Quantum dynamical microscopic approach to stellar carbon burning

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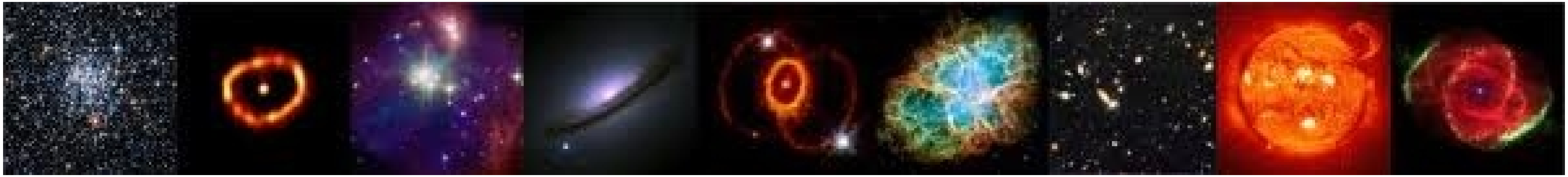
Outline

- Motivation
- Quantum wave-packet dynamics
- Molecular & compound nucleus resonances
- Conclusions & Outlook

Close, Stevenson & AD-T, PLB **870** (2025) 139881

Importance of Understanding $^{12}C + {}^{12}C$ Fusion

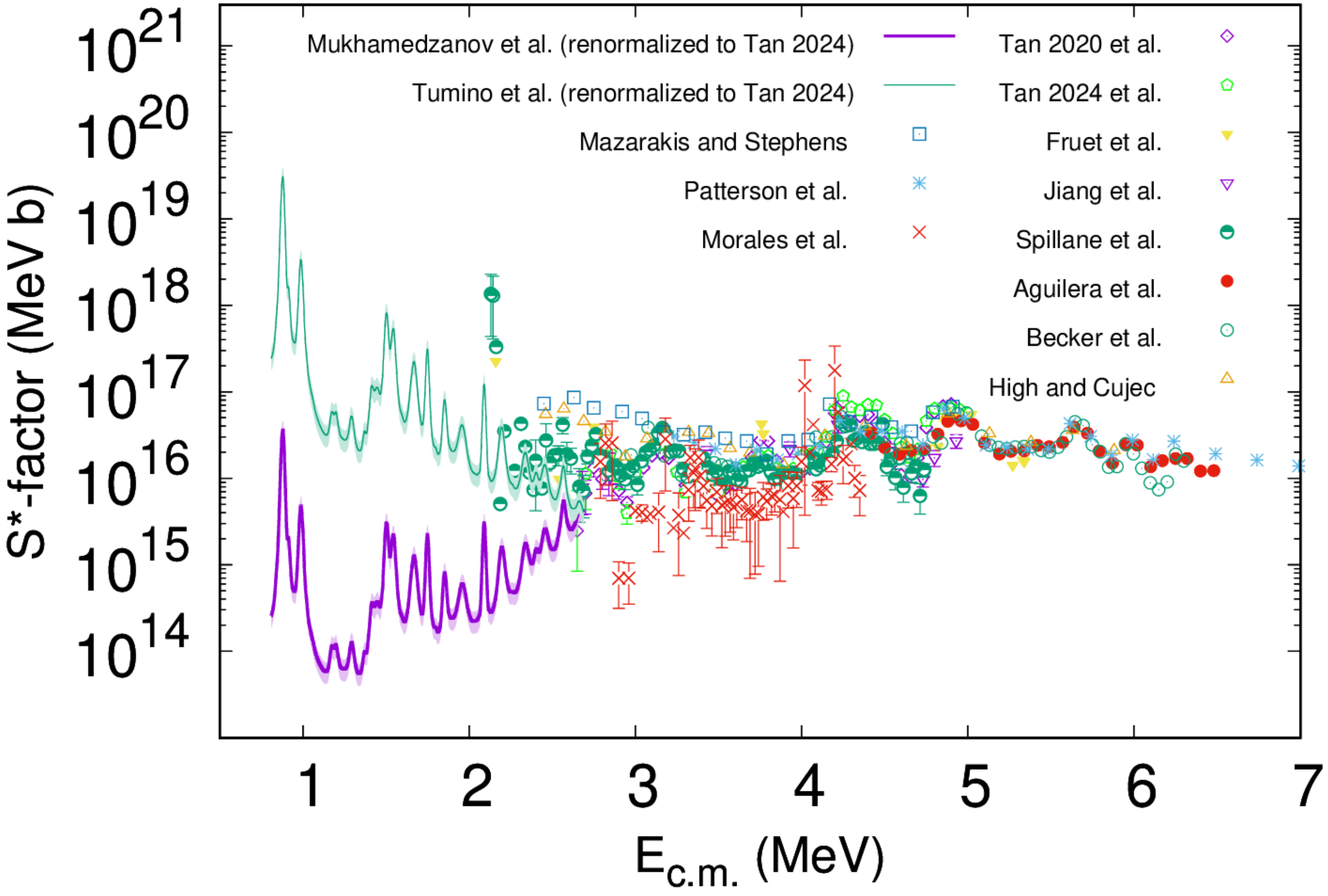


- This reaction is crucial for understanding the nucleosynthesis of ^{20}Ne and ^{23}Na as well as the subsequent evolution of massive stars (e.g., whether a star with $M \geq 8M_{\odot}$ evolves into a supernova).

Wiescher *et al.*, *Quantum Physics of Stars,* RMP **97** (2025) 025003-1-88.

Pignatari *et al.*, *The $^{12}C + {}^{12}C$ reaction and the impact on nucleosynthesis in massive stars,* Astrophys. J. **762** (2013) 31-1-23.

