AN EXPERIMENT TO MEASURE THE ELEMENTAL ABUNDANCES OF ULTRA-HEAVY COSMIC RAYS

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ABSTRACT

Measurements of the elemental abundances of galactic cosmic ray nuclei with charge $26 \leq Z \leq 92$ can provide important information that should help to resolve the question of cosmic-ray origin; i.e. whether cosmic rays originate from the acceleration of interstellar grain material or from preferential selection and acceleration of nuclei from stellar photosphere-chromosphere regions with $T \sim 10^4$ based on first ionization potential. They will also refine tests of whether freshly synthesized r-process material is a significant component in cosmic rays. The detector concept described utilizes an array of silicon detectors for dE/dx measurements, two Cherenkov counters with radiators of different refractive index for velocity determination (one using aerogel and one using a novel waveshifter readout approach), and scintillating fibers for a hodoscope/time-of-flight detector. The numbers of particles which can be collected with this approach and the expected charge resolution are discussed.

1. INTRODUCTION AND SCIENCE OBJECTIVES

Cosmic-ray nuclei are of great interest since they may include a sample of galactic matter that is freshly synthesized in supernovae (SN), or matter which is a sample of the interstellar medium (ISM). Experiments have shown that the abundances of individual nuclei measured so far ($1 \leq Z \leq 28$ and even-Z nuclei for $Z \leq 60$), when propagated back to the source, are similar to those of the solar system with the important exception that the abundances exhibit a fractionation relative to the solar system (SS) which can be ordered by the first-ionization potential (FIP) of the element. In general, nuclei with high-FIP are depleted with respect to those with low-FIP. Similar fractionation appears for solar energetic particles (SEP), most samples of the solar wind, and the solar corona. It is believed that on the sun nuclei with low-FIP are preferentially selected from an ion-neutral gas in the chromosphere and photosphere where $T \sim 10^4$K, and injected into the interplanetary, and eventually the interstellar medium. This is presumably also the case for other stars possessing a relatively low temperature chromosphere which can preferentially inject low-FIP particles into the corona (F through M stars). Essentially all samples of accelerated cosmic matter appear to exhibit this ordering. However, it has been pointed out by a number of authors (Bibring and Cezarsky (1981); Sakurai (1995)) that a fractionation of elements based on volatility rather than FIP could produce a very similar ordering since most elements with low-FIP are refractory and most with high-FIP are volatile. In addition, several of the most abundant elements (H, He, C, and O) fit the general SS-FIP picture rather poorly. The resolution of this question is quite crucial since it pertains directly to the origin of cosmic rays, one of the primary goals of galactic cosmic-ray investigations.

Two recent papers by Meyer, et al.(1997), and Ellison et al. (1997), have shown that substantially improved ordering can be obtained if one assumes that "highly volatile" elements (T_c<400K for the dominant molecular form in the ISM where T_c is the temperature at which 50% of the material is condensed at 10^{-4} atmospheres; Meyer et al.) are ordered by A/Q while "volatile, semi-volatile, and refractory" elements are ordered by their volatility. Moreover, they present a predictive model in which ISM and/or circumstellar dust grains and gas are accelerated simultaneously in a SN remnant. The refractory elements exist primarily in grains, some of which are weakly charged and therefore possess a very high rigidity. This enables them to be preferentially accelerated by the SNR blast wave to high energies. Their conclusion is that the elemental abundances measured so far can be accounted for by this model, after including Helium-burning contributions from WR stars which should enhance the measured abundances of ^{22}Ne, ^{12}C, and ^{16}O (Ellison et al. (1997)). In this model, galactic cosmic rays then would not have any significant "fresh" material synthesized in SN. Ultra-heavy elements ($Z \geq 30$) would then consist almost entirely of "old" r-process material in interstellar grains or alternately, if FIP is operative, in the protostellar material swept up to make the generation of stars now feeding into the ISM.

On the other hand, Ramaty et al. (1997) conclude, based on observations of Be and B in low-metallicity halo stars formed in the early galaxy, that cosmic rays must have been accelerated out of freshly nucleosynthesized matter. If that was true in the early galaxy then presumably it would be true in the current epoch.

