Double Scattering in Deuterium as a Probe of Hadron Structure

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Comparing hadron-deuteron and hadron-hadron data for various energies and reactions, we study the time development of hadronic matter and in particular test the Abramovskii-Gribov-Kancheli rules.

Hadron-nucleus collisions provide us with a unique means of studying the structure of hadrons. Since the nucleus is an extended object, the space-time development of hadronic matter is proved over distances and times large compared to those probed in ordinary hadron-hadron collisions. In this regard deuteron targets have particular advantages. Because the neutron and proton in a deuteron are loosely bound, it is possible to probe the incident hadron at two separate space-time points by isolating those interactions in which both proton and neutron have participated (double scattering). This is not possible with either ordinary hadrons or heavy nuclei as targets. In the former we can identify no constituents which retain their identity during the process to use as tags for multiple interactions, while in the latter the further interactions of struck nucleons before they escape the nucleus complicate the interpretation.

Recently, data on high-energy hadron-deuteron (hd) interactions have become available from the Fermilab 30-in. bubble chamber. In this Letter we organize these data and use them to test the Abramovskii-Gribov-Kancheli (AGK) cutting rules[1] which are a consequence of the absence of singular short-range forces.[2]

There exist data for interactions of π^+d and pd at 100 GeV,[3] π^-d[4] and pd[5] at 200 GeV, and pd at 300 GeV.[6] In these experiments, events are separated into two categories: those with odd and those with even charge multiplicity. The odd-multiplicity events can be interpreted as interactions with only the neutron, since the missing charge is most likely due to the unseen low-energy spectator proton of the deuteron. For each even charge multiplicity N, essentially twice the number of events with observed backward protons are subtracted and added to the $N-1$ odd-multiplicity events to form σ_N("hn"). This accounts for visible spectator protons. The partial cross sections for the remaining even-N events, designated σ_N("hp"), are due to single hp interactions plus interactions with both the neutron and proton. Because of the difficulties in correcting the one- and two-prong data, most experiments give results only for $N \geq 3$.

The "hp" and "hn" cross sections for $N \geq 3$ are compared with measured hp and derived hn cross sections in Table I.[7] We note that σ("hp") $-$ σ("hn") is considerably larger than $\sigma(hp) - \sigma(hn)$. This feature is interpreted as due to double scattering which takes events from the hn to the hp category. Thus an experimental measure of the amount of

TABLE I. Comparison of "hp" ("hn") with hp (hn) data.

	pd 100 GeV	pd 200 GeV	pd 300 GeV	π^+d 100 GeV	π^-d 200 GeV
σ("hp"), mb	31.24 ± 1.26	31.86 ± 0.68	33.76 ± 0.59	17.88 ± 0.97	20.25 ± 0.33
σ("hn"), mb	22.76 ± 0.95	23.19 ± 0.39	22.45 ± 0.48	15.12 ± 0.84	15.17 ± 0.25
$\sigma(hp)$, mb	26.49 ± 0.40	29.13 ± 0.45	30.39 ± 0.61	17.57 ± 0.34	19.33 ± 0.46
$\sigma(hn)$, mb	28.13 ± 0.45	30.36 ± 0.76	31.19 ± 0.81	19.56 ± 0.28	20.19 ± 0.54
$\langle N_-^{\mathrm{Pr}}$("$hp$")$\rangle$	2.79 ± 0.05	3.48 ± 0.05	3.78 ± 0.12	2.89 ± 0.10	3.45 ± 0.07
$\langle N_-^{\mathrm{Pr}}(hp)\rangle$	2.59 ± 0.02	3.16 ± 0.10	3.51 ± 0.02	2.62 ± 0.02	3.16 ± 0.03
Δ_{exp}, mb	10.12 ± 0.73	9.90 ± 0.98	12.12 ± 1.10	4.75 ± 0.49	5.94 ± 0.75
$2\delta\sigma$,[a] mb	8.28 ± 0.22	8.52 ± 0.22	8.66 ± 0.22	3.70 ± 0.25	3.62 ± 0.20
$(\Delta_{\mathrm{exp}} - 2\delta\sigma)$	1.8 ± 1.7	1.4 ± 1.2	3.5 ± 1.1	1.1 ± 0.6	2.3 ± 0.8

[a]Ref. 13.

double scattering for $N \geq 3$ is given by

$$\Delta \equiv [\sigma(\text{"}hp\text{"}) - \sigma(\text{"}hn\text{"})] - [\sigma(hp) - \sigma(hn)]. \quad (1)$$

In Table I we also give the average number of produced negative particles $\langle N_-^{\mathrm{Pr}}\rangle$ for both "hp" and hp interactions. We find $\langle N_-^{\mathrm{Pr}}(\text{"}hp\text{"})\rangle$ greater than $\langle N_-^{\mathrm{Pr}}(hp)\rangle$, consistent with the expectation that double scattering leads to higher multiplicities.

