Stopping molecules with a centrifuge

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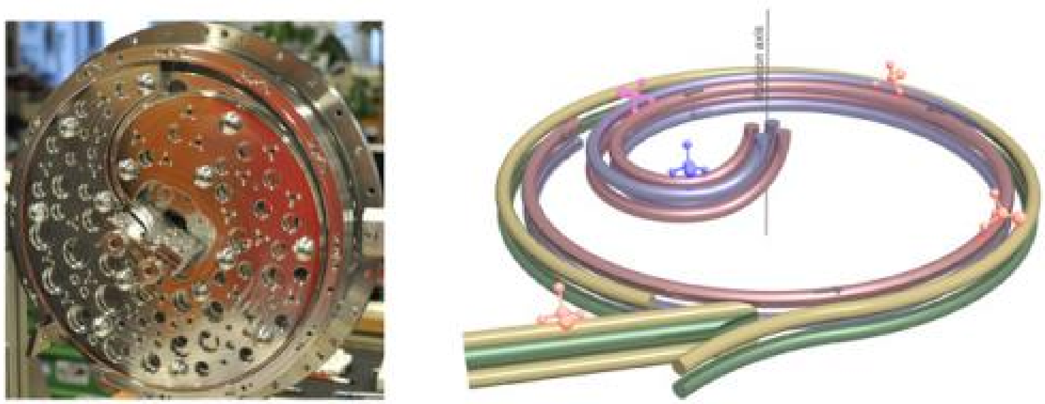

Fig. left: Photo of the 'centrifuge' / Fig. right: On a fast rotating disc, an electric quadrupole guide forces the molecules to move towards the rotation axis. As the molecules have to fight against the centrifugal force on their way, they lose kinetic energy and are slowed down to almost a complete halt. Credit: MPQ, Quantum Dynamics Division.

Does the electron possess an electric dipole moment? Will it be possible to achieve perfect control over chemical reactions between polyatomic molecules, or can one envisage quantum simulations and quantum computation with cold polar molecules? The fast-growing investigation of cold polar molecules holds promise for delivering answers to these long-standing questions that concern fundamental physics as well as future applications. Producing abundant samples of cold polyatomic molecules from thermal ensembles, however, is a formidable challenge. A key method for obtaining cold molecules is the deceleration of molecular beams. This has been achieved so far only in the pulsed mode, with a very low duty cycle. Thus the hitherto-implemented techniques cannot make use of the intrinsically high flux delivered by the available continuous molecular sources. To utilize the full potential of such sources, a continuous deceleration is warranted.

Towards this end, a team of scientists in the Quantum Dynamics Division of Professor Gerhard Rempe at the Max-Planck-Institute of Quantum Optics has now developed a versatile deceleration technique dubbed centrifuge decelerator, which makes possible for the first time the deceleration of continuous beams of polyatomic polar molecules (*PRL*, DOI: 10.1103/PhysRevLett.112.013001, 6 January 2014).

The stunning advances in atomic physics and quantum optics over the past three decades ensued to a great extent from the development of efficient laser cooling and deceleration techniques. Compared to atoms, molecules are more complex objects and possess a more involved internal-energy structure: in addition to the electronic states, molecules have also vibrational and rotational states. For this reason, the laser cooling and deceleration methods, which are the workhorses in atomic physics, are not applicable to molecules, in particular polyatomic ones.

A natural way to decelerate a molecule (as any other object) is to make it climb up a potential hill, thereby transforming its kinetic energy into a potential one. Such a hill can be provided through the interaction of a molecule with an external field, be it electric, magnetic or gravitational. For instance, the application of electric fields makes use of the dipole moment that a large number of molecules (unlike atoms) possess because of an uneven charge distribution within the molecule. The dipole moment interacts with the external electric fields, and by making the molecules move from a region with a weaker field to a region with a stronger field they lose kinetic energy. In a similar fashion magnetic molecules can be decelerated with external magnetic fields.

"The disadvantage of these two methods is that for most molecules of interest the typical height of electric or magnetic hills is of the order of 1 Kelvin, whereas molecules from our liquid-nitrogen-cooled source have initial kinetic energies of the order of 100 Kelvin", Dr. Sotir Chervenkov, leader of the experiment, explains. "Hence, the molecules have to climb up a sequence of around hundred hills. This implicates that one has to apply this process many times in succession, which leads to operation in the pulsed regime."

To circumvent this limitation, one has to provide a sufficiently high potential (~100 K) in order to decelerate molecules in one stretch. Such a high potential is provided by the gravitational field of the Earth, for instance. Simple calculations, however, show that for a molecule to be decelerated from around 200 metre per second down to a trappable velocity of around 20 metre per second it has to fly upwards in the gravitational field of the Earth for 2000 metres, which renders such an experiment impossible or at least very demanding. The alternative is to artificially create an analogue of a gravitational field in the laboratory.

"We are the first group worldwide which exploits this possibility", points out Dr. Chervenkov. "Everyone who has been on a merry-go-round has experienced the outward force, which exists in a rotating frame. This force can be much larger than the gravitational force of the Earth, and is exploited in centrifuges for a multitude of biological, chemical, medical and industrial applications." Xing Wu, a doctoral candidate who performed the first measurements, adds: "Now we employ a rotating frame for a conceptually different purpose, namely to decelerate a gas of neutral molecules from about 200 metre per second to almost a standstill." Martin Zeppenfeld, who initially proposed the idea, further elucidates the deceleration mechanism: "First the molecules propagate around the periphery of the centrifuge in a stationary storage ring with a diameter of 40 cm composed of two static and two rotating electrodes. Then a rotating spiral-shaped electric quadrupole guide picks up the molecules almost at any point around the storage ring and whirls them to the rotation axis. Thus the centrifuge deceleration is a two-step process: the velocity of the molecules decreases first upon their transition from the laboratory into the rotating frame, and further, while propagating in the rotating guide, as they are forced to climb up a huge potential hill and are continuously slowed down, eventually reaching the rotation axis at close-to-zero velocity."

The MPQ team demonstrated the capabilities and the universality of the new technique by deceleration of three species with different masses and a dipole moment of the order of 1.5 Debye, CH_3F, CF_3H, and CF_3CCH. In their experiment the scientists vary both the rotation speed of the disc and the voltage at the quadrupole guide. For optimal conditions they achieved continuous output beams with intensities of several billion molecules per square-millimetre per second for molecules with kinetic energies below 1 Kelvin.

"Novel features of the centrifuge decelerator are its continuous operation, high beam intensity, applicability to a large set of molecules, and ease of operation. Therefore it has the potential to become an extremely valuable method in the cold-molecule research," Professor Gerhard Rempe points out. "The universality of the centrifugal force might also enable one to slow down atoms that cannot be laser-cooled, and possibly even cold neutrons."

Accumulation of centrifuge-decelerated molecules in an electric trap and further cooling them via the recently demonstrated technique of Sisyphus cooling developed in the same group at the MPQ might allow for a dramatic increase of the phase-space density for controlled collision experiments with polyatomic molecules and pave the way to achieving quantum degenerate regimes with polar molecules.

More information: S. Chervenkov, X. Wu, J. Bayerl, A. Rohlfes, T.

Gantner, M. Zeppenfeld, and G. Rempe. "Continuous Centrifuge Decelerator for Polar Molecules." *Physical Review Letters*, DOI: 10.1103/PhysRevLett.112.013001, 6 January 2014

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