the Coulomb barrier, as discussed in Ref. [18]. Below the Coulomb barrier, the average increase in fusion probability was 15.5% and 36.9% for the 0.1 MeV and 0.5 MeV temperatures respectively. Above the Coulomb barrier, the increase quickly diminishes to a few percent.
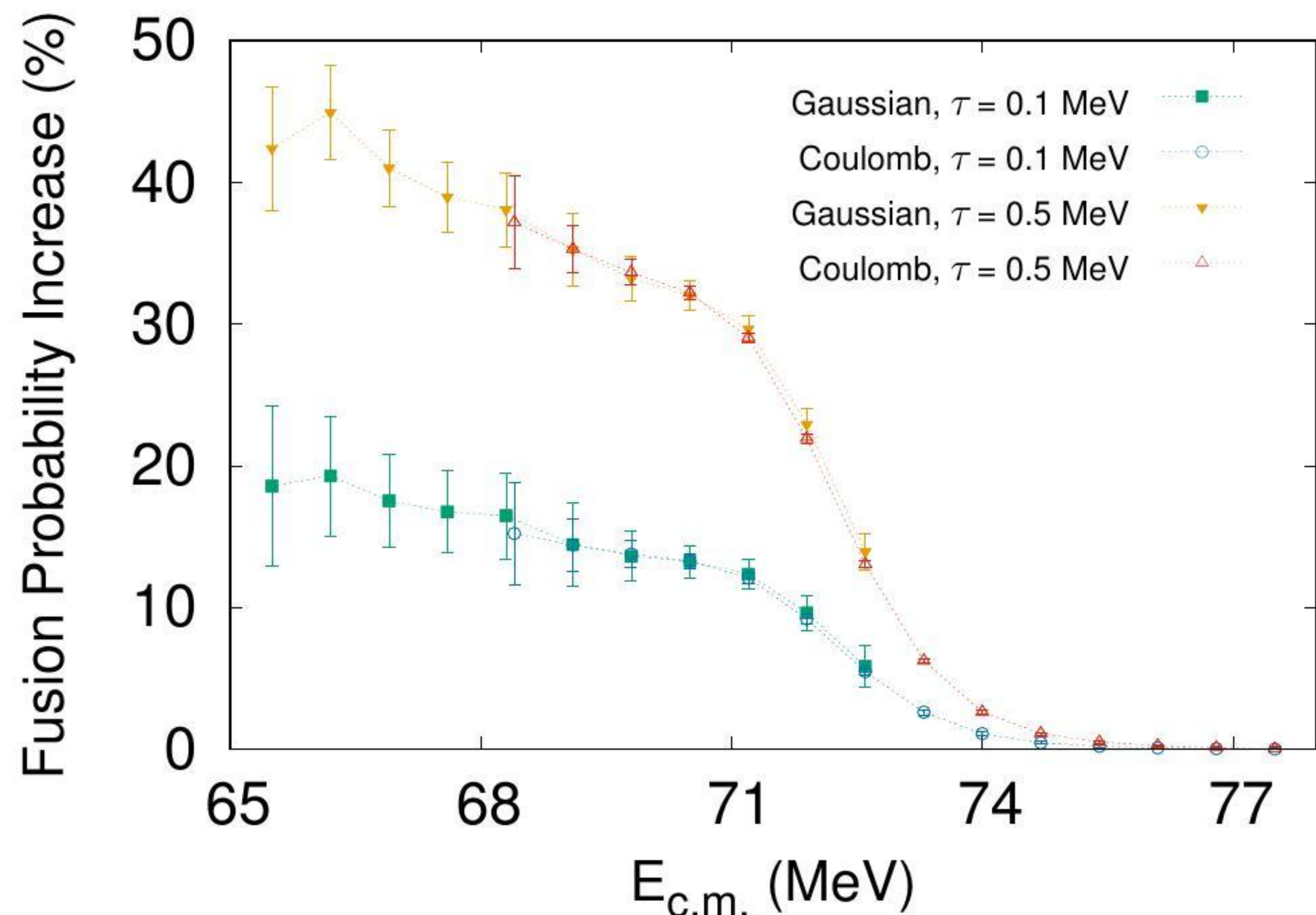

