GRAVITOMAGNETISM IN SUPERCONDUCTORS AND COMPACT STARS

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There are three experimentally observed effects in rotating superconductors that are so far unexplained. Some authors have tried to interpret such phenomena as possible new gravitational properties of coherent quantum systems: in particular, they suggest that the gravitomagnetic field of that kind of matter may be many orders of magnitude stronger than the one expected in the standard theory. Here I show that this interpretation would be in conflict with the common belief that neutron stars have neutrons in superfluid state and protons in superconductive one.

1. Introduction

Gravitomagnetic phenomena in superconductors were considered for the first time by DeWitt in Ref. 1. In the 90’s, Li and Torr suggested the fascinating possibility that superconductors were able to produce anomalous strong gravitomagnetic fields 2 and at that time experiments seemed to support their idea. 3 Today, there are three apparently unexplainable laboratory measurements on rotating superconductors 4 which have been addressed as a possible indication of new anomalous gravitational properties of coherent quantum systems (see 6, 7 and reference therein). The latter may be also connected with the nature of the so-called dark energy 8. Indeed, the observed effects would require gravitomagnetic fields of many order of magnitude larger than the one predicted by general relativity. The issue is that general relativity is well tested for classical objects like stars, planets and satellites, while these mysterious phenomena are seen only when the matter is in superconductive or superfluid state, below some critical temperature $T_c$.

In this paper I show that such a possibility is quite probably in conflict with the physics of very compact objects. According to the commonly accepted picture of neutron stars, the high density and low temperature of the matter inside these objects cause the neutrons to form $^3P_2$ Cooper pairs and to condensate to a superfluid state and the small fraction of protons to form $^1S_0$ Cooper pairs and to condensate to a superconductive state 9. Estimating the surface temperature of some young neutron stars, X-ray satellites support this picture 10. In addition to this, there is the possibility that inside neutron stars there are superfluid hyperons 11 and/or superfluid and superconductive quark matter 12. If this accepted picture were true and superconductors and superfluids produced anomalous stronger gravitomagnetic fields, at the levels suggested by laboratory experiments, gravitomagnetic effects like
the Lense-Thirring one should affect the motion of neutron star in binary systems as well. This is not seen and thus one of the above hypothesis is probably wrong. Even if the fraction of superfluid and superconductive matter inside neutron stars is quite model dependent, and hence it is difficult to find reliable constraints on new physics, the gravitomagnetic field suggested by laboratory experiments are 20 – 30 orders of magnitude stronger than the one expected by general relativity, so gravitomagnetic phenomena in binary systems should be observable even in the most pessimistic scenarios, because the standard theory predicts gravitomagnetic effects only about 5 orders of magnitude weaker than the main gravitoelectric ones and in any case the fraction of superfluid and superconductive matter is not less than some percent. Moreover, laboratory tests\cite{13} show also that superfluids and superconductors have usual gravitoelectric properties, so the orbital motion of neutron stars would be affected only by anomalous large gravitomagnetic contributions.

The content of the work is the following. In section 2 I review the gravitoelectromagnetism framework and, in section 3 the unexplained observed effects in rotating superconductors. In section 4 I discuss the possibility that superfluids or superconductors in compact stars produce gravitomagnetic fields as strong as one could expect from laboratory experiments and I show that this would be inconsistent with observations. In section 5 I report the conclusions of this work.

2. Gravitoelectromagnetism

In the weak field and slow motion approximation, Einstein gravitational field equations become formally equivalent to the ones of the electromagnetic field: we can define a gravitoelectric field \( \mathbf{E}_g \) and a gravitomagnetic field \( \mathbf{B}_g \) which satisfy Maxwell-like equations

\[
\nabla \cdot \mathbf{E}_g = 4\pi G_N \rho,
\]

\[
\nabla \cdot \left( \frac{1}{2} \mathbf{B}_g \right) = 0,
\]

\[
\nabla \wedge \mathbf{E}_g = -\frac{1}{c} \frac{\partial}{\partial t} \left( \frac{1}{2} \mathbf{B}_g \right),
\]

\[
\nabla \wedge \left( \frac{1}{2} \mathbf{B}_g \right) = \frac{1}{c} \frac{\partial}{\partial t} \mathbf{E}_g + \frac{4\pi G_N}{c} \mathbf{j},
\]

where \( \rho \) is the matter density and \( \mathbf{j} \) is the matter current. The factors 1/2 in front of the gravitomagnetic field \( \mathbf{B}_g \) arise from the spin-2 nature of the gravitational field. For an introduction on the gravitoelectromagnetic framework, see e.g. Ref. 14.

