Experimental studies of the tetra-neutron system by using RI-beam

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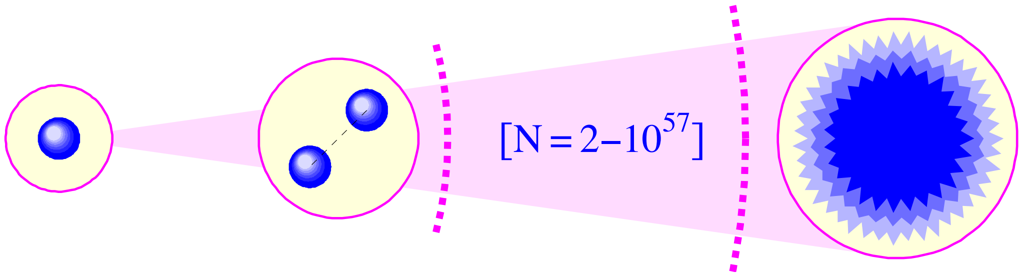
Tetra-neutron

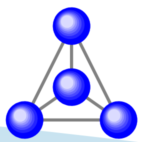
- Multi-neutron System
  - Neutron cluster (?) in fragmentation of ^{14}Be
    PRC65, 044006 (2002)
  - NN, NNN, NNNN interactions
    - T=3/2 NNN force
      -> 3-body force in neutron matter
    - Ab initio type calculations
  - Multi-body resonances
  - Correlations in multi-fermion scattering states

Neutral Nuclei : Tetraneutrons ?



- Facts :
  - the dineutron is unbound
  - neutron stars are bound
  - absolutely nothing in between
- Candidate systems ?
  - odd-even staggering favors even numbers
  - ideally look for 'magic' numbers (?)
  - hard to put many neutrons together !

  ⟹ best case is ^{4}n :



- Implications ?
  - bound multi-neutrons :
    - → Big Bang nucleosynthesis
    - → neutral ('dark') matter
    - → + few protons ? Matter 'islands' !
  - any multi-neutron :
    - → n-n interaction
    - → few-body (3-4) effects
    - → neutron stars ...

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)

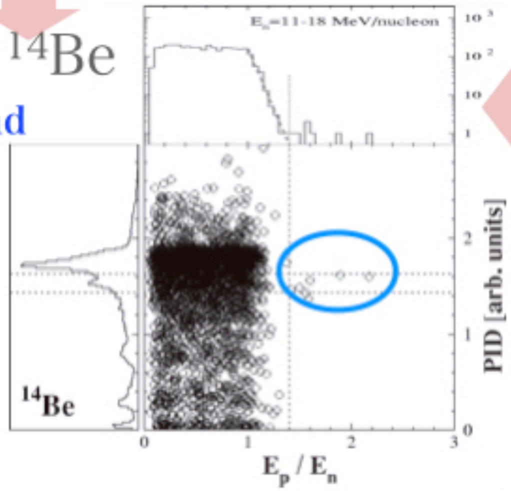
Bound state: No clear evidence.

2000s

Breakup of ^{14}Be

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

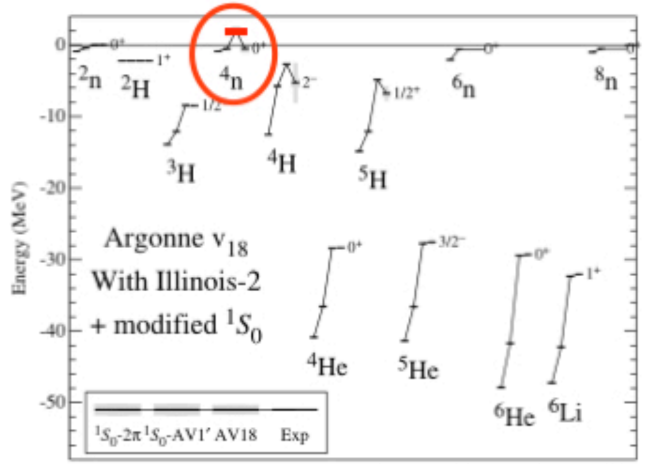
F. M. Marques, et al, Phys. Rev. C 65, 044006 (2002)



2000s

Theoretical work

- ab-initio calculation
  NN, NNN interaction

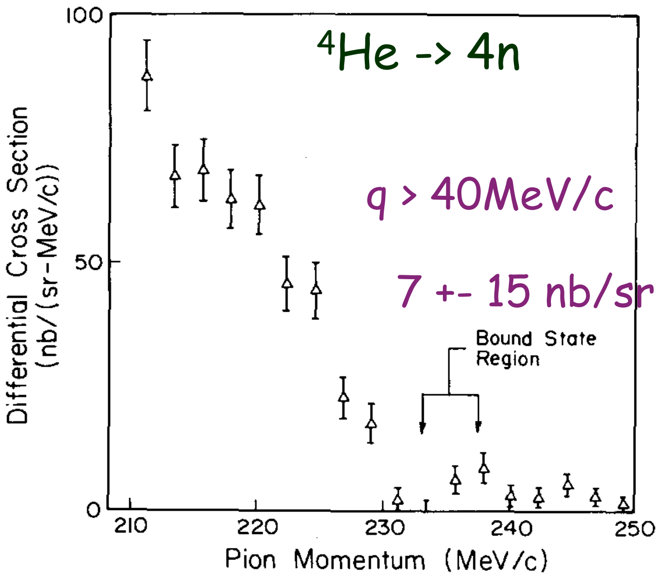


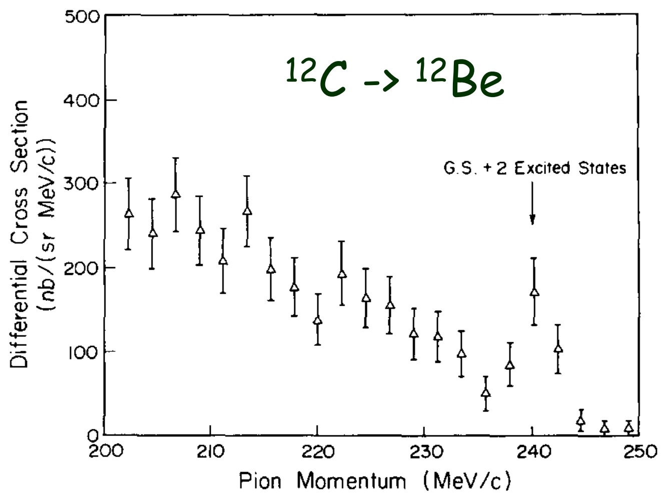
S. C. Piper, Phys. Rev. Lett. 90, 252501 (2003)

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

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

(π^-,π^+) reaction @ 165 MeV; $\theta_{\pi+}$ = 0 degree





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

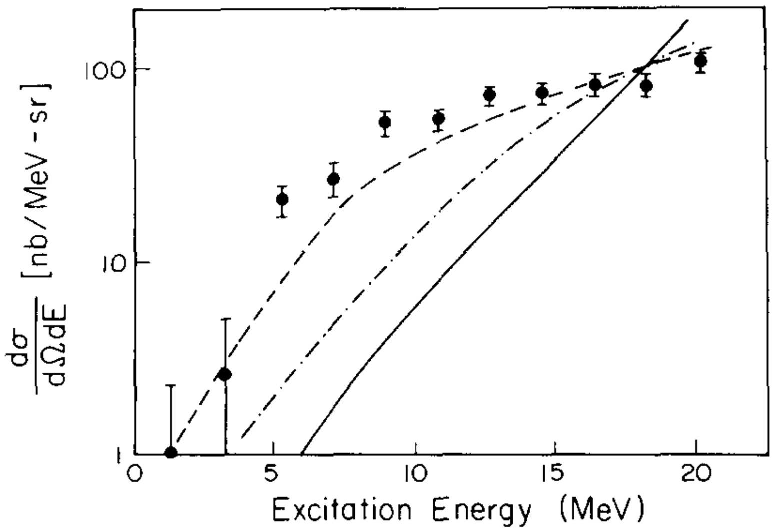
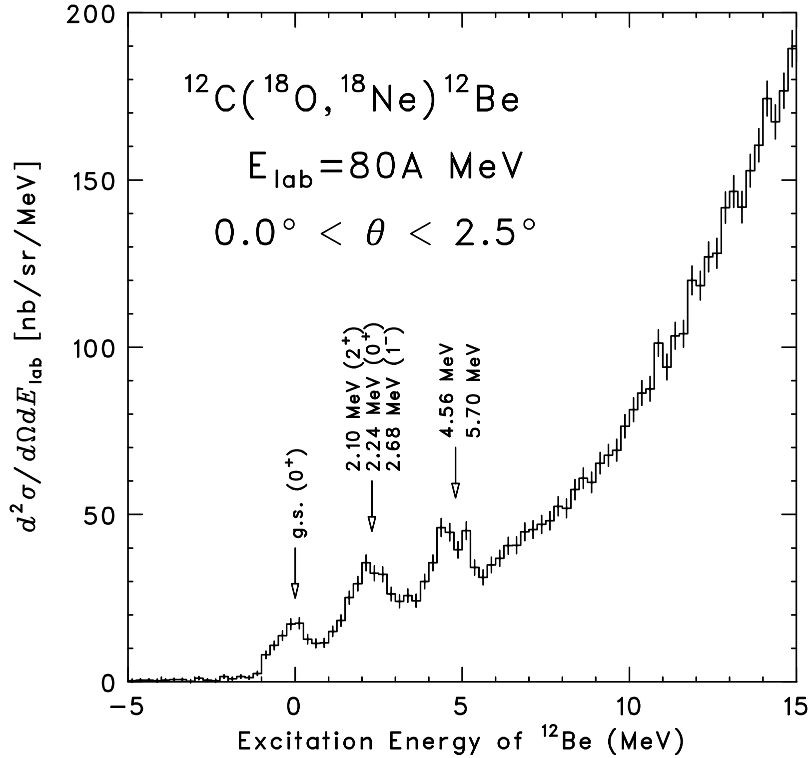


Fig. 3. The experimental results are plotted against the excitation of the final four-neutron state. The solid curve corresponds to the pure four-neutron phase space, while the dot-dashed and dashed curves are the four-neutron phase space curves with singlet state interactions in, respectively, one and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

