and horticulture, as well as to the application of gene editing. Gardeners are familiar with the process of taking cuttings from plants to propagate a new plant asexually. Cuttings are the basis of the horticulture industry and involve the induction of roots from cut pieces of a plant stem that will eventually regenerate a whole plant. This is a form of asexual reproduction and is important for the propagation of flowering plants for which sexual reproduction can take years to decades. Gene editing in most species to improve plant performance in shorter times than traditional plant breeding approaches (*7*) requires transformation through the induction of root tissue (a wound-induced root) from a mass of undifferentiated cells called a callus and subsequent root initiation, followed by shoot initiation. Omary *et al.* showed that subclass IIIA and IIIB genes are also required for wound-induced root initiation (see the figure). Mutation of the subclass IIIB *SBRL* in potato interfered with root induction from callus. In tomato, simultaneous mutation of *SBRL* and the class IIIA *BSBRL* and *BSBRL2* genes resulted in an inability to form wound-induced, shoot-borne, and lateral roots.

Roots are incredibly important to plant survival owing to their roles in the transport of water and mineral nutrients and the provision of mechanical support. The discovery of this superlocus provides a beautiful example of how localized gene duplications produce a more complex plant form. The origin of cells that undergo the transition to a specialized root as well as the patterning events associated with generating the primordia can be distinct, but the IIIA and IIIB LBD transcription factors execute the same transitory state to produce different root types. Determining whether differences in class IIIA and IIIB transcription factor expression or activity underlie differences in the capacity for plant transformation or the production of cuttings will further strengthen the impact of the findings of Omary *et al.* The production of different root types is an important component of a plant's ability to successfully respond to stresses in their environment, including withstanding flooding and high wind. In the face of climate change, subclass IIIB transcription factors may become important target genes to manipulate and produce plants with an increased capacity to adapt to adverse weather conditions. ■

REFERENCES AND NOTES

1. B. Steffens, A. Rasmussen, *Plant Physiol.* **170**, 603 (2016).
2. A. N. Hostetler *et al.*, *Curr. Opin. Plant Biol.* **59**, 101985 (2021).
3. M. Omary *et al.*, *Science* **375**, eabf4368 (2022).
4. B. Müller, J. Sheen, *Nature* **453**, 1094 (2008).
5. A. S. Chanderbali *et al.*, *Mol. Biol. Evol.* **32**, 1996 (2015).
6. Y. Okushima *et al.*, *Plant Cell* **19**, 118 (2007).
7. R. A. Nasti, D. F. Voytas, *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2004846117 (2021).

10.1126/science.abo2170

ULTRACOLD CHEMISTRY

Toward a coherent ultracold chemistry

Magnetic fields can be used to change chemical reaction rates by a factor of 100

By **Simon L. Cornish**[1] and **Jeremy M. Hutson**[2]

Collisions are fundamentally important to the study of atomic and molecular gases. For example, they dictate the lifetimes of ultracold samples and the efficiency of cooling by evaporation. Ultracold collisions are largely governed by quantum mechanics and are very sensitive to electromagnetic fields. Harnessing subtle interference effects, such as Feshbach resonances, has allowed the control of atomic collisions and revolutionized the study of atomic physics (*1*). Ramping an applied magnetic field across such a resonance is the key step in the formation of ultracold diatomic molecules (*2*). Opportunities for a broad range of scientific studies and applications will open up if molecular collisions can be controlled in the same way as atomic collisions. On page 1006 of this issue, Son *et al.* (*3*) used a magnetic Feshbach resonance to offer better-than-ever control over ultracold reactive collisions between sodium (Na) atoms and sodium-lithium (NaLi) molecules.

Ultracold molecule-molecule collisions have turned out to cause unexpectedly fast losses of molecules from the optical traps used to confine them (*4–6*). This loss happens even in systems in which two-body chemical reactions between the colliding species are not allowed (*7*). Most experiments have observed loss rates close to the so-called universal rate, at which all colliding pairs that reach short range are lost. The short-range loss is usually explained in terms of the formation of long-lived "complexes" during collisions (*8*). These complexes can be destroyed in a variety of ways, including by chemical reaction or absorption of light from the trapping laser (*9*). However, there is conflicting evidence on the lifetimes of the complexes and the mechanisms of their loss (*5, 6, 10, 11*).

Feshbach resonances occur at magnetic fields where a state of the collision complex has the same energy as the colliding species. They have not yet been observed for molecule-molecule collisions, but atom-molecule collisions provide a simpler case for study. Son *et al.* have observed a resonance due to a long-lived state formed in a collision between ^{23}Na atoms and ^{23}Na^{6}Li molecules. They have measured the rate of the reactive atom-molecule collision, NaLi+Na → Li+Na_2, in the vicinity of this resonance, reporting more than a factor of 100 variation as the magnetic field is tuned across the resonance.

