The Investigation of a Uniquely Quantum Signature in a Semi-Classical Process

Demonstrating a Quantum Effect on a Classical System by Comparing Intensities of Parametric X-rays from Positrons and Electrons

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I. Introduction

One of the most complex questions in modern physics is how to unify Classical Mechanics with Quantum Mechanics to create a Grand Unified Theory. Physicists understand that classical physics breaks down at the quantum scale, while quantum mechanics becomes negligible past a certain scale. Our experiment aims to investigate this realm between classical and quantum mechanics by observing a uniquely quantum effect in a semi-classical process. We will generate Parametric X-ray Radiation (PXR) with both electrons and positrons to identify a quantum signature by the differing intensities of produced PXR due to two-photon exchange during the scattering process.

II. Why We Want to Go

Many of our team members wish to pursue a career in the STEM field, and so far, the only experience we have had in the scientific field are either school labs or small personal projects. By being able to come to DESY, we would be able to learn from top scientists and see first-hand how experiments of international caliber are conducted. Furthermore, we would be able to realize our experiment without parameters such as resources and funding and maybe even make a small impact on the scientific community.

III. Experiment

Theory

Parametric X-Ray Radiation is generated when a relativistic particle traverses the periodic potential of a crystal. During the scattering process, virtual photons that surround the incident particle undergo Bragg Diffraction and transfer part of the particle's momentum to the surrounding atoms. As a result of the momentum transfer, the atoms in the crystalline medium recoil and release energy in the form of enhanced photons due to coherence in the X-ray range (Figure 1).

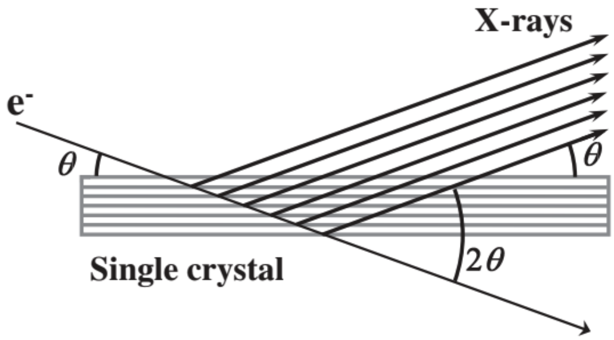

Figure 1. Parametric X-ray Radiation

Note: While conventional methods of PXR generation have used electron beams in the MeV range, the 1-6 GeV Beam at DESY will be suitable for our experiment, as the generation process depends on the spectrum of virtual photons and not of the electrons; as long as the electron beam is near relativistic, the spectrum of virtual photons will be suitable for PXR.

Though PXR is defined as a semi-classical process, we theorize that it can also exhibit a quantum effect through differing intensities of PXR generated by electrons versus those generated by positrons. According to the classical theory of force interactions, the two intensities would be the same, as both electrons and positrons would interact via the same force when scattering. On the other hand, the quantum interpretation of the exchangement of virtual particles would predict the intensities to be different, as electrons and positrons would differ during scattering due to two-photon exchange.[1] (Figures 2 & 3).

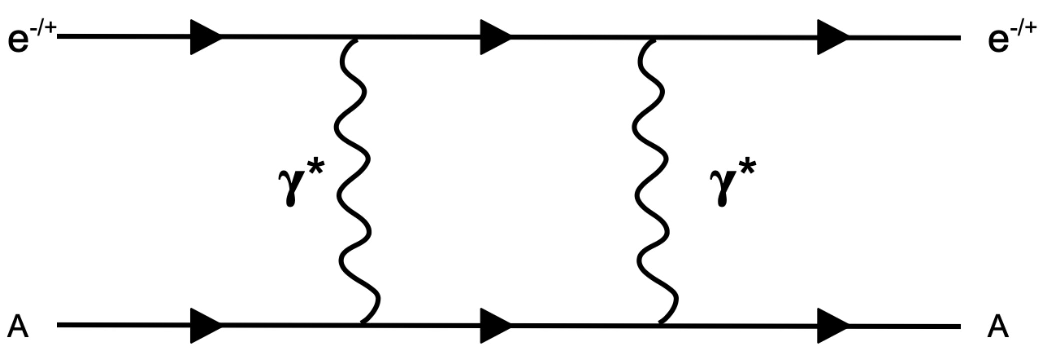

Figure 2. Box Two-Photon Exchange

[1] During the inelastic scattering of a charged particle beam, there is a possibility of the incident particle exchanging two virtual photons with the target. There is also the possibility of more than two photons being exchanged, but the scattering probability becomes so small that it is negligible in our experiment.

