How to measure Pomeron phase and discover odderon at HERA and RHIC

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Abstract

We suggest to measure Pomeron phase and discover odderon via the measurement of charge asymmetry of pions in the diffractive processes \(ep \rightarrow e\pi^+\pi^- p\), \(eA \rightarrow e\pi^+\pi^- A\) and in the processes \(AA \rightarrow AA\pi^+\pi^-\) with two rapidity gaps.

To measure the Pomeron (IP) phase in \(\gamma p\), \(\gamma A\) reactions and to discover the odderon (O) we suggest to study charge asymmetry of pions with small transverse momentum \(k_{\perp} = (p_+ + p_-)_{\perp}\) of a dipion with effective mass \(M = 1.1 \div 1.4\) GeV in the processes with two rapidity gaps \(ep \rightarrow e\pi^+\pi^- p\) at HERA (IP and O), \(eA \rightarrow e\pi^+\pi^- A\) at e-RHIC (IP and O), \(AA \rightarrow A\pi^+\pi^- A\) at RHIC (only IP). This charge asymmetry is due to the interference of the C–odd and C–even dipion production amplitudes. Small values of \(k_{\perp}\) are obtained at reasonable values of measurable pion transverse momenta \(p_{\pm} \sim 400 \div 500\) MeV providing good observability of the effects. This charge asymmetry can be seen even if the process with production of C–even dipion is below observation limit.

Motivation

The Pomeron and odderon are both the \(t\)–channel objects for hadronic \(2 \rightarrow 2\) processes with vacuum quantum numbers and the only difference: the Pomeron is C–even, while the odderon is C–odd (similarly to the photon).

At high energies the Pomeron amplitude \(A_{\text{IP}} \propto s^{\alpha_{\text{IP}}}\) describes small angle elastic scattering and total cross sections. The odderon amplitude \(A_{\text{O}} \propto s^{\alpha_{\text{O}}}\) describes difference of hadronic (h) cross sections \(\sigma_{hh} - \sigma_{hh}\) \(^2\) and small angle cross sections of processes \(2\) \(d\sigma(\gamma p \rightarrow f_{2p})\), \(d\sigma(\gamma p \rightarrow \pi^0 p)\),... Here \(\alpha_{\text{IP}}, \alpha_{\text{O}}\) are the Pomeron and odderon intercepts. Within perturbative QCD, the Pomeron and odderon are based on two–gluon and \(d\)–coupled three–gluon exchanges in \(t\)–channel \(^3\) meaning \(\alpha_{\text{O}}\), \(\alpha_{\text{IP}}\) \(\sim 1\) (gluon spin). (For more details and history see \(^4\), \(^5\), \(^6\).)

• The phase \(\delta_F\) of the forward high energy hadronic elastic scattering amplitude \(A\) (Pomeron phase) is given by \(A = |A|e^{i\delta_F} \equiv |A|\exp[i\pi(1 + \Delta_F)/2]\).
Each model has its own characteristic process-dependence of $\Delta F$.

\[ \Delta F = -(\alpha P - 1), \]
\[ \Delta F = -(\alpha P - 1 - \pi / (2 \ln(s/s_0))), \]
\[ \Delta F = -(\alpha P - 1) + \text{process dependent contribution of the branch cuts}. \]

The only reaction where such phase has been measured – high energy elastic $pp, \bar{p}p$ scattering near forward direction – involves detailed measurement of the cross section at extremely low transverse momentum of recorded particle, $p_\perp \approx \sqrt{|t|} \lesssim 50$ MeV (extremely small scattering angles) (see e.g. [7]). This will be a very difficult task at LHC.

- The odderon is necessary but elusive element of the QCD motivated hadron physics. The odderon-induced asymptotic difference $\sigma_{pp} - \sigma_{\bar{p}p}$ can be zero within experimental uncertainty. The attempts to discover the odderon via $\gamma p \rightarrow \pi^0 p'$, $\gamma p \rightarrow f_2 p'$ at HERA [8] were based on calculation of ref. [9] (containing inaccuracies, see [4] for details). New estimates of the same group [10] lie below the upper experimental limits. A reanalysis of HERA data on $\gamma p \rightarrow f_2 p'$, etc. is necessary due to inaccuracies of previous theoretical estimates.