Experimental Astrophysical S-Factor for $^{12}C + ^{12}C$ Fusion



Modified S-factor

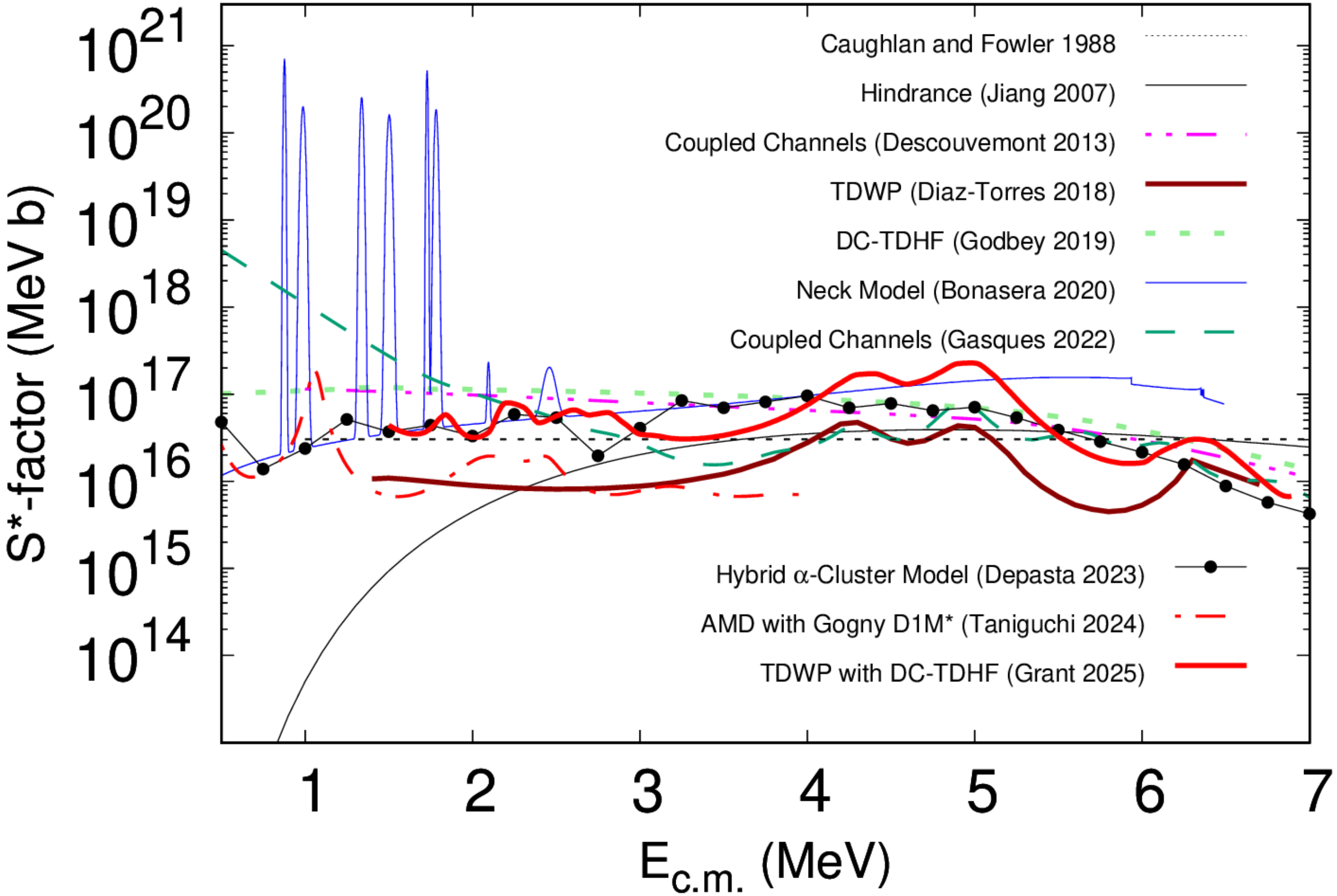
$$S^* = \sigma E \exp(2\pi\eta + gE),$$

$$S^*(E) = S(E)e^{(0.46E)}.$$

Wiescher *et al.*, *Quantum Physics of Stars*, RMP **97** (2025) 025003-1-88.

Chieffi *et al.*, *The Status of $^{12}C+^{12}C$ fusion process*, EPJA **61** (2025) 280-1-27.

Theoretical Astrophysical S-Factor for $^{12}C + ^{12}C$ Fusion



Wiescher *et al.*,
Quantum Physics of Stars,
RMP **97** (2025) 025003-1-88.

Chieffi *et al.*,
The Status of ^{12}C+^{12}C fusion process,
EPJA **61** (2025) 280-1-27.

Quantum Wave-Packet Dynamics

- **Preparation:** the initial state $\Psi(t=0)$

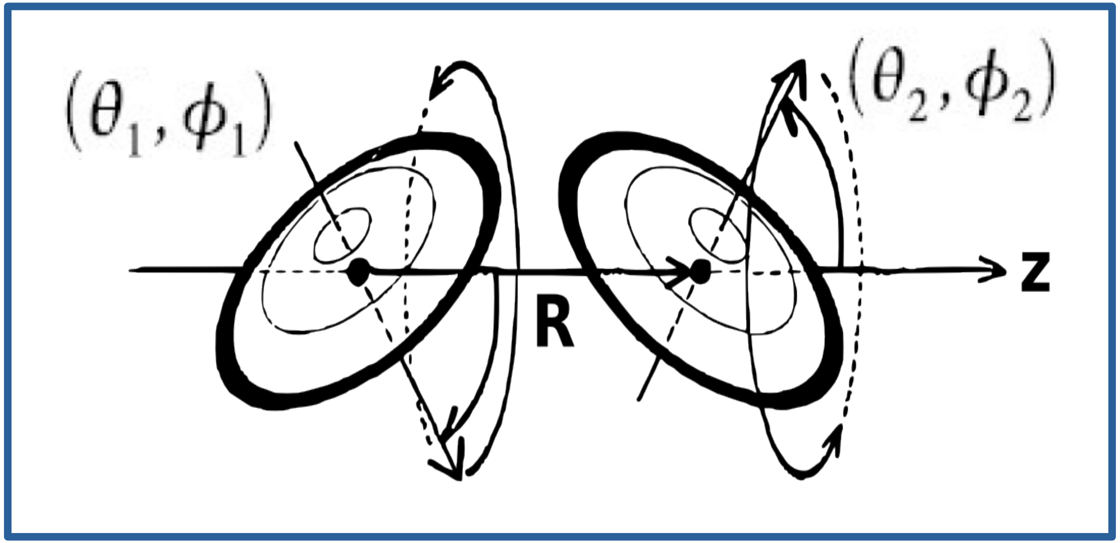
- **Time propagation:** $\Psi(0) \longrightarrow \Psi(t)$
  guided by the operator, $\exp(-i\,\hat{H}\,t/\hbar)$
  $\hat{H}$ is the model Hamiltonian

- **Analysis:** extraction of probabilities from the time-dependent wave function

