CHEMICAL REVIEWS

Editorial

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Introduction to Ultracold Molecules: New Frontiers in Quantum and Chemical Physics

Molecules cooled to ultralow temperatures provide fundamental new insights to molecular interaction and reaction dynamics in the quantum regime. In recent years, researchers from various scientific disciplines such as atomic, optical, and condensed matter physics, physical chemistry, and quantum science have joined force to explore many emergent and exciting research topics that are enabled by cold molecules, including cold chemistry, strongly correlated quantum systems, novel quantum phases, and precision measurement. This thematic issue provides a set of comprehensive reviews on this increasingly active and important research field, covering recent developments such as experimental techniques for preparing cold molecular gases, implementation of control for both internal and external molecular degrees of freedom, theory frameworks to describe molecular interactions and manipulation, and future outlook for many-body quantum physics and chemistry.

Building on the strong tradition of molecular beams in both physics and chemistry communities, researchers working on cold molecules have made steady advances in lowering the temperature of the beam and manipulating the beam for novel applications. In the paper "The buffer gas beam: An intense, cold, and slow source for atoms and molecules" by Hutzler, Lu, and Doyle, the authors provide a comprehensive review of the state-of-the-art in buffer gas cooling, which is fundamentally different from supersonic expansion-based cooling and can bring the temperature of a molecular sample to a few Kelvins in the lab rest frame. Another extremely powerful approach takes advantage of the capability in controlling the motion of neutral molecules via inhomogeneous electric or magnetic fields. In the review "Manipulation and control of molecular beams" by van de Meerakker, Bethlem, Vanhaecke, and Meijer, an authoritative description is provided of the molecular Stark decelerator and its application to a variety of pioneering experiments. The underlying design principles for the decelerator and a careful treatment of the interaction of molecules with electric fields is given, leading to elucidating discussions on the control of molecular packets in both position and velocity spaces, as well as the trapping of molecules in the laboratory frame. Similarly, based on the interaction of molecules with inhomogeneous magnetic fields, Narevicius and Raizen describe how molecular motions can be manipulated with magnetic fields in their review "Towards cold chemistry with magnetically decelerated supersonic beams". The unique capability of magnetic deceleration for both atoms and molecules greatly facilitates investigations of important atom−molecule collisions and reactions at low energies.

These powerful techniques have allowed a large variety of molecules to be brought to a few tens of milliKelvin or even a few milliKelvin and have enabled applications ranging from novel molecular scattering studies at low collision energies to high-resolution spectroscopy. The samples of cold molecules that are produced via these molecular beam technologies also provide excellent starting conditions for further cooling of molecules, with current experimental efforts exploring possibilities such as laser cooling and direct molecular evaporation.

In a completely different approach, atoms are cooled to ultralow temperatures and then brought together to form cold molecules via magneto-association or photoassociation or a combined process. In their review "Ultracold molecules formed by photoassociation: Heteronuclear dimers, inelastic collisions, and interactions with ultrashort laser pulses", Ulmanis, Deiglmayr, Repp, Wester, and Weidemüller discuss the methodology, benefits, and challenges in photoassociation of molecules out of ultracold atomic gases. To form a molecule from a pair of free atoms requires detailed theoretical knowledge of the interaction properties of the colliding atomic pair and the energy level structure of the target molecule and precise experimental control of optical and magnetic fields. This approach has produced some of the coldest samples of molecules in their ground state. Koch and Shapiro in their review of "Coherent control of ultracold photoassociation" provide an excellent discussion of fundamental concepts in coherent control in the context of producing cold molecules via photoassociation using adiabatic passage and spectrally shaped ultrashort laser pulses. These theoretical insights play an important role in improving the molecule production efficiency in experiment. By combining magnetoassociation and stimulated Raman adiabatic passage, the field has finally witnessed the production of ultracold molecules that are at the verge of quantum degeneracy. The precise control of both the internal and external degrees of freedom in a molecule has enabled the first experiments of ultracold chemistry where all degrees of freedom of the colliding species are controlled and quantized, including vibration, rotation, electron and nuclear spin, orientation, and translation. Quéméner and Julienne title their review "Ultracold molecules under control!" to emphasize this new scientific realm. Their paper provides an overview of theoretical tools that are being developed to treat the interactions, collisions, and reactions of ultracold molecules in the quantum regime, where the de Broglie wavelength of the colliding molecules is much larger than the typical range of chemical interactions. The intrinsic quantum dynamics of collisions thus becomes highly sensitive to weak long-range interactions that can be brought under experimental control.

An important scientific direction with ultracold molecules is the study of strongly correlated many-body quantum systems. Baranov, Dalmonte, Pupillo, and Zoller provide a review of this topic in "Condensed matter theory of dipolar quantum matter". The connections and differences between quantum gases of dipolar molecules and traditional condensed-matter systems are explained, highlighting the inherent interdisciplinary nature of

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these studies. Covering many recent theoretical developments on the study of dipolar many-body quantum systems, the authors discuss both the mean-field treatment for dipolar Bose–Einstein condensates and dipolar paired-fermion superfluids and the many-body analysis of strongly correlated dipolar gases in optical lattices and low-dimensional geometries. Finally, study of novel collision and reaction dynamics in the ultralow energy range is now opening a new chapter for quantum chemistry. Nesbitt provides some unique physical chemistry perspectives for the field of ultracold molecules in his review of "Toward state-to-state dynamics in ultracold collisions: Lessons from high-resolution spectroscopy of weakly bound molecular complexes". One of the most important goals in ultracold molecules research is to enable investigation of the most fundamental dynamics in the breaking and making of chemical bonds, under full control of both the internal and external quantum states of the molecules. Nesbitt provides an elegant connection between high-resolution molecular spectroscopy and ultracold collisional dynamics, where the wealth of high-resolution spectral signatures in weakly bound complexes permits access to collision and chemically reactive dynamics arising from pure quantum states of the complex, thus offering important insight and intuition into the dynamics of ultracold collisional processes.

