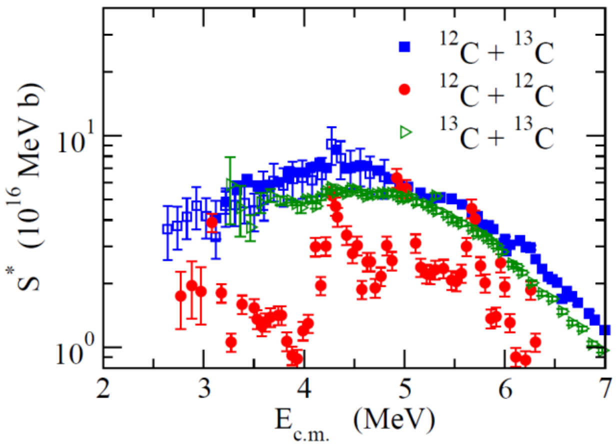
炭素原子核の核融合反応

萩野浩一（東北大学）
Neil Rowley（IPN Orsay）



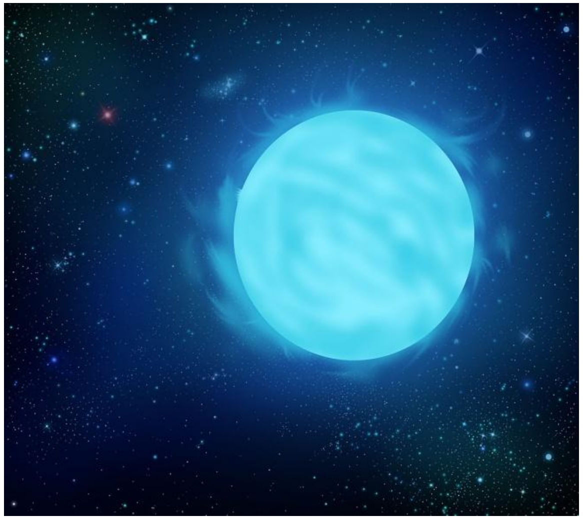
TOHOKU UNIVERSITY

1. 天体における $^{12}C + ^{12}C$ 核融合反応
2. 結合チャンネル法による分子共鳴現象の解析
   ～ $^{12}C + ^{12}C$ と $^{12}C + ^{13}C$ の比較～
3. まとめ

