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THEORY OF SPIN DEPENDENCE AT VERY HIGH ENERGIES

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THEORY OF SPIN DEPENDENCE AT VERY HIGH ENERGIES*

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ABSTRACT

The point of view I wish to take in this talk is to introduce a number of topics for possible discussion during the course of this workshop. In the first half of the talk, I will review some of the theoretical expectations for polarization phenomena assuming that hadrons are composite. In the second half of the talk I will consider polarization phenomena from an S-matrix point of view. The summary talk of Francis Low contains the conclusions which were reached during the course of this workshop.

HADRONS ARE COMPOSITE?

A popular notion is that hadrons are composite, and their constituents are spin 1/2 quarks and spin 1 gluons. The view is that the theory of strong interactions is an SU_3 gauge theory of color gluons, interacting with quarks which carry one of three color charges. This theory, Quantum Chromo-Dynamics (QCD)[1] is very similar in structure to Quantum Electro-Dynamics (QED). In such theories, the interaction of the fermions with the vector bosons is not arbitrary but fixed by the requirements of Lorentz invariance and local gauge invariance. If the theories are correct, then the observed spin dependence of the interaction must obey certain laws. In particular, in regions where single vector exchange dominates the interaction, the spin dependence of the interaction is expected to be quite simple. In what follows we will only consider processes where this is thought to be the case.

At the level of single vector gluon exchanges, QED and QCD are identical except for color factors. For scattering processes involving hadrons we must use some theory of composite object scattering to extract the underlying constituent interaction. (Possibly because of the SU_3 color symmetry, free quarks are not available for direct experimentation.) Experimenters are requested to think of the analogous problem of studying neutron interactions; one usually needs the Glauber theory to disentangle the underlying neutron hadron interaction from the more accessible deuteron hadron processes. For quarks, the theory which allows us to disentangle the quark interactions from hadron processes is the parton model. This model is reviewed in many places;[2] so we won't say more about it at this time. We shall concentrate instead on the underlying processes, in particular the spin structure of the fermion fermion scattering mediated by vector exchange and various instances of this in lepton-hadron and hadron-hadron scattering.

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A. Spinology

The discussion that follows will be at the level of the textbook of Bjorken and Drell[3]. The reader can refer to it for more details. The process we shall consider is sketched in Fig. 1.

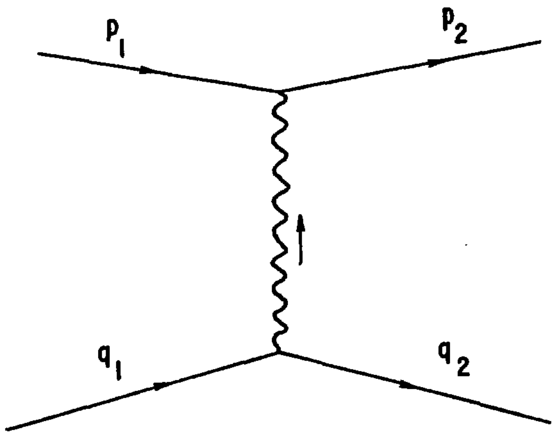


Fig. 1. One of the Feynman diagrams for $1/2^+ \, 1/2^+$ elastic scattering mediated by 1^- exchange.

We shall be interested in the structure of this diagram, which follows directly from an application of the Feynman rules:

$$M = \bar{u}(p_2)\gamma_\mu u(p_1) g^{\mu\nu} \bar{u}(q_2)\gamma_\nu u(q_1) \tag{1}$$

is proportional to the invariant amplitude for Fig. 1. We have dropped factors of i and e^2 as well as the momentum dependence of the vector propagator since we do not intend to use (1) to compute absolute rates, but rather wish to highlight the spin dependence. This spin dependence comes in through the fermion wave functions

$$u(p) = \sqrt{E+m} \begin{pmatrix} \chi \\ \frac{\sigma \cdot p}{E+m} \chi \end{pmatrix} \tag{2}$$

where χ is a two component spinor. The fermion is characterized by both a momentum 4-vector p_μ and a polarization 4-vector w_μ: in the rest frame $p_\mu = (m,0,0,0)$ and $w_\mu = (0,\hat{w}_x, \hat{w}_y, \hat{w}_z)$ with $\hat{w} \cdot \sigma\chi = \chi$. For computations with Dirac wave functions, it is convenient to recall the covariant projection operators

$$u(p)\,\bar{u}(p) = (\not{p}+m)\frac{(1+\gamma_5 \not{w})}{2} \, . \tag{3}$$

Using this fact we can evaluate the absolute square of M [Eq. (1)].

