Beam experiment at HIMAC secondary beam course for the isotope separation of ultra-heavy nuclei in space

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1. INTRODUCTION

Measurements of isotopic abundances for ultra-heavy nuclei, such as iron-group isotopes, in Galactic Cosmic Rays (GCRs) provide rich information of the origin, acceleration and propagation of GCRs [1, 2]. Since the flux of these particles in GCRs is very low, a large collecting power for the detector with an excellent mass resolution is required to observe the individual isotopes.

Solid state track detectors (SSTD) are very promising for the large-scaled observation of these nuclei in space. We expect that the CR-39 plates have a better resolution of performance, since the plastic track detectors such as CR-39 plates respond essentially to only low energy $\delta$-rays ejected by the “distant collisions” in ionization energy loss [3, 4]. Hayashi et al. [5] reported that the CR-39 plates had a mass resolution of $0.34 \pm 0.14$ amu in rms for iron nuclei by the experiment in 1982. Their experiment has been made to use $^{55}$Fe of rare events from the fragmentation of

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$^{56}$Fe beam in CR-39 plates, therefore they could not obtain the enough statistics to separate the ion masses. However, recently we are able to obtain any secondary particles produced on a target from the primary beam in accelerator. Consequently, it is possible to irradiate independently the isotope beam ($^{56}$Fe) on a same stack of CR-39 sheets. In addition, the properties of CR-39 plate have been improved in its quality and performance of particle identification by improvement of purification method for CR-39 monomer.

Therefore, we started to re-investigate in detail the mass resolution of the CR-39 plates for iron-group isotopes using isotope beams ($^{55}$Fe and $^{56}$Fe). In this paper, we present the isotope beam quality from accelerator in order to make the experiment for the mass separation in CR-39 plates.

2. PRINCIPLE OF MASS IDENTIFICATION BY SSTD

A fast charged particle passing through the SSTD leaves a chemically altered track that is called latent track, which can be exposed by etching in a suitable etchant. The etchant removes material in a very narrow region around the track at a rate ($V_b$), while it removes material from unaffected regions at the bulk etch rate ($V_t$). A conical etch-pit has appeared at SSTD surface as shown in Fig. 1, as consequence of etching. The ratio of track etch rate ($V_t / V_b - 1$) is a function of the 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 [3, 4]. Namely, this criterion for track registration assumes that the $\delta$-rays with energies greater than the cut off energy ($\omega_0$) carry away their energy from the track core region and do not contribute to the latent track formation. For CR-39 plates, the cut off energy ($\omega_0$) has been considered to be 200 eV [6]. Therefore, it is expected that an excellent mass resolution will be achievable in comparison with Si detector, because the statistics fluctuation in energy loss along the etched tracks in CR-39 plate is comparably small.

The ratio of track etch rate ($V_t / V_b - 1$) is a function of the charge and velocity of the incident ion, and the range of the ion with a definite charge at a velocity is proportional to the mass of the ion. In this work, we used the cone-length ($L$), $L = V_t \cdot T$ ($T$ is etching time), of the etch-pits on the each detector, and the residual range ($R$) for the ions. The difference of $R$ between $^{55}$Fe and $^{56}$Fe at the same $L$ is estimated to be 1.8 % by the Benton’s formula [3]. Therefore, the mass difference of the ions will be appeared in the scatter plot of $L$ values and $R$ values (“$L$-$R$” technique [7]) by the trajectory tracing
etch-pits as shown in Fig. 2. In general, this technique is analogous to the $\Delta E-E$ technique in electronic detectors. At the same time, this technique requires substantially so long time to get statistics, that we require the rate of $^{55}$Fe event for the isotope separation of $^{55}$Fe and $^{56}$Fe should be achieved the highest possible percentage in secondary beam.

![Etch-pit geometry of the CR-39 after etching.](image)

Fig. 1 Etch-pit geometry of the CR-39 after etching.

![Schematic drawing of etch-pits in CR-39 sheets.](image)

Fig. 2 Schematic drawing of etch-pits in CR-39 sheets. Cone-length ($L_i$) is defined as the distance between the etched surface and the tip of the etch-pit. Residual range ($R_i$) is the distance from the stopped point that is in a part of spherical end to the center point of the cone-length.
3. EXPERIMENTAL

We have performed the beam experiment using the secondary beam course (SB2 course) in the Heavy Ion Medical Accelerator in Chiba (HIMAC) at National Institute of Radiological Sciences (NIRS). In the SB2 course, the $^{55}$Fe beam was selected from the projectile fragments produced by $^{56}$Fe particles on a target by using the bending magnets and the momentum slits.

