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# Production of Neutral Weak Bosons in High-Energy Electron and Muon Experiments*

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We discuss the theoretical total and differential cross sections for $Z^0$ production in the reaction $l+N\rightarrow N'+Z^0+l$, including remarks about polarization effects and subsequent leptonic decays. Brief mention is made about production of $Z^0$'s by neutrino beams and of scalar mesons.

As experimental evidence for neutral weak currents continues to mount,[1] the neutral intermediate weak boson $Z^0$ appears to have gained equal footing with the other hypothetical spin-1 bosons $W^\pm$. Of course, the possibility that all three exist is strong in view of the prominent place which gauge theories hold in our present thinking about weak forces. It is fair to say that searches for $Z^0$ are of paramount importance in attempts to corroborate these ideas about the hierarchy of elementary interactions.

We describe here one attractive candidate reaction for this search, namely

$$l^\pm + N \rightarrow l^\pm + N' + Z^0. \qquad (1)$$

Specific attention is paid to the diagrams of Figs. 1(a) and 1(b) for weak "bremsstrahlung" by the lepton beam during electromagnetic scattering off of some nucleus $N$. The advantages of this particular mode lie in the fact that we can avoid certain large backgrounds present in searches via proton-proton collisions[2] and in the fact that we now have very high-energy lepton beams available. There is also no need to home in on a narrow resonance peak in contrast to production via $e^\pm$ colliding beams.

High-energy muons at Fermi National Accelerator Laboratory are the lepton beams we have uppermost in mind. It is interesting that the decided energy advantage of muons over neutrinos (from pion decay) is *not* ruined here for any dynamical reason. That is, we saw a few years ago[3] that theoretical cross sections for $W^\pm$ production by neutrino beams were 2 orders of magnitude larger on the average than those involving muon beams. The key to this difference is whether or not there is a muon in the final state; after a cancelation in a gauge-invariant set of graphs, the final muon propagator dominates. Thus, Reaction (1) gets the same enhancement seen in $\nu + N \rightarrow \mu + N' + W$, a circumstance which motivated the work described in this note.

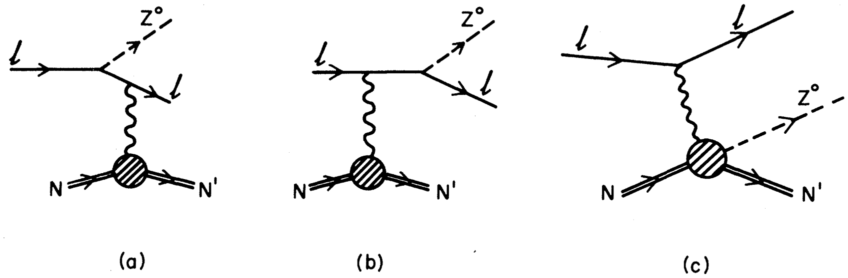


FIG. 1. Feyman diagrams for the production of $Z^0$ by leptons in the electromagnetic field of some nucleus.

The relevant weak-interaction Lagrangian is

$$\mathcal{L}_I = -\bar{\psi}_l \gamma^\mu (g_V - g_A\gamma_5)\psi_l Z_\mu{}^0. \qquad (2)$$

We pattern our calculations after some earlier $W$-production analyses,[4,5] particularly with regard to the phase-space integrations. The results are summarized below for proton targets.

Total cross sections are most easily found by representing the (analytically) integrated square of the lepton-$Z^0$ part as a second-rank conserved Lorentz tensor,[6] leaving two integrations to be done numerically. Table I shows the results for various values of unpolarized-beam energy and $Z^0$ masses ($M_Z$) with the couplings taken to be $g_V{}^2 = g_A{}^2 = 2^{-1/2}GM_Z{}^2$.

We see that the rates are essentially (within 10%) half those for $W$ production by neutrino beams, as expected from the dominant role of the final lepton propagator. Since lepton mass terms are negligible in the calculation, the cross section is proportional to $g_V{}^2 + g_A{}^2$ and the sign of $g_V/g_A$ does not enter until polarization effects are considered. This also makes conversion of our numbers to other choices of couplings quite easy. Where there is overlap, our numbers agree very well with $(g_V{}^2 + g_A{}^2)/e^2$ times the "heavy-photon" total cross sections calculated by Linsker.[7]

To get the differential distributions, the integrations are performed in a different order and all are done numerically. The results for the mass-energy range of Table I can be economically summarized: The $Z^0$ goes very much forward and carries most of the energy; 90% of the time it is inside a 1° opening angle and its average energy is greater than 90% of the beam energy. Also, the final (prompt) lepton is inside 25° more than 80% of the time and its average energy is less than 5% of that for the beam.