Introduction: $^{12}C + ^{12}C$ fusion

$^{12}C+^{12}C$ fusion : a key reaction in nuclear astrophysics

Carbon burning
in massive stars



$^{12}C+^{12}C \rightarrow \alpha + ^{20}Ne$

$^{12}C+^{12}C \rightarrow p + ^{23}Na$

stellar evolution

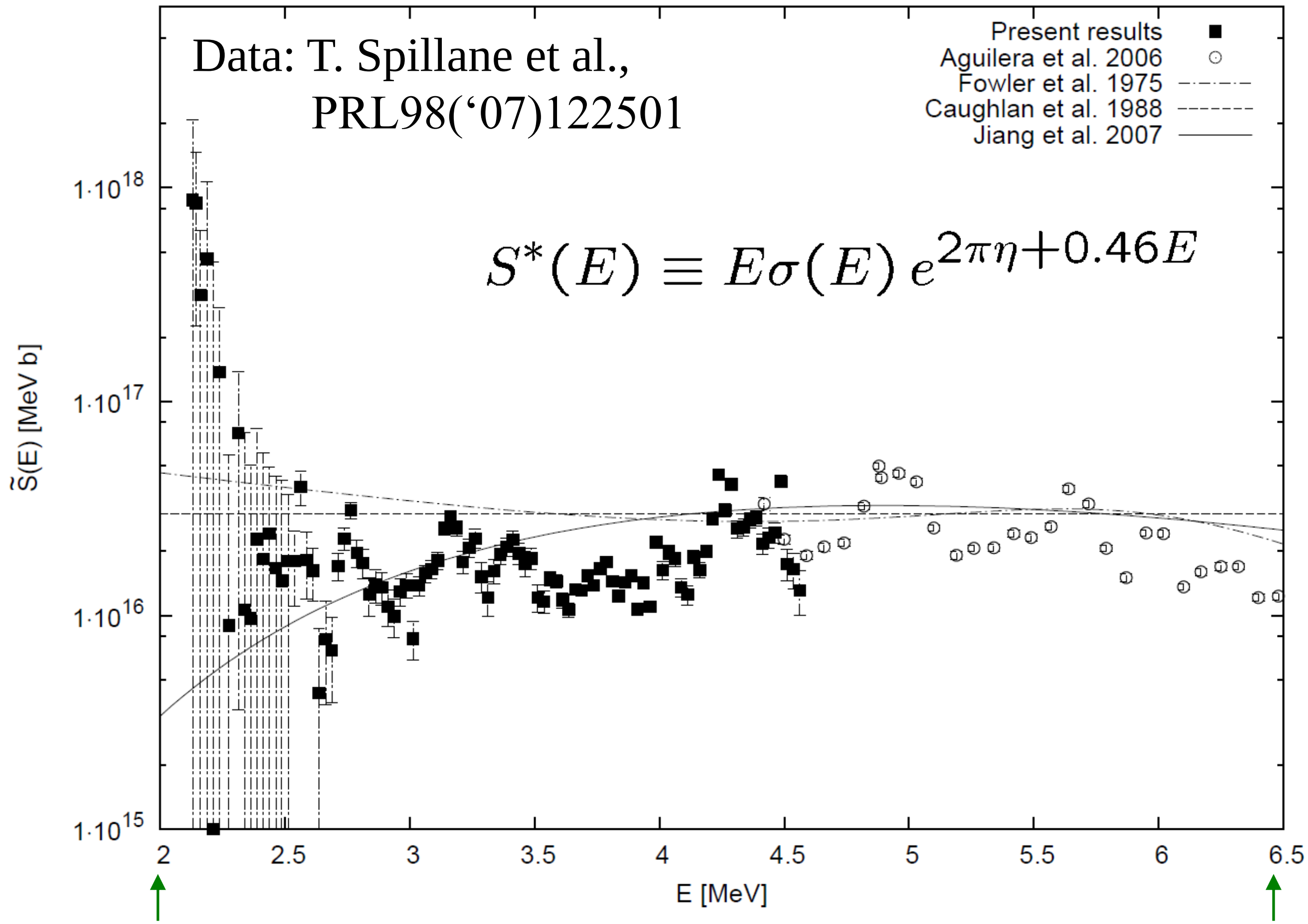
Type Ia supernovae

X-ray superburst

deep layer of the outer crust in accreting neutron stars

