

# Symposium Quantum Optics and Quantum Information with Rigid Rotors (SYQR)

jointly organised by  
the Quantum Information Division (QI),  
the Quantum Optics and Photonics Division (Q), and  
the Molecular Physics Division (MO)

Klaus Hornberger  
Universität Duisburg-Essen

Melanie Schnell  
Deutsches Elektronen-Synchrotron DESY  
Hamburg

This symposium aims at highlighting the potential offered by the intrinsic anharmonicity and non-commutativity of quantum rigid rotor dynamics for future technologies. Note that the associated session MO18/Q52/Q133 takes place already on Thursday, 14:30–16:30, in F102.

## Overview of Invited Talks and Sessions

(Lecture hall E415)

### Invited Talks

SYQR 1.1	Fri	11:00–11:30	E415	<b>Femtosecond timed imaging of rotation and vibration of alkali dimers on the surface of helium nanodroplets</b> — ●HENRIK STAPELFELDT
SYQR 1.2	Fri	11:30–12:00	E415	<b>Quantum toolbox for molecular state spaces</b> — ERIC KUBISCHTA, SHUBHAM JAIN, IAN TEIXEIRA, ERIC R. HUDSON, WESLEY C. CAMPBELL, MIKHAIL LEMESHKO, ●VICTOR V. ALBERT
SYQR 1.3	Fri	12:00–12:30	E415	<b>Coherent rotational state control of chiral molecules</b> — ●SANDRA EIBENBERGER-ARIAS
SYQR 1.4	Fri	12:30–13:00	E415	<b>Optically levitated rotors: potential control and optimal measurement</b> — ●MARTIN FRIMMER
SYQR 2.1	Fri	14:30–15:00	E415	<b>Rotational optomechanics with levitated nanodumbbells</b> — ●TONGCANG LI
SYQR 2.2	Fri	15:00–15:30	E415	<b>Quantum rotations of nanoparticles</b> — ●BENJAMIN A. STICKLER
SYQR 2.3	Fri	15:30–16:00	E415	<b>Quantum control of trapped molecular ions</b> — ●STEFAN WILLITSCH
SYQR 2.4	Fri	16:00–16:30	E415	<b>Full control over randomly oriented quantum rotors: controllability analysis and application to chiral observables</b> — ●MONIKA LEIBSCHER

### Sessions

SYQR 1.1–1.4	Fri	11:00–13:00	E415	<b>Quantum Optics and Quantum Information with Rigid Rotors 1</b>
SYQR 2.1–2.4	Fri	14:30–16:30	E415	<b>Quantum Optics and Quantum Information with Rigid Rotors 2</b>

## SYQR 1: Quantum Optics and Quantum Information with Rigid Rotors 1

Time: Friday 11:00–13:00

Location: E415

**Invited Talk** SYQR 1.1 Fri 11:00 E415  
**Femtosecond timed imaging of rotation and vibration of alkali dimers on the surface of helium nanodroplets** — ●HENRIK STAPELFELDT — Aarhus University, Aarhus, Denmark

Dimers of sodium or potassium, residing on the surface of helium nanodroplets, are set into rotation and vibration, through the dynamic Stark effect, by a moderately intense femtosecond pump pulse. Coulomb explosion of the dimers, induced by an intense, delayed femtosecond probe pulse, is used to record the time-dependent nuclear motion.

Concerning rotation, the measured alignment traces show a distinct, periodic structure that differs qualitatively from the well-known alignment dynamics of linear molecules in either the gas phase or dissolved in liquid helium. Instead, the observed alignment dynamics of Na<sub>2</sub> and of K<sub>2</sub> agree with that obtained from a 2D rigid rotor model, strongly indicating that the rotation of each dimer occurs in a plane, defined by the He droplet surface.

Concerning vibration, the Coulomb explosion probe method enables us to measure the distribution of internuclear distances as a function of time. For K<sub>2</sub>, we observe a distinct oscillatory pattern caused by a two-state vibrational wave packet in the initial electronic state of the dimer. The wave packet is imaged for more than 250 vibrational periods with a precision better than 0.1 Å on its central position and a resolution < 1 Å of its shape. Unlike the rotational motion, the vibration of the dimer is essentially unaffected by the presence of the He droplet.

