

Systematic study of breakup effects on complete fusion at energies above the Coulomb barrier

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PKU-CUSTIPEN Nuclear Reaction Workshop
"Reactions and Spectroscopy of Unstable Nuclei"
August 10-14, 2014, Peking University, Beijing

Aug. 11, 2014

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Breakup and fusion

Different fusion processes can take place in collisions of weakly bound projectiles.

- Direct complete fusion (DCF)
- Sequential complete fusion (SCF)
- Incomplete fusion (ICF)
- Noncapture breakup (NCBU)

Complete fusion (CF):

SCF “+” DCF



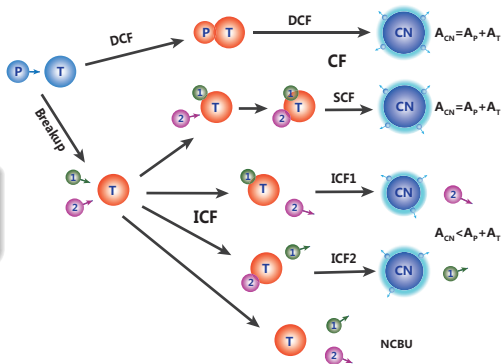
Canto et al., PR, 424, 1 (2006)



Keeley et al., PNP, 59, 579 (2007)



Back et al., RMP, 86, 317 (2014)



The influence of breakup channel on complete fusion

- 1 Suppression on CF cross section at energies above the Coulomb barrier have been confirmed
 - Coupled channel (CC) calculation.
[Hagino et al., PRC, 61, 037602 \(2000\)](#); [CPC, 123, 143 \(1999\)](#);
[Marta et al., PRC, 89, 034625 \(2014\)](#)
 - Single barrier penetration model (SBPM). [Wong, PRL, 31, 766 \(1973\)](#)
- 2 Systematic behavior for the CF suppression have been investigated

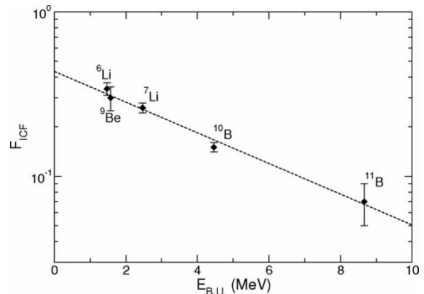
- A trend of systematic behavior as a function of the target charge is not achieved.
- Suppression are almost independent of the target charge for the reactions involving ${}^6\text{Li}$, ${}^7\text{Li}$, and ${}^{10}\text{B}$ projectiles.

[Gomes et al. PRC, 84, 014615 \(2011\)](#)

[Sargsyan et al. PRC, 86, 054610 \(2012\)](#)

[Gasques et al. PRC, 79, 034605 \(2009\)](#)

[Gasques et al. NPA, 834, 147c \(2010\)](#)



With targets of ${}^{208}\text{Pb}$ & ${}^{209}\text{Bi}$

[Gasques et al. PRC, 79, 034605 \(2009\)](#)

Evidence of ICF for reactions involving tightly bound nuclei

Evidence for ICF on tightly bound nuclei have been found.

- The CF suppression factor for ^{11}B on ^{209}Bi is 0.93 (compared with SBPM).
Gasques et al., PRC, 79, 034605 (2009)
- The CF cross sections have been measured for reactions involving $^{12,13}\text{C}$ and ^{16}O .
Singh et al., PRC, 77, 014607 (2008); Kalita, JPG, 38, 095104 (2011); Yadav et al., PRC, 85, 034614 (2012)

What we aim at?

- To explore the influence of the breakup on CF cross section at energies above the Coulomb barrier
- To perform a systematic study by comparing the fusion data with a uniform standard reference

The reduction methods

Reduce the data for systematic study of the influence of breakup on CF.

