VOLUME 21, NUMBER 12 PHYSICAL REVIEW LETTERS 16 SEPTEMBER 1968

FORWARD DIFFERENTIAL CROSS SECTIONS FOR THE REACTION $p+p\rightarrow d+\pi^+$ IN THE RANGE 3.4 TO 12.3 GeV/c*

H. L. Anderson, M. Dixit, H. J. Evans, K. A. Klare, D. A. Larson, and M. V. Sherbrook
University of Chicago, Chicago, Illinois

and

R. L. Martin
Argonne National Laboratory, Argonne, Illinois

and

K. W. Edwards and D. Kessler
Carleton University, Ottawa, Canada

and

D. E. Nagle and H. A. Thiessen
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico

and

C. K. Hargrove and E. P. Hincks†
National Research Council of Canada, Ottawa, Canada

and

S. Fukui
Nagoya University, Nagoya, Japan

(Received 26 July 1968)

A spark-chamber missing-mass spectrometer was used to measure the differential cross section for the reaction $p+p\rightarrow d+\pi^+$ at closely spaced intervals of incident momentum between 3.4 and 12.3 GeV/c and at small c.m. angle. The data confirm the existence of a prominent peak in the forward cross section at $E_{\text{c.m.}}\simeq 2.9$ GeV and show a hitherto unreported shoulder at $E_{\text{c.m.}}\simeq 3.6$ GeV. The results make evident the inadequacies of present one-pion-exchange and one-nucleon-exchange models.

Reactions of the type $p+p\rightarrow d+X^+$ were studied by detecting the deuteron in a high-resolution missing-mass spectrometer set up in the external proton beam area of the zero-gradient synchrotron (ZGS) at Argonne National Laboratory. Here X^+ stands for an isospin-1 boson. In the present Letter we will describe results obtained in the study of the particular reaction

$$p+p\rightarrow d+\pi^+. \qquad (1)$$

This reaction is one of the few two-body processes in high-energy physics accessible to direct measurement and has been extensively investigated by other groups, mainly at lower energy.[1-8] In the present work we measure differential cross sections for deuterons emitted close to 180° in the c.m. system with respect to the incoming proton. This is equivalent to angles correspondingly close to 0° due to the symmetry of the two protons. Data were taken at closely spaced momentum intervals of the incident proton beam in the range $p_0=3.4$ to 12.3 GeV/c, using the "front porch" feature of the ZGS.

The spectrometer resolution (full width at half-maximum) in missing-mass squared varied between 0.026 GeV^2, at the lowest incident momentum, and 0.096 GeV^2, at the highest momentum, and proved adequate to separate clearly the pion peak corresponding to Reaction (1) from the multipion background. The external proton beam at the target position had a cross section of about 3 cm^2 and an angular divergence of less than 5 mrad. The target was liquid hydrogen contained in a 3-in.-diam vertical cylinder made of 3-mil H-film. It was mounted in a vacuum chanber extending beyond the region seen by the spectrometer. The principal nonhydrogen background came from the walls of the cylinder and several layers of $\frac{1}{4}$-mil aluminized Mylar superinsulation in which it was wrapped. Runs with target full and target empty were therefore alternated to enable us to subtract this background. The spectrometer was set at a fixed angle of 5° with respect to the incident beam as shown in Fig. 1. It consisted of a quadrupole pair and two bending magnets in reverse bend configuration. The quadrupoles were set to values such that the deuteron beam came to a vertical focus 2 ft upstream from the center of the second bending magnet and to a horizontal focus near counter No. 3. The solid-angle acceptance of the spectrometer was determined by a lead collimator mounted in front of the first quadrupole and designed to prevent any particles within the selected momentum band from coming close to the walls of the magnets. The spectrometer acceptance, $(p_d - p_s)/p_s$ vs θ_d (where p_d and θ_d are the laboratory momentum and angle of emission of the deuteron and p_s is the nominal spectrometer setting), is shown in the inset to Fig. 1. Five optical spark chambers viewed by Vidicon cameras[9] were used to determine the trajectories of the particles, hence their momenta and angles of emission. The chambers were of the type previously described[10] and successfully used in a double-arm spectrometer experiment.[11] They were 10×10 in.^{2} and contained six 0.3-in. gaps separated by $\frac{1}{2}$-mil stretched aluminum foils. A vacuum beam transport was used between the target and the collimator and a series of helium bags beyond that point to minimize multiple scattering.

