Molecules in Slow Motion

In the microworld, slow means cold. Research on decelerated, ultracold atoms has recently yielded spectacular results—such as Bose-Einstein condensates, which have already become indispensable for quantum physics. Cold molecules should also have similar potential, but unfortunately, they are very difficult to produce. The group working with Gerard Meijer, Director at the Fritz Haber Institute of the Max Planck Society in Berlin, has developed an efficient system for slowing down molecules, and reports on it in this article.

Physicists seem to have a penchant for operations at full throttle: they use huge particle accelerators to spin components of all kinds of matter to the fastest speeds possible to make them collide. The subatomic traces of such collisions have actually been providing valuable information about the building blocks of our cosmos for decades.

But many physicists are also fascinated by extreme slowness. At the Fritz Haber Institute of the Max Planck Society, for example, we are working on techniques for decelerating molecules efficiently.

The molecules we use come from a jet of highly diluted gas. In a “normal” warm gas, most molecules zip around so quickly that only a supersonic jet could keep up. Our device allows us to slow them down and actually get a proper grip on them. Technologically speaking, this is no mean feat. But the effort is worth it, because we can conduct some fascinating basic research on the slow molecules.

To slow them down, we use methods developed in accelerator physics. We apply them with reverse effect, so we transform an accelerator into a trap. The slow molecules can be stored and studied very closely, looking, for instance, at the quantum properties of their complex electron shells. Or we use them to conduct further experiments, such as slow-motion soft collisions.

In physics, as soon as small particles are involved, slowness is nothing other than cold. Heat is kinetic energy. If we take it out of these molecules by “slamming on the brakes,” then we automatically cool it down.

In the case of atoms in dilute gases, physicists have since become very adept at such braking techniques. In the lab, they routinely achieve extremely low temperatures that would have still been pure science fiction 20 years ago. They are just a few millionths of a degree above absolute zero, which is minus 273.15 degrees Celsius. The consequences of this progress for science are very exciting, and sometimes completely unforeseen.

To create ultracold atom clouds, the experimenters combine the brake effect that laser light can exert on atoms with magnetic fields that confine the cold atoms. Such magneto-optical traps have been used successfully for a good 10 years to produce, for example, the famous Bose-Einstein condensates. A Bose-Einstein condensate is a collective quantum state in which a cloud is “condensed” from certain types of atoms when they are cooled to extremely low temperatures. What fascinates physicists about this trapped quantum collective is the property that it is completely freely accessible and manipulable from practically all sides.

Gold Rush in Quantumland

For this reason, it is much easier to research than other multi-particle quantum states: superconductivity, for example, hides in the interior of metals, which is very difficult to access. That is why the first successful...
First, the molecule hits the electric field of a braking element (top). Then it must climb a potential hill and slow down until it reaches the peak (center). Flying down the other side of the virtual hill would cause it to accelerate again, but that is prevented by turning off the electric field in due time (bottom).

**Firsthand Knowledge**

**Physical Braking only Works with Atoms**

So it is not surprising that physicists no longer want to limit this exciting game to atoms. Ultracold molecules may promise even more thrilling discoveries. But it is much more difficult to cool molecules down to extremely low temperatures than it is with atoms. Unfortunately, the laser cooling that has proven so effective with atoms usually fails. To put it simply, the atoms, with their electron shells, swallow the light quanta (photons) from the approaching laser beam. Later, they emit these photons again, usually in any direction at random. On the whole, the laser beam slows down the atom like a boxer does a charging opponent with targeted punches, while the latter—the atom—merely flails about with no effect.

Unfortunately, this physical braking doesn’t usually work with molecules. They are made up of multiple atoms and have far more complex spatial distributions than atoms do, and they hardly slow down at all. So we had to take a different route to develop an effective molecule brake. At present, only a few techniques are suitable for this. In Berlin, we use a small particle accelerator that we operate in reverse as a particle decelerator. Since late 2003, we use it to cool molecules down to a few thousandths of a degree above absolute zero. Our device is called the “Stark decelerator,” in memory of Johannes Stark, the German Nobel laureate in physics in 1919 for his discovery that an electric field changes the spatial distribution of the electric charges is somewhat irregular. These “polar” molecules behave like tiny antennas that react to the electric field of the Stark decelerator. The pulses jump along this cascade like a running light that grows continuously slower. Now, if a polar molecule hits a brake element at the right moment, then the briefyincreasing electric field acts like a small hill of pure energy. The molecule becomes slower— as if it had to roll up a virtual hill to reach the “energy peak” at the center of the element. However, when flying through, it would roll down the other side of the virtual hill. It would be just as fast at the end as it was at the beginning, and nothing would be gained. To prevent this, the field shuts down as soon as the molecules reaches the energy peak. The hill disappears right out from under the molecule’s feet, as it were, and it can’t accelerate again.

