Radiation from planar channeled 5 - 55 GeV/c positrons and electrons.

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Abstract:

The emission of radiation from 5 to 55 GeV/c planar channeled positrons and electrons passing through a 135 μ thick Silicon-crystal has been investigated. The intensity of the channeling-radiation is found to be 10 to 30 times the intensity of normal bremsstrahlung. For channeled electrons no structure is found in the spectrum, whereas strong and sharp peaks are found for positrons. This peak structure is extremely sharp at 5 GeV/c and for momenta above 20 GeV/c the structure disappears. For a classical description of channeling, but using an anharmonic potential, certain energies are found for which the maximum energy of the channeling radiation is practically independent of transverse energy. The possibility of making a monoenergetic γ -source in the energy range of 10-100 MeV is mentioned.

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Within the last two years a new type of radiation, called "channeling radiation", was discovered coming from electrons and positrons traversing single crystals along axial and planar directions. For such directions a strong steering effect occurs giving rise to an oscillatory motion in a plane perpendicular to the incident direction (the transverse plane). This motion results in a dramatic increase of the emitted low-energy bremsstrahlung in the forward direction. Pronounced sharp lines have been observed [1,2] for this radiation which can be associated with transitions between bound states in the transverse potential. Until now practically all investigations have been performed with projectiles in the MeV-region. In this energy range the energy of the channeling radiation is found to be proportional to $\gamma^{3/2}$, where γ is the Lorentz factor. In the GeV-region, this energy dependence is expected gradually to change into a $\gamma^{1/2}$ dependence. Experimentally only very preliminary experiments have been reported, [3,4]. Here we report on measurements of the emitted radiation from 5-55 GeV/c electrons and positrons traversing a 135 μ thick Silicon crystal along the (110) plane.

The experiment was performed at the tagged photon facility at the CERN SPS, [5]. Here 240 GeV/c protons hit a production target and produce a secondary beam of photons via the decay of π^0 . Charged particles are swept out of this secondary beam and the photons then produce electron-positron pairs in a lead converter. Electrons or positrons were then momentum selected and transported to the Si target. The beam contained about 1 % of pions. In this system, shown in fig. 1, the momentum of the particles incident on the Si target is determined by magnets and multiwire- or drift-chambers to within a few 100 MeV/c. The tagging system on the exit side consists of

MWPC's, two hodoscopes and a lead-glass array giving the exit momentum, to within 100 MeV/c, and particle identification. The silicon target was a disc of thickness 135 μ and diameter 50 mm mounted in a precision remote-controlled goniometer in vacuo. Just in front of the target the incident beam was bent 10 mrad to prevent radiation created upstream from hitting the photon detector, which was a 10"x12" NaI crystal with an energy resolution (FWHM) of around 4 %. The NaI crystal was surrounded with scintillators to discriminate against charged particle background and to increase the energy resolution. This detection system could handle photons up to 1.5 GeV, above which the tagging system was used. The absolute energy calibration was good to within 10 %. The NaI detector was shielded from the lead glass array so that the neutron-induced background above 7 MeV was negligible. The acceptance angle of the photon detector was around 25 mrad.

In fig. 2, the emitted radiation intensity for 10 GeV/c positrons (a) and electrons (b) is shown as function of photon energy and incident angle to the (110) plane. All spectra are normalized to that of incoherent bremsstrahlung. For large angles to the plane, the well-known coherent bremsstrahlung, where the photon energy is proportional to the angle to the plane, is seen as the two ridges. For incident angles smaller than ψ_p the coherent bremsstrahlung becomes superseded by channeling radiation. Here ψ_p is the critical angle for planar channeling, which from the Lindhard channeling model is given by

$$\psi_p^2 \approx 0.00033 (Z_2^2/\gamma\beta^2) (Na_0^2 d_p) \quad (1)$$

where Z_2 and N are the atomic number and atomic density of the target atoms, resp., $a_0 \approx 0.5A$ the Bohr radius and d_p the distance between

the atomic planes. For the (110) plane in Si, the critical angle at 10 GeV/c is 51 μ rad. This critical angle ψ_p is the basic quantity determining the conditions under which channeling effects occur. When particles enter a crystal at angles smaller than ψ_p to a plane, their trajectories are strongly affected by correlated collisions with the atoms in the plane, whereby electrons are focused around the nuclei in the plane and positrons kept away from the nuclei. The resulting oscillatory motion can be described as an interaction with a transverse continuum potential obtained by averaging the atomic potentials over the two dimensions of the plane. This transverse motion gives rise to the emission of channeling radiation with a characteristic line spectrum for a given angle of observation. Quantum mechanically the channeling radiation can be considered as energy emitted when a positron/electron jumps between energy levels in the planar potential, whereas coherent bremsstrahlung is due to the quantization of momentum transfers. Since planar channeled electrons and positrons move in different potentials the radiation is expected to be different. That this is the case can be seen from the low-energy part of fig. 2. The detailed spectra for the low-energy part of fig. 2 are shown in fig. 3. Here the incident angles are within ψ_p to the (110) plane which is our angular resolution at 10 GeV/c. For electrons a big increase in radiation intensity is obtained with a broad peak in the spectrum. For positrons a dramatic increase in intensity is seen, but here the spectrum consists of distinct peaks. These features may be understood by the following theoretical considerations.

