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Measurement of $p+p \rightarrow \pi^{+}+d$ at High Momentum Transfers*

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Three measurements of the differential cross section for $p+p \rightarrow \pi^{+}+d$ have been made at the Brookhaven AGS, at incident laboratory momenta 11.6, 15.0, and 22.9 BeV/c and corresponding deuteron angles 55.7°, 43.4°, and 34.7° in the center-of-mass system. The internal proton beam was made to strike a polyethylene target, and coincidences were taken between the outgoing pion and deuteron by placing counter telescopes both inside and outside the AGS ring. Both particles were momentum analyzed and the deuteron was identified by the use of a gas-filled differential Čerenkov counter. The pion was identified by time of flight. The total number of protons incident on the target was obtained by radiochemical analysis of the Be^7 spallation product from carbon. Differential cross sections in the region 10^{-35} to 10^{-34} cm^2/sr in the c.m. system were obtained. Our cross sections are $\sim 10^4$ times smaller than other measurements at lower energies and smaller angles; we conclude that this process decreases rapidly both with increasing energy and with increasing c.m. angle.

INTRODUCTION

IN a recent experiment at the Brookhaven National Laboratory alternating gradient synchrotron (AGS), a general investigation of the proton-proton elastic scattering at high momentum transfer has been carried out.[1,2] A by-product of this study has been the measurement of the differential cross section for the two-body process

$$p+p \rightarrow \pi^{+}+d$$

taken at three differing values of incident proton momentum and c.m. scattering angle. All three measurements involve high energies and large center-of-mass production angles. Previous studies[3–6] of this process have been carried out at lower incident momenta, ≤ 8.9 BeV/c. At smaller energies and angles, the one-pion exchange model[4,7] has been used to interpret the deuteron production data and accounts, in particular, for the maximum observed in the cross section corresponding to the first π-N resonance. At the higher momentum transfers involved in this experiment, there is no reason to expect that this model will continue to hold. In our 22.9-BeV/c experiment the squared four-momentum transfer between the target proton and one of the nucleons in the deuteron was $-t=18.5$ (BeV/c)^2. Our three high-energy cross sections when compared with those at lower energies indicate a strong decrease both with increasing energy and with increasing c.m. angle.

EXPERIMENTAL METHOD

The experimental arrangement for the 15.0-BeV/c measurement is shown in Fig. 1 and is almost the same as for one of the p-p elastic scattering measurements.[1] The internal proton beam of the AGS was made to strike a polyethylene target. The outgoing deuteron and pion passed through collimators placed at the appropriate laboratory angles. Both particles were deflected by bending magnets with fields set for the calculated momenta and both were detected by telescopes consisting of three scintillation counters. The "deuteron" channel had the further requirement that a particle be registered by a gas-filled differential Čerenkov counter tuned to select particles having the velocity of the deuteron. A 50-nsec-wide slow coincidence between the right (deuteron) and left (pion) telescopes was used to gate a time-to-height converter into which was fed the outputs of one right and one left scintillation counter. The time-of-arrival spectrum between the pulses from these two counters was displayed on a pulse-height analyzer. A peak $\sim 2\times 10^{-9}$ sec wide was observed in the time distribution and identified as $p+p \rightarrow \pi^{+}+d$ [Fig. 2(a)]. The position of the peak indicated that the particle passing through the left telescope had a $\beta > 0.99$, as required for the pion. Protons in the "pion" channel would have a much lower velocity, $\beta < 0.90$. The background due to

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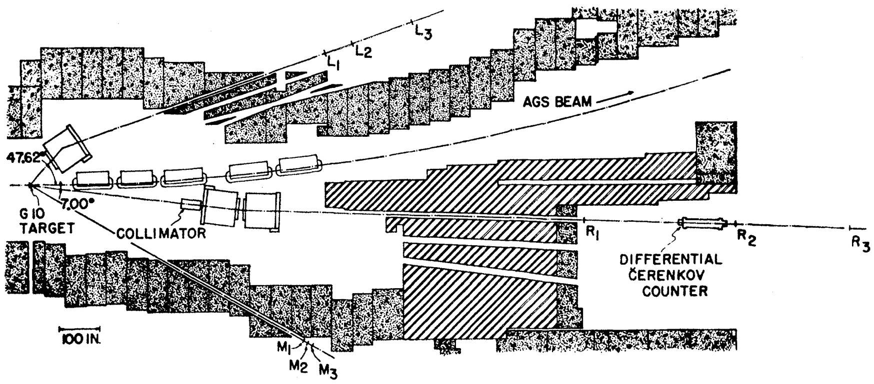