important to understand $^{12}C+^{12}C$ fusion at deep subbarrier energies

Experimental data at low energies



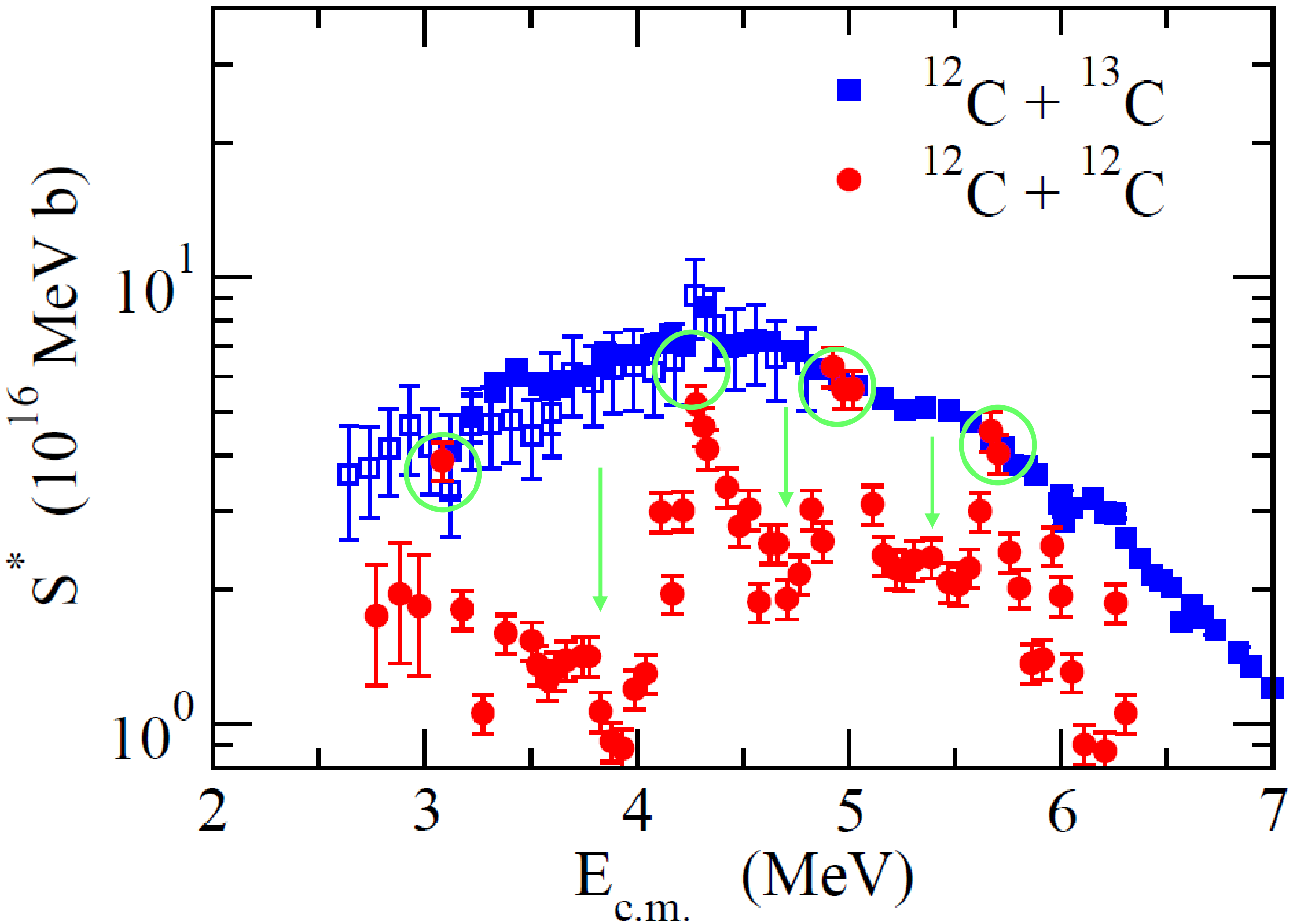
T. Spillane et al., PoS (NIC X) 016

$E_G \sim 2$ MeV (T=0.85 GK) $\sim V_b$

✓ pronounced resonance structures with $\Gamma \sim 100$ keV
"molecular resonances" (2^+ excitation: Nogami-Imanishi)

