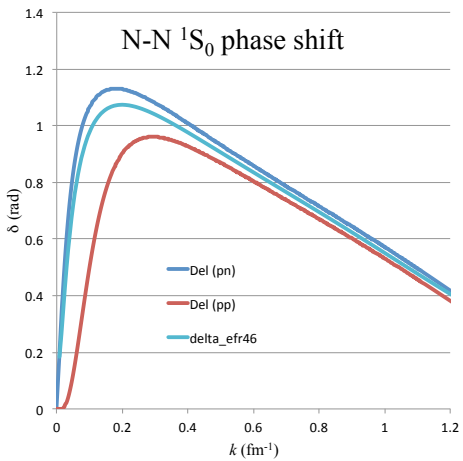
$\left| E_i J_i \pi_i T_i ; \xi_i \right\rangle$ and/or $\left| E_f J_f \pi_f T_f ; \xi_f \right\rangle$ energy eigen functions

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

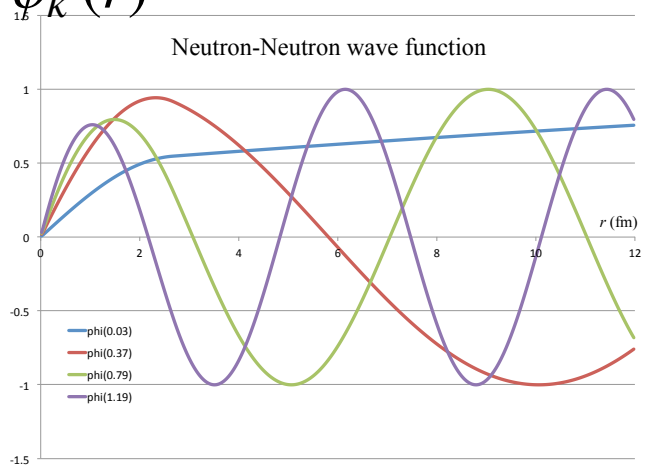
$\left| M_{if}(E_f) \right|^2$: Energy Spectrum

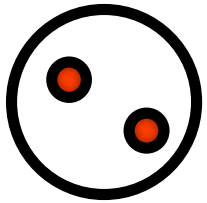
coherent sum of wave packets made by one-body action
"Collective wave packet" (not always energy eigen state),
e.g. coherent sum of 1p-1h for inelastic-type excitation

NN case with FSI



$\phi_k(r)$





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

^{2}n

Scattering state of correlated neutron pair

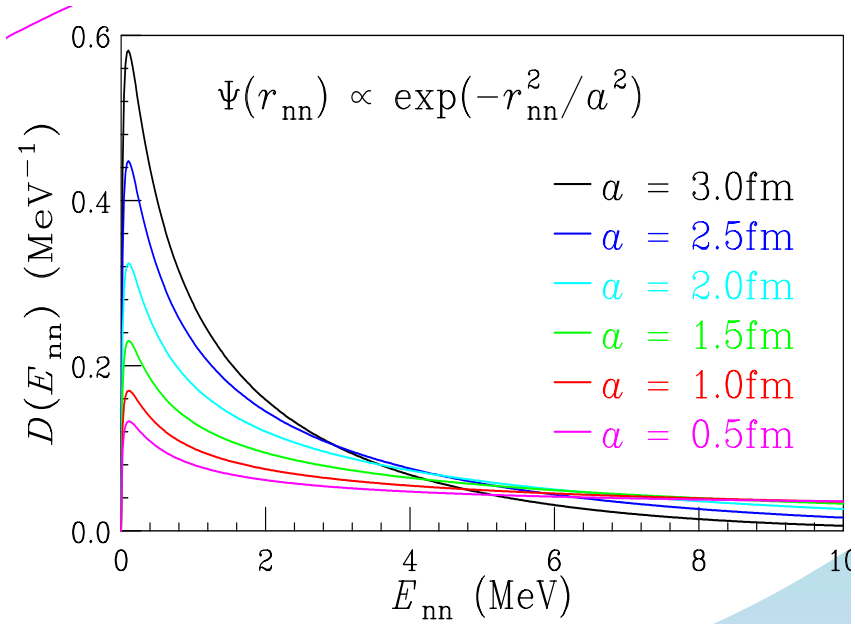
Density of State

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

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

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.)

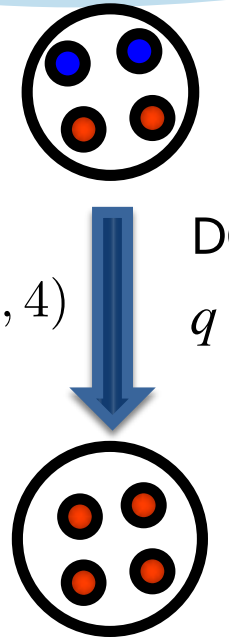


Direct Part

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

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

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



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

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

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

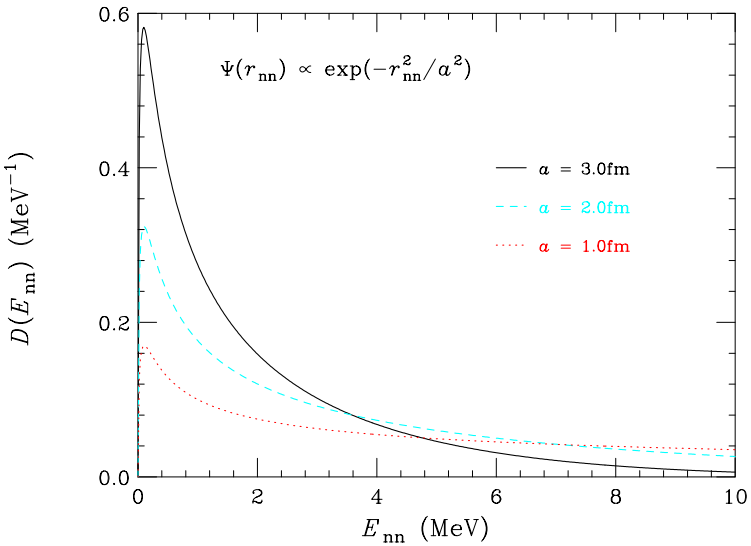
$$X = E/\epsilon_a \qquad \epsilon_a = \frac{\hbar^2}{m_N a^2} = 11\text{MeV}$$