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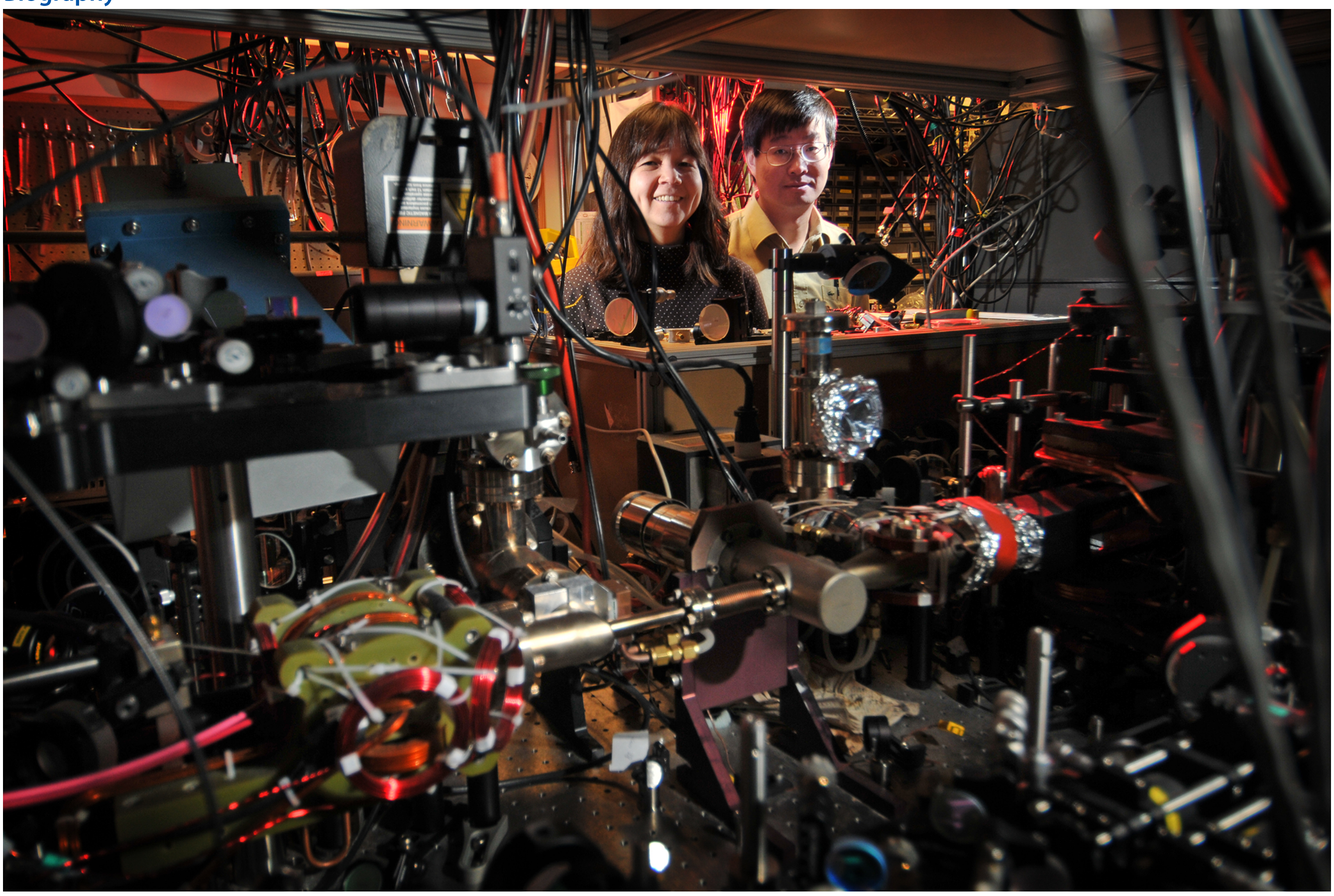
Biography



Deborah Jin (left) is an experimental physicist who studies ultracold quantum gases at JILA in Boulder, Colorado. She is a NIST Fellow, a JILA Fellow, and an Adjoint Professor of Physics at the University of Colorado. Dr. Jin is a member of the National Academy of Sciences and has received a MacArthur fellowship, the Benjamin Franklin Medal in physics, and Sigma Xi's William Proctor Prize for Scientific Achievement. Her research interests include experimental investigation of ultracold Fermi gases, the creation and exploration of an ultracold gas of polar molecules, and studies of strongly interacting Bose–Einstein condensates.

Jun Ye (right) is a Fellow of JILA, the National Institute of Standards and Technology and the University of Colorado. He is also a Fellow of NIST, a Fellow of the American Physical Society, a Fellow of the Optical Society of America, and a member of the National Academy of Sciences. His research focuses on the frontier of light-matter interactions and includes precision measurement, quantum physics and cold matters, optical frequency metrology, and ultrafast science and quantum control. Awards and honors include Frew Fellowship from the Australian Academy of Science, I. I. Rabi Prize from the American Physical Society, European Frequency and Time Forum Award, Carl Zeiss Research Award, William F. Meggers Award and Adolph Lomb Medal from the Optical Society of America, Arthur S. Flemming Award, Presidential Early Career Award for Scientists and Engineers, U.S. Commerce Department Gold Medals, Friedrich Wilhem Bessel Award from Alexander von Humboldt Foundation, and Samuel Wesley Stratton Award from NIST. His research group's web page is http://jila.colorado.edu/YeLabs/.

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