[3] J. S. Levinger, *Nuclear Photodisintegration* (Oxford Univ. Press, Oxford, England, 1960), pp. 97, 127.

[4] A. N. Gorbunov and V. M. Spiridonov, Zh. Eksp. Teor. Fiz. 34, 866 (1958) [Sov. Phys. JETP 34, 600 (1958)].

[5] An alternative to the use of Levinger's method in the calculation of the ^{4}He$(\gamma,pn)d$ amplitude is possible starting with a ^{4}He ground-state wave function which includes nucleon pair correlations together with the nucleon pair electromagnetic operator of M. Danos and E. G. Fuller, Annu. Rev. Nucl. Sci. 15, 29 (1967). This approach has been followed by T. E. Kopaleishvili and R. I. Dzhibuti, Zh. Eksp. Teor. Fiz. 42, 467 (1962) [Sov. Phys. JETP 15, 327 (1962)].

[6] J. S. Levinger, Phys. Rev. 84, 43 (1951).

[7] R. F. Frosch *et al.*, Phys. Rev. 160, 874 (1967).

[8] D. R. Lehman, Phys. Rev. C 6, 2023 (1972).

[9] The $E1$ term from effective range and a phenomenological fit for the $E2$ term were used so that an analytic off-shell deuteron photoamplitude was readily available for the calculation of the triangular diagram [Eq. (4)]. This with the addition of isotropic terms reproduces the physical amplitude used in Eq. (1). Isotropic terms do not contribute directly to the asymmetry coefficient.

Measurement of Charged-Pion Production by 7.28-GeV Nitrogen Ions*

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(Received 25 July 1974)

Cross sections for charged–pi-meson production by 7.28-GeV nitrogen ions on elemental targets were measured at a laboratory angle of 15° at the Princeton Particle Accelerator. At pion energies of ~ 260 and ~ 415 MeV, the data show the $A^{1/3}$ dependence predicted by an "effective number of nucleons" model. For π^- energies above ~ 415 MeV, the measured cross sections exceed those calculated from nucleon-nucleus data, even after the inclusion of Fermi-motion effects.

Double-differential cross sections for π^- production by 7.28-GeV ^{14}N nuclei (520 MeV/amu) were measured at a laboratory angle of 15° as a function of π^- energy. The dependence of these cross sections on target atomic weight A was measured at π energies of 257 and 415 MeV, for both π^- and π^+, on eight elemental targets. Polyethylene and Teflon targets were also used to obtain the H and F cross sections by subtraction.

The ^{14}N beam was extracted from the Princeton Particle Accelerator.[1] The experimental arrangement is shown in Fig. 1. A magnet ($M2$) was used to provide momentum analysis and the pion time of flight (TOF) was measured downstream with a counter telescope.[2] A pion event was defined by signals from three scintillators and a Cherenkov counter. The data were normalized by using two argon-filled ionization chambers in the primary ^{14}N beam.[3]

For each run, the normalized "target-out" TOF spectrum was subtracted from that for "target in." The former generally was less than 20% of pion events. The data then were corrected for the efficiency of the Cherenkov counter and the number of detected pions was obtained by integrating the events under the remaining pion TOF peak.

The TOF spectra were only used to eliminate background due to slow particles, and not to determine the pion velocity. The electron contamination was not measured directly, but is estimated to be less than 5%, based on target characteristics and published measurements of relative electron fluxes.[4]

The nitrogen beam intensity was ~ 5×10^5/sec during this experiment, and typically five pion events per second were observed. The experimental errors associated with data points are between 6 and 10%. These include the effect of the background subtraction, Cherenkov-counter efficiency, and the TOF cuts used to define the pion peak.

The following possible sources of systematic errors were considered: (1) monitor normalization, (2) acceptance calculation, and (3) mean pion energy and energy spread.

