Peculiarities of fusion and transfer reactions involving $^6$He nuclei at energies close to the Coulomb barrier

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1. What do we know about $^6$He?
2. What is known about the interaction of $^6$He

3. Experimental results at DRIBs:
   a. fusion reactions accompanied by evaporation neutrons
   b. transfer reactions (1-2 neutrons)
      i. in the energy range 5-10 MeV/A
      ii. in the above-barrier region
   C. total reaction cross section
   d. momentum distributions
In spite of the 30-year history of studying the He nucleus, the information on its properties is rather scarce. The structure of He has been studied in different microscopic theory tests for the (Be, Li, etc.) reactions induced by heavy ions (Be, Li, etc.). The structure of He is the simplest nucleus to study in a 3-body system. However, more or less agreeable results have been obtained only for the $2^+$ (1.8 MeV) state. The information about the spins and parities of the highly excited states is contradictory.
<table>
<thead>
<tr>
<th></th>
<th>Exp.</th>
<th>Calc.</th>
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<th>RNBT Coll.1997</th>
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<tr>
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<td>F.A.S. 1988</td>
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<tr>
<td>E J* (MeV)</td>
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<tr>
<td>g.s. 0+ 1.797 2+</td>
<td>g.s. 1.8</td>
<td>1.92 2+</td>
<td>1.8</td>
<td>1.894 2+</td>
</tr>
<tr>
<td>13.6 1- 12</td>
<td>5.6 2+</td>
<td>4.4</td>
<td>6.124 2+</td>
<td>1.81 2+</td>
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<td>25</td>
<td>14.6 1-2-</td>
<td>7.7 9.9 14.6</td>
<td>7.268 1+</td>
<td>3.5 2+</td>
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<tr>
<td></td>
<td>23.3</td>
<td></td>
<td>12.467 0+</td>
<td>3.78 1+</td>
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<td></td>
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<td></td>
<td>4.98 0+</td>
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<tr>
<td>6 He(p,p) 6 He</td>
<td>9 Be(14N,17F) 6 He (Q=-5,3 MeV)</td>
<td>7 Li(t,4He) 6 He (Q= +9,8 MeV)</td>
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</table>

Fig. 1. Fission excitation function for the reaction $^4$He + $^{209}$Bi (black triangles); the solid circles denote the excitation function of the $^{209}$Bi($^4$He, 4n) reaction, the open squares, the data on the $^{209}$Bi α-particle induced fission (present work and ref. [7]). The latter are in agreement with [15]. The relations between the excitation energy and the CM energy are given by the following relations: $E^* = E_{cm} + 0.59$ MeV for $^4$He + Bi reaction and $E^* = E_{cm} - 0.28$ MeV for the $^4$He particle.

Fig. 2. Excitation functions for the reaction $^4$He + $^{209}$Bi: the symbols denote the experimental data from the present work and from refs. [15,21], the solid, dotted, dash-dotted and dashed lines are the result of calculations.
The other groups studying fusion with unstable nuclei

J.J Kolata et al.
PRL 81, 4580 (1998)

\^6{He} + ^{209}{Bi}

Disadvantages:
• Comparison of experimental data only with theoretical calculation
• Different \( A_c \)

Low \( B_f \) value: genuine fusion or BU-fusion?

M. Trotta et al.
PRL 84, 2342 (2000)

\^6{He} + ^{238}{U}
$^6\text{He} + ^{238}\text{U}$ in Louvain-la-Neuve

No enhancement of fusion probability by the neutron halo of $^6\text{He}$

Large neutron transfer cross sections were obtained through direct measurements, and were found to be larger than those for breakup.

There are problems and it is difficult to obtain information on the interaction of $^{6}\text{He}$ with nuclei.

