The effect of positive $Q$-value neutron transfers on near-barrier fusion of heavy-ions

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13-17, May, Venice, Italy
Nuclear reactions of heavy-ions at near-Coulomb-barrier energies are processes which involve complex dynamic process between the two reactants.

The reaction mechanism for fusion of heavy-ions at near-barrier energies is important, but it is still not yet understand well up to now. It involves the basic quantual tunneling mechanism and the coupled-channels effect.

See G. Montagnoli's talk on 14 May.

The reaction mechanisms, such as the sub-barrier fusion enhancement correlated with \( xn \)-transfer channels and transfer/breakup-induced InComplete Fusion (ICF) are still current hot-topics.

c.f. \( ^7\text{Li}+^{209}\text{Bi} \), K.J. Cook \textit{et al.}, PRL 122, 102501 (2019).

The (multi-nucleon) transfer mechanism itself is still not very clear:

c.f. S. Silner's talk about pari-transfer on 13 May.
Near- and sub-barrier fusion (for smaller $Z_P Z_T$)

- The foremost theory base:
  Fusion can be seen as an inverse process of $\alpha$-decay which explain by George Gamow @1928, also by Ronald Wilfrid Gurney & Edward Uhler Condon.

- The 1st fusion-evaporation experiment:
  J.F. Miller et al., PR 81, 288 (1951)

- Discovery of the sub-barrier fusion enhancement:
  The anomalous isotopic dependence of the sub-barrier fusion cross sections.
  $^{16}\text{O} + ^{\text{A}}\text{Sm}$, R.G. Stokstad et al., PRL 41, 465 (1978);
  $^{58,64}\text{Ni} + ^{58,64}\text{Ni}$, M. Beckerman et al., PRL 45, 1472 (1980);

- Fusion barrier distribution (BD): [fingerprint of fusion dynamics]

- Many Explanations--Coupling effects:
  Nuclear structure (collective excitations)
  Reaction dynamics (transfer/breakup reactions)
Near- and sub-barrier fusion enhancement

The collective excitation effect can be well described by the coupled-channels theory. But the neutron transfer effect is still a problem.

● **Discovery:** $^{58,64}\text{Ni} + ^{58,64}\text{Ni}$, M. Beckerman *et al.*, PRL 45, 1472 (1980).

● ...the Positive $Q$-value Neutron Transfers (PQNT) effect:
...key idea: ...the increased kinetic energy after $+Q$-value neutron transfer channel (at large distance) enhances the transmission probability.

Based on a two-step process picture,
Also for V.I. Zagrebaev, PRC 67, 061601 (2003).

● DC-TDHF: Transfer (isovector) induces the barrier for $^{16}\text{O} + ^{208}\text{Pb}$ [depends on $Q_{\text{tr}}$ (isospin)]. see A.S. Umar's talk on 13 May.
How to study the transfer effect on fusion experimentally?

- to extract the fusion barrier distribution
  → a lower energy stretched barrier distribution (tail);
- to compare 2 nearby systems w/wo $+Q_{gs}$ neutron transfer channels;
- to correlate the enhanced fusion with the measured transfer cross sections (transfer strength):
  → two-step process
  → coupled-channels
About the neutron transfer effect on fusion

Substantial (additional) near- and sub-barrier fusion enhancement for the $+Q$-value $xn$-pickup channels.

- $^{40}$Ca+$^{48}$Ca, H.A. Aljuwair et al., PRC 30, 1223 (1984).
- $^{58}$Ni+$^{64}$Ni, M. Beckerman et al., PRL 45, 1472 (1980).
- $^{40}$Ca+$^{96}$Zr, H. Timmers et al., NPA 633, 421 (1998).

No substantial (additional) near- and sub-barrier fusion enhancement for the $+Q$-value $2n$-stripping channel.

- $^{30}$Si+$^{58}$Ni, A.M. Stefanini et al., PRC 30, 2088 (1984). (Kinematic mismatch)
- $^{18}$O+$^{115}$Sn, P. Jacobs et al., PLB 175, 271 (1986).
About the neutron transfer effect on fusion

A special case (for 2n stripping):
Only $^{18}\text{O} + ^{58}\text{Ni}$ ($Q_{-2n} = +8.20$ MeV) was claimed to show big enhancement due to the positive $Q$-value $2n$-stripping channel.