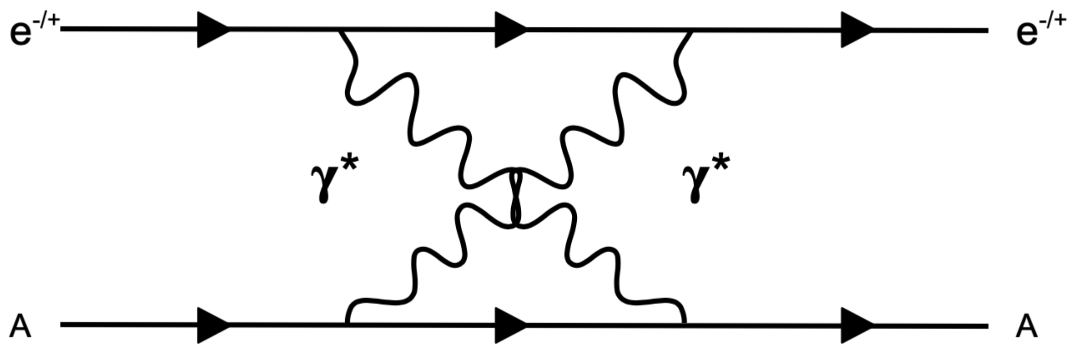

Figure 3. Cross Two-Photon Exchange

The intensity difference of the PXR due to two-photon exchange results from different cross sections. The differing cross sections arises from the number of powers of the coupling constants in the electric potential, which can be seen using Coulomb's Law[2] (1):

$$F = \frac{kq_1 q_2}{r^2} \tag{1}$$

In the case of a positron (+) scattering from a nucleus (+), the sign of F is positive, while in the case of an electron (-) scattering from a nucleus (+), the sign is negative.

This distinction does not make a difference in single-photon exchange, as the negative will be squared away when calculating the cross-section:

Cross-section = $|F|^2$ **kinematic factors*

However, if two photons are being exchanged, another power of F is needed:

Cross section = $|F + y * F^2|^2$ **kinematic factors*

Where *y* is a set of constants depending on the angle of scattering and incident particle energy.

In this case, there is a difference between positrons and electrons. The signs of the first term (F) and the second term (F^2) will be negative and positive respectively for electrons (thus subtracting from each other and decreasing the cross-section), while the signs of the terms will both be positive for positrons (thus adding to each other and increasing the cross-section), resulting in differing cross-sections for electrons and positrons.

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[2] Where q_1 is defined as the charge of the electron/positron, q_2 is defined as the charge of the protons in the crystal, and r is the distance between the two charges, and k is the Coulomb Constant($1/4\pi\varepsilon_0$)

Calculations

In order to calculate the optimal Bragg Angle, we have set the wavelength as 1 nm, the lattice distance as 0.357 nanometers, and the order of reflection as 1. Using the Bragg Equation[3] (2), we have calculated the Bragg Angle to be 23 degrees:

$$n\lambda = 2d * sin\theta_B \quad (2)$$

To determine the type of scintillator required to count the PXR beam rate, we have calculated using (3)[4] the energy peak to be 12 KeV. We have selected a Sodium Iodide Scintillator (of which we will bring ourselves), as it has excellent resolutions detecting soft and hard X-rays.

$$\hbar\omega_n[keV] = 1.974\frac{\pi}{d[\text{Å}]sin\theta_B}n \quad (3)$$

In order to compare the cross sections ($\frac{d\sigma}{d\Omega}$) between the electron and positron beam, we seek to measure 2 components:

1. The PXR beam rate ($\frac{dN}{d\Omega}$) in particles per steradian per second
2. The Initial beam flux (φ) in particles per cm^2 per second

We can calculate the cross-section by using $\frac{d\sigma}{d\Omega} = \frac{\frac{dN}{d\Omega}}{\varphi}$

As a reference of comparison during the experiment, we have graphed the theoretical angular distribution of PXR intensity using the first approximation of the perturbation theory[5]:

$$\frac{dN}{d\Omega} = \frac{e^2 n\omega L|\chi_g(\omega)|^2}{2\pi\hbar\varepsilon_0^3 V\left(c^* - \vec{V}\cdot\vec{\Omega}\right)} \times \frac{\left|\frac{\omega}{c^*}\vec{\Omega} \times \left(\frac{\omega}{c^{*2}}\vec{V} + \vec{g}\right)\right|^2}{\left\{\left|\frac{\omega}{c^*}\vec{\Omega}_\perp - \vec{g}_\perp\right|^2 + \frac{\omega^2}{V^2}\left[\gamma^{-2} + \frac{V^2}{c^2}(1-\varepsilon_0)\right]\right\}^2} \quad (4)$$

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[3] Where n is the order of reflection, lamba is the wavelength of the PXR, d is the lattice distance, and theta is the Bragg Angle

[4] Where d[Å] is the interplanar distance in Angstroms, ω is the angular frequency, and n is the order of reflection.

