PROCEEDINGS OF SCIENCE

Cosmic-ray isotope measurements with HELIX

J. J. Beatty[1], S. Coutu[2], M. Gebhard[3], N. Green[4], D. Hanna[5], B. Kunkler[3], M. Lang[3], I. Mognet[2], D. Müller[6], J. Musser[3], S. Nutter[7], N. Park[6]*, M. Schubnell[4], G. Tarlé[4], A. Tomasch[4], G. Visser[3], S. P. Wakely[6], and I. Wisher[6]

[1]*The Ohio University, Columbus, OH 43210 USA*
[2]*Pennsylvania State University, University Park, PA 16802 USA*
[3]*Indiana University, Bloomington, IN 47405 USA*
[4]*University of Michigan, Ann Arbor, MI 48109 USA*
[5]*McGill University, Montreal, Canada*
[6]*University of Chicago, Chicago, IL 60637 USA*
[7]*Northern Kentucky University, Highland Heights, KY 41099 USA*

HELIX (High Energy Light Isotope eXperiment) is a balloon-borne experiment designed to measure the chemical and isotopic abundances of light cosmic ray nuclei. Detailed measurements by HELIX, especially of ^{10}Be from 0.2 GeV/n to beyond 3 GeV/n, will provide an essential set of data for the study of propagation processes of the cosmic rays. HELIX consists of a 1 Tesla superconducting magnet with a high-resolution tracking system, time of flight detector, and a ring-imaging Cherenkov detector. The instrument is scheduled to have a long-duration balloon flight out of McMurdo Station during NASA's 2019/20 Antarctic balloon campaign. In this talk, we will discuss the scientific goals and the design of the experiment, and report on its current status.

35th International Cosmic Ray Conference–ICRC217–
10-20 July, 2017
Bexco, Busan, Korea

*Speaker.

PoS(ICRC2017)226

1. Introduction

Understanding the sources and acceleration mechanisms of the cosmic rays has been one of the main goals of astroparticle physics for more than a hundred years. To achieve this goal, we need to understand how particles propagate from their source sites to the Earth. A commonly selected observable to study the propagation is the elemental secondary-to-primary ratio, such as the boron-to-carbon (B/C) ratio. Based on the assumption that the local elemental abundance is similar to the abundance of the cosmic-ray source sites, an over-abundance of particles such as boron indicates that those 'secondary' particles are generated by spallation interactions during the propagation. The relative abundance of secondary particles to primary particles probes the total material path length of the cosmic rays over their containment time before they reach the Earth. While secondary-to-primary ratios are indispensable to unravel cosmic-ray histories of propagation, they by themselves are insufficient to fully constrain all parameters. In the case of diffusion models with halos, for example, they are sensitive only to the ratio of the halo size to the diffusion coefficient, leading to large degeneracies in the parameter space.

Abundance ratios of radioactive isotopes with known decay times can provide a direct measurement of the containment time of cosmic rays, removing some of the degeneracies. One of the most important such isotopes is the β–decay isotope beryllium-10 (^{10}Be), which decays with a half-life of 1.39 Myr. Because beryllium is mainly produced by interactions of heavier cosmic rays with the interstellar medium, the ratio of ^{10}Be to stable ^{9}Be is entirely determined by the propagation history of the cosmic rays. In diffusion halo models, the ^{10}Be/^{9}Be ratio can be used, together with constraints from stable secondary-to-primary ratios, to estimate values for the diffusion coefficient and the halo size [1, 2, 3]. High-quality ^{10}Be/^{9}Be measurements can also provide strong discrimination (especially at energies of $\sim$3 GeV/n) between entire classes of propagation models [2, 4, 5]

Also, the abundance measurements of other stable isotopes serve complementary roles to study the propagation of cosmic rays. They provide key tests of the 'universality' of cosmic-ray propagation histories, by examining species with different Z/A ratios and overall abundance levels [6, 7].

The importance of propagation studies of the cosmic rays has become more vital as recent measurements reveal interesting new cosmic-ray properties. For example, several elemental spectra show spectral index hardening around 200 GV, which was not expected. The most highly publicized recent result has been the remarkable increase observed in the positron fraction ($e^+/(e^+ + e^-)$) reported by the PAMELA, AMS-02 and Fermi/LAT collaborations. This behavior is in conflict with traditional models of cosmic-ray physics and has been attributed to a wide variety of phenomena, including particle production in nearby astrophysical objects, propagation physics, or more exotic sources, including the annihilation or decay of dark matter particles.

