Weak production and electroproduction of Δ(1236) in a Zucker-model calculation

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Zucker's model for weak production and electroproduction of Δ(1236) is reconsidered in the light of recent experimental data. We find that the disagreement between the predictions of the Zucker model and the experimental data can be significantly reduced by choosing a different form for ω exchange.

We consider in this paper the production of Δ(1236) from neutrinos scattering off nucleons within the context of a model due to Zucker and collaborators.[1,2] Although the data[3] for low values of the squared momentum transfer (k^2) agree with the predictions of an earlier model due to Adler,[4] the applicability of the Adler model is very limited. The model due to Zucker[1,2] and collaborators (hereafter referred to as the Zucker model) does not fit the entire set of data available[5–7]; however, the inherent simplicity and wider applicability of this model motivated us to improve upon the calculations without modifying the basic structure of the model. Zucker's model[1,2] is based on the premise that the denominator function in the N/D representation for the perturbation amplitude of a resonant state is independent of k^2 and the nature of the initial state; it depends only on the phase shifts in the final state and the hadronic mass (W) produced. $D(W)$ for a particular resonant final state (identified by isospin, angular momentum, and parity) is the same for all processes leading to the production of that state. Although in principle $D(W)$ can be determined from phenomenological eigen phase shifts, such determinations in practice depend on assumptions made about the asymptotic behavior of the eigen phase shifts. Therefore, $D(W)$ for any resonant state is estimated phenomenologically. The estimate is made by comparing the theoretical and experimental cross sections for production from a particular process in the following manner: In the resonant region the solution of the N/D equation for a helicity eigenamplitude can be approximately written as

$$A(W,k^2) \simeq A^{\rm LHS}(W,k^2)/D(W) , \quad (1)$$

where $A^{\rm LHS}(W,k^2)$ is the contribution from the unphysical left-hand region. If the resonance is sharp and $A^{\rm LHS}$ does not vary appreciably in going across it, then the cross section $d\sigma/dk^2$ is proportional to

$$\int |A(W,k^2)|^2 dW \simeq |A^{\rm LHS}(W_R,k^2)|^2 \times \int |D(W)|^{-2} dW . \quad (2)$$

The factor $\int |D(W)|^{-2}dW$ is termed the enhancement factor for the resonant channel and can be used for all processes in which the resonance is produced. For the πN-channel resonances Zucker and collaborators[1,2] use the electroproduction results to estimate the enhancement factor.

The electroproduction model of Zucker and collaborators[1,2] differs from the Adler model[4] in the Born-term content. Zucker and collaborators[1,2] include an extra ω-exchange diagram in the t channel

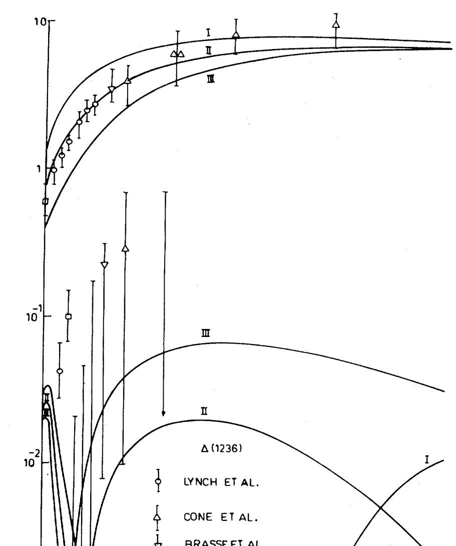

FIG. 1. Comparison of experimental electroproduction results (Refs. 5 and 6) for $1.6(|f_+|^2+|f_-|^2)/G_{Ep}{}^2$ and $|f_C|^2/2G_{Ep}{}^2$ with predictions of the Zucker model for (I) $\beta=-4$, (II) $\beta=-6$, and (III) $\beta=-8$. The lower three curves correspond to $|f_C|^2/2G_{Ep}{}^2$ and the graph normalized to the value at photoproduction.

