Measurement of proton-induced target fragmentation cross-sections in carbon

K.Matsushita^{a,b}, T.Nishio^b, S.Tanaka^c, M.Tsuneda^d, A.Sugiura^e, K.Ieki^a

^aDepartment of Physics, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshimaku, Tokyo, 171-8501, Japan

^bInstitute of Biomedical & Health Sciences, Hiroshima University, 1-2-3 Minamiku Kasumi, Hiroshima City, Hiroshima, 734-8551, Japan

^cDepartment of Nuclear Engineering and Management School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo, 113-8654, Japan

^dGraduate School of Biomedical & Health Sciences, Hiroshima University, 1-2-3 Minamiku Kasumi, Hiroshima City, Hiroshima, 734-8551, Japan

^eNational Institute of Radiological Sciences, Heavy Particle Medical Science Center Physical Engineering, 4-9-1 Inageku Anagawa, Chiba City, Chiba, 263-8555

Abstract

In proton therapy, positron emitter nuclei are generated via the target nuclear fragmentation reactions between irradiated proton and nuclei constituting a human body. The proton-irradiated volume can be confirmed with measurement of annihilation γ -rays from the generated positron emitter nuclei. To achieve the high accuracy of proton therapy, in vivo dosimetry i.e., evaluation of the irradiated dose during the treatment is important. To convert the measured activity distribution to irradiated dose, cross section data for positron emitter production is necessary, which is currently insufficient in the treatment area. The purpose of this study is to collect cross section data of $^{12}\text{C}(p, pn)^{11}\text{C}$ and $^{12}\text{C}(p, p2n)^{10}\text{C}$ reactions between the incident proton and carbon nuclei, which are important target nuclear fragmentation reactions, to estimate the range and exposure dose distribution in the patient's body. Using Planar-type PET capable of measuring annihilation γ -rays at high positional resolution and thick polyethylene target, we measured cross section data in continuous wide energy range. The cross section of $^{12}\text{C}(p, pn)^{11}\text{C}$ is in good agreement with existing experimental data. The cross section of $^{12}\text{C}(p, p2n)^{10}\text{C}$ is reported for the first data in the low energy range of 67.6 - 10.5 MeV near the Bragg-peak of proton beam.

Keywords: Cross section, Positron emitter, Fragmentation reaction, PET, Proton therapy

1. Introduction

Utilizing a high dose concentration near the end of proton range, a marked therapeutic effect is expected for proton therapy by applying a high dose to a tumor while minimizing the dose for normal tissue. However, if the proton beam is not accurately applied to the tumor, the cure rate may decrease and important organs may be impaired. To take maximum advantage of the superior characteristics of proton therapy, it is important to verify the range and irradiated region of the therapeutic proton beam irradiated to the patient's tumor. To confirm the proton beam-irradiated region in patients treated with proton therapy, a method has been proposed [1]: On-line PET imaging with the annihilation γ -ray generated through the target nuclear fragmentation reactions between a therapeutic proton beam and the elements of which a patient's body is composed. The proton beam-irradiated region in the patient's body is observed by measuring the intensity and position of annihilation γ -rays emitted by the generated positron emitters using PET. To achieve the high accuracy of proton therapy with an improved dose concentration of the proton beam in a tumor, it is important to observe the distribution of the dose to which the tumor is exposed in the irradiated region, that is, to realize in vivo dosimetry. To do so, it is necessary to determine the relation between the position and intensity distribution of annihilation γ -rays and physical reaction with the exposure dose [2].