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

Double charge exchange (DCX) reaction of HI

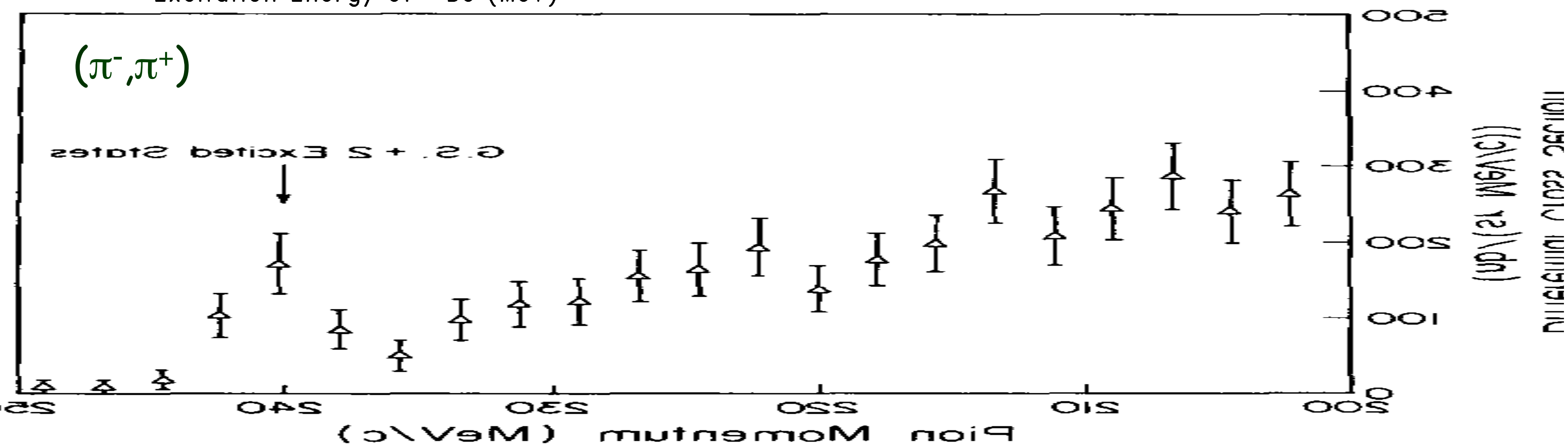


^{12}C -> ^{12}Be

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

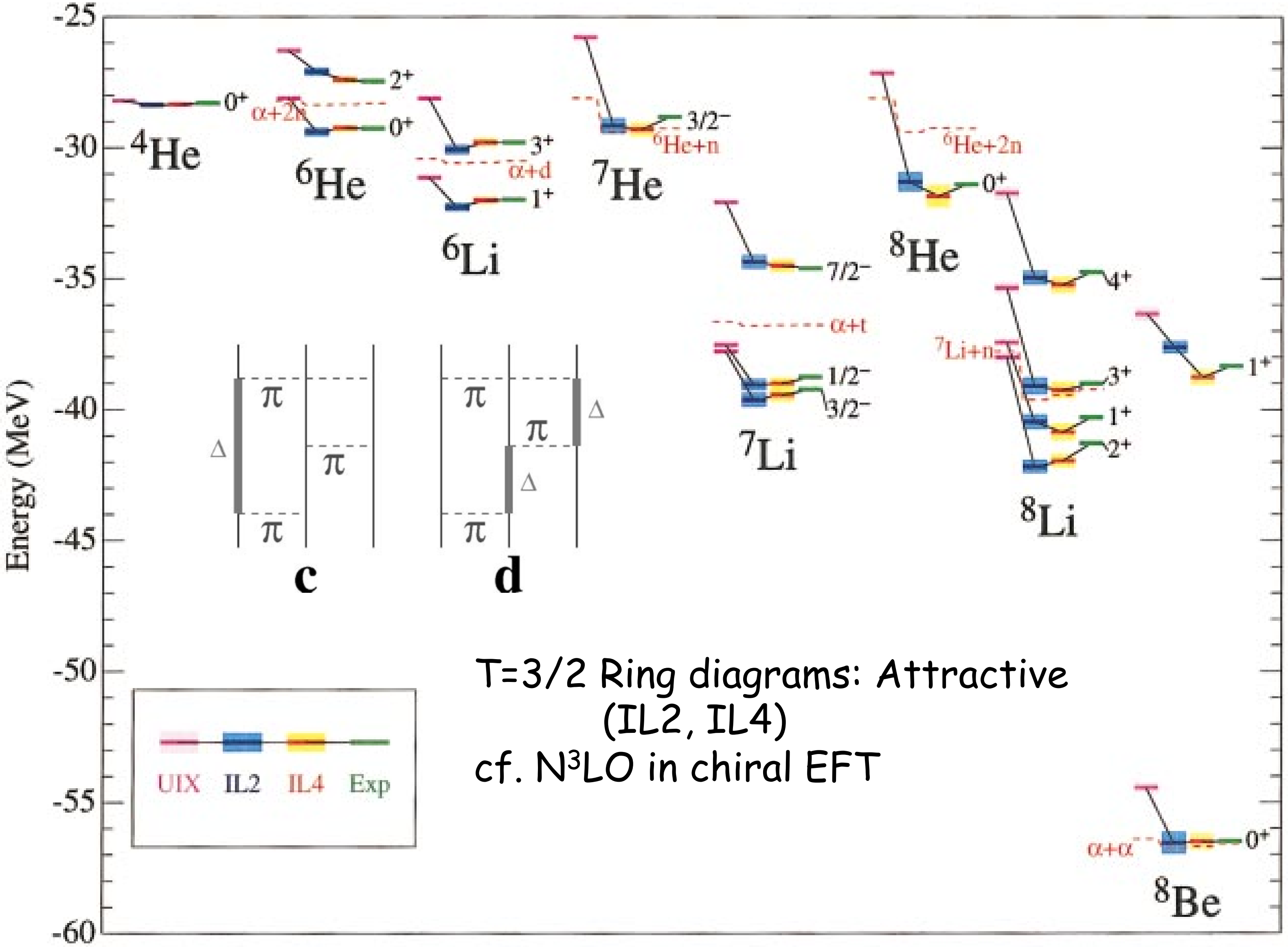
~70nb/sr (Gnd)
~200nb/sr (~2MeV)

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



3-body force

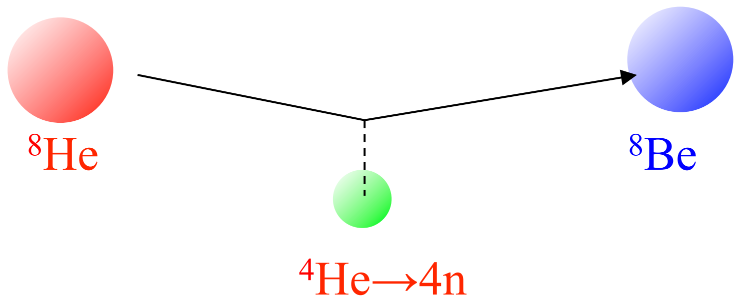
S. C. Pieper, et al., PRC 64, 014001



T=3/2 Ring diagrams: Attractive (IL2, IL4)

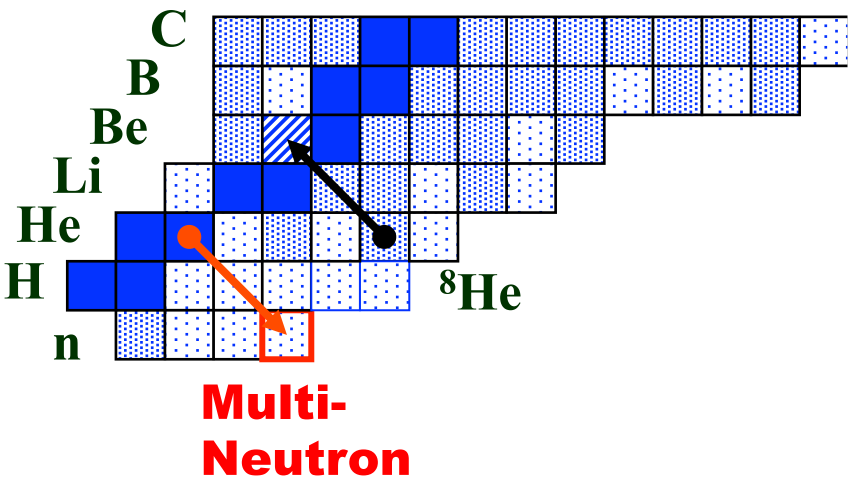
cf. N^3LO in chiral EFT

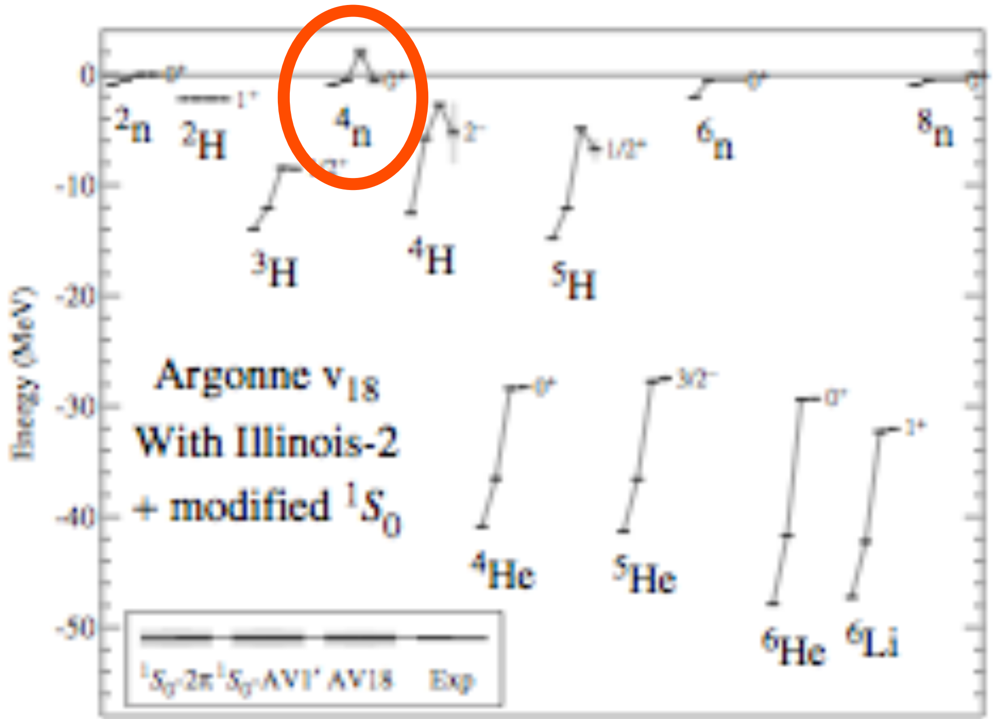
Tetra-neutron system produced by exothermic double-charge exchange reaction



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

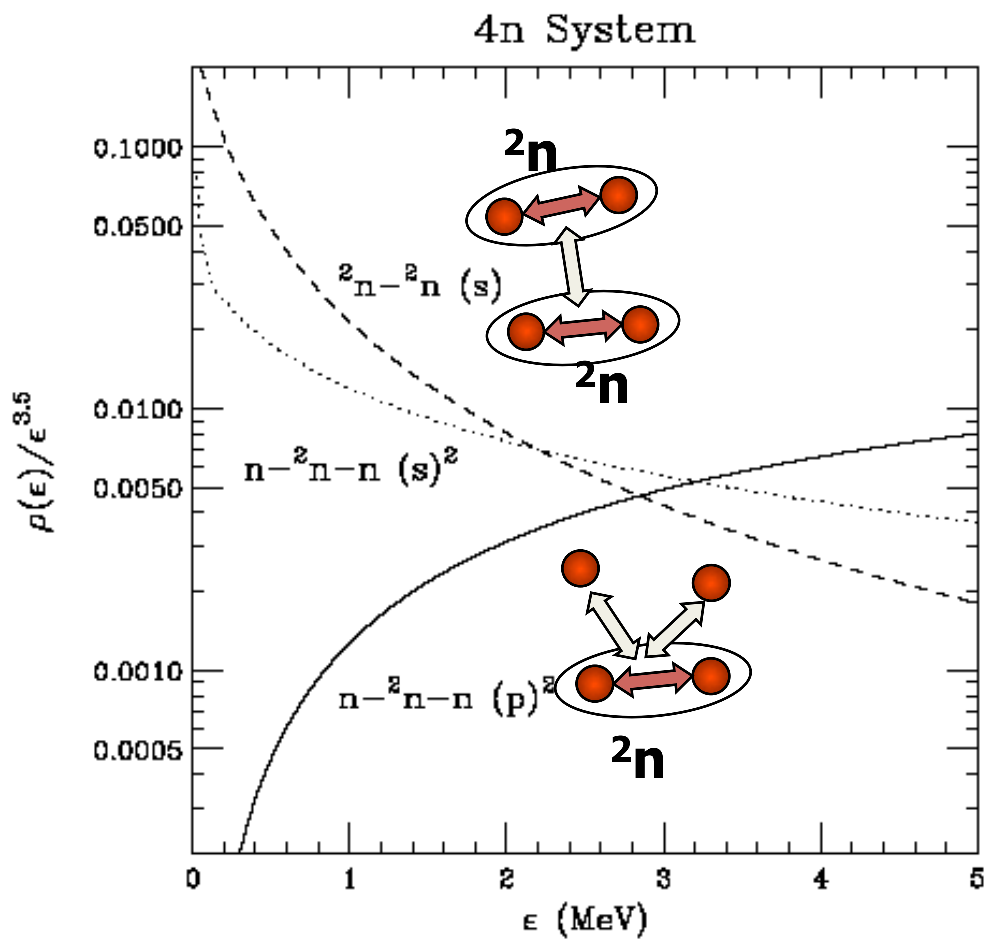




S.C. Pieper et al., PRL 90, 252501 (2003)