FIG. 3. The increase in fusion probability for a ^{16}O projectile and ^{188}Os target due to the presence of a thermal plasma environment. For each temperature ($\mathcal{T} = 0.1$ MeV and 0.5 MeV), the fusion probability increase is calculated using the ratio of averaged thermal environment calculations to averaged baseline calculations with no environment (Fig. 1). For the Gaussian wave packet, calculations were initiated with $E_0 = 60$, 63, 65, 67 and 70 MeV and for the Coulomb wavepacket, $E_0 = 65$, 67 and 70 MeV.

The results in Fig. 3 are an advancement on work that showed that sub-barrier fusion is enhanced when channel couplings are included, due to the fusion contribution of excited states [29]. The thermal increase in fusion probability can be explained by studying the radial wave function of the entrance channel,

$$\Psi_0(r) = \sqrt{1 - w_2} \cdot \psi_1(r) + \sqrt{w_2} \cdot \psi_2(r), \qquad (7)$$

where ψ_1 and ψ_2 are the radial wave functions of the ground state and excited state, and these wave functions also contain their respective energy basis states, $|1\rangle$ and $|2\rangle$. The excited state Boltzmann factor calculated in Eq. (4) is denoted by w_2. Two effective Coulomb barriers are created from a linear combination of two dynamically coupled wave functions, ψ_1 and ψ_2, as shown in Fig. 4. This combination is anti-symmetric and symmetric, defining two decoupled eigenchannels, $\chi_{1,2}(r)$,

$$\chi_{1,2}(r) = \frac{1}{\sqrt{2}} \left(\psi_1(r) \mp \psi_2(r)\right). \qquad (8)$$