Reminding the electromagnetic theory, it is easy to see that the gravitomagnetic field of a rotating body is proportional to its proper angular momentum \( \mathbf{J} \) and induces the spin precession for any orbiting spinning test-particle (the so-called Lense-Thirring effect). The angular velocity of such a precession is

\[
\Omega_{LT} = -\frac{G_N}{c^2} \frac{\mathbf{J} - 3 \hat{r} \cdot (\hat{r} \cdot \mathbf{J})}{r^3},
\]
where \( \mathbf{r} \) is the position vector of the test-particle with respect to the rotating body, \( r = |\mathbf{r}| \) and \( \hat{\mathbf{r}} = \frac{\mathbf{r}}{r} \). Just like in the electromagnetic case, one can also consider the whole orbit of the test-particle as a giant gyroscope affected by the precession of the longitude of the ascending node \( \Omega \) and of the argument of the pericenter \( \omega \). This causes a precession of the longitude of the pericenter \( \bar{\omega} = \Omega + \omega \) which is usually much smaller than the well known main gravitoelectric effect (and indeed at present we cannot observe it in the orbit of Solar System planets). The angular velocity of the pericenter precession is

\[
\dot{\bar{\omega}} = \frac{2G_N \mathbf{J} - 3 \hat{\mathbf{L}} (\hat{\mathbf{L}} \cdot \mathbf{J})}{c^2 a^3 (1 - e^2)^{3/2}}.
\]

Here \( \hat{\mathbf{L}} \) is the unit vector orbital angular momentum of the test-particle and \( a \) and \( e \) are respectively the semimajor axis and the eccentricity of the orbit of the test-particle. Evidences of the Earth’s gravitomagnetic field have been reported in Ref. [15] from an analysis of the laser ranged data of the satellites LAGEOS and LAGEOS II and represent one of the main targets of the Gravity Probe B mission [16].

3. Laboratory Experiments

It is well known that the gravitational force is much weaker than the electromagnetic and nuclear ones. This is certainly true for classical ordinary matter, where general relativity predictions are in agreement with observational evidences, but it may not be so for coherent quantum systems. Indeed, some observed effects in laboratory experiments may suggest that this kind of matter produces much stronger gravitomagnetic fields.

One of the unexplained result is the measurement of Cooper pair mass in rotating niobium superconductive rings [4]

\[
\Delta m = m_{Exp} - m_{Th} = 94.147249(21) \, \text{eV},
\]

where \( m_{Exp} \) is the measured mass and \( m_{Th} \) is the theoretically predicted one. Such a measurement could be explained including the gravitomagnetic term in the canonical momentum of the Cooper pair

\[
\Pi = m \mathbf{v} + \frac{e}{c} \mathbf{A} + \frac{m}{c} \mathbf{A}_g,
\]

where \( \mathbf{A} \) and \( \mathbf{A}_g \) are respectively the electromagnetic and the gravitoelectromagnetic vector potential (that is \( \mathbf{B}_g = \nabla \times \mathbf{A}_g \)). However, the mass excess can be explained only if the gravitomagnetic field \( \mathbf{B}_g \) is 30 orders of magnitude larger than the one predicted by the standard theory: indeed experimentally one would deduce \( \frac{|\mathbf{B}_g|}{\omega_{ring}} \sim c \frac{\Delta m}{m_{Th}} \sim 10^6 \, \text{cm/s} \),

while the standard theory would predict

\[ \frac{|\mathbf{B}_g|}{\omega_{ring}} \sim \frac{G_N m_{ring}}{c R} \sim 10^{-24} \, \text{cm/s} \]
as one can obtain straightforward from dimensional arguments. Here $m_{\text{ring}} = 2 \mu g$ is the mass of the rings in the experiment and $R = 5 \text{ cm}$ its radius.