- Eliminate completely the geometrical factors and static effects of the potential. [Canto et al. JPG, 36, 015109 \(2009\)](#); [NPA, 821, 51 \(2009\)](#)

$$E_{c.m.} \rightarrow x = \frac{E_{c.m.} - V_B}{\hbar\omega}, \quad \sigma \rightarrow F(x) = \frac{2E_{c.m.}}{R_B^2 \hbar\omega} \sigma. \quad \checkmark$$

The parameters R_B , $\hbar\omega$, and V_B are obtained from the double folding and parameter-free São Paulo potential.

- No free parameters.
- Data for different reaction systems can be compared directly.

The universal fusion function

At energies above Coulomb barrier, Wong's formula can describe the fusion cross section accurately. [Wong, PRL, 31, 766 \(1973\)](#)

$$\sigma_F^W = \frac{R_B^2 \hbar \omega}{2E_{c.m.}} \ln \left[1 + \exp \left(\frac{2\pi(E_{c.m.} - V_B)}{\hbar \omega} \right) \right].$$

$F(x)$ reduces to,

$$F_0(x) = \ln [1 + \exp(2\pi x)].$$

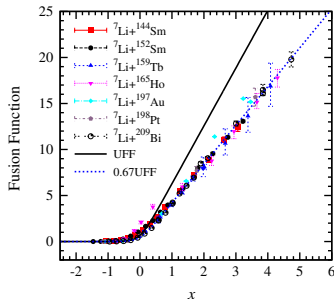
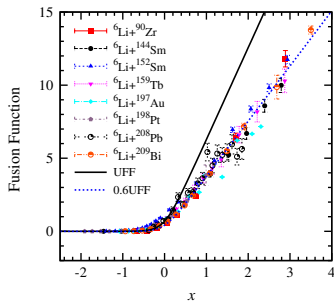
which is called the universal fusion function (UFF).



[Canto et al. JPG, 36, 015109 \(2009\); NPA, 821, 51 \(2009\)](#)

- Deviations of the fusion function, $F(x)$, from the UFF mainly arise from the effects of breakup on CF.

CF functions for weakly bound nuclei ${}^6,7\text{Li}$



The breakup channel and threshold for ${}^6\text{Li}$ is

$${}^6\text{Li} \rightarrow \alpha + d, \quad E_{\text{B.U.}} = 1.474 \text{ MeV.}$$

Suppression factor is defined as

$$F_{\text{B.U.}} = \frac{F(x)}{F_0(x)}.$$

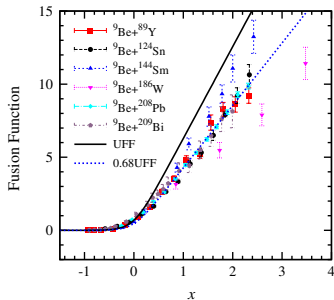
The breakup channel and threshold for ${}^7\text{Li}$ is

$${}^7\text{Li} \rightarrow \alpha + t, \quad E_{\text{B.U.}} = 2.467 \text{ MeV.}$$

Conclusions

- The suppression is independence of the target charge.
- The suppression is stronger for ${}^6\text{Li}$.

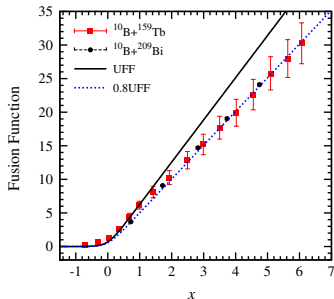
CF functions for weakly bound nuclei ^9Be and ^{10}B



- The breakup channel and threshold for ^9Be is



and the suppression factor is 0.68.

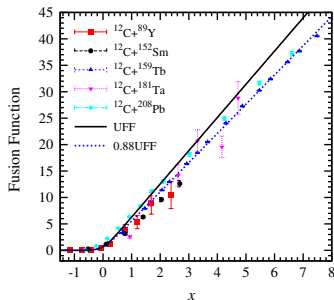
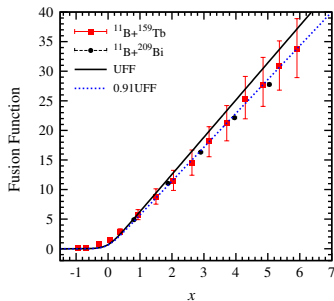


- The breakup channel and threshold for ^{10}B is



and the suppression factor is 0.8.