To address the questions related to the interpretation of these unexpected observations, improving the measurements that permit studies of cosmic-ray propagation is essential. The High Energy Light Isotope eXperiment (HELIX) is a new long-duration balloon payload designed to measure light isotopes from 0.2 GeV/n eventually up to $\sim$10 GeV/n. HELIX will be able to make precise measurements of important isotopic abundances, including the ^{10}Be/^{9}Be ratio, to energies over an order of magnitude higher than previously achieved, providing essential measurements to study the propagation.

2. Instruments

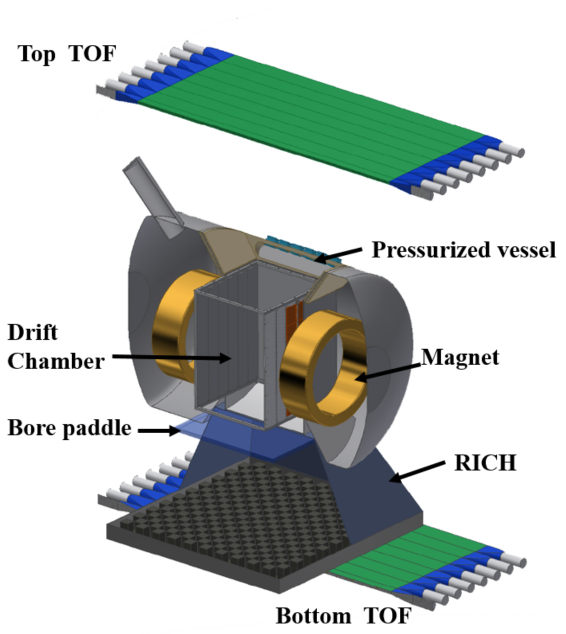

Figure 1: Partially sectioned 3D model of the High Energy Light Isotope eXperiment detector systems, showing superconducting magnet, drift chamber tracker, two time-of-flight layers and ring-imaging Cherenkov detector.

The HELIX instrument is a magnet spectrometer designed to measure the light isotopes, especially focusing on the isotopes of beryllium. As shown in Figure 1, the major components of the instrument, besides the magnet, are the scintillator paddles on the top and bottom of the instrument, a drift chamber tracker, a bore paddle, and a ring imaging Cherenkov Detector. The HELIX instrument is designed to fly on a long-duration balloon flight. With a geometric acceptance of 0.1 m^2sr and up to 14 days of flight time, HELIX is sufficient to pursue high-statistics measurements of isotopic ratios even at high energy.

With the 1 T magnetic field provided by the superconducting magnet and 65 μm spatial resolution provided by the gas tracking system, HELIX can achieve a rigidity resolution of $\sim$2.5% for ^{10}Be measurements up to $\sim$5 GeV/n. The combination of the time-of-flight system and the ring imaging Cherenkov detector system will allow HELIX to cover a wide energy range from 0.2 GeV/n up to $\sim$4 GeV/n with a velocity resolution of $\Delta\beta/\beta \sim 1\times10^{-3}$. These specifications provide the mass resolution needed for the ^{10}Be/^{9}Be measurements up to $\sim$3 GeV/n [8].

One of the challenges is to make an efficient readout under a 1 T magnetic field. Traditional photomultiplier tubes (PMTs) become inefficient under strong magnetic fields and require heavy magnetic shielding or delicate field alignments. HELIX utilizes the most recent development of silicon photomultiplier (SiPM) readout instead of PMT readout. SiPMs provide a high photodetection efficiency and an excellent single photoelectron resolution under magnetic field without special shielding. The bias voltage required for SiPM operation is much lower ($\sim$30 V), so the readout does not suffer from the same kind of high-voltage corona problem frequently encountered with PMTs. However, thermal noise, also known as dark current, is much higher than in PMTs and the performance has strong correlation with the temperature of the device. For stable operation, the HELIX readout system requires a careful thermal design and a compensation system based on the ambient temperature monitoring.