Vockerodt & AD-T, PRC **104** (2021) 064601

The $^{12}C + {}^{12}C$ Molecular Structure & Carbon Fusion

Greiner, Park & Scheid, in Nuclear Molecules, World Scientific, 1994

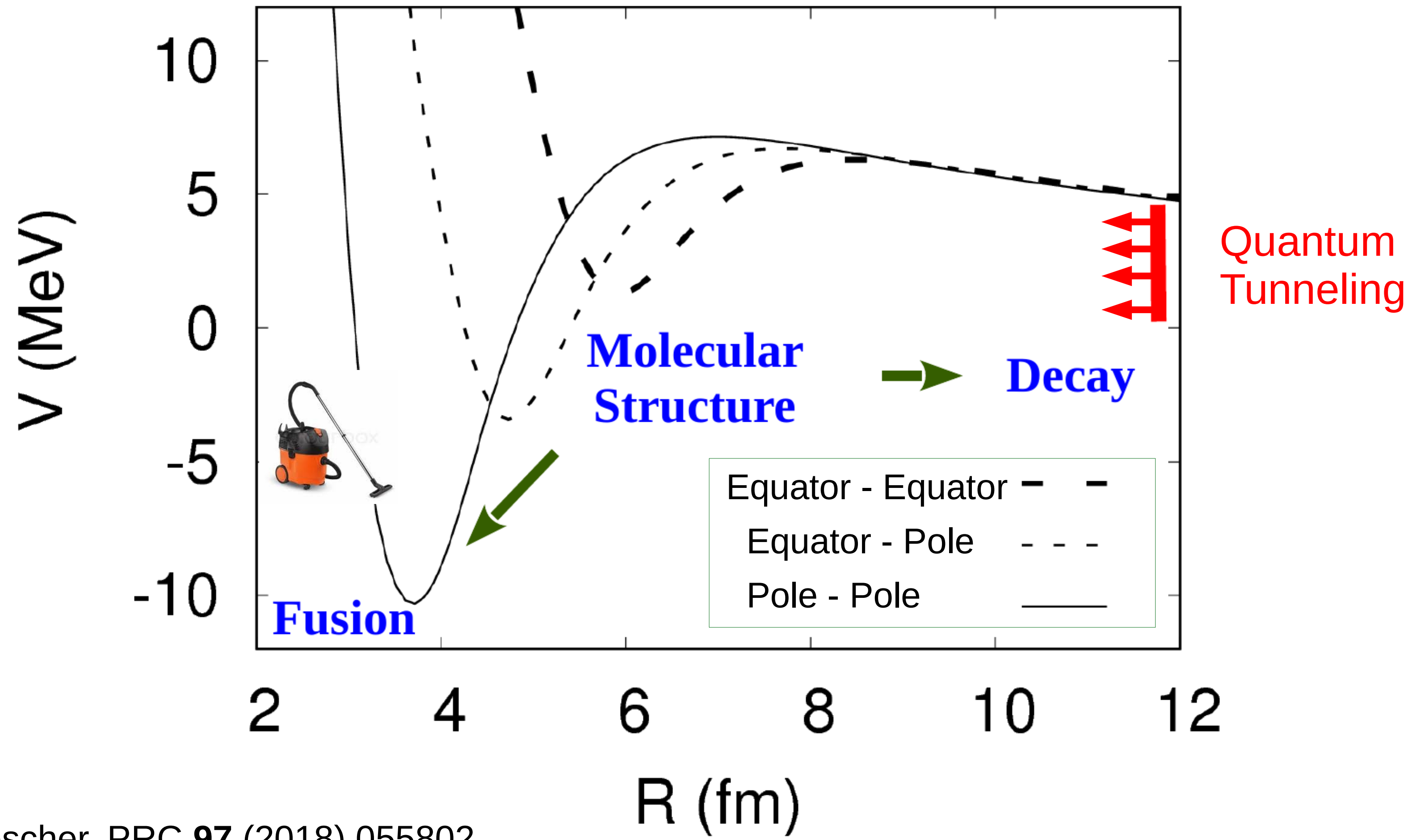


Experimental quadrupole deformation of ^{12}**C**: ~ **- 0.5**

How does this nuclear molecular structure affect fusion?

Potential Energy Landscape: Molecular structure influences fusion and decay rates

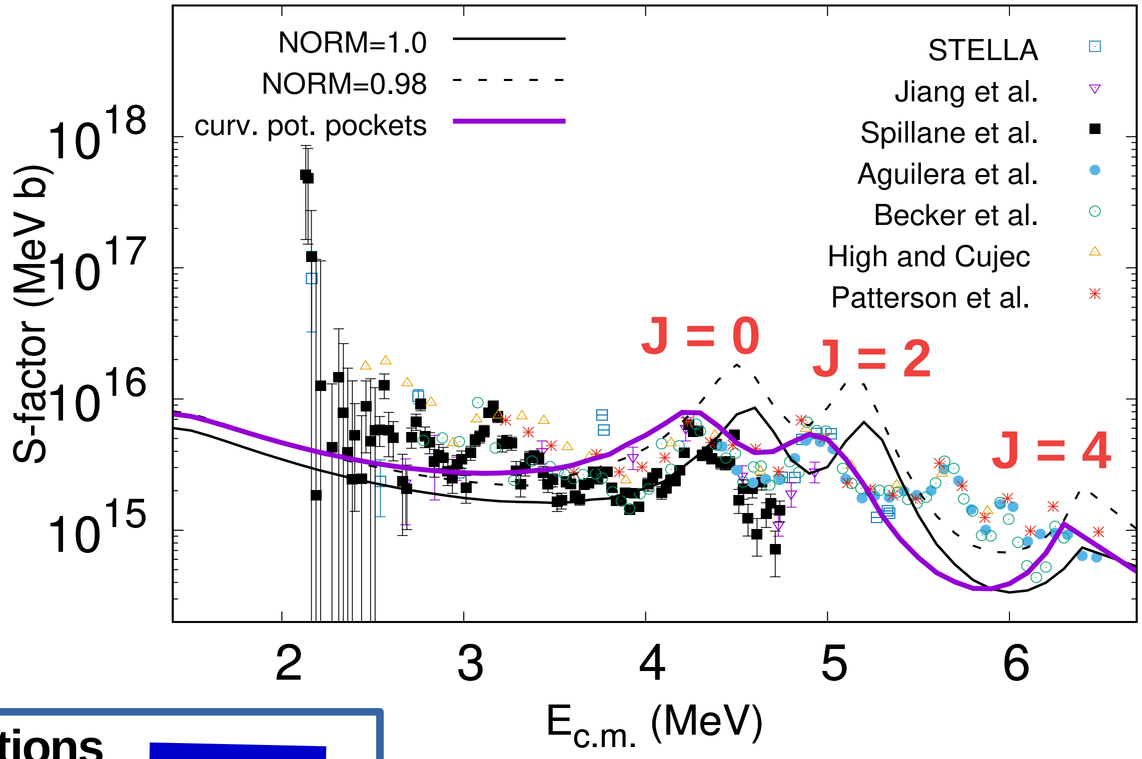
FRLDM & nuclear shapes from a TCSM model [AD-T, PRL **101** (2008) 122501]



