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*

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Tetra-neutron

- Multi-neutron System
  - Neutron cluster (?) in fragmentation of $^{14}\text{Be}$
    
  - 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/$r$-distribution
  - Skin/Halo
- Shell Structure
  - New magic #
  - Isospin / Deformation
- New modes
  - IVE1
  - ISE0, ISE1
- etc.

Direct Reactions

- 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

\[ ^8\text{He} \rightarrow ^8\text{Be} \]

Double GT

\[ ^4\text{He} \rightarrow 4\text{n} \]

Double Spin Dipole

\[
\left[ \left( \vec{\tau}_p \cdot \vec{\tau}_t \right) \left( \vec{\sigma}_p \cdot \vec{\sigma}_t \right) r_t Y_1(\hat{r}_t) \right]^2
\]
**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
- Large internal energy

iso-tensor excitations

$(q, \omega)$ inaccessible by stable beams

**Exothermic Charge Exchange Reactions**
Level diagrams

$q_{\text{min}} \sim 10\text{MeV}/c$
Historical Review
~ search for a bound state of 4n~

1960s

**Fission of Uranium**
- No evidence for particle stable state of tetra-neutron
  

1980s

**$^4$He($\pi^-, \pi^+$) reaction**
- Only upper limit of cross section was decided.
  

**Bound state: No clear evidence.**

2000s

**Breakup of $^{14}$Be**
- Candidates of bound tetra-neutron were observed.
  

**Theoretical work**

- ab-initio calculation
  - NN, NNN interaction
  

- **Bound $^4n$ 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

![Graph](image1)

![Graph](image2)

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.

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

\[ \text{\(^7\text{Li}(^{11}\text{B}, ^{15}\text{O})3n\)} \]
@E = 88 MeV  
@\( \theta = 8 \text{ deg} \)

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@E = 107 MeV  
@\( \theta = 5 \text{ deg} \)

\[ \text{\(^7\text{Li}(^{9}\text{Be}, ^{12}\text{N})4n\)} \]
@E = 107 MeV  
@\( \theta = 5 \text{ deg} \)
Double charge exchange (DCX) reaction of HI

\[ ^{12}\text{C}(^{18}\text{O},^{18}\text{Ne})^{12}\text{Be} \]

\[ E_{\text{lab}} = 80\text{A MeV} \]

\[ 0.0^\circ < \theta < 2.5^\circ \]

\[ 1^{2}\text{C} \rightarrow 1^{2}\text{Be} \]

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

\[ \approx 70\text{nb/sr (Gnd)} \]

\[ \approx 200\text{nb/sr (~2MeV)} \]

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

\[ (\pi^-,\pi^+) \]

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.
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

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


4n in breakup of $^{14}\text{Be}$ : Marques et al. PRC 65 (2002) 044006
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
Maximum rigidity 6.8 Tm
Momentum resolution $\frac{dp}{p} = 1/14700$
Angular resolution $\sim 1$ mrad
Momentum acceptance $\pm 1\%$
Angular acceptance $\sim 5$ msr
Readout system of $2\alpha$ ($^8\text{Be}$)
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 $2\alpha$
- 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 $^8\text{Be}(2^+)$ was 13% of that for $^8\text{Be}(0^+)$.
A few events could be from $^8\text{Be}(2^+)$.
Experimental Results

We estimated the shape and yields of a background in the present analysis. We obtained 27 events produced by the $4n$ reaction from the plastic scintillator around target area. From the tightly bound $^8\text{He}$, the peak position is $E_{\text{4n}} ∼ 4$ MeV) is approximated by the strength at the pion DCX reaction on the $^8\text{Be}$. The calculation allows to incorporate the dipole nature in the DCX reaction due to the Pauli blocking effects and final-state interaction in studies of unbound states for analyzing the present data. The initial structure of target nuclei, reaction mechanism, few-body e, and the ratio of the field strengths for the data. The spectral shape near the threshold is consistent with the missing-mass spectrum of two alpha particles. Another possible source of the background is estimated to be negligible, which are, for instance, events misidentified to the index $(0s)^2$ of the tetra-neutron system. The solid (red) line represents the shape of the background was reconstructed by using a shape, which is sum of the result of the calculation and the estimated background (see text). The dashed (blue) line represents the curve, which is ten times of the estimated background.

Counts/2 MeV

E$_{4n}$(MeV)
Transition Probabilities

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

if distortion is insensitive to \( \omega \)

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

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

e.g.