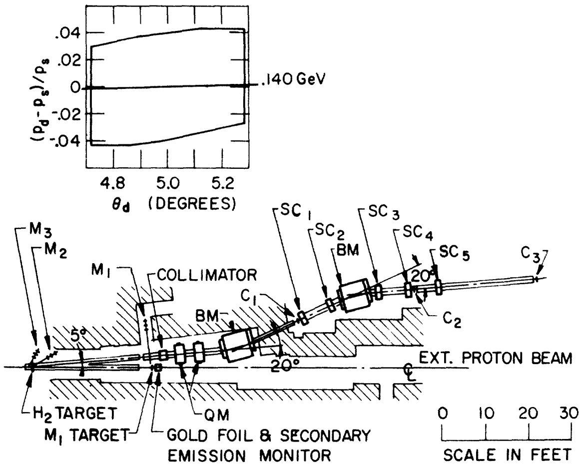

FIG. 1. Experimental layout. SC_1 to SC_5 are the spark chambers, C_1 to C_3 are the scintillation counters which measure time of flight, M_1 to M_3 are monitor telescopes. The spectrometer uses a quadrupole pair QM and two bending magnets BM. The inset shows the acceptance window of the spectrometer and the kinematic line for the missing pion mass (for incident momentum 6.1 GeV/c and spectrometer setting 1.255 GeV/c).

The Vidicon system has been described previously.[10] However, the data collection rate was increased by a factor of about 20 by reducing the number of scanning lines per view to 8 and reading the chambers in parallel rather than in series. All the data collected during a beam spill were stored in a buffer core memory and dumped onto magnetic tape between spills. A 15-msec dead time was imposed on the system to allow adequate time for the recovery of both the spark chambers and the vidicons after each event. In practice, 15 to 25 deuteron events were recorded during a 500-msec spill of 10^{11} protons.

The spark chambers were triggered by the counters C_1, C_2, and C_3 which selected deuterons by time of flight. The flight time was measured twice, over the whole flight path by the coincidence C_1C_3 and over the second half by C_2C_3. A coincidence between the two pairs was required to trigger the spark chambers. The rate of accidental triggers which could arise from the large flux of protons and pions traversing the spectrometer was thereby reduced to minor proportions.

Counters C_1 and C_2 were divided into five sections each and signals were taken from each section. If more than one section of a counter was triggered the event was vetoed. A pile-up gate driven by C_1 was used to reduce multiple tracks in the chambers and certain types of chance coincidences.

The time-of-flight spectra were recorded independently of the spark-chamber operation using a time-to-amplitude converter and pulse-height analyzer. Signals were taken from both ends of the scintillators and combined in a way that made the time-of-flight measurement independent of the position in the counter. The resolution obtained in this way was close to 0.8 nsec. A typical time-of-flight spectrum taken at $p_0 = 6.1$ GeV/c and $p_S = 1.255$ GeV/c is shown in Fig. 2(a). The π and p peaks, scaled down by a factor of 1000, appear on the right and the deuterons on the left. The deuteron distribution is made up of a sharp peak due to deuterons from Reaction (1) sitting on a broad base of nonhydrogen deuterons accepted by the spectrometer. It should be noted that the sharpness of the peak is due to the fact that the experiment was performed in the flat region of the p_d-θ_d diagram of Reaction (1) where p_d is almost constant.

