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

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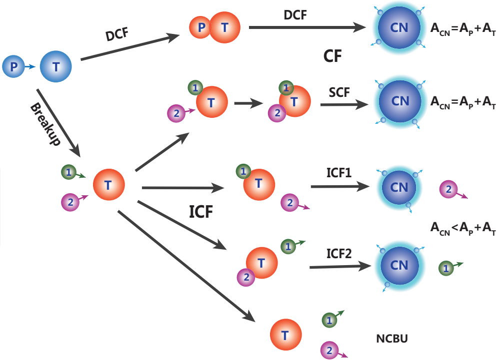
Contents

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)

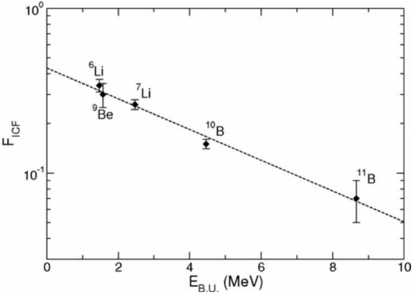
Keeley et al., PPNP, 59, 579 (2007)

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.
  Gomes et al. PRC, 84, 014615 (2011)
  Sargsyan et al. PRC, 86, 054610 (2012)
- Suppression are almost independent of the target charge for the reactions involving ^{6}Li, ^{7}Li, and ^{10}B projectiles.
  Gasques et al. PRC, 79, 034605 (2009)
  Gasques et al. NPA, 834, 147c (2010)



With targets of ^{208}Pb & ^{209}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}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)

$$E_{\rm c.m.} \to x = \frac{E_{\rm c.m.} - V_{\rm B}}{\hbar\omega}, \quad \sigma \to F(x) = \frac{2E_{\rm c.m.}}{R_{\rm B}^2 \hbar\omega}\sigma. \qquad \surd$$

The parameters $R_{\rm B}$, $\hbar\omega$, and $V_{\rm B}$ 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,

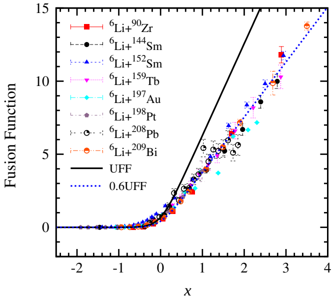
$$F_0(x) = \ln\left[1 + \exp(2\pi x)\right].$$

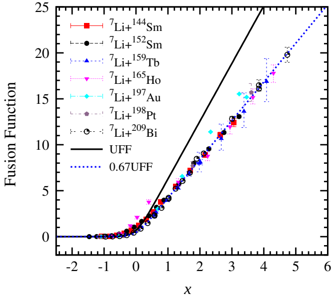
which is called the universal fusion function (UFF).

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}Li





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

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

Suppression factor is defined as

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

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

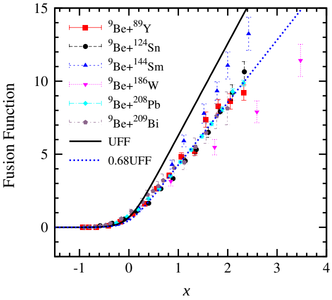
$$^{7}\mathrm{Li} \to \alpha + t, \quad E_{\mathrm{B.U.}} = 2.467 \text{ MeV}.$$

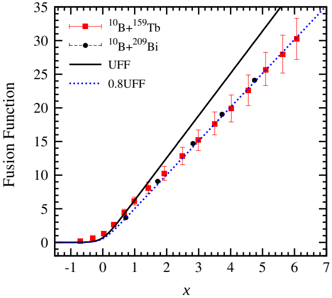
Conclusions

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

BW, Zhao, Gomes, Zhao, & Zhou. arXiv1407.5861

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





- The breakup channel and threshold for ^{9}Be is

$$^9\text{Be} \rightarrow 2\alpha + n, \quad E_{\text{B.U.}} = 1.573 \text{ MeV}.$$

and the suppression factor is 0.68.

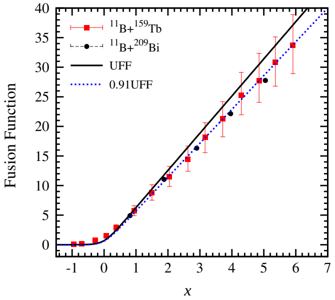
- The breakup channel and threshold for ^{10}B is

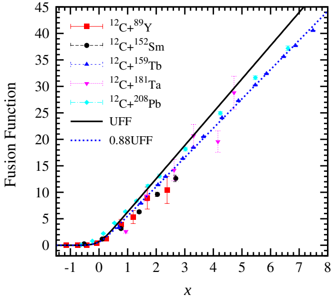
$$^{10}\text{B} \rightarrow \alpha + {}^6\text{Li}, \quad E_{\text{B.U.}} = 4.461 \text{ MeV}.$$

and the suppression factor is 0.8.

BW, Zhao, Gomes, Zhao, & Zhou. arXiv1407.5861

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





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

$$^{11}\mathrm{B} \to \alpha + {}^{7}\mathrm{Li}, \quad E_{\mathrm{B.U.}} = 8.665 \text{ MeV}.$$

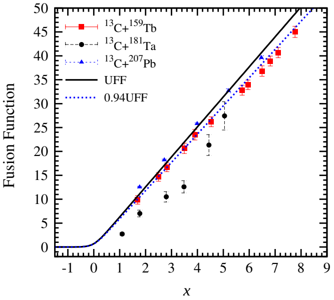
The breakup channel and threshold for ^{12}C is

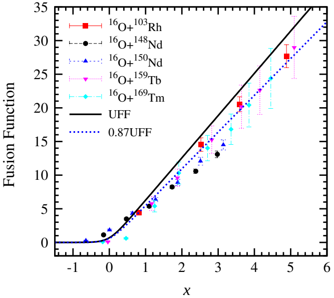
$$^{12}\mathrm{C} \to \alpha + {}^{8}\mathrm{Be}, \quad E_{\mathrm{B.U.}} = 7.367 \text{ MeV}.$$

Conclusions

- The suppression is confirmed.
- The $F_{\mathrm{B.U.}}$ 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

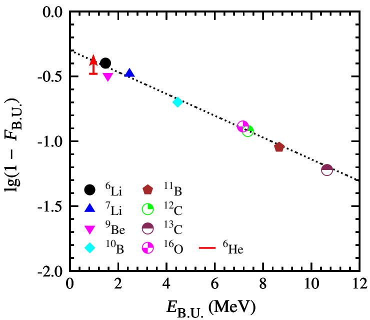
$$^{13}\mathrm{C} \to \alpha + {}^{9}\mathrm{Be}, \quad E_{\mathrm{B.U.}} = 10.648 \text{ MeV}.$$

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

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

Nucleus	$E_{\mathrm{B.U.}}$ (MeV)	$F_{\mathrm{B.U.}}$
^{6}Li	1.474	0.60
^{7}Li	2.467	0.67
^{9}Be	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 $F_{\mathrm{B.U.}}$ and $E_{\mathrm{B.U.}}$



This exponential relation is given as

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

or equivalently,

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

For halo nucleus ^{6}He

- The breakup channel and threshold energy is

$$^6\mathrm{He} \to \alpha + 2n, \quad E_{\mathrm{B.U.}} = 0.972\ \mathrm{MeV}.$$

- 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!