The effect of positive $Q_{xn}$-value neutron transfer and weakly bound projectile on near-barrier heavy-ion reactions

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**Part I.** Fusion of $^{32}$S+$^{90,96}$Zr, $^{16}$O+$^{76}$Ge and $^{18}$O+$^{74}$Ge

**Part II.** $^{17}$F+$^{12}$C quasi-elastic scattering

**Part III.** Summary

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Part I. Fusion of $^{32}\text{S}+^{90,96}\text{Zr}$, $^{16}\text{O}+^{76}\text{Ge}$ and $^{18}\text{O}+^{74}\text{Ge}$

Explanation for radioactive alpha-decay with quantum tunneling
Introduction

Single-channel $\rightarrow$ Coupled-channels

Fusion excitation function

Fusion barrier distribution (BD),

Why neutron-transfer effect?

Status: Difficult to describe, controversial results
(BD: Low-energy structure->low energy flat)

Neutron: neutral, occur at large distance->neutron flow -> fusion enhancement
Neutron Transfer with $+Q$-value-> fusion enhancement
SHE: neutron-deficient->New neutron-rich RIB facility
Experimental results

Electrostatic deflector
HI-13 tandem accelerator at CIAE

Separation: electrical rigidity $\eta = E/q$
Optimal high voltage:
Identification: TOF-$E$ (MCP+Si(Au))
Transmission efficiency:

Experimental results

---Fusion of $^{32}\text{S}+^{90,96}\text{Zr}$

Beam:

$^{32}\text{S}: E_{\text{lab}}=95$-130 MeV;

Targets:

$^{90}\text{ZrO}_2(98.87\%): 50 \ \mu \text{g/cm}^2, \Phi 3$;

$^{96}\text{ZrO}_2(86.4\%): 50 \ \mu \text{g/cm}^2, \Phi 3$;

\[
\begin{array}{|c|c|c|c|}
\hline
\text{Nucleus} & E_x (\text{MeV}) & \lambda^n & \beta_n \\
\hline
^{32}\text{S} & 2.230 & 2^+ & 0.30 \\
 & 5.006 & 3^- & 0.40 \\
^{90}\text{Zr} & 2.186 & 2^+ & 0.09 \\
 & 2.748 & 3^- & 0.22 \\
^{96}\text{Zr} & 1.751 & 2^+ & 0.08 \\
 & 1.897 & 3^- & 0.27 \\
\hline
\end{array}
\]

\[
\begin{array}{|c|c|c|}
\hline
\text{System} & ^{32}\text{S}+^{90}\text{Zr} & ^{32}\text{S}+^{96}\text{Zr} \\
\hline
+1\text{n} & -3.328 & 0.785 \\
+2\text{n} & -1.231 & 5.740 \\
+3\text{n} & -6.589 & 4.504 \\
+4\text{n} & -6.319 & 7.659 \\
+5\text{n} & -14.689 & 3.327 \\
+6\text{n} & -16.429 & 4.169 \\
\hline
\end{array}
\]
Experimental results

Experimental results


\[
T_l(E_{\text{c.m.}}) = \int f(B) \frac{1}{N_{\text{tr}}} \sum_k \int_{-E_{\text{c.m.}}}^{Q_0(k)} \alpha_k(E_{\text{c.m.}}, l, Q) \\
\times P_{\text{HW}}(B, E_{\text{c.m.}} + Q, l) dQ dB
\]

Experimental results

---Fusion of $^{16}\text{O}+^{76}\text{Ge}$ and $^{18}\text{O}+^{74}\text{Ge}$

Beams:

$^{16,18}\text{O}$: $E_{\text{lab}}$=38-61 MeV;

Targets:

$^{74}\text{Ge}(99.7\%)$: 120 $\mu$g/cm$^2$, $\Phi 3$;

$^{76}\text{Ge}(99.9\%)$: 50 $\mu$g/cm$^2$, $\Phi 5$;

