A Cross-Particle Comparison of Scintillator Characteristics

Finding scintillator efficiency over a range of energies and determining whether such characteristics differ between electrons and positrons

Charles Bonkowsky, Sam Bonkowsky, Sophie Byde, Derek Che,
Arianna Meinking, August Muller, Lam Nguyen, Melody Wolfarth
DESY Chain
West High School

I. Introduction

The test beamline at DESY is uniquely situated to test equipment such as scintillators for use in particle physics, given its reliability and uniqueness in providing multi-GeV particles[1]. Scintillators in this beamline (such as the EJ-200) have useful characteristics like a fast response time and variety of possible shapes[2], but suffer from issues like radiation damage[3] and a variable scintillation efficiency [4]. Apart from specialized physics usage, scintillators possess a range of everyday uses, such as detectors for cancer therapy[5,6] or dosimetry[7] for medical imaging. Given this range, it is important to characterize their efficiency in measurement and how such efficiency changes under different particles.

II. Why We Want to Go

Last year, our school participated in the BL4S competition for the first time. While our proposal fell short, it was a fascinating experience to gain greater insight into the physics and requirements that go into such accelerator experiments. We were driven by that same curiosity in this year's proposal, and throughout this year's odyssey have had the chance to expand on that through our research. The opportunity BL4S presents us would not only allow us to see such physics actualized — and in experiment! — but also to promote science in our own school: a high-profile showcase of what research and hard work can bring. Our studies have been such an amazing experience, and one we hope to have the chance to share.

III. Experiment

<u>Aim</u>

We aim to characterize the relationship between luminosity of and energy deposition in a scintillator with both electrons and positrons, using Birks' law as a model.

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[1] R. Diener, J. Dreyling-Eschweiler, H. Ehrlichmann, I.M. Gregor, U. Kötz, U. Krämer, N. Meyners, N. Potylitsina-Kube, A. Schütz, P. Schütze, M. Stanitzki. The DESY II test beam facility. Nuclear Instruments and Methods in Physics Research Section A, Volume 922, 2019,Pages 265-286, ISSN 0168-9002, https://doi.org/10.1016/j.nima.2018.11.133.

[2] Krammer, Manfred. "Scintillators." Institute of High Energy Physics, Vienna. https://www.hephy.at/fileadmin/user_upload/VO-5-Scintillators.pdf

[3] C. Patrignani et al. (Particle Data Group). Particle Detectors at Accelerators. Chin. Phys. C, 40, 100001 (2016)

[4] W. W. Moses, S. A. Payne, W. -. Choong, G. Hull and B. W. Reutter, "Scintillator Non-Proportionality: Present Understanding and Future Challenges," in *IEEE Transactions on Nuclear Science*, vol. 55, no. 3, pp. 1049-1053, June 2008. doi: 10.1109/TNS.2008.922802

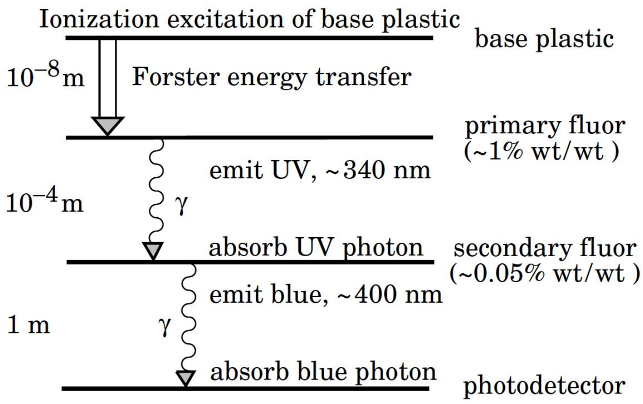
[5] Roemer, Katja & Pausch, Guntram & Bemmerer, David & Fiedler, Fine. (2015). Characterization of scintillator crystals for usage as prompt gamma monitors in particle therapy. Journal of Instrumentation. 10. P10033-P10033. 10.1088/1748-0221/10/10/P10033.

[6] Archambault L, Polf JC, Beaulieu L, Beddar S. Characterizing the response of miniature scintillation detectors when irradiated with proton beams. Phys Med Biol. 2008;53:1865. doi: 10.1088/0031-9155/53/7/004.

