Cryogenic photon-mass experiment

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We have conducted a Coulomb's-law experiment at 1.36 K, in a search for low-temperature phase-transition effects. Our null result establishes that the photon at 1.36 K has a mass of less than $(1.5 \pm 1.4) \times 10^{-42}$ g.

Maxwell's equations and their equivalent in quantum electrodynamics are among the most thoroughly understood and experimentally verified of nature's laws. However, modern theoretical attempts to understand the origin of parity violation and the finite masses of the carriers of the strong and weak interactions have lead to concepts such as spontaneous symmetry breaking.[1] These theories have utilized the concept of particles which are massless above a critical temperature T_c and acquire a mass below this temperature. Within this framework it is natural to speculate that the photon could also be massless above a critical temperature and acquire a rest mass below that temperature.[2] Convincing theoretical arguments seem to indicate that the absence of charged fermions lighter than the electron would suppress any massive-photon effects by the enormous factor of $\exp(-m_e c^2/kT)$, where m_e is the mass of the electron.[3] However, since a cryogenic Coulomb's-law experiment has never been done and theories are not always consistent with nature, we decided to attempt an experiment at 1.4 K, which is the area in which Primack and Sher speculated that a phase transition could occur.

Unlike a standard Coulomb's-law experiment, our method measures the current that flows between two closed surfaces in response to an impressed voltage difference, not the voltage difference itself. A closed surface (surface 2) is raised to a time-varying potential $V(t)$ with respect to an external ground (surface 1). Another closed surface (surface 3) is entirely contained within 2 and connected to surface 2 via some finite impedance; if there is a violation of Coulomb's law the inner surface 3 will not be at the same potential as 2, and a current will flow between the two surfaces as the potential oscillates. If this current flows through a solenoid located between the surfaces, then the flux changes that occur as the current flows can be detected outside the system by another concentric solenoid.

Figure 1 shows a view of our realization of this approach. In our case the two closed surfaces are an outer glass cylinder (surface 2) with closed ends, which has a 2000-Å-thick silver layer evaporated onto the inner surface, and a highly conductive ferromagnetic rod (surface 3) which lies entirely within the glass cylinder. A final silver-coated glass cylinder (surface 1) contains the two inner surfaces and serves as a ground-potential reference. The silver layer of surface 2 is attached to a voltage source which varies the potential of the surface sinusoidally at an angular frequency ω. A superconducting solenoid of 6300 turns is connected between surfaces 2 and 3, and the surface-1 cylinder is concentric with and contained in a conventional copper solenoid of 7200 turns. External magnetic radiation is shielded from the coils by an aluminum cylinder and a superconducting lead foil. The apparatus was suspended by nylon threads and immersed in a pool of liquid helium. A mechanical pump with a blower booster was used to lower the vapor pressure of the liquid helium to an ultimate pressure of 1.8

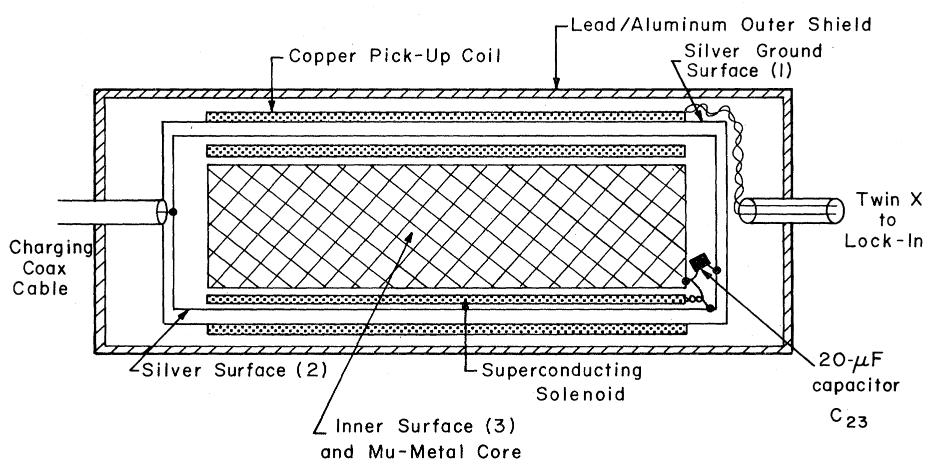

FIG. 1. A schematic of our apparatus. The width scale is exaggerated here for clarity. The actual length of the device was 20 cm for the inner mu-metal core and 22 cm for the outermost shield surface. The surface notation 1, 2, and 3 corresponds to Eq. (4) in the text.