To start with we assume only p_1 and p_2 are polarized. For unpolarized particles, we sum (3) over both polarization states w_μ and $-w_\mu$

$$\sum_{\text{spins}} u(q)\bar{u}(q) = (\not{q} + m) \ . \tag{4}$$

The resultant probability is

$$\sum_{\text{spins}} |M|^2 = \sum_{\text{spins}} \bar{u}(p_2)\gamma_\mu u(p_1)\ \bar{u}(p_1)\gamma_\rho\ u(p_2)$$
$$\times \sum_{\text{spins}} \bar{u}(q_2)\gamma^\mu\ u(q_1)\ \bar{u}\ (q_1)\gamma^\rho\ u(q_2) \ . \tag{5}$$

Using the projection operators in Eq. 3-4, we find

$$\sum_{\text{spin}} |M|^2 = \text{Tr}\left\{ (\not{p}_2 + m)\frac{(1+\gamma_5\not{w}_2)}{2}\gamma_\mu(\not{p}_1 + m)\frac{(1+\gamma_5\not{w}_1)}{2}\gamma_\rho \right\}$$
$$\times\ \text{Tr}\left\{ (q_2 + m)\gamma^\mu(\not{q}_1 + m)\gamma^\rho \right\} \ . \tag{6}$$

This has the form of the product of two tensors

$$\sum |M|^2 = \text{TOP}_{\mu\rho}\ \text{BOTTOM}^{\mu\rho} \ , \tag{7}$$

one associated with the top vertex of Fig. 1, the other the bottom vertex. Of course this decomposition would remain true if particles q_1 and q_2 were also polarized; then the two tensors would have the same forms. The possible spin structure of the interaction follows from considering only the top vertex.

If the fermions are transversely polarized, and their masses are negligible, the form of the top vertex simplifies

$$\text{TOP}_{\mu\nu} = \frac{1}{4}\ \text{Tr}\left\{ \not{p}_2(1+\gamma_5\not{w}_2)\gamma_\mu\not{p}_1(1+\gamma_5\not{w}_1)\gamma_\nu \right\} \tag{8}$$
$$= S_{\mu\nu} + D_{\mu\nu}$$

where

$$S_{\mu\nu} = \frac{1}{4}\ \text{Tr}(\not{p}_2\gamma_\mu\not{p}_1\gamma_\nu)$$
$$= p_{1\mu}p_{2\nu} + p_{1\nu}p_{2\mu} - p_1 \cdot p_2 g_{\mu\nu} \tag{9}$$
$$= S_{\nu\mu}$$

and

$$D_{\mu\nu} = \frac{1}{4}\,\mathrm{Tr}(\not{p}_2\not{s}_2\gamma_\mu\not{p}_1\not{s}_1\gamma_\nu)$$
$$= D_{\nu\mu} \quad . \tag{10}$$

There are no terms in $TOP_{\mu\nu}$ proprotional to a single fermion spin.

