Activation Properties of Schottky CdTe Diodes Irradiated by 150 MeV Protons

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***Abstract*— Cadmium Telluride (CdTe), with its high photon absorption efficiency, has been regarded as a promising semiconductor material for the next generation X/γ-ray detectors. In order to apply this device to astrophysics, it is essential to investigate the radiation hardness and background properties induced by cosmic-ray protons in orbit. We irradiated Schottky CdTe diodes and a CdTe block with a beam of mono-energetic (150 MeV) protons. The induced activation in CdTe was measured externally with a germanium detector, and internally with the irradiated CdTe diode itself. We successfully identified most of radioactive isotopes induced mainly via (p, xn) reactions, and confirmed that the activation background level of CdTe diode is sufficiently low in orbit. We compared energy resolution and leakage current before and after the irradiation, and also monitored the signals from a calibration source during the irradiation. There have been no significant degradation. CdTe diodes are tolerant enough to radioactivity in low earth orbit.**

***Index Terms*— CdTe, activation, radiation damage, proton.**

I. INTRODUCTION

ADVANTAGES such as high atomic number ($Z_{\rm Cd} = 48$, $Z_{\rm Te} = 52$) and room temperature operation have made Cadmium Telluride (CdTe) one of the most promising semiconductor materials to detect X-rays and γ-rays (10 keV - 1 MeV) [1]. At the same time, CdTe has inherent disadvantages, such as low mobility and short lifetime of holes. In order to overcome them, various methods have been proposed. One method we have developed is to utilize Indium as an anode electrode to form a Schottky diode [2][3]. By this technique, we can apply a higher bias with a lower leakage current, resulting in a good charge collection efficiency together with a good energy resolution.

CdTe can be applied not only to medical and industrial imaging, but also to detectors for astrophysics. In hard X-rays and soft γ-rays, signals from celestial objects are much weaker, whereas background is much higher than in the soft X-ray band. In order to acquire good signal-to-noise ratio, it is necessary to achieve extremely low background. For this purpose, we have been developing the Hard X-ray Detector for *Astro-E2* satellite, which consists of GSO/BGO phoswich counters and silicon PIN diodes, and characterized by an extremely low background level [4]. In view of next generation detectors, we are developing an improved instrument, utilizing CdTe as the main detector [5][6][7][8].

In order to operate CdTe in a space environment, we cannot neglect the activation background because of its high atomic number. For example, high-energy astronomy satellites launched from Japan will be put into approximately circular orbits with altitudes of $\sim$ 550 km and inclination angles of $\sim$ 30 degrees. In such an inclination of low earth orbit (LEO), the major origin of background is activation induced by cosmic rays, especially geomagnetically trapped protons in the South Atlantic Anomaly (SAA). CdTe is a relatively new material, and its activation properties are not yet understood very well. Therefore, we carried out beam irradiation experiments for CdTe. We utilized Schottky CdTe diodes which are the single crystals grown by the Traveling Heater Method by ACRORAD [2][3][9].

II. BEAM IRRADIATION EXPERIMENT

We irradiated CdTe on two occasions with mono-energetic protons ($\sim$150 MeV). In 0.5 mm thick CdTe diodes, a 150 MeV proton deposits an energy equivalent to 750 keV. Radioactive isotopes are induced in CdTe diodes mainly via (p, xn) reaction, and their decay produces the activation background.

The first beam irradiation experiment was performed on October 5, 2001, at the Heavy-Ion Medical Accelerator in Chiba (HIMAC). We irradiated a 155 MeV H$^+$ beam onto a 0.5 mm thick Schottky diode and a CdTe block, with the size and the irradiation condition given in Table I. The number of protons were directly monitored with two plastic scintillators with sizes of $10\ \rm mm \times 10\ mm \times 1\ mm$, one placed upstream and the other downstream of CdTe. The error in the beam counting is within a factor of 1.5. We estimate the irradiation rate in SAA to be 10^9 protons per year per CdTe diode with a size of $21.5\ \rm mm \times 21.5\ mm \times 0.5\ mm$, where 0.5 mm is the thickness of the detector, assuming that the CdTe is placed inside an active shield made of 6 cm thick BGO scintillator, just like the HXD for *Astro-E2* [10]. The total

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Manuscript received December 2, 2002.

