Spallation of Aluminum by 28-GeV Protons*

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In the bombardment of Al foils with 28-GeV protons the following cross sections (in mb) for production of the indicated nuclides were obtained: Be^7, 7.9±0.5; F^{18}, 6.0±0.3; C^{11}, 4.7±0.2; Na^{22}, 9.8±0.6; N^{13}, 1.18 ±0.07; Na^{24}, 8.3±0.5; O^{15}, 3.5±1.0; Mg^{27}, 0.067±0.006. An upper limit for the Ne^{24} cross section of 0.6 mb was obtained. The Mg^{27} cross section has been corrected for secondary reactions and represents only production by primary protons, presumably by the $(p,p\pi^+)$ reaction. The measurements were made relative to the production of C^{11} activity in polyethylene and polystyrene foils. The production of Be^7 in the plastic foils was also observed and corresponds to a cross section of 7.7±0.4 mb per carbon nucleus. By comparison of these cross sections with those at lower bombarding energies, no significant trend of the excitation functions is observable.

A RECENT absolute measurement[1] of the $C^{12}(p,pn)C^{11}$ cross section at 28 GeV has shown that this simple reaction has the same cross section at 28 GeV as at 2 and 3 GeV.[2] Since it might be expected that activation cross sections would reflect changes in the nucleon-nucleon interactions with increasing energy (e.g., increased multiplicity of meson production, shifts in energy spectra, etc.), it seemed to be of interest to determine if a wider variety of types of nuclear reactions also showed this lack of dependence on bombarding energy. The present paper reports the measurement of cross sections at 28 GeV for forming Be^7, C^{11}, N^{13}, O^{15}, F^{18}, Na^{22}, Na^{24}, and Mg^{27} from aluminum and Be^7 from carbon relative to that of the $C^{12}(p,pn)C^{11}$ reaction. Formation of these products has been extensively studied at lower energies.[3–5] Several of the cross sections reported here (F^{18}, Na^{24}, and Na^{22} from Al, Be^7 from C) will be of interest for beam monitoring purposes.

Of the above products, Mg^{27} is produced by a $(p,p\pi^+)$ reaction and it has been suggested by Cocconi *et al.*[6] that the cross section for this type of reaction might reflect the large number of inelastic events with small momentum transfers observed in nucleon-nucleon scattering studies at ultrarelativistic energies.

EXPERIMENTAL

Stacks of aluminum and polyethylene or polystyrene foils were irradiated in the internal beam of the Brookhaven alternating gradient synchrotron at an energy of 28 GeV (835 msec after the start of the magnet cycle). The target foils were attached to an electromechanical flip mechanism which kept the foils in a retracted position shielded by the upstream magnets until ≈25 msec before the desired energy was reached. A previous experiment had shown that no significant activation of the foils occurred when they were maintained in the retracted position for as long as eight hours of operation with accelerated beam for other experiments.

The two principal foil arrangements used in this work are shown in Fig. 1 and will be discussed in the section on results. The distribution of activity in the foils was measured and it was observed that the vertical half-width of the activity at the leading edge was 0.2 in. The decrease of activity in the radial direction was approximately exponential, dropping by a factor of 2 in

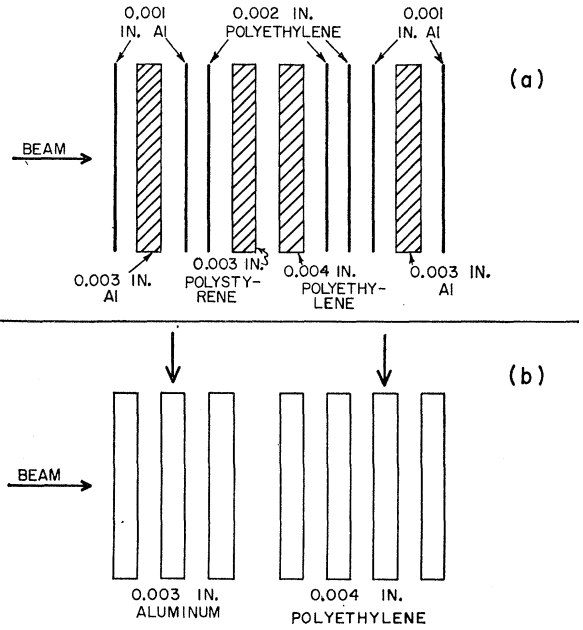

FIG. 1. Target arrangements used in the present experiment. (a) Arrangement for comparison of cross sections from aluminum with the $C^{12}(p,pn)C^{11}$ cross section. The thin foils serve for recoil compensation and protection of the thicker foils which were used for cross-section measurements. (b) Arrangement for measurements of the cross sections for forming Na^{22} and Be^7. The foils indicated by arrows were used for the measurements.

