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Multiplicity distributions in 28-GeV/c pd interactions and double scattering in deuterium

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We study the multiplicity distribution of charged particles produced in 28-GeV/c pd interactions in the BNL 80-inch deuterium bubble chamber. We find that $(18.3 \pm 2.9)\%$ of the three- and more-prong pd events result from double scattering in deuterium, a fraction observed to be constant from 28-to-400-GeV/c incident momentum. We extract pn topological cross sections from the odd-prong pd data by correcting for the effects of spectator visibility, double scattering, and Glauber screening. We find the dispersion of 28-to-400-GeV/c pd multiplicity distributions to have the same linear dependence on the mean multiplicity as found for pp data, while the pn data exhibit a different dependence. Both the pd and pn multiplicity distributions at 28 GeV/c are observed to be inconsistent with Koba-Nielsen-Olesen scaling.

I. INTRODUCTION

We have analyzed existing 28-GeV/c pd data to obtain pd and pn charged-prong topological cross sections. The pd and pn charged-particle multiplicity distributions are compared with that from 28-GeV/c pp collisions, as well as with data from higher-energy interactions. The effects of double scattering in pd collisions are examined, and its implications for the extraction of neutron-target data are discussed.

The pd data are of interest as examples of particle-nucleus collisions. Recent theoretical suggestions[1,2] indicate that particle production in nuclei may serve as a useful probe of the space-time development of the produced hadrons. The simplicity of the deuteron nucleus makes pd data uniquely valuable to test models of hadron production in particle-nucleus collisions.

An understanding of pd interactions is necessary to extract information on neutron-target collisions. Analyses of pd data from recent bubble-chamber experiments conducted at Fermilab[3-7] have used different, and contradictory, assumptions about the multiplicity dependence of double scattering in attempts to obtain pn charged-particle multiplicity distributions. The data presented here extend the energy range over which information on double scattering in pd collisions is available, and allow a determination of the dependence of double scattering on multiplicity.

II. EXPERIMENTAL PROCEDURE

The data reported here are from an 80 000 frame exposure of the Brookhaven National Laboratory (BNL) 80-inch deuterium-filled bubble chamber to a beam of 28-GeV/c protons from the Alternating Gradient Synchrotron. An inclusive sample of inelastic pd interactions was compiled by combining data used in the study of low-multiplicity coherent[8] and spectator-proton[9-11] events with previously unpublished data on non-spectator-proton and high-multiplicity spectator-proton events.

Events were classified as either spectator-proton-like or non-spectator-proton-like as part of the scanning procedure. A spectator-proton-like event was defined to include any odd-prong event and all even-prong events with a stopping track whose length projected into the film plane was less than 15 cm. The actual separation of events into spectator-proton and non-spectator-proton categories is based on measured data and is discussed below. Parts of the film were scanned at BNL for spectator-proton-like events with three, four, five, and six charged prongs, and at Vanderbilt University for higher-multiplicity spectator-proton-like events. A smaller sample of film was scanned at Vanderbilt for events of non-spectator-proton-like topologies.

The cross sections determined from the scan are given in column two of Table I as a function of the number of observed charged prongs. We note that 30% of the events have an odd number of observed prongs, corresponding to events with an invisible spectator proton.[12]

Events were rough-digitized both at Vanderbilt University and at BNL, and were measured with the BNL Flying Spot Digitizer (FSD) and reconstructed with the BNL version of the geometry program TVGP. Ionization estimates were com-

TABLE I. Topological cross sections in mb from 28-GeV/c pd interactions. Appropriate corrections have been applied to the data to account for unobserved Dalitz pairs. The corrections for unobserved vees and close secondaries are negligible and are ignored.

