Cross sections for the production of ^{11}C in C targets by ^{12}C at relativistic energies

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Cross sections for the production of ^{11}C in C targets were measured using ^{12}C ions with energies of 0.40, 1.05, and 2.1 GeV/nucleon. These measurements were undertaken for the purpose of establishing primary standards for use as beam monitors. Annihilation radiation from $^{11}C(T_{1/2}=20.34$ min) was counted using a large volume NaI detector. Cross sections of 63.5±0.5, 57.4±0.4, and 60.9±0.6 mb, respectively, were obtained for 0.40, 1.05, and 2.1 GeV/nucleon ^{12}C beams. The results are compared with earlier measurements of the cross sections in C targets using relativistic proton and α beams. Good agreement is found between the cross sections measured in this work and a simple Glauber theory.

[NUCLEAR REACTIONS $^{12}C(^{12}C,X)^{11}C$: $E(^{12}C)=0.40$, 1.05, and 2.1 GeV/nucleon; measured σ.]

I. INTRODUCTION

In experiments with relativistic heavy ions there is a need for reliable absolute cross section measurements for a number of different projectiles over a range of energies for use as beam intensity monitors. The reaction chosen as a standard should result in a final nucleus which is relatively insensitive to production by secondary particles which are copiously produced in relativistic heavy ion reactions. A program is underway at the Bevalac accelerator to determine a set of precise absolute cross sections for the production of ^{11}C from C targets using projectiles of p, ^{4}He, ^{12}C, ^{20}Ne, or ^{40}Ar with energies of 0.40, 1.05, and 2.1 GeV/nucleon.

Absolute cross section measurements for beam energies above 400 MeV/nucleon have been carried out previously in this laboratory for the production of ^{11}C from C targets using p and α beams, and are reported elsewhere.[1,2] We present in this work the results of absolute cross section measurements of ^{11}C from C targets [$^{12}C(^{12}C,X)^{11}C$] at beam energies of 0.40, 1.05, and 2.1 GeV/nucleon. In Sec. II the measurements are described and in Sec. III the results are reported and interpreted in terms of a simple Glauber model.

II. MEASUREMENT OF CROSS SECTIONS

The irradiations described below were carried out in the external ^{12}C beam of the Bevalac accelerator in three stages. First, a low intensity run was made in which the individual beam particles were counted with plastic scintillators and ^{11}C activity was produced in a thick graphite block. Next, the ^{11}C activity in a 0.159 cm thick polystyrene target was determined relative to a digitial readout ion chamber beam monitor in a high-intensity run. Finally, the ^{11}C activity in a thick graphite block was also determined at high beam intensity relative to the ion chamber. The $^{12}C(^{12}C,X)^{11}C$ cross section was calculated using data from the three runs.

A. Low intensity runs

For the low intensity runs, the element furthest upstream consisted of an ion chamber followed successively by a pair of plastic scintillators each 0.32 cm thick and a graphie target with a 5.08×5.08 cm area and a thickness of 2.54 cm. The large target was needed in order to produce enough ^{11}C activity to count using the NaI detector. Because of this large thickness, corrections for secondary reactions were significant, therefore additional high-intensity runs on both thin and thick targets were needed in order to obtain a precise value for the cross section.

The beam was first tuned at an intensity of 10^8 to 10^9 particles per pulse. Upstream and downstream multiwire proportional chambers were monitored to verify that the beam spot was no greater than 1 cm in diameter and that its size was approximately constant between the normal chamber positions. The beam spill time was then increased to ∼1 sec and its intensity reduced to averages ranging from 2.5×10^4 to 1.5×10^5 particles/pulse to minimize pileup in the scintillators. The ^{12}C particles in the beam were counted by observing both singles and coincident events in the two scintillators. The three readings were always the same to within 1%. In three separate low intensity runs, lasting from 10 to 30 min each, the beam intensity was varied by almost a factor of 10, but the ratio of scintillator counts to the ^{11}C activity in the graphite blocks remained constant, indicating that pileup in the scintillators was negligible.

