Experimental Test of the Effective-Photon Hypothesis

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The effective-photon hypothesis postulates a photon energy variable with light intensity according to a relation of the form \( \epsilon = hv/[1 - \beta f(I)] = hv_1 \). This hypothesis has been subjected to direct experimental test. A Mach–Zehnder interferometer is illuminated with a Q-spoiled Nd:glass laser and the time history of the interference fringes is recorded with an image converter camera. The experimental results show that indeed the laser pulse is not monochromatic and that a large frequency change occurs with light intensity. In addition, the analysis of the results indicates that the principle of conservation of energy is not in contradiction with the hypothesis of "effective photon," provided photons can exchange energy among themselves.

1. INTRODUCTION

The concept of the effective photon has been recently introduced in order to interpret ionization phenomena in gases irradiated with high-intensity laser beams.\(^\text{(1,2)}\) The concept departs from the usual notion of a photon indistinguishable and noninteracting with other light quanta. A photon–photon interaction force is postulated to exist and it is assumed that it becomes significant only at high photon densities such as those found in high-intensity laser beams. As a consequence of this hypothesis, the energy of a photon cannot be independent of light intensity. In fact, since the interaction force requires some work to be done in order to bring a photon near a collection of other photons, this work translates into a photon energy increase at high photon densities. At present, the mechanism whereby the energy increase occurs is unknown. However, if the effect is concisely represented through a new photon energy expression

\[
\epsilon = hv \exp[\beta f(I)] \approx hv/[1 - \beta f(I)] \quad (1)
\]

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where the symbols conserve the definition given in Ref. 1, then a whole new class of experimental investigations and theoretical analyses is established. In Refs. 1 and 2 a theoretical analysis of the consequences of assumption (1) has been worked out in detail in connection with ionization and breakdown of gases by high-intensity laser beams. A remarkable agreement has been shown to exist between the predictions of the theory and the experimental results. By contrast, the failure of classical theories, multiphoton and cascade, to explain the same phenomena of laser-induced gas ionization has yielded concomitant evidence that the usual photon concept cannot retain its validity in cases where extremely high light intensities are involved.

The effective-photon hypothesis then seems to be anchored on good ground. However, the far-reaching implications of the hypothesis, both in pure and applied physics, make it desirable to have it verified in as many independent ways as possible. The objective of this paper is to offer the first direct experimental evidence of the validity of the effective-photon concept. An interferometric method of frequency measurement of a high-intensity laser beam has been set up and the experimental results confirm that the photon frequency, hence the photon energy, indeed depends on light intensity.

We shall presently proceed with the description of the experimental apparatus and report on the results. However, before doing this, we should devote some discussion to another important point, namely whether or not Eq. (1) is in contradiction with the principle of conservation of energy. The following section will deal at length with this problem and it will be shown that conservation of energy is maintained.

2. COMPATIBILITY OF THE EFFECTIVE-PHOTON HYPOTHESIS WITH THE PRINCIPLE OF CONSERVATION OF ENERGY

We have mentioned that the initial motivation for the adoption of Eq. (1) has been the need to explain, in a unified and convincing form, the experimental results of laser-induced gas ionization. The success in this endeavor allows us now to move further with the analysis and inquire whether or not conservation of energy invalidates Eq. (1).

First, it is necessary to prove that an interaction force exists between photons and that this force opposes a mutual photon approach. To this end, we refer to an experiment done not long ago with a laser pulse of known length \( L_0 \) incident upon a medium whose refractive index \( n \) decreased linearly with time (Fig. 1). The experiment showed that the pulse emerged from the medium with a linearly increasing phase advance and grew shorter with an accompanying increase in frequency. A subsequent theoretical analysis of this result done with the help of Maxwell's equations proved that