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Possible Hadron Identification in a Beam Formed by a Bent Single Crystal*

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Abstract

Possible hadron identification in a beam formed by a bent single crystal is shown, based on the synchrotron part of the radiation spectrum of channeling particles. Identification efficiency and beam intensity are estimated for UNK.

At higher energies, traditional methods of measuring the fast charged particle γ-factor (e.g., Cherenkov counters) are not effective, so alternative methods are of great interest. Kumakhov[1] has proposed the use of channeling radiation for identification of electrons and positrons. This method, however, is not effective for heavier particles. In the present paper we will show the possibility of using the synchrotron part of the radiation spectrum of particles, channeling in a bent single crystal, for their identification.

In the radiation spectrum of particles, channeling in a bent single crystal, a soft synchrotron part appears,[2] which leads to a significant increase in the number of photons emitted per unit length. This can be illustrated in harmonic approximation, comparing the characteristics of the soft (synchrotron radiation) and the hard (channeling radiation) parts of spectrum. Radiation intensity is defined by the mean square of the radius of the charged particle trajectory curvature. The power emitted per unit length[4] is shown by

$$I = \frac{2}{3}e^2\gamma^4\left\langle\frac{1}{R_{loc}^2}\right\rangle . \tag{1}$$

For particles channeling in a bent single crystal,

$$\frac{1}{R_{loc}} = \frac{\dot{V}_x}{c^2} = \frac{\dot{V}_{x,s} + \dot{V}_{x,c}}{c^2}, \tag{2}$$

where $V_{x,s}$ is the transverse velocity averaged over a period (due to bend), $V_{x,c}$ is the transverse velocity of the channeling particle relative to planes, dot means derivative with respect to time. Due to the independence of $V_{x,s}$ and $V_{x,c}$, the mean square of Eq. (2) is equal to

$$\left\langle\frac{1}{R_{loc}^2}\right\rangle = \frac{1}{R^2} + \left\langle\frac{\dot{V}_{x,c}^2}{c^4}\right\rangle = \frac{1}{R^2} + \frac{1}{R_c^2}, \tag{3}$$

where R is the bending radius. For planar channeling and harmonic potential we have

$$\frac{1}{R_c^2} = \frac{\epsilon}{2}\cdot\frac{\theta_c^4}{x_c^2}, \tag{4}$$

where $\epsilon = E_x/E_{x,c}$ is the transverse energy normalized to the critical one, θ_c is the channeling critical angle, and x_c is the critical transverse coordinate. Introducing $\rho = R_T/R$

(R_T being the Tsyganov radius), we can rewrite Eq. (1) as:

$$I = \frac{2}{3} e^2 \gamma^4 \frac{\theta_c^4}{x_c^2} \left(\rho^2 + \frac{\epsilon}{2} \right). \tag{5}$$

The ϵ value could be 0 to $(1-\rho)^2$. So, for a large bend, $R \lesssim 3R_T$, the synchrotron radiation intensity is comparable to and even exceeds the channeling radiation intensity: $I_{\rm SR} \gtrsim I_{\rm CR}$. Characteristic frequencies of these parts of spectrum are very different:[1,4]

$$\omega_{\rm SR} = \frac{3}{2} c \frac{\gamma^3}{R}, \qquad \omega_{\rm CR} = 2 \left(\frac{2E_{x,c}}{m x_c^2} \right)^{1/2} \gamma^{3/2}, \tag{6}$$

where m is the particle's mass. For hadrons up to 20 TeV in any crystal, $\omega_{\rm CR}$ is many times greater than $\omega_{\rm SR}$.

Consider now the possible use of a particle's radiation for its identification. It was shown by Taratin and Vorobiev[3] that the spectrum at $\omega \lesssim \omega_{\rm SR}$ in the considered problem could be described by the synchrotron spectrum:[4]

$$\begin{aligned} I_{\rm SR}(\omega) &= I_{\rm SR} f(y), \qquad \omega = \frac{3}{2} c \frac{\gamma^3}{R} y \\ f(y) &= \frac{9\sqrt{3}}{8\pi} y \int_y^\infty K_{5/3}(x) dx. \end{aligned} \tag{7}$$

The number of emitted photons per unit length is defined practically by this part of the spectrum:

$$\frac{dN}{dz} = \frac{I_{\rm SR}}{\hbar \omega_{\rm SR}} \cdot \int \frac{f(y)}{y} dy = \frac{5\sqrt{3}}{6 \cdot 137} \cdot \frac{\gamma}{R}. \tag{8}$$

The energy-to-radius ratio is limited in a bent crystal; for planar channeling the value varies from 1 GeV/cm in silicon (typical working value) to 50 GeV/cm in tungsten (limit). One photon emission length:

$$L_i = 95 \frac{mc^2}{E/R}; \tag{9}$$

for pions in silicon, germanium, and tungsten at the critical bend, $L_i = 2.2$ cm, 1.1 cm, and 0.27 cm, respectively. For axial channeling, these numbers are one order of magnitude less. Actually, the bending radius should be a few times larger than the critical one. Dechanneling length at TeV energies amounts to tens of centimeters, so one can have a few tens of photons per each channeling particle. In other words, the particle emits $\gamma/95$ photons over one radian deflection.