B. High intensity runs

In-beam elements for the first of a pair of high-intensity runs were only the monitoring ion chamber, followed by a thin polystyrene target for ^{11}C production. The target consisted of a disk 3.81 cm diam inside a close-fitting annular ring with an outer diameter of 7.62 cm, both of 0.159 cm thickness. Polystyrene was chosen for the thin target material to minimize diffusion of ^{11}C out of the targets. Polystyrene, $(C_8H_8)_x$, is assumed to contain 92.26% carbon by weight. We have adopted the convention that the carbon in all target materials is assumed to be 100% ^{12}C (although the natural abundance of ^{12}C is 98.9%). Irradiation times for these and other high intensity runs ranged from 1 to 5 min, using beam intensities of about 10^9 particles per pulse. Less than 1% of the ^{11}C activity was found in the outer ring of the target assembly confirming the accuracy of beam-target alignment.

The second high intensity run was carried out using the same in-beam elements as were used for the low intensity runs. The ^{11}C activity in the graphite block from this run was compared to the ^{11}C activity in the thin polystyrene target from the previous run, via the relative monitor readings from the ion chamber, to establish an absolute detection efficiency for the NaI measurement of ^{11}C in the thick graphite block.

After irradiation, the yield of ^{11}C was determined by counting annihilation radiation using a NaI(Tl) detector 20.3 in diameter and 10.2 cm thick. The large diameter of the NaI crystal minimized corrections due to the radial distribution of the ^{11}C activity to the extent that they were negligible. Polystyrene targets were counted sandwiched between two square Cu plates 0.0625 cm thick by 7.62 cm on a side, to stop all positrons in a localized volume. It was not necessary to use these Cu plates when counting the thick graphite targets.

The ^{11}C activity was determined from a minimum of 5 counts lasting from 1 to 10 min and covering a total time span of at least one ^{11}C half-life. All data were collected by a multichannel pulse-height analyzer (PHA) system that was stabilized by a digitial gain stabilizer locked to the 511-keV peak. The only radionuclide observed other than ^{11}C was ^{7}Be($T_{1/2}=53.3$ d). The ^{7}Be correction was less than 0.001%. Corrections for variations of the beam intensity during irradiation were made for the ^{11}C activity. These corrections were determined by recording counts from either the ion chamber or scintillation counter at least once every minute during the irradiation period.

C. Previous calibrations

1. NaI(Tl) crystal γ-spectrometer system

The absolute detection efficiency of this γ-spectrometer system was determined for a range of thin polystyrene targets. Accurately machined polystyrene-base plastic scintillators were used as targets for ^{11}C production. The scintillators were all 3.81 cm in diameter and ranged from 0.159 cm to 0.636 cm in thickness. High-energy protons, deuterons, and alphas in beams with profiles that varied from as small as 1 cm diam to greater than the target diameter were directed onto each target.

^{11}C decay rate data were taken in the format of multichannel PHA singles spectra with both the NaI(Tl) crystal detector and with the scintillator mounted directly on a high-stability photomultiplier tube. In both cases a minimum of 10^6 counts were accumulated in the regions of interest from at least five sequential counts as follows: for the NaI system, in the 511 keV annihilation radiation peak using a gain-stabilized operating mode in the PHA system; for the scintillator-photomultiplier system, at a fixed threshold determined by repeated reference to the position of the 59.5 keV peak from ^{241}Am, in calibration runs that were interspersed with data runs. The absolute detection efficiency of each scintillator for internal ^{11}C positron decay was also determined by using an auxiliary NaI(Tl) crystal γ-spectrometer system in a coincidence scheme in which the γ gates came only from the 511 keV total absorption peak.

This absolute plastic scintillator efficiency value, when combined with the two singles-only measurements, permitted the accurate determination of the absolute efficiency of the NaI γ spectrometer for each scintillator thickness. The absolute detection efficiency of the NaI γ spectrometer for ^{11}C decay in the 0.159 cm thick polystyrene targets used in the present experiment was measured to be 0.484 ± 0.0005 by the procedure just described. The relative efficiency of the gain-stabilized NaI(Tl) γ spectrometer to an IAEA-certified ^{137}Cs source was also established at this time. It has been maintained ever since at the 0.05% level (one standard deviation in counting data). The ^{137}Cs measurement is repeated at least one time during each cross section measurement sequence.

