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THE USE OF CHARGE ASYMMETRY OF PIONS IN $ep \to e\pi^+\pi^-p'$ AT HERA FOR DISCOVERY OF ODDERON AND MEASUREMENT OF POMERON PHASE

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We discuss how to discover the odderon and measure the Pomeron phase via the study of charge asymmetry of pions in diffractive reaction $ep \to e\pi^+\pi^-p'$. We find kinematical regions suitable for independent solution of both problems in a single experiment at HERA.

Обсуждается путь открытия оддерона и способ измерения фазы померона путем исследования зарядовой асимметрии пиона в дифракционной реакции $ep \to e\pi^+\pi^-p'$. Находятся кинематические области, удобные для независимого решения обеих проблем в одном эксперименте на ускорителе HERA.

INTRODUCTION

We consider diffractive-type high-energy process

$$\gamma p \to \pi^+\pi^-p' \text{ studied via process } ep \to e\pi^+\pi^-p' \tag{1}$$

in the case when the exchanged photon virtuality $(p_e - p'_e)^2$ is very low (and the scattered electron can escape observation). Here p' is either proton or its low mass excitation, separated from the dipion produced by a large rapidity gap.

Denoting by $p_\pm$ the momenta of the $\pi^\pm$ and introducing

$$r^\mu = p_+^\mu - p_-^\mu\,, \quad k^\mu = p_+^\mu + p_-^\mu\,, \quad M = \sqrt{k^2}, \quad \beta = \sqrt{1 - 4m_\pi^2/M^2}\,, \tag{2}$$

we define the z axis as the γp collision axis and label the (transverse) vectors orthogonal to this axis by $\perp$. We consider process (1) at the typical HERA energies, $\sqrt{s_{\gamma p}} \sim 100 \div 200$ GeV, and at

$$M < 1.45 \text{ GeV}, \qquad k_\perp < 1 \text{ GeV}. \tag{3}$$

• The main mechanism of reaction (1) is diffractive production of dipions in the C-odd state (the ρ meson and its «tails») via the vacuum quantum number exchange in the t channel, which we call the «real Pomeron». Besides, dipions can be produced in the C-even state. We discuss these mechanisms in Sec. 2.

The interference of amplitudes of the C-odd and C-even dipion production provides charge asymmetry of the observed pion distribution. In this paper we discuss how the experimental study of this charge asymmetry can be used for the discovery of the odderon [1, 2] (see also [4, 5]) and for measurement of the Pomeron phase [1, 3].

• *The odderon exchange* is yet an elusive but necessary element of the QCD motivated hadron physics. One can treat the Pomeron and odderon as t channel objects for the $2 \to 2$ processes, that have vacuum quantum numbers with the only difference: the Pomeron is C-even, while the odderon is C-odd (similarly to the photon). Pomeron exchange describes small angle elastic and total cross sections at high energies. The odderon is responsible, again at high energies, for the difference $\sigma^{\rm tot}_{pp} - \sigma^{\rm tot}_{\bar{p}p}$ [7] and for processes like $\gamma p \to f_2 p$, $\gamma p \to \pi^0 p$ with the change of C parity in the boson vertex [8]. The energy dependence of the Pomeron and odderon amplitudes at large s is given by factors $f_{\mathbb{P}} \propto s^{\alpha_{\mathbb{P}}}$, $f_{\mathcal{O}} \propto s^{\alpha_{\mathcal{O}}}$, where $\alpha_{\mathbb{P}}$ and $\alpha_{\mathcal{O}}$ are the intercepts of the Pomeron and the odderon, respectively. An inequality $\alpha_{\mathcal{O}} \leqslant \alpha_{\mathbb{P}}$ must hold, since $|\sigma^{\rm tot}_{pp} - \sigma^{\rm tot}_{\bar{p}p}| < \sigma^{\rm tot}_{pp} + \sigma^{\rm tot}_{\bar{p}p}$.

Within perturbative QCD, the Pomeron and odderon are based on two-gluon and d-coupled three-gluon exchanges in t channel, respectively [9]. Hence, both the Pomeron and odderon intercepts are expected to be close to the gluon spin, $\alpha_{\mathcal{O}}$, $\alpha_{\mathbb{P}} \sim 1$. It is well known that the Pomeron exchange amplitude is predominantly imaginary. The odderon exchange amplitude is C-odd, it has the opposite signature, therefore this amplitude is predominantly real. The experimental data and BFKL calculations show that the Pomeron intercept $\alpha_{\mathbb{P}}(0) > 1$.

The odderon has not been observed till now, and at the moment there is no widely accepted approach that would give reliable estimates of the cross sections of the odderon-induced processes like $\gamma p \to f_2 p'$ for real photons. Recent experiments [10] gave upper bounds to these cross sections but only for the case when p' is a proton excitation (this needless constraint was implemented following poorly justified proposal of Ref. 11 — see Ref. 2 for explanation and for discussion of the status of the modern estimates for odderon).

• *Pomeron phase*. The phase δ_F of the forward amplitude of the hadronic elastic scattering (*Pomeron phase*)

$$\mathcal{A} = |\mathcal{A}|\, \mathrm{e}^{i\delta_F} \equiv |\mathcal{A}| \exp\left[i\frac{\pi}{2}(1+\Delta_F)\right] \qquad (4)$$

is an important object in hadron physics whose nature is not completely clear now. In the naive Regge-pole Pomeron model, this phase is related directly to the Pomeron intercept, $\Delta_F = \alpha_{\mathbb{P}} - 1$, in the model with a simple Regge cut

$\Delta_F = \alpha_{I\!P} - 1 + c/\ln(s/m_p^2)$. The measurement of Pomeron phase will be a useful step towards clarification of its nature.

Up to the moment, this phase was measured at high enough energy in a single type of experiments, namely, via the study of Coulomb interference in pp or $\bar{p}p$ elastic scattering (see [6] and references therein). However, such experiments demand a difficult measurement of the cross section at extremely low transverse momentum of the recorded particle, $p_\perp \approx \sqrt{|t|} \lesssim 30$ MeV, which translates into very small scattering angles.

1. KINEMATICS, ETC.

• *γp collision.* The initial momenta of the photon and proton are $q = p_e - p'_e$ and P, respectively, $s = (q+P)^2$, $t = (q-k)^2 \approx -k_\perp^2$, initial photon polarization vector is $\mathbf{e}$. Let us denote by z_+ and z_- the standard light cone variables for each charged pion, $z_\pm \approx (\epsilon_\pm + p_{\pm z})/(2E_\gamma) = (p_\pm P)/(qP)$ ($z_+ + z_- = 1$, with very high precision).