Experimental study for $n$ transfer (pickup/stripping) effect on fusion

- Electrostatic deflector
- HI-13 tandem accelerator at CIAE

- Separation:
  electrical rigidity $\eta = E/q$;
  Optimal high voltage;

- Identification:
  TOF-$E$ (MCP + QSD);

- Angular distribution;

- Transmission efficiency.

- **Beam**: $^{16,18}\text{O}$, 2-20 pnA, 31.8 – 60.0 MeV, energy step 2.4/1.2/0.6 MeV.
- **Target**: $^{58}\text{Ni}$, 99.80% isotope enrichment, thin, C backing.
- **Beam monitors**: 4 Si detectors at $\theta_{\text{lab.}} = 17^\circ$.

Experimental study for $n$ transfer (pickup/stripping) effect on fusion
### pickup

<table>
<thead>
<tr>
<th>System</th>
<th>+1n</th>
<th>+2n</th>
<th>+3n</th>
<th>+4n</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{32}\text{S} + ^{90}\text{Zr}$</td>
<td>-3.33</td>
<td>-1.23</td>
<td>-6.59</td>
<td>-6.32</td>
</tr>
<tr>
<td>$^{32}\text{S} + ^{94}\text{Zr}$</td>
<td>+0.42</td>
<td>+5.10</td>
<td>+3.45</td>
<td>+6.15</td>
</tr>
<tr>
<td>$^{32}\text{S} + ^{96}\text{Zr}$</td>
<td>+0.79</td>
<td>+5.74</td>
<td>+4.50</td>
<td>+7.66</td>
</tr>
</tbody>
</table>

### stripping

\[
^{16}\text{O} + ^{76}\text{Ge} \\
^{18}\text{O} + ^{74}\text{Ge} \\
Q_{-2n} = +3.75 \text{ MeV}
\]

<table>
<thead>
<tr>
<th>System</th>
<th>-1n</th>
<th>-2n</th>
<th>-3n</th>
<th>-4n</th>
<th>$V_{\text{B}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{18}\text{O} + ^{50}\text{Cr}$</td>
<td>+1.22</td>
<td>+9.11</td>
<td>+1.39</td>
<td>-2.12</td>
<td>27.19</td>
</tr>
<tr>
<td>$^{18}\text{O} + ^{52}\text{Cr}$</td>
<td>-0.10</td>
<td>+5.47</td>
<td>-3.95</td>
<td>-8.92</td>
<td>26.98</td>
</tr>
<tr>
<td>$^{18}\text{O} + ^{58}\text{Ni}$</td>
<td>+0.96</td>
<td>+8.20</td>
<td>+0.36</td>
<td>-2.27</td>
<td>31.21</td>
</tr>
</tbody>
</table>
Experimental result

pickup

H.Q. Zhang et al., PRC 82, 054609 (2010).
Experimental result
stripping

H.M. Jia et al., PRC 86, 044621 (2012).
Only modest enhancement (if exists) for the system with positive $Q_{\text{tr}}$-value $2n$-stripping channel, compared to the pickup channel (considering its high $Q_{\text{tr}}$ and high $Q_{\text{tr}}/V_B$).
A self-consistent RE Analysis (to reduce the data)

Here 'self-consistent' means 'the effect of excitation states is 'calibrated' by the experimental data'.

**RE definition:**
Residual enhancement (RE) (except the main inelastic coupling effect)

\[ \text{RE} = \frac{\sigma_{\text{Exp}}}{\sigma_{\text{CC}}} \]

**Benchmark:** RE ~ 1 for the reference systems without expected PQNT effect (to 'calibrate' the effect of collective excitations).

**Experimental consideration:** some fusion data are inconsistent → choose the data set from the same setup.

**Theoretical consideration:** different models (parameters) give different explanations → to use the CCFULL code – ‘the coupling effect to the main inelastic can be well described’).

- ...bare Akyüz-Winther energy-independent potential;
- ...coupled-channels effect due to collective excitations.

A self-consistent RE Analysis (to reduce the data)

...really shows correlation with $Q_{gs}$-values.

A self-consistent RE Analysis (to reduce the data)

...agree with the argument of no direct correlation between RE and $Q_{tr}$-values.

Discussion: something still need to calrify for collective excitation?

1. ...the effect of $3_1^-$ state of $^{40}\text{Ca}$ in fusion? (the response of the extraced strucutral inofrmation with its effect in fusion?)

... a reduced $\beta_3 \sim 0.27$ as for the system of $^{40}\text{Ca}+^{90}\text{Zr}$ [NPA 633, 421 (1998)] (~60% of 0.43)....

2. …still lack of a benchmark for the coupling effect of the collective excitation states of $^{94}\text{Zr}$.

