High-energy $e^-/e^+$ spectrometer via coherent interaction in a bent crystal

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Is it possible to measure the $e^+ / e^-$ ratio with a 1 cm bent crystal?
Outline

• Channeling:
  • Channeling
  • De-channeling
  • Channeling in bent crystals

• The idea
  • Basic scheme
  • Positron to electron ratio measurement

• Experimental Data
  • CERN SPS-H4 line

• Conclusions
  • Spin precession & Enhanced bremsstrahlung
  • Conclusions
CHANNELING

Entrapment of charged particles by the ordered pattern of crystalline atoms
Channeling

- A crystal is a microscopically ordered pattern of atoms.

HRTEM image of a silicon (Si) [110] crystallographic zone axis.

Ki-Bum Kim, SPIE Newsroom, DOI: 10.1117/2.1200812.1396
Channeling

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- The periodic arrangement of atoms generates a series of crystal planes.
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- The ordered charges of the planes generates a strong electromagnetic field.

Inter-planar electric field for Si (110)

ECHARM - E. Bagli, V. Guidi, V. A. Maisheev, PRE 81, 026708 (2010)
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- The e.m. field generates a potential well able to constrain charged particles.

Inter-planar potential for Si (110)

ECHARM - E. Bagli, V. Guidi, V. A. Maisheev, PRE 81, 026708 (2010)
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- Channeling occurs when the angle between the particle trajectory and the crystallographic plane is lower than the channeling critical angle, i.e. when the potential energy is lower than the potential well barrier.

\[ K = \frac{1}{2} p \beta \theta^2 \]
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- Channeling occurs when the angle between the particle trajectory and the crystallographic plane is lower than the channeling critical angle, i.e. when the potential energy is lower than the potential well barrier.

- The channeling critical angle is proportional to the square root of the well depth of the inter-planar potential divided by the particle energy. Therefore, channeling is a directional process, especially for high-energy particles.

\[ |\theta| < \theta_c = \sqrt{\frac{2U_0}{p\beta}} \]

Channeling in bent crystals

- In 1976 E. N. Tsyganov asks himself an interesting question.

"What will happen with the trajectory of the channeled particles if we bend the crystal? Up to some critical value of the bending radius a particle trajectory will repeat the shape of a bent crystal."

Channeling in bent crystals

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W. Scandale et al., “Observation of channeling for 6500 GeV/c protons in the crystal assisted collimation setup for LHC” Physics Letters B 758 (2016), 129

Channeling in bent crystals

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- Channeling in bent crystals was observed from 195 MeV/c e⁻ (MAMI) to 6.5 TeV/c proton (LHC).

- Curvature affects particle motion causing a centrifugal force, lowering the potential well barrier.

- The maximum achievable bending angle is determined by the critical radius, proportional to the particle momentum-velocity. At $10R_c$ the efficiency is almost the maximum achievable.

\[ R_c = \frac{p\beta}{U'_{\text{max}}} \]

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Dechanneling

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  - A positively charged particle that oscillates between two planes rarely interacts with the atomic nuclei.
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- Channeling depends on particle charge sign:
  - A positively charged particle that oscillates *between* two planes *rarely* interacts with the atomic nuclei.
  - A negatively charged particle that oscillates *over* two planes *frequently* interacts with the atomic nuclei.
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• Channeling depends on particle charge sign:
  • A positively charged particle that oscillates between two planes rarely interacts with the atomic nuclei.
  • A negatively charged particle that oscillates over two planes frequently interacts with the atomic nuclei.

• Electrons dechannel more frequently than Positrons
THE IDEA
Basic scheme

Different dechanneling rate for positive and negative particles

Basic scheme

Different dechanneling rate for positive and negative particles

Deflection of charged particles under channeling in bent crystals

Basic scheme

Different dechanneling rate for positive and negative particles

Deflection of charged particles under channeling in bent crystals

Positron to electron ratio measurement via channeling

Positron to electron ratio measurement

- By analysing a beam deflection distribution after the interaction with a bent crystal it is possible to determine the ratio between positrons and electrons.
Positron to electron ratio measurement

By analysing a beam deflection distribution after the interaction with a bent crystal it is possible to determine the ratio between positrons and electrons.

Two ingredients are needed:

- e^+ / e^- 1 TeV/c beam
- Si (220) Crystal – 1 cm long and 1 mrad bending
Positron to electron ratio measurement

By analysing a beam deflection distribution after the interaction with a bent crystal it is possible to determine the ratio between positrons and electrons.

