Symposium Hot topics in cold molecules: From laser cooling to quantum resonances (SYCM)

jointly organized by
the Molecular Physics Division (MO),
the Atomic Physics Division (A), and
the Quantum Optics and Photonics Division (Q)

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Laser cooling and trapping techniques are successfully implemented in the atomic physics community, and nowadays constitute a basic step for the preparation and manipulation of atoms in the quantum regime. Motivated by these achievements, there is an ongoing effort to realize the radiative cooling of molecules, optomechanical devices, plasmas, and condensed-phase systems, which has been leading to a remarkable progress across these fields.

Since molecular systems exhibit several additional degrees of freedom compared to atoms, cold molecules offer many new and exciting research perspectives, encompassing precision measurements, tests of fundamental physics theories and the control of inelastic and reactive collisions.

In recent years, several diatomic molecules have successfully been laser cooled, and nowadays, even the laser cooling of polyatomic molecules is possible. In parallel, other direct and indirect cooling methods have been developed further.

This symposium aims to showcase the recent advances in the field of cold molecules and to trigger discussions between the different divisions about new research perspectives which may soon be within reach.

Overview of Invited Talks and Sessions

(Lecture hall Audimax)

Invited Talks

SYCM 1.1	Fri	14:00–14:30	Audimax	**Collisions between laser-cooled molecules and atoms** — •Michael Tarbutt
SYCM 1.2	Fri	14:30–15:00	Audimax	**Trapped Laser-cooled Molecules for Quantum Simulation, Particle Physics, and Collisions** — •John Doyle
SYCM 1.3	Fri	15:00–15:30	Audimax	**Quantum-non-demolition state detection and spectroscopy of single cold molecular ions in traps** — •Stefan Willitsch
SYCM 1.4	Fri	15:30–16:00	Audimax	**Quantum state tomography of Feshbach resonances in molecular ion collisions via electron-ion coincidence spectroscopy** — •Edvardas Narevicius

Sessions

SYCM 1.1–1.4	Fri	14:00–16:00	Audimax	**Hot topics in cold molecules: From laser cooling to quantum resonances**

SYCM 1: Hot topics in cold molecules: From laser cooling to quantum resonances

Time: Friday 14:00–16:00 Location: Audimax

Invited Talk SYCM 1.1 Fri 14:00 Audimax

Collisions between laser-cooled molecules and atoms — •Michael Tarbutt — Centre for Cold Matter, Blackett Laboratory, Imperial College London, London SW7 2AZ, UK

Ultracold molecules can be used to test fundamental physics, simulate many-body quantum systems, process quantum information, and study ultracold chemistry. We capture CaF molecules in a magneto-optical trap (MOT) [1,2], cool them to a few microkelvin [3], trap them magnetically [4], and coherently control their rotational state [5,6]. To increase the phase-space density, we aim to sympathetically cool the molecules using ultracold atoms. For this purpose, we have developed a dual-species MOT for CaF and Rb. I will present our first studies of collisions between these two species in the MOT and in a magnetic trap.

[1] S. Truppe et al., Nature Physics 13, 1173 (2017) [2] H. J. Williams et al., New J. Phys. 19, 113035 (2017) [3] L. Caldwell et al., Phys. Rev. Lett. 123, 033202 (2019) [4] H. J. Williams et al., Phys. Rev. Lett. 120, 163201 (2018) [5] J. A. Blackmore et al., Quantum Sci. Technol. 4, 014010 (2019) [6] L. Caldwell et al., arXiv:1908.11839 (2019)

Invited Talk SYCM 1.2 Fri 14:30 Audimax

Trapped Laser-cooled Molecules for Quantum Simulation, Particle Physics, and Collisions — •John Doyle — Harvard University, Cambridge, USA

Due to the controllable complexity of cold polar molecules - in particular the body frame fixed electric dipole of polar molecules - they are a potentially powerful platform for quantum simulation. This has led to significant efforts to control molecules at the quantum level. We report on laser cooling and trapping of molecules and the creation of optical tweezer arrays of ultracold CaF molecules in a single quantum state. We have also conducted collision studies using optical tweezers, demonstrating the potential for exploring state-selective ultra-cold quantum chemistry on a molecule by molecule basis. These methods can be extended beyond diatomic molecules to polyatomic molecules, which have additional features that are advantageous for quantum computation and particle physics. For example, we have advanced a scheme for quantum computation using symmetric top molecules in optical tweezers. We will also discuss progress toward laser cooling of polyatomic molecules such as CaOH, YbOH, CaSH, and $YbOCH_3$, and their potential use in experiments, including precision searches for new particles (beyond the standard model) and quantum information.

Invited Talk SYCM 1.3 Fri 15:00 Audimax

Quantum-non-demolition state detection and spectroscopy of single cold molecular ions in traps — •Stefan Willitsch — Departement Chemie, Universität Basel, Klingelbergstrasse 80, 4056 Basel, Schweiz

Trapped atoms and ions are among the best controlled quantum systems which find widespread applications in quantum science. For molecules, a similar degree of control is currently lacking owing to their complex energy-level structure. Quantum-logic protocols in which atomic ions serve as probes for molecular ions are a promising route for achieving this aim, especially with homonuclear species that decouple from black-body radiation. In this talk, a quantum-non-demolition protocol on single trapped N_2^+ molecules is presented which enables the detection of the spin-rovibronic state of the molecule with more than 99% fidelity. The protocol is based on the state-dependent coherent motional excitation of the cold molecular ion and the subsequent detection of the motion by a co-trapped atomic ion. Utilising this scheme, we also demonstrate the measurement of spectroscopic transitions within the molecule without the need to destroy the initial molecular quantum state. The present method lays the foundations for new, non-invasive approaches to molecular spectroscopy, for studies of state-to-state chemistry on the single-particle level and for the implementation of molecular qubits.

Invited Talk SYCM 1.4 Fri 15:30 Audimax

Quantum state tomography of Feshbach resonances in molecular ion collisions via electron-ion coincidence spectroscopy — •Edvardas Narevicius — Weizmann Institute of Science, 76100 Rehovot, Israel

During collisions coupling between the relative and internal atomic and molecular degrees of freedom lead to the formation of Feshbach resonances. The large phase space volume that particles explore in this metastable scattering state supports interference between many different quantum channels that include inelastic and reactive processes. We present a new method that allows us to measure simultaneously all the quantum channels for the Feshbach resonances that appear in collisions between vibrationally excited H_2^+ ion and noble gas atoms. Our quantum state mapping is based on coincidence ion-electron velocity map imaging spectroscopy.