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0.13 in. For the present measurements, half-in.-diam disks were punched out of the foil stacks a few mm back from the leading edge to reduce any effect of misalignment. The weight of each foil disk was obtained with a microbalance either before or after the activity measurements.

The nuclides O^{15}, N^{13}, C^{11}, and F^{18} were assayed in well-type NaI(Tl) scintillation counters with lower discriminators. The foils were placed in copper jackets sufficiently thick to stop all beta particles, and the annihilation radiation was detected. The efficiency of these detectors was measured with C^{11} sources which had been assayed absolutely by measurement of coincidences between positrons and annihilation radiation, by incorporation in the counting gas of a proportional counter, and by comparison with calibrated Na^{22} and Sr^{85} sources.

The nuclide Na^{24} was assayed either in the well-type scintillation detectors where the 1.37- and 2.75-MeV gamma rays are detected or with end-window beta proportional counters which detect primarily the 1.4-MeV beta spectrum. The efficiency of each type of detector for Na^{24} was measured with Na^{24} sources which had been calibrated by β-γ coincidence counting. It was also checked by 4π beta counting.

The assay of Na^{22} involved intercomparison with a National Bureau of Standards Na^{22} standard with both 3 in.$\times$3 in. and well-type NaI(Tl) scintillation counters. Pulse-height analysis was used to select for comparison a spectral region to which Be^7 did not contribute. The comparisons were made at times sufficiently long after the end of the irradiations so that the contribution of Na^{24} activity was negligible.

The Be^7 produced in the plastic foils was assayed in the several scintillator geometries used for Na^{22}. Only the 477-keV gamma ray was observed, and the Be^7 disintegration rates were calculated from the areas of the photopeaks and from a curve of photopeak efficiency vs energy determined with Hg^{203}, Au^{198}, C^{11}, Sr^{85}, and Nb^{95} standards. In the aluminum foils a composite peak of the 477-keV gamma ray from Be^7 and the annihilation radiation from Na^{22} was observed. The contributions of annihilation radiation to the composite peaks were subtracted with the aid of a pure Na^{22} sample. To check this procedure, beryllium was chemically isolated from the aluminum targets by first precipitating $AlCl_3$ and then by precipitating $Be(OH)_2$ several times in the presence of sodium carrier. After correction for chemical yield it was found that the Be^7 disintegration rates in the chemically separated samples agreed with those obtained by the Na^{22} subtraction procedure. Results from both methods were averaged.

The 834-keV gamma ray of Mg^{27} was detected by the 3 in.$\times$3 in. NaI(Tl) crystal. In one irradiation of a 100 mg/cm^2 target no chemical separation of Mg was performed. The 834-keV photopeak was resolved from the gamma-ray spectrum. The major interferences with this resolution were the contributions of the Compton distributions of the Na^{24} gamma rays and the annihilation of positrons in flight. The efficiency for detecting this photopeak was measured with a Mn^{54} source calibrated by the National Bureau of Standards. No contribution to the region of the 834-keV peak was observed from the 878-keV gamma ray of 3.4-min Ne^{24}. In another irradiation, magnesium was chemically separated from a 7-mg/cm^2 thick aluminum foil. This target was dissolved in HCl containing sodium and magnesium carriers. A portion of the solution was saved and assayed later for Na^{24}. To the remainder a large excess of NaOH was added to precipitate $Mg(OH)_2$ but not aluminum. The magnesium was reprecipitated with eight-hydroxyquinoline mounted for gamma-ray measurements.

The half-lives which were used in the analysis of the data and the abundances of the radiations that were detected for each nuclide are listed in Table I.