[5] *dN* is the discrete amount of energy emitted at the solid angle *dΩ*. *n* is the amount of particles having charge *e*, mass is *m*, and total energy is E_t . The thickness of the crystalline medium, *L*. $\gamma = E_t / mc^2$ is the Lorentz factor, the velocity $V = |V|$, *g* is the reciprocal lattice vector of the crystalline medium, and $\Omega\perp$ *and* $g\perp$ are perpendicular components to *V*. χ_g *(w)* is the refers to the variable part of the dielectric susceptibility Fourier component. Ω is the unit vector in the direction of the PXR emission, ω is the angular frequency, and *g* is the reciprocal lattice vector of the crystalline medium.

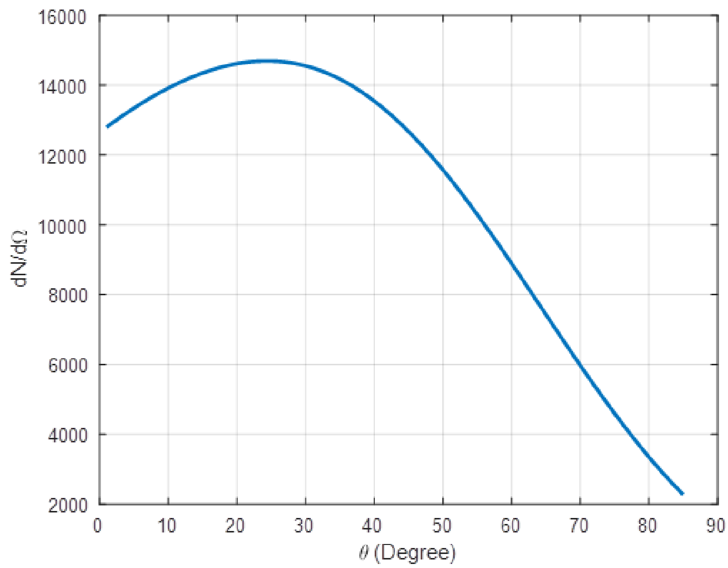

Figure 4. Angular Distribution of PXR Intensity

Experimental Setup

Diagrams

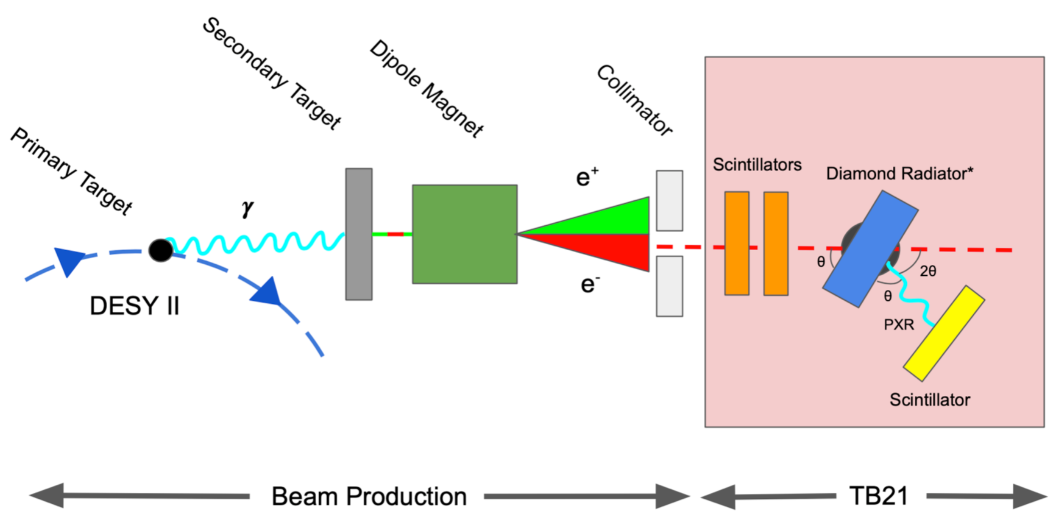

Figure 5(a). Electron Schematic

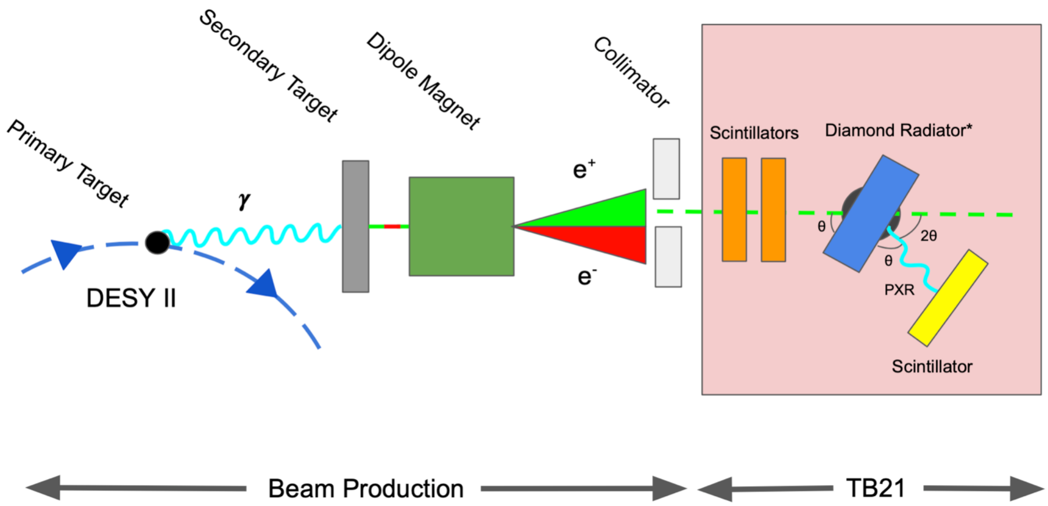

Figure 5(b). Positron Schematic

**The Diamond will be placed on a motorized stand to adjust the Bragg Condition*

Procedure

1) The beamline is collimated to select for particles (electrons first and then positrons) with a momentum of 2 GeV/c. We will conduct trials with only electrons and then only positrons.
2) The particle beam passes through the particle counters (scintillators), which will determine the initial beam rate.
    a) There are two scintillators for coincidence counting to ensure that only electrons/positrons are being counted.
3) The beam then traverses the diamond radiator crystal to generate PXR.
    a) If the PXR does not occur or is too weak, the stand will be adjusted closer to the Bragg Angle.
4) A scintillator placed at double the Bragg Angle from the initial beam (see above diagrams) will count the particle rate of the PXR.

IV. What We Hope to Take Away

Aside from expanding our knowledge about particle physics as a whole, we hope to learn the way of thinking and experimenting that physicists at DESY/CERN use on a daily basis. We hope to better understand how physicists go about tackling the mysteries of the universe, as well as how they deal with and solve obstacles along the way. Furthermore, since many of our classmates have not yet taken physics, we wish to be able to share this opportunity with them, in hopes of kindling the same passion for physics that we believe the world should share.

