Quantum Disappearance of a Bose-Einstein Condensate

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As the coldest form of matter known to exist, atomic Bose-Einstein condensates are unique forms of matter where the constituent atoms lose their individual identities, becoming absorbed into the cloud as a whole. Effectively, these gases become a single macroscopic object that inherits its properties directly from the quantum world.
In a paper accepted by *Physical Review Letters* (cond-mat/0412738), Massachusetts Institute of Technology physicists George E. Cragg and Arthur K. Kerman describe the quantum properties of a unique kind of condensate where the atoms have an enhanced propensity to pair, thereby leading to a molecular character which coexists with the atoms.

Remarkably, the addition of this molecular component is found to induce a quantum instability that manifests itself as a collective decay of the gas as a whole. Being a purely quantum mechanical effect, there exists no mechanical picture illustrating this process. Consequently, the results presented by MIT researchers can serve as a model for other condensed matter systems that have similar underlying physics.

Since their experimental creation in 1995, atomic Bose-Einstein condensates have generated much excitement as the coldest form of matter known. Equally appealing, is the notion that these are singular macroscopic objects, whose properties are directly inherited from the microscopic quantum world. Recently, new hybrid condensates have been realized where the atoms exhibit an increased propensity to pair, thereby creating a coupling to a second condensate component consisting of molecules. Known as a Feshbach resonance, this pairing phenomenon can be externally controlled by the Zeeman effect using an applied magnetic field. Since the appearance of these molecules effectively alters the interatomic interactions, experimentalists have a direct handle on the interparticle forces in the assembly.

For sufficiently dilute, low-temperature systems, the microscopic potentials are characterized by the s-wave scattering length, which is positive for repulsion but negative for attraction. Above some critical atom number, condensation is impossible for species with innately negative scattering lengths as the resulting attraction renders the collective unstable against collapse. However, utilizing a Feshbach resonance to tune the scattering length to a positive value can manifest a stable condensate. Although this intuition has been backed by experiment, a full many-body analysis of the coupled atom-molecule system reveals a much richer physical picture.

In this work, physicists find that in spite of being tuned to the positive scattering length regime, the hybrid system admits a ground state that retains the inherent instability against collapse, implying that the experiment must represent an excited state. Through the analysis, it is found that this excited state has a complex-valued chemical potential, quantifying its time of decay into collective phonon excitations of the collapsing ground state. In addition to these interpretational aspects of the work, there exist much broader implications within the context of existing physical theories.

From his pioneering work on quantum electrodynamics, Julian Schwinger predicted that a constant, uniform electric field would polarize the vacuum, creating electron-positron pairs leading to the destruction of the field that initially created them. Drawing from this observation, researchers demonstrated that such an instability may also arise in coherently coupled atom-molecule systems, with the atomic condensate serving as the analog of the electric field. Concomitantly, the statistical mechanics definition of the chemical potential has been generalized to include complex values as well, where the imaginary part indicates a coherent many-body decay while the real part assumes the standard interpretation. Also, there could be further application in condensed matter bosonic systems described by a similar coherent coupling structure. Most importantly, this theory predicts novel decay rate dependencies, on both the full scattering length as well as on the density, that can be experimentally tested.

Publication: Complex chemical potential: Signature of decay in a Bose-Einstein condensate, George E. Cragg and Arthur K. Kerman, to be published in *Physical Review Letters*.

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