✓ difficult to extrapolate down to E_G

Comparison with other C+C systems



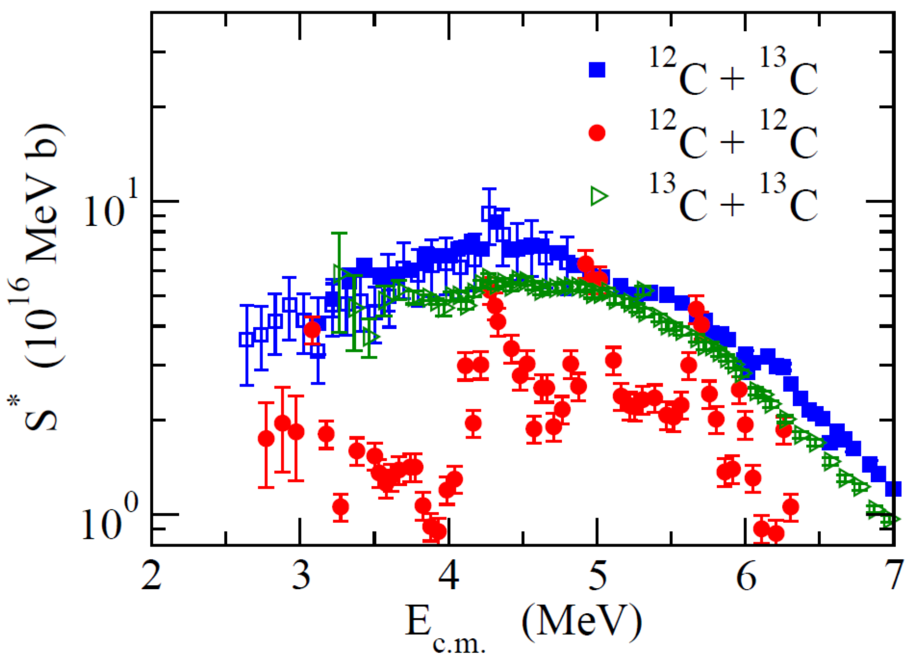
M. Notani, X.D. Tang et al., PRC85('12)014607

fusion cross sections for $^{12}C+^{13}C$, $^{13}C+^{13}C$: much less structured

off-resonance: fusion inhibition

on-resonance: match with $^{12}C+^{13}C$

Comparison with other C+C systems



fusion cross sections for $^{12}C+^{13}C$, $^{13}C+^{13}C$: much less structured

How can one understand the systematics?
- from $^{12}C+^{12}C$ to $^{12}C+^{13}C$, $^{13}C+^{13}C$

origins for the resonances?

cf. most of the previous studies: $^{12}C+^{12}C$ only

Jiang's conjecture: C.L. Jiang et al., PRL110('13)072701

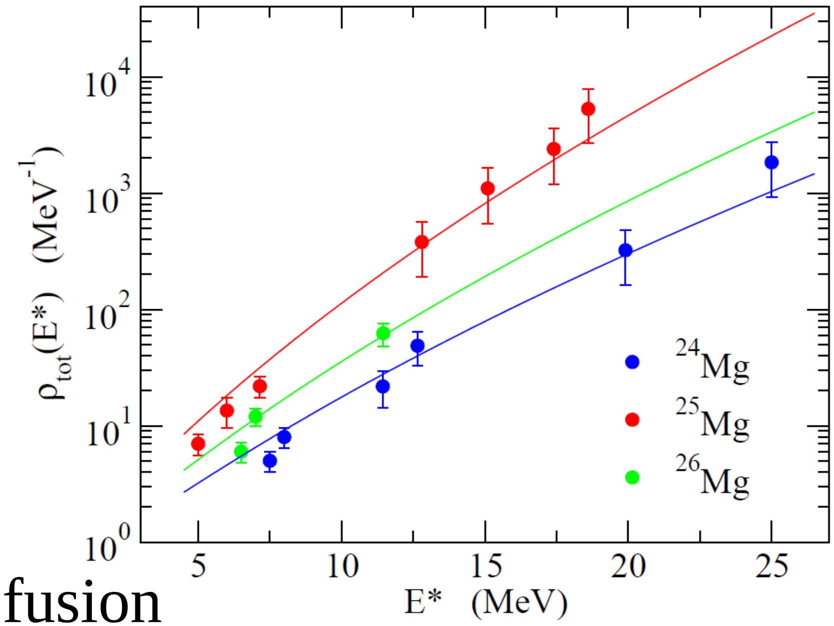
properties of compound nucleus (^{24}Mg)?

