New Experimental Limit on the Photon Rest Mass with a Rotating Torsion Balance

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A rotating torsion balance method is used to detect the product of the photon mass squared and the ambient cosmic vector potential $\boldsymbol{A}_e$. The signal is modulated by rotating the torsion balance to ensure the effectiveness of detection for all possible orientations of the vector potential. The influences of sidereal disturbances of environment are also removed by virtue of this modulation method. The experimental result shows $\mu_\gamma^2 A_e < 1.1 \times 10^{-11}$ T m/m^2, with μ_γ^{-1} as the characteristic length associated with photon mass. If the ambient cosmic vector potential $\boldsymbol{A}_e$ is 10^{12} T m due to cluster level fields, we obtain a new upper limit on photon mass of 1.2×10^{-51} g.

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The triumphs of Maxwellian electromagnetism and quantum electrodynamics set a constraint on the rest mass of a photon that is ordinarily proposed to be zero. Even so, the nonzero photon mass could exist at such a low level that the present experiment cannot reach. According to the uncertainty principle, the photon mass m_γ could be estimated as $m_\gamma \approx \hbar/(\Delta t)c^2$ in the magnitude of about 10^{-66} g as the age of the universe is about 10^{10} years. Although such infinitesimal mass is extremely difficult to be detected, some far-reaching implications for nonzero photon mass, for example, the wavelength dependence of the speed of light in free space [1], the deviations of Coulomb's law [2] and Ampère's law [3], the existence of longitudinal electromagnetic waves [4], and the additional Yukawa potential of magnetic dipole fields [5,6], were seriously studied. These consequences are the useful approaches for the cosmological observations [5,7] or the laboratory experiments to determine the upper limit on the photon mass.

The fully consistent theory of massive electromagnetic fields is described by the Maxwell-Proca equations [8]

$$\nabla \cdot \boldsymbol{E} = \frac{\rho}{\varepsilon_0} - \mu_\gamma^2 \phi, \tag{1}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}, \tag{2}$$

$$\nabla \cdot \boldsymbol{B} = 0, \tag{3}$$

$$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J} + \mu_0 \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t} - \mu_\gamma^2 \boldsymbol{A}, \tag{4}$$

where $\boldsymbol{E}$ and $\boldsymbol{B}$ are the electric and the magnetic fields. ρ and $\boldsymbol{J}$ are the charge and the current densities, respectively. ϕ and $\boldsymbol{A}$ are the scalar and the vector potentials, and $\mu_\gamma^{-1} = \hbar/(m_\gamma c)$ is an effective range of the electromagnetic interaction, with m_γ as the photon mass. The static electric and magnetic fields would exhibit an exponential, $\exp(-r/\mu_\gamma^{-1})$, falloff at distances $r > \mu_\gamma^{-1}$ from sources [5], and other new features mentioned above would emerge. If $m_\gamma = 0$, the Maxwell-Proca equations would be reduced to Maxwell's equations. Gauge invariance is lost if the photon mass is assumed to be nonzero, and the potentials themselves give physical significance, not just through their derivatives. The large cosmic magnetic vector potential $\boldsymbol{A}_e$ described by the Maxwell-Proca equations is observable since the potential acquires an energy density $\mu_\gamma^2 \boldsymbol{A}_e^2/\mu_0$ [1]. Lakes [9] reported an experimental approach based on a toroid Cavendish balance to evaluate the product of photon mass squared and the ambient cosmic magnetic vector potential. The basic idea is to generate a magnetic dipole vector potential moment $\boldsymbol{a}_d$ via a suspended toroidal coil. This magnetic dipole vector potential moment interacts with the ambient cosmic magnetic vector potential to produce a torque $\boldsymbol{\tau} = \boldsymbol{a}_d \times \mu_\gamma^2 \boldsymbol{A}_e$ on the torsion balance. The component along with the fiber (set as z direction in the laboratory frame) can be expressed as follows [10]:

$$\tau_z = A_e \mu_\gamma^2 a_d (\cos\theta \cos\theta_A \cos\lambda - \cos\theta \sin\theta_A \sin\Omega t \sin\lambda - \sin\theta \sin\theta_A \cos\Omega t), \tag{5}$$

where θ is the angle between the latitude and the $\boldsymbol{a}_d$ in the laboratory frame, θ_A is the angle between $\boldsymbol{A}_e$ and the Earth's rotation axis, λ is the latitude, and Ω is the rotation frequency of the Earth. If $\sin\theta_A \neq 0$, the torque will vary with the rotation of the Earth. This is the case considered by Lakes. Consequently he gave $\mu_\gamma^2 A_e < 2 \times 10^{-9}$ T m/m^2, and the corresponding limit on the photon mass is 2×10^{-50} g, if the ambient magnetic vector potential is $A_e \approx 10^{12}$ T m due to cluster level fields. However, if $\sin\theta_A = 0$, which means the cosmic ambient vector potential were to be fortuitously aligned with Earth's rotation axis, in spite of very small probability, then Lakes's scheme would be invalid.

