Rydberg Electrons in a Bose-Einstein Condensate

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Impurities in a Bose-Einstein condensate (BEC) have attracted much attention and motivated the investigation of a wide range of phenomena e.g., probing the superfluid dynamics or polaron physics in BECs.

In this presentation, we explore Rydberg atoms immersed in a homogeneous BEC, as sketched in Fig. 1(a). Within the s-wave approximation, the interaction between the quasi-free Rydberg electron and a ground state atom at $r$ can be approximated the effective interaction

$$V_R(r) \approx \frac{2\pi\hbar^2 A_s}{m_e} \left| k(r) \right| |\Psi_e(r)|^2,$$

which leads to an attraction for $A_s < 0$. The electron density $|\Psi_e(r)|^2$ and corresponding oscillatory potential are sketched in Fig. 1(b) for a Rydberg $ns$ state.

The interaction of Rydberg electrons with BEC atoms results in collective excitations (phonons). Phonon exchange leads to a Yukawa potential

$$V_Y(r - r') = -\tilde{Q}^2 e^{-|r-r'|/\xi}/|r-r'|,$$

where its range $\xi$ is the BEC healing length, and $\tilde{Q}$ its “effective charge”. Under appropriate conditions, we find two regimes [1]: for a small $\xi$, the Yukawa potential is short-ranged, and distorts the BEC locally, “mapping” the electron density onto the BEC density. Fig. 2 shows the BEC density distortion for different BEC scattering length $a_B$. For a large $\xi$, the Yukawa potential is long-ranged and the electron wave function is “averaged” out. However, because of the small mass of the electron, the effective charge $\tilde{Q}^2 \approx 4\pi\hbar^2 a_e^2 \rho_B m_B/m_e^2$ can give a large enough attractive Yukawa interaction able to bind Rydberg atoms and form a new type of “ultra-long-range” molecule. We discuss the conditions leading to such bindings, and how such “synthetic” Coulomb potentials can be generated between neutral particles and their sign can be modified by using different Rydberg states for the two impurity atoms.