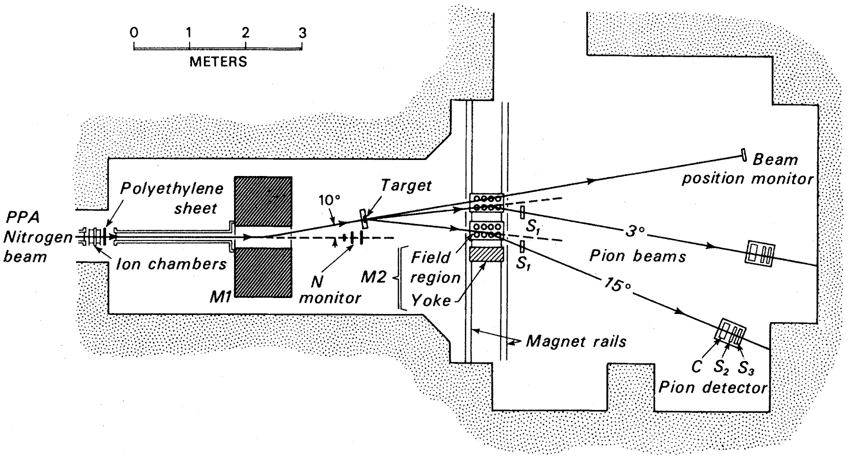

FIG. 1. Experimental layout. S_1, S_2, and S_3: scintillation counters; C: Plexiglas Cherenkov counter. Two dipole magnets were used: $M1$ to deflect the primary nitrogen ion beam, and $M2$ to define the momentum of the pion beams. Overall normalization for the experiment was provided by the ionization chambers in the primary beam. A relative-beam-intensity monitor was provided by the "N monitor," which detected neutral particles produced in the polyethylene sheet.

The monitor-normalization uncertainty of 7.1% stems from the uncertainty in the accuracy of the ionization-chamber calibrations[3] (6.7%) and the precision of their output (2.5%). The normalization of the data taken during the early runs has a further systematic uncertainty. This was associated with a beam misalignment detected after about 40% of the data had been collected and a failure of the electronic gating circuits due to overheating. The net effect was a systematic shift in the observed detection efficiency of a factor of 1.90 ± 0.08 as obtained from a direct comparison of runs before and after the discontinuity. The "early" data and their errors have been scaled by the above factor and its estimated uncertainty. Residual systematic effects are believed to be negligible because of the following: (1) The ionization chambers were calibrated near the end of the experiment, by using a carbon activation measurement of the absolute beam intensity. This calibration agreed with their calculated response, and with a prior x-ray calibration. (2) A preliminary test of this experiment was made by using entirely different apparatus.[2] The errors associated with the preliminary data are larger (~ 20%). However, a χ^2 test indicates that the data belong to the same set with a 60% probability. (3) No systematic discrepancy between "early" and "late" data is found, either as a function of pion energy or target atomic weight.

The detector position and magnet setting defined an acceptance function (the fraction of π's produced that are detected) which covered a band of pion energies, occasionally as large as ± 30% from the mean energy. Corrections to the calculated acceptance included (1) π decay, (2) detection of μ's, (3) Coulomb scattering, and (4) nuclear scattering.[2] All of these corrections are energy dependent, and the latter two are dependent on the production target material. The acceptance uncertainty (7.6%) has three dominant contributions: (1) The solid-angle calculation has an uncertainty of 5.4% which includes the uncertainty inherent in the vertical-focus correction and the error due to the precision of the method of calculation. (2) The uncertainty in the magnetic field was 5%. (3) The uncertainty in the corrections was less than 2%.

Figure 2 shows the measured differential cross sections for π^- pions of 257 and 415 MeV, and for π^+ at 411 MeV taken at 15°, as a function of the target atomic weight. The cross sections are seen to agree well with an $A^{1/3}$ dependence, as would be expected for an interaction localized on the nuclear surface.[5]

It is necessary to account for the effects of Fermi motion in the interacting nuclei to compare the cross section as a function of energy with nucleon-nucleon data. Insofar as the target is concerned, we have assumed that these effects are included in measurements of nucleon-*nucleus* cross sections. The following momentum distri-

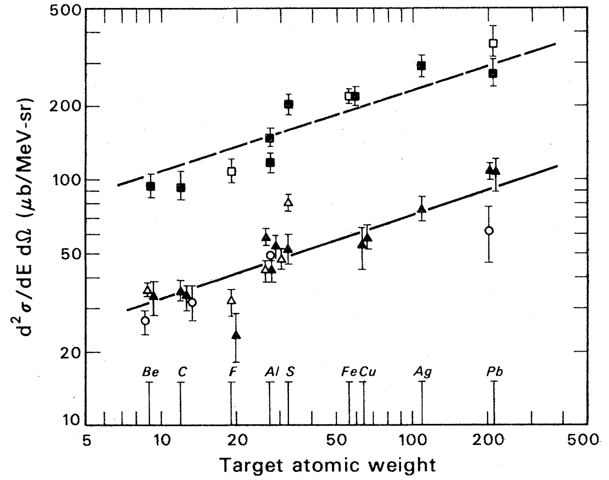

FIG. 2. Measured double-differential π production cross sections as a function of target atomic weight for 7.28-GeV incident ^{14}N ions giving 247- and 415-MeV π^- and 411-MeV π^+ at a 15° laboratory angle. Squares: $T_{\pi^-}=257$ MeV; triangles: $T_{\pi^-}=415$ MeV; circles: $T_{\pi^+}=411$ MeV. The open symbols are "early" data, scaled as described in the text; the filled symbols are unscaled data. The lines have a slope of $A^{1/3}$ and were hand-fitted to the data.