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$E_x$ (MeV)</th>
<th>$\lambda^\pi$</th>
<th>$\beta_\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{16}\text{O}$</td>
<td>6.13</td>
<td>3$^-$</td>
<td>0.71</td>
</tr>
<tr>
<td>$^{18}\text{O}$</td>
<td>1.98</td>
<td>2$^+$</td>
<td>0.36</td>
</tr>
<tr>
<td>$^{74}\text{Ge}$</td>
<td>0.60</td>
<td>2$^+$</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>2.54</td>
<td>3$^-$</td>
<td>0.16</td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>0.56</td>
<td>2$^+$</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>2.69</td>
<td>3$^-$</td>
<td>0.14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>reaction</th>
<th>$Q_0(-1n)$ (MeV)</th>
<th>$Q_0(-2n)$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{18}\text{O}+^{74}\text{Ge}$</td>
<td>-1.54</td>
<td>+3.75</td>
</tr>
<tr>
<td>$^{16}\text{O}+^{76}\text{Ge}$</td>
<td>-9.59</td>
<td>-14.09</td>
</tr>
</tbody>
</table>
Experimental results

$^{18}\text{O} + ^{74}\text{Ge}$

$E_{\text{lab}} = 42.89$ MeV
Experimental results


Akyüz-Winther Potential

<table>
<thead>
<tr>
<th>System</th>
<th>$V_0$ (MeV)</th>
<th>$r_0$ (fm)</th>
<th>$a$ (fm$^2$)</th>
<th>$V_B$ (MeV)</th>
<th>$R_B$ (fm)</th>
<th>$\hbar\omega$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{16}\text{O}+^{76}\text{Ge}$</td>
<td>56.48</td>
<td>1.173</td>
<td>0.649</td>
<td>34.77</td>
<td>9.89</td>
<td>3.80</td>
</tr>
<tr>
<td>$^{18}\text{O}+^{74}\text{Ge}$</td>
<td>56.46</td>
<td>1.174</td>
<td>0.643</td>
<td>34.45</td>
<td>9.98</td>
<td>3.59</td>
</tr>
</tbody>
</table>
Discussion - complicated $-Q$-value multi-neutron transfer

Transfer is important
But
Extra 8 neutrons effect
More-positive Q-values effect


Discussion - $+Q$-value 1 and/or 2 neutrons transfer

<table>
<thead>
<tr>
<th>System</th>
<th>$Q_{1n}$ (MeV)</th>
<th>$Q_{2n}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{18}$O+$^{24}$Mg</td>
<td>-0.71</td>
<td>+6.24</td>
</tr>
<tr>
<td>$^{18}$O+$^{30}$Cr</td>
<td>+0.84</td>
<td>+9.11</td>
</tr>
<tr>
<td>$^{18}$O+$^{58}$Ni</td>
<td>+0.96</td>
<td>+8.20</td>
</tr>
<tr>
<td>$^{18}$O+$^{74}$Ge</td>
<td>-1.54</td>
<td>+3.75</td>
</tr>
<tr>
<td>$^{18}$O+$^{97}$Mo</td>
<td>+0.03</td>
<td>+5.56</td>
</tr>
<tr>
<td>$^{18}$O+$^{118}$Sn</td>
<td>-1.56</td>
<td>+3.41</td>
</tr>
<tr>
<td>$^{40}$Ca+$^{48}$Ca</td>
<td>-1.58</td>
<td>+2.62</td>
</tr>
</tbody>
</table>

$^{18}$O+$^{58}$Ni enhanced (QEL-BD also);

$^{36}$S+$^{58}$Ni, $^{18}$O+$^{118}$Sn: kinematically mismatched;

$^{18}$O+$^{74}$Ge: more kinematically matched;

More $^{18}$O induced results: maybe helpful;

$^{40}$Ca+$^{48}$Ca: -$Q_{1n}$ not inhibit the enhancement.
Discussion

DC-TDHF
(Density-Constrained-Time Dependent Hatree-Fock)

The promotion of kinetic energy in the initial channel due to the \( +Q \) neutron transfer.

For $^{17}$F:

- The binding energy of its valence proton is 601 keV.
- Only one bound state below the breakup threshold (the first excited state, $E_x=495$ keV, $J^\pi=1/2^+$) [1, 2].
- The first excited state is a proton halo structure [1, 2].
- It plays an important role in the CNO cycle [3].

