Beyond Silicon: Comparing Crystal Channelling Properties of Carbon Nanotubes Across Varying Parameters

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I. Why we want to come to CERN

During a Zoom call, we found ourselves hooked on a lively discussion about particle physics. Eager to learn more, we reached out to an Imperial College Ph.D. student who works at CERN and, to our delight, she gave us a window into the fascinating world of experimental physics. This unexpected conversation inspired us to participate in the Beamline for Schools competition. We firmly believe that research is the key to giving back to society and making a real difference. CERN represents the pinnacle of scientific exploration, and we are determined to be a part of this incredible journey.

II. The Experiment

A. Introduction

Crystal lattices trap and channel particle beams along major crystallographic directions, better known as crystal channelling. In a bent crystal, the channelled particles follow the bend, making the basis for an elegant technique of beam steering [1]. Research at facilities like the LHC at ultra-high energy settings [2] has opened doors to eventual applications in techniques like beam-halo cleansing [3], separation of short-lived CHARM particles, and precise measurements of magnetic moments of charmed baryons [4]. Recognising the need to further optimise and explore the phenomenon, the proposed experiment harnesses the high-energy conditions of the T9 Beamline to explore channelling efficiencies in a new material, carbon nanotube, under temperature variations. Since Carbon Nanotubes have higher dechannelling lengths as compared to crystals, the dechannelling effect at given length is lower than that of a crystal [5]. This weaker dechannelling combined with a greater channel width for Carbon Nanotubes allows particles to travel over much greater distances in Nanotubes as compared to in crystals [6].

B. Theory

The proposed fixed-target experiment aims to study the effects of 10 GeV proton beams on bent silicon crystals and carbon nanotubes. While experiments have been conducted at very high energies and low energies [7][8], the energy range offered by the T9 beamline remains relatively unexplored. As an extensively researched material, Silicon is considered the best standard material for channelling. Exploring in this new energy range, Silicon will be used as a benchmark to evaluate the performance of carbon nanotubes in crystal channelling.

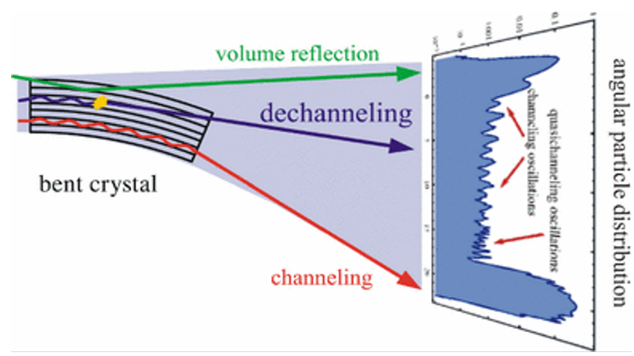

Fig. 1: Sketch of the angular particle distribution of particles passed through a bent crystal

Source: The European Physics Journal, Article No: 77

Both materials will be compared on channelling efficiency based on performance for a fixed bending angle of the beam (Θ_d). For that fixed angle, the dimensional parameters of the materials will be set to a hypothesised optimal performance configuration. These dimensional parameters, radius of curvature (r) and (L), are labelled in fig.(2) for geometrical understanding. The arc with length L represents the material where the beam enters (tangentially) from one end of the arc and exits (tangentially) from the other end. The deflection angle, radius of curvature, and length of the material are related in this manner: ($L = \alpha R$) [9]. Additional dimensional parameters of silicon and carbon nanotubes are discussed in Mathematical Framework: Crystal Channelling