In our analysis we estimate the observability of the odderon signal in $\gamma p \rightarrow f_2 p$ if its cross section is larger than 1 nb (0.03 from upper limit given by experiment [8]).

**Notation**

We consider kinematics of process having in mind $\gamma p \rightarrow \pi^+ \pi^- p$ or $\gamma A \rightarrow \pi^+ \pi^- A$ subprocess. We denote dipion momentum as $k = p_- + p_+$, where $p_\pm$ is momentum of $\pi^\pm$, $M = \sqrt{k^2}$, $\beta = \sqrt{1 - 4m_{\pi}^2/M^2}$, $z_\pm = (\epsilon_\pm + p_\pm)/ (2E_\gamma)$ = $(p_\pm P)/(qP)$, $J$ and $\lambda_{\pi \pi}$ are spin and helicity of dipion, $\lambda_\gamma$ is the photon helicity. Besides we define some angles in the dipion c.m.s by relation $(p_+ - p_-)_{\text{cms}} = \beta M(0, \sin \theta \cos \phi, \sin \theta \cos \phi, \cos \theta)$. We describe forward–backward (FB) and transverse (T) asymmetries by variables

\[ FB : \xi = \frac{z_+ - z_-}{\beta(z_+ + z_-)}, \quad T : v = \frac{p_{\perp}^2 - p_{\perp}^2 - \xi k_\perp^2}{\beta M |k_\perp|}. \] (1)

They can be written via c.m.s. angular variables as $\xi = \cos \theta$, $v = \sin \theta \cos \phi$.

We describe

\[ \Delta \sigma_T = \int d\sigma_{v>0} - \int d\sigma_{v<0}, \quad \Delta \sigma_{FB} = \int d\sigma_{\xi>0} - \int d\sigma_{\xi<0} \] (2)

and $\sigma_{\text{bkgd}} = \int d\sigma$ with integration over (identical) suitable region of final phase space. For the integrated luminosity $\mathcal{L}$, the statistical significance of the result is

\[ SS_{T,FB} = \mathcal{L} \Delta \sigma_{T,FB} / \sqrt{\mathcal{L} \sigma_{\text{bkgd}}}. \] (3)

**Amplitudes**

Let $A_-$ and $A_+$ be amplitudes of production of C–odd and C–even dipions with helicities $\lambda_{\pi \pi}^-, \lambda_{\pi \pi}^+$. Then

\[ d\sigma \propto |A_-|^2 + |A_+|^2 + 2 Re(A_+^* A_+). \] (4)
The interference term $2Re(A_-^*A_+)$ describes the charge asymmetric contribution. At odd or even $\lambda_\pi^+ - \lambda_\pi^-$ we have T or FB asymmetry, respectively.

The amplitude $A_- \equiv A_{P}^\text{Re}$ is described by Pomeron exchange. The amplitude $A_+$ is given by the sum of the photon, odderon and $\rho/\omega$-Regge exchanges, $A_+ = A_\gamma^O + A_\rho^O + A_\omega^O$.

We present Pomeron and odderon amplitudes in the form

$$A_\pm = \sum_{Jn} A_{\pm, Jn}(s, t, M^2) D_J(M^2) \mathcal{E}_J^{\lambda_\gamma, \lambda_\pi}.$$  \hspace{1cm} (5)

Here $A_{\pm, Jn}$ and $A_{+ Jn}$ are the proper Pomeron and odderon amplitudes for dipion production, $D_J(M)$ describes dipion $\rightarrow \pi^+\pi^-$ decay (e.g. normalized resonance propagator). For Pomeron we use fit from [11] (with running $\rho$ width and $\rho'/\rho''$ states), for odderon – $f_2(1280)$ propagator. Factor $\mathcal{E}_J^{\lambda_\gamma, \lambda_\pi}$ describes the angular distribution of pions; in their c.m.s. frame, $\mathcal{E}_J^{\lambda_\gamma, \lambda_\pi} = Y_{J, \lambda_\gamma, \lambda_\pi}(\theta, \phi)e^{-i\lambda_\gamma \psi}$, where $\psi$ is azimuthal angle of photon polarization vector ($\psi$ disappears after azimuthal averaging over momenta of scattered electrons or nuclei). The amplitude $A_{\pm}$ is the same as in the $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$ and is well known.

