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Odderon and spin dependence of high energy proton-proton scattering

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The sensitivity of the spin dependence of high energy pp scattering, particularly the asymmetry A_{NN}, to the odderon is demonstrated. Several possible ways of determining the spin dependence of the odderon coupling from small-t data are presented.

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The odderon is a latecomer to the family of Regge poles and, to date, there is not any firm experimental evidence for it. It is the putative negative charge conjugation partner to the Pomeron, the dominant Regge singularity at high energy. The exact nature of the Pomeron is even now not well understood. Two aspects are virtually certain, almost by definition: (1) it is a singularity, no doubt more complicated than a simple pole, in the t-channel angular momentum plane that lies at $J=1$ when the momentum transfer $t=0$, and (2) it has charge conjugation $C=+1$, signature $(-1)^J=+1$ and isospin $I=0$. The odderon, also by definition, will lie at or a little below $J=1$ at $t=0$. It too has $I=0$ but $C=(-1)^J=-1$. The possiblity of such a Reggeon was first recognized in [1] and its properties and implications have been extensively explored in [2–5]. The work of Lipatov and his collaborators [6] on the Pomeron in QCD strongly suggests that the odderon exists on equal footing with the Pomeron [7]. The QCD Pomeron is generated by the exchange of two Reggeized gluons in a $C=1$, colorless state while the odderon is generated by three Reggeized gluons in a $C=-1$, colorless state. The QCD calculations yield a Pomeron intercept slightly above 1 and an odderon slightly below 1. We know from unitarity that ultimately the Pomeron intercept will lie at (or below) 1 in order to satisfy the Froissart bound; we do not know quantitatively what such effects will do to the odderon. (We do know that it cannot ultimately lie *above* the Pomeron in order for both the pp and $\overline{p}p$ total cross sections to be positive.) In the following we shall simply assume that both singularities are very close to 1. At BNL Relativistic Heavy Ion Collider (RHIC) energies the effective intercepts may even be slightly above 1.

The most clear-cut implication of the existence of the odderon is that it would lead to asymptotically different amplitudes for the scattering of a particle and its anti-particle off the same target. This means that the total cross sections and the differential cross sections for, say, pp and $\overline{p}p$ scattering at high energy will remain different as $\sqrt{s}$, the total center-of mass energy, increases; in the absence of an odderon they would become the same, roughly as $1/\sqrt{s}$. Unfortunately, a decisive test of this feature is not possible because of the absence of data at the same energy for the two cases. There are suggestions that the odderon might be important because the difference between the pp and $\overline{p}p$ differential cross sections in the dip region appears to persist as the energy grows [8,9]. At the same time fits to $\sigma_{\rm tot}$ and $\rho(t=0)$, the ratio of real to imaginary parts of the forward, helicity-diagonal amplitudes, over a wide energy range for both pp and $\overline{p}p$ leave little room for the odderon at $t=0$ [10,11]. Recently new methods for observing the odderon in $\pi p\to\rho n/p$ [12], in pseudoscalar production [13] or charm versus anti-charm jets [14] in ep collsions have been proposed.

The spin dependence of high energy proton-proton elastic scattering provides a new and sensitive tool to search for the odderon at small t. The reason for this is that the asymptotic phase of the scattering amplitude is closely tied to the $C=(-1)^J$ of the exchanged system; thus, in leading order, if the Pomeron and odderon have the same asymptotic behavior, up to logarithms, then they are out of phase by 90° [15]. This phase condition is well established and can be arrived at in several ways; the most direct is to note that a Regge singularity at $J=\alpha(t)$ in a positive signature amplitude has the behavior $[s^{\alpha(t)}+(-s)^{\alpha(t)}]/\sin\pi\alpha(t)$ while for negative signature it is $[s^{\alpha(t)}-(-s)^{\alpha(t)}]/\sin\pi\alpha(t)$; these are each to be multiplied by functions of t which real analyticity requires to be real in the s-channel physical region. Spin dependent asymmetries depend on various real and imaginary parts of products of amplitudes and so the odderon can dominate some asymmetries to which the Pomeron cannot contribute. The objective of this Brief Report is to point out some asymmetries which might be especially sensitive to the presence of the odderon.

