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ELECTRON SCATTERING BY AN INTENSE POLARIZED PHOTON FIELD*

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Compton scattering by starlight quanta has been postulated by Feenberg and Primakoff to be a mechanism for the energy degradation of high-energy electrons in interstellar space.[1] We shall discuss here the possibility of observing this phenomenon directly in the laboratory by scattering a multi-GeV electron beam against the intense flux of visible photons produced by a typical laser. It will be shown that using existing laser systems and electron accelerators, one may expect to obtain of the order of several thousand collimated high-energy scattered photons during each accelerator pulse, and that these quanta retain to a high degree the polarization of the original beam of optical photons.

The kinematic formulas for Compton scattering on moving electrons are given by Feenberg and Primakoff.[2] We shall consider the special case of an extreme-relativistic electron of energy $E=\gamma mc^2$, $\gamma=1/(1-\beta^2)^{1/2}\gg 1$, incident head-on upon a beam of photons of energy $k_i=(1-3)$ eV propagating in the opposite direction. An observer moving with the incident electron will see a photon of energy $k_0=2\gamma k_i$. In Table I are listed for various laboratory electron energies, E, the corresponding values of k_0, tabulated in terms of $\lambda=k_0/mc^2$, for incident 6943Å ruby-laser photons ($k_i=1.79$ eV). If we let θ_0 equal the photon scattering angle in the electron rest frame, and $x=\cos\theta_0$, then the laboratory energy of the scattered photon will be given approximately by

$$k_f=E\{\lambda(1-x)/[1+\lambda(1-x)]\}. \quad (1)$$

The approximation fails only near $x=1$, for which $k_f=k_i$ is required. However, for large $\gamma=E/mc^2$ the bulk of the scattered photons is folded back and emerges in the laboratory in the direction of motion of the incident electron, making angles with that direction given by $\theta=2\tan(\frac{1}{2}\theta)=(1/\gamma)\times\cot(\frac{1}{2}\theta_0)$. Thus for 1-GeV electrons, all photons having $23°<\theta_0<180°$ will end up within 0.0025 radian of the electron direction. We shall confine our discussion to these high-energy quanta. The

Table I. Energy, λ, polarization, and cross section for highest energy photons produced by ruby-laser photons scattered on electrons of energy E. The quantity $\sigma_{1/2}$ is the cross section for higher half of k_f spectrum.

E (GeV)	λ	$(k_f)_{max}$ (MeV)	P_{max}	$\sigma_{1/2}$ (mb)
1.02	0.014	28	1.00	320
2.92	0.040	216	1.00	310
4.16	0.057	426	0.99	300
4.60	0.063	515	0.99	290
5.11	0.070	628	0.99	290
5.48	0.075	715	0.99	290
5.84	0.080	806	0.99	280
6.21	0.085	903	0.99	280
6.57	0.090	1.00×10^3	0.99	280
8.76	0.120	1.69×10^3	0.98	260
11.69	0.160	2.83×10^3	0.96	250
20.8	0.285	7.55×10^3	0.91	220
41.6	0.570	22.1×10^3	0.77	180
58.4	0.800	35.9×10^3	0.67	160

maximum emergent photon energy, $(k_f)_{max}$, occurs for $x=-1$, and is also listed in the table for ruby-laser photons. Note that $(k_f)_{max}=4\gamma^2 k_i$ when $\lambda \ll 1$, but approaches E for $\lambda \gg 1$.

The differential cross section for the scattering process is given by the Klein-Nishina formula which is usually expressed in the rest system of the incident electron.[3] Note from the table that under currently practical conditions the scattering is nearly classical ($\lambda=0$) so that the total cross section approaches the Thomson cross section, $\sigma_0=665$ mb. We are concerned only with those photons which emerge in the laboratory essentially in the direction of motion of the incident electron, and we present here the differential cross sections for the two components polarized parallel and perpendicular to the plane of polarization of an incident plane-polarized visible photon. These cross sections have been averaged over azimuthal angle and, using Eq. (1), are expressed as distributions in the fractional outgoing photon energy (k_f/E). Thus,[4]

$$\frac{1}{\sigma_0}\frac{d\sigma}{d(k_f/E)}=\frac{3}{16\lambda}\left[\frac{\lambda^2(1-x)^2}{1+\lambda(1-x)}+\tfrac{1}{2}Q\right], \tag{2}$$

where $Q=(3-2x+3x^2)$ and $(1+x)^2$ for parallel and perpendicular polarizations, respectively. The outgoing photons are partially polarized to a degree $P(x)$ which may be defined as the difference of the two expressions in Eq. (2) divided by their sum. The maximum polarization, P_{max}, occurs for $x=-1$, corresponding to the highest energy photons. Values of P_{max} are also listed in the table. The unpolarized cross section is obtained by adding the two forms of Eq. (2). It and the function P are plotted in Fig. 1 for representative

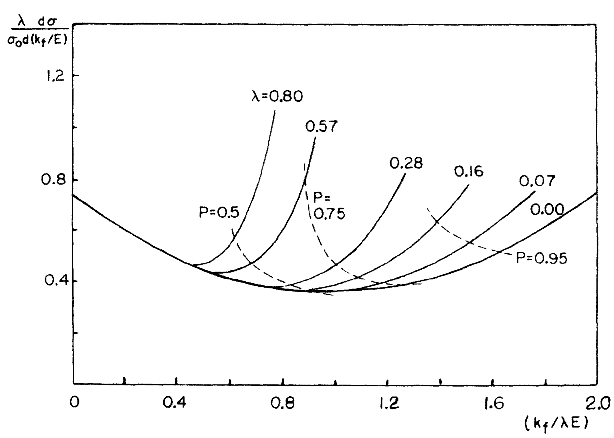

FIG. 1. Scattered photon energy distribution and polarization.

values of the parameter λ, and are given as functions of the ratio $(k_f/\lambda E)$. The ordinate is chosen so that the areas under the curves yield directly the total cross sections as a fraction of $\sigma_0=665$ mb. The cross sections for the production of the higher half of each photon energy spectrum are listed in the table. We shall assume in the following intensity calculations an effective cross section of 300 mb for typical processes of interest.

