ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
2004. Т. 35. ВЫП. 7

УДК 539.12: 539.171

REGGE-DUAL MODEL OF THE PROTON STRUCTURE FUNCTION F_2

Z. Dzezyk [1,2,*], *A. Flachi* [3,**], *L. L. Jenkovszky* [2,***], *V. K. Magas* [2,4,****]

[1] Institute of Nuclear Physics, Academy of Sciences of Ukraine, Kiev
[2] Bogolyubov Institute for Theoretical Physics, Academy of Sciences of Ukraine, Kiev
[3] IFAE, Campus UAB, Bellaterra (Barcelona), Spain
[4] Departament de Física Teórica, Universitat de Valéncia, Burjassot (Valéncia), Spain

In a series of papers a two-dimensional dual model, combining resonance-Regge and quark–hadron duality was developed. Here we present fits to the recently measured inclusive electron–proton cross section in the nucleon resonance region, performed with the CLAS detector at the JLAB. The helicity structure of the scattering amplitudes is discussed.

Развитая в серии статей двумерная модель, учитывающая дуальность между реджеонами и резонансами и между кварками и адронами, применена для фитирования данных CLAS. Обсуждается спиральная структура амплитуд рассеяния.

In this paper we report on our previous study [1], where a two-dimensionally dual model, combining resonance-Regge and quark–hadron duality is constructed and fitted to the recently measured electron–proton cross section at JLAB.

The main idea behind the model (for details we address the reader to Refs. 2, 1) is the use of a dual amplitude with Mandelstam analyticity continued off the mass shell, which incorporates complex, nonlinear Regge trajectories with a limited number of resonances on each trajectory. Two-component duality is implied: resonances are dual to ordinary (or «secondary») Regge exchanges, while the direct-channel, nonresonant background is dual to a Pomeron exchange in the t channel. This second, «diffractive» component is of special interest, since the separation of the resonances from the background is not unique. To be specific, in most of the models describing low-energy inclusive *ep* scattering, including those recent from the CLAS collaboration at JLAB (see [3]), the background is modeled empirically by a smooth function with the parameters fitted to

*E-mail: dss.sachar@list.ru
**E-mail: flachi@ifae.es
***E-mail: jenk@gluk.org
****E-mail: Volodymyr.Magas@ific.uv.es

the data. The advantage of our approach to the background is that the background is treated on the same ground as the nondiffractive component [4, 5].

The difference between the two components is quantitative rather than qualitative. The real part of the exotic trajectories, providing for the nonresonant background was constrained by an upper limit set below the appearance of any physical resonance. Now, as the existence of exotic resonances cannot be excluded any more, the parameters of the relevant trajectories may require revision with the account for the spectroscopy of the newly discovered (and expected) exotic states (see, e.g., [6] for a recent review on this subject). The reparameterization of the trajectories will not change the model, however the possible existence of exotic trajectories can be interpreted in terms of the quark model: contrary to the «traditional» interpretation of the exotic trajectories and the Pomeron as made of gluons only and the ordinary trajectories made of quarks, all trajectories correspond to mixtures of quarks and gluons.

Regge-Dual Structure Function. The inclusive, inelastic *ep* cross section is related to the unpolarized structure function (SF), $F_2(x, Q^2)$, by

$$F_2(x, Q^2) = \frac{Q^2(1-x)}{4\pi\alpha(1+4m^2x^2/Q^2)}\sigma_t^{\gamma^* p}, \tag{1}$$

where the total cross section, $\sigma_t^{\gamma^* p}$, includes, by unitarity, all possible intermediate states allowed by energy and quantum number conservation. We follow the norm

$$\sigma_t^{\gamma^* p}(s) = \operatorname{Im} A(s, Q^2) \tag{2}$$

used in Refs. 2, 1. The centre-of-mass energy of the $\gamma^* p$ system, the negative squared photon virtuality Q^2, and the Bjorken variable x are related by

$$s = W^2 = Q^2(1-x)/x + m^2. \tag{3}$$

In a Regge-dual model we write the scattering amplitude as a pole decomposition of the dual amplitude:

$$\left[A(s, Q^2)\right]_{t=0} = N\left\{\sum_{r,n} \frac{f_r^{2(n-n_r^{\min}+1)}(Q^2)}{n-\alpha_r(s)} + [A(s, Q^2)]_{t=0}^{\mathrm{BG}}\right\}, \tag{4}$$

where N is an overall normalization coefficient; r runs over all trajectories allowed by quantum number conservation (in our case $r = N_1^*,\ N_2^*,\ \Delta$) while n runs from $n_r^{\min}$ (spin of the first resonance) to $n_r^{\max}$ (spin of the last resonance), and $[A(s, Q^2)]_{t=0}^{\mathrm{BG}}$ is the contribution from the background. The functions $f_r(Q^2)$ and $\alpha_r(s)$ are respectively form factor and Regge trajectory corresponding to the rth term*.

