Bose polarons at finite temperature and strong coupling

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Introduction

Mobile impurities in a quantum bath play a fundamental role in a wide range of systems including metals, semiconductors, Helium mixtures, and high-$T_c$ superconductors. The case of impurities in a Fermi sea is by now relatively well understood (see, e.g., the recent $[1,2]$, and refs. therein).

Recently, two experimental groups embedded impurities in a Bose-Einstein condensate (BEC) and observed long-lived quasiparticles coined Bose polarons $[3,4]$. On general grounds, the properties of Bose polarons should depend significantly on temperature, since the low-energy density of states in a Bose gas changes dramatically below the BEC transition.

Indeed, we show that the attractive polaron fragments into two quasiparticles for $0<T<T_c$, whenever $\omega_0 \gtrsim m_B$.

The upper quasiparticle disappears at $T_c$, while the lower one remains well-defined across the critical temperature.

System

- A single impurity of mass $m$
- Bath: bosons of mass $m_B$, density $n_0$, and temperature $T$
- $\hbar k_B = 1$
- Momenta and energies in units of $E_0 = k_B^2/2m_B$
- Weakly-interacting bath ($\omega_0 \ll k_B T < 1$)
- Impurity-bath scattering length: $a$
- Spectrum at $T=0$:

Model

- Bath treated with Bogoliubov theory
  - Critical temperature: $\omega_c = \frac{\pi}{2k_B T} \left[ \frac{\hbar^2 k_B}{2m_B} \right]^{1/2}$
  - Condensate density: $n_0 = \langle 1 - (T/T_c)^{1/2} \rangle$
- Bath chemical potential: $\mu_B = T \rho_B n_0$
- Bath scattering matrix: $\rho_B = 4a^2 n_0 / m_B$
- Dispersion of the excitations: $E_B = k_B^2 (\omega_k^2 + 2\mu_B)$
- Free bosons: $\omega_k^2 = k^2 / 2m_B$
- Impurity-bath coupling treated non-perturbatively by means of finite temperature Green’s functions.
- Polaron energy: $\omega_p = \omega_c + \text{Re}[\Sigma(\omega_p)]$
- Polaron residue: $Z_p = \frac{1}{1 - \partial_\omega \text{Re}[\Sigma(\omega_p)] / \omega_p}$

Extended ladder approximation

- Impurity Green’s function ($\Sigma(\omega_p)$)
- Ladder T-matrix: $T^L(p_{\perp},\omega_p) = T^L_c(p_{\perp},\omega_p)$
- Extended T-matrix: $T^E(p_{\perp},\omega_p) = T^E_c(p_{\perp},\omega_p) - \Sigma(p_{\perp},\omega_p)$
- Extended self-energy: $\Sigma(p_{\perp},\omega_p) = \int \frac{dp_{\parallel}}{(2\pi)^d} G(p_{\perp}^0,\omega_p) \Sigma(p_{\perp}^0,\omega_p)$

The attractive polaron(s) fragments into two quasiparticles for $0<T<T_c$.

- Weak attraction: $\langle h_0 \alpha = -1 \rangle$
- Unitarity: $\langle h_0 \alpha = 0 \rangle$

Attractive polaron(s) across the Feshbach resonance

- $T=0$
- $T=0.5 T_c$
- $T=T_c$

Understanding fragmentation

- Weak coupling, low temperature behavior of $\Sigma$: $\Sigma(\omega,\alpha) = N V_0$, $V_0 = 0$ and $\Sigma(\omega,\alpha = 0)$
- $\Sigma(\omega,\alpha = 0)$: single polaron on the right $T=0$
- $\Sigma(\omega,\alpha)$: equal splitting $T=0$
- $\Sigma(\omega,\alpha)$: dressed propagator inside $\Sigma$

Repressive polarons

- At this level of approximation, in a neighborhood of $T_c$ the repulsive polaron is replaced by a very broad peak centered at $\alpha = 0$

- The continuum however should start at the energy of the repulsive polaron; self-consistent theory is needed…

Outlook and conclusions

- Upon increasing the temperature, the attractive polaron present at $T=0$ fragments into two quasiparticles
- Purely non-perturbative effect, due to the presence of a dressed propagator inside $\Sigma$
- Physically, the effect arises due to the large low-energy density of states available at small $k_B T$ and finite $T$
- The fragmentation should be observable in state-of-the-art experiments
- Open question: does the fragmentation of the attractive polaron at $T>0$ arise also in lower dimensions?

References


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Source: Jørgensen et al., Ref. [3]