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Cross section for the ^{12}C(^{139}La,X)^{11}C reaction at relativistic energies

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The cross section for the ^{12}C(^{139}La,X)^{11}C reaction was measured using 1.26-GeV/nucleon ^{139}La ions. Annihilation radiation from the decay of ^{11}C was counted using a large volume NaI(Tl) detector. The resulting cross section for ^{139}La was 147.9 ± 2.0 mb. The results are compared with similar measurements using relativistic ^{4}He, ^{12}C, ^{20}Ne, and ^{56}Fe projectiles and the predictions of a linear transport model.

There is an ongoing program at the Bevalac accelerator to determine, precisely, absolute cross sections for the ^{12}C(RHI,X)^{11}C reaction, where RHI stands for various relativistic heavy ions. These cross sections can then be used as beam intensity monitors for other RHI reactions and for absolute beam intensity determination in many other RHI experiments. The above reaction has the advantage that ^{11}C is relatively insensitive to production by secondary particles copiously generated in RHI reactions. We report here the results of a measurement of the cross section for the ^{12}C(^{139}La,X)^{11}C reaction using 1.26, GeV/nucleon ^{139}La projectiles. Cross section measurements on p, ^{4}He, and ^{12}C at 2.1 GeV/nucleon,[1-3] ^{20}Ne at 1.05 GeV/nucleon,[4] and ^{56}Fe at 1.7 GeV/nucleon[4] have been reported previously.

The cross section measurements were made in the external ^{139}La beam from the Bevalac accelerator. The experimental procedures and target configurations are essentially identical to those reported for the ^{12}C(^{12}C,X)^{11}C cross section measurements reported earlier[3] and will be described briefly. The Bevalac beam spill was stretched to about 1.0 s, and the demand was imposed that the beam spot be less than 1.5 cm in diameter. First a low-intensity run was made in which the beam particles that traversed a thick graphite target were counted with a scintillator telescope pair located upstream from the target. Both singles and coincidence events were monitored, and the three rates differed by less than 1.5%. The ^{11}C activity from the 2.54-cm thick graphite block was measured. Three such low-intensity runs were carried out with beam intensities of approximately 5×10^4, 2.5×10^4, and 1.0×10^4 particles per beam pulse, respectively. Each run lasted between 15 and 22 min. The beam intensity varied by a large amount from pulse to pulse. In order to correct for variations in beam intensity, the total count from the telescope pair was recorded every minute. These 1-min counts varied from the average by less than a factor of 2. The 1-min differentials were used to make a rate-dependent correction to the ^{11}C activity.

The above ^{11}C measurements alone were not sufficient for determination of the ^{12}C(^{139}La,X)^{11}C cross section because of secondary reactions from low mass fragments that can also produce ^{11}C in the graphite target. Thus in the next step, the ^{11}C activity produced by exposure of a thin (0.159-cm thick) polystyrene target was measured relative to an ion chamber monitor, using high intensities of about 2×10^6 particles/pulse. This run was carried out in order to minimize ^{11}C production due to secondary processes. The above runs were then linked by a third high-intensity run lasting 5 min in which the ^{11}C activity in a 2.54-cm thick graphite block was determined relative to an ion chamber reading. The ion chamber reading linked the third run to that using the thin polystyrene

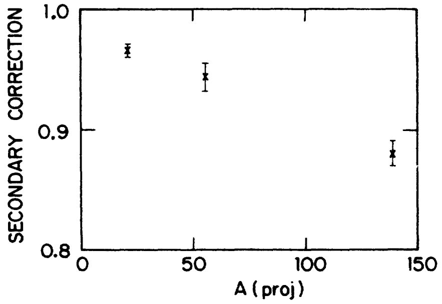

FIG. 1. Secondary correction to the ^{12}C(RHI,X)^{11}C cross section measured for 1.05 GeV/nucleon ^{20}Ne, 1.7 GeV/nucleon ^{56}Fe, and 1.26 GeV/nucleon ^{139}La projectiles.

TABLE I. Cross section for the ^{12}C(^{139}La,X)^{11}C reaction.

Beam energy (GeV/nucleon)	Average beam intensity (ions/pulse)	Cross section[a] (mb)	Mean cross section[b] (mb)	Cross section with secondary correction (mb)
1.26	5×10^4	169.7±1.8		
1.26	2.5×10^4	166.0±2.0	168.1±1.2	147.9±2.0
1.26	1.0×10^4	168.0±3.0		

[a] Errors are statistical only.

[b] See text for explanation of error.

and the ^{11}C activity in the graphite blocks linked the third run to the one at low intensity using the counter telescope. The ^{11}C activity produced in the above runs was determined by counting annihilation radiation using a large well-calibrated NaI(Tl) detector. The NaI(Tl) system and counting procedures have been described in detail previously.[3]

In the final step, a study was made of the contribution to ^{11}C production from secondary particles in the thin polystyrene target. Comparison was made between ^{11}C produced in a 0.159- and a 0.318-cm target. In the past it was assumed[1–4] that the correction was negligible for low-mass RHI but might be significant for ^{139}La. Using beams available to us at the Bevalac, studies were carried out using 1.05 GeV/nucleon ^{20}Ne, 1.7 GeV/nucleon ^{56}Fe, and 1.26 GeV/nucleon ^{139}La projectiles. The correction to the cross section measured for the 0.159-cm target as a function of projectile mass is shown in Fig. 1.

