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EFFECTS ON SPIN ASYMMETRIES OF SPECIAL EFFECTS AT 90°*

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Hadron and quark exchange contributions introduce additional spin asymmetries in hadron elastic scattering which are a maximum at 90° but go away at small angles, where such exchanges always involve one backward scattering with a much higher momentum transfer than the direct forward scattering with only gluon exchanges. Double-flip and nonflip contributions to $\sigma_{\uparrow\uparrow}$ are incoherent, while direct and exchange contributions to each are coherent. For $\sigma_{\uparrow\downarrow}$ the direct nonflip and exchange double-flip amplitudes are coherent and vice versa. At 90° even if the direct amplitude is spin independent and dominantly nonflip, the nonflip coherence in $\sigma_{\uparrow\uparrow}$ can introduce a factor of 2 in $\sigma_{\uparrow\uparrow}/\sigma_{\uparrow\downarrow}$, while small double-flip amplitudes which are coherent with nonflip in $\sigma_{\uparrow\downarrow}$ but incoherent in $\sigma_{\uparrow\uparrow}$ can introduce further large factors.

Recent measurements of spin effects in elastic scattering of polarized protons[1] show a very small value for the asymmetry parameter $A_{nn} = -2 \pm 16\%$ at $P_t^2 = 4.7$ (GeV/c)^2. This is in sharp contrast with the previous value near 60% obtained at the same value of P_t but at the lower energy of 12 GeV/c. However, the 12 GeV/c measurement was taken at a scattering angle of 90°, while the 18.5 GeV/c measurement was taken at a scattering angle of 49° in the center of mass system.

The difference between 90° and 49° is crucial because of both symmetry and dynamical effects. For the scattering of identical particles, any measurement sums the scattering at an angle θ and an angle $\pi-\theta$, and the sum may be coherent or incoherent, depending upon the particular spin states involved. At high momentum transfer, where the scattering amplitude is expected to fall off rapidly with increasing scattering angle, this effect should be negligible at 49°, since the scattering amplitude at 131° is expected to be very much smaller. At 90°, however, the effects of particle interchange are a maximum and can easily produce large spin asymmetries even if the

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asymmetries at angles like 49° are very small. Such effects have been shown to produce a value of $A_{nn} = 1/3$ at 90° for completely spin-independent scattering which gives $A_{nn}=0$ at small angles.[2] We shall see here that small additional spin-dependent amplitudes that have a negligible effect at small angles can give $A_{nn} = 0.6$ at 90°.

There are also important differences in QCD dynamics between 90° and small angle scattering. The dominant mechanisms for hadron scattering in QCD are gluon exchange and quark exchange. The question of which is more important in different kinematic regions remains open. Single-gluon exchange between color singlet hadrons is forbidden in QCD; any scattering without quark exchange must involve at least two exchanged gluons. The question at high momentum transfers where all interactions are suppressed is whether the price paid for an additional gluon is greater than the price paid for a quark exchange.

At small angles, one might expect gluon exchange without quark exchange to dominate, because any quark exchange involves a "backward scattering" at the quark level with a much larger momentum transfer than forward scattering. At 90°, however, there is no difference between forward and backward; quark exchange involves the same momentum transfer at the quark level as pure gluon exchange without quark exchange. Thus there may be a transition between quark-exchange dominance and gluon-exchange dominance at some intermediate scattering angle.

In order to unscramble these effects and obtain a true picture of the dynamics of spin dependence, it is necessary to separate out the 90° coherence effects from energy dependence, and look for possible transitions between quark exchange dominance and gluon exchange dominance. This can be done by measurements taken at different energies either all at 90° or all at small angles where coherence effects are negligible. Measurements of angular distributions at a given energy would also reveal the existence of peculiar behavior at 90° and possible transitions. Measurements of final state polarization may also be relevant as discussed below.

The peculiar conditions at 90° can be seen explicitly as follows. Consider the scattering of protons transversely polarized normal to the scattering plane; i.e. transversity eigenstates. The physics is particularly simple in the transversity basis, where the number of contributing amplitudes is small. Since angular momentum and parity conservation require transversity conservation modulo 2, there are only nonflip and double-flip transitions; single transversity flip is forbidden.

