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Development of High Resolution Solid-State Track Detector for Ultra Heavy Cosmic Ray Observation

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Abstract: The observation of trans-iron nuclei in galactic cosmic rays ($Z \geq 30$) requires a high performance cosmic ray detector telescope with a very large exposure area because of their extremely low fluxes. It is realized by the use of solid-state track detector of CR-39, which has an advantage of easy extension of exposure area. The verification of mass and nuclear charge identifications with the CR-39 detector newly developed for the observation of heavy cosmic ray particles has been made using Fe ions from NIRS-HIMAC. Mass and charge resolutions for Fe nuclei are found to be ~0.22 amu and ~0.22 cu in rms, respectively. Moreover, it is necessary to raise the Z/β detection threshold in order to suppress background tracks produced by galactic cosmic rays with Z/β <30. The new track detectors of copolymers of CR-39 and DAP (diallyl phthalate) have been developed and verified as for their performances. It was found that the newly CR-39 detector has a capability to observe trans-iron nuclei in galactic cosmic rays.

Introduction

The precise measurement of nuclear components including isotopes with various half-lives in ultra heavy galactic cosmic rays ($Z \geq 30$; UH-GCRs) gives crucial constraints on the physical conditions at the source of GCRs, the stellar nucleosynthesis and the chemical history of galactic material, and offers new possibilities for the study of the acceleration and propagation mechanisms of charged particles in space [1]. Although the elemental composition of UH-GCRs has been observed by several previous experiments [2, 3], the elemental abundance from $Z = 30$ to 60 has not only been individually resolved but also the grouping of charges for $Z > 60$ was necessary for meaningful abundance measurements. The actinide element (Th, U, Pu, Cm) has not yet been observed. Moreover, the isotopes of UH-GCRs have not yet been observed because of the extremely low flux in GCRs and the difficulty of mass identification of such massive particles. In this paper, we present the performance of the newly developed solid-state track detector to measure the isotopic and elemental compositions of UH-GCRs.

New CR-39 detector

The solid-state track detectors (SSTD) such as the CR-39 detector are very promising for the large-scale observation of these nuclei in space. This is due to the fact that it is easy to fabricate a low-cost large detector array. We plan to observe isotopic composition of $30 \leq Z \leq 58$ with the energy of $<$ 500 MeV/n and elemental composition up to actinide elements in the relativistic energy region [1].

The CR-39 detector thus employed is so-called BARYOTRAK and manufactured by Fukuvi Chemical Industry in Japan. BARYOTRAK is polymerized from a special high-purity monomer. Hence, the uniformity of detector response is very high and the surface quality after the etching is very clear, as shown in Fig. 1. Moreover, we developed the high performance and high speed microscopic measurement system of the SSTD. The details of measurement system are decribed elsewhere [4].

Performance of new CR-39 detector

For the verification of the particle identification power of new CR-39 detector and the effect of its response due to the exposure environments such as temperature and vacuum, we have performed the heavy ion beam experiment in the Heavy Ion Medical Accelerator in Chiba (HIMAC) at National Institute of Radiological Sciences (NIRS).

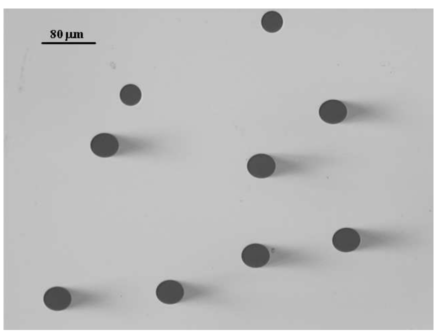

Figure 1: Microscopic image of etch pit of Fe ions produced in the CR-39 detector.

Principle of charged particle detection

A swift charged particle passing through the CR-39 detector leaves a radiation damage trail called a ”latent track”, that can be enlarged by chemical etching in a suitable etchant. The etchant removes material in a very narrow region around the latent track at rate V_t, while it also removes material from undamaged regions at bulk etch rate V_b. As a consequence of chemical etching, a conical etch pit appears in the SSTD, as shown in Fig. 1.The track registration sensitivity ($S = V_t/V_b - 1$) is a function of restricted energy loss (REL) of the incident ion. REL is defined as an energy loss rate that is deposited in the track core region near the particle trajectory [5]. Therefore, the nuclear charge and mass of incident charged particle are determined using S value derived from the track geometry of etch pit and its range (R) in the CR-39 detectors.