TABLE I. Total cross sections for $l + p \to p + Z^0 + l$ in units of $10^{-38}$ cm$^2$.

| $M_Z$ (GeV/$c^2$) \ Beam energy (GeV) | 50 | 200 | 400 | 800 | 1000 |
|---|---|---|---|---|---|
| 5 | 1.4 | 23 | 45 | 74 | 84 |
| 10 | | 2.3 | 11 | 29 | 37 |
| 20 | | | 0.10 | 3.1 | 5.6 |
| 30 | | | | 0.04 | 0.28 |

We may determine the polarization of the $Z^0$ by an adaptation of the $W$ analysis by Bell and Veltman.[8] The general result is that the $Z^0$ follows the helicity of the incoming lepton. Since the lepton mass can always be neglected, the $V-A$ ($V+A$) interaction picks out the left- (right-) handed $l^-$'s and vice versa for the $l^+$'s. Then, if $g_V = g_A$, the $Z^0$ is predominantly left- (right-) circularly polarized for $l^-$ ($l^+$) beams. If $g_V = -g_A$, the reverse is true. For $g_V = 0$ or $g_A = 0$, unpolarized beams lead to vanishing average $Z^0$ helicity.[9] The more energetic muons from pion decay, by the way, have the wrong polarization for $V-A$ interactions[10] and it is important to integrate this effect over the muon flux, especially for $g_V = g_A$.

In view of the fact that the $Z^0$ carries almost all of the beam energy (and is thus collinear with the beam direction), one can transform, by hand, the rest-frame decay distributions to the laboratory frame. Specifically, the leptonic decay $Z^0 \to l^+l^-$ (avoiding for now the problems associated with hadronic channels) has the rest-frame distribution $1 \pm 2r\cos\theta^* + \cos^2\theta^*$ for $l^\pm$, where $\theta^*$ is the angle of the lepton with respect to the $Z^0$ laboratory direction, $r \equiv 2g_Vg_A/(g_V{}^2 + g_A{}^2)$, and the $Z^0$ has negative helicity. For positive helicity, $\cos\theta^* \to -\cos\theta^*$.

There is very little to be changed in the above remarks when inelastic channels and coherent nuclear effects are considered. In fact, to a good approximation the general spectrum discussion in Ref. 5 can be taken over here. A new feature, however, is provided by the possibility that the $Z^0$ is produced by the hadron current [see Fig. 1(c)] with a comparable rate[11]; such events would not have the same sharp experimental signature. A more serious problem is the background of leptons. We have in mind two sources: trident production and hadron decays. Here, the difference in transverse-momentum distributions should be the key. The decay products of heavy $Z^0$'s can have large transverse momenta and, in contrast, electroproduction of hadrons[12] and tridents[13] are severely limited in $p_\perp$ distributions. This difference may also be vital in the event that the $Z^0$ decays mainly into hadrons—a circumstance suggested by a conserved-vector-current argument and the recent Stanford Linear Accelerator Center colliding-beam results. By the way, the Cline-Mann-Rubbia idea[14] for separating the $W$-boson hadronic decay from the deep inelastic channels will not work here since the electroproduction background is too large. Small momentum transfers are enhanced and the $\sqrt{G}$ coupling is absent in this background.

The neutrino reaction,

$$\nu + N \to N' + Z^0 + \nu, \qquad (3)$$

deserves an estimate[15] even though the absence of charges and the lower beam energies seriously hamper production. Without charge-conjugation invariance, we can consider a $Z^0$ with anomalous dipole moment $\sim e/M_Z$ and quadrupole moment $\sim e/M_Z^2$. This leads to cross sections on the order of 5% of those in Table I.

The Weinberg model[16] predicts larger couplings for $Z^0$ than we have considered, but concomitantly larger $M_Z$. With $M_Z \gtrsim 80$ GeV/$c^2$, Reaction (1) would then be of interest only in the next generation of colliding beams. But at this point, muon experiments in the Fermi National Accelerator Laboratory energy regime can set a lower limit on $M_Z$ comparing favorably with that for $M_W$ in neurino experiments. Kinematically, one could hope for the production of a $Z^0$ with mass $\gtrsim 20$ GeV/$c^2$, although taking account of the low rates and considering energies $\lesssim 300$ GeV suggests that $M_Z \approx 10$ GeV/$c^2$ might be a more realistic limit at present.

We have modified our programs in order to study the related production of scalar mesons $\varphi$,[17]

$$l + N \to N' + \varphi + l. \qquad (4)$$

For $L_I = g\bar{\psi}_l\psi\varphi$ and $g = g_V$ (of course $g$ is much smaller in some gauge theories), we find spectra similar to the $Z^0$ case, and total rates about a factor of 4 smaller than those of Table I.

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