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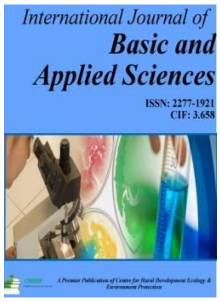

Full Length Research Paper

B-E Condensate in toroidal trap as an analog of the dc SQUID.

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ABSTRACT

Some of the most striking properties of superconductors are predicted by Josephson. The used experimental arrangement was a superconductor-insulator- superconductor sandwich. Josephson predicted that a supper current will flow through a weak link even in the absence of any voltage difference and this actually happened. One more interesting effect was also obtained, called the superconducting quantum interference device (SQUID). The dc superconducting quantum interference device was created to study and utilize the quantum interface of currents flowing in parallel through Josephson junctions connected in superconducting loop. SQUIDS are the basis of some sensitive magnetometers. An "atom SQUID" is an analogous quantum interference device that uses a super fluid dilute gas B-E condensate flowing through potential barriers in a trap [3,4]. The atom SQUID is specially attractive for rotation sensing and for addressing basic questions in quantum Physics. This is because of the Bose-Einstein Condensate advantages of easy detection of atom number and phase, along with the existence of accurate microscopic theories.

Introduction

The essential ingredients of an atom SQUID are multiply connected geometry trap and potential barrier Josephson effects. The toroidal traps create Bose-Einstein Condensates using a magnetic trap with a repulsive optical trap at the centre, superpositions of attractive and repulsive optical dipole potentials and a painted potential [5]. Recently [6,7], a laser beam was used to create a barrier that acted as a weak link for atoms in a toroidal trap and induced phase slips. The painted potential technique was used to create and manipulate a Bose-Einstein Condensate in toroidal trap containing a pair of Josephson junctions, which behaves as the analog of the dc SQUID. Their behavior agrees with the prediction of the Josephson equations for ideal Josephson junctions with a phase relation $i = i_c \sin\varphi$, where the junction current i has maximum value equal to the critical current i_c, and φ is the phase difference across the junction.

This research was undertaken to create a pair of Josephson junctions on a toroidal Bose- Einstein Condensate and demonstrate Josephson effects in a toroidal BEC by showing the transition between the dc and ac Josephson regimes and by measuring the critical current of the junctions. This study will also show that the atom SQUID can be well understood from microscopic theories without relying on phenomenological models, simplifying design and interpretation in future atom squid research.

The significance of this research topic lies in the fact that the current phase relation for the Josephson junction obtained from JPE solutions is sinusoidal and in excellent agreement with the prediction $i = \frac{2E_j}{\hbar N} \sin\varphi$. This finding is consistent with theoretical studies of the current- phase relation for BEC flow through a ID square barrier [8,9]. The validity of the Josephson equation implies that the system reported here is analogous to the ideal dc SQUID, and so super fluid analogs of the phenomena seen in the device should be observable in the dc atom SQUID.

There was a research gap to be fulfilled. A super fluid in a loop with Josephson junctions has been studied for the past several decades because of its unique quantum phenomena and applications in quantum sensing[1] and information processing[2]. One of the most important quantum phenomena in such a system is the quantum interface currents, after which superconducting quantum interference devices (SQUIDS) were named. In a conventional SQUID, the electrons in superconductors are subject to phase twists due to the external magnetic field and the periodic modulation of critical currents that results from quantum interference led to the development of the direct current (DC) SQUID as one of the most sensitive magnetometers. Using neutral atoms of super fluid helium, it has been shown that the phase twist induced by the physical rotation of the device creates quantum interference of currents, making rotation possible. Furthermore, the atomtronic SQUID, an atomtronic analog of a SQUID that uses a Bose-Einstein Condensate (BEC), has been developed to explore quantum phenomena of a SQUID with a dilute gas. The atomtronic SQUID offers the possibility to study macroscopic quantum effects by utilizing its ability to detect various many body states with high resolution and sensitivity. With this unique capability, it may be possible to simulate and study many quantum phenomena of the conventional SQUID to solve various urgent open equations regarding the nature of macroscopic quantum states, so our interest in this topic was arosed even after a long gap of time since discovery of SQUID.

Methodology

Experimental description

The painted potential technique [10,11] realizes complex dynamic potentials for Bose-Einstein Condensates by moving laser beams to create time-averaged optical dipole potentials. This is comparable to the Bose-Einstein Condensate healing length and the painted barriers can exhibit significant tunneling rates. The experimental set-up consists of a horizontal scanning beam which creates a flat two dimensional potential for supporting atoms against gravity. The vertical painting beam of the set-up creates a complex dynamic potential. This high resolution system enables the painting of many varieties of complex and dynamic Josephson junctions on a toroidal trap. The two main things i.e beam intensity distribution and the corresponding Bose –Einstein Condensate has been observed and is shown in given figure-1.