Charge resolution of heavy nuclear particle

Using Fe ion beam with the energy of 389 MeV/n, the charge resolution in CR-39 detector was verified by a simple method to measure the track area size of etch pit produced on the CR-39 detector. Fig. 2 shows the track area size distribution of each etch pit. Nuclei lighter than Fe are fragment particles produced by the fragmentation in thick carbon target placed in front of the CR-39 detector. As a result, we obtained a good charge resolution of 0.22 cu (charge unit) in rms for iron nuclei. Thus, it is possible to identify nuclear charge with a good charge resolution using simple and easy technique when the incident energy is given.

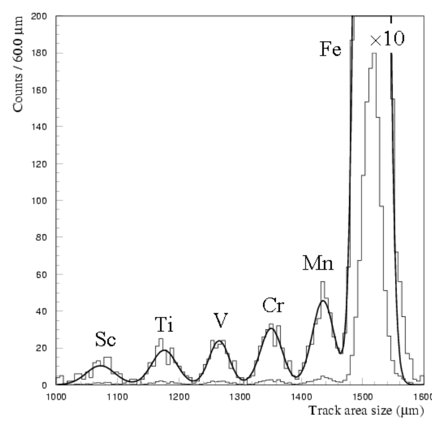

Figure 2: Track area distribution in the CR-39 detector. Nuclei lighter than Fe are seen as products of the fragmentation reaction.

Mass resolution of heavy nuclear particle

Using Fe isotope beams with the energy of 460 MeV/n, we have verified the capability of the CR-39 detector for isotope identification [7]. The mass of an incident charged particle was determined using the L-R technique [8]. In the measurement techniques of mass identification, some measurement errors are included, which degrades the mass resolution [8]. The drastic improvement of accuracies in microscopic image analysis and detector

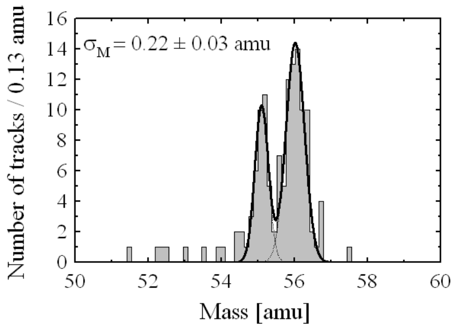

Figure 3: Mass distribution for iron nuclei in the CR-39 detector [6].

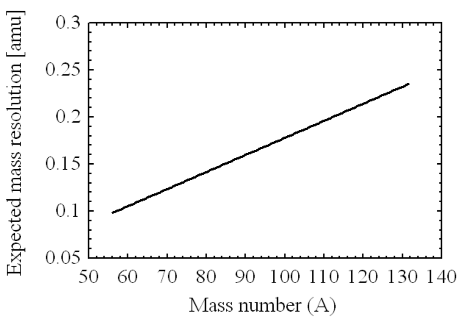

Figure 4: Variation of mass resolution expected for region $56 \leq A \leq 132$ in the CR-39 detector [6].

thickness measurement led us to identify iron isotopes with high mass resolution in the CR-39 detector. As a consequence of reducing the systematic errors, the mass resolution for iron isotopes in the CR-39 detector was obtained to be 0.22 ± 0.03 amu in rms, as shown in Fig. 3 [6]. A possible mass resolution achievable theoretically was estimated by calculation on the basis of the experimental results. As a consequence of reducing the random error, it is predicted that the mass resolution for iron isotopes will ultimately approach $\sim$ 0.1 amu in the CR-39 detector. Furthermore, we simulated the expected mass resolution for trans-iron nuclei ($Z \geq 30$) using the obtained mass resolution for iron isotopes. Fig. 4 shows the the expected mass resolution for the region of $56 \leq A \leq 132$. This capability of the CR-39 detector for mass identification will allow us to clearly resolve adjacent trans-iron isotopes in the region of $30 \leq Z \leq 54$.

