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BREMSSTRAHLUNG IN THE ELASTIC PROTON-PROTON SCATTERING

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Abstract

Maisheev V.A., Mikhalev V.L. Bremsstrahlung in the Elastic Proton-Proton Scattering: IHEP Preprint 92-163. – Protvino, 1992. – p. 6, figs. 2, refs.: 2.

It is shown, that the bremsstrahlung in the elastic proton-proton scattering exceeds the same intensity at the Coulomb interaction several tens of times. Some applications of this radiation are discussed.

Аннотация

Маишеев В.А., Михалев В.Л. Тормозное излучение при упругом протон-протонном рассеянии: Препринт ИФВЭ 92-163. – Протвино, 1992. – 6 с., 2 рис., библиогр.: 2.

Рассмотрено низкоэнергетическое тормозное излучение γ-квантов при упругом протон-протонном рассеянии и обсуждается возможность его использования в экспериментах на коллайдерах.

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Маишеев В.А., Михалев В.Л.
Тормозное излучение при упругом протон-протонном рассеянии.
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The proton-proton interaction plays an important role in experiments in high energy physics. The number of such experiments will increase with putting into operation new proton colliders with luminosity up to $10^{32} - 10^{33}$ cm^{-2}/sec.

Let us consider elastic proton-proton scattering. In experiment, this channel of the reaction may be provided by the proper choice of the trigger. At the same time we consider a process of proton-proton interaction which differs from the first one by the emission of an additional single photon (see fig.1).

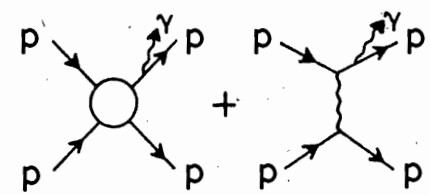

Figure 1. Bremsstrahlung diagrams at the proton-proton elastic scattering. The rest diagrams may be received by rearrangements of the external photon line.

This is the quasiclassical process and its cross section may be determined by the following expression [1,2]

$$d\sigma_\gamma = \frac{d\sigma_p dI}{\omega}, \tag{1}$$

where $d\sigma_p$ is the elastic cross section of the proton-proton interaction, ω is the photon energy and I is the radiation intensity. The function I was borrowed from the work on the two spinor particles with equal masses m ($c = \hbar = 1$)

$$dI = \frac{4\alpha d\omega}{\pi}\{\Phi(t) + \Phi(u) + \Phi(s) - 1\},$$

$$\Phi(x) = \frac{4m^2 - 2x}{\sqrt{|x^2 - 4m^2 x|}} \cdot ln\left\{\frac{\sqrt{|x|} + \sqrt{|4m^2 - x|}}{2m}\right\}, \tag{2}$$

where α is the fine structure constant, s is the square of the center-of-mass energy, t is the square of the four-momentum transfer and $u = 4m^2 - s - t$.

Formula (2) is the result of the integration over photon emission angles and is symmetrical relative to the variables t and u. This means that in the center-of-mass system, the small t (large u) corresponds to the emission in the direction of proton motion. On the contrary, the small u (large t) corresponds to the emission in the direction of motion of the other proton. If $|t| << 4m^2$ and $s >> m^2$ then

$$dI = -\frac{4\alpha t d\omega}{3\pi m^2}. \tag{3}$$

The cross section σ_p can be written as [3]

$$\frac{d\sigma_p}{dt} = \frac{d\sigma_c}{dt} + \frac{d\sigma_a}{dt} + \frac{d\sigma_i}{dt}, \tag{4}$$

where

$$\frac{d\sigma_c}{dt} = \frac{4\pi\alpha^2 F^4(t)}{t^2}, \tag{5}$$

$$\frac{d\sigma_a}{dt} = \sigma_T^2(1+\rho^2)exp(Bt)/16\pi, \tag{6}$$

$$\frac{d\sigma_i}{dt} = \frac{\alpha F^2(t)}{t} \cdot \sigma_T exp\left\{\frac{Bt}{2}\right\}(\rho cos\phi + sin\phi), \tag{7}$$

where σ_c and σ_a are the Coulomb and nuclear elastic cross sections for protons, ρ is the real-to-imaginary ratio, B is the slope parameter, σ_i is the term arising due to the electromagnetic and nuclear interference, $\phi = -\alpha(ln(R_c^2 t) + 0.577)$ is the Coulomb scattering phase, R_c=1,48 fermi, F is the formfactor. The cross sections $\frac{d\sigma_c}{dt}$ and $\frac{d\sigma_a}{dt}$ are considerable in the range $|t| << m^2$. We find the cross section of the production bremsstrahlung photons (emitted in the direction of motion of one proton at the elastic proton scattering) by integrating expression (1) over t and multiplication by 1/2. Hence, it follows that