The reasons for this are:

- The low intensity of the secondary $^{6}\text{He}$ beams.
- The necessity to decrease the energy from 70 MeV/A (fragmentation method) down to sub-barrier energies of 3-5 MeV/A.
- The necessity to perform experiments with high efficiency and at forward angles.
**RIB ACCELERATOR COMPLEX OF THE FLNR (JINR) - DRIBS-1**

**THE $^6$He BEAM PROFILE:**

$X = 7$ mm; $Y = 8$ mm

**FIRST BEAM - DECEMBER 2004**

E ($^6$He) = 60.3 MeV

FWHM = ± 0.4 MeV

INTENSITY = $10^7$ pps
These difficulties were taken into account in our experiment at DRIBs:

- Intensity $10^7$ pps.

- Energy 3-10 MeV/A with energy resolution 1 %.

- A magnetic spectrometer was used at $0^\circ$ and with $\theta = 5^\circ$. 
EXPERIMENTAL SETUP
for measuring excitation functions of fusion reactions

- **6He** measured on **197Au-foils**
- **6He** measured on **206Pb-foils**

Reactions:

- $^6\text{He} + ^{197}\text{Au} \rightarrow ^{203}\text{Tl}^*$
- $^6\text{He} + ^{206}\text{Pb} \rightarrow ^{212}\text{Po}^*$
- $^6\text{He} + ^{197}\text{Au} \rightarrow 196, 198, 199\text{Au}$
SETUP FOR ACTIVATION MEASUREMENTS WITH MSP-144

Excitation function $^6$He+$^{197}$Au - February 2006 experiment

For $E < 40$ MeV (1n,2n) → MSP-144 (focal plane)

$\Delta E = \pm 0.4$ MeV/target at focal plane;

$\cdots E = 16-25$ MeV

MSP-144

Focal plane

Ionization chamber

Monitors

Si-detectors

Au-targets

Strip-detector

Reaction chamber

Monitor

Degrader
Off-line gamma activity measurements

Data:
- 9 foil 1, 2, 3, 4, 5 measurements

Model: ExpDec

\[ N(t) = N_0 \times \exp(-0.693 \times t/T_{1/2}) \]

\[ c_2 = 1.009 \]

\[ N_0 = 851 \pm 55 \]

\[ T_{1/2} = 7.31 \pm 0.47 \text{ h} \]

\[ 3^\text{n}^{199}\text{Tl} \]
\[ 4^\text{n}^{199}\text{Tl} \]
\[ 5^\text{n}^{199}\text{Tl} \]
\[ 6^\text{n}^{199}\text{Tl} \]

\[ \text{6He+}^{197}\text{Au} \rightarrow \text{203}\text{Tl}^* + 2^\text{n} \]

\[ \text{Resolution} \]
\[ \Delta\text{E} = 2 \text{ KeV} \]

<table>
<thead>
<tr>
<th>(x_n)</th>
<th>Residue nuclei</th>
<th>Half life (T_{1/2}), (hour)</th>
<th>(E_g), KeV (1%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2\text{n}</td>
<td>(^{201}\text{Tl})</td>
<td>72.91</td>
<td>167.4 (10%)</td>
</tr>
<tr>
<td>3\text{n}</td>
<td>(^{200}\text{Tl})</td>
<td>26.1</td>
<td>367.9 (87%)</td>
</tr>
<tr>
<td>4\text{n}</td>
<td>(^{199}\text{Tl})</td>
<td>7.42</td>
<td>247.26 (9.3%)</td>
</tr>
<tr>
<td>5\text{n}</td>
<td>(^{198}\text{Tl})</td>
<td>5.3</td>
<td>587.2 (52%)</td>
</tr>
<tr>
<td>6\text{n}</td>
<td>(^{197}\text{Tl})</td>
<td>2.84</td>
<td>152.2 (7.3%)</td>
</tr>
<tr>
<td>7\text{n}</td>
<td>(^{196}\text{Tl})</td>
<td>1.84</td>
<td>344.9 (2%)</td>
</tr>
</tbody>
</table>
$^{212}_{\text{Po}}$ 