In our experiment, the motion of the torsion balance is modulated by a turntable with frequency ω [let $\theta = \omega t$ in Eq. (5)], which is usually higher than the Earth's rotation frequency Ω. In this case, the torque acted on the torsion balance is expressed as

$$\tau_z(\omega) = \mu_\gamma^2 A_e a_d C \cos(\omega t + \theta_0), \tag{6}$$

where

$$C^2 = (\cos\theta_A \cos\lambda - \sin\theta_A \sin\Omega t \sin\lambda)^2 + (\sin\theta_A \cos\Omega t)^2. \tag{7}$$

Obviously, the parameter C in Eq. (6) is time dependent and τ_Z has no steady amplitude. If $\theta_A = 90°$, then the frequencies of τ_Z, the signal to be determined, are both the sum and difference of the turntable and the sidereal rotation frequencies. In the general case ($\theta_A \neq 90°$), τ_Z will have a steady component with the turntable frequency besides the variable components with the frequencies mentioned above. It means that at least three peaks will be seen on the spectral power density of the fast Fourier transformation (FFT) if we use it to process the experimental data. For estimating the magnitude of the parameter C, we can average it in a sidereal period (24 h) and its root mean square (rms) can be given as

$$\bar{C} = \sqrt{\langle C^2 \rangle} = \sqrt{\frac{3}{4} - \frac{1}{8}\sin^2\theta_A} \geq \frac{\sqrt{10}}{4}, \tag{8}$$

here we have selected the experimental condition with $\cos\lambda = \sqrt{3}/2$. Nonzero $\bar{C}$ means that the modulation method can ensure the effectiveness of detection for all possible orientations of the ambient cosmic vector potential during a sidereal day. Meanwhile the limitation of $1/f$ noise could be reduced and the sidereal noises due to environmental fluctuations are eliminated due to a high modulation frequency.

The novel scheme of a rotating torsion balance for determination of the photon mass is shown in Fig. 1. A toroidal coil of 1720 turns wound on steel carries an electric current of 16.4 mA, which is supplied by a constant current source through a fine aluminum spring, to generate a magnetic dipole vector potential moment in the axial direction without magnetic leakage. This steel toroid, with an inner diameter of 45.0 mm and a cross section of 24.0 mm in diameter, is suspended by a tungsten fiber of 100 μm in diameter and 136.4 cm in length. The magnitude of the magnetic dipole vector potential moment $\boldsymbol{a}_d$ generated by the toroid is $(1.45 \pm 0.08)\ \mathrm{A\,m^3}$. The experimental result shows that the stiffness of the aluminum spring, compared to that of the tungsten suspension fiber, can be neglected, and the oscillating period of the torsion balance with current is (168.0 ± 0.3) s as shown in Fig. 2. The inertial moment of the torsion balance is $(8.55 \pm 0.04) \times 10^{-4}\ \mathrm{kg\,m^2}$, and the torsion constant is deduced to be $k = (1.20 \pm 0.01) \times 10^{-6}\ \mathrm{N\,m/rad}$ subsequently. The small angular displacement caused by the external torque is detected by an optical lever system with resolution of 2.9×10^{-6} rad. The outputs from both sides of the sensor (L signal and R signal) are summed to get $\sum = R + L$ and subtracted to get $\Delta = R - L$ by a preamplifier. The position of the torsion balance gives as $\Delta/\sum$, which can reduce the effect of the laser's intensity variation. A square wave signal of 100 kHz output from a high-stability quartz oscillator was divided into 2 Hz by means of a transistor-transistor-logic frequency-division circuit. It was considered as a standard clock reference and used to control the host personal computer sampling and save the data output from an A/D (analog-to-digital) converter. A digital proportional-integral-differential algorithm calculates the feedback voltage (ΔU), and then it was sent to a D/A (digital-to-analog) converter. The output voltage was incorporated with a forward bias U_0 to get $U_+ = U_0 + \Delta U$ and $U_- = U_0 - \Delta U$ through an amplifier, which are applied to both capacitive plates, respectively. Under the action of feedback control, the external torque was compensated and the torsion balance was maintained in its initial equilibrium state through the parallel capacitive plates. Thus the feedback voltage of the capacitive