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TABLE I

CONDITIONS OF THE EXPERIMENTS

ID	Beam	Total number of protons	Target size [mm^3]	Activation Measurement
1	155 MeV, H$^+$	1.4×10^{10}	$18 \times 18 \times 18$	Externally (Ge)
2	155 MeV, H$^+$	2.0×10^{10}	$21.5 \times 21.5 \times 0.5$	Internally (CdTe)
3	150 MeV, H$^+$	1.7×10^{10}	$10 \times 10 \times 0.5$	Internally (CdTe)

number of irradiated protons hence corresponds to that to be accumulated in 20 years in an LEO. After the irradiation, we measured activation of the irradiated CdTe block (ID 1) externally using a high purity germanium detector, and that of the irradiated CdTe diode (ID 2) using its own signal. The size we will utilize as an actual detector is large and thin just like ID 2, while the large volume of ID 1 has an advantage in external measurements because of its high counting rate of the activation background. In addition, we compared the energy resolution and leakage current of the CdTe diode (ID 2) before and after the irradiation in order to study radiation damage. We also performed the experiment with a less intense beam, simulating the SAA passage with a small CdTe diode kept in operation. We measured the signals from a calibration isotope (^{241}Am) during and right after the irradiation.

The second beam irradiation experiment was performed on July 30, 2002, at the Research Center for Nuclear Physics (RCNP) in Osaka University in order to study activation background of CdTe with a better energy resolution. We therefore employed a Schottky CdTe diode with a smaller dimension, and exposed it to a 150 MeV proton beam (ID 3 in Table I). In this experiment, we monitored the number of protons scattered by polyethylene film (2 mm thick) with two plastic scintillators, one placed at 25 degree and the other 65 degree off the proton beam. This indirect method, however, failed to derive a precise estimation of total dose. We adopt a total number of protons estimated by comparing the activation background of reference GSO and BGO with that of our experiment utilizing similar size of crystals [10]. The total dose of protons thus estimated corresponds to that for 17 years in an LEO, and comparable to that in the HIMAC experiment. After the irradiation, we measured the activation background spectrum of the CdTe diode using its own signal.

III. ACTIVATION BACKGROUND

A. External Measurements

With a germanium detector, we can detect γ-rays emitted from radiative decays of the induced radioactive isotopes. This allows us to identify individual isotopes, estimate the yields produced, and calculate experimental cross sections.

After the irradiation at HIMAC, we measured 40 keV to 2 MeV spectra of the CdTe block, with a germanium detector having an energy resolution of about 3 keV. We shielded the irradiated CdTe block and the sensor head of the germanium detector with 5 cm thick lead blocks. The obtained spectra are shown in Fig. 1. Compared with the background before the irradiation, the continuum level increased nearly by an order of magnitude, and many emission lines appeared. We have derived the decay curves for major lines, and determined their decay time constants as shown in Figure 2. We have successfully identified ~ 90 % of all line features in the spectra, with radio-isotopes in the mass-number range from 95 to 130, by comparing their center energy and decay time with those in the reference [11]. The results are summarized in Table II. Most of the identified radio-isotopes are induced via (p, xn) or (p, xpyn) reactions.

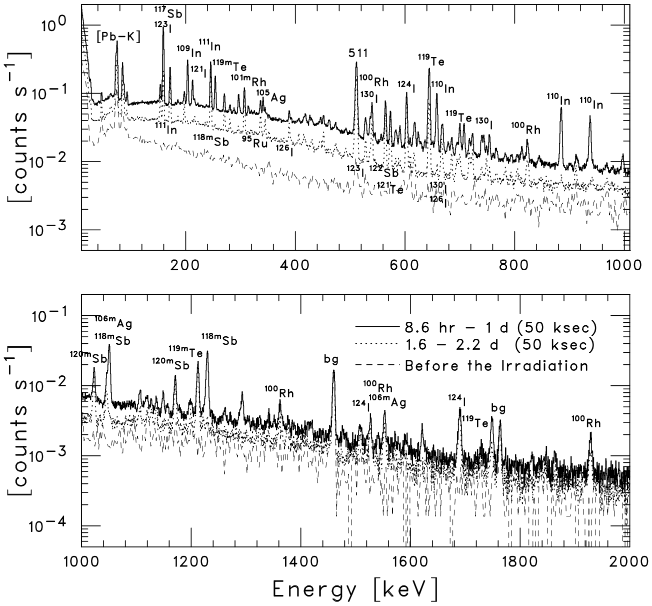

Fig. 1. The spectra of the irradiated CdTe block (ID 1) measured with the germanium detector. The solid and dotted line is the spectrum of radiative background from 8.6 hours to 2.2 days after the irradiation. Major lines with secure identification are labeled. The background before the irradiation is shown with dashed line.

