The effect of the positive *Q*-value neutron transfers on near-barrier heavy-ion fusion

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- * Background
- * Fusion measurement at CIAE
- * A self-consistent systematic analysis
- * Conclusions

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Discovery of the sub-barrier fusion enhancement:

anomalous isotopic dependence of the sub-barrier fusion cross sections

R.G. Stokstad et al., PRL 41, 465 (1978);

M. Beckerman et al., PRL 45, 1472 (1980);

W. Reisdorf et al., PRL 49, 1811 (1982);

Explanation--Coupling effects:

Nuclear structure (inelastic excitations)

Reaction dynamics (transfer/breakup reactions)

Background

A number of models have been proposed:

...due to the quite numerous mechanisms involved in the subbarrier fusion of complex nuclei.

Semiclassical:

G. Pollarolo, PRC 62, 054611 (2000).V.I. Zagrebaev, PRC 67, 061601(R) (2003)

Microscopic treatment (promising): * DC-TDHF:

T.K. Steinbach et al., PRC 90, 041603(R) (2014). - include the effect of pairing on the fusion cross section.

* DCFHF:

C. Simenel et al., in preparation- include the Pauli exclusion principle.

Cf:

Nakatsukasa Takashi, R5, Sept. 13 Simenel Cedric, R5, Sept. 13 Scamps Guillaume, R5, Sept. 13 Courtin Sandrine, R5, Sept. 15 Colucci Giulia, R5, Sept. 15 Stevenson Paul, R5, Sept. 15

. . .

...the Positive *Q*-value Neutron Transfers (<u>PQNT</u>) effect:

...idea core: ...<u>the increased kinetic energy after +Q-value neutron</u> <u>transfer channels enhances the transmission probability</u>.

Cf. Broglia et al., PLB 133, 34 (1983); PRC 27, R2433 (1983).

Background



Seems not
unreasonable!



A purely experimental proof for enhancement!

A.M. Stefanini et al., PRC 76, 014610 (2007).

But: some are enhanced... some not enhanced...

The real dynamical reaction mechanism:

...the coupling form factor F(r)?

... the coupling strength?

• • •

...a long-standing but still unsolved problem.

The selected systems:

• ${}^{32}S + {}^{90,94,96}Zr$

Further study the fusion enhancement occurs in the similar systems.

- ${}^{18}O + {}^{74}Ge, {}^{16}O + {}^{76}Ge$
- ${}^{18}\text{O} + {}^{50,52}\text{Cr}, {}^{58}\text{Ni}$

...with smaller $Z_P Z_T$, bigger Q_{-2n} -value.

To study why no enhancement in ¹⁸O+⁹²Mo,^ASn systems, but occurs in ¹⁸O+⁵⁸Ni.



V.I. Zagrebaev, PRC 67, 061601(R) (2003).

Experimental data from A.M. Borges et al., PRC 46, 2360 (1992).

'qe': quasi-elastic scattering, including the direct processes of elastic, inelastic and transfer...

...a sign of a larger quasielastic flux deviated to fusion.

$$D_{\text{QEL}}(E) = -\frac{d}{dE} \left[\frac{d\sigma_{\text{QEL}}}{d\sigma_{\text{Ru}}}(E) \right]$$

...a complex barrier distribution. ...the lower energy stretch means fusion enhancement!

A special case for ¹⁸O-indeced fusion.





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:

H.Q. Zhang et al., Chin. Phys. C 34, 1628 (2010)

CCDEF: J. Fern ández-Niello *et al.*, Comput.Phys. Commun. **54**, 409 (1989).

+ Zagrebaev's model: PRC 67, 061601(R) (2003)

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



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





CCFULL: K. Hagino *et al.*, Comput. Phys. Commun.**123**, 143 (1999)

Aky üz -Winther Potential







γ₁₁₅₇ 1499.43 († 100.02)

M1+E2: δ=-0.123 *16* γ₀*2656.41* (†,12.6*2*) E2

2n stripping shows some effect, but rather modest!

Some reliable conclusions due to the imperfection of the theoretical models.

Residual enhancement (RE) (except inelastic coupling effect)

 $\mathrm{RE} = \sigma_{\mathrm{Exp}} / \sigma_{\mathrm{CC}}$

 $\sigma_{\rm CC}$: not included the neutron transfer coupling effect.

CCFULL

...bare Aky üz-Winther energy-independent potential

+ inelastic coupled-channels effect.

<u>Benchmark</u>: RE ~ 1 for the reference systems without expected PQNT effect.

H.M. Jia et al., PLB **755**, 43 (2016).





H.M. Jia et al., PLB **755**, 43 (2016).



...agree with the argument of no direct correlation between RE and *Q*-values.

...still lack of a benchmark for the coupling effect of the collective inelastic states for ⁹⁴Zr.

H.M. Jia et al., PLB **755**, 43 (2016).



...also shows obvious PQNT effect.

J.F. Liang et al., PRC **94**, 024616 (2016).

- More systems were measured and analyzed.
- The relevant problem is complicated and still unsolved.
 The transfer mechanism itself and transfer coupling...
 The potential role of isospin, stiffness...

<u>Qs:</u>

- ... underlying dynamical reaction mechanism?
- ... benchmark for experiment/theory?
- ...roadmap for studying this?
- ...still need to go on.

Thanks for your attention!