Low-Temperature Upper Limit of the Photon Mass: Experimental Null Test of Ampère's Law

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We describe a new method to set an upper limit of the photon mass m_γ at low temperatures, based on a null test of Ampère's law. The result of our measurement, expressed as the upper limit of the photon mass at 1.24 K, is $m_\gamma \leq (8.4 \pm 0.8) \times 10^{-46}$ g.

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According to current wisdom the distinction between the electromagnetic and the weak interaction that occurred in the very early Universe at very high temperatures also led to the creation of massive gauge particles promoting the weak interaction, the W and Z particles. Considering an analogous event, Primack and Sher [1] suggested that electromagnetic gauge invariance might possibly also break down at some critical temperature T_c, and the photon thereby might acquire a mass m_γ below T_c, while remaining strictly massless above T_c. Since they could not name a plausible mechanism for this transition, neither an estimate for the critical temperature nor a time scale for it to happen could be made. Hence there is no theoretical prediction for a possible nonzero value of the photon mass. Nevertheless, they pointed to the fact that most of the previous photon-mass experiments had been carried out at 300 K and none at temperatures lower than 2.7 K, the background radiation of the Universe [2]. As far as we know, the only photon-mass experiment performed previously at a temperature below 2.7 K was a null test of Coulomb's law [3] which resulted in an upper limit of the photon mass of $m_\gamma \leq (1.50 \pm 1.38) \times 10^{-42}$ g at 1.36 K.

In view of an experimental determination of m_γ the electromagnetic fields are supposed to obey the Proca equations [4,5]. In principle they are modifications of Maxwell's equations in the form of additional mass-dependent terms changing the electric and magnetic fields on a scale given by the Compton wavelength $\lambda\!\!\!^{-}_\gamma = \hbar/m_\gamma c$ of the hypothetical massive photon. Thus, any effect admissible to experiment is related to $\lambda\!\!\!^{-}_\gamma$ and the measured upper limit of the photon mass is inversely proportional to the scale of the experiment [6]. Therefore the sensitivity expected in cryogenic photon-mass experiments is considerably reduced because of size limitations.

Although we are aware of a note of Abbot and Gavela [7] seriously questioning any temperature effect on the photon mass, we decided to try another experimental approach to this problem. We expected to gain a significant improvement of the upper photon-mass limit from a laboratory cryogenic measurement by using an experimental method based on *a null test of Ampère's law* and utilizing a very sensitive SQUID magnetometer as a detector of changes of magnetic flux. Below we describe the method and present our result for the upper limit of the photon mass at the lowest test temperature yet achieved in such experiments, 1.24 K. We believe that this method is also well suited to explore the temperature range below 1 K.

In the case of a nonzero photon mass and in the quasistatic limit the magnetic field obeys [4,5]

$$\mathrm{rot}\mathbf{B} = (4\pi/c)\mathbf{J} - \mu^2\mathbf{A}\,, \tag{1}$$

where $\mu = \lambda\!\!\!^{-}_\gamma{}^{-1} = m_\gamma c/\hbar$ is the inverse Compton wavelength of the photon and $\mathbf{A}$ is defined by $\mathbf{B} = \mathrm{rot}\mathbf{A}$. An experimental test of Ampère's law is based on the measurement of the line integral of a magnetic field $\mathbf{B}$ along a closed curve C, which in the case $m_\gamma \neq 0$ becomes

$$\oint \mathbf{B}\cdot dl = \frac{4\pi}{c}\int_C \mathbf{J}\cdot d\mathbf{f} = \mu^2 \int_C \mathbf{A}\cdot d\mathbf{f}\,. \tag{2}$$