We direct the x axis along the vector $\mathbf{k}_\perp$ and define by ψ the azimuthal angle of the linear photon polarization with respect to the fixed lab frame of reference; for instance, for the virtual photon in the process $ep \to e\pi^+\pi^-p'$, that is the azimuthal angle of the electron scattering plane. The polarization vector of the initial photon with helicity $\lambda_\gamma = \pm 1$ can be written as $\tilde{\mathbf{e}}^\lambda = -\mathrm{e}^{-i\lambda_\gamma\psi}(\lambda_\gamma, i)/\sqrt{2}$.

It is useful also to consider polar and azimuthal angles of π^+ in the dipion c.m.s., θ and ϕ, so that $r_{\text{c.m.s}} = \beta M(0,\, \sin\theta\cos\phi,\, \sin\theta\cos\phi,\, \cos\theta)$. We denote by J the total angular momentum (total spin) of dipion, by λ_γ and $\lambda_{\pi\pi}$ the helicities of photon and produced dipion, respectively, and by $n = |\lambda_\gamma - \lambda_{\pi\pi}|$ and $n_p = |\lambda_p - \lambda_{p'}|$ the values of helicity flip in the (photon $\to$ dipion) and proton vertices, respectively, for each amplitude.

We describe the *forward–backward (FB) and transverse (T) charge asymmetries* by variables

$$\begin{aligned}
&\text{FB:}\quad \xi = \frac{z_+ - z_-}{\beta(z_+ + z_-)} = \cos\theta,\\
&\text{T:}\quad v = \frac{p_{+\perp}^2 - p_{-\perp}^2 - \xi k_\perp^2}{\beta M|k_\perp|} \equiv \frac{(\rho_\perp k_\perp)}{\beta M|k_\perp|} = \sin\theta\cos\phi;\quad \rho_\perp = r_\perp - \xi k_\perp.
\end{aligned} \tag{5}$$

The amplitude of the dipion production $\mathcal{A}$ is normalized so that

$$\begin{aligned}
d\sigma = |\mathcal{A}|^2\, \beta dM^2\, dk_\perp^2\, d\cos\theta\, d\phi\, \frac{d\psi}{2\pi} =\\
= \frac{2}{\sqrt{1-\xi^2-v^2}}\, |\mathcal{A}|^2\, \beta dM^2\, dk_\perp^2\, d\xi\, dv\, \frac{d\psi}{2\pi}\,.
\end{aligned} \tag{6}$$

• *ep collision.* In the description of ep collision we direct z axis along ep collision axis and keep almost all previous notations. The main contribution to the observable cross section is given by very low values of photon virtuality $-q^2 = -(p_e - p'_e)^2$, i.e., very small values of photon transverse momentum $q_\perp$ (we assume no recording of electrons). Therefore, the z axes for ep and γp collisions practically coincide, and the variable ξ is the same as in γp collision. The total transverse momentum of dipion is now

$$\mathbf{K}_\perp = \mathbf{q}_\perp + \mathbf{k}_\perp. \tag{7}$$

The measured value of transverse variable v is given by the equation of the same form as above (5) but with the change $k_\perp \to K_\perp$.

• We describe below the magnitude of the asymmetry by quantities

$$\Delta\sigma_{\rm FB} = \int d\sigma(\xi > 0) - \int d\sigma(\xi < 0), \quad \Delta\sigma_{\rm T} = \int d\sigma(v > 0) - \int d\sigma(v < 0). \tag{8}$$

Value of the given asymmetry is determined by its *statistical significance* SS defined via the numbers of signal and background events integrated over some charge symmetric domain. With the integral luminosity $\mathcal{L}$ the statistical significance SS and its local value $\mathrm{SS}(M)$ are

$$\mathrm{SS} = \frac{\mathcal{L}|\Delta\sigma_w|}{\sqrt{\mathcal{L}\sigma_{\rm bkgd}}}, \quad \mathrm{SS}(M) = \frac{\mathcal{L}|d\Delta\sigma_w/dM^2|}{\sqrt{\mathcal{L}d\sigma_{\rm bkgd}/dM^2}} \quad (w = \mathrm{FB} \;\text{ or }\; \mathrm{T}). \tag{9}$$

(Note that $\mathrm{SS} \neq \int \mathrm{SS}(M) dM^2$.) The study of shape of this $\mathrm{SS}(M)$ helps us in the choice of cuts in M for data processing.

In the numerical estimates we use for definiteness the luminosity integral (HERA)

$$\mathcal{L}_{ep} = 100\ \mathrm{pb}^{-1}. \tag{10}$$

2. AMPLITUDES

We assume that the amplitude of dipion photoproduction can be factorized as

$$\mathcal{A} = \sum A^\pm(s, t, M^2|J, \lambda_\gamma, \lambda_{\pi\pi}, \lambda_p, \lambda_{p'})\ D_J(M^2)\ \mathcal{E}_J^{\lambda_\gamma, \lambda_{\pi\pi}}. \tag{11}$$

The first factor A is the helicity amplitude for the production of a dipion state (perhaps, as a resonance) with angular momentum J. The superscript $+$ or $-$ marks the C parity of produced dipion, with $J = 1, 3, \ldots$ for C-odd dipions and $J = 0, 2, \ldots$ for C-even dipions. Assuming integration over final states of p', we do not write similar factors D and $\mathcal{E}$, related to the pp'

vertex and omit below signs $\lambda_p,\ \lambda_{p'}$. Besides, due to the P-parity conservation, $A^\pm(s,t,M^2|J,\lambda_\gamma,\lambda_{\pi\pi}) = A^\pm(s,t,M^2|J,-\lambda_\gamma,-\lambda_{\pi\pi})$. So that we will write all equations for the case $\lambda_\gamma = 1$ and omit this sign later. Finally, we use below shorter notation $A^\pm(s,t,M^2|J,\lambda_\gamma,\lambda_{\pi\pi},\lambda_p,\lambda_{p'}) \to A^\pm_{J,\lambda_{\pi\pi}}(s,t,M^2)$.

The second factor $D_J(M)$ describes the decay of this dipion state to pions. (In numerical estimates we assume usually that the M dependence of the amplitude is accumulated in these D_J.) For example, near the resonance R pole the factor D_J is described well by the standard Breit–Wigner factor (together with coupling of this resonance to charged pions)

$$D_J(M^2) = \frac{\sqrt{m_R\Gamma_R Br(R\to\pi^+\pi^-)/\pi}}{-M^2+m_R^2-im_R\Gamma_R} \ \text{ at } \ |M-m_R| \ll m_R\,. \tag{12}$$

The third factor $\mathcal{E}_J^{\lambda_\gamma,\lambda_{\pi\pi}}$ describes the angular distribution of pions in their centre-of-mass frame, $\mathcal{E}_J^{\lambda_\gamma,\lambda_{\pi\pi}} = Y^{J,\lambda_{\pi\pi}}(\theta,\phi)\,\mathrm{e}^{-i\lambda_\gamma\psi}$.