AD-T & Wiescher, PRC **97** (2018) 055802

Astrophysical S-Factor for $^{12}C + ^{12}C$ Fusion

AD-T & Wiescher, PRC **97** (2018) 055802

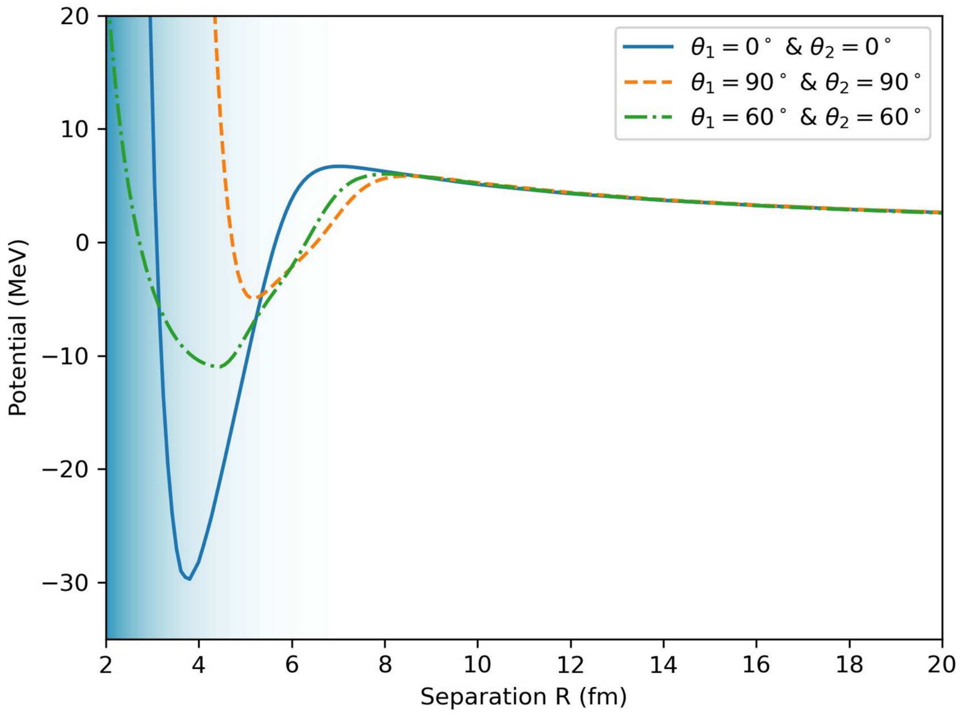


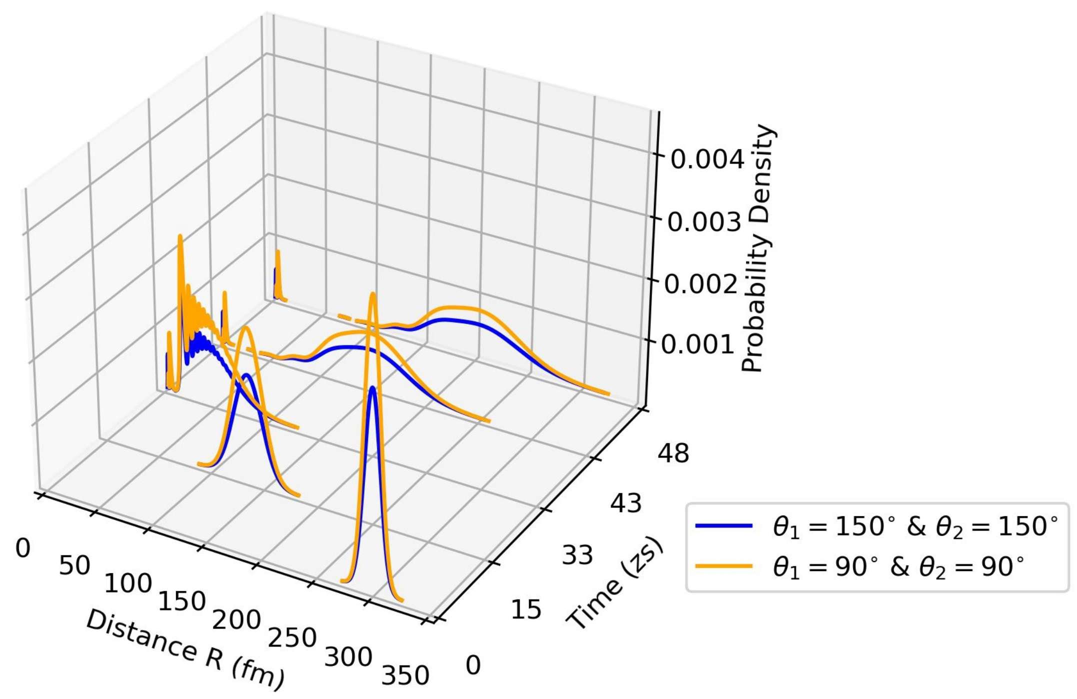
range of cross sections at this energy window

1pb 1nb

Microscopic Study of the Astrophysical S-Factor for $^{12}C + ^{12}C$ Fusion

Close, Stevenson & AD-T, PLB **870** (2025) 139881

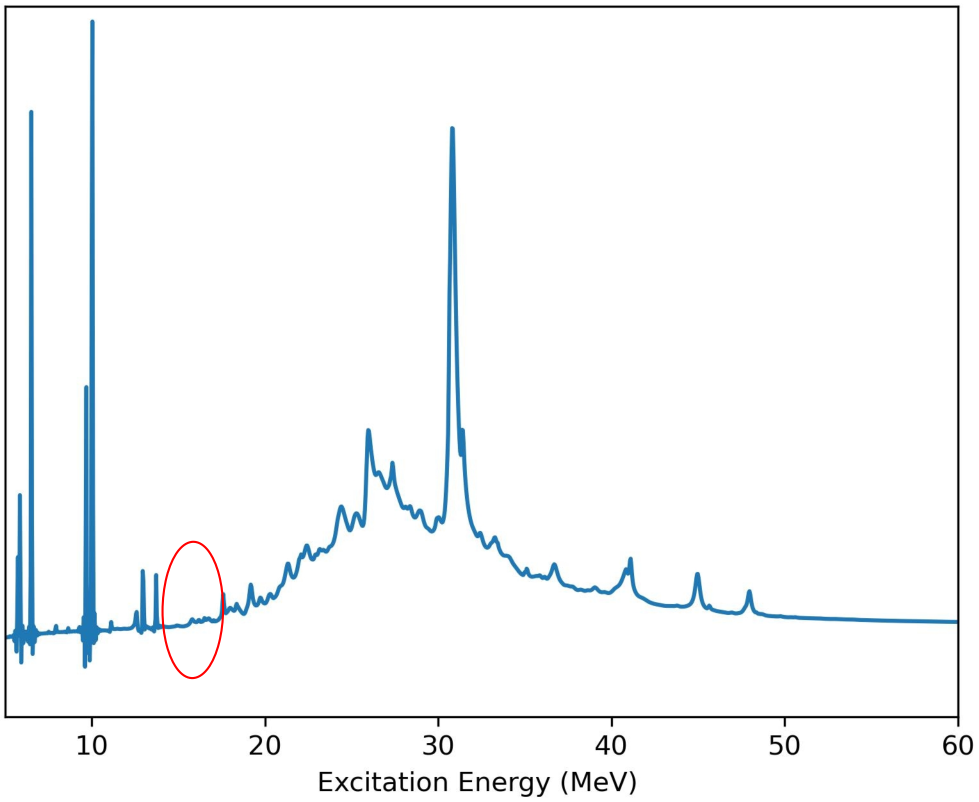




Microscopic Study of the Astrophysical S-Factor for $^{12}C + ^{12}C$ Fusion

Close, Stevenson & AD-T, PLB **870** (2025) 139881

Isovector giant quadrupole excitation spectrum of ^{24}Mg



$$\sigma_{BW}(E,J) = \frac{\pi\hbar^2}{\mu E}(2J+1)\frac{\Gamma_{in}\Gamma}{(E-E_r)^2+\frac{\Gamma^2}{4}}$$