Experimental setup

- Primary beam: $101\text{MeV}^{16}\text{O}$, $d(^{16}\text{O}, n)^{17}\text{F}$
- $^{17}\text{F}$ beam intensity: $4 \times 10^5 \text{pps}$, purity: $\sim 90\%$
- Target: 1) deuteron gas target, 210 Torr;
  2) $^{12}\text{C}$ target, $435 \mu\text{g/cm}^2$

- Detector: six sets of detector telescopes which is composed of
  DSSD (thickness: $65 \mu\text{m}$, area: $50 \times 50 \text{mm}^2$, 16 strips at each sides,
  strip widths: $3 \text{mm}$, strip span: $0.1 \text{mm}$) and SSD (thickness: $300 \mu\text{m}$)
The actual photo for detectors in the experiment
The typical energy spectra of silicon strip detectors at different angles in the frame of the laboratory system. (a) 5°; (b) 9°; (c) 13°; (d) 17° in frame of Lab system.
Real parts of the OMPs for $^{16}$O and $^{17}$F with $^{12}$C at 3.529MeV/nucleon.

<table>
<thead>
<tr>
<th></th>
<th>projectile</th>
<th>$V$ (MeV)</th>
<th>$r_V$ (fm)</th>
<th>$a_V$ (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$^{16}$O</td>
<td>295.4</td>
<td>0.832</td>
<td>1.400</td>
</tr>
<tr>
<td>II</td>
<td>$^{17}$F</td>
<td>295.4</td>
<td>0.923</td>
<td>1.545</td>
</tr>
</tbody>
</table>

Experimental data of angular distributions of the cross sections for the $^{17}$F quasi-elastic scattering from $^{12}$C at 60 MeV and their comparisons with: i) single-channel optical model calculations (EL, solid curve), ii) coupled channel calculation including the first $2^+$ state of $^{12}$C (CC, dashed curve), and iii) $^{16}$O elastic scattering from $^{12}$C at 56.5 MeV
(1) Optical model calculation

- It should be better to evaluate the energy dependence of the optical potential by means of a simultaneously fitting for several sets of experimental data which cover a certain range of incident energies.

- Unfortunately, for the $^{17}$F elastic scattering from $^{12}$C there are only two sets of data available, namely, the one at 10 MeV/nucleon [8] and the present one, at 60 MeV, which could not allow such kind of study.

Therefore the energy dependence of the OMP of the $^{16}$O+$^{12}$C system was investigated by analyzing its angular distributions of the elastic scattering at 75, 80, 94.8, 100, 115.9, and 124 MeV [10], from this analysis the OMP parameters for the $^{16}$O+$^{12}$C system at 56.5 MeV were obtained by extrapolation.


The real part [11]:

$$V(r) = \frac{-V}{\left[1 + \exp \left(\frac{r - R_V}{a_V}\right)\right]^2}$$

The imaginary part[11]:

$$W(r) = \frac{-iW}{\left[1 + \exp \left(\frac{r - R_W}{a_W}\right)\right]^2} + \frac{-4iW_D \exp \left[(r - R_D)/a_D\right]}{\left[1 + \exp \left(\frac{r - R_D}{a_D}\right)\right]^2}$$

Comparison between optical model calculations with the energy dependent parameters and experimental data for $^{16}$O elastic scattering on $^{12}$C at the incident energies.

<table>
<thead>
<tr>
<th>$E_{\text{inc}}$</th>
<th>$V$</th>
<th>$W$</th>
<th>$r_W$</th>
<th>$W_D$</th>
<th>$r_D$</th>
<th>$a_D$</th>
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</thead>
<tbody>
<tr>
<td>75.0</td>
<td>293.9</td>
<td>12.85</td>
<td>1.086</td>
<td>4.083</td>
<td>1.373</td>
<td>0.3056</td>
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<tr>
<td>80.0</td>
<td>281.1</td>
<td>10.17</td>
<td>1.248</td>
<td>5.595</td>
<td>1.312</td>
<td>0.2997</td>
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<tr>
<td>94.8</td>
<td>276.4</td>
<td>10.29</td>
<td>1.122</td>
<td>3.405</td>
<td>1.398</td>
<td>0.3695</td>
</tr>
<tr>
<td>100.0</td>
<td>280.2</td>
<td>10.51</td>
<td>1.121</td>
<td>4.227</td>
<td>1.361</td>
<td>0.4071</td>
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<tr>
<td>115.9</td>
<td>277.3</td>
<td>15.85</td>
<td>1.129</td>
<td>5.665</td>
<td>1.329</td>
<td>0.4031</td>
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<tr>
<td>124.0</td>
<td>266.8</td>
<td>12.66</td>
<td>1.118</td>
<td>6.546</td>
<td>1.340</td>
<td>0.4183</td>
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<tr>
<td>average</td>
<td>12.06</td>
<td>1.137</td>
<td></td>
<td>1.352</td>
<td>0.3672</td>
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(2) CDCC calculation

