time is about equal to the median delay. The Agassiz experiment was carried out at sea level. Let us assume that the electron radius of curvature scales with elevation in the same manner as the Moliere unit. Then at a distance from the axis equal to one Molière unit we expect a time spread of about 0.01 μsec, which is much smaller than 0.1 μsec. However, the lateral distribution measurements extended to about 400 m from the axis, or 5 Molière units. At the latter distance we expect the time spread to be about 0.3 μsec. The pulses observed at such great distances were small, and there is a tendency for fluctuations from the average distribution in arrival time to be beneficial. However, there is no doubt that for distances greater than $r\sim1$ shower densities were underestimated, in that experiment, by an amount which increased with distance. We would expect errors of a few percent at $r=2$, 20 or 30% at $r=3$, and a factor of 2 at 4 or 5 Molière units. We must expect that the lateral distributions which were derived from the density measurements are too steep at large distances. Disagreement of the type expected is found, in fact, between the lateral distribution measured in the present experiment (integration time 1.0 μsec) and the one measured at Agassiz.[17]

When one goes to greater elevations, the integration time must be increased in order to avoid errors of this type. The assumptions used in analyzing the sea-level experiment imply that the spread in arrival time (in μsec) at a given distance from the axis (in Molière

units) should increase with elevation in the same manner as the Molière unit (in meters). In the Bolivian-MIT El Alto experiment the integration time used at an elevation of 630 g cm^{-2} was the same as that used in the Agassiz experiment, and one would expect an increased distortion of the lateral distribution at large distances. In fact, the preliminary measured lateral distribution agrees with NKG(1.0) rather than NKG(1.3), which fitted the Agassiz measurements.[11,18,19]

ACKNOWLEDGMENTS

[18] J. Hersil, I. Escobar, G. Clark, S. Olbert, C. Moore, and D. Scott, J. Phys. Soc. Japan 17, Suppl. A-III, 243 (1962).
[19] *Note added in proof.* By NKG(s) we mean the Greisen approximation to the lateral distribution function calculated by Nishimura and Kamata, for age parameter s.

Al^{27}($p,3pn$)Na^{24}/C^{12}(p,pn)C^{11} Cross-Section Ratio in the GeV Region*

J. B. Cumming, J. Hudis, A. M. Poskanzer, and S. Kaufman†
Chemistry Department, Brookhaven National Laboratory, Upton, New York
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The Al^{27}($p,3pn$)Na^{24}/C^{12}(p,pn)C^{11} cross-section ratio has been measured at nine energies between 0.4 and 17 GeV. Corrections have been applied for the loss of C^{11} by diffusion from the thin plastic foils which were used, and the effects of this loss on existing data are discussed. From the measured ratios and published absolute cross sections for the C^{12}(p,pn)C^{11} reaction, an excitation function for the standard monitor reaction, Al^{27}($p,3pn$)Na^{24}, was obtained. The cross section at 3 GeV was found to be 9.1±0.5 mb, lower than the previously accepted value of 10.5 mb. Cross sections relative to the Al^{27}($p,3pn$)Na^{24} cross section were also obtained for the production of Na^{22}, F^{18}, N^{13}, C^{11}, and Be^{7} from aluminum and for Be^{7} from carbon in this energy region. These cross sections are essentially independent of energy between 6 and 28 GeV. An exception is Be^{7} production from aluminum, which increases slightly between 3 and 28 GeV.

INTRODUCTION

THE first attempts[1,2] to obtain absolute activation cross sections in the GeV region utilized an indirect method to obtain the Al^{27}($p,3pn$)Na^{24} cross section. It was found to be 8.8 mb at 2.2 GeV and 8.1 mb at 3 GeV, indicating decreases from the value of 10.8 mb at 0.45 GeV[3] which had been used for normalization. When direct measurements of the absolute[4] σ_C(C^{11}) became available at 2 and 3 GeV [5] and at 3, 4.5, and 6

† Present address: Department of Chemistry, Princeton University, Princeton, New Jersey.
[1] A. Turkevich, Phys. Rev. 94, 775 (1954).
[2] G. Friedlander, J. Hudis, and R. L. Wolfgang, Phys. Rev. 99, 263 (1955).