Effect to the track registration sensitivity due to the exposure environment

S-value in the CR-39 detector is known to depend on the exposure environment such as temperature and vacuum [9, 10]. These effects were verified to determine the strategy for the control of temperature and pressure around the CR-39 detector in cosmic ray exposure environment. The CR-39 detectors which were controlled their temperatures from -60 to $+60$°C were exposed to Fe ion beam. Figure 5(a) shows the variation of S in the CR-39 detector for irradiation temperature. It was found that S was approximately constant in the region between -60 and -30°C. When observation is carried out by balloon, it is found that the temperature effect is very small because the temperature at balloon altitude is about -35°C on average.

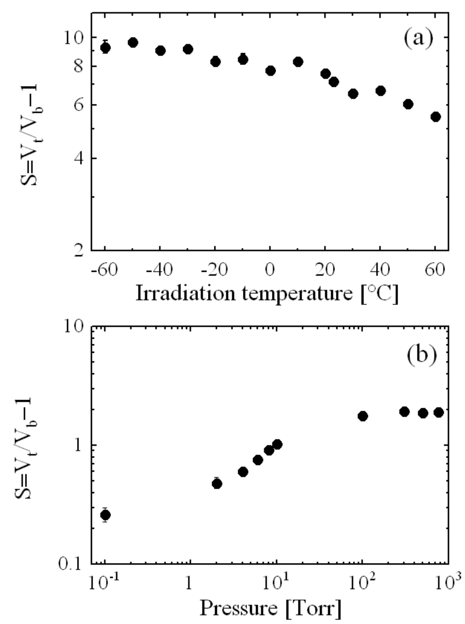

Figure 5: The variation of S in the CR-39 detector for irradiation, (a) temperature and (b) pressure.

CR-39 detectors which were controlled their pressure from 0.1 Torr to 760 Torr were also exposed to Fe beam. Figure 5(b) shows the variation of S in the CR-39 detector for irradiation pressure. It was found that the variation of S was approximately constant in the order of several 100 Torr.

The pressure around the CR-39 detector should be controlled > 100 Torr for balloon experiment.

Novel CR-39 detector with variable detetion threshold

It is necessary to increase the Z/β detection threshold in order to suppress background tracks produced by nuclei lighter than Fe-group ($Z < 30$) with extremely higher flux than UH-GCRs. This is attributed to the high sensitivity for lighter nuclei in the CR-39 detector. By the copolymerization of CR-39 and DAP (diallyl phthalate) with various DAP concentration, we have found that it is possible to control the Z/β detection threshold of copolymers by changing DAP concentration. The optimum DAP concentration is to be approximately 50 $\%$ to discriminate light nulei for $Z/\beta < 30$, as shown in Fig. 6 [11].

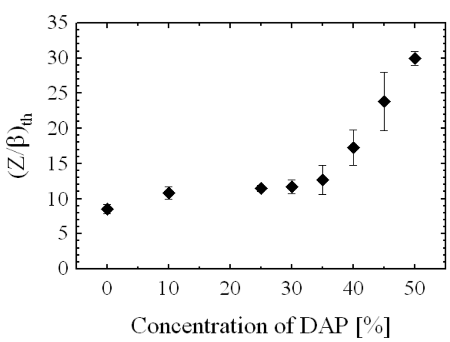

Figure 6: The detection threshold (Z/β)th as a function of DAP concentration in copolymers.

Summary

A cosmic ray detector with large collecting power is required to measure the abundances of elements and their isotopes for $Z \geq 30$. From the point of large exposure area and precise measurement, the use of SSTD is most attractive and challenging to meet scientific objectives within a reasonable budget. It is found from the experimental results that the new CR-39 detector has good charge and mass resolutions of 0.22 cu and 0.22 amu, respectively, the irradiation temperature in the CR-39 detector should be controlled within -45 ± 15°C, and the irradiation pressure should be also controlled higher than 100 Torr. The novel CR-39 detector of copolymerization with DAP of 50 $\%$ concentration could greatly reduce background events from light nulei for $Z/\beta < 30$. It is found that the newly CR-39 detector allows to observe trans-iron nuclei in galactic cosmic rays.

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