In order to attain a high sensitivity of the experiment, we chose a coil configuration for which no current passes through a surface bound by the closed curve C, which automatically yields *a null result*, if Ampère's law applies. If, however, $m_\gamma \neq 0$, the line integral of magnetic field $\mathbf{B}$ along C is given by

$$\Gamma_C = -\mu^2 \int_C \mathbf{A}\cdot d\mathbf{f}\,. \tag{3}$$

Figure 1 schematically shows the configuration of the experiment. The magnetic field $\mathbf{B}$ is induced by a wire-wound toroidal coil carrying a current I. The line integral of the magnetic field $\mathbf{B}$ along a circle C around the axis of the source coil is monitored, to a high approximation, by the toroidal pickup coil, placed inside the hole of the source coil. The cylindrical superconducting shield acts as a "Proca filter." It causes no attenuation of the φ component of the magnetic field, which in this configuration can only be induced by a violation of Ampère's law. However, any magnetic field which has no φ component can be shielded in this manner; i.e., it is sup-

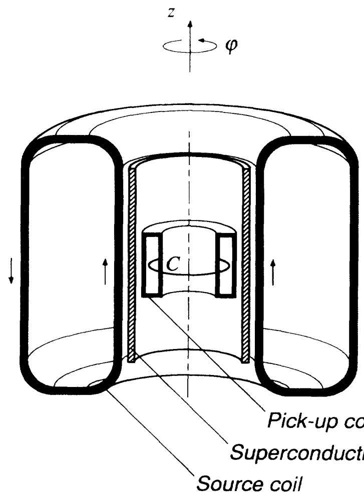

FIG. 1. Diagram illustrating the principle of the coil arrangement and the superconducting shield. This shield does not inhibit the hypothetical part of the magnetic field which violates Ampère's law.

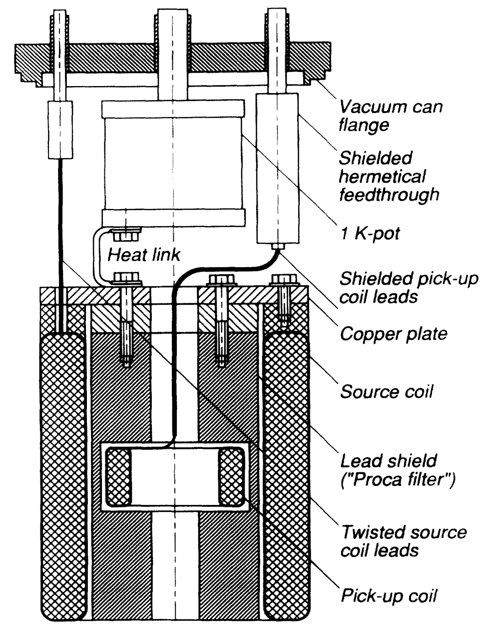

FIG. 2. Schematic diagram of the experimental setup.

pressed at least by a factor of $e^{-0.62a/r}$, where a is the height and r is the radius of the shield.

The limit of the photon mass as determined by a possible magnetic-flux change through the pickup coil can be easily deduced if the wire-wound toroidal source coil with N turns is approximated by an equivalent current-carrying surface. In the region of the pickup coil the vector potential $\mathbf{A}$, induced by the current I in the source coil, has only a z component and is given by

$$A_z=(2G/c)NI\ln(R_o/R_i)[1+O(D^2\mu^2)]\,, \tag{4}$$

where R_i and R_o are the internal and external radii of the source coil, respectively, and the factor G accounts for the finite height h of the source coil [8]. The parameter D denotes the physical size of the experiment. The corresponding change in the magnetic flux through the toroidal pickup coil with inner radius r_i, outer radius r_o, height b, and n wire turns is

$$\delta\phi=\mu^2(G/2c)NI\ln(R_o/R_i)nb(r_o^2-r_i^2)\,. \tag{5}$$

A fraction $L_i/(L_p+L_i)$ of this magnetic-flux change is transferred to the SQUID, where L_i is the self-inductance of the SQUID input coil and L_p is the self-inductance of the pickup coil. The change $\Delta\phi$ of the magnetic flux measured by the SQUID thus determines the limit of the photon mass by

$$m_\gamma\le\hbar\left(\frac{L_p+L_i}{L_i}\,\frac{2}{GcN\ln(R_o/R_i)nb(r_o^2-r_i^2)}\,\frac{\Delta\phi}{I}\right)^{1/2}. \tag{6}$$