Torr or 1.36 K.

The final magnetic core consisted of a multiple-layer rod, constructed of mu-metal sheet and heat-treated in a hydrogen-atmosphere furnace to obtain maximum permeability, estimated to be greater than 20 000. The final inductance of the coil at room temperature was 4.89 H. Tests of the mutual inductance of the entire system were carried out by driving the inner coil with a signal generator and measuring the voltage that appeared across the external coil. The voltage ratio V_{out}/V_{in} was flat at 1.14 from 50 Hz to 1 kHz at both 293 and 4.5 K, indicating both that the induced eddy currents in the silver layers did not appreciably shield the flux changes and that the increase in conductivity of the silver coating at low temperatures did not significantly affect the flux transfer.

The Proca equation[4] for a massive photon can be used to predict the potential induced between the two inner surfaces. The massive-photon-induced electric field should die off within a closed surface as

$$E_{\text{inner}} = E_0 \exp(-kr) \ , \tag{1}$$

where

$$k^2 = (mc/\hbar)^2 + (\omega/c)^2 \ , \tag{2}$$

and E_0 is the field at $r=0$ determined by the charge density, m is the mass of the photon, c is the speed of light, and $\hbar$ is Planck's constant. Integration of this field between two cylinders of outer radius r_2 and inner radius r_3 yields (if $mc/\hbar$ is much greater than ω/c) gives

$$V_{23}/V_{12} = k^2(r_2^2 - r_3^2)/4 \ , \tag{3}$$

where V_{23}/V_{12} is the ratio of the voltage V_{23} across the innermost and middle cylinder to the driving voltage V_{12}.

In our technique we do not directly measure V_{23}, but instead we measure an induced emf. It is simpler in the circuit analysis to view the breakdown of Coulomb's law as causing an effective capacitance C_{13} between the innermost cylinder and the outer ground. If Coulomb's law holds, then C_{13} would be zero since no charge would reside on the innermost surface due to shielding. Thus, C_{13} is both a geometrical factor and a result of a breakdown in the $1/r$ potential, and a determination of it is a measure of the photon mass. We now calculate the induced voltage in our solenoid due to this capacitance.

The charges on surfaces 1, 2, and 3, called Q_1, Q_2, and Q_3, respectively, are given by the intersurface capacitances:

$$\begin{aligned} Q_1 &= C_{13}V_{13} + C_{12}V_{12} \ , \\ Q_2 &= C_{12}V_{12} + C_{23}V_{23} \ , \\ Q_3 &= C_{13}V_{13} - C_{23}V_{23} \ . \end{aligned} \tag{4}$$

As can be seen by the equivalent circuit in Fig. 2(a), Q_3 must equal zero. The applied voltage V_{12} is also given by

$$V_{12} = V_{23} + V_{13} \ , \tag{5}$$

and as can be seen from Fig. 2(a)

$$V_{23}/V_{13} = C_{13}/C_{23} \ ; \tag{6}$$

thus,

$$V_{23}/V_{12} = 1/(1 + C_{23}/C_{13}) \ . \tag{7}$$

If we know V_{12} and C_{23}, and are able to determine C_{13}, then it is possible from Eq. (7) to determine V_{23}.

To relate V_{23} to the measured voltage V_{out}, note that the complex impedance of the tank circuit formed by L, R, and C_{23} in Fig. 2(b) is

$$Z_{\text{tank}} = [i\omega C_{23} + (i\omega L + R)^{-1}]^{-1} \ , \tag{8}$$

where $(-1)^{1/2} = i$. The resistance R here does not represent a real resistance in the coil, which is a superconductor, or surface resistance in the thin silver coatings, which is less than 0.1 Ω, but represents the hysteresis loss in the paramagnetic core of the inner inductor. The voltage across the tank V_T is

$$V_T = V_{12}[Z_{\text{tank}}/(Z_{\text{tank}} + 1/i\omega C_{13})] \tag{9}$$

and the voltage across the external solenoid V_{out}, which is what we measure, is

$$V_{out} = \frac{M}{L} | V_T iL/(i\omega L + R) | \ , \tag{10}$$

where M is the mutual inductance of the two solenoids ($M = 1.4L$). Substitution of Eqs. (8) and (9) into (10)

