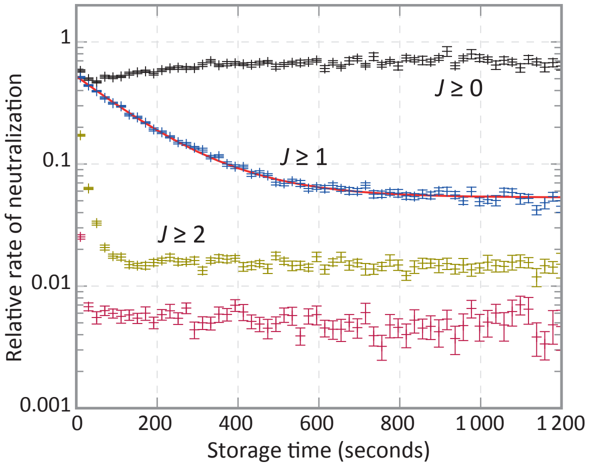

Rotational cooling of OH^- ions in the CSR. A laser neutralizes the OH^- ions. The rotational quantum states J are excited to different degrees. Even the lowest excited state ($J = 1$) disappears after about 10 minutes. Thereafter, all OH^- ions except a few % are found to be in the ground state $J = 0$.

cally charged molecules at low temperatures. This quantum physics plays an important role in interstellar space, in the outer atmospheres of Earth and other planets, and in many fields of chemistry and biology.

Using laser radiation and sensitive particle detectors, it could be verified that molecules after some minutes of storage time in fact cool down far below the usual laboratory temperatures and approach space conditions with respect to their inner motions. This permits detailed investigations of reaction processes. One of the experimental procedures relies on the interaction of a well-controlled, cold electron beam in such a way that the reaction conditions match the temperature of the interstellar medium. This simulates a reaction in which interstellar molecular ions are decomposed into their atomic constituents by surrounding electrons. The more effective these reactions are, the shorter the molecular ions can survive in interstellar clouds.

The new experiments at the CSR demonstrate that the reaction rates are strongly reduced when compared to previous measurements at the usual laboratory temperatures. Surprisingly, only a few of the many possible reaction pathways are conserved at these low temperatures. The particle detectors in the CSR are also able to determine the spatial distribution of the atomic constituents formed in this reaction, and this way additional detailed information on the remaining reaction pathways can be inferred.

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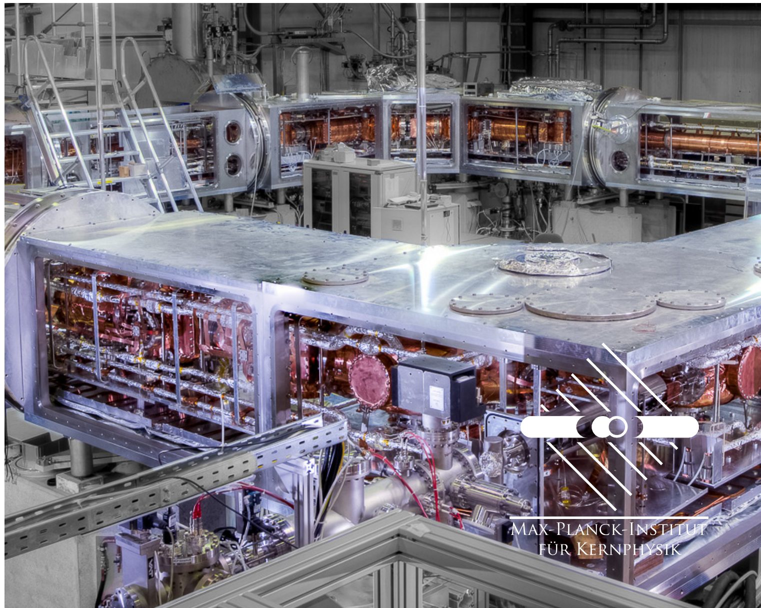
The Cryogenic Storage Ring CSR



The Cryogenic Storage Ring CSR

A novel, world-wide unique cryogenic storage ring (CSR), for experiments with atomic, molecular and cluster ion beams, is operated at MPIK. Stored at extremely low temperature, just barely exceeding absolute zero, the ion beams enable studies of molecular reactions as individual processes. The conditions in the CSR are similar to those prevailing, for example, in interstellar clouds.

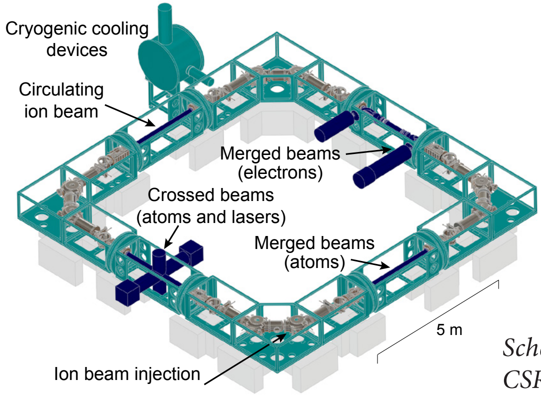
Molecular ions in extreme vacuum

The internal motion in molecules is determined by the quantum dynamics of their atomic nuclei and electrons. Ambient influences such as interactions with other molecules, light, or thermal radiation, can act on the atoms in the molecules and induce internal motion. This may trigger chemical reactions or make molecules emit light. Sensitive observation of molecular interactions thus provides insight into the submicroscopic many-body quantum dynamics inside the molecules: the basis of all chemistry.

