B Factory via Conversion of 1-TeV Electron Beams into 1-TeV Photon Beams

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We derive formulas which describe the interaction of laser beams with electron beams. Specializing to the case of 1-TeV electron beams from the future generation of electron linear accelerators, we calculate the production rate of backscattered 1-TeV photons, and using these photons, we show that it is possible to organize the photoproduction of beauty particles so as to measure 10^9 $b\bar{b}$ pairs per year. This should be adequate to study rare decays and *CP* violation in *B*-meson decay.

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The study of *CP* violation and rare decays of beauty particles is one of the most pressing problems in high-energy physics. It is known that one should analyze at least of the order of 10^8 or 10^9 beauty decays. Thus, numerous proposals for beauty factories are being discussed now, although various ones of these projects are likely to supply much smaller numbers of beauty events.

At the same time, at present there exist several projects such as CLIC (Cern Linear Collider) to build linear e^+e^- colliders with beam energies up to 1 TeV. The aim of this work is to show that there exists the possibility to use the unique features of the discussed TeV electron linacs to obtain a facility for the production of beauty via photoproduction off nuclei. Unique features of high-energy photoproduction are (i) the rather large fraction ($\sim 2\times 10^{-4}$) of events with beauty at $E_\gamma \sim 1$ TeV, and (ii) the fact that beauty particles are produced with about equally large momenta $\sim 0.5E_\gamma$ and at rather large transverse momenta $p_t \sim m_b$.

We take advantage of previous work on producing high-energy photon beams (cf. Refs. 1-4). Thus, the following scheme can be envisioned. The 1-TeV electron beam is Compton scattered off a low-energy ($\sim$1-eV) laser pulse whose beam size has been matched to that of the electron beam by the use of focusing mirrors (see Ref. 4, Sec. 5). The laser photons are thus converted into a highly collimated beam of energy $E_\gamma \sim E_e$, directed along the electron's original line of motion. Moreover, the properties of the 1-TeV photon beam are remarkably insensitive to the laser-electron-beam crossing angle (see Ref. 2 and Ref. 4, Sec. 5). These 1-TeV photons are subsequently scattered onto a nuclear target to produce $b\bar{b}$ pairs.

We can imagine using the same electron bunch to convert ~ 100 low-energy laser beams into high-energy photon beams. This is done over a distance of approximately 100 m. After each electron-photon bunch crossing the electron bunch is deflected by a trim dipole through an angle of $\sim 10^{-4}$ rad before scattering with the next laser pulse. The dipoles are randomly oriented so that the high-energy-photon hits on the nuclear target are scattered in the transverse plane and are not along a line. We envision the 100 miniphoton beams being separated by 10^{-4} rad, with the angular divergence of each being limited to $\leq 10^{-5}$. In this way, one of the new detector technologies, such as scintillation fibers, should be able to cope with the rather large number of beauty particles being produced. In fact, in our scheme the number of beauty particles is not limited by the production rate (we could photoproduce many more than 10^9 per year); but rather the limitation is how fast the detector can process the events.

In Sec. I, we derive the formulas which describe the interaction of a laser beam with an electron beam, explicitly showing the dependence on the accelerator lattice functions and beam parameters. In Sec. II, we give a numerical example using CLIC design parameters and we offer concluding remarks.

I. Rate of γ conversion.— The production rate of high-energy photons from Compton scattering (see Fig. 1) of low-energy photons on 1-TeV electrons is given by the relativistic "golden rule":[5,6]

$$\frac{dN}{dt} = \int d^3x\, d^3p_i\, d^3\kappa\, \rho_\gamma(\mathbf{x},\boldsymbol{\kappa})\rho_e(\mathbf{x},\mathbf{p}_i) \times \left[\int \frac{d^3p_f}{(2\pi)^3} \frac{d^3k'}{(2\pi)^3} \frac{m^2}{E_i E_f} \frac{1}{4\kappa k'} \times (2\pi)^4 \delta^{(4)}(p_f + k' - p_i - \kappa) |\overline{\mathcal{M}}|^2 \right], \quad (1)$$

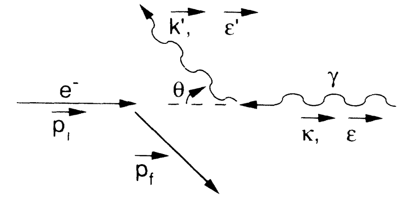

FIG. 1. Compton scattering diagram.