The incident beam was continuously monitored by a separate counter telescope M_1 which viewed

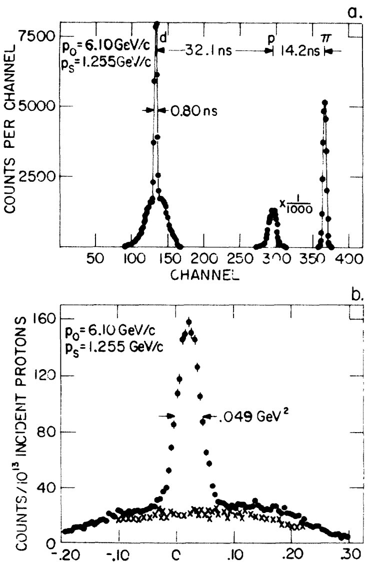

FIG. 2. (a) Typical time-of flight spectrum showing the deuteron, proton, and pion peaks, the latter two scaled down by a factor of 1000. (b) Typical spectrum of missing-mass squared in the pion region. The upper (circles) and lower (crosses) spectra show the target-full and target-empty data, respectively, normalized to the same number of protons incident.

a Lucite target 25 ft downstream from the hydrogen target. The counting rate of this telescope was calibrated in terms of absolute beam intensity by gold-foil activation measurements at most of the momentum settings used.[12]

The University of Chicago IBM-7094/7040 and the Los Alamos Scientific Laboratory CDC-6600 computers were used for processing the magnetic tapes. Tracks were reconstructed from the digital readout and trajectories fitted through the spark chambers SC_1 to SC_4. The deuteron momentum was deduced from the calculated curvature in the second bending magnet. The trajectory was then traced back through the first bending magnet and the quadrupole pair towards the target. Events which were incomplete or ambiguous, gave a poor fit, or did not retrace properly to the target were rejected. The program kept track of the number of events rejected for each reason so that the proper corrections could be applied in the calculation of the cross section. The information from the last spark chamber, SC_5, was not used directly in the determination of the kinematic quantities but served for consistency checks and in the removal of ambiguities of multiple tracks.

The missing-mass spectra obtained for runs at various incident momenta showed clearly separated pion peaks with low background so that the number ν of events corresponding to Reaction (1) could be easily determined. A representative missing-mass spectrum is shown in Fig. 2(b). The peak centered at 0.020 GeV^2 is clearly due to single-pion production. The width, 0.049 GeV^2, agrees with the calculated instrumental resolution. The background due to the target walls is shown by the data obtained without hydrogen in the target. An additional background effect is due to deuterons produced in the walls of the vacuum chamber by secondary particles from the hydrogen.

The cross section $d\sigma/d\omega$ in the c.m. system was calculated from the relation

$$\nu = \epsilon Q N_{\mathrm{H}} (d\sigma/d\omega)(d\omega/d\Omega)\Delta\Omega, \tag{2}$$

where Q is the number of protons traversing the target, N_{H} is the number of hydrogen atoms/cm^2 in the target traversed by the beam, $d\omega/d\Omega$ is the solid angle transformation from the c.m. to the lab. system, $\Delta\Omega$ is the solid angle subtended by the spectrometer (2.08×10^{-4} sr), and $\epsilon = \epsilon_c \times \epsilon_a \epsilon_s$ is the product of three correction factors. The efficiency ϵ_c of the triggering system including dead-time corrections and losses due to vetoed triggers was 0.96 ± 0.02. The calculated transmission probability ϵ_a of the deuteron from the point of production inside the target to the far end of the spectrometer was 0.95 ± 0.01 due to nuclear absorption. Finally, ϵ_s reflects the losses due to multiple scattering as determined by a Monte Carlo calculation and was between 0.95 and 0.98 over the range of momenta covered.

