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Theoretical estimates for photoproduction and leptoproduction of neutral vector bosons*

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We give estimates for the production of neutral vector bosons in several reactions. These reactions involve the collisions of photons and leptons (electrons, muons, and neutrinos) with protons. The possible mechanisms considered are diffraction, parton (constituent) scattering, and electromagnetic recoil through the boson's anomalous moments. We address ourselves to both the case when the boson is a hadron and the case when it is not, although the emphasis is on the latter.

I. INTRODUCTION

Some important aspects of elementary-particle physics revolve around two families of massive vector bosons. One family is predicted, along with other spin states, in the charm version of the quark model.[1] The other consists of the gauge bosons needed in unified theories (e.g., the Weinberg-Salam model[2]) of weak and electromagnetic interactions. Proof of the existence of either family would be major progress.

Precisely this kind of progress seems to be at hand. The exciting Brookhaven[3] and Stanford[4] discoveries may be compatible with a charm-anticharm picture, particularly in view of the recent photoproduction experiments at Fermilab and SLAC[5] where the size and the diffractive nature of the cross section indicate that these narrow states are hadrons. The discovery of weak neutral currents[6] gives hope for the existence of a triplet of charged and neutral intermediate vector bosons, hinting in turn that gauge theories could be accurate pictures of the world. Thus members of the first family and indirect effects of the second family may have already been seen.

Much experimental effort will now go into new production modes for the J (ψ) particles as well as the continued search for the weak bosons. We consider in this paper some reactions of interest in the production of the *neutral* members and give some crude estimates of their rates.[7] The types of estimates that we have in mind will complement our earlier work on weak-vector-boson production.

We begin in Sec. II with the photoproduction of vector bosons on proton targets. With rather large minimum momentum transfers, coherent scattering off nuclear targets may be ignored. (This is also true for the lepton-induced reactions). For the weak-boson case, we apply the phenomenological form factor model[8] and the quark-parton model[9] used earlier in charged-boson studies. A diffractive mechanism is also compared where, as *input*, the information gleaned from the ψ-production experiments[5] is put to use.

We next consider muon (and electron) beams and proton targets in Sec. III. Projectile fragmentation (weak bremsstrahlung by the charged lepton) in such an experiment has already been studied for weak bosons[10]; the interest here is in target fragmentation, where the photoproduction models of the previous section are put to use.

Lastly, neutrino-proton collisions round out the reactions and are discussed in Sec. IV. We once again look at the photoproduction models mentioned above. For weak neutral bosons, there is an added inhibition: We can have no lowest-order electromagnetic recoil if the bosons are self-conjugate, so only some sort of hadronic emission after a weak excitation is imaginable. But if such bosons are not self-conjugate and have anomalous moments, electromagnetic recoil is possible. We calculate the rates for this possibility. Final remarks comparing the various estimates are collected together in Sec. V.

II. PHOTOPRODUCTION

A division into the two cases where the vector boson is a hadron and where it is not is made below and in later sections. For the sake of convenience, we shall use the labels "strong boson V^0" and "weak boson Z^0" for these cases, respectively. The reader should be warned that the emphasis is, for the most part, on the strong-boson case as *input* into the weak-boson calculations.

A. Strong boson V^0

We wish to extract some information from known experimental results for later use. The starting point is the consideration of vector-meson V^0 photoproduction off protons at high energy. The diffractive description of such a reaction leads to

$$\frac{d\sigma}{dt}(\gamma + p \to V^0 + p) \cong A e^{bt}, \qquad t<0, \quad b>0. \tag{2.1}$$

The total cross section then is

$$\sigma(\gamma + p \to V^0 + p) \cong \frac{A}{b}\left[\exp(-b|t|_{\min}) - \exp(-b|t|_{\max})\right]. \tag{2.2}$$

As justification, experiment tells us that such scattering is highly diffractive: Exchanges other than the Pomeron seem to be negligible, and the total cross sections are only weakly energy-dependent (at high energies). From a search of the literature we find the following numbers[5,11]:

$$\begin{aligned}
&\sigma(\gamma p \to \rho^0 p) \cong 13.5\ \mu b, \quad E_\gamma \approx 10\ \text{GeV},\\
&\sigma(\gamma p \to \omega p) \cong 1.5\ \mu b, \quad E_\gamma \approx 10\ \text{GeV},\\
&\sigma(\gamma p \to \phi p) \cong 0.5\ \mu b, \quad E_\gamma \approx 10\ \text{GeV},\\
&\sigma(\gamma p \to \psi p) \cong 4\ \text{nb}, \quad E_\gamma \approx 20\ \text{GeV},\\
&\sigma(\gamma p \to \psi' p) < 70\ \text{nb}, \quad E_\gamma \approx 20\ \text{GeV},
\end{aligned} \tag{2.3}$$

and, in units of $(\text{GeV}/c)^{-2}$,

$$\begin{aligned}
&b_{\rho^0} \cong 7, \quad b_\omega \cong 7,\\
&b_\phi \cong 5, \quad b_\psi \cong 4.
\end{aligned} \tag{2.4}$$

The next piece of information of use to us is the prediction of vector dominance. For our particular reactions, it reads

$$\frac{d\sigma}{dt}(\gamma + p \to V^0 + p) \cong \frac{\alpha}{\alpha_V}\frac{d\sigma}{dt}(V^0 + p \to V^0 + p), \qquad \alpha_V \equiv \frac{f_V^2}{4\pi}. \tag{2.5}$$

This is true for a given transverse polarization of the beam and for unpolarized beams (assuming that longitudinal polarization for the incoming V^0 gives an equal contribution), and we use the invariant normalization

$$\langle 0 | J_\mu^{\text{em}} | V^0 \rangle = \frac{m_V^2}{f_V}\epsilon_\mu. \tag{2.6}$$

From colliding-beam measurements,[12] the vector-meson-dominance coupling constants are

$$\alpha_\rho = 2.3, \quad \alpha_\omega \cong 18.4, \quad \alpha_\phi \cong 12.2, \quad \alpha_\psi \cong 13. \tag{2.7}$$

One can get, in the usual way, total cross sections from the optical theorem;

$$\left.\frac{d\sigma}{dt}(V^0 + p \to V^0 + p)\right|_{t=0} \cong \frac{1}{16\pi}\sigma_T^2(V^0 + p), \tag{2.8}$$

with a dominantly imaginary forward amplitude (a strongly absorptive reaction). One may consider Eq. (2.8) correct for unpolarized beams if all of the initial states contribute equally. Depending upon which quantity is given, A of Eq. (2.1) can be determined by various combinations of the above formulas. We find and use $A \cong 94.5$, $10.5, 2.5, 0.0195$ for ρ, ω, ϕ, ψ respectively, in units of $10^{-30}\ \text{cm}^2\ \text{GeV}^{-2}$.