The schematic view of experimental set up for particle identification system is given in Fig. 3. Secondary particles produced in the target (Au: 0.333 mm thick) passed through the energy degrader (Al: 3.5 mm central thick), two plastic scintillation counters (0.5 mm thick for each, TOF (time-of-flight) counter) and Si detector (0.325 mm thick, $\Delta E$ counter). The flight path length between the TOF start and stop counter is 10 m. The secondary particles lose their energy depending on the nuclear charge ($Z$) in the energy degrader. The mass number ($A$) and nuclear charge ($Z$) of the secondary particles are identified from the information of velocity and energy loss measured by these detectors. Details for these instruments are described in elsewhere [8, 9].

We have tuned the secondary particles to change the magnetic field of the bending magnets and the width of the momentum slits. At the beginning, we set the momentum ($\Delta P/P$) of 0.5 % to change the width of the slits. We have searched the $B\rho$ parameters of the bending magnets that give the maximum yield of $^{55}$Fe, where $B$ is the magnetic flux intensity and $\rho$ is the curvature radius, while monitoring of the TOF-$\Delta E$ signals. Finally, a stack of CR-39 plates was irradiated to both 460 MeV/n $^{55}$Fe and $^{56}$Fe beam.
4. RESULTS

4.1 Beam quality

Fig. 4 shows the scatter plot of TDC (ch.) and ADC (ch.) that were detected by TOF counters and $\Delta E$ counter. The signals of TDC and ADC correspond to the TOF (ns) and $\Delta E$ (MeV) of the particle, respectively.

![Scatter plot of TDC (ch.) and ADC (ch.)](image)

Figs. 4 The scatter plot of TDC (ch.) and ADC (ch.) for $^{55}$Fe beam.

![Histograms](image)

Fig. 5 (a) The histogram of ADC (ch.), (b) the histogram of TDC (ch.).
Fig. 5(a) shows the histogram of ADC signal. The Fe yield for all events was to be $76.3 \pm 0.6 \%$. TDC signal in Fe region is shown in Fig. 5(b). Besides the $^{55}$Fe, $^{56}$Fe and unknown peaks have been observed. These are the events from the tail of the momentum distribution of $^{56}$Fe (primary beam). The rate of $^{55}$Fe in all Fe events was estimated to be $87.1 \pm 0.7 \%$. As a result, the yield of $^{55}$Fe for all particles was to be about $66.5 \pm 0.5 \%$. This yield has been enough to test the mass separation in CR-39 plates. In addition, the production rate of $^{55}$Fe (secondary) for $^{56}$Fe (primary) was $0.0481 \pm 0.0004 \%$ in this experiment.

We have also compared this production rate to the simulation using the program of LISE++ [10, 11]. This program is now used to calculate the transmission and yields of fragments (fusion residues) produced and collected in a fragment separator. We have calculated the production rate of $^{55}$Fe (secondary) for $^{56}$Fe (primary) under the experimental condition (described above). Calculation results of $\Delta E$ (nuclear charge information) and TOF (nuclear mass information) are shown in Fig. 6(a) and 6(b).

![Fig. 6 (a) Results of calculation for (a) $\Delta E$ (MeV) and (b) TOF (ns) signals.](image)

As for the charge distribution, the experimental result has been reproduced by this calculation. The production rate of $^{55}$Fe was computed to be $0.0126 \%$. This value and the experimental result are in agreement by the factor 4. The result of the production rate for the secondary particles calculated by LISE++ gives an indication of the quality of secondary beam.