Meyer et al.(1997) and Binns et al.(1996) point out a number of elements with unknown or poorly known abundances in the GCRs that can, in principle, enable us to distinguish between the volatility-A/Z model and SS-FIP models. Among these are the UH elements $_{33}$As, $_{35}$Br, $_{37}$Rb, $_{47}$Ag, $_{48}$Cd, $_{49}$In, $_{50}$Sn, $_{51}$Sb, $_{52}$Te, $_{55}$Cs, $_{79}$Au, $_{81}$Tl, and $_{83}$Bi. In addition, the element pairs $_{34}$Se, $_{37}$Rb and $_{52}$Te, $_{55}$Cs are r-process nuclei with one member having a low-FIP and the other a moderately high-FIP with all four elements being volatile. The existence of a FIP enhancement for these elements would indicate that they are not fresh r-process nuclei, lending credence to the volatility-A/Z model. A next-generation experiment capable of measuring the elemental abundances for $83 \geq Z \geq 30$ nuclei with single charge resolution and adequate statistics should provide the capability to distinguish between these models of cosmic ray origin.

2. EXPERIMENT CONCEPT

The instrument concept which is currently being developed as the UH detector for ACCESS (The Access Collaboration (1997)) utilizes silicon dE/dx detector arrays, two Cherenkov counters with radiators of different refractive index for velocity measurements, and scintillating fibers as a hodoscope/time-of-flight detector. Fig. 1 is a cross-section drawing of the instrument. The overall dimensions of the detector are 2 meters square by 0.3 meters deep. This provides a useful radiator area of 156 cm square and a total geometry factor of 5.5m^{2}sr for entry in one direction.

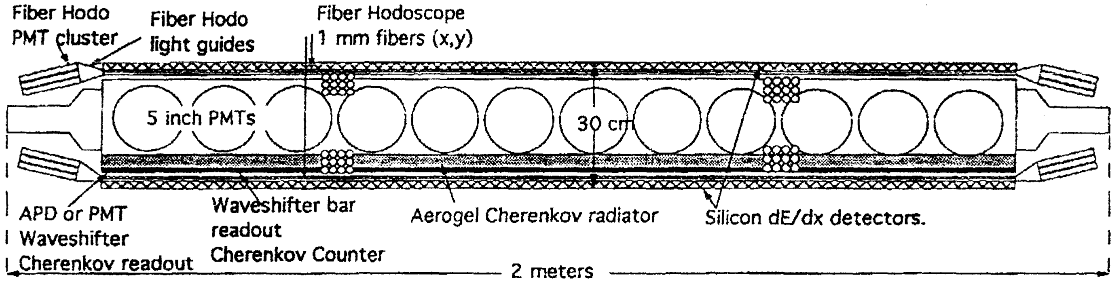

Fig. 1. Instrument cross-section

Arrays of ion-implanted silicon wafers which are square with a 10 cm diagonal and thickness 380μm are located on top and bottom of the detector stack. Such large arrays have become common in high energy physics experiments. VLSI circuitry would be used to read out these detectors. In addition to providing dE/dx measurements the silicon detectors also serve as a coarse hodoscope.

Just inboard of each silicon array is a scintillating fiber hodoscope. Each of the four hodoscope layers (2 x,y pairs; one pair top and one pair bottom) are read out by 4 clusters of PMTs (two clusters on each end of a fiber layer). Each cluster consists of twelve 0.5 inch PMTs which view a fiber output width of 78 cm (780 fibers). The fibers are coded differently on either end so that the position of a particle traversing a contiguous group of $(12)^2=144$ fibers (output length 14.4 cm) can be unambiguously resolved. There will be a position degeneracy of order 5 or 6 (depending upon the fiber traversed) for each coordinate from the fiber information alone. This degeneracy is then resolved by the silicon detectors which give position accurate to about 7 cm in each coordinate. The position resolution that will be achieved from the combined fiber/silicon wafer hodoscope is ~300μm. The fiber readout PMTs will also provide time-of-flight measurements to a precision that is sufficient to distinguish upward from downward moving trajectories.

A light collection box Cherenkov counter ($C_{1.04}$) which utilizes a 3 cm thick aerogel (n~1.04) radiator is located just below the top fiber detector. The light box is viewed by ~44 five inch PMTs. The threshold energy for this detector is ~2.5 GeV/n. Just below that is a second Cherenkov counter

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($C_{1.49}$) which uses an acrylic or PVT based Cherenkov radiator. In the baseline instrument this is a total-internal reflection (TIR) detector which is read out with waveshifter bars coupled to PMTs. We are studying combinations of waveshifter dyes for use both in the radiator and waveshifter bars that will increase the ratio of detected light that is isotropic to that which is directional (i.e. the ratio of waveshifted to non-waveshifted primary Cherenkov light), thereby decreasing the directional component of detected light. We are also studying the use of a more conventional TIR counter in which Cherenkov light is detected without the use of waveshifter bars.