[3] L. Marquez, Phys. Rev. 86, 405 (1952).
[4] We will use subsequently the notation $\sigma_X(Y)$ to denote the cross section for producing Y from target X.
[5] J. B. Cumming, G. Friedlander, and C. E. Swartz, Phys. Rev. 111, 1386 (1958).

GeV,[6] These values and experimental values of the σ_{Al}(Na^{24})/σ_C(C^{11}) ratio[7] were used to obtain σ_{Al}(Na^{24}). This procedure led to a generally accepted value of 10.5 mb for the monitor reaction σ_{Al}(Na^{24}) in the GeV region. The discrepancy between the 10.5-mb figure and the 8.8 and 8.1 values at 2.2 and 3 GeV was not considered significant since they were within the 30% systematic error limit estimated for the indirect method. It has now been shown[8,9] that polyethylene foils similar to those used in the early σ_{Al}(Na^{24})/σ_C(C^{11}) ratio measurements[7] lose $\approx 12\%$ of their C^{11} activity by a diffusion process. In addition the C^{11} counting efficiency used in the early measurements was not directly measured. The present experiment was undertaken to supply accurate data on the σ_{Al}(Na^{24})/σ_C(C^{11}) ratio in the energy range available at the Brookhaven Cosmotron. It was extended both to 0.42 GeV and to 17 GeV to join with existing data near 400 MeV and at 28 GeV.[10] A number of additional cross sections for products from aluminum and σ_C(Be^7) were also obtained in this energy region. These will be of interest for examining the energy dependence of a variety of nuclear reactions in light target nuclei. Since they have been obtained in one laboratory under nearly identical conditions, small effects may be observed which might not be apparent if data from different laboratories were compared. The values of σ_{Al}(Na^{24}), σ_{Al}(F^{18}), σ_{Al}(C^{11}), σ_{Al}(Na^{22}), and σ_C(Be^7) will be of use for beam monitoring purposes.

EXPERIMENTAL

Stacks of aluminum and polyethylene (or in some cases polystyrene) foils were irradiated in the internal proton beams of the Brookhaven Cosmotron or Alternating Gradient Synchrotron (AGS). The general target arrangement is shown in Fig. 1. Some initial studies were performed in 2.0 and 2.9 GeV external beams at the Cosmotron. In these irradiations and in a few subsequent irradiations in the internal beam the 0.001-in. aluminum guard foils were omitted. Corrections for losses of Na^{24}, F^{18}, and C^{11} from the 0.003-in.

TABLE I. Efficiency of the well-type scintillation counter for C^{11} as determined by different methods of calibration of C^{11} sources.

Source calibration method	Efficiency
β^+-511 keV coincidence counting	0.738±0.014
Combustion and internal counting in gas proportional counter	0.753±0.020
Comparison with NBS Sr^{85} source	0.743±0.022
Comparison with calibrated Na^{22} source	0.726±0.014
Adopted value	0.737±0.011

[6] N. Horwitz and J. J. Murray, Phys. Rev. 117, 1361 (1960).
[7] R. L. Wolfgang and G. Friedlander, Phys. Rev. 96, 190 (1954); 98, 1871 (1955).
[8] H. Fuchs and K. Lindenberger, Nuclear Instr. & Methods 7, 219 (1960).
[9] J. B. Cumming, A. M. Poskanzer, and J. Hudis, Phys. Rev. Letters 6, 484 (1961).
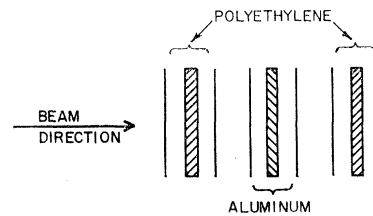[10] J. B. Cumming, G. Friedlander, J. Hudis, and A. M. Poskanzer, Phys. Rev. 127, 950 (1962).