If the incident protons have parallel transverse spins, the scattered protons also have parallel transverse spins, either nonflipped or double-flipped. In either case interchanging the two protons gives the same final state and it is impossible to distinguish between scattering by θ and by $\theta-\pi$. The two amplitudes are coherent and must be added before they are squared. If the incident protons have antiparallel transverse spins, the scattered protons also have antiparallel transverse spins, but interchanging the two scattered protons gives a different final state with both transversities flipped. Thus for antiparallel transversities, the nonflip amplitude at angle θ leads to the same final state and is coherent with the double-flip amplitude at angle $\theta-\pi$ and vice versa. Thus:

$$\sigma_{\uparrow\uparrow}(\theta) = |N_{\uparrow\uparrow}(\theta) + N_{\uparrow\uparrow}(\theta-\pi)|^2 + |D_{\uparrow\uparrow}(\theta) + D_{\uparrow\uparrow}(\theta-\pi)|^2 \qquad (1a)$$

$$\sigma_{\uparrow\downarrow}(\theta) = |N_{\uparrow\downarrow}(\theta) + D_{\uparrow\downarrow}(\theta-\pi)|^2 + |D_{\uparrow\downarrow}(\theta) + N_{\uparrow\downarrow}(\theta-\pi)|^2 , \qquad (1b)$$

where $\sigma_{\uparrow\uparrow}$ and $\sigma_{\uparrow\downarrow}$ denote the cross sections and $N_{\uparrow\uparrow}$, $D_{\uparrow\uparrow}$, $N_{\uparrow\downarrow}$ and $D_{\uparrow\downarrow}$ denote the nonflip and double-flip amplitudes respectively for the states of parallel and antiparallel transverse spins.

The angular distribution of the scattering is expected to be forward peaked. Thus at small angles, where all backward scattering by an angle $\theta-\pi$ can be neglected, the relations (1) simplify to give

$$\sigma_{\uparrow\uparrow}(\theta) = |N_{\uparrow\uparrow}(\theta)|^2 + |D_{\uparrow\uparrow}(\theta)|^2 \qquad (2a)$$

$$\sigma_{\uparrow\downarrow}(\theta) = |N_{\uparrow\downarrow}(\theta)|^2 + |D_{\uparrow\downarrow}(\theta)|^2 \qquad (2b)$$

$$\frac{\sigma_{\uparrow\uparrow}(\theta)}{\sigma_{\uparrow\downarrow}(\theta)} = \frac{|N_{\uparrow\uparrow}(\theta)|^2 + |D_{\uparrow\uparrow}(\theta)|^2}{|N_{\uparrow\downarrow}(\theta)|^2 + |D_{\uparrow\downarrow}(\theta)|^2} \equiv S(\theta) . \qquad (2c)$$

The quantity $S(\theta)$ defined by Eq. (2c) gives a direct measure of the spin dependence of the average of the nonflip and double-flip cross sections.

At 90 degrees, where $\theta = \frac{\pi}{2}-\theta$, and we assume equal amplitudes with a positive relative phase at θ and $-\theta$, the relations (1) simplify to give

$$\sigma_{\uparrow\uparrow}(\theta) = 4|N_{\uparrow\uparrow}(\theta)|^2 + 4|D_{\uparrow\uparrow}(\theta)|^2 \qquad (3a)$$

$$\sigma_{\uparrow\downarrow}(\theta) = 2|N_{\uparrow\downarrow}(\theta) + D_{\uparrow\downarrow}(\theta)|^2 \qquad (3b)$$

$$\frac{\sigma_{\uparrow\uparrow}(90^0)}{\sigma_{\uparrow\downarrow}(90^0)} = 2\,\frac{|N_{\uparrow\uparrow}(90^0)|^2 + |D_{\uparrow\uparrow}(90^0)|^2}{|N_{\uparrow\downarrow}(90^0) + D_{\uparrow\downarrow}|^2} = 2\,\frac{(1+\varepsilon^2)}{(1+\varepsilon)^2}\,S(90^0) \qquad (4a)$$

where

$$\varepsilon = \frac{D_{\uparrow\downarrow}(90^0)}{N_{\uparrow\downarrow}(90^0)} \ . \tag{4b}$$

This result (4) shows that the ratio $\sigma_{\uparrow\uparrow}/\sigma_{\uparrow\downarrow}$ at 90° contains an additional factor $2(1 + \varepsilon^2)/(1 + \varepsilon)^2$ which is completely unrelated to the spin dependence of the scattering amplitude and depends only on the coherence effects between the nonflip and double-flip antiparallel amplitudes.