TABLE II

RADIO-ISOTOPES IDENTIFIED VIA EXTERNAL MEASUREMENTS.

Half Life	Isotopes
T < 1 d	^{130}I, ^{129}Sb, ^{128}Sb, ^{123}I, ^{121}I, ^{120}I, ^{119}Te, ^{117}Te, ^{116}Te, ^{116}Sb, ^{115m}In, ^{110}In, ^{109}In, ^{108}In, ^{104}Ag, ^{103}Ag, ^{101}Pd, ^{99m}Rh, ^{95}Ru.
1 d < T < 10 d	^{127}Sb, ^{124}I, ^{122}Sb, ^{120m}Sb, ^{119m}Te ^{111}In, ^{106m}Ag, ^{101m}Rh, ^{100}Rh, ^{97}Ru.
10 d < T	^{129m}Te, ^{127m}Te, ^{126}I, ^{125m}Te, ^{121}Te, ^{105}Ag, ^{99}Rh.

The decay curves also enable us to estimate the yields of

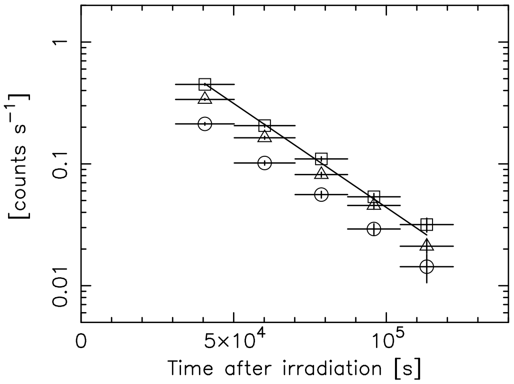

Fig. 2. The decay curves of γ-rays from ^{110}In with the half-life of 4.9 hours. Square shows the 657.8 keV component, triangle 884.7 keV, and circle 937.5 keV, with their relative intensities being 98.3 %, 92.9 % and 68.4 %, respectively [11]. The solid line is the best fit decay curve for the 657.8 keV component. These include the efficiency of the germanium detector.

TABLE III

EXPERIMENTAL AND SEMI-EMPIRICAL CROSS SECTIONS, $\sigma_{\rm exp}$ AND $\sigma_{\rm st}$ [12].

Isotope	$\sigma_{\rm exp}$ [mb]	$\sigma_{\rm st}$ [mb]	Isotope	$\sigma_{\rm exp}$ [mb]	$\sigma_{\rm st}$ [mb]
^{130}I	2.1	1.8	^{119}Te	31	30
^{126}I	36	25	^{117}Sb	29	14
^{124}I	53	38	^{111}In	31	20
^{123}I	54	42	^{110}In	13	24
^{121}I	32	41	^{109}In	28	26
^{121}Te	62	41			

the radioactive isotopes. As shown in Fig. 2, we fitted each measured decay curve with that predicted by the isotope table [11], extrapolated it to obtain the count rate at the beam stop, and then we calculated the experimental cross section, considering efficiency of the germanium detector, absorption by the CdTe block itself and the total number of irradiation protons.

With this experiment, we acquired the data for only one particular proton energy, 150 MeV, while we need to know the effects induced by the spectrum of trapped protons in SAA. Therefore, we will in future calculate the actual activation background with the help of a semi-empirical formula [12], after calibrating it with our measurements. As summarized in Table III, we have confirmed that the semi-empirical cross sections agree, within a factor of two, with the experimental ones derived from our measurements. The largest uncertainty is that in the proton beam intensity in our experiments.

B. Internal Measurements

The α, β and low-energy γ-rays which are stopped inside CdTe can be detected only with the irradiated CdTe itself. Actually, these are to be observed as the radiation background in the space environment. In this section, we present the results from the experiment at RCNP, because of the excellent energy resolution ($\Delta E \sim 2.5$ keV at 122 keV) of the diode (ID 3) used in that experiment. They are consistent with those taken at the HIMAC experiment (ID 2) when considering the different energy resolution ($\Delta E \sim 7$ keV at 122 keV) since their total number and energy of protons are comparable and both of them are with the thickness of 0.5 mm.

