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PHOTON COLLIDING BEAMS IN A STORAGE RING
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A b s t r a c t

The possibility is studied to use for obtaining polarized positrons and electrons the effects of pair production in the collision of two photon beams with opposite helicities. In this case the particles produced near threshold have a high polarization degree.

We propose to use as an intense source of polarized photon beams two helical ondulators installed in the straight section of an electron-positron storage ring. Also discussed is the possibility to apply this method of obtaining colliding photon beams to experiments on scattering light by light. The numerical examples are given.

1. With an increase of the energy of electron-positron storage rings the colliding polarized beam experiments acquire greater and greater interest. As at the present time a method of acceleration of polarized particles has been suggested which eliminates the influence of depolarizing factors [1, 2], it seems that utilization of intense sources of polarized can provide an ideal method of obtaining polarized beams. There exist by now the sources of polarized electrons, which generate $10^{10} \div 10^{11}$ particles per second, whereas even a possibility to create a source of polarized positrons has not yet been discussed.

In this paper it is proposed to apply the electron-positron pair production effect in the collision of two photon beams with opposite helicities for producing the polarized positrons (electrons). Note that positrons (electrons) produced near threshold have a high degree of polarization.[1)]

The cross section of the electron pair production in the collision of two photons is $\sim 10^{-25}$ cm^2. Thus, in the case when the luminosity of photon-photon beams is $\sim 10^{35}$ cm^2 sec^{-1}, we have a source of polarized positrons (electrons) which yields

1) A system of two photons with opposite helicities can be only in the states with a positive parity and a total angular momentum $j \geq 2$, and a projection j on the direction of motion of photon beams $j_z = 2$ [3]. Due to parity conservation, the electron-positron pairs can be produced only in the states with an odd orbital momentum ℓ. Since the occurrence of the pair production with $\ell = 3$ is suppressed, compared to $\ell = 1$, due to nonrelativistic motion of the produced particles, in practice, all the pairs(with an accuracy $(\frac{v}{c})^4$) will be produced in the state $j = 2$, $\ell = 1$, $j_z = 2$.

$\sim 10^{10}$ particles per second, i.e. as many as the best sources of polarized electrons produce.

2. Differential cross sections of the electron pair production in the collision of two photons with the same and opposite helicities are equal, respectively, to (in the center-of-mass system):

$$\frac{d\sigma_{\uparrow\uparrow}}{dO} = \frac{z_e^2}{2\gamma^2}\,\frac{\beta(1-\beta^4)}{(1-\beta^2\cos^2\theta)^2},$$

$$\frac{d\sigma_{\uparrow\downarrow}}{dO} = \frac{z_e^2}{2\gamma^2}\,\frac{\beta^3\sin^2\theta\,(2-\beta^2\sin^2\theta)}{(1-\beta^2\cos^2\theta)^2}, \qquad (1)$$

where $z_e = \frac{e^2}{m}$ $(c=1)$, $\gamma = (1-\beta^2)^{-1/2}$ - is the relativistic factor, θ is the angle between the positron velocity and the photon wave vector.

The polarization degree of produced positrons (electrons) is equal to[2] $(\hbar = c = 1)$:

$$\vec{\zeta} = \frac{\vec{K} + \frac{\vec{P}(\vec{K}\vec{P})}{m(\omega+m)}}{m + \frac{P^2}{2m}(1+\cos^2\theta)}, \qquad (2)$$

where ω is the frequency of colliding photons, $\vec{K}$ is the wave vector of the photon with positive helicity $(|\vec{K}| = \omega)$, $\vec{P}$ is the momentum of the positron (electron). Note that the projection $(\vec{\zeta}\frac{\vec{K}}{\omega}) = \zeta_{\vec{K}}$ near threshold is equal, in practice, to unity. So, for example, if β = 0.6 (i.e. ω = 1.25 m), the polarization degree $\zeta_{\vec{K}} \geq 0.98$ for the whole region of angles .

2) The author is deeply grateful to E.A.Kuraev and V.S.Fadin for calculation of expressions (1) and (2).