### 4.2 Mass resolution for Fe-Isotopes in CR-39 plates

Fig. 7 shows the $L$-$R$ scatter plots for $^{55}$Fe and $^{56}$Fe tracks. We have plotted the measured $L_i$ values for $R_i$, and fitted it to a curve of 6th polynomial function using the
least-square fitting. We have independently obtained the mass distribution for $^{55}\text{Fe}$ and $^{56}\text{Fe}$ ions by assuming each mass value to be $A=55$ and $A=56$, and finally estimated the mass resolution of $\sim 0.28\text{amu}$ in rms for iron-isotopes in CR-39 plates. These procedures are described in detail in Ref. [12]. We have also estimated the contributions of the measured parameter errors to the mass resolution, and discussed about the improvement of the measurement technique in order to eliminate the measurement errors. Finally, we conclude that the mass resolution for iron isotopes in CR-39 plates would be improved to be $\sim 0.20\text{amu}$.

5. FUTURE PROSPECTS

We will perform the beam experiment to evaluate the mass resolutions for the ultra-heavy isotopes of $^{84}\text{Kr}$ and $^{83}\text{Kr}$ ($Z=36$) for several kinds of SSTD not only CR-39 plates but glass detectors etc. in order to find the candidate material(s) for space experiment. In the SB2 course, it is difficult to identify the secondary particles from $^{84}\text{Kr}$ with the resolution of the current detectors in the beam line, since $^{84}\text{Kr}$ is heavier than $^{56}\text{Fe}$. For this reason, we have performed the calculation using LISE++ in order to decide the design of experimental setup for Kr experiment. The flight path length of TOF counters is to be 20 m from 10 m, and the thickness of $\Delta E$ counter is to be 500 $\mu$m from 325 $\mu$m. Fig. 8(a) shows the simulated TOF-$\Delta E$ scatter
plot in case of the previous condition, which the flight path length of TOF counters is 10 m and the thickness of $\Delta E$ counter is 325 $\mu$m. Fig. 8(b) shows the new condition under which the flight path length is 20 m and the thickness of $\Delta E$ counter is 500 $\mu$m. It is found that the secondary particles are well identified under the next condition, as can be seen from Fig. 8(a) and 8(b).

Fig. 8 Simulated TOF-$\Delta E$ scatter plot: (a) the flight path length of TOF counters is 10 m and the thickness of $\Delta E$ counter is 325 $\mu$m, (b) the flight path length of TOF counters is 20 m and the thickness of $\Delta E$ counter is 500 $\mu$m.

Fig. 9(a) and 9(b) show the histograms of $\Delta E$ signals from $^{83}$Kr ($Z=36$) and TOF signals for $^{80}$Br and $^{81}$Br ($Z=35$) in case that the flight path length of TOF counters is 10 m and the thickness of $\Delta E$ counter is 325 $\mu$m, while Fig. 10 (a) and 10(b) show them in case that the flight path length of TOF counters is 20 m and the thickness of $\Delta E$ counter is 500 $\mu$m.

Fig. 9 In case of the flight path length of TOF counters: 10 m and the thickness of $\Delta E$ counter: 325 $\mu$m, (a) the histogram of $\Delta E$ (MeV), (b) the histogram of TOF (ns) for $^{80}$Br and $^{81}$Br.
These histograms were converted to the nuclear charge and mass, as the result, it is found that the charge resolution for Kr will be improved to be $0.24e$ from $0.29e$ and the mass resolution for $^{81}$Br will be improved to be $0.24$amu from $0.53$amu. Therefore, we consider that the detectors at this new condition have enough resolutions to identify the secondary particles for their tuning. We will test the mass separation by SSTD using these ultra-heavy isotope beams.

6. CONCLUSION

The goal of our investigation is the measurement of elemental and isotopic composition for ultra-heavy nuclei in GCRs. The observation of nuclear composition in GCRs covers a wide range of scientific themes including the origin, the stellar nucleosynthesis, the chemical evolution of the galaxy and the history of the interstellar material, and offer new possibilities for the study of the charge particle acceleration and propagation mechanism in space. For this purpose, we have verified the performance of the mass separation for SSTD such as CR-39 plates using $^{55}$Fe and $^{56}$Fe beam at HIMAC-SB2 course. Moreover, we have measured that the yield of $^{55}$Fe for all secondary particles from the reaction of $^{56}$Fe with Au target using TOF and $\Delta E$ counters.
The yield was to be 66.5 ± 0.5 % and the production rate of $^{55}$Fe was also estimated to be 0.0481 ± 0.0004 %. These values were compared with calculation using LISE++. These results agreed approximately with the calculation. We found LISE++ gives a good indication of the quality of secondary beam.

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