A brief description of the main components follows:

2.1 Superconducting Magnet

The superconducting magnet that will be used for HELIX can provide an approximately uniform 1 T field within a rectangular warm bore. Two superconducting coils centered along the cryostat axis are immersed in a liquid-helium (LHe) bath to keep the temperature below the critical temperature of 9.8 K. The LHe capacity of the magnet is 260 liters, which provides a hold time of approximately seven days. The magnet was built by Cryomagnetics Incorporated and originally designed for the HEAT experiment. It has been used in five successful balloon campaigns [9].

2.2 Drift Chamber Tracker

The bore of the magnet will house a drift chamber tracker (DCT) to continuously track particles through the magnetic field. To minimize the source of Coulomb scattering and maximize the tracker's size, the DCT utilizes the entire tracking volume as a multi-wire drift chamber. HELIX will employ a flat-geometry design with 72 sense layers, segmented into three drift cells per layer. The DCT is designed to achieve a mean spatial resolution of $\sim$65 μm for Z>3 particles by utilizing low-diffusion drift gas, a moderate drift field of $\sim$1 kV/cm, and high-speed sampling readout electronics. The DCT will be placed inside a pressurized vessel that tightly fits inside the bore of the magnet to maintain 1 atm pressure during the flight.

2.3 Time-of-Flight and Charge System

The HELIX time-of-flight (TOF) and charge system will measure the velocity of the particles up to $\sim$1 GeV/n and the charge of the particles from proton up to neon (Z=10). It consists of two layers of 1.5-cm thick fast plastic scintillator paddles, located at the top and bottom of the instrumentation stack, with a total separation of 2.3 m. The paddles will be 1.6 m long, and will be read out by three SiPM at each each of each paddle Using the planned 10 psec TDC system, we expect the TOF system to achieve a timing resolution of <50 ps for Z>3. The combination of the TOF system and a bore paddle, a small scintillator paddle located under the DCT, will provide a system-wide trigger.

2.4 Ring Imaging Cherenkov Detector

For measurements of particle velocities at high energy, where the TOF system cannot provide a discriminating measurement, HELIX will use a proximity-focused aerogel ring imaging Cherenkov detector (RICH). On the basis of extensive GEANT4 Monte Carlo simulations, we adopt the following configuration: 10 mm thickness aerogel radiator with refractive index of 1.15 (threshold energy of $\sim$1 GeV/n), and expansion length 500 mm. The 1.32 m^2 focal plane will consist of an array of 64-channel Hamamatsu SiPMs with pixel size 6$\times$6 mm^2. Because the RICH will have low pixel photon occupancies (average photons per pixel <3 for Z=4), it is important to minimize the dark counts from the SiPMs. We will accomplish this by cooling the focal plane. To reduce costs, the focal plane will be partially populated with sensors arranged in a checkerboard pattern. This lowers the velocity resolution of the device, but still enables measurements of the ^{10}Be/^{9}Be ratio up to about 4 GeV/n. The details of the RICH design and testing for HELIX can be found from the other HELIX contribution in this conference [10].

3. Expected Performance and Results

HELIX is designed to measure the mass of nuclei with a resolution of $\sim$2.5% from 0.2 GeV/n to $\sim$3 GeV/n. The charge of incident particles will be measured for protons (Z=1) up to neon (Z=10) by complementary detectors–the TOF and RICH systems. With this performance, HELIX can provide good mass separation for adjacent light isotope measurements.

