An Experimental Investigation Into Particle Therapy with Unconventional and Strange Particles

2023 Beamline for Schools (BL4S) Proposal

"Physics is about questioning, studying, probing nature. You probe, and, if you're lucky, you get strange clues."

— Lene Hau, Physicist

The Strange Therapy Group

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Why Do We Want To Go?

As a group of five students on the East Coast of the United States, we often felt, like many of our peers, that the physics we learned in the classroom seemed detached from the "real world."

This perception changed dramatically when we discovered that the father of one of our group members had been diagnosed with cancer. Our research led us to the emerging field of proton therapy, and ultimately, BL4S. No other initiative provides high school students with the opportunity to work with the resources and flexibility offered by the T9 beamline at CERN.

This project represents a culmination of correspondences with professors, continuous revision, and a deeply personal motivation to help someone we know. Ultimately, we hope our story and experiment will not only contribute to cancer research but also ignite a passion in our community, demonstrating that anyone—even high school students—can come together to make a meaningful difference.

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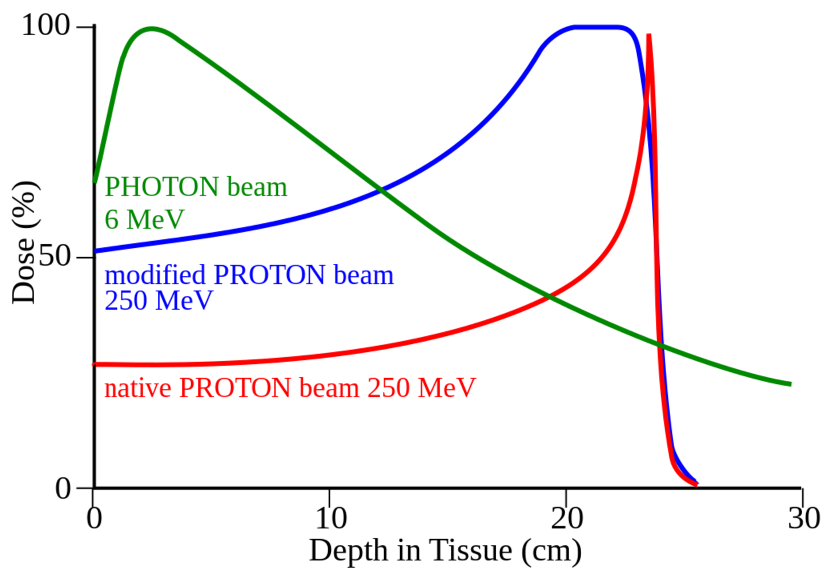
1.1 Motivation & Background

This proposal is motivated by a lack of experimental results regarding the Bragg peaks of unconventional particles. A tighter Bragg peak implies a) a higher amplitude dose of radiation and b) increased precision in particle therapy methodology. Traditionally, particle therapy has relied on proton and neutron beamlines, and has developed to become a crucial tool in treating complex forms of cancer. We recognize that particles like kaons and positrons have been theorized to release energy in a similar fashion to protons and exhibits unique properties like strangeness, which could potentially improve results. [1] [2] We aim to be the first group to test this hypothesis experimentally, while also aiming to recreate and refine past experiments on the muon. [3]

The relativistic Bethe-Bloch Formula (1) calculates the mean energy deposition for a particle of speed v, charge z, energy E, and distance x on a target of electron density n and excitation energy I, which can be used to calculate the linear energy transfer (LET) and derive the Bragg peak geometry. It is used by medical professionals to accurately assess the correct particles and energy for the appropriate dose and range of particles to effectively treat the cancer while minimizing damage to healthy tissue. There has also been renewed scholarship regarding experimentation with novel particles. [4]

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[\ln \left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right] \tag{1}$$

Our final goal is to provide experimental evidence for the particle therapy potential of kaons, muons, and positrons—of which the kaon is literally strange, but all are figuratively "strange" particles. Hence our group's name: Strange Therapy.



We hope to extend this paradigm further.

Figure 1: Sample Bragg peak distributions retrieved from conventional proton experimentation. Notice the spike in energy of protons than allow for a higher dose concentration in comparison to traditional forms of radiation therapy, such as x-rays. Furthermore, newer therapy techniques with a modified proton beam (shown in blue) create a spread out Bragg Peak (SOBP) for treatment of tumors with larger volume and 3D shapes. These newer approaches show medical interest in developing specific particle therapy techniques geared toward more specialization in tumor treatment. [4]

1.2 Setup

The CERN T9 beamline has the capability to accelerate protons, positrons, kaons, and muons.[1] [5] A magnet system can be used to isolate these "strange" particles to encounter the target. Figure 2 depicts our experimental setup.