^{12}C+^{12}C reaction:

- ✓ level density of ^{24}Mg : small (e-e)
- ✓ small fusion Q-value

Q = +13.9 MeV (^{12}C+^{12}C)
+16.3 MeV (^{12}C+^{13}C)
+22.5 MeV (^{13}C+^{13}C)

⟶ small E^* for ^{24}Mg in ^{12}C+^{12}C fusion



$$\sigma \sim \sum_J \sigma^J_{\rm cap}\left[1 - e^{-2\pi\Gamma_J/D_J}\right]$$

large hindrance factor

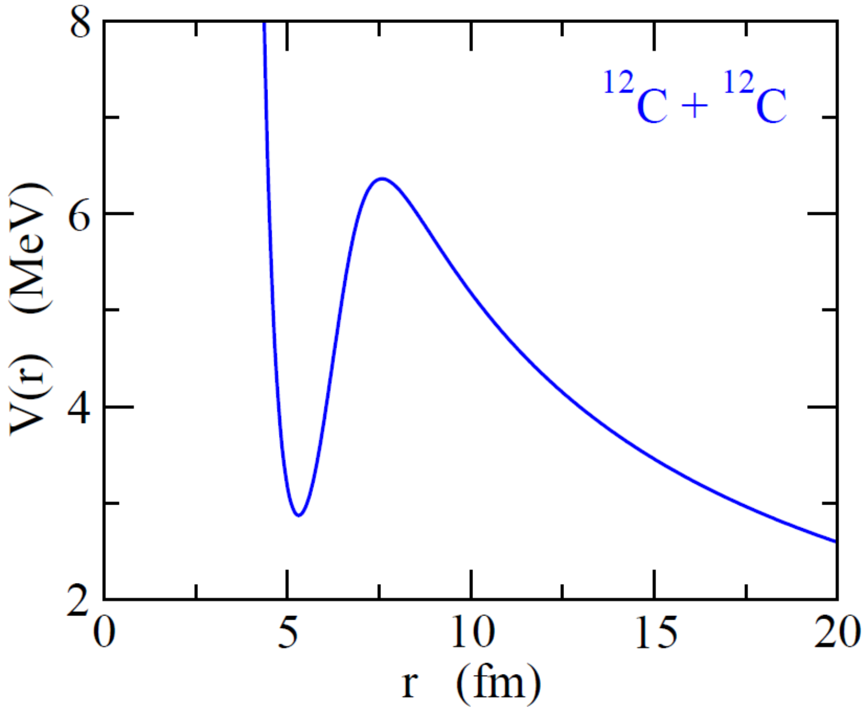
$D_J = 1/\rho_J$
Γ_J : CN width

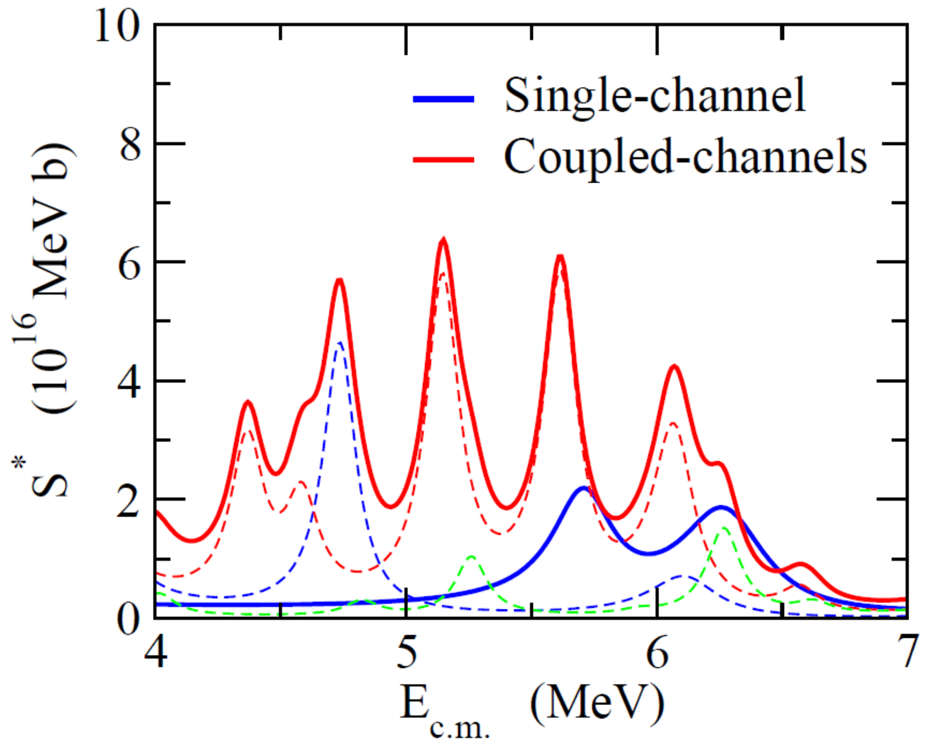
incorporate this idea in the coupled-channels calculations?