At RCNP, after the irradiation, we measured the induced radiation background of the CdTe diode (ID 3) placed in a cave of lead blocks at room temperature with a bias voltage of 300 V. The spectra thus acquired within 1.2 hours of the beam stop are shown in Fig. 3. Characteristic lines and continuum from radiative isotopes are clearly observed. We can see that the continuum increased nearly by three orders of magnitude compared with the background before the irradiation.

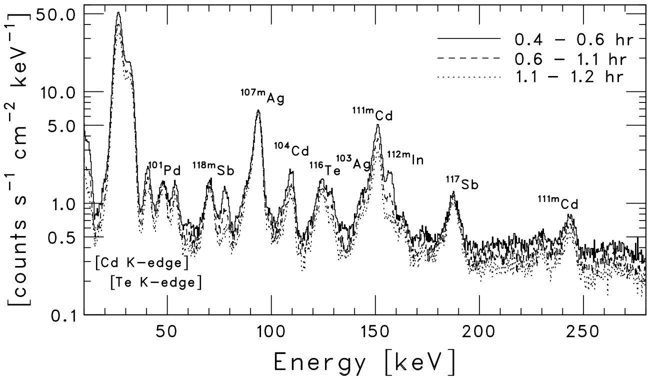

Fig. 3. The spectra measured with the Schottky CdTe diode (ID 3) within 1.2 hours after the irradiation. The background level before the irradiation is about 3×10^{-4} counts s^{-1} cm^{-2} keV^{-1}.

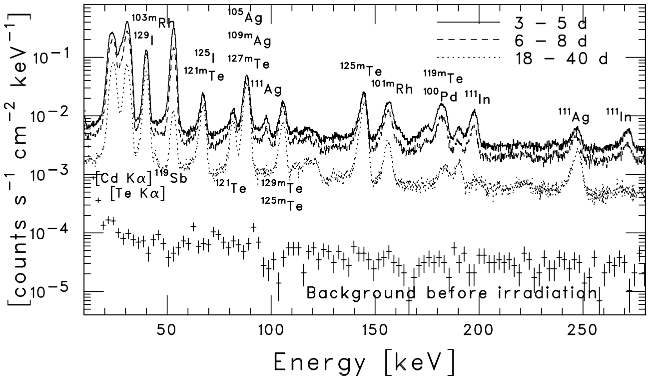

Fig. 4. The spectra measured with the Schottky CdTe diode (ID 3) from 3 to 40 days after the irradiation. The background before the irradiation is shown with crosses.

Using the spectra, we have identified short-lived radioisotopes, in the way similar to that used in the external measurements. The obtained identifications are summarized in Table IV. In these internally measured spectra, we notice meta stable isotopes, so-called 'isomer', were also produced; for example, $^{111\rm m}$Cd (T = 49 minutes), which is a meta stable isotope of ^{111}Cd.

In order to measure the activation background internally with a better energy resolution, we brought the irradiated CdTe (ID 3) back to our laboratory, and continuously measured at -20 °C. We put the CdTe diode inside an Al case, and placed it in the bottom of a well-type CsI scintillator. They were covered with 0.2 cm thick Sn sheet and 5 cm thick lead blocks, and placed in a thermostatic chamber. The bias voltage was

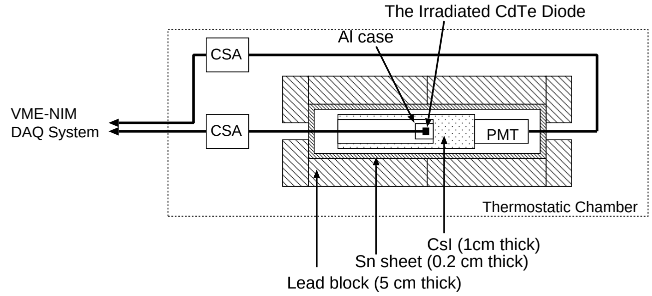

Fig. 5. The measurement setup of the CdTe diode (ID 3) at our laboratory. The thermostatic chamber was filled with dry air and kept at $-20\,^{\circ}$C. We utilized charge sensitive amplifiers by CLEAR-PULSE.