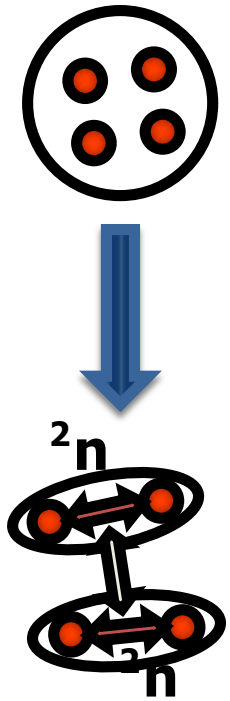
NN FSI

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

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

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

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

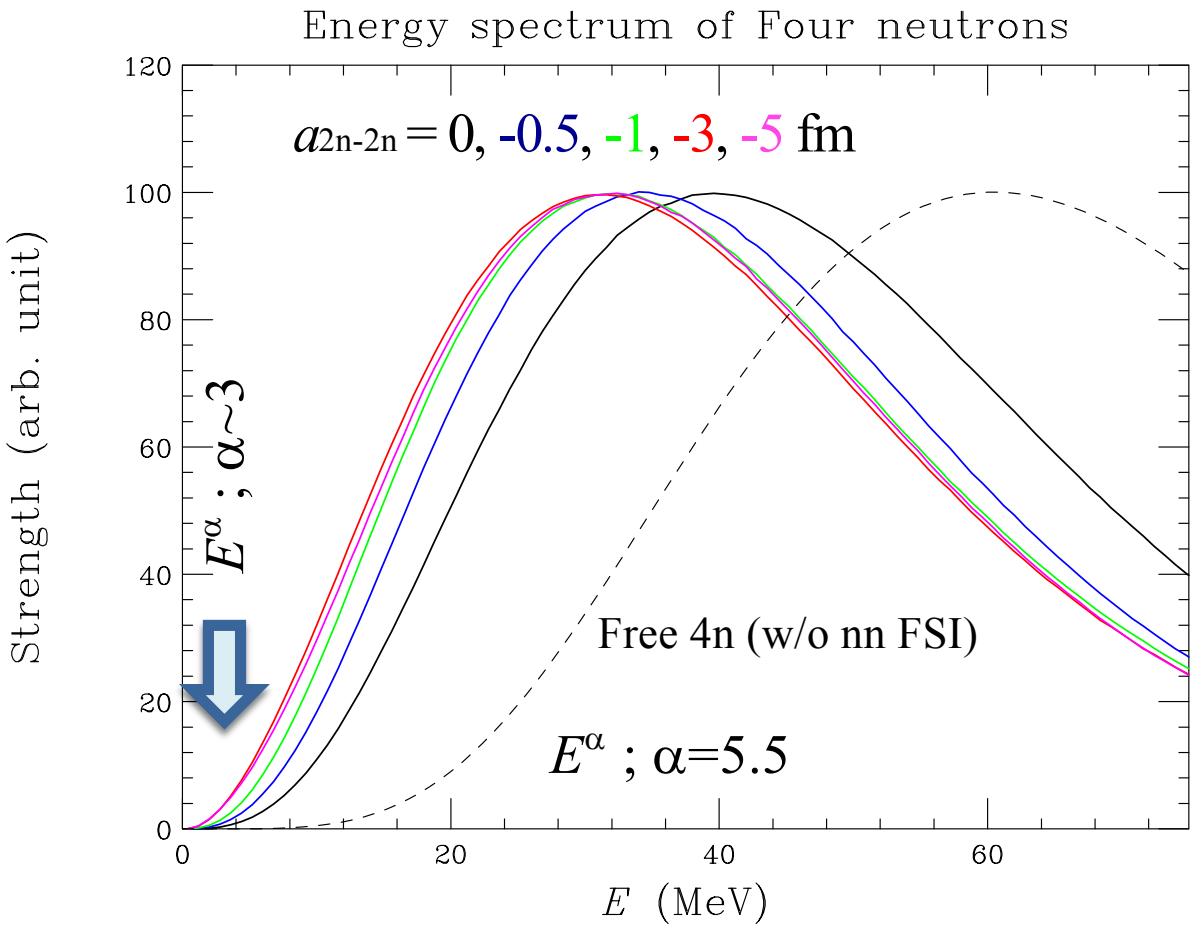
Expand $\mathcal{A}\Phi_0$ with correlated n-n scattering wave $\phi_k(r)$

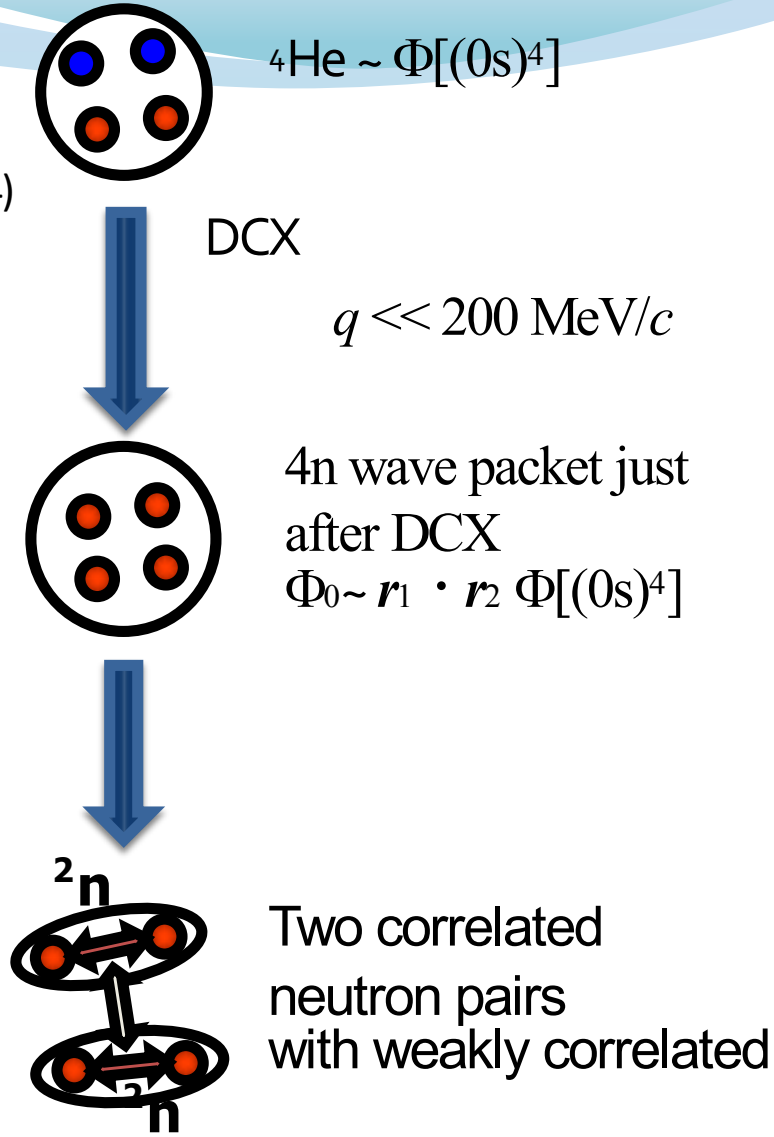
$A(k)$'s are used instead of Fourier component