$$d\sigma_\gamma = d\sigma_{c\gamma} + d\sigma_{a\gamma} + d\sigma_{i\gamma}, \tag{8}$$

$$d\sigma_{c\gamma} = \frac{8}{3}\alpha r_o^2 \frac{d\omega}{\omega} ln\left\{-\frac{m^2}{t_o}\right\}, \tag{9}$$

$$d\sigma_{a\gamma} = \frac{2\alpha\sigma_a}{3\pi m^2 B} \cdot \frac{d\omega}{\omega}, \tag{10}$$

$$d\sigma_{i\gamma} = -\frac{4}{3}\frac{\alpha^2}{\pi}\frac{\sigma_T \rho}{m^2 B}\frac{d\omega}{\omega}, \tag{11}$$

where $r_o \doteq e^2/m$, e is the proton charge, t_o is the minimum value of the four-momentum transfer squared. When the proton momentum after scattering and photon momentum are along the momentum of the proton before the reaction,

where t is momentum transfer squared. If the elastic scattering cross section is known, then the cross section of bremsstrahlung is

$$d\sigma_\gamma = -\frac{2e^2 d\omega}{3\pi m^2 c^3 \hbar\omega} \int_o^{t_{max}} t d\sigma_p. \tag{3}$$

From the lower limit of integral (1) we find the following limitation on the photon frequency

$$\omega\tau = \frac{2\omega R}{c} << 2\gamma^2, \tag{4}$$

where R is effective proton radius. This condition in the rest system of proton emitting a photon with the wavelength equal λ is

$$\frac{\lambda}{2\pi} >> 2R. \tag{5}$$

This limitation is weaker than the limitation $\omega << E$ for high energy proton collision. Nevertheless, in the number of cases this condition determines the upper limit of the bremsstrahlung, for example, when the particles radiate in a short magnet [2].

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t equals t_o. In the center-of-mass system t_o is $-m^6\omega^2/(16E^6)$ (E is the proton energy), and in the laboratory system t_o is $-m^4\omega^2/(4E^4)$ for the fast proton and t_o is $-m^2\omega^2/(2E^2)$ for the recoil proton. The t_o is small enough and we can take $t_o = 0$ for the nuclear scattering because the radiation maximum is at $t = B^{-1}$. The probability of the Coulomb scattering is large at small t. Therefore one is to integrate in (1) from $t = t_o$ in this case and the value of the cross section $\sigma_{c\gamma}$ may be calculated with the logarithmic accuracy. This calculation method does work, when $\omega << E$. Another limitation in the laboratory system under the condition $\omega << E$ is

$$\frac{\omega}{E} << \frac{E}{m^2 R}, \tag{12}$$

where R is the radius of interaction in proton-proton nuclear collisions. This limitation is essential only at low proton energies ($E/m < 5$).

We have estimated these values of the cross sections $\sigma_{c\gamma}$, $\sigma_{a\gamma}$, $\sigma_{i\gamma}$, in the center of mass system for 250-GeV/c proton momentum. In this case, the experimental data allow us to get σ_T=60 mbarn, σ_a=10 mbarn, B=15 (GeV/c)$^{-2}$. The photon spectrum have been calculated from 10^{-3} to 10 GeV. We have received the following results: $\sigma_{c\gamma} = 3.5 \cdot 10^{-31}$ cm^2, $\sigma_{a\gamma} = 1.1 \cdot 10^{-29}$ cm^2, $\sigma_{i\gamma} = -1 \cdot 10^{-31}$ cm^2. One can see, that $|\sigma_{i\gamma}| >> \sigma_{a\gamma}$ and $\sigma_{c\gamma} << \sigma_{a\gamma}$. Thus radiation from the Coulomb interaction is about 3% of the radiation in the elastic proton scattering. We would remind, that the $\sigma_{a\gamma}$ and $\sigma_{c\gamma}$ are cross sections of the photon radiation in the direction of motion only per one proton. The total cross section of the bremsstrahlung radiation is the sum of the cross sections of both protons.

In the ultrarelativistic case, particles are emitted forward into the angle range $\gamma^{-1} = m/E$ relative to the direction of their motion. When $|t| << m^2$ the scattering angles of protons are much smaller than γ^{-1}, then the radiation concentrates inside a cone with the open angle γ^{-1}. However the emission angle distribution of the recoil proton is almost isotropical in the laboratory system.