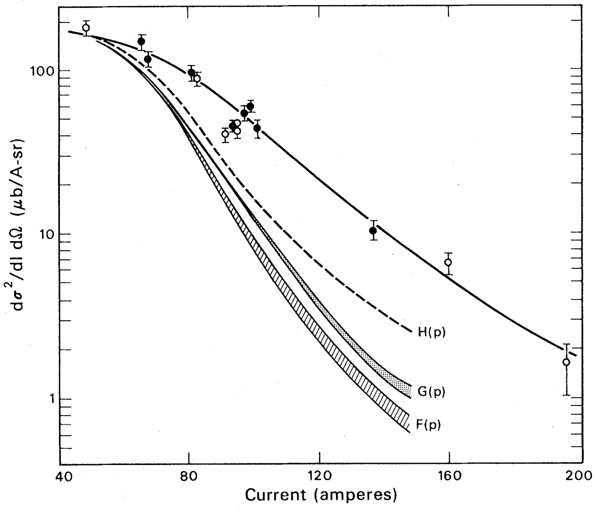

FIG. 3. Differential cross section for π^- production as a function of the current in the momentum-analyzing magnet (I). The open circles are "early" data, scaled as described in the text; the filled circles are unscaled data. The curves are calculated by using the functional forms indicated for the projectile momentum distribution. The $F(p)$ curve was calculated by using $g_1(p)$ in Eq. (1). $H(p)$ corresponds to the projectile momentum distribution of Eq. (2), and $G(p)$ is based on a simple Gaussian distribution, calculated by using $g_2(p)$ in Eq. (1).

butions were postulated for the nucleons in the projectile nucleus:

$$f_1(\vec{p})\,d^3p \propto \{[1+\exp g_i(p)]\}^{-1}d^3p, \qquad (1)$$

where $\vec{p}$ is the momentum in the projectile frame of reference, $i=1$ or 2, and $g_1(p)=(p-p_0)/\lambda$, $g_2(p)=(p^2-p_0^2)/\lambda$.

A distribution of the form of Eq. (1), with $g_1(p)$, was used successfully by Piroue and co-workers[6] to fit measurements of antiproton production below the nominal nucleon-nucleus threshold. The parameter p_0 was obtained from the average nucleon energy due to Fermi motion. The width used was $\lambda = 0.05$ GeV/c.

A second distribution, reported to give acceptable fits in some cases,[6,7] was also tried:

$$f_2(\vec{p})\,d^3p \propto [(p^2+\alpha^2)(p^2+\beta^2)]^{-1}d^3p, \qquad (2)$$

where $\alpha = 0.047$ GeV/c and $\beta = 7\alpha$ as used in Ref. 6.

These distributions were integrated over momenta perpendicular to the direction of motion and transformed into the laboratory frame of reference. The relative width of the distribution (λ/p) was kept constant under the transformation.

The π^- production cross section for a given π^- energy and incident nucleon momentum was computed by interpolation of p-nucleus data[5,8] (n-nucleus data are only available at one neutron energy in our range[4]). The neutron and proton contributions to π^- production were added by using the π^+/π^- ratios given by the isobar model.[9,10] These "nucleon-nucleus" double-differential cross sections were then scaled by the "effective number of nucleons" contributing to the interaction.[5,11,12] Finally, the cross sections were folded with one of the laboratory momentum distributions to give a "Fermi-smeared" nucleus-nucleus differential cross section, σ_F.

The measured π^- cross sections for aluminum are presented in Fig. 3 directly as a function of spectrometer-magnet ($M2$) current. To eliminate the uncertainty involved in unfolding the acceptance from the measured pion spectrum, σ_F was folded with the known acceptance. The measured π^- production cross sections at $M2$ currents above ~90 A can be seen to be significantly larger than the calculation based on nucleon-nucleus data predicts. This corresponds to π^- energies above ~415 MeV. Similar results were obtained for a lead target, where data were collected up to 160 A (nominally ~600 MeV). Data for other targets were only obtained at lower pion energies. The resolution of our apparatus was so broad that it was not possible to investigate the mechanism for this effect.

It would have been desirable to measure the cross sections as a function of A at the higher pion energies to ascertain whether deviations from the $A^{1/3}$ dependence exist. Such deviations might point toward the existence of "coherent" effects[13-16] (volume effects, which also would produce deviations from this dependence,[17] are not likely to affect the high-energy pion tail). Alternatively, the observed discrepancy may indicate the emission of pions from nuclear excited states of the incident projectile (or from a residual fragment). A similar effect has been observed[18,19] for proton-induced π^- production on D, He, C, and N targets. The interpretation in terms of residual excited states in this case is also supported by theory.[20]

It is a pleasure to thank Professor Milton G. White for his encouragement and support, Mr. Marius Isaila and Mr. Joseph Fennimore for their help during parts of this experiment, and the entire Princeton Particle Accelerator staff for their devotion and achievement in the face of the imminent shutdown of the facility. The experiment was made possible by the generous support of the Fannie E. Rippel Foundation, the Princeton University Physics Department, and the assistance of the U. S. Atomic Energy Commission.