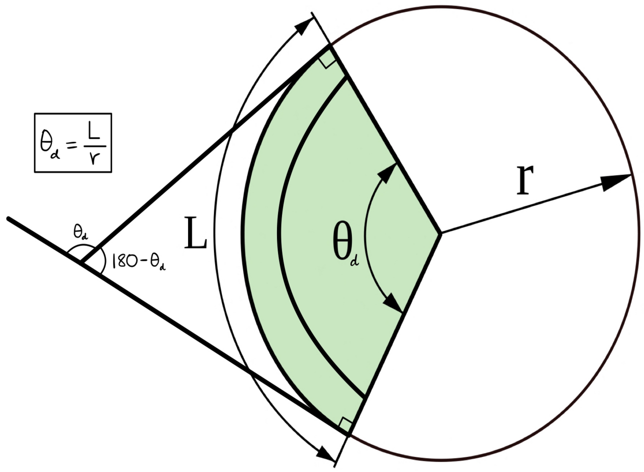

Fig. 2: Material Dimensions

I. Dimensions of Silicon: As shown in fig.(3), for a 10 GeV proton beam and deflection angle, α = 20 mrad, the optimal bending radius of a silicon <110> crystal is 10 cm, yielding an efficiency of 25%. The corresponding crystal thickness is 2 mm [10].

II. Dimensions of Carbon Nanotubes: Simulations conducted by A.A. Greenenko and N.F. Shul'ga in [11] (fig.(4)) show the channelling efficiency at varying thicknesses of carbon nanotubes for a 10 GeV proton beam and bending radius = 20 cm. To achieve a bending angle of 20 mrad with 20 cm radius, the length of the material will be 4mm. We created a regression model to extrapolate the efficiency results of the simulations to find a predicted efficiency of 30% for this dimensional configuration.

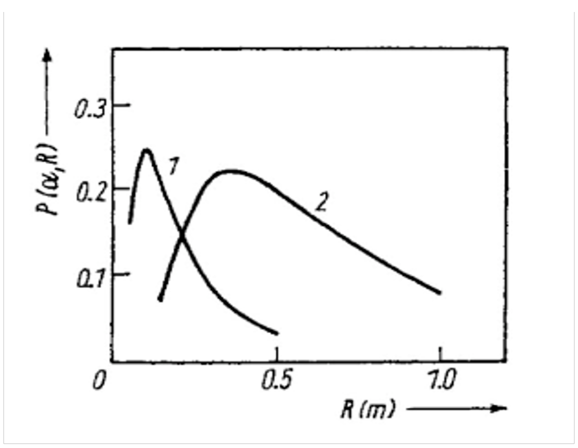

Fig. 3: Dependence of the deflection efficiency of protons with E=10 GeV (1) and 40 GeV (2) at the angle α=20 mrad on the bending radius R

Source: A. M. TARATIN et al. : Theory of Planar Channeling of Relativistic Protons

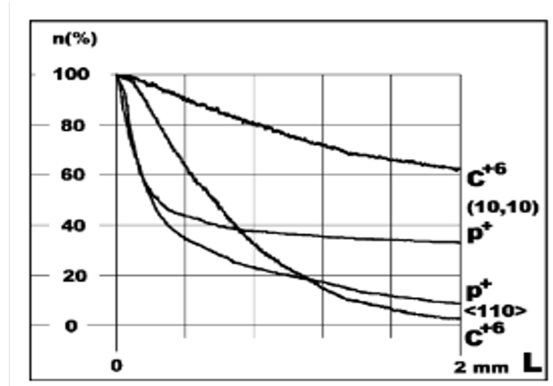

Fig. 4: Dependence of the deflected beam fraction with target length for beam deflection by a bent nanotube rope and diamond crystal. The crystal curvature radius R=20 cm, the beam momentum p=10 GeV/c. Simulation statistics is 1000 particles.

