Tetraneutron system populated by double-charge exchange reactions using RI beam

- Motivation
- Idea for populating 4n system at rest
  - Exothermic double-charge exchange ($^8\text{He},^8\text{Be}$)
- Experimental result
- Analysis
  - Continuum spectrum with correlation
  - Remarks on reaction to the continuum

- No strangeness, but strange (?) phenomena

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Tetra-neutron

• **Multi-neutron System**
  
  – Neutron cluster (?) in fragmentation of $^{14}\text{Be}$
    
    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

1980s
$^4\text{He}(\pi^-, \pi^+)\text{ reaction}$
- Only upper limit of cross section was decided.

Bound state: No clear evidence.

2000s
Breakup of $^{14}\text{Be}$
- Candidates of bound tetra-neutron were observed.

Theoretical work
- ab-initio calculation
  NN, NNN interaction

- Bound $^4\text{n}$ cannot exist
- Possible resonance state ~2 MeV

Resonance state: Possibility of the state is still an open and fascinating question.
\((\pi^-,\pi^+)\) reaction @ 165 MeV; \(\theta_{\pi^+} = 0\) degree

We have measured the momentum spectrum of \(\pi^+\) produced at 0° by 165 MeV \(\pi^-\) on \(^4\text{He}\). A \(\Delta P/P = 1\%\) beam of \(10^6\) \(\pi^-\) 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 \(^4\text{He}\) with windows of 18 mg/cm\(^2\) Kapton served as the target [15]. An

![Graphs and figures]

We show the momentum spectra for \(^4\text{He}\) and \(^{12}\text{C}\) in these experiments. 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.

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 $^4\text{He}(^8\text{He}, ^8\text{Be})4n$ reaction at 200 A MeV (0.63 c)

$n+p$ elastic @ 200 MeV
Level diagrams

\( q_{\text{min}} \sim 10 \text{MeV/c} \)
Reaction Mechanism

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

$^4\text{He} \rightarrow 4n$

Double GT

$\left[ (\vec{\tau}_p \cdot \vec{\tau}_t)(\vec{\sigma}_p \cdot \vec{\sigma}_t) r_t Y_1(\hat{r}) \right]^2$
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 is a HIGH-RESOLUTION magnetic spectrometer constructed by University of Tokyo – RNC collaboration.

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

\(^8\)He beam (2 Mcps; 190 A MeV)
Maximum rigidity
Momentum resolution
Angular resolution
Momentum acceptance
Angular acceptance

6.8 Tm
d$p/p = 1/14700$
~ 1 mrad
± 1%
~ 5 msr
Readout system of $2\alpha$ ($^{8}\text{Be}$)

Liquid He target

8He beam (2 Mcps; 190 A MeV)
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

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

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

Cross Section \( \propto \left| M_{if} \right|^2 \); Lifetime \( \propto 1/\left| M_{if} \right|^2 \)

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

e.g.

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

\[ \left| E_i J_i \pi_i T_i ; \xi_i \right\rangle \text{ and/or } \left| E_f J_f \pi_f T_f ; \xi_f \right\rangle \text{ energy eigen functions} \]

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

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

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
Density of State

\[ D (E_{nn}) = \frac{|A (k)|^2}{k}; \quad E_{nn} = \frac{\hbar^2 k^2}{m_N} \]

\[ A (k) = \int dr \psi (r) \phi_k (r) \]

Expand \( \psi_0 \) with correlated n-n scattering wave \( \phi_k (r) \)
\( A(k) \)'s are used instead of Fourier component

Effective Range Theory:
\[ \phi_k (r) \sim \sin \delta (k) \times f(r) \quad \text{for small } r \]
\[ D \sim (\sin \delta)^2 / k \] (Watson-Migdal approx.)
Direct Part

