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Cross sections for the production of ^{11}C in C targets by ^{20}Ne and ^{56}Fe at relativistic energies

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Cross sections for the reactions $^{12}C(^{20}Ne,X)^{11}C$ and $^{12}C(^{56}Fe,X)^{11}C$ were measured using 1.05 GeV/nucleon ^{20}Ne and 1.7 GeV/nucleon ^{56}Fe ions. Annihilation radiation from ^{11}C was counted using a large volume NaI(Tl) detector. Values of 80.4 ± 1.9 mb and 99.5 ± 1.1 mb were obtained for ^{20}Ne and ^{56}Fe, respectively. The results are compared with earlier measurements of ^{11}C production from C targets using relativistic p, ^4He, and ^{12}C projectiles. The $^{12}C(RHI,X)^{11}C$ cross sections are well described by a linear transport model, but are not in agreement with the predictions of strong factorization.

I. INTRODUCTION

There is a need for reliable absolute cross section measurements for a variety of different relativistic projectiles and energies. The cross sections can then be used as beam intensity monitors in relativistic heavy ion (RHI) reactions. A program is underway at the Bevalac accelerator to determine a set of precise absolute cross sections for the $^{12}C(RHI,X)^{11}C$ reaction. This reaction was chosen since the final nucleus ^{11}C is relatively insensitive to production by the secondary particles copiously produced in RHI reactions. Cross section measurements on p, ^4He, and ^{12}C projectiles have been reported previously.[1–3] We report in this work on cross sections for the $^{12}C(^{20}Ne,X)^{11}C$ and $^{12}C(^{56}Fe,X)^{11}C$ reactions at 1.05 and 1.7 GeV/nucleon, respectively. Results for all $^{12}C(RHI,X)^{11}C$ cross sections measured are interpreted in terms of a linear transport model in which geometric considerations have been incorporated.

II. MEASUREMENT OF CROSS SECTIONS

The cross section measurements were carried out in external RHI beams from the Bevalac accelerator in three stages. First a low intensity run was carried out in which the beam particles were counted with a scintillator telescope pair. Both singles and coincident events were monitored and the two singles and coincidence rates differed by less than 1%. The ^{11}C activity from a 2.54 cm thick graphite block was also measured. The above ^{11}C measurement was not suitable for determination of the $^{12}C(RHI,X)^{11}C$ cross section due to production of ^{11}C from secondary reactions produced in the target. It was thus necessary to determine the ^{11}C activity produced in a thin polystyrene target (0.159 cm thick) relative to an ion chamber monitor in a high-intensity run. Finally a bridge was needed to link the ^{11}C activity produced in the thick graphite block in the low intensity run to the ion chamber reading from the high intensity run. This was provided by a third run at high beam intensity in which the ^{11}C activity in a thick graphite block was determined relative to an ion chamber reading.

The experimental procedures and target configurations used in this work were almost identical to those used previously[3] in measuring $^{12}C(^{12}C,X)^{11}C$ cross sections and will not be repeated in detail. For the low intensity runs the beam was tuned at intensities of 10^7 to 10^9 particles/pulse, and the demand was imposed that the beam spot be less than 1 cm in diameter. The beam spill time was next increased to ~1 sec and its intensity reduced to about 10^4 to 10^5 particles/pulse. The low intensity runs were typically 10 to 20 min each. Subsequently, high intensity runs were carried out with beam intensities ranging from 10^8 particles/pulse for ^{20}Ne to 10^7 particles/pulse for ^{56}Fe. The ^{11}C activity produced in the polystyrene or graphite blocks was determined by counting annhiliation radiation using a large well-calibrated NaI(Tl) detector. The irradiation and counting procedures and NaI(Tl) system have been described in detail previously.[3]