The fact that effects completely unrelated to spin dependence arise at 90° is clearly seen in the simplest case of spin independent scattering, where

$$N_{\uparrow\uparrow}(\theta) = N_{\uparrow\downarrow}(\theta) \tag{5a}$$

$$D_{\uparrow\uparrow}(\theta) = D_{\uparrow\downarrow}(\theta) \quad . \tag{5b}$$

In this case, for small angles

$$\frac{\sigma_{\uparrow\uparrow}(\theta)}{\sigma_{\uparrow\downarrow}(\theta)} = S(\theta) = 1 \tag{6a}$$

and the asymmetry parameter A_{nn} is then

$$A_{nn} = 0 \tag{6b}$$

as expected for spin-independent scattering.

However, for angles near 90°,

$$\frac{\sigma_{\uparrow\uparrow}(90^0)}{\sigma_{\downarrow\uparrow}(90^0)} = \frac{2(1 + \varepsilon^2)}{|1 + \varepsilon|^2} \ . \tag{7a}$$

This can vary rather wildly, depending upon ε, even though $S(\theta) = 1$. For $\varepsilon \sim 0$, the asymmetry parameter A_{nn} is

$$A_{nn} = +1/3 \ . \tag{7b}$$

From these specific cases, we see that it is risky to compare the values of A_{nn} at small angles with those at 90°. A value near zero at small angles can increase to a value of 1/3 at 90° for reasons of permutation symmetry which have no implications for the dynamics.

Note that the value of A_{nn} at 90° is very sensitive to small double-flip amplitudes which can interfere destructively in the antiparallel cross section (2b). Consider, for example, the case where $\varepsilon = -0.1$ so that the double-flip cross section is only 1% of the nonflip cross section. Then

$$\frac{\sigma_{\uparrow\uparrow}(90^\circ)}{\sigma_{\uparrow\downarrow}(90^\circ)} = 2.5\ S(90^\circ)\ , \tag{8a}$$

If $S(\theta) = 1$, as would be the case if the nonflip and double-flip amplitudes are both spin-independent, i.e. they satisfy Eqs. (5), the asymmetry parameter A_{nn} is

$$A_{nn} = +0.43\ . \tag{8b}$$

This is very different from the value (7b) obtained without the small double-flip amplitude.

The observed value at 90° of $A_{nn} = 0.6$ is obtained, with $A_{nn} = 0$ at small angles, if $S(\theta) = 1$ and $\varepsilon = -0.27$; i.e. the double-flip cross section is 7% of the nonflip cross section for antiparallel spins and the amplitudes have a negative relative phase. Thus it is possible to have $A_{nn}=0$ at small angles and 60% at 90° with only a small double-transversity-flip amplitude in addition to an amplitude which gives $A_{nn} = +1/3$ at 90°.

Since most models based upon QCD use helicity amplitudes, and helicity is conserved in high-momentum scattering processes with emission and absorption of vector gluons, it is interesting to see the role of helicity conservation in these considerations. We first note that helicity conservation is confused by exchange effects of two kinds, hadron exchange and constituent exchange. In proton-proton scattering where the initial protons have opposite helicities, a given detector will observe protons of both helicities, even if helicity is conserved, because of the exchange of the two protons. This effect can be very large at 90°, but is expected to be small at small angles like 49°.

If the dominant mechanism for the scattering is constituent interchange, then even if helicity is conserved at the quark level, the exchange of quarks with opposite helicity between the two protons can give an effective helicity flip at the proton level. This effect is not expected to be strongly dependent on angle or particularly strong at 90°, since it does not depend upon the particles being identical. Quark exchange can give an effective helicity flip even in meson-baryon scattering, where there is no question of identical particles.[3] Note, however that all these exchange effects can produce only a double helicity flip and never a single helicity flip, as the overall helicity of the two-particle system must be conserved. Note also that the effective double-helicity-flip due to exchange can only occur for initial states of opposite helicity. If both particles have the same helicity, there is no way to obtain a double flip by any exchange.