If the fermions are longitudinally polarized and the masses are negligible, we can replace $(1+\gamma_5\not{s})$ by the helicity projection operator $(1+\lambda\gamma_5)$ for a helicity state $\lambda = \pm 1$. The form of the top vertex again simplifies

$$TOP_{\mu\nu} = \frac{1}{4}\,\mathrm{Tr}\left\{\not{p}_2(1+\lambda_2\gamma_5)\gamma_\mu\not{p}_1(1+\lambda_1\gamma_5)\gamma_\nu\right\}$$
$$= (1+\lambda_1\lambda_2)S_{\mu\nu} + (\lambda_1+\lambda_2)A_{\mu\nu} \tag{11}$$

where $S_{\mu\nu}$ is as before [Eq.9] and

$$A_{\mu\nu} = -\frac{1}{4}\,\mathrm{Tr}\left\{\gamma_5\not{p}_2\gamma_\mu\not{p}_1\gamma_\nu\right\}$$
$$= i\,\varepsilon_{\alpha\beta\mu\nu}p_2^\alpha p_1^\beta = -A_{\nu\mu} \quad . \tag{12}$$

Equation (11) shows the interaction conserves helicity, and furthermore allows a spin dependence if only one of the fermions is polarized. In this case, Parity requires the other vertex to have one fermion with definite helicity.

If both transverse and longitudinal spins are allowed, we can combine (8) and (11) to obtain

$$TOP_{\mu\nu} = (1+\lambda_1\lambda_2)S_{\mu\nu} + (\lambda_1+\lambda_2)A_{\mu\nu} + D_{\mu\nu} \;, \tag{13}$$

since one can easily show there are no interference terms between longitudinal and transverse polarization states.

We draw the following conclusions from [Eq. 13]:

(1). If only one fermion is polarized at one vertex, the interactions will be independent of its polarization unless one fermion at the other vertex is also polarized. When one fermion at each vertex is polarized, the interaction will be independent of their polarizations unless both fermions have longitudinal polarizations.

(2). When only longitudinal polarizations are considered, each vertex conserves the helicity of the fermion [i.e. $\lambda_1 = \lambda_2$ in (Eq.13) or the vertex vanishes].

(3). Transverse spin dependence occurs only when both fermions at one [or both] vertices have non zero transverse polarization.

In the discussions that follow, we consider only longitudinal polarizations, in which case we have helicity conservation at each vertex. We do not exclude however, interesting effects for transverse polarized fermions. There is the effect (4) above, as well as the possibility of interchange effects [e.g. the cross diagram to Fig. 1] causing non-zero dependence on the transverse spins.

As a final comment on spinology, for those of you who are familiar with the $pp \to pp$ Jacob and Wick helicity amplitudes[4,5]

$$\begin{aligned}
\phi_1 &= \langle ++|\phi|++\rangle \\
\phi_2 &= \langle --|\phi|++\rangle \\
\phi_3 &= \langle +-|\phi|+-\rangle \\
\phi_4 &= \langle +-|\phi|-+\rangle \\
\phi_5 &= \langle ++|\phi|+-\rangle \quad ,
\end{aligned} \tag{14}$$

I quote their value, for the Feynman diagram of Fig. 1, up to an overall numerical constant

$$\begin{aligned}
\phi_1 &= \frac{s}{t} \\
\phi_2 &= 0 \\
\phi_3 &= -\frac{u}{t} \\
\phi_4 &= 0 \\
\phi_5 &= 0 \quad .
\end{aligned} \tag{15a}$$

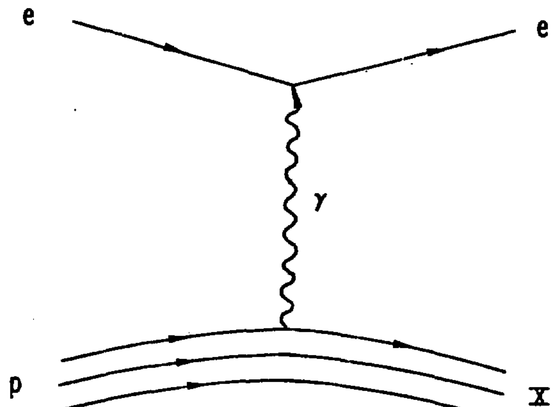
If the crossed graph is added, recalling that the fermions are identical, the full expressions are

$$\begin{aligned}
\phi_1 &= s\left(\frac{1}{t} + \frac{1}{u}\right) \\
\phi_2 &= 0 \\
\phi_3 &= -\frac{u}{t} \\
\phi_4 &= \frac{t}{u} \\
\phi_5 &= 0 \quad .
\end{aligned} \tag{15b}$$