B. Weak boson Z^0

1. *Elastic Born approximation*

Previous estimates of charged-boson production can be simply adapted for this discussion. We first consider a phenomenological dispersion Born approximation corresponding to the diagrams in Fig. 1 and analogous to the Born terms in Ref. 8. Since the Z^0 is neutral, this approximation requires no extra terms to ensure electromagnetic gauge invariance, unlike the $W^\pm$ case.

Our Born amplitude for nuclear targets is[13]

$$\mathfrak{M}_{\text{Born}} = -i\bar{u}(p')\left[\Gamma_\mu^{Z^0}(k)\frac{1}{\not{p} + \not{q} - m_p}\Gamma_\nu^\gamma(q) + \Gamma_\nu^\gamma(q)\frac{1}{\not{p}' - \not{q} - m_p}\Gamma_\mu^{Z^0}(k)\right]u(p)\epsilon_{Z^0}^{\dagger\mu}\epsilon_\gamma^\nu. \tag{2.9}$$

In this, the form factors correspond to on-shell protons since we merely ask that the residues of the poles be given correctly. For low energies

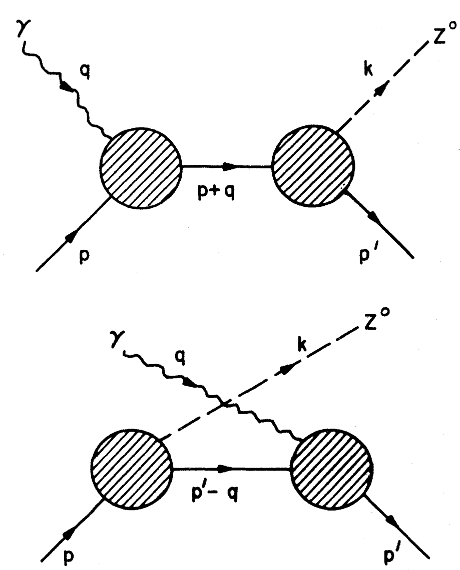

FIG. 1. The dispersion Born amplitude for $\gamma + p \to Z^0 + p$. The shaded blobs represent form factors with the proton legs on the mass shell.

TABLE I. Total cross sections in units of picobarns (1 pb$=10^{-36}$ cm^2) for (a) $\gamma+p\to Z^0+p$ with point protons and (b) $\gamma+p\to Z^0+X$. The energy is in units of GeV and the mass is in GeV/c^2 units.

E_γ \ m_Z	5 (a)	5 (b)	10 (a)	10 (b)	15 (a)	15 (b)
50	6.2	1.1				
100	4.5	3.8	10	0.087		
200	2.8	6.6	8.1	1.7	13	0.055
300	2.1	7.9	6.5	3.5	11	0.65
600	1.1	9.2	4.0	6.5	7.5	3.3
1000	0.70	9.6	0.026	8.2	5.3	5.6

(near threshold) it is expected that (2.9) would be a fair approximation. But with a timelike form factor which vanishes as $(k^2)^{-2}$ or even as slowly as $(k^2)^{-1}$ at large $k^2=m_Z{}^2$, the resulting cross section is very small. An example of such form-factor suppression can be found in Ref. 8; in our case, a dipole fit reduces point-proton results by more than eight orders of magnitude when $m_Z=10$ GeV. Even the effect of the anomalous magnetic moment of the proton, which is to increase the high-energy behavior of such a picture by powers of the laboratory energy,[8] pales into insignificance in view of this reduction. Besides, such terms should not be taken too seriously at high energies, where unitarity would step in in the form of neglected intermediate states.

We mentioned the point-proton result. By this we mean

$$\begin{aligned}\Gamma_\mu^\gamma &= |e|\gamma_\mu,\\ \Gamma_\mu^{Z^0} &= (\sqrt{2}\,Gm_Z{}^2)^{1/2}(g_V^p\gamma_\mu+g_A^p\gamma_\mu\gamma_5),\end{aligned} \tag{2.10}$$

where $g_V^p=-0.3$ and $g_A^p=0.5$. This choice follows from somewhat capricious criteria: Take the Weinberg angle seriously and ignore proton structure (anomalous moments, form factors, and renormalization of the axial charge). We thus use $\sin^2\theta_W\cong 0.4$ as determined by Gargamelle data analysis[14] in the proton form factor discussion given by Weinberg,[15] cleansing the formulas of strong-interaction effects. The corresponding point cross section is now completely defined and straightforwardly calculated. We present numbers in Table I for comparison with the parton model and to which the reader's choice for the timelike Z^0 form factor can be applied.

There is a matter of principle which must be made clear. In (2.10) one sees $(\sqrt{2}\,Gm_Z{}^2)^{1/2}$ rather than $|e|/\sin 2\theta_W$ because we do not wish to restrict ourselves to the exceedingly large $m_Z\geqslant 74.6$ GeV/c^2 lower limit of the Weinberg-Salam model. We can thus make use of the Weinberg angle as a "summary" of the present data (current-current interactions where m_Z cancels out even for the lower values we consider) and yet not get spuriously large couplings for Z^0 *emission*. Although the point-proton couplings are unimportant, our proton couplings (discussed later) should be viewed with this in mind.

2. *Diffraction scattering*

If the form-factor suppression exhibited in (2.9) is present in any reasonable approximation near threshold, where production cross sections are small anyway, we have to turn to much higher energies. If we consider quasielastic Z^0 production (no other new particles appear), it is natural to look at the picture in Fig. 2 where the photon couples to a vector meson which diffracts off the proton and then couples to the Z^0.