Source: Greenenko, A. A., & Shul'ga, N. F. (2003), Fast ion passing through straight and bent nanotubes

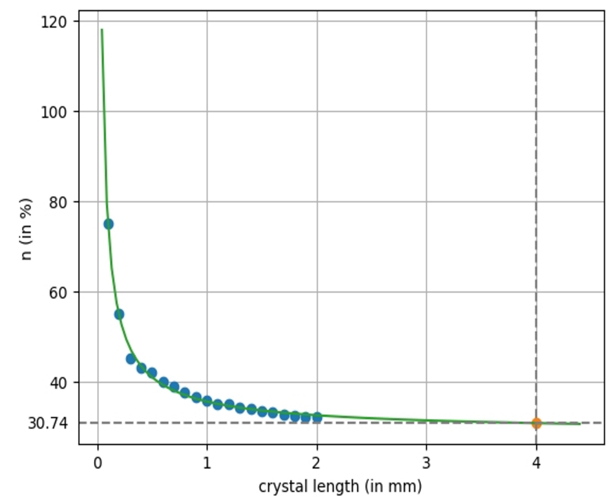

Fig. 5: Polynomial extrapolation of channelling efficiency results of Greenenko et al.(2003)

The experiment will involve testing the materials at cryogenic temperatures, around 150 K, as well as room temperature. The thermal motion of lattice atoms affects a crystal's ability to channel, as the amplitude of oscillations relates to the Debye temperature which varies with temperature (fig.(6)). At higher temperatures, larger thermal motion amplitudes cause a decrease in the potential barrier, reducing the crystal's channelling efficiency [12]. Therefore, it is hypothesised that at cryogenic temperatures, the materials will display higher channelling efficiency due to smaller atomic displacements and a higher potential barrier (fig.(7)).

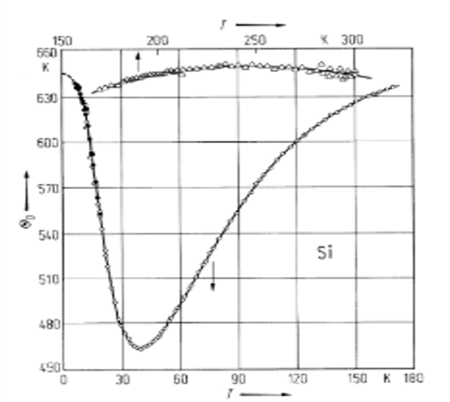

Fig. 6: Evolution of the Debye temperature ΘD in Silicon as a function of the absolute temperature T . The bottom curve stands for temperature 0 to 170 K (bottom scale). The top curve applies for temperatures from 170 to 300 K (top scale)

Source: Monte Carlo Modeling of Crystal Channeling at High Energies by CERN

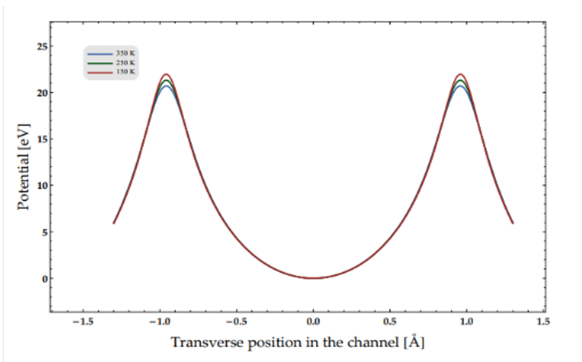

Fig. 7: The planar, continuous potentials for adjacent (110) planes in Silicon and the straight crystal potential obtained from their addition (thin solid line).

Source: Monte Carlo Modeling of Crystal Channeling at High Energies by CERN

By analysing the data collected by detectors, the overall deflection angle (20 mrad ± 1 mrad) will be calculated to validate the trials. The intensity of the light produced by the detectors is proportional to the energy deposited by the charged particles, and hence, can be used to measure the beam intensity before and after channelling to calculate the efficiency of both materials.

C. Experimental Setup (fig.(8))

1) High quality samples of silicon and carbon nanotubes will be installed on a goniometer positioned precisely in the beam's path. The alignment of the crystals with respect to the beam is provided by this goniometric system which has a precision of about an order of magnitude higher than the Lindhard critical angle computed at the experiment energy. The beam must be incident perpendicular to the crystal face.