The total cross sections of pair production are equal to[3]:

$$\sigma_{\uparrow\uparrow} = \frac{\pi z_e^2}{\gamma^4}(1+\beta^2)\left[\beta\gamma^2 + \frac{1}{2}\ln\frac{1+\beta}{1-\beta}\right],$$

$$\sigma_{\uparrow\downarrow} = \frac{\pi z_e^2}{\gamma^2}\left[\beta^3 - 5\beta + \frac{5-\beta^4}{2}\ln\frac{1+\beta}{1-\beta}\right]. \qquad (3)$$

In the case of collision of the photons with different frequencies ω_1 and ω_2, it is possible to use the above formulae with $\omega = \sqrt{\omega_1\omega_2}$ taken into account [3].

3. The helical ondulator (helical magnetic field) [4] can be utilized as an intense source of circularly-polarized photons with $\omega > m$. In order to produce the photon colliding beams, two ondulators with the same direction of the magnetic field helix should be located in the straight section of a storage ring, on both sides from the interaction point of the electron and positron beams. Here, one photon beam is radiated by electrons in the first ondulator, and another - by positrons in the second one. The mean radiation power from the ondulator is apparently equal to:

$$W = \frac{2}{3} z_e^2 H_0^2 \gamma^2 N_e f \ell$$

where ℓ is the ondulator length, H_0 is the magnetic field strength, N_e is the number of electrons (positrons) circulating in the storage ring; f is the revolution frequency. The spectral composition and the angular divergence of radiation depend on the ondulatorness factor $\mathcal{K} = \frac{eH_0\lambda_0}{2\pi m}$, where λ_0 is the magnetic field period length in the ondulator. In the case when $\mathcal{K} \ll 1$ is the highest frequency of radiated photons $\omega_0 =$

3) The cross section for nonpolarized photons may be expressed via $\sigma_{\uparrow\uparrow}$ and $\sigma_{\uparrow\downarrow}$, an explicit form of σ_n is presented in [3]: $\sigma_n = \frac{1}{2}(\sigma_{\uparrow\uparrow} + \sigma_{\uparrow\downarrow})$.

$= \frac{2\gamma^2 \lambda_c^{-1}}{1+\mathcal{K}^2}$ $(\lambda_c = \frac{\lambda_0}{2\pi})$, and the radiation diverging at an angle θ has a frequency $\omega = \frac{\omega_c}{1+(\gamma\theta)^2}$, $(\gamma \gg 1)$. Note, that the number of photons with typical frequencies $\omega \sim \omega_c$ is independent of γ and is determined by the ondulator parameters and the circulating beam current only.

When calculating the number of positrons produced per unit time, $\dot{N}$, and their polarization degree ζ , it is necessary to take into account both nonmonochromaticity of ondulator radiation and the fact that the photons of either helicities are present in each beam. Further, we shall assume that $\mathcal{K} \ll 1$, and the area of photon beams at the interaction point coincides with that of the beams circulating in the storage ring. Then, we have:

$$\dot{N} = \frac{1}{fS} \int_{m^2/\omega_c}^{\omega_c} d\omega_1 \int_{m^2/\omega_1}^{\omega_c} d\omega_2 \left\{ \left[\frac{dN^+}{d\omega_1}\frac{dN^+}{d\omega_2} + \frac{dN^-}{d\omega_1}\frac{dN^-}{d\omega_2} \right] \sigma_{\uparrow\downarrow} + \left[\frac{dN^+}{d\omega_1}\frac{dN^-}{d\omega_2} + \frac{dN^-}{d\omega_1}\frac{dN^+}{d\omega_2} \right] \sigma_{\uparrow\uparrow} \right\}, \quad (4)$$

where S is the area of photon beams at the interaction point, $dN^{\pm}/d\omega$ is the spectral density of the photons with a positive helicity and negative one, respectively, which are radiated from the ondulator per second; the explicit expressions for them can be found in [4]. The values of $\sigma_{\uparrow\downarrow}$ and $\sigma_{\uparrow\uparrow}$ in the integrand are calculated according to (3) at $\omega = \sqrt{\omega_1\omega_2}$.

Note that the frequency m^2/ω_0 being a lower limit for the spectrum of "useful" photons determines also their angular divergence. So, for example, in the case when ω_0 = 1.2 m, the "useful" photons are radiated at an angle θ_{us} = $0.7/\gamma$ [4].