The c.m. differential cross sections over the range of incident proton momentum 3.4 to 12.3 GeV/c derived from the missing-mass spectra are shown in Fig. 3. They are indistinguishable from the cross sections calculated using the time-of-flight data. The relative cross sections have errors which are in general less than 10%. This includes, besides the statistical errors, a 4.4% uncertainty arising principally from the gold-foil measurements. In specifying the absolute cross sections an additional uncertainty of about 5% from the yield of Tb^{149} α particles from Au should be included.

In the present experiment $\cos\theta_{\mathrm{c.m.}}$ varied from 0.9928 to 0.9985 and p_d from 1.14 to 1.33 GeV/c. The transverse momentum was rather small (~0.1 GeV/c) and fairly constant over the whole range of incident momenta. Thus, the variation

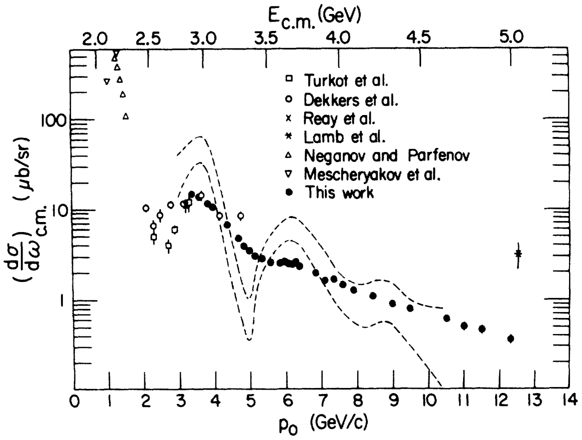

FIG. 3. Forward ($0.99 \leq \cos\theta_{c.m.} \leq 1.00$) differential cross sections for the reaction $p+p \rightarrow d+\pi^+$ as a function of incident momentum p_0 and of total c.m. energy $E_{c.m.}$, including previously published work (Refs. 1, 2, 5-8). The dashed curves are from a calculation of the one-pion-exchange contribution by Silbar according to the model of Yao. The upper and lower bounds correspond to the lack of knowledge of the charge-exchange cross sections.

of the forward differential cross section observed here is due principally to the change in c.m. energy from 2.89 to 5.00 GeV.

In Fig. 3 we also show the data from comparable experiments for which $0.99 \leq \cos\theta_{c.m.} \leq 1.00$. These show the well-known narrow peak in the vicinity of $E_{c.m.} = 2.2$ GeV which is attributed to the excitation of the $\Delta(1236)$ isobar in an intermediate state.[13-15]

A second pronounced maximum in the forward differential cross section is observed in the neighborhood of $E_{c.m.} = 2.9$ GeV. This peak results from the combined data of Turkot, Collins, and Fujii,[2] Dekkers et al.,[5] Reay et al.,[8] and the present experiment. The existence of this peak in the differential cross section was first demonstrated by Cocconi et al.[3] Cocconi's point (not shown in Fig. 3) at 3.6-GeV/c incident momentum is considerably lower than ours, namely 6.6 ± 0.9 μb/sr vs 13.3 ± 0.6 μb/sr. This difference is presumably due to the fact that Cocconi's experiment was performed at a larger angle in the c.m. system ($\cos\theta_{c.m.} = 0.97$) than ours ($\cos\theta_{c.m.} = 0.993$) at this incident momentum. A factor of 2 in the differential cross sections between these two angles is compatible with the angular distribution measurements of Overseth et al.[4] It now appears that this peak is even more striking than was the case in Cocconi's presentation. It should be noted, however, that in the data of Dekkers et al.,[5] deduced by detailed balance from a measurement of cross sections for the inverse reaction $\pi^+ + d \rightarrow p + p$, the peaking is less pronounced. Their differential cross sections taken at $\cos\theta_{c.m.} = 0.99$ should be directly comparable with our results and reasonably close to those of Turkot, Collins, and Fujii.[2] The appearance of a much flatter behavior in the region of the peak is due principally to the one point at $E_{c.m.} = 3.3$ GeV which lies considerably above our curve.