*Note that only for the first resonance at each trajectory we have squared form factor, while for the recurrences the powers of form factors are growing, according to the properties of DAMA [1, 2].

Helicity Structure. The form factors can be written as a sum of three terms [7,8], $G_+(Q^2)$, $G_0(Q^2)$, and $G_-(Q^2)$, corresponding to $\gamma^* N \to R$ helicity transition amplitudes in the rest frame of the resonance R:

$$G_{\lambda_\gamma} = \frac{\langle R, \lambda_R = \lambda_N - \lambda_\gamma | J(0) | N, \lambda_N \rangle}{m}, \tag{5}$$

where λ_R, λ_N, and λ_γ are the resonance, nucleon, and photon helicities; $J(0)$ is the current operator; λ_γ takes the values $-1, 0$ and $+1$. The explicit form of these form factors is known only near their thresholds $|\mathbf{q}| \to 0$, while their large-Q^2 behaviour is constrained by the quark counting rules. According to the quark counting rules, the large-Q^2 behavior of G's is assumed to be

$$G_+ \sim Q^{-3},\ G_0 \sim Q^{-4},\ G_- \sim Q^{-5}. \tag{6}$$

Let us note that while this is reasonable (modulo logarithmic factors) for elastic form factors, it may not be true any more for inelastic (transition) form factors. Our Regge-dual model, Eq. (4), predicts that the powers of the form factors increase with increasing excitation (resonance spin). The experimental data [9] seem to confirm this trend.

The authors of Ref. 8, combining threshold and asymptotic behavior, suggest the following expressions:

$$\begin{aligned} |G_\pm|^2 &= |G_\pm(0)|^2 q^{2J-3} c^{2J-3}(Q_0') c^{m_\pm}(Q_0), && (7) \\ |G_0|^2 &= C^2 \frac{q_0^2}{|\mathbf{q}|^2} q^{2J-1} c^{2a+m_0}(Q_0) c^{2J-1}(Q_0') && (8) \end{aligned}$$

for the normal transitions and

$$\begin{aligned} |G_\pm|^2 &= |G_\pm(0)|^2 q^{2J-1} c^{2J-1}(Q_0') c^{m_\pm}(Q_0), && (9) \\ |G_0|^2 &= C^2 \left(\frac{q_0^2}{|\mathbf{q}|^2}\right)^{2J-1} c^{2a+m_0}(Q_0) c^{2J+1}(Q_0'), && (10) \end{aligned}$$

for the anomalous ones. Here $m_+ = 3$, $m_0 = 4$, $m_- = 5$ and

$$|\mathbf{q}| = \frac{\sqrt{(M^2 - m^2 - Q^2)^2 + 4M^2Q^2}}{2M}, \quad q_0 = \frac{M^2 - m^2 - Q^2}{2M}, \tag{11}$$

where M is a resonance mass; C and a are free parameters. For notation convenience we have introduced the functions

$$q = \frac{|\mathbf{q}|}{|\mathbf{q}|_{Q=0}}, \quad c(z) = \frac{z^2}{Q^2 + z^2}. \tag{12}$$

Finally, the form factors at $Q^2 = 0$ are related to the helicity photoproduction amplitudes $A_{1/2}$ and $A_{3/2}$ by

$$|G_{+,-}(0)| = \frac{1}{\sqrt{4\pi\alpha}}\sqrt{\frac{M}{M-m}}|A_{1/2,3/2}|. \tag{13}$$

Regge Trajectories. The use of (s channel) Regge trajectories, including all possible intermediate states in the resonance region and appearing as recurrences on the trajectories, allows us to deal with the large number of resonances to be taken into account. The form of the Regge trajectories is constrained by analyticity, requiring the presence of threshold singularities, and by their asymptotic behaviour, imposing an upper bound on their real part. Here, based on [10], we consider a simple model based on a sum of square root thresholds, according to which the trajectory takes the form

$$\alpha(s) = \alpha_0 + \alpha_1 s + \alpha_2(\sqrt{s_0} - \sqrt{s_0 - s}), \tag{14}$$

where $s_0 = (m_\pi + m_p)^2$.

