Mesoscopic molecular ions in Bose-Einstein condensates

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We study the possible formation of large (mesoscopic) molecular ions in an ultracold degenerate bosonic gas doped with charged particles (ions). We show that the polarization interaction $-C_4/2r^4$ can lead to the capture of large numbers of atoms into weakly bound states, resulting in the rapid formation of mesoscopically large molecular ions. We study the spontaneous dynamics of the molecular ion formation and describe the evolution of the number of atoms $N_v$ in the bound level $v$ of the polarization potential by (see Fig. 1a)

$$\frac{dN_v}{dt} = W_v^{\text{cap}}(N_v + 1) - (W_v^{\text{down}} + W_v^{\text{up}})N_v,$$

(1)

where $W_v^{\text{cap}}$ is the capture rate from the condensate, and $W_v^{\text{down}}$ and $W_v^{\text{up}}$ are the loss rates to more deeply bound states and back to the condensate, respectively. The degenerate nature of the condensate and the properties of collective excitations (phonons) lead to

$$W_v^{\text{cap}} = \frac{4\mu_e\xi(\sqrt{1+\xi^2} - \xi)^{3/2}}{h} \left[ 1 + \left( \frac{\sqrt{1 + \xi^2} - \xi}{\sqrt{1 + \xi^2}} \right)^2 \right] (n_{q_0} + 1),$$

(2)

with $\xi = 8\pi a_0^2 a$ for an infinitely massive ion, where $\mu_e$ is the chemical potential, and $a$ and $a_0$ are the atom-atom scattering length and the extent of the bound wavefunction, respectively.

As $N_v$ increases, the level $v$ is pushed up, and thermal equilibrium is reached when its binding energy $\sim k_B T$, at which point $W_v^{\text{cap}} = W_v^{\text{up}}$ (see Fig. 1b). For a sodium ion (Na$^+$) in a sodium condensate with $n \sim 10^{14}$ cm$^{-3}$ and $a = 52 a_0$, and using $a_0 \sim 2000 a_0$ [1], we obtain $\xi \sim 0.066$, and neglecting $n_{q_0}$, $W_v^{\text{cap}} \sim 600$ s$^{-1}$. At thermal equilibrium, $N_v \sim 600$.

Beside the fundamental interest of studying the formation of such large many-body objects, the effects described here may open up new ways to manipulate cold atoms.

![Diagram](image)

Figure 1: In (a), diagram of atom capture by an ion. In (b), $W_v^{\text{cap}}$ as a function of $\xi$ for various $a_e$. The equilibrium points for Na and Rb at 10 nK are also shown.