Structure change in light neutron-rich nuclei via nucleon transfer reaction

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Inverse Kinematics w/ RI beam (30-100 MeV/u)

- RI beam \((0.1 - 10^5 \text{ pps}; \Delta E\sim \text{a few } \% )\)
- Exc. States
- Interaction
- Target as probe \((50 - 300 \text{ mg/cm}^2 )\)
- Decay
- \(\gamma\) rays
- Fragments

- **Formation** of Excited States of Exotic Nuclei
  - Direct reactions and their selectivities
- **In-beam spectroscopy** measuring decay products
  - Invariant-mass/\(\gamma\)-ray spectroscopy
    - Particle detectors at forward angles (kinematical focus)
    - Gamma detectors surrounding target (Doppler shift)
Probes for direct reactions (30-100 MeV/u)

- Heavy Nuclei: Strong Coulomb Field
  - Coulomb Excitation, Coulomb Dissociation
    - E1, E2, (M1) / Isovector

- H, D, $^4\text{He}$ [Liquid targets]
  - Inelastic Scattering
    - Collective / single-particle states (odd nuclei)
    - Isovector (H) / Isoscaler (H, D, $^4\text{He}$)
    - Spin-Flip (H, D) / Spin-Non-Flip (H, D, $^4\text{He}$)
  - Charge Exchange
    - Fermi type (H) / Gamow-Teller type (H, D)

- Nucleon Transfer
  - $(\alpha,t)$, $(\alpha,^3\text{He})$ Reaction

- Knockout
  - Hole states

- Other (Be, C, etc.)
  - Inelastic Scattering
  - Knockout / Fragmentation
Motivation for transfer reactions

Structure information of nuclei as functions of $N$ and $Z$

Shell Evolution: Single particle states

- Spectroscopy of proton (unoccupied) single particle states in neutron-rich nuclei
Nucleon (Proton) Transfer

- $(d,n)$, $(^3\text{He},d)$, $(\alpha,t)$, ...

<table>
<thead>
<tr>
<th>Incident energy higher than 30 MeV/u</th>
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<tbody>
<tr>
<td>✓ Thicker target (100~200 mg/cm²)</td>
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<tr>
<td>✓ Less distortion effect</td>
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<td>✓ Less multi-step process</td>
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<td>✓ Same optical potential as inelastic excitation</td>
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<td>✓ Identification by comparing with other direct reactions</td>
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But

✗ Momentum mismatch
Momentum Matching Condition

- As if “Getting off from the moving train (projectile) to platform (target)”
  - Internal motion in the train (Fermi motion in the projectile) along the opposite direction of the train (target)
  - Motion on the platform (Fermi motion of the nucleon on the target) along the direction of the train
\[
[c] \\
\begin{bmatrix}
C \\
\end{bmatrix} \\
\begin{bmatrix}
C' \\
\end{bmatrix}
\]

\[
a + A \rightarrow b + B
\]

\[
a = (b + x)
\]

\[
B = (A + x)
\]

**Plane Wave Born Approx.**

\[
T_{PW}^{\text{Post}} = \langle \phi_c' | V_{xb} + V_{bA} | \phi_c \rangle
\]

\[
T_{PW}^{\text{Prior}} = \langle \phi_c' | V_{xA} + V_{bA} | \phi_c \rangle
\]

\[
\langle \phi_c' | V_{xb} | \phi_c \rangle = -\frac{1}{(2\pi)^3} \frac{\hbar^2}{2\mu_{xb}} \left( k_{xb}^2 + \kappa_a^2 \right) \int d^3r_{xb} \psi_a (\vec{r}_{xb}) e^{i\vec{k}_{xb} \cdot \vec{r}_{xb}}
\]

\[
\langle \phi_c' | V_{xA} | \phi_c \rangle = -\frac{1}{(2\pi)^3} \frac{\hbar^2}{2\mu_{xA}} \left( k_{xA}^2 + \kappa_B^2 \right) \int d^3r_{xA} \psi_B * (\vec{r}_{xA}) e^{-i\vec{k}_{xA} \cdot \vec{r}_{xA}}
\]

\[
\vec{k}_{xb} = \left( \frac{b}{a} \right) \vec{k}_c - \vec{k}_c', \quad \vec{k}_{xA} = \vec{k}_c - \left( \frac{A}{B} \right) \vec{k}_c,
\]

\[
\frac{\hbar^2 \kappa_a^2}{2\mu_{xb}} = \varepsilon_a, \quad \frac{\hbar^2 \kappa_B^2}{2\mu_{xA}} = \varepsilon_B
\]

Fourier Transforms of wave functions of nucleon \((x)\) in \(a\) and \(B\)

Same value but different expressions

Same value but different expressions

Binding energies of \(a\) and \(B\)
Proton Transfer in Momentum Space

$^{12}\text{Be}(d,n)$ at 50 A MeV

$^{12}\text{Be}(\alpha,t)$ at 50 A MeV

$q_z$ (fm$^{-1}$)