2) Fire a 'clean' beam of protons at the crystal with energy 10 GeV. Place a collimator in its path to restrict the cross-sectional area of the beam, reducing its intensity

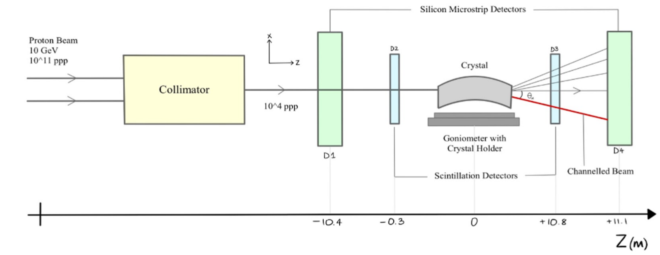

Fig. 8: Experimental Setup

from 10^{11} to 10^{4}. High-precision tracking of individual particle trajectories before and after the interaction with crystals will be performed by means of silicon microstrip detectors and scintillation detectors[13]. If necessary, shield the detectors from background radiation to minimise the noise in the measurements.

3) Cryogenically cool the materials using liquid nitrogen (vacuum chamber) and repeat the experiment[14].

Trial	Material	Bending Radius	Deflection Angle	Temperature
1	Silicon	10 cm	20 mrad	298 K
2	Silicon	10 cm	20 mrad	150 K
3	Carbon Nanotubes	20 cm	20 mrad	298 K
4	Carbon Nanotubes	20 cm	20 mrad	150 K

D. Results and Observations

Quantity Measured	Method	Observation	Interpretation
Incident Angle (θ_i)	Analyse beam position for D1 and D2	Expected = $\pi/2$ rad Tolerance = 10 mrad	Used to find deflection angle Values outside tolerance range will be discarded
Outgoing Angle (θ_o)	Analyse beam position for D3 and D4	Expected = 20 mrad	Used to find deflection angle
Deflection Angle (θ_d)	$\theta_o - \theta_i$	Expected = 20 mrad Tolerance = 1 mrad	Verify that the deflection angles are identical for control
Channelling Efficiency	(Intensity of channelled protons / Intensity of protons incident on the crystal) x 100%	Compare the channelling efficiencies of both materials at room and cryogenic temperatures	Our results are predicted to support a correlation between lowering temperature and increasing channelling efficiency, a concept theoretically proposed but to be experimentally proven for the first time

III. What we hope to take away from this experience

Expecting improvements in channelling efficiency for carbon nanotubes and silicon in novel energy and temperature conditions, we hope to contribute to the excitement for new research in the field. Working at CERN will equip us with skills in designing experiments and elevate our pursuits as budding researchers. We aspire to learn from the distinguished researchers at CERN, Which will install an explorative mindset in us as some of us are planning to take the first step toward our careers in physics. Most importantly, this experience will help us pursue our passion for physics in a professional setting and quench our scientific curiosity.

IV. Science Outreach Activity

"We are among those who think that science has great beauty"- Marie Curie

The beauty of understanding science and physics lies in the joy of experimentation and the thrill of observing physical phenomena. We believe that there is something inherently magical about discovering the underlying principles that govern our universe. We are committed to sharing this beauty with those who lack the resources to experience science firsthand and firmly hold that collaboration is key to unlocking a bright future for humanity.

To fulfil this goal, we plan to conduct a series of DIY (Do it Yourself) enjoyable science experiments for the 500 underprivileged girls who are a part of our school's social initiative in India. By offering hands-on experiences, we hope to spark their interest in physics, because we believe that it is only when you experience science directly that you can truly appreciate the magnificence of nature.

Moreover, we plan to utilize the Virtual Reality infrastructure available at our team member's private school in London to create an immersive simulation of our proposed experiments. Our virtual experiments will cater to visual-based learners, including those with learning disabilities, offering a cognitive learning platform.

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