It is convenient to use the amplitudes which have simple symmetry properties for the scattering of identical particles developed using the H-spin formalism[2,4] because the scattering matrix is nearly diagonal in this basis, and independently discovered in another context[5] because they behave simply under reflection about 90°.

$$N = \phi_s = (\phi_1 - \phi_2)/2 \ , \tag{9a}$$

$$S = \phi_t = (\phi_1 + \phi_2)/2 \ , \tag{9b}$$

$$L = \phi_T = (\phi_3 - \phi_4)/2 \ , \tag{9c}$$

$$V = \phi_\tau = (\phi_3 + \phi_4)/2 \ , \tag{9d}$$

$$F = \phi_5 \ , \tag{9e}$$

where N,S,L,V and F are the notation of ref. 2, ϕ_s, ϕ_t, ϕ_T and ϕ_τ are the notation of ref. 5, and

$$\phi_1 = \langle ++|++\rangle \tag{10a}$$

$$\phi_2 = \langle ++|--\rangle \tag{10b}$$

$$\phi_3 = \langle +-|+-\rangle \tag{10c}$$

$$\phi_4 = \langle +-|-+\rangle \tag{10d}$$

$$\phi_5 = \langle ++|+-\rangle \tag{10e}$$

are conventional helicity amplitudes[5].

In terms of these amplitudes, the asymmetry parameter A_{nn} is given by

$$A_{nn} = (|S|^2 + |L|^2 + 2|F|^2 - |N|^2 - |V|^2)/ (|S|^2 + |L|^2 + 2|F|^2 + |N|^2 + |V|^2). \tag{11}$$

For the case where helicity is conserved except for exchange effects,

$$\phi_2 = 0 \tag{12a}$$

$$\phi_5 = 0 \ , \tag{12b}$$

but ϕ_4, which is an apparent double-flip amplitude, can occur as a result of exchange effects. In the notation (9) these conditions become

$$N = S \tag{13a}$$

$$F = 0 \tag{13b}$$

and

$$A_{nn} = (|L|^2 - |V|^2)/(2|N|^2 + |L|^2 + |V|^2) . \tag{14}$$

The five amplitudes (9) were chosen to have simple properties under reflection about 90°. The amplitudes N, S, and L are even and need not vanish at 90°; the amplitudes V and F are odd and vanish at 90°. Thus

$$A_{nn}(90°) = (|L|^2)/(2|N|^2 + |L|^2) . \tag{15}$$

When H-spin[2,4] is conserved, as in the constituent interchange model,

$$N = S = L , \tag{16a}$$

and

$$A_{nn} = (1/3) - (4/3)(|V|^2)/(3|L|^2 + |V|^2) \leq 1/3 \tag{16b}$$

$$A_{nn}(90°) = 1/3 . \tag{16c}$$

The value (16c) is in disagreement with the large value of A_{nn} observed at 90°. indicating that H-spin is not conserved and that the constituent interchange model does not give the complete amplitude for the process. If we still assume that helicity is conserved in the process, we can obtain the value $A_{nn}(90°) = 0.6$ by setting

$$|L|^2 = 3|N|^2 . \tag{17a}$$

At angles far from 90°, we can obtain $A_{nn} = 0$ by setting

$$V = L . \tag{17b}$$

Note that the condition (17b) implies the vanishing of the double-helicity-flip amplitude ϕ_4, which is nonvanishing in the constituent interchange model, where it results from interchange of quarks with opposite helicity between the two protons. If the standard SU(6) wave function is used for the proton, the constituent interchange model gives for small angles

$$V = (3/31)L . \tag{17c}$$

This is very different from the value (17b) and predicts that A_{nn} is within 2% of 1/3.

We thus see that there are two different ways to get agreement with the present experimental results. A small transversity-flip amplitude added to a spin-independent transversity conserving amplitude can give agreement with experiment, as shown by eqs. (8). However these amplitudes violate helicity conservation even at the constituent level. Alternatively, helicity conservation at the hadron level (which means no interchange of quarks with opposite helicity between hadrons) can give agreement with the recent low asymmetry at 49° while the coherent effect at 90° can give the high value of A_{nn} observed if the helicity amplitude for oppsite opposite helicity scattering at 90° is greater than the amplitude for the same helicity scattering by a factor of $\sqrt{3}$.

In order to determine what is really happening, experimental data are needed both at 90° and at smaller angles for the same values of momentum transfer, or there should be measurements of the transversity flip. Only in this way will it be possible to disentangle large effects depending upon transverse momentum from comparatively small effects enhanced at 90° by these peculiar coherence effects.

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