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HELICITY CONSERVATION IN DIFFRACTION SCATTERING†

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ABSTRACT

We discuss the possibility that diffraction scattering of hadrons conserves the s-channel helicities of the particles involved. Presently available experimental data is examined and shown to support conservation of s-channel helicity, and not the hypothesis of no helicity flip in the t-channel. Further tests are suggested and restrictions imposed on various models of diffraction scattering, in particular, t-channel exchange models, are discussed.

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Diffractive processes are an important if not key part of high energy hadron-hadron collisions. Yet in many ways such processes are the least understood. Diffraction phenomena seem to lie outside the picture which connects s-channel resonances and some t-channel exchanges[1]. Within the Regge model the nature of diffraction, whether fixed or moving pole, or cut, or both, is still an unsettled question. One often hears the lore within a Regge pole context that diffraction or "pomeron exchange" has an energy dependence like that due to exchange of a spin one particle and couplings like that due to exchange of a spin zero particle. We discuss here the possibility that diffraction scattering of hadrons occurs with conservation of the s-channel helicities of the particles involved. If a t-channel picture is adopted, this means that the exchanged object must (in general) flip helicities in the t-channel and hence does not act like exchange of a spin zero particle as far as couplings are concerned. In fact, the t-channel spin flip and spin non-slip couplings must be related in a very special way in order to obtain helicity conservation in the s-channel.

A rather spectacular example of the conservation of s-channel helicity in a diffractive process occurs in $\gamma + p \rightarrow \rho^0 + p$, diffractive photoproduction of rho mesons on protons. Starting from relatively low energies this has all the earmarks of a diffractive process: approximately constant differential and total cross sections, a t-dependence at high energies like that of πN scattering, and almost complete dominance by natural spin-parity exchange[2].

If the scattering proceeded with no flip of helicities in the t-channel, then only t-channel helicity amplitudes with the rho having helicity ± 1, equal to that of the photon, would occur. Such a behavior of the t-channel helicity amplitudes can be experimentally tested through an examination of the density matrix of the rho meson in the rho rest frame, quantizing the spin along the incident (photon) beam direction, i.e., the so-called Gottfried-Jackson frame[3]. With no flip of t-channel helicities we expect $\rho_{00}^{G-J} = \rho_{10}^{G-J} = \rho_{1-1}^{G-J} = 0$. Similarly, no flip of s-channel helicities would mean that $\rho_{00}^{H} = \rho_{10}^{H} = \rho_{1-1}^{H} = 0$, where the quantization axis for the helicity frame is the direction of the rho's three-momentum in the center of mass (minus the direction of the recoil proton's three-momentum in the rho rest frame). For fixed t and $s \to \infty$, the angle between the two quantization axes in the rho rest frame goes to a constant and is given by[4]

$$\cos\chi = \frac{1 + \frac{t}{m_\rho^2}}{1 - \frac{t}{m_\rho^2}} , \qquad \sin\chi = \frac{2\sqrt{\frac{-t}{m_\rho^2}}}{1 - \frac{t}{m_\rho^2}} . \tag{1}$$

For values of t of a few tenths of a $(\mathrm{GeV}/c)^2$, the angle between the two frames is appreciable and one can clearly see from the data[5] that the rho has spin component equal ± 1 in the helicity frame, but not in the Gottfried-Jackson frame. For example, at a value of $t = -0.2$ $(\mathrm{GeV}/c)^2$ and $k_\gamma = 4.7$ GeV, $\rho_{00}^{G-J} \simeq 0.4$ while $\rho_{00}^{H} \simeq 0.0 \pm 0.05$. The data strongly shows that the rho has the helicity of the photon in the s-channel and not the t-channel.

A second example is provided by pion-nucleon elastic scattering. Here the situation is most easily stated in terms of the invariant amplitudes A(s, t) and B(s, t), defined in terms of the Feynman amplitude for $\pi(q_1) + N(p_1) \to \pi(q_2) + N(p_2)$ by

$$\bar{u}(p_2)\,T\,u(p_1) = \bar{u}(p_2)\left[A(s,t) - i\gamma\cdot\frac{q_1+q_2}{2}B(s,t)\right]u(p_1)\;. \tag{2}$$

The helicity amplitudes in the s-channel center of mass as $s \to \infty$ at fixed t are given by

$$\begin{aligned} f^s_{\frac{1}{2}0,\frac{1}{2}0} &\xrightarrow[s\to\infty]{} A + \frac{s}{2M_N}B \\ f^s_{-\frac{1}{2}0,\frac{1}{2}0} &\xrightarrow[s\to\infty]{} \frac{\sqrt{-t}}{2M_N}(A + M_N B)\;. \end{aligned} \tag{3}$$

