HOW TO MEASURE POMERON PHASE AND DISCOVER ODDERON AT HERA AND RHIC*

I.F. Ginzburg[a], I.P. Ivanov[a,b]

[a] Sobolev Institute of Mathematics
Siberian Branch of the Russian Academy of Sciences
4 Acad. Koptyug avenue, 630090 Novosibirsk, Russia
[b] INFN, Gruppo Collegato di Cosenza
Ponte P. Bucci — cubo 31C, I-87036 Arcavacata di Rende (Cosenza), Italy

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

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To measure the Pomeron ($\mathbb{P}$) phase in γp, γA reactions and to discover the odderon ($\mathbb{O}$) 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 $ep \to e\pi^+\pi^- p$ at HERA ($\mathbb{P}$ and $\mathbb{O}$), $eA \to e\pi^+\pi^- A$ at e-RHIC ($\mathbb{P}$ and $\mathbb{O}$), $AA \to A\pi^+\pi^- A$ at RHIC (only $\mathbb{P}$). 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 $(p_\pm)_\perp \sim 400 \div 500$ 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.

1. Motivation

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

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At high energies the Pomeron amplitude $A_{\mathbb{P}} \propto s^{\alpha_{\mathbb{P}}}$ describes small angle elastic scattering and total cross sections. The odderon amplitude $A_{\mathbb{O}} \propto s^{\alpha_{\mathbb{O}}}$ describes difference of hadronic (h) cross sections $\sigma_{hh} - \sigma_{h\bar{h}}$ [1] and small angle cross sections of processes [2] $d\sigma(\gamma p \to f_2 p)$, $d\sigma(\gamma p \to \pi^0 p)$,.... Here $\alpha_{\mathbb{P}}$, $\alpha_{\mathbb{O}}$ are the Pomeron and odderon intercepts, respectively. Within perturbative QCD, the Pomeron and odderon are based on two-gluon and d-coupled three-gluon exchanges in t-channel [3] meaning $\alpha_{\mathbb{O}}$, $\alpha_{\mathbb{P}} \sim 1$ (gluon spin). (For more details and history see [4–6].)

• The phase $\delta_{\rm F}$ of the forward high energy hadronic elastic scattering amplitude A (Pomeron phase) is given by $\mathcal{A} = |\mathcal{A}|e^{i\delta_{\rm F}} \equiv |\mathcal{A}| \exp{[i\pi(1+\Delta_{\rm F})/2]}$.

Each model has its own characteristic process-dependence of $\Delta_{\rm F}$.

▼ In the naive Regge-pole Pomeron model $\Delta_{\rm F} = -(\alpha_{\mathbb{P}} - 1)$,
▼ in the model of a dipole Pomeron $\Delta_{\rm F} = -(\alpha_{\mathbb{P}} - 1) - \pi/(2\ln(s/s_0))$,
▼ for the model with Regge pole and cuts $\Delta_{\rm F} = -(\alpha_{\mathbb{P}} - 1) +$ (process dependent contribution of the branch cuts).

The only reaction where such phase has been measured is high energy elastic pp, $\bar{p}p$ scattering near forward direction. It 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 $\sigma_{pp} - \sigma_{p\bar{p}}$ can be zero within experimental uncertainty. The attempts to discover the odderon via $\gamma p \to \pi^0 p'$, $\gamma p \to f_2 p'$ 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 $\gamma p \to f_2 p'$, etc. is necessary due to inaccuracies of previous theoretical estimates.

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

2. Notation

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

(FB) and transverse (T) asymmetries using variables

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

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

We denote

$$\Delta\sigma_{\mathrm{T}} = \int d\sigma_{v>0} - \int d\sigma_{v<0}\,, \quad \Delta\sigma_{\mathrm{FB}} = \int d\sigma_{\xi>0} - \int d\sigma_{\xi<0} \tag{2}$$

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

$$SS_{\mathrm{T,FB}} = \mathcal{L}\Delta\sigma_{\mathrm{T,FB}}/\sqrt{\mathcal{L}\,\sigma_{\mathrm{bkgd}}}\,. \tag{3}$$

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

$$d\sigma \propto |A_-|^2 + |A_+|^2 + 2\mathrm{Re}\,(A_-^* A_+)\,. \tag{4}$$

The interference term $2\mathrm{Re}(A_-^* A_+)$ describes the charge asymmetric contribution. At odd or even difference $\lambda^+_{\pi\pi} - \lambda^-_{\pi\pi}$ we have T or FB asymmetry, respectively.