In view of the reported loss of C^{11} activity from thin plastic foils,[7,8] the polystyrene and polyethylene used in the present experiments were taken from the same batches as had been used for previous gas loss measurements. The retention of C^{11} activity by 0.004-in. polyethylene was measured[9] to be 0.880$\pm$0.018, and that for 0.003-in. polystyrene, 0.970$\pm$0.020. It has been observed that the half-time for diffusion of C^{11} activity out of polystyrene foils is comparable to the nuclear half-life of C^{11}; hence, C^{11} is observed to decay with an apparently shorter half-life. To reduce this effect, the polystyrene foils were sealed between two layers of Scotch tape $\approx$40 min after the end of irradiation and prior to the start of activity measurements. The loss measurements had been made under comparable conditions.

Gas loss from polyethylene is complete within less than 10 min and after that length of time, all polyethylene foils decayed with a 20.4-min half-life. From the ratio of the measured retentions, the specific activity per mg of carbon in a polyethylene foil should be 0.907$\pm$0.026 times that of a polystyrene foil in the same irradiation. In three irradiations of the present experi-

TABLE I. Decay properties of the nuclides studied.

Isotope	Half-life	Radiation	Abundance
Be^7	54 days	0.477 γ	0.12
C^{11}	20.4 min	β^+	1.00
N^{13}	10.0 min	β^+	1.00
O^{15}	2.05 min	β^+	1.00
F^{18}	110 min	β^+	0.97
Na^{22}	2.59 yr	1.28 γ	1.00
Na^{24}	15.0 h	β^-	1.00
		2 γ's	1.00 each
Mg^{27}	9.5 min	0.834 γ	0.70
Ne^{24}	3.4 min	0.878 γ	0.08
		0.472 γ	1.00

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[8] J. B. Cumming, A. M. Poskanzer, and J. Hudis, Phys. Rev. Letters 6, 484 (1961); 6, 646(E) (1961).

[9] Reference 8 and further measurements of the gas collection type described therein.

TABLE II. Cross sections in mb for formation of various nuclides in bombardments of C and Al with 28-GeV protons.

	Bombardment								
	3[a]	7	17	23	19	21	25	37[a]	Mean[b]
Al target									
Be^{7}					7.9 ±0.14	7.87±0.18			7.89 ±0.29
C^{11}	4.77±0.21	4.74±0.09	4.71±0.09	(4.65±0.10)			(4.03 ±0.10)	(4.37 ±0.10)	4.73 ±0.10
N^{13}		1.18±0.06	1.13±0.10				1.21[e] ±0.09	1.17[e]±0.09	1.18 ±0.05
O^{15}							3.8[e] ±1.5	3.3[e] ±1.3	3.5 ±1.0
F^{18}	5.96±0.09	6.04±0.09	6.10±0.09	(6.03±0.09)			(5.78 ±0.09)	(5.82 ±0.09)	6.03 ±0.11
Na^{22}					9.86±0.15	9.82±0.20			9.85 ±0.31
Na^{24}	8.39±0.13	8.44±0.13	8.55±0.13	(8.99±0.13)					8.34[d] ±0.23
Ne^{24}					<0.8		<1.0	<1.3	<0.6
Mg^{27}					0.14±0.02		0.072±0.004		0.067[d]±0.005
C target									
Be^{7}					7.60±0.14	7.74±0.14			7.67 ±0.25
Target type[c]	*A*	*A*	*A*	*A′*	*B*	*B*	*C*	*D*	

[a] Incident energies for bombardments 3 and 37 were 30 and 31 GeV, respectively.
[b] Errors include estimates of systematic effects but do not include the 4.6% error in the $C^{12}(p,pn)C^{11}$ cross section. Values in parentheses have not been included in calculating the averages. See text for details.
[c] Target type *A* is shown in Fig. 1(a). Type *A′* is the same as *A* sandwiched between two pieces of Al each 224 mg/cm² thick. Type *B* is shown in Fig. 1(b). Type *C* was one piece of 0.001-in. Al. Type *D* was 0.002-in. Al.
[d] Corrected for secondary effect.
[e] Corrected for recoil loss based on the C^{11} and F^{18} measurements.

ment containing both foil materials this ratio was observed to be 0.925±0.004. Results from polystyrene and polyethylene have been averaged in calculating cross sections. The residual error due to the uncertainties in the gas retention values should then be ≈1.5%.