[7] Esfandi, Fatemeh & Saramad, Shahyar & Rezaei Shahmirzadi, Mohsen. (2017). Characterizing and simulation the scintillation properties of zinc oxide nanowires in AAO membrane for medical imaging applications. Journal of Instrumentation. 12. P07004-P07004. 10.1088/1748-0221/12/07/P07004.

Theory

Plastic scintillators are composed of a base and a fluor(s). As ionizing radiation passes through the scintillator, the molecules of the base are excited and emit photons. These photons are absorbed by the fluors which then emit them at a wavelength which is more convenient for detection and less at-risk for self-absorption. The mechanism is shown in the following picture (from [3], p. 11):



However, plastic scintillators do not emit luminescence directly proportional to the energy deposited, due to quenching that reduces luminescence return on ionization density[6]. A causal interpretation is that proposed by Birks[8] which proposes that the excitons created by the ionizing radiation may be annihilated without creating a photon[7]. This is described by Birks' law[9],

$$\frac{dL}{dx} = L_0 \frac{\frac{dE}{dx}}{1+k_B\frac{dE}{dx}}$$

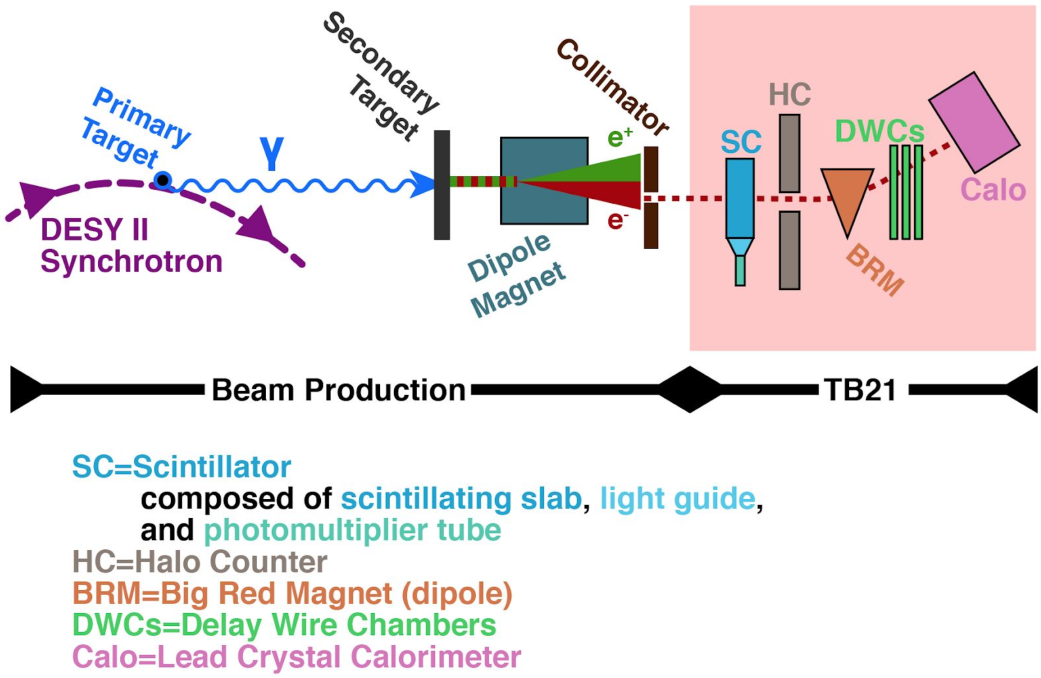
which is a widely-accepted model used across organic scintillators. In reference to those at DESY, Birks' law fits the experimental data (R^2=0.9992) in a study with the similar EJ-309 scintillator[10] (albeit at lower energy levels).

[8] Birks, J. B. "Scintillations from Organic Crystals: Specific Fluorescence and Relative Response to Different Radiations." *Proceedings of the Physical Society. Section A*, vol. 64, no. 10, Oct. 1951, pp. 874–877, doi:10.1088/0370-1298/64/10/303.

[9] Where *dL/dx* is the luminescence per path length, *dE/dx* the stopping power (energy deposited) and k_B Birks' parameter

[10] Norsworthy, Mark A., et al. "Evaluation of Neutron Light Output Response Functions in EJ-309 Organic Scintillators." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 842, Jan. 2017, pp. 20–27, doi:10.1016/j.nima.2016.10.035.

