Submitted to Physical Review C

Spallation of aluminum by 300 GeV protons*

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Activation cross sections were measured for the nuclides ^{7}Be, ^{11}C, ^{13}N, ^{18}F, ^{22}Na, and ^{24}Na formed by the interaction of 300 GeV protons with aluminum. The measurements were made relative to the production of ^{11}C in polyethylene and graphite foils. The cross section ratios are the same within experimental error as those observed at 28 GeV.

[NUCLEAR REACTIONS Al(p,x)^{7}Be, ^{11}C, ^{13}N, ^{18}F, ^{22}Na, ^{24}Na, E = 300 GeV; measured σ relative to $^{12}C(p,pn)^{11}C$.]

*Work performed under the auspices of the Division of Nuclear Physics of the Department of Energy.

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INTRODUCTION

The activation of aluminum foils by high-energy protons is a convenient method of measuring beam intensity which has been extensively used.[1] The highest proton energy at which the activation cross sections for various radionuclides have been previously measured is 28 GeV.[2] A number of recent experiments[3-11] have reported cross section measurements performed at the Fermilab accelerator using 300 GeV protons, in which aluminum served as the beam monitor. The cross section for forming ^{24}Na from aluminum was assumed in these measurements to be the same at 300 GeV as the "adopted values" of Cumming[1] at 10 and 28 GeV, i.e., 8.6 mb. We report here measurements of the cross sections at 300 GeV for forming the radionuclides ^{7}Be, ^{11}C, ^{13}N, ^{18}F, ^{22}Na, and ^{24}Na from aluminum. The measurements were made relative to the cross section for formation of ^{11}C from carbon, for which the absolute cross section at 300 GeV has recently been determined[12] to be 24.6±1.6 mb.

EXPERIMENTAL

The measurements were made by exposing a stack of target and guard foils in the external proton beam in the Meson Hall of the Fermilab accelerator. The exposures were made by mounting the target, enclosed in an evacuated polyethylene bag, on a model electric train which was then moved by remote control to a location beneath the beam line in an air gap, so that the beam passed through the center of the target stack. The proton intensity varied from ca. 10^{11} to 10^{13} protons per pulse during the course of these experiments, with a pulse repetition rate of $\sim$8 sec.

Three types of target arrangements were used. In the first, the targets consisted of three or four aluminum foils and three polyethylene foils. The middle one or two aluminum foils were 14 mg/cm^2 thick and were guarded by 1.8 mg/cm^2 aluminum foils; the polyethylene foils were all 12 mg/cm^2 thick. In the second arrangement, graphite foils of thickness 23 mg/cm^2 were substituted for the polyethylene. It has been established in irradiations at lower energies[13-15] that thin polyethylene foils lose part of their induced ^{11}C activity as low molecular weight gases. The loss of gas occurs within a few minutes of formation and the remaining ^{11}C is retained in the foil. The retention factor is[15] 0.880±0.018 for foils of the thickness used here; we assume that this factor does not depend on the beam energy. The retention factor for graphite is taken to be 1.0. The agreement between the two sets of measurements is a confirmation of these assumptions.

The third target consisted only of aluminum foils; this was used to measure the cross sections for production of ^{7}Be and ^{22}Na relative to that for ^{24}Na, with irradiations lasting several hours. The irradiation lengths for the aluminum plus carbon targets varied from 1 to 8 min, depending on beam intensity. A total of 9 irradiations were done, 3 for each of the types of targets. Following each irradiation the targets were counted in several different ways to measure the amounts of the various nuclides present.

The positron emitters, ^{11}C, ^{13}N, and ^{18}F, were counted using an annihilation-radiation coincidence technique. The target was positioned between two NaI detectors and Be absorbers used to stop the positrons. Single-channel windows were set on the 511-keV peak, and the coincidence rate followed as a function of time. The decay curves were resolved into components of 9.97 min, 20.4 min, and 109.7 min, corresponding respectively to ^{13}N, ^{11}C, and ^{18}F. The ^{24}Na in the aluminum gave rise to a small amount of a 15.0-hr component, which was subtracted from the data. The polyethylene and graphite targets exhibited a single component of 20.4-min half-life. The coincidence counting efficiency was measured with a standard source of ^{22}Na, whose disintegration rate had been measured by β-γ coincidence counting. A small correction was applied to take into account the loss of coincidences due to summing of a 511-keV photon with the 1275-keV γ-ray of ^{22}Na. The number of positrons per disintegration of ^{22}Na was taken to be 0.906.

