Examining the Effects of Bond Length on Electron Channeling Across a Body-Centered Cubic Crystal

Crystonic Channelers

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1 Introduction

Hello, we are the Crystonic Channelers! Our team is comprised of eight highly interested and motivated students from the United States and Canada. For us, the CERN BL4S competition provides a unique and enriching experience in which we can break past the theoretical bounds of the classroom and explore physics in its most pure form. Working with the DESY II Synchrotron provides us a once-in-a-lifetime opportunity to analyze particles at the most fundamental levels. As our team name suggests, we will be using the DESY II Synchroton to gain a better understanding of electron interaction within crystals. Specifically, we will analyze planar channeling in tungsten, iron, and vanadium, which have identical crystal structure but differing unit cell edge length.

2 Why we want to go to DESY

For many of us, our schools have only provided us with a textbook view of physics. Yet, physics is too beautiful to be learned in just the classroom; an experimental exposure to physics is critical for any young scientist's understanding of the subject. Undoubtedly, being able to attend DESY through BL4S will allow us to not only deeply enrich our physics understandings, but our love for it as well. Unfortunately, the physics department in our high schools lack the equipment needed to complete a deep dive into experimental physics, so we hope to use this opportunity presented at DESY to get a hands on experience with amazing equipment we have only dreamed of working with. DESY is also one of the world's most advanced research centers and is always on the forefront of physics research. This will be the first time we get to work with such sophisticated equipment used in physics research, and it will be a journey we will never forget. After coming away from DESY, we hope to have had a wonderful first encounter with the world of particle physics.

3 Experiment

3.1 Background

The particle accelerator at DESY is one of the strongest in the world. The operating range of the DESY II Synchrotron is between 0.5 GeV/c to 6.3 GeV/c[9], and these values determine the scale at which the electrons interact. This can be found by looking at the relativistic de Broglie wavelength[4] of the electrons, which has a value around the order of $10^{-15}m$ for the given momentum range. The bond lengths in a crystal structure usually are in the order of $10^{-10}m$. This difference in magnitudes suggests the electrons would not diffract significantly in the crystal, making tasks like finding the structure of a molecule very difficult. With this challenge at hand, we looked into electron channeling as a method of investigating how bond length affects electron interactions on a subatomic level.

3.2 Purpose

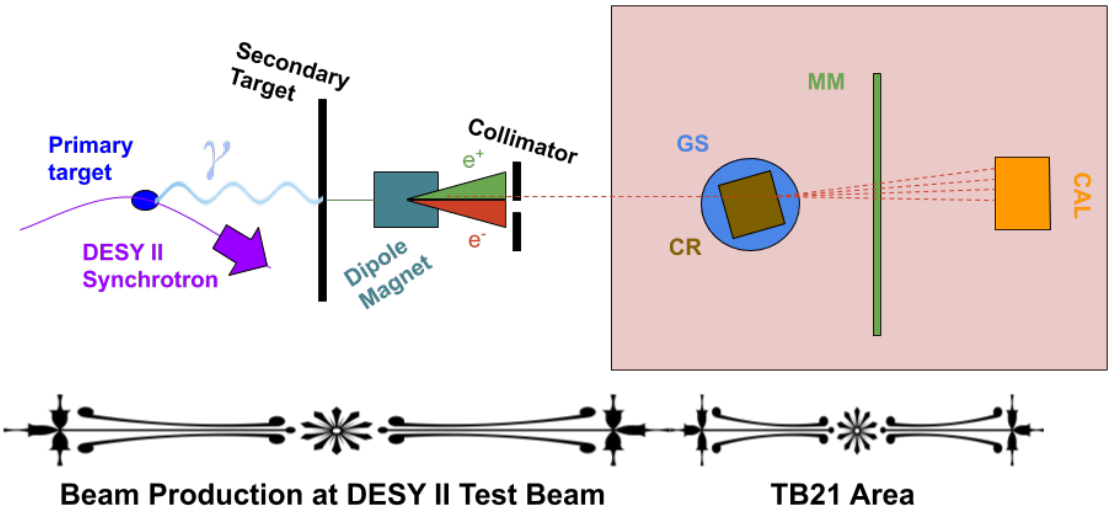
The purpose of this experiment is to qualitatively see how bond length affects the maximum potential well and the frequency at which the electrons channel in crystal structures.

3.3 Experimental Method and Design

In the experiment, electrons with momentum 2 GeV/c will be shot at body-centered cubic[3] tungsten, iron, and vanadium crystals, with their lattice initially angled 5μrad across the horizontal, perpendicular to the direction of the electron's motion. 5μrad was chosen because similar studies have used angles around that order of magnitude[2]. Since the crystals are cubical in structure, their shape allows for easy identification of the axis of the bonds within the lattice.

The experimental setup is as outlined.

1. Initially, $\theta_{in} = 5\mu$rad.



MM = MicroMegas Detector

CR = Crystal Structure

CAL = Lead Crystal Calorimeter

GS = Goniometric Stage

2. The beamline is set to produce positrons and electrons with a particle momentum of 2 GeV/c for maximum particle production. The collimator blocks off the positrons so only an electron beam enters the TB21 area.

3. The beam of electrons hits the 5 x 5 x 5 mm tungsten crystal, causing channeling and dechanneling.

4. The MicroMegas Detectors determine the positions of the electrons, allowing us to identify channeled and dechanneled particles.