V. Acknowledgments

We are indebted to Dr. Richard Jones (University of Connecticut), for all the time and support he has given our team. He has truly been exceptional in guiding us through the scientific process-facilitating discussions, answering our questions, and most of all, encouraging our passion for physics. We truly could not have created this proposal without him.

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Always Quantumplating,
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VI. References

Baryshevsky, V. G., Feranchuk, I. D., & Ulyanenkov, A. P. (2005). *Parametric X-Ray Radiation in Crystals: Theory, Experiment and Applications: Vol. 213. Springer Tracts in Modern Physics*. Springer-Verlag GmbH.

Hayakawa, Y., Takahashi, Y., Kuwada, T., Sakae, T., Tanaka, T., Nakao, K., Nogami, K., Inagaki, M., Hayakawa, K., & Sato, I. (2013). X-ray imaging using a tunable coherent X-ray source based on parametric X-ray radiation. *Journal of Instrumentation*, *8*(08), C08001. https://doi.org/10.1088/1748-0221/8/08/C08001

Hayashi, Y., Kando, M., Kotaki, H., Kawase, K., Homma, T., & Bulanov, V. (2010, January). *Measurement of the Parametric X-Rays with the Rocking Curve Method*. Japan Atomic Energy Agency.

Lufaso, M. (Presenter). (n.d.). *Physical Methods for Characterizing Solids*. Lecture presented at University of North Florida, , FL, United States.

Takahashi, Y., Hayakawa, Y., Kuwada, T., Tanaka, T., Sakae, T., Nakao, K., Nogami, K., Imagaki, M., Hayakawa, K., & Sato, I. (2012). Parametric X-ray radiation as a novel source for X-ray imaging. *X-Ray Spectrometry*, *41*(4), 210-215. https://doi.org/10.1002/xrs.2403

Tomasi-Gustafsson, E., & Pacetti, S. (2018). Two-Photon Exchange: Myth and History. *Few-Body Systems*, *59*(5). https://doi.org/10.1007/s00601-018-1416-5