Other two unexplained outcomes in experiments involving rotating superconductive rings have been performed at the Austrian Research Centers. One of them measures the azimuthal acceleration $g$ in the central hole of different rotating superconductive rings and finds an anomalous acceleration directly proportional to the ring angular acceleration $\dot{\omega}_{\text{ring}}$, with the coupling between $g$ and $\dot{\omega}_{\text{ring}}$ depending on the superconductor but typically at the level

$$\left. \frac{g}{\dot{\omega}_{\text{ring}}} \right|_{\text{Exp}} \sim -10^{-4} \text{ cm}. \quad (11)$$

Even this result can be interpreted as a gravitoelectromagnetic phenomenon, because a time varying gravitomagnetic field must induce a gravitoelectric field (Faraday-like induction law). However, the predicted effect in the standard theory is completely negligible: a rough estimate suggests

$$\left. \frac{g}{\dot{\omega}_{\text{ring}}} \right|_{\text{Th}} \sim -\frac{G m_{\text{ring}}}{c^2} \sim -10^{-26} \text{ cm}, \quad (12)$$

where $m_{\text{ring}} = 350 \text{ g}$ is the mass of the rings in the experiment. In order to account for the observed effect, the gravitomagnetic field of the superconductor should be about 22 orders of magnitude larger than its expected value.

The second experiment at the Austrian Research Centers measures the phase difference between two beams of coherent electromagnetic radiation with the same frequency $\nu_0$ and propagating in opposite directions along a closed optical fiber. The experiment finds a coupling constant between the phase difference $\Delta \varphi$ and the constant angular velocity $\omega_{\text{ring}}$ of a rotating niobium superconductive ring in the neighborhood. The phase difference induced by a gravitomagnetic field $B_g$ would be

$$\Delta \varphi = \frac{4 \nu_0}{c^3} \mathbf{S} \cdot \mathbf{B}_g, \quad (13)$$

where $\mathbf{S}$ is the area vector of the optical fiber whose direction is orthogonal to the fiber plane. If we interpret such a phase shift as a gravitomagnetic phenomenon, we find the relation

$$\left. \frac{|\mathbf{B}_g|}{\omega_{\text{ring}}} \right|_{\text{Exp}} \sim 10^2 \text{ cm/s}. \quad (14)$$

On the other hand, from simple dimensional arguments, we can find that the standard theory would predict

$$\left. \frac{|\mathbf{B}_g|}{\omega_{\text{ring}}} \right|_{\text{Th}} \sim \frac{G m_{\text{ring}}}{c R} \sim 10^{-16} \text{ cm/s}, \quad (15)$$

with $R = 7 \text{ cm}$ the radius of the ring. The gravitomagnetic field of the niobium superconductive ring should be some 18 orders of magnitude larger than expected in order to account for the observed effect.
Lastly, anomalous large gravitomagnetic fields might be produced by superfluid matter as well. Indeed, the authors of Ref. 6 argue that such a possibility would be suggested by the unexplained generation and deletion of vortices in superfluids reported in 17. So, roughly speaking, coherent quantum systems would be able to produce anomalous strong gravitomagnetic fields. On the other hand, other laboratory measurements confirm that the (gravitoelectric) mass of superconductors does not change between the normal and the superconductive state13; in other words, coherent quantum systems seem to have standard gravitoelectric properties but extraordinary gravitomagnetic ones. This consideration simplifies the picture and allows us for using the standard theory for the description of neutron star motion and for discussing separately the (unobserved) anomalous gravitomagnetic phenomena.

4. Astrophysical Observations

Neutron stars are the end-product of heavy stars after supernova explosion18. Their mass is typically about 1.5 Solar masses and their radius approximately 10 km; at such high densities, matter would be made of neutrons, with a smaller fraction of protons and electrons. In the inner part there could be also pions, kaons or free quarks. Since we expect that the matter inside neutron stars is at relatively low temperature, it is common belief that neutrons form 3P 2 Cooper pairs and are in superfluid state and protons form 1S 0 Cooper pairs and are in superconductive state9. Like ordinary stars, two neutron stars can form a binary system and, if at least one of them is detectable as radio pulsar, we can perform high precision test of relativistic celestial mechanics. Indeed, typical orbital velocities are at least an order of magnitude larger than the ones of planets in the Solar System, they have very short orbital period, which is favorable for the observation of secular phenomena, and tidal effects can usually be ignored, since the orbital separation is much larger than their size. Today we know 5 neutron star–neutron star binary systems which allow for high precision measurements of this kind10.