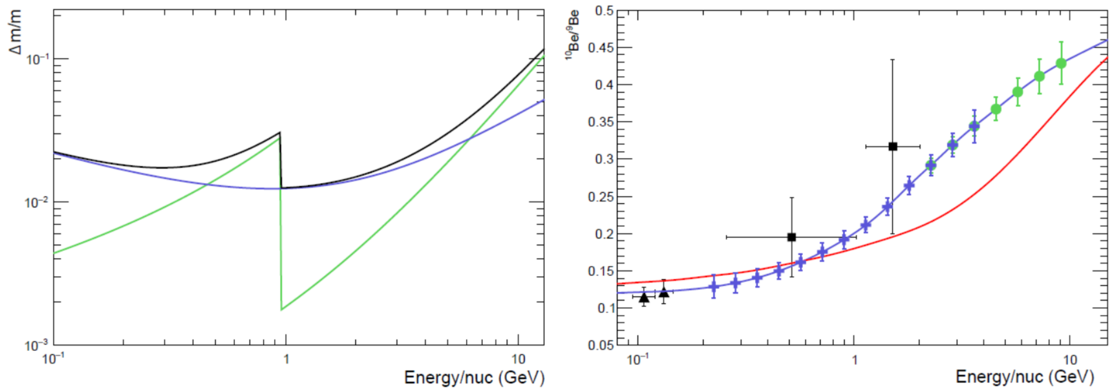

Figure 2: Left: Predicted relative mass resolution vs. energy per nucleon for the HELIX instrument with ^{10}Be incident particles. The blue line is the contribution to the mass resolution from the spectrometer; the green line is the γ^2-weighted contribution from the velocity-determining instrument: the TOF below 1 GeV/n and the RICH above 1 GeV/n. The black line is the quadrature sum of the two. Right: Anticipated beryllium isotope ratio measured by HELIX. The blue crosses show results for a 14-day Antarctic flight with the instrument configuration described here. The green dots show results for a future 28-day exposure with an upgraded instrument. The blue line represents a Leaky Box model with a low-density Local Bubble and the red line represents a diffusion halo model with re-acceleration [4]. Also shown on the plot are the results of ACE/CRIS (triangles) and ISOMAX (squares).

The black line in the left panel of Figure 2 shows the expected relative mass resolution of HELIX versus kinetic energy per nucleon for ^{10}Be nuclei. This plot is based on full Monte Carlo simulations based on the instrument configuration described above. As shown in the plot, HELIX can provide less than 3% relative mass resolution for ^{10}Be nuclei from a few hundred MeV/n all the way to $\sim$4 GeV/n, which corresponds to 0.3 a.m.u. separation between ^{9}Be nuclei and ^{10}Be nuclei. With 14 days of Antarctic flight, HELIX will provide data that can be compared with ACE/CRIS measurements in the low energies and well beyond the low-statistics measurement by ISOMAX at 1.1-2.0 GeV/n as shown in the right panel of Figure 2. In addition to the results from the 14-day flight discussed here, expected results from a future 28-day exposure in an upgraded configuration are also shown. Clearly, even the initial HELIX results will provide very strong constraints on the behavior of the ^{10}Be/^{9}Be ratio, reaching with good statistics well into the region where time dilation significantly affects the radioactive isotope lifetime. From this 14-day flight alone, more than 1500 ^{10}Be nuclei are expected above 2 GeV/n, an area where no measurements currently exist.

In addition to the ^{10}Be/^{9}Be ratio, HELIX will measure several other important isotopic abundance ratios for light elements from proton up to neon. For isotopes lighter than beryllium, such as the ^{3}He/^{4}He ratio, HELIX can provide good measurements up to $\sim$8 GeV/n because the relative mass difference between these lighter isotopes is large. These isotopic measurements, secondary-to-primary ratio or secondary-to-secondary ratio, can provide unique information about the propagation process. Furthermore, isotope abundance ratios are not subject to modification by atomic properties such as condensation temperature or first ionization potential, and thus can provide crucial information on the origin of cosmic-ray particles [11]. HELIX will also measure the light elementary particle fluxes up to 800 GV.

4. Current status and plan

Up to now, we have focused on the finalization of the detector design, including the selection of SiPMs based on their performance test and simulation, and selection of the readout system. For this, we have developed smaller scale prototype detectors to test the performance and evaluate overall design. Now we are moving toward flight-ware production aiming to start the instrument integration in 2018. After environment and ground tests, we are planning to have a long-duration balloon flight out of McMurdo Station during NASA's 2019/20 Antarctic balloon campaign.

References

[1] J. A. Simpson & M. Garcia-Munoz, 1988, Space Sci. Rev. 46, 205

[2] M. Simon, 1999, 27^{th} ICRC proceeding

[3] A. W. Strong et al., 2007, Annual Review of Nuclear and Particle Science 57, 285

[4] T. Hams et al., 2004, ApJ 611, 892

[5] A. Putze et al., 2010, A&A 516, A66

[6] B. Coste et al., 2012, A&A 539, A88

[7] N. Tomassetti, 2012, Ap&SS 342, 131

[8] S. Wakely et al., 2015, 34^{th} ICRC proceeding

[9] J. J. Beatty et al., 2004, Phy. Rev. Lett. 93, 241102

[10] I. Wisher et al., 2017, 35^{th} ICRC proceeding

[11] N. Prantzos, 2012, A&A 542, A67