†Research sponsored by the U. S. Atomic Energy Commission under contract with Union Carbide Corporation.

[1]G. W. Greenlees, V. Hnizdo, O. Karban, J. Lowe, and W. Makofske, Phys. Rev. C 2, 1063 (1970); G. W. Greenlees, G. J. Pyle, and Y. C. Tang, Phys. Rev. 171, 1115 (1968).

[2]N. Austern, *Direct Nuclear Reaction Theories* (Interscience, New York, 1970).

[3]G. E. Brown, *Unified Theory of Nuclear Models and Forces* (Wiley, New York, 1967).

[4]M. Reeves and L. W. Owen, J. Comput. Phys. 4, 572 (1969).

[5]D. Slanina and H. McManus, Nucl. Phys. A116, 271 (1968).

[6]The optical model search code GENOA of F. G. Perey was used.

[7]M. P. Fricke, E. E. Gross, B. J. Morton, and A. Zucker, Phys. Rev. 156, 1207 (1967); C. B. Fulmer, J. B. Ball, and A. Scott, Phys. Lett. 24B, 505 (1967); G. R. Satchler, Nucl. Phys. A92, 273 (1967); F. D. Becchetti and G. W. Greenlees, Phys. Rev. 182, 1190 (1969).

[8]G. R. Satchler, in *Isospin in Nuclear Physics,* edited by D. H. Wilkinson (North-Holland, Amsterdam, 1969).

[9]P. C. Sood, Nucl. Phys. 89, 553 (1966).

[10]N. Austern, Phys. Rev. 137, B752 (1965).

[11]F. G. Perey and B. Buck, Nucl. Phys. 32, 353 (1962).

Direct Measurement of *n-p* and *n-d* Total Cross Sections from 700 to 2900 MeV/*c**

R. E. Mischke
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540

and

T. J. Devlin,† W. Johnson, J. Norem, and K. Vosburgh
Physics Department, Rutgers, The State University, New Brunswick, New Jersey 08903

and

W. Schimmerling
Princeton-Pennsylvania Accelerator, Princeton, New Jersey 08540
(Received 22 October 1970)

Neutron-proton and neutron-deuteron total cross sections have been measured directly at the Princeton-Pennsylvania Accelerator using time of flight to determine the incident neutron momentum. The results cover the region from 700 to 2900 MeV/*c* with a typical accuracy of 0.8% for each of 26 momentum bins. The data are not consistent with the most precise previous measurements in the same momentum range.

We have made direct measurements of neutron-proton and neutron-deuteron total cross sections for incident neutron momenta between 700 and 2900 MeV/*c*. The statistical accuracy is better than 1% for most of the 26 momentum bins. The total systematic error is believed to be less than 1%. Both the *n-p* and *n-d* cross sections are systematically lower by 1.5-2 mb than measurements of *p-d* and *p-n* cross sections reported by the Cambridge-Rutherford (CR) group.[1] The CR *p-n* cross sections were obtained from $\sigma_{pd}-\sigma_{pp}$ with a correction for the Glauber screening effect.[2]

A neutral beam containing a broad spectrum of neutron momenta was produced at 20° by the 3-GeV internal proton beam of the Princeton-Pennsylvania Accelerator. The beam was defined by collimators. A lead filter near the production target attenuated gamma rays, and magnets were used to remove charged particles.

The momentum of each detected neutron was determined by its time of flight (TOF). The proton beam struck the internal target at 67-nsec intervals with bunches less than 1 nsec wide. A Cherenkov counter placed near the internal target gave a signal when each proton bunch struck the target. The neutron detector was located 120 ft away; it provided the other signal for the TOF measurement. The resolution of the system was 2 nsec (full width at half-maximum) corresponding to a momentum resolution of 0.7% at 700 MeV/*c* and 9.5% at 2900 MeV/*c*. There was an ambiguity in the TOF since a slow neutron could be overtaken by a fast neutron from the next bunch. This was eliminated by a range requirement in the detector which provided a low-momentum cutoff.

The target system was located 104 ft from the production target and consisted of three identical cylindrical flasks of 4-in. diam and 36-in. length. One flask was evacuated; the ones containing hydrogen and deuterium were sealed to prevent boiling. All three were surrounded (except at the ends) by a jacket of liquid hydrogen fed from a common reservior. The targets were automatically cycled into the beam at frequent intervals to minimize the effects of any aspect of the experiment which changed systematically with time. The lengths of the full flasks were measured to 0.1% during the experiment by means of optical telescopes sighted through viewing ports in the target walls.

