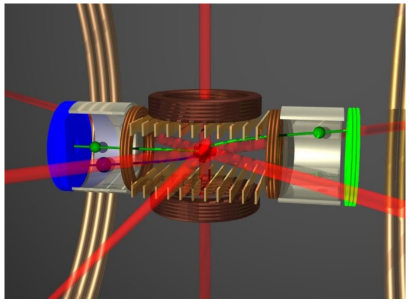
A Detector with Atomic Resolution – the Reaction Microscope

The goal is to get deep insight into collision processes and the atomic and molecular reactions they induce. In our experiments, this is realised by measuring the momenta, that is the velocities and flight directions of all the atomic fragments. For this purpose, the negatively charged electrons and the positively charged ions are accelerated in opposite directions by means of an electrical field and recorded by two detectors. An additional superimposed magnetic field helps to collect all electrons (which are relatively fast due to their small mass) and to guide them to the detector on a spiral track. The initial momenta of the particles can be reconstructed from the measured impact positions and their times of flight. After a large number of repeated measurements, an accurate picture of the velocity and direction distribution of all the atomic or molecular fragments is obtained.

Ultracold Dynamics

Very cold atomic gases with quantum properties can be produced by means of laser cooling. The lithium atoms which we use for this purpose show different behaviour depending on the choice of their mutual interaction. In the so-called bosonic regime they form weakly bound pairs with mutual distances of the atoms which can be controlled experimentally. With our reaction microscope, we are investigating this exotic form of matter. For example, by ionization of all atoms in bound pairs or in few-particle systems and determination of all ion momenta, it is possible to deduce the initial spatial configuration of the particles. Here practically instantaneous ionisation is caused by an intense femtosecond-pulsed laser flash. Whether and how the quantum state of the gas influences its ionisation dynamics is also of interest.



Laser cooling of atoms in a magneto-optical trap integrated in a reaction microscope.

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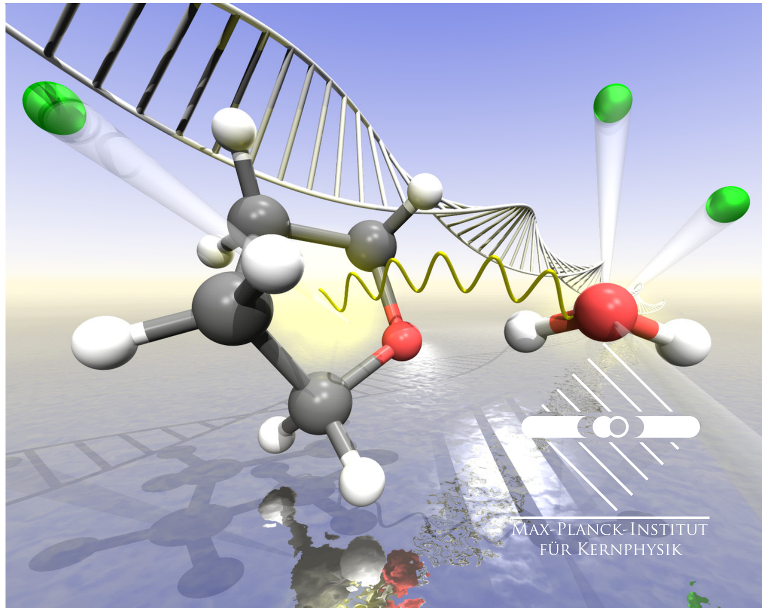
The Max-Planck-Institut für Kernphysik (MPIK) is one of 86 institutes and research establishments of the Max-Planck-Gesellschaft. The MPIK does basic experimental and theoretical research in the fields of Astroparticle Physics and Quantum Dynamics.

Atoms and Molecules under Bombardment

From Electron-Atom Collisions to Fundamentals of Tumor Therapy



Atoms and Molecules under Bombardment From Electron-Atom Collisions to Fundamentals of Tumor Therapy

Collisions of electrons with atoms and molecules are quite common in our environment and also play an important role in technology and medicine. In our laboratory, we investigate these ionization processes as detailed as possible by detecting all charged fragments, i.e., electrons and ions, with a reaction microscope. Collision partners range from simple atoms for fundamental studies up to organic molecules such as building blocks of DNA.

Electron Collisions in Nature, in Applications ...