$^{13}\text{B}^*(10\text{MeV})$

$^{12}\text{Be}$

$\alpha$

$^{13}\text{B}^*(10\text{MeV})$

$d$

$n$

$t$
Exotic Magic Number at N=16 (Z≈8)

Spin-orbit splitting between $v_d^{3/2}$ & $v_d^{5/2}$ depend on the number of protons in $d_{5/2}$ orbit attracting $v_d^{3/2}$ orbit by $V_{\sigma\tau}$

Change of Fluorine Proton Shell as a function of Neutron number

Excitation energy of $3/2^+$ S.P. state in $^{17}$F & $^{23}$F ?
Known Energy Levels of Fluorine Isotopes

\[ \begin{align*}
\frac{3}{2}^+ & \quad \pi s_{1/2} \\
\frac{7}{2}^- & \quad \pi f_{7/2} \\
\frac{3}{2}^+ & \quad \pi d_{3/2} \\
\frac{5}{2}^+ & \quad \pi d_{5/2} \\
\end{align*} \]

\( N = 8 \quad 10 \quad 12 \quad 14 \)

\( \text{Ex}(O(2^+)) \quad 6.92 \quad 1.99 \quad 1.64 \quad 3.21 \)
$^4\text{He}(^{22}\text{O}, ^{23}\text{F}_\gamma)$, $^4\text{He}(^{23}\text{F}, ^{23}\text{F}_\gamma)$, $^4\text{He}(^{24}\text{F}, ^{23}\text{F}_\gamma)$, $^4\text{He}(^{25}\text{Ne}, ^{23}\text{F}_\gamma)$

- Use of Cocktail beam ($^{22}\text{O}$, $^{23}\text{F}$, $^{24}\text{F}$, $^{25}\text{Ne}$)
- Gamma ray measurement coincident with $^{23}\text{F}$ ejectile

Three Different Reactions Approaching $^{23}\text{F}$

1. $^4\text{He}(^{22}\text{O}, ^{23}\text{F}_\gamma)$: Proton Pickup Reaction
2. $^4\text{He}(^{23}\text{F}, ^{23}\text{F}_\gamma)$: Inelastic Scattering
3. $^4\text{He}(^{24}\text{F}, ^{23}\text{F}_\gamma)$: Knockout

1. Proton S.P. states ($\frac{5}{2}^+, \frac{1}{2}^+, \frac{3}{2}^+$)
2. Collective states; Non-spin-flip states ([core $2^+] \otimes \text{S.P. state, etc}$)
3. Neutron hole states
\textbf{\( {^4}\text{He}(^{22}\text{O},^{23}\text{F} \gamma) \)}

\textbf{\( {^4}\text{He}(^{23}\text{F},^{23}\text{F} \gamma) \)}

\textbf{\( {^4}\text{He}(^{24}\text{F},^{23}\text{F} \gamma) \)}

\textbf{\( {^4}\text{He}(^{25}\text{Ne},^{23}\text{F} \gamma) \)}

\textbf{\( \gamma \text{ ray spectra} \)
Level Scheme of $^{23}$F

Fitting using response functions by GEANT3 simulations

$^4$He($^{22}$O, $^{23}$F$\gamma$) $\gamma$

Coincidence with 2.92-MeV $\gamma$-ray
Angular Distributions for the 4.06- and 2.37-MeV state

$J^\pi$ and spectroscopic factors of excited states by DWBA analysis.

- Optical Potentials of the $^{22}\text{O}+\alpha$ and the $^{23}\text{F}+t$ channels deduce from angular distributions for $^{22}\text{O}(\alpha,\alpha')$ and $^{23}\text{F}(\alpha,\alpha')$

The 4.06-MeV state:
Single particle state in $d$.

The 2.27-MeV state: consistent with Single particle state in the $s$. 
Comparison with Shell Model Calculations

LS splitting of proton single particle energy may be larger than stable nuclei because of neutron-richness

\[ V_{LS} \propto \frac{1}{r} \frac{d}{dr} V(r)(\vec{l} \cdot \vec{s}) \]

[2] T.Otsuka, private communication.: predicts N=16 magic number
**N-rich N=8 Nuclei**

Spin-orbit splitting between $\nu p_{1/2}$ & $\nu p_{3/2}$ depend on the number of protons in $dp_{1/2}$ orbit attracting $\nu p_{1/2}$ orbit.

- **12Be**
  - Low-lying $2^+$ state
  - Low-lying $1^-$ state
  - Low-lying $0^+_2$ state
  - Magicity loss in N=8
  - Deformed ground state

**Change of Boron Proton Shell as a function of configuration**

- Spherical ground state
- How about excited states?
  - Deformed core + proton?