2.1. Amplitudes of C-Odd Dipion Photoproduction. The C-odd dipion diffractive production is described by the «real Pomeron». It has been studied both in theory and in experiment as a production of C-odd resonances, mainly $\rho(770)$ meson with well-known properties. In the mass interval under discussion main contribution is given by dipions with $J=1$. It can be parameterized roughly as

$$\begin{gathered} A^{\mathbb{P}}_{J,\lambda_{\pi\pi}} \equiv A^-_{J,\lambda_{\pi\pi}} = \zeta(\mathbb{P})\,\mathrm{e}^{i\delta_F}\frac{g_{J,\lambda_{\pi\pi}}}{\sqrt{n!}}\sqrt{\sigma_{\mathbb{P}}B_{\mathbb{P}}}\,|B_{\mathbb{P}}k_\perp^2|^{n/2}\,\mathrm{e}^{-B_{\mathbb{P}}k_\perp^2/2},\\ \zeta(\mathbb{P})=1,\quad \sum g^2_{J,\lambda_{\pi\pi}}=1,\quad \sigma_{\mathbb{P}}\approx 11\ \mu\text{b},\quad B_{\mathbb{P}}\approx 10\,\text{GeV}^{-2}. \end{gathered} \tag{13}$$

Here the s dependence of the cross section is included in the quantity $\sigma_{\mathbb{P}}$. Factors $g_{J,\lambda_{\pi\pi}}$ describe relative magnitudes of different helicity flips. Factor $\zeta(\mathbb{P})$ is written here to describe in future other exchanges with similar notation, it represents the signature factor in the standard definition. Factor $|B_{\mathbb{P}}k_\perp^2|^{n/2}$ describes weak violation of helicity conservation near the forward direction.

The (approximate) s-channel helicity conservation (SCHC) takes place at small t — the dipion helicity coincides with that of an initial photon, it means that

$$g_{J=1,1}\approx 1, \qquad |g_{J=1,0}|,|g_{J=1,-1}| \ll 1. \tag{14}$$

In the same manner SCHC means that the helicities of p and p' coincide. Besides, the vertex $p\mathbb{P}p'$ is the most significant one when p' coincides with proton p (the admixture from proton dissociation to excited states with masses $M' \lesssim 2$ GeV is below 25%). As mentioned above, we omit all factors related to the proton vertex and helicities there.

In the considered dipion mass interval (3) the main part of dipions is produced as $\rho(770)$ meson. Here the factor D_1 is approximated well by the well-known

Breit–Wigner form (12). Far from resonance this factor is naturally modified. At $2m_\pi < M < M_\rho$ one can use for D_1 the well-known Gounaris–Sakurai approximation obtained for the pion form factor. At $M > M_\rho$ one should take into account also ρ', etc. states similarly to what is done for the pion form factor (see, e.g., [13]).

2.2. Amplitudes of C-Even Dipion Photoproduction. The C-even pion pairs can be produced diffractively via the following t-channel exchanges: ρ/ω Regge exchange, odderon exchange, and via the photon exchange (Primakoff effect).

• The contribution of *the ρ/ω Reggeon exchanges* is estimated with the standard Regge extrapolation from the low energy data. In the considered energy interval it is below 0.2 nb [2] (in γp collision), and it is neglected below.

• *The Primakoff effect* is dipion production in collision of the incident photon with the photon emitted by the proton. Its amplitude can be written in the form of Eq. (11), it is the same as that in the two-photon processes $e^+e^- \to e^+e^-\pi^+\pi^-$ [12, 14]. In the regions under interest (3), the dominant contribution is given by the almost real photon exchanges with both an electron and a proton. Therefore, the total helicity of the initial two-photon state and respectively of dipions can be 0 and 2.

Beginning from the threshold, the pions interact strongly in the $I = J = 0$ state (which is described by f_0 resonances). The other partial waves are described well with QED approximation for point-like pions (with known small modifications). The QED amplitude with $I = 0$, $J = 2$ is relatively large starting from $M = 0.5-0.7$ GeV. The other amplitudes can be neglected everywhere in our problem.

At $M^2 \ll s_{\gamma p}$, the amplitude of the Primakoff $\gamma p \to Rp$ process can be written [12] via the two-photon decay width $\Gamma^R_{\gamma\gamma}$ of the resonance R with spin J as

$$A_\gamma = \sqrt{\sigma_2}\frac{|k_\perp|}{\mathbf{k}_\perp^2 + Q_m^2} \quad \text{with} \quad \sigma_2 \equiv \frac{8\pi\alpha\Gamma^R_{\gamma\gamma}(2J+1)}{m_R^3}\,, \quad Q_m = \frac{m_p M^2}{s_{\gamma p}}, \quad (15a)$$

Q_m^2 is the minimal value of the virtuality of the exchanged photon, typically $Q_m < m_e$.

In our numerical estimates we will concentrate on the mass interval $1.1 < M < 1.4$ GeV. Here the main contribution is given by the $I = 0$, $J = 2$ partial wave (other partial waves being negligible), the f_2-meson ($J = 2$) production dominates and for more precise calculation also the QED contribution should be accounted. In rough estimates we consider only f_2 contribution. We define by g_0 and g_2 the relative probability amplitudes of the dipion production in the states with helicity 0 and 2; $g_0^2 + g_2^2 = 1$. According to the data, the contribution of total helicity $\lambda_{\pi\pi} = 2$ dominates, i.e., $g_2^2 \gg g_0^2$ (see, e.g., [15]). Similarly to (11), the amplitude of the process can be written as (with $\lambda_\gamma = \pm 1$)

$$\mathcal{A}^+ = A_\gamma D_2(M^2)\,(g_2 Y_{2,2}(\theta,\phi) + g_0 Y_{2,0}(\theta,\phi))\ \mathrm{e}^{-i\lambda_\gamma\psi} \equiv$$

$$\equiv A_\gamma D_2(M^2)\sqrt{\frac{15}{32\pi}}\left[g_2(1-\xi^2)\,\mathrm{e}^{2i\lambda_\gamma\phi} + g_0\sqrt{\frac{2}{3}}(3\xi^2-1)\right]\ \mathrm{e}^{-i\lambda_\gamma\psi}. \quad (15b)$$

• We assume *the odderon* to be a Reggeon-like object so that the odderon amplitude can be written in the same form (11), (13) as the Pomeron amplitude but with $J = 0,\,2$ (instead of 1) and with naturally different values of numerical parameters g, $\sigma_{\mathbb{P}} \to \sigma_{\mathcal{O}}$, $B_{\mathbb{P}} \to B_{\mathcal{O}}$ and different signature factor $\zeta(\mathbb{P}) \to \zeta(\mathcal{O}) = i$. Certainly, in this case all parameters g $\sigma_{\mathcal{O}}$, and $B_{\mathcal{O}}$ are unknown. In numerical estimates we assume

$$B_{\mathcal{O}} \sim B_{\mathbb{P}}, \quad 100 \geqslant \sigma_{\mathcal{O}} \geqslant 1 \text{ nb} \sim (10^{-2} \div 10^{-4})\sigma_{\mathbb{P}}. \quad (16)$$

(At $\sigma_{\mathcal{O}} > 100$ nb the odderon should be definitely seen as a small bump in the $\pi^+\pi^-$ effective mass distribution near $M = 1270$ MeV or as $\pi^0\pi^0$ peak in this mass region. If $\sigma_{\mathcal{O}} < 1$ nb, it will be difficult to distinguish odderon effect from the $\rho\omega$ exchange.) In the reggeized 3-gluon exchange quark-diquark model [16] (which was also used — in some specific variant — in Ref. 11) the coupling of the odderon to the proton is roughly similar to that of the Pomeron. Therefore, we assume the amplitudes with $p' = p$ and proton helicity conservation to be either dominant or contributing not less than other amplitudes.