C.C. calculations with level-density-dependent imaginary potential

^{12}C-^{12}C potential (Kondo, Matsuse, Abe, PTP('78))

- ✓ two-range Woods-Saxon + Coulomb for the real part
- ✓ a Woods-Saxon for the imaginary part (weak absorption)





C.C. calculations with level-density-dependent imaginary potential

^{12}C-^{12}C potential (Kondo, Matsuse, Abe, PTP('78))

- ✓ two-range Woods-Saxon + Coulomb for the real part
- ✓ a Woods-Saxon for the imaginary part (weak absorption)

$$W(r) = -W_0 \cdot f_{\rm WS}(r) \to -w_0\, \rho_J(E^*) \cdot f_{\rm WS}(r)$$

G. Helling, W. Scheid, W. Greiner, PL 36B ('71) 64
H.-J. Fink, W. Scheid, W. Greiner, NPA188 ('72) 259
J.M. Quesada, M. Lozano, G. Madurga, PLB125 ('83) 14
M.V. Andres, Quesada, Lozano, Madurga, NPA443 ('85) 380

- ✓ *E* and *J* dependent imaginary potential
- ✓ system dependence through ρ(*E*)

cf. Fermi's golden rule

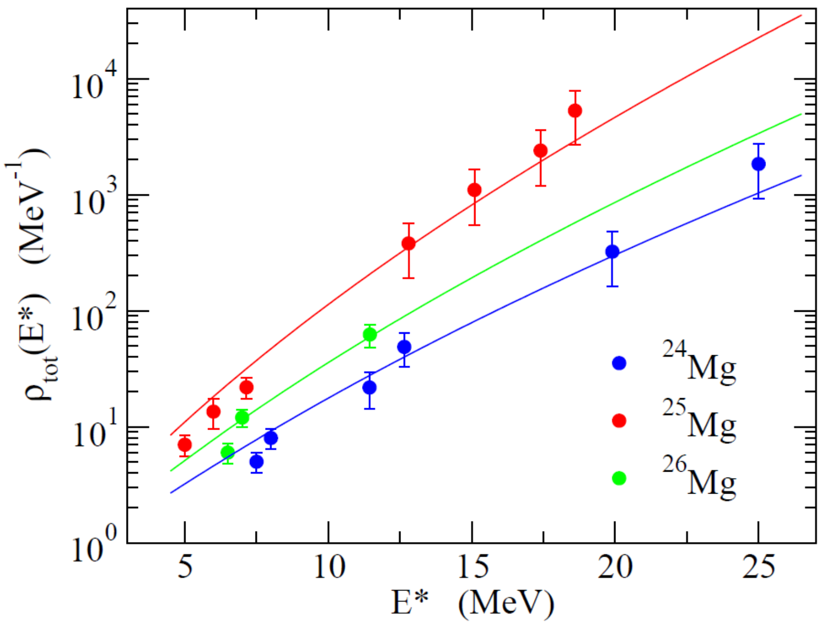
$$\frac{dw}{dt} = \frac{2\pi}{\hbar}\, |\langle \psi_{\rm CN} | V_{\rm int} | \psi_{\rm elastic} \rangle|^2 \rho_J(E^*)$$

