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NONLINEAR COMPTON SCATTERING OF 46 GeV ELECTRONS

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Abstract

The 46 GeV electron beam at the Stanford Linear Accelerator Center was scattered from the focus of an intense laser beam ($\omega_0 = 2.34$ eV) with peak intensity 4×10^{16} W/cm^2. The momentum spectrum of the recoil electrons beyond the kinematic limit for single photon Compton scattering was measured. These electrons reflect two-photon Compton scattering as well as multiple scattering in the laser focus. The observed rate is in qualitative agreement with the predicted values.

The interaction of high energy particles with the electromagnetic field can be adequately described by the emission and absorption of a single photon. However at high field strengths several photons may be absorbed in a single interaction, resulting in nonlinear Compton scattering. We report on the first observation of such nonlinear Compton scattering of 46.6 GeV electrons in the field of a short, tightly focussed intense laser pulse. The analogous effect for atomic systems is the well studied multiphoton absorption which involves bound rather than free electrons.

The experiment was carried out at the Stanford Linear Accelerator Center using the Final Focus Test Beam (FFTB) [1]. The laser consisted of a Nd: YLF oscillator followed by three Nd:glass amplifiers and is described in detail in ref. [2]. Chirped pulse amplification was used to deliver 1.5 - 3.0 ps long pulses at $\lambda = 1054$ nm with energy in the IR pulse as high as 2.4 J. The laser pulse was frequency doubled to $\lambda = 527$ nm (green) and transported to the interaction point where it was focussed onto the electron beam with an $f/D = 6$ parabolic mirror; the crossing angle between the two beams was 17°. The laser pulse was refocussed after traversing the focus and returned to the laser room where its focal, and temporal profiles were characterized and the pulse energy was measured. In general, the focal spot area was of order 50 ± 20 $\mu\mathrm{m}^2$ and the pulse width varied from 1.2 to 3.5 ps, higher energy pulses tending to be longer. The laser was pulsed at a rate of 0.5 Hz.

The electron beam was operated at 46.6 GeV with 6×10^9 e^-/pulse; at the interaction point the area was typically 400 $\mu\mathrm{m}^2$, whereas the longitudinal extent was of order 3 ps. To maintain collisions the laser and electron beam must be synchronized to within few picoseconds. This is achieved by driving the mode locker in the laser oscillator with a subharmonic (119.0 MHz) of the linac radiofrequency in a phase locked loop [3]. An optical delay line was used to find and set the correct laser timing. Overlap of the two beams in the transverse plane was achieved by steering the electron beam and/or scanning the position of the laser focus.

After passing the interaction point the electron beam is directed to the dump by six permanent magnets which provide a total bend of 18 mrad. Electrons that are scattered by the laser loose energy and therefore are bent more strongly in the field and are deflected out of the vacuum chamber. Recoil electrons with momentum $p_e < 25$ GeV can reach a total absorption silicon calorimeter [4]. The rate of backscattered photons was monitored by another silicon calorimeter placed in the forward direction, as well as by a sampling Cerenkov counter suitably calibrated for measuring high flux (up to 2×10^7 photons/pulse were observed) [5]. The layout of the interaction region and of the detectors is shown schematically in Fig.1.

The electron calorimeter consists of 21 layers of silicon (...... thick) interleaved with tungsten sheets (...... thick). It is divided into 4 columns and 12 rows, each pad (or tower) having an area of 16×16 mm^2 in the direction transverse to the beam. Since the transverse momentum of the recoil electrons is of order of the electron mass, they are hardly deflected in the horizontal plane and therefore impact only the two central columns of the calorimeter. The vertical position of the calorimeter was remotely adjustable allowing us to select the momentum band covered by a particular tower.

The silicon layers within a tower were ganged into four segments which were read out by amplifiers/latches [6]. The calorimeter was calibrated using secondary electrons during SLC operations and was found to have a resolution $\Delta E/\sqrt{E} = 0.33/\sqrt{E}$ in agreement with calculation [7]. Furthermore, it was possible to calibrate the momentum scale of the spectrometer, which was found to be in agreement with the values calculated from the magnet map.