One can then refer to the literature for the expressions of any spin observable in terms of these helicity amplitudes.[6]

B. Applications

With the formalities now out of the way we propose to give a qualitative description of several processes of possible interest, starting with deep inelastic electron scattering. One can refer to standard references[7] for the kinematics of the process (cf Fig. 2).



$$\nu = \frac{p \cdot e}{m}$$

$$x = \frac{Q^2}{2m\nu}$$

Fig. 2. Deep Inelastic Scattering: $ep \to eX$ where ν is the lab. momenta of the incident electron, $q^2 = -Q^2$ is the 4-momentum transfer and x is the quark's fraction of the proton longitudinal momentum. The proton is viewed as three quarks (as is the final state X).

The elementary subprocess is electron quark elastic scattering via the exchange of a photon. If both incident fermions are in states of definite helicity, we would expect an asymmetry A_0 in comparing the cross section for aligned helicities against non-aligned:

$$A_0 = \frac{\sigma(++) - \sigma(+-)}{\sigma(++) + \sigma(+-)} \quad . \tag{16}$$

where $\sigma(\lambda_e \lambda_q)$ is the elementary (differential) cross section for an electron with helicity λ_e to scatter from a quark with helicity λ_q. Now we can prepare electrons in pure helicity states, but the quarks will in general not be 100% polarized since they are bound.

The quark parton argument[8] is that there is a certain probability to find a quark with the fraction x of the proton's longitudinal momentum, and with helicity λ_q given that the proton had definite helicity λ_p. This probability or structure function is a measure of the quark's wave function inside the proton. Because of this structure function, the quark will in general have a polarization $P(x)$ along the direction of the proton's helicity, in addition to the usual probability $G(x)$ for finding the quark.

Using these quite crude arguments, we expect an asymmetry A in $ep \to eX$ which is A_0 diluted by the quark polarization. More precisely, in the deep inelastic region

$$A = \frac{\sum_i Q_i^2 P_i(x) G_i(x)}{\sum_i Q_i^2 G_i(x)} A_0 \tag{17}$$

where the sum goes over the quarks in the proton and Q_i is the quark charge. If one is not at high q^2, there is an additional kinematic dilution in (17). For those wishing more details, I refer to an excellent review by R. Field.[9]

We now consider the Drell-Yan[10] process $p\bar{p} \to \mu^+\mu^- X$. The elementary process is the crossed reaction to Fig. 2: $q\bar{q} \to \mu^+\mu^-$ through a single photon. The kinematics are different, but the same structure functions enter. The expected asymmetry A for longitudinally polarized protons and antiprotons to annihilate into μ pairs plus anything is[8]

$$A = \frac{\sum_i Q_i^2 \int dx_1 dx_2 G_i(x_1)\bar{G}_i(x_2)\ \delta(M^2 - sx_1x_2) P_i(x_1) P_i(x_2) A_0}{\sum_i Q_i^2 \int dx_1 dx_2 G_i(x_1)\bar{G}_i(x_2)\ \delta(M^2 - sx_1x_2)} \tag{18}$$

where A_0 is the asymmetry for the elementary process. Thus A is the same as the elementary asymmetry modulo a dilution factor, and so A can in principle reflect the underlying dynamics.

Next we turn to the Drell-Yan processes $pp \to \mu^+\mu^- X$ (Fig. 3).

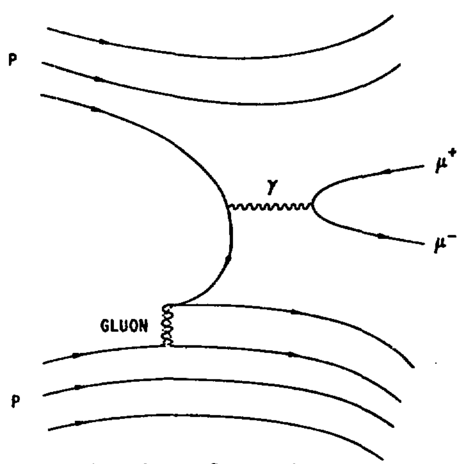


Fig. 3. Drell-Yan production of μ-pairs.

