Induced Light-by-Light Scattering Experiment

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Abstract

Past suggestions for a demonstration of light-by-light scattering by a variation of four-wave mixing may be realizable in the near future with tabletop teraWatt lasers.

Introduction

During the Workshop Alexander Varfolomeev pointed out that light-by-light scattering at optical frequencies can be enhanced by use of a third laser beam [1]. Norman Kroll remarked that he had also considered this in the 60's [2]. Here we consider whether a 1-teraWatt laser, such as that built at U. Rochester for SLAC E-144 [3], could be used to perform such an experiment, and conclude that rates are still somewhat low. Perhaps with the recently reported 50-teraWatt lasers [4] the signal can be seen.

The cross section for light-by-light scattering is very small [5]:

$$\sigma = \frac{973}{10125\pi}\alpha^2 r_e^2 \left(\frac{\hbar\omega}{mc^2}\right)^6 \approx 0.03\alpha^2 r_e^2 \left(\frac{\hbar\omega}{mc^2}\right)^6 \approx 7.4 \times 10^{-66}\mathrm{cm}^2 \left(\frac{\hbar\omega}{1\ \mathrm{eV}}\right)^6,$$

where ω is the frequency of the incident photons in the cm frame, and $r_e = e^2/mc^2$ is the classical electron radius.

For example, suppose we collide two laser beams of N photons each at right angles (as would be convenient for the 3-beam experiment discussed below) after focusing them to a spot size of order λ, the laser wavelength. If the laser pulsewidth is τ seconds then the only a fraction $\lambda/c\tau$ of the photons in each beam occupies the interaction volume ($\approx \lambda^3$) at any moment. We may regard the scattering as consisting of $c\tau/\lambda$ successive experiments in which $N\lambda/c\tau$ photons from each beam interact with each other. The total scattering rate would then be

$$\text{Rate} \approx \frac{c\tau}{\lambda}\left(\frac{N\lambda}{c\tau}\right)^2 \frac{\sigma}{\lambda^2} = \frac{N^2\sigma}{\lambda c\tau}.$$

For example, if we have 1 Joule of photons of 1-eV energy ($\lambda = 10^{-4}$ cm) with a pulse length of 1 psec (as for the present Rochester T^3 laser), then the rate is only about 10^{-24} per pulse!

Four-Wave Mixing

The observation of Kroll and Varfolomeev is that when a third laser beam is present and aligned along the direction of a possible final-state photon, the scattering rate is enhanced by the number of photons in the third beam (during each of the subexperiments described above). That is, for N photons in each of the three beams,

$$\text{Rate} \approx \frac{c\tau}{\lambda}\left(\frac{N\lambda}{c\tau}\right)^3 \frac{\sigma}{\lambda^2} = \frac{N^3\sigma}{(c\tau)^2}.$$

On using the above expression for the cross section, we arrive at the form of Kroll:

$$\text{Rate} = \Gamma\alpha^4 \frac{\lambda_C^5}{\lambda^3(c\tau)^2}\left(\frac{\mathcal{E}}{mc^2}\right)^3 \approx 10^{-6}\frac{(\mathcal{E}[\text{Joules}])^3}{(\tau[\text{psec}])^2},$$

where $\mathcal{E} = N\hbar\omega$ is the pulse energy, $\lambda_C = \hbar/mc$ is the Compton wavelength of the electron, and the numerical factor Γ is roughly π when the spot size is $\approx \lambda$.

To reach a rate of one scatter per pulse, we would need, for example, 10 Joules in each beam, whose pulselengths have been compressed to 30 fsec.

Configuration of the Laser Beams

It will be highly useful for the fourth photon to have a different frequency from the other three, and to be produced at an angle not along any of the incoming beams. Since $\omega_4 = \omega_1 + \omega_2 - \omega_3$ it is sufficient that $\omega_3 \neq \omega_1$, while we may keep $\omega_1 = \omega_2$ for convenience. In practice, it may be best to choose ω_3 to be the laser frequency, and take $\omega_1 = \omega_2 = 2\omega_3$ by use of a doubling crystal. Then $\omega_4 = 3\omega_3 = 1.5\omega_1$.

To separate beam 4 from the other three, we can make the collision of beams 1 and 2 at some crossing angle less than 180°, and set the pump beam 3 out of the plane of 1 and 2. (Other arrangements are possible as well.) Let θ be the angle between beam 1 and the bisector of the angle between beams 1 and 2. We arrange beam 3 to be in the plane perpendicular to the plane of beams 1 and 2 that contains the bisector. Let θ_3 and θ_4 be the angles between the bisector and beams 3 and 4, respectively. See the Figure.