2. Thick graphite blocks

The thick graphite blocks, 2.54 cm thick by 5.08 cm on a side, were calibrated by in-beam irradiations, since blocks of identical dimensions can vary in density by as much as 5%. Each block (eight blocks total) was placed behind a precisely machined polystyrene block of identical cross sectional area and irradiated with protons at the Bevatron. Each object was counted on the gain-stabilized NaI(Tl) γ spectrometer, to obtain a total of at least 10^6 counts in the 511 keV peak from five or more sequential countings. Comparisons were then made in decay-corrected ^{11}C activities of polystyrene and graphite pairs, to generate a correction factor for each graphite block.

Among the graphite blocks used in this experiment, no correction factor was greater than 3%. No correlation was observed between graphite block correction factors and values for the measured ^{11}C production cross sections.

III. RESULTS AND DISCUSSION

The cross sections determined in this work for the ^{12}C(^{12}C,X)^{11}C reaction are given in Table I. For each beam energy the individual cross sections determined from the low intensity runs are given along with average cross sections. The statistical error in the cross section arises almost entirely from counting of the ^{11}C activity in the graphite blocks and was always less than 2.0%. One class of systematic errors results from the variation of various parameters from run to run at a given energy.

TABLE I. Cross sections for the $^{12}C(^{12}C,X)^{11}C$ reaction.

^{12}C beam energy (GeV/nucleon)	Average beam intensity (ions/pulse)	Cross section[a] (mb)	Mean cross section (mb)
0.40	2.5×10^4	63.6 ± 1.2	
0.40	7.3×10^4	63.2 ± 0.9	63.5 ± 0.5
0.40	1.2×10^5	63.7 ± 0.8	
1.05	4.0×10^4	57.2 ± 0.8	
1.05	9.0×10^4	57.4 ± 0.6	57.4 ± 0.4
1.05	1.2×10^5	57.6 ± 0.6	
2.10	4.7×10^4	60.9 ± 0.9	60.9 ± 0.6
2.10	1.5×10^5	60.9 ± 0.7	

[a]Measurements at 0.4, 1.05, and 2.10 GeV/nucleon were carried out in the same beam line using the same equipment.

They include shifting of beam position, variations in placement and angle of the targets, and losses in counting ^{12}C ions due to pileup or coincidence problems. Several runs were performed at each energy and the variation between them was less than 1.5% (within counting statistics) indicating that errors of the above type were less than 1.5%.

Another class of systematic errors involve beam counting and production of ^{11}C by secondary particles other than ^{12}C ions. In order to minimize these effects the beam was stopped far downstream and no runs were accepted where obstruction of the beam image was observed on a Polaroid photograph. The run with the thin polystyrene target also minimized secondary corrections. The effects of secondary particles cancel to some degree since counting of these particles by the in-beam scintillator tends to reduce the measured cross section, whereas production of ^{11}C in the targets tends to increase the cross section. The errors for the $^{12}C(^{12}C,X)^{11}C$ reaction cross sections quoted in Table I reflect only statistical errors. We do not know the exact magnitude for the sytematic errors discussed above but estimate that they are no larger than those for the statistical errors. The overall error for the measurements should then be less than 3%.

The cross section for the $^{12}C(^{12}C,X)^{11}C$ reaction as a function of ^{12}C beam energy is shown in Fig. 1. The results are compared with similar data for the $^{12}C(^{4}He,X)^{11}C$ reaction[2,3] and the $^{12}C(p,X)^{11}C$ reaction.[1,4–6] The earlier data for $^{12}C(p,X)^{11}C$ has been summarized in a review article by Cumming[7] and recently the $^{12}C(p,X)^{11}C$ cross section has been determined[8,9] at 0.8 GeV. For each projectile the cross section is a little higher at 0.4 GeV/nucleon but appears to have essentially reached a plateau above 1 GeV/nucleon. The results obtained for the $^{12}C(^{4}He,X)^{11}C$ reaction from 160 to 700 MeV/nucleon by Radin *et al.*[3] are in good agreement with values obtained in this laboratory[2] for the same reaction between 0.4 and 2.1 GeV/nucleon.

