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The abundances of actinide nuclei in the cosmic radiation as clues to cosmic-ray origin

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Abstract. The solid-state nuclear-track detector (SSNTD) array of the DIAS-ESTEC Ultra Heavy Cosmic Ray Experiment (UHCRE) on the *Long Duration Exposure Facility* (LDEF) collected approximately 3000 cosmic-ray nuclei with Z>65 in the E>1.5 GeV/nucleon energy region during an exposure of approximately 150 m^2 sr yr in Earth orbit. Following further analysis and extensive experimental work to improve charge resolution, the upgraded charge spectrum for the actinides is presented.

1 Introduction

Recent measurements of the elemental cosmic-ray composition have provided useful constraints on the possible origins of galactic cosmic-ray (GCR) seed nuclei. The ^{82}Pb depletion evident from the HEAO 3 (Binns et al., 1989), ARIEL 6 (Fowler et al., 1987) and UHCRE (Thompson et al., 1993) instruments has been confirmed by TREK (Westphal et al.,1998). These results disfavour a sun-like or protosolar source with either first ionisation potential preferential acceleration or non-preferential acceleration, which renders the possibility of a cosmic-ray source based on ionised gas of local galactic composition unlikely.

Isotopic analysis has also proven insightful. Data from the *Advanced Composition Explorer* (ACE) spacecraft (Wiedenbeck et al., 1999) have shown depleted ^{59}Ni in the GCR due to the electron K-capture decay $^{59}\text{Ni} \rightarrow {}^{60}\text{Co}$ (τ=1.1 × 10^5 yr). This implies that the time between the nucleosynthesis of the seed nuclei and their subsequent acceleration is >10^5 yr, rendering the acceleration of fresh SN ejecta an unlikely source. The focus has turned to time scales >10^6 yr, which are readily investigated by the abundances of the longer-lived GCR actinides – ^{90}Th, ^{92}U, ^{93}Np, ^{94}Pu and ^{96}Cm.

HEAO 3 and ARIEL 6 provided the first statistically significant data on ultra-heavy (Z≥60) abundances (including three possible actinides) while TREK, with improved resolution, detected six actinides. The UHCRE had the largest exposure factor in the ultra-heavy region. During its 69 months aboard the earth-orbiting LDEF it collected approximately 3000 cosmic-ray events (with Z>65 and energies in the GeV/n range), including a total of 30 actinides. Details of experiment design, calibration and processing may be found in Thompson et al. (1993), O'Sullivan et al. (1995), Donnelly et al. (2001).

2 Results and discussion

Processing of the UHCRE's SSNTD stacks involves etching in an aqueous NaOH solution. Improved charge resolution was achieved by compensating for varying etching conditions in the solution using beams of 10.1 GeV/n Au and 158 GeV/n Pb nuclei, which acted as track etch rate monitors. This eliminated a mean systematic standard deviation of 6.3% in signal strength (or ±1.0e in the actinide region) due to etching variations. The resulting new maximum charge assignment error is $^{+1.4e}_{-1.5e}$ [$^{+1.2e}_{-1.4e}$ (statistical), ±0.6e (systematic)] for the actinide charge region. The improved charge spectrum is shown in fig. 1.

Prominent ^{90}Th and ^{92}U peaks are present, as was expected of the longest-lived isotopes in the actinide region. Since cosmic-ray actinides have similar cross sections and the nuclear interactions they undergo during their traversal of the galaxy mainly result in fission, they

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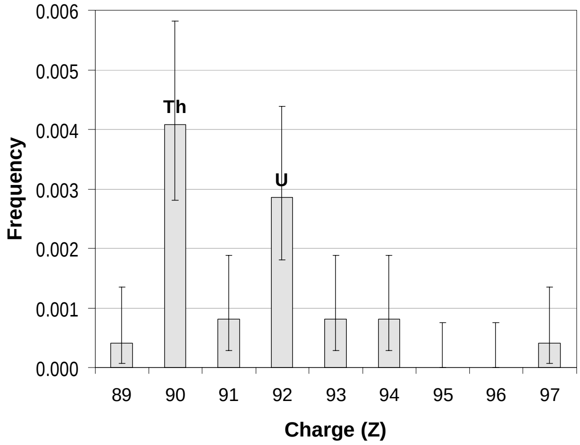

Fig. 1. *Frequency distribution charge spectrum for galactic cosmic ray actinides as measured by UHCRE (normalised to the entire UHCRE sample). Statistical error bars correspond to 1σ confidence limits (Gehrels, 1986)*

will largely maintain their source relative abundances. The immediate qualitative information we infer from the distribution is that there is no large excess of ^{92}U over ^{90}Th, indicating that the GCR actinides have had time to decay somewhat between nucleosynthesis and acceleration. In fact, a comparison of the UHCRE (U+Np)/Th ratio ($0.91^{+0.55}_{-0.38}$) with predictions of r-process production and subsequent decay (Meyer and Goriely, 1998; Goriely and Arnould, 1996; Goriely and Clerbaux, 1999) suggest an 'age' of the GCR actinides $>3\times10^6$ yr and $<10^9$ yr.

This result is consistent with the K-capture decay constraints from ACE and provides interesting (though as yet inconclusive) data for assessing the validity of the superbubble origin theory (Higdon et al., 1998). In this theory, cosmic ray acceleration must occur at least 3×10^5 yr after nucleosynthesis (the mean time between successive SNae in these hot, low density bubbles) and before tens of Myr have passed (their lifetimes).

Another interesting feature of the spectrum is the presence of a probable ^{96}Cm event (of estimated Z=$96.6^{+1.4}_{-1.5}$), binned under ^{97}Bk. There is a 3.2% chance of a single Pu event shifting to this charge assignment.

Attempts will be made to improve charge resolution in this region even further by analysing new ultra-heavy nuclei beams in the same detector plates as the actinide events themselves to enhance further the data available to cosmic ray origin theories.

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