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

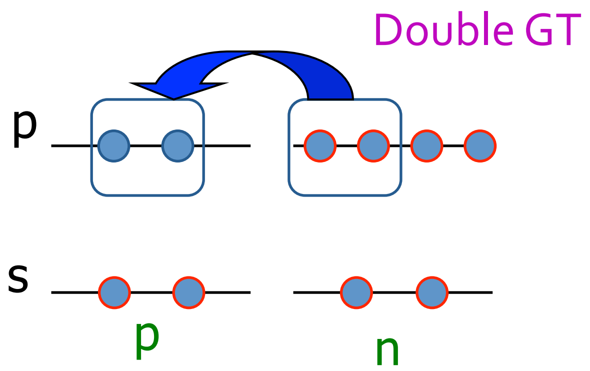
Correlation in multi-body continuum



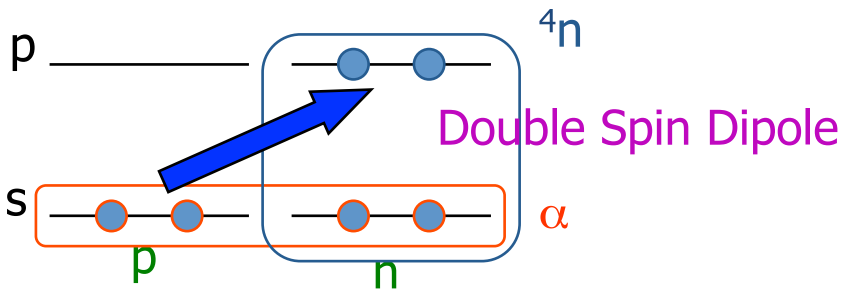
- Deviation from four-body phase space informs us the final state interaction(s) of sub-system

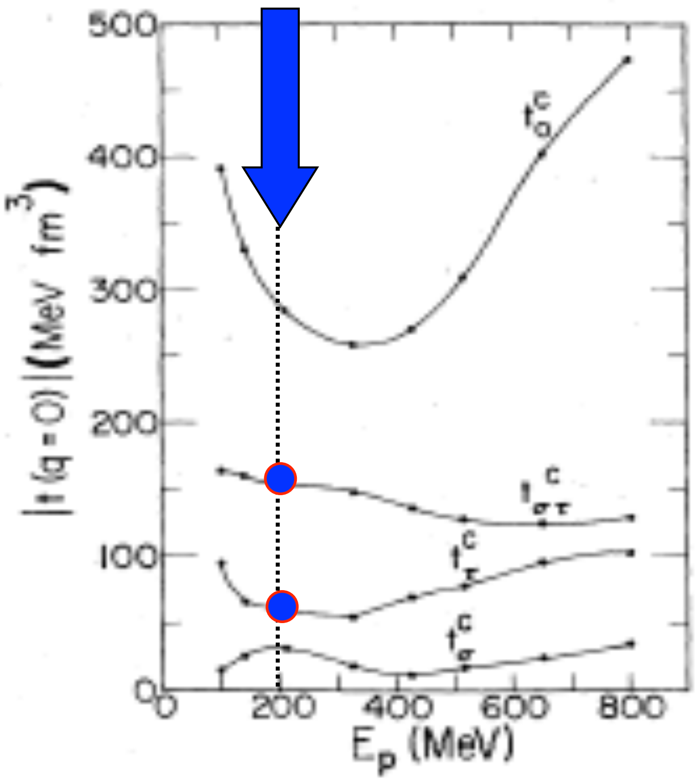
Reaction Mechanism

^{8}He → ^{8}Be



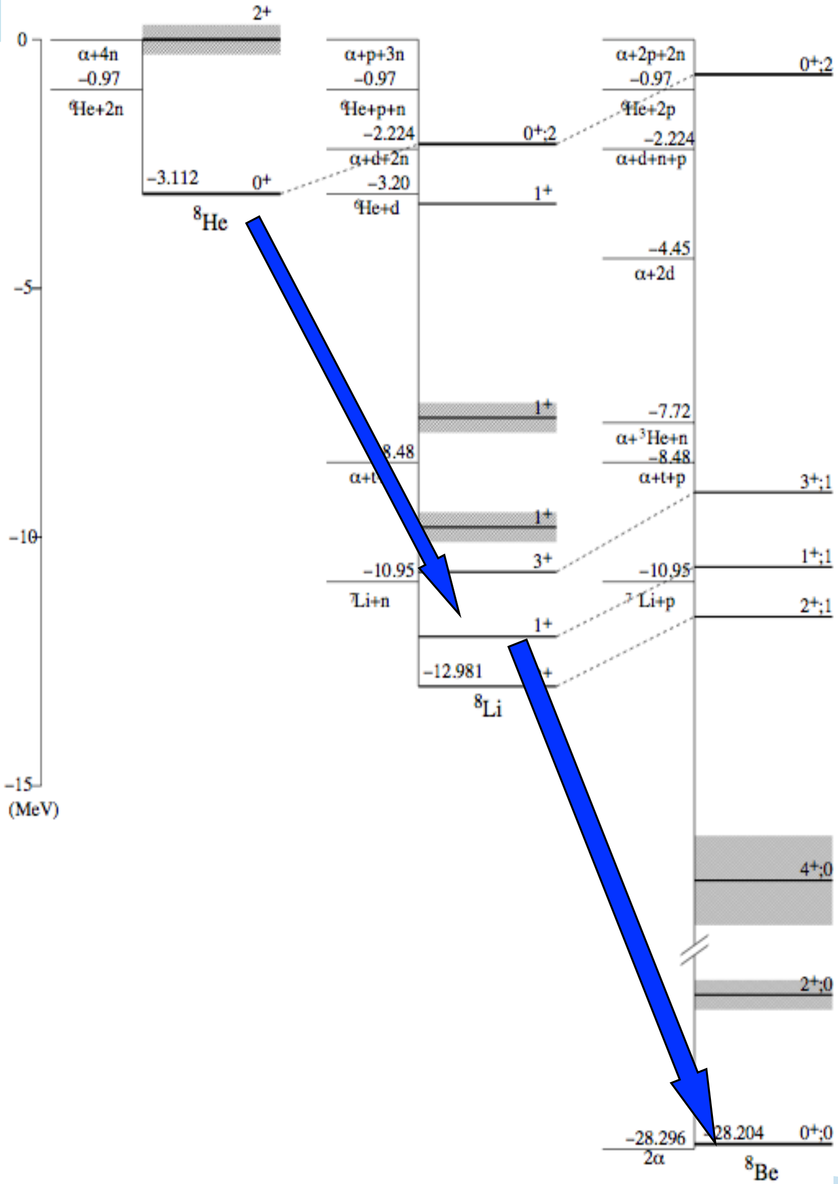
^{4}He → 4n

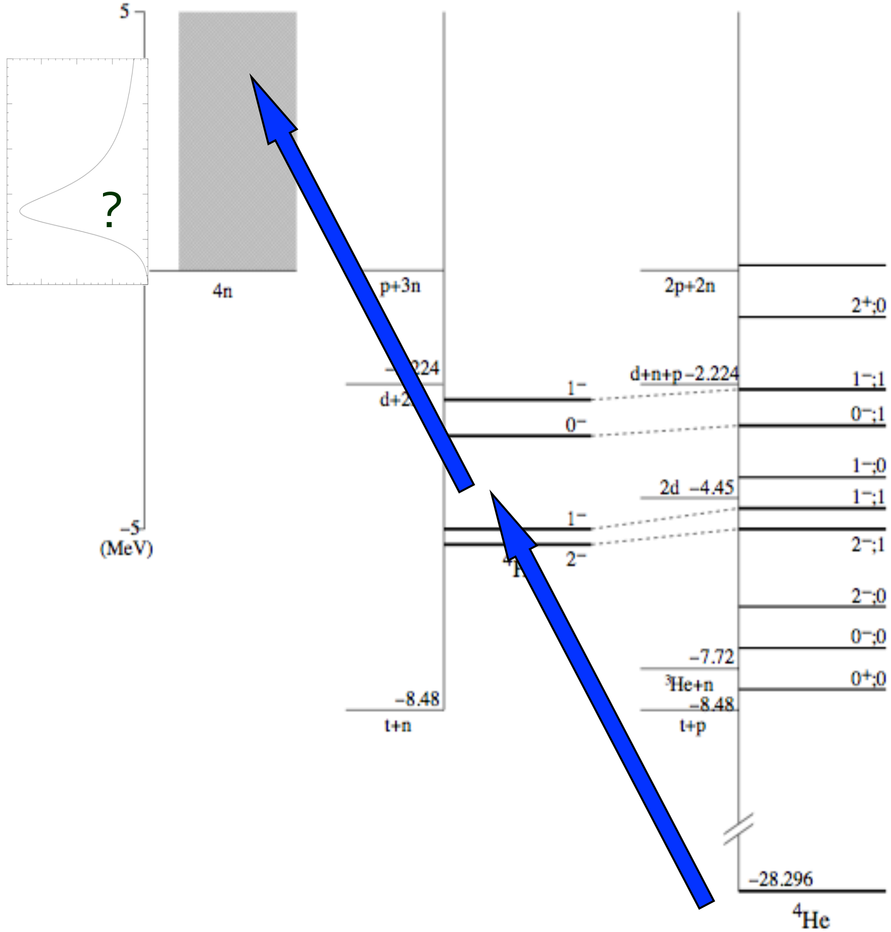




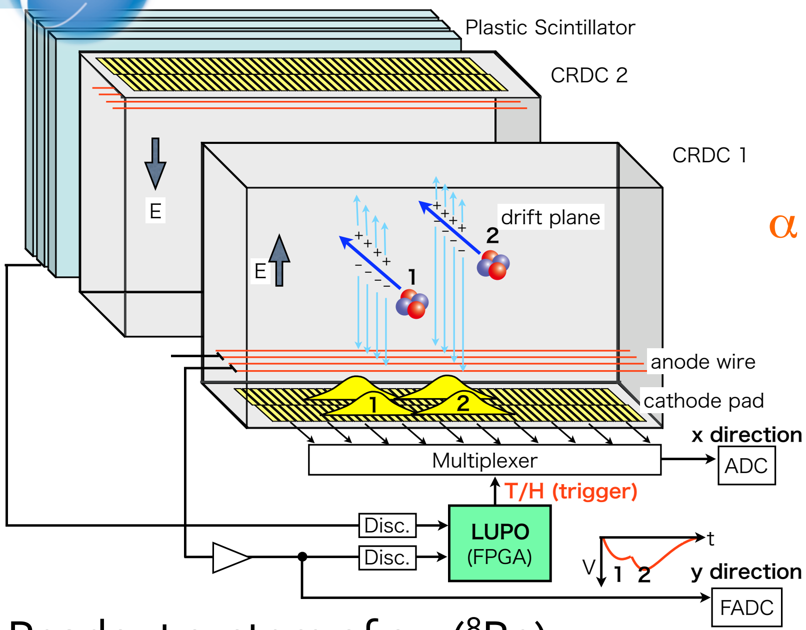
$$\left[\left(\vec{\tau}_{\mathrm{p}}\cdot\vec{\tau}_{\mathrm{t}}\right)\left(\vec{\sigma}_{\mathrm{p}}\cdot\vec{\sigma}_{\mathrm{t}}\right)r_{\mathrm{t}}Y_1\left(\hat{r}_{\mathrm{t}}\right)\right]^2$$