Let us assume that a flux of photons of energy k_i and intensity I can interact over a distance L with a countermoving beam of extreme-relativistic electrons ($\beta=1$) having an interaction cross section σ. The interaction probability, N, per electron is given by $N=(2\sigma IL/ck_i)$, where c is the velocity of light. In practical units,

$$N=(0.41\times10^{-3})\times I(\text{watts/cm}^2)\times L(\text{m})\times\sigma(\text{barns})/k_i(\text{eV}).$$

For ruby-laser photons and a 300-mb cross section, this reduces to $N=(7.0\times10^{-15})\times I(\text{watts/cm}^2)\times L(\text{m})$. These rates are most easily deduced by noting that total cross sections are Lorentz-invariant and that the relative photon-electron velocity in the laboratory is twice the velocity of light.

Typical ruby lasers can put of the order of 1 joule of light energy into a quarter-inch diameter beam during a millisecond or less.[5] For such pulses $I=3140$ watts/cm^2. Let us consider that such a beam is passed into a one-meter-long straight section of a strong-focusing electron synchrotron that has accelerated 10^{11} electrons to multi-GeV energies and which has an orbital frequency of 1.3 Mc/sec.[6] We assume that the electrons are sufficiently focused to remain within the laser beam over the interaction path, but one may readily scale the results to other conditions. Then one would expect 2.2 scatterings per revolution, and a total of 2900 over the 10^{-3}-second laser pulse. It is evident that insofar as the electrons remain within the laser beam over the interaction region, the total number of scatterings will be independent of the duration of the light pulse and will depend only upon the total light energy per unit area of the beam. Thus, with a laser of limited total light output, the pulse length might be chosen to optimize the repetition rate of the laser or the duty cycle of a detector. On the other hand, were a linear accelerator the electron source, one would wish to maximize the temporal overlap of the pulsed electron and light beams.

The laser parameters assumed above appear to be relatively modest, in view of the present state of the art.[7] Polarizations upwards of 90% are to be expected from suitably excited X-cut crystals without external filtering by birefringent or Brewster's-angle devices.[8,9] It is reasonable to anticipate that plane-polarized laser beams an order of magnitude more energetic than assumed in this discussion will presently become available. Moreover, it may prove possible to incorporate the electron-photon interaction region in the "resonant" optical path of a laser and thus achieve another order of magnitude increase in power density.[10,11]

Bremsstrahlung from electron scattering on residual gas molecules will compete with the Compton scattering on laser photons. The radiation length of air at STP is about 330 m, or 2.5×10^{11} m at a pressure of 10^{-6} mm Hg, whereas 0.5×10^{11} m is the effective mean free path in a 3140-watt/cm^2 laser beam. Therefore use of a high vacuum and perhaps of short, high-power-density light pulses may be required.

Although a beam of 10^3-10^4 high-energy photons in a pulse occurring every few seconds is weak by ordinary synchrotron standards, it is appropriate for use in bubble chambers. Indeed, the Compton-scattered beam has a much harder spectrum than even a "hardened" bremsstrahlung beam and is correspondingly more desirable even apart from its polarization features. Were an increase by a factor of 10^2 or 10^3 to be obtained by the use of more powerful lasers, improved coupling of the laser to the electron beam, increased repetition rate, or increased electron current, such a beam would be appropriate for some spark chamber experiments.

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[1]E. Feenberg and H. Primakoff, Phys. Rev. 73, 449 (1948).

[2]Reference 1, p. 459.

[3]W. Heitler, The Quantum Theory of Radiation (Oxford University Press, New York, 1954), 3rd ed., p. 217.

[4]Care is required in transforming the polarization vectors between electron and laboratory frames. One may note that the normal to the plane of scattering and the angle between this normal and the polarization vector of the outgoing photon are both invariant with respect to Lorentz transformations parallel to the direction of the incident photon. The formulas of Eq. (2) assume that in the laboratory the higher energy photons of interest propagate essentially parallel to the direction of motion of the incident electron.

[5]As commercial examples, the Hughes Aircraft Company, Model 200, the Maser Optics, Inc., Series 600, and the Raytheon Company, Model LH2-LR2 laser systems all have specifications near these values.

[6]These are the design parameters of the 6-GeV Cambridge Electron Accelerator.

[7]A. Javan and P. Pershan (private communication).

[8]I. D. Abella and H. Z. Cummins, J. Appl. Phys. 32, 1177 (1961).

[9]S. J. Sage, Appl. Optics 1, 173 (1962); and (private communication).

[10]A. Javan (private communication).

[11]It has come to my attention that Thomson scattering of a laser beam on 2-keV electrons has recently been observed in the laboratory. G. Fiocco and E. Thompson, Phys. Rev. Letters 10, 89 (1963).