Apart from the resonances, lying on the N^*'s and Δ s-channel trajectories, dual to an effective bosonic (f-)trajectory in the t channel, one has to consider the contribution from a smooth background. Following our previous arguments [1,2], we model it by nonresonance pole terms with exotic trajectories, dual to the Pomeron, leading to

$$\left[A(s,Q^2)\right]_{\mathrm{BG}} = \sum_{b=E,E'} G_b \frac{c^4(Q_b)}{n_b - \alpha_b(s)} \tag{15}$$

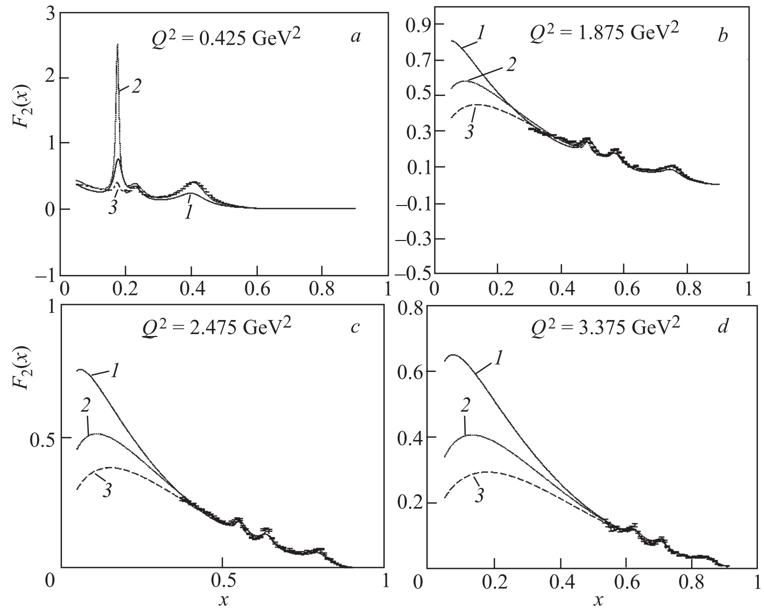
with dipole form factors, given by $c^2(Q_b)$. The exotic trajectories are chosen in the form

$$\alpha_b(s) = \alpha_b(0) + \alpha_{1b}(\sqrt{s_0} - \sqrt{s_0 - s}), \tag{16}$$

where the coefficients $\alpha_b(0)$, α_{1b}, and the Q_b^2 are the free parameters. To prevent any physical resonance, they are constrained in such a way that the real part of the trajectory terminates before reaching the first resonance on the physical sheet. An infinite sequence of poles, saturating duality, appears on the nonphysical sheet in the amplitude; they do not interfere in the smooth behaviour of the background (for more details see [4]).

Comparison with the CLAS Data. With the above model at hand, we have fitted the CLAS data for the $F_2(Q^2, s)$ [3]. A few representative plots are shown in the Figure and the fitted parameters presented in the table.

To start with, we made a fit keeping the parameters of the Regge trajectories and the photoproduction amplitudes fixed, close to their physical values. Also, a single-term background was used. As a result we obtain fit 1 shown in the Table.



Structure function $F_2(x)$ for $Q^2 = 0.425-3.375$ GeV^2. Data are from [3], and the lines show results of three different fits (see text for details). *1* — fit 1; *2* — fit 2; *3* — fit 3

Parameters of the fits (see text)

	Parameters	Fit 1	Fit 2	Fit 3
N_1^*	α_0	–0.8377*	–0.8377*	–0.8377*
	α_1, GeV^{-2}	0.9500*	0.9551	0.9825
	α_2, GeV^{-1}	0.1473*	0.1500	0.0920
	$A^2(1/2)$, GeV^{-1}	0.0484E–2*	0.0031	0.8647E–2
	$A^2(3/2)$, GeV^{-1}	0.2789E–1*	0.0216	0.9634E–2
N_2^*	α_0	–0.3700*	–0.3700*	–0.3700*
	α_1, GeV^{-2}	0.9500*	0.9646	0.9551
	α_2, GeV^{-1}	0.1471*	0.0699	0.0949
	$A^2(1/2)$, GeV^{-1}	0.0289E–2*	0.0156	0.9724E–2
	$A^2(3/2)$, GeV^{-1}	0.1613*	9.5363E–07	5.1973E–11
Δ	α_0	0.0038*	0.0038*	0.0038*
	α_1, GeV^{-2}	0.8500*	0.8815	0.8605
	α_2, GeV^{-1}	0.1969*	0.1622	0.2005
	$A^2(1/2)$, GeV^{-1}	0.0199*	0.0033	5.3432E–08
	$A^2(3/2)$, GeV^{-1}	0.0666*	0.1023	0.0866