**Invited Talk** SYQR 1.2 Fri 11:30 E415  
**Quantum toolbox for molecular state spaces** — ERIC KUBISCHTA<sup>1</sup>, SHUBHAM JAIN<sup>1</sup>, IAN TEIXEIRA<sup>1</sup>, ERIC R. HUDSON<sup>2</sup>, WESLEY C. CAMPBELL<sup>2</sup>, MIKHAIL LEMESHKO<sup>3</sup>, and ●VICTOR V. ALBERT<sup>1</sup> — <sup>1</sup>Joint Center for Quantum Information and Computer Science, NIST and University of Maryland, College Park, MD, USA — <sup>2</sup>UCLA Center for Quantum Science and Engineering & Department of Physics and Astronomy, Los Angeles, California, USA — <sup>3</sup>Institute of Science and Technology Austria (ISTA), Am Campus 1, 3400 Klosterneuburg, Austria

Rotational states of symmetric- and asymmetric-top trapped molecules, modeled by infinite-dimensional Hilbert spaces of various quantized rigid bodies, present new opportunities for both the development of basic science and for the storage and processing of quantum information.

This work adapts basic quantum tools from established discrete- and continuous-variable systems to symmetric rigid bodies, developing a set of “position-state” labels for molecular orientations and a Pauli-type group of unitary operations. Our approach builds on the conjugate relationship between states of fixed angular momentum and fixed orientation and can be extended to incorporate nuclear spin.

We also study different types of noise present in molecular systems. We show that some noise can be highly non-local in the molecule’s orientation-momentum “phase” space, characterizing instances where conventional (i.e., exact) error-correction can fail. We comment on the different strategies that can circumvent this no-go result.

**Invited Talk** SYQR 1.3 Fri 12:00 E415  
**Coherent rotational state control of chiral molecules** — ●SANDRA EIBENBERGER-ARIAS — Fritz-Haber-Institut der Max-Planck-Gesellschaft, Berlin, Germany

Chiral molecules are ubiquitous in nature and they are of great importance in many biological and chemical processes. They are also at the center of some interesting fundamental physics questions, for example whether there is parity violation in chiral molecules, which has been long predicted but never experimentally observed.

I will present important recent experimental developments targeted at the understanding and the control of cold, chiral molecules in the gas phase. I will discuss enantiomer-specific state transfer (ESST) [1], an all-coherent method to populate a chosen rotational state preferentially with one enantiomer, providing a way of quantum-controlled chiral separation. In recent experiments [2,3], we realize increased control of chiral molecules. We employ a quantitative comparison between experiment and theory for the transfer efficiency of ESST. Straightforward extensions to our scheme will allow to create a molecular beam with an enantiomer-pure rotational level, holding great prospects for future spectroscopic and scattering studies.

[1] S. Eibenberger, J. Doyle, D. Patterson, *Phys. Rev. Lett.* 118, 123002 (2017) [2] A. O. Hernandez-Castillo, J. Bischoff, J. H. Lee, J. Langenhan, M. Karra, G. Meijer, and S. Eibenberger-Arias, *Phys. Chem. Chem. Phys.* 23, 7048-7056 (2021) [3] J. H. Lee, J. Bischoff, A. O. Hernandez-Castillo, B. Sartakov, G. Meijer, and S. Eibenberger-Arias, *Phys. Rev. Lett.* 128, 173001 (2022)

**Invited Talk** SYQR 1.4 Fri 12:30 E415  
**Optically levitated rotors: potential control and optimal measurement** — ●MARTIN FRIMMER — Photonics Laboratory, ETH Zürich, Switzerland

Optically levitated nanoparticles have attracted significant attention recently and especially their rotational degrees of freedom offer exciting opportunities for sensing and quantum physics. The quantum control recently achieved for the center-of-mass motion of a levitated scatterer is to be extended to the orientational degrees of freedom of anisotropic scatterers. In this talk, we address the problem of optimally detecting the librational degrees of freedom of an anisotropic dielectric scatterer. Furthermore, we discuss a method to tune the conservative potential governing the librational degrees of freedom in an optical focus while keeping the center-of-mass motion trapped.