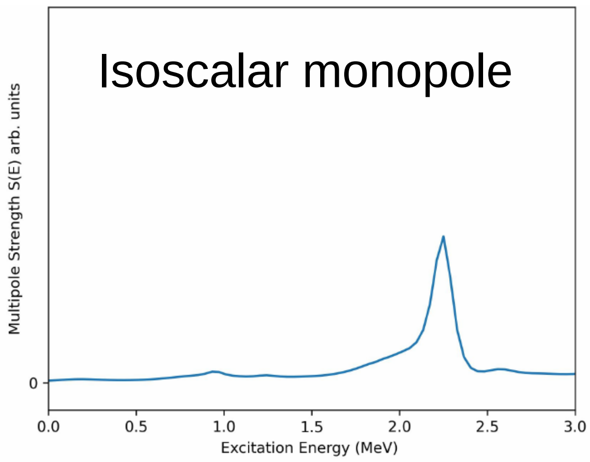
$$\Gamma_{in}(J) = T_J(E)\Gamma(J).$$

Entrance channel partial width

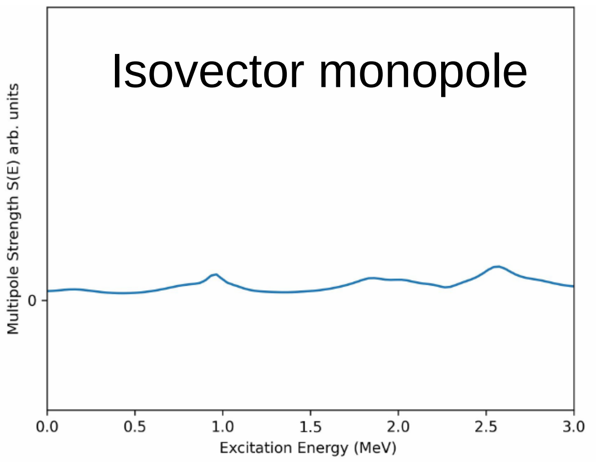
$$\sigma_{CN} = \sum_J \sigma_{BW}(E,J)$$

Indirect component of the total fusion cross-section

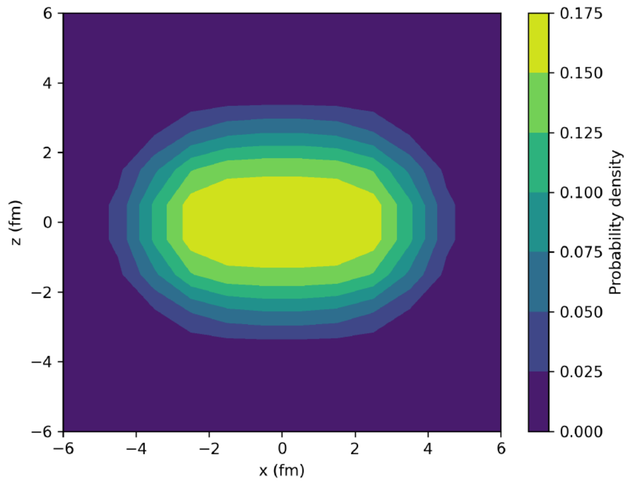
Giant Monopole & Quadrupole Resonances of ^{24}Mg

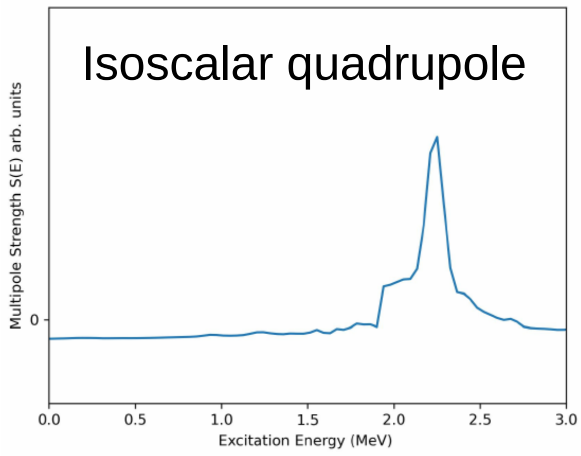


(a) Energy spectrum for the ISGMR excitation.

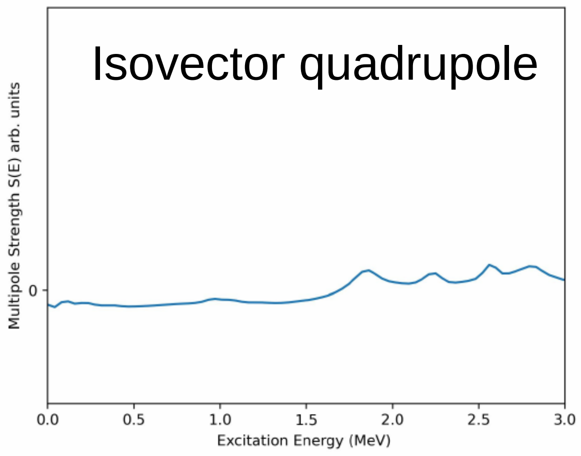


(b) Energy spectrum for the IVGMR excitation.





(c) Energy spectrum for the ISGQR excitation.

