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ULTRACOLD CHEMISTRY

Collision detection with logic

Controlling chemistry at the single-collision level is one of the main goals of experiments at ultralow temperatures. A method based on quantum logic techniques has now been shown to detect inelastic collisions in a hybrid ion–atom platform.

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Getting a deeper understanding and better control of chemical reactions is one of the goals of the field of ultracold matter. Cooling down systems of atoms and molecules below 1 K allows the preparation of reactants in selected quantum states and enhances their control with external electromagnetic fields. As they report in *Nature Physics*, Or Katz and colleagues have now developed a technique to observe elastic, inelastic and chemically reactive collisions of individual pairs in a cold mixture of ions and atoms[1].

Hybrid ion–atom platforms have been an active field of research since their first experimental realizations[2,3]. The individual control of ions is one of their main advantages, but the need for different trapping techniques for neutral and charged particles have posed a challenge for perfecting quantum control over ion–atom mixtures[4]. Only recently have technical improvements in controlling ion–atom collisions permitted the observation of pure quantum effects, like shape resonances[5] and magnetic Feshbach resonances[6].

In their experiment, Katz and colleagues trapped two strontium ions in a Paul trap, which confines ions using an electric field. Their protocol for detecting individual ion–atom collisions relied on a 'quantum logic' technique, which consists of reading out the internal state of an ion by monitoring an auxiliary coupled one. These have been developed to prepare and measure atomic and molecular ions that cannot be cooled and detected with a laser and are thus inaccessible by conventional methods[7,8]. In these cases, it is possible to map the internal state and the dynamics of an inaccessible ion onto the quantum state of a second one, coupling their motion through strong Coulomb forces.

Katz and co-workers selected a $^{88}Sr^+$ ion as the auxiliary 'logic' ion and coupled it to a second Sr^+ ion chosen from all four stable isotopes ($^{84}Sr^+$, $^{86}Sr^+$, $^{87}Sr^+$, $^{88}Sr^+$), designed as the 'spectroscopy' ion.

Although this proof-of-concept experiment involved two ions of the same element, the method is suitable to any other atomic or molecular species acting as the spectroscopy ion. Laser-cooling the logic ion also sympathetically cools the coupled spectroscopy ion, leading to the formation of a so-called Coulomb crystal close to its motional ground state.

The ions prepared in this way were then collided with an ultracold cloud of rubidium atoms loaded into an optical lattice. The team prepared the atoms in different sublevels of an excited hyperfine state. During an inelastic collision with a Sr^+ ion, a rubidium atom could relax to its ground hyperfine state and release its internal energy. This would then convert into kinetic energy, affecting the motion of the spectroscopy ion. Katz and colleagues measured the collision outcome and the increased kinetic energy of the spectroscopy ion by monitoring the motional state of the logic ion (Fig. 1). The achieved level of control also allowed the team to distinguish between elastic and inelastic collisions and to measure probabilities and absolute rate coefficients for the latter.

Some limitations of this setup arise from the micro-motion of the ions, induced by the electric fields in the Paul trap. This has several adverse effects, such as heating the ions interacting with atoms. Although the micro-motion heating of the ions limits the exploration of a fully quantum regime[4], the presented data may still reveal signatures of quantum interference effects[9]. These results also represent the advantage of hybrid ion–atom setups with respect to other platforms for the study of chemical reactions, such as optical tweezer arrays of ultracold atoms and molecules[10]. Indeed, these are limited to atoms that can be efficiently cooled and coherently arranged with lasers.

Or Katz and colleagues applied their technique to inelastic atomic collisions in a chemically simple model system. However, sympathetic cooling of translational motion and their quantum logic detection method can be applied to any charged particles.

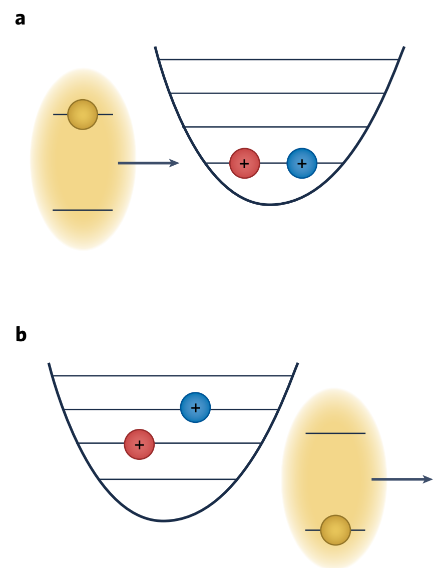

Fig. 1 | Quantum logic detection of an exothermic inelastic collision. a, Spectroscopy (blue) and logic (red) ions are cooled down close to their motional quantum ground state, and collide with ultracold atoms (yellow) in an excited hyperfine state shuttled through an ion trap. **b**, After a single ion–atom collision, the internal energy of the atom is converted into kinetic energy of the spectroscopy ion, coupled to the logic ion. Monitoring the state of the logic ion reveals if an inelastic collision involving the spectroscopy ion took place.

Understanding of cold chemical reactions can have wide-ranging implications, from atomic physics and quantum technologies to astrochemistry and atmospheric chemistry. By employing molecular ions and neutral molecular gases, quantum logic detection may also provide new insights into the underlying physics of chemical reactions. Finally, the level of quantum control reached in this work may enable quantum-controlled chemistry, where coherent effects such as quantum resonances, superposition of reactant states, or quantum entanglement can significantly affect chemical transformations. ❐

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Competing interests

The author declares no competing interests.

STATISTICAL PHYSICS

Return of the bats

When humans move through known areas they rely on their existing knowledge of the space around them to choose their route. Recent analyses of foraging data suggest that certain animals also rely on their memory when they search for food. Bats, for example, return to the same food source in a manner reminiscent of a reinforcement learning strategy rather than following a purely random search. Mobility models should therefore include an animal's ability to use information of previous visits when deciding which route to follow. Ohad Vilk and colleagues have now shown that a model incorporating memory of previously visited locations can describe the movements of wild fruit bats (*Phys. Rev. Lett.* **128**, 148301; 2022).

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A version of this model was previously used to investigate human mobility and considers both exploration of new locations and preferential returns, that is, the tendency of an individual to return to previously visited sites. Vilk and colleagues generalized the model to include variability in the bat population and considered a nonlinear variation of the likelihood of return visits as the number of visits to a particular site increased. As the nonlinear parameter representing the tendency to return was varied, the team observed a phase transition in the dynamics of foragers. Above a critical value of the parameter, the animals revisited the same sites many times, but below the critical value there were almost no returns.

Vilk and colleagues compared their model predictions with data of wild Egyptian fruit bat (pictured) movements. They found that the bats were less adventurous in summer, visiting fewer new locations than in winter. The summertime abundance of fruit likely lowered the motivation for risky journeys to search for new fruit trees. Overall, the bat mobility data appeared to fit the model at the critical value of the preferential returns parameter. This suggests that bats choose to balance adventures to unknown locations with returns to known sources of food.

Including memory in mathematical models is a challenge and models such as the one by Vilk and colleagues might be useful for other time-dependent problems where decisions are based on past situations, for example human migration or mobility following COVID-19 lockdowns. ❐

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