RESULTS

The results of the present series of measurements are shown in Table II. Targets of the type shown in Fig. 1(a) were irradiated in bombardments numbered 3, 7, and 17 to obtain cross sections for producing Na^{24}, F^{18}, C^{11}, and N^{13} from aluminum relative to the 25.9±1.2 mb cross section[1] of the $C^{12}(p,pn)C^{11}$ reaction. The thin aluminum and plastic foils in the target compensated the thicker foils for recoil losses and protected them against recoil contamination. Results from the two thick Al foils were averaged. The duration of each irradiation was less than 10 sec. The errors on the individual values have been compounded from the errors due to counting statistics (negligible for Na^{24} and F^{18}) and a 1.5% error to allow for uncertainties in weighing and foil line-up and for small day-to-day variations of the counter efficiencies from the calibrated values. The effects on these cross-section ratios of secondary particles produced in the target stacks (100 mg/cm² thick) were evaluated from the results of irradiation 23 shown in Table II. In this irradiation the same type of target used in irradiations 3, 7, and 17 was bombarded while sandwiched between two 224-mg/cm² aluminum plates. The data in Table II show that the apparent $Al^{27}(p,3pn)Na^{24}$ cross section is increased by 6.2% from the average value in the three 100-mg/cm² targets. A linear dependence of this effect on target thickness has been assumed and the Na^{24} cross section from the 100-mg/cm² targets has therefore been lowered by 1.4% to obtain the mean thin-target value of 8.34 mb shown in Table II.

Examination of Table II shows that the apparent F^{18} cross section does not increase with target thickness; hence, the $Al^{27}(p,5p5n)F^{18}$ and $C^{12}(p,pn)C^{11}$ reactions must be affected to approximately the same extent by secondaries.[10] The C^{11} production from aluminum in the two target thicknesses is also the same within the errors. We have not applied corrections for secondary effects to any of the cross sections reported except those for forming Na^{24}, and Mg^{27} which will be discussed below.

To determine the cross sections of reactions leading to the longer-lived products, Be^{7} and Na^{22} from aluminum, and Be^{7} from carbon, two 10-min irradiations, numbers 19 and 21, were performed with the type of target shown in Fig. 1(b). The production of Na^{24} in the center Al foil served as the monitor of the beam intensities. An effective cross section of 8.46 mb was used to include the effects of secondary particles in these foil stacks which were comparable in thickness to the earlier irradiations. In irradiation 19 which was at full beam intensity, the last two polyethylene foils on the downstream side of the target fused together. A correction of 1.2% for Be^{7} recoil loss was applied to the sum of the activity of these two foils based on the ratio of the separate foils from irradiation 21 which was at ≈1/7 of the beam intensity of irradiation 19.

The nuclide Mg^{27} is produced both by a primary reaction, presumably $(p,p\pi^{+})$, and also by the relatively probable secondary (n,p) reaction. The apparent cross section for producing Mg^{27} was measured in a 100-mg/cm² target (irradiation 19 of Table II) and in a

[10] From the data of reference 1 on the absolute $C^{12}(p,pn)C^{11}$ cross-section measurements it can be calculated that the secondary effect on the $C^{12}(p,pn)C^{11}$ reaction should be ≈0.5% in a 100-mg/cm² target.

7-mg/cm^2 target (irradiation 25). The latter was a single unguarded aluminum foil. Assuming that the secondary neutron flux increases linearly with total target thickness, one calculates from the two measurements a secondary effect of about 75 μb per 100 mg/cm^2. The cross section listed in the last column of Table II has been extrapolated to zero target thickness with this slope. It was assumed that the recoil loss of Mg^{27} produced by the $(p,p\pi^+)$ reaction in 0.001-in. Al is negligible. The Na^{24} activity observed in this foil, which served as the internal monitor, was increased by 3.5% to correct for recoil loss.[11] Since Mg^{27} would not have been resolved from N^{13} in the data obtained with the well-type scintillators, the contribution of Mg^{27} was estimated, based on the apparent Mg^{27} cross section and the Mg^{27} counting efficiency in the well counters. This lowered the N^{13} cross sections reported in Table II by 0.07 mb for bombardments 3, 7, and 17.