These data can be understood quantitatively[8] by use of the conventional picture of the space-time development of hadronic interactions, in which the assumed absence of a singular short-range force means that intermediate states containing particles with virtual mass $k^2 \equiv E^2 - \vec{k}^2 \gg m_c^2$ (some cutoff of order 1 GeV^2) give only small contributions.[2] In the laboratory frame, this yields the following qualitative picture of high-energy hadron-hadron interactions. The incident high-energy hadron of momentum $\vec{p}_h$ and mass m_h decays into two (or more) constituents of momenta $\vec{k}_i$, where $\vec{p}_h = \sum \vec{k}_i$. Energy conservation is violated by an amount $\Delta E = E_h - \sum E_i$, where $E_i = (\vec{k}_i^2 + k_i^2)^{1/2}$. For constituents with momenta $|\vec{k}_i| \sim |\vec{p}_h|$, $\Delta E \sim m_c^2/p_h$. This virtual state can therefore last for a time (or distance) of order p_h/m_c^2. The constituents can themselves continue to decay until constituents of momenta $|\vec{k}| \sim m_c$ are produced which have an appreciable amplitude for interacting with the target. Figure 1(a) shows an example of such a process.

To investigate the implications of this picture for hadron-deuteron interactions we study the forward elastic hadron-deuteron amplitude A_{hd} which via unitarity determines inelastic cross sections. The amplitude A_{hd} is a sum of single- and double-scattering processes. Single scattering yields a contribution to $\mathrm{Im}A_{hd}$ proportional to $\sigma_T(hp) + \sigma_T(hn)$ while double scattering yields cross-section defect $\delta\sigma \equiv \sigma_T(hp) + \sigma_T(hn) - \sigma(hd)$.

A simple double-scattering process is shown in Fig. 1(b) where two constituents of the incident hadron of momenta k_1 and k_2 elastically scatter from the proton and neutron, respectively, yielding constituents of momenta $k_1 + q$ and $k_2 - q$. The salient point is that in order for the constituent of momentum k_2 to be able to interact with the neutron which is at a distance r from the proton, it must live a time of the order r. Thus, the hadronic time scale $|\vec{k}_2|/m_c^2$ must be at least of the order of the distance between the neutron and proton in the deuteron; i.e., $|\vec{k}_2| \gtrsim m_c^2 r$. Since approximately 90% of the time the proton and neutron in the deuteron are greater than 1 fm apart, the dominant contribution to the second scattering arises from constituents of momentum $|\vec{k}_2| \gtrsim m_c^2 r \approx 5$ GeV. Processes involving double scattering of "slow" constituents, $|\vec{k}_2| \approx m_c$, should be substantially suppressed because they cannot live long enough to reach the second nucleon and will be neglected. Of particular interest are processes involving double scattering from *very* fast constituents $|\vec{k}_2| \gg m_c^2 r$, since in this case the hadronic time scale is much greater than the separation r between nucleons. Then the nuclear physics separates cleanly from the hadronic physics and there results the simple relation

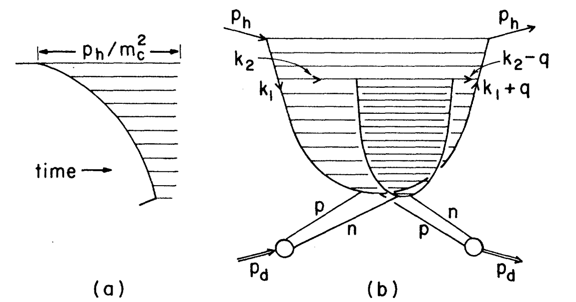

FIG. 1. Examples of hadronic interactions.

$$\Delta \approx 2\delta\sigma. \quad (2)$$

From Table I we see that Eq. (2) accounts for most of the observed double scattering (Δ), although there is a systematic underestimate of its magnitude.[9]

To obtain Eq. (2) we first note that for $|\vec{k}_i| \gtrsim m_c^2 r$, the double-scattering contribution to A_{hd} takes on the form depicted in Fig. 2(a). Its unitarity discontinuity can be divided into three classes represented by Figs. 2(b_0), 2(b_1), and 2(b_2) with corresponding partial cross sections, $\sigma(0)$, $\sigma(1)$, and $\sigma(2)$, respectively. Any of the graphs of Fig. 2 for which the intermediate physical states contain a proton directly connected to the deuteron wave function which limits the proton momentum will contribute predominantly to $\sigma(\text{"}hn\text{"})$. Thus, the graphs of Figs. 2(b_1) and 2(b_0) contribute only to $\sigma(\text{"}hn\text{"})$, while in the remaining graphs all the produced charged particles result from hadronic interactions and hence contribute to $\sigma(\text{"}hp\text{"})$. The contribution of diffractive production process, Fig. 2(b_0), to $\sigma(\text{"}hn\text{"})$ is small for $N \geq 3$ since the main contribution to this graph comes from the elastic state.[10] Furthermore, the graph in Fig. 2(b_1) and its interchange