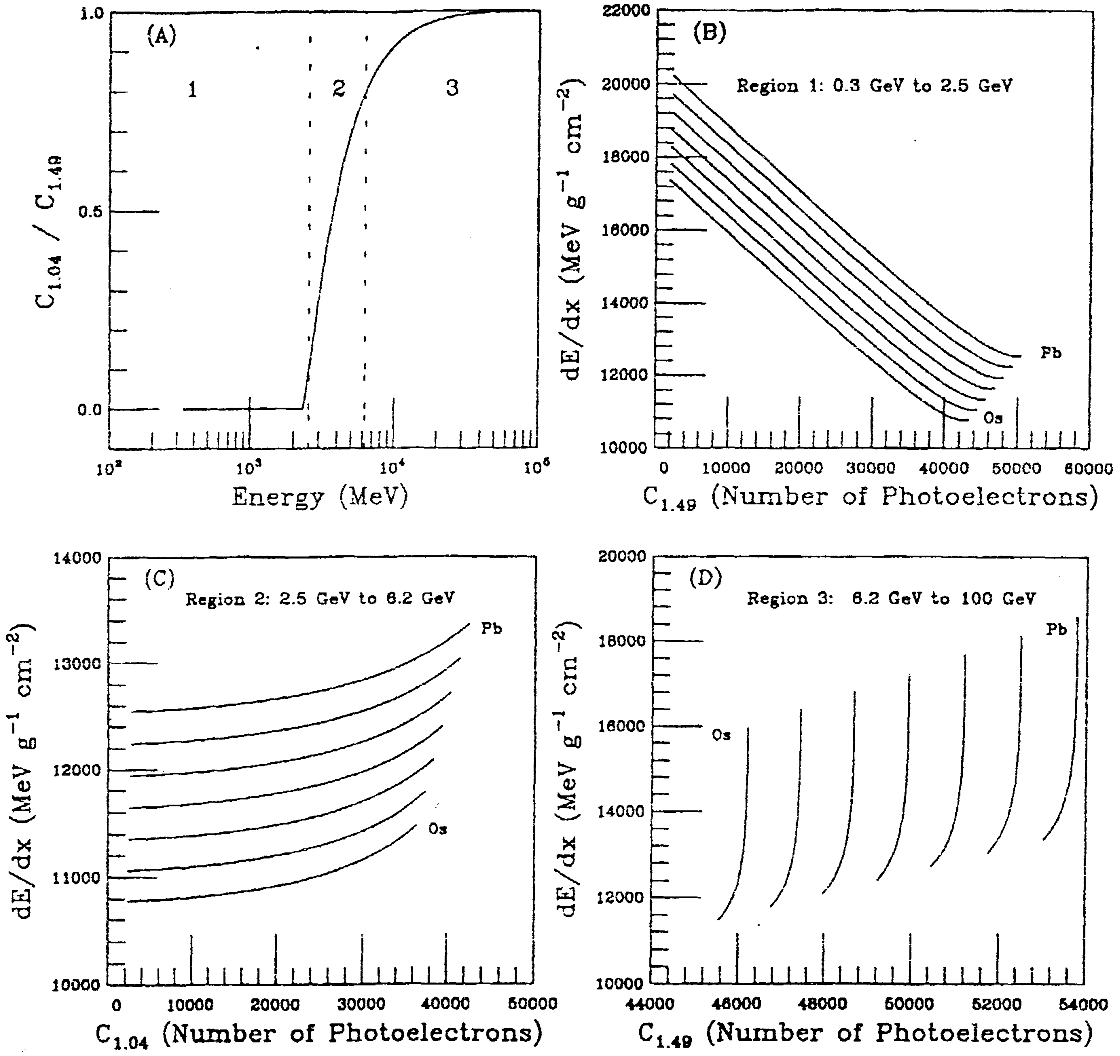

Fig. 2 In panel A, the ratio of the Cherenkov signal from the aerogel to that of the acrylic radiators is plotted vs. energy. The vertical dashed line indicates the three regions described in the text. Panels B, C, and D show plots of dE/dx vs. the relevant Cherenkov signal for each of the three energy regions.