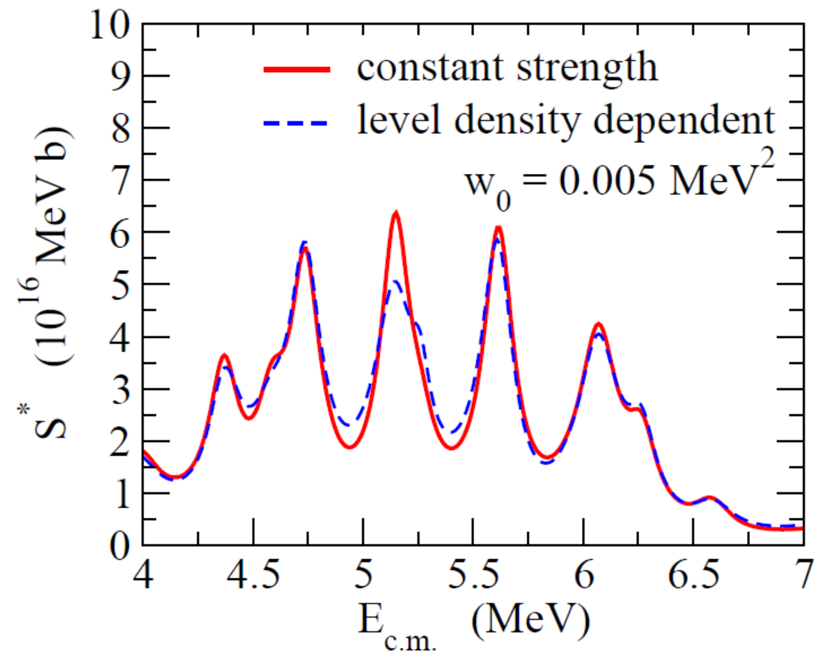
C.C. calculations with level-density-dependent imaginary potential

^{12}C-^{12}C potential (Kondo, Matsuse, Abe, PTP('78))

- ✓ two-range Woods-Saxon + Coulomb for the real part
- ✓ a Woods-Saxon for the imaginary part

$$W(r) = -W_0 \cdot f_{\rm WS}(r) \rightarrow -w_0\,\rho_J(E^*) \cdot f_{\rm WS}(r)$$