\section*{ep and eA collisions at HERA and e-RHIC}

For the ep collisions at HERA, we take $L_{ep} = 100 \text{ pb}^{-1}$, the same values of $SS_T$ are obtained at e–RHIC with $L_{eA} = 40 \text{ pb}^{-1}$.

$20 < k_\perp < 100 \text{ MeV}$, Pomeron phase [4]

Here C–even dipion is produced mainly via the Primakoff effect – photon exchange with target ($\gamma\gamma$ collision) ($A_{0}^\gamma, A_{\rho, \omega}^O$ negligible). Only transverse asymmetry appears due to the s–channel helicity conservation (SCHC) for Pomeron.

Integration over intervals $0.2 < y < 0.8, 1.1 < M < 1.4 \text{ GeV}$ results in

$$\Delta \sigma_T \approx 0.13 \text{ nb}, \quad \sigma_{ep}^{\text{bkgd}} \approx 1.5 \text{ nb} \Rightarrow SS_T \approx 34.$$  \hspace{1cm} (6)

Discovery of the odderon, $k_\perp \gtrsim 200 \text{ MeV}$ [6]
At these $k_\perp$ C–even dipion can be produced only via odderon exchange (photon contribution disappears at these $k_\perp$; $\rho, \omega$ Regge exchange contributions are negligibly small $\sigma_{\rho\omega} < 0.15$ nb for HERA, $\sigma_{\rho\omega} < 3$ nb for e-RHIC).

We estimated effect, assuming that the $t$-dependence of odderon amplitude is roughly the same as for Pomeron (but $M$-dependence is given by $f_2$ contribution). The shape of local statistical significance in this region is roughly similar to that for Pomeron–photon interference. We denote total cross section of $\gamma p \to f_2 p$ by $\sigma_0$. Different opportunities for helicity of produced C–even dipion result in different estimates for asymmetry.

∇ If SCHC holds also for the odderon amplitude, the main charge asymmetry is forward–backward. The integration over $k_\perp > 0$ and over $y = 0.2 − 0.8$ results in

$$\sigma_{ep,bkg,T}^P = 22 \text{ nb}, \quad \Delta \sigma_{IP-O,FB} = 0.83 \sqrt{\sigma_0/\text{nb}}$$

$$\Rightarrow SS_{FB} = 56 \sqrt{\sigma_0/\text{nb}} > 56.$$  \hfill (7)

∇ If SCHC is violated strongly for odderon, the main charge asymmetry is the transverse one, in this case one can integrate over the region $k_\perp > 300$ MeV, to avoid photon exchange contribution. In this case

$$\sigma_{ep,bkg,T}^P \approx 9 \text{ nb}; \quad \Delta \sigma_{IP-O,T} = 0.34 \sqrt{\sigma_0/\text{nb}}$$

$$\Rightarrow SS_T = 35 \sqrt{\sigma_0/\text{nb}} > 35.$$  \hfill (8)

In these equations numbers 35 and 56 correspond $\sigma_0 = 1$ nb.

Therefore, both the measurement of Pomeron phase and discovery of odderon with high sensitivity are possible at both colliders.

■ $A_1A_2 \to \pi^+\pi^-A_1A_2$ at $k_{\perp}^{\pi\pi} < 60$ MeV, $|k_{z}^{\pi\pi}| < 3$ GeV

This case corresponds to modern RHIC experiments with $Au$ nuclei. In this kinematical region the two-photon production of C–even $f_2$ with cross section $\propto Z^4$ dominates. C–odd dipion is produced in the collision of almost mass shell photon, radiated e.g. by $A_1$, with nuclei $A_2$ and vice versa. The interference of these amplitudes results in charge asymmetry which changes sign at transition from $k_{z}^{\pi\pi} > 0$ to $k_{z}^{\pi\pi} < 0$. The upper limit for $k_\perp$ is given by nuclear form-factor. Calculations similar to that presented above show that the statistical significance $SS_T \approx 30$ can be obtained at luminosity integral about 10 nb$^{-1}$.

Therefore, the measurement of Pomeron phase is possible here. Unfortunately, no definite predictions can be presented for larger $k_\perp$, and discovery of odderon is doubtful.

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