A second technique used to assay the annihilation radiation from the positron emitters was by means of a calibrated Ge(Li) spectrometer. The target foil was sandwiched between Be absorbers and placed in a standard position, 10 cm from the face of the crystal. The photopeak efficiency as a function of energy was determined using a variety of calibrated sources; including ^{85}Sr (514 keV) and ^{22}Na (511 keV). As with the coincidence counting technique, spectra were recorded as a function of time and the decay curve of the 511-keV peak resolved into its components. The ^{24}Na content of the targets was also determined in two ways: by β-γ coincidence counting and by use of the Ge(Li) spectrometer to measure the intensity of the 1368.5-keV and 2753.9-keV γ-rays. The ^{7}Be and ^{22}Na were assayed with the Ge(Li) spectrometer.

Possible systematic errors in the determination of absolute disintegration rates are estimated to be 3% for the annihilation-radiation coincidence technique, arising from the uncertainty in the ^{22}Na disintegration rate and the summing correction. The calibration of the Ge(Li) efficiency is estimated to be accurate to about 4%, based on the deviation of individual points from a smooth curve. The β-γ coincidence technique used for ^{24}Na is estimated to have a 2% systematic error, based on the magnitude of the correction[16] for detection of γ-rays in the β-detector. When a single sample was counted by two different techniques, the agreement in all cases was within these limits. The decay characteristics of the nuclides measured are given in Table I.

RESULTS

The experimental cross section ratios of the aluminum spallation products to ^{11}C produced in polyethylene were multiplied by the factor 0.880 to correct for loss of ^{11}C from polyethylene.[15] After this correction there was no significant difference between the ratios measured with polyethylene and with graphite. The average values of all measurements are given in Table II, both as cross section ratios to the $^{12}C \rightarrow {}^{11}C$ cross section and in mb, using the experimental value[12] of 24.6±1.6 mb for the latter reaction. The ratios at 28 GeV[2] are also given for comparison.

It is clear from Table II that the relative cross sections for these spallation reactions are the same at 28 GeV and 300 GeV, and therefore are probably constant between these two energies. The cross sections themselves, however, are smaller than those given in Ref. 2 by about 8%. This is because the standard against which they are measured, the $^{12}C \rightarrow {}^{11}C$ cross section, is smaller at 300 GeV than at 28 GeV[17] by 8%. However, a recent measurement[18] of ^{24}Na from aluminum gave a value of 8.0 mb, in good agreement with the present measurement at 300 GeV.

The general lack of energy dependence of formation cross sections above ca. 10 GeV proton energy has been commented on in previous publications.[3-11] It appears to be due to the lack of cascading inside the nucleus of the secondary particles produced in nucleon-nucleon collisions at relativistic energies and a consequent saturation of deposition energy.

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TABLE I. Decay characteristics of nuclides measured

Nuclide	Half-life	Radiation	Abundance
^{7}Be	53.4 d	477.6 γ	0.104
^{11}C	20.4 min	511 γ (β^{+})	2 x (1.00)
^{13}N	9.97 min	511 γ (β^{+})	2 x (1.00)
^{18}F	109.7 min	511 γ (β^{+})	2 x (0.97)
^{22}Na	2.60 y	1274.5 γ	1.00
^{24}Na	15.02 h	1368.5 γ, 2753.9 γ	1.00

TABLE II. Cross sections and cross section ratios for spallation products of aluminum with 300 GeV and 28 GeV protons.

Nuclide	σ (300 GeV) (mb)[a]	σ/σ ($^{12}C \rightarrow {}^{11}C$) 300 GeV	σ/σ ($^{12}C \rightarrow {}^{11}C$) 28 GeV[b]
^{7}Be	8.7 ± 0.7	0.353 ± 0.020[c]	0.354 ± 0.015
^{11}C	4.23 ± 0.31	0.172 ± 0.006	0.184 ± 0.008
^{13}N	1.25 ± 0.11	0.051 ± 0.003	0.045 ± 0.003
^{18}F	5.58 ± 0.43	0.227 ± 0.009	0.232 ± 0.009
^{22}Na	9.4 ± 0.8	0.383 ± 0.024[c]	0.380 ± 0.017
^{24}Na	8.04 ± 0.58	0.327 ± 0.010	0.322 ± 0.009

[a]Calculated using σ($^{12}C \rightarrow {}^{11}C$) = 24.6±1.6 mb.[12]

[b]Data from Ref. 2

[c]Determined indirectly from ^{24}Na ratio.

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