CF functions for tightly bound nuclei ^{11}B and ^{12}C



The breakup channel and threshold for ^{11}B is

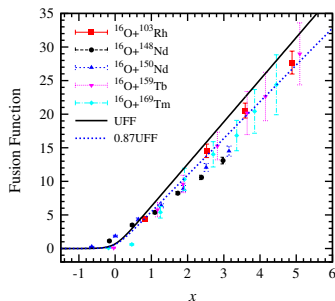
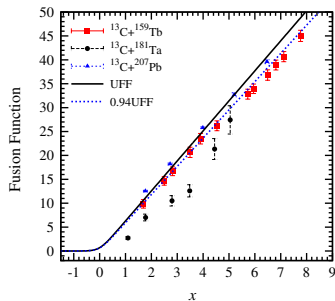


The breakup channel and threshold for ^{12}C is



Conclusions

- The suppression is confirmed.
- The $F_{\text{B.U.}}$ are larger than that for weakly bound nuclei.
- The suppression are independence of the target charge.

CF functions for tightly bound nuclei ^{13}C and ^{16}O 

- The breakup channel and threshold for ^{13}C is

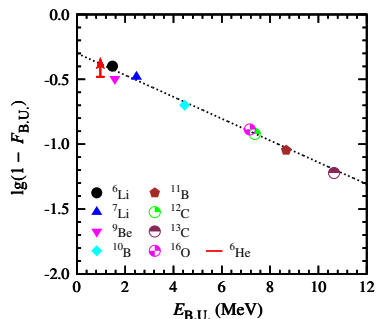
$$^{13}\text{C} \rightarrow \alpha + ^9\text{Be}, \quad E_{\text{B.U.}} = 10.648 \text{ MeV.}$$

- The breakup channel and threshold for ^{16}O is

$$^{16}\text{O} \rightarrow \alpha + ^{12}\text{C}, \quad E_{\text{B.U.}} = 7.162 \text{ MeV.}$$

Nucleus	$E_{\text{B.U.}}$ (MeV)	$F_{\text{B.U.}}$
^6Li	1.474	0.60
^7Li	2.467	0.67
^9Be	1.573	0.68
^{10}B	4.461	0.80
^{16}O	7.162	0.87
^{12}C	7.367	0.88
^{11}B	8.665	0.91
^{13}C	10.648	0.94

Relation between the $F_{B.U.}$ and $E_{B.U.}$



This exponential relation is given as

$$\lg(1 - F_{B.U.}) = -0.3 - 0.084E_{B.U.},$$

or equivalently,

$$\ln(1 - F_{B.U.}) = -0.69 - 0.193E_{B.U.}.$$

For halo nucleus ${}^6\text{He}$

- The breakup channel and threshold energy is



- Suppression factor for total fusion is 0.67 (Upper limit for CF suppression).

[Canto et al. PR, \(2014\); NPA, 821, 51 \(2009\)](#)

Conclusions

- The suppression effect of breakup on CF may indeed depend on the breakup threshold energy

[BW, Zhao, Gomes, Zhao, & Zhou. arXiv1407.5861](#)

Summary

- ★ We perform a systematic study of the breakup effects on the complete fusion at energies above the Coulomb barrier
- ★ The reduced fusion functions are compared with the UFF and suppressed by the breakup of projectiles
 - The suppression for reaction induced by the same projectile is independence of the target charge. The suppression mainly determined by the lowest energy breakup channel of the projectile.
 - There holds a good exponential relation between the suppression factor and the energy corresponding to the lowest breakup threshold.
 - The physics behind the good exponential relation is unclear.

Thanks for your attention!

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Thanks for your attention!