## SYQR 2: Quantum Optics and Quantum Information with Rigid Rotors 2

Time: Friday 14:30–16:30

Location: E415

**Invited Talk** SYQR 2.1 Fri 14:30 E415  
**Rotational optomechanics with levitated nanodumbbells** — ●TONGCANG LI — Purdue University, West Lafayette, USA

Thanks to its geometry, an optically levitated nanodumbbell is ideal for studying rotational optomechanics. We have synthesized and optically levitated silica nanodumbbells in a high vacuum. With a linearly polarized laser, we observed the torsional vibration (liberation) of a levitated nanodumbbell. With a circularly polarized laser, we drove a nanodumbbell to rotate beyond 1 GHz. We show an optically levitated nanodumbbell is an ultrasensitive torque detector. Recently, we levitated a nanodumbbell near a surface to study surface interactions.

**Invited Talk** SYQR 2.2 Fri 15:00 E415  
**Quantum rotations of nanoparticles** — ●BENJAMIN A. STICKLER — University of Duisburg-Essen, Duisburg, Germany

Rotations of rigid bodies exhibit pronounced quantum phenomena that do not exist for their center-of-mass motion. By levitating nanopar-

ticles in ultra-high vacuum, researchers are developing a promising platform for observing and exploiting these quantum effects in an unexplored mass and size regime [1]. This talk will discuss the prospects of observing orientational quantum revivals [2], quantum tennis racket flips [3], and spin-controlled interference [4] with nanoscale particles. I will review how rotational cooling into the quantum regime can be achieved [5] and how environmental decoherence impacts quantum experiments with nanoscale rotors [6].

[1] Stickler, Hornberger, and Kim, *Nat. Rev. Phys.* 3, 589 (2021) [2] Stickler, Papendell, Kuhn, Millen, Arndt, and Hornberger, *New J. Phys.* 20, 122001 (2018). [3] Ma, Khosla, Stickler, and Kim, *Phys. Rev. Lett.* 125, 053604 (2020). [4] Rusconi, Perdriat, Hétet, Romero-Isart, and Stickler, *Phys. Rev. Lett.* 129, 093605 (2022). [5] Schäfer, Rudolph, Hornberger, and Stickler, *Phys. Rev. Lett.* 126, 163603 (2021). [6] Stickler, Papendell, and Hornberger, *Phys. Rev. A* 94, 033828 (2016).

**Invited Talk** SYQR 2.3 Fri 15:30 E415

**Quantum control of trapped molecular ions** — ●STEFAN WILLITSCH — University of Basel, Department of Chemistry, Klingelbergstrasse 80, 4056 Basel, Switzerland

Molecules are quantum systems of prime significance in a variety of contexts ranging from physics over chemistry to biology. In spite of their importance, the development of quantum technologies for molecules has remained a long-standing challenge due to their complex energy-level structures. Trapped molecular ions are particular attractive in this context as it is possible to observe, manipulate and control single isolated molecules under precisely controlled conditions. In the talk, we will highlight new experimental methods for the detection, preparation and manipulation of the quantum states of single trapped molecular ions and discuss applications of these techniques in the realms of precision molecular spectroscopy, quantum science and chemistry.

**Invited Talk**

SYQR 2.4 Fri 16:00 E415

**Full control over randomly oriented quantum rotors: controllability analysis and application to chiral observables** —

●MONIKA LEIBSCHER — Dahlem Center for Complex Quantum Systems and Fachbereich Physik, Freie Universität Berlin, Berlin, Ger-

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Full quantum control over randomly oriented molecules requires complete breaking of the rotational symmetry by external fields. We present a graphical method to analyze the controllability of quantum asymmetric tops and determine the number, polarization and frequencies of the external fields which are required to fully control the rotational dynamics [1,2]. The results of the controllability analysis allow us to design pulse sequences which drive the molecules to the desired target states. We apply this strategy to observe and control chiral properties in randomly rotating molecules [1]. As an example, we discuss the creation of chiral wavepackets in achiral molecules. Planar molecules can become temporarily chiral upon coherent excitation of the out-of-plane vibration [3]. With the help of controllability analysis, we identify different excitation schemes that result in a net chiral signal and simulate the resulting ro-vibrational dynamics.

[1] M. Leibscher, E. Pozzoli, C. Pérez, M. Schnell, M. Sigalotti, U. Boscain, C. P. Koch, *Commun. Phys.* 5, 110 (2022). [2] E. Pozzoli, M. Leibscher, M. Sigalotti, U. Boscain and C. P. Koch, *J. Phys. A: Math. Theor.* 55, 215301 (2022). [3] D. S. Tikhonov, A. Blech, M. Leibscher, L. Greeman, M. Schnell, and C. P. Koch, *Science Advances* in press (2022).