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Author

Smith, Alan R.

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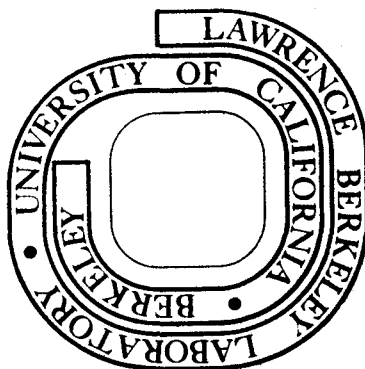
Alan R. Smith and Ralph H. Thomas

November 1975

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THE PRODUCTION OF ^{11}C BY THE INTERACTION
OF 375 MeV/AMU Ne^{10+} IONS WITH
CARBON*

Alan R. Smith and Ralph H. Thomas

Health Physics Department
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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ABSTRACT

We have measured the reaction cross section for production of ^{11}C from ^{12}C in a polystyrene target with incident 375-MeV/amu Ne^{10+} ions at the Lawrence Berkeley Laboratory's Bevalac. We used a broad beam irradiation, and determined both beam profile and absolute particle fluence with LiF thermoluminescent dosimeters, which had been calibrated by track counting in nuclear emulsions; the induced target activity was measured with a NaI(Tl)-crystal, γ -ray spectrometer. The reaction cross section was 75 ± 7 mb.

Energetic heavy-ion beams of intensities usable for both physics and radiobiological experiments have recently become available at the Lawrence Berkeley Laboratory Bevalac facility.¹ The beam intensity available decreases with ion mass, but intensities of 10^7 to 10^8 Ne^{10+} ions/sec have been produced at energies up to ~ 2 GeV/amu.

The response characteristics of ionization chambers and secondary-emission chambers, the traditional beam-monitoring instruments for high-intensity beams of singly-charged particles, are not yet well known for the high dE/dx heavy ions now produced by the Bevalac. Thus the determination of reaction cross sections, of fundamental interest in itself, is also of great value in providing techniques for absolute determination of ion beam intensities. This paper describes preliminary studies of the reaction cross section for the production of ^{11}C from the interaction of 375-MeV/amu Ne^{10+} ions with ^{12}C .

Experimental Technique

A beam of Ne^{10+} ions was extracted from the Bevalac at an energy of 400 ± 4 MeV/amu,² and transported to a polystyrene target. From the known thickness of material in the beam path and specific energy losses,³ the beam energy at the target was computed to be 372 ± 6 MeV/amu.

The ions were focused into a broadly distributed beam designed for the irradiation of small mammals for radiobiological studies.⁴ The radial distribution of the beam was effectively Gaussian in form with a standard deviation, s , of 4.24 cm.

Two polystyrene discs, each 3.00-in. diam. by 0.250-in. thick, were irradiated in this beam with thermoluminescent dosimeters placed on the surface of the disc in which the ion beam entered. The dosimeters, which

had been absolutely calibrated, were used to determine the incident particle fluence. Two polystyrene discs were used to estimate the degree of activation buildup with thickness of target material. The irradiation time was 510 sec, at nominal total beam intensity of $\approx 2 \times 10^7$ ions/sec, of which $\approx 6 \times 10^6$ ions/sec were incident on the discs.

Activation Measurements

Each irradiated disc was counted five times in a period of 30 minutes using a NaI(Tl) scintillation crystal γ -spectrometer. The only radio-nuclide observed was ^{11}C , which decays by positron emission with a half-life of 20.34 min.; the counts in each target confirmed this half-life. The γ -ray spectrometer used here has previously been described by Radin et al.⁵ The detector, an 8-in. diam., 4-in. thick NaI(Tl) crystal, is coupled through a linear pulse amplifier to a 1600-channel pulse height analyzer. Measurements were made in the Lawrence Berkeley Laboratory low-background facility,⁶ in which the background counting rate is constant to within 2%.

After a small correction was made for the distribution of activity across the sample, the efficiency of the γ -spectrometer was calculated to be $45.0 \pm 0.5\%$ under the experimental conditions described here, based on the work of Radin and Smith.⁷ Small corrections were applied to the data for dead time and counting loss.

Measurement of Incident Fluence

The radial distribution of ion fluence across the target was shown to be

$$\phi(r) = \phi_0 \exp(-r^2/2s^2) \quad (1)$$

where ϕ_0 is the maximum fluence occurring at $r = 0$, and s is the standard deviation of the distribution.

The standard deviation may be determined from the beam profile, and had the value $s = 4.24$ cm.