FIG. 1. Schematic diagram of the target arrangement. The thick foils are 0.004-in. polyethylene and 0.003-in. aluminum; the thin foils are 0.002-in. polyethylene and 0.001-in. aluminum. The thin foils serve for recoil protection and compensation.

foils were made using the existing data on the recoil losses of these isotopes.[11,12]

After irradiation of a target stack, a $\frac{1}{2}$-in.-diam circle was punched through the stack to reduce errors arising from misalignment of the foils. The foil disks were weighed on a microbalance. In many of the irradiations the C^{11} activities of the upstream and downstream plastic foils were assayed separately. The maximum observed difference in specific activity was 2.5% and the general agreement was better than 1%. The results from the separate foils in these experiments were averaged in the calculation of cross-section ratios.

The proton energies during the 0.42- and 0.62-GeV irradiations were determined by measurements of the revolution frequency of the proton bunch and from the orbit radius at the time of turnoff of the accelerating voltage. These energies are believed accurate to 10 MeV. The higher energies were determined from magnetic measurements by the Cosmotron and AGS staffs. The foil stacks were kept in a shielded position during the early part of the acceleration cycle to prevent low-energy protons from striking them. Except in the 0.42- and 0.62-GeV irradiations the targets should have seen no significant number of protons below the desired energy. At the lowest energies the time required to insert the target became an appreciable fraction of the total acceleration time and, therefore, the protection from low-energy protons may not have been as good as in the irradiations at 1 GeV and higher. The irradiations for determination of the σ_{Al}(Na^{24})/σ_C(C^{11}) ratio were not longer than 10 min.

The C^{11} activity in the plastic foils and the β^+ emitting isotopes in the aluminum foils, C^{11}, N^{13}, and F^{18}, were assayed in well-type NaI(Tl) scintillation counters. Samples were placed in copper jackets sufficiently thick to stop all beta particles. The efficiency of these detectors for annihilation radiation from C^{11} was measured in several ways which are summarized in Table I. The agreement between different methods of calibration of the C^{11} sources is good and the estimated systematic error in the efficiency for detecting annihilation radiation is 1.5%. The Na^{24} in the 0.003-in. aluminum foils was assayed with end-window beta proportional counters

[11] R. Wolfgang and G. Friedlander, Phys. Rev. 94, 775 (1954).
[12] A. M. Poskanzer, J. B. Cumming, and R. Wolfgang, Phys. Rev. (to be published).

whose efficiency had been measured by means of Na^{24} samples calibrated by $\beta-\gamma$ coincidence measurements and by 4π counting. The decay curves of the plastic and aluminum foils were analyzed by a least-squares program, as had been done previously in a similar study at 28 GeV.[10]

LOSS OF C^{11} ACTIVITY FROM PLASTIC FOILS

A C^{11} atom produced in a nuclear reaction will possess sufficient kinetic energy to break chemical bonds. The chemical forms in which such a recoil will ultimately appear depend upon the nature of the parent compound and, possibly, upon the conditions during the irradiation. In the case of polyethylene and polystyrene, part of the C^{11} activity appears in low molecular weight fragments[9] (including CH_4, C_2H_2, C_2H_6, and C_2H_4) which are gaseous and may diffuse out of the foils. The apparent retention of C^{11} by a particular foil then depends on two factors: firstly, the intrinsic fraction of C^{11} which ends up in gaseous chemical forms, and secondly on the rate at which such compounds diffuse out of the foil. If the mean time for diffusion is comparable to the half-life of C^{11}, one would expect to observe an abnormally rapid decay of the sample. This has been reported for 0.315- and 0.059-in. polyethylene, but in the case of 0.008-in. polyethylene no such deviation was observed.[8] With the 0.004-in. polyethylene foils (and also 0.002-in.) used in the present experiment, no deviations from a 20.4-min half-life were observed. It, therefore, appears that diffusion of C^{11} from polyethylene foils thinner than 0.008 in. was complete before activity measurements could be commenced. In one irradiation[9] of polyethylene foils at low temperature (80°K), the bulk of the gaseous products were retained and their loss was observed only when the samples were allowed to warm up. The apparent half-life for loss of the activity (including warming-up time) was less than ≈ 2 min, and no further loss except by decay was observed after 10 min from start of warm-up.