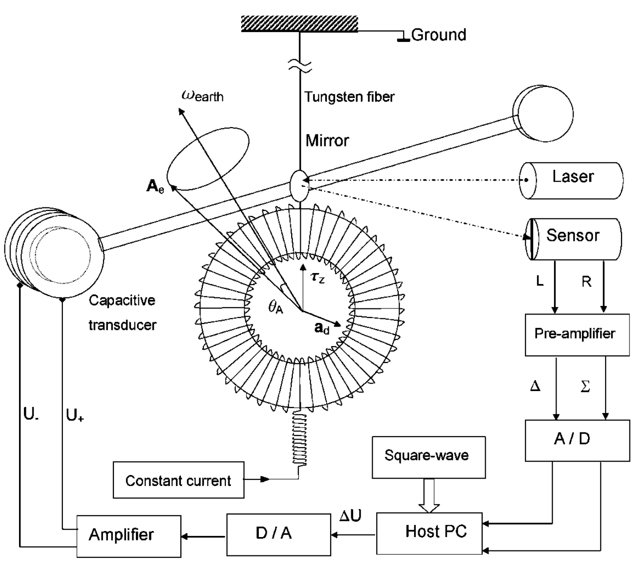

FIG. 1. The experimental setup of the rotating torsion balance. The magnetic dipole vector potential moment $\boldsymbol{a}_d$ arising from the toroidal coil interacts with the cosmic vector potential $\boldsymbol{A}_e$ to produce a torque on the torsion balance. This torque associated with the effect of photon mass varies with time according to the rotation of the torsion balance.

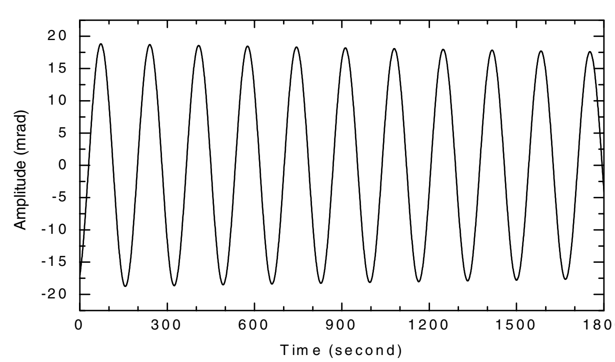

FIG. 2. The free oscillation of the torsion balance with current. A typical segment data of half an hour is shown with the natural period of (168.0 ± 0.3) s.

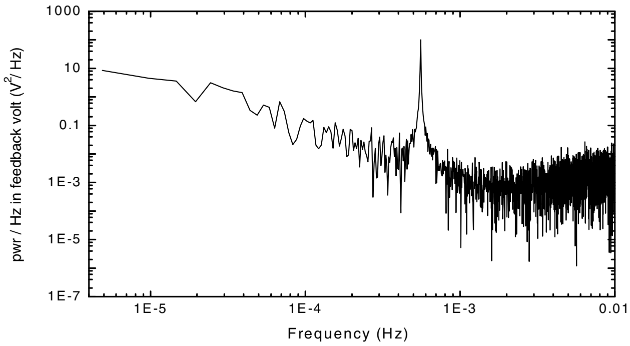

FIG. 3. The power density spectrum of the feedback voltage over 72 hours. The most obvious peak at half an hour is due to the gravitational gradient effect of the experiment site, which is the double frequency of the modulation. The rise of the low energy tail above 2×10^{-3} Hz is due to the damped free resonance of the pendulum.

transducer represents the torques generated by the external noises and the interaction between $\boldsymbol{A}_e$ and $\boldsymbol{a}_d$. The whole system was constructed in a vacuum chamber maintained at 1×10^{-2} Pa, and was rotated with a period of 1 hour by means of a precise turntable. The total apparatus is located in our cave laboratory, on which the least thickness of the cover is more than 40 m [11].