This could be compared with the Transition Radiation Detector, where the typical length of one photon emission amounts to 5–10 cm.[7] Emission probability there has threshold dependence on the γ-factor. Photon energy is proportional to the γ-factor and has the same order (for TeV beams) as $h\omega_{SR}$, about 100 keV.

Synchrotron photon energy strongly depends on particle mass:

$$\hbar\omega = \frac{3}{2} \cdot \frac{hc}{(mc^2)^3} \cdot \frac{E^3}{R} \sim \frac{E^2}{m^3}, \tag{10}$$

because $E/R \simeq$ const. At high energies, radiation energy loss becomes comparable with ionization loss—10 TeV pion during planar channeling could lose due to radiation up to 1 MeV/cm in silicon and up to 60 MeV/cm in tungsten. So one method of particle identification could be the measurement of channeling particle energy loss in the crystal and calculation of the increase $dE/dz \sim 1/m^4$ due to radiation, if all photons are absorbed. The existing technique[11] allows one to measure the dE/dz of channeling particle with 10 keV accuracy (for 1 GeV protons); the Landau distribution of ionization loss width is about 20%. The minimal energy when this increase could be seen is about 3 TeV for muons and 5 TeV for pions in germanium for planar channeling, and about one order less for axial channeling.

More obvious methods of particle identification are (1) emitted photons number measurement ($\sim 1/m$), (2) photon energies measurement ($\sim 1/m^3$), and (3) use of different absorption lengths of photons with different energies.

Taking into account synchrotron quanta absorption in a crystal and background, two schemes for UNK hadron beam tagging could be proposed.

In the simpler one (Figure 1a), synchrotron photons are spatially extracted from background particles (due to high directivity of radiation) and from a hadron beam (due to crystal bend). A channeling hadron emits photons in a narrow angular cone of order $1/\gamma$; in the bend direction photons are distributed in an angle from 0° to the crystal bend angle. If the crystal length is not larger than the photons' mean free path in the crystal, photons come out in approximately one direction between the undeflected hadron beam and the deflected one; this "photon beam" could be used for a fast trigger. The background, mainly of δ-electrons, is roughly isotropic in angle and does not affect tagging efficiency.

Let us roughly estimate the tagged beam intensity and tagging efficiency with the example of the 1.5 TeV positive secondary beam in channel H3 of the UNK project.[11] Using strongly bent tungsten crystal (channel (110)) with $pv/R = 30$ GeV/cm, the energy

$\hbar\omega_{SR}$ of emitted quanta is about 1 MeV; the mean free path of these quanta in tungsten is about 1 cm. One photon emission length $L_i = 4$ mm for pions. So, one could get an average of 2 photons per pion; photons will be distributed in the bend direction 0 to 20 mrad, in transverse direction ± 0.1 mrad. Photons emitted by heavier particles are absorbed in crystal. For secondary beam intensity 6×10^{10} hadrons/10^{14} protons per cycle and emittance 0.4π mrad mm, 1 mm thickness of crystal gives 7×10^5/s for tagged beam intensity.

Because the dechanneling length is very large at these energies (120 cm in straight W(110) channel for 2 TeV positive beam), and because short (about 1 cm) crystal is needed, the same scheme could be used for negative beam tagging. The UNK beam intensity at 2–2.5 TeV (and the same tagging efficiency) will be 1–2 orders less than the previous estimate.

Tagging efficiency is not large, so we consider a second scheme—using long crystals, limited by dechanneling (Figure 1b). Let us take a 20-cm Ge(111) crystal with $pv/R =$ 6 GeV/cm; along this length a pion emits an average of 9 photons; a kaon, 2.6; and a proton, 1.4. For photons with $\hbar\omega_{SR}^{\pi} \simeq 150$ keV energy, the mean free path in germanium is equal to 9 mm. This photon scattering is mainly Compton, with angles of the order of 1 rad. The photon exit probability is defined by the crystal transverse dimension compared to the mean free path. So we should expect most photons emitted by pions to exit the crystal if the thickness is of the order of 1 mm. The photons emitted by heavy particles (K and p) have a mean free path of about 10^{-3} cm in this case and are absorbed in the crystal.