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

We present the Pomeron and odderon amplitudes in the form

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

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

4. *ep* and *eA* collisions at HERA and e-RHIC

For the *ep* collisions at HERA, we take $\mathcal{L}_{ep} = 100$ pb^{-1}, the same values of $SS_{\rm T}$ are obtained at e-RHIC with $\mathcal{L}_{eA} = 40$ pb^{-1}.

4.1. $20 < k_\perp < 100$ *MeV, Pomeron phase [4]*

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

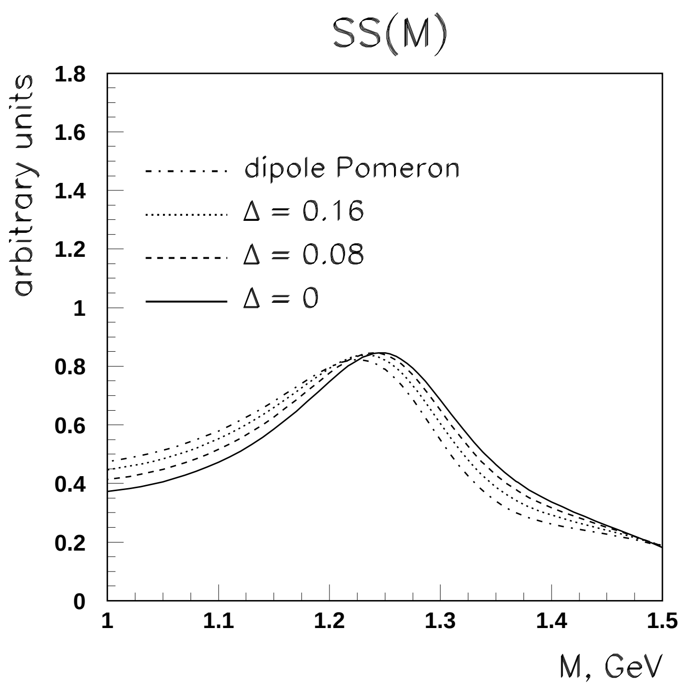

Fig. 1. The local statistical significance of the charge asymmetry (arbitrary units).

Integration over intervals $0.2 < y < 0.8$, $1.1 < M < 1.4$ GeV results in

$$\Delta\sigma_{\rm T} \approx 0.13 \text{ nb}\,, \quad \sigma^{ep}_{\rm bkgd} \approx 1.5 \text{ nb} \Rightarrow \quad SS_{\rm T} \approx 34\,. \qquad (6)$$

4.2. Discovery of the odderon, $k_\perp \gtrsim 200$ *MeV [6]*

At these $k_\perp$ C-even dipion can be produced only via odderon exchange (photon contribution disappears at these $k_\perp$; ρ,ω 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 the 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 the Pomeron–photon interference. We denote total cross section of $\gamma p \to f_2 p$ by $\sigma_{\mathbb{O}}$. 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

$$\begin{aligned} \sigma^{ep}_{\rm bkgd} &= 22\,{\rm nb}\,, \\ \Delta\sigma_{\mathbb{P}-\mathbb{O},{\rm FB}} &= 0.83{\rm nb}\,\sqrt{\sigma_{\mathbb{O}}/{\rm nb}} \Rightarrow\; SS_{\rm FB} = 56\sqrt{\sigma_{\mathbb{O}}/{\rm nb}} > 56\,. \end{aligned} \tag{7}$$

▼ 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. We get

$$\begin{aligned} \sigma^{ep}_{\rm bkgd,T} &\approx 9\,{\rm nb}\,, \\ \Delta\sigma_{\mathbb{P}-\mathbb{O},{\rm T}} &\approx 0.34\sqrt{\sigma_{\mathbb{O}}/{\rm nb}}\,{\rm nb} \Rightarrow SS_{\rm T} = 35\sqrt{\sigma_{\mathbb{O}}/{\rm nb}} > 35\,. \end{aligned} \tag{8}$$

In these equations values 35 and 56 correspond $\sigma_{\mathbb{O}} = 1$ nb.

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

5. $A_1A_2 \to \pi^+\pi^- A_1A_2$ 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 $SS_{\rm T} \approx 30$ can be obtained at luminosity integral about 10 nb^{-1}. *Therefore, the measurement of the 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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