..need to 'calibrate' the effect of inelastic collective state of $^{94}\text{Zr}$.

Do we really know the effect of (higher energy) collective excitation states in fusion as well as usually claimed?
The recent experiment for $^{18}\text{O},^{7}\text{Li}+^{238}\text{U}$ reaction mechanism

- MNT transfer mechanism
- Tr/ICF for weakly-bound projectile

A. Pal et al., *PRC* **99**, 024620 (2019);
K.J. Cook et al., *PRL* **122**, 102501 (2019);

$^{18}\text{O}$: 93.5 MeV
$^{7}\text{Li}$: Two beam energies ($\sim$2.5 pnA):
- 37.0 MeV (1.10 $V_B$);
- 34.6 MeV (1.03 $V_B$);

$^{238}\text{U}(3\#)$:
C $50 \, \mu\text{g/cm}^2 + ^{238}\text{U} 148.5 \, \mu\text{g/cm}^2 + \text{Al} 13.5 \, \mu\text{g/cm}^2$

...by using the correlation measurement of the fission fragment of target-like nucleus with $^4\text{He}$.

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$^{238}\text{U}(3\#)$:

$^{238}\text{U}(3\#)$:

-> PPAC:
isobutane, 4.07 Torr, -530 V
(...insensitive to $^7\text{Li}$)
The recent experiment for $^7\text{Li}+^{238}\text{U}$ reaction mechanism

- **2 PPACs:** Fission fragment
- **4 Telescopes:** (112° & 153°)
  - 20 µm SSSD +
  - 300 µm SSSD/QSD +
  - 1000 – 1500 µm QSD
  - Fiss. + Trans. + Eva.
- **4 Monitors:** PIN-diodes
  - ±15° (L&R), φ.5 mm, 3.8 pps;
  - ±20° (U&D), φ1 mm, 4.9 pps.
...calibrate the isotopes by using the low-energy elastic scattering
Strong $^{14}\text{C}$…similar with $^{18}\text{O}+^{208}\text{Pb}$ in D.C. Rafferty et al., PRC 94, 024608 (2016).

For transfer mechanism: measured final products → primary transfer products?
The recent experiment for $^7\text{Li}+^{238}\text{U}$ reaction mechanism

37.0 MeV (1.10 $V_B$, 390 mb) $^7\text{Li}+^{238}\text{U} @\text{Rn0381}$ some spectra

Raw

$^7\text{Li}$ N=452

$^4\text{He}$ N=216

With FF

$^7\text{Li}$ N=7

$^4\text{He}$ N=35

20 $\mu$m SSSD: 300 $\mu$m SSSD

300 $\mu$m SSSD: 1500 $\mu$m QSD

- Projectile-like products correlated with 2FFs
The recent experiment for $^7\text{Li}+^{238}\text{U}$ reaction mechanism

34.6 MeV (1.03 $V_B$, 140 mb) $^7\text{Li}+^{238}\text{U} @\text{Rn0444}$ some spectra

$^7\text{Li}$ $^2\text{He}$ $^4\text{He}$

N=252
N=175
N=20
N=3

$\bullet$ Projectile-like products correlated with 2FFs

Raw
With FF

20 $\mu$m SSSD: 300 $\mu$m SSSD
20 $\mu$m SSSD: 300 $\mu$m SSSD
20 $\mu$m SSSD: 300 $\mu$m SSSD
20 $\mu$m SSSD: 300 $\mu$m SSSD

PPAC_F: PPAC_B

300 $\mu$m SSSD: 1500 $\mu$m QSD

2019-5-14
Summary / Conclusion

● The experimental fusion excitation functions show different correlations with positive $Q$-value neutron transfer channels.

...2$n$-stripping channel shows only **modest** sub-barrier fusion enhancement compared with the corresponding $xn$-pickup channels.

● A **self-consistent** systematic analysis was proposed to reduce the calculation uncertainties, based on CCFULL code and really provides a further reliable proof for the occurrence of the PQNT effect.

...gives a visualized sub-barrier fusion enhancement excluding the inelastic coupling effect.

...also shows a complex correlation of the enhancement effect with the positive $Q$-value neutron-transfer channels.

● **Strong** $^{14}$C emerges for near-barrier $^{18}$O+$^{238}$U.

Substantial **direct** $^4$He, which is correlated with FFs, emerges for near-barrier $^7$Li+$^{238}$U by using a coincident measurement.

Thanks for your attention!
Preliminary