In Table I the results of measurement of the ^{12}C(^{139}La,X)^{11}C cross section are presented. The individual cross sections are those determined in the low-intensity runs but corrected by the thin-thick ratios discussed above using procedures presented in detail in Ref. 3. The mean cross sections are also given. The errors in the individual cross sections are statistical from ^{11}C counting. The mean cross section was determined from a weighted average of the individual measurements using the standard errors as weighting factors. The error of the mean cross section was the standard deviation as determined by statistical methods. Finally a correction was made for secondary reactions in the thin polystyrene target. The final cross section obtained for the ^{12}C(^{139}La,X)^{11}C reaction was thus measured to be 147.9±2.0 mb.

In Table II a summary is given of ^{12}C(RHI,X)^{11}C cross sections measured at the Bevalac for RHI ranging in mass from ^{4}He to ^{139}La. The values previously reported were not corrected[2–4] for secondary reactions in the thin polystyrene target. The reported values are tabulated along with the new values corrected for secondary processes using information from Fig. 1. The corrections extrapolated for ^{4}He and ^{12}C beams are of the order of 1–2 %. Since they have not been measured we do not feel confident in correcting the previously measured values. As expected the secondary correction decreases as the A of the projectile decreases.

The cross section for the reaction ^{12}C(RHI,X)^{11}C is shown in Fig. 2 as a function of (projectile mass)$^{1/3}$ for beams from ^{4}He to ^{139}La. The energies are 1.05 GeV/nucleon for ^{4}He, ^{12}C, and ^{20}Ne, 1.7 GeV/nucleon for ^{56}Fe, and 1.26 GeV/nucleon for ^{139}La. The concept of limiting fragmentation (cross section constant with energy) has been established to be approximately correct above 1.0 GeV/nucleon for target fragmentation leading to one-neutron out products.[3–5]

Also shown in Fig. 2 is a calculated value for the

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

Projectile	Beam energy (GeV/nucleon)	Cross section uncorrected (mb)	Cross section with secondary correction[a] (mb)
^{4}He[b]	1.05	42.5±1.1	
^{12}C[c]	1.05	57.4±0.4	
	2.1	60.9±0.6	
^{20}Ne[d]	1.05	80.4±1.9	77.5±1.9
^{56}Fe[d]	1.7	99.5±1.1	93.9±1.6
^{139}La[e]	1.26	167.9±3.0	147.9±2.0

[a] See text for explanation of secondary correction. The correction for ^{4}He and ^{12}C has been estimated from Fig. 1 to be between 1% and 2% but has not been applied since measurements are not available.

[b] Reference 2.

[c] Reference 3.

[d] Reference 4.

[e] This work.

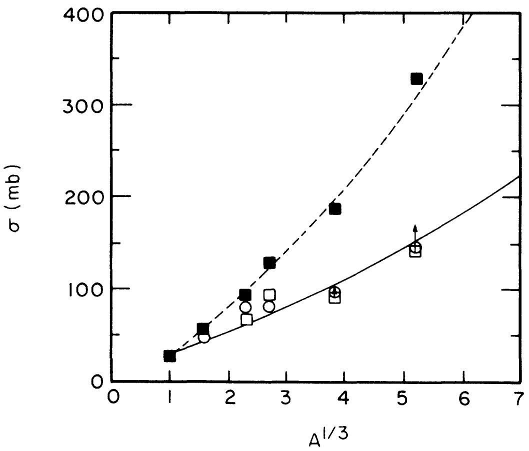

FIG. 2. Cross sections for the $^{12}C(RHI,X)^{11}C$ reaction for various projectiles with energies in the range from 1.05 to 1.7 GeV/nucleon. Experimentally measured values from Table II are given as open circles. The open squares represent the cross sections calculated according to the linear transport model and normalized to a cross section of 31 mb for the $^{12}C(^{1}H,X)^{11}C$ reaction. The arrows represent the additional contribution due to electromagnetic dissociation (ED). For $A<56$ the ED cross section was less than 3 mb and is 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 $^{12}C(^{1}H,X)^{11}C$ and calculated assuming strong factorization (Ref. 11). The results are approximated by the dashed curve.

$^{12}C(RHI,X)^{11}C$ cross section. The calculated values were taken from Ref. 4 for ^{4}He through ^{56}Fe projectiles and are described in detail there. Briefly, the nuclear interaction was calculated using a semiclassical linear transport model which is an extension of the soft spheres model.[6] It is used to calculate the projectile-target single nucleon collision probability which, in combination with the appropriate ^{12}C spectroscopic factor, would yield the ^{11}C production cross section. Rather than compound the calculation with an estimate of the common spectroscopic factor, the relative cross sections were all normalized at the best determined target, hydrogen. We used a value of 31 mb for the $^{12}C(^{1}H,X)^{11}C$ cross section based on recent measurements[7] at 800 MeV. The electromagnetic dissociation[8] contribution to the cross section was calculated using the Weizsäcker-Williams method[9] and $^{12}C(\gamma,n)^{11}C$ cross sections from the National Bureau of Standards Digital DATA Library.[10] The above calculation for 1.26 GeV/nucleon ^{139}La projectiles gave 139 mb for the nuclear contribution and 24 mb for the electromagnetic dissociation contribution yielding a total cross section for the $^{12}C(^{139}La,X)^{11}C$ reaction of 163 mb.

The results shown in Fig. 2 are an extension to ^{139}La projectiles of information given earlier.[4] The agreement between experiment and the above calculation is reasonable as can be seen from the figure. Also shown on the figure are the predictions for the $^{12}C(RHI,X)^{11}C$ cross section given by strong factorization.[11] This calculation was also normalized to 31 mb for the $^{12}C(^{1}H,X)^{11}C$ reaction. The experimental results typically are less than the strong factorization predictions by about a factor of 2 even though electromagnetic dissociation has been included.

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