Direct Part

Continuum spectrum with n-n FSI

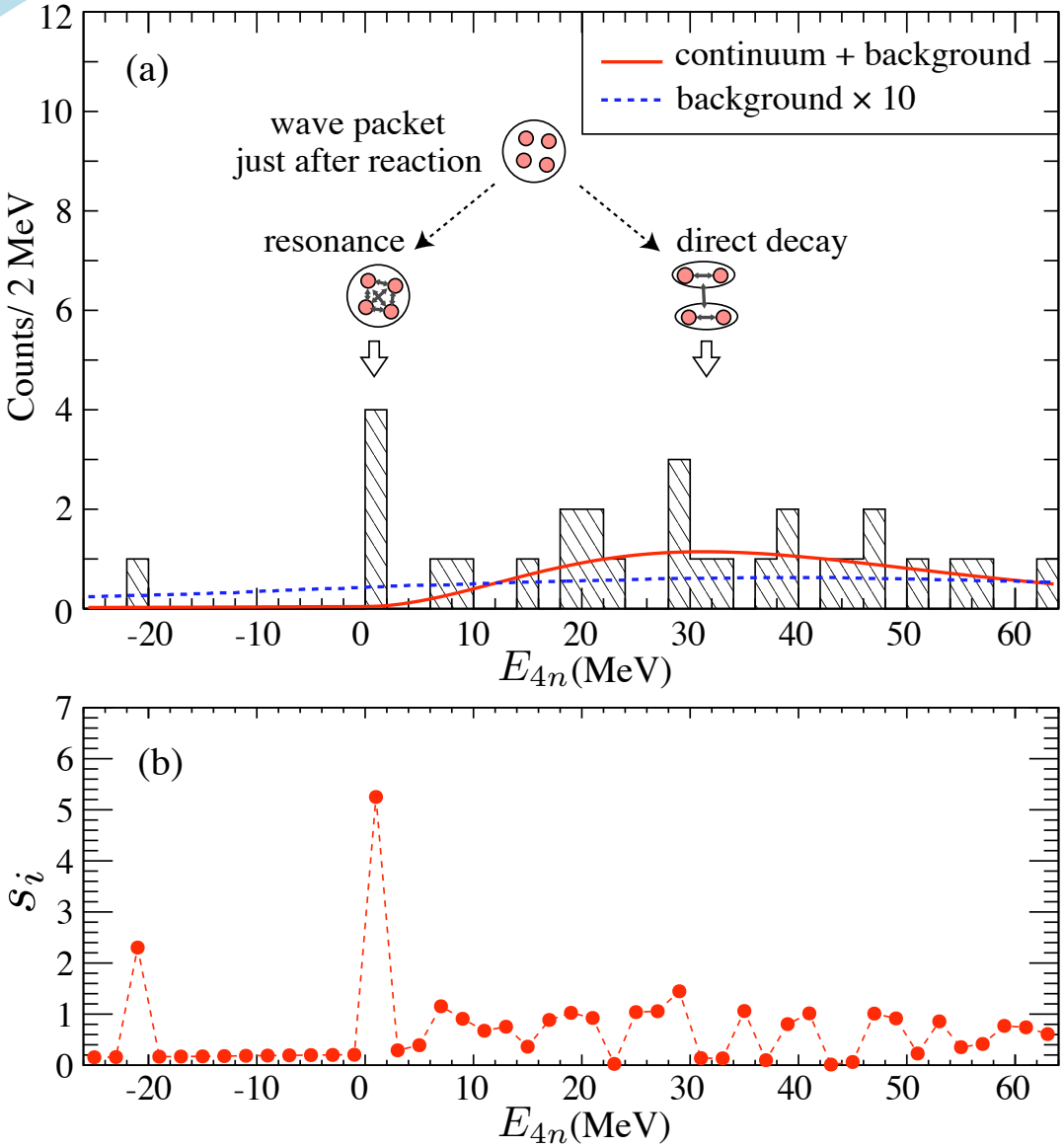
c.f.
L.V. Grigorenko, N.K. Timofeyuk, M.V. Zhukov, Eur. Phys. J. A 19, 187 (2004)





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 approach

- ^{29}F (knockout 1p) -> ^{28}O -> ^{24}O + 4n
- ^{8}He (knockout α 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

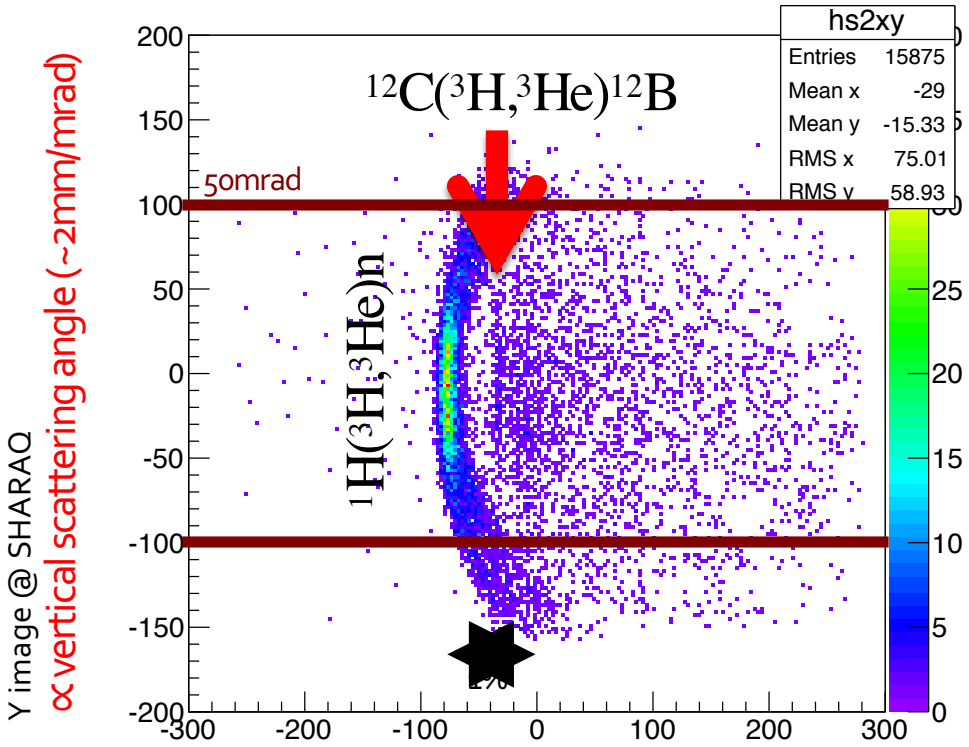
Improve efficiencies (redundancy)

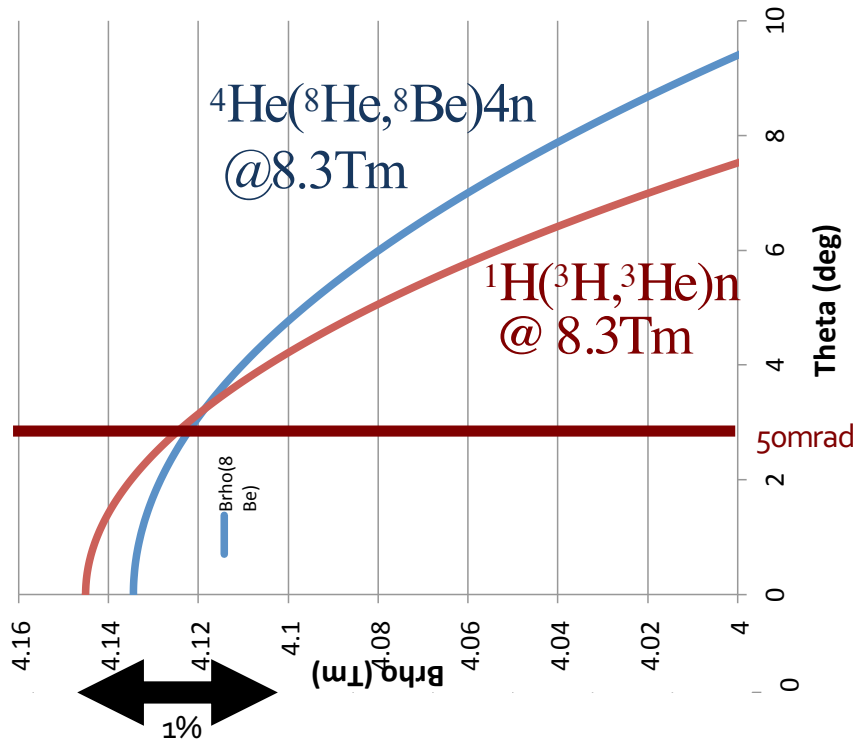
$E_{4n} = 0.83 \pm 0.65(\text{stat.}) \pm 1.25(\text{sys.})$ MeV