with an isoscalar charge coupling $ig_{\omega NN}\bar{\psi}\gamma_\mu\psi\omega_\mu$ at the ωNN vertex and a $\omega\pi\gamma^*$ vertex of the form

$$V_{\omega\pi\gamma^*}=ig_{\omega\pi\gamma}\delta_{\alpha 3}\epsilon_{\mu\nu\rho\sigma}k_\mu e_\nu \omega_\rho q_\sigma ,$$

where γ^* refers to the virtual photon exchanged, α is the isospin index of the pion produced, ω_ρ the ω^0 polarization vector, and e_ν the polarization of the current. The coupling strength of the ω-exchange diagram is treated as a parameter through

$$\beta=-g_{\omega\pi\gamma}g_{\omega NN}/[\tfrac{1}{2}g_{\pi NN}F_2^V(0)]$$

with an arbitrary choice $F_2^V(k^2)$ for the k^2 dependence of $F_{\omega\pi\gamma^*}(k^2)$ and $\beta=-6$ is identified as the choice which best fits the electroproduction data for various πN resonances. In the above $g_{\omega\pi\gamma}$, $g_{\omega NN}$, and $g_{\pi NN}$ refer to the coupling constants at the $\omega\pi\gamma$, ωNN, and πNN vertices and $F_2^V(k^2)$ is the nucleon isovector magnetic form factor. The electroproduction and photoproduction data available for $\Delta(1236)$ are the following:

(i) Ratio of multipoles E_{1+}/M_{1+} at $k^2=0$.

(ii) Electroproduction data separated into a transverse part

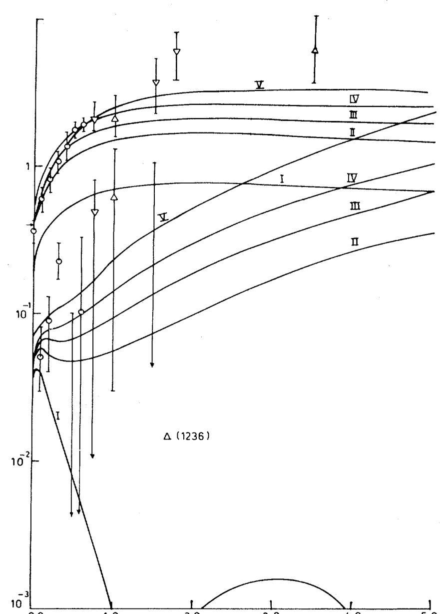

FIG. 2. Same as in 1 except that the theoretical predictions for $(|f_+|^2+|f_-|^2)/G_{Ep}{}^2$ have been plotted and the curves for positive values have to be scaled before comparing with the experimental points. The predictions are for the Zucker model. The value of β_1 and the factors by which the curves have to be multiplied are (I) $\beta_1=-4$, (II) $\beta_1=2$, multiplying factor 1.7, (III) $\beta_1=4$, multiplying factor 1.4, (IV) $\beta_1=6$, multiplying factor 1.2, and (V) $\beta_1=S_K$. The arrow indicates the $\beta_1=4$ prediction for photoproduction.

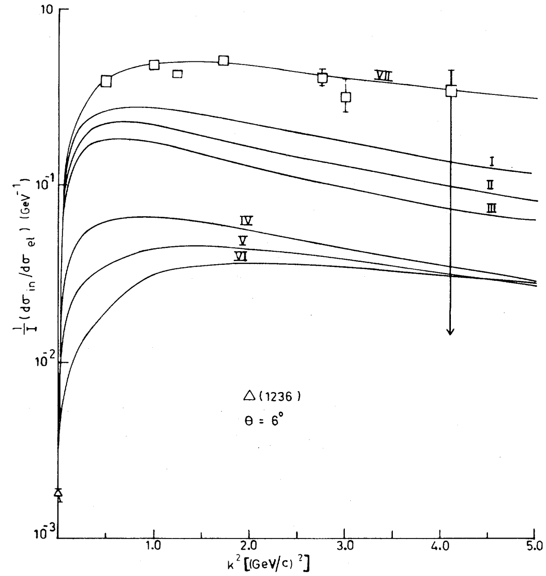

FIG. 3. Comparison of experimental electroproduction results for $(d\sigma_{\rm in}/d\sigma_{\rm el})(\theta=6°)$ with predictions of the Zucker model. Theoretical predictions have to be multiplied by a suitable enhancement factor to match the experimental data. Curve I corresponds to $\beta_1=6$, II to $\beta_1=4$, and III to $\beta_1=2$. Similarly, curve IV corresponds to $\beta=-4$, V to $\beta=-6$, VI to $\beta=-8$, and VII to $\beta_1=S_K$. The experimental points are from Lynch *et al.*, Ref. 6. The photoproduction point is from Ref. 8.

$$\frac{|f_+|^2+|f_-|^2}{G_{Ep}{}^2}$$

and a Coulomb part $f_C{}^2/G_{Ep}{}^2$ where

$$G_{Ep}=(1+k^2/0.71)^{-1} ;$$

see Figs. (1) and (2).