III. RESULTS AND DISCUSSION

The cross sections measured in this work for the $^{12}C(^{20}Ne,X)^{11}C$ and $^{12}C(^{56}Fe,X)^{11}C$ reactions are given in Table I. The individual cross sections are those determined in the low intensity runs but corrected by the thin-thick ratios as discussed in Sec. II. The mean cross sections are also given. The errors in the individual cross sections are almost entirely from counting of the ^{11}C activity in the graphite blocks and are purely statistical in nature. The mean cross section was determined from a weighted average of the individual measurements using the statistical errors as weighting factors. The error of the

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

Projectile	Beam energy (GeV/nucleon)	Average beam intensity (ions/pulse)	Cross section[a] (mb)	Mean cross section[b] (mb)
^{20}Ne	1.05	4.1×10^{4}	79.0 ± 0.4	80.4 ± 1.9
^{20}Ne	1.05	1.7×10^{5}	81.7 ± 0.4	
^{56}Fe	1.7	6.6×10^{3}	99.3 ± 1.4	
^{56}Fe	1.7	1.6×10^{4}	98.7 ± 0.4	99.5 ± 1.1
^{56}Fe	1.7	5.7×10^{4}	100.8 ± 0.5	

[a]Errors are statistical only.
[b]See the text for explanation of mean cross section and its error.

mean cross section was the standard deviation as determined by statistical methods.[4] Systematic errors arising in this experiment have been discussed in detail earlier.[3] We do not know the exact magnitude of the systematic errors but estimate them to be no larger than the statistical errors. The overall error for the measurement should be less than 3%.

In a previous paper[3] we noted the discrepancy between our target fragmentation cross sections for the $^{12}C(^{12}C,X)^{11}C$ reaction and the lower values obtained for cross sections for the projectile fragmentation reaction $^{12}C(^{12}C,^{11}C)X$ by Olsen *et al.*[5] One might expect the cross sections to be the same, since the one-neutron removal target and projectile fragmentation processes are symmetric. This discrepancy persists for higher Z projectiles or targets. This can be seen by a comparison of our cross sections of 80.4 ± 1.9 mb and 99.5 ± 1.1 mb for the $^{12}C(^{20}_{10}Ne,X)^{11}C$ and $^{12}C(^{56}_{26}Fe,X)^{11}C$ target fragmentation processes, respectively, compared to values[5] of 59.5 ± 3.1 mb and 81.4 ± 6.3 mb for the $^{27}_{13}Al(^{12}C,^{11}C)X$ and $_{29}Cu(^{12}C,^{11}C)X$ projectile fragmentation processes, respectively, using 2.1 GeV/nucleon ^{12}C.

The cross section for the reaction $^{12}C(RHI,X)^{11}C$ as a function of projectile mass from ^{1}H to ^{56}Fe is shown in Fig. 1 for the highest measured projectile energies ranging from 1.05 to 2.1 GeV/nucleon. It has been established that the concept of limiting fragmentation (cross section constant with energy) is approximately correct above 1.0 GeV/nucleon for one-neutron out processes in target fragmentation ranging from ^{12}C to ^{197}Au targets.[1–3,6]

In Table II measured $^{12}C(RHI,X)^{11}C$ cross sections are compared with calculated values. The calculated total cross section consisted of two parts representing nuclear and electromagnetic interactions, respectively. The nuclear interaction was calculated using a semiclassical linear transport model which is an extension of the soft spheres model[7] that has been successful in the calculation of total reaction cross sections and their energy dependence for heavy ions at relativistic energies. The probability of a single nucleon-nucleon collision during the transport of a projectile through the ^{12}C target is calculated as a function of impact parameter. Interactions only with the target "valence" nucleons are considered since just their removal leaves the particle-bound residue, ^{11}C. In-

TABLE II. Comparison of measured $^{12}C(RHI,X)^{11}C$ cross sections with one-neutron removal calculations.