The most important component for the above investigation is the cross section for positron emitters production within the energy range of 250 MeV or lower used in proton therapy [3]. The human body is mainly composed of hydrogen, carbon, oxygen, and calcium nuclei, and the production cross section of positron emitters (^{10}C , ^{11}C , ^{13}N , ^{14}O , ^{15}O , ^{38}K , ^{38}Ca , and ^{39}Ca) generated between the 3 elements excluding hydrogen and incident proton nucleus are important to estimate the range and exposure dose distribution in the patient's body. The cross section of ^{11}C , ^{15}O and ^{13}N were measured at several proton energy[4–22], however, those quantity and accuracy is insufficient yet. The cross section of ^{10}C , ^{14}O , ^{38}K and ^{39}Ca were measured only a few point[11, 23, 24]. And the cross section of ^{38}Ca is not yet measured in energy region of proton therapy. Thus, the amount and accuracy of cross section at the energy range currently used in proton therapy are insufficient, so far.

The reactions between incident proton and carbon nuclei, $^{12}\text{C}(p, pn)^{11}\text{C}$ and $^{12}\text{C}(p, p2n)^{10}\text{C}$, in the patient's body are important to estimate the exposure dose distribution in human adipose, soft, and bone tissues. In previous studies, the cross section of the $^{12}\text{C}(p, pn)^{11}\text{C}$ reaction was measured at several proton energy with intervals of several MeV [4–13].

Email address: k_matsushita@rikkyo.ac.jp (K.Matsushita)

The cross section starts to increase at about 20 MeV, peaks at about 30-40 MeV, and then slowly decreases. However, it varies in the range of 80-100 mb at about 30-40 MeV, showing wide variation among experiments, in 2 patterns for the energy range of 50-200 MeV. The cross section of the $^{12}\text{C}(p, pn)^{11}\text{C}$ reaction derived by measuring annihilation γ -ray activity after target irradiation using PET for medical use have recently been reported, in which the experimental value was about 70-80 mb, being slightly lower than those in other reports, although the data were collected only at only 4 proton beam energy of 32.5, 47.5, 59.4, and 69.6 MeV [18]. For the $^{12}\text{C}(p, p2n)^{10}\text{C}$ reaction, the cross section have been reported at only 2 proton energies of 143 and 155 MeV [11, 23].

The purpose of this study is to collect consistent cross section data of multiple reactions, i.e. $^{12}\text{C}(p, pn)^{11}\text{C}$ and $^{12}\text{C}(p, p2n)^{10}\text{C}$ reactions between the incident proton and carbon nuclei, which are important to estimate the range and exposure dose distribution in the patient's body, in a wide energy range with a single irradiation.

2. Materials and methods

A proton beam at a nominal value of 70 MeV supplied by the AVF930 cyclotron of the National Institute of Radiological Sciences was used. The target was irradiated to proton beams, and annihilation γ -rays emitted by positron emitters generated in the target were measured. The cross section was derived from the measured decay curve and activity distribution in the depth direction. A $8 \times 8 \times 12\text{-cm}^3$ high-density polyethylene ($(\text{CH}_2)_n$ 0.95 g/cm³) block was used as a target. Since the range of a proton beam with a nominal energy of 70 MeV in polyethylene is about 4 cm, all protons incident to the target stopped and the cross section for whole energy region was measured. Recoil movement of the positron emitter after the reaction is order of μm and is ignored.

2.1. PET system with planar-type detector head

For activity measurement, planar-type PET was used. In a detector unit, 36 blocks of Position Sensitive PMT (R8520-00-C12, HAMAMATSU PHOTONICS) equipped with $2 \times 2 \times 20\text{-mm}^3$ BGO scintillators positioned in an 11×10 arrangement were placed on a $167.2 \times 165\text{ mm}^2$ plane. The distance between the detectors could be changed continuously from 30 to 90 cm and the maximum event coincidence rate was about 4 kcps/cm². The positional resolution was about 3 mm at FWHM, The detection efficiency was about 1%, and absolute value of decay number on PET was calibrated with a Na-22 point source ($3.22\text{ MBq} \pm 3\%$).