The height of the Coulomb barrier for the symmetric eigenchannel (χ_2) is significantly smaller than that of the anti-symmetric eigenchannel (χ_1), leading to an increase
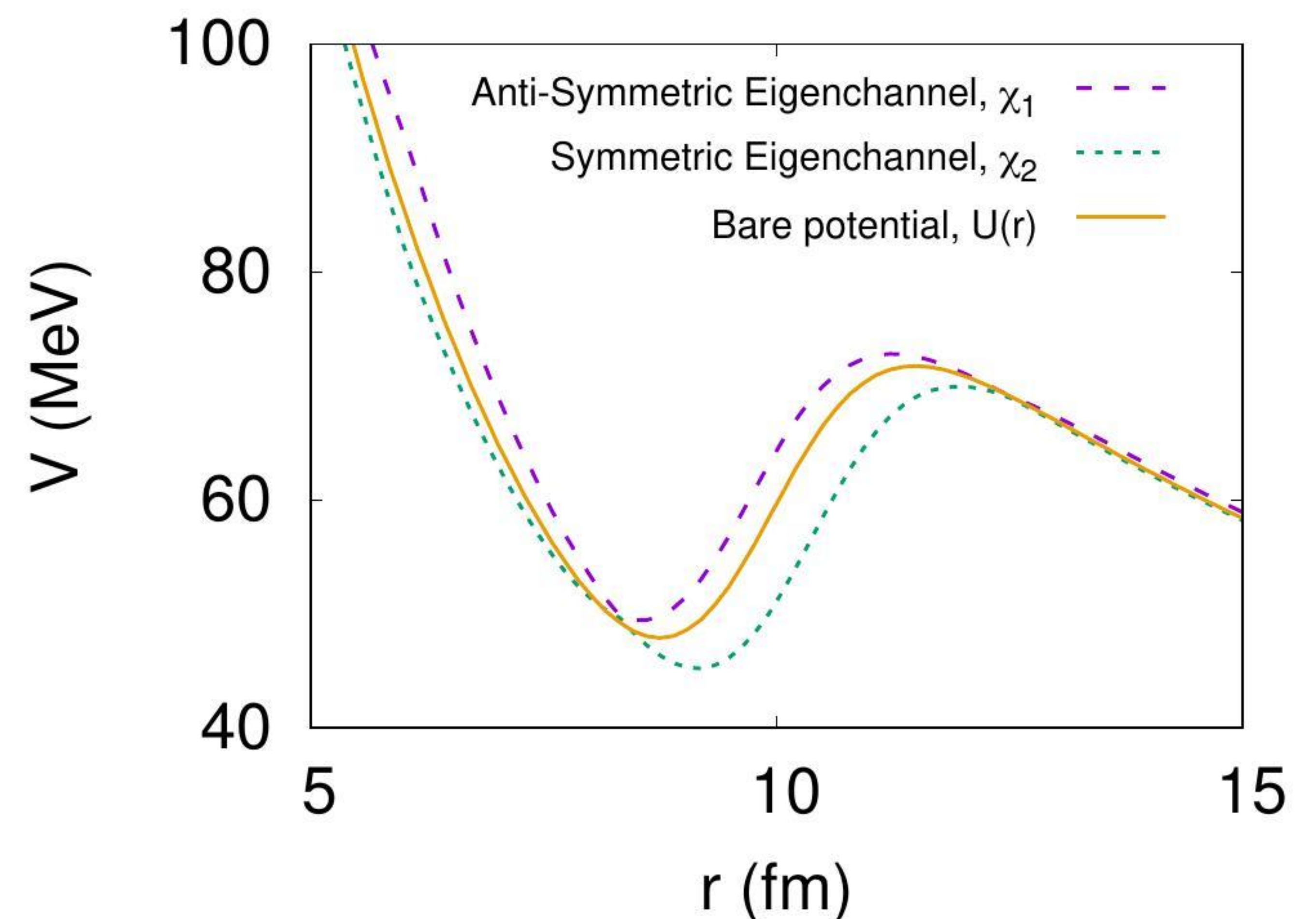

FIG. 4. The Coulomb barriers of the decoupled eigenchannels. The symmetric barrier is the lowest, dominating the fusion process at energies below the nominal, 71.7 MeV Coulomb barrier of the bare potential, U(r).

of the fusion probability relative to a single channel calculation involving the state $\psi_1(r)$ only.

Temperature affects the fraction of the eigenchannels contained in the entrance channel configuration in Eq. (7),

$$|\langle \chi_1 | \Psi_0 \rangle|^2 = \frac{1}{2} - \sqrt{(1 - w_2)\, w_2}, \qquad (9)$$

$$|\langle \chi_2 | \Psi_0 \rangle|^2 = \frac{1}{2} + \sqrt{(1 - w_2)\, w_2}. \qquad (10)$$

The inclusion of temperature leads to an increase in the initial population of the excited state, w_2, and consequently there is a larger fraction of the eigenchannel χ_2 (with the lowest Coulomb barrier) in the entrance channel configuration. The effect is more prominent with increasing temperature, which is supported by our results in Fig. 3. Hence there is an enhancement of fusion probability in comparison to coupled channels calculations without temperature ($w_2 = 0$).

Summary. We have addressed an area of unexplored territory by assessing the need for the inclusion of a reaction medium in stellar heavy-ion fusion calculations. The coupled-channels density-matrix method, which is based on the theory of open quantum systems, unambiguously include thermal and atomic effects on subbarrier fusion dynamics. The calculations show that plasma temperature strongly enhances fusion probability. This pioneering effort suggests that careful considerations should be made when modeling or performing experiments on collision partners with low-lying excited states at high temperature. Despite no changes in fusion probability due to atomic effects, there is scope to reintroduce these effects when more experiments are completed and new theoretical studies are published.