Cocconi et al.[3] measured four more points in the region $p_0 = 4$-9 GeV/c. Their differential cross sections lie lower than our corresponding points by a factor of 2 to 4. It is reasonable to believe that this difference reflects the behavior of the angular distribution. Their $\cos\theta_{c.m.} = 0.95$-0.96 whereas in our case $\cos\theta_{c.m.} \simeq 0.998$. On the other hand, we have no explanation for the large difference between our results taken at $\cos\theta_{c.m.} = 0.998$ and the point of Lamb et al.[7] at 12.5 GeV/c taken at $\cos\theta_{c.m.} = 1.000$.

A conspicuous shoulder, not previously reported, is seen near 6-GeV/c incident momentum or $E_{c.m.} \simeq 3.6$ GeV. It is interesting to note that the one-pion-exchange model of Yao[15] predicts a pronounced peak in this region[16,17] as it does at $E_{c.m.} = 2.2$ and 2.9 GeV. However, the structure, which arises from the behavior[18,19] of the backward pion-proton elastic scattering, is much more pronounced than is seen in the experiment (see Fig. 3), well outside the errors. Aside from these striking discrepancies the general trend of the calculations follows the data fairly well. This is particularly true of the relatively smooth region above 7-GeV/c incident momentum where the agreement with the calculation is well within the bounds set by the lack of knowledge of the charge exchange cross section. On the other hand, in spite of some success at lower energy,[20] a calculation[16] of the contribution of one-nucleon exchange gives cross sections which are too high by an order of magnitude in the region between 7- and 12-GeV/c incident momentum. Since both one-pion-exchange and one-nucleon-exchange should contribute to the process (1) the lack of agreement emphasizes the inadequacies of the present models.

We would like to express our thanks to E. P. Steinberg for his advice concerning the measurement of absolute beam intensity and for putting his equipment at our disposal, and to R. Silbar for bringing his calculations of one-pion-exchange to our attention. It is a pleasure to acknowledge the contributions of R. L. Armstrong, G. Black,

R. Gabriel, C. L. Hung, J. P. Legault, J. Lillberg, J. Michelassi, P. Plowe, J. Redfern, R. Ryan, and R. Wilberg in the construction of the apparatus and the running of the experiment, and the help of V. Stovall and A. LaRotonda in the data reduction. We are indebted to the entire ZGS staff for their help in setting up the experiment, providing the external proton beam for our use, and carrying out the gold-foil standardizations.

---

*Research supported by the National Science Foundation, the U. S. Atomic Energy Commission, and the National Research Council of Canada.

†Also at Carleton University, Ottawa, Canada.

[1] M. G. Mescheryakov, B. S. Neganov, N. P. Bogachev, and V. M. Sidorov, Dokl. Akad. Nauk SSSR 100, 673 (1955); M. G. Mescherayakov and B. S. Neganov, Dokl. Akad. Nauk SSSR 100, 677 (1955); B. S. Neganov and L. B. Parfenov, Zh. Eksperim. i Teor. Fiz. 34, 767 (1958) [translation: Soviet Phys.—JETP 7, 528 (1958)].

[2] F. Turkot, G. B. Collins, and T. Fujii, Phys. Rev. Letters 11, 474 (1963).

[3] G. Cocconi, E. Lillethun, J. P. Scanlon, C. A. Ståhlbrandt, C. C. Ting, J. Walters, and A. M. Wetherell, Phys. Letters 7, 222 (1963).

[4] O. E. Overseth, R. M. Heinz, L. W. Jones, M. J. Longo, D. E. Pellett, M. L. Perl, and F. Martin, Phys. Rev. Letters 13, 59 (1964); R. M. Heinz, O. E. Overseth, D. E. Pellett, and M. L. Perl, Phys. Rev. 167, 1232 (1968).