The point is to use vector dominance on the weak neutral current, defining an h_V by

$$\langle 0|J_\mu^{Z^0}|V^0\rangle=\frac{m_V{}^2}{h_V}\epsilon_\mu, \tag{2.11}$$

which is to be compared with Eq. (2.6). Only the vector part of J_μ contributes to (2.11). This part is assumed to be conserved here (no k_μ term). We can ignore axial-vector dominance since a vector meson cannot diffract into an axial-vector meson. Alone, each vector meson would give forth a contribution (using the current normalization in Ref. 15)

$$\frac{\sqrt{2}\,Gm_Z{}^2}{h_V{}^2}\left(\frac{m_V{}^2}{m_Z{}^2-m_V{}^2}\right)^2\frac{d\sigma}{dt}(\gamma+p\to V^0+p) \tag{2.12}$$

to $d\sigma/dt\,(\gamma+p\to Z^0+p)$ or

$$\frac{\sqrt{2}\,Gm_Z{}^2}{h_V{}^2}\left(\frac{m_V{}^2}{m_Z{}^2-m_V{}^2}\right)^2 \times\exp[b(|t|_{\min}^{V^0}-|t|_{\min}^{Z^0})]\sigma(\gamma+p\to V^0+p) \tag{2.13}$$

to $\sigma(\gamma+p\to Z^0+p)$, ignoring the $|t|_{\max}$ terms and the difference in phase-space factors. So far so good, but what are the values of h_V? We take $h_V\cong f_V$ inasmuch as the electromagnetic and weak

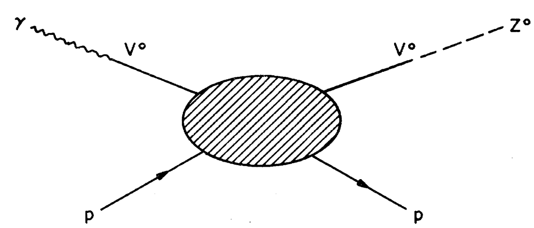

FIG. 2. The vector-dominance approximation for the diffractive photoproduction of the neutral weak boson Z^0 off protons.

currents have comparable normalization and for the estimates here we only need orders of magnitude. (Note: In certain gauge models a *marked* suppression can occur for some V^0's, especially for $\sin^2\theta_W \cong \frac{3}{8}$.)

Suppose $m_Z = 5$ GeV/c^2 and $E_\gamma = 100$ GeV in the lab frame. Assuming that the cross sections in (2.3) can be extrapolated (as constants) to this higher energy and noting that the $|t|_{\min}$ effects are negligible, the expression (2.13) is seen to lead to (relatively) small numbers. We find in picobarns (1 pb $= 10^{-36}$ cm^2) 0.11, 0.0016, 0.0025, 0.0037 for $V^0 = \rho^0, \omega, \phi, \psi$ respectively. These would be somewhat reduced if we were careful with the relation between h_V and f_V. Also, it is clear that larger m_Z give even smaller rates.

Besides the h_V values, a more careful analysis should include amplitude interference and possible higher-mass vector states which seem to be needed for agreement with inelastic lepton-nucleon inclusive reactions.[16] [Moreover, there is always the $\rho'(1600)$.] We might replace the sum over the amplitudes of the higher states (from m_0 on up, say) by an integral like

$$\int_{m_0^2}^{\infty} \frac{\sigma(m^2)dm^2}{m_Z^2 - m^2 - im\Gamma},$$

where the density $\sigma(m^2)$ has in it the mass dependence of h_V and other factors in (2.13). Then a quantitative assessment of what happens when the Z^0 falls between higher and lower states can be made. For instance, if $\sigma \sim 1/m^2$, then we get merely a $\ln m_Z/m_0$ enhancement over the m_0 contribution for $m_Z \gg m_0$ from all of the higher levels.

3. Inelastic channels and the parton model

The famous lack of momentum-transfer damping in the deep-inelastic lepton-nucleon scattering data makes inelastic photoproduction a prime candidate for our studies, and, happily, we have the parton model as a theoretical tool. We can consider an adaptation of a previous calculation[9] which estimated the inelastic photoproduction of charged weak bosons, and we leave out of our discussion those details which can be located in Ref. 9.

The basic ingredient will be the amplitude of Fig. 1, but with point partons as "targets," so Eq. (2.8) is what we want if

$$\Gamma_\mu^\gamma = Q^i |e| \gamma_\mu, \qquad \Gamma_\mu^{Z^0} = (\sqrt{2}\, G m_Z^2)^{1/2}(g_V^i \gamma_\mu + g_A^i \gamma_\mu \gamma_5) \tag{2.14}$$

for the ith parton. From Ref. 15,

$$g_V^i = \tfrac{1}{2} - \tfrac{4}{3}\sin^2\theta_W \,(-\tfrac{1}{2} + \tfrac{2}{3}\sin^2\theta_W)$$

for the up and charmed (down and strange) quarks, and likewise $g_A^i = -\frac{1}{2}$ $(+\frac{1}{2})$. We emphasize again that, choosing[14] $\sin^2\theta_W \cong 0.4$ and $(\sqrt{2}\, G m_Z^2)^{1/2}$ normalization, we will be consistent with present neutral-current experiments where m_Z cancels out (for $m_Z \gtrsim 5$ GeV/c^2, say). But we have relaxed the constraint between m_Z and θ_W in order to consider the production of accessible m_Z, and in consequence we are outside that particular gauge model. Such a model has a large $|e|/\sin 2\theta_W$ coupling for emission but a correspondingly large $m_Z = |e|/[(\sqrt{2}\, G)^{1/2}\sin 2\theta_W]$.

Equation (3.4) in Ref. 9 is to be replaced by

$$\frac{d\sigma}{d\nu dt} = \frac{\sqrt{2}\, G m_Z^2 \alpha}{x^2 s^2 \nu} \times \left[1 + \frac{m_p}{s}\frac{\nu^2 + (m_Z^2/2m_p x)^2}{(s/2m_p) - \nu - (m_Z^2/2m_p x)}\right] \times \sum_i x P_i(x)(Q^i)^2[(g_V^i)^2 + (g_A^i)^2] \tag{2.15}$$

in terms of the variables used there. Things are simplified here by the absence of a photon-boson coupling, and one can check that, by replacing the square bracket in (2.15) by $(Q^i e)^2/(\sqrt{2}\, G m_Z^2)$ and letting $m_Z \to 0$, we achieve the Compton result of Bjorken and Paschos.[17] The parton distributions (three valence quarks plus the infinite sea of quark pairs) are taken from Ref. 18.