We assume that — as it is customary for other phenomena at $M \lesssim 1.5$ GeV — the pion pairs are produced mainly via resonance states (f_0 and f_2 mesons). At $M \gtrsim 1.1$ GeV, we deal here with *the* $\gamma\mathcal{O}f_2(1270)$ *vertex*. We have no information about the helicity structure of the $\gamma\,\mathcal{O}\,(\pi\pi)$ vertex. Therefore, we consider both variants, SCHC in this vertex, with $\lambda_{\pi\pi} = \lambda_\gamma$, and violation of SCHC with the same dipion helicity as in the Primakoff case, $\lambda_{\pi\pi} = 2$ or 0 at $\lambda_\gamma = 1$.

• It is seen that the Primakoff effect contribution is concentrated at very low $k_\perp$, while the odderon contribution has a much flatter $k_\perp$ dependence. This is a key to a clean separation of studying the effects due to these two exchanges.

3. DIFFERENTIAL CROSS SECTION. γp COLLISIONS

In this section we present equations for the mass interval $1.1 < M < 1.4$ GeV. Here we have $\beta = 1$ with high precision, and omit this factor in the results. (The corresponding equations for $M < 1.1$ GeV can be easily written in the similar form.)

The differential cross section of the dipion photoproduction averaged over the initial photon polarizations is

$$d\sigma = 2\frac{|\mathcal{A}^- + \mathcal{A}^+|^2}{\sqrt{1-\xi^2-v^2}} dM^2 dk_\perp^2 d\xi dv = d\sigma_{\rm sym} + d\sigma_{\rm asym},$$
$$d\sigma_{\rm sym} = d\sigma_{I\!P} + d\sigma_{\mathcal{O}} + d\sigma_{\rm Pr} + d\sigma_{\mathcal{O}-{\rm Pr}},\ d\sigma_{\rm asym} = d\sigma_{I\!P-\mathcal{O}} + d\sigma_{I\!P-{\rm Pr}}. \tag{17}$$

We introduced here evident notation: $d\sigma_{I\!P}$ is the contribution to cross section from the Pomeron; $d\sigma_{\mathcal{O}}$ — from the odderon; $d\sigma_{\rm Pr}$ — from the Primakoff effect, and $d\sigma_{\mathcal{O}-{\rm Pr}}$ is the contribution of the Primakoff-odderon interference. All these contributions are charge symmetric. The charge asymmetric contribution to cross section is the sum of Pomeron-odderon ($d\sigma_{I\!P-\mathcal{O}}$) and Pomeron–Primakoff ($d\sigma_{I\!P-{\rm Pr}}$) interference terms.

3.1. Charge Symmetric Background. In our problem of studying the charge asymmetric contribution, the charge-symmetric contribution presents background so that here it is sufficient to consider only the main part of $d\sigma_{\rm sym}$. Here the dominant contribution is given by the Pomeron contribution, while contributions $d\sigma_{\mathcal{O}}$ and $d\sigma_{\mathcal{O}-{\rm Pr}}$ can be neglected in our analysis. For estimates, we present main contribution here (both differential and integrated over ξ and v)

$$d\sigma^{\gamma p}_{\rm sym} \approx d\sigma^{\gamma p}_{I\!P} \approx \frac{3}{4\pi}|A^{I\!P}(s,t)|^2 |D_1(M^2)|^2 (1-\xi^2)\frac{dM^2 dk_\perp^2 d\xi dv}{\sqrt{1-\xi^2-v^2}} \Rightarrow$$
$$\Rightarrow \sigma_{I\!P} B_{I\!P} |D_1(M^2)|^2\, {\rm e}^{-B_{I\!P} k_\perp^2} dM^2 dk_\perp^2. \tag{18}$$

The Primakoff effect contribution is generally also small but it is strongly peaked at small $k_\perp$. So, it is necessary to calculate it in more detail,

$$d\sigma^{\gamma p}_{\rm Pr} = \sigma_2 \frac{k_\perp^2}{(k_\perp^2 + Q_m^2)^2} |D_2(M^2)|^2 \frac{15}{16\pi} T(\xi,v) \frac{dM^2 dk_\perp^2 d\xi dv}{\sqrt{1-\xi^2-v^2}} \Rightarrow$$
$$\Rightarrow \sigma_2 \frac{k_\perp^2}{(k_\perp^2 + Q_m^2)^2} |D_2(M^2)|^2 dM^2 dk_\perp^2,$$
$$T(\xi,v) = \Bigg[g_2^2 (1-\xi^2)^2 + \frac{2}{3}\, g_0^2 (3\xi^2 - 1)^2 + + 2 g_0 g_2 \sqrt{\frac{2}{3}}\, (3\xi^2-1)(2v^2+\xi^2-1)\Bigg]. \tag{19a}$$

For the numerical estimates, it is useful to calculate the total cross section of the f_2 production and the cross section integrated over some regions of $k_\perp$. Simple integration over $k_\perp^2$ and M with dipole form factor of proton (with the scale $\sim m_\rho^2$) results in

$$\begin{aligned} \sigma^{\gamma p,\mathrm{tot}}_{\mathrm{Pr},f_2} &= \sigma_2 \left[2\ln\left(\frac{m_\rho s_{\gamma p}}{M_f^2 m_p}\right) - 2.8\right] \approx (14 \div 16)\, \sigma_2 \approx 7 \text{ nb}, \\ \sigma_{\mathrm{Pr},f_2}(k_\perp^2 \leqslant k_m^2 \ll m_\rho^2) &= \sigma_2 \left[2\ln\left(\frac{k_m s_{\gamma p}}{M_f^2 m_p}\right) - 1\right]. \end{aligned} \tag{19b}$$

Therefore, more than 90% of cross section is concentrated at $k_\perp \leqslant 100$ MeV, while the regions $k_\perp > 200$ MeV or $k_\perp > 300$ MeV give respectively 0.5 or 0.2 nb. The latter quantities can be neglected in all calculations.