The production of shorter-lived products from Al was further investigated in irradiations 25 and 37 of Table II. The former irradiation was made primarily to measure the $Al^{27}(p,p\pi^+)Mg^{27}$ cross section as described above. In the latter, a 14-mg/cm^2 aluminum foil was irradiated as part of another experiment. In both cases a small piece of the leading edge of the foil was placed in a well counter $\approx$8 min after the end of the irradiation. The decay curves obtained were analyzed by a least-squares computer program into components having half-lives of 1.2 min (O^{14}, F^{17}, Na^{25}), 2.05 min (O^{15}), 3.4 min (Ne^{24}), 10.0 min (N^{13}, Mg^{27}), 20.4 min (C^{11}), 110 min (F^{18}), 15 h (Na^{24}), and a small long-lived tail. The effects of varying some of these half-lives on the intercepts of other components and on the goodness-of-fit to the curve were investigated. Without exception the best fits to all of the aluminum decay curves in the present work were obtained with a 110-min half-life for F^{18} in agreement with recent literature values.[12–14] When a 2.05-min half-life is used for O^{15}, no significant amount of Ne^{24} could be detected in the decay curves. Upper limits have been set for the cross sections in Table II at a 98% confidence level (2σ). An upper limit of 9 mb could be set for the sum of the O^{14}, F^{17}, and Na^{25} cross sections. One consequence of the possible presence of the 1.2- and 3.4-min components is a 40% uncertainty in the O^{15} intercept. If it had been assumed that these components were absent, the error on the O^{15} intercept would have been only $\approx$5%. The larger errors have been used in Table II to indicate the sensitivity of O^{15} to the resolution procedure. The N^{13} cross sections reported in Table II for these two bombardments have been lowered by 0.04 mb to correct for the Mg^{27} contribution.

Since irradiations 25 and 37 were not compensated for recoil losses, corrections must be applied in calculating cross sections. The recoil losses of Na^{24}, the internal monitor, were taken from existing data.[11] The apparent cross sections for forming C^{11} and F^{18} in bombardments 25 and 37 (shown in parentheses in Table II) are seen to be lower than the mean cross sections for these products obtained in the recoil-compensated foil stacks. We calculate that 0.001-in. Al foils lose (15$\pm$2)% of the C^{11} activity and (5$\pm$2)% of the F^{18} by recoil. On the basis of these data, corrections of (11$\pm$2)% and (8$\pm$2)% were applied to the N^{13} and O^{15} data from bombardment 25, and corrections of one-half these amounts to the data of bombardment 37 (0.002-in. foil).

The mean cross sections shown in Table II have been obtained by averaging the individual measurements. Results shown in parentheses were not included. In the case of Na^{24} and Mg^{27}, corrections for the production of these isotopes by secondary particles have been made. The errors assigned to the mean cross sections were obtained by root-mean-square addition of the statistical errors and estimates of the various possible systematic errors. In all cases, a 1.5% uncertainty in the value of the C^{11} gas retention was included. Since essentially the same radiations were detected in measurements of C^{11}, N^{13}, O^{15}, and F^{18} as in C^{11} from the $C^{12}(p,pn)C^{11}$ monitor reaction, no systematic error for absolute counting need be added to these cross sections. When different radiations are detected in a ratio measurement, the systematic errors in the absolute determination of each nuclide must be included. These are estimated to be 1.5% each for C^{11} and Na^{24}, 2% each for Be^7 and Na^{22}, and 5% for Mg^{27}. The errors in Table II do not include the 4.6% error assigned to the $C^{12}(p,pn)C^{11}$ absolute cross section. This additional error has been included in the results presented in the abstract.

DISCUSSION

The cross section of the $Al^{27}(p,3pn)Na^{24}$ reaction at 28 GeV, 8.3$\pm$0.5 mb, is lower than the 10.5-mb value which has been commonly used in the 2–6 GeV region.[2,3,5] However, it should be noted that the values at these lower energies which were determined relative to the $C^{12}(p,pn)C^{11}$ cross section, did not take into account the effects of radioactive gas loss from the thin plastic foils. New measurements[15] at 2.9 GeV give a value of (9.2$\pm$0.4) mb for the $Al^{27}(p,3pn)Na^{24}$ cross section at that energy. Hence, the decrease from 3 to 28 GeV is (10$\pm$7)% and may not be significant.[16]

Although the published absolute values of aluminum spallation cross sections measured at lower energies[3–5]

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[16] N. Horwitz and J. J. Murray, Phys. Rev. **117**, 1361 (1960) have reported a (29.5$\pm$1.6)-mb cross section for the $C^{12}(p,pn)C^{11}$ reaction at 3 GeV (when corrected to the same basis as reference 1). If this value and the ratio measured in reference 15 are combined, a (10.1$\pm$0.6)-mb $Al^{27}(p,3pn)Na^{24}$ cross section is obtained. The decrease from 3 to 28 GeV is then (18$\pm$8)%.