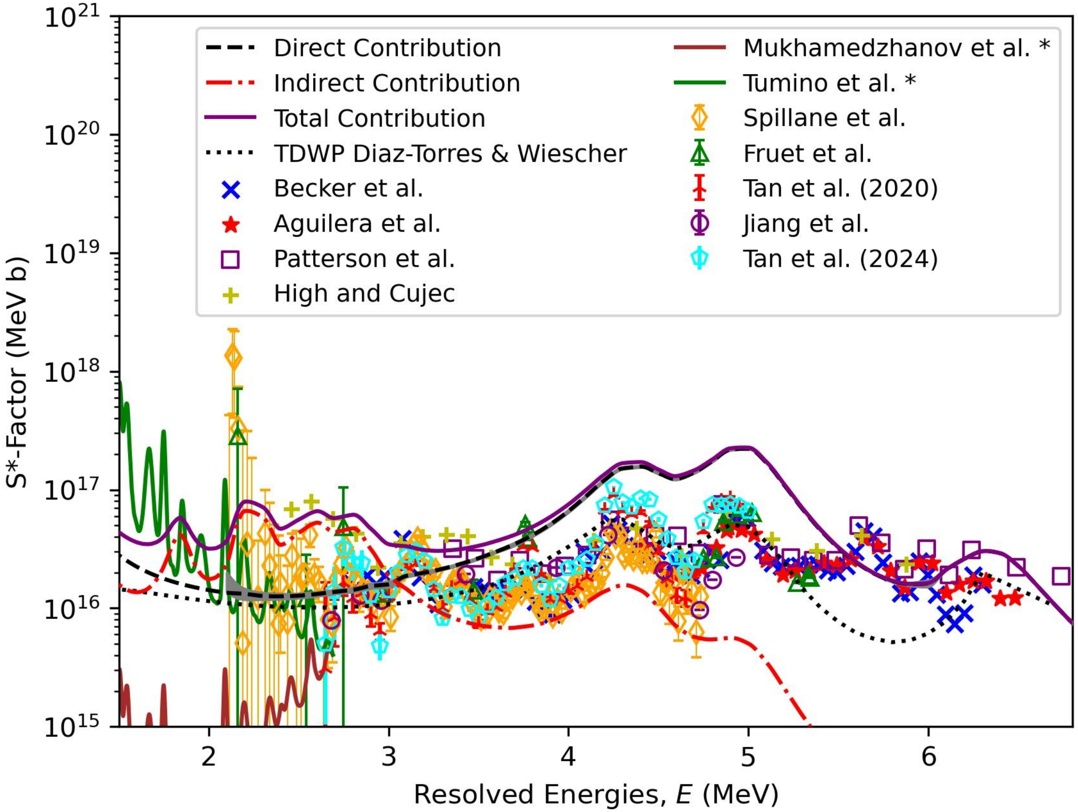


(d) Energy spectrum for the IVGQR excitation.

Grant Close,
PhD Thesis, Surrey, 2025

Microscopic Study of the Astrophysical S-Factor for $^{12}C + ^{12}C$ Fusion

Close, Stevenson & AD-T, PLB **870** (2025) 139881



Key Messages & Outlook

Science and Technology Facilities Council

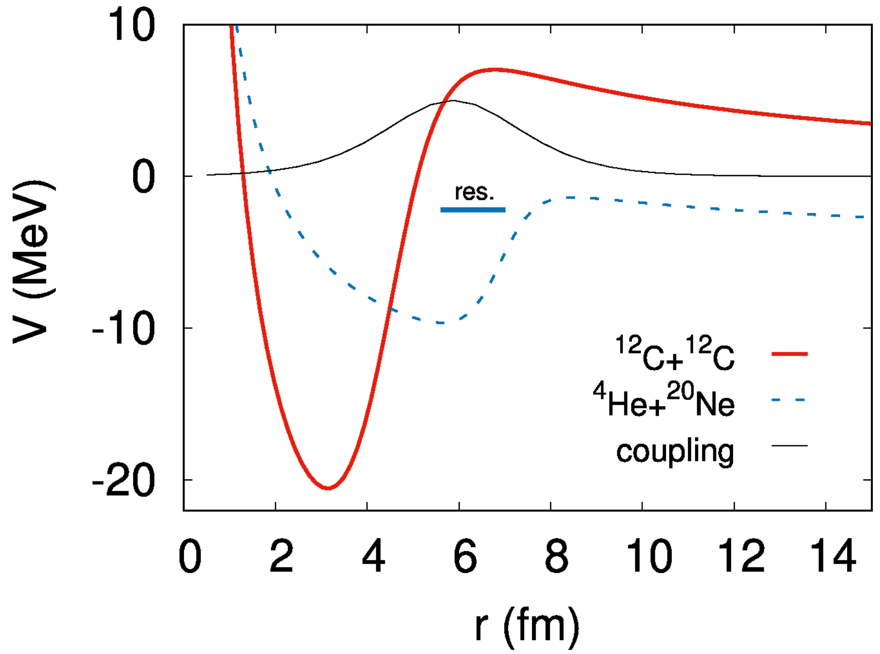
- Some resonant structures in the $^{12}C+^{12}C$ astrophysical S-factor are due to both the role of **triaxial nuclear molecular configurations** and **giant resonances** of the ^{24}Mg compound nucleus.

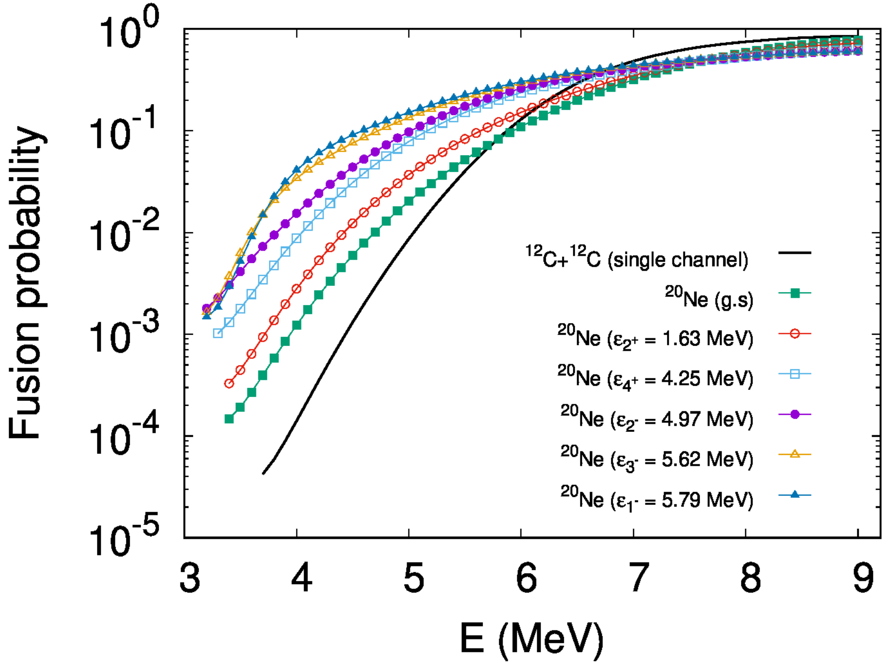
- The role of **clusters in the nuclear molecule** are being investigated. See e.g., AD-T, Gasques & Antonenko, PLB **849** (2024) 138476.

