discrete single crystals, although transport in these systems can also involve long-lived dark excitons (*7*, *8*). The PDHF nanofibers reported by Jin *et al.* are highly crystalline, with favorable molecule orientation that leads to efficient Förster transfer. Long exciton diffusion lengths are realized for luminescent excitons without a contribution from long-lived dark states.

As researchers strive to exert greater control over energy transport in conjugated systems, it is clear that progress is needed on multiple fronts. The work of Jin *et al.* reinforces the notion that crystalline order plays an important role in facilitating exciton diffusion. More specifically, low disorder and strong π-orbital overlap can enable more effective exciton transport. However, Jin *et al.* note that these factors alone are insufficient to explain the reported long exciton diffusion lengths.

"The PDHF nanofibers reported by Jin et al. are highly crystalline, with favorable molecule orientation that leads to efficient Förster transfer."

Indeed, they highlight the possible role played by exciton delocalization and coherence. In order to realize paradigm-shifting improvements in exciton transport, it is essential to fully escape the limitations of the diffusive or subdiffusive transport regimes and realize ballistic transport (*9*). Whether through exciton delocalization and coherence, or through the design of architectures that remove the normal isotropy of energy transfer, the realization of ballistic transport in thin film would offer new frontiers of interesting science, as well as new device applications that extend beyond the realm of photoconversion. ■

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10.1126/science.aat6009

CHEMISTRY

Cold chemistry with two atoms

Two atoms react to form a molecule in an optical "beaker"

By **Edvardas Narevicius**

For centuries, chemists have written equations representing chemical reactions by using symbols for atoms and molecules; for example, $2H_2O + 2Na \rightarrow 2NaOH + H_2$. This short notation shows only four reacting particles, but even in a classroom demonstration where a small piece of sodium is dropped in water, the total number of reactants will be on the order of Avogadro's number ($\sim 6 \times 10^{23}$). On page 900 of this issue, Liu *et al.* (*1*) instead study a chemical reaction taking place between a minimal number of participants. In their experiment, exactly two atoms collide, absorb a photon, and form a molecule in the excited state. And this time, the reaction equation, $Na + Cs \rightarrow NaCs^*$ (where the asterisk denotes an excited molecule), describes exactly the process that takes place in the laboratory.

During room-temperature liquid-phase reactions, local interactions and conditions vary widely, with many quantum states contributing to the reaction dynamics. Ensemble averaging can be helpful for describing these reactions, and thermodynamic properties such as the Gibbs free energy can be used together with classical dynamics calculations to reliably predict reaction rates and outcomes.

At another extreme are reactions between reactants in interstellar space, where particle densities are 10 orders of magnitude lower than in a liquid and where reactions happen only when two reactants collide. Herschbach, Lee, and co-workers were the first to experimentally explore this regime with low-density cold molecular beams (*2*). Removing interactions with the environment allowed direct observation of reaction mechanisms.

In the past decade, scientists have been able to observe reactions at ever-lower collision energies. At low collision energies, quantum-mechanical wavelike behavior plays a central role, necessitating use of quantum statistics (*3*) and consideration of quantum tunneling (*4*) and quantum scattering resonances (*5*–*7*). Liu *et al.* now measure inelastic collisions between only two trapped atoms, achieve formation of an individual molecule, and perform molecular spectroscopy.

It is surprising that the authors could construct a molecule by a reaction between two atoms. Usually, chemists increase densities until the collision frequency is high enough for products to be formed. Liu *et al.* instead use a clever technique to confine the two atoms in a small (several cubic micrometers) trap that is sufficiently deep to keep atoms with a temperature of 1 millikelvin (mK). They create the trap with tightly focused laser beams that confine particles in the region with the highest laser field intensity. Similar to laboratory tweezers, atoms trapped inside can be moved around by translating the laser beams in space.

To be able to place the atoms in optical tweezers, the authors first had to lower the kinetic temperature down to tens of microkelvin. To achieve this temperature, the authors used one of the most successful tools of modern atomic and optical physics, laser cooling (*8*). They laser-cooled Na and Cs atoms in individual optical tweezer traps and detected them using a fluorescence signal, leading to a ~33% success rate in the preparation of two reactants in a well-defined initial state.

After cooling the atoms and trapping them in individual laser tweezers, the authors adiabatically merged the two traps and formed an optical "beaker" containing both Na and Cs. The next step was to show and prove that collisions between the two atoms are detectable. To do so, the authors prepared a beaker containing two atoms in which excited hyperfine states were populated. Hyperfine states form through interactions between electron and nuclear spins within an atom, with excitation energies on the order of 100 mK. During a collision, the internal excitation energy can be released in the form of kinetic energy, and atoms will be ejected out of the shallow optical trap. The atoms are lost after several milliseconds, indicating a high collision rate. The inelastic collisions can be strongly suppressed by controlling the initial quantum state of the atoms. If atoms are driven to the lowest energy state, their lifetime in the trap increases to several seconds.

The long trapping lifetimes enabled the authors to perform the impressive feat of building a single molecule out of two atoms. In principle, a collision between two ground-state atoms cannot produce a

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bound molecule. A third body is needed to carry away the excess bonding energy. Usually, interaction with another atom or molecule serves this purpose. In Liu *et al.*'s study, photons take care of energy conservation.

