Aerogel Refractive Index Measurements for the HELIX Cosmic Ray Detector

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We request two days of electron beam time at the National Research Council 35 MeV linear accelerator (linac) to measure the refractive index of aerogel tiles from the ring imaging Cherenkov detector for the HELIX cosmic ray detector. The time would be used to ensure the combination of the electron beam and the test system built to detect the Cherenkov ring can measure variations in the refractive index to $\sim 10^{-4}$. We will test this by doing an initial refractive index scan of one aerogel tile.

1 Scientific Justification

1.1 Astrophysical Motivation

Cosmic rays are high energy particles and nuclei that propagate at close to the speed of light. Traditionally, there were two dominant models of how cosmic rays propagate through the interstellar medium and magnetic fields: the diffusive halo and the leaky box model. One of the reasons for the interest in cosmic ray propagation models comes from results from PAMELA and AMS-02. They detected a higher positron fraction in cosmic rays than predicted by any cosmic ray model.[1][2] Several phenomena have been used to explain this result, but they cannot be properly tested without measurements of the cosmic ray isotopic composition. One of the isotope abundance ratios of interest is $^{10}Be/^{9}Be$, which is unobserved >2GeV/n[2] where it would be easier to distinguish the models as in Fig.1. ^{9}Be is stable, but ^{10}Be is a clock isotope that decays with $t_{1/2}$=1.39Myr and whose abundance is entirely dependent on the cosmic ray propagation mechanism so measurements of the abundances at >2GeV/n are key in refining current propagation models.[2]

1.2 The HELIX Experiment

The High Energy Light Isotope eXperiment (HELIX) is a balloon-borne cosmic ray detector whose first phase detector will launch during the NASA 2020/2021 Antarctic balloon campaign[1]. It will measure abundances of light isotopes such as the $^{10}Be/^{9}Be$ ratio to constrain the cosmic ray propagation models with a mass resolution of $\frac{\Delta m}{m}$=0.025[2]. HELIX allows for measurements of these light isotopes up to an order of magnitude higher energy than current data[2] as shown in Fig.1. There is good model discrimination at the currently unobserved 3GeV/n which is within HELIX's energy range of 1-3GeV/n for its first flight and 3-10GeV/n for the second flight[2]. The mass of isotopes are distinguished by the mass resolution $\left(\frac{\Delta m}{m}\right)^2 = \left(\frac{\Delta R}{R}\right)^2 + \gamma^4 \left(\frac{\Delta \beta}{\beta}\right)^2$ where β=v/c, R is the rigidity and γ is the Lorentz factor[2]. The rigidity is a measure of the effect of a magnetic field on a charged particle.[2] The detector has four main components to make these measurements. A gas drift chamber and a 1T superconducting magnet measure the rigidity. The velocity is measured using time-of-flight counters for E<1GeV/n and a ring imaging Cherenkov detector for E>1GeV/n.[2][3] The Cherenkov detector consists of a square array of 36 10 x 10 x 1 cm aerogel tiles with n_{avg} ≈1.15 [4]. The Cherenkov photons are read out 50cm away by sillicon photomultipliers[3].

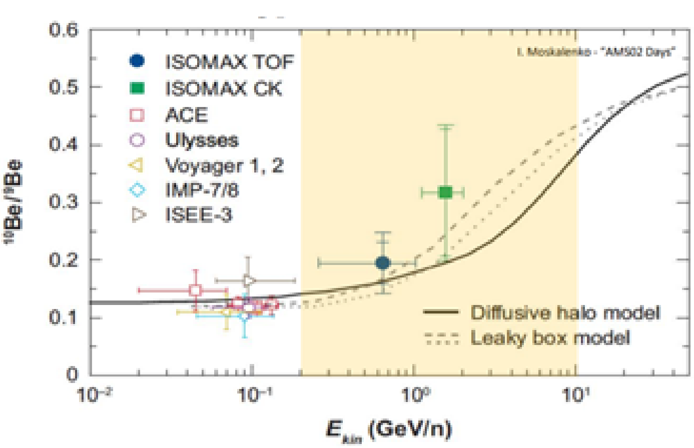

Figure 1: Current experimental observations of the $^{10}Be/^{9}Be$ cosmic ray ratio compared to the two classic propagation models.[1] HELIX will make measurements in the coloured background range of 1-10GeV/n. From (Park, 2017)[1]