**13Bgs**

**13B**

- Spherical ground state
- How about excited states?
  - Deformed core + proton?
$^4\text{He}(^{12}\text{Be},^{13}\text{B}\gamma) \@ 50 \text{ A MeV}$

Deformed $^{12}\text{Be}$ core + 1 proton?

$C^2S(BM) \sim 0.27$

for $\delta=0.4$

$\beta(^{12}\text{Be}(p,p')) \sim 0.6-0.7$

Spherical G.S.

Deformed Excited $1/2^+$?

$\varepsilon_2 \sim \delta \sim 0.95\beta$

$[101]1/2$

$[220]1/2$

$[101]3/2$

$[110]1/2$
Spectra of $^{14}\text{C}$, $^{12}\text{Be}$, $^{11}\text{B}$, and $^{13}\text{B}$

$^{14}\text{C}$

$^{12}\text{Be}$

$^{11}\text{B}$

$^{13}\text{B}$
$^4\text{He}(^{12}\text{Be}, ^{13}\text{B}\gamma) \ @ \ 50 \text{ A MeV}$

3.71 & 4.83 MeV states strongly excited by ($\alpha$, t)

Different transferred $L$

$^{12}\text{Be} \ beam$

GRAPE NaI(Tl) array

Liq. He target

### Table
$^4\text{He}(^{12}\text{Be}, ^{13}\text{B}) \gamma$ @ 50 $\text{A MeV}$

Angular Distribution of $^{13}\text{B}$ coin. with 4829 keV $\gamma$

FR-DWBA (DWUCK5)
Optical Potential:
$^{12}\text{C} + ^4\text{He}$ (entrance)
$^{12}\text{C} + ^3\text{He}$ (exit)
$L=0 \rightarrow J^{\pi} = 1/2^+$

$C^2S = 0.1 - 0.2$

$	ext{dep. on Potentials}$
$\rightarrow$ Proton “single particle” state on $^{12}\text{Be}$
$^{4}\text{He}(^{12}\text{Be},^{13}\text{B}) \gamma @ 50 \text{ A MeV}$

Proton “single particle” state on $^{12}\text{Be}$

$^{1/2+} : 0.30$
$^{1/2+} : 0.003$
$^{1/2+} : 0.03$
$^{1/2+} : 0.01$
$^{5/2+} : 0.87$
$^{3/2+} : 0.15$
$^{3/2+} : 0.30$
$^{3/2-} : 0.15$
$^{1/2+} : 0.03$

Shell model

PSDFU
1/2+ state in 13B* Configuration

| 12 Be_{gs} \rangle = \alpha |(\pi p)^2 (vp)^6\rangle + \beta |(\pi p)^2 (vp)^4 (vsd)^2\rangle + \ldots

|\alpha|^2 \sim |\beta|^2 \sim 0.5

deformation

| 13 B^* (1/2^+) \rangle = \alpha' |(\pi p)^2 (\pi sd)(vp)^6\rangle + \beta' |(\pi p)^2 (\pi sd)(vp)^4 (vsd)^2\rangle + \gamma' |(\pi p)^2 (vp)^6 (vsd)\rangle + \delta' |(\pi p)^2 (vp)^4 (vsd)^3\rangle + \ldots

C^2 S = \langle 13 B^* (1/2^+) | 12 Be_{gs} + p(\ell = 0) \rangle \approx \alpha \alpha' + \beta \beta'$
1/2+ state in $^{13}\text{B}^*$ by AMD

Kanada-Enyo prelim.

- 变形した状態
  - 陽子励起状態
    - 陽子の基底状態の配位混合を反映した状態

- 球形の状態
  - 13B(1/2+)

- 本実験では、12Be(0+)状態が励起
Summary

- $(\alpha, t)$ and $(\alpha, ^3\text{He})$ reactions at intermediate energy can be used for spectroscopy of single-particle states in exotic nuclei.
- Spectroscopy of $^{23}\text{F}$ was also performed by $(\alpha, t)$ reaction combined with inelastic and knock-out reactions.
- Level scheme was constructed for $^{23}\text{F}$.
- Spin-orbit splitting of $3/2^+$ and $5/2^+$ was not so small as predictions of shell models.
- $\gamma$-ray spectroscopy of $^{13}\text{B}$ excited by Proton Transfer ($^{12}\text{Be}, ^{13}\text{B}\gamma$) reaction was measured.
- The 4.8-MeV state have $J^\pi$ of $1/2^+$ and an proton $S$-factor of $=0.1\sim 0.2$ by DWBA analysis.
  - Differs from standard shell-model prediction.
  - It might be contain [220]$1/2^+$ configuration on the deformed $^{12}\text{Be}$ core.
  - $1/2^+_1$ state in AMD calculation.
- $(\alpha, t)$, $(\alpha, ^3\text{He})$ reaction on $^{32}\text{Mg}$ and $^{34}\text{Si}$ was measured recently by using position-sensitive Ge array, GRAPE. N-rich nuclei around N$\sim$20.