The Energetic Trans-Iron Cosmic-ray Experiment (ENTICE)

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Abstract. **The ENTICE experiment is one of two instruments that comprise the "Orbiting Astrophysical Spectrometer in Space (OASIS)", which is presently undergoing a NASA "Astrophysics Strategic Mission Concept Study". ENTICE is designed to make high precision measurements of the abundances of individual elements from neon through the actinides and, in addition, will search for possible superheavy nuclei in the galactic cosmic rays. The ENTICE instrument utilizes silicon detectors, aerogel and acrylic Cherenkov counters, and a scintillating optical fiber hodoscope to measure the charge and energy of these ultra-heavy nuclei for energies greater than 0.5 GeV/nucleon. It is a large instrument consisting of four modules with a total effective geometrical factor of ∼20 m^{2}sr. Measurements made in space for a period of three years with ENTICE will enable us to determine if cosmic rays include a component of recently synthesized transuranic elements ($_{94}$Pu and $_{96}$Cm), to measure the age of that component, and to test the model of the OB association origin of galactic cosmic rays. Additionally, these observations will enable us to study how diffusive shock acceleration of cosmic rays operates differently on interstellar grains and gas.**

Keywords: **cosmic rays–Galaxy:abundances**

I. INTRODUCTION

The Orbiting Astrophysical Spectrometer in Space (OASIS) mission [1] is composed of two experiments, the ENergetic Trans-Iron Cosmic-ray Experiment (ENTICE) and the High Energy Particle Calorimeter Telescope (HEPCaT) [2]. In this paper, we describe the ENTICE science objectives and instrument.

The large area of ENTICE gives it an effective geometrical factor of ∼20 m^{2}sr, enabling it to measure the elemental composition of the cosmic rays with unprecedented statistical precision up to the heaviest nuclei, $_{90}$Th, $_{92}$U, and very probably $_{94}$Pu and $_{96}$Cm. Its configuration of detectors will give charge resolution fine enough to resolve individual elements over the entire range from $_{10}$Ne through the actinides.

II. SCIENTIFIC OBJECTIVES

Measurements of cosmic-ray isotopes [3] and elements $_{31}$Ga, $_{32}$Ge, $_{34}$Se, and $_{38}$Sr [4][5][6] have given strong support for a model of cosmic-ray origin in which the cosmic-ray source material is the interstellar gas and dust of OB associations - a mixture of about 80% material of the same composition as the solar system and 20% material of the outflow of massive stars, which are found in those associations. Where individual elements have been resolved (for atomic number $Z \leq 38$) the data further indicate preferential acceleration of refractory material found in interstellar dust grains over volatile material found in interstellar gas, with both of these components exhibiting a mass dependent preference for heavier elements. The ENTICE data, giving high statistical precision for many more elements and in a mass range not previously measured with individual-element resolution, will enable a stringent test and refinement of this emerging model.

Figure 1 shows numbers of events expected to be recorded by ENTICE over a three-year period in orbit. (Since individual elements have not been measured in most of this range of cosmic-ray elements, the plotted numbers are based on previous measurements of groups of elements [7] with plausible guesses at the numbers expected for individual elements in the groups.) The only measurement to date of individual actinide elements [10] identified only six events as actinides, with four of them assigned individual element identification. ENTICE will record at least a hundred actinides. The expected number of actinides and their individual element abundances depends on the nature and age of the cosmic-ray source. Three plausible distributions are shown in figure 1 - one assuming abundances entirely like the solar system (which would have no Pu or Cm), one assuming abundances