3.2. The Charge Asymmetric Part of Cross Section. *3.2.1. Type of Asymmetry.* In respect of ep collisions, we consider the cross sections averaged over electron scattering angle. For γp collision it corresponds to averaging over initial photon spin states. When we consider product $(A^+)^\dagger A^-$, the integration over ψ leaves, in the result, only the terms with identical λ_γ in A^+ and A^-. Besides, due to P invariance, for real photons ($\lambda_\gamma = \pm 1$) the other factors in Eq. (11) depend only on the helicity flip $n = |\lambda_{\pi\pi} - \lambda_\gamma|$, not on the value of the helicity itself. Therefore, denoting by λ_+ and λ_- the helicities of C-even and C-odd dipion systems, respectively, the interference effects become proportional to sums over opposite initial photon helicities with simultaneous change of the sign of the final dipion helicities

$$\mathcal{E}^{*J,\lambda_-}_{\lambda_\gamma} \mathcal{E}^{J,\lambda_+}_{\lambda_\gamma} + \mathcal{E}^{*J,-\lambda_-}_{-\lambda_\gamma} \mathcal{E}^{J,-\lambda_+}_{-\lambda_\gamma} \propto \cos\left[(\lambda_- - \lambda_+)\phi\right]. \tag{20}$$

Since $|J_+ - J_-|$ is odd, this quantity changes sign with $\theta \to \pi - \theta$, $\phi \to \pi + \phi$ (i.e., $p_- \leftrightarrow p_+$). In particular:

The terms with odd $\lambda_+ - \lambda_-$ change sign with $\phi \to \pi + \phi$, i.e., with $v \to -v$. They are *responsible for the T asymmetry*.

The terms with even $\lambda_+ - \lambda_-$ remain invariant under $\phi \to \pi + \phi$. Therefore, they must change sign with $\theta \to \pi - \theta$, i.e., they *are responsible for the FB asymmetry.*

3.2.2. The Shape of M Dependence. In our approximation (11) the M dependence of the interference of the C-odd and C-even dipion production at $M > 1.1$ GeV is given by the helicity-independent *overlap functions*, related to the difference between Pomeron and odderon intercepts $\delta_F - \delta_{\mathcal{O}}$, or the Pomeron intercept and the Primakoff phase, respectively, for the Pomeron-odderon and Pomeron–Primakoff contributions, as

$$\mathcal{I}_Z(M) = \mathrm{Re}\left[D_1 D_2^\dagger \mathrm{e}^{i\Delta}\right] \quad \text{with } \Delta = \begin{cases} \delta_F - \delta_{\mathcal{O}} - \dfrac{\pi}{2} & \text{for} \quad Z = \mathbb{P} - \mathcal{O}, \\ \delta_F & \text{for} \quad Z = \mathbb{P} - \mathrm{Pr}. \end{cases} \tag{21}$$

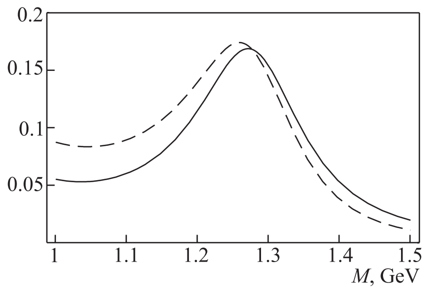

Fig. 1. Overlap function $\mathcal{I}_Z$ for $\Delta-\pi/2 = 0$ and 0.25, respectively, Z is $\mathbb{P} - \mathcal{O}$ or $\mathbb{P} - \mathrm{Pr}$

The shapes of these overlap functions are independent of the helicity structure of the dipion production amplitude, i.e., of the interrelation among coefficients g_i. Besides, if the odderon intercept is close to 1, i.e., $\delta_{\mathcal{O}} \approx \pi/2$, these two overlap functions are close to each other. For preliminary estimate we use for both D_1 and D_2 the Breit–Wigner form (12) for ρ and f_2 mesons, respectively (see Fig. 1). As it was discussed above that is a good approximation for D_2, and it should be improved for D_1 at $1.1 < M < 1.4$ GeV.

Since the Pomeron intercept is close to 1, the overlap function is large (~ 1) when the phase shift between two Breit–Wigner factors is close to $\pi/2$. This happens in a wide enough region around the resonance peaks, where the D_{R_1} (one resonance) is almost real while the D_{R_2} (the other one) is almost imaginary.

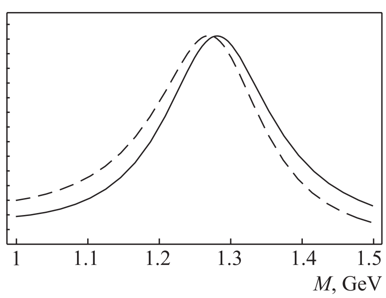

Fig. 2. The local statistical significance of the charge asymmetry, in notations of Fig. 1

• The numerical estimates given below show that the charge symmetric background is described with high precision by the Pomeron contribution $\propto |D_1(M^2)|$ only.

Therefore the local statistical significance (9), SS $\propto \mathcal{I}_{12}/\sqrt{|D_1(M^2)|}$ reproduces roughly the shape of the f_2 peak (and weakly depends on details of D_1), as it is shown in Fig. 2. Therefore, the largest statistical significance comes from the region under the f_2 peak $m_f - \Gamma_f < M < m_f + \Gamma_f$ which can be recommended for the data analysis (real cuts can be even more narrow without loss of SS). Integration of $|D_i|^2$ and of the overlap function $\mathcal{I}_{\mathbb{P}-\mathcal{O}}$ over this range gives at $\Delta - \pi/2 = 0$

$$\begin{gathered}(m_f - \Gamma_f < M < m_f + \Gamma_f) \;\Rightarrow\; \Delta\mathcal{I}_Z = \int dM^2 \mathcal{I}(M^2) = 0.09;\\ C_1 = \int dM^2 |D_1(M^2)|^2 = 0.038; \quad C_2 = \int dM^2 |D_2(M^2)|^2 = 0.40.\end{gathered} \tag{22}$$

Note that the value of $\Delta\mathcal{I}_Z$ depends on phase difference Δ only weakly.

3.2.3. Pomeron–Primakoff Interference. The charge asymmetry given by an interference of Pomeron with Primakoff amplitude can be substantial only at very small $k_\perp \leqslant 100$ MeV. Here the $k_\perp$ dependence of Pomeron amplitude and helicity flip contributions are negligible. Due to SCHC for Pomeron amplitude, in this case $|\lambda_+ - \lambda_-| = 1$ and consequently main asymmetry is transverse one,

$$d\sigma^{\gamma p}_{\mathbb{P}-\mathrm{Pr}} = v\sqrt{\sigma_2 \sigma_{\mathbb{P}} B_{\mathbb{P}}}\, \mathcal{I}_{\mathbb{P}-\mathrm{Pr}}(M) Z(\xi) \frac{|k_\perp|}{k_\perp^2 + Q_m^2} \frac{dM^2 dk_\perp^2 d\xi dv}{\sqrt{1-\xi^2-v^2}},$$
$$Z(\xi) = \frac{3\sqrt{5}}{4\pi}\left[g_2(1-\xi^2) + g_0\sqrt{\frac{2}{3}}(3\xi^2-1)\right]. \tag{23}$$

This asymmetry is peaked at small $k_\perp$.