1.3 Cherenkov Effect for Refractive Index Measurement

The standard equation describing Cherenkov radiation is $cos\theta = \frac{1}{n\beta}$ where θ is the opening angle of the Cherenkov ring. The size of the ring depends directly on the velocity and hence the energy of the incident cosmic rays. The radius of the ring is measured in the experiment and θ can be calculated using that radius and the aerogel-detector distance. To measure the mass to within the $\frac{\Delta m}{m} = 0.025$ target resolution, $\frac{\Delta\beta}{\beta}$ must be measured to 10^{-3} [3] which requires the uniformity of the refractive index to be $\frac{\Delta n}{n} < 7 \times 10^{-4}$[2]. If maximum difference in the refractive index across the whole tile is less than this limit then an average n can be used in the analysis since the variations are on a smaller scale than the error limit. If it is not within that limit the tile cannot be considered uniform so n must be finely mapped to note the variations across every aerogel tile. The aerogel manufacturer accepts the completed aerogel tiles if they have $\frac{\Delta n}{n} \leq 5 \times 10{-}3$ across the entire tile from the mean value as shown in Fig.2. This is greater than the 7×10^{-4} limit to be treated as uniform which necessitates a fine mapping of the refractive index on the scale of $\sim 10^{-4}$. During flight, the Cherenkov detector will determine β from the radius of the Cherenkov ring assuming that n is known at the location on the aerogel where the cosmic ray interacted. Results from tests requesting time in this proposal would be the first step to make those fine refractive index measurements.

If the refractive index, n, of the point where of where a cosmic ray interacts with the aerogel is known to the $\sim 10^{-4}$ target scale then it will be possible to achieve the mass resolution to distinguish ^{10}Be from ^{9}Be as well as other light isotope pairs like $^{3}He/^{4}He$[2]. One way to map n is to use a standardized charged particle source beam incident on aerogel so the position and energy of the interaction is controlled leaving only a measurement of θ of the resulting Cherenkov ring to find n. An electron linac is the ideal particle source for these measurements because the β will have some thin distribution about a mean energy and the beam can be directed to interact at specific points in the aerogel. This electron beam and the aerogel will produce a Cherenkov ring with a consistent radius and this ring of photons can be measured using CCDs which collect the Cherenkov photons over some finite CCD exposure. Then by moving the aerogel so that the beam interacts at different points on it, any change the Cherenkov ring radius will be due to small variations in n.

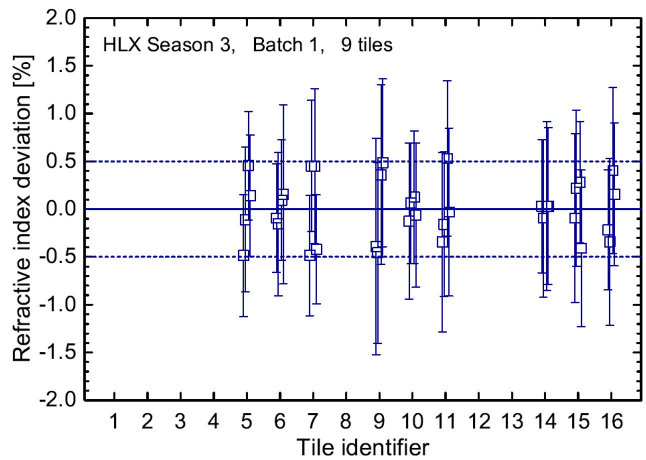

Figure 2: The refractive index deviation across the aerogel tiles. The manufacturer accepts the tile if $\frac{\Delta n}{n} \leq 5 \times 10{-}3$ across the entire tile. The tile cannot be considered uniform in the calculation of the mass since the variations are generally higher than the 7×10^{-3} limit. This necessitates fine measurements of the refractive index to $\sim 10^{-4}$. From (Tabata, 2018)[4]

1.4 National Research Council (NRC) Linear Accelerator

We propose to use the 35MeV $60\mu A$ Vickers research linac[5] located at NRC in Ottawa to do the refractive index measurements. This linac is the only research electron accelerator currently idle within a reasonable travel distance to transport our equipment that has the potential to measure n to the target scale. Based on previous simulation for HELIX, this linac should be capable to measuring variations in n on the scale of 3×10^{-4}[6]. The Cherenkov method we are following is based on research done for the aerogel used on AMS and CREAM[7] using a 500MeV Frascati electron beam which read out photons by photographic plates with errors of n on the order of 3×10^{-4}[7]. That energy is higher than the Vicker's linac HELIX proposes to use and the aerogel has a lower n_{avg}=1.05, but the use of CCDs for a digital signal compared to the photographic plates and an imaging system means that we would likely have better spatial resolution of the Cherenkov rings. Additionally, that test took three days to map two tiles while our aerogel mapping system can scan a single tile in 20 minutes. The goal of the proposed test is to achieve comparable accuracy in the measuring the changes in n of aerogel using a similar electron beam Cherenkov ring technique.

