PROPOSED EXPERIMENT TO DETECT THE MASS SHIFT OF AN ELECTRON IN AN INTENSE PHOTON FIELD

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We propose an experiment in which a frequency shift in atomic spectra would be sought as evidence of the theoretically predicted mass shift of an electron in an intense photon field. It is shown that the effect would be readily measurable if it exists.

Within recent years, a number of theoretical papers have been published[1] in which it appears that a free electron acquires an additional mass when in the presence of a plane-wave electromagnetic field. The existence of this effect has been a focus of interest, and a certain amount of controversy has arisen[2] on the subject. Direct experimental evidence on this matter would not only settle the immediate question of the existence of the mass shift, but would also clarify related theoretical questions about the proper definition of electron momentum in the presence of an intense photon field.[3]

Several articles relating to possible measurement of the mass shift have been published[4] recently. However, there still does not appear to be a suggestion that would lead to an unambiguous observation of the mass-shift effect without encountering severe experimental difficulties.

The experiment being suggested here depends upon the fact that the frequencies of the spectral lines of an atom are proportional to the mass of the atomic electron. Thus, if the spectrum of an atom in an intense photon-field environment is compared with the normal spectrum, an increase in mass of the atomic electron engaged in a transition between atomic energy levels would manifest itself as an increase in frequency, i.e., as a violet shift.[5] For simplicity of exposition, it will be presumed that the experiment is to be done with a hydrogen atom. Some other atom would probably be more convenient for the experiment, but the conclusions obtained from the hydrogen atom discussion will still be pertinent. In particular, the relative frequency shift will be the same. The hydrogen atom will be described by a second-order relativistic wave equation with the spin term neglected, which is a justifiable approximation for the relevant experimental conditions. The four-vector potential that occurs in this Klein-Gordon equation will be taken to contain both the Coulomb field and a monochromatic plane-wave field. Since one field is longitudinal and the other transverse, there are no cross terms between them, and the equation can be written

$$[(i\partial^\mu)^2-2ieV\partial^0+e^2V^2 -m^2-2ieA_\mu\partial^\mu+e^2A^2]\psi=0 \tag{1}$$

where $\hbar=c=1$. Here V represents the Coulomb field and A^μ the plane-wave field. The first four terms in Eq. (1) constitute the conventional hydrogen-atom problem. The last term gives the mass shift.[3,6] The resulting mass squared of an electron in a monochromatic photon field is given by

$$M^2=m^2+\Delta m^2,$$

where m is the free electron mass, and Δm^2 is the field-strength-dependent quantity

$$\Delta m^2/m^2=2\rho\lambda e^2/m^2.$$

Here, ρ is the density of photons and λ is the wavelength of the electromagnetic field. For all experimentally realizable photon densities $(\Delta m^2/m^2)\ll 1$, so the relative mass change, and thus the relative frequency shift of the atomic spectrum toward the violet, is

$$(M-m)/m\approx\tfrac{1}{2}(\Delta m^2/m^2).$$

A laser suggest itself as a source of the intense photon field because of the high power densities available and because the laser comes closest to approaching the monochromatic field condition which is employed in the derivation of the mass shift. For a pulsed ruby laser with focusing, $(M-m)/m$ is presently limited to about 10^{-6}. A spectral frequency shift of one part in 10^6 should be detectable.

When written in terms of power P, wavelength λ, and cross-sectional area A of the photon beam, it can be shown that

$$\Delta m^2/m^2\propto P\lambda^2/A.$$

This suggests the investigation of a long-wavelength source. In particular, since 3×10^6 W of 10-cm pulsed microwave power can be achieved in a wave guide of 30-cm^2 cross-sectional area, then it is found that $(M-m)/m\approx 2\times10^{-4}$. This leads to a frequency shift in atomic spectra which is of easily detectable magnitude.

The monochromatic assumption made here is not critical. It has been shown that the mass-shift effect persists even when the photon beam is not purely monochromatic. Also, because the characteristic atomic transition time of about 10^{-15} sec is so much shorter than either laser or microwave pulses, the wave-packet nature of the photon field would hardly be discernible to the atom.

According to the discussion up to this point, the last term in Eq. (1) can be added on to the first four terms as a mass increment, so that if not for the next to last term, Eq. (1) would describe a simple hydrogen atom with an electron of mass M. The term $-2ieA_\mu\partial^\mu$ in Eq. (1) can be treated by a simple nonperturbative approximation method.[8] The effect of this term is to cause a broadening of the spectral line for the transition between the $n=2$ and $n=1$ levels in hydrogen with a full width $(12\omega/e^2)(\Delta m^2/m^2)^{1/2}$. The mass-shift effect for this transition is $\frac{3}{16}me^4\Delta m^2/m^2$. The ratio of the mass-shift effect to the broadening is thus

$$R=\tfrac{1}{64}(me^6/\omega)(\Delta m^2/m^2)^{1/2}.$$

For the laser parameters mentioned above, R has the value $\frac{1}{4}\times10^{-5}$. A laser source, therefore, does not appear to be feasible for this experiment. On the other hand, the microwave environment specified above leads to a value of R of about 5. Thus, the microwave experiment possesses the dual advantage that the mass-shift effect has the relatively large magnitude of two parts in 10^4 of the unshifted spectral line, and the shift will not be masked by the broadening which is a concomitant effect of the plane-wave field.

In summary, measurement of the spectra of atoms excited in an intense microwave-field environment should make possible the observation of a frequency shift in the spectra due to an intensity-dependent mass increase of the atomic electrons. In fact, any high-resolution measurement involving electron phenomena will serve the same purpose as long as the phenomena have a dependence on the mass of the electron. For example, one could seek a change in resonant frequency in an atomic-beam magnetic-resonance experiment due to corrections to the magnetic moment arising from the mass-shift effect. This relative change would also be about two parts in 10^4 in the microwave environment described above.

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[4]J. H. Eberly, Phys. Rev. Letters 15, 91 (1965); T. W. B. Kibble, ibid. 16, 1054 (1966); Phys. Rev. 138, B740 (1965). N. J. Phillips and J. J. Sanderson, Phys. Letters 21, 533 (1966).

[5]This frequency-shift effect is quite distinct from the intensity effects arising from higher order corrections to transition energies as calculated by M. Mizushima, Phys. Rev. 133, A414 (1964); and from the shift arising from near-resonant virtual transitions described by C. Cohen-Tannoudji, in Advances in Quantum Electronics, edited by J. R. Singer (Columbia University Press, New York, 1961), p. 114.

[6]As discussed in Ref. 3, $-e^2A^2=\text{constant}\equiv\Delta m^2$ for circular polarization. For plane polarization other terms also occur, but they will be similar in effect to the $ieA_\mu\partial^\mu$ term and of smaller magnitude.

[7]H. R. Reiss, Bull. Am. Phys. Soc. 11, 96 (1966).

[8]This method is moderately accurate for the laser values used here, and very accurate for the microwave case. A paper on this subject is in preparation.