The FB asymmetry in this case has no peak at small $k_\perp$, its absolute value is no more than $1 \div 3\%$ of the T asymmetry at $k_\perp < 100$ MeV.

3.2.4. Pomeron-Odderon Interference. The charge asymmetric contribution given by an interference of Pomeron and odderon has more complex structure. Neglecting contributions with higher helicity flips $n > 1$ one can write the interference contribution to the cross section in the form

$$d\sigma^{\gamma p}_{\mathbb{P}-\mathcal{O}} = \frac{3\sqrt{5}\mathcal{I}_{\mathbb{P}-\mathcal{O}}(M)}{2\pi}\sqrt{\sigma_{\mathbb{P}}\sigma_{\mathcal{O}} B_{\mathbb{P}} B_{\mathcal{O}}}\, \mathrm{e}^{-(B_{\mathbb{P}}+B_{\mathcal{O}})k_\perp^2/2} \times$$
$$\times\, (\xi T_\xi + v|k_\perp| T_v) \frac{dM^2 dk_\perp^2 d\xi dv}{\sqrt{1-\xi^2-v^2}};$$

$$T_\xi = g_{1,1}g_{2,1}(1-\xi^2) + g_{1,0}\sqrt{B_{\mathcal{O}} B_{\mathbb{P}}}\, k_\perp^2 \times$$
$$\times \left[\frac{1}{\sqrt{2}} g_{2,2}(2v^2+\xi^2-1) + \frac{1}{\sqrt{3}} g_{2,0}(3\xi^2-1)\right], \tag{24}$$
$$T_v = g_{1,1}\left[\frac{1}{2} g_{2,2}(1-\xi^2) + \frac{1}{\sqrt{6}} g_{2,0}(3\xi^2-1)\right]\sqrt{B_{\mathcal{O}}} + g_{1,0}g_{2,1}\xi^2\sqrt{B_{\mathbb{P}}}.$$

Here the term T_ξ, with even $\lambda_+ - \lambda_-$, describes the FB asymmetry, while the term T_v, with odd $\lambda_+ - \lambda_-$, describes the T asymmetry. If the SCHC holds for the odderon, then the principal effect would be the FB asymmetry. The T asymmetry is dominant in the case of strong s-channel helicity nonconservation for odderon, for instance, if the f_2 meson is produced in the state with maximal helicity $\lambda_f = \pm 2$.

• It is useful to compare the Pomeron–Primakoff and the transverse Pomeron-odderon charge asymmetries. For definiteness, we consider the case of maximal SCHC violation for odderon with $g_{2,2} \approx 1$ and $g_2 \approx 1$ for the Primakoff effect at $B_{\mathcal{O}} k_\perp^2 < 1$. In this case the ratio of transverse asymmetries given by an interference of Pomeron with Primakoff effect and odderon can be written in very simple form

$$\frac{d\sigma^{\gamma p}_{\mathbb{P}-\mathrm{Pr}}}{d\sigma^{\gamma p}_{\mathbb{P}-\mathcal{O}}} = \frac{K_*^2}{k_\perp^2} \quad \text{with} \quad K_*^2 = \sqrt{\frac{\sigma_2}{\sigma_{\mathcal{O}}}}\frac{1}{B_{\mathbb{P}}}. \tag{25}$$

Therefore, the Pomeron-odderon contribution can be neglected at $k_\perp < K_* \approx$ 80 MeV even for very large odderon photoproduction cross section $\sigma_{\mathcal{O}} = 100$ nb, while the Primakoff contribution can be neglected at $k_\perp > K_* \approx 260$ MeV even at very low $\sigma_{\mathcal{O}} = 1$ nb.

4. ep COLLISIONS. PHYSICAL PROBLEMS

In real experiments, e.g., at HERA, the γp reactions are studied in ep collisions. In our opinion, the most efficient way of studying the problems under interest here is to consider dipion production without recording of the scattered electrons. The dominant part of the ep cross section comes from the region of very small virtuality of the exchanged photon $-q^2 \equiv -(p_e - p'_e)^2$. Here transverse component of photon momentum $q_\perp$ is small, the photon energy ω with high accuracy coincides with the total dipion energy and the equivalent photon approximation has very high precision (see, e.g., [12]). In this approximation the flux of the equivalent photons with energy $\omega = yE_e$ and transverse momentum $q_\perp$ is

$$dn_\gamma = \frac{\alpha}{\pi}\frac{dy}{y}\left[\nu(y) - (1-y)\frac{q_e^2}{q_\perp^2}\right]\frac{q_\perp^2\, dq_\perp^2}{(q_\perp^2 + q_e^2)^2}$$

$$\text{with} \;\; q_e^2 = \frac{m_e^2 y^2}{1-y}, \;\; \nu(y) = 1 - y + \frac{y^2}{2}. \tag{26}$$

We present all results here for the measurable values of $K_\perp$, that is $K_\perp^2 \gg Q_m^2,\, q_e^2$.

The ep cross section is given by a convolution of the virtual photon flux originating from the electron with the cross section of the γp subprocess under condition (7). In the numerical estimates below we integrate cross sections over interval $0.1 \leqslant y \leqslant 0.9$.

4.1. Possible Discovery of Odderon, $1.1 < M < 1.45$ **GeV.** In the discussion of odderon, the main problem is *to detect its signal*. In our opinion, the observation of the discussed charge asymmetry of pions provides the best solution for this problem. To estimate the feasibility of this observation, we consider the (Pomeron) background and the corresponding Pomeron-odderon charge asymmetry in ep collisions. In this estimate the logarithmic accuracy suffices. To simplify equations below we assume $B_{\mathcal{O}} \approx B_{\mathbb{P}}$ (accounting for the difference is trivial with the above equations).

In this case the background is given by integration of the above-mentioned convolution of the photon flux with the Pomeron contribution over $K_\perp$. In this integration one should take into account also the dependence of hadronic contribution on q^2 (form factor) which scale $m_r \sim m_\rho$,

$$d\sigma^{ep}_{\mathbb{P},\mathrm{tot}} = N_{\mathbb{P},\mathrm{tot}}\,\sigma_{\mathbb{P}}|D_1|^2 dy dM^2,\ N_{\mathbb{P},\mathrm{tot}} = \frac{\alpha}{\pi y}\left[\nu(y)\log\left(\frac{m_r^2}{q_e^2}\right) - (1-y)\right]. \tag{27}$$

The results for asymmetry depend on (still unknown) helicity structure of the odderon amplitude.