Number of charged prongs	Observed cross section	Inelastic pd cross section	Inelastic pn cross section
1			4.32 ± 0.86[b]
2		10.94 ± 1.36[a]	
3	5.65 ± 0.22		10.37 ± 0.57
4	14.92 ± 0.55	20.57 ± 0.60	
5	4.65 ± 0.18		8.53 ± 0.47
6	10.37 ± 0.42	15.02 ± 0.46	
7	2.81 ± 0.08		5.16 ± 0.25
8	5.00 ± 0.20	7.81 ± 0.22	
9	0.81 ± 0.03		1.49 ± 0.08
10	1.72 ± 0.09	2.53 ± 0.10	
11	0.19 ± 0.02		0.35 ± 0.04
12	0.36 ± 0.03	0.55 ± 0.04	
13	0.044 ± 0.010		0.081 ± 0.019
14	0.054 ± 0.012	0.098 ± 0.016	
15	0.010 ± 0.005		0.018 ± 0.009
16	0.005 ± 0.003	0.015 ± 0.006	
17	...		
18	0.003 ± 0.003	0.003 ± 0.003	
Total	46.60 ± 0.79	57.54 ± 1.58	30.31 ± 1.16

[a] Estimated with Eq. (2) (see text).
[b] Estimated with Eqs. (1) and (2) (see text).

puted from the FSD digitizations in a procedure identical to that used in the analysis of 28.5-GeV/c pp data,[10,13] resulting in reliable identification of protons with momenta less than 1 GeV/c. The measured data correspond to about a 1-μb/event sample of spectator-proton events and a 3-μb/event sample of non-spectator-proton events.

III. DATA ANALYSIS

A. pd multiplicity distribution

We examine first the multiplicity distribution of charged particles produced in pd collisions. The invisible spectator protons in the odd-prong events are included in the prong count to obtain the pd topological cross sections tabulated in column three of Table I. Because of the extreme difficulty in reliably detecting one- and two-prong inelastic pd events in the bubble chamber, it is necessary to estimate the two-prong inelastic pd cross section. We assume, following a spectator model of pd collisions, that

$$P_2(pd) = 0.5[P_1(pn) + P_2(pp)]\,, \tag{1}$$

where $P_N(px) = \sigma_N(px)/\sigma_{\text{inel}}(px)$ is the probability of an inelastic N-prong px collision. We further assume that the one-prong inelastic pn cross section may be estimated by[14]

$$P_1(pn) = (0.6 \pm 0.1) P_2(pp)\,. \tag{2}$$

The 28-GeV/c pd charged-particle multiplicity distribution is compared with that from pp collisions[13,15] in Fig. 1, where the curve is a parametrization of 28-GeV/c pp data.[16] The mean $\langle N \rangle$ and dispersion D of these distributions are given in Table II. We observe both the mean and dispersion to be larger in pd than in pp interactions.

The dependence of the dispersion on the mean multiplicity in pd collisions[3-7] is compared with that of pp collisions[13,15,17-24] in Fig. 2, where values of D are plotted as a function of $\langle N \rangle$ for incident proton momenta between 28 and 400 GeV/c. At all momenta, Eqs. (1) and (2) are used to estimate the inelastic two-prong pd cross section using pp data at that same beam momentum.

The dispersion of pp multiplicity distributions has been found to be a linear function of the mean multiplicity: $D = a(\langle N \rangle - b)$, with the parameter b equal to 1[25]; i.e.,

$$D_{pp} = a(\langle N \rangle_{pp} - 1)\,. \tag{3}$$

The dispersion of proton-nucleus multiplicity distributions has been observed to obey a similar

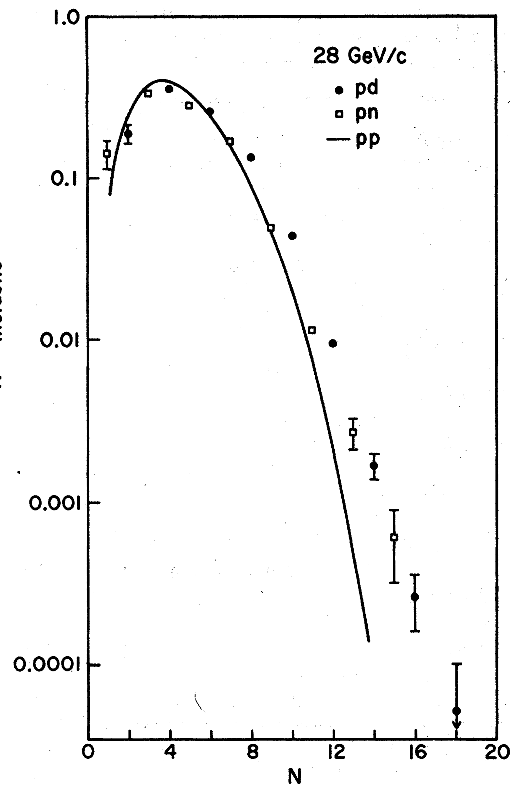

FIG. 1. Multiplicity distribution of charged particles produced in 28-GeV/c pd and pn interactions. The curve is a parametrization of the 28-GeV/c pp data from Refs. 13 and 15.

