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Quantum Dynamical Microscopic Approach to Stellar Carbon Burning

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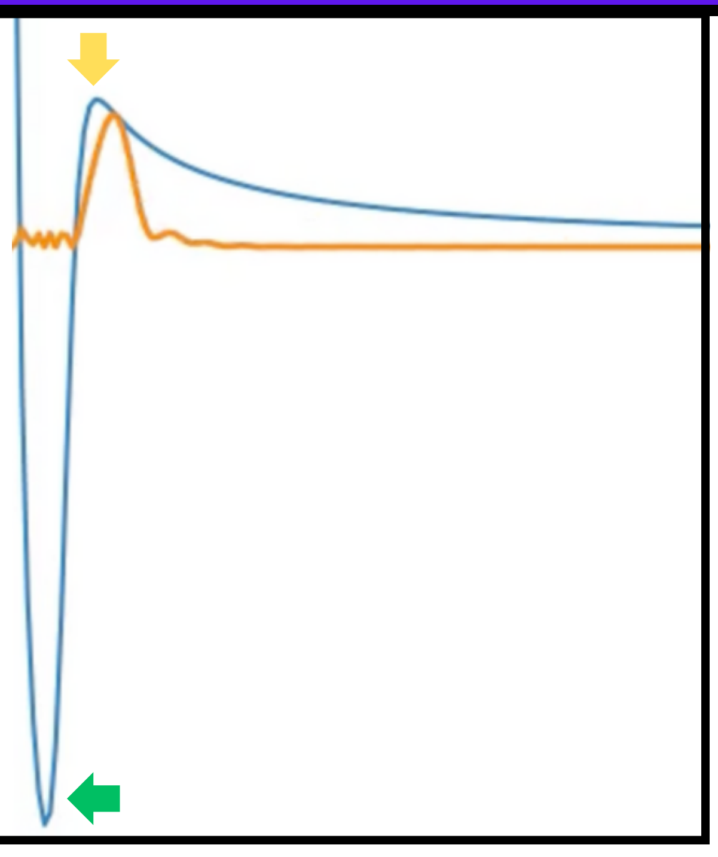
Carbon burning is an important process in the late-stage evolution of massive stars, playing a major role in the ignition conditions to certain types of supernovae. This nuclear fusion process occurs at high temperatures (approximately 500–1000 million Kelvin), where carbon nuclei overcome their electrostatic repulsion primarily through quantum tunnelling. Additionally, carbon burning involves nuclear molecular resonances, which enhance reaction rates and influence the nucleosynthesis of heavier elements.

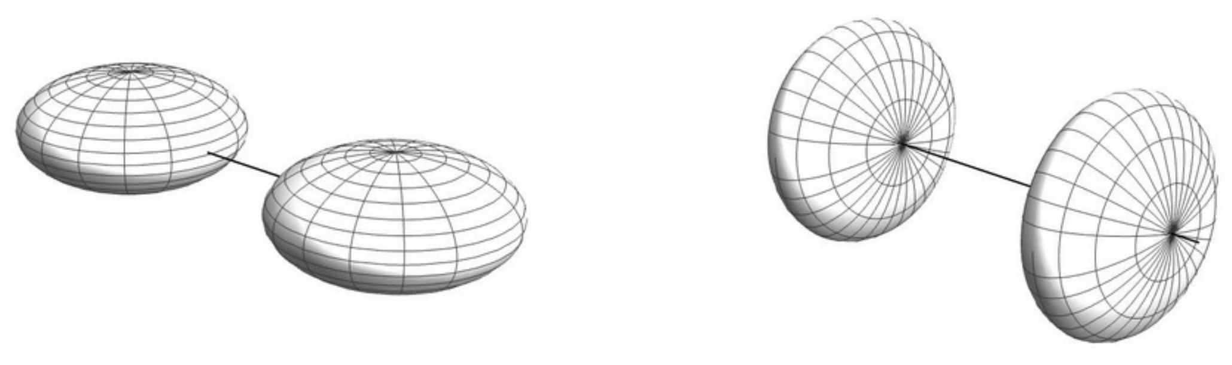
Quantum Mechanics in Stars

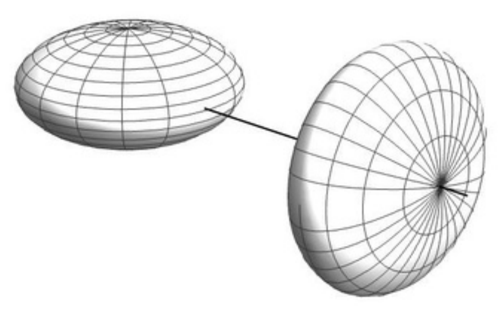


Quantum Tunnelling

- Carbon nuclei, positively charged, strongly repel each other due to the Coulomb barrier (⬇).
- At typical stellar temperatures, the majority of carbon nuclei don't have enough energy to overcome this barrier.
- However, quantum mechanics allows them to "tunnel" through the barrier into the potential well (⬅), enabling the fusion reactions that powers stars.