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

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

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

\[ \vec{r}_\alpha = \frac{\vec{r}_1 + \vec{r}_2}{2} - \frac{\vec{r}_3 + \vec{r}_4}{2} \]

\[ \chi (i, j) = \frac{1}{\sqrt{2}} \begin{pmatrix} \uparrow (i) \downarrow (j) - \downarrow (i) \uparrow (j) \\ \uparrow (i) \uparrow (j) \end{pmatrix} \]

\[ \vec{X} (i, j) = \begin{pmatrix} \frac{1}{\sqrt{2}} (\uparrow (i) \downarrow (j) + \downarrow (i) \uparrow (j)) \\ \downarrow (i) \downarrow (j) \end{pmatrix} \]

Fourier Transform: \((r_{12}, r_{34}, r_\alpha) \rightarrow (k_{12}, k_{34}, k)\)

\[ \int |A\Phi_0|^2 d^3k d^3k_{12} d^3k_{34} \delta(E - \epsilon - \epsilon_{12} - \epsilon_{34}) \propto X^{11/2} \exp (-X) \]

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

\[ X = E/\epsilon_a \]

\[ \epsilon_a = \frac{\hbar^2}{m_Na^2} = 11\text{MeV} \]
Equation (47) may be used for where the coefficients are shown in the left panel of Fig. 1. Examples of eq. (47) are also shown in Fig. 1. See also Appendix A.3. The phase shift 

\[ \delta_n(E_{n\nu}) = \exp\left(-\frac{r_{n\nu}^2}{a^2}\right) \]

The density of states 

\[ D(E_{n\nu}) = \frac{\hat{A}_{ns}(k)}{k} \]

(\(E_{n\nu}\) in MeV) 

(\(a = 3.0\text{fm}\), \(a = 2.0\text{fm}\), \(a = 1.0\text{fm}\))

Continuum spectrum with n-n FSI

$c.f.$


Density of State

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

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

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

4n wave packet just after DCX

\[ \Phi_0 \sim r_1 \cdot r_2 \, \Phi[(0s)^4] \]

Two correlated neutron pairs with weakly correlated

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

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

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


Energy spectrum of Four neutrons

\[ a_{2n-2n} = 0, -0.5, -1, -3, -5 \text{ fm} \]

Free 4n (w/o nn FSI)

\[ E^\alpha ; \alpha \approx 3 \]

\[ E^\alpha ; \alpha = 5.5 \]

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

4n wave packet just after DCX

\[ \Phi_0 \sim r_1 \cdot r_2 \Phi[(0s)^4] \]

Two correlated neutron pairs with weakly correlated

DCX

\[ q << 200 \text{ MeV/c} \]
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 $0.83 \pm 0.65$ (stat.) $\pm 1.25$ (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
Further experimental approach

- $^{29}\text{F} \text{ (knockout 1p)} \rightarrow ^{28}\text{O} \rightarrow ^{24}\text{O} + 4\text{n}$
- $^{8}\text{He} \text{ (knockout } \alpha \text{ by proton)} \rightarrow 4\text{n}$
- $^{8}\text{He} \text{ (knockout proton by proton)} \rightarrow ^{7}\text{H} \rightarrow 4\text{n+t}$
- $^{4}\text{He}(^{8}\text{He}, ^{8}\text{Be})4\text{n again for more statistics}$

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 ($^4\text{He}(^8\text{He},^8\text{Be})4n$ @ 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 $^1\text{H}(^3\text{H},^3\text{He})n$ with same rigidity $^3\text{H}$ beam (310 MeV/u) as $^8\text{He}$

Preliminary achievement: $< 100$ keV

Resolution & Statistics are consistent with expected

On-line X image @ SHARAQ corrected by beam momentum

$\propto$ momentum ($\sim 60$ mm/%)
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

- $^4\text{He}(^8\text{He},^8\text{Be})4\text{n}$ has been measured at 190 A MeV at RIBF-SHARAQ
- Missing mass spectrum with very few background
- Although statistics is low, 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 $\sigma$ significance)
  \[\rightarrow \text{candidate of 4n resonance at } 0.83 \pm 0.65(\text{stat.}) \pm 1.25(\text{sys.}) \text{ MeV; } \Gamma < 2.6 \text{ MeV}\]
- Preliminary result of the new experiment looks consistent with the published result.
Recent theoretical works

E. Hiyama et al., PRC 93, 044004 (2016)

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

\[ V_{ijk}^{3N} = \sum_{T=1/2}^{3/2} \sum_{n=1}^{2} W_n(T) e^{-\frac{(r_i^2 + r_j^2 + r_k^2)}{a_n^2}} P_{ijk}(T), \]

Too strong attraction is necessary for 4n resonance, which makes 4H bound!