2 Technical Justification

2.1 The Aerogel Calibration Detector

The aerogel calibration system is HELIX's detector to measure the aerogel Cherenkov ring from the electron beam. The electron beam interacts at different points on the aerogel's surface by moving the aerogel in the fixed electron beam's path. This is done by mounting the aerogel in a frame and placing it on a three-axis stepper motor system. Photons are detected using 16 equally angular spaced linear CCDs consisting of 3694 $8\mu m$ pixels and aligned radially as shown in Fig. 3. The center of each CCD is 20cm from the detector center so the CCDs trace out points on a circle. The distance from the aerogel to the CCD is adjusted so that Cherenkov ring falls in the CCDs. A microcontroller attached to a DAQ allows the user to send the readout trigger to collect the data from the CCDs and to set the CCD exposure time to control the signal levels. A custom graphical user interface (GUI) allows the user to set the CCD exposure, move the motors and trigger the CCD readout.

In this test, the electron beam is centered with the detector and then a scanning routine is run from the GUI. It takes a desired number of samples at one position, moves the aerogel by a step and repeats the process completing a grid pattern over the entire 10×10cm surface. For the test, the aerogel will move in 5mm increments totalling 441 measurement points per aerogel tile. At the measurement position, we will take 100 samples of the CCD readout for each of the 16 CCDs. The CCD exposure time depends on the detected signal during the installation of the system in the beam that provide a high signal without saturating the CCDs.

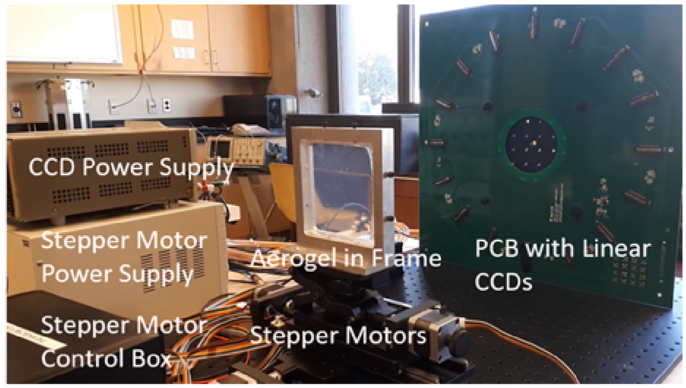

Figure 3: Diagram of the aerogel calibration system showing all essential components to be used in the electron beam test. The entire set up will be covered by a box to shield the CCDs from outside light.

2.2 Expected Signal and Background

HELIX needs to measure the refractive index 10^{-4} scale to get the mass resolution required to distinguish the key isotope abundances. A Geant4 simulation was conducted to provide an estimate of the Cherenkov ring distribution[1]. It consisted of 1000 35 MeV electrons in a 1mm radius beam going through a 1cm n=1.15 piece of aerogel detected on a screen 28.5cm away. The simulation produced 119000 photons. Fig. 4 is the resulting Cherenkov ring at that distance to simulate the spread to what should be an analogous situation to the beam test. Fig. 5 is the expected signal in the CCDs as the number of photons at the distance where the CCD pixels are located. The gaussian has σ=595 pixels so out to 3σ of the signal is captured in the 3694 CCD pixels if the peak is centered in the CCD. The uncertainty in the refractive index will be due to the width of the gaussian fit signal. The noise visible in the plot is due to a low number of electrons simulated with a small area of the CCD for photon detection. A previous simulation for HELIX showed that the NRC beam should be capable of measuring n to 3×10^{-4}[6]. The exact signal strength expected is unknown because it depends on the beam's current energy distribution and the beam size which are parameters we do not have access to without measuring them ourselves.

Based on lab tests we estimate that to get a signal that is visible in the CCDs without saturating will require an exposure time of 50-100μs using the 35MeV $60\mu A$ electron beam. Exposure is one of the most important factors to consider in this test as it dictates what amount of signal and noise that can be detected. The beam properties are the largest sources of uncertainty in the test results because of those factors' effect on the peak spread and noise of the Cherenkov ring. If the beam has a larger spatial or energy dispersion, the CCD signal would be noisier and wider making it difficult to fit a gaussian with the accuracy required. This would be true especially if the beam is not centered on the detector, giving a Cherenkov ring that does not peak at the same point on each CCD or may only be visible in some of the CCDs and miss others.

