on the production of W's, etc., one requires plausible models for production and decay, a commodity in rare supply these days. Data on massive-photon production would be even more useful.[4]

It is a pleasure to thank the staff of the Fermi National Accelerator Laboratory and especially of the proton section for their efforts. We are also deeply indebted to Mr. T. E. Nurczyk, Mr. F. H. Pearsall, and Mr. S. J. Upton and the Nevis Laboratories for their help in the design and implementation of the apparatus.

*Permanent address: Laboratoire de l'Accélérateur Linéaire, Orsay, France.

†Present address: Rutherford High Energy Laboratory, Chilton, Didcot, Berkshire, England.

‡Research supported by the National Science Foundation.

§Research supported by the U.S. Atomic Energy Commission.

[1]A preliminary report of this work has been given: H. P. Paar et al., Bull. Amer. Phys. Soc. 19, 446 (1974).

[2]L. M. Lederman and D. H. Saxon, Nucl. Phys. B63, 313 (1973).

[3]J. A. Appel et al., preceeding Letter [Phys. Rev. Lett. 33, 719 (1074)].

[4]Such an experiment is scheduled to run at Fermi National Accelerator Laboratory (E-288) in late 1974.

[5]See, for example, G. R. Farrar, California Institute of Technology Report No. CALT-68-422, 1974 (to be published); H. P. Paar and E. A. Paschos, Phys. Rev. D (to be published); R. Savit and M. B. Einhorn, Phys. Rev. Lett. 33, 392 (1974).

[6]J. P. Boymond et al., post-deadline paper presented at the Spring Meeting of the American Physical Society, Washington, D.C., 22–25 April 1974 (unpublished), and Phys. Rev. Lett. 33, 112 (1974).

[7]D. Bintinger et al., post-deadline paper presented at the Spring Meeting of the American Physical Society, Washington, D.C., 22–25 April 1974 (unpublished).

[8]F. W. Busser et al. (CERN–Columbia University–Rockefeller University–Saclay Group), in Proceedings of the Seventeenth International Conference on High Energy Physics, London, England, 1–10 July, 1974 (to be published), and private communication.

Neutron-Proton Total Cross Sections from 30 to 280 GeV/c*

Michael J. Longo, Cyril A. Ayre, H. Richard Gustafson, Lawrence W. Jones, P. V. Ramana Murthy,† and Patrick Skubic
Department of Physics, University of Michigan, Ann Arbor, Michigan 48104

and

Bruce Cork
Lawrence Berkeley Laboratory, University of California, Berkeley, California 74720
(Received 1 July 1974)

We present results of measurements of the n-p total cross section between 30 and 280 GeV/c. The measurements were carried out with a neutron beam by using the standard transmission technique and a liquid-hydrogen target. A total-absorption calorimeter was used to determine the neutron energy. Our measurements, which have an accuracy of ~1%, indicate a smooth rise of approximately 1.5 mb between 50 and 280 GeV/c. The combined n-p and p-p data above 20 GeV/c are well fitted by the expression $\sigma = 38.4 + 0.85\,|\ln(s/95)|^{1.47}$ mb.

In this article we present the results of a series of measurements of neutron-proton total cross sections from 30 to 280 GeV/c. The measurements were carried out in a neutron beam at the Fermi National Accelerator Laboratory. The standard transmission technique was employed with a 1.2-m liquid-hydrogen target. A total-absorption ionization calorimeter was used to detect the neutrons and measure their energy.

The neutron beam was taken off at an angle of 1 mrad from a beryllium target in the external proton beam. Most of the data were taken with an incident proton momentum of 300 GeV/c; some data were also taken with 200-GeV/c protons. The beam was defined by a steel collimator 1.58 mm in diameter, placed 198 m from the production target. Sweeping magnets before and after the defining collimator removed charged particles from the beam. Two lead filters, one 5 cm thick ahead of the defining collimator and the other 1.3 cm thick following the collimator, removed most of the high-energy γ rays. The