$^{6}_{\text{He}} + ^{206}_{\text{Pb}} \rightarrow ^{212}_{\text{Po}}$

- $^{210}_{\text{Po}}$ 
  - $^{123}_{\text{d}}$ 
  - $E_a = 5.3\text{MeV}$

- $^{211}_{\text{Po}}$ 
  - $^{25}_{\text{s}}$ 
  - $E_a = 8.8\text{MeV}$

- $^{212}_{\text{Po}}$ 
  - $^{45}_{\text{s}}$ 
  - $E_a = 11.6\text{MeV}$

- $^{209}_{\text{Po}}$ 
  - $^{102}_{\text{a}}$ 
  - $E_a = 4.88\text{MeV}$

- $^3n$ 
- $^2n$ 
- $^1n$ 
- $^0n$
\( ^6\text{He} + ^{197}\text{Au} \rightarrow ^{203}\text{Tl}^* \rightarrow xn + (203-x)\text{Tl} \)

\( \sigma_{xn}, \text{mb} \)

\( E_{lab}, \text{MeV} \)

2n \((^{201}\text{TI})\)
3n \((^{200}\text{TI})\)
4n \((^{199}\text{TI})\)
5n \((^{198}\text{TI})\)
6n \((^{197}\text{TI})\)
7n \((^{196}\text{TI})\)

\textit{Gamma spectra measurements}

\textit{Statistical model of excited nucleus decay}
Sub-barrier Fusion: $^6\text{He} + ^{206}\text{Pb}$

$^6\text{He} + ^{206}\text{Pb}$

$^5\text{He} + ^{207}\text{Pb}$ (Q=+13MeV)

$^4\text{He} + ^{208}\text{Pb}$ (Q=+13MeV)

Zagrebaev. PRC 67 (2003)

$^{206}\text{Pb}(^6\text{He},2n)^{210}\text{Po}$

$\sigma$, mb vs $E_{\text{lab}}$, MeV

$n$-transfer, stat. model

Zagrebaev. PRC 67 (2003)
The promising reactions such as \( ^{6,8}\text{He} + ^{206,204}\text{Pb} \) leading to \( A_{CN} = ^{212}\text{Po} \), the same as the \( ^{4}\text{He} + ^{208}\text{Pb} \) reaction. In the first case a high Q-value neutron transfer is present

\[
^{6}\text{He} + ^{206}\text{Pb} \rightarrow ^{5}\text{He} + ^{207}\text{Pb} \ (Q_0 = 4.9 \text{ MeV})
\]

\[
\rightarrow ^{4}\text{He} + ^{208}\text{Pb} \ (Q_0 = 13.1 \text{ MeV}) \rightarrow ^{212}\text{Po}.
\]

Predictions are that the high Q-value for neutron transfer, may increase the effective energy with respect to the barrier (which is about 20 MeV) and will increase the fusion probability.

*Zagrebaev. PRC 67 (2003)*
TRANSFER EXCITATION FUNCTION
FOR THE REACTION $^6\text{He} + ^{197}\text{Au}$

$^6\text{He} + ^{197}\text{Au}$

\[ Q_{thr} \]

\[ B_c \]

$\sigma, \text{mb}$

$E_{lab}, \text{MeV}$

$^{198}\text{Au} (+1n)$

$^{196}\text{Au} (-1n)$
EVR ($^6\text{He}+^{197}\text{Au}$)

$^{198}\text{Au}$ (+1n transfer)

$^{196}\text{Au}$ (-1n transfer)

$\sigma$, mb

$E_{cm} - B_c$, MeV
CONCLUSIONS

concerning fusion and transfer-reaction excitation functions

- The data for near-barrier fusion (the 2n-channel for the $^{206}$Pb+$^6$He and $^{197}$Au+$^6$He reactions) are not in agreement with predictions of the statistical model.

- Good agreement is observed with the predictions of the sequential fusion model for reactions of $^6$He+heavy nuclei.

- Transfer reactions – deep sub-barrier transfer of 1 neutron from $^6$He to $^{197}$Au is observed ($E_{cm}(+1n)-B_c=10$ MeV).
Cooperation

JINR, FLNR, Dubna
ErPI, Armenia
NPI of ASCR, Czech Republic
INRNE, Sofia, Bulgaria
INP, Almaty, Kazakhstan
GANIL, Caen, France
IPN, Orsay, France
Cyclotron Laboratory, Jyvaskyla, Finland
Thank you!