→ 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

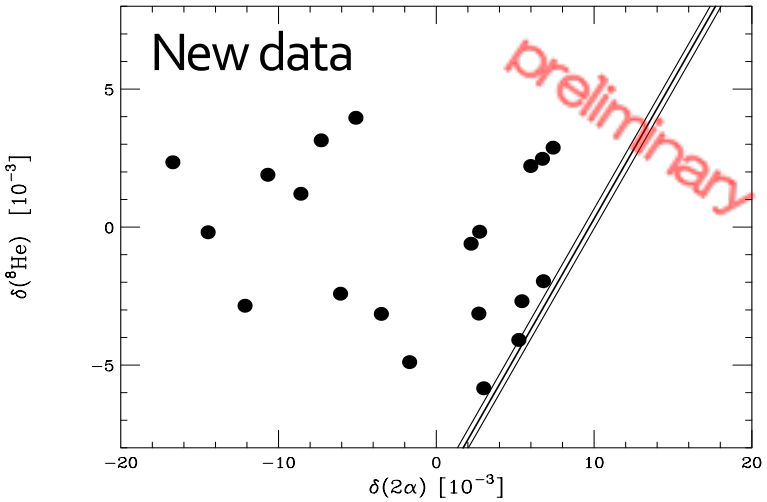
preliminary achievement : < 100 keV





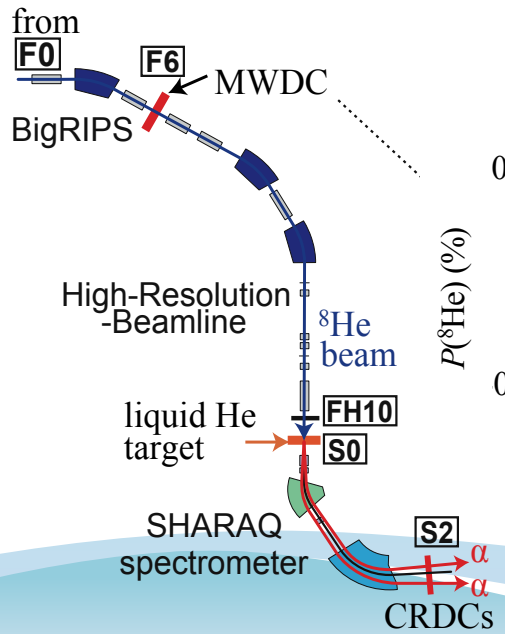
Resolution & Statistics are consistent with expected

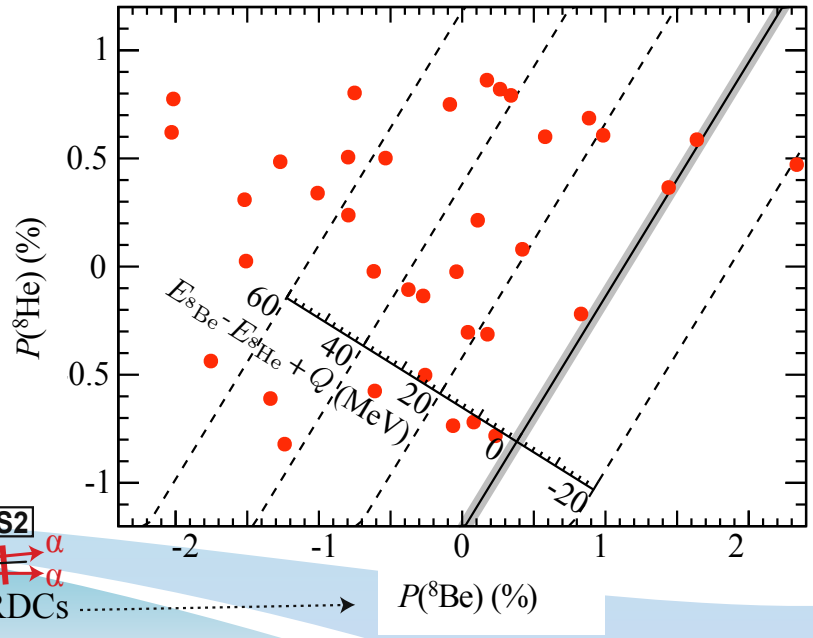
Very preliminary result



accuracy ~ 100 keV;
resolution ~ +/-2 MeV, which is to be improved

Although low statistics, similar spectrum where a few events are just above threshold.





Summary

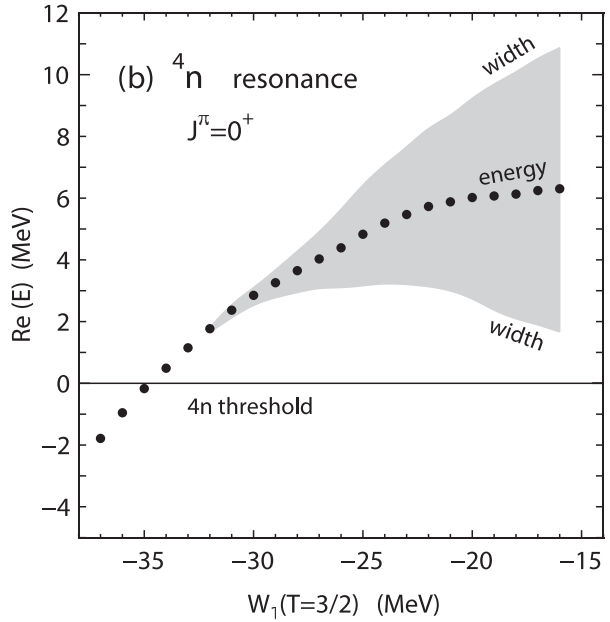
- $^{4}He(^{8}He,^{8}Be)4n$ has been measured at 190 A MeV at RIBF-SHARAQ
- Missing mass spectrum with very few background
- Although statistics is low, spectrum looks two components (continuum + peak)
- Continuum is consistent with direct breakup process from $(0s)^2(0p)^2$ wave packet
- Four events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

  $\rightarrow$ candidate of 4n resonance

  at 0.83 $\pm$ 0.65(stat.) $\pm$ 1.25(sys.) MeV; Γ < 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!

K. Fossez, et al., PRL 119, 032501 (2017) shows similar results

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

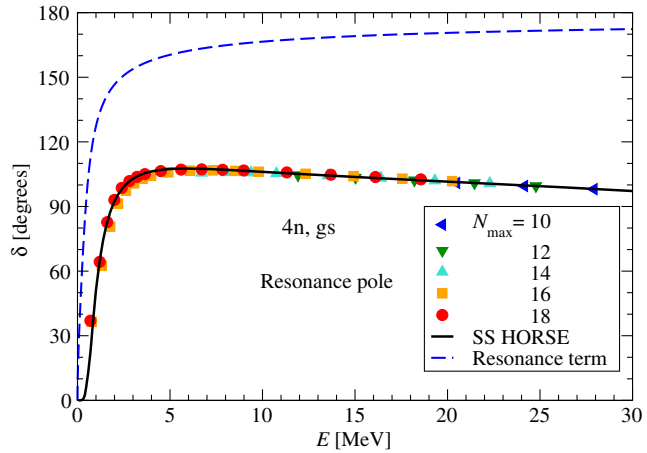


FIG. 2. The 4 → 4 scattering phase shifts: parametrization with a single resonance pole (solid line) and obtained directly from the selected NCSM results using Eq. (2) (symbols). The dashed line shows the contribution of the resonance term.

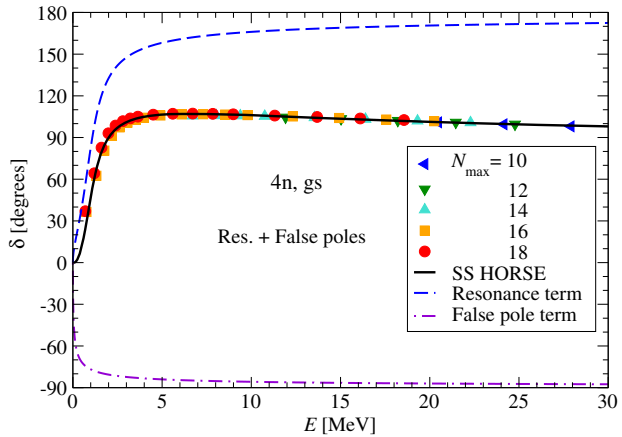


FIG. 3. The same as Fig. 2 but for the parametrization with resonance and false state poles. The dashed-dotted line shows the contribution of the false state pole term.