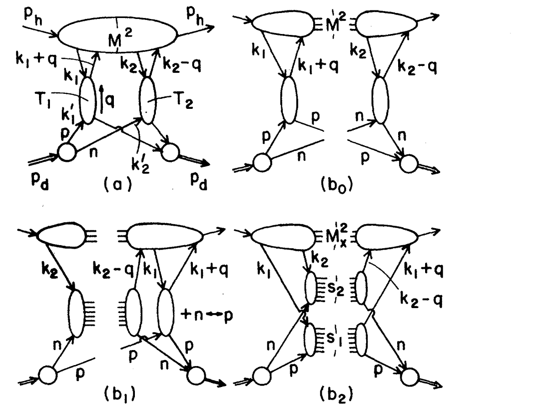

FIG. 2. *hd* elastic scattering graph and its discontinuities.

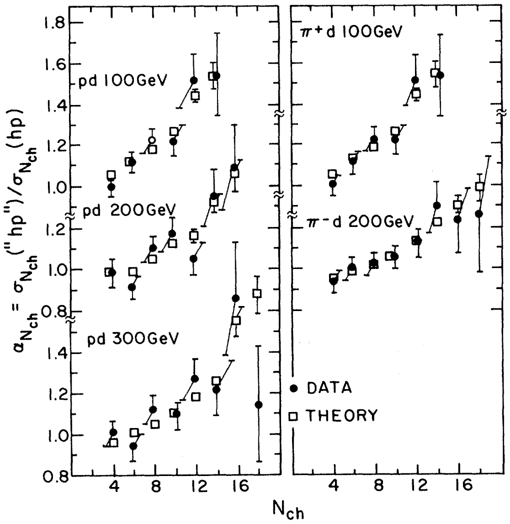

FIG. 3. Comparison of predicted α_N with data.

$n \leftrightarrow p$ yield equal contributions of $\frac{1}{2}\sigma(1)$ to $\sigma(``hn")$ and $\sigma(``hp")$.[11] We thus obtain

$$\sigma(``hp") \approx \sigma(hp) + \tfrac{1}{2}\sigma(1) + \sigma(2), \tag{3a}$$

$$\sigma(``hn") \approx \sigma(hn) + \tfrac{1}{2}\sigma(1). \tag{3b}$$

We now invoke the AGK rules,[1]

$$\sigma(0) = \delta\sigma, \quad \sigma(1) = -4\delta\sigma, \quad \sigma(2) = 2\delta\sigma, \tag{4}$$

which together with Eqs. (1) and (3) yield Eq. (2). The AGK rules apply to the contribution to $\sigma(1)$ and $\sigma(2)$ from the region $|\vec{k}_i| \gg m_c^{\,2} r$ discussed above, which corresponds to small M^2 in the upper blob of Fig. 2. Thus Eq. (2) holds if small-M^2 contributions dominate $\sigma(1)$ and $\sigma(2)$, as is true for $\sigma(0)$.[10] Equation (2) makes clear the advantage of studying inelastic collisions in deuterium. The double-scattering cross section Δ and the cross-section defect $\delta\sigma$ can be compared while corresponding quantities cannot be isolated in a model-independent way from interactions on nucleon targets. Thus, *hd* interactions may provide the first unambiguous tests of the AGK rules.

The data on multiplicity distributions σ_N provide a further check of the space-time picture. We denote the N-charged-particle contribution to the cross sections of Eq. (3) by $\sigma_N(``hp")$ and equations identical to Eq. (3a) hold for each $N$. The ratio $\sigma_N = \sigma_N(``hp")/\sigma_N(hp)$ measures the relative multiplicity distribution of double scattering. Since $\sigma_N(1)$ and any double-scattering processes not included in the AGK results [Eq. (2)] are expected to have distributions similar to $\sigma_N(hp)$, the N-particle contribution to Eq. (3a) yields

$$\alpha_N \approx C + \sigma_N(2)/\sigma_N(hp), \tag{5}$$

where $C = [\sigma(``hp") - 2\delta\sigma]/\sigma(hp)$ and $\sum \sigma_N(2) = 2\delta\sigma$. Therefore a measurement of α_N provides a check on the AGK contribution, $2\delta\sigma$, to double scattering which does not depend on the magnitude of other processes.