(iii) Ratio of $(d\sigma_{\rm in}/d\sigma_{\rm el})_\theta$, where $d\sigma_{\rm in}/dk^2$ refers to the differential cross section for the production of $\Delta(1236)$ from electron scattering of protons, with θ the lepton scattering angle in the laboratory frame, and $d\sigma_{\rm el}/dk^2$ refers to the electron-proton initial state going into itself with different momenta but the same lepton scattering angle; see Figs. 3 and 4.

The predictions for the choice $\beta=-6$ compare reasonably well with the data for electroproduction of $\Delta(1236)$. However, the prediction for the photoproduction Born ratio $(E_{1+}^B/M_{1+}^B)_{k^2=0}=-0.34$ is very different from the experimental number $\sim 0.$[7] Although the ratio of the full multipoles could be very different from their Born ratio and in the Zucker model it is only possible to estimate the change in an eigenchannel which is a combination of these multipoles, the calculations of Chew, Goldberger, Low, and Nambu[8] (CGLN) for photoproduc-

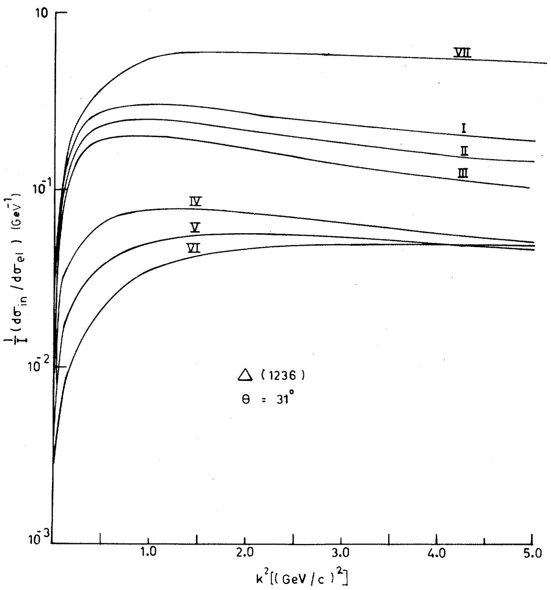

FIG. 4. Same as in Fig. 3, except that the electron scattering angle θ is 31°.

tion suggest that the change in the ratio is not large enough to compensate for the difference. Their calculations imply that the final-state interaction adds to a part of $|M_{1+}|$ and subtracts from $|E_{1+}|$. And even though the ratio of the full multipoles $|E_{1+}|/|M_{1+}|$ is smaller than the Born ratio it cannot agree with the experimental number. A study of the ratio of the multipoles as a function of β reveals that as β is made less negative the ratio continuously decreases towards the experimental result. If other estimates from model-dependent analyses of $\omega_0 \to e^+e^-$, nucleon-nucleon scattering, and low- and high-energy fits to π^0 photoproduction with ω_0 exchange are considered, a fair spread in β [$|\beta| \leq 4$ (Ref. 9), $\beta=2.7$ (Ref. 10), and $|\beta| \simeq 5$

TABLE I. Comparison of enhancement factor, the Born-electric-to-magnetic-multipole ratio at $k^2=0$, and $(d\sigma_{in}/d\sigma_{el})$ at $k^2=0$ for different values of β with $F_{\omega\pi\gamma}(k^2) \propto F_2^V(k^2)$ in the Δ(1236) region. The experimental value for $(E_{1+}/M_{1+})_{k^2=0}$ is -0.04 ± 0.08 and for $(d\sigma_{in}/d\sigma_{el})_{k^2=0}$ is $(1.65\pm0.3)\times10^{-3}$ at $\theta=6°$.

β	I (GeV)	E_{1+}^B/M_{1+}^B	$\left[\frac{d\sigma_{in}}{d\sigma_{el}}\right]_{photo}$ (10^{-3})
0.0	3.5	−0.176	3.0
−2.0	5.0	−0.206	3.05
−3.0	6.2	−0.228	3.0
−4.0	7.4	−0.255	2.72
−5.0		−0.292	
−6.0	10.8	−0.344	2.2
−8.0	13.6	−0.57	1.31

TABLE II. Enhancement factor, Born-multipole ratio at $k^2=0$, and $(d\sigma_{in}/d\sigma_{el})$ at $k^2=0$ for different values of β_1 with $F_{\omega\pi\gamma}(k^2) \propto F_1^V(k^2)$ in the Δ(1236) region.