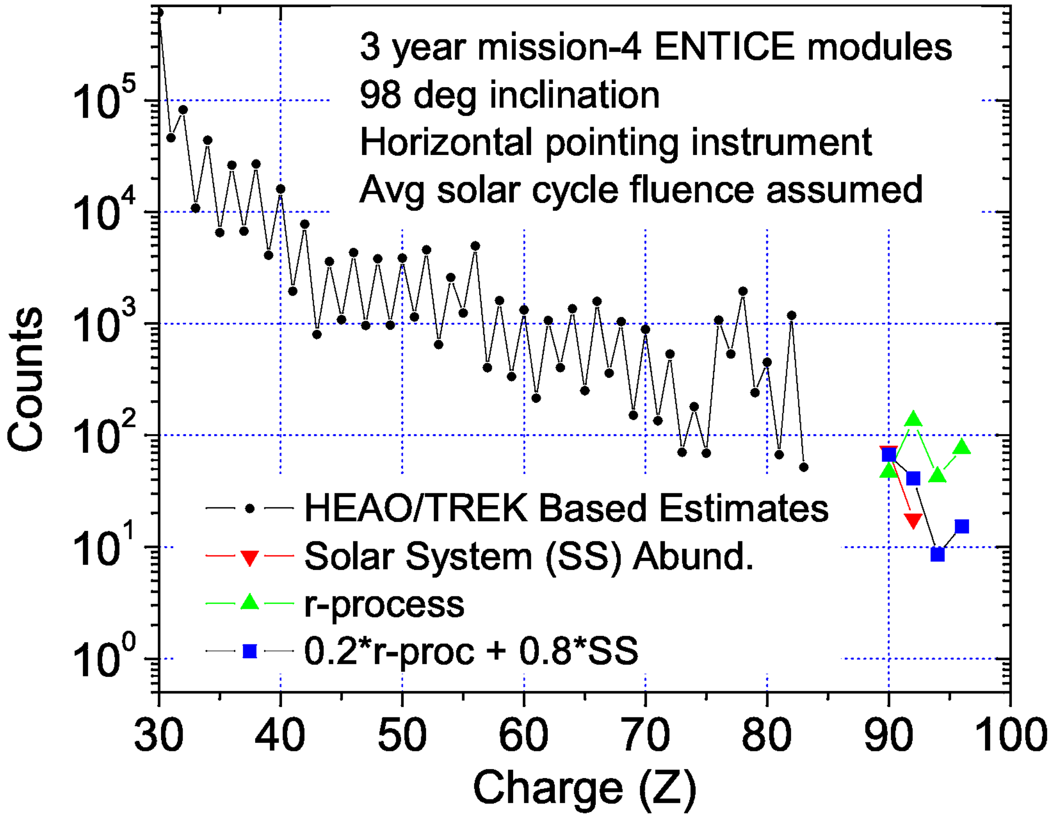

Fig. 1. The number of events that we estimate that we will detect is plotted vs. nuclear charge. The actinide abundances show three possible estimates:a)assumed solar system abundances, b) assumed pure r-process abundances, and c) a mix of 20% r-process material with 80% interstellar material with solar system composition.

dominated by freshly synthesized r-process material, and one assuming a mix of 20% freshly synthesized material and 80% interstellar material with solar system composition as suggested by the measurements of much lighter elements.

Figure 2 shows more clearly how ENTICE will distinguish among models of the cosmic-ray source material. Panel (a) shows a likely result if the cosmic-ray source material is entirely recently synthesized nuclei. Here we have a substantial number of Pu and Cm events and a high U/Th ratio. Panel (c) shows a likely result if the cosmic-ray source material is entirely old, similar to the composition of the solar system. Here we have no Pu or Cm, and a low U/Th ratio. Panel (b) shows a likely result if the cosmic-ray source is indeed a mixture of about 80% old (solar-system-like) material and 20% young freshly synthesized products of massive stars. Here we have about ten tranuranic events, and approximately equal numbers of U and Th. For comparison, panel (d) displays the only element-resolved cosmic-ray actinide measurements to date [10].

In addition to the certain results described in the previous paragraphs, ENTICE has the potential to discover super-heavy elements in nature. Nuclear structure calculations indicate that there could be long-lived super-heavy elements in an "island of stability" near $^{A}Z = {}^{288}110$ and $^{290}110$ [9]; however the predicted lifetimes for such nuclides is uncertain by orders of magnitude. The best hope of finding such isotopes is among the cosmic rays, the youngest sample of matter in nature to which there is direct access. If such super-heavy nuclides have life-times of the order of 10^6 years or more, and if the cosmic rays do indeed include significant numbers of Pu and Cm, then ENTICE might well detect samples of those new elements.

