Registration of gravimagnetism by the He^4 superfluid state

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One of essential consequences of General Relativity is the influence of rotating mass on spatially-time relations that is existence of gravitational analog to Ampere's law. The experimental circuit of quantum interferometer is suggested, working medium of which is a superfluid liquid He^4. The scheme is provided to measure very slow rotations and investigate Lense-Thirring effect. Estimations of the device scale and its sensitivity are given.

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As a rule, the property of resistance to change of velocity vector (the inertia) and the capability to be the source of a static gravity field are correlated with mass. In Lense-Thirring effect another property of mass is occurred. When object with mass *m* moves, it produces other components of a gravity field - the gravitomagnetic field.

The gravitomagnetism phenomena as one of General Relativity consequences studied by Thirring [1], the quantitative description of effect for astronomical case was given in work of Lense and Thirring [2]. The effect essence is in the drift of the inertial frame by the gyrating mass. The effect has the analogy in electrodynamics (the gravitational analog of Ampere law) and as the magnetic forces are weaker than the electric ones in **v/c** times, then the gravitomagnetism is weaker than the static gravitation in **v/c** times. The detection of gravitomagnetism effect would allow to estimate the component of the vortex phenomena in overall picture of Universe (aero- and hydrodynamics, magnetism, theory of superconductivity II, gravitomagnetism, theory of planetary motions, cosmology). Beyond that, the gist of the effect is associated with Mach principle.

Schiff suggestion [3], developed by Everitt [4], was based on the mechanical proof of an effect existence. It was also suggested to check this effect in electrodynamics experiments. In particular, to check precisely the dependence of a light frequency deviation as a function of an angular velocity of the ring interferometers, because Lense-Thirring effect. It resembles with Sagnac effect (but the effect is fewer by ten orders of, when an angle measurement on rotary Earth are carried out) [5]. There are the performing variants of processing of experimental result on gravitational lensing taking into account Lense-Thirring effect [6].

Recently the successful checking of Lense-Thirring effect in a space experiment has been held [7]. Over next eleven years during LAGEOS program, the drift of the gyroscope located on a satellite was observed. The satellite orbited (there were two scientific research satellites really) at an altitude of about 12200 km. The rotary Earth mass causes the turning of the coordinate system, connected with the satellite. The angular rotation resulted in the drift of a gyroscope axis relative to a suspension system, which was joined with satellite housing. Let us mention that the subtle magnitude of the effect ($\sim 10^{-10}\,\omega_{\oplus}$) makes the particular demands for high precision of the gyroscope itself and to noises of an installation.

Fundamentally new experiments with the promising sensitivity reserve are discussed here. The experimental circuit of quantum interferometer using the superfluid state of He^4 is offered. It is expected that the application of modern technology will provide the adequate experimental accuracy.

As it is known [8] that at temperatures $T<T_{\lambda}=2.17K$ (below λ-point) He^4 transfers into the superfluid state and in these conditions the macroscopic coherent effects occur in helium. Such effects satisfy the dissipationless processes, i.e. the frictionless current of fluid and superthermoconductivity.

It was repeatedly taken attempts of search for macroscopic quantum coherent effects in He^4 below λ-point.

In several papers [8-10] the detection of non-stationary Josephson effect in He^4 was affirmed. In this case "the quantum restrictor" (or submicron aperture array [10]) in the membrane of nano-size thickness plays the role of tunnel Josephson transition (the direct analogy with well-known Dayem bridge in Josephson technique [11]). A short coherence length in superfluid He^4 essentially determines very small dimensions of Josephson weak link [12].

In order to implement the analog of stationary Josephson effect, or in other words, to manufacture a "superfluid analog" of DC-SQUID, it is necessary in the annular tube (torus), filled by the superfluid liquid (fig. 1), to locate two quantum throttles (1 and 2 on fig. 1).