β_1	I (GeV)	E_{1+}^B/M_{1+}^B	$\left[\frac{d\sigma_{in}}{d\sigma^{el}}\right]_{photo}$ (10^{-3})
$S_K(0.0)$	2.0	−0.176	1.8
2.0	2.8	−0.166	2.87
4.0	2.25	−0.156	2.69
6.0	1.9	−0.147	2.64
−4.0	5.9	−0.207	3.44

(Ref. 7)] is seen. The magnitude of β is therefore uncertain and its sign debatable. In fact the only estimate[10] which chooses a sign of β suggests that the sign is positive in contrast to the choice $\beta=-6$ made by Zucker and collaborators.[1,2]

Besides this, electroproduction experiments in the second-resonance region[11] performed after the work of Zucker *et al.*[2] suggest that the cross section for the low-J states does not fall as steeply with k^2 as is predicted by theoretical calculations performed using a negative value of β. Also, the fact that with positive β the Born cross section for producing the nonprominent low-J states is larger than the Born cross section for the production of the experimentally dominant higher-J states can be accounted for by using low enhancement factors for the nonprominent resonances.[12,13] These factors can be so chosen that the nonprominent resonances have cross sections of the order of 5% of the cross section for the prominent resonance. It is therefore reasonable to attempt a phenomenological fit to Δ(1236) production using a positive value of β. We have studied the electroproduction of Δ(1236) for various values of β and find that although the enhancement factor and the multipole ratio (Table I) vary with β the shape of the $d\sigma_{in}/d\sigma_{el}$ curves for all β is nearly the same (Fig. 1). However, for positive values of β the high-k^2 behavior of $d\sigma_{in}/d\sigma_{el}$ starts disagreeing with the experimental measurements[5-7] unless a k^2-dependent enhancement factor is used. Within the context of a Zucker-type model such an enhancement factor cannot exist and alternative mechanisms are needed. We find that the high-k^2 behavior can be approximately matched by taking a positive $\beta_1=F_2^V(0)\beta$ and choosing $F_{\omega\pi\gamma}(k^2)$ to have the form $F_1^V(k^2)$ (Ref. 14) and that the $\beta_1=4$ results are in reasonable agreement with the experimental results (Figs. 1 and 3 and Table II) for Δ(1236) production.

However, if the Zucker model with $\beta_1=4$ is used for the electroproduction of $N^*(1520)$ it disagrees with the experimental data, the high-k^2 predictions of the model being lower than the experimental results (Figs. 5 and 6 and Table III).

Since in the Zucker model the integrals are cut off at the upper edge of the resonances the contributions from the higher exchanges are not included.[4] In the s and u channels the additional particles exchanged are the resonances themselves.[4(b)] In the t channel apart from the π and ω, other particles can also be exchanged. Also as was pointed out by Adler, it is the high-k^2 region of the crossed-channel diagram which is affected when integrals are cutoff. Therefore, we have used a k^2-dependent coupling constant for β_1. We choose $\beta_1=0$ at $k^2=0$ so that it repro-