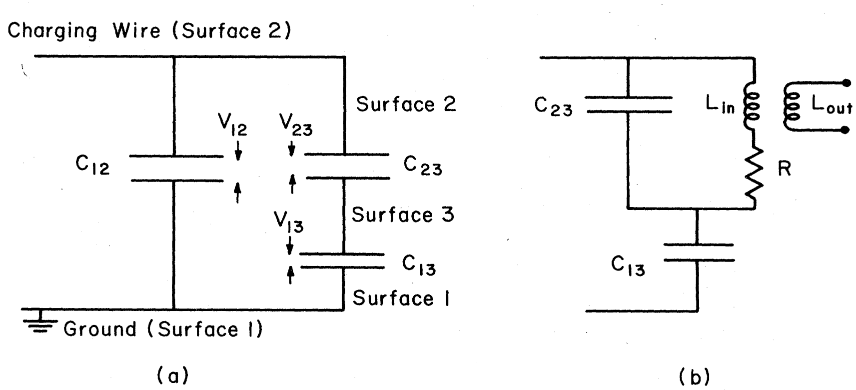

FIG. 2. (a) The static-capacitor arrangement corresponding to Eq. (4) in the text. V_{12} is the driving voltage from the signal generator, V_{23} is the voltage that appears across the two innermost surfaces due to a breakdown in Coulomb's law, and C_{13} is the capacitance that from Eq. (4) can be used to calculate V_{23}. (b) The actual equivalent circuit used in our experiment. R is an effective resistance that accounts for the Q of the mu-metal core of internal inductor L_{in}, and L_{out} is the pick-up inductor.

yields the desired connection between V_{out} and C_{13}, and use of Eq. (7) then yields V_{23}.

The sensitivity of the apparatus is directly proportional to C_{23} and is maximal at the resonance frequency $(LC_{23})^{-1/2}$. The resonance frequency should be as low as possible to avoid spurious relaxation effects. This can be done by making both L and C_{23} as large as possible, but it was difficult to increase the inductance of the solenoid greater than a factor of about 100 from the air-core value of 0.04 H due to the air-return flux path.

The capacitance C_{23} between the cylinders for our system is very small (about 10 pF) and would have required driving the system at frequencies close to the relaxation time of the surface; thus we were forced to add an additional capacitance C'_{23} between the two cylinders. We added a 2.0×10^{-5}-F monolithic capacitor (Centralab Capacitors). In the following discussion, we will set $C_{23}=C'_{23}$.

There are two reasons that Eq. (3) is still valid even in the presence of the 20-μF capacitor added: (i) the volume of the capacitor is much less than the volume between the cylinders and is therefore a minor perturbation on the fields, and (ii) the capacitor charges to the highest voltage driving the system, which is V_{23} in Eq. (3) with the extremum $(r_2{}^2-r_3{}^2)$. Therefore if the photon has mass m, the concentric cylinders will have a potential difference whose magnitude is given by Eq. (3), where the radii in Eq. (3) are those of the cylinders.

In the experiment we have four unknowns, C_{13} and the low-temperature values of L, R, and C_{23}. The monolithic capacitor C_{23}, in particular, has a large temperature dependence. To calibrate the instrument and determine the values of the parameters in Eqs. (8), (9), and (10), two preliminary tests were performed with one of the conductive end caps on surface 2 removed. Removal of the end cap allows leakage of the E field into the inner volume and results in a finite C_{13}. Relaxation calculations gave an estimate of $C_{13}=10^{-13}$ F. A 20-V (peak-peak) variable-frequency generator supplied the voltage V_{12} and supplied a synchronization signal to a vector lock-in amplifier (Brookdeal). At room temperature the tank is highly overdamped because of the 1.6-kΩ resistance of the warm niobium superconducting coil. However, the plateau value of V_{out}/V_{12} for frequencies much greater than the natural resonance frequency is

$$V_{out}/V_{12}=(M/L)C_{13}/C_{23} \ . \qquad (11)$$

In this test we knew C_{23} was 2.0×10^{-5} F so we determined that C_{13} for the open end was 2.0×10^{-13} F.

The second open-end test was performed at 4.2 K, using the above value of C_{13} as given, to determine the other (temperature-dependent) values. Equations (8), (9), and (10) were used to calculate the predicted voltage versus frequency. The combination of plateau value (C_{13}/C_{23}), resonance frequency (LC_{23}), and $Q(L/R)$ then gives three equations in three unknowns. The results are plotted in Fig. 3(a). We found $L=0.85$ H, $R=200$ Ω (giving a Q at 386 Hz of 10.3), $C_{23}=2.0\times10^{-7}$ F, and $C_{13}=2.0\times10^{-13}$ F. Fits were done by using a computer to evaluate the χ^2 between data and the theoretical predictions, but adjustment of the parameters was done manually. The standard deviation of the data was determined by measurement of the noise at a particular frequency. Our best fits yielded χ^2 less than 2, but we did not attempt error analysis on the best-fit values.