Nuclear Molecules





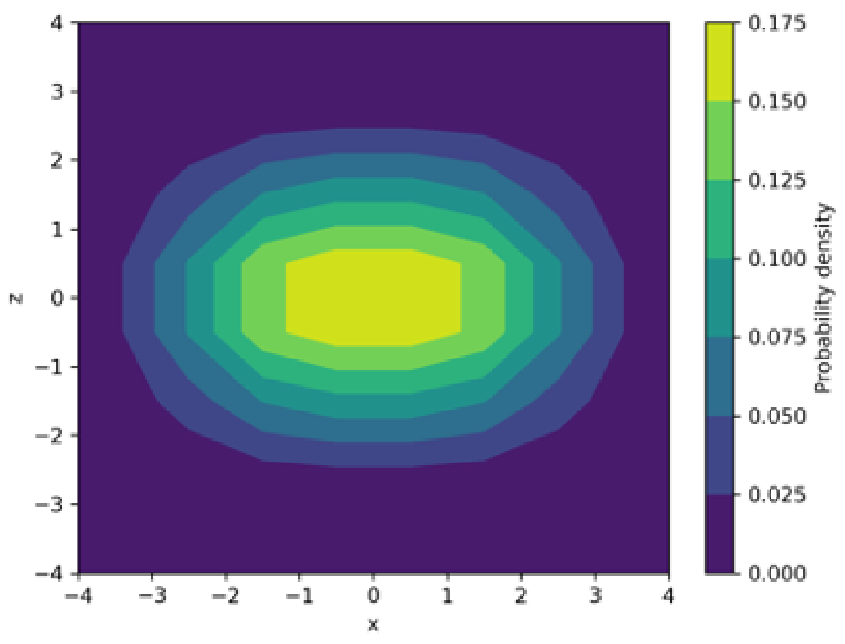
In some cases, two carbon nuclei don't immediately fuse but form a nuclear molecule. These nuclear molecular states arise due to the interplay of the strong nuclear and electromagnetic force. Nuclear molecules are analogous to electronic molecules but are governed by nuclear interactions.

Resonant States

In a nuclear reaction, the interacting nuclei can become trapped in a potential pocket, which is in inside a potential barrier, giving rise to resonant states. This phenomenon lengthens the duration of scattering and results in a enhancement of the fusion probability at the corresponding energy.

Our Methodology

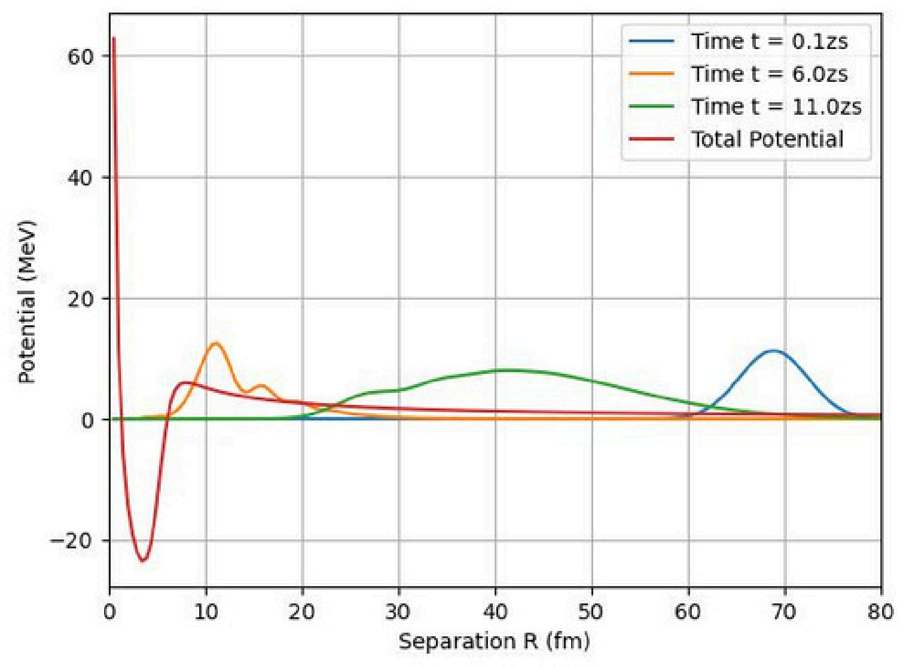
Producing Microscopic Potentials (DC-TDHF Method)



- Builds the nucleus from nucleon-nucleon interactions.
- Includes all the dynamical effects that would occur from within the nucleus. For example, neck formation and single-particle excitations.
- Generating the potentials for all the necessary orientations

Controlling the Dynamics of the Reaction (TDWP Method)

- Initiates the reaction with the nuclei in their ground state, meaning that there is an isotropic distribution of orientations.
- The Hamiltonian prepared for the reaction ensures that radial and rotational effects are included in all stages of the reaction.
- The parts of the wave-packet absorbed in the potential wells contribute to fusion.