The loss of C^{11} activity from the 0.004-in. polyethylene foils used in the present experiment has been previously reported[9] and additional measurements have also been performed. The most accurate method of measurement has been to irradiate the foils in a helium atmosphere in a closed aluminum container. The gaseous species in the helium carrier gas are Toepler pumped into a counting tube and assayed, and the C^{11} remaining in the foils is also assayed. After a small correction for recoils from the container, retentions (fractions of activities produced which are retained by the foils) of 0.907 and 0.880 were obtained in duplicate runs. It was shown that $\approx 99\%$ of the active gas was removed in one pumping. The low-temperature irradiation set a limit of ≤ 0.91 for the retention. A direct comparison of the specific activity of C^{11} in 0.004-in. polyethylene with that in a graphite disk gave a retention of 0.856. This comparison was hindered by nonuniform thickness of the graphite sample and is less reliable than the direct measurement

TABLE II. $\sigma_{A1}(Na^{24})/\sigma_C(C^{11})$.

Proton energy (GeV)	Measured ratios[a]	Mean value[b]
0.42	0.309, 0.304	0.304 ± 0.009
0.62	0.339, 0.341, 0.354	0.342 ± 0.010
1.0	0.388, 0.375, 0.369, 0.367, 0.370	0.371 ± 0.011
1.4	0.366	0.363 ± 0.012
2	0.358 ± 0.008,[c] 0.356 ± 0.012,[c] 0.345, 0.349	0.347 ± 0.011
2.9	0.355 ± 0.011,[c] 0.350 ± 0.016,[c] 0.354 ± 0.007,[c] 0.336, 0.351, 0.340	0.342 ± 0.010
6	0.324	0.322 ± 0.010
10	0.323	0.320 ± 0.010
17	0.325	0.322 ± 0.010
28[d]		0.322 ± 0.009

[a] The standard deviations of the individual values are 1.5 % except where shown otherwise.
[b] Mean values from 0.42 to 6 GeV have been reduced by 0.7 % to correct for production of Na^{24} by secondary particles formed in the target stacks. At 10 and 17 GeV a 1 % correction was applied.
[c] These results were obtained from irradiations in external beams.
[d] Data from reference 10.

of the gases lost. We have adopted a retention of 0.880 ± 0.018 for 0.004-in. polyethylene where the standard deviation is estimated to inlcude systematic effects. Fuchs and Lindenberger[8] have reported that the retention of C^{11} by 0.008-in. polyethylene is 0.87. The present experiment has shown that 0.002- and 0.004-in. polyethylene have the same retention within 1%. Singh and Alexander[13] have reported that 0.001-in. polyethylene shows a retention of 0.90 (measured relative to our 0.004-in. polyethylene). We have assumed in correcting the data of others that all polyethylene thinner than 0.008 in. has a retention of 0.88.

The apparent retention of C^{11} by polystyrene is considerably higher than that of polyethylene of comparable thickness. However, the mean time for diffusion is comparable to the half-life of C^{11} and decay curves of polystyrene targets show initially an apparently shorter half-life. That this was due to diffusion loss, and not short-lived radioactive impurities, was demonstrated by irradiating 0.003-in. polystyrene foils in the aluminum container described above. It was shown that gaseous C^{11} activity could be "milked" from the foils by repeated pumping for as long as 50 min after irradiation. For the assay of C^{11} activity in polystyrene in the present experiment the foils were sealed between Scotch tape ≈ 40 min after the end of irradiation as had been done in the 28-GeV work.[10] The retentions, determined by the measurement of the liberated gas and foil activities at comparable times, were 0.964 and 0.975. We have adopted 0.970 ± 0.020 as the retention of 0.003-in. polystyrene under these conditions.