[5] D. Dekkers, B. Jordan, R. Mermod, C. C. Ting, G. Weber, T. R. Willitts, K. Winter, X. De Bouard, and M. Vivargent, Phys. Letters 11, 161 (1964).

[6] J. Oostens, P. Chavanon, M. Crozon, and J. Tocqueville, Phys. Letters 22, 708 (1966).

[7] R. C. Lamb, R. A. Lundy, T. B. Novey, D. D. Yovanovitch, and R. Lander, Phys. Rev. Letters 17, 100 (1966).

[8] N. W. Reay, A. C. Melissinos, J. T. Reed, T. Yamanouchi, and L. C. L. Yuan, Phys. Rev. 142, 918 (1966).

[9] H. L. Anderson and A. Barna, Rev. Sci. Instr. 35, 492 (1964).

[10] E. P. Hincks, H. L. Anderson, H. J. Evans, S. Fukui, D. Kessler, K. A. Klare, J. W. Lillberg, M. V. Sherbrook, R. L. Martin, and P. I. P. Kalmus, in *Proceedings of the International Conference on Instrumentation for High Energy Physics, Stanford, 1966* (International Union of Pure and Applied Physics and U.S. Atomic Energy Commission, Washington, D.C., 1966), p. 63.

[11] H. L. Anderson, S. Fukui, D. Kessler, K. A. Klare, M. V. Sherbrook, H. J. Evans, R. L. Martin, E. P. Hincks, N. K. Sherman, and P. I. P. Kalmus, Phys. Rev. Letters 18, 89 (1967).

[12] The absolute proton fluxes were measured using the counters and Au-foil techniques established for the external proton beam of the ZGS by E. P. Steinberg, A. F. Stehney, C. Stearns, and I. Spaletto (to be published). See also E. M. Franz and G. Friedlander, Nucl. Phys. 76, 123 (1966).

[13] S. Mandelstam, Proc. Roy. Soc. (London), Ser. A 244, 491 (1958).

[14] Z. Fraenkel, Phys. Rev. 130, 2407 (1963).

[15] Tsu Yao, Phys. Rev. 134, B454 (1964).

[16] D. J. Brown, to be published.

[17] R. Silbar, private communication.

[18] A. S. Carroll, J. Fischer, A. Lundby, R. H. Phillips, C. L. Wang, F. Lobkowicz, A. C. Melissinos, Y. Nagashima, and S. Tewksbury, Phys. Rev. Letters 20, 607 (1968).

[19] S. W. Kormanyos, A. D. Krisch, J. R. O'Fallon, K. Ruddick, and L. G. Ratner, Phys. Rev. Letters 16, 709 (1966).

[20] D. J. Brown and M. K. Sundaresan, Nuovo Cimento 55A, 346 (1968).

ALGEBRA OF CURRENTS, DIVERGENCE OF STRANGENESS-CHANGING VECTOR CURRENTS, UNSUBTRACTED DISPERSION RELATIONS, AND THE K_{l3} FORM FACTORS*

Kyungsik Kang
Department of Physics, Brown University, Providence, Rhode Island 02912

(Received 19 July 1968)

On the basis of current algebra, the Nambu-Sakurai hypothesis of partial conservation of strangeness-changing vector currents, and unsubtracted dispersion relations for $f_+(q^2)$ and $q^2f_-(q^2)$, the K_{l3} parameters ξ, λ_+, and λ_- are found to be consistent with the present experimental indications. The only input in the theory is $F_K/F_\pi f_+(0) = 1.28$ from the Cabibbo theory. The mass of the conjectured κ is in agreement with the recently reported result of broken chiral symmetry.

About two and a half years ago, Callan and Treiman[1] successfully applied the equal-time commutation relations of current algebra and the hypothesis of partially conserved axial-vector current (PCAC) to K_{l3} decay and obtained a nontrivial relation between the two K_{l3} form factors, which holds at an unphysical point. Since then, a number of authors[2-6] have discussed this problem either by making vari-