FIG. 1. Experimental arrangement for the 15.0-BeV/c measurement.

accidental coincidences was counted over the 50-nsec interval and is shown as the horizontal dashed line in Fig. 2(a). The corresponding proton-proton elastic peak on the pulse-height analyzer would be displaced by 14×10^{-9} sec, as shown in Fig. 2, and this was verified by setting the beam energy, deflecting magnets, and timing within each telescope to that calculated for the elastic scattering.

With the beam energy set for π^++d production, the geometry of the experiment was such that it was impossible for the two scattered protons from p-p elastic scattering to enter both the left and right channels, and as seen in Fig. 2, none were observed. In the 11.6- and 22.9-BeV/c measurements, the relative timing of the scintillation counters in the pion telescope was set such that a proton of the same momentum as the pion could not give a triple coincidence. Since about 80% of the particles were protons, this reduced the left-right accidental coincidence rate by about a factor of 5.

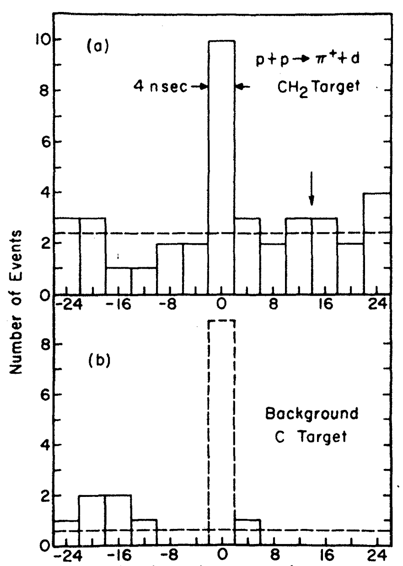

FIG. 2. Time distribution from pulse-height analyzer for the 22.9-BeV/c results. Arrow indicates time position for p-p elastic scattering coincidences. (a) With CH_2 target. Accidental coincidence rate indicated by dashed line. (b) With carbon target. If the effect observed with CH_2 target was due to the carbon only, the dashed line peak in (b) should have been observed.

A reduction factor of several hundred in the accidental coincidences was obtained by using the gas-filled Čerenkov counter,[8] whose $\Delta\beta/\beta$ resolution was set at 1.2×10^{-3}. The counter was adjusted to select deuterons, which were present in the right-hand channel to only about 1 in 10^4, by counting protons having half the momentum of the deuterons. These protons possessed the same β as the deuterons and required the same Čerenkov gas pressure. Čerenkov resolution and counting efficiency for the deuterons were determined by measuring the resolution and efficiency for these protons with the same β. An example of a Čerenkov resolution curve is given in Fig. 3. This was used to determine the efficiency for counting protons of one-half the deuteron momentum. The main reason for the low "deuteron" efficiency of $\sim$50% is that the 5% momentum resolution of this beam gave a $\Delta\beta/\beta$ somewhat worse than the value for which the Čerenkov counter was set.

Accurate setting of kinematic parameters for $p+p\rightarrow\pi^++d$ was possible by extrapolating from those for the p-p elastic scattering at the same laboratory angles, which had a much higher cross section. With this technique, the beam energy and the deflecting magnet field strengths could be set to $\pm0.5\%$, and timing within each telescope and between the R and L telescopes could be set to ±0.5 nsec by making the calculated changes of a few percent from the empirically determined values for proton-proton elastic scattering.