Two photons are needed to create a molecule out of two separate atoms (see the figure). The first photon that starts the reaction is absorbed by an atom. However, the photon energy is tuned just below the atomic transition and can only be absorbed if a molecular state is reached (see the figure). By scanning the laser frequency, the authors could detect several bound molecular levels on the electronically excited potential and assign them to particular molecular vibrations, demonstrating that molecular spectra can be measured with only two atoms. The electronically excited molecule quickly emits a photon and a molecule in a vibrationally excited level. Formation of a molecule is detected as a simultaneous loss of fluorescence of the Na and Cs atoms. Here again, the authors harness the low temperatures that can be achieved with laser cooling. The transition probability between free atoms and bound molecular state depend on the overlap between corresponding wave functions. To form a molecule, two atoms have to spend sufficient time at distances on the order of the length of a molecular bond. This time can be increased by reducing the relative kinetic energies that correspond to temperatures in the range of several microkelvin. This leads to higher excitation probabilities that do not require high-intensity laser fields (*9*).

Liu *et al.*'s method opens many interesting avenues for research. The authors plan to demonstrate that with the help of an additional laser field, molecules can be coherently transferred into a single selected vibrational level. Such a degree of quantum state control would allow studies of quantum state–resolved collisions and reactions between molecules. The ability to work with well-defined numbers of atoms will provide unprecedented precision in unraveling the microscopic mechanisms of complex interactions. Another interesting application for "designer" cold molecules would be the assembly of a lattice of strongly interacting polar molecules that could serve as qubits or as a tool to investigate unusual quantum phases. ■

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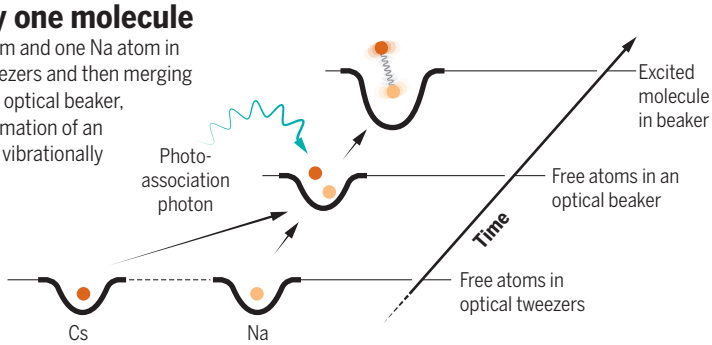
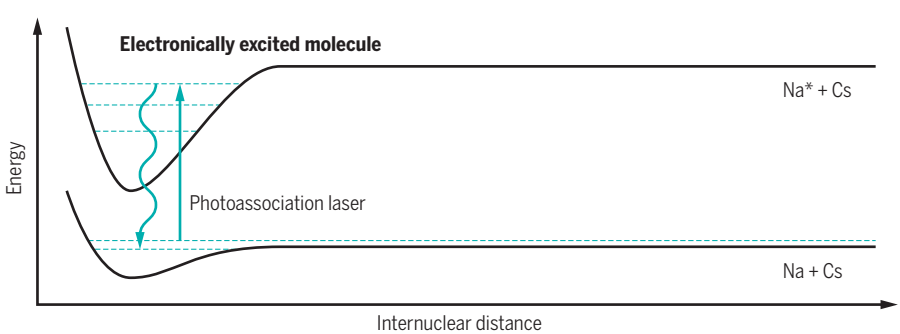
10.1126/science.aat7917

Making exactly one molecule

By confining one Cs atom and one Na atom in separate molecular tweezers and then merging the tweezers to form an optical beaker, Liu *et al.* achieve the formation of an individual molecule in a vibrationally excited state.



Photoassociation process
Free Na and Cs atoms collide, absorb a photon, and form an electronically excited molecule, which emits another photon and forms a stable molecule.



SYNTHETIC BIOLOGY

Illuminating dark depths

Microelectronic processing and engineered bacteria provide real-time insights into the gut

By **Peter R. Gibson** *and* **Rebecca E. Burgell**

The inner workings of human physiology remain one of the final frontiers of science. In particular, the gastrointestinal (GI) microenvironment is incompletely understood. On page 915 of this issue, Mimee *et al.* (*1*) have developed an ultralow-power ingestible sensor of various compounds (ingestible microbio-electronic device, IMBED) by combining engineered bioluminescent bacteria and microelectronic processing. This has the potential to unlock a wealth of information about the body's structure and function, its relationship with the environment, and the impact of disease and therapeutic interventions.

Tiny sensors can now be made through advances in semiconductor microelectronics and microfabrication, and their signals can be computed and communicated wirelessly to remote receivers (*2*). Furthermore, the increasingly low power demands of such devices, developments in battery technology, and advances in wireless signal transmission have permitted deeper, more durable exploration within the body (*2*). Such technology can be used to study the luminal content of the GI tract, as understanding its physiology and pathology is limited, largely owing to difficulties in access. Although devices can be inserted into regions close to the exterior, few provide measurements under truly physiological conditions. For example, access to the colon generally involves bowel cleansing, which disrupts normal physiology. Inaccessibility almost precludes such approaches to most of the small intestine. This negatively affects our comprehension of inflammatory intestinal disorders such as Crohn's disease, celiac disease, and irritable bowel syndrome, which are prevalent worldwide (*3*, *4*).

The design of biosensors in the form of capsules, no greater in size than a large vitamin pill, has revolutionized the ability

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Science **360** (6391), 855-856.
DOI: 10.1126/science.aat7917