2.2. Proton beam irradiation and activity measurement (experimental setup)

To measure cross section, it is necessary to measure the number of incident protons and the generated positron emitters. Incident protons were measured using by a beam monitor and number of generated positron emitter measured using by the planar-type PET. However, the PET and the beam monitor could not be set together on the beam line due to space limitation. Hence two experimental setups were prepared using 2 beam courses : wobbler beam irradiation as setup 1 (Fig.1-a) and pencil beam irradiation as setup 2 (Fig.1-b).

In the wobbler course, we have employed the spread-out flat proton beam with 30-50 nA currents by using the wobbler magnets. The beam passing through the $10 \times 10\text{ cm}^2$ lead window was collimated to be 2 cm in diameter with a brass collimator. The collimated beam was then irradiated to the carbon target for 3-15 sec. The number of incident particles(N_{0_setup1}) was directly evaluated using a beam monitor set on the beam line. This beam monitor was calibrated beforehand using an ionization chamber(PTW Type-23343). The in the target in setup 1, N_{0_setup1} , was determined using the following equation:

$$N_{0_setup1} = \frac{D \cdot S \cdot \rho}{dE/dx} \quad (1)$$

where D represents the exposure dose [Gy = J/kg] measured by the beam monitor, S represents the irradiated area by collimator, ρ represents the polyethylene density, and dE/dx represents proton beam energy loss per unit length in polyethylene. In each measurement, the statistical error of the beam monitor was less than 1.5%, and the systematic error of dose-energy conversion is estimated to be about 2.6%. Upon irradiation at 50 nA for 15 sec, the exposure dose was about $53.83 \pm 0.39\text{ Gy}$, and the number of incident particles was $N_{0_setup1} = 1.02 \times 10^{11}$ ($\pm 0.7\% \pm 2.6\%$) (statistical and systematic error). After proton irradiation, the target was immediately moved to PET detectors for measuring the activity during 15-30 min. Since the time for movement to PET after the completion of irradiation took several minutes, ^{10}C with a half-life of 19.29 sec had decayed out when the target was placed in PET. Therefore, we measure only ^{11}C activity in setup 1.

The measurement of $^{10}\text{C} + ^{11}\text{C}$ activity was performed at the pencil beam course. In the pencil beam course, PET can be set on the beam line, but as there is no beam monitor, the number of incident particles(N_{0_setup2}) could not be directly measured. A proton beam was applied at 5-10 nA for a short time (about 3 sec), and activity of $^{10}\text{C} + ^{11}\text{C}$ was measured for 15-30 min from initiation of beam irradiation. The size of beam was measured by the fluorescent screen, and it's size was $5\text{ mm} \times 8\text{ mm}$ (FWHM). The number of incident particles in setup 2 was determined by comparing the amount of ^{11}C generated and the number of incident particles obtained in the measurement at setup 1.

Fig. 1: Schematic drawing of setup (a) setup 1: The beam monitor measures the irradiation dose. The target was moved for the PET measurement after the irradiation. (b) setup 2: The PET for activity measurement can be set on the beam line during the beam irradiation. Right bottom picture shows an actual setup.

2.3. Technique for determining cross section

As the proton energy is directly related to the reaction position in the target, the measured activity distribution in the depth shows the energy dependence of the cross section. The energy dependent cross section was derived using following equation:

$$\Delta N_1 = \sigma n N_0 \Delta x \quad (2)$$

where N_1, N_0, σ, n , and x represent the generated amount of the target nucleus (^{10}C and ^{11}C), the number of incident particles, the cross section, the nuclear density of the target, and the target thickness (measured each position in PET), respectively. The position was converted into the proton energy using the range-energy relation. The nuclear density of the polyethylene target, n , is calculated from the density of polyethylene with Avogadro's constant and the molecular weight of polyethylene (CH_2)_n.