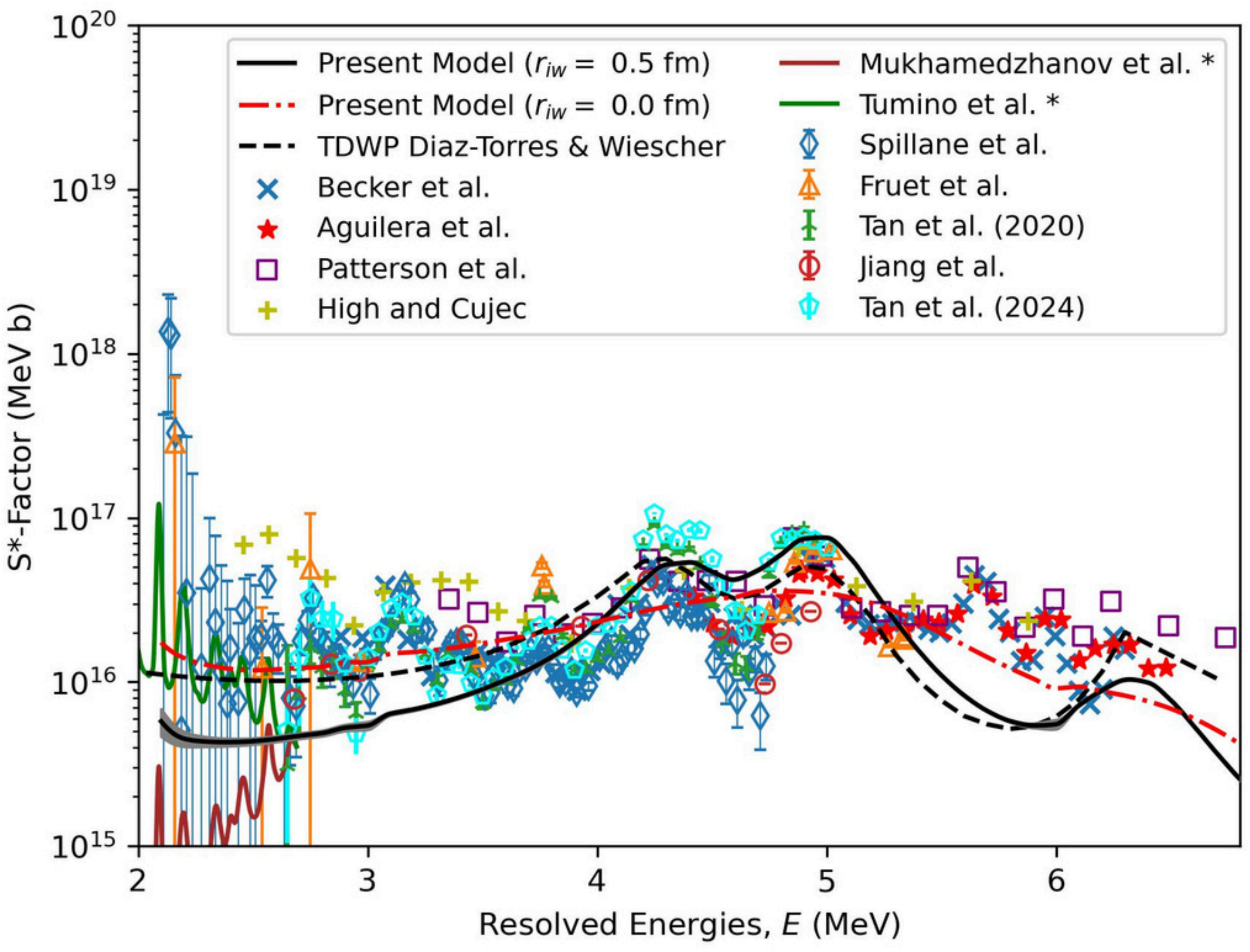


Results

Comparison with Previous Studies

Measured in the astrophysical S-factor, which is a function of the cross-section of fusion. This removes the Coulomb effects, enabling the study of nuclear effects on the excitation function.

Previous studies (black-dashed line) used a macroscopic approach to calculate the interaction potentials. This allowed for parameters to change the location of the resonance peaks.



Findings and Conclusion

By isolating the region of absorption to mainly axially-symmetric orientations, we can attribute the resultant resonance peaks to be a result of nuclear molecules.

Since our microscopic method does not have parameters to change the location of the observed resonance peaks, it shows the importance of nucleon-nucleon interactions in the fusion process.