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

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

Recent theoretical works

A. Deltuva, PL 782, 238 (2018)

AGS equation (momentum space)

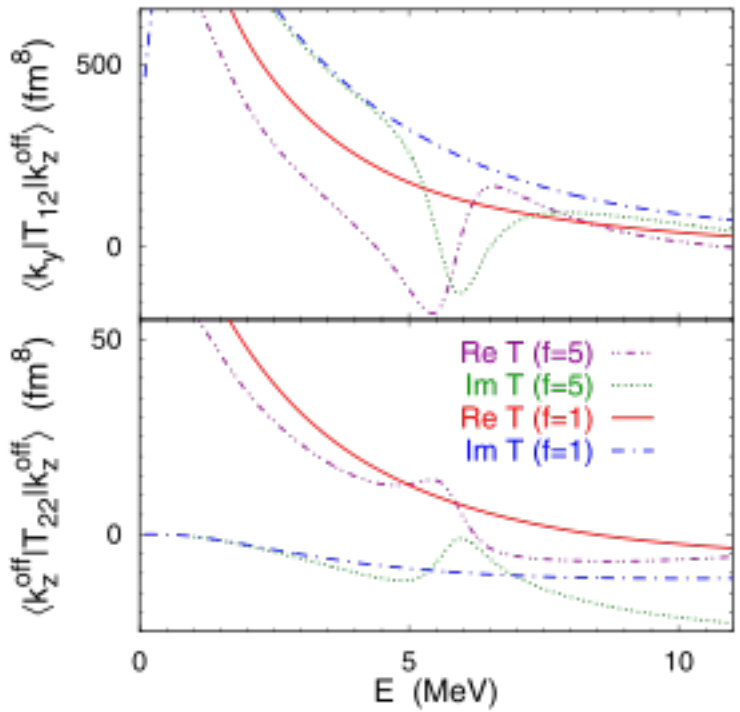
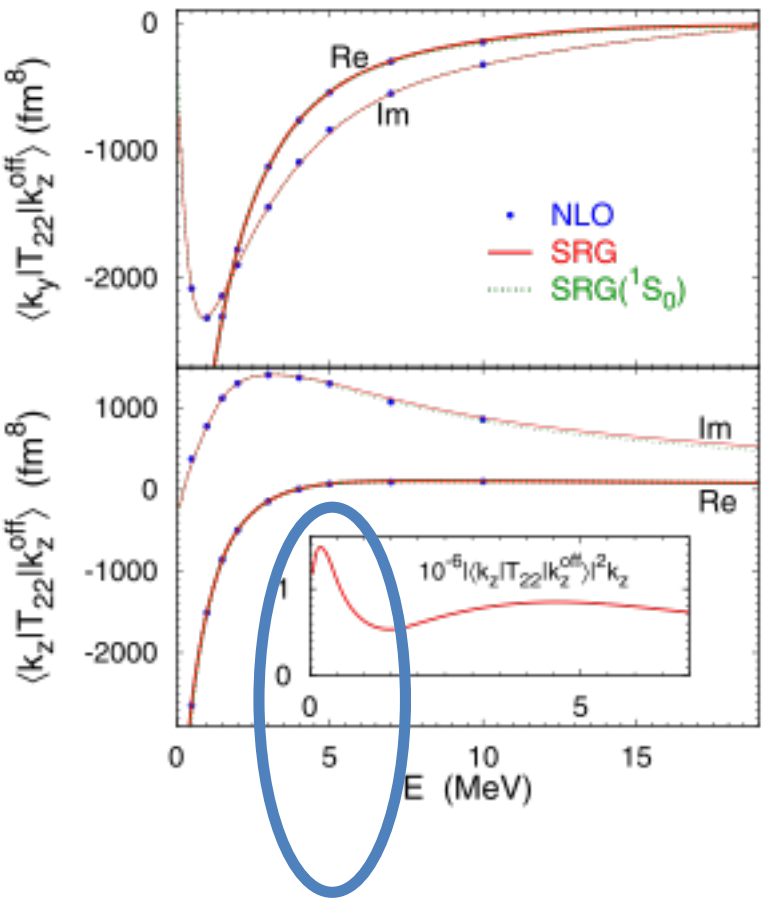


Fig. 1. (Color online) Energy dependence of real and imaginary parts of selected $\mathcal{J}^{\Pi} = 0^+$ four-neutron transition matrix elements calculated using the SRG potential with higher wave enhancement factors $f = 1$ and 5.



Virtual state (?)

In order to produce resonance, 5 times more attraction is necessary

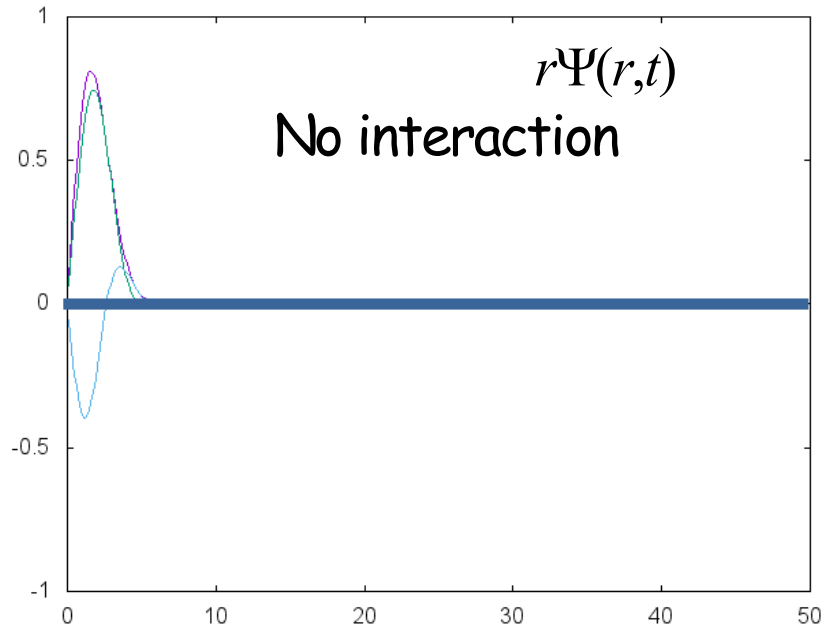
Virtual state (time-dependent wave packet)

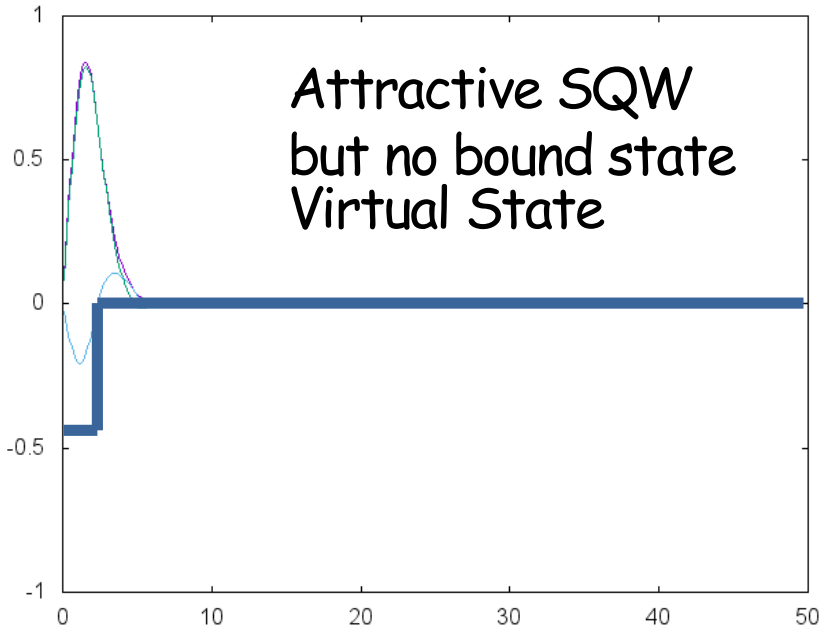
Time propagation of wave packet $\Psi(t)$:

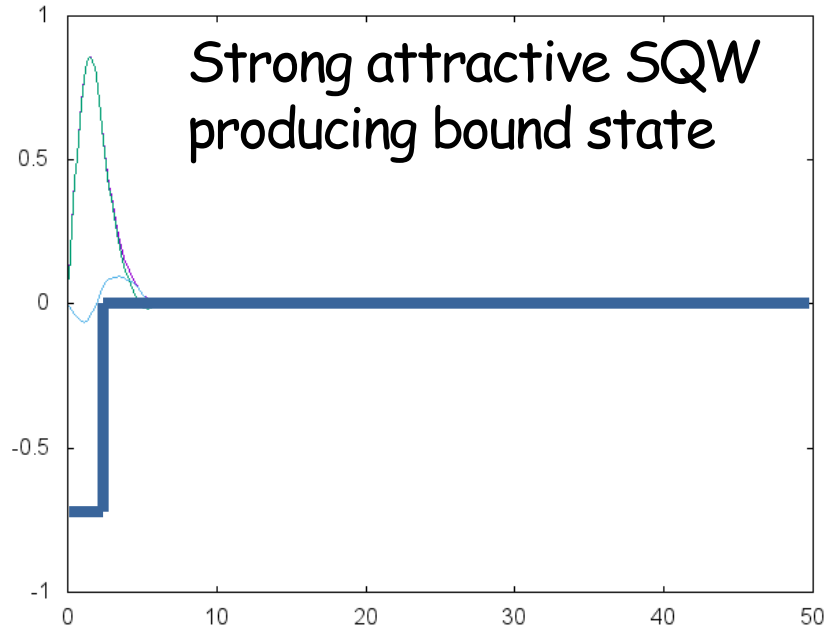
$$
\begin{aligned}
i\hbar\frac{\partial}{\partial t}\Psi(t) &= H\Psi(t) \\
\Psi(t+\Delta t) &= \exp\left(-i\frac{H}{\hbar}\Delta t\right)\Psi(t) \\
&\simeq \frac{1-\frac{i}{2}\frac{H}{\hbar}\Delta t}{1+\frac{i}{2}\frac{H}{\hbar}\Delta t}\Psi(t)
\end{aligned}
$$

➡ Numerical solution

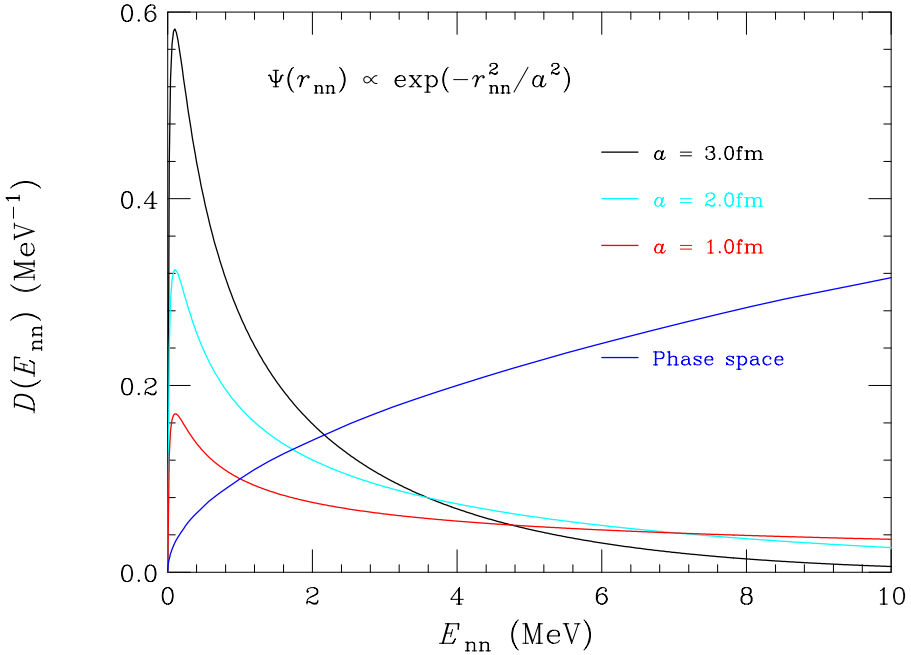
Cf. N. Watanabe and M. Tsukada, Phys. Rev. E 62 (2000) 2914