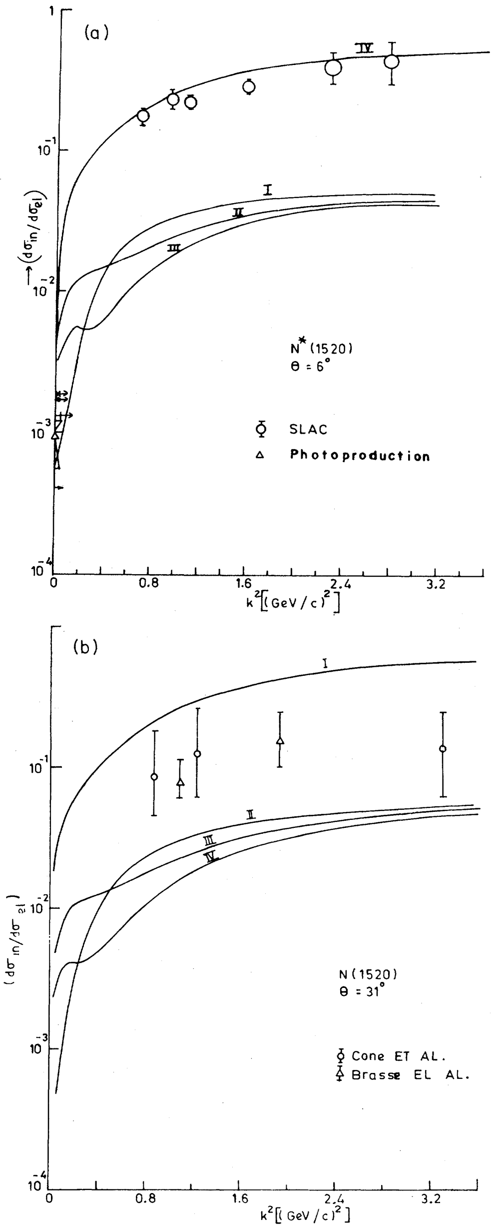

FIG. 5. (a) Comparison of the experimental electroproduction results of $N^*(1520)$ for $(d\sigma_{\text{in}}/d\sigma_{\text{el}})=6°$ with the predictions of the Zucker models with (I) $\beta=-6$, (II) $\beta=4$, (III) $\beta=0$, and (IV) $\beta_1=S_K$. Curves I and III have to be multiplied by their enhancement factors. (b) Same as (a) except that $\theta=31°$ and curve I refers to $\beta_1=S_K$, curve II is for $\beta=-6$, curve III is for $\beta_1=4$, and curve IV is for $\beta=0$. Curves III and IV have to be multiplied by their enhancement factors.

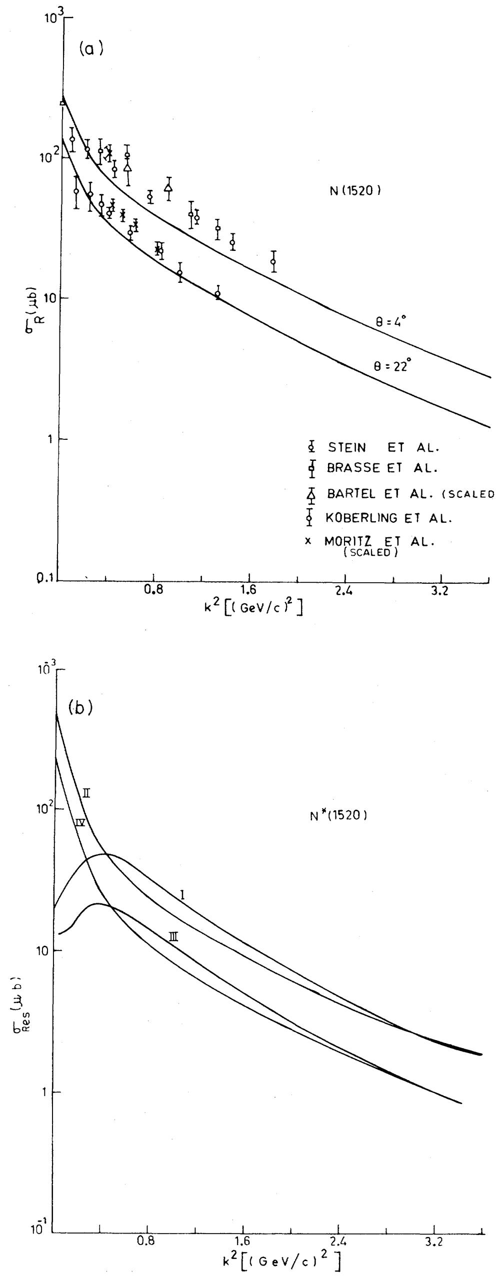

FIG. 6. (a) The resonant cross section for $N^*(1520)$ within a Zucker model with $\beta_1=S_K$ compared with the experimental results at $\theta=4°$ and 22°. The data and the curve for $\theta=22°$ have been divided by 2 throughout. (b) Same as in (a) with $\beta=-6$ (curves I and III) and $\beta_1=4$ (curves II and IV). Curves I and II are for $\theta=4°$ and curves III and IV are for $\theta=22°$.

TABLE III. Comparison of $(M_{2-}^{B}/E_{2-}^{B})_{k^2=0}$ with the experimental data in the $N^*(1520)$ region for different values of β. For negative β, $F_{\omega\pi\gamma}(k^2)\propto F_2^V(k^2)$. Cross-section results for the photoproduction of $N^*(1520)$ are also presented for the same values of β. For positive β_1, $F_{\omega\pi\gamma}\,|\,k^2)\propto F_1^V(k^2)$.