EXTRA SLIDES

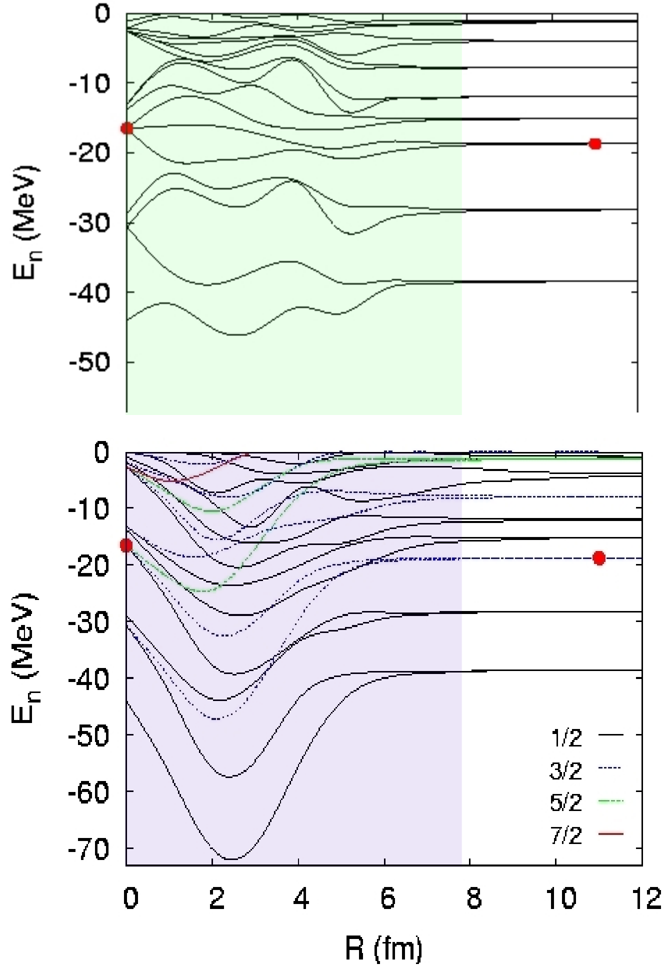
Cluster effects on low-energy carbon burning

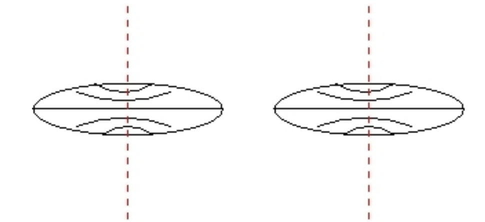
AD-T, Gasques & Antonenko, PLB **849** (2024) 138476.





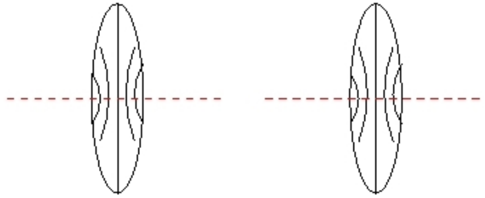
Sensitivity of Molecular Shell Structure to the ^{12}C Alignment





$$V = \sum_{s=1}^{2} e^{-i\mathbf{R}_s\hat{k}}\, \hat{U}(\Omega_s)\, V_s\, \hat{U}^{-1}(\Omega_s)\, e^{i\mathbf{R}_s\hat{k}}$$

$$\boxed{V_s \approx \sum_{\nu\mu}^{N} |s\nu\rangle\, V^s_{\nu\mu}\, \langle s\mu|}$$