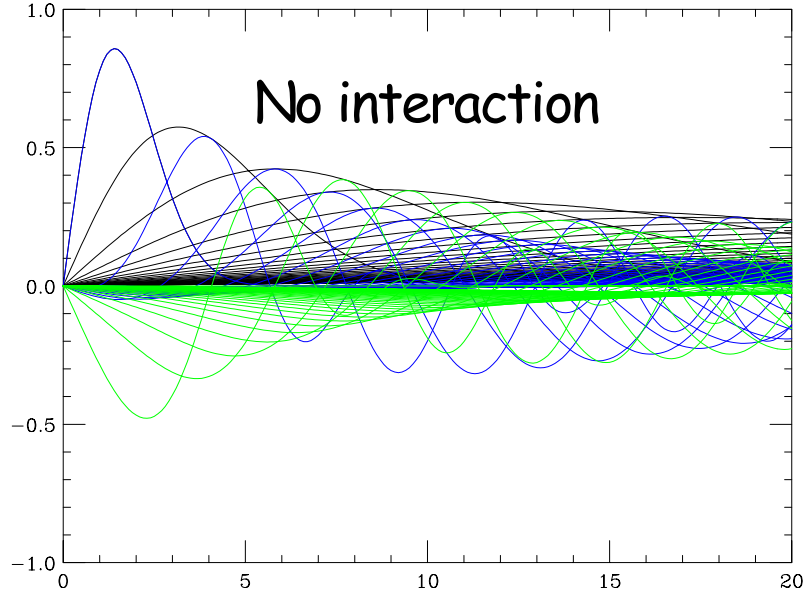


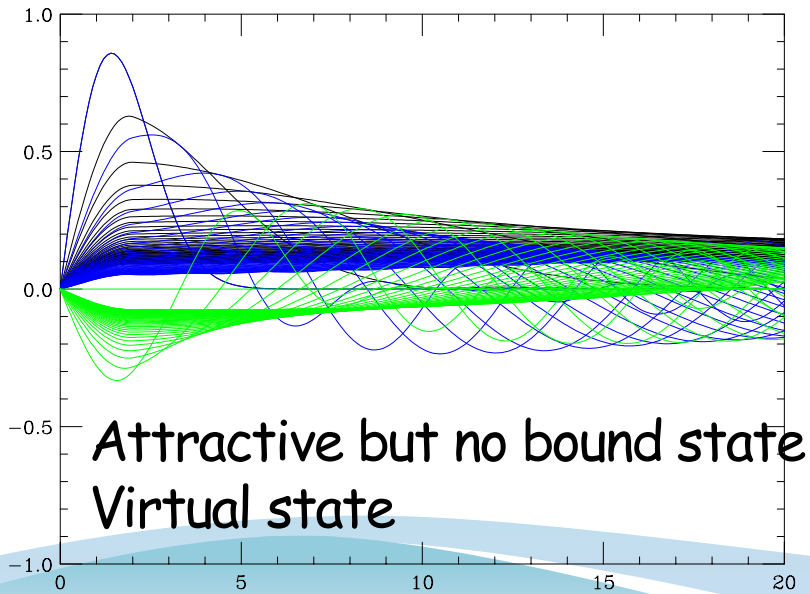


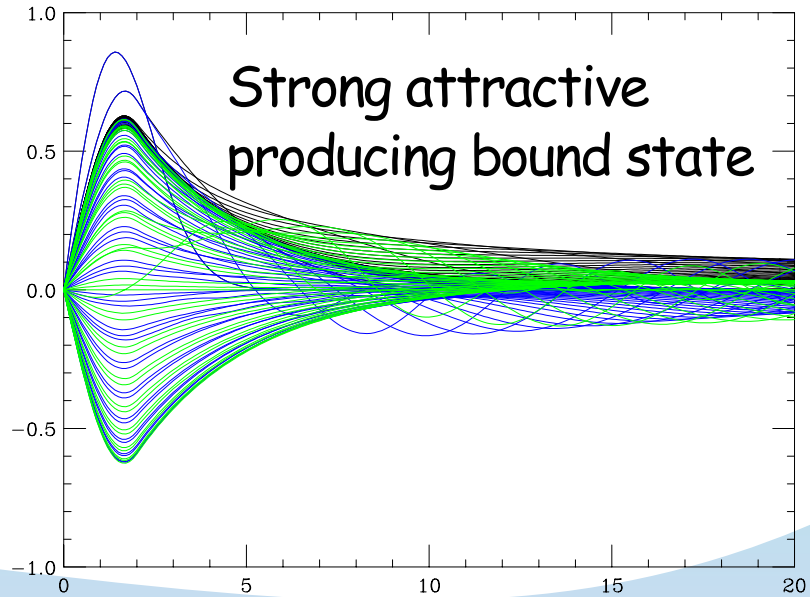


Time-dependent wave packet (2n case)









Thank you for your attension

One-dimensional three-body system (Nucleon 1, 2 and Core 3 with infinite mass)

Hamiltonian:

$$
\begin{aligned}
H &= -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x_1^2} - \frac{\hbar^2}{2m}\frac{\partial^2}{\partial x_2^2} + V_1(x_1) + V_2(x_2) + V_{12}(x_1 - x_2) \\
&= -\frac{\hbar^2}{4m}\frac{\partial^2}{\partial X^2} - \frac{\hbar^2}{m}\frac{\partial^2}{\partial x_{12}^2} + V_1\left(X + \frac{x_{12}}{2}\right) + V_2\left(X - \frac{x_{12}}{2}\right) + V_{12}(x_{12}) \\
&= -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x_\alpha^2} - \frac{\hbar^2}{2m}\frac{\partial^2}{\partial x_\beta^2} + V_1\left(\frac{x_\alpha + x_\beta}{\sqrt{2}}\right) + V_2\left(\frac{x_\alpha - x_\beta}{\sqrt{2}}\right) + V_{12}\left(\sqrt{2}\, x_\beta\right)
\end{aligned}
$$

$$x_{12} = x_1 - x_2 \; ; \; X = \frac{x_1 + x_2}{2}$$

$$x_\alpha = \frac{x_1 + x_2}{\sqrt{2}} \; ; \; x_\beta = \frac{x_1 - x_2}{\sqrt{2}}$$

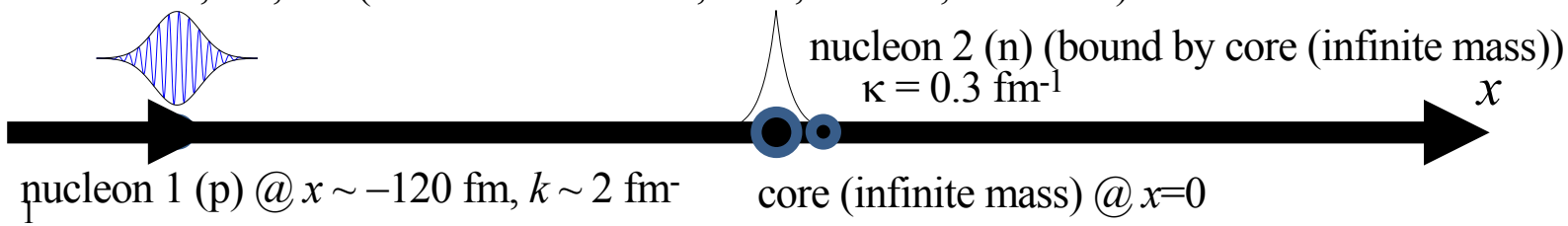
Time propagation of wave packet $\Psi(t)$:

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

$$\Psi(t + \Delta t) = \exp\left(-i\frac{H}{\hbar}\Delta t\right)\Psi(t)$$

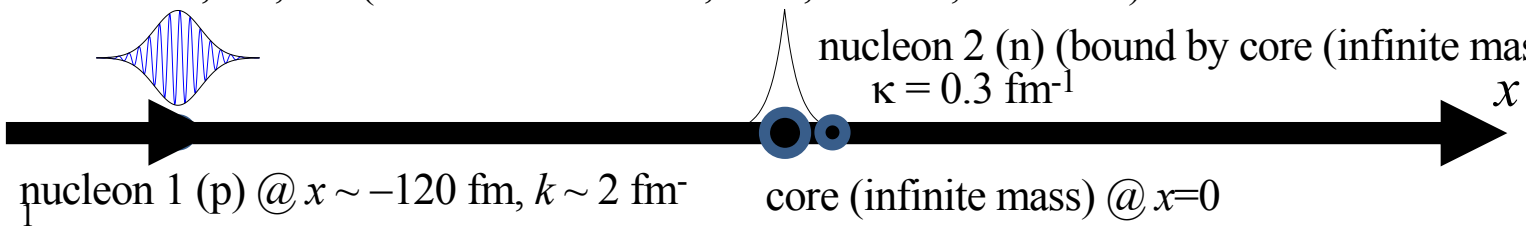
Cf. N. Watanabe and M. Tsukada, Phys. Rev. E 62 (2000) 2914

Interaction: V_{1c}, V_{2c}, V_{12} (~δ-function at x_1=0, x_2=0, x_1-x_2=0; attractive)