β	$(M_{2-}^{B}/E_{2-}^{B})_{k^2=0}$	$(d\sigma_{\rm in}/d\sigma_{\rm el})_{\rm photo}$
S_K (0.0)	0.42	1.2×10^{-3}
-6.0	-0.44	0.4×10^{-3}
4.0	0.51	1.4×10^{-3}
Expt.	0.48 ± 0.2	$(0.8\pm0.3)10^{-3}$

duces the CGLN model for photoproduction. The form chosen for β_1 is

$$\beta_1=6.3(1-G_{Ep})=S_K\ .$$

We find that with the above choice for β_1 the electroproduction and photoproduction results for both $\Delta(1236)$ and $N^*(1520)$ are in agreement with experiments.

For the weak production of $\Delta(1236)$ using $\beta=-6$ the predictions of the Zucker model at low k^2 are so large that even by a large change in the ρ coupling constant they do not compare well with the experimental results. In fact even if the constraint imposed on the sign of the ρ coupling is overlooked and the sign of the ρ coupling reversed, the theoretical predictions, although decreased substantially, remain far above the experimental results[15] at low k^2. It should be noticed that the Zucker model can only predict the Born multipoles and the enhanced amplitudes. The sign and the magnitude of an undetermined coupling strength can be arbitrary to the extent that the predicted cross section agrees with the experimentally measured cross section, and if partial conservation of the axial-vector current (PCAC) is respected, satisfies the forward lepton theorem of Adler.[16] This theorem relates the weak-production cross section to the production cross section for πN scattering calculated for an incident pion having energy equal to the virtual-photon energy and a mass squared equal to k^2 instead of $-m_\pi{}^2$.[16] But an Adler-type model[4] permits us to determine the ρ coupling from a study of neutrino production of πN at threshold. At threshold PCAC relates the weak axial-vector longitudinal multipole $\mathscr{L}_{1+}$ and the pion-pole part of the axial-vector scalar multipole $\mathscr{H}_{1+}^{\pi}$ to the πN partial-wave scattering amplitude $f_{l\pm}$ through the equations

$$\left.\begin{matrix}(l+1)\\ l\end{matrix}\right\}\times\mathscr{L}_{l\pm}(0,W)\,|\,\vec{k}\,|=\frac{8\pi W g_A}{g_r}\frac{|\,\vec{k}\,|^{l}}{|\,\vec{q}\,|^{l}}f_{l\pm}(W)$$

and

$$\left.\begin{matrix}(l+1)\\ l\end{matrix}\right\}\times\mathscr{H}_{l\pm}^{\pi}(0,W)=\frac{8\pi W g_A k_0\,|\,\vec{k}\,|^{l}}{g_r\,|\,\vec{q}\,|^{l}}f_{l\pm}(W)\ . \qquad (3)$$

We find that taking the ρ coupling strength to be the value specified by PCAC in the Adler model, together with $\beta_1=4$ and $F_{\omega\pi\gamma}(k^2)=F_1^V(k^2)$, the cross section for the weak production of $\Delta(1236)$, calculated with the enhancement factor extracted from the electroproduction data, agrees with the experimental data up to fairly large values of k^2 (Figs. 7, 8, and 9).

The total cross section for the process

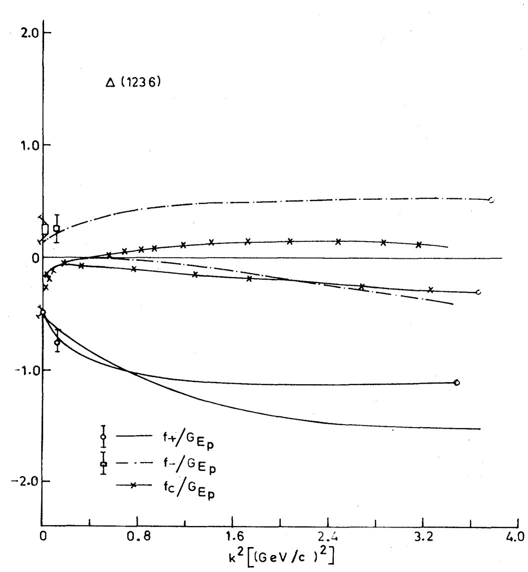

FIG. 7. f^+/G_{Ep}, f^-/G_{Ep}, and f_C/G_{Ep} are plotted as a function of k^2 for $\Delta(1236)$. The values of β chosen are $\beta=-6$, $\beta_1=4$. The β_1 curves have a circle at their end.

