Multi-nucleon transfers using two-neutron halo $^6$He on $^{12}$C at 30 MeV using the SHARC and TIGRESS arrays at TRIUMF ISAC-II

Fred SARAZIN, Duane SMALLEY
Colorado School of Mines
Outline

• Motivation

• SHARC + TIGRESS @ ISAC-II

• Data analysis
  • Elastic / inelastic scattering
  • $^{12}$C($^6$He,$^4$He)
  • $^{12}$C($^6$He,$^8$Be)

• Conclusion and outlook
(\(^6\)He,\(^4\)He): an alternate surrogate reaction for 2n-transfer

- (t,p):
  - Used very successfully in the past
  - Tritium beams now hard to come by
  - State-of-the-art detectors at RIB facilities
  - Tritium (implanted) target challenging

- (\(^6\)He,\(^4\)He):
  - A few RIB facilities now have intense \(^6\)He beam (>10\(^7\) pps) in the few A.MeV range
    - Most intense \(^6\)He beams likely at SPIRAL and ISAC
  - Potentially more favorable than (t,p)
    - Large Q-value: higher excited states, more direct?
      - \(^6\)He \(S_{2n}=1.867\) MeV
      - Triton \(S_{2n}=6.257\) MeV
    - Influence of the \(^6\)He halo / study of the 2n-correlation
  - Disadvantages:
    - stable (or long-lived) target
    - More challenging from the reaction theory standpoint
Influence of the $^6$He halo?

$^{65}$Cu($^6$He,$^4$He) @ SPIRAL:

$\sigma_{(6\text{He},4\text{He})} = 10 \sigma_{(6\text{He},5\text{He})}$

Dineutron configuration:

- Favors 2n-transfer

Cigar-like configuration:

- Favors 1n-transfer

Benchmark experiment: \( ^{12}\text{C}(^{6}\text{He},^{4}\text{He})^{14}\text{C}^{*} \)


- Use a reaction for which (t,p) was well measured.
- States in the recoil nucleus well known.
- Angular distributions for bound states.

$^{12}\text{C}$(\(^{6}\text{He},^{6}\text{He}\)) elastic / inelastic scattering


- First minimum not covered by data
- No good fit of the inelastic scattering
  - CCBA calculation: magnitude, but still not shape
  - Need more information
**S1201: $^{12}\text{C}(^{6}\text{He},^{4}\text{He})$**

**July 15-22, 2010**

<table>
<thead>
<tr>
<th>07/13</th>
<th>07/14</th>
<th>07/15</th>
<th>07/16</th>
<th>07/17</th>
<th>07/18</th>
<th>07/19</th>
<th>07/20</th>
<th>07/21</th>
<th>07/22</th>
<th>07/23</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Schedule 117**

- 12C  
- 6He

**Experiment delayed (cryoplant) - New schedule for S1201**

**Actual**

- Stable beam ready early!
- SHARC target assembly leak
- Beam tuning starts
- --- Proton therapy ---
- End of exp.  
  Cryopanl needs to be fixed…
- Maintenance delayed by 1 day

**Intensity requested:** $5 \times 10^6$ pps  
**Intensity received:** $\sim 8 \times 10^5$ pps

**Beam time requested:** 16 shifts  
**Beam time received:** $\sim 7$ shifts  
(2 shifts lost by the experimentalists)

**Integrated current requested:** 1100 nC  
**Integrated current received:** 77 nC
Radioactive beam

Target - Source

500 MeV proton
Up to 100μA

Fred Sarazin (fsarazin@mines.edu)
Physics Department, Colorado School of Mines

DREB March 2012
ISAC-I and –II @ TRIUMF

Target/Source + Mass Separator (Underground)
TRIUMF Cyclotron – p^+ 500 MeV ; I<100µA

Fred Sarazin (fsarazin@mines.edu)
Physics Department, Colorado School of Mines

DREB March 2012
SHARC + TIGRESS

Fred Sarazin (fsarazin@mines.edu)
Physics Department, Colorado School of Mines

DREB March 2012
Target:
- 200 μg/cm² ¹²C (~1μm)