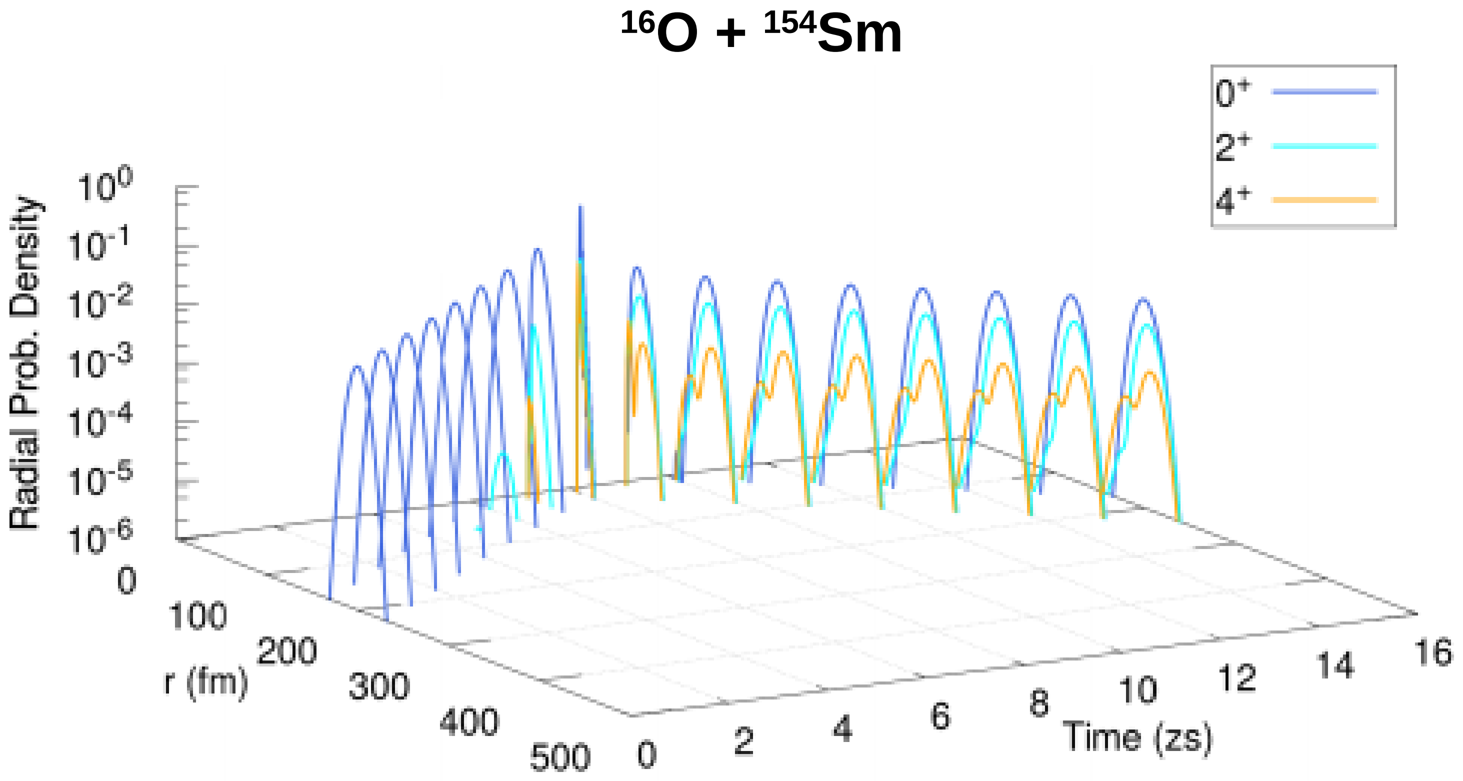


Potential Separable
Expansion Method

AD-T, PRL **101** (2008) 122501

Quantum Coupled-Channels Wave-Packet Dynamics

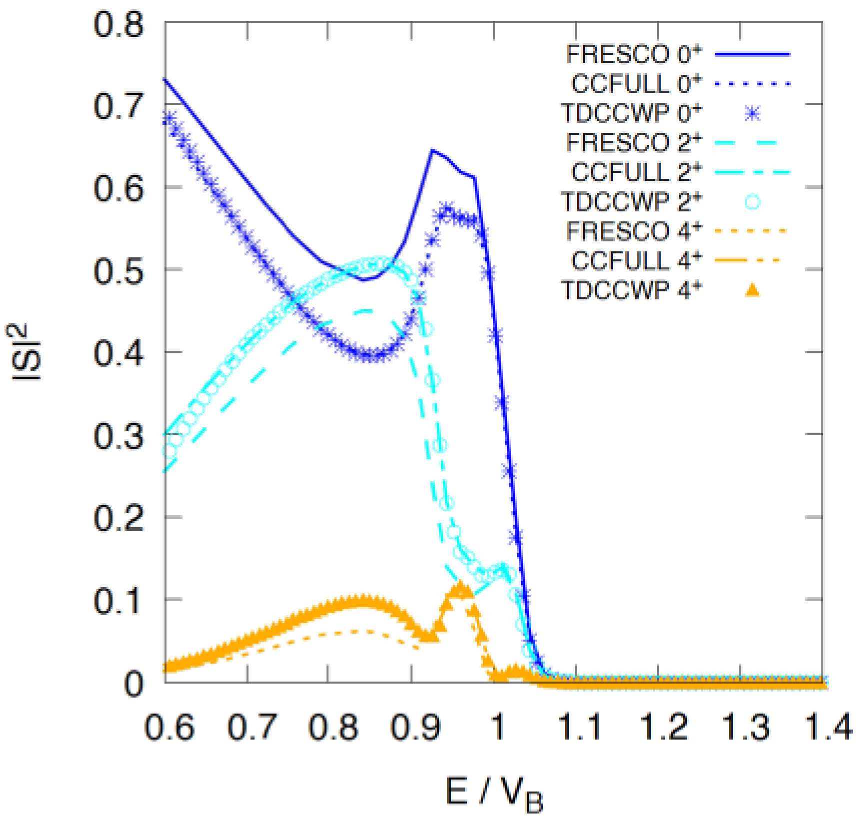
Vockerodt & AD-T, PRC **104**, 064601 (2021); PRC **100**, 034606 (2019)



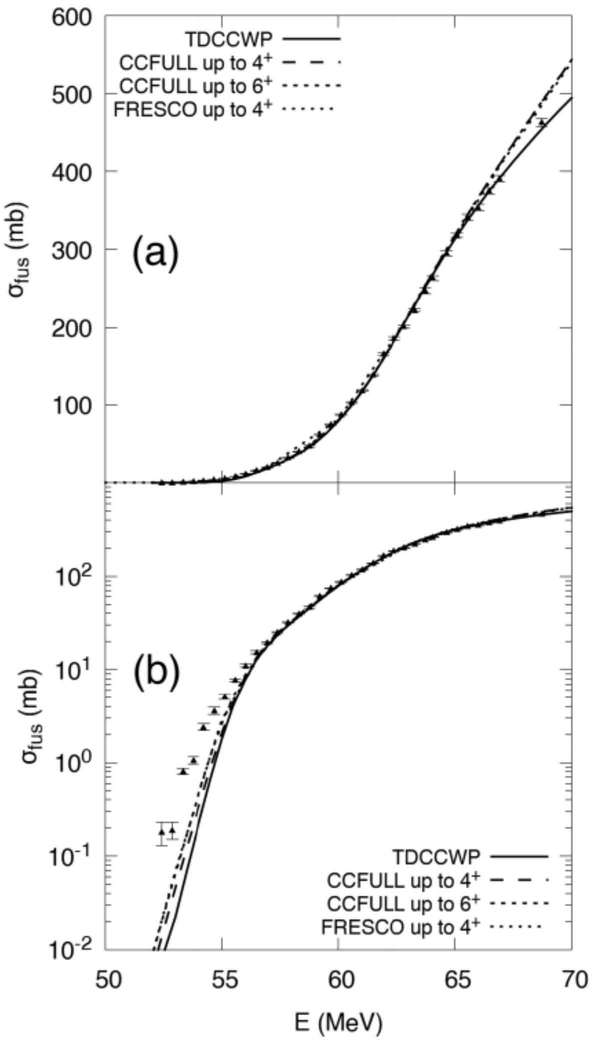
Quantum Coupled-Channels Wave-Packet Dynamics

Vockerodt & AD-T, PRC **104**, 064601 (2021)

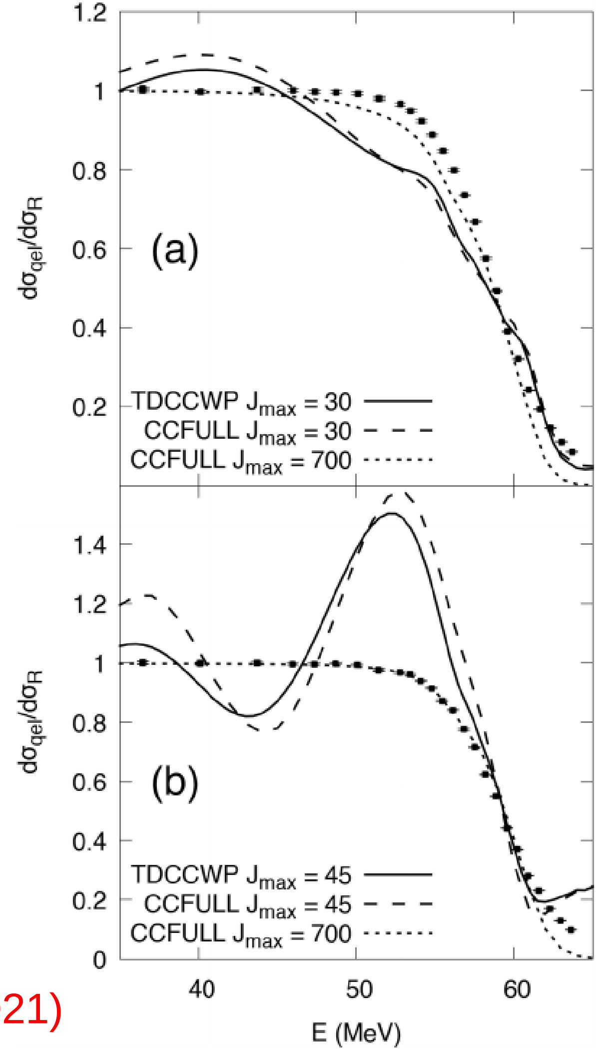
Reflection Coefficient



FUSION $^{16}O + ^{154}Sm$



QUASI-ELASTIC SCATTERING



$^{16}O + ^{154}Sm$

$\theta = 175^\circ$

$^{16}O + ^{152}Sm$

Vockerodt & AD-T
PRC **104**, 064601 (2021)