The only difference between this process and the last is that the anitquark must come from the sea. In order to see an effect, one must believe that a polarized proton causes the sea to be polarized.[11]

From graphs such as Fig. 3, this is possible. The asymmetry is otherwise the same as (18).[8]

The last example is large p_T hadron production

$$\begin{aligned} &pp \to \pi X \\ &pp \to \text{jet } X \\ &pp \to \pi\pi X \\ &pp \to \text{jet jet } X \quad . \end{aligned} \tag{19}$$

The only change from Fig. 3 is that the subprocess $q\bar{q} \to \mu^+\mu^-$ is replaced by $q\bar{q} \to q\bar{q}$ via a color vector gluon, and one includes in (18) the redressing probability for a quark to become a hadron (π, K, jet, etc.). Again the asymmetry measurement will reflect the elementary asymmetry modulo a dilution factor.

In summary we have seen qualitatively how the vector interaction might be studied through polarization measurements. The main effect of scattering composite objects is to dilute the effect. Now in presenting these arguments we have not been too careful with the form of the dilution factor. Indeed, the main difficulty lies in calculating such a factor since the pieces which make it up are not well known. One needs the u and d quark's polarization separately, as well as that of the sea quarks. At present, there is not enough experimental information from deep inelastic scattering data to determine these. Moreover, theoretical arguments are probably suspect though naive arguments do give about the right results for the asymmetry seen for A (Eq. 17) at SLAC.[12]

There are thus a number of questions to be answered before one considers these polarization experiments. If one hopes to establish in hadron reactions that gluons are spin-1 objects, one should first be in a region where the large p_T production rate falls as p_T^{-4} (modulo logarithmic, calculable corrections).[13] One also needs to establish that quarks are polarized, and know quantitatively how much so that the various dilution factors can be calculated.

The constituent picture may also be relevant in understanding soft collisions. The above arguments are not of much use since one certainly has a large number of vector gluon interactions instead of only one. Perhaps bags are of some use in this context. It is amusing that Low's calculation of the spin dependence of $pp \to pp$ near the forward direction gives an explanation for helicity conservation of the bare Pomeron using bag model arguments.[14] Perhaps these arguments can be extended to other processes such as $\Lambda p \to \Lambda p$, $\Lambda\Lambda \to \Lambda\Lambda$ or inelastic diffraction processes.

STRONG INTERACTION PHENOMENOLOGY

However much one likes the idea that the correct theory for all processes is a gauge field theory, one must face up to the difficulties of making quantitative predictions about purely strong interaction processes. We will here take the point of view that one way of learning about how to make such predictions is to study the data. There has developed a number of phenomenological models and ideas which have helped elucidate general properties of the S matrix, properties one might one day hope to establish from an underlying theory. Even if one never achieves such a connection with field theory, the study of the S-matrix may eventually lead to a satisfactory phenomenology of strong processes.

In this workshop we are focussing on spin, and what we might learn from studying how particles with spin interact. At energies below 100 GeV, the study of two body and quasi-two body processes has uncovered a vast number of regularities and near regularities of the S-matrix. There is every reason to believe that detailed studies at high energies will also reveal interesting physics.[15] So much has been written on S-matrix physics,[16] in this talk I need to do little more than mention a few highlights relevant for this workshop.