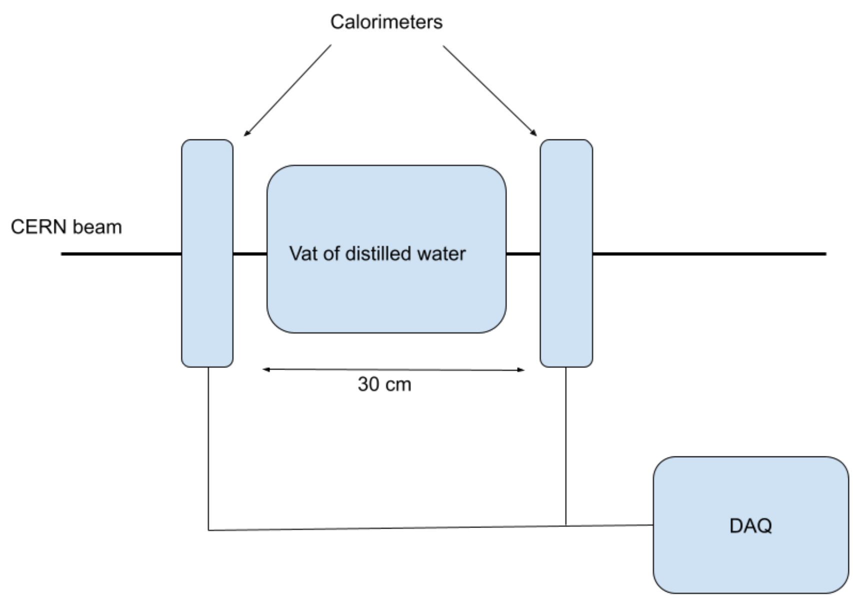


Figure 2: Our proposed fixed-target experiment layout with unconventional particles to measure their effective Bragg peaks in certain mediums. The calorimeters on either end of the target serve as start/stop triggers. The target itself is a 30 cm long container that holds either distilled water or high-density polyethylene (HDPE). In-line with the beam, calorimeters are on either side of the vat to operate as dosimeters: they count how much radiation passes through certain points to yield radiation dose as a function of depth. Hadronic calorimeters will be used for kaons and muons while electromagnetic calorimeters will be used for positrons.

1.3 Methodology

A periodic readout of dose deposition as a function of depth of the particle beam will be taken. The dose deposition will be measured by placing a hadronic calorimeter before and after the target vat and measuring the ratio of signals collected, as shown in Figure 2. The signals will be compared with a calibration curve (2) (3) previously obtained by observing the electrical signals emitted by the hadronic calorimeter from known amounts of radiation. The function to fit to the data is a modified Gaussian proposed by Koen Lambrechts [6]:

$$D(x) = \alpha e^{\frac{\tau^2\sigma^2}{2}+\tau(x-\mu)} \operatorname{Erfc}\left(-\frac{\mu - x}{\sigma\sqrt{2}} + \frac{\tau\sigma}{\sqrt{2}}\right) \tag{2}$$

where x is the depth in tissue (in mm), α, τ, σ, and μ are the fitting parameters to be determined. Erfc is the error function defined as:

[1] We do not exclude the possibility of conducting this experiment with positrons and electrons (as a control) at DESY II [2], however, we strongly prefer the T9 CERN beamline due to its wide selection of "strange" particles.

$$\text{Erfc}(z) = 1 + \frac{2}{\sqrt{\pi}} \int_0^z e^{-x^2} dx \quad (3)$$

A kaon, muon, and position run at 5 energies from 0.5 GeV to 1 GeV would give a range of observable Bragg curves. Typical particle therapy runs from 50 MeV to 250 MeV, so we aim to best match these typical ranges with the T9 beamline's lower spectrum of energies since its main purpose is not geared toward particle therapy. If the results from using higher energy beams are not productive, we can use an energy degrader or magnet system to to reduce the energy of the beam. Furthermore, the calorimeters themselves can absorb significant amounts of energy from the beam. Analysis of the peak energy, depth of penetration, and potential Bragg curve tail would give insight into specific approaches and novel strange particles to treating tumors with particle therapy.