The observable quantities of the binary systems are the so-called “non-orbital parameters”, 5 “Keplerian parameters” and 5 “Post-Keplerian parameters”, all deduced by fitting the arrival times of pulses. Since the Post-Keplerian parameters depend on the theory of gravity, their measurement can be used as testbed of general relativity20,21. In particular, in general relativity, for the case of negligible spin effects, the Post-Keplerian parameters depend only on the Keplerian ones and on the neutron star masses, implying that the measurement of 3 or more of them overconstrains the theory. At present, all the observations are in agreement with the standard theory up to v2/c2 corrections and effects of the gravitomagnetic fields are so far unobserved21 (but they may be in a near future22). On the other hand, if matter in superfluid or superconductive state generates gravitomagnetic field much larger than the one produced by ordinary matter, 20 – 30 orders of magnitude as possibly suggested by the unexplained laboratory experiments, the mentioned
There are essentially three effects of a possible non-negligible gravitomagnetic field in a binary system: the gravitomagnetic precession of the pericenter, the gravitomagnetic time delay and the gravitomagnetic precession of the stellar spin. Unfortunately, all the observable parameters of the binary system arise from data fitting, so the most correct procedure would require to consider a particular theory (in our case a theory capable of producing anomalous large gravitomagnetic fields) and find the new orbital parameters. If the theory is overconstrained, observational data may reject the model. On the other hand, the purpose of the present work is to remain as general as possible, showing that binary systems of compact stars disfavor anomalous gravitomagnetic properties for superfluids and/or superconductors: so, it suffices to require that the possible gravitomagnetic effect is not larger than the observed gravitoelectric one. Moreover, laboratory experiments support the idea that only the gravitomagnetic fields of coherent quantum systems are anomalous, whereas the gravitoelectric ones seem to be standard at a high level of accuracy, so we can reasonably take the standard description of neutron star orbital motion and discuss possible anomalous contributions, bearing in mind that the theory of general relativity is in agreement with observations better than the percent. Neglecting extraordinary fine tuning, this is a very conservative picture and more particular cases certainly are able to put much stronger constraints.

4.1. Orbital precession

The gravitoelectric orbital precession is

$$\dot{\omega}_{\text{GE}} = 3 \left( \frac{T}{2\pi} \right)^{-5/3} \left( \frac{G_N M}{c^3} \right)^{2/3} (1 - e^2)^{-1},$$

(16)

where $T$ is the orbital period and $M$ the total mass of the system. For the known neutron star–neutron star binary systems, we typically find $\dot{\omega}_{\text{GE}} \sim 1-10$ degrees/yr, with a relative uncertainty in the range $10^{-3} - 10^{-6}$. On the other hand, from Eq. (6) one find that the gravitomagnetic contribution in general relativity is

$$\dot{\omega}_{\text{GM}} \sim \frac{G_N J}{c^2 a^3} \sim 10^{-5} \text{ degrees/yr}.$$

(17)

Here I took $J \sim M_\odot R_N^2 \omega_{NS}$, with $R_N \sim 10$ km the neutron star radius and $\omega_{NS} \sim 100 \text{ rad/s}$ the neutron star rotation frequency, and $a \sim 10^{11} \text{ cm}$ as standard stellar separation distance. If neutrons in superfluid state and proton in the superconductive one produced a gravitomagnetic field just $\sim 5$ orders of magnitude stronger than the expected one, the gravitomagnetic orbital precession contribution would be at the same level of the gravitoelectric effect, with disagreement between theory and observational data. Of course one can reasonably argue that the fraction of the star in superconductive and superfluid state is model dependent and that the fraction of coherent quantum matter may be as low as some percent. However, even if this is certainly possible, such a consideration can only change of 2 or 3

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orders of magnitude our previous estimates and can hardly save the idea of strong
gravitomagnetic fields from superfluids and superconductors.