The vapor pressure above each target flask was measured every 2 h. To insure accurate measurements of the temperature in the flask, the liquid-vapor interface was kept well inside the target flask. Our concern was prompted by unexplained differences[3] of ~0.5°K between the calculated temperatures of the liquid-hydrogen jacket and liquid-deuterium flask in two previous experiments.[1,4] Using the same tables of vapor pressure, temperature, and molar volume[5] as used previously, our calculated hydrogen and deuterium temperatures agreed to better than 0.1°K.

A schematic drawing of the neutron detector is shown in Fig. 1. The scale has been expanded along the beam direction to separate the components. The detector was 24×24 in. transverse to the beam and it was 13 in. thick. The neutron converters in the four modules were 5, 8, 10.3, and 12 in. in diam but the amount of material was kept nearly uniform over the full size of the detector. Thus in each module, the Lucite conversion region (a) was surrounded by a liquid scintillator veto (b), and the solid-angle–defining counter (c) was surrounded by a Lucite spacer. Counter (c) was placed in coincidence with the following full-sized counter (d) which also served as a charged-particle veto for the next module. The counters preceding, in the middle of, and following the 3-in. Fe absorber were required for events from all modules. In order to increase the range of solid angles subtended by the modules, data were taken with the detector at different distances from the transmission targets.

The neutron flux was monitored by scintillation counter telescopes. Two counter telescopes were placed upstream of the primary collimator, a third detected particles scattered from the collimator, and a fourth counted particles emerg-

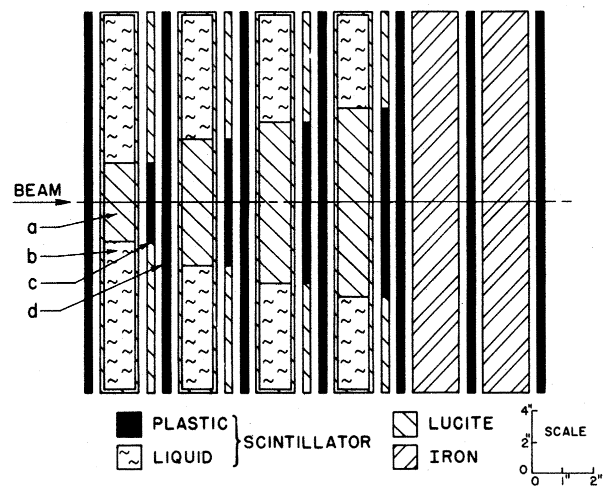

FIG. 1. Schematic of the neutron total cross-section detector. The labeled components are (a) cylindrical neutron converter, (b) veto surrounding converter, (c) solid-angle defining counter, and (d) dual coincidence and veto counter.

ing at wide angles from a converter in the beam. This redundancy allowed deletion of any monitor which temporarily malfunctioned. χ^2 tests on monitor comparisons between target-full and target-empty data indicated that fluctuations were purely statistical (0.3% for a typical run).

Data runs were 4-10 h long with each cycle of the three targets taking about 15 min. A neutron TOF spectrum was accumulated for each detector module and each target in twelve 256-channel banks of a pulse-height analyzer. A signal routing system separated all scaler data by target. These data included beam monitors, accidentals rates, counting rates of the detector modules, and monitors of the gain stability of the detector counters.

Data were taken with the detector at 10 and 15 ft from the targets. After extensive measurements established that accidental counts from the modules contaminated the data at the 1% level, several steps were taken to reduce the accidentals. The voltages were lowered on the solid-angle–defining counters. (They had been operating well above plateau voltage.) The beam size at the detector was reduced from 3- to 2.5-in. diam. Many of the signals in the electronics logic were made narrower. These changes reduced the accidentals correction to the cross sections to less than 0.2%. Following these improvements data were taken at 10, 15, and 20 ft from the targets.

Cross sections were calculated for the two sets of data separately. The two sets are consistent to 0.5%, with the residual discrepancy dominated by uncertainty in the accidentals correction to the earlier data. Additional data were taken with a reduced range requirement (1.5 in. Fe) and 134 nsec between proton bunches to extend the momentum range down to 700 MeV/c. Above 900 MeV/c, where the data with different range requirements overlap, the cross sections are consistent.

The results, presented in Fig. 2, are based on a fit to all the data. For each momentum bin the partial cross section measured by each module at each position was plotted as a function of the solid angle subtended. A linear extrapolation was made to find the intercept at zero solid angle.[6] Momentum bins were chosen in a manner consistent with the TOF resolution of the apparatus. The data of the CR group (renormalized as suggested in a subsequent paper[3]) and selected other data[7-10] are also shown in Fig. 2. Most previous np data have large errors and have been omitted for clarity.