III. INSTRUMENT DESCRIPTION

ENTICE uses the dE/dx-Cherenkov method to identify the charge (Z) of all cosmic-ray nuclei heavier than neon (Z=10) with E$\sim\geq$500 MeV/nuc. Energy spectra of individual elements are obtained from 0.5 to 10 GeV/nuc. ENTICE consists of four identical modules, one of which is shown in Figure 3. Each module operates independently and is essentially symmetrical front-to-

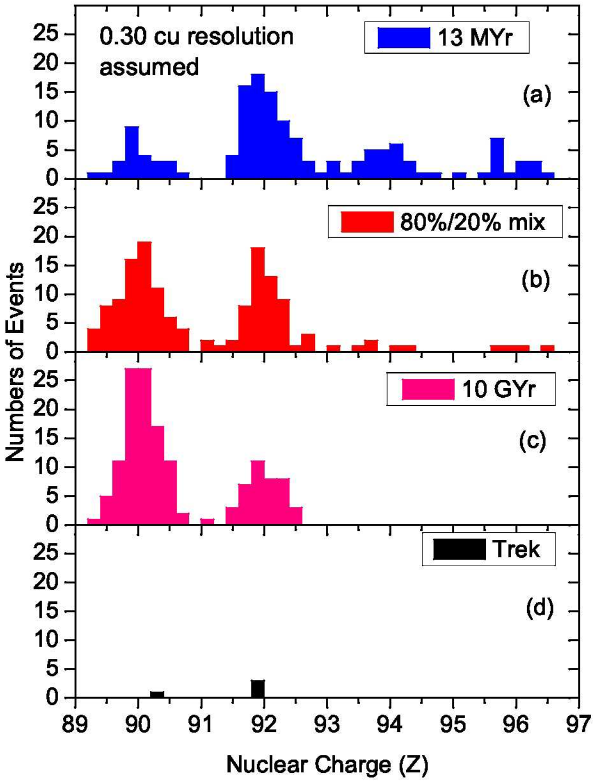

Fig. 2. Panels a, b, and c show Monte-Carlo calculation results of three years of ENTICE data for various assumptions of the age and origin of cosmic-ray source material. Panel d shows the only available charge-resolved data to date.

back so that particles entering from either direction can be detected equally well. Each module utilizes three detector subsystems (silicon detector arrays, Cherenkov counters, and scintillating fiber hodoscopes). An exploded view of the module, revealing the individual detectors, is shown in Figure 4. ENTICE uses three layers of silicon detectors for dE/dx, one covering each entrance aperture and one near the center of the instrument. It uses two Cherenkov counters, one with acrylic radiator of index of refraction 1.5 (and thus energy threshold 0.35 GeV/nuc) and the other with aerogel radiator of index of refraction 1.04 (and thus energy threshold 2.5 GeV/nuc). The cosmic-ray trajectory through the instrument is determined with a scintillating fiber hodoscope composed of three x-y layers, one near each end and one near the center of the instruments. The effectiveness of this technique has been demonstrated by the TIGER experiment [4] [5]. The dE/dx measurement using Si detectors improves upon the TIGER measurement, which relied on plastic scintillator.

The modules have a large field-of-view with an acceptance half-angle of 60 degrees from either front or back. The instrument axis points in a direction perpendicular to the orbit plane. The instrument has a field-of-view extending from the limb of the Earth to within 30 degrees of the zenith.