The most promising asymmetry for this purpose is the double transverse-spin asymmetry A_{NN} which will be measured in the new RHIC spin program [16,17]:

$$A_{NN}\frac{d\sigma}{dt}=\frac{4\pi}{s^2}\{2|\phi_5|^2+\mathrm{Re}(\phi_1^*\phi_2-\phi_3^*\phi_4)\}. \qquad (1)$$

As shown by the methods in [18], the shape of the small-t dependence of this quantity determines separately the real and imaginary parts of the double-helicity flip pp amplitude ϕ_2. ϕ_1 and ϕ_3 are the two non-flip amplitudes and ϕ_5 de-

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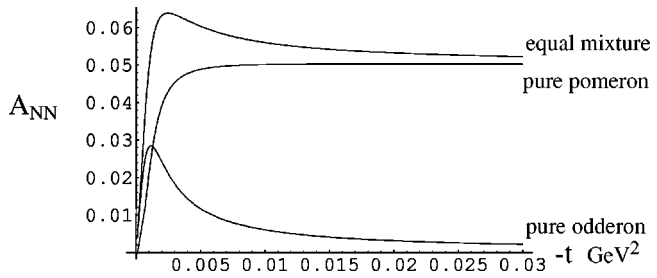

FIG. 1. This illustrates the enhancement of the odderon contribution to A_{NN} due to interference with the one-photon exchange. The three curves correspond to $\phi_2/\phi_+ = 0.05\,i$ (pure odderon), $\phi_2/\phi_+ = 0.05$ (pure Pomeron) and $\phi_2/\phi_+ = 0.05(1+i)$ (equal mixture). The ''pure odderon'' curve is typical of the level of sensitivity expected for the RHIC $pp2pp$ experiment [17].

notes the single-flip amplitude. (ϕ_4 denotes the double-flip amplitude which vanishes by angular momentum conservation as $t \to 0$. It will be disregarded here.) The notation $\phi_\pm = (\phi_1 \pm \phi_3)/2$ is frequently used. Because of the interference between the one-photon exchange and the strong, QCD amplitude, $A_{NN} d\sigma/dt$ has a pole at $t=0$. The coefficient of this pole is proportional to $\alpha\,\mathrm{Re}(\phi_2)$. As $t \to 0$ after the pole is extracted the remainder is proportional to $\rho\,\mathrm{Re}(\phi_2) + \mathrm{Im}(\phi_2)$. (This formula assumes only that the two non-flip forward amplitudes ϕ_1 and ϕ_3 are equal. The quantum numbers of both the Pomeron and the odderon are such that this is so, though lower lying trajectories such as the a_1 could contribute to their difference but should be quite negligible at RHIC energies [18].) Because of the singularity, these terms are of comparable size for $|t|$ between 10^{-3} and 10^{-2}. The part coming from the Coulomb enhancement, proportional to $\alpha\,\mathrm{Re}(\phi_2)$, gives a characteristic peak in A_{NN} near $t = -3 \times 10^{-3}$, while the purely strong interference between ϕ_1 and ϕ_2 is virtually constant in the small $|t|$ region. This is completely analogous to the so-called CNI peak in A_N which arises from the interference of the one-photon exchange contribution to ϕ_5 with the imaginary part of ϕ_+. Since the odderon contribution is nearly real—exactly real if it is a simple pole at $J=1$—it will be enhanced by the CNI effect.

This effect is illustrated in Fig. 1 where curves for A_{NN} are given for three cases. The case in point (''pure odderon'') shows the peak resulting from a 5% odderon contribution; precisely, $\phi_2 = 0.05\,i\,\phi_1$. This magnitude is chosen because it gives a value for A_{NN} which is roughly at the limit of the early RHIC experiments [17]. For comparison, we show a ''pure Pomeron'' of the same magnitude but 90° out of phase: $\phi_2 = 0.05\,\phi_1$. The shape is quite distinct. Finally an ''equal mixture'' $\phi_2 = (0.05\,i + 0.05)\,\phi_1$ is shown. (In all of these cases ϕ_1 is taken to have a ρ value of 0.13.) Evidently, the odderon should be detectable if it is this large. Since we do not know how large the odderon double-helicity flip coupling is, or if it exists at all, we cannot predict how large this effect will be. This illustrates how small a coupling we can hope to learn about in the not-too-distant future.