TABLE IV
RADIO-ISOTOPES IDENTIFIED WITHIN THE CDTE DIODE.

Half Life	Isotopes
T $<$ 1 h	$^{130\mathrm{m}}$I, $^{113\mathrm{m}}$Sn, $^{111\mathrm{m}}$Cd, ^{104}Cd.
1 h $<$ T $<$ 1 d	^{117}Sb, ^{116}Te, $^{107\mathrm{m}}$Ag.
1 d $<$ T $<$ 10 d	$^{119\mathrm{m}}$Te, $^{118\mathrm{m}}$Sb, ^{111}In, ^{111}Ag, $^{101\mathrm{m}}$Rh, ^{100}Pd.
10 d $<$ T	$^{129\mathrm{m}}$Te, $^{127\mathrm{m}}$Te, ^{125}I, $^{125\mathrm{m}}$Te, $^{121\mathrm{m}}$Te, $^{109\mathrm{m}}$Ag, ^{105}Ag, $^{103\mathrm{m}}$Rh.

set at 400 V. This measurement setup is shown in Fig. 5. The spectra obtained from 3 to 40 days after the irradiation are shown in Fig. 4. After 40 days, the continuum decreased to a level which is an order of magnitude higher than the background before the irradiation. Based on the center energies and decay curves, and the results from the measurement with the germanium detector, we successfully identified almost all noticeable line features in these spectra with those radio-isotopes of which the half-lives are longer than 2 days. The results are summarized in Table IV.

By scaling the experimental data, we roughly estimated the activation background level in a space environment. Since the number of irradiation protons in our experiments corresponds to a total dose over 17 years in an LEO, the background due to the fast-decay isotopes, accumulated in orbit typically for one day, will reach only 5×10^{-5} counts s^{-1} cm^{-2} keV^{-1}. In contrast, on the time scale of a few years, which is the general life of a satellite, the long-lived components will be accumulated and not negligible. Scaling the background later than 18 days after the irradiation in Fig. 4, we estimate the annual increase in the activation background as 4×10^{-5} counts s^{-1} cm^{-2} keV^{-1}, which is rather mild. Furthermore, the improved energy resolution of the CdTe diode (e.g., ID 4) will be of great help in removing the activation emission lines from the spectra to be obtained in orbit, as has been demonstrated by our internal measurements. Thus, the activation background of CdTe diodes is expected to be sufficiently low to be operated in an LEO.

To achieve a still higher sensitivity, we need to reduce the activation background beyond the level described above. One promising way is to utilize anti-coincidence, e.g., by reading out signals from the CsI scintillator used in our internal measurement (Fig. 5). If at least one γ-ray is emitted in the radioactive decay, and it escapes out of the CdTe diode and is detected by the CsI scintillator, the event can be rejected by anti-coincidence. In the same way, continuum components created by γ-ray Compton scattering in CdTe can be suppressed. In order to examine such a possibility, we actually read out simultaneously the signals from the CsI scintillator in Fig. 5 with a photomultiplier tube. Then, as shown in Fig. 6, the continuum has almost been halved, and some lines have been successfully eliminated. This means that the activation background can be decreased efficiently with an active shield. However, this method cannot suppress the continuum caused by β-rays; unmodeled time variations in such continuum components will ultimately limit the sensitivity of our LEO observations. It is therefore necessary to identify those radio-isotopes which significantly contribute to the activation continuum, and include them correctly in the background modeling.

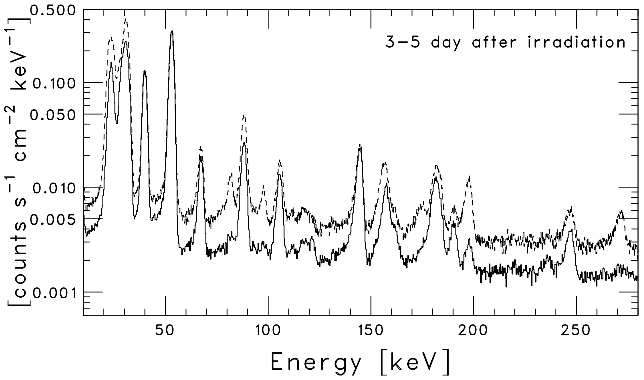

Fig. 6. The spectra measured with the Schottky CdTe diode (ID 4) from 3 to 5 days after the irradiation. The spectrum without the anti-coincidence rejection is shown with a dashed line, while that after the rejection with a solid line.