Table I contains total cross sections obtained upon numerical integration of (2.15)—the phase-space limits were given earlier[9]—for an array of m_Z and E_γ values. We have neglected the charm part of the sea, which is presumably small anyway; besides, the answers in Table I are relatively insensitive to the sea contribution. Further comments about these results will be found in the discussion section.

III. LEPTOPRODUCTION: ELECTRON AND MUON BEAMS

Continuing a treatment of reactions initiated by beams of particles which are not hadrons, we address ourselves now to charged-lepton scattering off protons. Uppermost in mind are the high-energy muon beams at Fermilab and CERN II, but there are also future electron-proton colliding beam possibilities.

A. Strong boson V^0

Once again we develop certain vector-hadron production rates as input for use in the weak-boson estimates. The general (lowest order in α) matrix element is illustrated in Fig. 3. The differential cross section of interest is the familiar

$$\frac{d\sigma}{dQ^2 dW^2} = \frac{\alpha}{\pi}\frac{K}{4m_p E^2 Q^2} \times \frac{1}{1-\epsilon}[\sigma_T(Q^2, W^2) + \epsilon\sigma_L(Q^2, W^2)] \tag{3.1}$$

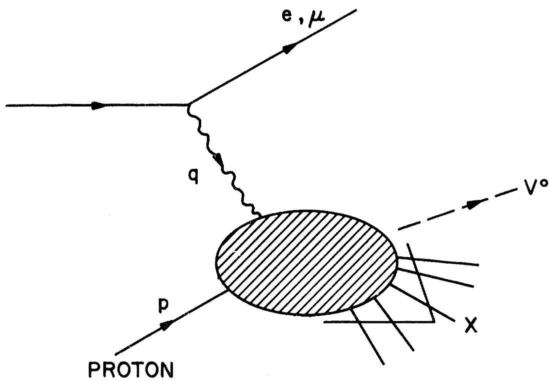

FIG. 3. The Feynman diagram for the (charged) leptoproduction of a strong vector meson off a proton target. The blob represents strong interaction to all orders and X stands for additional hadrons which may be produced along with V^0.

(lepton masses are neglected) in terms of the transverse and longitudinal virtual-photon total cross sections. As in everything else, we consider unpolarized beams and targets and the variables are defined in many places.[19]

The data on electroproduction of ρ^0 mesons[20] show diffractive characteristics and show in addition that the Q^2 dependence (aside from $|t|_{\min}$ effects) of the quantity in square brackets in (3.1) is described well by the ρ propagator alone and that the longitudinal contribution is not important for the total cross section (although it seems to play a role in angular decay distributions). Thus, for our estimates, we shall apply the vector-meson-dominance diffraction model once again for all of our V^0's and replace the quantity in square brackets by

$$\left(\frac{m_V^2}{Q^2+m_V^2}\right)^2 \frac{A}{b}\left[\exp(-b|t|_{\min}) - \exp(-b|t|_{\max})\right], \tag{3.2}$$

with

$$|t|_{\max,\min} = |m_V^2 - Q^2 - 2q^0V^0 \mp 2|\vec{q}||\vec{V}||$$

$$\sim \begin{cases} W^2 \\ \dfrac{m_p^2(m_V^2+Q^2)^2}{W^4} \end{cases} \quad \text{for large } W^2,$$

$$q^0 = \frac{W^2 - Q^2 - m_p^2}{2W}, \quad |\vec{q}| = (q^{02}+Q^2)^{1/2}, \tag{3.3}$$

$$V^0 = \frac{W^2 + m_V^2 - m_p^2}{2W}, \quad |\vec{V}| = (V^{02} - m_V^2)^{1/2}.$$

These reduce to the values used in the photoproduction analysis at $Q^2 = 0$ and W = c.m. energy, and (3.2) vanishes at threshold.

We now integrate Eq. (3.1) numerically after inserting (3.2) and looking up the Q^2 and W^2 limits in, say, Ref. 21. A family of curves for the set of

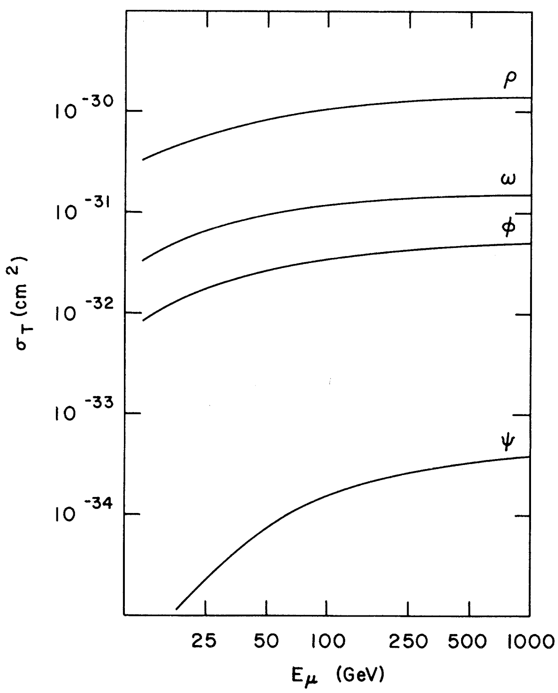

FIG. 4. Total cross sections for $\mu p \to \mu V^0 p$ as functions of beam energy. The target proton is at rest. The larger electron-beam results can be estimated from these via the Weizsäcker-Williams approximation discussed in the text.

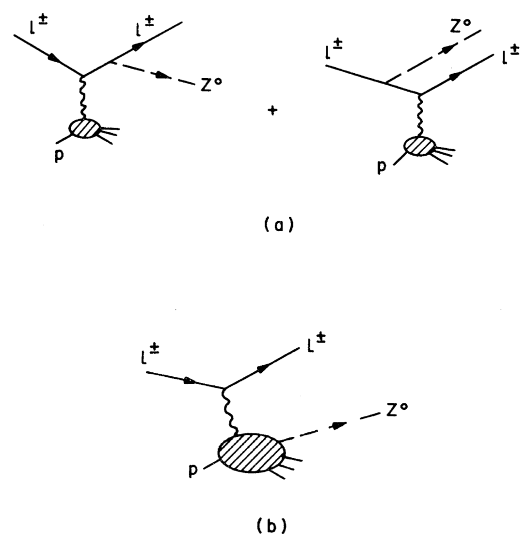

FIG. 5. Feynman diagrams for the production of Z^0 by leptons via (a) "weak bremsstrahlung" with an electromagnetic recoil off of a proton and (b) hadronic emission as a result of proton excitation.