It is interesting to compare our cross sections for the $^{12}C(^{12}C,X)^{11}C$ reaction where we measure the yield of ^{11}C produced in the target with the corresponding reaction $^{12}C(^{12}C,^{11}C)X$, where the yield of ^{11}C produced by fragmentation of the ^{12}C projectile was measured. The projectile fragmentation cross sections have been measured by Lindstrom *et al.*[10] to be 44.7 ± 2.8 and 46.5 ± 2.3 mb, respectively, for beam energies of 1.05 and 2.10 GeV/nucleon compared to our values for target fragmentation of 57.4 ± 0.4 and 60.9 ± 0.6 mb, respectively. One might expect the cross sections to be the same, since the target and projectile fragmentation processes are symmetric. We have no explanation for this difference at the present time.

In Fig. 2 we compare measured and calculated cross sections for the production of ^{11}C from ^{12}C targets through target fragmentation by different projectiles at 1 GeV/nucleon incident laboratory energy. Measured values for protons at 0.8 GeV are also included since the cross sections at 0.8 and 1.0 GeV are expected to be about the same. The calculation is based primarily on a simple Glauber picture for the nuclear processes, but a coherent electromagnetic dissociation process based on the measured photoneutron cross section for ^{12}C is included. In addition the Glauber picture is corrected for important fi-

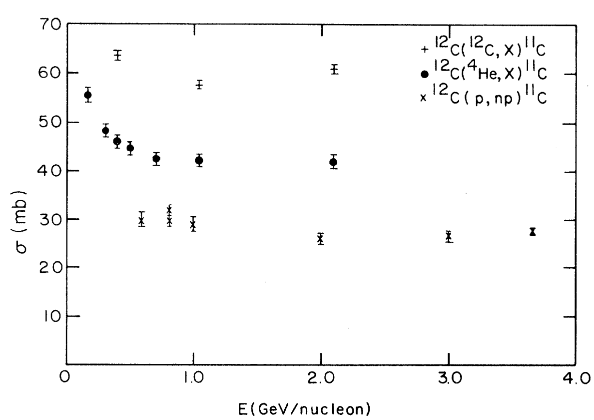

FIG. 1. Excitation function for ^{11}C production by various projectiles on ^{12}C with energies between 0.4 and 4 GeV/nucleon. +, $^{12}C(^{12}C,X)^{11}C$, this work; ●, $^{12}C(^{4}He,X)^{11}C$, Refs. 2 and 3; ×, $^{12}C(p,X)^{11}C$ values at 0.59, 0.8, 1.0, 2.0, 3.0, and 3.66 GeV from Refs. 1, 4–6, 8, and 9.

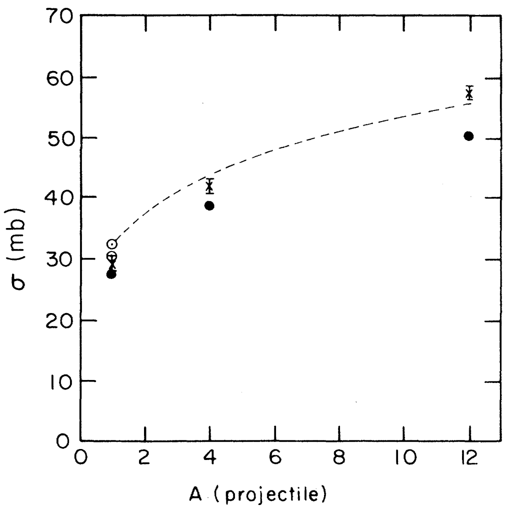

FIG. 2. Comparison of cross sections for ^{11}C production by various projectiles of energy 1 GeV/nucleon with a Glauber theory including final state interactions. ×, experimental values from Refs. 5 and 2 and this work; ⊙, experimental values for the ^{12}C(p,X)^{11}C reaction at 0.8 GeV from Refs. 8 and 9; ●, Glauber calculation.

nal state interactions when the struck target neutron recoils through the residual ^{11}C nucleus causing additional nucleon knockout. The Glauber result, even when reduced by the final state interactions, dominates the calculated results shown here since the electromagnetic dissociation process does not exceed a few percent of the total.

The agreement between the Glauber calculation and the experimental data is quite good if the more recent values[8,9] for the ^{12}C(p,X)^{11}C cross sections at 0.8 GeV are used except that the theoretical values are too low by about 10%. An approximate "renormalized" theoretical curve is shown as a dashed line in Fig. 2. The above deviation is easily within the error associated with the absolute normalization which is discussed in more detail in a forthcoming publication[11] describing the Glauber calculation.

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