Level diagrams

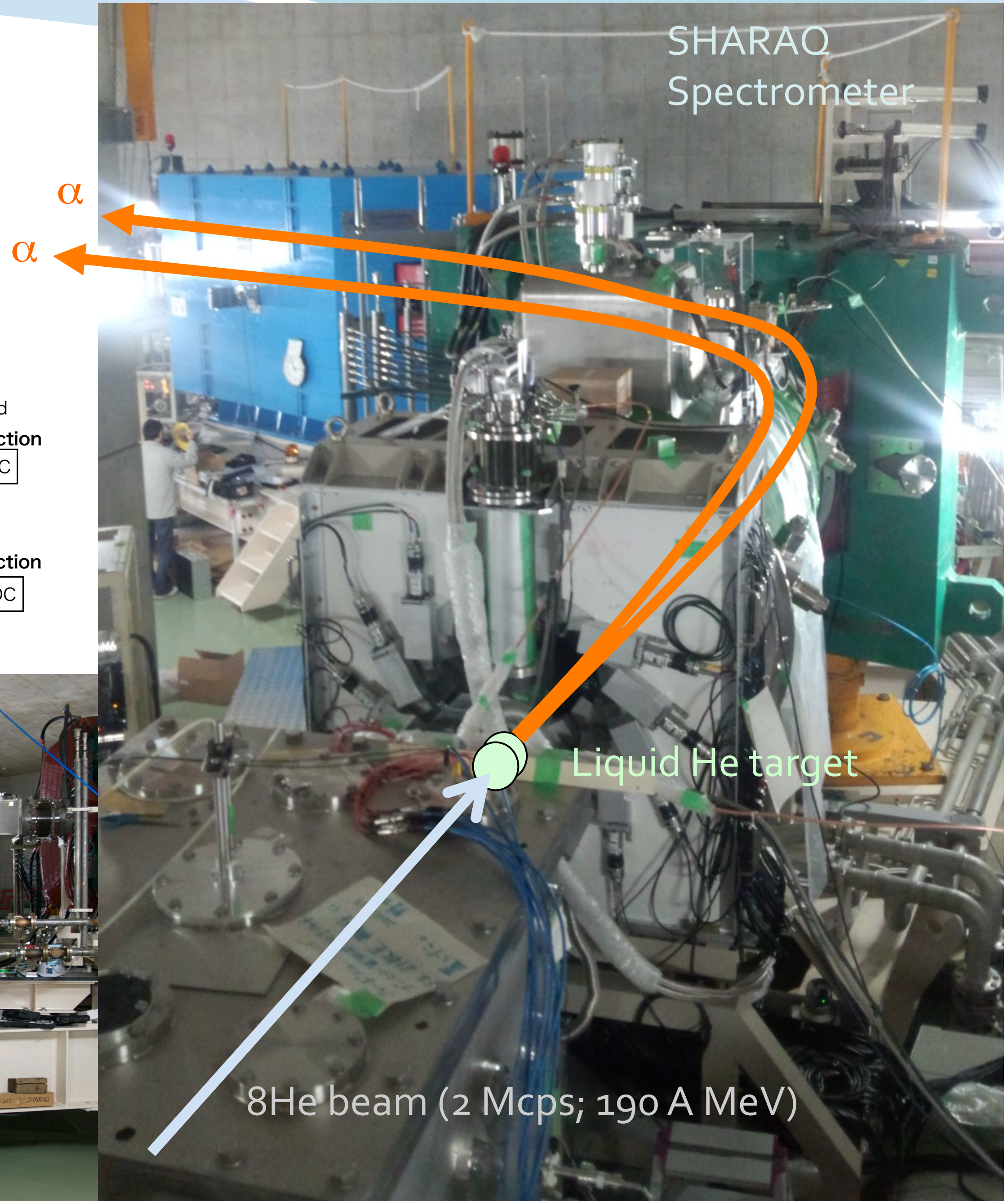




q_{min} ~ 10MeV/c

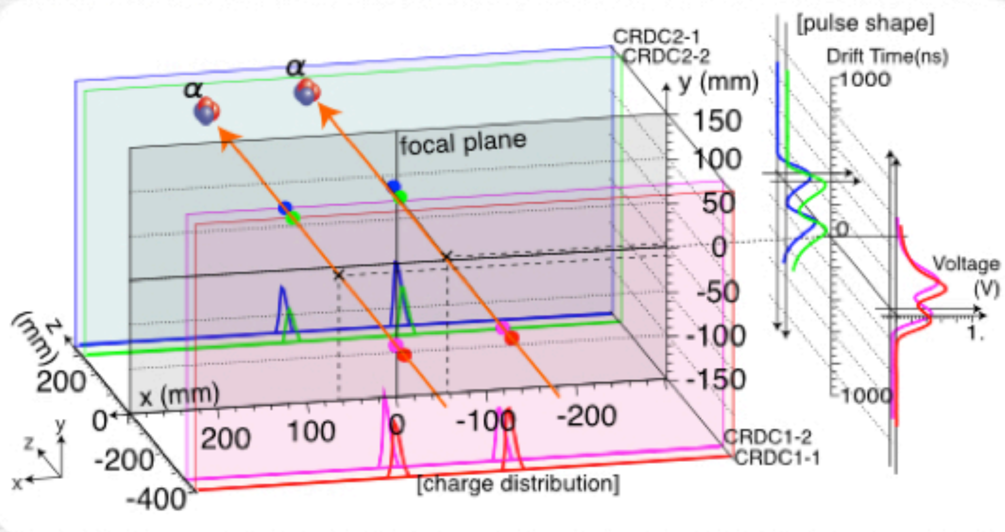


Readout system of 2α (^{8}Be)

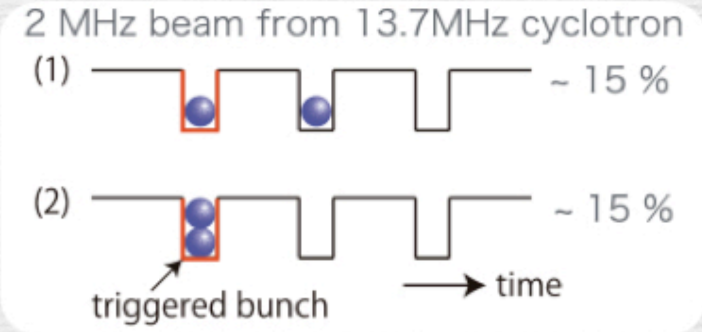


Analysis

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



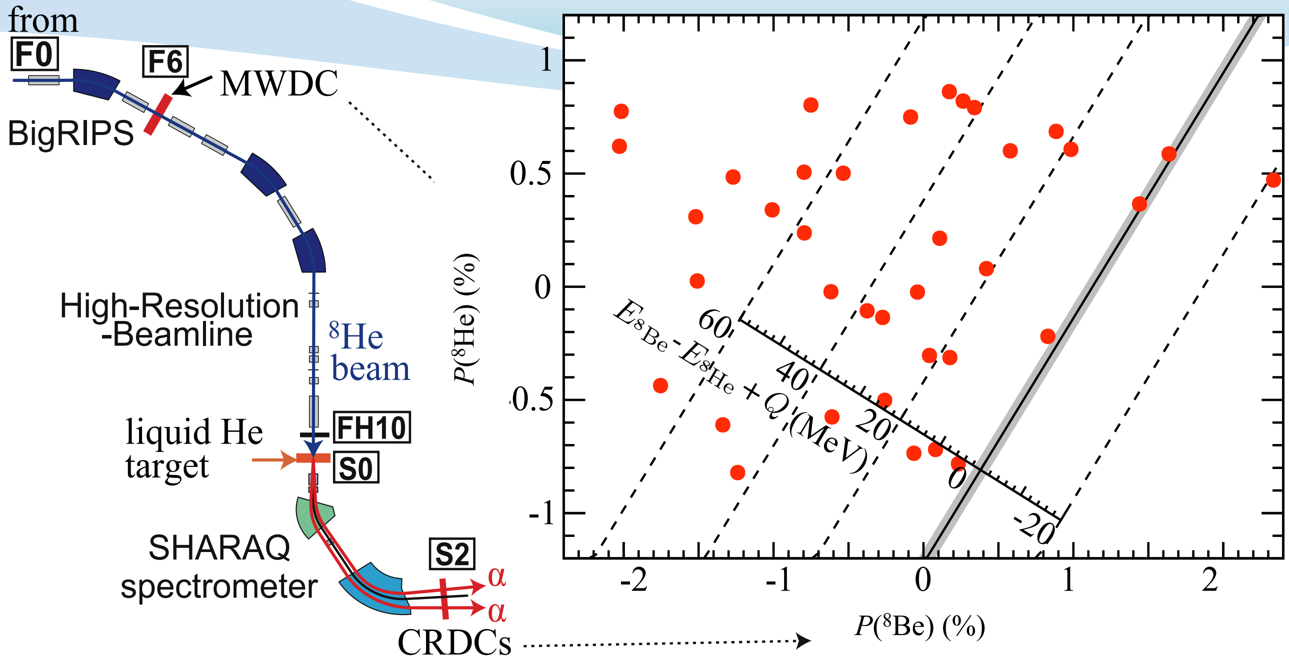
Background process:
Breakup of two ^{8}He in the same beam bunch to two alpha particle
Identified by multi-hit in F6-MWDC

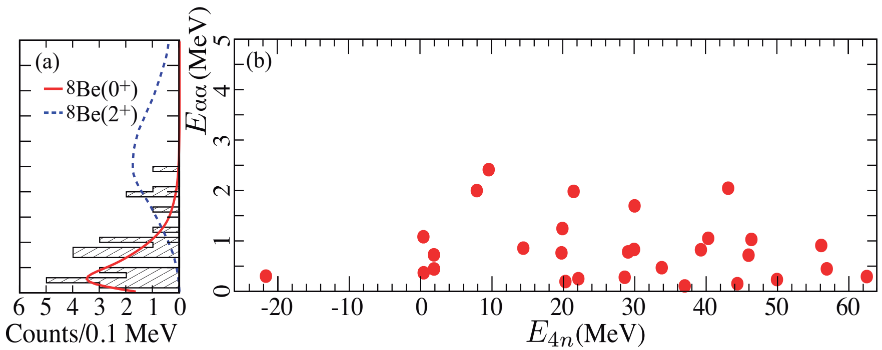


- Background Estimation
  - Shape in spectrum: random 2α
  - Number of events:
    - failure of the multi-particle rejection at MWDC
    - multi-particle in one cell of MWDC

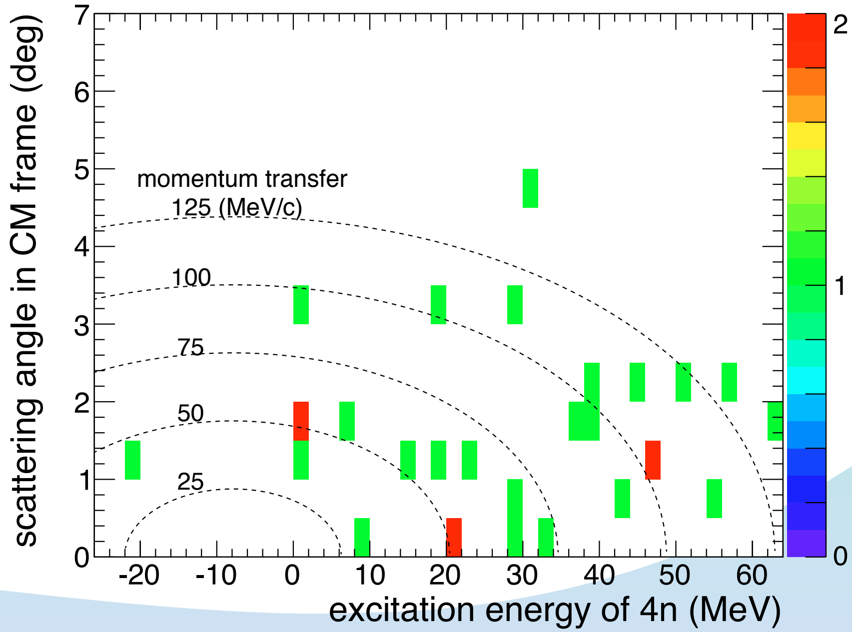
Backgrounds after analysis:
Finite efficiency of multi-hit events at F6-MWDC

