# MATTERS ARISING

## Absence of thermal effects on photon mass measurements

THE mass of the photon[1,2] is known to be less than $10^{-16}$ eV. However, in a letter to *Nature*, Primack and Sher[3] have questioned the validity of this result. They suggest that electrodynamics may undergo a phase transition at low temperature, and point out that all of the photon mass experiments took place at temperatures above a few degrees Kelvin. Thus, they claim that the above mass limit may only apply to a high-temperature phase ($T > T_c$ where $T_c$ could be as large as a couple of degrees Kelvin), and that when measured at lower temperatures the photon mass could be as large as about $10^{-4}$ eV. Apparently, low-temperature photon mass experiments are presently being considered[4]. We explain here why we believe that the scenario proposed by Primack and Sher[3] is, in fact, impossible. We find that the limit of $10^{-16}$ eV on the mass of the photon is unaffected by the fact that the relevant experiments were performed at finite temperature. It is therefore completely valid and applies to experiments regardless of whether they are carried out at room temperature or at absolute zero.

To analyse thermal effects on measurements of the photon mass we must define what is meant by a phase transition in finite temperature field theory[5–7]. At zero temperature, the vacuum and the various particle states are described by definite state vectors. We can study vacuum expectation values of different field operators and we can measure the photon mass by examining how a photon propagates through the vacuum. At non-zero temperature, the system is described by a density matrix. We can no longer consider vacuum expectation values, but instead we deal with thermal expectation values. At finite temperature space is filled with thermal radiation and to measure the photon mass we must determine how a photon propagates through this thermal radiation. It is important to note that the vacuum does not change with temperature. However, quantities like field expectation values or particle masses can change because at non-zero temperatures they are measured not in the vacuum but in a thermal ensemble.

Therefore, we must ask what is the nature of the thermal fluctuations which occur at or below room temperature, and how can these affect the measured value of the photon mass? In particular, are the interactions of the photon with the thermal fluctuations at these temperatures strong enough to make a massive photon appear massless? The mass of a field sets a lower limit on the energy of its small fluctuations so a field of mass $m$ will only experience significant fluctuations at temperatures $kT \geqslant m$. At room temperature or below the only relevant thermal radiation consists of blackbody photons. Note that if there existed a fundamental or composite scalar field with a small vacuum expectation value which gave the photon a mass, then this field would only experience significant thermal fluctuations at normal temperatures if it produced a charged scalar particle with a mass of a fraction of an eV. If the associated charge scalar were heavier than this then thermal fluctuations of this scalar field would be exponentially suppressed. Since no such light charged particle exists we conclude that there is no way for thermal fluctuations to change the expectation value of such a field and thereby change the photon mass from some non-zero low-temperature value to zero at room temperature. However, we must still consider the effect of thermal photons on the photon mass at finite temperature.

The real-time thermal propagator for a particle of mass $\mu$ is

$$\frac{i}{k^2-\mu^2}+\frac{2\pi}{e^{E/kT}-1}\,\delta(k^2-\mu^2) \qquad (1)$$

The temperature-dependent term in this propagator is multiplied by $\delta(k^2-\mu^2)$ so thermal effects are completely absent, to lowest order in $\alpha$, for off-shell, virtual photons. The best limits on the photon mass come from measurements of the static magnetic field produced by Jupiter and these involve virtual photons. The second term in equation (1) is only relevant for real, on-shell photons of energies $E \leqslant kT$. For these photons this term represents the stimulated emission effect which the presence of thermal photons produces. Equation (1) is of course modified by order $\alpha$ corrections due to the interactions between thermal photons and a propagating virtual photon. However, such interactions occur only through loops of charged particles and are suppressed by a factor $e^{-m/kT}$ where $m$ is the mass of the charged particle. The lightest charged particle is the electron and it produces polarization factors,

$$\Pi_{\mu\nu}\,\alpha\, e^2 m_e^2\left(\frac{m_e}{kT}\right) e^{-m_e/kT} \qquad (2)$$

At temperatures of order room temperature or below, the factor $e^{-m_e/kT}$ is a gigantic suppression factor so these thermal effects are completely negligible. Thus, a virtual photon propagating through thermal radiation at normal experimental temperatures is completely unaffected by the presence of that radiation simply because no mechanism exists for it to interact in any appreciable way with the thermal photons. It follows that experiments which determine how a virtual photon propagates, like the photon mass experiments, will be unaffected as well. The photon mass limit of $10^{-16}$ eV is therefore valid at low temperature.

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L. F. ABBOTT
M. B. GAVELA*

*The Martin Fisher School of Physics,*
*Brandeis University,*
*Waltham,*
*Massachusetts 02254, USA*

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* Permanent address: Laboratoire de Physique Theorique et Hautes Energies, University Paris-Sud, 91405 Orsay, France.

1. Goldhaber, A. S. & Nieto, M. N. *Rev. mod. Phys.* **43,** 277–296 (1971).
2. Davis, L., Goldhaber, A. S. & Nieto, M. N. *Phys. Rev. Lett.* **35,** 1402–1405 (1975).
3. Primack, J. R. & Sher, M. A. *Nature* **268,** 680–681 (1980).
4. Dombey, N. *Nature* **288,** 643–644 (1980).
5. Dolan, L. & Jackiw, R. *Phys. Rev.* **D9,** 3320–3341 (1974).
6. Weinberg, S. *Phys. Rev.* **D9,** 3357–3378 (1974).
7. Linde, A. D. *Prog. theor. Phys.* **42,** 389–435 (1979).

SHER AND PRIMACK REPLY—In our paper, we explained that neither spontaneous nor dynamical symmetry breaking could lead a mass for the photon at low temperature; but we speculated that some other physical mechanism could conceivably do it, and we pointed out that the question could be decided experimentally. Abbott and Gavela argue again that spontaneous symmetry breaking (the 'Higgs mechanism') will not work. The essential physical point they make is that "... a field of mass $m$ will only experience significant fluctuations at temperatures $kT \geqslant m$." We agree. The question is whether the absence of charged particles (either bosons, mentioned by Abbott and Gavela, or fermions) lighter than the electron excludes an electromagnetic phase transition at $kT < m_e$, even one arising from a hitherto unknown mechanism. We are persuaded that their argument indeed excludes this possibility.

It should be noted that this argument could affect other, more realistic calculations. There have been many calculations of supercooling in both $SU_5$ and the Weinberg–Salam model. In some of these, the mass (at $T=0$) of the scalar before the transition vanishes (Coleman–Weinberg); the field can then experience significant fluctuations. In some, however, the scalar does have a small but non-zero mass $m$ (see ref. 1). The argument of Abbott and Gavela appears to rule out a transition at $T \ll m$; completing a transition at such a temperature may not be possible (if only the Higgs potential is considered; *massless* fermions could condense and drive the transition if the coupling constant is large enough).

MARC A. SHER
JOEL R. PRIMACK

*Physics Department,*
*University of California,*
*Santa Cruz,*
*California 95064, USA*

1. Cook, G. P. & Mahanthappa, K. T. *Phys. Rev.* **D23,** 1321–1336 (1981).

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