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## Reactive tunneling and vibrational quenching collisions in a cryogenic multipole trap

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Quantum tunneling reactions play an important role in chemistry when classical pathways are energetically forbidden [1]. Binary collisions of atomic with molecular hydrogen belong to the most fundamental molecular systems and are simple enough to be theoretically investigated using first-principle calculations. The rate of the tunneling reaction  $\text{H}_2 + \text{D}^- \rightarrow \text{H}^- + \text{HD}$  has been calculated [2] but has until now lacked verification. Here we present high-sensitivity measurements of the reaction rate carried out in a cryogenic 22-pole ion trap. A deviation of the reaction rate from linear scaling, which is observed at high  $\text{H}_2$  densities, can be traced back to previously unobserved heating dynamics in radiofrequency ion traps. Our measured value agrees with quantum tunneling calculations, serving as a benchmark for molecular theory and advancing the understanding of fundamental collision processes [3].

Further work has focused on inelastic collisions of  $\text{C}_2^-$ , which has been proposed as a candidate for laser cooling due to the existence of multiple stable electronic states. We have demonstrated vibrational state control of  $\text{C}_2^-$  via a novel scheme that uses optical pumping in conjunction with inelastic collisions of  $\text{H}_2$  and measured the vibrational quenching rate [4]. Additionally, we precisely determined the proposed laser-cooling transitions of  $\text{C}_2^-$ . We resolve the spin-rotation splittings and use it to perform accurate thermometry in our newly-developed wire trap [5].

[1] McMahon, R. J. Chemical reactions involving quantum tunneling. *Science* 299, 833–834 (2003).

[2] Yuen, C. H., Ayouz, M., Endres, E. S., Lakhmanskaya, O., Wester, R., Kokoouline, V. Quantum-tunneling isotope-exchange reaction  $\text{H}_2 + \text{D}^- \rightarrow \text{HD} + \text{H}^-$ . *Phys. Rev. A* 97, 022705 (2018).

[3] Wild, R., Nötzold, M., Simpson, M., Tran, T. D., Wester, R. Tunneling measured in a very slow ion–molecule reaction. *Nature* (2023).

[4] Nötzold, M., Wild, R., Lochmann, C., Rahim, T., Melath, S. P., Mant, B., Franz, J., Gianturco, F., Wester, R. (in preparation)

[5] Nötzold, M., Wild, R., Lochmann, C., Wester, R. Spectroscopy and ion thermometry of  $\text{C}_2^-$  using laser-cooling transitions, *Phys. Rev. A* 106, 023111 (2022).

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