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*Work supported by the Fannie E. Rippel Foundation and Grant No. AT-(30-1)-3071 (University of Pennsylvania). The three Princeton authors were supported by the Princeton University Physics Department during the early stages of the data analysis.

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[1] M. G. White, M. Isaila, K. Prelec, and H. L. Allen, Science 174, 1121 (1971); M. V. Isaila, W. Schimmerling, K. G. Vosburgh, M. G. White, R. C. Filz, and P. J. McNulty, Science 177, 424 (1972).

[2] See K. Koepke, Ph.D. thesis, New York University, 1973 (unpublished), for additional details.

[3] W. Schimmerling, K. G. Vosburgh, A. Appleby, and P. W. Todd, to be published.

[4] K. O. Oganesyan, Zh. Eksp. Teor. Fiz. 54, 1273 (1968) [Sov. Phys. JETP 27, 679 (1968)].

[5] W. Hirt, E. Heer, M. Martin, E. G. Michaelis, C. Serre, P. Sharek, and B. T. Wright, European Organization for Nuclear Research Report No. CERN 69-24, 1969 (unpublished).

[6] P. A. Piroue and A. J. S. Smith, Phys. Rev. 148, 1315 (1966); see also D. E. Dorfan, J. Eades, L. M. Lederman, W. Lee, C. C. Ting, P. Piroue, M. Stuart Smith, J. L. Brown, J. A. Kadyk, and G. H. Trilling, Phys. Rev. Lett. 14, 995 (1965).

[7] G. F. Chew and M. L. Goldberger, Phys. Rev. 77, 470 (1950).

[8] D. R. F. Cochran, P. N. Dean, P. A. M. Gram, E. A. Knapp, E. R. Martin, D. E. Nagle, R. B. Perkins, W. J. Shlaar, H. A. Thiessen, and E. D. Theriot, Phys. Rev. D 6, 3085 (1972).

[9] S. J. Lindenbaum and R. M. Sternheimer, Phys. Rev. 105, 1874 (1957).

[10] L. C. L. Yuan and S. J. Lindenbaum, Phys. Rev. 103, 404 (1956).

[11] B. Margolis, Nucl. Phys. B4, 433 (1968), and Phys. Lett. 26B, 524 (1968).

[12] K. S. Kolbig and B. Margolis, Nucl. Phys. B6, 85 (1968).

[13] J. Jaros, J. Papp, L. Schroeder, J. Staples, H. Steiner, and A. Wagner, in *Proceedings of the Fifth International Conference on High-Energy Physics and Nuclear Structure, Uppsala, Sweden, 1973,* edited by G. Tibbell (Elsevier, New York, 1974), p. 407

[14] A. M. Baldin, N. Ghiodanescu, A. D. Kirillov, V. A. Kuznetsov, N. S. Moroz, V. B. Radomanov, V. N. Ramazhin, V. N. Stavinsky, V. A. Sviridov, M. I. Yatsuta, and V. N. Zubarev, in *Particles and Fields—1971,* edited by A. C. Melissinos and P. F. Slattery, AIP Conference Proceedings No. 2 (American Institute of Physics, New York, 1971), p. 131.

[15] C. Bemporad, W. Beusch, A. C. Melissinos, E. Polgar, D. Websdale, J. D. Wilson, J. P. Dufey, K. Freudenreich, R. Frosch, F. X. Gentit, P. Muehlemann, J. Codling, J. G. Lee, M. Letheren, G. Bellini, M. di Corato, and G. Vegni, Nucl. Phys. B33, 397 (1971).

[16] C. Bemporad, W. Beusch, A. C. Melissinos, E. Polgar, D. Websdale, J. P. Dufey, K. Freudenreich, R. Frosch, F. X. Gentit, P. Muehlemann, J. Codling, J. G. Lee, M. Letheren, G. Bellini, M. di Corato, and G. Vegni, Nucl. Phys. B42, 627 (1972).

[17] M. M. Sternheim and R. R. Silbar, Phys. Rev. D 6, 3117 (1972), and Phys. Rev. C 8, 492 (1973).

[18] K. Gabathuler, J. Rohlin, J. J. Domingo, C. H. Q. Ingram, S. Rohlin, and N. W. Tanner, Nucl. Phys. B40, 32 (1972).

[19] J. J. Domingo, B. W. Allardyce, C. H. Q. Ingram, S. Rohlin, N. W. Tanner, J. Rohlin, E. Rimmer, G. Jones, and J. P. Giradeau-Montant, Phys. Lett. 32B, 309 (1970).

[20] J. M. Eisenberg, R. Guy, J. V. Noble, and H. J. Weber, Phys. Lett. 45B, 93 (1973).