Because the Pomeron is certainly not a simple pole at $J=1$ [11,20], the Pomeron will contribute a small piece to the real part to the amplitude ϕ_2. Correspondingly the odderon will contribute a small piece to the imaginary part. To have a framework for discussing the corrections required by these pieces, we follow [18] and write, for $t \to 0$,

$$\frac{t}{\sigma_{\mathrm{tot}}} A_{NN} \frac{d\sigma}{dt} = \alpha\, a_{NN} + \frac{\sigma_{\mathrm{tot}}}{8\pi} b_{NN}\, t + \cdots, \tag{2}$$

which separates the Coulomb enhanced piece into a_{NN} and the purely strong piece into b_{NN}. We disregard ϕ_5 because it does not enter our consideration and we assume that ϕ_- can be neglected as mentioned earlier. Then the expressions for a_{NN} and b_{NN} are

$$a_{NN} = \frac{\mathrm{Re}(\phi_2)}{2\,\mathrm{Im}(\phi_+)} \tag{3}$$

and

$$b_{NN} = \rho\, a_{NN} + \frac{\mathrm{Im}(\phi_2)}{2\,\mathrm{Im}(\phi_+)}, \tag{4}$$

where

$$2\,\mathrm{Im}(\phi_+) = \frac{s}{4\pi}\sigma_{\mathrm{tot}}. \tag{5}$$

For this discussion we will consider explicitly only the dominant Pomeron and the odderon. We will allow the two contributions to have slightly different energy dependences but will assume that the energy dependences of the contributions to ϕ_1 and ϕ_2 are the same so that the phases of the Pomeron piece and of the odderon piece are the same in both amplitudes. This may not be exactly true and may need to be corrected for, but it should not change things in an important way.

So we will write the amplitudes $\phi_+ = (\phi_1 + \phi_3)/2$,

$$\phi_+ = A_+^P\, e^{i\delta_P} + A_+^O\, e^{i\delta_O},$$

$$\phi_2 = A_2^P\, e^{i\delta_P} + A_2^O\, e^{i\delta_O}, \tag{6}$$

with $\delta_P \approx \delta_O + \pi/2$. The A's are real functions of s. Then from Eqs. (3)–(5),

$$A_2^P \cos\delta_P + A_2^O \cos\delta_O = \frac{s\sigma_{\mathrm{tot}}}{4\pi} a_{NN} \tag{7}$$

and

$$A_2^P \sin\delta_P + A_2^O \sin\delta_O = \frac{s\sigma_{\mathrm{tot}}}{4\pi}(b_{NN} - \rho\, a_{NN}). \tag{8}$$

We also have

$$\rho = \frac{A_+^P \cos\delta_P + A_+^O \cos\delta_O}{A_+^P \sin\delta_P + A_+^O \sin\delta_O} \approx \cot\delta_P + \frac{A_+^O \cos\delta_O}{A_+^P \sin\delta_P}, \tag{9}$$

since the magnitude of the non-flip odderon amplitude is less than a few percent of the Pomeron [10,11] and in addition one expects that $\sin\delta_O \approx \rho$ so the neglected term is tiny.

Note that the cross-section difference for parallel and antiparallel transverse spins is given by

$$\sigma_{\mathrm{T}} = -\frac{8\pi}{s}\mathrm{Im}(\phi_2) = -\frac{8\pi}{s}(A_2^P \sin\delta_P + A_2^O \sin\delta_O) \tag{10}$$

and so contains no additional information. However, it can be used as a consistency check on the measurement of a_{NN} and b_{NN} since, from Eq. (8),