End of Table

	Parameters	Fit 1	Fit 2	Fit 3
E_1	G_{E_1}	6.5488	2.8001	3.6049
	α_0	0.3635	0.7499	0.3883
	α_2, GeV^{-1}	0.1699	0.1575	0.3246
	$Q^2_{E_1}$, GeV^2	5.2645	4.300	3.9774
	s_{E_1}, GeV^2	1.14*	1.1740	1.14*
E_2	G_{E_2}	—	—	–0.6520
	α_0	—	—	–0.8929
	α_2, GeV^{-1}	—	—	1.7729
	$Q^2_{E_2}$, GeV^2	—	—	2.4634
	s_{E_2}, GeV^2	—	—	1.14*
	s_0, GeV^2	1.14*	1.14*	1.14*
	$Q_0'^2$, GeV^2	0.4089	0.4699	0.9998
	Q_0^2, GeV^2	3.1709	2.5499	1.8926
	N, GeV^{-2}	0.0408	0.0559	0.0567
	$\chi^2_{\mathrm{d.o.f.}}$	12.92	2.8824	1.3005

*Fixed parameters.

For the next fit (fit 2) some of these parameters were varied. Consequently the χ^2 has significantly improved, although still remains unsatisfactory. Finally, we added the second term in the background, what led to the best fit with $\chi_{\mathrm{d.o.f.}} = 1.30$ (fit 3). More details can be found in [1].

To conclude, let us remind that although our fits concern only the resonance region, typical of the CLAS experiment, the model is potentially applicable in all kinematical regions, in particular in the Regge domain, where many data from HERA are available. To proceed further along these lines we intend to use more realistic baryonic trajectories, study alternative parameterizations of the background, study in detail the behavior of the transition form factors as well as the spin structure functions.

Acknowledgements. We thank M. Osipenko for a useful correspondence. L. J. and V. M. acknowledge the support by INTAS under Grant 00-00366. The work of A. F. is supported by the European Community via the award of a «Marie Curie» postdoctoral Fellowship and by FEDER under project FPA 2002-00748.

REFERENCES

1. *Fiore R. et al.* hep-ph/0308178; Phys. Rev. D (to appear).
2. *Jenkovszky L. L., Magas V. K., Predazzi E.* // Eur. Phys. J. A. 2001. V. 12. P. 361; nucl-th/0110085;
   Jenkovszky L. L., Magas V. K. hep-ph/0111398;
   Fiore R. et al. // Eur. Phys. J. A. 2002. V. 15. P. 505; hep-ph/0212030; Ukr. Fiz. Zh. 2003. V. 48. P. 507.
3. *Osipenko M. et al.* // Phys. Rev. D. 2003. V. 67. P. 092001; hep-ex/0309052.
4. *Bugrij A. I., Jenkovszky L. L., Kobylinsky N. A.* // Lett. Nuovo Cim. 1972. V. 5. P. 389.
5. *Jenkovszky L. L., Kononenko S. Yu., Magas V. K.* // Proc. of the NATO Advanced Research Workshop «DIFFRACTION 2002», Alushta, Crimea, Aug. 31 – Sep. 6, 2002. Kluwer Academic Publishers, 2003. P. 117; hep-ph/0211158.
6. *Roy D. P.* hep-ph/0311207.
7. *Bjorken J. D., Walecka J. D.* // Ann. Phys. 1966. V. 38. P. 35;
   Carlson C. E. // Phys. Rev. D. 1986. V. 34. P. 2704;
   Carlson C. E., Mukhopadhyay N.C. // Phys. Rev. D. 1998. V. 58. P. 094029.
8. *Davydovsky V. V., Struminsky B. V.* // Ukr. Fiz. Zh. 2002. V. 47. P. 1123; hep-ph/0205130.
9. *Paschos E. A., Yu J.-Y.* hep-ph/0308130.
10. *Cohen-Tannoudji G. et al.* // Lett. Nuovo Cim. 1972. V. 5. P. 957;
    Bugrij A. I., Kobylinsky N. A. // Ann. Phys. 1975. V. 32. P. 297;
    Trushevsky A. A. // Ukr. Fiz. Zh. 1977. V. 22. P. 353;
    Jenkovszkly L. L. // Fortschr. Phys. 1986. V. 34. P. 791;
    Fiore R. et al. // Eur. Phys. J. A. 2001. V. 10. P. 217; Nucl. Phys. Proc. Suppl. 2001. V. 99A. P. 68;
    Brisudova M. M. et al. nucl-th/0303012.