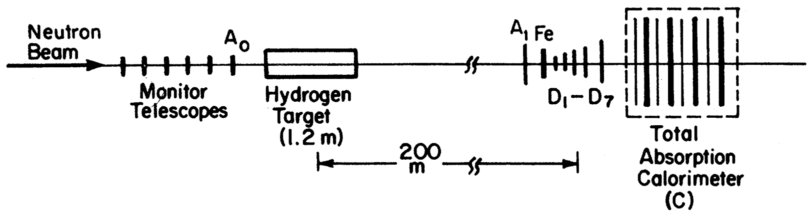

FIG. 1. Schematic of experimental arrangement. *Not to scale.*

neutron spectrum peaked strongly near 230 GeV/c. Below about 100 GeV/c, the beam contained a significant admixture of $\bar{n}$'s, K^{0}'s, and γ rays.[1]

The experimental arrangement is shown schematically in Fig. 1. Relative beam intensity was measured by two monitor telescopes placed in the beam just ahead of the hydrogen target. Each telescope consisted of a veto counter followed by a 1.6-mm-thick Lucite converter and three small scintillation counters in triple coincidence. The liquid-hydrogen target was a flask 1.2 m long and 5 cm in diameter operated near atmospheric pressure. Mounted next to the target in the same vacuum jacket was an evacuated dummy target. During data taking the two targets were interchanged about once per minute. The length of the target was found to be 121.53 ± 0.03 cm at liquid-hydrogen temperature.[2] The target pressure was monitored continuously so that the hydrogen density could be determined accurately. Sufficient time elapsed between filling the target and taking data to insure that the orthohydrogen-to-parahydrogen transition was complete. Hydrogen-density and vapor-pressure data were taken from a recent U. S. National Bureau of Standards compilation.[3] The uncertainty in the final cross sections due to uncertainties in the target length, density, hydrogen purity, and other target properties is estimated to be $< 0.2\%$.

The ratio of the beam transmitted by the hydrogen target to that by the dummy target was measured by placing a 1.25-cm iron converter in the beam, followed by seven circular transmission counters and a total-absorption calorimeter (see Fig. 1). The transmission counters D_1–D_7 ranged from about 1 to 5 cm in radius, compared to the beam radius of approximately 0.2 cm. The smallest counter was in contact with the iron converter and the largest was about 1.3 cm away. Charged particles formed by neutron interactions in the iron converter tend to go nearly along the direction of the incident neutron so that the transmission counters saw a charged-particle distribution which closely approximated the distribution of transmitted neutrons at the iron converter.[4]

The calorimeter was placed just downstream of the transmission counters and provided a measure of the energy of the incident neutron. The calorimeter and its properties are discussed by Jones *et al.*[5] Briefly, it consisted of thirty iron plates, each 30 g cm^{-2} thick, interspersed with thirty scintillators. The light output from the scintillators was optically added and brought to four RCA 8575 phototubes. The summed output pulse from these was roughly proportional to the energy of the incident neutron. Measurements taken with a monoenergetic proton beam show that the calorimeter had an energy resolution (standard deviation) of 12 GeV at 200 GeV and 17 GeV at 300 GeV.

A total of 64 coincidences of various kinds were scaled and recorded. Most of these were of the type $\bar{A}_0\bar{A}_1 D_j D_{j+1} C_i$, where A_0 and A_1 are the veto counters shown in Fig. 1 and C_i represents a pulse from one of seven discriminators which were set to trigger only if the pulse height from the calorimeter exceeded some minimum δ_i. The δ_i corresponded to energies deposited in the calorimeter of approximately 14, 52, 104, 154, 206, 231, and 252 GeV/c. The neutron spectrum could thus be divided into the seven momentum ranges given in Table I by subtracting counts in successive momentum bins (e.g., $\bar{A}_0\bar{A}_1 D_j D_{j+1} C_i - \bar{A}_0\bar{A}_1 D_j D_{j+1} C_{i-1}$). The other scaler channels recorded the beam monitors, accidental coincidences of various kinds, singles rates, proton beam intensity, etc.

The scaler counts were recorded on magnetic tape after every beam pulse. This allowed the later editing of occasional bad beam pulses. Data were taken in "runs" lasting from 30 to 90 min. For each run the pulse-to-pulse variations in scaler-to-monitor ratios were checked. These were consistent with expected statistical fluctuations in most cases; if not, a larger error was

TABLE I. Measured cross sections and corrections.