3. Results

3.1. Measured activity

The activity distributions and decay curves measured in setups 1 and 2 are shown in Fig.2 and Fig.3, respectively. The measured activity is shown as a function of position from the target surface (depth) in Fig.2(a) and Fig.3(a) for setup 1 and setup 2, respectively. The distribution is almost flat and decreases near the end of range. The activity is also shown as a function of time after the irradiation in Fig.2(b) and Fig.3(b). They represent the decay of ^{11}C for setup 1 and $^{10}\text{C} + ^{11}\text{C}$ for setup 2.

The overall counts of activity was 1,948,875 upon irradiation at 50 nA for 15 sec in setup 1 and 2,195,814 upon irradiation at 10 nA for 3 sec in setup 2, respectively. The amounts of generated ^{11}C and ^{10}C were determined from the measured activity distribution and decay curve.

3.2. Amount of incident protons and produced positron emitters

3.2.1. Amount of positron emitters generated in setup 1

The amount of positron emitter generated in setup 1, N_{1_setup1} , is determined as follows: Using a Na-22 point source (3.22 MBq $\pm$ 3%), the relation between the decay number and measured activity was obtained as shown in Fig.4. The decay number after the irradiation, dN , was determined using a calibration line as shown in Fig.4.

The initial number of positron emitter of PET measurement was then calculated from the decay number during measurement. The number of positron emitters at time t , $N(t)$, is expressed as

$$N(t) = N_{1_mes} \left(\frac{1}{2} \right)^{\frac{t}{T}} \quad (3)$$

N_{1_mes} represents the number of positron emitters at the initiation of PET measurement and T represents the half-life. Designating the start time of PET measurement after completion of irradiation as t_1 and the duration of PET measurement as t_2 , the relation between the number of positron emitters in the target, N_{1_stop} , and dN at the completion of beam irradiation is expressed as

$$dN = N_{1_stop} \left(\frac{1}{2} \right)^{\frac{t_1}{T}} \left(1 - \left(\frac{1}{2} \right)^{\frac{t_2}{T}} \right) \quad (4)$$

Fig. 2: Measurement result for setup 1:(a) Activity distribution in the depth. (b) Measured activity decay curve for polyethylene target taken after proton beam irradiation

Fig. 3: Measurement result for setup 2:(a) Depth distribution of the activity. (b) Measured decay curve for polyethylene target activity starting from initiation of beam irradiation. Solid lines are results of fitting to Equation.6

Fig. 4: Relation between decay number and activity. Decay number during measurement was determined from this correlation.

The t_1 is determined from the time for movement to PET after the completion of irradiation. It appears as background between end of the irradiation and start of measurement as shown in Fig.2-(b). The t_2 is the duration time of PET measurement as shown in Fig.2-(b).

As there were no fluctuation in the proton beam intensity provided by the cyclotron over time during target irradiation, the intensity can be regarded as a constant. Accordingly, the positron emitter generation rate during irradiation is also regarded as constant. Designating the beam irradiation time as t_0 , the amount of positron emitters generated during beam irradiation, N_1 , is expressed, adopting N_{1_stop} in consideration of attenuation during irradiation, as [1]:

$$N_{1_stop} = N_{1_setup1} \frac{T}{t_0 \ln 2} \left(1 - \left(\frac{1}{2} \right)^{\frac{t_0}{T}} \right) \quad (5)$$

Applying this equation, the amount of ^{11}C among overall activity generated by irradiation at 50 nA for 15 sec was obtained to be $N_{1_setup1} = 1.13 \times 10^9 (\pm 1.9\% \pm 3.0\%)$ (statistical and systematic error).