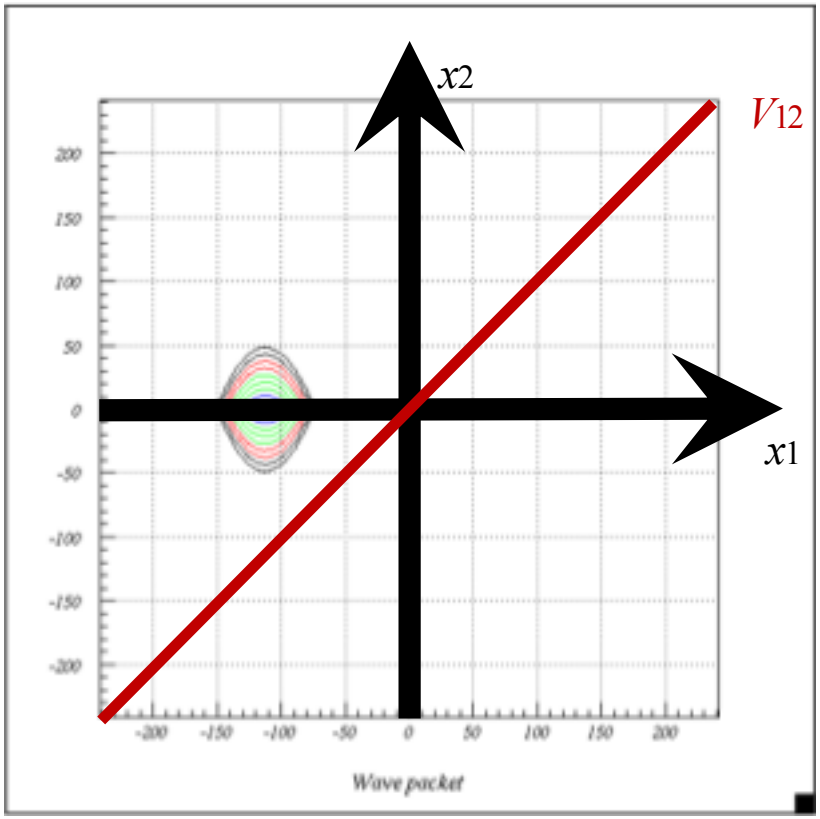


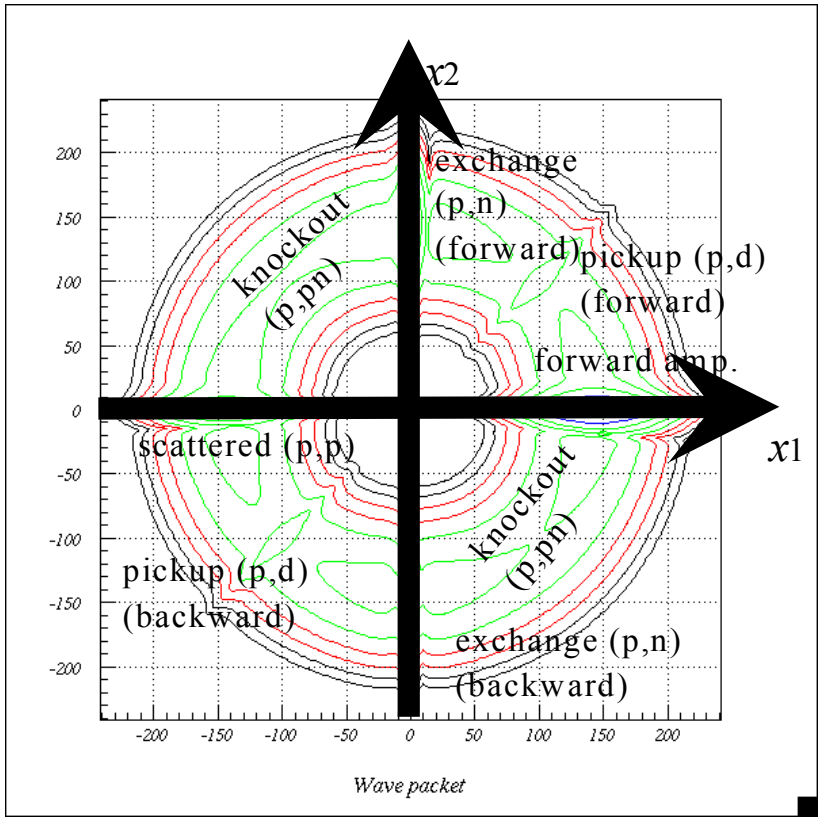
Interaction: V_{1c}, V_{2c}, V_{12} (~δ-function at x_1=0, x_2=0, x_1-x_2=0; attractive)

Case1:



forward amp.: transmitted + forward scattering

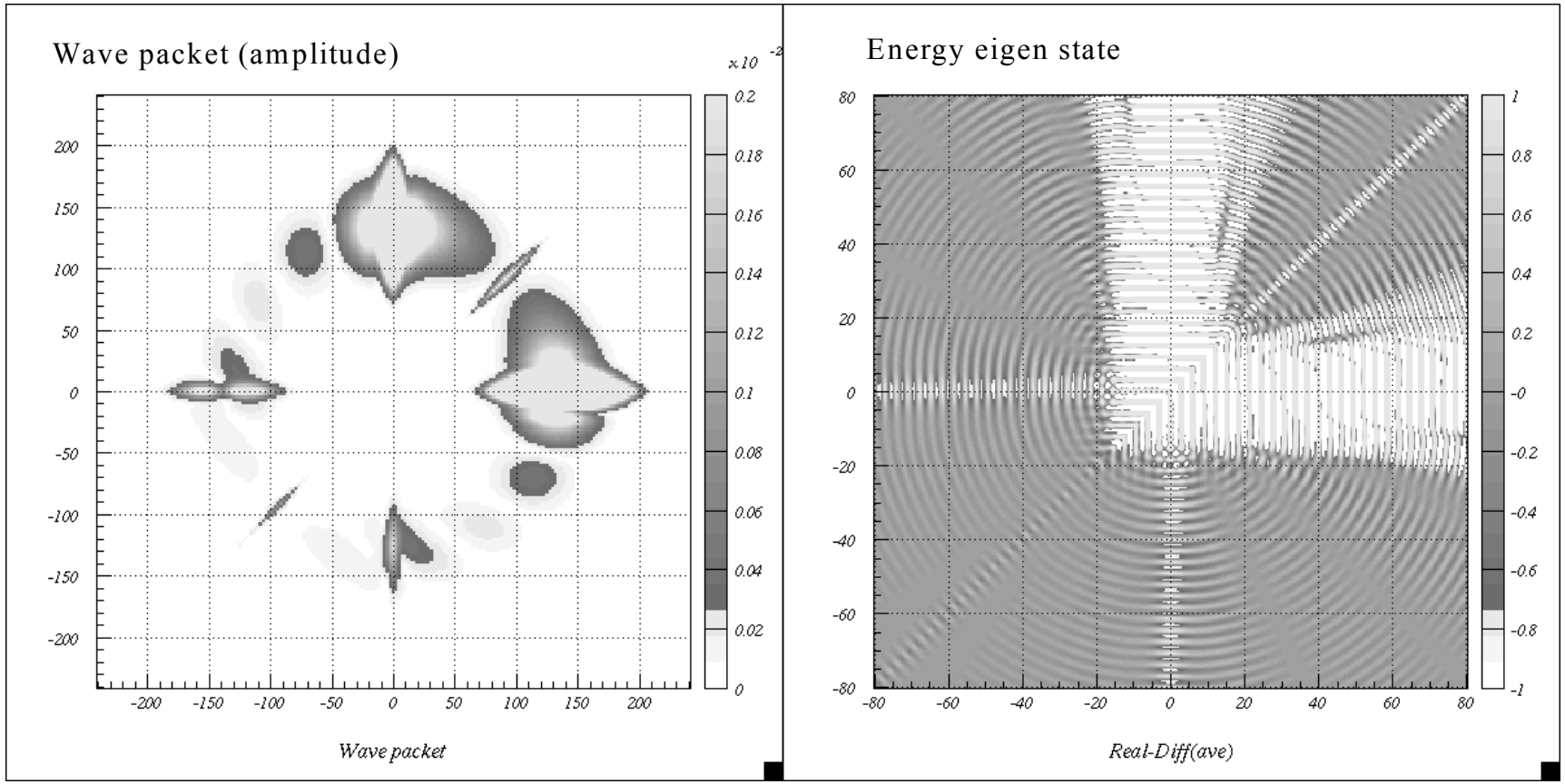




Time-dependent wave packet: $$\Psi(t,x) = \int_{-\infty}^{\infty} d\omega\ \Phi_\omega(x) \exp(i\omega t)$$

Energy eigen state: $$\Phi_\omega(x) = \int_{-\infty}^{\infty} dt\ \Psi(t,x) \exp(-i\omega t)$$

Energy eigen state is calculated by time dependent wave packet:



Other experiments

Inverse kinematics of $^{8}He(p,p\alpha)4n$