RIO: The R-process Isotope Observer

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Abstract

The source of galactic cosmic-ray nuclei is unknown, but there is a general consensus that galactic cosmic rays are accelerated by supernova shocks in the interstellar medium. The evidence in support of this picture is strong but indirect. However, the fact that the cosmic-ray spectrum extends continuously, without steps or peaks, to more than five orders of magnitude in energy beyond the limit of supernova shock acceleration appears to be incompatible with this picture, at least without extreme fine-tuning of models. A "smoking gun" is needed to definitively establish that supernova shocks are indeed the accelerator of galactic cosmic rays. If galactic cosmic rays are accelerated in supernova shocks, they will be enhanced in freshly-synthesized r-process material. We are currently studying the R-process Isotope Observer (RIO) as a Mission of Opportunity for the International Space Station. RIO will make the first measurements of the isotopic abundances of the "ultraheavy" galactic cosmic rays (those in the range $32 \leq Z \leq 42$) and will determine the fractional contribution of freshly-synthesized r-process material in galactic cosmic rays through the measurement of several key isotopic ratios.

1. Introduction

Reuven Ramaty and collaborators [4,5] have pointed out that supernovae explode preferentially in OB associations—regions which have recently been the site of massive star formation. A supernova exploding in an OB association sends a shock into a local interstellar medium which is enriched in freshly-synthesized material from previous supernovae. A signature of cosmic-ray acceleration by supernova shocks is an enhancement in r-process material. Such an enhancement may already have been seen in elemental abundance measurements by HEAO 3 [1] and Large Trek [9] among elements with $Z > 60$, although the situation is complicated by elemental fractionation effects.

There is a distinct advantage to determining the s-process to r-process mix by measuring isotopic ratios, since these ratios are immune to elemental fractionation effects. A detector of very large collecting power is required to measure the abundances of isotopes for $Z > 30$. In the Fe-Ni region, a mass

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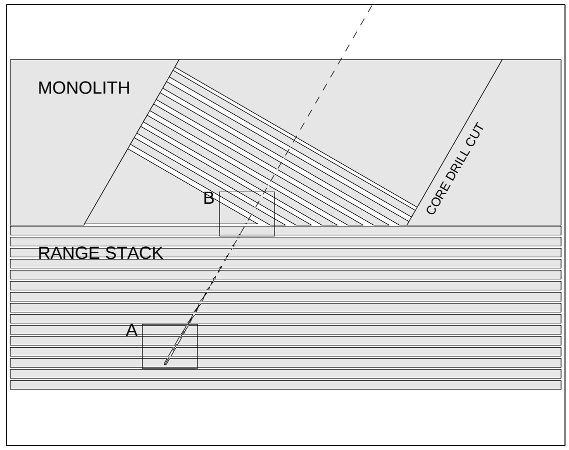

Fig. 1. RIO block diagram showing the monolith above and range stack below. The trajectory of a sample cosmic ray is shown as a dashed line.

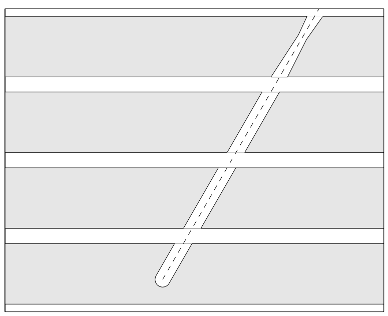

Fig. 2. Region A of Fig. 1., showing the particle forming a test-tube at the end of its range.

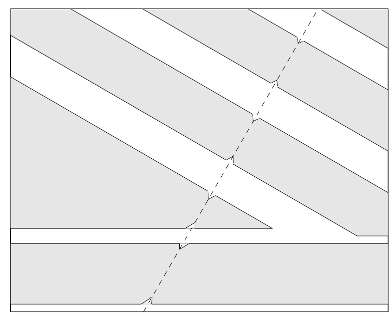

Fig. 3. Region B of Fig. 1., showing track-etch cones in the wafered monolith and the upper part of the range stack.

resolution of 0.25 amu corresponds to a fractional error in mass measurement of about 0.5%, but at $Z = 40$ ($A \sim 100$) this same mass resolution requires a fractional error of no more than 0.25%. An instrument composed of glass track-etch detectors is a robust and inexpensive way to meet both challenges.