Experimental Results

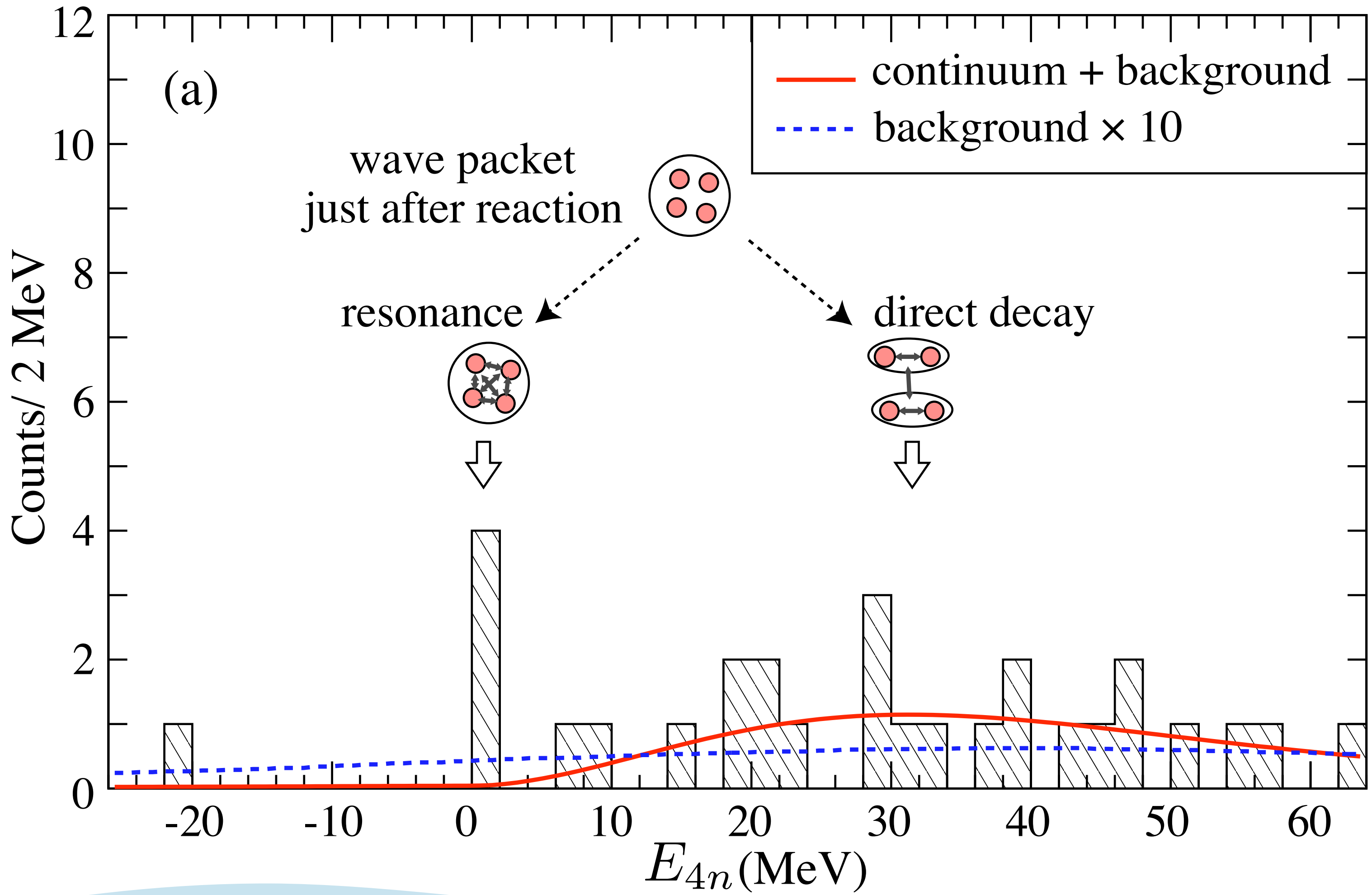




Acceptance for ^{8}Be(2+) was 13 % of that for ^{8}Be(0+)
A few events could be from ^{8}Be(2+).



Experimental Results

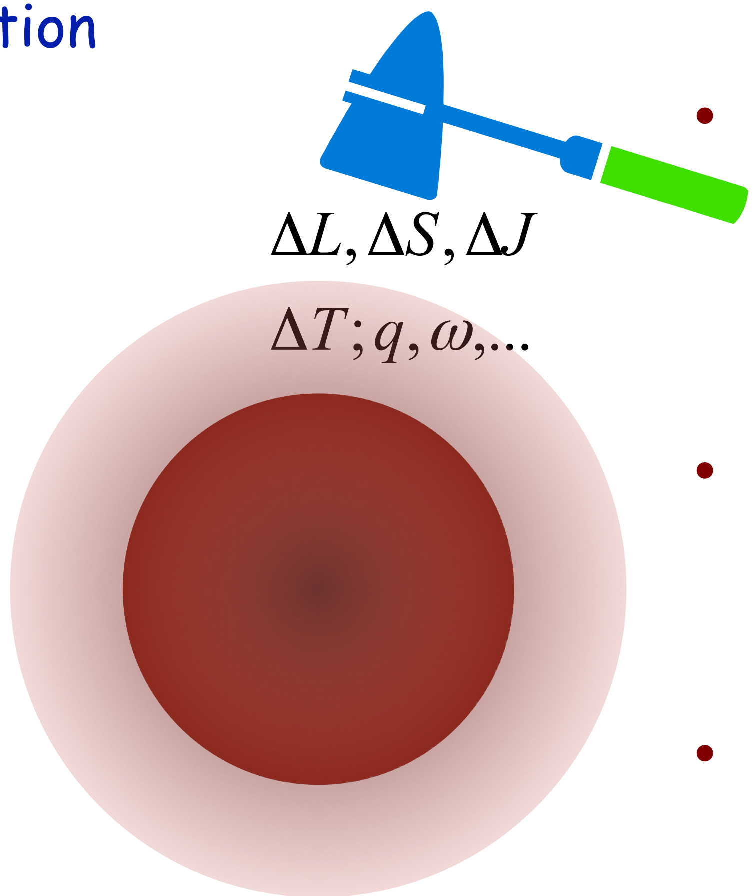


Studies of Nuclei via Direct reactions

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

"Hit and analyze the sound"

Direct Reactions



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

Transition Probabilities

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

if distortion is insensitive to ω

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

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

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

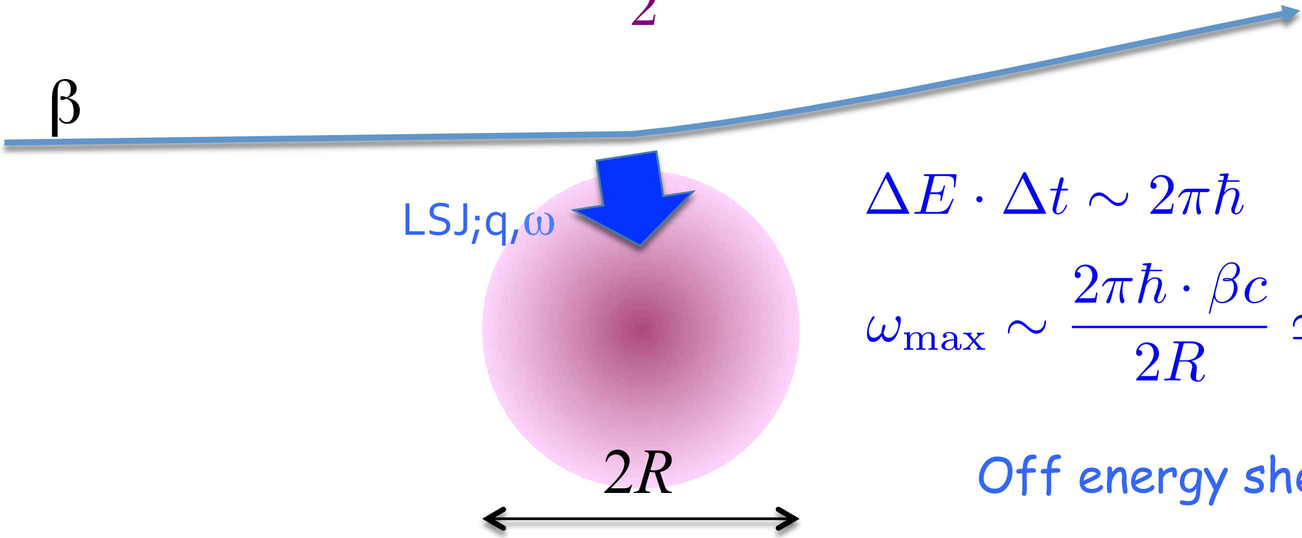
$\left|M_{if}(E_f)\right|^2$: Energy Spectrum

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

Decoupling of "Scattering" and "Transition" for intermediate-energy "inelastic scattering"

Criteria for decoupling

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



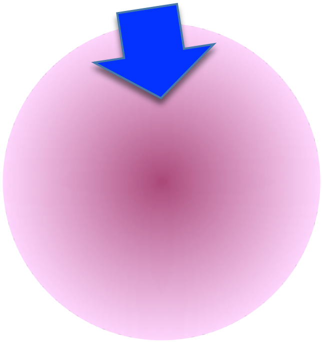
$$\Delta E \cdot \Delta t \sim 2\pi\hbar$$