RESULTS

A. $\sigma_{A1}(Na^{24})/\sigma_C(C^{11})$ Cross-Section Ratio

The measured $\sigma_{A1}(Na^{24})/\sigma_C(C^{11})$ ratios are listed in Table II together with their errors. In nearly all of the

[13] S. Singh and J. M. Alexander, Phys. Rev. 128, 711 (1962).

internal beam experiments the statistical errors in counting C^{11} and Na^{24} were negligible and the dominant factor is a 1.5% error added to include day-to-day counter-efficiency variations and foil misalignments. Where several irradiations had been performed at the same energy, the results have been combined in a weighted average. These averages have been corrected for the effects of secondary particles formed within the target stacks. Comparison of one irradiation at 2.9 GeV, where the standard target stack was sandwiched between two 0.040-in. aluminum plates, with the average of the unsandwiched irradiations indicates that the σ_{Al}(Na^{24})/σ_C(C^{11}) ratio increases 1.1% per 100 mg/cm^2 of target thickness. An increase of 1.4% per 100 mg/cm^2 has been reported for 28-GeV protons.[10] The present targets were ≈ 70 mg/cm^2 thick and the mean σ_{Al}(Na^{24})/σ_C(C^{11}) ratios in Table II have been lowered by 0.7% from 0.42 to 6 GeV and by 1% at 10 and 17 GeV. The standard deviations of the mean values in Table II also include systematic errors in the measurements. These uncertainties are estimated to be 1.5% each for the counting efficiencies of C^{11} and Na^{24} and 1.8% for the C^{11} retention of the plastic foils. The over-all standard deviations of the means are $\approx 3\%$. These data have been plotted in Fig. 2. The σ_{Al}(Na^{24})/σ_C(C^{11}) curve is seen to rise from 0.4 GeV to 1 GeV and then decrease to a constant value of 0.32 for energies above 6 GeV. The maximum at ≈ 1 GeV was unexpected, but is well outside the errors on the points. This is particularly true when it is realized that the shape of the curve is limited by the smaller statistical errors on the points ($\approx 1.5\%$) rather than the full errors shown in Fig. 2. Data from other observers have also been included in Fig. 2. The point at 28 GeV was obtained in this laboratory.[10]
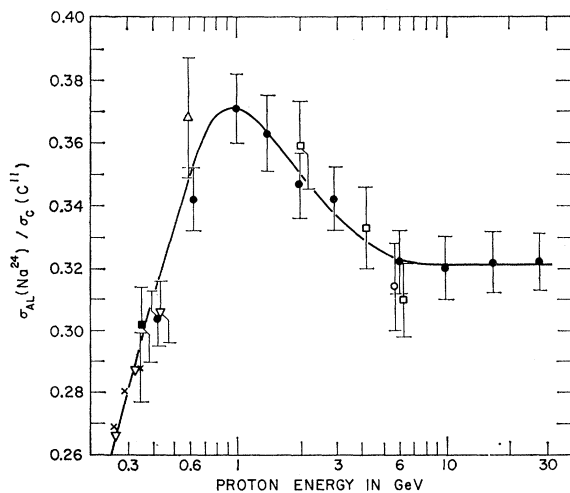

FIG. 2. The σ_{Al}(Na^{24})/σ_C(C^{11}) ratio as a function of bombarding energy. The symbols refer to the work of: this paper and reference 10, (●); P. A. Benioff, reference 14, (○); W. E. Crandall and G. Millburn, reference 15, (□); H. P. Yule and A. Turkevich, reference 16 (▽); W. E. Crandall et al., reference 17, (■); V. Parikh, reference 18, (✕); K. Goebel et al., reference 19, (△).

TABLE III. Retentions of C^{11} by plastic foils assumed in correcting existing data.

Author and reference	Foil material and thickness	C^{11} retention
Benioff (reference 14)	$\approx$0.003-in. polyethylene	88%
Crandall and Millburn (reference 15)	0.005-in. polystyrene	98%
Crandall et al. (reference 17)	polystyrene	98%
Yule and Turkevich (reference 16)	$\approx$0.004-in. polyethylene	88%
Rosenfeld et al. (reference 20)	$\approx$0.0015-in. polyethylene	88%
Burcham et al. (reference 21)	$\approx$0.002-in. polystyrene	96%
Cumming et al. (reference 5)	0.030-in. polystyrene	99.2%

