Negative Gravitational Mass in a Superfluid Bose-Einstein Condensate

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Newton's 2nd law of motion tells us that objects accelerate in the same direction as the applied force. However, recently it was shown experimentally that a Superfluid Bose-Einstein Condensate (BEC) accelerates in the *opposite direction* of the applied force, due to the inertial mass of the BEC becoming *negative* at the specifics conditions of the mentioned experiment. Here we show that is not the inertial mass but the *gravitational mass* of the BEC that becomes *negative*, due to the electromagnetic energy absorbed from the trap and the Raman beams used in the experimental set-up. This finding can be highly relevant to the gravitation theory.

Key words: Negative Gravitational Mass, Bose-Einstein Condensates, Superfluids.

1. Introduction

A recent paper described an experiment that shows a Superfluid Bose-Einstein Condensate (BEC) with *negative* mass, and accelerating in the *opposite direction* of an applied force [1]. The experiment starts with a BEC of approximately 10^5 ^{87}Rb atoms confined in a cigar-shaped trap oriented along the x-axis of a far-detuned crossed dipole trap. Using an adiabatic loading procedure, the BEC is initially prepared such that it occupies the lowest minimum of the lower spin-orbit coupled (SOC) BEC. By suddenly switching off one of the two dipole *trap beams*, the condensate is allowed to spread out along the x-axis. Then, the BEC is imaged in-situ for expansion times of 0, 10 and 14 ms. In the negative x-direction, the BEC encounters an essentially parabolic dispersion, while in the positive x-direction, it enters a *negative mass* region. This leads to a marked asymmetry in the expansion.

Obviously, *negative mass* does not mean *anti-matter*. Anti-matter is simply matter which has the opposite electric charge from normal matter, whereas negative mass means more exactly *negative gravitational mass*. If one particle had ordinary positive gravitational mass, and one had *negative* gravitational mass, then the gravitational force between the masses would be *repulsive* differently of in the case of two positive gravitational masses where the force would be of attraction.

In this article, we show that is not the inertial mass but the *gravitational mass* of the BEC that becomes *negative*, due to the electromagnetic energy absorbed from the trap and the Raman beams used in the experimental set-up. The consequences of this finding can be highly relevant to the gravitation theory.

2. Theory

Some years ago I wrote a paper [2] where a correlation between gravitational mass and inertial mass was obtained. In the paper I pointed out that the relationship between gravitational mass, m_g, and *rest* inertial mass, m_{i0}, is given by

$$\chi = \frac{m_g}{m_{i0}} = \left\{1 - 2\left[\sqrt{1 + \left(\frac{Un_r}{m_{i0}c^2}\right)^2} - 1\right]\right\} \qquad (1)$$

where U is *the electromagnetic energy absorbed or emitted by the particle;* $n_r = c/v$ is the index of refraction of the particle; c is the speed of light.

Equation (1) can be rewritten as follows

$$\chi = \frac{m_g}{m_{i0}} = \left\{1 - 2\left[\sqrt{1 + \left(\frac{W}{\rho c\ v}\right)^2} - 1\right]\right\} \quad (2)$$

where ρ is the matter density, v is the velocity of radiation through the particle, and W is the density of absorbed electromagnetic energy. Substitution of the well-known relation $W = 4D/v$ into Eq. (2) yields

$$\chi = \frac{m_g}{m_{i0}} = \left\{1 - 2\left[\sqrt{1 + \left(\frac{4D}{\rho c v^2}\right)^2} - 1\right]\right\} \quad (3)$$

where D is the power density of the radiation *absorbed* by the particle.

In order to apply the Eq. (3) to the BEC previously mentioned, we start calculating the *rest* inertial mass of the BEC, which is given by

$$m_{i0(BEC)} \cong 1\times10^5\left(86.909187\times1.66\times10^{-27}kg\right) =$$

$$= 1.4\times10^{-20}kg$$

Assuming that the average radius of the BEC is approximately 40 μm (See reference [1]), then we can calculate the density of the BEC, i.e.,

$$\rho_{BEC} = \frac{m_{i0(BEC)}}{V_{BEC}} = \frac{1.4\times10^{-20}kg}{\frac{4}{3}\pi\left(40\times10^{-6}m\right)^3} \cong 5.2\times10^{-8}kg.m^{-3}$$

Substitution of the values of ρ_{BEC} into Eq. (3) gives

$$\chi_{BEC} = \frac{m_{g(BEC)}}{m_{i0(BEC)}} = \left\{1 - 2\left[\sqrt{1 + 0.065\frac{D^2}{v_{BEC}^4}} - 1\right]\right\} \quad (4)$$

The variable D, in Eq. (4), refers now to the total power density of the radiation *absorbed* by the BEC (from t*he trap and the Raman beams*, used in the experimental set-up of reference [1]). According to the authors of the experiment the power of the Raman beams are of approximately 3mW (2.9 *m*W in one of the two beams,3.3 *m*W in the other), focused to a beam waist of 120 microns ($60\mu m$ radius); the absorption coefficient is $1E_R/2.5E_R = 0.4$. Thus, we can write that

$$D = \frac{P_{abs}}{S_{BEC}} = \frac{0.4P_{beams}}{4\pi\left(60\times10^{-6}m\right)^2} =$$

$$= \frac{0.4\times\left(2.9mW + 3.3mW\right)}{4\pi\left(60\times10^{-6}m\right)^2} \cong 5.4\times10^4 W.m^{-2} \quad (5)$$

Substitution of this value into Eq. (4) gives

$$m_{g(BEC)} = \left\{1 - 2\left[\sqrt{1 + \frac{1.8\times10^8}{v_{BEC}^4}} - 1\right]\right\}m_{i0(BEC)} \quad (6)$$

Note that, for $v_{BEC} < 109.5m.s^{-1}$ the *gravitational mass* of the BEC ($m_{g(BEC)}$) becomes *negative*. Lene Hau et al., [3] showed that light speed through a BEC reduces to values much smaller than $100m.s^{-1}$.

Consequently, we can conclude that it is the *gravitational mass* of the BEC of ^{87}Rb atoms that becomes *negative* and not its inertial mass.

Also it was deduced in the reference [2] a generalized expression for the Newton's 2nd law of motion, which shows that the expression for *inertial forces* is given by

$$\vec{F} = m_g\vec{a} \quad (7)$$

The presence of m_g in this equation shows that the inertial forces have origin in the *gravitational interaction* between the particle and the others particles of the Universe, just as *Mach's principle* predicts. In this way, the new equation expresses the incorporation of the Mach's principle into Gravitation Theory, and reveals that the inertial effects upon a body can be strongly reduced by means of the decreasing of its gravitational mass. Note that only when m_g reduces to m_{i0} is that we have the well-know expression ($\vec{F} = m_i\vec{a}$) of the Newton's law.

Taking Eq. (6) for an arbitrary value of $v_{BEC} < 109.5m.s^{-1}$, we obtain $m_{g(BEC)} = -Km_{i0(BEC)}$, where K is a positive number. Substitution of this equation into Eq. (7) yields

$$\vec{F}_{BEC} = -Km_{i0(BEC)}\vec{a} \quad (8)$$

The sign $(-)$ in this expression reveals clearly why the BEC accelerates in the *opposite direction* of the *applied force*, i.e.,

$$\overleftarrow{F}_{BEC} = -\vec{F}_{BEC} = Km_{i0(BEC)}\vec{a} \quad (9)$$

References

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