Experimental Setup



1. The beamline is collimated to select for a specific momentum and polarity. We will iterate through a range of momenta (1-6 GeV) for both electrons and positrons.
2. The beamline passes through a plastic scintillating slab, which fluoresces. Photons pass through the light guide and are recorded by the PMT. Multiple scintillator thicknesses will be used at each beam momentum.
3. The electrons/positrons continue through a halo counter. The opening will be set to the experimentally-determined divergence of a beam (with no targets) by that distance.
    a. This allows us to record any unlikely particles which scattered significantly on the scintillator.
4. The electrons/positrons pass through the BRM and their paths are bent. Subsequently, they pass through a set of three DWCs[11] oriented orthogonal to the beamline direction. The angle deflected due to the BRM can be inferred from the impact point on the DWC.
5. Finally, the electrons/positrons impact the calorimeter so their final energy can be measured.

Methods

By varying the thickness of the scintillator, we are able to vary the amount of energy deposited by the electrons/positrons in it. This energy is then the difference between the known initial energy the beam was collimated for and the final energy, as determined by the calorimeter or from the DWC-determined momentum (which we can find given the equation $E^2 = (pc)^2 + (m_0c^2)^2$). Using both methods helps verify our accuracy. These measurements, in addition to the luminescence obtained from the PMT, allow us to determine three relationships:

- Luminescence as a function of energy deposited, L(E)

[11] We propose to use DWCs instead of MicroMegas because, although having a lower resolution, they allow faster particle tracking

- Luminescence as a function of distance the particle traversed in the scintillator (scintillator thickness), L(x)
- Energy loss of the particle as a function of distance travelled in the scintillator, E(x)

Using this, we can obtain the scintillator efficiency and proportionality, as well as the fit to Birks' law:

- The scintillator efficiency is the rate at which deposited energy is converted into photons, corrected for the PMT efficiency.
- The proportionality of the scintillator is the linearity of the L(E) graph.
- Birks' law is a multi-step process:
    1. *dL/dx* and *dE/dx* can be obtained by numerically differentiating L(x) and E(x).
    2. At low ionization densities (low *dE/dx*) $k_B \cdot \frac{dE}{dx}$ is negligible[12] so $dL/dx \propto dE/dx$. Thus, by measuring with thinner scintillators, we can find L_0
    3. We may then use thicker scintillators to find k_B and the closeness of fit of Birks' law to the data.

By repeating this procedure at different beam momenta, we can shift the energy levels and get better data for L(E) over greater ranges of E.

Furthermore, this will be done for both positrons and electrons. This will allow us to find the difference between electrons and positrons in terms of efficiency, scintillator proportionality, and applicability of the model. Based on previous research[13] and an evaluation of the positron-annihilation probability[14] we expect a slightly lower luminescence for positrons, but not more than 1-2%.

IV. What We Hope to Take Away

While working on our proposal, we explored a huge range of ideas, from Askaryan radiation to channeling radiation in crystals. While we ultimately landed on an investigation of scintillators, the process of exploring the world of particle physics was extremely rewarding. Not only was there the chance to learn about (and use to evaluate feasibility) scattering cross sections and reaction rates, there was also the invaluable experience of reaching out to the physics community at our local university. We hope that going to DESY would help us expand and develop the skills we relied on as we developed our experiment, and that we can come back to our school better able to share this method with those around us.

V. Acknowledgments

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[12] M. Hirschberg, R. Beckmann, U. Brandenburg, H. Bruckmann and K. Wick, "Precise measurement of Birks kB parameter in plastic scintillators," *Conference Record of the 1991 IEEE Nuclear Science Symposium and Medical Imaging Conference*, Santa Fe, NM, USA, 1991, pp. 183-186 vol.1.
doi: 10.1109/NSSMIC.1991.258896

[13] Meiring WJ, van Klinken J, Wichers VA (1991) Differences between electrons and positrons interacting with detector material. Phys Rev A 44:2960–2967

[14] https://github.com/sambonkov/BL4S-Desy-Chain/blob/master/BL4S%20Appendix.pdf