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Laser cooling, slowing and trapping of a diatomic molecule

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Roughly three decades ago, laser cooling and trapping succeeded in producing ultracold ions and atoms, sparking a revolution in atomic physics and subsequently becoming workhorse techniques within the field. These techniques require a "cycling transition," where the particle of interest is repeatedly driven by a photon into an excited electronic state and quickly decays back to the initial ground state, allowing the process to repeat. Because photon absorption transfers momentum to the particle, application of force is possible. Adjusting the geometry and frequency of the applied photons allows creation of a damping (cooling) force. Further addition of a quadrupole magnetic field allows for a restoring (trapping) force. Prior to this thesis, straightforward extension of these methods to molecules was considered a practical impossibility; electronic decays in molecules tend to populate multiple rotational and vibrational states, preventing creation of a cycling transition. While a variety of ultracold molecular species is desirable to satisfy a range of applications, the only other production method is limited to species where the constituent atoms are themselves amenable to laser cooling. For other species, a different technique is required. Here we outline the methods and experiments in which laser cooling and trapping were first applied to molecules. By careful molecule choice, by using a cooling transition that exploits selection rules, and by counteracting dark states with a magnetic field, we create a cycling transition for the diatomic molecule strontium monofluoride (SrF). We show the power of this technique by demonstrating Doppler and sub-Doppler cooling in 1-D, radiation pressure slowing and stopping of a molecular beam, and finally a 3-D magneto-optical trap (MOT). Our MOT produces the coldest trapped sample of directly-cooled molecules to date, with a temperature of T $\sim$ 2.5 mK. This method is viable for several classes of diatomic molecules with a variety of energy level configurations. This work should allow advances in a range of ultracold molecule applications, from precision measurements to quantum information and quantum simulation, to studying ultracold chemical reactions.