TABLE III. Cross sections relative to that of the $Al^{27}(p,3pn)Na^{24}$ reaction as a function of bombarding energy.

Target and product	2.2–3 GeV[a]	5.7 GeV[b]	28 GeV
Aluminum			
Be^{7}	0.95±0.15	0.79±0.04	0.95 ±0.03
C^{11}	0.59±0.06	0.57±0.04	0.57 ±0.02
N^{13}	0.14±0.04	0.16±0.02	0.14 ±0.01
O^{15}	0.65±0.20	0.43±0.18	0.42 ±0.12
F^{18}	0.68±0.07	0.73±0.03	0.72 ±0.02
Na^{22}	1.52±0.15	1.62±0.13	1.18 ±0.04
Ne^{24}		0.15±0.06	<0.06
Mg^{27}		0.10±0.07	0.080±0.006
Carbon			
Be^{7}	0.9 ±0.2	1.05±0.07	0.92 ±0.03

[a] Averages of the 2.2- and 3.0-GeV data of references 3 and 4. The cross sections have been corrected to the branching ratios given in Table I.
[b] Reference 5.

are presumably in error because of the neglect of the gas-loss correction just discussed, relative values for the formation cross sections of various products may be directly compared for different proton energies. Such a comparison of cross sections for forming various products relative to the $Al^{27}(p,3pn)Na^{24}$ cross section at 2.2–3,[3,4] 5.7,[5] and 28 GeV is shown in Table III. These relative cross sections are surprisingly independent of energy. Only Be^{7} and Na^{22} production from aluminum show differences. In the case of Be^{7}, the 28-GeV result is significantly higher than the 5.7-GeV value, but agrees with the value at 2.2–3 GeV. However, the error of the 2.2–3-GeV value is so large that the data are consistent with a monotonic increase in the Be^{7}/Na^{24} ratio with bombarding energy. It does not appear that the differences can be ascribed to any errors in Be^{7} counting efficiencies, since the same authors report cross sections for Be^{7} formation from carbon which, relative to the $Al^{27}(p,3pn)Na^{24}$ cross section, show no significant trend with proton energy.

The relative Na^{22} cross section at 28 GeV appears to be significantly lower than the value at either 2.2–3 or 5.7 GeV. The Na^{22}/Na^{24} cross section ratio has been measured,[15] using the same counting techniques described above, in one foil which had been irradiated at an energy of 2 GeV in the Brookhaven Cosmotron. The observed ratio, 1.29±0.06, is lower than either the 2.2–3 or 5.7 GeV results reported in Table III. Thus, the decrease with energy, if real, is not as pronounced as the presently published data would indicate.

From the data of Table III on aluminum spallation products in the mass range $7 \leqslant A \leqslant 27$ it appears that the mass yield curve from a low-atomic-weight target element does not change significantly as the bombarding energy is increased from ≈ 3 to ≈ 30 GeV. Thus, one might conclude that the spectrum of deposition energies and the number of nucleons removed by the knock-on cascade also might be relatively independent of bombarding energy. If this is correct then the energy carried off by the mesons and nucleons in the prompt cascade must increase.

The cross section of Mg^{27} produced by a $(p,p\pi^{+})$ reaction is of particular interest. Cocconi *et al.*[6] have suggested such reactions should reflect the large number of inelastic events with small momentum transfers which have been observed in nucleon-nucleon scattering studies at ultrarelativistic energies. These events have been interpreted in terms of the one-pion-exchange model. The observed Mg^{27} cross section is very small and thus the nuclear effects, such as availability of Fermi momentum to cancel the recoil momentum, must strongly limit the probability of radiochemically observing this one-pion-exchange effect in a complex nucleus[17].

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[17] *Note added in proof.* Recent theoretical calculations by T. Ericson, F. Selleri, and R. T. van de Walle give a $(p,p\pi^{+})$ cross section in reasonable agreement with the measured value.