The thermoluminescent dosimeters were first calibrated in terms of incident neon ion fluence by exposing them simultaneously with Kodak nuclear track films (NTA). Packages of two dosimeters were placed at the center of the film and exposed at 45° to the beam direction.

The track densities in the emulsions, as determined by two different scanners, were in agreement within the statistical accuracy of their measurements, and the accuracy of the final calibration was $\pm 4.8\%$.

The absolute value of $\phi(r)$ was determined by placing ^7LiF thermoluminescent dosimeters across the upstream face of the irradiated target. Table 1 summarizes measurements of $\phi(r)$ and the calculated value ϕ_0 obtained was $(6.40 \pm 0.09) \times 10^7$ ions cm^{-2} . The statistical uncertainty in this value for maximum fluence is calculated to be $\pm 5\%$, but it is possible that systematic errors in the techniques used could lead to an absolute error as high as $\pm 10\%$.

Determination of Buildup Correction

The ratio of the ^{11}C activities in the two polystyrene discs was used to determine the magnitude of ^{11}C activity buildup with target thickness. The ratio of disc activities, taken in the sense (rear disc)/(front disc), was found to be 1.152 ± 0.002 . We assumed a linear buildup of ^{11}C activity with target thickness; therefore, the front disc activity was decreased by the factor 0.928 for purposes of reaction cross-section calculation.

Calculation of Reaction Cross Section

The reaction cross section, σ , is given by:

$$\sigma = \frac{T}{2\pi\phi_0 s^2(1-e^{-R^2/2s^2})} \cdot \frac{M}{\rho L} \cdot \frac{B(t) C_0}{\epsilon[1-\exp(-\lambda T)]}$$

where C_0 is the counting rate due to ^{11}C observed in the sample at the end of the irradiation.

ϵ is the efficiency of the γ -spectrometer detector

M is the molecular weight of polystyrene

L is Avogadro's number

T is the irradiation time

λ is the decay constant for ^{11}C

R is the radius of the target

t is the target thickness

$B(t)$ is the buildup correction in a target thickness t , and the other symbols have already been defined. We substitute values in the above equation:

$$\phi_0 = 6.40 \times 10^7 \text{ ions cm}^{-2}$$

$$s = 4.24 \text{ cm}$$

$$\rho = 1.05 \text{ g cm}^{-3}$$

$$t = 0.635 \text{ cm}$$

$$\epsilon = 0.450$$

$$C_0 = 1.332 \times 10^3 \text{ counts sec}^{-1}$$

$$M = 13.01 \text{ grams/per mole}$$

$$L = 6.02 \times 10^{23} \text{ molecules/gram-mole}$$

$$\lambda = 5.68 \times 10^{-4} \text{ sec}^{-1} \text{ (half-life = 20.34 min)}$$

$$T = 510 \text{ sec}$$

$$R = 3.81 \text{ cm}$$

$$B = 0.928$$

The chemical formula for polystyrene is $(\text{CH})_n$, and is therefore 92.3% carbon by weight. Elemental carbon is considered to be entirely ^{12}C , in accordance with the usual convention.⁸

We then obtain a value for the reaction cross section, σ :

$$\sigma = 75 \pm 7 \text{ mb} ,$$

where uncertainty in the value arises mainly from the estimated inaccuracy of the absolute fluence determination by the thermoluminescent dosimeter method. Improvements in this method should permit cross-section determinations to accuracies in the 3 to 5% range.

Summary

We have measured the reaction cross section for production of ^{11}C from ^{12}C in a polystyrene target with incident 375-MeV/amu Ne^{10+} ions, and find a value of 75 ± 7 mb. The absolute particle fluence in the broad beam incident on the targets was determined by thermoluminescent dosimeters which were calibrated by track-counting in nuclear emulsions. The thermoluminescent dosimeter monitor permitted the irradiation to be done at high beam intensity, which resulted in relatively large activation in the target. This high intensity insured that accuracy of the cross-section value would not be limited by measurement of target activity, as is often the case when particle counting is used as the absolute monitor at low beam intensity.

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TABLE 1. Absolute determination of ϕ_0

Distance of dosimeter from beam axis (cm)	$\phi(r)$ ions cm^{-2}	ϕ_0 (ions cm^{-2})
0	6.15×10^7	6.15×10^7
0	6.63×10^7	6.63×10^7
1.70	5.88×10^7	6.37×10^7
1.70	6.05×10^7	6.56×10^7
3.30	4.50×10^7	6.09×10^7
3.30	4.85×10^7	6.57×10^7
Mean $(6.40 \pm 0.09) \times 10^7$ ions cm^{-2}		

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