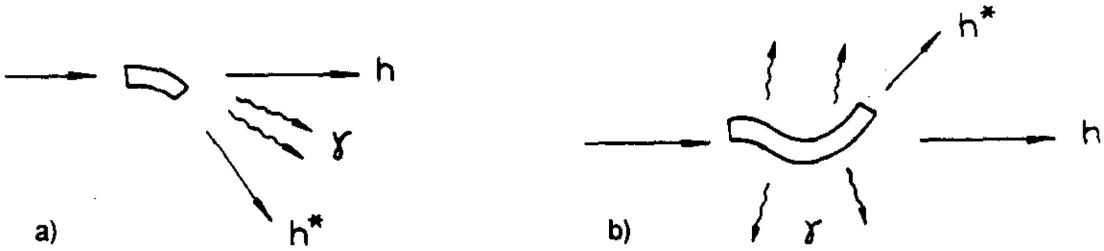

Figure 1. Tagging Schemes: h—Undeflected Beam, h^*—Tagged Beam, γ—Photons.

Detector count rate is limited (a few MHz, typically), and part of the beam, captured into channeling, is small. So it will be better to form at first by a short crystal a beam with θ_c divergence and 2×10^6/s intensity, deflecting it by about 1 mrad onto the second crystal, equipped with a photon detector. The required thickness of the crystal is about 1.5–2 mm. About half of the deflected beam is captured in the second crystal. So, tagged beam intensity will be about 10^6/s. "Snake" bend is possible to form a tagged beam in any required direction.

The background created by channeling particles consists mainly of δ-electrons. Their number per unit length is

$$\frac{dN}{dz} = 0.35\,\frac{\mathrm{MeV}}{\mathrm{cm}}\,\frac{1}{T_{\min}}, \tag{11}$$

where $T_{\min}$ is the δ-electron minimal energy. The ratio of δ-electrons to synchrotron quanta (for pion) amounts to $\delta/\gamma \simeq 0.8\,\mathrm{MeV}/T_{\min}$. Due to absorption, only δ-electrons with energy $T_{\min} \gtrsim 1\,\mathrm{MeV}$ could exit the crystal. That gives $\delta/\gamma \lesssim 1$. This background could be removed by (1) spectra difference: $E_\delta \gtrsim 1\,\mathrm{MeV}$, $E_\gamma \lesssim 0.3\,\mathrm{MeV}$; (2) use of field 1 Tesla to remove electrons with $E_\delta \lesssim 100\,\mathrm{MeV}$, which gives $\delta/\gamma \lesssim 10^{-2}$; and (3) use of stronger absorption of electrons with $E < 10\,\mathrm{MeV}$ to get $\delta/\gamma \lesssim 0.1$. The energy of most δ-electrons is much less than the critical one (about 20 MeV in germanium), so their bremsstrahlung could be neglected here.

Many of these numbers are rather rough estimates; accurate computer simulation, taking into account all radiation spectrum and its interaction with crystal and detector, could significantly change them.

Efficiency of the considered method of particle identification increases with energy increase, because the number of emitted photons is proportional to the energy, and detecting efficiency increases due to the photons' higher energy. Some proposals for bent crystal use in particle physics could be accompanied by radiation detection.

For example, in a proposed[8] scheme of secondary particle extraction from the intersection region of the Superconducting Super Collider (SSC) one should deflect by 4.1 mrad hadrons with 10–15 TeV energy. Under this deflection, a pion emits 3–5 photons, which can be used for identification. Another project often discussed is the separation of short-lived particles,[9,10] where deflection of 50–100 mrad is required. Under this deflection, each particle emits $\gamma/1000$ photons.

There exists also the possibility of observing synchrotron radiation of 70–200 GeV protons in bent silicon crystals, because photons with a wavelength larger than 1–2 μm are not absorbed in silicon. The wavelength is

$$\lambda_{\mathrm{SR}} = \frac{4}{3}\pi\frac{R}{\gamma^3} = 10^{-5}R \tag{12}$$

for 70 GeV protons. Bending radius in IHEP experiments achieved 55 cm.[6] For $\lambda_{\mathrm{SR}} \simeq 5.5\,\mu$m, about 10^{-3} photons/proton are emitted in the interval 1 to 4 μm over 1 cm length. In the experiment[6] up to 2.5×10^7 protons were deflected per cycle of U-70. For observation of proton radiation, Planck spectrum should be removed from the detector view. At 77 K Planck photon fluence in the interval 0–4 μm, equals 0.1 photon/cm^2/sec.

The method of particle identification considered here could be effective only for a beam formed by a bent single crystal, because as a rule crystal acceptance is too low.

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