Now the question remains how we get the molecules to the Stark decelerator. One is a small storage ring—an apparatus never has exactly the same speed. Thus, with every revolution around the ring, the packets drift further and further apart. To increase the “parking time,” we built into the ring a segment that uses specially formed fields to push the molecule packet back together with each revolution. This works so well that we can now also store multiple packets in succession in the ring. However, the molecules still require a certain, not-too-low residual speed to remain visible for a short period of time. For ND3, for instance, this is around 100 meters per second. To experiment further with the slow molecules, our lab has various apparatuses that can connect behind the Stark decelerator. One is a small storage ring—a storage ring never has exactly the same speed. Thus, with every revolution around the ring, the packets drift further and further apart. To increase the ‘parking time’, we built into the ring a segment that uses specially formed fields to push the molecule packet back together with each revolution. This works so well that we can now also store multiple packets in succession in the ring. However, the molecules still require a certain, not-too-low residual speed to remain visible for a short period of time. For ND3, for instance, this is around 100 meters per second. If we want to store very slow, cold molecules, we need another technique. To this end, we use a special molecular trap. Using an electric field, it captures the decelerated molecule as if in a pillow. As soon as the molecule is properly confined, the trap switches its field to take on the form of an energy funnel. The molecule is then trapped in this funnel and can only wobble back and forth at a few meters per second. When this happens, its temperature can drop to about one fifth-thousandth of a degree above absolute zero.

To date, we have caught ND3 and the OH radical with the trap. The OH is of particular interest to us in principle, it is a water molecule (H2O) that has lost a hydrogen atom (H). This makes it highly chemically reactive. OH plays an important role in....

**Molecular Physics**

The trap arrests the decelerated molecule (gray cloud) with its electric field like a pillow (left). Now the molecule is confined, with the field acting like a funnel (right).

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nature, for example in cosmic gas clouds and in the chemistry of the Earth’s atmosphere, as well as in combustion processes.

OH also recently helped us conduct another fundamental experiment (J. Gilijamse et al., Science 2006, vol. 313, 1617). For this, we intersected the path of the decelerated OH molecules after they left the Stark decelerator with a beam of xenon atoms. The OH molecules look roughly like billiard balls, but rather absorbed the collisions with the xenon atoms: they no longer bounced off elastically like billiard balls, but rather absorbed a portion of the impact energy.

**Molecular Billiards with Great Finess**

That is what theoretical chemist Gerrit Groenenboom from Nijmegen had predicted. According to his quantum theoretical calculations, at these threshold values, the total energy of the collision is just enough for the striking xenon to stimulate the next higher energy quantum of the OH rotation. We obtained excellent confirmation of Groenenboom’s predictions. We clearly understand the physics of such impacts quite well. However, in this collision experiment, one of the partners in the impact was still an atom, and a hot one at that. In the future, we want to have two molecules that are both truly cold collide gently. To do this, we must also send the intersecting molecular beam through a second Stark decelerator. We hope that these slow-motion molecular collisions will give us finely detailed information about the quantum structure of their electron shells. From this we hope to learn, for example, how stable molecular complexes, which play an important role in nature, are created.

With two Stark decelerators, we can also study how chemical reactions between the cold molecules proceed. We know that their low energy will then just barely suffice for a reaction. Physical chemistry predicts that, in this case, quantum effects should dominate the behavior of the reaction partners. But no one can yet predict precisely what will happen. Perhaps there will be a reward for the long years of development work—one that is as spectacular as the discoveries made with ultracold atomic gases. But we do not yet know where the discovery of molecular slowness will take us. We are just setting off into this unknown world.

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**FIRSTHAND KNOWLEDGE**

Steven Horstens makes some adjustments to the first part of the vacuum machine that produces the beam of OH molecules.