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Cold and ultracold molecules

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Atomic physics was radically transformed by the ability to produce and manipulate cold and ultracold atoms. Achieving ultralow temperatures has led to many breakthroughs — from realizing long-sought phases of matter to the world's most precise clocks. Pivoting on this progress, exploring the possibilities offered by cold and ultracold molecules emerged as a natural next step. With this Insight, we showcase recent advances in this field, which not only deepen our understanding of fundamental physics and chemistry but also propel the development of new quantum applications.

Compared to atoms, molecules are vastly more complex. Their additional rotational, electronic and vibrational degrees of freedom generate intricate internal structures, making the direct application of cooling and trapping techniques that worked for atoms challenging. But as Tim Langen et al. describe in their Review, researchers have come a long way in refining approaches for the efficient preparation and control of ultracold molecular gases.

Thanks to their complex internal structure, cold and ultracold molecules are promising platforms for probing fundamental physics, including symmetry violations and extensions to the Standard Model — as David DeMille et al. explain. Long lifetimes and low field sensitivity also make them candidates for a new generation of clock devices.

Unlike most atoms, polar molecules possess long-range dipole–dipole interactions that can be controlled by external electric fields. Simon Cornish et al. discuss how, combined with the properties of rotational states, this offers the opportunity to explore the physics of interacting spin models that are outside the reach of atomic-based quantum simulators.

Lastly, quantum gases of molecules and molecular ions provide a unique source of collisions and chemical reactions at cold and ultracold temperatures. Tijs Karman et al. turn the spotlight on the power of theory to predict directions in ultracold chemistry research, whereas Markus Deiß et al. provide an overview of recent experimental progress, focusing on cold molecular ions and hybrid atom–ion platforms.

After decades of efforts, the time appears ripe for cold and ultracold molecules to assume a key role in the landscape of emergent quantum technologies, while continuing to improve our understanding of fundamental physical and chemical phenomena. This Insight is a testament to that.

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