Projectile	Beam energy (GeV/nucleon)	Cross section (mb)	Calculated cross section (mb) σ_{nucl}[a]	σ_{ED}	σ_{total}
^{1}H[b]	0.8	30.0 ± 1.1	31.0	0.02	31.0
	0.8	32.0 ± 1.0	31.0	0.02	31.0
	1.0	29.0 ± 1.3	31.8	0.02	31.8
	2.0	26.0 ± 0.9	31.8	0.02	31.8
^{4}He[c]	1.05	42.5 ± 1.1	54.6	0.07	54.7
^{12}C[d]	1.05	57.4 ± 0.4[f]	79.3	0.46	79.8
	2.1	60.9 ± 0.6[f]	79.3	0.57	79.9
^{20}Ne[e]	1.05	80.4 ± 1.9	93.5	1.15	94.7
^{56}Fe[e]	1.7	99.5 ± 1.1	107.2	7.40	114.6

[a]Normalized to average ^{1}H-induced reactions at 800 MeV.
[b]Reference 13.
[c]Reference 2.
[d]Reference 3.
[e]This work.
[f]Errors are statistical only.

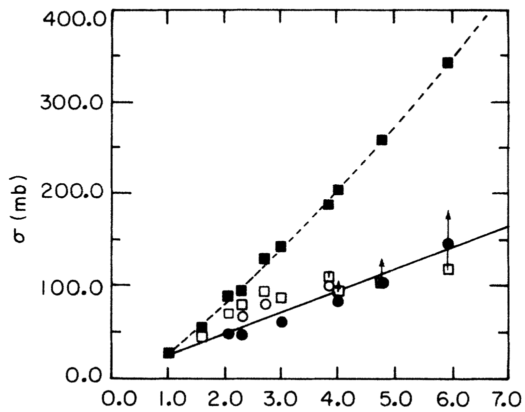

FIG. 1. Cross sections for the ^{12}C(RHI,X)^{11}C reaction for various projectiles with energies at ~2 GeV/nucleon are shown as open circles. The complete list of projectile energies and the corresponding cross sections are given in Table II. Also shown for comparison as closed circles are the projectile fragmentation cross sections for production of ^{11}C from 2.1 GeV/nucleon ^{12}C from Ref. 5. The open squares represent the neutron knockout cross sections from ^{12}C for various spectators normalized to hydrogen and calculated according to the linear transport model. The arrows represent the additional contribution to ^{12}C fragmentation due to ED from spectators with $A \geq 56$. The ED contribution for spectators with smaller A was less than 3 mb and is thus not shown in the figure. The solid line approximates the observed trend. Closed squares (which do not include ED contributions) are the neutron knockout cross sections normalized to hydrogen calculated according to the predictions of factorization and approximated by the dashed curve.

tegration over impact parameter yields a single-collision inclusive cross section that is directly proportional to the ^{11}C production cross section. Ratios of calculated values for different projectiles relative to that for a proton where electromagnetic dissociation (ED) is negligible allows neglect of nuclear structure details and the consequential avoidance of superfluous uncertainties. The single collision model results are compared to experiment in Fig. 1 along with the predictions of strong factorization[8] in which the ^{12}C(RHI,X)^{11}C cross section is proportional to the total reaction cross section for the RHI with ^{12}C.

Electromagnetic dissociation (ED),[9,10] a purely electromagnetic process, also contributes to one-neutron removal reactions induced by relativistic heavy ions. The Weizsäcker-Williams method[11] was used to calculate σ_{ED}. The necessary ^{12}C(γ,n)^{11}C cross sections were obtained from the National Bureau of Standards Digital DATA Library.[12] The calculational procedure has been described in a previous paper.[10] The ED contribution is essentially negligible (less than 1.5 mb) for light projectiles but becomes appreciable for ^{56}Fe projectiles in ^{12}C target fragmentation and Cu targets in ^{12}C projectile fragmentation.

As can be seen from Fig. 1 the agreement is satisfactory between the experimental data and a calculation using a semiclassical linear transportation model with an added contribution due to electromagnetic dissociation. The data is not in agreement with the predictions of strong factorization which overestimates the ^{12}C one-neutron removal cross section by typically a factor of 2. The estimate of the contribution due to ED may also be systematically a bit too high, but measurements of the ^{12}C(RHI,X)^{11}C cross section with A(RHI) > 56 are needed to help clarify this point.

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