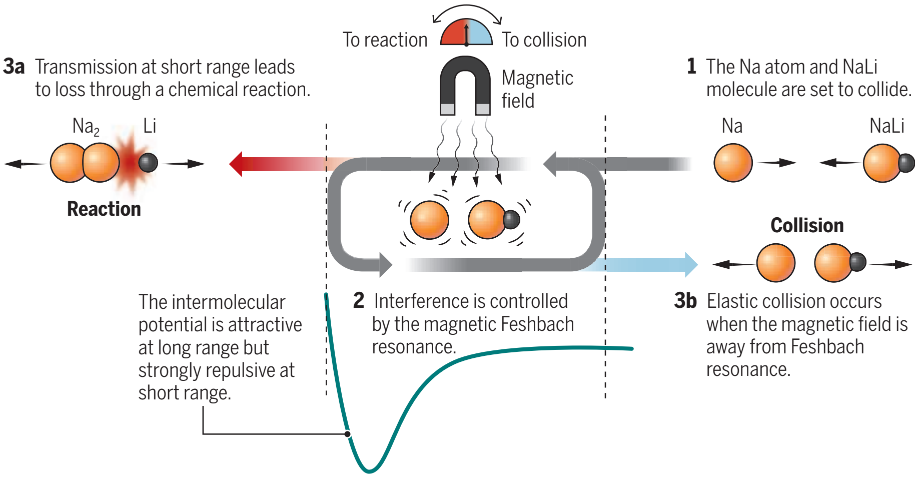
To understand the results reported by Son *et al.*, it is useful to consider a simple physical picture of ultracold molecular collisions. As atoms and molecules approach one another from afar, they experience an attractive van der Waals force. At ultracold temperatures, the colliding particles behave as matter waves—a consequence of wave-particle duality in quantum mechanics—and experience partial reflection from the attractive potential. As the colliding particles get closer to each other, the atom-molecule pair either remains in the initial state and is reflected off the repulsive core of the potential or is converted to a different state in which chemical reaction can occur (see the figure). If the colliding species are completely lost at short range, the overall loss rate is determined by the quantum reflection of the matter-wave from the attractive potential at long range. However, if the loss at short range is very small, the reflection from the short-range interaction may be followed by a second partial reflection from the attractive potential. This can continue ad infinitum, with multiple reflections back and forth within the molecular potential before the pair separates.

Son *et al.* sought to explain this behavior by adapting the existing model for the reflection of light inside a cavity with partially reflecting mirrors. The light wave escaping from such a cavity interferes with the wave originally reflected from the mirror where the light was first introduced. This interference can be either constructive or destructive depending on the spacing of the mirrors, leading to either enhanced or reduced overall reflection respectively. In the case of colliding particles,

[1]Department of Physics, Durham University, South Road, Durham DH1 3LE, UK. [2]Department of Chemistry, Durham University, South Road, Durham DH1 3LE, UK. Email: s.l.cornish@durham.ac.uk

Ultracold chemical reaction using a magnetic field

Multiple reflections within the intermolecular potential result in quantum interference that strongly affects the chemical reaction. Changing the magnetic field can tune the loss of NaLi molecules during collisions. Weak loss at short range leads to a large range of control in the overall loss rate.



treated as matter-waves, the presence of a magnetic Feshbach resonance allows the interference to be tuned with the applied magnetic field, akin to changing the spacing between the mirrors. This allows the probability of a reactive collision to be controlled.

The long-lived state of the complex formed during the collision that causes the resonance produces very little loss at short range. This is analogous to a highly reflecting inner mirror. The resulting high-contrast interference leads to large changes in the overall loss rate, from far below the universal rate to far above. Using a quantum mechanical scattering model based on an absorbing boundary condition at short range that is analogous to the optical cavity model, Son *et al.* estimated that only about 4% of the colliding pairs that reach short range are lost, which is far below the 100% loss at short range associated with the universal rate. The much lower loss at short range leads to a large variation in the reaction rate across the resonance. The authors contrast this resonance with a weaker one at a higher magnetic field, where the associated state of the complex is much shorter-lived, which results in a far smaller variation in the reaction rate across the resonance.