$$\rho\, a_{NN} - b_{NN} = \frac{\sigma_T}{2\sigma_{\mathrm{tot}}}. \tag{11}$$

With knowledge of the energy dependence of the Pomeron and the odderon, either from theory, a model or data, one can separately determine the phases; thus if they are simple poles behaving as s^{α_P} [20] and s^{α_O}, respectively, their phases will be constants given by $\sin\delta_P = \sin(\pi\alpha_P/2)$ and $\sin\delta_O = \cos(\pi\alpha_O/2)$. Alternatively, in the asymptotic region where a description in terms of the Froissaron and the maximal odderon [2,19] is valid, then $\cot\delta_P = \pi/\log s$ and $\tan\delta_O = \pi/\log s$. Obviously, more complex behaviors are possible; so, e.g., one must correct for contributions from lower lying trajectories. The important point is that, because the Pomeron and the odderon have different signature $(-1)^J$, one can determine their magnitudes from pp data without needing to use $\overline{p}p$ data. Explicitly

$$A_2^O \sin(\delta_P - \delta_O) = \frac{s\sigma_{\mathrm{tot}}}{4\pi}\{(1+\rho\cot\delta_P)\, a_{NN} - \cot\delta_P\, b_{NN}\}. \tag{12}$$

Then, if the odderon phase (or energy dependence) is assumed to be known, this equation fixes A_2^O and, via Eq. (7), determines the Pomeron double-flip amplitude A_2^P.

Even without knowledge of the phases it may be possible to identify effects of the odderon through the spin dependence. Thus from Eqs. (7) and (8) one sees that, in the absence of any odderon couplings,

$$a_{NN} = \rho\, b_{NN}/(1+\rho^2) \approx \rho\, b_{NN}. \tag{13}$$

If this equality is not true, then one can conclude that the odderon is present in A_{NN} (though the converse is not true) and can attempt to extract more specific information from Eqs. (7) and (8). Evidently, one cannot extract in a model-independent way the two odderon amplitudes and the Pomeron double-flip amplitude from this limited number of measurements. However, rather plausible assumptions may enable one to learn something interesting here.

For example, it seems reasonable to suppose that the odderon intercept is close enough to 1 that $|\sin\delta_O|$ is of the order of or less than ρ, as we have already done. If, in addition, we assume that the odderon amplitudes are both, in magnitude, less than about 10% of the Pomeron amplitudes, then to lowest order in these small quantities we can learn that, to a very good approximation,

$$b_{NN} = \frac{1}{2}\left\{\frac{A_2^P}{A_+^P}\right\}. \tag{14}$$

This last gives us directly an experimental determination of the double-flip amplitude for Pomeron exchange and is insensitive to the odderon. Next, in this approximation

$$\frac{s\sigma_{\mathrm{tot}}}{4\pi}(a_{NN} - \rho\, b_{NN}) = A_O^+ \cos\delta_O\left(\frac{A_2^O}{A_+^O} - \frac{A_2^P}{A_+^P}\right). \tag{15}$$

The odderon enters here in several ways; the most notable thing is that if the spin structure of the Pomeron and the odderon are the same,

$$\frac{A_2^O}{A_+^O} = \frac{A_2^P}{A_+^P}, \tag{16}$$

then the term involving the odderon directly drops out and one learns the spin structure of the odderon coupling but nothing about the magnitude beyond that contained in ρ. Model calculations by Ryskin [4] suggest that this may be nearly so. Clearly, this measurement will be most interesting if the spin dependence of the odderon coupling is very different from that of the Pomeron, in particular if its flip to non-flip ratio is large, as it is for some ordinary Regge poles.

One should note, of course, that the RHIC pp program will give data for ρ in an energy range which overlaps existing $\overline{p}p$ data and one can use

$$\frac{A_+^O}{A_+^P} \approx [\rho(pp) - \rho(\overline{p}p)]/2 \tag{17}$$

to determine A_+^O in a model-independent way. With this in hand Eq. (14) and Eq. (15) or (16) will yield the remaining amplitudes A_2^P and A_2^O.