Where necessary, corrections to existing data[14–19] have been applied for loss of C^{11} activity by the plastic foils which had been used. These corrections are summarized in Table III. The existing data of Benioff[14], and Crandall and Millburn[15] in the 2- to 6-GeV region are in good agreement with the present results and confirm the decrease in this region. At the lower energies the present data join smoothly with the ratio measurements of Yule and Turkevich,[16] Parikh,[18] and with the ratio of absolute cross sections measured by Crandall et al.[17] The ratio of absolute measurements at 0.59 GeV reported by Goebel et al.[19] is somewhat high. They used 300-mg/cm^2 polyethylene targets and it is possible that a 1–2% correction for C^{11} loss should be applied in view of the fact that a 3% loss from 150 mg/cm^2 polyethylene has been reported.[8] It is also possible that some low-energy protons may have intercepted the target stacks of the present experiment which would lead to too low a ratio. The curve drawn in Fig. 2 has been drawn slightly above the present points for this reason. This effect should be negligible at 1 GeV and higher energies.

B. Absolute Cross Sections

Absolute values of σ_C(C^{11}) from the literature[5,6,17,19–23] have been plotted in Fig. 3. The data have been corrected to the production rate in normal isotopic carbon and, where necessary, for loss of C^{11} activity by diffusion (see Table III).

[14] P. A. Benioff, Phys. Rev. 119, 316 (1960).
[15] W. E. Crandall and G. P. Millburn (unpublished).
[16] H. P. Yule and A. Turkevich, Phys. Rev. 118, 1591 (1960).
[17] W. E. Crandall, G. P. Millburn, R. V. Pyle, and W. Birnbaum, Phys. Rev. 101, 329 (1956).
[18] V. Parikh, Nuclear Phys. 18, 638 (1960).
[19] K. Goebel, D. Harting, J. C. Kluyver, A. Kusumegi, and H. Schultes, Nuclear Phys. 24, 28 (1961); also reports CERN 60-3 and CERN 60-17, Geneve, 1960 (unpublished).
[20] A. H. Rosenfeld, R. A. Swanson, and S. D. Warshaw, Phys. Rev. 103, 413 (1956).
[21] W. E. Burcham, J. L. Symonds, and J. D. Young, Proc. Phys. Soc. (London) A68, 1001 (1955), and J. L. Symonds, J. Warren, and J. D. Young, ibid. A70, 824 (1957).
[22] V. Parikh, Nuclear Phys. 18, 628 (1960).
[23] J. B. Cumming, G. Friedlander, and S. Katcoff, Phys. Rev. 125, 2078 (1962).

TABLE IV. Cross sections relative to $\sigma_{Al}(Na^{24})$ for producing various nuclides from aluminum and carbon by bombardment with protons.

Proton energy (GeV)	$\sigma_{Al}(F^{18})$	$\sigma_{Al}(C^{11})$	$\sigma_{Al}(N^{13})$[a]	$\sigma_{Al}(Na^{22})$	$\sigma_{Al}(Be^{7})$	$\sigma_{C}(Be^{7})$
0.42	0.71±0.02	0.21±0.01	0.10±0.01			
0.62						0.90±0.07
1	0.77±0.02	0.41±0.02	0.14±0.01			0.86±0.09
2	0.77±0.02	0.55±0.02	0.14±0.01	1.29±0.06		0.93±0.05
2.9	0.75±0.02	0.56±0.02	0.13±0.01	1.21±0.04	0.82±0.04	0.90±0.03
5.7[b]	0.73±0.03	0.57±0.04	0.16±0.02	1.62±0.13	0.79±0.04	1.05±0.07
6	0.76±0.02	0.57±0.02	0.16±0.02			
10	0.74±0.02	0.56±0.02	0.16±0.02			
17	0.73±0.02	0.54±0.02	0.16±0.02			
28[c]	0.72±0.02	0.57±0.02	0.14±0.01	1.18±0.04	0.95±0.03	0.92±0.03

[a] The N^{13} data have been reduced by 0.01 to subtract the contribution of Mg^{27} which was not resolved. This correction is based on preliminary data on the apparent cross section for forming Mg^{27} and the efficiency of the well counter for this nuclide.
[b] From reference 14.
[c] From reference 10.