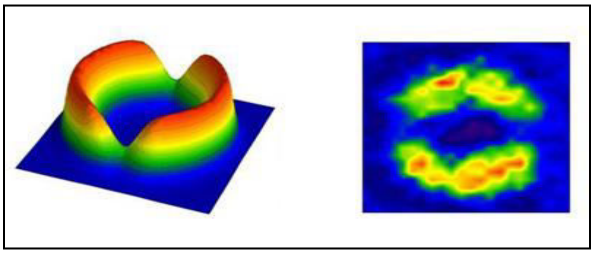

Fig 1. Physics.aps.org

It was found that the full-width at half maximum of the barrier is 2 μm, which is small enough for a Bose-Eintein Condensate to have a significant tunneling rate. It is of the order of a few hundred Hz for the typical density- weighted Bose-Einstein Condensate of healing length, $\varepsilon \sim 0.5$ μm. Josephson oscillations in this system cannot be observed directly because of their small amplitude. The main idea to study the Josephson effects is moving the Josephson junctions circumferentially toward each other leaves the Bose-Einstein Condensate density unchanged as long as atoms can tunnel through the junctions to maintain the same chemical potential in both sector of torus. This phenomenon of a current of atoms flowing without a chemical potential difference is called the dc Josephson effect in this system. The current will increase with barrier velocity until the critical current of the Josephson junctions is reached. At that point the system switches to the ac Josephson regime. Therefore, at barrier velocities greater than the speed limit imposed by the critical current, the moving Josephson junctions push the atoms. This results in compression of atoms in one side and expansion in the other.

Theoretical Analysis

The simplest theoretical model is based on the Josephson equations developed for a Bose-Einstein Condensate [12,13] . Here it is assumed that the system is framed as two condensates connected by a single Josephson junction. Let N_1 and N_2 are the number of atoms in the two sides of the torous and their corresponding phases are φ_1 and φ_2. Thus the phase difference, $\varphi = \varphi_1 - \varphi_2$. From the definition the relative population difference is expressed as

$$z = \frac{N_1 - N_2}{N_1 + N_2} \quad \text{...} \quad (1)$$

Thus Josephson equations becomes

$$\dot{z} = I_c \sqrt{1 - z^2}\ \text{Sin}\varphi \quad \text{..} \quad (2)$$

And

$$\dot{\varphi} = -w_c\,(z - z_0) - I_c \frac{z}{\sqrt{1-z^2}}\,\text{Cos}\varphi \quad \text{........................} \quad (3)$$

Where, $I_c = \frac{2E_j}{\hbar N}$ is the critical normalized current, E_j is the Josephson coupling energy and $N = N_1 + N_2$ is the total number of atoms. Again, $Wc = \frac{E_c}{2\hbar N}$, where E_c is the capacitance energy and Z_0 is the population difference. Where the chemical potential difference $\mu = \mu_1 - \mu_2 = \hbar w_c (Z - Z_0)$ is zero . (μ_1 and μ_2 are the chemical potentials in the two sides of the torus)

The derivative $\dot{Z}$ is a nomalized atom current with a maximum value of Ic. An effective bias current $\dot{Z}_0$ is created by relative movement of the Josephson junctions against the Bose Einstein Condensate to change the equilibrium population difference Z_0.

Experimental Observations

The Horizontal trapping beam with wavelength λ = 1064 nm and waist w_0 = 11 μm was scanned horizontally at 14 kHz over a width of 47 μm . The vertical trapping beam with λ = 830 nm and w_0 = 1.5 μm at frequency of 25 kHz and it was observed an 8 μm diameter ring with two intensity minima form Josephson junctions. In order to derive evaporation the depth of the vertical painting potential was fixed at 75 nK and the horizontal trap depth was lowered from 40 to 1.1 μK in very small interval of time nearly 2.5s. Interference patterns were observed and was found that the phase fluctuations in the thin Bose Einstein Condensate were negligible [14,15]. At the end of the evaporation stage the barrier height was increased to 44 nK in 100 ms. The barriers were accelerated at a constant rate to the desired constant velocity to prevent plasma oscillation and to establish the bias current automatically. The total compression angle for each Josephson junction was found $\frac{\pi}{8}$ and the compression angle after the acceleration stage was found 0.06π. when the bias current is increased then clear change is seen in the density distribution between the dc and ac Josephson effect. The model based on the Josephson equations by considering a sinusoidal current-phase relation shows changes in E_j and E_c as the barriers move.

Conclusion
Finally a pair of Josephson junctions was created on a toroidal Bose- EC and transition between the dc and ac Josephson effect was shown by measuring the critical current of the junctions. The experimental data for dc atom SQUID geometry are good in agreement with the assumptions of the ideal Josephson equations and it was found that the JJ current phase relation has the ideal sinusoidal form.

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