Reactions which are initiated by microscopic collisions of energetic particles with atoms are relevant in various areas of our environment, in technical applications and in medicine. E. g., in lightning flashes and in fluorescent tubes atoms are stimulated to emit light in collisions with fast electrons. In tumor therapy, cancer cells are destroyed efficiently by x-rays or by fast and energetic ions. In the Heidelberg ion-beam therapy centre (HIT), patients are treated with ion beams of protons or carbon ions. In both therapy methods the injected beams produce a large number of free electrons in the tissue. These can destroy very easily the DNA which is the molecule in the cellular nucleus carrying the genetic information.

... and on an Atomic Scale

But what happens on a microscopic scale, when highly energetic, e. g. fast electrons or ions penetrate a gas or tissue? We do research to answer this question by investigating collisions between electrons and single atoms, the building blocks of matter. A decisive reaction channel is collision-induced ionisation, in which electrons initially bound in the atom are kicked out by the impact of the projectile electron. This process, however, is up to now not fully understood. Unsolved problems are for example: How fast and in which direction do the ejected electrons escape? How often are two, three or more electrons ejected from the atom? Which role does the atomic nucleus play in this process? Using sophisticated experimental techniques, we try to find answers to these questions.

The Many-Particle Problem

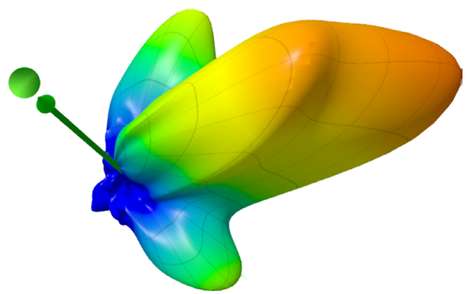
Similar to planets circling around the sun, the electrons in an atom are moving around the nucleus, where all particles interact with each other through the Coulomb force.

Quantum theory, which has been formulated already in the first half of the last century, describes the motions of the atomic building blocks. Even though this theory was confirmed in numerous experiments and, moreover, the force between the electrons and the atomic nucleus is well known, exact solutions of the quantum-mechanical equations may be derived only for the simplest system, the hydrogen atom (consisting of a nucleus and one electron only). As soon as more than two particles are involved, either approximations or computer-aided, computationally extensive numerical procedures have to be applied. In order to test the validity of these approximations, a comparison with experimental results is essential.

Dynamics in Collisions

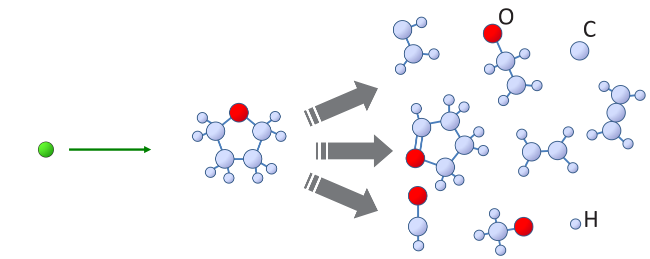
In contrast to the motion of planets, the bound electrons in an atom are not observable directly. Here, a trick has to be used: We bombard single atoms with electrons and select only those events where one or more electrons are kicked out. The kinetic energies and emission directions of the escaping electrons provide valuable information about their motion just before the collision, a state when they are still bound in the atom.

Further, we also study collisions between electrons and molecules with increasing size. We could observe for the first time how the spatial structure and the alignment of a molecule influence the electron emission pattern.



Distribution of emission directions of the escaping electrons in electron-atom collistions. Blue/orange correspond to low/high probability for emission in the corresponding direction.

In the collision, the molecule may also disassemble in several fragments. In biological tissue this process plays a decisive role since, for example, the DNA molecule, which carries the genetic information of the cell, can be modified or destroyed. We study how the building blocks of DNA behave, if they are hit by electrons by detecting the resulting fragments. The final reaction products depend on which of the molecular electrons is knocked-out. These experimental results may in the future contribute to an improved understanding of the formation of tumors and their destruction by radiation therapy.



Detected fragments of tetrahydrofuran after bombardment with energetic electrons.

In recents years, particularly exciting experiments focused on reactions, which become possible by the embedding of the molecules in, for example, a natural water environment. We found that single water molecules catalyse the break-up of molecular rings such as tetrahydrofuran (title picture). If the water molecule is ionised first, energy transfer to the organic molecule follows which thereby loses electrons and may subsequently break up. The released electrons are still sufficiently energetic to initiate further damage.

On the other hand, if the tetrahydrofuran molecule is directy hit, its fate depends on the amount of energy transferred and on its neighborhood: if only one water molecule is present, it catalyses the ring break-up. Interestingly, this destruction does not occur if several water molecules are bound, since the energy can be distributed among many molecules representing efficient cooling. The local aqueous environment in which biomolecules are embedded thus acts as a protective shield.