SHARC configuration:
- Upstream, only E
  - 4 x 1mm BB11 box
  - 1 x 1mm QQQ2 CD
- Downstream
  - 4 x 140μm BB1 box (DE)
  - 4 x 1mm pad (E)
  - 3 x 80μm QQQ2 CD (DE)
  - 1 x 45μm QQQ1 CD (DE)
  - 4 x 1mm QQQ1 pad
    - DoCD3 not working

SHARC angular resolution:
- DCD / UCD ~ 1.5°
- DBx / UBx ~ 0.5°
$^{12}\text{C}(^{6}\text{He},^{4}\text{He})^{14}\text{C}^* @ 30 \text{ MeV}$

- 6-7.3 MeV bound states separation require $\gamma$-tagging
SHARC angular Coverage

Fred Sarazin (fsarazin@mines.edu)
Physics Department, Colorado School of Mines

DREB March 2012
Particle identification (downstream)

\[ ^{12}\text{C Foil} \]

\[ ^{6}\text{He Beam} \]

Fred Sarazin (fsarazin@mines.edu)
Physics Department, Colorado School of Mines

DREB March 2012
TIGRESS Angular Coverage

11 HPGe clovers

Fred Sarazin (fsarazin@mines.edu)
Physics Department, Colorado School of Mines

DREB March 2012
Elastic and inelastic scattering

• States expected to be populated
  • $0^+(\text{gs})$, $2^+ (4.4\text{MeV})$, $3^- (9.64\text{MeV})$
• Fixes microscopic optical potential for $^6\text{He}+^{12}\text{C}$
  • Normalization on elastic scattering data
  • Inelastic gets model parameters for nuclear excitation – challenging!
- **DCD**
  - Particle identification
- **DBx**
  - $^6$He elastic don’t punch through
  - $^6$He and $^{12}$C detected simultaneously
  - Data cut done on this
- **UmBx, UmCD**
  - No elastic or inelastic scattering observed past 90°
• Particle identification
• As yet undetermined heavy scattering
  • Interferes with first few channels of ground state and one channel in inelastic (4.4MeV)
• $^6$He(p,t)
  • Presumably due to water condensation on the target (also evidence of $^{16}$O elastic scattering)
• Resolution limited by angular resolution
  • Confirmed with simulations
• $^{6}\text{He} + ^{12}\text{C}$ two body reaction in a plane
  • $|\phi_{6\text{He}} - \phi_{12\text{C}}| = \Delta \phi = \pi$
• Energy of $^{6}\text{He} + ^{12}\text{C}$ a constant
  • $E_{6\text{He}} + E_{12\text{C}} = 30$ MeV
  • Energy loss in target foil, dead layers cause $E_{6\text{He}} + E_{12\text{C}} < 30$ MeV
• Data cuts made to maximize data minimize background
  • $\Delta \phi = 5^\circ$
  • $\Delta E = 3$ MeV GS, 1 MeV 4.4 MeV state
  • Energy spread mainly due to $^{12}\text{C}$ straggling
Detection efficiency

- GS efficiency
  - Little background
  - Mostly interstrip and corner detection effects
- $2^+ 4.4\text{MeV}$
  - Higher background
  - Stricter $\Delta E$ cuts
  - Coincident detection

Fred Sarazin (fsarazin@mines.edu)
Physics Department, Colorado School of Mines

DREB March 2012
Elastic/Inelastic angular distributions

Elastic

Inelastic (preliminary)

Need further background subtraction

Fred Sarazin (fsarazin@mines.edu)
Physics Department, Colorado School of Mines

DREB March 2012
PRELIMINARY

- Optical model from $^6$Li on $^{12}$C at 30MeV
  - Mass adjusted for $^6$He
  - Normalized
• 2\(^+\) to 0\(^+\) 4.438MeV \(\gamma\)-ray transition observed
  • Black: raw spectrum
  • Red: Doppler corrected
• A few % efficiency at 4MeV
• Not enough statistics for \(\alpha-\gamma\) tagging for angular distribution
- 6.09MeV to 7.34MeV excited states
  - $\alpha$–$\gamma$ tagging required
  - High $\gamma$-efficiency
- $^{12}\text{C}(^{6}\text{He},^{4}\text{He})$ angular distribution
  only measured for 8.32MeV (unbound) state
$^{12}\text{C}(^{6}\text{He},^{4}\text{He})^{14}\text{C}^{*} \text{ E vs}$