Particles carrying electric charge – the positively charged atomic nuclei and the negatively charged electrons – play an eminent role in matter. Usually, positive and negative charges neutralize each other. However, the predominance of one of the charge signs leads to positive or negative molecular ions. Free molecular ions are highly reactive. Extreme vacuum is required to keep them in the laboratory for extended periods of time. But then, remarkably, they can be manipulated individually with the aid of electric and magnetic fields and stored for precision experiments.

Single reactions with molecular ion beams

To study individual reaction processes, molecular ion beams are accelerated to high velocities. Using these fast beams, molecular ions of different composition as well as the atomic constituents of molecules can be collided or merged at any desired relative speed and thus brought to reaction. Combined with particle detectors observing these reactions as individual processes, a wide research field opens for exploring the molecular structure of matter.



Scheme of the CSR.

The Cryogenic Storage Ring CSR

The cryogenic storage ring CSR at MPIK represents a novel, unique tool for these studies. It stores ion beams in extremely high vacuum that is generated by extremely low temperatures. The CSR is also capable of storing heavy molecules and even clusters of several molecules. On their race track through the storage ring, the ions pass four linear interaction sections. Here they collide with other atomic particles or with externally controlled laser beams; high-performance detector systems collect data on individual molecular reaction processes.

As the goal of this storage ring is to permit experiments with very heavy molecules or clusters, purely electrostatic ion optics are used, as suitable magnetic deflection systems would have prohibitively large dimensions. In contrast to a magnetic system, the electrostatic units for deflecting and focusing of the ion beam are placed inside the vacuum chamber. Overall, the ion optics consists of 16 quadrupole units to focus the beam and 16 deflection units, which serve to keep the ions on their 35 m long orbit for up to many minutes. For this, much better vacuum than in other ion storage rings is required: in CSR the residual gas must have a density as low as 10^{-16} of that in the standard atmosphere (pressure around 10^{-13} mbar).

A vacuum chamber at –265 °C

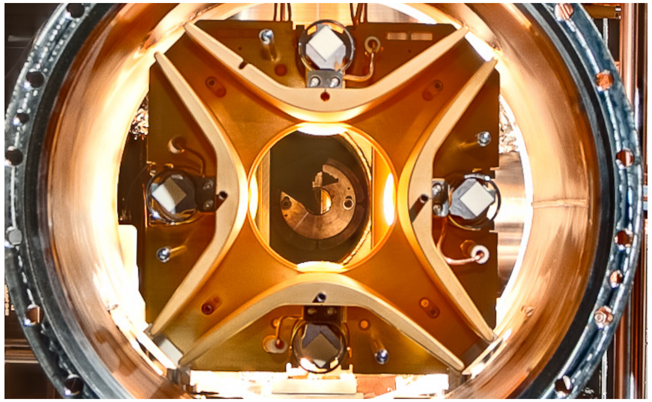
In the cryogenic vacuum chamber of the storage ring – shielded from thermal radiation and atmospheric gas – the stored molecules reach their lowest quantum mechanical states as a prerequisite for precise studies. Furthermore, laboratory measurements can be performed under optimal conditions on many astrochemical reaction steps occurring in interstellar space. Such reactions play important roles in the formation of stars and planets and in the creation of interstellar molecules such as water or interstellar dust particles.

The vacuum chamber surrounding the ion beam in the CSR has a temperature of about –265 °C. Even lower temperatures (close to –269 °C) are generated at 28 cold spots distributed around the ring, where ultracold surfaces freeze out even the most volatile atmospheric gases. A refrigeration plant pumps liquid helium through a system of tubes that circle the ring many times. All these components are placed in an outer vacuum system, the insulation vacuum. It prevents thermal conduction from the outside. Inner layers held at –240 °C, gradually rising to about –200 °C, serve as shields against the Earth's thermal radiation.

The mechanical design is governed by the low-temperature requirements. Nearly all materials shrink on cooling: a stainless-steel tube of 1 m length by about 3 mm between 20 °C and –265 °C. Flexible metal bellows decouple the mechanical components, and all ion-optical elements are individually mounted on massive concrete supports.

Experiments with cold ion beams

The experimental sections of the CSR are low-temperature zones which are complemented with novel sensitive particle detectors and additional electron and atom beams merged with the stored molecules. Several experimental campaigns per year use this equipment. The experimental focus is on sub-microscopic many-body quantum dynamics of electri-



View along the CSR ion beam onto the quadrupole focusing electrodes made of gold-plated aluminium. The ion beam is conducted in the 10 cm wide aperture.