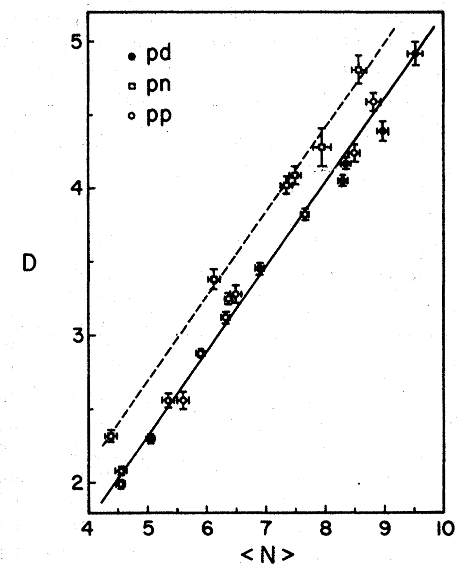

FIG. 2. Dispersion as a function of mean multiplicity for 28-to-400-GeV/c pd, pn, and pp charged-particle multiplicity distributions. The curves are results of fits to the data and are discussed in the text.

relationship.[26] A fit of the pd data to the form

$$D_{pd} = a(\langle N\rangle_{pd} - 1) \quad (4)$$

results in a value of the parameter consistent with that of Eq. (3). From a simultaneous fit of the pp data between 28 and 400 GeV/c, we obtain $a = 0.575 \pm 0.009$.

The solid line in Fig. 2 represents the simultaneous fit of the data to Eqs. (3) and (4). We conclude that the dispersion of pd charged-particle multiplicity distributions is consistent with the same linear dependence on the mean multiplicity as found for pp collisions.

TABLE II. Mean and dispersion of 28-GeV/c charged-particle multiplicity distributions.

	Reaction		
	pd	pp [a]	pn
$\langle N\rangle$	5.05 ± 0.07	4.54 ± 0.07	4.38 ± 0.10
D [b]	2.30 ± 0.03	2.04 ± 0.02	2.32 ± 0.04

[a] The values quoted are averages of the results of Refs. 13 and 15.

[b] $D \equiv (\langle N^2\rangle - \langle N\rangle^2)^{1/2}$.

B. Double scattering in pd collisions

A primary motivation for performing pd experiments in a bubble chamber is the desire to extract information about inelastic pn interactions. A spectator model, in which one of the nucleons within the deuteron is assumed to take no part in the interaction, is often the starting point of such an analysis.

A pure spectator model of three- and more-prong pd collisions predicts a fraction of spectator-proton (i.e., neutron-target) events

$$f_{\text{expected}} = \frac{\sigma_{\text{inel}}(pn) - \sigma_1(pn)}{[\sigma_{\text{inel}}(pn) - \sigma_1(pn)] + [\sigma_{\text{inel}}(pp) - \sigma_2(pp)]} \,. \quad (5)$$

To evaluate Eq. (5) we assume the inelastic pp and pn cross sections to be equal, and estimate $P_1(pn)$ with Eq. (2). Using 28-GeV/c pp data, we obtain $f_{\text{expected}} = 0.529 \pm 0.013$. The value of f_{expected} is different from 0.5 as a result of excluding the one-prong pn and two-prong pp cross sections from Eq. (5).

We measure the fraction of events with a spectator proton using only invisible spectator-proton (i.e., odd-prong) events and even-prong events with an identified proton whose production angle is backward with respect to the beam direction in the laboratory. The number of forward-spectator-proton events is obtained by weighting the observed backward-spectator-proton events by appropriate Moller flux factors.[27] We obtain a cross section for spectator-proton events with three or more prongs of (20.12 ± 0.40) mb, which is a fraction $f_{\text{observed}} = 0.432 \pm 0.011$ of the three-prong and greater *pd* cross section.