The bremsstrahlung in the elastic proton-proton scattering is a particular case of such radiation in hadron interactions. Analogous bremsstrahlung should also occur in the scattering production and decays of elementary particles.

The bremsstrahlung in the elastic proton-proton scattering may be useful for the beam-intensity monitoring, the experimental precise determination of the total and differential cross sections in elastic interactions and the calibration of detecting apparatus.

This radiation may be registrated when the elastic channal of the reaction is picked out by a special trigger. In the elastic scattering experiment the measuring of the intensity radiation (see fig.2) permits one to determine the elastic

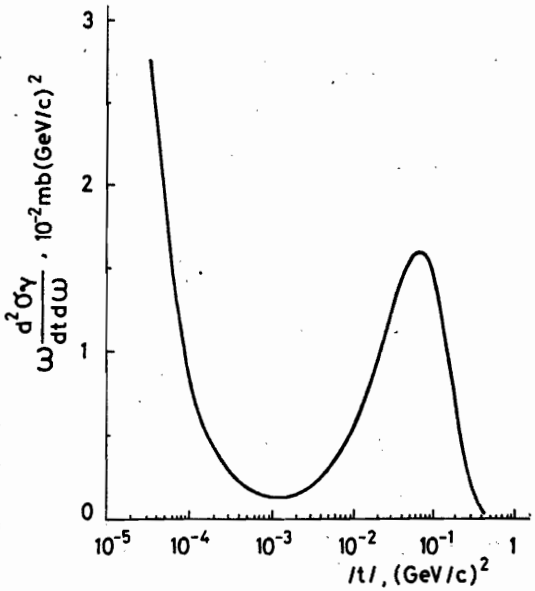

Figure 2. The transfer four-momentum squared dependence of the differential cross section $\omega\frac{d^2\sigma_\gamma}{d\omega dt}$. The proton momentum is 250 GeV/c in center of mass system.

cross section value by correlations (1)-(3). The comparison of both experimental results decreases the systematic errors. Simultaneous measurement of the cross section σ_p (by detecting radiation and scattering protons) allows one to calibrate the detecting apparatus, determine the transfer momentum squared t. Indeed, for $|t| < 0.1 - 0.2$ (GeV/c)^2

$$\frac{N_\gamma}{N_p} = -\frac{4}{3}\frac{\alpha}{\pi m^2} ln\left(\frac{\omega_2}{\omega_1}\right) < t >, \tag{13}$$

where N_p is the number of detected scattered protons, N_γ is the corresponding number of photons with energies from ω_1 to ω_2, $< t >$ is the mean value of variable t in the distribution scattered protons N_p.

In particular, this calibration may be useful when measuring left-right asymmetry in the scattering of polarized protons in the Coulomb-nuclear interference region in order to determine the absolute value of beam polarization. In this case, one should, maybe, first to remove false asymmetry because of the acceptance differences for detectors and, secondly, determine the average analyzing power of this process.

In conclusion, we should note that M.Sogard [5] considered electromagnetic corrections in the elastic hadron scattering in order to take into account them in the experimental measurement of the elastic cross sections.

We would like to thank S.B.Nurushev and V.G.Vasil'chenko for stimulating discussions.

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APPENDIX

Here we offer an elementary conclusion of the correlation for bremsstrahlung cross section. It is useful, because we have received some limitations on the radiation energy of photons. In the case of small deflection angles of particles ($\theta << mc^2/E$, m and E are the mass and energy) the spectral distribution of the radiation energy is [1]

$$d\varepsilon_\omega = \frac{e^2\omega d\omega}{2\pi c^3}\int\limits_{\omega/2\gamma^2}^{\infty}\frac{|\vec{F}_{\omega'}|^2}{m^2\gamma^2}\left[1 - \frac{\omega}{\omega'\gamma^2} + \frac{\omega^2}{2\omega'^2\gamma^4}\right]d\omega', \tag{1}$$

where $\vec{F}_\omega = \int\limits_{-\infty}^{\infty}\vec{F}(t)e^{i\omega t}dt$ is the Fourier-component of the transverse force, acting per particle with a charge e, c is the light velocity, $\gamma = E/mc^2$, ω is the photon frequency. When the force acts for a short time τ, such as that $\omega\tau << 1$, then $\vec{F}_\omega \approx \int\limits_0^\tau F(t)dt$ and expression (1) becomes simpler

$$d\varepsilon_\omega = \frac{2e^2 d\omega}{3\pi m^2 c^3}|\int\limits_0^\tau F(t)dt|^2 = -\frac{2}{3}\frac{e^2 t d\omega}{\pi m^2 c^3}, \tag{2}$$