- **DCD**
  - Particle ID
  - Fusion-evaporation
- **DBx**
  - Particle ID
  - Only the highest energy $^{4}\text{He}$ punch through
- **UmBx / UmCD**
  - Large Q-value ($Q=12.15\text{MeV}$): few contaminants

Fred Sarazin (fsarazin@mines.edu)
Physics Department, Colorado School of Mines

DREB March 2012
$^{12}\text{C}(^6\text{He},^4\text{He})^{14}\text{C}^*$ excitation and $\gamma$ spectra

**SHARC**

**SHARC + TIGRESS**

Proof of principle

Fred Sarazin (fsarazin@mines.edu)

Physics Department, Colorado School of Mines
8.32 MeV angular distribution

$^6\text{He}(p,t)$ contamination


Fred Sarazin (fsarazin@mines.edu)
Physics Department, Colorado School of Mines

DREB March 2012
\(^{12}\text{C}(^{6}\text{He},^{8}\text{Be})^{10}\text{Be}^*\)

\(^{12}\text{C}(^{6}\text{He},^{8}\text{Be})\ Q=0.140\text{MeV}\)

- Suggested a 2p direct transfer by Milin et al., PRC 70 (2004) 044603
  - \(S_{2p}^{(^{12}\text{C})} = 27.2\ \text{MeV}\)
  - Differential cross section with a factor of 20 larger than \(^{12}\text{C}(^{6}\text{Li},^{8}\text{B})\) at 80 MeV lab beam energy

- Alternate possibility: \(\alpha\)-transfer on \(^{6}\text{He}\)?
  - \(S_{\alpha}^{(^{12}\text{C})} = 7.4\ \text{MeV}\)
  - A look at the 3\(\alpha\)-like structure of \(^{12}\text{C}_{gs}\)?
  - Reaction mechanism involving excitation through the Hoyle state?

Fred Sarazin (fsarazin@mines.edu)
Physics Department, Colorado School of Mines
$^{12}\text{C}(^{6}\text{He},^{8}\text{Be})^{10}\text{Be}^*$ kinematics

Fred Sarazin (fsarazin@mines.edu)
Physics Department, Colorado School of Mines

DREB March 2012
2α coincidence detection

Simulation:
- Kinematics of $^{12}\text{C}(^{6}\text{He},^{8}\text{Be})^{10}\text{Be}$ and $^{8}\text{Be}$ breakup at 30MeV

Data – reconstruction from multiple cuts
- $\alpha$-energy < 11.5MeV, $\alpha$s don’t punch through
  - 2 hits in $\Delta E$
- $\alpha$-energy > 11.5MeV, $\alpha$s punch through
  - Recoverable events:
    - 2 hits in different front strips
    - 2 hits in same front / different back strips
  - Non-recoverable events:
    - 2 hits in the same front / back strips
    - Just one alpha detected
$^8$Be $\rightarrow$ $2\alpha$ (Q=92keV – assuming $^8$Be$_{gs}$)
10Be excitation spectrum

- GS and 2+ 3.3 MeV states clearly separated
  - Angular distributions OK, but requires 2α detection efficiency calculation
- 5.9 MeV to 6.3 MeV region
  - Observed, but individual states not separable with SHARC only
  - Not enough statistics for TIGRESS γ-tagging
- Beyond 6.3 MeV (S_n=6.8 MeV)
  - Neutron unbound states
  - Fusion-evaporation background

2α detection efficiency and angular distributions (DCD only)

PRELIMINARY

2α detection efficiency
(from G4 simulation)

Fred Sarazin (fsarazin@mines.edu)
Physics Department, Colorado School of Mines

DREB March 2012
Few $^{10}$Be ID’ed in the thinnest front detectors

→ 2p transfer (indeed)

favored

Reaction mechanism? Can we learn something about $^{12}$C(gs)? $\alpha$-clustered states in $^{10}$Be?
**6He + 12C @ 30 MeV with SHARC + TIGRESS**

- Elastic / inelastic scattering
  - Angular distributions extracted for elastic and inelastic (4.4 MeV)
  - First fit on elastic, more work to be done on inelastic