All the ideas presented above lead to the following experimental arrangement. To provide a shielding against external interferences, the cryostat containing the magnetometer was installed inside a shielded room and mounted on a concrete plate. A schematic drawing of the magnetometer is shown in Fig. 2. The SQUID sensor (model SP magnetometer probe [9], $L_i=2$ μH) is located above the top flange of the vacuum can and housed inside an additional cylindrical lead shield with a length-to-diameter ratio $l/d\approx 12$. Suspended inside the vacuum can are a continuously filled pumped ^{4}He bath (1 K-pot), a shielded hermetical feedthrough (model SEC remote terminal board [9]) to provide the flux transformer wires from the outer helium bath to the pickup coil, and a copper plate which provides mechanical support for the coils and which is thermally anchored to the 1 K-pot. The source coil, wound on a toroidal core machined from Stycast 1266 epoxy, contains two sections of 180 turns of copper-cladded 0.3-mm Nb-Ti wire, each wound in the same sense around the cross section of the toroid but in the opposite sense around the axis of the toroid. The source coil was screwed to the copper plate and thermally coupled to it by aluminum tape, covering all of the outside surface of the coil. The pickup coil, containing 30 turns of 0.13-mm-diam Nb-Ti wire, was fabricated in the same way as the source coil on a core with 30-mm i.d., 45-mm o.d., and 20-mm height ($L_p=1.46$ μH). The pickup coil is mounted inside the superconducting shield and is anchored to it with vacuum grease. The shield in turn is housed inside the source coil and screwed to the copper plate. The pickup coil leads are twisted and shielded within a 0.5-mm-i.d., 1-mm-o.d. Pb-Sn tube filled with vacuum grease. An external cylindrical superconducting shield made of a 0.2-mm-thick lead foil surrounds the vacuum can and the sensor at a diameter of

110 mm and a length of 600 mm. It freezes in place any external magnetic field (e.g., Earth's field) during the initial cooldown, so that the experimental volume is shielded from subsequent fluctuations in external magnetic fields during the experiment. A detailed description of the magnetometer and a discussion of its performance limit will be published elsewhere.

The flux resolution of the magnetometer with the source coil driven by a dc current is restricted by the dc stability of the rf SQUID output. Under typical conditions, with the SQUID sensor shielded from external fields (superconducting shortage between input terminals) and operated in a helium bath at atmospheric pressure, the drift referred to input is typically within $\pm 2\times 10^{-4}\phi_0$ ($\phi_0 = 2.068\times 10^{-7}$ G cm^2) over a period of 1 h. In order to achieve a better flux resolution, we used a low-frequency ac excitation of the source coil and a narrow-band detection of the signal. The most favorable frequency range turns out to be around 0.1 Hz, because the noise power spectrum of the SQUID obeys a $1/f$ dependence below approximately 0.1 Hz, and above this frequency the noise is white. In our experiment, the integration time available to enhance the signal-to-noise ratio was restricted by the holding time of the helium Dewar (approximately 10 h). Attempted careful helium transfers induced SQUID output fluctuations at the level of $10^{-2}\phi_0$. These fluctuations are most likely due to the SQUID output dependence on temperature because the sensor is mounted directly in the outer helium bath.

The experiment was controlled by a Macintosh IIx computer. The source coil was driven by a highly monochromatic sine-wave excitation signal synthesized by the computer. Simultaneously the SQUID signal was measured by an analog-to-digital converter and stored on a disk for further Fourier analysis. Details about controlling the primary current and the SQUID output monitoring will again be published elsewhere.

The final measurements were performed at 1.24 K. The source coil was driven with a current amplitude between 0 and 10 A at a frequency of 0.11719 Hz. Data sets were recorded containing 262 144 data points at a sample interval of 0.133 s or 64 data points during one period of the excitation sine wave. The data analysis was done by performing a fast Fourier transform on the entire data set with a frequency resolution of 2.86×10^{-5} Hz, as given by the duration of the measurement.

