News & views

Atomic physics

Molecules find the sweet spot for collisions

Sebastian Will & Tanya Zelevinsky

Engineering the energies of ultracold molecules when they collide has been shown to enhance the probability that they will form complexes — an exciting prospect for precisely controlled chemistry. **See p.54 & p.59**

When atoms are cooled to ultralow temperatures, roughly one microkelvin above absolute zero, they can be assembled into molecules. If the relative energies of these molecules hit a sweet spot known as a resonance, the probability that they briefly bind into a complex on collision can be enhanced. This boost offers the potential for precise control of chemical reactions, for example, or the creation of new quantum phases, but it has remained unclear whether such collisional resonances actually exist. Now, on page 54, Park *et al.* report[1] that they do — observing strongly enhanced reactions of ultracold sodium–lithium (NaLi) molecules by applying a constant magnetic field. And Chen *et al.* (page 59) show[2] that this enhancement can be controlled by using oscillating microwave radiation to engineer resonances in systems of sodium–potassium (NaK) molecules.

Park *et al.* took advantage of what is known as a magnetic Feshbach resonance, which can arise when two ultracold atoms or molecules collide and briefly form a complex (Fig. 1a). The resonance can be induced by adjusting the strength of a constant magnetic field. This shifts the energies associated with various internal states of the molecules by influencing their spin (their intrinsic angular momentum), ensuring that the bound state of the complex has the same energy as that of the colliding pair. Feshbach resonances have previously been observed in systems of colliding atoms[3], atom–molecule pairs[4,5] and very weakly bound molecules that retain some atomic properties[6].

The question of whether tightly bound molecules could exhibit Feshbach resonances has been a topic of debate. One argument against it has been that the molecular complexes might be too short-lived to form a resonance[7]. Park and colleagues' results provide evidence of such a molecule–molecule resonance, in which the rate of

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inelastic collisions (those that change the internal properties of the molecules) is up to 230 times higher than its value in the absence of a resonance. The authors found that a single resonance occurred at a specific magnetic-field value at which two quantum states of a colliding NaLi molecule pair have nearly the same energy, one being the initial state of the pair, and the second being the state to which the complex is expected to decay.

Feshbach resonances are a valuable tool for states that can be affected by a magnetic field, but they are less useful for molecules that are in a low-energy non-magnetic state. Chen *et al.* demonstrated a different method, called field-linked resonance, that doesn't require a magnetic response, and which has the added advantage of offering a general technique for controlling collisional resonances.

A field-linked resonance arises in molecules for which a bound state doesn't naturally exist, but is instead created by applying a microwave field that alters the molecular energies[8,9]. Such states are very sensitive to the properties of the field — its frequency, power and polarization — and this dependence makes field-linked resonances highly tunable. Chen and colleagues demonstrated this for NaK molecules by varying the polarization of the microwave radiation (Fig. 1b). As a result, they varied the rate of inelastic collisions by a factor of 1,000.

They were also able to manipulate elastic interactions, in which molecules forcefully collide but do not change their internal properties, and the rate of these collisions reached about ten times that of inelastic collisions. This

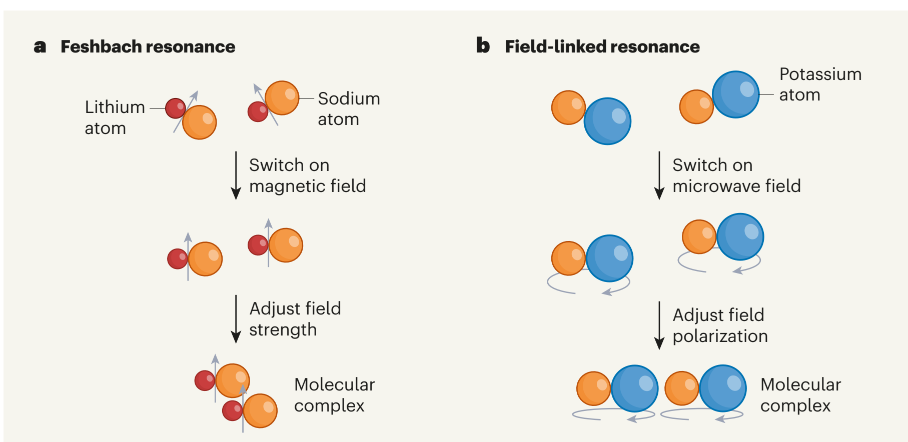

Figure 1 | Manipulating ultracold molecules. When ultracold molecules collide, the formation of complexes can be enhanced if the relative energies of the molecules have particular values known as a resonance. **a**, Park *et al.*[1] adjusted the strength of a magnetic field applied to ultracold sodium–lithium molecules. In doing so, they shifted the energies of the molecules by influencing their spin (intrinsic angular momentum; grey arrows), such that the bound state of the complex had the same energy as that of the colliding pair, achieving what is known as a Feshbach resonance. **b**, Chen *et al.*[2] applied an oscillating microwave field to sodium–potassium molecules, causing them to rotate. By adjusting the polarization of the field, they could manipulate the molecules into complexes by inducing a type of resonance called field-linked resonance.

enhancement is a crucial step towards cooling molecules using evaporative cooling, a powerful technique for driving hot particles from a system to reduce its temperature.