TABLE II. Total cross sections as a function of the incident lepton beam energy and the Z^0 mass for the reaction $\mu^{\pm}+p\rightarrow\mu^{\pm}+Z^0+X$. The energy is in GeV units and the mass is in GeV/c^2 units. The cases are (a) point-proton target, $X=p$; (b) Fig. 5(b), parton model, Weizsäcker-Williams approximation; (c) Fig. 5(a), $X=p$. The units are 10^{-37} cm^2.

E_μ \ m_Z	5 (a)	5 (b)	5 (c)	10 (a)	10 (b)	10 (c)	15 (a)	15 (b)	15 (c)
50	0.60	0.028	0.048						
100	1.4	0.24	0.28	0.27	0.93×10^{-3}	1.6×10^{-3}			
200	2.4	0.80	0.78	1.2	0.064	0.077	0.29	0.53×10^{-3}	0.72×10^{-3}
300	3.0	1.3	1.2	1.9	0.21	0.22	0.84	0.015	0.019
600	4.0	2.6	2.1	3.2	0.80	0.70	2.2	0.21	0.20
1000	4.7	3.8	2.9	4.3	1.5	1.3	3.3	0.60	0.52

V^0's showing the energy dependence of the total cross sections is seen in Fig. 4.

B. Weak boson Z^0

In lowest order, as far as the weak and electromagnetic couplings are concerned, there are two possibilities. We have a "projectile-fragmentation" mode, which is depicted in Fig. 5(a) and which has been analyzed in detail separately.[10] It is the purpose here to consider the "target fragmentation" shown in Fig. 5(b), especially in comparison to the other, less model-dependent, mode.

1. Elastic Born approximation

To start with, we could approximate the blob in Fig. 5(b) by the elastic dispersion Born term (Fig. 1 with an off-mass-shell photon) for an estimate near threshold. As in the photoproduction case, however, any reasonable timelike form factor would really drag this down, and the cross section is small anyway for heavy-particle production near threshold. Be that as it may, we have carried out the computation of the cross section for a point proton (no form factor) with the couplings of Eq. (2.10). This serves as a comparison for the parton results described later, and also, when multiplied by the reader's choice of weak timelike form factor, can be used as the aforementioned threshold estimate. (The spacelike proton form factor reduces the result further, but is not so crucial since $Q_{\min}^2$ is yet rather small.)

The point-proton numbers for a muon beam are laid out in Table II. These were found by taking the computer programs for the numerical work in Ref. 10 and switching the role of the lepton and the proton, removing the electromagnetic form factor, and finding the proton energy appropriate to the muon rest frame. Table II also contains the corresponding rates for the reaction of Ref. 10 [Fig. 5(a)], but with a change of lepton-Z^0 couplings. Again [see the discussion after (2.10)], wishing to be consistent with experiment, yet desiring smaller m_Z values than in the Weinberg-Salam model, we use $g_V^l=\frac{1}{2}-2\sin^2\theta_W\cong-0.3$ and $g_A^l=0.5$ and the over-all normalization $(\sqrt{2}\,Gm_Z^2)^{1/2}$. This is nothing other than the point-proton couplings in (2.10), as expected. Interference between the amplitudes of the two modes would not be important, since their main contributions arise from different phase-space regions.

2. Diffractive production

The apparatus developed in the estimate for diffractive production of a neutral vector hadron (see Sec. III A) is now put to good use here. As in photoproduction, we picture the Z^0 coupling to the V^0 according to (2.11). Thus we replace the quantity in square brackets in (3.1) by

$$\left(\frac{m_V^2}{Q^2+m_V^2}\right)^2\frac{A}{b}\left[\exp(-b|t|^{Z^0}_{\min})-\exp(-b|t|^{Z^0}_{\max})\right]\times\left(\frac{m_V^2}{m_Z^2-m_V^2}\right)^2\frac{\sqrt{2}\,Gm_Z^2}{h_V^2}\qquad(3.4)$$

and integrate over W^2 and Q^2 (with limits now depending upon m_Z). This then gives us some idea of the high-energy production, $l+p\rightarrow l+p+Z^0$, where no other particles have been coproduced. Expression (3.4) vanishes at threshold ($W_{\min}^2$), as desired.

Focus now on a particular case: muon beams and $m_Z=5$ GeV/c^2. The individual vector-meson contributions are plotted as a function of energy in Fig. 6; the $h_V\cong f_V$ approximation has been made once again. Interference between the various vector-meson-dominated amplitudes is neglected, but the numbers seen are small in any case. The remarks about amplitude interference in Sec. II B 2 are relevant here as well.

3. Inelastic channels and the parton model

We look to the deeply inelastic channels in target fragmentation as an important possibility, particularly in view of the absence (in the parton picture) of both the electromagnetic and the timelike weak

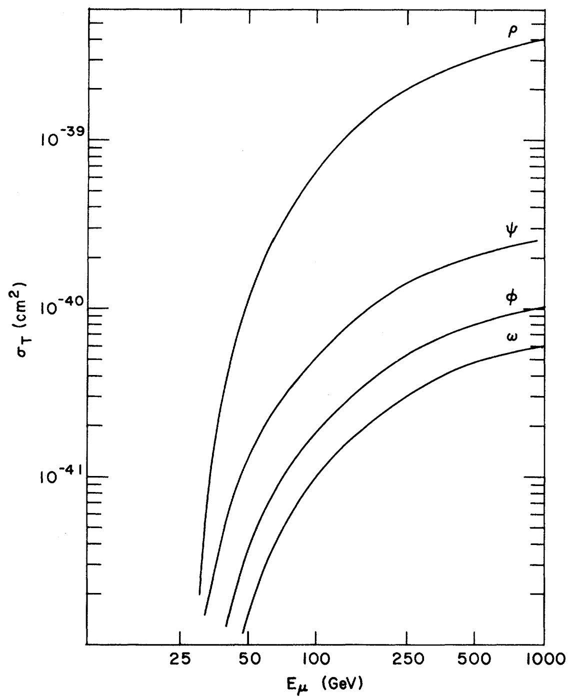

FIG. 6. Total cross sections as functions of beam energy for the diffractive production $\mu p \to \mu p Z^0$ in a vector-dominance approximation (only the individual V^0 contributions are shown). $m_Z = 5$ GeV/c^2. The larger electron-beam numbers can be estimated as in the caption of Fig. 4.

form factors. The latter, of course, is missing in beam fragmentation but presumably would be crucial in the quasielastic channels.