4) Note that the requirement of coincidence of the area of photon beams with that of particle beams in a storage ring imposes the following limitations on the ondulator length: $\ell\theta_{us}$ should be much smaller than transverse dimensions of the particle beam. If the angular spread of particles in a storage ring is $\sim 1/\gamma$, then formulae (4) and (5) are also valid in the case when the photon beam area is larger than the particle beam area at the interaction point.

If $\omega_0 \sim m$, the polarization degree of produced positrons is of the form:

$$\zeta = \frac{1}{\dot{N}} \int d\omega_1 \int d\omega_2 \left[\frac{dN^+}{d\omega_1}\frac{dN^+}{d\omega_2} - \frac{dN^-}{d\omega_1}\frac{dN^-}{d\omega_2} \right], \quad (5)$$

where $\dot{N}$ is calculated according to (4). In the case when $\mathcal{K} \ll 1$, the expressions for $\frac{dN^{\pm}}{d\omega}$ are of the following simple form:

$$\frac{dN^+}{d\xi} = \frac{\alpha}{\lambda_c} \mathcal{K}^2 \xi^2 N_e f \ell ,$$
$$\frac{dN^-}{d\xi} = \frac{\alpha}{\lambda_0} \mathcal{K}^2 (1-\xi)^2 N_e f \ell , \quad (6)$$

where, for convenience, $\xi = \frac{\omega}{\omega_0}$, $\alpha = e^2$ - is the fine structure constant[5].

Let us consider a numerical example.[6] For the ondulator

5) When $\mathcal{K} \gtrsim 1$, the electron radiation spectrum contains, in the accompanying reference system, higher harmonics multiple λ_c^{-1} . Then expressions (6) divided by $1+\mathcal{K}^2$ describe the contribution of the first harmonic in the region where $(1-\xi) \ll 1$. In this case, they give the lower estimation for $\frac{dN^{\pm}}{d\xi}$.

6) The parameters characterizing a storage ring are consistent with the project LEP [5].

with a period λ_c = 1 cm and a magnetic field strength H_c = = 5 kGs at the particle energy E = 28 GeV in the storage ring, the highest photon frequency ω_0 = 1.2 m. If the circulating current in each of the beams is assumed to be equal to 0.25 A and the area at the interaction point to be of the order of magnitude of the area of circulating currents and equal 10^{-3} cm^2, then according to formulae (4)-(6), $2 \cdot 10^{10}$ positrons will be produced per second with an average polarization degree ζ = 0.9 in the collision of photon beams. Here the power of each beam will be 630 kw.

Polarized positrons may be stored under some conditions in a magnetic trap whose magnetic field is directed along the motion of photon beams. If the electrostatic plugs with a positive potential $U > \omega_c - m$ are created at the ends of the trap, then the positrons will be stored in it.

Let us consider the motion of a particle spin in the trap. The spin projection on the magnetic field direction $S_{\vec{H}}$ and the rotation angle ψ of the spin around $\vec{H}$ represent the "action-phase" variables. In our case, when the particle motion is nonrelativistic, the spin precession frequency $\dot{\psi}$ is equal to the cyclotron frequency $\Omega = \frac{eH}{m}$. The characteristic time of variation of the magnetic field acting upon the particle at its motion in the trap is not, at least, shorter than L, where L is the distance between electrostatic plugs. In the case when $\Omega L \gg 1$, motion of the particle and, hence, that of its spin, is adiabatic, i.e. $S_{\vec{H}}$ is an adiabatic invariant. Therefore, the action of such a trap on the spin will not be depolarizing. The field of the particle circulating beam, possibly quite large,

may be one of the depolarizing factors. Thus, it will be likely required to deviate the circulating beams from the interaction point of photon beams.

In conclusion, note that the scheme proposed in this paper may be applied in the experiments on a study of the scattering light by light. Here the scattering cross section near the pair production threshold is of an order of 10^{-30} cm^2 (see, e.g., [6]). Thus, at the parameters indicated in the numerical example above the number of photon-photon scatterings will be of an order of 10^6 per second. Note that the use of the ondulator as a source of photon beams allows to study the scattering of the photons with given helicities. Moreover, the ondulator enables us to carry out the light-light scattering experiments for the frequencies ω = 0.2-0.3 m 7), i.e. in X-ray range, that may be of great importance from the viewpoint of photon detection.

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7) For the storage rings PEP, PETRA, at an energy $E \sim 15$ GeV the counting rate of the order of 1 event per second seems possible.

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