• *If SCHC takes place also for odderon amplitude,* i.e., $g_{2,1} \approx 1$, *the main charge asymmetry is the forward–backward one.* In this case the Pomeron–Primakoff background is practically absent, and no additional cuts in $K_\perp$ are necessary. The integrated FB charge asymmetry can be written in the form like (27) with the same total photon flux $N_{\mathbb{P},\mathrm{tot}}$ and T_ξ (24),

$$d\sigma^{ep}_{\mathbb{P}-\mathcal{O},\mathrm{tot}} = \xi N_{\mathbb{P},\mathrm{tot}}\,\frac{3\sqrt{5}\mathcal{I}_{\mathbb{P}-\mathcal{O}}(M)}{2\pi}\sqrt{\sigma_{\mathbb{P}}\sigma_{\mathcal{O}}}\ \ T_\xi\frac{dy\,dM^2 dK_\perp^2\,d\xi dv}{\sqrt{1-\xi^2-v^2}}. \tag{28}$$

The first term in T_ξ (24) is dominant in charge asymmetry at small $k_\perp$. With the growth of $k_\perp$, the terms with helicity flip both for the Pomeron and odderon become essential, and, generally, not small. Note that upon the azimuthal integration over entire region of v variation, the contribution from production of f_2 in the state with helicity-2 vanishes because $\int \cos 2\phi d\phi = 0$.

The subsequent integration over M around the f_2 peak (22) and over y (with $\int N_{\mathbb{P},\mathrm{tot}}dy = 0.053$) gives (with logarithmic accuracy) the total background $\sigma^{ep}_{\mathrm{bkgd}}$. To estimate the value of charge asymmetry $\Delta\sigma_{\mathrm{FB}}$ (8) we assume additionally that $g_{1,1} \approx g_{2,1} \approx 1$ and for the calculation of statistical significance of the FB asymmetry measurement (9) we use HERA luminosity (10). For $\sigma_{\mathcal{O}} = 1 \div 100$ nb we have (see (22))

$$\begin{gathered}\sigma^{ep}_{\mathrm{bkgd,FB}} = 0.053\,\sigma_{\mathbb{P}}\,C_1 = 22\ \text{nb},\\ \Delta\sigma_{\mathbb{P}-\mathcal{O},\mathrm{FB}} = \frac{3\sqrt{5}}{4}\,0.053\,\sqrt{\sigma_{\mathbb{P}}\sigma_{\mathcal{O}}}|\Delta\mathcal{I}_{\mathbb{P}-\mathcal{O}}| = 0.83\ \text{nb}\sqrt{\frac{\sigma_{\mathcal{O}}}{\text{nb}}} \Rightarrow\\ \Rightarrow\ \mathrm{SS}_{\mathrm{FB}} = 56\sqrt{\frac{\sigma_{\mathcal{O}}}{\text{nb}}} = 56 \div 560.\end{gathered} \tag{29}$$

• *If SCHC is violated strongly for odderon amplitude,* i.e., for example, $g_{2,2} \approx 1$ (as for the photon exchange), *the main charge asymmetry is the transverse one*, its relative value increases with growth of $k_\perp$. Here Pomeron–Primakoff interference is also essential. However, the latter decreases with growth of $k_\perp$, and cut in $K_\perp$ from below at $K_\perp = K_m \approx 300$ MeV eliminates this contribution (see estimates (25)). Besides, the relative growth of transverse charge asymmetry with $k_\perp$ provides improvement of signal-to-background ratio with the growth of K_m. With the cut $K_\perp \geqslant K_m < 1/\sqrt{B_{\mathbb{P}}}$, the background contribution

(27) is reduced by factor $e^{-B_{I\!P}K_m^2}$, while the transverse charge asymmetry is given by

$$d\sigma^{ep}_{I\!P-\mathcal{O},T} = \\ = vK_\perp N_{I\!P,\mathrm{tot}}\, R_T \frac{3\sqrt{5}\mathcal{I}_{I\!P-\mathcal{O}}(M)}{2\pi} \sqrt{\sigma_{I\!P}\sigma_{\mathcal{O}}B_{\mathcal{O}}}\; T_v\; \frac{dy\, dM^2 dK_\perp^2\, d\xi dv}{\sqrt{1-\xi^2-v^2}}, \qquad (30)$$

$$R_T = \int\limits_{B_{I\!P}K_m^2}^{\infty} \sqrt{x}\, e^{-x} dx.$$

In the numerical estimates with $K_m = 300$ MeV it gives, similarly to (29),

$$\sigma^{ep}_{\mathrm{bkgd},T} \approx 9\,\mathrm{nb}; \quad \Delta\sigma_{I\!P-\mathcal{O},T} \approx 0.34\sqrt{\frac{\sigma_{\mathcal{O}}}{\mathrm{nb}}}\,\mathrm{nb} \Rightarrow \mathrm{SS}_T = 35\sqrt{\frac{\sigma_{\mathcal{O}}}{\mathrm{nb}}} = 35 \div 350. \qquad (31)$$

• The numbers in (29), (31) are very promising. They offer certain confidence that the odderon signal is indeed within the reach of the current experiments even with very low value for the odderon-induced cross section 1 nb.

4.2. Small $K_\perp$. Measuring Pomeron Phase, $1.1 < M < 1.45$ **GeV.** In this subsection we consider effects at $K_{\min} = 20$ MeV $< K_\perp \leqslant K_{\max} = 80$ MeV, where the Pomeron-odderon interference contribution can ne neglected with good confidence (25). Here the Pomeron–Primakoff interference dominates in charge asymmetry. Since Primakoff contribution is either well known (at $1.1 < M < 1.4$ GeV) or can be established well (at $M < 1.1$ GeV), it is suggested [3] to use the measurement of charge asymmetry at these $K_\perp$ to extract the Pomeron phase from the data.

Let us stress a vital feature of our suggestion. The procedure we propose *does not* demand the measurement of very small scattering angles of pions. The pions that hit the detector have transverse momenta $p_{\pm\perp} \sim M/2 \sim 500$ MeV, which looks not so difficult for the measurement. It is the sum of the transverse momenta of the two pions $k_\perp$ that is supposed to be small and measurable. So, in order for this method to be efficient, we need a reasonable resolution of the reconstruction of each pion's transverse momentum. The choice of the lower bound $K_{\min}$ in $K_\perp$ corresponds to the anticipated accuracy of this measurement.

The upper bound $K_{\max} = 80$ MeV is chosen in accordance with Eq. (25) for the case of extremely high odderon-induced f_2 production cross section of 100 nb with prevalent helicity 2 production. The study of $K_\perp$ dependence of the transverse charge asymmetry at $K_\perp > 100$ MeV will allow one to either determine this odderon cross section or set up its upper bound. After that, the upper limit $K_{\max}$ can be increased. Fortunately, the statistical significance of the discussed effect (34) changes very little even if $K_{\max}$ varies from, e.g., 70 up to 150 MeV.