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

Off energy shell

E/A > 100 MeV satisfies the decoupling conditions
E/A ~ 10 MeV may be marginal

"Transition" as time-dependent action



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

$$\Psi\left(t\right)=\sum_i a_i\left(t\right)\psi_i\exp\left(-iE_it/\hbar\right)$$

$$H\psi_i=E_i\psi_i$$

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

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

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

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

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

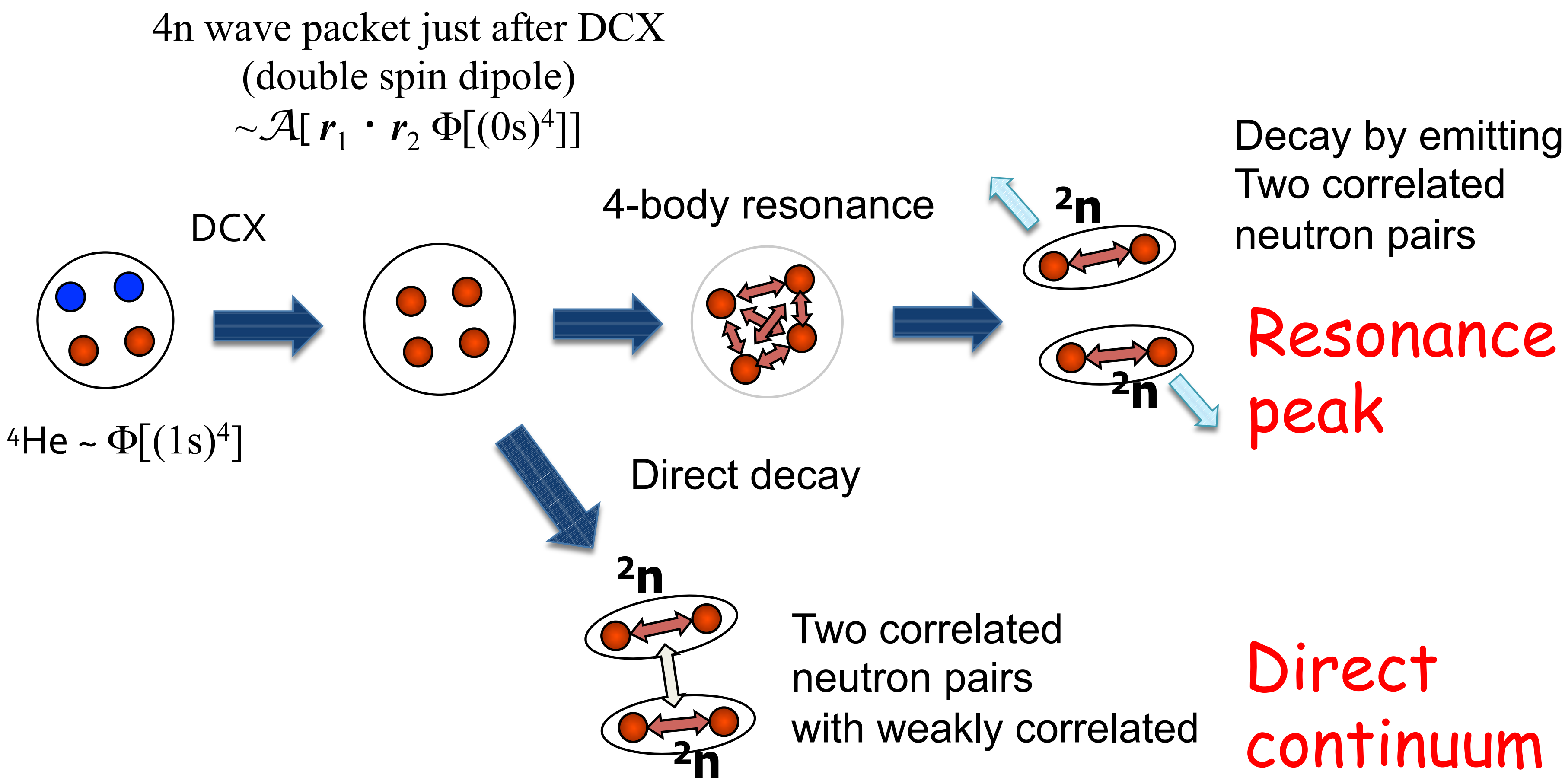
Perturbation

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

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

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

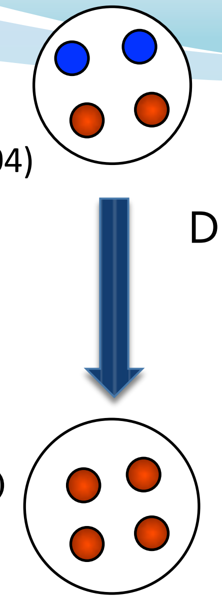
Picture of ^{4}He DCX reaction @ 200 A MeV



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

$q << 200$ MeV/c

4n wave packet just after DCX

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

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

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

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

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

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

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

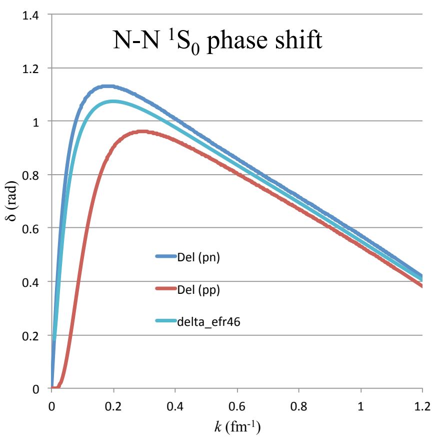
$$\int \left|\mathcal{A}\tilde{\Phi}_0\right|^2 d^3k\, d^3k_{12}\, d^3k_{34}\, \delta(E - \epsilon - \epsilon_{12} - \epsilon_{34}) \propto X^{11/2}\exp(-X)$$

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

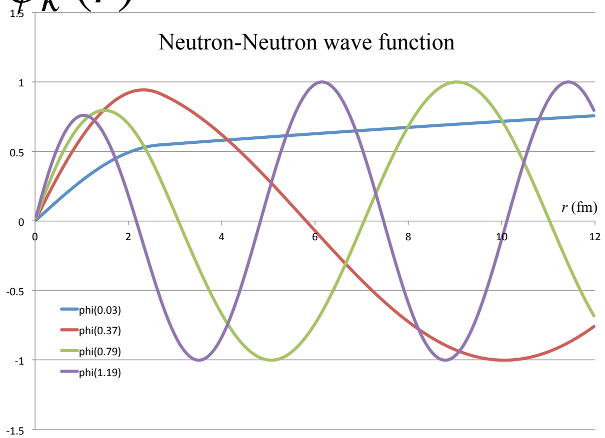
$$X = E/\epsilon_a \qquad \epsilon_a = \frac{\hbar^2}{m_N a^2} = 11\text{MeV}$$

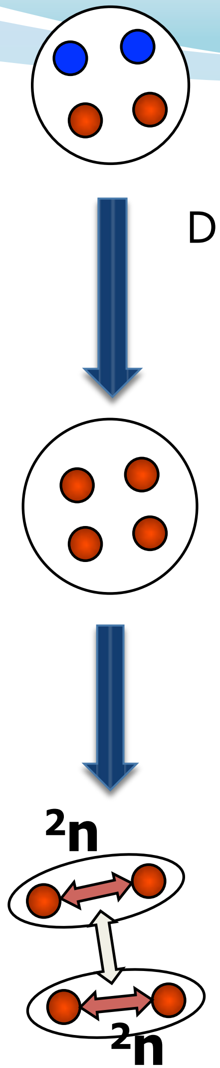
NN FSI

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

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

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

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

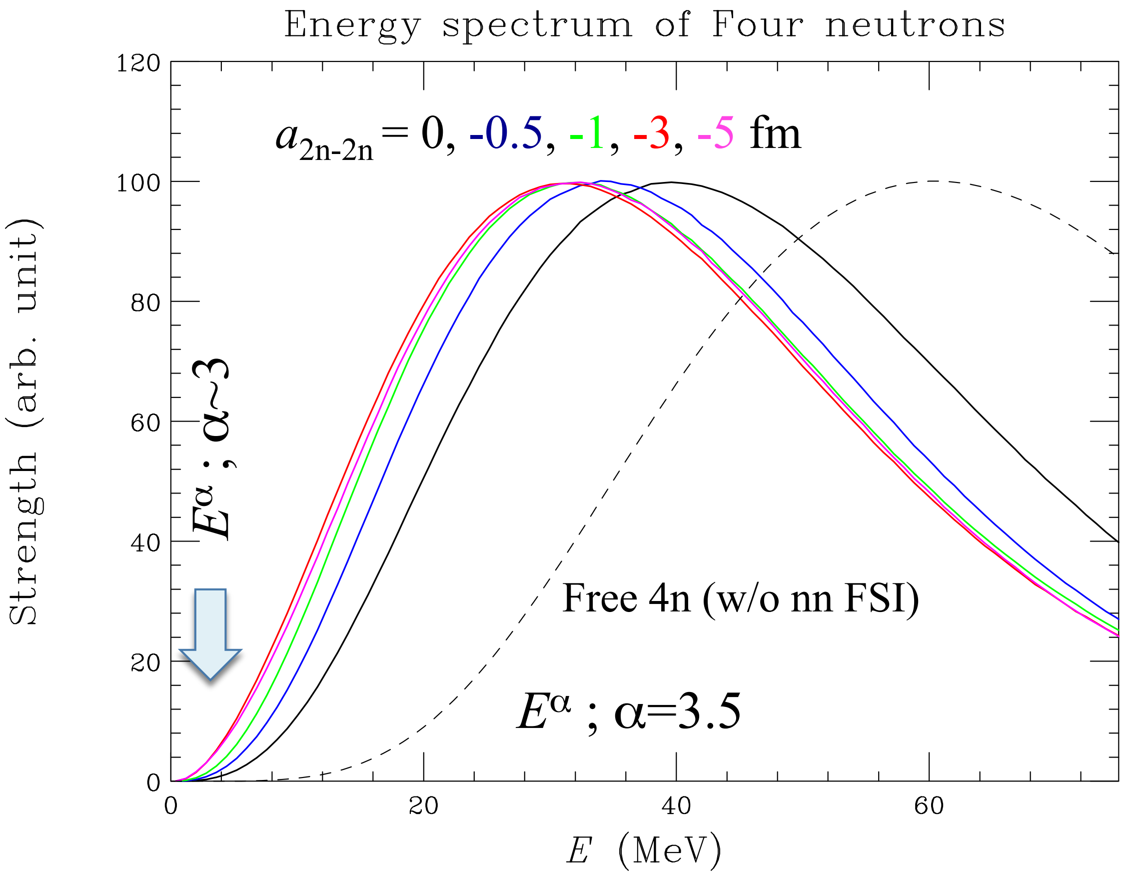
Expand $\mathcal{A}\Phi_0$ with correlated n-n scattering wave $\phi_k(r)$

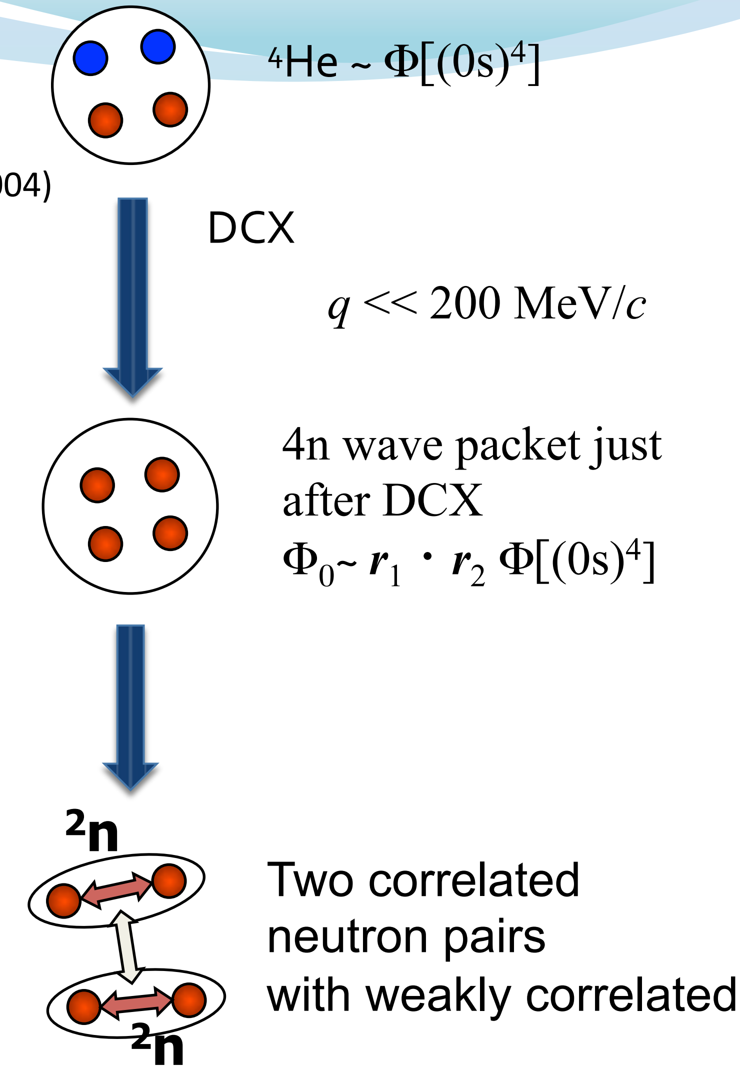
$A(k)$'s are used instead of Fourier component