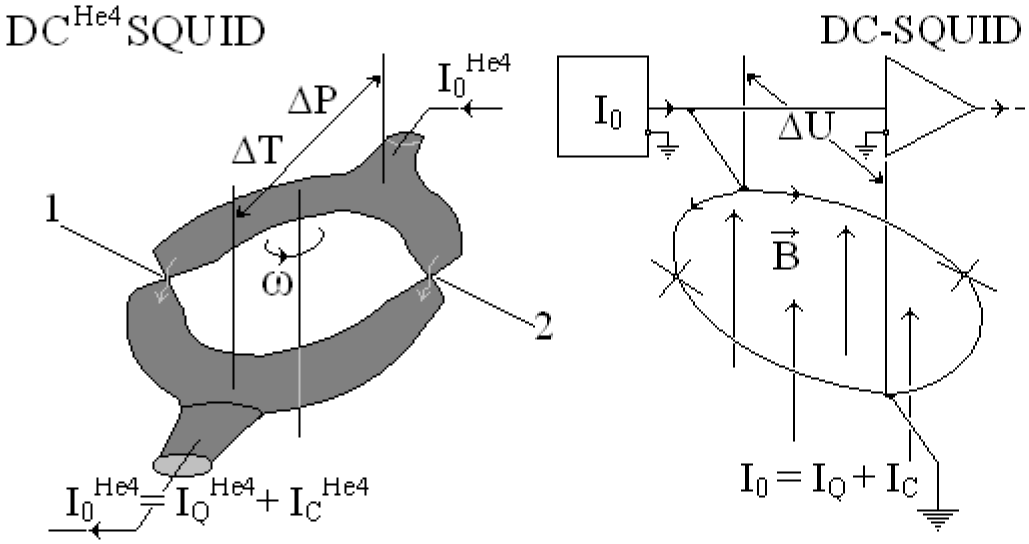

Fig. 1

An additional condition of creation of such gadget is the development of recording methods of the above-critical flow He^4. For the understanding, a superfluid SQUID work let conduct the analogy with work of conventional DC-SQUID. The above-critical flow is analog to component

$$I_Q = I_0 - I_C(\Phi/\Phi_0)$$

of total current I_0, introduced and extended through poles of a superconducting ring in the DC-SQUID. As is known [8,11], the resultant critical current I_C of the ring with two Josephson junctions is the periodic function of an outer magnetic flux, threading the ring and measured by the SQUID, $I_C = I_C(\Phi/\Phi_0)$, where $\Phi_0 = 2\pi\hbar/2e = 2.07\times10^{-15}$ Wb is a magnetic flux quantum. The periodical dependence arises here as the consequence of a superconducting condensate interference. The spreading of the condensate is occurred on two interfering trajectories, i.e. through the first Josephson junction and the second one [12]. The Aharonov-Bohm effect [13] determines the phase difference at the crossing. Due to it, it is possible to observe the difference $I_C = I_0 - I_Q$, gauging component I_Q when fixed I_0. Then the value of magnetic flux Φ to accuracy of integer quantum Φ_0 [11] is determined also.

The registration of component I_Q^{He4} when fixed total flow of helium I_0^{He4} (on fig. 1 components are labeled by "large" arrows) will allow to determine superfluid component of helium flow I_C^{He4} and its phase. The phase bears the information on parameters, measured by DC^{He4}SQUID. The process of I_Q^{He4} registration may be based either on the detection of pressure differential, arising when helium flows through a weak link, or on the detection of heat transfer by excitations of above-critical component (there is no entropy of superfluid component) (see fig. 1). In the first, the differential ΔP of pressures before and after the ring can be measured. If the pressure differential to apply to the third weak link, then as a consequence of non-stationary Josephson effect the acoustic vibrations must be generated. The Josephson frequency Ω is proportional to ΔP. It should be emphasized that according to elementary theory of non-stationary Josephson effect [8] an amplitude of these oscillations P_0 has to be much less than ΔP. The realistic estimations of P_0 point on need for developing of a high-sensitive microphone, which is able to pick up the acoustic vibrations with amplitude at the level of fraction of pikoPascals [8]. In the second, it is possible to measure the entropy growth, transferred by above-critical current component I_Q at the exit from the ring of the superfluid interferometer [15] thermally connected with the working medium of magnetocalorimeter [16].

What parameters and signals can be measured by DC^{He4}SQUID? In conditions of super fluidity, it is difficult to find the direct analog of magnetic field [17], however it is possible to examine the difference of quantum phases, describing the coherent states, in both devices. The phase difference, determining the resultant critical current $I_C=I_C(\varphi)$ in conventional SQUID, is identified as

$$\varphi-\varphi_0=\frac{1}{\hbar}\oint \vec{\mathrm{P}}d\vec{r}=\frac{1}{\hbar}\oint(\vec{p}-q\vec{A})d\vec{r}\ .$$