To extract Pomeron phase from the data, accurate calculations should be made. In the text below we will mark the point where these accurate calculations are changed to estimates that are necessary for understanding the potential of this approach.

At $K_\perp \leqslant 150$ MeV the proper $k_\perp$ dependence of the Pomeron amplitude becomes inessential except for its scale given by $\exp(-B_{I\!P} k_\perp^2)$. To simplify integration, we change this dependence to $1/(1 + B_{I\!P} k_\perp^2)$ (that is good approximation at $B_{I\!P} K_\perp^2 < 0.1$). Now the charge symmetric part of cross section (background) is (see also (19))

$$\begin{aligned}
&d\sigma^{ep}_{\mathrm{bkgd},*} = d\sigma^{ep}_{I\!P,*} + d\sigma^{ep}_{\mathrm{Pr}};\\
&d\sigma^{ep}_{I\!P,*} = \sigma_{I\!P} B_{I\!P} |D_1(M^2)|^2 \frac{3}{4\pi}(1-\xi^2) N_{I\!P,*} \frac{dy\, dM^2\, dK_\perp^2\, d\xi\, dv}{\sqrt{1-\xi^2-v^2}},\\
&N_{I\!P,*} = \frac{\alpha}{\pi y}\left[\nu(y)\left(\log\left(\frac{1}{B_{I\!P} q_e^2}\right) - 1\right) - (1-y)\right];\\
&d\sigma^{ep}_{\mathrm{Pr}} = N_\gamma \frac{dy\, dM^2\, dK_\perp^2\, d\xi\, dv}{\sqrt{1-\xi^2-v^2}} \frac{\sigma_2 |D_2(M^2)|^2}{K_\perp^2 + Q_m^2 + q_e^2} \frac{15}{16\pi} T(\xi, v),\\
&N_\gamma = \frac{\alpha}{\pi y}\left[\nu(y)\left(\log\left(\frac{(K_\perp^2)^2}{Q_m^2 q_e^2}\right) - 2\right) - (1-y)\right].
\end{aligned} \tag{32}$$

Here we keep term $Q_m^2 + q_e^2$ in the denominator which is negligible at the measurable values of $K_\perp$ but useful in an estimate of the total cross section.

The Pomeron–Primakoff interference term describes transverse asymmetry, it can be written in the form (cf. Eq. (23))

$$\begin{aligned}
&d\sigma^{ep}_{I\!P-\mathrm{Pr}} = v N_{I\!P\gamma} \frac{dy\, dM^2\, dK_\perp^2\, d\xi\, dv}{\sqrt{1-\xi^2-v^2}} \sqrt{\sigma_{I\!P} B_{I\!P}\, \sigma_2} \frac{|K_\perp|}{K_\perp^2} \mathcal{I}_{I\!P-\mathrm{Pr}}(M^2) Z(\xi),\\
&N_{I\!P\gamma} = \frac{\alpha}{\pi y}\left[\nu(y)\left(\log\frac{K_\perp^2}{q_e^2} - \frac{1}{2}\right) - \frac{1-y}{2}\right].
\end{aligned} \tag{33}$$

For good extraction of Pomeron phase from the data one should have more accurate equations for D_i as it was mentioned above. That is the subject of the forthcoming work.

To estimate experimental possibilities, it is sufficient to use simple resonant approximations written above. In this estimate we also neglect Primakoff contribution to background. After integration over y, at integral luminosity (10) we obtain similar to (29)

$$\sigma^{ep}_{\mathrm{bkgd}} \approx 1.1 \text{ nb}, \quad \Delta\sigma_{I\!P-\mathrm{Pr,T}} \approx 0.1 \text{ nb} \quad \Rightarrow \quad \mathrm{SS_T} \approx 30. \tag{34}$$

This value of the integral SS shows that the effect is observable at HERA with good confidence. We hope that after dedicated specification of the models for D_i, a detailed study of the M shape of this charge asymmetry will allow for extraction of the Pomeron phase δ_F with reasonable precision.

4.3. The Case $M < 1.1$ GeV. Certainly, the region of effective masses below 1.1 GeV can be also used for the discovery of the odderon and for measuring the Pomeron phase. Just as above, the observation of FB charge asymmetry or transverse asymmetry at $K_\perp > 300$ MeV will be a clear signal of the existence of the odderon. Unfortunately, we have no motivated understanding what would be the odderon amplitude in this mass interval.

The observation of transverse charge asymmetry at $K_\perp \lesssim 100$ MeV can be a source of information about the Pomeron phase. A more detailed model for the $\gamma\gamma \to \pi^+\pi^-$ is necessary to make more accurate predictions for the study of Pomeron phase. This model can be verified by measurement of similar charge asymmetry in the process $e^+e^- \to e^+e^-\pi^+\pi^-$ at modern e^+e^- colliders [14]. That is the subject of the forthcoming studies.

Preliminary estimates show that below the ρ peak the phases of factors D_1 and $D_0^{I=0}$ are close to each other, so that the contribution of this term to the considered asymmetry is small, and the dominant contribution to the charge asymmetry is given by the $\rho-\text{QED}$ interference. The best statistical significance of charge asymmetry is given in the region $M = 0.4-0.8$ GeV.

5. DISCUSSION AND CONCLUSIONS

We have shown that the measurement of charge asymmetry of pions in diffractive process $ep \to e\pi^+\pi^-p'$ at HERA allows one to discover the odderon and to measure the Pomeron phase. We assume here experiments without tagging of scattered electrons (or with antitagging of scattered electrons with the transverse momentum $q_\perp > 300 \div 600$ MeV).

For the odderon discovery, one only needs to observe the signal of charge asymmetry at not too small dipion transverse momenta. Our estimates show that HERA has very large potential in this problem, and this potential does not depend on any particular model of the odderon.

In order to measure the Pomeron phase δ_F, one needs to perform detailed measurements of charge asymmetry at sufficiently small dipion momenta. The suggested approach avoids problems associated with the measurement of very small transverse momenta of the detected particles, in contrast to the strong-Coulomb interference in elastic pp scattering (where one should measure transverse momenta $p_\perp \lesssim 100$ MeV). Here, detected pions have typical transverse momenta $|p_{\pm\perp}| \sim 500$ MeV, which should be measurable with good precision.

Equations written in the text allow one to obtain preliminary estimate for δ_F and find its s dependence with accuracy limited by details of experimentation. A more precise extraction of the absolute value of δ_F demands more accurate models for both Pomeron and Primakoff amplitudes. The main features of these models are well known, and these models can be further improved right in the course of dedicated experiments on charge asymmetries (both at high-energy lepton-hadron and low-energy e^+e^- colliders). The sketch of how predictions can be made more precise is given in the text. For each mass interval, these problems should be studied separately.

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