It is possible to generalize the mathematics in Sec. II B 3 to $q^2 \neq 0$ and carry out what would be four integrations numerically. If all we want is a crude estimate, however, the Weizsäcker-Williams method can be exploited. Consider the following approximation[22]:

$$\sigma[\text{Fig. 5(b)}] \cong \frac{\alpha}{\pi} \ln \frac{s}{m_\mu^2} \int_{m_Z^2}^{s} \frac{dW^2}{W^2} \left(1 - \frac{W^2}{s} + \frac{W^4}{2s^2}\right) \sigma_{\gamma p}(W^2), \tag{3.5}$$

where $\sqrt{s}$ = c.m. energy. We can now easily integrate the cross-section formulas described in Sec. II B 3 on the computer, with the expectation that our answers will get better and better the higher the energy. The results for muon beams are shown in Table II and from past experience[21] are overestimates. Just how much we have overestimated the "exact" parton-model result is not so crucial (it may be by factors of 2–10), since the beam fragmentation [of Fig. 5(a)] is seen to be as large (Table II) (it is more reliably calculated). We should mention that the $Q_{\min}^2$ values are smaller for electron beams [corresponding to $m_\mu \to m_e$ in the logarithm of (3.5)]; this enhances the probability of target fragmentation relative to beam fragmentation (beam fragmentation is essentially independent of the lepton mass). Those numbers are found trivially by multiplying the deep-inelastic entries in Table II by $[1 + \ln(m_\mu^2/m_e^2)/\ln(s/m_\mu^2)]$.

IV. LEPTOPRODUCTION: NEUTRINO BEAMS

This discussion centers on neutral-vector-boson production in neutrino-proton collisions, phenomena particularly relevant to the dimuon events reported recently.[23] We will see, however, that this component of possible new particle sources is not likely to account for many of those events. It seems that new hadrons (charged vectors, pseudoscalars, and baryons) must be included as well; we have not done so.

A. Strong boson V^0

A diffractive picture is assumed once again, with V^0 coupling to the neutrino through the Z^0 (see Fig. 7). We employ Eq. (2.11) and the neutrino-Z^0 coupling

$$(\sqrt{2}\, G m_Z^2)^{1/2} (\tfrac{1}{2}\gamma_\mu - \tfrac{1}{2}\gamma_\mu \gamma_5) \tag{4.1}$$

as in Ref. 15. Antineutrino couplings are $V+A$, of course, but the sign change is of no consequence in what follows. Incidentally, one could diffract an axial-vector meson in the same way. With no pseudotensor term in the $V^0 p \to V^0 p$ amplitude, vector dominance leads to a differential cross section similar in form to Eq. (3.1) [note (3.2) and (3.3)]:

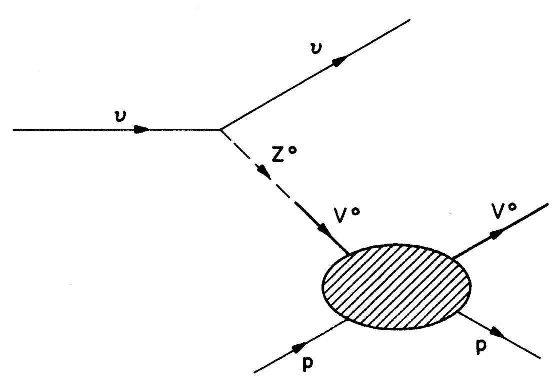

FIG. 7. The Feynman diagram for diffractive neutrinoproduction of a strongly interacting vector meson off a proton target.

$$\frac{d\sigma}{dQ^2dW^2}=\frac{G^2}{8\pi^2}\,\frac{KQ^2}{m_pE^2}\,\frac{1}{1-\epsilon}\left(\frac{m_Z{}^2}{Q^2+m_Z{}^2}\right)^2\frac{1}{4\pi\alpha}\left(\frac{f_V}{h_V}\right)^2\left(\frac{m_V{}^2}{Q^2+m_V{}^2}\right)^2\frac{A}{b}\left[\exp(-b|t|_{\min})-\exp(-b|t|_{\max})\right]. \tag{4.2}$$

The Q^2 dependence of the V^0p amplitude is said to be given wholly by the vector-meson propagator, as before.

We imitate Sec. III A in the numerical integration of Eq. (4.2). We choose $m_Z=5$ and 75.5 GeV/c^2; the latter value corresponding to the boson mass in the Weinberg theory with $\sin^2\theta_W=0.4$, and for it the weak-boson propagator is essentially shorted out. The results are displayed in Fig. 8.

B. Weak boson Z^0

The first thought about neutrino-induced production of the Z^0 brings one to consider weak excitation of the proton with a consequent weak emission by the hadronic "blob." Most probably, we would have charged-current excitation with a lot of hadrons produced together with the Z^0 as in Fig. 9. Cross sections for this would be $O(G^3)$, or around 10^{-43} cm^2, which is rather small for present experimental plans.

On the other hand, if the Z^0 is not self-conjugate so that we have a pair (at least) of weak neutral vector bosons ($Z^0, \bar{Z}^0$), there can be electromagnetic interactions. In other words, the Z^0 may have a magnetic dipole moment and an electric quadrupole moment which we characterize as anomalous simply because they are not present in the usual gauge theories. Since there is no hadronic cloud, the origin of such moments would have to be lumped together with questions such as those concerning the electron-muon mass difference and/or whether their values are perhaps tied in with renormalizability (the need for cancellations of certain amplitudes which are individually badly behaved at high energy).