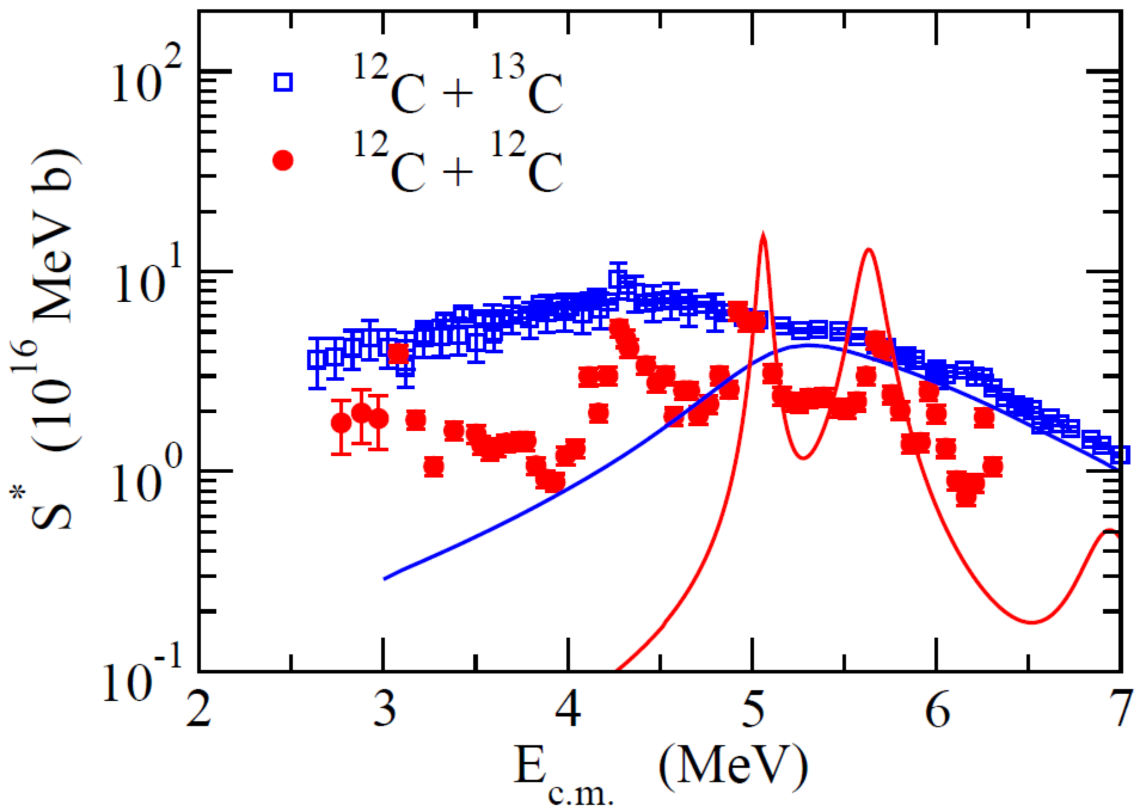




$$\rho_J(E^*) = \frac{(2J+1)e^{-(J+1/2)^2/2\sigma^2}}{4\sigma^3\sqrt{2\pi}}\,\frac{\sqrt{\pi}}{12}\,\frac{e^{2\sqrt{aE^*}}}{a^{1/4}(E^*)^{5/4}}$$

$$\left(\sigma^2 = 0.088\,aA^{2/3}\sqrt{\frac{E^*}{a}}\right)$$

Results of coupled-channels calculations



^{12}C (0^+, 2^+: 4.44)
^{13}C ($1/2^-$, $3/2^-$:3.68)
+ mutual excitations

✓ structured ^{12}C+^{12}C
✓ smooth ^{12}C+^{13}C

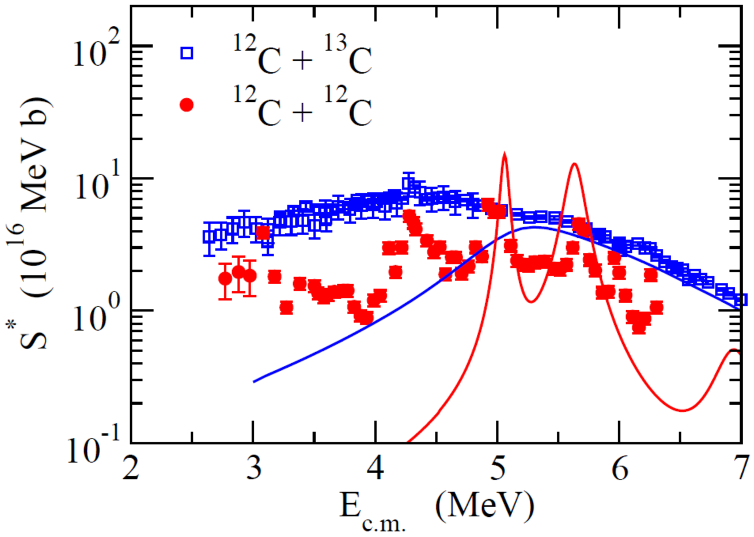
system dependence: qualitatively reproduced

underestimate of fusion cross sections at deep subbarrier energies:
⟶ couplings to 3^- and 0_2^+ (Hoyle state)? alpha transfer channel?

cf. role of Hoyle state in ^{12}C+^{12}C:
M. Assuncao and P. Descouvemont, PLB723 ('13) 355

Summary

Molecular resonances in fusion of C+C systems



^{12}C +^{12}C : well pronounced resonance structure

^{13}C + ^{13}C, ^{12}C + ^{13}C : rather smooth

CN ^{24}Mg: low level density (low Q-value, e-e nucleus)

cf. Jiang's conjecture

coupled-channels calculations with level density dependent imaginary potential