The measured mean-noise spectral density of the magnetic flux in the frequency range between 0.115 and 0.119 Hz was typically $S_\phi = (1.5\pm 0.8)\times 10^{-4}\phi_0/\text{Hz}^{-1/2}$, which corresponds to a mean noise of $(7.9\pm 4.3)\times 10^{-7}\phi_0$ within the bandwidth of 2.86×10^{-5} Hz. For amplitudes of the driving current of less than 2 A no signal at the excitation frequency above the noise level was observed [Fig. 3(a)]. For amplitudes exceeding 2 A we have observed a signal at the excitation frequency [Fig. 3(b)], whose spectrum showed the expected frequency resolution. The observed signal showed a linear variation with

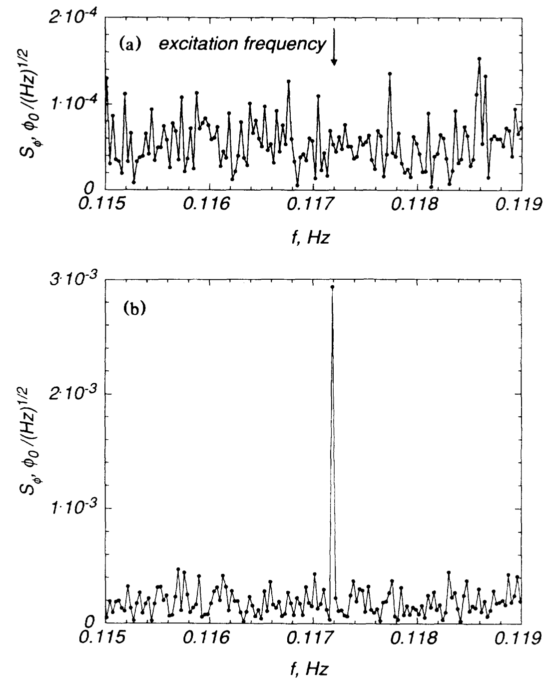

FIG. 3. Spectral density of the magnetic flux in the frequency range 0.115–0.119 Hz. (a) The amplitude of the driving current is 1.5 A. No signal above the noise level is observed at the excitation frequency. (b) The amplitude of the driving current is 10 A. The spurious signal at the excitation frequency serves as an instrumental test signal. It shows the expected frequency resolution.

the amplitude of the excitation current, and therefore is compatible with an inductive coupling between the source coil and the pickup coil. At this point we cannot distinguish between an inductive coupling resulting from an assumed nonzero photon mass and the coupling induced by nonperfect shielding between the source coil and the pickup coil. However, the upper limit of the photon mass can in any case be derived from the slope of the magnetic flux change with the amplitude of the excitation current in the range from 2 to 10 A,

$$d\Delta\phi/dI = (13.9\pm 2.7)\times 10^{-7}\phi_0/\text{A}\,. \tag{7}$$

Substitution of this result into Eq. (6) gives our upper limit of the photon mass at 1.24 K,

$$m_\gamma \le (8.4\pm 0.8)\times 10^{-46}\,\text{g}\,. \tag{8}$$

In order to locate the origin of the observed signal the measurements were also performed at 4.2 K, because the best upper limit of the photon mass of $m_\gamma \le 8\times 10^{-49}$ g was reported for $T = 2.7$ K [10]. At 4.2 K, similar signals for current amplitudes exceeding 2 A to those observed at 1.24 K were monitored. We note that the magnetic flux change compatible with an upper limit of the photon mass of 8×10^{-49} g might be observed in our experiment, provided the shielding between the source coil and the pickup coil is perfect, only at an excitation-current amplitude of the order of 10^6 A. Thus we interpret the observed magnetic flux changes for excitation-current amplitudes exceeding 2 A as a spurious inductive pickup due to nonideal performance of the shielding between the source coil and the pickup coil.

The result given by Eq. (8) implies a reduction of the upper m_γ limit from a cryogenic laboratory experiment by more than 3 orders of magnitude. Experimental attempts to further reduce both the upper limit of the photon mass and the measuring temperature are in progress.

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[8] $G(h\to\infty)=1$ and $G(h=0)=0$. For our source coil $G=0.68$. Because of this factor, our Eq. (5) is not in obvious contradiction to the Goldhaber-Nieto theorem [6], which we wish to quote in the form "think big or be precise."

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