The two papers report types of resonance that are distinct in character from those observed in other systems. Both teams used the quantum properties of molecules, applying the complexity of the molecules' internal states and the way they can be coupled to applied fields. And they both addressed a crucial gap in this line of research: the ability to flexibly control inelastic and elastic collisions between ultracold molecules. They also provide benchmarks for future calculations in theoretical quantum chemistry.

Despite sharing many features, the two techniques are distinct. The Feshbach resonance reported by Park *et al.* is enticing from a fundamental point of view, because it seems to prove that long-lived metastable complexes of two NaLi molecules can exist, despite the fact that the molecules are chemically reactive. This is unexpected, and indicates that collisional processes are not entirely understood – even for simple molecules. By contrast, Chen and colleagues' field-linked resonances are appealing because they can be applied to non-magnetic molecules and are highly controllable using microwave radiation. Such capabilities are widely sought after, and could be applied to other ultracold molecules to offer a general technique for creating molecular quantum matter and controlling chemical reactions.

In the past two decades, it has become possible to prepare ultracold molecules in precisely controlled quantum states. Manipulating polar molecules, such as those used by both sets of authors, is of particular interest, because it would enable new forms of exotic quantum matter[10,11], including certain superfluids (materials that flow without friction) and supersolids (their spatially ordered counterparts). However, such control would require molecular gases to be driven to even lower temperatures and higher densities – enough to enhance interactions and grant access to many-body quantum phases – than are currently accessible.

The findings of both teams could prove key to reaching these goals. Because the concepts described by the authors are broadly applicable, it is exciting to anticipate similar findings with other ultracold molecules. We can hope that many further developments will be built on these results, and will yield fascinating insights into ultracold chemistry and molecular many-body physics.

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Neuroscience

Dual role for dopamine in shaping spontaneity

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The neurotransmitter dopamine has well-established roles in reward-driven behaviours, such as searching for food. The discovery that it also shapes spontaneous behaviour reveals parallels between these two phenomena. **See p.108**

Some actions that people take are geared towards specific goals, and others are triggered by stimuli in the environment. However, much of our time is spent in spontaneous, self-motivated activity, which often takes the form of habitual actions. Although research has revealed a lot about how deliberate behaviours are learnt, much less is known about the way in which spontaneous behaviour is organized and turned into habits. Markowitz *et al.*[1] show on page 108 that spontaneous behaviour in mice is regulated by dopamine, a neurotransmitter that is better known for its role in reinforcing rewarding actions.

The authors studied the brain mechanism by which action elements (stereotypical motions such as turning left or pausing during running) are combined into spontaneous behaviour. They focused on the dorsolateral striatum (DLS), a key brain region involved in the selection, refinement, sequencing and control of actions as they form habits[2]. Dopamine released in the DLS reinforces and invigorates rewarding actions[3,4]; Markowitz *et al.* asked whether it might also have a role in unplanned, unstructured behaviour.

The group studied mice engaged in spontaneous behaviour in an open arena in the dark, devoid of external cues or rewards. To visualize the release of dopamine in the DLS, they used a real-time imaging technique called fibre photometry, along with proteins designed to fluoresce in response to binding by dopamine. Cameras captured the animals' behaviour in 3D, and a previously developed machine-learning algorithm[5] then classified the various behavioural sequences of the mice into action elements, which the authors refer to as syllables.

Markowitz *et al.* showed that behavioural syllables were reliably associated with bouts of dopamine release into the DLS – similar to the pattern observed in reward-learning situations. The fluctuations in dopamine had two effects on behaviour, on two timescales (Fig. 1). First, high levels of dopamine release were followed within seconds by increased variability in the actions performed by the mice. Thus, on the immediate timescale, dopamine promotes randomness. Second, syllables that coincided with a large release of dopamine were more likely to be repeated in the subsequent minutes than were those associated with lower levels of the neurotransmitter. Thus, in the long term, dopamine serves to reinforce spontaneous actions.

To ascertain causality, the researchers performed stimulation experiments in which they artificially induced dopamine release when specific, pre-chosen syllables (including 'walk' and 'pause and turn') were detected. This reproduced both scales of effect: after dopamine stimulation, the mouse performed the chosen syllables more frequently; and immediately after stimulation, behaviour became more variable.

What are the consequences of these seemingly contradictory effects of dopamine on behaviour? The shaping of behaviour benefits from both reinforcing well-travelled paths and trying new trajectories – a combination that ensures a repertoire that is robust but also flexible. This effect resonates with a well-known challenge to the theory of reinforcement learning, known as the exploration–exploitation trade-off[6,7]: should a hungry animal return to a known feeding site, or should it explore in the hope of finding a