Since at fixed t, $A(s,t) \to s^{\alpha(t)}$ and $B(x,t) \to s^{\alpha(t)-1}$, where $\alpha(t)$ is the leading singularity in the J-plane (supposedly the pomeron with $\alpha(0) = 1$), the non-flip amplitude $f^s_{\frac{1}{2}0,\frac{1}{2}0}$ will dominate the flip amplitude $f^s_{-\frac{1}{2}0,\frac{1}{2}0}$ at fixed t only if the invariant amplitude A gets no contribution from the pomeron to leading order in s. Precisely this possibility has been proposed recently and found consistent with what is known about πN scattering by Hohler and Strauss[6]. These authors make the even stronger hypothesis that the P' (with $\alpha(0) \simeq \frac{1}{2}$) as well as the P (with $\alpha(0) = 1$) decouple from the A amplitude, in which case the possibility exists that the $A^{(+)}$ amplitude obeys an unsubtracted dispersion relation.

This is also in qualitative agreement with work of Barger and Phillips[7] using phase shifts and continuous moment sum rules, who find that the t-channel non-flip amplitude A' ($\approx A + \nu B$) and the t-channel flip amplitude B are related by $A' \approx \nu B$, i.e. $A \approx 0$, for the P and P' Regge trajectories.

In other words, pion-nucleon elastic scattering also appears to show that while the t-channel amplitudes have both appreciable spin non-flip and spin flip parts, in the s-channel the diffraction scattering (pomeron exchange) is such as to conserve the helicity of the nucleons. At high energy, A = 0 or s-channel helicity conservation corresponds to a scattering amplitude in terms of Pauli spinors proportional to $\chi_2^+\left[1 + \cos\theta - i\vec{\sigma}\cdot(\hat{q}_1 \times \hat{q}_2)\right]\chi_1$. A direct verification of this at high energy awaits the measurement of the A and R parameters of Wolfenstein[8]. Preliminary results[9] for π^-p scattering at 6 GeV/c already exist and rule out the possibility of the t-channel spin-flip amplitude (B(s, t)) vanishing, but are consistent with A(s, t) = 0.

In searching for a theoretical basis for a general principle of conservation of s-channel helicities by diffraction scattering, one immediately must face the fact that we have no general, reliable model of diffractive processes for hadrons. Much of the "theory" extant starts by neglecting all "inessential" spin complications, or, if not that, assumes a parametrization (including spin dependence) which is then iterated in some way[10]. One of the few calculations that might be relevant is the recent work of Cheng and Wu[11] on the high energy behavior of quantum electrodynamics where a high energy behavior corresponding to diffraction is found and the "impact factors" of the electron and photon are presented. The impact factor of the electron does conserve s-channel helicity, but it appears that the photon impact factor does not. Also the prediction of Cheng and Wu using their QED impact factors that $\gamma + p \rightarrow \rho^o + p$ will exhibit a rho polarization with respect to the production plane even with an unpolarized photon beam is not supported by the data[5]. We devote the remainder of this letter to pointing out further tests and consequences of the hypothesis of s-channel helicity conservation in diffraction scattering.

Aside from KN elastic scattering, the only other well studied elastic diffractive process is nucleon-nucleon scattering. Here there are five invariant amplitudes, conveniently taken to be $F_S(s,t)$, $F_T(s,t)$, $F_A(s,t)$, $F_V(s,t)$, and $F_P(s,t)$, the Fermi invariants[12]. An examination of the helicity amplitudes shows that the s-channel helicity non-flip amplitudes dominate the flip amplitudes at high energies if F_S, F_T, and F_P, which ordinarily have the asymptotic behaviors[12] $s^{\alpha(t)}$, $s^{\alpha(t)-1}$, and $s^{\alpha(t)}$ for exchange of spin $\alpha(t)$ respectively, receive no contribution from "pomeron exchange" to leading order to s. Thus helicity conservation corresponds to F_V and/or F_A giving the dominant contribution to the helicity amplitudes in diffractive nucleon-nucleon scattering. If true, this means in particular that the two non-flip forward amplitudes, $f^s_{\frac{1}{2}\frac{1}{2},\frac{1}{2}\frac{1}{2}}$ and $f^s_{\frac{1}{2}-\frac{1}{2},\frac{1}{2}-\frac{1}{2}}$, dominate the double flip amplitude, $f^s_{-\frac{1}{2}-\frac{1}{2},\frac{1}{2}\frac{1}{2}}$, by at least a fractional power of s. A direct verification of the prediction of s-channel helicity conservation for nucleon-nucleon scattering at high energy should be possible by means of experiments analogous to those already performed to measure the A and R parameters of πN scattering[9].