Direct Part

Continuum spectrum with n-n FSI

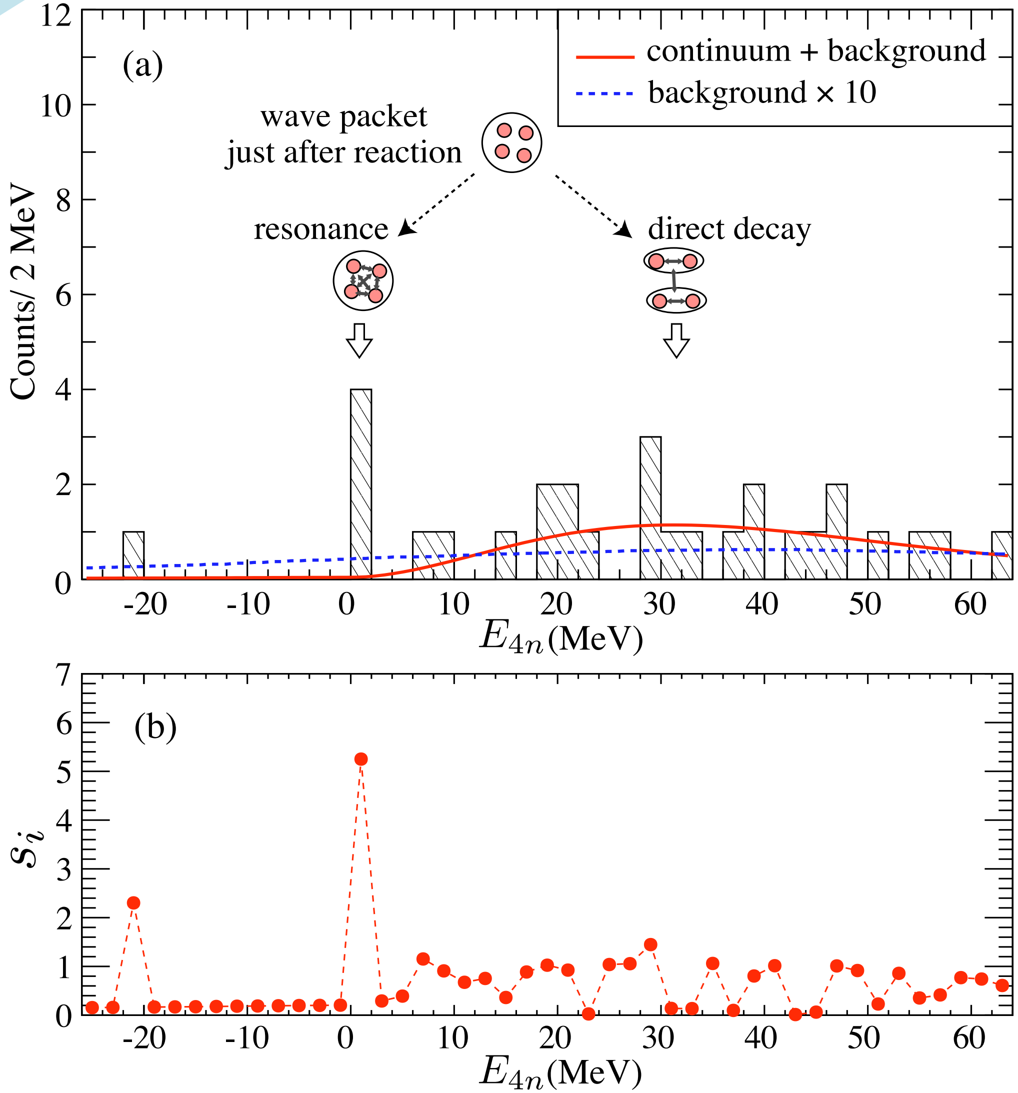
c.f.
L.V. Grigorenko, N.K. Timofeyuk, M.V. Zhukov, Eur. Phys. J. A 19, 187 (2004)





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 $\theta_{cm}< 5.4$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

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

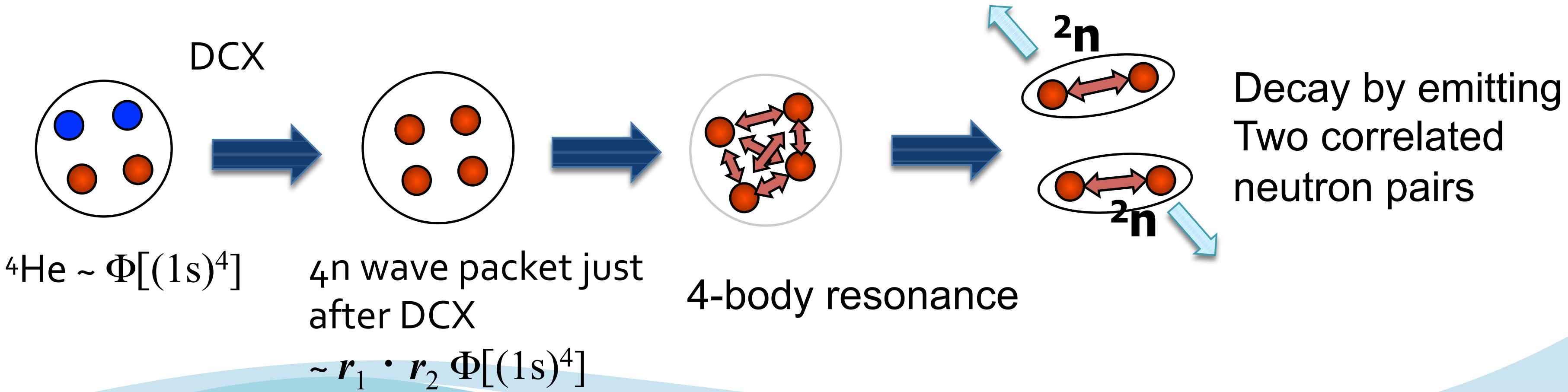
Re: Width of possible 4n resonance

$$W\left(E,\epsilon_{12},\epsilon_{34}\right) \propto \frac{2\gamma_{\mathrm{2n-2n}}^{2} P\left(E-\epsilon_{12}-\epsilon_{34}\right)}{\left(E-E_{0}\right)^{2}+\left[\frac{1}{2}\Gamma\left(E\right)\right]^{2}} D_{\mathrm{nn}}\left(\epsilon_{12}\right) D_{\mathrm{nn}}\left(\epsilon_{34}\right)$$

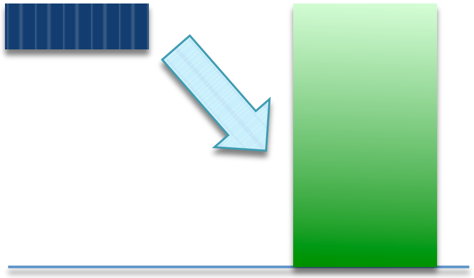
$$\begin{aligned}\Gamma\left(E\right) &= 2\gamma_{\mathrm{2n-2n}}^{2} \int\int d\epsilon_{12} d\epsilon_{34} P\left(E-\epsilon_{12}-\epsilon_{34}\right) D_{\mathrm{nn}}\left(\epsilon_{12}\right) D_{\mathrm{nn}}\left(\epsilon_{34}\right) \\ &= 2\gamma_{\mathrm{2n-2n}}^{2} P_{\mathrm{eff}}\left(E\right)\end{aligned}$$

$$W\left(E\right) \propto \frac{\Gamma\left(E\right)}{\left(E-E_{0}\right)^{2}+\left[\frac{1}{2}\Gamma\left(E\right)\right]^{2}}$$

$$\gamma_{\mathrm{2n-2n}}^{2} \simeq \frac{3\hbar^{2}}{2m_{\mathrm{N}}a_{\mathrm{ch}}^{2}} \simeq 8.2\ \mathrm{MeV}$$

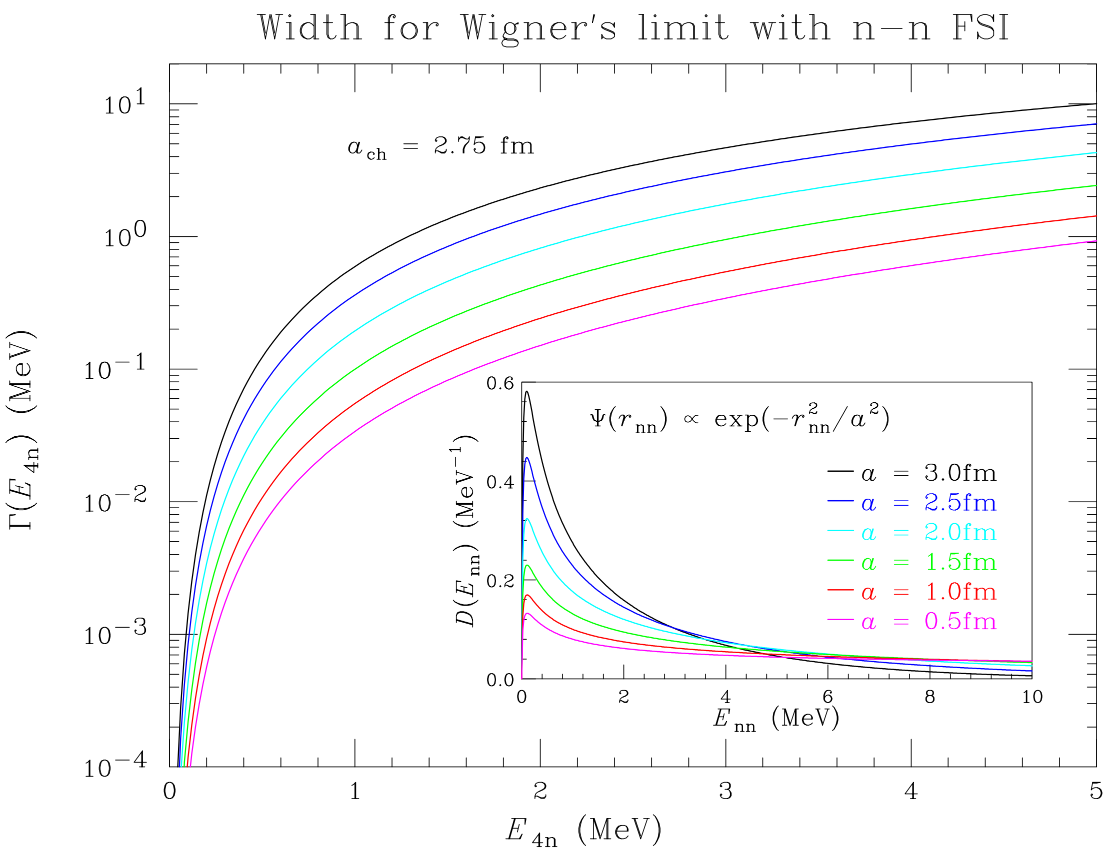


Width for Wigner's limit



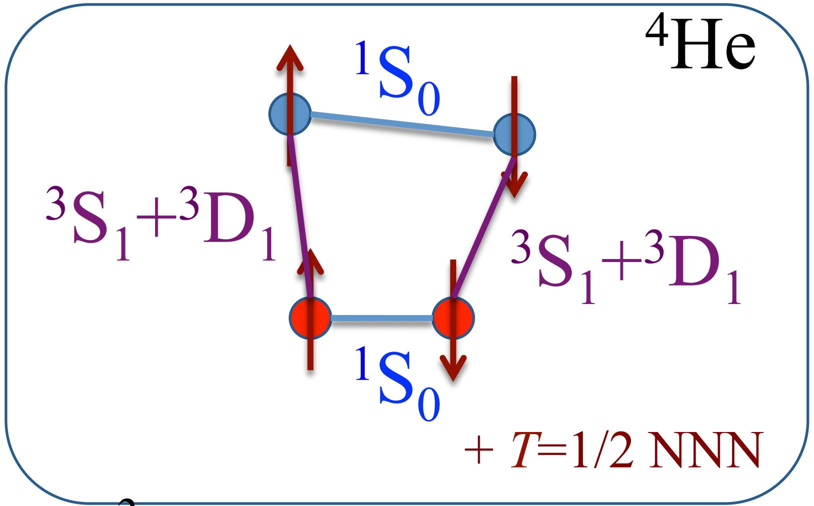
$$\Gamma = 20 \sim 700\ \mathrm{keV}$$
$$@\ E_0 \sim 1\mathrm{MeV}$$

