Laser Cooling of Molecules for Precision Tests of Fundamental Symmetries

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Molecules are emerging as powerful platforms for precision measurement science, offering unique sensitivity for high-resolution spectroscopy and tests of fundamental symmetries. These experiments can probe energy scales and interactions that complement searches at high-energy collider facilities, opening new avenues for discovering physics beyond the Standard Model in previously unexplored regimes.

Achieving the required level of control over molecules demands precise manipulation of both internal quantum states and external motion, as well as long coherence times. Laser cooling provides a versatile route to meet these requirements [1].

While well-established techniques enable control over molecular vibrational and rotational degrees of freedom, extending laser cooling to heavy species remains challenging. In particular, complex hyperfine structures arising from multiple nuclear spins significantly complicate the realization of efficient optical cycling. Yet it is precisely these heavy, complex molecules that are especially promising candidates for searches for nuclear parity and time-reversal violation.

In this talk, I will introduce novel laser-cooling strategies designed to address these challenges [2,3]. I will present experimental implementations of these techniques and their application to several isotopologues of barium monofluoride (BaF) [4], and discuss their scalability and prospects for cooling other molecular species - including radioactive ones - relevant to precision tests of fundamental symmetries [5,6]. Finally, I will outline a new experiment based on laser-cooled BaF molecules aimed at probing nuclear-spin-dependent parity violation and the weak interaction.

References

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