Obvious candidates for study in photon initiated reactions are $\gamma + p \rightarrow g + p$ and $\gamma + p \rightarrow B + p$, where g and B are $C = -1$, $I = 1$, $J^P = 3^-$ and 1^+ resonances respectively. Note that nothing prohibits diffractive photoproduction of the B within our hypothesis, and it appears to have been observed already in a missing mass experiment by Anderson et al.[13] Unfortunately the decay $B^0 \rightarrow \omega\pi^0$ is extremely difficult to observe, as therefore also is the helicity of the B.

The simplest possibilities for further experimental test lie at present in the realm of hadron diffraction production processes. Such inelastic diffractive processes are also interesting because they may be different from the elastic diffractive processes in an s-channel picture —

occurring more at the surface of the nucleon and thereby involving more strongly the higher partial waves.

Particularly accessible for study are the reactions $\pi + N \rightarrow A_1 + N$ and $K + N \rightarrow Q + N$, where A_1 and Q are defined as $J^P = 1^+$ states which decay into 3π's and $K\pi\pi$ respectively. If the A_1 or Q are produced with spin component equal to zero along a given direction (we predict this to be the direction of their line of flight in the center of mass system), then the distribution in the angle between this direction and the normal to the 3π or $K\pi\pi$ decay plane should be $\sin^2\theta$. For moderate values of the momentum transfer, t, the angle between the helicity frame (s-channel helicity conservation) and the Gottfried-Jackson frame is fairly large so that there should be a distinct difference[14]. A possible complication here is the problem of separating resonance and background contributions[15].

Similarly, one can study diffractive processes of the kind $\pi N \rightarrow \pi N^*$, $KN \rightarrow KN^*$, and $NN \rightarrow NN^*$. For the decay $N^* \rightarrow \pi N$, the angular distribution of the decay pion with respect to the N^* line of flight in the center of mass system should be constant, $1 + 3\cos^2\theta$, and $1 - 2\cos^2\theta + 5\cos^4\theta$ for $J = 1/2$, $3/2$, and $5/2$ nucleon resonances respectively. Given enough data, this is easy to test versus the hypothesis of no t-channel spin flip since the differences between t-channel and s-channel helicity conservation are large at moderate values of t. Here again there may be resonance-background separation problems[15].

Clearly, in all these processes the t-channel couplings must be related in a special way if they are to result in conservation of s-channel helicity. One is led to ask if it is even possible to maintain a consistent picture of a t-channel object being exchanged with factorizable couplings. We have checked that it is possible to have a t-channel pomeron exchange with factorizable couplings which conserves s-channel helicities in the processes $\pi\pi \to \pi\pi$, $\pi N \to \pi N$, and $NN \to NN$. Similarly, we have verified the same thing for $\pi\pi \to \pi\pi$, $\pi\pi \to \pi A_1$, and $\pi\pi \to A_1A_1$. We conjecture that it is always possible to do so. Thus our hypothesis is not in contradiction with diffraction scattering proceeding by exchange of a Regge pole with factorizable couplings. However, even if it does turn out to be a t-channel object, it would obey constraints which are much more easily seen in the s-channel. In this respect, at least, the pomeron would act like other "t-channel exchanges".

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14. For example, for the process $\pi + N \to A_1 + N$ at high energies, the angle between the helicity and Gottfried-Jackson frames is $\approx 45^{\circ}$ for $t = -0.2$ GeV^2.

15. We note that in the reaction $\gamma + p \to \pi^+ + \pi^- + p$, taking $\pi^+\pi^-$ invariant masses away from the rho mass results in a decreasing dominance by natural spin-parity exchange and increasing amounts of s-channel helicity flip (see reference 5). Thus our hypothesis may not hold for "background". A preliminary look at some data for 3π and $K\pi\pi$ production in the A_1 and Q regions, respectively, does not give evidence for either no helicity flip in the s-channel or the t-channel. We have not tried to separate the "background" from the resonances, if any, in these reactions however. We thank in this regard Drs. K. Moriyasu and S. Flatté for their study of the 3π and $K\pi\pi$ data respectively.