Under the assumption that $\omega_1 = \omega_2$ energy and momentum conservation then read:

$$2\omega_1 = \omega_3 + \omega_4,$$

$$2\omega_1 \cos\theta = \omega_3 \cos\theta_3 + \omega_4 \cos\theta_4,$$

and

$$\omega_3 \sin\theta_3 = \omega_4 \sin\theta_4.$$

After some algebra we find

$$\cos\theta_3 = \frac{\omega_3 - \omega_1 \sin\theta}{\omega_3 \cos\theta}.$$

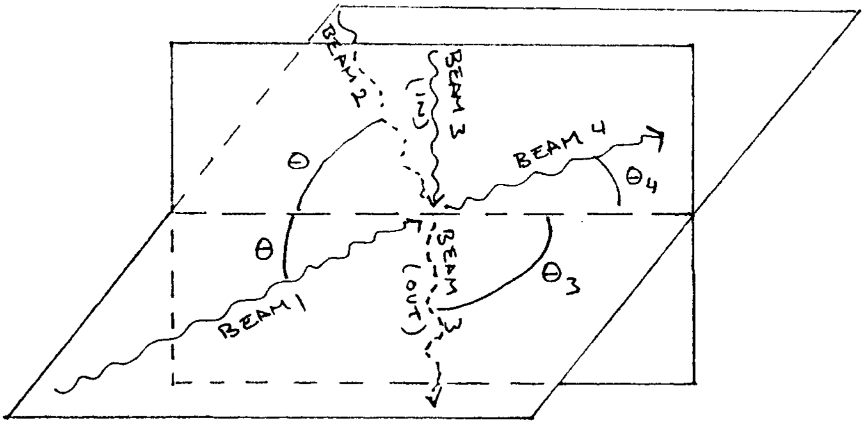

Figure 1: Possible arrangement of the laser beams for the induced light-by-light scattering experiment. Beams 3 and 4 are in the plane perpendicular to the plane of beams 1 and 2 that contains the bisector of the angle 2θ between beams 1 and 2.

A convenient configuration is that $\theta_3 = 90°$, which holds when $\sin\theta = \sqrt{\omega_3/\omega_1}$. In our example where $\omega_3/\omega_1 = 1/2$ we require that $\theta = 45°$, so the angle between beams 1 and 2 is 90°, as mentioned above. Finally, $\sin\theta_4 = \omega_3/\omega_4 = 1/3$, or $\theta_4 = 19.5°$. The angular separation between photon 4 and the other 3 beams is nearly maximal.

Vacuum Requirements

Background photons might come from residual gas atoms in the scattering chamber vacuum that are ionized by the intense laser beams. Ionization will be probable for any atoms in fields of intensity greater than about 10^{13} Watts/cm^2. The fields at the collision point will be about 10^{21} Watts/cm^2, and the Rayleigh range $\approx \lambda$ for a very strong focus. Then the volume over which ionization is probable is of order $(\sqrt{10^8}\lambda)^3 \approx 1$ cm^3. At 1-atmosphere pressure there are about 3×10^{19} atoms/cm^3, so we would require a vacuum of about 10^{-16} torr. As only about 10^{-10} torr might be achieved in practice, there would be about 10^6 ionized atoms/pulse. There seems a nonzero prospect that several of these atoms would emit radiation at frequency ω_4, for which $\lambda_4 = \lambda_{\text{laser}}/3 = 353$ nm. A narrow interference filter at this wavelength could be used to limit the bandwidth, but if the laser pulse has been compressed to 30 fsec its bandwidth is several percent.

A first step would be to focus the present laser beam in vacuum, and search for ionization photons at 3ω.

References

[1] A.A. Varfolomeev, *Induced Scattering of Light by Light*, Sov. Phys. JETP **23** (1966) 681.

[2] N.M. Kroll, *Parametric Amplification in Spatially Extended Media and Application to the Design of Tuneable Oscillators at Optical Frequencies*, Phys. Rev. **127** (1962) 1207, footnote 9; also, pp. 31-32 of *Quantum Theory of Radiation*, in *Quantum Optics and Electronics* (Les Houches, 1964), ed. by C. DeWitt, A. Blandin, and C. Cohen-Tannoudji (Gordon and Breach, New York).

[3] K.T. McDonald *et al.*, *Study of QED at Critical Field Strength*, in *Workshop on beam-Beam and Beam-Radiation Interactions: High Intensity and Nonlinear Effects*, ed. by c. Pelligrini, T. Katsouleas and J. Rosenzweig (World Scientific, Singapore, 1992) p. 127.

[4] A brief notice on the work of the Limeil group appeared on p. 6 of Lasers & Optronics **11**, No. 11 (Oct. 1992).

[5] See for instance Sec. 127 of V.R. Berestetskii, E.M. Lifshitz and L.P. Pitaevskii, *Quantum Electrodynamics*, 2nd ed., (Pergamon Press, 1982).