The conventional superconducting SQUID responds to the second term in contour integral (q=2e is the charge of Cooper pair). If the magnetic field is threading the SQUID ring, then with the help of Stoke theorem, it is possible to pass from vector potential $\vec{A}$ to flux density $\vec{B}$. Next, relate it to a magnetic flux quantum:

$$\frac{q}{\hbar}\oint \vec{A}d\vec{r}=\frac{2e}{\hbar}\iint \vec{B}d\vec{S}=\frac{2\pi\Phi}{\Phi_0}.$$

At the same time, the contribution of the first term to integral could be excluded in the result of the gauge transformation. In super fluidity of He^4 case the integrand appears to be a single, because $q=0$. Under the condition of He^4 rotation (real or imaginary) along the toroidal pipe with radius r with angular frequency ω the momentum of helium with mass m will amount to $p=m\omega r$, but $|d\vec{r}|=rd\theta$, where $0<\theta<2\pi$. At that, the circulation can be correlated to Planck constant $\hbar$ through the momentum of superfluid He Λ

$$\frac{1}{\hbar}\oint \vec{\mathrm{P}}d\vec{r}=\frac{1}{\hbar}\oint m\omega r^2 d\theta=\frac{2\pi\Lambda}{\hbar}.$$

So the helium current I_C^{He4} appears to be periodic function of phase $2\pi\Lambda/\hbar$: $I_C^{He4}(2\pi\Lambda/\hbar)=I_0^{He4}-I_Q^{He4}$ [5] by analogy with superconductivity.

It is known that there is possibility to measure the magnetic flux by DC-SQUID in a fraction of Φ_0 (the sensitivity of a modern commercial SQUID not worse than $10^{-5}\Phi_0/\sqrt{Hz}$ [10]). Similarly, the registration by DC^{He4}-SQUID the phase $2\pi\Lambda/\hbar$, in a measurement process

$$I_C^{He4}(2\pi\Lambda/\hbar)=I_0^{He4}-I_Q^{He4},$$

will allow to determine the momentum of superfluid He^4 in a fraction of Planck constant.

Integration of DC^{He4}SQUID and a magnetic calorimeter [16], or DC^{He4}SQUID and an ultrasensitive microphone [18] into a unified system is analogous to construction of a modern two-stage SQUID.

These facilities were created for the signal registration in the gravitational antenna of a resonant type. Two-stage SQUID is so constructed that the second direct current SQUID plays the role of the integrated low-noise amplifier of electric signals, entering from the first DC-SQUID [19, 20]. In our case, DC^{He4}SQUID will play the role of the first stage by analogy. The second stage will be organized basing on a magnetic calorimeter (if the entropy growth is measured) or a magnetostrictive converter (if the change of pressure on "third" weak link is measured). Both these steps possess the enormous gain factor of a registered signal. The first stage does through Josephson nonlinearity in He^4, the second one possesses as the magnetic transducer with the "conventional" SQUID at the output.

Now describe the conception of a rotational velocity sensor for super low angular velocities. It is the quantum interferometer on superfluid He^4, combined into a single system with a magnetic transducer. A conventional SQUID indicates the output signal of a converter. The sensor appears to be a universal detector of ultra weak mechanical angular oscillations in his reference system. The creation of such appliance will allow performing the test of non-trivial prediction of General Relativity, such as Lense-Thirring effect.

Estimate the angular momentum, transmitted to the input signaling ring of $DC^{He4}SQUID$, if the ring plane is perpendicular to axial spin vector. By definition

$$\Lambda = mvR = m\omega R^2 = \frac{2}{5}\frac{mr_g R^2}{r_\oplus}\omega_\oplus \ ,$$

where m is helium mass, filling a ring tube, r_g is Earth gravitational radius, $r_\oplus$ is Earth radius, R is a ring radius, $\omega_\oplus$ is Earth angular velocity. For m = 0.1kg, $r_g = 0.9\cdot10^{-2}$ m, $r_\oplus = 6.4\cdot10^6$ m, $\omega_\oplus = 0.73\cdot10^{-4}$ 1/s the transmitted angular momentum is to be about $\Lambda = 10^{17}\hbar$ of quantum of action, when R = 0.1 m. At that, the energy sensitivity of two-stage SQUID, used in a resonant antenna, is estimated by the value better than $120\hbar$ [19].

Thus it is shown the principle opportunity of super slow rotations measuring and observing of such weak effects as Lense-Thirring one with the help of $DC^{He4}SQUID$, by registration either acoustic response with the help very sensitive microphone or thermal response by magnetic calorimeter.

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