Two ingredients are needed:
- Experimental deflection distribution
Positron to electron ratio measurement

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- Experimental deflection distribution
- Monte Carlo
Positron to electron ratio measurement

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- Two ingredients are needed:
  - Experimental deflection distribution
  - Monte Carlo

- As a result, it is possible to determine the ratio of positrons over electrons with channeling.
EXPERIMENTAL DATA

Test beam at the CERN SPS-H4 line
CERN SPS-H4 line

(a) Channeling

Positrons
Electrons

(b) Free Direction

Normalized Counts [dN/N]

Deflection Angle [μrad]

CERN SPS-H4 line

(a) Positrons
Electrons

(b) Positrons
Electrons

Channeling
Free Direction

Normalized Counts [dN/N]

Deflection Angle [μrad]

Calorimeter
Silicon
Crystal on Goniometer
Silicon
Silicon
Scintillator

CERN SPS-H4 line

(a) Positrons
Electrons

(b) Positrons
Electrons

Deflection Angle [μrad]
Free Direction

Electrons interact more frequently than positrons with nuclei, leading to an increase in the r.m.s. of the deflection distribution in the free direction.

- **Positrons/Electrons Not Aligned**
  - Electrons: 10.3 ± 0.2 µrad
  - Positrons: 7.6 ± 0.4 µrad

- **Electrons Channeling**
  - Electrons: 10.3 ± 0.2 µrad

- **Positrons Channeling**
  - Positrons: 8.8 ± 0.1 µrad

The channeling efficiency is by far greater for positrons rather than for electrons.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Channeling Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+$</td>
<td>$54 \pm 2$</td>
</tr>
<tr>
<td>$e^-$</td>
<td>$2 \pm 2$</td>
</tr>
</tbody>
</table>

CERN SPS-H4 line

Channeling

Normalized Counts [dN/N]

Particle Channeling Efficiency (%)

Positrons

Electrons

CONCLUSIONS

And other usages of coherent effects
Spin precession

- The spin precession of a charged particle is induced by the interaction of its electromagnetic dipole moments, e.g. MDM and EDM, with external electromagnetic fields.

- The intense electric field between the crystal planes, $E$, which deflects charged particles, transforms into a strong electromagnetic field $E^* = \gamma E$, $B^* = -\gamma \beta \times E/c$ in the instantaneous rest frame of the particle and induces spin precession. In the limit of large boost, the spin precession induced by the MDM is:

$$\phi = \frac{g - 2}{2} \gamma \theta_c$$

- Thanks to the extremely large magnitude of the electric field, the spin rotation angle in the crystal of several centimetres in length can reach several radians.

- V. G. Baryshevsky, Pis’ma. Zh. Tekh. Fiz. 5 (1979), 182
Compact Calorimeters with Oriented Crystals

Presenter: Laura Bandiera, INFN Sezione di Ferrara - bandiera@fe.infn.it

Motivation

The radiation length in an oriented crystal is strongly reduced!!

PWO $X_0$ reduction for electrons aligned to crystal axes

- **FIXED-TARGET EXPERIMENT**: forward e.m. calorimeters/preshower with reduced volume.
- **BEAM DUMP**: compact active beam dump with an increase of sensitivity to dark photons.
- **SATELLITE BORNE GAMMA-RAY TELESCOPE**: Containing e.m. showers for energies $>10$ GeV in a smaller volume. Cost reduction, increase of sensitivity and energy resolution!

PbWO$_4$ scintillator crystal $X_0$, standard = 8.9 mm

Crystal lattice effect

$X_0 = 8.9$ mm $X_0 = 1.6$ mm

L. Bandiera et al, ArXiv: 1803.10005

Calorimetry - Poster Session – Tuesday 29
Is it possible to measure the $e^+/e^-$ ratio with a 1 cm bent crystal?

1. Particles impinging on a bent crystal with a radius greater than the critical radius and an incoming angle lower than the critical angle undergo the channeling effect, which was used to deflect particles from GeVs up to TeVs energies.

2. The deflection efficiency is not constant and varies with the particle charge: for negative particles is strongly limited, while positive particles have optimal deflection efficiency at high-energy.

Due to the beam-splitting capability, channeling can be used to measure the positron to electron ratio of a fraction of particles in astrophysics experiments that do not involve the use of a magnet. In fact, a bent crystal, e.g. Si or Ge, for deflection via channeling would be a non-cryogenic passive device, i.e., with no energy consumption.
THANK YOU FOR THE ATTENTION

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