In order to determine σ_N we need a model for $\rho_N(2) \equiv \sigma_N(2)/\sigma(2)$. We take the simplest possibility where the incident particle of momentum p_h decays into two particles each having momentum $p_h/2$ [$M_x^{\,2} = 0$ in Fig. 2(b$_2$)] and convolute the relevant measured distributions taken from *hp* interactions at momentum $p_h/2$.[12] Our predictions for α_N are compared with data in Fig. 3 and the agreement is good.

In summary, we have argued that the most important contribution to double scattering comes from those processes where the nuclear time scale is small compared to the hadronic time scale and simple relations following from the AGK rules hold. The resulting predictions for the double-scattering cross section and multiplicity are in good agreement with experiment. However, better data and a detailed phenomenological analysis are necessary to estimate contributions from interactions of slower constituents for which the nuclear scale is not negligible.[9]

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[7]The procedures for obtaining $N \geqslant 4$ ($N \geqslant 3$) hp (hn) cross sections are discussed by M. Baker, H. J. Lubatti, E. O. Rogers, and J. H. Weis, to be published.

[8]See Baker *et al.*, Ref. 7.

[9]The most likely source of the excess is processes involving slower constituents $m_c^2 r \geqslant |\vec{k}_i| \geqslant m_c$ (see Ref. 8).

[10]For $\pi^- d$ at 200 GeV $\delta\sigma = 1.8$ mb and the elastic state contributes 1.4 mb. See J. Kwieciński *et al.*, Nucl. Phys. B28, 257 (1974).

[11]This occurs if the proton momentum distribution from these contributions is forward-backward symmetric, which requires the longitudinal momentum transfer to the proton, and consequently the large-M^2 contribution to the upper blob, to be small.

[12]For pd interactions we convolute the averaged $\pi^\pm p$ distribution (πN) at $p_h/2$ with pp at $p_h/2$, and for πd interactions we convolute πN with itself. The data used are as follows: (i) $\pi^- p$, 50 GeV, A. Akopdjanov *et al.*, Nucl. Phys. B75, 401 (1974); 100 GeV, E. L. Berger *et al.*, Nucl. Phys. B77, 365 (1974); 147 GeV, D. Fong *et al.*, Nucl. Phys. B102, 386 (1976); 205 GeV, D. Ljung *et al.*, Fermilab Report No. FERMILAB-PUB-76/92-EXP (unpublished). (ii) $\pi^+ p$, 50 GeV, A. Akopdjanov *et al.*, Nucl. Phys. B75, 401 (1974); W. M. Morse *et al.*, Phys. Rev. D 15, 66 (1977). (iii) pp, 50 GeV, V. V. Ammosov *et al.*, Phys. Lett. 42B, 519 (1972); 100 GeV, W. M. Morse *et al.*, Phys. Rev. D 15, 66 (1977); 200 GeV, G. Charlton *et al.*, Phys. Rev. Lett. 29, 515 (1972), 300 GeV, A. Firestone *et al.*, Phys. Rev. D 10, 2080 (1974).

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Comparison of the Line-Reversed Channels $\bar{p}p \to \pi^-\pi^+$ and $\pi^+ p \to p\pi^+$ at 6 GeV/c

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Differential cross sections have been measured for $\bar{p}p \to \pi^-\pi^+$ (1) and its line-reversed partner $\pi^+p \to p\pi^+$ (2) in the range $t_{min} > t > -1.5$ (GeV/c)^2 at 6 GeV/c. Clear structure is seen in the differential cross section for Reaction (1) at $t \sim -0.4$ (GeV/c)^2. However, this feature is quite different from the striking dip seen in (2) at $t \sim -0.15$ (GeV/c)^2, indicating a failure of line reversal and disagreement with simple Regge models.

The line-reversed reactions $\bar{p}p \to \pi^-\pi^+$ (1) and $\pi^+p \to p\pi^+$ (2) proceed via nucleon and Δ exchange in the t channel.[1] Simple models predict that if the scattering is dominated by a single amplitude, then the differential cross sections for the two reactions will have the same shape and that at asymptotic energies backward elastic scattering will be twice the annihilation reaction.

In recent years, workers have employed Regge models[2] and absorption models[3] to explain the detailed structure of baryon-exchange reactions. These models, with large numbers of free parameters, have successfully explained the t structure in related processes.[4] However, in order to limit such models, new high-quality data with small and/or canceling systematic errors are needed. Reactions (1) and (2) are especially interesting to study since π^+p backward elastic scattering[5] displays one of the most striking dips in high energy physics at $t' \equiv t - t_{min} \sim -0.2$ (GeV/