It has been pointed out that the data obtained in this laboratory at[5] 2 and 3 GeV and at[23] 28 GeV are consistent with a $\sigma_C(C^{11})$ which is independent of energy in this region. The data of Horwitz and Murray[6] at 3, 4.5, and 6 GeV are somewhat higher but the difference is probably within the limits of systematic errors of both measurements. A weighted least-squares line has been drawn in Fig. 3 extending from 27.2 mb at 2 GeV to 26.8 mb at 28 GeV. The $\sigma_C(C^{11})$ curve has been extended smoothly to 0.3 GeV. The shape of the curve from 0.35 to 0.66 GeV is consistent with the relative measurements of Prokoshkin and Tiapkin.[24] Unfortunately, the absolute data of Burcham et al.[21] are sub-

FIG. 3. Absolute cross sections for the $C^{12}(p,pn)C^{11}$ and $Al^{27}(p,3pn)Na^{24}$ reactions. Data points are taken from: J. B. Cumming et al., reference 5, (●); N. Horwitz and J. J. Murray, reference 6, (○); W. E. Crandall et al., reference 17, (▨); K. Goebel et al., reference 19 (△); A. H. Rosenfeld et al., reference 20, (▽); W. E. Burcham, et al., reference 21, (+); V. Parikh, reference 22, (×); J. B. Cumming et al., reference 23, (□); L. Marquez, reference 4, (◇); H. G. Hicks et al., reference 25, (⊠). The $Al^{27}(p,3pn)$-Na^{24} curve has been obtained from the carbon cross section curve and the smooth ratio curve in Fig. 2.

[24] Iu. D. Prokishkin and A. A. Tiapkin, J. Exptl. Theoret. Phys. U.S.S.R. 32, 177 (1957) [translation: Soviet Phys.—JETP 5, 148 (1957)].

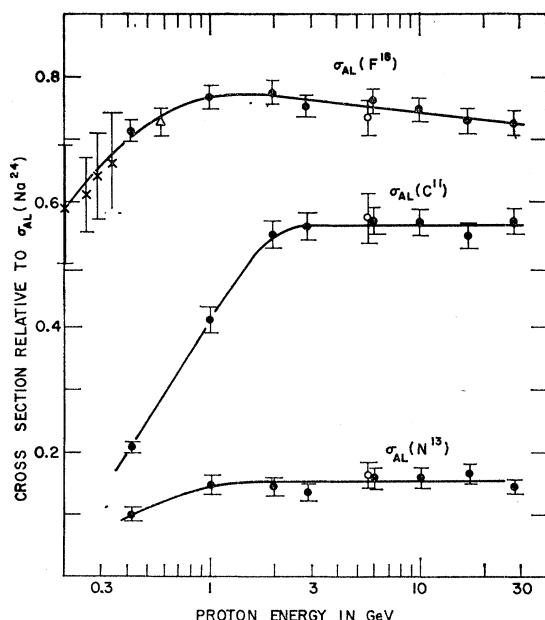ject to large uncertainties due to neutron contamination of their proton beams. Additional data between 0.6 and 2 GeV are desirable to determine the shape of the $\sigma_C(C^{11})$ curve.

The $\sigma_{Al}(Na^{24})$ curve in Fig. 3 has been obtained from the $\sigma_C(C^{11})$ curve and from the smooth ratio curve in Fig. 2. This cross section is nearly energy independent from 28 to 6 GeV and then rises slowly to a plateau value of ≈ 10.7 mb in the region 0.35 to 0.7 GeV. The absence of energy dependence between 0.35 and 0.66 GeV has been reported in the relative data of Prokoshkin and Tiapkin.[24] In the region between 2 and 30 GeV, $\sigma_{Al}(Na^{24})$ given by Fig. 3 has an estimated standard deviation of 6%. Between 2 and 0.8 GeV the uncertainty is larger since no reliable absolute data are available. The $\sigma_{Al}(Na^{24})$ points shown in Fig. 3 at the lower energies are direct absolute measurements.[3,17,19,25] The curve passes within their errors. A more detailed discussion of absolute measurements is beyond the scope of the present work. We have shown that $\sigma_{Al}(Na^{24})$ in the GeV region is lower than at 0.4 GeV, in general agreement with the early indirect measurements.[1,2] Furthermore, it can be seen that the observed maximum in the ratio curve (Fig. 2) does not imply that either $\sigma_C(C^{11})$ or $\sigma_{Al}(Na^{24})$ show such structure.