- $^{12}\text{C}(6\text{He},4\text{He})^{14}\text{C}^*$
  - Proof-of-principle of a-g tagging with SHARC+TIGRESS
  - Angular distribution of 8.32 MeV (unbound) state in $^{14}\text{C}^*$
  - Not enough energy resolution with SHARC only (expected) to extract individual angular distributions of the states in 6-7 MeV range.
  - Not enough statistics to produce $\gamma$-tagged angular distributions

- $^{12}\text{C}(6\text{He},8\text{Be})^{10}\text{Be}^*$
  - Angular distributions extracted for gs and first excited (3.3 MeV) states
  - Two-proton transfer favored, need angular distribution fits
  - Something to be learned on $^{12}\text{C}_{gs}$? $\alpha$-clustered states in the ~6 MeV region?
Millicent Audrey Smalley (b. Mar 22, 2012)

Duane Smalley
(PhD student)
The SHARC / TIGRESS Collaboration:

- University of York
- University of Manchester
- University of Surrey
- University of Birmingham
- University of Liverpool
- Daresbury Laboratory
- Colorado School of Mines
- Louisiana State University
- TRIUMF
- Mc Master University
- Simon Fraser University
- St Mary’s University
- Université de Montreal
- University of Guelph
- LPC Caen

© Sherman's lagoon
BACKUP SLIDES
Elastic/Inelastic Future Work

- Link inelastic scattering of DCD to DBx
- Create theory model
  - Current model is adjusted mass parameters of $^6\text{Li}+^{12}\text{C}$ optical potential
  - Create model of $^6\text{He}+^{12}\text{C}$
  - Collaboration with F. Nunes at NSCL/MSU
- Theory model then basis for further transfer reaction studies
  - Elastic scattering fits normalization parameter
  - Inelastic fits nuclear excitation model
Future Work

- Complete analysis of 8.32 MeV angular distribution
- Add the 2n transfer to the reaction model
  - Can compare to Milin et al.
  - Will help expand transfer model
- Reaction can be compared to (t,p) reaction
  - Enhance of transfer?
  - Population of states
## Work Time line

<table>
<thead>
<tr>
<th>February 2012</th>
<th>Winter/Spring 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defend Thesis proposal</td>
<td>Develop microscopic model in collaboration with F. Nunes</td>
</tr>
<tr>
<td>Winter 2012</td>
<td>Use microscopic model to test hypothesis of $^{12}\text{C}(^{6}\text{He},^{8}\text{Be})^{10}\text{Be}$ reaction mechanism</td>
</tr>
<tr>
<td>Continue data analysis</td>
<td>Spring/Summer 2012</td>
</tr>
<tr>
<td>Extract all angular distributions</td>
<td>Make final conclusions</td>
</tr>
<tr>
<td>$2^+ 4.4$ MeV inelastic</td>
<td>October 2012</td>
</tr>
<tr>
<td>$2^+ 8.32$ MeV 2n transfer</td>
<td>Defend thesis</td>
</tr>
<tr>
<td>$0^+$ ground state $(^{6}\text{He},^{8}\text{Be})$</td>
<td></td>
</tr>
<tr>
<td>$2^+ 3.3$ MeV $(^{6}\text{He},^{8}\text{Be})$</td>
<td></td>
</tr>
</tbody>
</table>
Benchmarking \((^6\text{He}, ^4\text{He})\) against \((t,p)\)

- **Goal:**
  - Compare cross-sections & angular distributions for selected states in a nucleus well studied by \((t,p)\)
  - Enhancement due to \(^6\text{He}\) halo?

\(^{12}\text{C}(t,p)\) studied by F. Ajzenberg-Selove et al., Phys. Rev. C17 (1978) 1283

\(^{12}\text{C}(^6\text{He}, ^4\text{He})\) measured once by Milin et al., Nucl. Phys. A730 (2004) 285

- Same states populated
- Different intensities for some states
- Only one angular distribution extracted by Milin et al. (8.32MeV)

Efficiency Cuts

- Inter-strip distance between strips taken into account
  - Simulations distribute charge collected proportionally according to distance between inter-strip
  - DCD lower efficiency at low angles because of greater surface area of inter-strip to total surface area of strip ratio
    - 24 back strips of 0.1 mm distance over a smaller surface area
    - Coincident cuts lower efficiency due to dual detection of particles inter-strip efficiency Ex. At ~32 deg 6He efficiency is .70 and 12C eff at .8, coincident eff is .7*.8 = 0.55