where

$$\rho_\gamma(\mathbf{x},\boldsymbol{\kappa}) = \frac{N_\gamma \delta(\boldsymbol{\kappa}-\mathbf{k})}{(2\pi)^{3/2} l_\gamma \sigma_\gamma^2} e^{-x^2/2\sigma_\gamma^2} e^{-z^2/2\sigma_\gamma^2} e^{-(s-\bar{s})^2/2l_\gamma^2}, \quad (2)$$

$$\rho_e(\mathbf{x},\mathbf{p}_i) = \frac{N_e}{\Gamma} e^{-S(\mathbf{x},\mathbf{p}_i)}, \quad (3)$$

$$\Gamma = \int d^3x\, d^3p\, e^{-S(\mathbf{x},\mathbf{p}_i)}, \quad (4)$$

$$S(\mathbf{x},\mathbf{p}) = S^{(H)} + S^{(V)} + S^{(l)}, \quad (5)$$

$$S^{(H)} = \frac{\beta_H}{2\varepsilon_H} x_\beta'^2 - \frac{\beta_H'}{2\varepsilon_H} x_\beta x_\beta' + \frac{1}{2\varepsilon_H \beta_H}(1+\tfrac{1}{4}\beta_H'^2) x_\beta^2, \quad (6)$$

$$S^{(V)} = \frac{\beta_V}{2\varepsilon_V} z_\beta'^2 - \frac{\beta_V'}{2\varepsilon_V} z_\beta z_\beta' + \frac{1}{2\varepsilon_V \beta_V}(1+\tfrac{1}{4}\beta_V'^2) z_\beta^2, \quad (7)$$

$$S^{(l)} = \frac{\delta^2}{\sigma_\eta^2} + \frac{(s-\bar{s})^2}{2\sigma_s^2}, \quad (8)$$

$$|\overline{\mathcal{M}}|^2 = \frac{e^4}{4m^2}\left\{ \frac{k'\cdot p_i}{\kappa\cdot p_i} + \frac{\kappa\cdot p_i}{k'\cdot p_i} + 4(\epsilon'\cdot\epsilon)^2 - 2 \right\}, \quad (9)$$

and

$$\varepsilon_H = \sigma_H^2/\beta_H, \quad (10)$$

$$\varepsilon_V = \sigma_V^2/\beta_V, \quad (11)$$

$$\sigma_\eta = \sigma_p/\bar{p}, \quad (12)$$

$$x_\beta = x - \eta_H(s)\delta, \quad (13)$$

$$x_\beta' = x' - n_H'(s)\delta, \quad (14)$$

similarly for z_β, and

$$x' \equiv \delta p_x/\bar{p}, \quad (15)$$

$$z' \equiv \delta p_z/\bar{p}, \quad (16)$$

$$\delta \equiv \delta p_s/\bar{p}. \quad (17)$$

The parameters x, z, and s measure beam position along the horizontal, vertical, and longitudinal directions, and the prime denotes the derivative with respect to s. $\beta_H, \beta_V, \eta_H, \eta_V$ are the accelerator lattice functions, ε_H and ε_V are the electron-beam horizontal and vertical transverse emittances, σ_H, σ_V, and σ_s are the rms electron-beam width, height, and length, m is the mass of the electron, E_i and E_f are the initial and final electron energies, ϵ and ϵ' are the initial and final photon polarization vectors, σ_γ is the rms photon pulse width and height (assuming round pulses), l_γ is the rms photon pulse length, N_e is the number of electrons in a bunch, N_γ is the number of photons in each laser pulse, and $\mathcal{M}$, the invariant Compton scattering amplitude, has been squared, averaged over initial electron spins, and summed over final electron spins. Also, for bunched beams the total phase-space volume can be written as

$$\Gamma = (2\pi)^3 \beta^3 \gamma^3 m^3 \varepsilon_H \varepsilon_V \sigma_\eta \sigma_s. \quad (18)$$

In Eq. (1), the expression in square brackets can be evaluated in the electron's rest frame where the dynamics is easiest, averaged over initial and summed over final photon polarizations, and Lorentz boosted back to the laboratory frame. The final result one obtains after many integrations is

$$\frac{dN}{d\Omega_{k'}dt} = \left(\frac{\pi}{2}\right)^{3/2} \frac{N_\gamma}{l_\gamma \sigma_\gamma^2} \frac{N_e}{\Gamma \mathcal{C}_H \mathcal{C}_V \mathcal{C}_s \mathcal{D}_H \mathcal{D}_V \mathcal{A}} \frac{\alpha^2}{2m^2} \frac{(1-\beta)}{(1+\beta)} \left(\frac{k'}{k}\right)^2$$
$$\times \left\{ \frac{k'}{k} \frac{1+\beta\cos\theta}{1+\beta} + \frac{k}{k'} \frac{1+\beta}{1+\beta\cos\theta} - \sin^2\theta \frac{1-\beta^2}{[1+\beta\cos\theta]^2} \right\}, \quad (19)$$