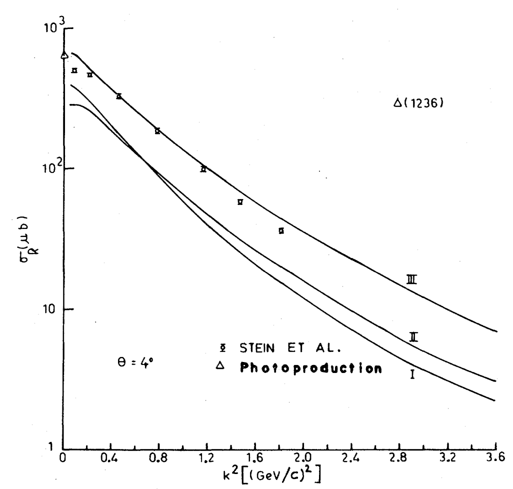

FIG. 8. Comparison of the electroproduction results of Stein *et al.* at $\theta=4°$ with the Zucker-model results for (I) $\beta_1=4$, (II) $\beta_1=S_K$, and (III) $\beta=-6$. Curves I and II have been reduced by a factor of 2.

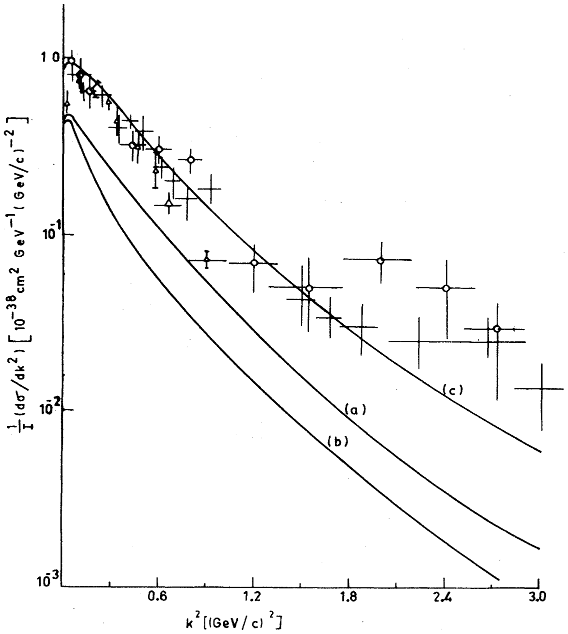

FIG. 9. Comparison of experimental weak production $d\sigma/dk^2$ data for $\nu p \to \mu^- \Delta^{++}(p\pi^+)$ results with predictions of the Zucker model [curve (b) with $\beta = -6$ and curve (a) with $\beta_1 = +4$]. To compare with the experimental points the curves have to be enhanced by their enhancement factors. The experimental points are from Allen *et al.*, Ref. 16 (crosses), and Bell *et al.*, Ref. 1 (open circles). Curve (c) is the enhanced $\beta_1 = S_K$ curve.

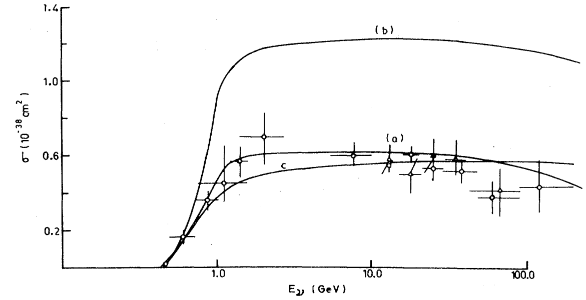

FIG. 10. Comparison of total weak production experimental cross-section results for the process $\nu p \to \mu^- \Delta^{++}(p\pi^+)$ with Zucker-model predictions. Curve (a) corresponds to $\beta_1 = 4$, curve (b) to $\beta = -6$, and curve (c) to $\beta_1 = S_K$. The experimental points are taken from Barish *et al.*, Ref. 16 (solid circles), Bell *et al.*, Ref. 1 (open triangles), and Allen *et al.*, Ref. 16 (open circles).