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

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

energy eigen functions

\[ O(lsj \tau; \xi) \big| E_i J_i \pi_i T_i; \xi_i \rangle = \sum_{i} M_{if} \left( E_f \right) \begin{cases} M_{if} \left( E_f \right) \end{cases} : \text{Energy Spectrum} \]

distortion is insensitive to \( \omega \)

"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"

\[ \omega \ll \mu c^2 \left( \gamma - 1 \right) \approx \frac{1}{2} \mu c^2 \beta^2 \]

\[ \Delta E \cdot \Delta t \sim 2\pi \hbar \]

\[ \omega_{\text{max}} \sim \frac{2\pi \hbar \cdot \beta c}{2R} \approx 100\beta \text{ MeV} \]

Off energy shell

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

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

Response

\[ |M_{if} (E_f)|^2 : \text{Energy Spectrum} \]
Two step?

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

\[ \beta \]

\( L_1 S_1 J_1; q_1, \omega_1 \quad \rightarrow \quad L_2 S_2 J_2; q_2, \omega_2 \)

\[ \{L S J; q, \omega\} = \{L_1 S_1 J_1; q_1, \omega_1\} \oplus \{L_2 S_2 J_2; q_2, \omega_2\} \]

\[ \Delta E \cdot \Delta t \sim 2\pi \hbar \]

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

\[ \Delta t = \Delta t_1 + \Delta t_2 \]

“Intermediate state”: Not energy eigen state

\sim wave packet consists of “eigen states” over 200\beta \text{ MeV}

\sim closure approximation \sim almost one-step
Picture of $^4$He DCX reaction @ 200 A MeV

4n wave packet just after DCX (double spin dipole)
\[ \sim A[ r_1 \cdot r_2 \Phi[(0s)^4]] \]

Decay by emitting Two correlated neutron pairs

"Resonance" peak

Direct decay

Two correlated neutron pairs with weakly correlated

Direct continuum
Direct Part

\[ \mathcal{A}\Phi_0(r_{12}, r_{34}, r_{\alpha}) \sim \]

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

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

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

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

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

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

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

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

\[ X = E/\epsilon_a \]

\[ \epsilon_a = \frac{\hbar^2}{m_N a^2} = 11 \text{MeV}, \]
NN FSI

Continuum spectrum with n-n FSI

\[ D_{ns} (\epsilon_{nn}) = \frac{|\hat{A}_{ns}(k)|^2}{k} \quad \text{for } n = 1, 2 \; ; \; \epsilon_{nn} = \frac{\hbar^2 k^2}{4 m_N} \]

\[ \hat{A}_{1s}(k) = \int_{0}^{\infty} dr \; r \psi_{1s}(r) \phi_k(r) = 2 \left( \frac{1}{\sqrt{\pi a^3}} \right)^{1/2} k A_{1s}(k) \]

\[ \hat{A}_{2s}(k) = \int_{0}^{\infty} dr \; r \psi_{2s}(r) \phi_k(r) = 2 \sqrt{\frac{2}{3}} \left( \frac{1}{\sqrt{\pi a^3}} \right)^{1/2} k A_{2s}(k) \]

Expand \( A\Phi_0 \) with correlated n-n scattering wave \( \phi_k(r) \)
\( A(k)'s \) are used instead of Fourier component
Continuum spectrum with n-n FSI


c.f. 4He ~ Φ[(0s)^4]

Direct Part

Energy spectrum of Four neutrons

a_{2n-2n} = 0, -0.5, -1, -3, -5 fm

Free 4n (w/o nn FSI)

E^α ; α~3

E^α ; α=5.5

4n wave packet just after DCX

Φ₀ ~ r₁ · r₂ Φ[(0s)^4]

q << 200 MeV/c

Two correlated neutron pairs with weakly correlated

Correlation is taking into account for 2n-2n relative motion by using scattering length
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 $\theta_{cm} < 5.4\text{deg}$: $3.8_{-1.8}^{+2.9}\text{nb}$

- **likelihood ratio test**
  \[ \chi^2_{\lambda} = -2 \ln \left[ \frac{L(y; n)}{L(n; n)} \right] \]

- **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

$\mu^n e^{-\mu} / n! \approx 10^{-6}$ for $\mu = 0.07$, $n = 4$
Better statistics and accuracy of energy than previous experiment ($^4$He($^8$He,$^8$Be) @ 186 MeV/u)

4 events $\rightarrow$ 5 times or more: Improve efficiencies (redundancy)

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

$\rightarrow$ better than 0.3 MeV both for stat. and syst.

Calibration using $^1$H($^3$H,$^3$He)$n$ (($CH_2)_n$ target)

with same rigidity $^3$H beam (310 MeV/u) as $^8$He
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 (4.9 $\sigma$ significance)
  \[ \rightarrow \text{candidate of } 4\text{n resonance} \]
  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