The authors show that ultracold collisions between Na and NaLi can be understood with relatively simple models. Their experiment provides an excellent testing ground for refining the understanding of ultracold chemistry. Looking to the future, tunable Feshbach resonances may ultimately form the basis of a coherent ultracold chemistry, in which bimolecular reactions are performed coherently across an entire sample of molecules. Such a chemistry will allow polyatomic molecules to be built up from their constituent parts while maintaining them all in a single quantum state. This contrasts with the form of coherent control achieved with femtosecond lasers (*12*), in which coherence exists within a single molecule but not across the entire sample.

The ability to control ultracold molecular collisions will benefit many applications. For example, molecules with dipole moments offer fascinating opportunities to study quantum many-body physics in the presence of long-range interactions. This may help understand complex phenomena, such as superconductivity and exotic forms of magnetism. However, achieving this will undoubtedly require the ultracold chemistry to be under control. ■

REFERENCES AND NOTES

1. C. Chin, R. Grimm, P. Julienne, E. Tiesinga, *Rev. Mod. Phys.* **82**, 1225 (2010).
2. K.-K. Ni *et al.*, *Science* **322**, 231 (2008).
3. H. Son *et al.*, *Science* **375**, 1006 (2022).
4. P. D. Gregory *et al.*, *Nat. Commun.* **10**, 3104 (2019).
5. R. Bause *et al.*, *Phys. Rev. Res.* **3**, 033013 (2021).
6. P. Gersema *et al.*, *Phys. Rev. Lett.* **127**, 163401 (2021).
7. P. S. Żuchowski, J. M. Hutson, *Phys. Rev. A* **81**, 060703 (2010).
8. M. Mayle, G. Quéméner, B. P. Ruzic, J. L. Bohn, *Phys. Rev. A* **87**, 012709 (2013).
9. A. Christianen, M. W. Zwierlein, G. C. Groenenboom, T. Karman, *Phys. Rev. Lett.* **123**, 123402 (2019).
10. Y. Liu *et al.*, *Nat. Phys.* **16**, 1132 (2020).
11. P. D. Gregory, J. A. Blackmore, S. L. Bromley, S. L. Cornish, *Phys. Rev. Lett.* **124**, 163402 (2020).
12. C. Brif, R. Chakrabarti, H. Rabitz, *New J. Phys.* **12**, 075008 (2010).

ACKNOWLEDGMENTS

The authors acknowledge support from the UK Engineering and Physical Sciences Research Council (EPSRC) through grants EP/P01058X/1 and EP/P008275/1.

10.1126/science.abn1053

QUANTUM INFORMATION

A new Hall for quantum protection

Long-range vacuum fluctuations break the integer quantum Hall topological protection

By **Angel Rubio**[1,2]

Cavitronics—a portmanteau of cavity and electronics—are devices with certain properties that can be controlled by the light waves bouncing inside the cavity in which the device sits. In quantum mechanical terms, this interaction between light and matter is done by the standing light waves inside the cavity known as vacuum field states. A major advantage of this setup for generating light-matter coupling is the ability to induce certain properties inside a material that otherwise require the use of a strong external electric or magnetic field (see the image). On page 1030 of this issue, Appugliese *et al.* (*1*) provide a special case of cavitronics. Their experimental setup modifies one of the most prominent quantum phenomena in materials, known as the quantum Hall effect (QHE). They found a drastic change in its Hall resistance, opening the path to designing materials functionalities by vacuum-field engineering.

When an electric current is passed through a conductor under the influence of a magnetic field, an electrical voltage perpendicular to the current is induced by the magnetic field. This is known as the Hall effect. However, this “sideways” voltage sometimes happens in steps rather than linearly as a function of the magnetic field (*2*, *3*). This constitutes the QHE, namely a quantized version of the classical Hall effect (*2*), in which the Hall conductance exhibits steps, or Hall plateaus, at precisely integer and fractional multiples of the inverse of the quantum of resistance (*4*).

Whereas conventional resistance de-

[1]Max Planck Institute for the Structure and Dynamics of Matter and Center for Free-Electron Laser Science, Luruper Chaussee 149, 22761 Hamburg, Germany. [2]Center for Computational Quantum Physics (CCQ), The Flatiron Institute, 162 Fifth Avenue, NY 10010, USA. Email: angel.rubio@mpsd.mpg.de

GRAPHIC: KELLIE HOLOSKI/*SCIENCE*

Toward a coherent ultracold chemistry

Simon L. CornishJeremy M. Hutson

Science, 375 (6584), • DOI: 10.1126/science.abn1053

Science (ISSN 1095-9203) is published by the American Association for the Advancement of Science. 1200 New York Avenue NW, Washington, DC 20005. The title *Science* is a registered trademark of AAAS.