3.2.2. Amount of positron emitters generated in setup 2

The amounts of ^{10}C and ^{11}C generated in setup 2 are presented as their ratio by fitting the measured decay curve to the following equation:

$$N_{act}(z, t) = B_{T_{long}}(z) \left(\frac{1}{2} \right)^{\frac{t}{T_{long}}} + B_{T_{short}}(z) \left(\frac{1}{2} \right)^{\frac{t}{T_{short}}} \quad (6)$$

$N_{act}(z, t)$ represents activity (cps) at depth z and time t . T_{long}, T_{short} represents the half-life of ^{11}C (1218.94 sec) and ^{10}C (19.28 sec), $B_{T_{long}}(z), B_{T_{short}}(z)$ represents the activity (cps) of ^{11}C and ^{10}C at a depth of z and $t=0$, respectively. The $^{11}\text{C}/^{10}\text{C}$ ratio was determined by fitting in overall activity, and the amounts of generated ^{11}C and ^{10}C were calculated using the relationship between the activity and decay number and Equation(6). When irradiated at 10 nA for 3 sec, the ratio was $^{11}\text{C}/^{10}\text{C} = 25.9 \pm 3.7\%$, and the generated amounts among the overall activity were $N_{1_11C_setup2} = 1.76 \times 10^9 (\pm 5.3\% \pm 3.0\%)$ (statistical and systematic error) and $N_{1_10C_setup2} = 5.41 \times 10^7 (\pm 6.7\% \pm 3.0\%)$ (statistical and systematic error).

3.2.3. Effect of scattering in polyethylene target

Scattering of annihilation γ -rays in polyethylene should be taken into consideration. The amount of annihilation γ -rays incident into PET was compared in a simulation calculating using Geant4 [25, 26] which considered with generated position, with or without polyethylene. The reduction factor was found to be 1.45-1.67 (setup 1) and 1.38-1.53 (setup 2).

3.2.4. Number of incident protons for setup 2

The number of incident particles in setup 2 was determined by comparing the amount of ^{11}C generated and the number of incident particles obtained in the measurement at setup 1. The number of incident particles in setup 2 was derived from the number of incident particles/generated amount ratio ($N_{1_setup1}/N_{0_setup1}$) = $1.09 \times 10^{-2} (\pm 0.7\% \pm 2.6\%)$ (statistical and systematic error). The error of the ratio determined by fitting was less than 3.9% in each measurement. The statistical and systematic errors of the ratio in setup 1 were 0.7% and about 2.6%, respectively. Upon irradiation at 10 nA for 3 sec, the number of incident particles in setup 2 was $N_{0_setup2} = 1.28 \times 10^{11} (\pm 5.4\% \pm 2.6\%)$ (statistical and systematic error).

3.3. Derivation of incident proton energy

The incident proton energy was determined so as to reproduce measured Percent Depth Dose (PDD) in Geant4 (Fig.5). PDD was measured by using the water-phantom and pinpoint ionization chamber. The error of measured PDD is less than 1%. The incident energy was found to be 70.8 ± 0.5 MeV. The range in polyethylene at this energy is 41.6 ± 0.9 mm.

Fig. 5: Relative depth doses for the measurement (marked x) and Geant4 simulation (line) are compared. The incident proton energy was determined so as to reproduce this relation.

3.4. Derivation of cross section

3.4.1. The $^{12}\text{C}(p, pn)^{11}\text{C}$ reaction

Due to the finite position resolution of the PET, the activity near target surface could not be measured correctly. Therefore, the activity at a depth of 3.3 mm or greater from the target surface were used and the cross section of 67.6-10 MeV energy was derived. In each measurement, the statistical error was less than 2.4% and systematic error was about 3.9%. Systematic error is evaluated as a root of sum of squares of systematic errors of N_0 and N_1 . In Fig.6, the cross section is shown as a function of proton energy. The horizontal axis of the measured activity distribution in the depth direction (i.e. reaction position) was converted to proton energy and then the activity was converted to the cross section. The cross section of ^{11}C in setup 2 was also derived. They has the same energy dependence and agree with each other within the error as shown in Fig.6-(a). The data summary of setup 1 and 2 is shown in Fig.6-(b). The influence of flux variation due to the positional resolution of the PET is also take into account (see Discussion for detail).