The freedom in choosing these two moments (the third for a spin-one system, the electric monopole moment, must remain zero, of course) can be exploited simply by picking out the corresponding electromagnetic-interaction terms for the charged bosons.[24] Converting to our metric, we have

$$\begin{aligned}\mathcal{L}_I&=ie\kappa F^{\mu\nu}Z_\mu^\dagger Z_\nu+ie\frac{\lambda}{m_Z{}^2}F^{\mu\nu}G^\dagger_{\mu\rho}G_\nu{}^\rho+O(e^2),\\ F_{\mu\nu}&=\partial_\mu A_\nu-\partial_\nu A_\mu,\\ G_{\mu\rho}&=\partial_\mu Z_\rho-\partial_\rho Z_\mu.\end{aligned}\tag{4.3}$$

The Feynman rules to be used are the κ and λ terms of Kim and Tsai,[25] whose work also tells us that the dipole and quadrupole moments here are

$$\begin{aligned}\mu&=\tfrac{1}{2}(\kappa+\lambda)\frac{e}{m_Z},\\ Q&=(\lambda-\kappa)\frac{e}{m_Z{}^2}.\end{aligned}\tag{4.4}$$

We might well have redefined $e\kappa=\kappa'$ and $e\lambda=\lambda'$, but by letting e equal the W^+ charge direct comparison can be made with previous calculations.

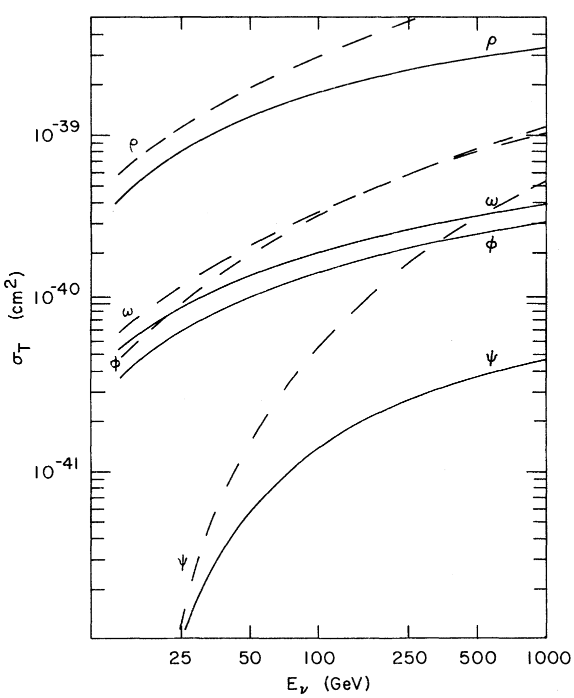

FIG. 8. Total cross sections as functions of beam energy for $\nu p\rightarrow\nu pV^0$. The mass of the neutral intermediate boson is taken to be 5 (75.5) GeV/c^2 for the solid (dashed) curves.

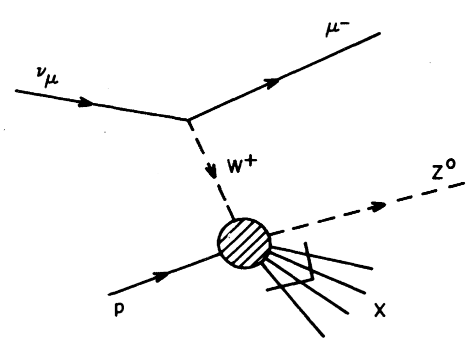

FIG. 9. The Feynman diagram for weak excitation and deexcitation of a target proton in Z^0 production. The doubly charged set of hadrons coproduced is designated by X.

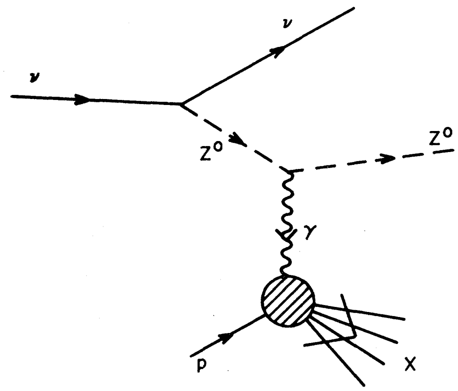

FIG. 10. The lowest-order Feynman diagram for Z^0 production in neutrino-proton collisions if the Z^0 has anomalous electromagnetic interactions.

This choice would follow if the bosons were doublets (W^+, Z^0) and $(W^-, \bar{Z}^0)$ with similar static properties.

The reaction $\nu + p \to \nu + Z^0 + X$ can now proceed with an amplitude depicted in Fig. 10. Looking back at the coupling (4.1) and using the techniques of previous work,[10,26] we now know how to go about calculating the cross sections. Veltman's algebraic computer program, SCHOONSCHIP, was combined with numerical integrations. Table III displays our results for the quasielastic final state, $X = p$, over the Fermilab energy regime. It is seen that the probability rates are roughly 1–2% of those for charged-boson production with neutrino beams (e.g., $\nu_\mu p \to \mu^- W^+ p$).[26] Nearer threshold the dipole term dominates, and at higher energies the quadrupole term is more important. Remember that such high-energy behavior is suspect until the renormalization question is fully explored. By the way, it is possible to check the κ contribution alone by extracting the κ^2 part of the old $W^\pm$ results and multiplying it by $\frac{1}{2}$ [in view of the change in coupling to (4.1)]. Although we used a Feynman–Gell-Mann coupling $[(1/\sqrt{2})Gm_Z{}^2]^{1/2}\gamma_\mu(1-\gamma_5)$ in our earlier report[10] of this electromagnetic recoil possibility, the *percentages* quoted there are unchanged inasmuch as such a coupling was also used in the muon-induced reaction.

V. DISCUSSION

We have presented a collection of estimates for neutral-weak-boson production. The input for some of these calculations, production of neutral vector hadrons, is interesting in its own right, but first let us organize our thoughts about the Z^0.

Including estimates for proton-proton collisions,[27] most of the reactions considered for $W^\pm$ searches now have been extended to the Z^0 case. That, in short, was our purpose. Theoretical expectations for a reachable m_Z of 10–15 GeV/c^2 are necessary for experimental plans of searching for the neutral member. The $W^\pm$ lower limit of about 10 GeV/c^2 by direct production and by absence of propagator effects[28] has no comparable Z^0 counterpart.