Momentum Range (GeV/c) Min.	Max.	Mean	σ (D_1D_2)[a] (mb)	Typical Rate Correction (mb)	Extrap. to zero solid angle (mb)	Beam Contam. Corr. (mb)	Total Cross section (mb)	Average
252	300	273	40.20±0.22	(-0.8±0.06)	+0.12±0.06		40.32±0.23	
231	252	240	39.58±0.23	(0±0.05)	+0.08±0.04		39.66±0.24	
206	231	215	39.71±0.23	(+0.2±0.06)	+0.08±0.04		39.79±0.24	
154	206	180	39.55±0.19	(+0.3±0.06)	+0.07±0.04		39.62±0.20	39.52±0.18
154	206	175[b]	39.17±0.36	(-0.4±0.22)	+0.04±0.02		39.21±0.36	
104	154	131	38.78±0.22	(+0.25±0.06)	+0.09±0.05	+0.27±0.08	39.14±0.24	39.17±0.19
104	154	133[b]	39.10±0.30	(+0.25±0.20)	+0.06±0.03	+0.05±0.04	39.21±0.30	
52	104	80	37.56±0.25	(+0.3±0.07)	+0.11±0.06	+1.35±0.37	39.02±0.45	38.98±0.33
52	104	80[b]	38.30±0.34	(+0.25±0.20)	+0.22±0.07	+0.43±0.20	38.95±0.40	
14	52	34	34.52±0.38	(+0.20±0.10)	+0.37±0.15	+2.95±0.81	37.84±0.91	38.2±0.9
14	52	34[b]	35.09±0.60	(+0.15±0.41)	+1.5±0.35	+2.23±0.84	38.82±1.09	

[a] Corrected for rate effects. [b] Taken with a 200-GeV proton beam.

assigned or the data were rejected. The final sample includes data from 80 runs with 300-GeV/c incident protons and 40 runs with 200-GeV/c protons. Over the course of the measurements, which spanned about 10 months, accelerator performance (in particular, duty cycle and beam stability) improved markedly. Despite the wide range of conditions the measured cross sections showed a high degree of consistency after small corrections for a rate effect were made as discussed below. Corrections to the cross sections were ~1% except for the lowest momentum bin. These are described below and numerical values are given in Table I.

Rate effects.—Because we are making cuts on the neutron pulse-height spectrum to determine the neutron energy, any shift in the pulse-height spectrum between target empty and target full will cause a systematic error in the cross sections. Some variation of the cross sections with beam rate was observed. This was due to pileup of pulses from the calorimeter[6] which occurs more frequently with the target empty. This effect is expected to give an error which is a nearly linear function of beam rate. Corrections were made by extrapolating the cross sections linearly to zero rate. Table I gives typical values for this correction.

Finite solid angle.—The measured cross sections were extrapolated to zero solid angle in the usual way. The smallest counter subtended an extremely small solid angle so that this correction was quite small as shown in Table I.

Beam contamination.—The lowest three energy bins contained a nonnegligible admixture of K^0's. The procedure for determining the fraction of K^0's in the beam and the K^0 total cross sections is described in Ref. 1. The lowest energy bin also contained a significant admixture of γ rays and $\bar{n}$'s. The $\bar{n}/n$ ratio was assumed to be the same as the $\bar{p}/p$ ratio in a similar charged beam.[7] Because this assumption is open to question, a large uncertainty was assigned to this correction.

The final cross sections are given in Table I. The assigned errors include the statistical errors and the uncertainties in the rate corrections, the extrapolation to zero solid angle, and the beam contamination, all combined in quadrature. Our results are compared to available n-p data[8] and p-p data[9] in Fig. 2. Our data connect smoothly

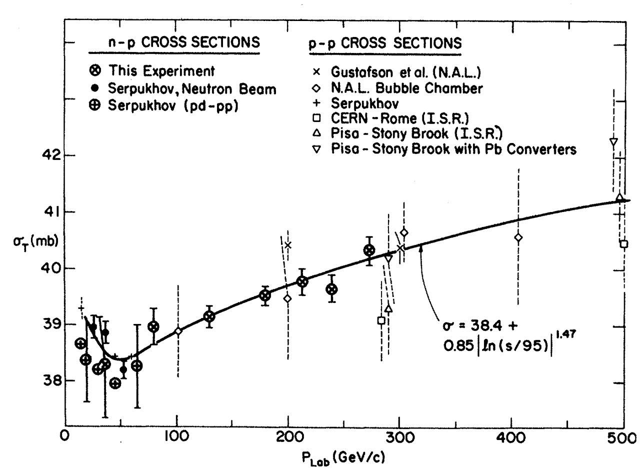

FIG. 2. n-p and p-p total cross sections. Not all the data below 60 GeV/c are shown.