To start, let us recall some of the more obvious spin dependent interactions. In the previous section we looked at the consequences of a fermion-vector

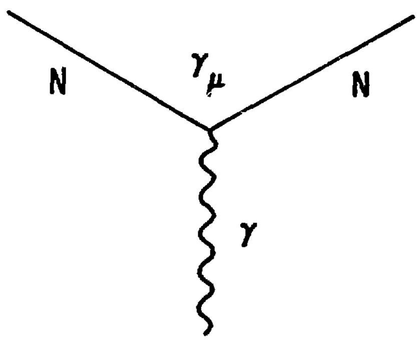


Fig. 4.

interaction. Another simple interaction is that of a nucleon with a pion at very low energies. To lowest order

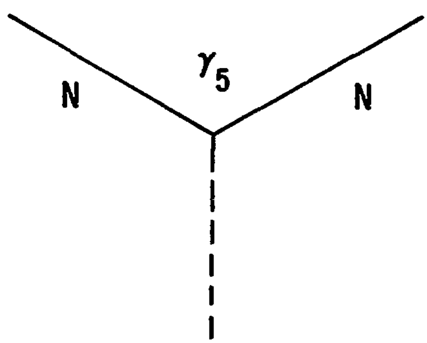


Fig. 5

the interaction is $\bar{u}\gamma_5 u$ and leads to a helicity flip interaction. One of the most distressing features of strong interactions is that such simple and obvious mechanisms are never exactly correct.

The simple couplings follow from requirements of Lorentz invariance and some notion of the fields interacting weakly. In the case of nucleons coupling to pions, the coupling $g^2/4\pi \approx 15$ is not weak. Nevertheless analysis of the high partial waves of low energy NN phase shifts shows evidence of elementary pion exchange. The more correct interpretation is in terms of the analyticity of the S-matrix: there is evidence for a t-channel singularity at the position of the pion, whose strength can be determined from the phase shift data, and is found to have a value $g^2/4\pi \approx 15$.

What is quite amazing is that there is also evidence in high energy processes for pion exchange. Reactions such as $np \to pn$[17] and $pp \to n\Delta^{++}$ [18], show evidence of the pion exchange pole, and all give $NN\pi$ couplings compatible with the low energy phase shift value.

Also significant is that both at low energies and at high energies the simple Feynman graph result is not precisely valid. For the NN phase shift region there are large correction terms to the one pion exchange potential at short distances. Only at large distances is the pion exchange clearly evident. At higher energies, one invokes the ubiquitous "cuts" or "absorption corrections" to modify all but the peripheral attributes of the pion exchange.

Why one needs to made such modifications, and why such a simple spin interaction can be seen after such drastic modifications is an interesting puzzle. It is not obvious what will happen to the pion exchange in the TeV region; it may prove to be enlightening and should be studied.

One has learned from data less obvious spin dependences.[19] For example, NN elastic scattering at high energies behaves as though the Pomeron is the dominant exchange. As determined from pp experiments, the helicity conserving amplitude is the one that dominates. There is a wealth of such regularities, and many reviews can be consulted for details.[20] What may concern us at this workshop is what are interesting things to look for as we go to higher energies.

One possibility is that the Regge and multiparticle phenomenology learned over the last several years extends naturally to the higher energy domain. There are problems however. Because Regge cuts are expected to become more important at higher energies, we should perhaps see the beginning of that trend at FNAL. For example, one should expect $\pi^- p \to \pi^\circ n$ to have a noticably different t-dependence at 200 GeV/c than at 20 GeV/c. The data are on the contrary rather simple. This may indicate important gaps in our understanding about cuts, and hence about even low energy physics.[21] Thus, bread and butter experiments on low t, two body and quasi-two body reactions should prove useful.

What about multiparticle processes? Our present phenomenology finds few departures in multiparticle events from the expectation that the process is a composition of many "few body, low subenergy" processes.[22] The spin dependence of such reactions might lead to progress in our understanding.[15]

We know the spin averaged total cross section rises through the ISR energy range. We might learn something about the underlying mechanism by studying whether pure spin cross sections such as $\Delta\sigma_T$ and $\Delta\sigma_L$ also rise at the higher energies.[23]

At very high energies, there have been speculations that strong processes might interfere with weak processes.[24] Spin is a good tool to use to find parity violation effects. One side benefit is that one might learn something about the absolute phase of the strong S-matrix in an analogous manner as one learns about phases from Coulomb interference. In the case of weak-strong interference, this might extend to very high p_T.

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