Our estimates required knowledge of how the Z^0 couples to leptons or quarks, and so we have assumed a Weinberg-Salam vector–axial-vector form with normalization modified so that smaller m_Z could be considered. Since the data are often presented in terms of the Weinberg angle and since m_Z cancels out in the lower-energy neutral-current data, we have opted for this form. The specific V,A mixture is unimportant in our total cross sections anyway. At this point, further embellishments in couplings, beam polarization, targets (neutron, nuclei), and form factors should wait for experimental signs of encouragement.

If we have not abused the parton model too much in the timelike region (see Refs. 17 and 29 for justification), a photoproduced Z^0 will be accompanied by significant hadron production. The Born term and the vector-meson-dominated diffraction

TABLE III. Total cross sections in units of femtobarns (1 fb$=10^{-39}$ cm^2) as a function of the incident neutrino beam energy, the Z^0 mass, and κ,λ values for the reaction of Fig. 10 where $X=p$. The energy (mass) is in GeV (GeV/c^2) units. The cases are (a) pure dipole, $\kappa=1$, $\lambda=0$; (b) pure quadrupole, $\lambda=1$, $\kappa=0$.

E_ν \ m_Z	5 (a)	5 (b)	10 (a)	10 (b)	15 (a)	15 (b)
50	0.28	0.085				
100	2.8	1.3	0.0028	0.000 55		
200	13	8.5	0.28	0.090	0.000 25	0.000 15
300	26	22	1.4	0.48	0.033	0.0080
600	62	83	7.5	4.2	1.0	0.31
1000	110	200	19	14	3.8	1.8

modes are suppressed by form factors and Z^0 propagators, respectively. It is the absence of a timelike form factor in the parton description that is so important. It is interesting that the "point proton" cross sections (to which the reader can apply the timelike form factor of her choice for a threshold estimate) are of the Compton type and differ from the parton results, particularly in energy dependence. The similarity seen in $W^{\pm}$ photoproduction[9] is fortuitous; there the W's electromagnetic interaction comes into play. Incidentally, the coupling $Gm_Z{}^2$ can make the point result grow in m_Z for a given energy, explaining one feature of Table I.

It is also true of the electron and muon beams that emission of the Z^0 by the target is most probable when hadrons are coproduced. But here we have the attractive possibility discussed before[10]: The lepton can recoil electromagnetically off a target with weak Z^0 "bremsstrahlung." Just how projectile and target fragmentation compare was one of the issues of interest. Even in the Weizsäcker-Williams approximation, the target breakup is no bigger. Table II shows numbers which are almost the same right down the line. This means that the amplitude of Fig 5(a), which does not involve unknown strong-interaction or Z^0-quark dynamics, leads to a useful lower limit on the production cross section. We should mention that the couplings employed in this paper are not the same as those of Ref. 10 but the results are easily translated. The cross sections in Ref. 10 can be multiplied by 0.34 and those in Ref. 26 by $\frac{1}{2}\times 0.34$ for the production in question. (The latter reference thus provides deep-inelastic, coherent, and neutron contributions for the interested reader.)

Because of the present state of the experimental art, we have ignored Z^0 production by neutrinos unless the Z^0 has anomalous electromagnetic interaction (beyond higher-order corrections, seagull terms, etc.). In view of the uncertainty in such interactions and since the numbers turn out on the order of 1% of the $W^{\pm}$ rates at the lower energies, this does not look to be an important possibility. Theoretically, we need a more complete framework in which unitarity bounds could be satisfied; perhaps additional interactions could be concocted (as in the unified gauge theories) which would cancel out bad high-energy behavior. For example, we would violate unitarity limits at beam energies around $10m_Z$ in $e^+e^-\to Z^0\overline{Z}^0$ with these anomalies present.[30] One could add a further complication by affixing a parity-violating (and time-reversal-violating) electric dipole moment to the Z^0 (see Ref. 31); we have not done so.

For consistency, the anomalous electromagnetic interactions should be fed back into the photon and charged-lepton beam cases. But by picking out the κ^2 contribution in an $a+b\kappa+c\kappa^2$ fit to the charged-boson rates for photoproduction and leptoproduction[8,21,26,32] the magnetic dipole term, at least, is seen to be important only at very high energies. In contrast to colliding beams, the average momentum transfer through the boson electromagnetic vertex is not proportional to the beam energy. Before leaving the $Z^0, \overline{Z}^0$ model, we should add that the schizon scheme[33] requires such doublets, but with small (or vanishing) Z^0-lepton couplings and no mention of anomalous electromagnetic interactions.

There are several general remarks to be made concerning the Z^0 reactions discussed above. The important signature distinguishing such events from the variegated muon background is the large transverse momenta in the decay products of this presumably heavy particle. As for the decay modes and their branching ratios, we have in mind muon pairs and refer the reader to earlier remarks.[10] Going on, one may very well expect the expanded *diffractive dissociation*, $V^0+p\to Z^0+X$, to supersede what we have been looking at. In some sense, however, this overlaps with the parton model (generalized vector dominance[34] is designed to give the same scaling seen in constituent models) and could be double counting. Lastly, much of our work carries trivally over to heavy-photon production,[35] since polarization effects have not been considered here.

The hadron V^0 production considered in this paper centered around a diffractive $V^0p\to V^0p$ channel which served mainly as input to Z^0 search estimates. In its own right, the $V^0=\psi$ case is obviously in the limelight these days; our electroproduction calculation is essentially the same as that of Chen and Yao.[36] Moreover, there have been a number of papers[37] reporting estimates of diffractive charmed-vector-boson production in the neutrino reaction, aiming at an explanation of the dimuon pair events.[23] Can the ψ explain any part of these? No, the cross section is small and the muon branching ratio pushes it out of sight. (Besides, the dimuon mass spectrum is not at all sharp.) A complete picture of ψ production should include coproduced hadrons (diffractive dissociation), but this will not affect our conclusions about the dimuon events. A consistent calculation of h_V, within a gauge model, say, could even *decouple* the ψ. (The reader will have to adapt our numbers by relating h_V in the model of interest to f_V and scaling the results down.) In any case we have not seriously addressed ourselves to V^0 experiments, our choices of constant A's and b's are crude, we have neglected ρ' and other higher-massed V^0's, and this is where we came in.

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