Fig. 6: Measured cross section:(a) Measured cross section in setup 1 and 2. They has the same energy dependence and agree with each other within the error (b)Comparison with previous studies. The present work is shown as an average of setup 1 and setup 2.

Those data can be classified in the group of a lower cross section such as Measday *et al.*, Gauvin, Akagi *et al.*, and Panofsky *et al.* [8, 9, 13, 18], and higher cross section such as Whitehead *et al.*, Hintz *et al.*, and Aamodt *et al.* [4, 10, 12]. Also, the errors in both energy and cross section of some data (Gauvin, Whitehead *et al.*, Hintz *et al.* and Aamodt *et al.*) were not given in the EXFOR database. Our results were in good agreement with the lower cross section group. The tendency of cross section was similar with the higher data group. The cross section values were about 10 mb smaller than the higher data group. The obtained cross section are summarized in Table.1.

3.4.2. The $^{12}\text{C}(p, p2n)^{10}\text{C}$ reaction

The cross section of $^{12}\text{C}(p, pn)^{11}\text{C}$ in setup 1 and setup 2 was consistent within the error. Therefore it indicates the validity of this method, and it is possible to determine the cross section of $^{12}\text{C}(p, p2n)^{10}\text{C}$ reaction simultaneously. In Fig.7, the cross section is shown as a function of proton energy. The proton energy was converted from the activity position and designated as horizontal axis. In each measurement, the statistical error was less than 6.7% and systematic error was about 3.9%. Systematic error is a root of sum of squares of systematic errors of N_0 and N_1 . The $^{11}\text{C}/^{10}\text{C}$ ratio at each depth was determined by fitting the measured decay curve using Equation(6). The determined cross section are

Fig. 7: Measured cross-section of $^{12}\text{C}(p, p2n)^{10}\text{C}$

summarized in Table.1.

4. Discussion

The cross section data of positron emitters production between the incident proton and carbon nuclei in a wide energy range and plural reactions with a single irradiation will allow to estimate the range and exposure dose contribution in the patient's body. The cross section of $^{12}\text{C}(p, pn)^{11}\text{C}$ reaction were in good agreement with previous experimental data. It starts to increase at about 20 MeV, peaks at about 30-40 MeV. We measured the first data of cross section of $^{12}\text{C}(p, p2n)^{10}\text{C}$ reaction in this energy region. It makes a peak at around 60 MeV. $^{12}\text{C}(p, p2n)^{10}\text{C}$ reaction is necessary to take strip one more neutron than $^{12}\text{C}(p, pn)^{11}\text{C}$ reaction. Thus it is reasonable to suppose that makes a peak at higher energy than $^{12}\text{C}(p, pn)^{11}\text{C}$ reaction. The order of cross section is appropriate in comparison with the Clegg *et al.* and Valentin *et al.*[11, 23]. However, there are three issues in errors to be addressed: 1) error of reaction position - proton energy conversion which is attributable to the finite resolution of PET and energy straggling of the proton, 2) systematic error which is attributable to attenuation of flux within the range of positional resolution of PET, and 3) error due to the contamination of secondary protons.

As the proton energy is directly related to the reaction position in the target, in the analysis, the reaction position measured with PET was converted into the proton energy. The finite resolution of PET and energy straggling of the proton, induce the energy distribution. This effect was evaluated with Geant4 simulation. For the case of fixed point of 36.3 mm, the energy distribution was found to be asymmetrical in energy as shown in Fig.8. So we adopted the energy as the mean value of the distribution and the error was estimated from the $\pm 34\%$ area of the distribution, which corresponds to 1 sigma value of equivalent gaussian distribution(see Fig.8). This error is shown as the horizontal error bars in Fig.6 and Fig.7. The error on the low-energy side was larger.

Fig. 8: The depth(i.e. reaction points)-energy relation was evaluated with Geant4 simulation. Due to the finite resolution of PET and energy straggling, the distribution is found to be asymmetrical. This figure shows the energy distribution up to 23 MeV (corresponding to 36.3 mm depth reaction point).