We define a double-scatter event as an inelastic incoherent *pd* collision in which both nucleons withing the deuteron participate in the interaction. Since double scattering is unlikely to result in an event used to measure the fraction of spectator-proton events (i.e., an odd-prong or backward-proton even-prong event), we identify the difference between the expected and observed spectator-proton fractions as due to double scattering within the deuteron. We define the double-scatter fraction F_{ds} as

$$F_{\text{ds}} = \frac{f_{\text{expected}} - f_{\text{observed}}}{f_{\text{expected}}}, \tag{6}$$

where f is the fraction of three- and more-prong *pd* events with a spectator proton. We find $F_{\text{ds}} = 0.183 \pm 0.029$ for 28-GeV/*c* *pd* collisions.

The existence of such a large fraction of double-scatter events in *pd* collisions is a potential complication in extracting neutron-target cross sections from *pd* data. In particular, we wish to obtain the *pn* charged-particle multiplicity distribution from the spectator-proton events. If the double-scatter probability is multiplicity-dependent, the multiplicity distribution of spectator-proton events will be distorted from that of free *pn* interactions. It is difficult to investigate the possibility of such an effect using data from a single experiment when the free *pn* multiplicity distribution is unknown. However, by comparing the double-scatter fraction at 28 GeV/*c* with that observed at higher momentum, we may determine the dependence of the double-scatter fraction on the mean multiplicity.

We display in Fig. 3 the fraction of three- and more-prong *pd* events in which double scattering occurs as a function of incident momentum. At all momenta, F_{ds} is calculated with Eq. (6), using the value of f_{observed} measured with the invisible and backward spectator-proton events,[5,7,28] and

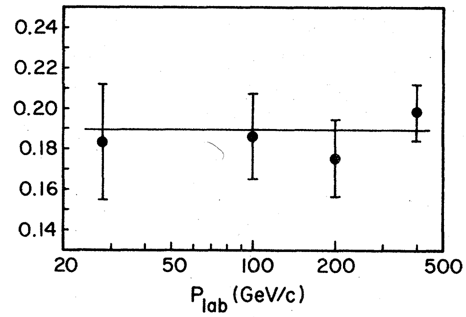

FIG. 3. Fraction of three- and more-prong *pd* events which result from double scattering in deuterium as a function of incident proton momentum between 28 and 400 GeV/*c*. The line represents the weighted average of the data.

the value of f_{expected} calculated from Eq. (5). As before, we assume the inelastic *pp* and *pn* cross sections to be equal, and estimate $P_1(pn)$ with Eq. (2) using *pp* data at the incident proton momentum of each *pd* experiment. Values of f_{expected}, f_{observed}, and F_{ds} for 28-to-400-GeV/*c* *pd* collisions are tabulated in Table III.

The double-scatter fractions displayed in Fig. 3 are consistent with their average value of 0.189 ± 0.010 independent of incident momentum between 28 and 400 GeV/*c*, as indicated by the solid line in the figure. Over this same momentum range the mean multiplicity in *pp* interactions increases by about a factor of 2. We conclude that the double-scatter probability in *pd* collisions is independent of the mean multiplicity, and assume that F_{ds} is also independent of multiplicity at fixed values of incident momentum.

C. *pn* multiplicity distribution

We obtain the topological cross sections for 28-GeV/*c* *pn* collisions from the invisible-spectator-proton events. We assume the odd-prong *pd* events to be an unbiased sample of *pn* interactions, and calculate the *pn* cross sections with the equation

$$\sigma_N(pn) = \frac{\sigma_N(pd \to \text{odd})}{(1-V)(1-F)(1-G)}, \tag{7}$$

TABLE III. Fraction of three- and more-prong *pd* events with a spectator proton and fraction of double-scatter events for 28-to-400-GeV/*c* *pd* interactions.