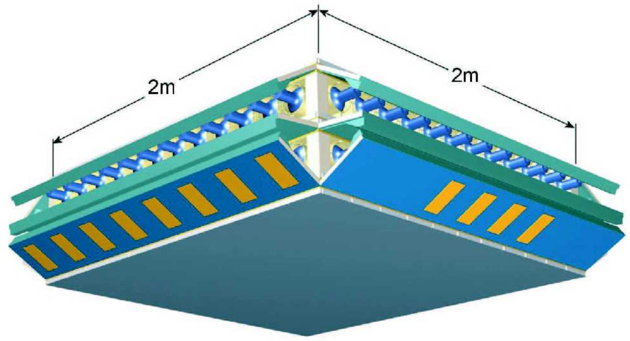

Fig. 3. One of four ENTICE modules

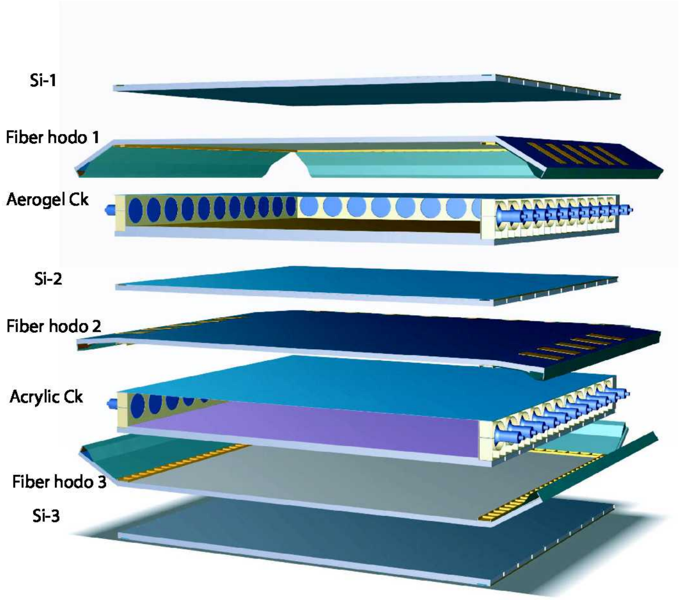

Fig. 4. Expanded view of an ENTICE module

A. Silicon Detectors

There are three silicon detector modules (Si-1, 2, 3). Each module is composed of a 20 × 20 array of 10 cm square, 380 μm thick, silicon wafers. Only two silicon dE/dx measurements are required for particle charge identification. However, a third silicon plane is included to enable measurement of the charge of particles exiting the side of the instrument. The detector signals are read out by a custom VLSI circuit. The charge resolution for high-energy, ultraheavy ($Z \geq 30$) nuclei with two silicon layers was measured to be σ_Z=0.20e using a 10.6 GeV/nuc fragmented gold nuclei beam (Z=79) obtained from the AGS accelerator at Brookhaven National Laboratory [8].

B. Cherenkov Counters

The Cherenkov counters are located on either side of the center silicon and hodoscope modules. The radiators are mounted in light diffusion boxes viewed by five-inch photo-multiplier tubes (PMTs). The acrylic Cherenkov counter radiator has a threshold energy of 0.3 GeV/nuc and the aerogel Cherenkov radiator has a threshold of 2.5 GeV/nuc. The light output achieved with prototype acrylic and aerogel detectors using a beam of 10.6 GeV/nuc fragmented gold nuclei (Z=79) was sufficient to achieve a charge resolution of 0.23e above 2.5 GeV/nuc [8].

C. Scintillating Fiber Hodoscopes

The hodoscope is used to determine particle trajectory. Each hodoscope plane measures an x-y pair. Since ENTICE measures particles entering from either end (Si-1 or Si-3 entry) and the Cherenkov signal depends (weakly) on traversal direction, a time-of-flight (TOF) measurement is needed to distinguish particle direction. The hodoscope makes this measurement. There are three fiber hodoscope modules, one each just inboard of Si-1 and Si-3 and a third next to Si-2. Only two hodoscope planes are required for particle charge identification. However, as for the third silicon detector, a third hodoscope plane is included to enable identification of particles exiting the side of the instrument and for redundancy. Each fiber layer consists of 0.75-mm square-cross-section scintillating fibers coupled on each end to 16-channel multi-anode PMTs. Each MAPMT reads out approximately 20 fibers on each pixel, with the fibers coded differently on opposite ends [12]. Signals from the two MAPMTs uniquely locate the particle's trajectory to within <1 mm. The MAPMT output is split with anode signals going to an ACE or STEREO VLSI chip for pulse height analysis and the dynode signals going to a Labrador ASIC [11] for TOF analysis. We have demonstrated a timing resolution with fibers of 48 ps for argon nuclei at energy 155 MeV/nuc obtained from the MSU National Superconducting Cyclotron Laboratory (NSCL) [12].

IV. SUMMARY

In summary, we have developed a mission and an instrument concept that has both the required collecting power and the charge resolution to measure the abundances of all elements with $Z \geq 10$ in the cosmic radiation through the actinides. Additionally, ENTICE will have sufficient dynamic range to search for possible super-heavy elements which may exist in the cosmic rays. We expect that these measurements will enable us to conclusively determine both the origin of the material and the site of the acceleration of galactic cosmic rays.

V. ACKNOWLEDGEMENTS

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