2. The RIO Detector

RIO is based on the track-etch detector [2] BP-1, a barium-phosphate glass developed at Berkeley [6]. BP-1 has been used successfully in measurements of the isotopic and elemental composition of cosmic rays by the Small Trek detector [7]. We have adopted an initial design consisting of a 30 cm $\times$ 30 cm $\times$ 1.5 cm BP-1 monolith. One side of this monolith will be tiled with a 1.5 cm thick stack of thin, polished sheets of BP-1, constituting a range stack similar to Small Trek (Fig. 1.). Each 30 cm $\times$ 30 cm module would have a mass of 8.1 kg.

After exposure in space, we will disassemble the detector modules and expose the range stacks to a relativistic ion beam at multiple angles for purposes of the range measurement described below. Then we will etch the range stacks. As illustrated in Fig. 2., a "test-tube" forms at the point where a cosmic ray stops in the range stack. We are developing automated methods for locating stopping ultraheavy cosmic rays in the RIO range stack. We will use the range stack to determine the stopping depth. The calibration beam will allow a highly accurate measurement of both the thicknesses of detector sheets and the amount of material removed during etching.

Unlike Small Trek, the range stack will be used only to identify ultraheavy cosmic rays and determine stopping depth and trajectory. The cosmic-ray signal will be measured in the monolith. We will core the monolith along the track of the particle so that the track is centered on the axis of the core. The resulting cores will be exposed to a relativistic ion beam at multiple angles. We will then slice the core into wafers. The wafers will be polished and etched, and the track-etch signal on each surface will be measured with our automated scanning system. The use of crossed calibration beams allows an accurate measurement of position within the core and provides an accurate measurement of the amount of material removed during etching. In addition, the calibration beam signal provides a reference signal in the wafer to correct for small variations in detector sensitivity.

We have demonstrated [10] that the process of wafering and polishing has no effect on the signal measured in the detector and the dispersion in signal. Because polishing produces no shift in signal, we can repolish a wafer which has already been analyzed, allowing us to further sample a particle track inside the detector. To achieve sufficient mass resolution for RIO, we require two cycles of repolishing in addition to the original analysis.

The measurement of cosmic-ray mass requires range as well as signal. As mentioned above, we first accurately measure the stopping depth of the cosmic ray within the range stack. Using crossed calibration beams, we can determine the position of the wafer surface within the core. We have demonstrated that this technique determines absolute position to better than 2.5 μm accuracy [10]. All that remains is to "connect" these two measurements. As Fig. 3. illustrates, a wedge-shaped piece of glass remains between the wafers and the range stack. We will etch this piece of glass and measure the distance along the cosmic-ray track. Once we have signal and range for the particles, we can identify charge bands as was done in Small Trek. Within a charge band, range is proportional to mass.

The most important contribution to mass dispersion is the intrinsic detector dispersion, due to real fluctuations in detector signal on small scales [8]. We expect that the intrinsic dispersion for ultraheavy cosmic rays will be smaller than that for Fe, since we have measured smaller intrinsic dispersions for Au and Xe beams, but to be conservative we have used the Fe value in our estimates of mass resolution. To estimate the mass resolution for RIO, we have taken the intrinsic dispersion measured for cosmic-ray Fe nuclei and combined it with a response function also measured for cosmic-ray Fe nuclei. The study of additional sources of dispersion is ongoing. Intrinsic dispersion contributes approximately 0.20 amu to total dispersion. The registration temperature effect—a weak dependence of detector signal on detector temperature at the time of track formation—is also important and contributes approximately 0.12 amu for temperature fluctuations of order 2 K rms. We have also investigated dispersions due to electronic straggling, charge-state switching, and multiple Coulomb scattering and found these negligible in comparison. We have assumed a mass measurement similar to Small Trek, such that errors in signal are converted into errors in range. Within a charge band, mass is proportional to range, so for a fixed fractional error in range, the error in mass is proportional to the mass. More massive cosmic rays will in general have higher charges and produce a longer region of measurable signal in the detector. Thus the tendency for the error in mass to grow with particle mass is compensated for by the additional number of measurements which become possible for a more massive particle. We expect to achieve a mass resolution of 0.25 amu. We emphasize that most pure r-process isotopes are separated from their nearest stable neighbors by two mass units.

3. Conclusion

Measurement of ultraheavy cosmic-ray isotopes has long been identified as an important goal of cosmic-ray research [3]. RIO is both inexpensive and reliable, since the sophistication of the detector is in the laboratory, not on orbit. RIO is therefore an excellent candidate to measure ultraheavy cosmic-ray isotopes in the near future.

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