Proton flux rapidly decreased near the range, and flux was evaluated using the position. Therefore this attenuation of flux within the limits of positional resolution of PET become the systematic error of the flux correction. Proton flux rapidly decrease a near the range. Although this position dependence of the flux is already corrected in the evaluation of the number of the incident particles, finite position resolution of the PET induces a systematic error of N_0 at low energy. Since it is difficult to reduce the error at low energy due to the positional resolution and energy straggling, it may be necessary to use a low energy proton beam to measure the cross section in the low energy region. However, as the cross section is small near the Bragg peak in the therapeutic region, and is less important, the measurement of this study may be sufficient. Elevation of detection efficiency is also necessary to reduce the statistical error, and this can be improved using 2 planar-type PETs simultaneously.

The rates of secondary protons and other secondary particles among the number of incident protons in a simulation using Geant4. Secondary particles other than secondary protons accounted for less than 10%, with no particles emitting 511 keV γ -rays. Thus, the measurements was not influenced by secondary particles. Proton energy loss in polyethylene with a specific thickness was determined using Geant4 in the process of converting the exposure dose for the target to the number of incident particles, but there was 2.6% deviation due to energy fluctuation, which influenced the results as a systematic error. It may be necessary to use a monitor directly measuring the number of incident particles, such as a Faraday cup.

5. Conclusion

The cross section for positron emitters production by the reaction between nuclei constituting the human body and proton was measured to confirm the irradiated region and range in proton therapy and achieve in vivo dosimetry. It was clarified that the series of the cross section from the incidence to the stopping of a proton can be measured using PET. The influence of PET positional-resolution-dependent error is substantial at low energy, markedly influencing the final result. The findings of the $^{12}\text{C}(p, pn)^{11}\text{C}$ reaction were consistent with existing data. Regarding the $^{12}\text{C}(p, p2n)^{10}\text{C}$ reaction, the cross section was successfully measured in an energy range not previously reported.

This study clarified that the cross section of positron emitter generation by the target nuclear fragmentation reaction between the nucleus of carbon, an important element constituting the human body, and proton can be measured using PET. This method may also be applicable for measurement of the cross section for other elements constituting the human body (^{16}O , ^{40}Ca).

Tables

Tables of the measured cross section describe this section. Cross section is presented as $\sigma \pm \delta\sigma_{ran} \pm \delta\sigma_{sys}$.