1.4 Simulation of Biological Medium

Historically, beamline data on inorganic mediums have been a mediocre estimator for their effects on biological tissue. Thus we will also conjoin our methodology with recent developments in scientific computing. Sato et al. report successful results using improved code coupled with a microdosimetric kinetic model for simulation of particles for radiotherapy (particle) treatment of tumors. [7] We plan to use the improved PHITS, the Particle and Heavy Ion Transport Code System, to run particle transport simulations for estimating biological dose from charged-particle therapy. A sample can be seen in Figure 3. The code can specifically analyze the production of positrons, muons, and kaons. For muons specifically, we hope that this improvement in data processing can yield better results than historic measurements.

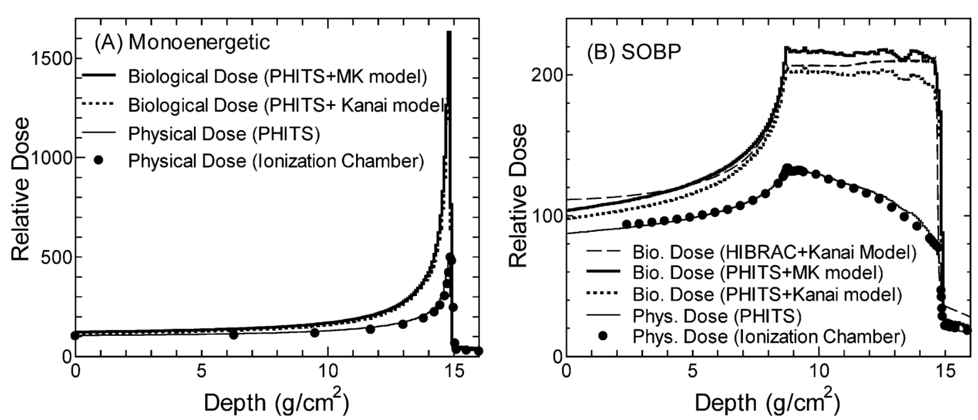


Figure 3: Simulated calculations of Bragg peaks using the PHITS toolkit of nucleon carbon-ion beams as measured by an ionization chamber. [7]

2 What We Hope to Take Away

On one hand, this experiment aims to explore the potential benefits of using unconventional particles in particle therapy, focusing on the Bragg peaks and the implications for treatment precision and dose deposition. This could have implications in the future direction of particle therapy, regardless of whether the "strange" particles we test are advantageous.

On the other, we hope to use this as a method to show that particle physics is not only really cool, but also accessible. We love physics, and we want to be able to help our closest friends and family with it. We want to not only take away an unforgettable experience, but also dream of sharing this love with our greater community—in photographs, presentations, and outreach programs.

2.1 Proposal of Joint Outreach Program

From the beginning, sharing a love of physics has been baked into the fabric of our team. Our three initial members—Eric, Nick, and Eddy—first met as fellow volunteer co-instructors, teaching solid-state physics to local New Haven students through the Yale Pathways to Science Summer Program. The founders of international platforms like IntMAX Learning and learn2prgm.com, members of our team have taught coding, data science, and machine learning to a worldwide audience of over 500 students.

We hope that BL4S will help us further share our physics story and our love of teaching. If our team is selected to perform our experiment, we plan to first host a panel discussion open to all, about our scientific journey. Furthermore, we would start a free mentorship program for other students hoping to participate in BL4S next year. We also hope to use our pre-existing platforms, IntMAX Learning and learn2prgm.com, to teach biomedical applications of physics and the results from our own study. Finally, we would like to continue our tradition and hold another enrichment course through Yale Pathways to Science, celebrating the exciting interdisciplinary biomedical applications of particle physics that can hopefully show that physics is not only beautiful, but impactful.

3 Acknowledgements

We would first like to thank Dr. Yu He (Yale, Applied Physics) for inspiring our scientific pursuits and for helpful discussions. In addition, we would like to thank Mr. Kenneth Cecire (QuarkNet National Staff at Notre Dame) for useful feedback.

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4 Appendix

4.1 Preliminary Proposed Schedule

Days 1-4: Installing experimental setup
Day 5: Proton run at 5 energies [0.5-1 GeV] as a control group and calibration test
Day 6: Kaon run at 5 energies [0.5-1 GeV]
Day 7: Muon run at 5 energies [0.5-1 GeV]
Day 8: Positron run at 5 energies [0.5-1 GeV]
Day 9-11: Contingency