to the lower-energy n-p data. They indicate a smooth rise of about 1.5 mb in the n-p total cross section between 50 and 280 GeV/c. In general, the n-p and p-p total cross sections seem to be approximately equal over the range 30 to 300 GeV/c. Our highest-energy n-p points agree farily well with the p-p total cross sections at 200 and 300 GeV/c measured previously by our group.[10] The combined n-p and p-p data above 20 GeV/c can be well fitted with the expression $\sigma = 38.4 + 0.85|\ln(s/95)|^{1.47}$ mb.

We would like to express our gratitude to the National Accelerator Laboratory staff for their help and cooperation. We also wish to thank F. Ringia, D. Koch, J. Stone, J. Chanowski, and C. DeHaven for their invaluable help in various aspects of the experiment.

*Work supported by the National Science Foundation and the U. S. Atomic Energy Commission.

†On leave from Tata Institute for Fundamental Research, Bombay, India.

[1]For a detailed description of the beam see, M. J. Longo *et al.*, University of Michigan Report No. UM HE 74-18 (unpublished).

[2]The target length was measured at room temperature and at liquid-nitrogen temperature. Since the flask was made of a known aluminum alloy, the length at hydrogen temperature could be easily calculated from thermal-expansion data. The change in length from nitrogen to hydrogen temperature was only 0.2%.

[3]H. M. Roder *et al.*, *Survey of the Properties of the Hydrogen Isotopes below Their Critical Temperatures*, U. S. National Bureau of Standards Technical Note No. 641 (U. S. GPO, Washington, D. C. 1973).

[4]Because of the finite opening angle of the cone containing the charged secondaries, the effective size of the transmission counters was somewhat larger than their geometrical size. The effective size was determined by scanning the beam stepwise across the iron converter. This gave the probability of detecting a neutron as a function of distance from the beam axis.

[5]L. W. Jones *et al.*, University of Michigan Report No. UM HE 73-24 (to be published).

[6]This is a partial coincidence of two pulses from the calorimeter which shifts one or both pulses to a higher energy bin.

[7]W. F. Baker *et al.*, "Measurement of π^+, $K^\pm$, p, and $\bar{p}$ Production by 200 and 300 GeV/c Protons" (to be published).

[8]Serpukhov neutron-beam data: A. Babaev *et al.*, Institute of Theoretical and Experimental Physics Report No. ITEP-11 (to be published). Serpukhov pd-pp data: Yu. P. Gorin *et al.*, Sov. J. Nucl. Phys. 17, 157 (1973).

[9]References to the p-p total cross section data are given by H. R. Gustafson *et al.*, Phys. Rev. Lett. 32, 441 (1974). The 300-GeV/c bubble-chamber measurement is that of A. Firestone *et al.*, Phys. Rev. D (to be published). Their result is 40.68 ± 0.55 mb.

[10]Gustafson *et al.*, Ref. 9.

Pion-Nucleon Form Factor in the Chew-Low Theory*

C. B. Dover
Brookhaven National Laboratory, Upton, New York 11973

and

D. J. Ernst, R. A. Friedenberg, and R. M. Thaler
Physics Department, Case Western Reserve University, Cleveland, Ohio 44106
(Received 1 July 1974)

We suggest a form of the off-shell pion-nucleon amplitude which is motivated by simple field-theoretic considerations. This amplitude contains a momentum-dependent form factor $v(k)$ which we determine by solving an inverse scattering problem, using the experimental phase shifts and inelasticities as input.

Phenomenological pion-nucleon interactions have been of the form of zero-range interactions,[1] of separable energy-independent potentials,[2] and of separable energy-dependent potentials.[3] Each approach yields a different off-shell two-body T matrix, even though the on-shell data may be reproduced. The sensitivity of the pion-nucleus cross sections to the off-shell behavior has been explored by various authors.[4]

Here, we attempt a somewhat more fundamental view. We seek as much guidance as possible from an underlying field theory, even though such guidance may be incomplete. We use a nonrelativistic