$\nu p \to \mu^- \Delta^{++}(p\pi^+)$ as a function of the incident neutrino energy is plotted in Fig. 10 along with the experimental points.[17] Zucker's results are clearly far above the experimental numbers and even reversing the sign of the ρ coupling (so that the contribution from ρ exchange helps reduce rather than add to the total cross section) decreases the cross section by 30% only. This is still 2–3 times more than the experimental number. The reason being that with a negative β the ω-exchange diagram interferes destructively with the rest of the vector amplitude for $\Delta(1236)$. Therefore, in order to match the electroproduction data for $\Delta(1236)$ a large enhancement factor is needed. Since, in the axial-vector amplitude no such term is present when the same enhancement factor is used for the axial-vector contribution, the cross section becomes too large and the ρ-exchange diagram cannot reduce the cross section sufficiently. The predictions made for $\beta_1 = 4$ or $\beta_1 = S_K$ with $F_{\omega\pi\gamma}(k^2) = F_1^V(k^2)$ agree closely with the experimental data (Fig. 6). Also from Tables IV and V it can be seen that the total cross section for the production of $\Delta(1236)$ from $\bar{\nu}p$ scattering, with $\beta_1 = 4$, and $\beta_1 = S_K$, is also closer to the value extracted from the $\bar{\nu}p$ experimental data.[18] We have also looked at the weak production and electroproduction of other resonances, with $\beta_1 = 4$ or $\beta_1 = S_K$

TABLE IV. Weak production of $\Delta(1236)$ in particular channels from high-energy neutrino and antineutrino scattering off nucleons. (a) Sign of ρ coupling opposite to Zucker model and (b) sign of coupling same as Zucker model. The coupling constant $\gamma_\rho^2/4\pi = 0.8$. The experimental value of the total cross section for the process $\nu p \to \mu^- \Delta^{++}(p\pi^+)$ is $(0.59 \pm 0.06) \times 10^{-38}$ cm^2 and for $\bar{\nu}p \to \mu^+ \Delta(p\pi^-)$ is 6.5×10^{-40} cm^{-2} where high-energy neutrino and antineutrino beams were incident. The $\omega\pi\gamma$ form factor $F_{\omega\pi\gamma} \propto F_2^V$.

		$\sigma(\nu p \to \mu^- p\pi^+)$ (10^{-38} cm^2)		$\sigma(\bar{\nu}p \to \mu^+ \Delta(p\pi^-))$ (10^{-40} cm^2)	
β	$\gamma_\rho^2/4\pi$	(a)	(b)	(a)	(b)
−3.5	0.80	1.1	1.35	11.2	12.6
−4.0	0.80	1.15	1.43	11.8	13.2
−6.0	0.80	1.34	1.92	14.2	18.3
−3.5	0.44	0.89	1.26	8.8	10.1
−4.0	0.44	0.95	1.32	9.1	10.6
−6.0	0.44	1.2	1.72	10.8	15.2

TABLE V. Weak $\Delta(1236)$ production for neutrino and antineutrino scattering off nucleons, with different β_1. Results are presented for $\gamma_\rho^2/4\pi = 0.44$ and for $\gamma_\rho^2/4\pi = 0.80$. (a) and (b) are as in Table IV.

		$\sigma(\nu p \to \mu^- p\pi^+)$ (10^{-38} cm^2)		$\sigma(\bar{\nu}p \to \mu^+ \Delta(p\pi^-))$ (10^{-40} cm^2)	
β_1	$\gamma_\rho^2/4\pi$	(a)	(b)	(a)	(b)
4.0	0.80	0.414	0.594	4.35	6.26
6.0	0.80	0.395	0.545	4.16	5.77
S_K	0.80	0.44	0.6	4.65	6.55
4.0	0.44	0.38	0.5	3.66	4.89
5.0	0.44	0.361	0.462	3.48	4.52
S_K	0.44	0.40	0.51	3.92	6.0

and $F_{\omega\pi\gamma}(k^2)=F_1^V(k^2)$, and find that the agreement with the experimental data is better than that for negative β and $F_{\omega\pi\gamma}(k^2)=F_2^V(k^2)$.[13]

In conclusion, the form of the model used here with an effectively k^2-dependent value of β_1 retains the low-k^2 structure of the Born diagrams used in the photoproduction model of CGLN and the weak-production model of Adler. It satisfies the observable PCAC constraints and agrees reasonably with all available data. To test the reliability of the model electroproduction and weak-production experiments for higher hadron energies should be performed. From the data obtained the resonant cross section for the higher resonances can be extracted[5,18] and compared with the Zucker-model predictions for $\beta_1=S_K$.

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