We close with a couple of related observations: (1) The pp single-spin asymmetry A_N has the well-known Coulomb enhanced peak, the height of which depends on the imaginary part of the amplitude ϕ_5; for $|t|$ greater than about 10^{-2} the purely strong interference will dominate if there is a significant phase difference between ϕ_5 and ϕ_1 [18]. If both amplitudes have the same asymptotic behavior, they will be in phase unless the odderon couples to one or the other, and so a measurement of A_N above the CNI peak which does not decrease rapidly with energy is another signal for odderon coupling. See however [4]. (2) A very similar discussion could be carried through for the double longitudinal spin asymmetry A_{LL} with ϕ_- replacing ϕ_2. Since the odderon has the wrong quantum numbers to couple to this amplitude—it requires $(-1)^J = -C$—a non-zero value asymptotically for a_{LL}, which is proportional to $\mathrm{Re}(\phi_-)$, would be a strong indication for yet another Regge singular-

ity near $J=1$. This is not subject to corrections coming from the Pomeron since it cannot couple to ϕ_- at all. We are not aware of any theoretical argument for such a singularity; thus, the observation of such an asymmetry would be extremely interesting.

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[1] L. Łukaszuk and B. Nicolescu, Lett. Nuovo Cimento Soc. Ital. Fis. **8**, 405 (1973).
[2] D. Joynson, E. Leader, and B. Nicolescu, Nuovo Cimento **30**, 345 (1975).
[3] P. Gauron, E. Leader, and B. Nicolescu, Phys. Lett. B **397**, 126 (1997).
[4] M. G. Ryskin, Yad. Fiz. **46**, 611 (1987) [Sov. J. Nucl. Phys. **46**, 337 (1987)].
[5] A. Donnachie and P. V. Landshoff, Nucl. Phys. **B348**, 297 (1991).
[6] L. N. Lipatov, Zh. Éksp. Teor. Fiz. **90**, 1536 (1986) [Sov. Phys. JETP **63**, 904 (1986)]; in *Perturbative QCD*, edited by A. H. Mueller (World Scientific, Singapore, 1989), p. 411.
[7] P. Gauron, L. N. Lipatov, and B. Nicolescu, Phys. Lett. B **260**, 407 (1991); L. N. Lipatov, JETP Lett. **59**, 571 (1994); L. D. Fadeev and G. P. Korchemsky, Phys. Lett. B **342**, 311 (1994); G. P. Korchemsky, Nucl. Phys. **B443**, 255 (1995); **B462**, 333 (1996). For more recent calculations indicating that the odderon lies slightly below $J=1$ at $t=0$, see J. Wosiek and R. A. Janik, Phys. Rev. Lett. **79**, 2935 (1997); N. Armesto and M. A. Braun, Z. Phys. C **75**, 709 (1997); M. A. Braun, P. Gauron, and B. Nicolescu, Nucl. Phys. **B542**, 329 (1999).
[8] P. Gauron, E. Leader, and B. Nicolescu, Phys. Lett. B **328**, 406 (1990).
[9] A. P. Contogouris and F. Lebissis, in *New Frontiers in Physics*, edited by T. Gill (Hadronic Press, Palm Harbor, FL, 1996), Vol. II.
[10] A. Donnachie and P. V. Landshoff, Phys. Lett. B **296**, 227 (1992).
[11] M. M. Block, B. Margolis, and A. R. White, hep-ph/9510290.
[12] A. P. Contogouris *et al.*, Phys. Lett. B **298**, 432 (1993).
[13] W. Kilian and O. Nachtmann, Eur. Phys. J. C **5**, 317 (1998).
[14] S. J. Brodsky, J. Rathsman, and C. Merino, Phys. Lett. B **461**, 114 (1999).
[15] R. J. Eden, Rev. Mod. Phys. **43**, 15 (1971).
[16] Y. I. Makdisi, in *Polarization in Hadron-Induced Processes at RHIC*, Proceedings of ''Spin 96,'' 12th International Symposium on High Energy Spin Physics, Amsterdam, 1996, edited by C. W. de Jager *et al.* (World Scientific, Singapore, 1997), p. 107.
[17] W. Guryn *et al.*, *PP2PP* Proposal to Measure Total and Elastic pp Cross Sections at RHIC (unpublished).
[18] N. H. Buttimore, B. Z. Kopeliovich, E. Leader, J. Soffer, and T. L. Trueman, Phys. Rev. D **59**, 114010 (1999).
[19] P. Gauron, B. Nicolescu, and E. Leader, Nucl. Phys. **B299**, 640 (1988).
[20] A. Donnachie and P. V. Landshoff, Nucl. Phys. **B244**, 322 (1984); **B267**, 690 (1986); Phys. Lett. B **185**, 403 (1987).