The solid angle for π^++d production was defined by one of the counters in the deuteron telescope; the solid angles subtended by the pion telescope counters were made larger to allow for uncertainties in incident momentum, magnetic fields, and multiple scattering in target and air. All solid angles, momentum resolutions, target assembly, and beam spill were similar to those in the proton-proton elastic experiment.[1,2]

The background contribution from carbon in the CH_2 target was measured directly by using a carbon target

[8] T. F. Kycia and E. W. Jenkins, Nucl. Electronics 1, 63 (1962) [Proceedings of the International Atomic Energy Agency Conference on Nuclear Electronics, Belgrade, Yugoslavia, 1961], p. 724.

in place of the CH_2 target in the case of the lowest cross section reported (the 22.9-BeV/c measurement), and as seen in Fig. 2(b) no background was observed within the limited statistics. This implied that all coincidences were due to interactions with hydrogen in the polyethylene. This result was verified in the equivalent proton-proton elastic scattering measurements, where the background due to carbon was found to be less than 2%, as would be expected due to the Fermi motion of the protons in carbon.

In order to obtain an absolute cross section, a monitor telescope was used (M1, M2, M3 in Fig. 1). It was calibrated in terms of the number of incident protons passing through the target by counting the 0.48-MeV gamma ray following the decay of the Be^7 spallation product from carbon. We used the value 9.5 mb for the Be^7 spallation cross section[9] and 10.32% for the branching ratio to the 0.48-MeV gamma ray.[10]

RESULTS

The results of the experiment are listed in Table I and are plotted in Fig. 4, together with some of the data obtained in other experiments at lower energies. Statistical errors on all three measurements are ±30%. Errors due to uncertainties in momenta, counter alignment, and geometry are estimated to be +10%, −0%. The Čerenkov counter efficiency for detecting deuterons was measured indirectly using protons of the same velocity, but with poorer momentum resolution than the deuterons. Because of this discrepancy in momentum resolutions, the Čerenkov counter efficiency for deuterons may be higher than that measured for protons of the same velocity. This is taken into account by assigning an upper limit of 80% for the Čerenkov counter efficiency for the 11.6-BeV/c measurement, and 90% for the other two measurements.

In addition to correcting for Čerenkov counter efficiency, counting rates were corrected for the fraction of deuterons removed from the beam by scattering, absorption, and stripping reactions in the CO_2 gas of the Čerenkov counter. Since no high-intensity deuteron beam was available, this fraction was calculated from

TABLE I. The $p+p \rightarrow \pi^+ + d$ cross sections measured in this experiment.

P_0 (BeV/c)	$\theta_{c.m.}$ (deg)	$E_{c.m.}^{total}$ (BeV)	Deuteron absorption factor	Čerenkov efficiency	$(d\sigma/d\omega)_{c.m.}$ (cm²/sr)
11.6[a]	55.7[b]	4.85	4.1±1.0	$0.4_{-0.1}^{+0.4}$	$(1.1_{-0.5}^{+1.1})\times10^{-34}$
15.0	43.4	5.48	2.3±0.4	$0.6_{-0.1}^{+0.3}$	$(1.1_{-0.5}^{+1.1})\times10^{-34}$
22.9	34.7	6.70	1.7±0.1	$0.6_{-0.1}^{+0.3}$	$(9.7_{-5}^{+9})\times10^{-36}$

[a] All internal beam momenta P_0, have an error of ±1%.
[b] All center-of-mass scattering angles have an error of ±0.2°.

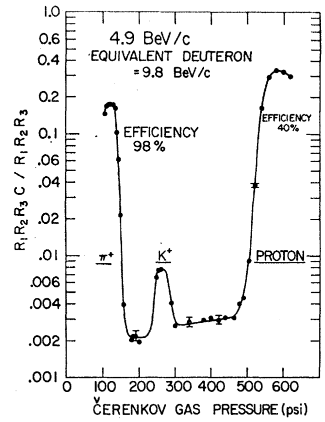

FIG. 3. Čerenkov counter pressure curve for the 11.6-BeV/c measurement.

the fraction of protons removed from the beam. In the worst case, the 11.6-BeV/c experiment, proton loss amounted to 43% at a CO_2 pressure of 605 lb/in², or 30 g/cm² of CO_2 in the beam. The proton loss was determined by measuring R_{123}/R_{12} as a function of the gas pressure, and was checked with the result expected from known proton-nuclear total cross sections.