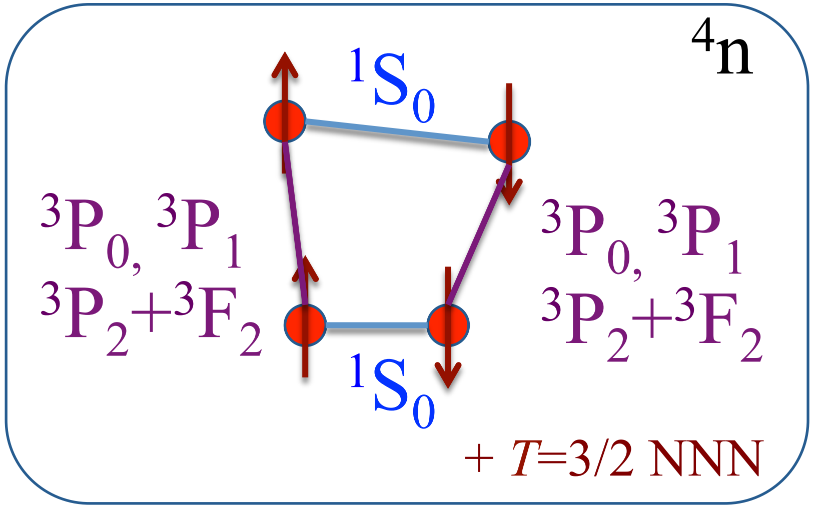
There might be sharp resonance due to small phase space for four-body decay, even for s-wave



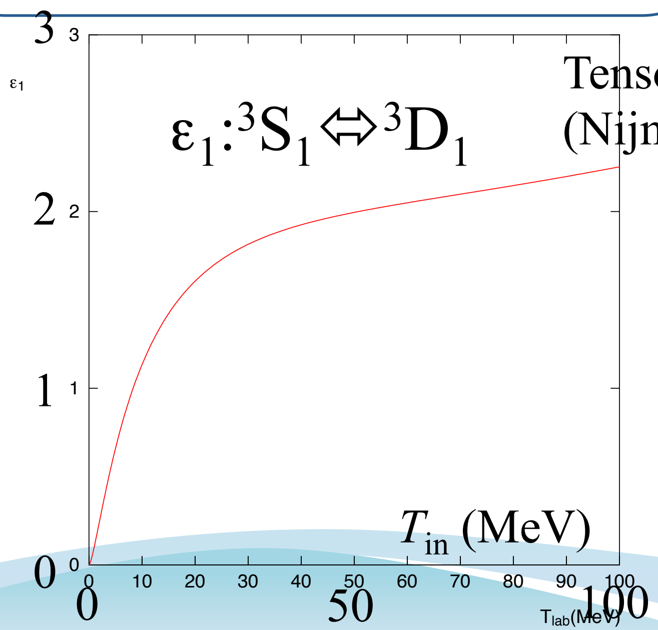
Speculation: Relation between ^4He and ^4n (if any)

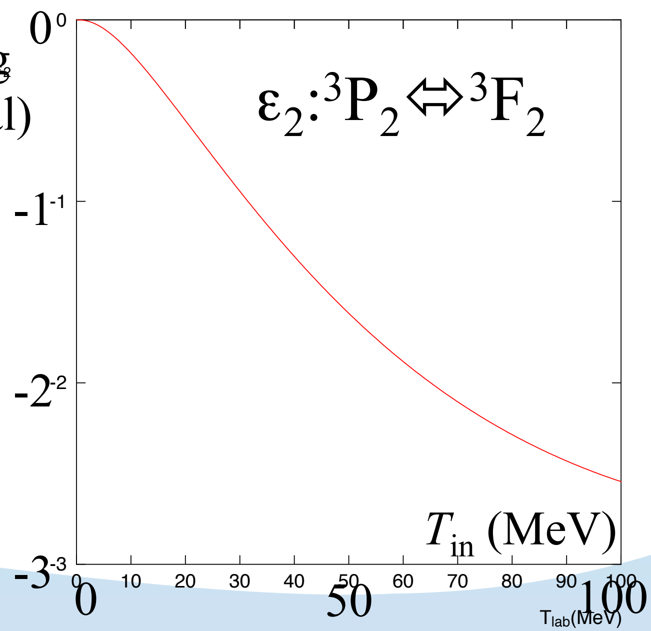
Exact Four-body calculation is expected to be performed, but ...





Tensor Coupling
(NijmII potential)





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

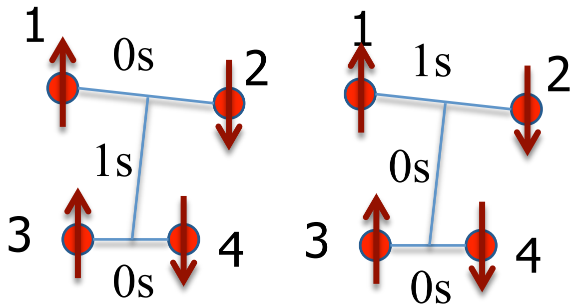
All of three can produce recoil-less condition

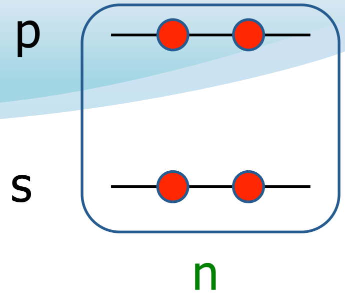
Three approaches produce different initial wave packets of 4n

- resonance/continuum will be different

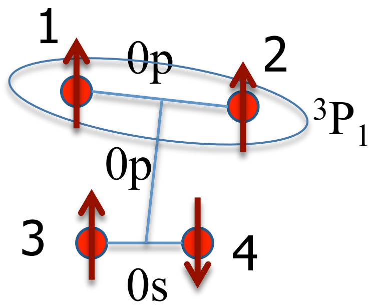
Missing consideration

4n wave packet of 0^+ just after DCX:
we assume
$\Phi_0 \sim \boldsymbol{r}_1 \cdot \boldsymbol{r}_2\, \Phi[(0s)^4]\, \chi(1,2)\chi(3,4)$





but another is possible:
$\Phi_0^{3P} \sim (\boldsymbol{r}_1 \times \boldsymbol{r}_2) \cdot \boldsymbol{X}(1,2)\, \Phi[(0s)^4]\, \chi(3,4)$
$\sim (\boldsymbol{r}_{12} \times \boldsymbol{r}_\alpha) \cdot \boldsymbol{X}(1,2)\, \Phi[(0s)^4]\, \chi(3,4)$
$[{}^3P_1 \times L=1]_{J\pi=0+}$ ***X***(1,2): Spin Triplet WF



jj coupling ⇔ *LS* coupling

$$\Psi^{l_1 l_2}_{JM}(j_1, j_2) = \sum_{L,S} \hat{j}_1 \hat{j}_2 \hat{L} \hat{S} \begin{bmatrix} l_1 & s_1 & j_1 \\ l_2 & s_2 & j_2 \\ L & S & J \end{bmatrix} \Phi^{l_1 l_2}_{JM}(L, S)$$

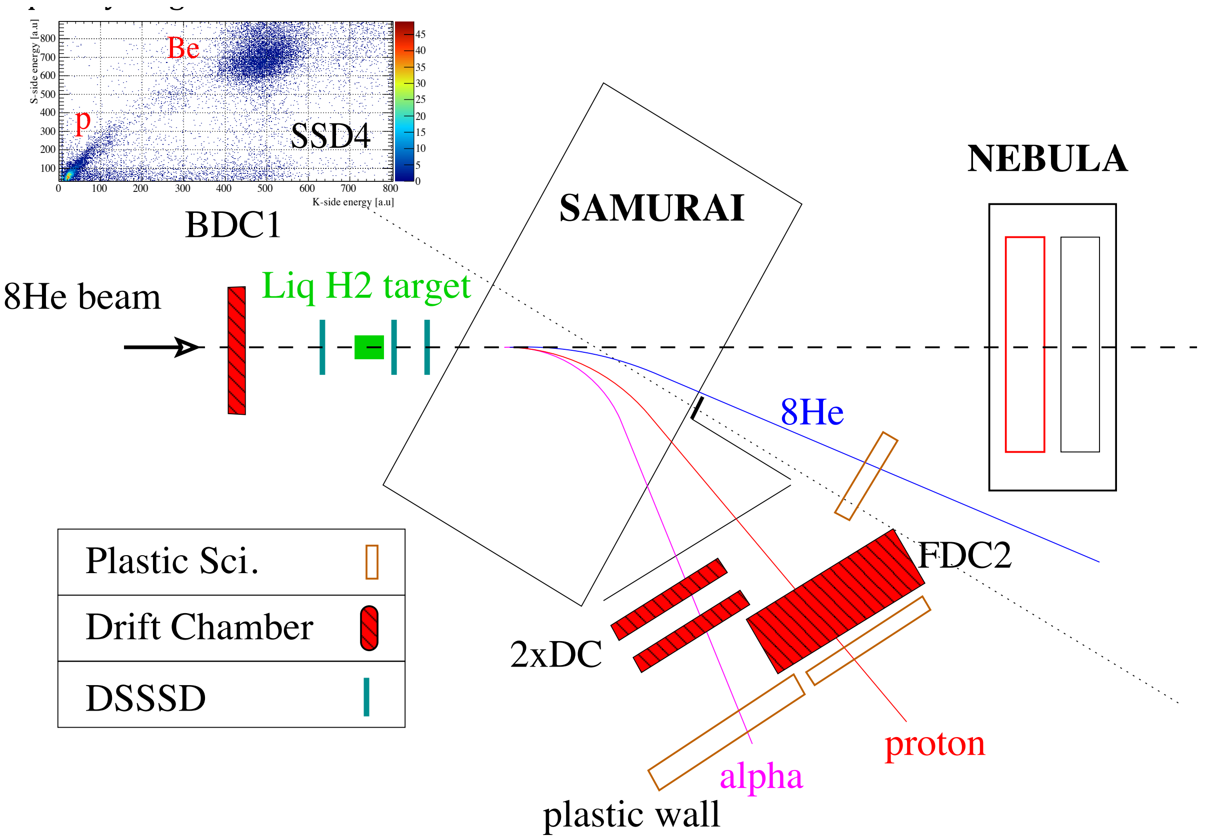
For J=0 Spin Triplet ($^3P_1$)

$$\Psi^l_0(j_<) = \sqrt{\frac{l}{2l+1}}\Phi^l_0(0) + \sqrt{\frac{l+1}{2l+1}}\Phi^l_0(1)$$

$$\Psi^l_0(j_>) = \sqrt{\frac{l+1}{2l+1}}\Phi^l_0(0) - \sqrt{\frac{l}{2l+1}}\Phi^l_0(1)$$

Other experiments

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



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)

  $\rightarrow$ candidate of 4n resonance

  at 0.83 ± 0.65(stat.) ± 1.25(sys.) MeV; Γ < 2.6 MeV
- Constraint to T=3/2 three-body force