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Josephson effect in coherent roton aggregates

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A localized microwave electromagnetic field in liquid helium behaves as a laser of rotons: it produces a coherent roton aggregate. We show that the whispering gallery mode of the dielectric resonator excites multiple coherent aggregates simultaneously and predict a Josephson effect between them. The superfluid velocity around the resonator acts as a "voltage across the weak link" in superconducting Josephson junctions. Josephson frequency-velocity relation agrees with existing experimental data.

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Possibilities for the Bose–Einstein condensation of rotons have been discussed in literature since 1980 [1–3]. Such state comprises a coherent aggregate of rotons with equal and finite momentum. Unfortunately the equilibrium Bose–Einstein condensation of single rotons has not yet been observed experimentally. It was shown earlier [4, 5] that certain existing experiments [6] can be interpreted as formation of another macroscopically coherent non-equilibrium state with high occupation number of roton pairs. The Coherent Aggregate of Roton Pairs (CARP) is excited around a dielectric resonator by an electromagnetic field in the microwave range. Experimentally, the CARP build-up manifests [6] as an ultra-narrow peak in the resonator loss at the frequency of $f_0 = \Delta/(2\pi\hbar) \sim 180\,\mathrm{GHz}$, where Δ is the roton energy gap. The coupling of the microwave radiation to the CARP is due to the dependence of individual roton energy ε on the electric field $\mathbf{E}(t)$:

$$\delta\varepsilon \sim \alpha\frac{E^2}{2},$$

where α is the roton polarizability. Elementary process of such parametric excitation is the transformation of two photons into two rotons. This process resembles the parametric laser operation in optics [7] and justifies the name "laser of rotons".

For each elementary act the energy of the photon pair $4\pi\hbar f$ in the initial state is equal to the energy of the roton pair $2\varepsilon = 2\Delta$. The photon momentum was earlier [5] neglected because it is much smaller than that of a roton. This momentum is in fact responsible for an interesting effect described below.

An electromagnetic field in a whispering gallery disk resonator is a superposition of two traveling modes – a counterclockwise wave and a clockwise wave. The azimuthal projection of the wave vector for these modes is

$$k = \pm\frac{N}{R},$$

where R is the resonator radius and N is the mode number. The azimuthal momentum of the roton pair may therefore take one of three possible values:

$$p_- = -\frac{2\hbar N}{R},\quad p_0 = 0,\ \text{or}\ p_+ = \frac{2\hbar N}{R}.$$

This means that three CARPs are excited by the parametric resonance rather than just one. Suppose a weak interaction exists between these coherent particle reservoirs. The internal Josephson effect is to be expected in such system. The Josephson currents between the CARPs would be determined by the phase differences between them.

Roton pairs of different azimuthal momenta in a motionless liquid have equal energy 2Δ. This degeneracy may be removed by a superfluid velocity v_s. Imagine an axially symmetric vortex superflow tangential to the disk circumference. The energy of the roton pair then becomes

$$2\varepsilon_{\{-,0,+\}} = 2\Delta + v_s p_{\{-,0,+\}}.$$

Note that v_s here is not arbitrary; it depends on the number of quantized vortices n pinned by the resonator:

$$v_s = \frac{n\hbar}{Rm_{\mathrm{He}}}.$$

The time-dependent parts of the phase differences are simply $\Omega_n t$ and $2\Omega_n t$, where

$$\Omega_n = \frac{v_s p_+}{\hbar} = \frac{2\hbar N n}{R^2 m_{\mathrm{He}}} = 2\pi n\cdot 0.0043\,\mathrm{Hz}. \qquad (1)$$

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Here, $R = 9.5\,\mathrm{mm}$ and $N = 78$ (see [8]). With the frequency Ω_n both the Josephson currents and CARPs population oscillate. The latter is directly probed in microwave experiments. Indeed, the step-like behavior and the low frequency modulation of the resonator loss have been observed [8]. In this experiment, the superfluid circulation around the disk was generated by two oppositely directed "heat guns" and the modulation amplitude changed stepwise with continuous alteration of a single gun power. It was possible to eliminate the modulation altogether by compensating the flow produced the guns. The amplitude steps can be attributed to the circulation quantization. It should be possible to extract the oscillation frequency step corresponding to one vortex quantum. Unfortunately, available data [8] leave certain amount of uncertainty about the exact value of this step, but it is probably confined within the range 0.002–0.04 Hz in good agreement with (1).

It is possible that small Josephson oscillations are masked in experiment by some spurious beat-frequency interference between electromagnetic waves absorbed by CARPs of different momenta. The lowest beat frequency is $\Omega_n/2$.

In conclusion we have shown that electromagnetic field of the dielectric disk resonator should simultaneously populate three coherent aggregates of roton pairs. The energy of the roton pairs in the different aggregates are biased by the superflow around the disk. This creates conditions for the internal Josephson effect: aggregates population oscillate with a frequency determined by the superfluid velocity.

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