If the photon mass is not zero, the torque produced by the interaction between the magnetic dipole vector potential moment $\boldsymbol{a}_d$ in the toroidal electrical steel and the ambient vector potential $\boldsymbol{A}_e$ would vary with time according to Eq. (6). On the other hand, the compensative torque generated by the feedback voltage on both capacitive plates would take the form as

$$\Delta\tau_f = k\Delta\theta = k\beta\Delta U, \tag{9}$$

where $\Delta\theta$ is the angle variation of the torsion balance, and β is a constant dependent on the parameters of the capacitive transducer. To calibrate the value of β, first, the capacitive transducer keeps an initial feedback voltage to let the beam fall on the middle of the sensor, which is (320 ± 1) mm far from the mirror. Then, the feedback voltage is increased about (91.9 ± 1.6) mV, which changed the rest position of the torsion balance, so the beam shifted (1.00 ± 0.02) mm on the sensor. It means that the angle variation per unit voltage of the torsion balance is $\beta = (17.0 \pm 0.5)$ mrad/V. Setting the compensative torque equal to the external torque resulted from the nonzero photon mass, and the following relation can be obtained as

$$\mu_\gamma^2 A_e \leq \frac{k\beta\Delta U}{Ca_d}. \tag{10}$$

The experimental data are taken over 72 hours at a sampling interval of 0.5 s. To eliminate high frequency fluctuation, the data were averaged over 100 data points, and then we performed a FFT on the entire data set. A typical power spectral density of the feedback voltage applied on the capacitive transducer is shown in Fig. 3. Because the apparatus was set in a corner of the laboratory, the gravitational gradient effect of the laboratory environment acted on the steel toroid is approximately $3 \times 10^{-4}\cos(2\omega t)$ rad, with the rotating frequency of the torsion balance ω. This double frequency effect is the most obvious peak at half an hour while the torsion balance is operated at 1 cycle per hour. However, the double frequency effect can be removed by means of the low-pass filter.

From Fig. 3, we can find the mean value of the power spectral density near the modulation frequency is about 1.6×10^{-2} V^2/Hz. The uncertainty of the modulation frequency and the resolution of FFT are 3.83×10^{-8} Hz and 4.88×10^{-6} Hz, respectively, which are both smaller than the sidereal frequency of 1.16×10^{-5} Hz. Therefore, we should select the bandwidth of 2.32×10^{-5} Hz to estimate the uncertainty of the feedback voltage, which is about 0.61 mV. According to Eq. (9), the corresponding torque uncertainty is about 1.2×10^{-11} N m. Thus the product of photon mass squared and the cosmic vector potential are estimated as $\mu_\gamma^2 A_e < 1.1 \times 10^{-11}$ $\mathrm{T\,m/m^2}$. The cosmic vector potential can be conservatively estimated by considering galactic magnetic fields [12,13] (≈ 1 μG) and its reversal position ($\approx 1.9 \times 10^{19}$ m) toward the center of the Milky Way, then $A_e \approx 2 \times 10^9$ T m. Accordingly, the upper limit on the photon mass is 2.6×10^{-50} g. If the ambient cosmic vector potential is 10^{12} T m, corresponding to the Coma galactic cluster [14] (0.2 μG over a distance of 4×10^{22} m), the

TABLE I. Several important photon mass experiments.

Author	Date	Ref.	Experimental scheme	Upper limit of m_γ (g)
Williams *et al.*	1971	[2]	Test of Coulomb's law	2×10^{-47}
Crandall	1983	[15]	Test of Coulomb's law	8×10^{-48}
Chernikov *et al.*	1992	[3]	Test of Ampere's law	8.4×10^{-46}
Schaefer	1999	[16]	Measurement of the speed of light	4.2×10^{-44}
Fischbach *et al.*	1994	[6]	Analysis of Earth's magnetic field	1×10^{-48}
Davis *et al.*	1975	[7]	Analysis of Jupiter's magnetic field	8×10^{-49}
Lakes	1998	[9]	Static torsion balance	2×10^{-50}
Our result	2002		Dynamic torsion balance	1.2×10^{-51}

upper limit on the photon mass should be 1.2×10^{-51} g. As for comparison with other experiments, this result extends the upper limit on the photon mass by an order at least, and several important experiments of measuring photon mass are presented in Table I.

In conclusion, the most important innovation in our experiment is the modulation method, which is efficacious no matter what the crossing angle between the cosmic magnetic vector potential $\boldsymbol{A}_e$ and the Earth's rotation axis is. Meanwhile the limitation of $1/f$ noise could be greatly reduced and the sidereal noises due to environmental fluctuations are easily eliminated in this method.

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