Quantal effects on thermonuclear reactions

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Stellar nuclear fusion reactions take place in a hot, dense plasma within stars. To account for the effect of these environments, the theory of open quantum systems is used to conduct pioneering studies of thermal and atomic effects on fusion probability at a broad range of temperatures and densities. Since low-lying excited states are more likely to be populated at stellar temperatures and increase nuclear particle interaction rates, a ^{188}Os nucleus was used as a target that interacts with an inert ^{16}O projectile. Key results showed thermal effects yield an average increase in fusion probability of 15.5% and 36.9% for our test nuclei at temperatures of 0.1 and 0.5 MeV respectively, compared to calculations at zero temperature.

Keywords: Nuclear fusion, Nuclear plasma interactions, Open quantum systems, Thermal plasma effects

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Introduction. Understanding the cosmic origins of heavy elements is one of the biggest problems in science. Nuclear fusion reactions, which often occur in high energy density plasmas, are some of the most relevant reactions contributing to nucleosynthesis and stellar evolution. These environments are hot, and contain a mixture of ions and electrons. Low-energy fusion experiments in laboratories are often subject to the target medium, and the current focus is on the use and improvement of radioactive beams to produce the nuclei needed for these reactions [1, 2]. Recreating the stellar environments where these reactions take place is challenging, and hence computational models offer a path to understanding this complex problem. Our unique study showcases a novel method to include the influence of an external physical environment (a plasma) on low-energy fusion reactions, using the theory of open quantum systems. This study suggests that coupling-assisted tunneling in nuclear fusion is strongly enhanced by thermal effects.

The impact of plasma on a reaction may be dominated by either thermal or Coulomb effects. A first order estimation of their relative importance can be carried out by calculating a Coulomb parameter, Λ, which is essentially a ratio between Coulomb and thermal energies [3–5],

$$\Lambda \equiv \frac{\langle Z_i e\rangle^2}{a_i \mathcal{T}}, \tag{1}$$

where $\langle Z_i e\rangle$ is the average ion charge in the plasma, a_i is the average inter-ionic distance and $\mathcal{T}$ is the temperature in MeV. When $\Lambda \ll 1$, the Coulomb energy is insignificant to thermal energy and a Debye-Hückel potential is assumed [6], and for $\Lambda \gg 1$, the Coulomb energy dominates the plasma interaction, and this regime is modeled with an ion-sphere potential. Electron screening potentials effectively reduce the Coulomb barrier, and these become increasingly complex in astrophysical environments. An extensive inclusion of electron screening would include higher density effects such as ion-ion and ion-electron correlations [7], and relativistic effects such as pair production at high temperatures ($\approx$ 1 MeV or higher). Reviews on weak- and strong-screening regimes in astrophysical scenarios can be found in Refs. [8–10]. For the ^{16}O projectile and ^{188}Os target used in this work, the screening effects may be significant at some temperatures ($0-1$ MeV) and densities ($10-10^5$ gcm^{-3}) studied. For simplicity, we focus our study on the effects of plasma temperature and the role of nuclear plasma interactions (NPIs) on low-energy fusion reactions, with the latter expected to affect stellar nucleosynthesis [11, 12]. Examples of processes involving NPIs are nuclear excitation by electron capture (NEEC) or transition (NEET). These have been observed experimentally but still are not well-understood [13, 14]. The ^{16}O+^{188}Os reaction, which may happen in the envelop of AGB stars [15], is used as a test case because (i) this reaction simplifies the model calculations, and (ii) the ^{188}Os target allows one to maximise both NPI and thermal effects.

The thermal population of low-lying excited states has been previously considered in neutron capture studies using the Hauser-Feshbach statistical model [16, 17]. The neutron cross sections were weighted with temperature-dependent population probabilities of target's excited states, leading to a stellar enhancement factor. However, these effects were ignored in heavy ion fusion studies, since the reactions of interest would typically involve inert nuclei or nuclei with high excitation energy states of several MeV. In stellar environments, residual heavy nuclei that have low-lying excited states are potential explanations for unaccounted stellar fusion reaction rates.

For the first time, the present work studies thermal and NPI effects on nuclear fusion using a dynamical, quantum coupled-channels model. The coupled-channels density-matrix method has demonstrated the ability to calculate energy-resolved fusion probabilities using an open quantum system approach [18].

Thermal effects. A thermal environment is expected to change the initial population of the intrinsic energy eigenvalues, $\{e_\alpha\}$, of nuclei that it encompasses. To model the thermal effects on a fusion reaction, we introduce Boltzmann factors, w_α, into the initial density matrix,