- The inelastic scattering cross sections to the first excited state of $^{17}$F are negligible compared to those of the ground state.

- The differences between calculations with and without couplings to continuum states are small, which indicates that the breakup effects to the elastic and inelastic scattering channels are small.

Angular distributions of the elastic and inelastic scattering cross sections of $^{17}$F on $^{12}$C at 60 MeV.

The continuum bins were calculated with P-$^{16}$O separation $r_{bin}<100$ fm and $l$ up to 2; For each $l$, the continuum states were discretized into 8 bins with P-$^{16}$O relative energy up to 12 MeV. The first excited state of $^{17}$F was included; Using WS potential with $r_0=1.25$ fm, $a_0=0.65$ fm CDCC equation were solved with P-T separation up to 800 fm with partial wave up to $L_{max}=400$. 

The inelastic scattering cross sections to the first excited state of $^{17}$F are negligible compared to those of the ground state.
(3) Total reaction cross section and comparison

- The coupling to the breakup channel for weakly bound nuclei which have the small breakup thresholds may strongly affect the fusion cross sections at energies near-and sub-barrier.

- The long tail of density for these weakly bound nuclei reduces the barrier height and the barrier curvature, and this may enhance the fusion cross sections.

- Due to the coupling with the breakup channel there may be a strong dynamic effect. However, the consequence is harder to assess. So it is difficult to clarify and assess if the fusion cross sections are enhanced or hindered in the reactions induced by weakly bound nuclei at the energies near and below the Coulomb barrier.

- Canto et al. [12] suggested the use of a universal function $F(x)$, where static effect arising from the weakly bound nuclei would be considered by taking into account the characteristic of the barrier for each systems. This method was modified by Shorto et al. [13] by replacing fusion cross section with the total reaction cross section.

$$x = \frac{E_{cm} - V_B}{\hbar \omega} \quad F(x) = \frac{2E_{cm}}{\hbar \omega R_B^2} \sigma_R$$


\[ F_0(x) = \ln(1 + e^{2\pi x}) \]

\[ V_B = 7.856 \text{MeV} \]
\[ R_B = 9.0 \text{fm} \]
\[ h\omega = 2.844 \text{MeV} \]
\[ \sigma_R = 1444.4 \text{mb} \]
\[ x = 5.97 \]
\[ F(x) = 31.14 \]

Part III. Summary

1. Fusion excitation functions of $^{32}\text{S}+^{90,96}\text{Zr}$, $^{16}\text{O}+^{76}\text{Ge}$ and $^{18}\text{O}+^{74}\text{Ge}$ at near and below barrier energies were measured with an electrostatic deflector and fusion barrier distributions were extracted;

2. $^{32}\text{S}+^{96}\text{Zr}$ shows the effect of positive $Q$-value multi-neutron transfer in subbarrier fusion enhancement, but $^{18}\text{O}+^{74}\text{Ge}$ does not show positive $Q$-value $2n$ transfer effect in fusion enhancement. The neutron transfer effect is not clear yet. Further study is needed.

3. Quasi-elastic scattering angular distribution of $^{17}\text{F}$ on $^{12}\text{C}$ was measured at 60MeV. The experimental data have been compared with the optical model and CDCC calculations. The results show that the coupling breakup effect of projectile on elastic scattering channel is very weak.

4. Total reaction cross sections were obtained from OM and CDCC calculations. The universal functions $F(x)$s of different projectiles including weakly and tightly bound nuclei bombarding $^{12}\text{C}$ target were compared with $F_0 (x)$. It shows that the breakup channel is not important for weakly bound projectiles on light targets.
Thanks for all the collaborators:

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Thank you!
Thank you for your attention