Energy[MeV]	δE_{higher}	δE_{lower}	$^{12}C(p, pn)^{11}C$ [mb]	$^{12}C(p, p2n)^{10}C$ [mb]
67.61	1.01	1.16	$73.47 \pm 0.56 \pm 2.90$	$2.56 \pm 0.26 \pm 0.10$
66.50	1.04	1.18	$74.58 \pm 0.57 \pm 2.95$	$2.66 \pm 0.27 \pm 0.11$
65.39	1.04	1.24	$74.49 \pm 0.57 \pm 2.95$	$2.68 \pm 0.27 \pm 0.11$
64.26	1.07	1.28	$75.58 \pm 0.58 \pm 2.99$	$2.78 \pm 0.28 \pm 0.11$
63.12	1.09	1.31	$76.54 \pm 0.58 \pm 3.03$	$2.79 \pm 0.28 \pm 0.11$
61.97	1.11	1.36	$78.69 \pm 0.60 \pm 3.11$	$2.91 \pm 0.29 \pm 0.12$
60.80	1.12	1.40	$82.20 \pm 0.62 \pm 3.25$	$2.89 \pm 0.29 \pm 0.11$
59.62	1.14	1.44	$83.11 \pm 0.63 \pm 3.29$	$3.01 \pm 0.30 \pm 0.12$
58.42	1.16	1.48	$82.10 \pm 0.62 \pm 3.25$	$2.93 \pm 0.29 \pm 0.12$
57.20	1.19	1.52	$81.91 \pm 0.62 \pm 3.24$	$2.84 \pm 0.28 \pm 0.11$
55.96	1.20	1.57	$82.54 \pm 0.63 \pm 3.26$	$2.87 \pm 0.28 \pm 0.11$
54.70	1.24	1.60	$83.54 \pm 0.63 \pm 3.30$	$2.82 \pm 0.28 \pm 0.11$
53.42	1.26	1.64	$83.40 \pm 0.63 \pm 3.30$	$2.82 \pm 0.28 \pm 0.11$
52.12	1.29	1.68	$83.98 \pm 0.64 \pm 3.32$	$2.73 \pm 0.27 \pm 0.11$
50.80	1.32	1.70	$84.51 \pm 0.64 \pm 3.34$	$2.65 \pm 0.26 \pm 0.10$
49.44	1.36	1.73	$83.67 \pm 0.63 \pm 3.31$	$2.65 \pm 0.26 \pm 0.10$
48.06	1.39	1.79	$83.75 \pm 0.63 \pm 3.31$	$2.54 \pm 0.24 \pm 0.10$
46.65	1.43	1.83	$83.46 \pm 0.63 \pm 3.30$	$2.48 \pm 0.24 \pm 0.10$
45.20	1.47	1.84	$86.58 \pm 0.66 \pm 3.43$	$2.38 \pm 0.23 \pm 0.09$
43.72	1.51	1.90	$87.08 \pm 0.66 \pm 3.45$	$2.26 \pm 0.22 \pm 0.09$
42.19	1.56	1.93	$86.69 \pm 0.66 \pm 3.43$	$2.23 \pm 0.21 \pm 0.09$
40.62	1.62	1.98	$87.53 \pm 0.66 \pm 3.47$	$2.07 \pm 0.20 \pm 0.08$
39.00	1.68	2.03	$84.75 \pm 0.64 \pm 3.36$	$1.96 \pm 0.19 \pm 0.08$
37.32	1.75	2.10	$85.11 \pm 0.65 \pm 3.37$	$1.79 \pm 0.17 \pm 0.07$
35.58	1.82	2.18	$81.65 \pm 0.62 \pm 3.24$	$1.59 \pm 0.15 \pm 0.06$
33.76	1.90	2.28	$78.06 \pm 0.60 \pm 3.10$	$1.37 \pm 0.13 \pm 0.05$
31.85	2.00	2.40	$70.69 \pm 0.54 \pm 2.81$	$1.17 \pm 0.11 \pm 0.05$
29.84	2.10	2.54	$59.56 \pm 0.47 \pm 2.37$	$0.98 \pm 0.09 \pm 0.04$
27.71	2.23	2.70	$45.06 \pm 0.36 \pm 1.79$	$0.80 \pm 0.08 \pm 0.03$
25.44	2.39	2.94	$29.08 \pm 0.25 \pm 1.16$	$0.60 \pm 0.06 \pm 0.02$
22.98	2.57	3.25	$15.76 \pm 0.15 \pm 0.64$	$0.47 \pm 0.06 \pm 0.02$
20.28	2.83	3.64	$8.23 \pm 0.09 \pm 0.37$	$0.34 \pm 0.04 \pm 0.02$
17.24	3.18	4.26	$4.23 \pm 0.05 \pm 0.65$	$0.23 \pm 0.03 \pm 0.04$
13.79	3.63	5.18	$2.86 \pm 0.04 \pm 1.37$	$0.19 \pm 0.02 \pm 0.10$
10.53	3.92	5.17	$2.29 \pm 0.04 \pm 2.05$	$0.05 \pm 0.00 \pm 0.05$

Table 1: Cross section of $^{12}C(p, pn)^{11}C$ and $^{12}C(p, p2n)^{10}C$ by this experiment

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