	Incident proton momentum (GeV/*c*) 28	100	200	400
f_{expected}	0.529 ± 0.013	0.517 ± 0.007	0.510 ± 0.005	0.509 ± 0.005
f_{observed}	0.432 ± 0.011	0.421 ± 0.009	0.421 ± 0.009	0.408 ± 0.006
F_{ds}	0.183 ± 0.029	0.186 ± 0.021	0.175 ± 0.019	0.198 ± 0.014

where V is the fraction of spectator-proton events with a visible spectator, F is the fraction of events which double scatter and hence are lost to the odd-prong sample, and G is a Glauber screening correction

$$G=\frac{\sigma_t(pp)+\sigma_t(pn)-\sigma_t(pd)}{\sigma_t(pp)+\sigma_t(pn)}.$$

Each of the factors V, F, and G in Eq. (7) are taken to be independent of multiplicity. From the data, we calculate $V=0.296\pm0.011$, and use the value of F determined above. We obtain $G=0.052\pm0.006$ from total-cross-section measurements.[29]

We tabulate the pn topological cross sections at 28 GeV/c in column four of Table I, where we have used Eq. (2) to estimate the one-prong inelastic cross section. The 28-GeV/c pn multiplicity distribution is compared with the pp and pd distributions in Fig. 1. We include in Table II values of the mean and dispersion of the pn charged-particle multiplicity distribution, and note that $\langle N\rangle$ is smaller in 28-GeV/c pn collisions than in pp collisions, while D is larger for the pn data.

The dependence of the dispersion on the mean multiplicity in pn collisions[3-7] is shown in Fig. 2, where pn results between 28 and 400 GeV/c are compared with pp and pd data. At all momenta, the odd-prong pd events are assumed to give the pn charged-particle multiplicity distribution, and we use Eq. (2) to estimate the inelastic one-prong contribution.

A fit of the 28-to-400-GeV/c pn data to the form

$$D_{pn}=a(\langle N\rangle_{pn}-b) \tag{8}$$

results in a value of a consistent with that of Eqs. (3) and (4). We make a satisfactory fit of the pn data to Eq. (8) by fixing $a=0.575$, and obtain $b=0.346\pm0.029$, as indicated by the dashed line in Fig. 2.

IV. SUMMARY AND CONCLUSIONS

We have examined the multiplicity distribution of charged particles produced in 28-GeV/c pd collisions. A pure spectator model of inelastic pd collisions is found to be inconsistent with the observed fraction of pd events which have a spectator proton. We identify the deficiency in the observed number of spectator-proton events as due to double scattering within the deuteron in a fraction $F_{ds}=0.183\pm0.029$ of the three-prong and greater pd events. The multiplicity-increasing effects of inelastic double scattering are revealed in the broadening of the pd multiplicity distribution, compared to the pp and pn distributions. The fraction of pd events which double scatter is observed to be constant for pd collisions between 28 and 400 GeV/c incident momentum.

The observation that the double-scatter probability in pd collisions is independent of incident momentum is strong evidence against particle-cascade models of hadron-nucleus interactions. In such models the fraction of events which double scatter would increase with increasing momentum, proportional to the multiplicity of particles produced in hadron-nucleon interactions. The observation that the fraction of events which double scatter is independent of momentum over a region where the mean multiplicity changes by a factor of 2 leads us to assume that the double-scatter fraction is also independent of multiplicity at fixed values of incident momentum.

We extract the pn charged-particle multiplicity distribution from the invisible-spectator-proton events. The pn topological cross sections are calculated by correcting the data for the effects of spectator-proton visibility, double scattering, and Glauber screening.

The dispersions of both the pd and pn charged-particle multiplicity distributions are observed to be linear functions of the mean charged multiplicity, as was previously known for pp collisions. Fits of the pd, pn, and pp data from 28 to 400 GeV/c to the form $D=a(\langle N\rangle-b)$ result in a value of $a=0.575\pm0.009$ independent of the target particle. The pd data is found to have the same dependence as the pp data, with $b=1.0$, while a value of $b=0.346\pm0.029$ describes the pn data.

It has recently been observed[7] that the 100-to-400-GeV/c pd multiplicity distributions are consistent with the same Koba-Nielsen-Olesen (KNO) scaling function[30] as pp data in the same incident-momentum range, while the 100-to-400-GeV/c pn data are consistent with a different KNO scaling function. The dependence of the dispersion on the mean multiplicity noted above is evidence that the 28-to-400-GeV/c data are inconsistent with KNO scaling. If KNO scaling were valid, the parameter b in the relation $D=a(\langle n\rangle-b)$ would be zero. It has been previously observed[31] that 28-GeV/c pp data are inconsistent with the approximate KNO scaling obeyed by 100-to-300-GeV/c data. The data presented here show that, in addition, both pd and pn multiplicity distributions at 28 GeV/c are inconsistent with the KNO scaling seen at higher energies.

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