Our n-d results and the CR p-d cross sections should be equal under the assumption of charge independence. The CR p-d cross sections are systematically higher than our n-d results and other p-d cross sections.[4,11] A precise measurement of the p-p and p-d total cross sections at 3 GeV/c by a Brookhaven National Laboratory (BNL) group[4] yields a p-d cross section 1.17 ± 0.09 mb less than the CR value while the p-p results are in agreement. The CR p-d data also overlap another p-d measurement[11] between 6 and 8 GeV/c and are ~1.5 mb higher in this range. An arbitrary subtractive renormalization of the CR data to agree with the BNL value at 3 GeV/c brings the p-d cross sections much closer to the n-d results. There still remain momentum-dependent systematic differences of ≲0.5 mb.

We note that the n-d cross sections do not need a correction for Coulomb scattering and they require a smaller extrapolation to zero solid angle than the p-d data. Also, as mentioned above, this experiment had much better internal consistency for the hydrogen and deuterium temperature measurements than either the BNL or CR group. Assuming that charge independence holds, we conclude from our n-d cross sections and the BNL p-d result that the CR p-d cross sections are too high. This implies that the CR p-n cross sections are probably also too high.

The CR p-d data and our n-d data can be compared with a p-d cross section synthesized from

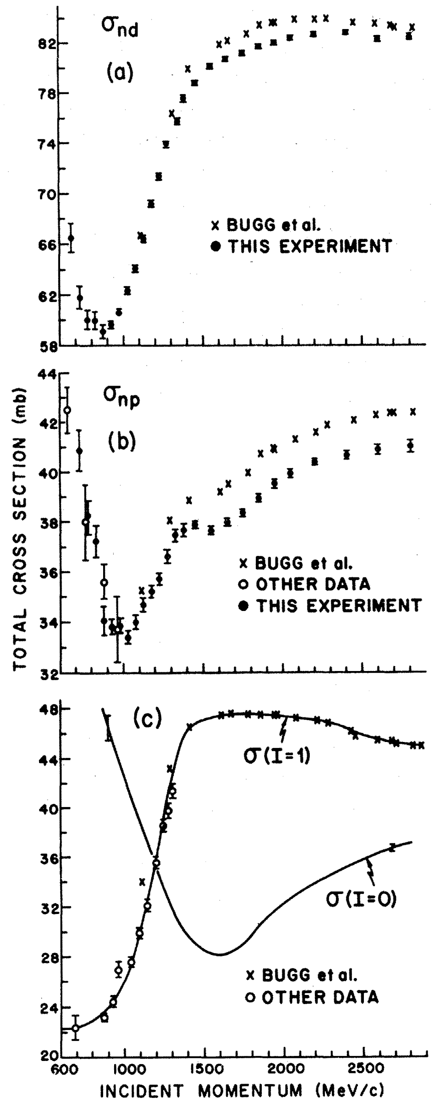

FIG. 2. (a) Neutron-deuteron total cross sections from this experiment and p-d data from Ref. 1 (see also Ref. 3). (b) Neutron-proton total cross sections from this experiment, derived p-n cross sections from Ref. 1 (see also Ref. 3), and selected n-p cross sections from other experiments (Refs. 7-10). (c) Total cross sections for the separate isospin components. The $\sigma(I=1)$ curve is a hand-drawn fit to the pp data from Refs. 1 and 15 (see also Ref. 3) which ignores the point at 1111 MeV/c from Ref. 1. The statistical uncertainty in $\sigma(I=0)$ is indicated by the two error flags.

our n-p data, the CR p-p data, and a Glauber screening correction (δ_G). Using the approximation[2]

$$\delta_G = (1/4\pi)\langle r^{-2}\rangle \times [\sigma_{np}\sigma_{pp} - (4\pi/k)^2 \operatorname{Re} f_{pp}(0) \operatorname{Re} f_{pn}(0)],$$

we have asked what value of $\langle r^{-2}\rangle$ is needed to synthesize a p-d cross section equal to the measured values. Since the results are not independent of energy we have considered only the data above 2 GeV/c. A value of $\langle r^{-2}\rangle = 0.03$ mb^{-1} gives agreement with our nd results and is consistent with previously accepted values.[1,12] The best value for the CR data is $\langle r^{-2}\rangle = 0.022$ mb^{-1} which is considerably lower, but cannot be excluded.[13,14] A complete discussion of the screening correction is outside the scope of this Letter.