IV. RADIATION DAMAGE

Semiconductor detectors, such as Si and Ge, are generally subject to damage when exposed to a large quantity of radiation. With our experiment at HIMAC, we measured leakage current and energy resolution of the Schottky CdTe diode (ID 2) before and after the irradiation with the flux of 8.9×10^{5} cm^{-1} s^{-1} and the duration of 4900 s, which corresponds to an absorbed dose of 0.2 krad.

The leakage current significantly increased by ~ 50 %, immediately after the irradiation, but it recovered within an hour. The dependence of the degradation on the irradiation rate was demonstrated by a previous work [13]. Considering that the counting rate of the irradiated protons was more than 10^{3} times higher than that expected in SAA, we expect the increase in leakage current negligible in actual LEO conditions. The spectra of a calibration isotope, ^{57}Co, were obtained before and after the irradiation, yielding the energy resolution of 3.9 keV and 3.8 keV at 122 keV, respectively. There have been no detectable degradation.

In addition, we monitored the signals from a calibration source, ^{241}Am, during the irradiation, in order to study whether we can normally operate CdTe diodes under exposure

TABLE V

ENERGY RESOLUTION UNDER THE LOW RATE IRRADIATION.

Time [min]	Beam	Flux [protons s^{-1} cm^{-2}]	ΔE at 59.5 keV
0	OFF	–	2.0 keV
8	ON	4.0×10^3	2.0 keV
13	ON	4.0×10^3	2.0 keV
19	OFF	–	1.9 keV
23	ON	5.3×10^4	2.1 keV
28	ON	5.3×10^4	2.1 keV
33	OFF	–	2.0 keV

to protons in the SAA condition. We actually irradiated a small CdTe diode ($2\ \mathrm{mm} \times 2\ \mathrm{mm} \times 0.5\ \mathrm{mm}$) at a rate of 10 and 100 times higher than in SAA, as described in Table V, while continuously supplying a bias of 300 V to the CdTe diode. The time sequence of the experiment and the measured energy resolution on each time are also summarized in Table V. We confirmed that the resolution did not degrade significantly. It is hence possible to operate CdTe diodes during and right after passage through the SAA.

In the previous two works of ohmic detectors ($4\ \mathrm{mm} \times 4\ \mathrm{mm} \times 2\ \mathrm{mm}$) and Schottky diodes ($2\ \mathrm{mm} \times 2\ \mathrm{mm} \times 1\ \mathrm{mm}$), the degradation had been observed [13] [14]. The former work adopted the detectors with the different electrode structure from our detectors, and the latter had much higher irradiation rate ($10^9\ \mathrm{protons}\ \mathrm{s}^{-1}\ \mathrm{cm}^{-2}$). In our experiments, we confirmed the CdTe diodes have not been degraded significantly under the condition in an LEO.

V. CONCLUSION

Through these beam irradiation experiments, we have confirmed that the Schottky CdTe diode is tolerant to the radioactivity to be encountered in an LEO.

The experiment has also allowed us to quantitatively evaluate the activation of CdTe induced by proton bombardments. The results generally agree with the prediction of the semi-empirical formula for (p, xn) reactions. A first-cut estimate suggests that the activation of CdTe in an LEO is relatively low, thus making it a promising material for use in space observatories.

Our next task is to establish a quantitative model for the background spectrum of activated CdTe diodes. For this purpose, we may utilize the semi-empirical formula, under a necessary calibration by our external and internal measurements. The model goodness may be evaluated by studying whether it can reproduce the internally-measured background spectra of the irradiate Schottky CdTe diode, including both lines and continuum.

ACKNOWLEDGMENT

The authors would like to thank the HIMAC staff, especially Prof. T. Murakami and Dr. H. Iwata, for their support during the preparation and the experiment. This experiment was performed under the Program No. 13P130 at the HIMAC. We would also like to express our gratitude to the RCNP staff, especially Prof. K. Hatanaka and Dr. H. Fujita, for their continuous support throughout the experiment. This experiment was performed under the Program No. R42 at the RCNP.

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