4.2. Time delay

Let us now turn to the gravitational time delay, that is the time delay of light rays
emitted by the pulsar when they pass near the other neutron star, with respect to the
case the spacetime was flat. The gravitoelectric effect is the well-known Shapiro time
delay. In the case of a binary system, we can quantify the phenomenon considering
the gravitational delay of the light when the pulsar is in front of and behind the
companion

$$\Delta t_{GE} = \frac{2G_N m}{c^3} \ln \left( \frac{4a^2}{d^2} \right),$$

(18)

where \( m \) is the mass of the companion and \( d \) the impact parameter of the light ray,
which we can take of order of the radius of the neutron star companion. On the
other hand, the gravitomagnetic effect is given by

$$\Delta t_{GM} = \frac{-2G_N \mathbf{J} \cdot \hat{n}}{c^3 d},$$

(19)

where \( \hat{n} \) is the unit vector normal to the plane formed by \( \mathbf{x}_1 \) and \( \mathbf{x}_2 \) and directed
along \( \mathbf{x}_1 \wedge \mathbf{x}_2 \), \( \mathbf{x}_1 \) and \( \mathbf{x}_2 \) being the position vectors respectively of the pulsar and
of the observer with respect to the rotating body. Plugging typical binary system
parameters into Eqs. (18) and (19), we find a gravitoelectric time delay at the level
of 0.1 ms and a gravitomagnetic contribution of about \( 10^{-5} \) ms. If the superfluid
neutrons and the superconductive protons produced a gravitomagnetic field \( \sim 5 \)
orders of magnitude stronger than ordinary matter, once again the successful picture
would be destroyed. Moreover, the effect could be somehow well recognizable, be-
cause while the gravitoelectric contribution depends only on the impact parameter \( d \),
the gravitomagnetic one becomes positive or negative, depending on the sign of \( \mathbf{J} \cdot \hat{n} \).

4.3. Spin precession

The last effect we can consider is the spin precession. The geodesic (or de Sitter)
precession depends on the velocity of the spinning test-particle \( \mathbf{v} \) and on the gradient
of the gravitational potential \( \Phi_g \), which is related to the gravitoelectric field \( \mathbf{E}_g \) by

$$\mathbf{E}_g = -\nabla \Phi_g - \frac{1}{c} \frac{\partial}{\partial t} \left( \frac{1}{2} \mathbf{A}_g \right).$$

(20)

On the other hand, it is independent of the gravitomagnetic field of the source \( \mathbf{B}_g \).
The geodesic angular frequency is

$$\Omega_G = \frac{3}{2} \mathbf{v} \wedge \nabla \Phi_g.$$

(21)
A rough estimate is
\[ \Omega_G \sim \frac{G_N M v}{c^2 r^2} \sim 10^{-2} \text{rad/yr}, \] (22)
where \( v \sim 300 \text{km/s} \) is the typical neutron star velocity. Such a simple evaluation is compatible with observations\textsuperscript{[21].} On the other hand, the contribution of the gravitomagnetic field of the neutron star companion in the standard theory is the Lense-Thirring precession, which can be evaluated
\[ \Omega_{LT} \sim \frac{G_N}{c^2} \frac{J}{r^3} \sim 10^{-7} \text{rad/yr}. \] (23)

Even in this third case, the gravitomagnetic effect is expected to be about 5 orders of magnitude smaller than the gravitoelectric one, so that it is quite improbable that superfluids and superconductors produce a gravitomagnetic field 20 – 30 orders of magnitude larger than the one of ordinary classical matter.

5. Conclusions

The possibility of anomalous strong gravitomagnetic fields from coherent quantum system has been considered by various authors. In particular there are three unexplained observed phenomena occurring in experiments involving rotating superconductive rings and one involving superfluid matter that may support this fascinating idea. On the other hand, general relativity is well tested only for classical macroscopic bodies like planets or satellites, so that new gravitational properties of non-common matter is certainly worthy of investigation.

However, in the commonly accepted picture, neutron stars are made of neutrons in superfluid state and proton in superconductive one, with also the possibility of superfluid hyperons and quarks. Since we know 5 neutron star–neutron star binary systems where at least one of the star is a radio pulsar and where we can perform high precision tests of celestial mechanics, in principle we would be able to check the hypothesis of the anomalous strong gravitomagnetic field produced by superfluids and superconductors. The standard theory works perfectly, while the possible anomalous large gravitomagnetic field suggested by laboratory experiments would make gravitomagnetic effects larger than the gravitoelectric ones. Even if the amount of matter in superfluid and superconductive state is model dependent, the laboratory experiments require so strong gravitomagnetic fields that we can at least conclude that present knowledge of neutron star physics strongly disfavors the idea suggested in Refs.\textsuperscript{[6]} and \textsuperscript{[7]} as solution to the unexplained results in Refs.\textsuperscript{[4]} and \textsuperscript{[5]}.

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