The primary reason for using two Cherenkov counters with different refractive index is to resolve the degeneracy in charge identification for nearby charges that occurs due to relativistic rise in ionization. This measurement effectively allows us to divide the parameter space into three regions. In Fig. 2A we show the ratio of $C_{1.04}/C_{1.49}$ as a function of energy and indicate the three energy regions. Region 1 is for $E \leq 2.5$ GeV/n where the charge identification is based primarily on dE/dx with a velocity correction from the n=1.49 index counter ($C_{1.49}$); region 2 is for $2.5 \mathrm{GeV/n} \leq E \leq 6.3 \mathrm{GeV/n}$ where charge identification is based on dE/dx with a small velocity correction from $C_{1.04}$; and region 3 is for $E \geq 6.3$ GeV/n where the charge is obtained primarily from $C_{1.49}$ with a velocity correction from dE/dx. Figs. 2B, 2C, and 2D are charge contours for nuclei in the $_{76}$Os-$_{82}$Pb charge range for each of these regions. We see that this method essentially eliminates the charge contour cross-over problem that exists in dE/dx-single-Cherenkov measurements.

3. EXPECTED NUMBERS OF EVENTS AND CHARGE RESOLUTION

We have calculated the number of events that can be obtained using this detector configuration for a three year mission in a 51° orbit at solar minimum (Fig. 3). We see that sufficient particles can be collected to measure abundances for all elements with $Z \leq 56$ to a statistical precision of $\leq 12\%$ and most elements with $56 < Z \leq 82$ to a precision of $\leq 20\%$.

Once adequate statistics have been obtained, it is necessary to achieve excellent resolution in charge to accurately determine the elemental abundances. In paper OG 5.1.7 we present results from a calibration at Brookhaven using 11 GeV/n Au nuclei that shows a charge resolution of 0.2cu for the Silicon detectors. This resolution should improve at lower energies since contributions from knock-ons are decreased. We are planning to fly both aerogel and acrylic based Cherenkov counters as a part of the TIGER experiment to study the resolution of both detectors.

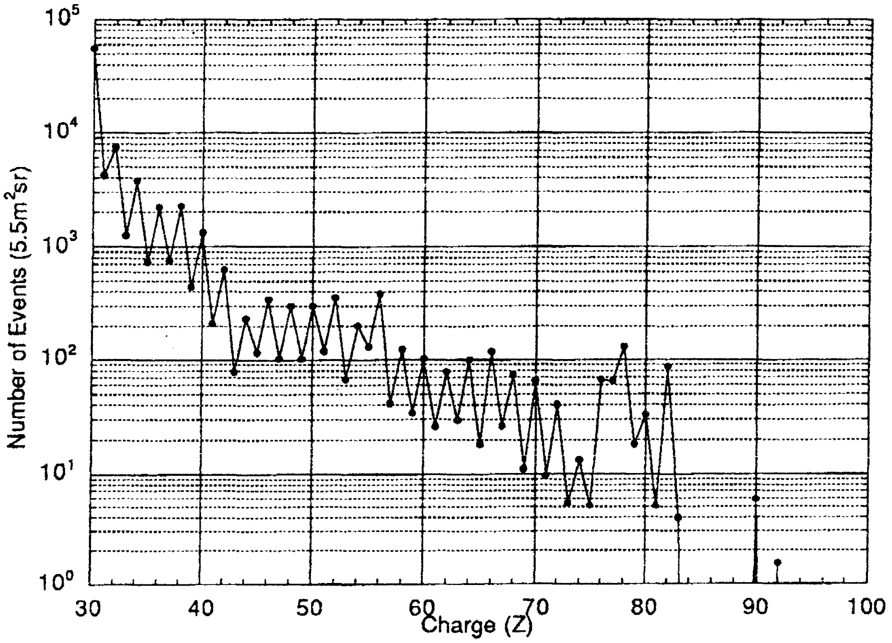

Fig. 3 This estimate of the number of events detected assumes a module with active detector area 156 cm square having a 30 cm vertical dimension (geometry factor 5.5 m^2sr), a 51° orbit, 3 year flight at solar minimum. Particles which interact in the detector have been excluded.

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