where β is v/c for the electron and

$$k' = \frac{k(1+\beta)}{1+\beta\cos\theta + k(1-\cos\theta)/m\gamma}, \quad (20)$$

$$\mathcal{B}_H = 1 + \beta_H'^2/4, \quad (21)$$

$$\mathcal{C}_H = \left[\frac{1}{2\sigma_\gamma^2} + \frac{1+\beta_H'^2/4}{2\varepsilon_H \beta_H}\right]^{1/2}, \quad (22)$$

$$\mathcal{D}_H = \frac{1}{p}\left[\frac{\beta_H}{2\varepsilon_H} - \frac{\beta_H'^2}{16\varepsilon_H^2 \mathcal{C}_H^2}\right]^{1/2}, \quad (23)$$

and similarly for $\mathcal{B}_V$, $\mathcal{C}_V$, and $\mathcal{D}_V$,

$$\mathcal{C}_s=\left[\frac{1}{2l_\gamma^2}+\frac{1}{2\sigma_s^2}\right]^{1/2}, \tag{24}$$

$$\begin{aligned}\mathcal{A}=\Bigg\{\frac{1}{\sigma_p^2}&-\left[-\frac{\beta_H'\eta_H}{2\varepsilon_H}+\frac{\beta_H'^2\eta_H'}{8\mathcal{C}_H^2\varepsilon_H^2}+\frac{\beta_H'\eta_H\mathcal{B}_H}{4\varepsilon_H^2\mathcal{C}_H^2\beta_H}-\frac{\beta_H\eta_H'}{\varepsilon_H}\right]^2\Big/4\mathcal{D}_H^2p^4\\
&-\left[-\frac{\beta_V'\eta_V}{2\varepsilon_V}+\frac{\beta_V'^2\eta_V'}{8\mathcal{C}_V^2\varepsilon_V^2}+\frac{\beta_V'\eta_V\mathcal{B}_V}{4\varepsilon_V^2\mathcal{C}_V^2\beta_V}-\frac{\beta_V\eta_V'}{\varepsilon_V}\right]^2\Big/4\mathcal{D}_V^2p^4\\
&-\left[\frac{\beta_H'^2\eta_H'^2}{4\varepsilon_H^2}+\frac{\mathcal{B}_H^2\eta_H^2}{\varepsilon_H^2\beta_H^2}+\frac{\beta_H'\eta_H'\eta_H\mathcal{B}_H}{\varepsilon_H^2\beta_H}\right]\Big/4\mathcal{C}_H^2p^2-\left[\frac{\beta_V'^2\eta_V'^2}{4\varepsilon_V^2}+\frac{\mathcal{B}_V^2\eta_V^2}{\varepsilon_V^2\beta_V^2}+\frac{\beta_V'\eta_V'\eta_V\mathcal{B}_V}{\varepsilon_V^2\beta_V}\right]\Big/4\mathcal{C}_V^2p^2\\
&+\left[\frac{\beta_H\eta_H'^2}{2\varepsilon_H}+\frac{\beta_H'\eta_H'\eta_H}{2\varepsilon_H}+\frac{\mathcal{B}_H\eta_H^2}{2\varepsilon_H\beta_H}\right]\Big/p^2+\left[\frac{\beta_V\eta_V'^2}{2\varepsilon_V}+\frac{\beta_V'\eta_V'\eta_V}{2\varepsilon_V}+\frac{\mathcal{B}_V\eta_V^2}{2\varepsilon_V\beta_V}\right]\Big/p^2\Bigg\}^{1/2}.\end{aligned} \tag{25}$$

Now that we have derived an expression which gives the rate of 1-TeV photon production and its dependence on the beam parameters and the accelerator lattice functions, in the next section we use a set of CLIC design parameters to calculate the photoproduction rate of $b\bar{b}$.

