Combining Ultrafast and Ultracold

Ronnie Kosloff[1]

[1] *Department of Physical Chemistry and The Fritz Haber Research Center, The Hebrew University, Jerusalem 91904, Israel*

Atoms and molecules at temperatures below one milli-Kelvin can only be understood as quantum mechanical objects - they represent the extreme quantum limit. At these temperatures quantum interference effects are not washed out by thermal averaging, the state of matter is almost pure and well characterized. For this reason ultracold matter becomes an ideal candidate for coherent control which relies on interferences between matter waves. Such conditions make experiment and theory converge allowing a direct test of controllability.

Ultrafast: The wave particle duality is a corner-stone of the interpretation of physical reality. Coherent control has emerged from the appreciation of the wave nature of matter. In a nutshell, coherent control employs constructive interference to steer the outcome of a dynamical process to a desired one while suppressing undesired outcomes by destructive interference. Formulated in the time domain, a coherent control process starts from an initial quantum state and then an external field is employed to direct the system to a final quantum state. Impressive progress has been achieved experimentally using shaped femtosecond electromagnetic fields in state-to-state coherent control employing adoptive feedback control. The challenge is to find mechanisms of control where interference plays a crucial role.

Ultracold: The capability to cool matter to temperatures very close to the absolute zero is one of the hottest topics in contemporary physics. Such forms of matter exist in the extreme quantum regime where the de Broglie wavelength of a single atom can extend to macroscopic dimensions. When the wavelength of the atoms exceeds the average inter-atomic separation their individual identity is lost. This is the source of macroscopic quantum effects such a Bose-Einstein condensation (BEC) and Fermi degeneracy. The phenomenon is not limited to atoms. Ultracold molecules have been produced from cold atoms through photoassociation and from an atomic condensate by Feshbach resonances. Ultracold ion-molecule chemical reactions have been reported in laser cooled Coulomb crystals in ion traps.

These chemical phenomena are the twilight of the dawn of a new era of Ultracold Chemistry. The quantum nature of cold matter requires novel tools of chemical synthesis, naturally leading to coherent control as the basic synthetic scheme. Existing methods for synthesizing molecules from ultracold atoms suffer from the fact that the molecules are created in highly excited vibrational level, in some cases in the very last bound level of the potential well. The fragile nature of these molecules makes them very unstable to external perturbations and collisions. Frequently such events destroy the condensate phase leading to trap loss. Ultracold chemistry means therefore a synthetic method which can stabilize the product. In the traditional thermal chemistry the products are stabilized by dissipative forces supplied by the interaction with the surrounding thermal bath. In coherent ultracold chemistry either the molecules should be created in the ground stable level in the first place or other means of stabilization need to be found. An example is stabilization by spontaneous emission which can be considered as an interaction with the radiation bath.

Ultracold atoms and molecules represent the extreme quantum limit and are therefore ideal candidates for coherent control which relies on making use of quantum interferences. Optimal control theory can be employed to find non-intuitive mechanisms for the process of interest such as molecule formation. The cold matter condition, define an extremely well defined initial state for coherent control. Progress in the field has been hampered by averaging on undefined initial conditions which reduce the visibility of the interference required to achieve control. Under ultracold conditions compose ideal conditions to compare theory and experiment.

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