This experiment provides detailed data on the n-p cross section above the threshold for inelastic processes. There is a maximum at an incident momentum near 1350 MeV/c, just above the threshold for $\Delta(1236)$ production. The cross sections for the separate isospin components have been calculated from $\sigma(I=1)=\sigma_{pp}$ and $\sigma(I=0) = 2\sigma_{np} - \sigma_{pp}$. The results, shown in Fig. 2(c), are based on our n-p and other p-p data.[1,15] As shown previously,[1,16] $\sigma(I=1)$ rises very rapidly above the inelastic threshold while $\sigma(I=0)$ continues to fall until above the multipion thresholds. The bump in σ_{np} is due to the maximum in $\sigma(I=1)$ occurring at a momentum just below the minimum in $\sigma(I=0)$. Since the cross sections for both isospin components are smooth in this region the data do not offer evidence of a resonance.

We appreciate the excellent support of Professor M. G. White, Professor W. Wales, and the staff of the Princeton-Pennsylvania Accelerator and the technical assistance of Mr. C. Muehleisen. We wish to thank Professor G. F. Chew and Professor R. J. Tapper for helpful comments. We are grateful to Dr. R. Ehrlich for his assistance in the analysis.

---

*Work supported in part by U. S. Atomic Energy Commission under Contract No. AT(30-1)-4159 and National Science Foundation Grants No. GU-1592 and No. GP-14703.

†Address until September 1971: CERN, 1211 Geneva 23, Switzerland.

[1]D. V. Bugg, D. C. Salter, G. H. Stafford, R. F. George, K. F. Riley, and R. J. Tapper, Phys. Rev. 146, 980 (1966).

[2]R. J. Glauber, Phys. Rev. 100, 242 (1955).

[3]K. F. Riley, Phys. Rev. D 1, 2481 (1970).

[4]R. J. Abrams, R. L. Cool, G. Giacomelli, T. F. Kycia, B. A. Leontić, K. K. Li, and D. N. Michael, Phys. Rev. D 1, 2477 (1970).

[5]R. J. Tapper, Rutherford Laboratory Report No. NIRL/R/95, 1965 (unpublished).

[6]The exponential extrapolation discussed in Ref. 3 cannot change our result by more than 0.2% for the worst case: the high-momentum deuterium data. All our data are consistent with a linear fit.

[7]Yu. M. Kazarinov and Yu. N. Simonov, Zh. Eksp. Teor. Fiz. 43, 35 (1962) [Sov. Phys. JETP 16, 24 (1963)].

[8]J. DeJuren, Phys. Rev. 80, 27 (1950).

[9]A. Ashmore, R. G. Jarvis, D. S. Mather, and S. K. Sen, Proc. Phys. Soc., London, Sect. A 70, 745 (1957).

[10]V. A. Nedzel, Phys. Rev. 94, 174 (1954).

[11]W. Galbraith, E. W. Jenkins, T. F. Kycia, B. A. Leontić, R. H. Phillips, A. L. Read, and R. Rubinstein, Phys. Rev. 138, B913 (1965).

[12]R. L. Cool, G. Giacomelli, T. F. Kycia, B. A. Leontić, K. K. Li, A. Lundby, J. Teiger, and C. Wilkin, Phys. Rev. D 1, 1887 (1970).

[13]W. F. Baker, E. W. Jenkins, T. F. Kycia, R. H. Phillips, A. L. Read, K. F. Riley, and H. Ruderman, in *Proceedings of the International Conference on Elementary Particle Physics, Sienna, Italy, 1963,* edited by G. Bernardini and G. P. Puppi (Società Italiana de Fisica, Bologna, Italy, 1963), Vol. 1, p. 634.

[14]A. A. Carter, K. F. Riley, R. J. Tapper, D. V. Bugg, R. S. Gilmore, K. M. Knight, D. C. Salter, G. H. Stafford, E. J. N. Wilson, J. D. Davies, J. D. Dowell, P. M. Hattersley, R. J. Homer, and A. W. O'Dell, Phys. Rev. 168, 1457 (1968).

[15]V. P. Dzhelepov, S. V. Moskalev, and S. V. Medved, Dokl. Akad. Nauk SSSR 104, 380 (1955); O. Chamberlain, G. Pettengill, E. Segrè, and C. Wiegand, Phys. Rev. 93, 1424 (1953); O. Chamberlain, E. Segrè, and C. Wiegand, Phys. 81, 284 (1951); J. R. Holt, J. C. Kluyver, and J. A. Moore, Proc. Phys. Soc., London 71, 781 (1958).

[16]W. Galbraith, Rep. Progr. Phys. 32, 547 (1969).