In the GeV region a classical description of channeling is a good approximation, since the number of quantum states in the transverse

phase space is big, [8]. So the classical theory for the emission of channeling radiation, as obtained by Kumakhov and others (see [6], where an expression for the maximum photon energy is derived), can be used; for a review, see [7]. This formula for the maximum photon energy in the n 'th harmonic as function of transverse energy, $E_{\perp}$, and Lorentz factor γ can be rewritten as

$$\omega_m(E_{\perp}, \gamma) = \frac{4\pi n \gamma^{3/2}}{A'(E_{\perp}) + \gamma A(E_{\perp})/m_e c^2} \quad (2)$$

where the derivative of the action $A(E_{\perp})$, is given as $A'(E_{\perp}) = P(E_{\perp}, \gamma)/\sqrt{\gamma}$, where $A(0) = 0$ and m_e is the electron mass. Here $P(E_{\perp}, \gamma)$ is the period of the oscillation, which depends on the form of the potential; for details see [9]. The channeled particles have a distribution in $E_{\perp}$ due to beam divergence and surface transmission. For each $E_{\perp}$ the spectral intensity in each harmonic increases until $\omega = \omega_m$ and then drops to zero, and the intensity increases with $E_{\perp}$. The total channeling radiation is a superposition of the radiation for each $E_{\perp}$; thus the dependence of ω_m on $E_{\perp}$ causes a broadening of the peaks associated with each n . For the case of a harmonic potential, $V(x) = V_0 x^2$, ω_m decreases monotonically with $E_{\perp}$, since $P(E_{\perp}, \gamma) = 2\pi(m\gamma/2V_0)^{1/2}$ is independent of $E_{\perp}$. However, for the Moliere potential ω_m becomes practically independent of the transverse energy for a certain value of γ . In order to get an analytical expression for ω_m , we have used a tangent square potential, $V(x) = b \tan^2 ax$, where the constants a and b have been determined so that the period of oscillation as a function of $E_{\perp}$ for this potential approximates to the period of oscillation for the Moliere potential. This approximation is very good, as shown in [10]. For the tangent square potential the period of oscillation has the simple form

$$P(E_{\perp}, \gamma) = \pi \sqrt{2m_e \gamma / b a^2} / \sqrt{1 + E_{\perp} / b} \quad (3)$$

and (2) becomes practically independent of the transverse energy at $\gamma = \gamma_c$, where $\gamma_c \approx 3m_e c^2 / 8b$. In the case of the (110) plane in Si, where $a = 0.879 \text{ \AA}^{-1}$ and $b = 20.7 \text{ eV}$, this occurs for a positron energy of 4.7 GeV. Since the harmonic and anharmonic potentials give a very different $E_{\perp}$ -dependence of the period in the 1-50 GeV/c region (see [9]), the spread in ω_m will also be very different especially for those projectiles with large transverse energy, which gives the highest intensity. This explains why the first harmonic for 5 GeV/c positrons, shown in fig. 4, is very intense and sharp on the high-energy side, although the angular resolution at 5 GeV/c is nearly $\pm 2\psi_p$. The above description also explains why the peaks seen on fig. 3 (a) smear out at higher energies, as seen on fig. 4, where the photon spectra are shown for 5, 10, 20 and 55 GeV/c positrons channeled between the (110) planes. In fig. 4 is shown the spread in ω_m obtained from the harmonic, the Lindhard and the Moliere potential models and with $0 < E_{\perp} < V(d_p/2 - \rho/\sqrt{2})$. The maximum transverse energy has been chosen to $V(d_p/2 - \rho/\sqrt{2})$, where ρ^2 is the mean square vibrational amplitude of the target atoms perpendicular to the plane, because the thermal vibrations of the atoms in the plane rounds off the potential, giving a maximum approximately equal to $V(d_p/2 - \rho/\sqrt{2})$. The constant V_0 in the harmonic potential has been chosen so that the harmonic potential at the plane agrees with the thermally averaged Moliere potential at the plane, in agreement with what is done in [4]. Although the difference between the three potentials at first sight seems small, the agreement between the ω_m -values and the high-energy side of the first harmonic is the best for the Moliere potential, but apparently this effect is very sensitive to the choice

of the potential.

The fact that ω_m for certain values of γ becomes practically independent of the transverse energy is the reason for the sharp peak at 5 GeV/c in the photon spectrum. This opens up a very interesting possibility of making monoenergetic γ -sources in the photon energy range 15-100 MeV by choosing different crystals and planar directions. Since at these projectile energies the photon energy is nearly independent of incident angle direction within the critical channeling angle, thicker crystals can be used because the gradual increase in transverse energy for increasing crystal thickness due to multiple scattering do not change the ω_m value. For 5 GeV/c positrons incident on a 2 mm thick Si crystal around 1 photon in the energy range 10-30 MeV per incident positron would be emitted.

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FIGURE CAPTIONS

Figure 1. Schematic drawing of the experimental setup.

Figure 2. Radiation-intensity shown as function of photon-energy and angle to the (110)-plane for 10 GeV/c positrons (a) and electrons (b). The channeling radiation is seen as the intense peaks on the plane and the coherent bremsstrahlung stands out as the two ridges. The intensity is given relative to the yield from an amorphous foil of the same thickness (random yield).

Figure 3. Photon spectra for 10 GeV/c (a) positrons and (b) electrons channeled along the (110) plane normalized to random yield.

Figure 4. Photon spectra for 5, 10, 20 and 55 GeV/c positrons channeled along the (110)-plane in Silicon normalized to random yield. The horizontal lines represents the interval of ω_m values for the harmonic (H), the Lindhard (L) and the Moliere (M) potential.

Fig. 1

b)

10 GeV/c

e^-

a)

10 GeV/c

e^+

Fig. 2

Fig. 3

Fig. 4