The minimum energy of the recoil electrons depends on the number of absorbed photons and is given by

$$\mathcal{E}_{\min} = \frac{\mathcal{E}_0}{1+x} \quad , \quad x = \frac{2n\omega_0\mathcal{E}_0}{m^2}\,(1+\cos\delta) \tag{1}$$

Here $\mathcal{E}_0 = 46.6$ GeV is the incident electron energy; $\omega_0 = 2.34$ eV the laser photon energy; m the electron mass and $\delta = 17^\circ$ the crossing angle. The number of absorbed photons is given by n. For $n = 1$, $\mathcal{E}^{(1)}_{\min} = 17.6$ GeV which represents the "Compton edge" for this experiment. Observation of recoil electrons with energies $\mathcal{E}_r < \mathcal{E}^{(1)}_{\min}$ is evidence for the absorption of two or more photons from the laser field and/or for multiple scattering of the incident electrons in the laser focus.

The observed number spectrum dN/dp of recoil electrons beyond the Compton edge is shown in Fig.2 as a function of the central momentum of the calorimeter row. Two sets of data are shown and each set consists of three "runs" at different positions of the calorimeter. The data set spanning the range $18 > \mathcal{E}_r > 12$ GeV corresponds to a laser energy $U_L = 4 \pm 0.4$ mJ, whereas for the set in the range $15 > \mathcal{E}_r > 8$ GeV the laser energy $U_L = 40 \pm 4$ mJ. The rate dN/dp (GeV^{-1}) refers to the scattering of a single pulse of 6×10^9 electrons.

The rate of observed recoils depends on the spatial and temporal overlap of the electron and laser pulses, the number of laser photons (pulse energy) and number of electrons. This dependence can be factored out by measuring the number of forward going photons from the collision and forming

$$\frac{1}{N_\gamma}\frac{dN}{dp} = \frac{1}{\sigma_0}\frac{d\sigma}{dp} \tag{2}$$

Here σ_0 is the total cross section for $n = 1$ Compton scattering; $\sigma_0 = 3 \times 10^{-25}$ cm^2 for this experiment. The data are represented in this form in Fig.3.

The differential cross section $d\sigma/dp$ for $n > 1$ is expected to depend on the strength of the electric field in the laser focus, namely on the laser intensity which we define as

$$I = U_L/A_\omega \tau \tag{3}$$

where A_ω is the $1/e^2$ focal area and τ the FWHM of the pulse duration. The peak electric field for linear polarization (used in this experiment) is then given by $E_0 = \sqrt{2IZ_0}$ with Z_0 the impedance of free space. The expected dependence is apparent in Fig.3, where the two data sets correspond to laser intensities of $I = 4 \times 10^{15}$ W/cm^2 and $I = 4 \times 10^{16}$ W/cm^2; the ratio of the differential cross sections for the two data sets is approximately 10, for $\mathcal{E}_r < 14$ GeV.

Nonlinear Compton scattering was treated theoretically thirty years ago in a series of papers [8] as well as recently [9]. In that treatment multiphoton effects are dependent on two invariants

$$\eta = \frac{eE}{m\omega_0 c} \quad , \quad \Upsilon = 2\gamma\frac{eE\hbar}{m^2c^3} \tag{4}$$

where E is the electric field strength and $\gamma = \mathcal{E}_0/m$. For circularly polarized light the differential cross section can be given in closed form [8,10] and reduces to the Klein-Nishina result in the limit $\eta \to 0$. For small values of η progressively higher orders of multiphoton scattering scale as η^2, and this is supported by the data of Fig.3 where the two data sets correspond to $\eta = 0.020$ and $\eta = 0.062$; the respective values of Υ are $\Upsilon = 0.017$ and $\Upsilon = 0.052$.

The theoretical prediction for the normalized cross section $(1/\sigma_0)\ d\sigma/dp$ for linear polarization has been integrated over the interaction region including the effects of multiple scattering; in the range of the data, the two effects contribute equally. The resulting prediction, [after smearing for the resolution of the calorimeter, NB: this has not been done as yet] is shown by the two curves in Fig.3 evaluated at the same laser intensity as the data. While these data establish a qualitative agreement with the calculated model a more precise comparison must be based on measurement of the spectrum of the forward going photons. Such an experiment will be carried out in the near future [11].

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Figure Captions

Fig. 1 Schematic layout of the experiment.

Fig. 2 Number spectrum dN/dp of recoil electrons beyond the Compton edge. The two data sets correspond to laser energies $U_L = 4$ mJ and $U_L 40$ mJ respectively.

Fig. 3 Normalized momentum spectrum for recoil electrons from nonlinear and multiple scat -tering in the laser focus. The two data sets correspond to laser intensities $I = 4 \times 10^{15}$ W/cm^2 and $I = 4 \times 10^{16}$ W/cm^2. The curves are the prediction of the theoretical model [9] evaluated at the same laser intensity.

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