One goal of this proposed electron beam time is to assess whether it could be used for a larger full scale mapping of all of HELIX's aerogel tiles. This is only possible if the noise is low from the beam and the Cherenkov

[1]Simulation done by T. Rosin based on the thesis simulation by R. Prechelt[6], but data analyzed by author

ring does not get too wide. Tests of the background noise due to the DAQ readout, CCDs and light leakage showed that it is constant for all exposures $< 5ms$ within 0.001V and varies across each CCD by σ=0.01V. We expect this noise to be minimal compared to the potential beam noise.

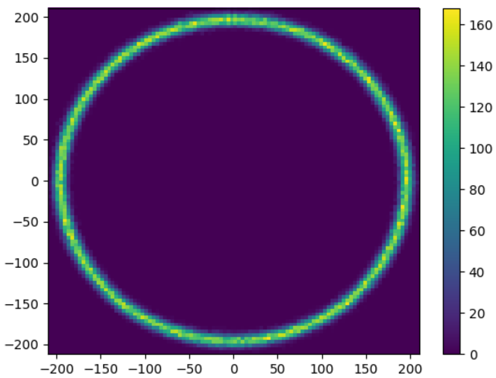

Figure 4: Cherenkov ring histogram, scale in mm from the center of the detector where the electron beam would hit in the absence of the aerogel

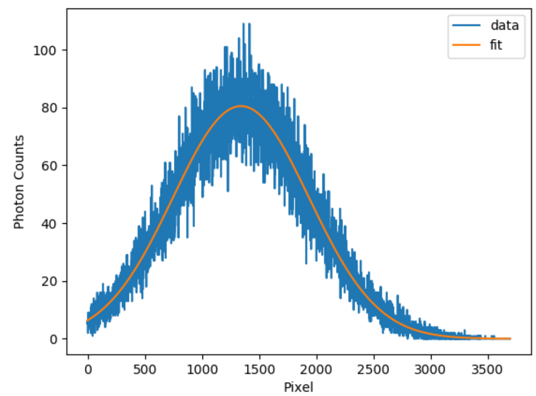

Figure 5: Distribution of Cherenkov photons in the CCD covering radius range. Given in the number of photons in each pixel

During the aerogel calibration test, the multiple samples at each CCD taken consecutively are averaged and fit with a gaussian. The Cherenkov ring radius is found by mapping that fit to its physical position on the circuit board (Fig. 3) and using a circle optimization routine to find the radius. Since the distance from the CCDs to the aerogel is known, θ is trivial to find and β can be calculated from the specifications of the linac. Using the equation of Cherenkov radiation described earlier, this allows for a measurement of the refractive index.

2.3 Technical Requirements of the Electron Beam Test

We request use of the linac for an initial testing period of two days to conduct the aforementioned test. There would be four people that would work with NRC staff to run the test equipment and linac. This initial visit would allow the team to install the calibration system in the beam line, adjust the distance from the aerogel to the CCDs and check light levels on the first day. The second day would consist of additional debugging and doing a detailed scan of a single aerogel tile for later analysis. The plan would be to scan in a 5mm grid over the entire 10cmx10cm tile which takes ~20 minutes. We would also request that the linac room be kept as dark as possible, in addition to the box that already covers the calibration system, to limit background in the CCDs. During these two days we would also like to conduct two additional tests. A dark run would be taken just before turning on the electron beam to characterize the background signal in the same conditions as in the beam test. We would use some time to measure the Cherenkov ring in optically uniform n=1.5 glass to test our n reconstruction accuracy to see if our method can get the desired refractive index accuracy of $\sim 10^{-4}$.

If this initial scan of a single aerogel tile is successful and makes measurements of n to $\sim 10^{-4}$ accuracy, there will be a proposal for a follow-up experiment to scan the 48 HELIX aerogel tiles including those for the flight and backups.d Using the same procedure and number of measurement points per aerogel tile as the proposed test, this second phase test would take three weeks to scan all the . It would be followed up by some additional lab tests. By late 2019, the aerogel will be installed onto the HELIX balloon payload in time for the 2020/2021 launch.

[1] N. Park, "Cosmic-ray isotope measurements with HELIX," in *International Cosmic Ray Conference*, 2017.

[2] HELIX Collaboration, "HELIX Proposal,"

[3] HELIX Collaboration, "Cosmic-ray isotope measurements with HELIX," *Proceedings of Science*, 2017.

[4] M. Tabata, "Developing a silica aerogel radiator for the HELIX ring-imaging Cherenkov system," 2018.

[5] National Research Council, "Ionizing Radiation Standard Facilities," 2018.

[6] R. Prechelt, "Measurement of the Refractive Index of Aerogel for RICH Detectors," Master's thesis, UChicago, 2017.

[7] Y. Sallaz-Damaz, "Characterization study of silica aerogel for cherenkov imaging," 2010.