C. Other Data

The present experiment has also yielded cross sections for producing Na^{22}, F^{18}, N^{13}, C^{11}, and Be^{7} from aluminum and Be^{7} from carbon. The F^{18} and N^{13} were assayed in the same manner as the C^{11} and the same efficiency was assumed. The fraction of F^{18} nuclei, which decay by positron emission, was taken to be 0.97. The counting techniques for determining Be^{7} and Na^{22} were the same as described previously.[10,25a] The final results are presented in Table IV as cross sections relative to $\sigma_{Al}(Na^{24})$. Some

[25] H. G. Hicks, P. C. Stevenson, and W. E. Nervik, Phys. Rev. 102, 1390 (1956).
[25a] Note added in proof. Recent measurements [J. G. V. Taylor and J. S. Merritt, Can. J. Phys. 40, 926 (1962)] indicate that the gamma branching ratio of Be^{7} is 0.103 instead of 0.12 as used in this paper and reference 10. Thus, the Be^{7} cross sections should be multiplied by 1.16.

FIG. 4. Cross sections for producing F^{18}, N^{13}, and C^{11} from aluminum, relative to σ_{Al}(Na^{24}). Data points are taken from: this work and reference 10, ($\bullet$); P. A. Beinoff, reference 14, ($\circ$); V. Parikh, reference 18, ($\times$); and K. Goebel et $al.$, reference 19, ($\triangle$).

of the data are also plotted in Fig. 4. The agreement with recently published data is generally good. The present experiment, however, has found a significantly lower relative Na^{22} yield from aluminum at 2 and 2.9 GeV than has been reported by Benioff[14] at 5.7 GeV. The σ_{Al}(Na^{22}) and σ_C(Be^{7}) should be of use in monitoring beam intensities in irradiations too long for practical use of σ_{Al}(Na^{24}). The values of σ_{Al}(F^{18}) and σ_{Al}(C^{11}) may be of use in irradiations of thick targets where secondary particles may contribute significantly to Na^{24} production.

CONCLUSIONS

The tentative conclusions on the energy dependence of cross sections of reactions in light target nuclei which were drawn in a previous paper[10] may now be examined in more detail, since the present data have been obtained under nearly identical experimental conditions. From the results presented above, it is clear that the cross sections for forming, in aluminum, products having masses between 11 and 24 (i.e., C^{11}, N^{13}, F^{18}, Na^{22}, and Na^{24}) exhibit nearly the same energy dependence between ≈ 2 and 28 GeV, which is illustrated by σ_{Al}(Na^{24}) in Fig. 3. That is, small decreases in cross sections may occur between ≈ 2 and ≈ 6 GeV, but the cross sections stay essentially constant above 6 GeV. The production of Be^{7} and C^{11} from carbon is nearly independent of energy over an even wider range. The sole exception to this trend is the σ_{Al}(Be^{7}) which increases from 7.5 mb at 2.9 GeV to 8.2 mb at 28 GeV. However, it is quite possible that other products in the low mass region ($A \leq 10$) which have not been observed may also show increases in the same energy region.

The general lack of any strong energy dependence of these cross sections in aluminum and carbon implies that increasing the kinetic energy of the projectile from 3 to 28 GeV does not result in any marked change in the deposition energy spectrum or the number of cascade nucleons. [Some slight increase in deposition energy may be deduced from the increase of σ_{Al}(Be^{7}).] The additional energy presumably appears as an increase in the number and energy of the mesons produced in the intranuclear cascade. These mesons must be relatively inefficient in transferring energy to the target nucleus. It has been pointed out[26] that the role of meson production and reabsorption in the intranuclear cascade has a much larger effect on the deposition-energy spectrum in a heavy targer nucleus than in a light one. The present results may just reflect the high probability of meson escape from small target nuclei.

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