In order to test Coulomb's law the surface 2 was closed and the pickup of the outer coil was measured as a function of temperature from 4.2 to 1.36 K at 20-V peak-peak drive. We assume that the finite signal seen at 4.2 K is due to small pinholes and leaks in our silver-paint seals and not due to a breakdown of Coulomb's law, since the astronomi-

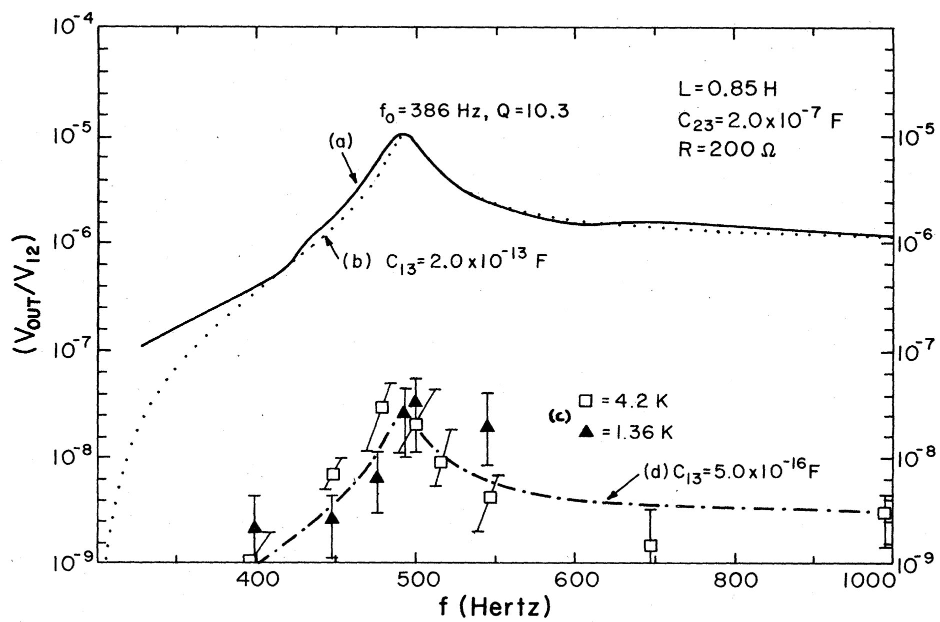

FIG. 3. (a) The response of the system with one end of the cylinder 2 open. (b) The predicted response of the system from Eq. (7) with the circuit values shown in the upper right-hand corner. (c) Measured values of the system with the cylinder 2 closed at 4.2 K (open squares) and 1.36 K (closed triangles). The error bars represent standard deviations of three measurements. (d) The best fit to the data allowing only C_{13} to vary.

cal magnetic field tests of Coulomb's laws are presumably at 3 K and offer impressive limits to any violation of Coulomb's law. Thus, we looked for any changes in the size of the signal seen as the sample was cooled from 4.2 to 1.36 K. These data are shown in Fig. 3(c).

Since we know from the open-end experiment all the parameters but C_{13}, it was possible to fit the closed-end data for the best value of C_{13}. Error bars for these data were determined by three separate measurements and computation of a rough standard deviation. A least-squares computer fit using Eqs. (8), (9), and (10) and restricting C_{13} to be the only variable, yielded values of C_{13} at both 4.2 and 1.36 K. We find that the upper limit on an increase of C_{13} at 1.36 K was $5.0 \pm 4.0 \times 10^{-17}$ F (error bars are 1 standard deviation). From Eq. (7) this yields that V_{23}/V_{12} was 2.5 ± 10^{-10}. Equation (3) with $r_3 = 0.8$ cm and $r_2 = 1.1$ cm yields

$$m \leq (1.5 \pm 1.38) \times 10^{-42} \text{ g at } 1.36 \text{ K} ,$$

or

$$m \leq (9.0 \pm 8.1) \times 10^{-10} \text{ eV} .$$

Although the best terrestrial experiments give $m \leq 2 \times 10^{-47}$ g, this experiment could be easily scaled to yield lower values. In principle our device can be put into a dilution refrigator and use SQUID (superconducting quantum-interference device) detection of magnetic field changes for a test at mK temperatures and with greatly enhanced sensitivity.

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