II. Rate of beauty production.— We now want to calculate the rate of production of beauty particles. To bend the electron beam through 10^{-4} rad using the shortest possible trim dipoles, we use the formula $\varphi\sim eBl/pc$ in the cgs system of units to obtain the trim length $l=20$ cm and $B=1.6$ T for $pc=1$ TeV. For the electron beam and accelerator lattice functions we use values under consideration for CLIC. The laser parameters should not be difficult to meet. Thus, we take the following values: transverse beam size (for round beams) $=\sigma_{H,V}=\sigma_\gamma=2$ μm at the center point of the array of trim dipoles, beam bunch length $=\sigma_s=l_\gamma=3$ ps, $N_e=10^9$, $N_\gamma=10^{17}$ (~16 mJ, for a single photon energy of 1 eV), accelerator repetition rate $=2$ kHz, electron-beam transverse emittance $\varepsilon_N^{H,V}=2\times10^{-6}$ m $=\gamma\sigma^2/\beta_{H,V}\rightarrow\beta_{H,V}=4$ m $\equiv\beta_0$ at the center point of the array of trim dipoles, and for the electron beam $\delta p/p=0.1\%$.

In actual practice, we would like to space the trim dipoles an optimal distance apart, but to facilitate the calculation of average accelerator β and dispersion functions in the region of γ conversion let us place them close together. Assuming that the dispersion is zero at the exit of the electron linac and that it is equally shared between horizontal and vertical directions, it is easy to show that

$$\bar{\eta}_{H,V}=\frac{1}{2}\frac{eB}{pc}\frac{s_0^2}{6}\sim0.004\text{ m}, \tag{26}$$

$$\bar{\eta}'_{H,V}=\frac{1}{2}\frac{eB}{pc}\frac{s_0}{2}\sim1.25\times10^{-3}, \tag{27}$$

where $s_0=10$ m is the position of the center point of the array of trim dipoles. Also, assuming that $\beta_0=4$ m is a minimum at s_0 with no quadrupoles in the region of γ conversion, we find

$$\bar{\beta}_{H,V}=\beta_0[1+s_0^2/3\beta_0^2]\sim12.3\text{ m}, \tag{28}$$

$$\bar{\beta}'_{H,V}=-s_0/\beta_0\sim-2.5. \tag{29}$$

Using these numerical values, Eq. (19) gives

$$\frac{N}{\text{bunch crossing}}=\frac{dN}{d\Omega_{k'}dt}\Delta\tau\Delta\Omega_{k'}=4.57\times10^4, \tag{30}$$

where $\Delta\tau=l_\gamma/c$ and $\Delta\Omega_{k'}\sim10^{-13}$, corresponding to accepting all photons with energy ≥900 GeV having a minibeam opening angle of 10^{-7} rad.

Finally, we arrive at the number of $b\bar{b}$ pairs photoproduced per year:

$$\begin{aligned}N_{b\bar{b}}/\text{yr}=&[4.57\times10^4]\text{ (from Eq. (30))}\times[100]\text{ (number of mini photon beams)}\\
&\times[2\times10^{-4}]\text{ (probability of } b\bar{b}\text{ production on nucleus with } A\sim20\text{; see Refs.7-9)}\\
&\times[2\times10^3\text{ Hz] (CLIC repetition rate)}\times[3\times10^7]\text{ (s/yr)}\\
&\times[10^{-2}]\text{ (hadronic interaction length of target)}\\
&\times[10^{-2}]\text{ (fraction of photon-nucleon interactions which are hadronic)}\\
=&5\times10^9\, b\bar{b}\text{'s/yr}.\end{aligned} \tag{31}$$

Note that we have fixed the intensity of our minibeams so that only on the order of one hadronic interaction per electron pulse should occur on the average (i.e., $\sim10^4$ photons for a target of 10^{-2} hadronic interaction length), otherwise the detector would not be able to analyze the events since the pulse is very short. Modern detectors of the fiber type operate independently so that events occurring simultaneously in different points in the transverse plane can be analyzed.

In conclusion, we have derived formulas which describe the interaction of a laser beam with electrons in an accelerator, showing the explicit dependence on accelerator lattice functions and beam parameters. But more importantly, we have described a scheme for producing the required 10^9 pairs of beauty particles per year needed to study *CP* violation and rare decays of the $B^0\bar{B}^0$-meson system. Our scheme is dependent upon advances in the design of electron linacs of the future, but much progress is being made in that direction. Further, our scheme is not limited by the number of $b\bar{b}$'s produced per year; for example, orders of magnitude more beauty particles could be produced per year simply by increasing the number of photons in the 1-eV laser flash. On the contrary, our scheme is limited by the ability of the detector to analyze the abundance of beauty particles which are produced. Thus, the new scintillating fiber technology is an attractive possibility. We encourage further investigations along these lines.

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