We would expect the effective deuteron loss factor to be significantly worse since the cross section for deuterons on carbon and oxygen is larger than for protons. From deuteron-carbon stripping data at 620 MeV,[11] and from the known proton-carbon cross sections, V. Franco has computed the deuteron-carbon total cross section to be approximately 860 mb.[12] This compares with a proton-carbon total cross section of

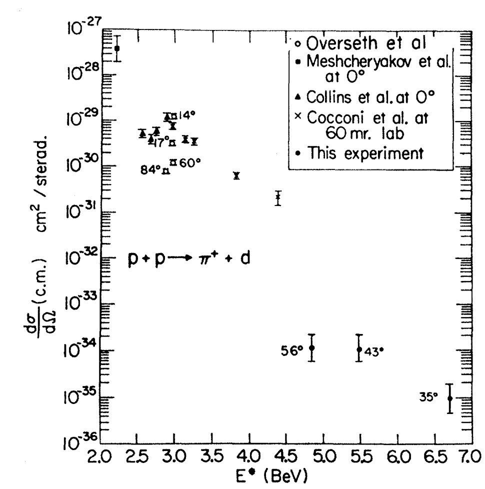

FIG. 4. Results. E^* is the total energy in the c.m. system. Angles are in the c.m. system.

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[12] Victor Franco, thesis, Harvard University (unpublished).

285 mb at the same nucleon energy. However, not all of the deuteron total cross section contributes in our geometry, since some of the stripped protons continue on through our telescope. Using the results of Franco,[12] we estimate that the mean free path for deuterons in CO_2 is 0.5 ± 0.1 times the mean free path for protons in the same gas for the 11.6-BeV/c measurement. For this measurement the combined absorption factor for all material in the beam is 4.1. The over-all correction factor for the 11.6-BeV/c measurement which includes the efficiency of the gas Čerenkov for deuterons of this velocity comes to 10.8.

The final cross-section values, given in Table I, have an estimated overall uncertainty of $+100\%$, -50%.

Differential cross sections in the region 10^{-34} to 10^{-35} cm^2/sr in the c.m. system were obtained, which represent a decrease over previous experimental values by a factor of $\sim 10^4$. The differential cross section is strongly dependent on the c.m. scattering angle, and upon the total energy involved in the interaction.

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Sum Rules for Coupling Constants in Broken SU(3) Symmetry

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The coupling constant sum rules for the decay of an octet, icosuplet and 27-plet to the two octets are derived in the broken SU(3) symmetry scheme.

I. INTRODUCTION

We have recently given sum rules for the coupling constants of the unitary decuplet to two unitary octets for the broken SU(3) symmetry.[1] As one of these sum rules was entirely in terms of the observed decay widths of $N^*(1238) \to N\pi$, $Y_1^*(1385) \to \Lambda\pi$ and $\Sigma\pi$, $\Xi^*(1530) \to \Xi\pi$, it could be checked against experimental data. The agreement was very good. Apart from qualitative predictions[2] about multiplet structure and spin-parity assignments, this result and the mass sum rules[3] are the only quantitative results in the broken SU(3) symmetry[4] which have had experimental confirmation. This makes one have more confidence in SU(3) symmetry with the usual breaking term, i.e., the one having transformation properties of the $I=0$, $Y=0$ component of a unitary octet. As in the domain of coupling constant sum rules, there are further obvious possibilities of deriving useful results, we extend our previous work here. Since, experimentally, the most interesting case is the one in which, out of three multiplets involved, the two are octets. We only consider this case in the present paper.

The following cases of interest arise:

(a) $B^*(8) \to B(8)+M(8)$, where B^*, B, and M refer to meson-baryon resonance; baryon and meson octets, respectively.

(b) Icosuplet $\to$ octet+octet, where the two octets are different in general.

(c) $B^*(27) \to B(8)+M(8)$ and also the case of a meson 27-plet, $M(27) \to M(8)+M'(8)$.

In all the calculations we treat the $I=0$, $Y=0$ breaking term to first order only. Further, we use the "spurion octet" technique (outlined in Ref. 1) and de Swart's tables[5] for the SU(3) Clebsch-Gordan coefficients throughout the paper.

II. SUM RULES FOR $B^*(8) \to B(8)+P(8)$

The coupling-constant sum rules for the particular case when the two of the three octets are the same have already been given by Glashow and Muraskin.[6] We generalize their results to the case when all the three

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