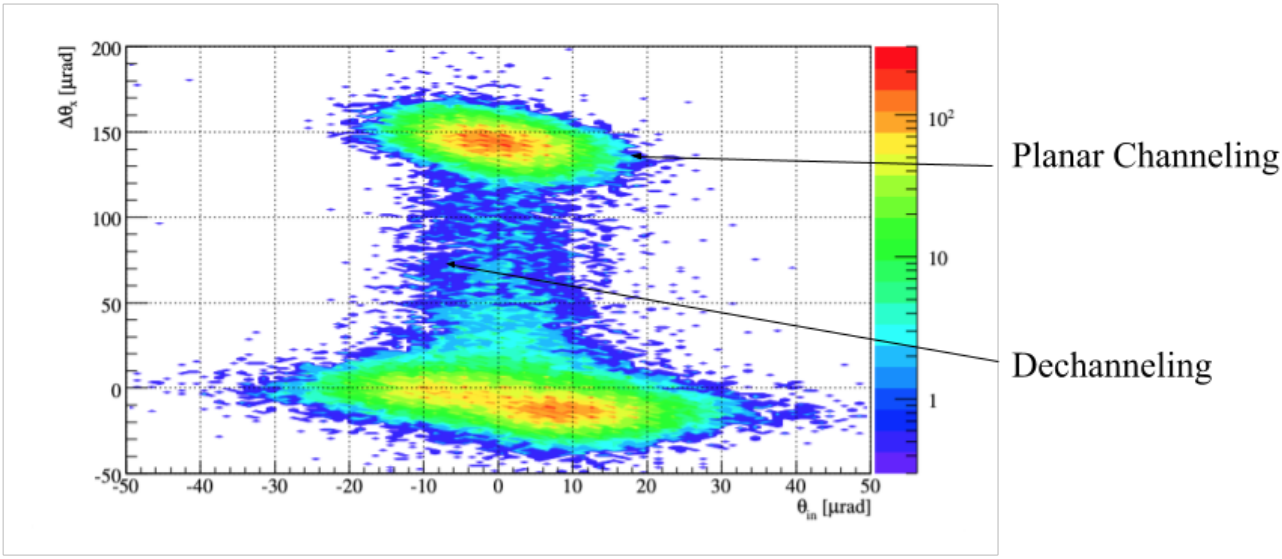
5. Electrons proceed to hit the Calorimeter, allowing us to measure the final energies of the group of electrons.

6. We iterate θ_{in} up to 50μrad by increasing θ_{in} 5μrad each trial.

7. We repeat the experiment using iron and vanadium.

Since dechanneling causes an electron to lose energy, a calorimeter will be used to

confirm that the variation seen is due to dechanneling[7]. After collecting data and plotting the angular deflection, $\Delta\theta_x$, for each particle as a function of the electron beam's angle of incidence, θ_{in}, we will produce graphs similar to the one below[7]. From the graphs we can examine how channeling differs between the crystals.



3.4 Hypothesis

We hypothesize tungsten has higher channeling of electrons than iron and vanadium. We chose tungsten, iron, and vanadium because they have identical crystal structure but different bond length. Thus any difference in channeling will come from either bond length, number of protons, or distribution of electrons. Iron has a bond length of 287 pm, vanadium of 303 pm, and tungsten of 317 pm[6]. Due to larger bond length, it will be more difficult for electrons to reach the required potential to dechannel, and thus we expect tungsten to have the greatest channeling[1].

3.5 Theory

The derivation below shows how to find the maximum potential well. $U(x)$ is the electric potential when setting the potential at the middle of a bond (where the potential is the lowest) to zero. d_p is the length of the channel, which is determined by the length of the bond, and x is the deviation of a particle from the center of the channel.

$$U(x) \approx U_{\max}\left(\frac{2x}{d_p}\right)^2 \text{ [7]}$$

For channeling to occur, under standard notations, the following condition[2] must hold:

$$\begin{aligned}
\frac{p^2c^2}{2E}\theta_{in}^2 + U(x) &\leq U_{\max} \\
\frac{p^2c^2}{2E}\theta_{in}^2 + U_{\max}\left(\frac{2x}{d_p}\right)^2 &\lessapprox U_{\max} \\
\frac{p^2c^2}{2E}\theta_{in}^2 &\lessapprox U_{\max}\left(1 - \left(\frac{2x}{d_p}\right)^2\right) \text{ [7]}
\end{aligned}$$

Let f be the fraction of channeled electrons, and x be the furthest distance for which the expression above is true, causing an equality. Assuming the electrons are evenly distributed at the scale of the bonds, and the interaction with the crystal before going into a channel is negligible [8]:

$$\begin{aligned}
x &\approx \frac{d_p f}{2} \\
\frac{p^2c^2}{2E}\theta_{in}^2 &\approx U_{\max}\left(1 - f^2\right) \\
\frac{p^2c^2}{2E\left(1 - f^2\right)}\theta_{in}^2 &\approx U_{\max}
\end{aligned}$$

A higher $U_{\max}$ will result in higher channeling of electrons, and will help us understand the role of bond length in channeling[5].

3.6 Limitations

1. Our analysis assumes the incoming electrons are evenly distributed at the scale of the bond lengths. Otherwise $x \approx \frac{d_p f}{2}$ will not hold.

2. The order of magnitude of $U_{\max}$ is unknown since no previous analysis was conducted on the crystal structures, possibly making finding $U_{\max}$ difficult.

3. $U(x) \approx U_{\max}\left(\frac{2x}{d_p}\right)^2$ [7] assumes, there's only potential from closest plane.

4. The atom in the center of the cell can change the structure of the channel, potentially invalidating our original equations.

4 Acknowledgements

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