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

FIG. 2. The 4 \to 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.

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

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

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.
Recent theoretical works

A. Deltuva, PL 782, 238 (2018)

AGS equation (momentum space)

In order to produce resonance, 5 times more attraction is necessary
Virtual state (time-dependent wave packet)

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

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

$$\Psi(t + \Delta t) = \exp\left(-i \frac{H}{\hbar} \Delta t\right) \Psi(t) \approx \frac{1 - i \frac{H}{\hbar} \Delta t}{1 + i \frac{H}{\hbar} \Delta t} \Psi(t)$$

Numerical solution

Time-dependent wave packet (2n case)

\[ \Psi(r_{nn}) \propto \exp\left(-r_{nn}^2/a^2\right) \]

- \( a = 3.0 \text{fm} \)
- \( a = 2.0 \text{fm} \)
- \( a = 1.0 \text{fm} \)

- Phase space

No interaction

Strong attractive producing bound state

Attractive but no bound state
Virtual state
Thank you for your attention
One-dimensional three-body system (Nucleon 1, 2 and Core 3 with infinite mass)

Hamiltonian:

\[ H = -\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x_1^2} - \frac{\hbar^2}{2m} \frac{\partial^2}{\partial x_2^2} + V_1 (x_1) + V_2 (x_2) + V_{12} (x_1 - x_2) \]

\[ = -\frac{\hbar^2}{4m} \frac{\partial^2}{\partial X^2} + V_1 \left( X + \frac{x_{12}}{2} \right) + V_2 \left( X - \frac{x_{12}}{2} \right) + V_{12} (x_{12}) \]

\[ = -\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x_\alpha^2} - \frac{\hbar^2}{2m} \frac{\partial^2}{\partial x_\beta^2} + V_1 \left( \frac{x_\alpha + x_\beta}{\sqrt{2}} \right) + V_2 \left( \frac{x_\alpha - x_\beta}{\sqrt{2}} \right) + V_{12} \left( \sqrt{2} x_\beta \right) \]

\[ x_{12} = x_1 - x_2 \]; \( X = \frac{x_1 + x_2}{2} \)

\[ x_\alpha = \frac{x_1 + x_2}{\sqrt{2}} \]; \( x_\beta = \frac{x_1 - x_2}{\sqrt{2}} \)

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

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

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


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

- Nucleon 1 (p) @ \( x \sim -120 \) fm, \( k \sim 2 \) fm\(^{-1}\)
- Nucleon 2 (n) (bound by core (infinite mass)) @ \( x=0 \), \( \kappa = 0.3 \) fm\(^{-1}\)
- Core (infinite mass) @ \( x=0 \)
Interaction: $V_1$, $V_2$, $V_{12}$ ($\sim \delta$-function at $x_1=0$, $x_2=0$, $x_1-x_2=0$; attractive)

Case 1:

- Nucleon 1 (p) @ $x \sim -120$ fm, $k \sim 2$ fm
- Nucleon 2 (n) (bound by core (infinite mass)) $\kappa = 0.3$ fm$^{-1}$
- Core (infinite mass) @ $x=0$

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 $^8\text{He}(p,p\alpha)4n$

**Figure 1.** Schematic drawing of the setup for the proposed experiment. The charged particles will be detected behind the target with Si strip detectors. The focal plane will be equipped with two detection systems, FDC2 at larger angles for alpha particles, and two drift chambers plus a plastic wall at smaller angles for protons.

8He beam

Liq H2 target

BDC1

8He beam

Plastic Sci.

Drift Chamber

DSSSD