SEARCH FOR INTERMEDIATE VECTOR BOSONS AND OTHER PROCESSES USING HIGH-ENERGY NEUTRINOS AND FE-MAGNET SPARK CHAMBERS

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ABSTRACT

We have extended previous discussions of spark-chamber W searches to the entire range of interesting W masses. We have emphasized the detector system described in the 1968 Summer Study Report B.1-68-68 and our standard of comparison has been the neutrino facility described in SS-146. Our conclusion is that the (200 GeV) W search is quite feasible for masses up to 8 GeV/c^2 but that significant improvement in the beam is both possible and highly desirable for this experiment.

I. RATES AND BACKGROUNDS

We should like to take a look at the rates and backgrounds for spark-chamber searches for the W so far as we can "guesstimate" them at this time. A similar discussion has been made by Mann (SS-16) for the case of Al detectors and $M_W = 5$ GeV.

Cross Sections

Following the ground rules adopted by the group assembled to study neutrino reactions in the 25-ft chamber, we have calculated rates for the neutrino beam spectrum of Fig. 24, Appendix IX, of the report SS-146. The percentage contributions of various energy neutrinos to production cross sections are summarized in the appendix to this report so that the results may be easily scaled to other beams. It will become apparent later that one frequently gains in signal-to-noise by cutting out the lower energy part of the neutrino beam spectrum since the cross sections of interest go up faster with neutrino energy than does the background.

We have used the W production calculations of A. C. T. Wu[1] scaled to production in Fe. These calculations include both coherent and incoherent production although the former becomes increasingly important as the neutrino energy increases past W production threshold. We obtain the following cross sections (in units of cm^2/(Fe nucleus-m^2-10^{12} proton on the target) for various W masses (in GeV/c^2):

Table I.

Mass of W	σ_W in units of $\frac{\mathrm{cm}^2}{(\text{Fe nucleus-m}^2\text{-}10^{12}\text{ protons})}$
3	5.0×10^{-28}
5	3.5×10^{-29}
8	6.4×10^{-31}
10	1.75×10^{-32}

These cross sections fall nicely on a straight line when plotted against M_W as shown in Fig. 1.

Detector

We shall consider the detector scheme described in the 1968 Summer Study by D. Frisch.[2] This detector consists of modules, each comprising one 5-meter long W production chamber followed by an iron magnet-scintillator-spark chamber for analysis. The W production module consists of 500 Fe spark-chamber plates with 1/2 cm Fe alternating with 1/2 cm of gap. Each W production module is thus 1970 g/cm^3 long and is 1 meter in radius. The analyzer following is to provide charge identification and rough momentum analysis of the μ^- and μ^+ from the reaction

$$\nu_\mu + Z \rightarrow Z' + \mu^- + W^+ \hookrightarrow \begin{cases} \mu^+ + \nu \\ e^+ + \nu \ . \end{cases}$$

Frisch suggests that there be four such modules (production + analyzer). We are primarily concerned with the $\mu^+ + \nu$ decay mode of the W^+, although the $e^+ + \nu$ decay mode should be quite identifiable as well with a high-energy shower in the spark chamber labeling the relatively high energy (> 10 GeV) and large transverse momentum of the electron from W^+ decay.

With the production modules 1 meter in radius and taking four modules (and assuming the same neutrino flux at each) we must multiply σ_W by 10^3 cm/55.9 g $\times$ $\times$ 7.9 g/cm^3 $\times 6 \times 10^{23}$ nuclei $\times$ 3.14 m^2 = 2.66×10^{26} Fe nuclei - m^2/cm^2.

If we assume a branching ratio into $\mu^+ + \nu$ of 10^{-1}, an efficiency for the detector of 25%, 2×10^{13} protons on the target for this experiment and 2×10^4 pulses/day we get the counting rates for various mass W's of Table II and Fig. 2.

Table II.

M_W	W's per pulse	W's per day
3	0.7	1300
5	4.7×10^{-3}	94
8	8.5×10^{-5}	1.7
10	2.3×10^{-6}	4.7×10^{-2}

Since the current limit is $M_W \leq \sim 2$ GeV counting rate appears to be no problem in significantly extending the limit (if the W is not, in fact, found!). On the basis of counting rate only, exploration past 8 GeV seems a definite possibility. As can be seen from Table A. I of the appendix, the contribution to production of W's of mass ≥ 8 is only from $E_\nu > 60$ GeV. It is the case that the beam chosen arbitrarily for this analysis is not optimized for high energy. It is not out of the question to imagine an increase of $\geq 2\times$ for the neutrino flux above 60 GeV. The detection rate of W's, of course, is only part of the story. The "signature" for the events of interest is not a unique one but may be summarized as follows:

1. A low energy μ^- ($E_{\mu^-} \leq 2$ GeV) primarily in the incident neutrino direction (so far as it is known).

2. A high energy μ^+ (or e^+) with $E_+ > 10$ GeV and significant transverse momentum which can be taken to be larger as the M_W sought increases, $P_{\perp_\ell} / P_{tot_\ell} > 0.1$, say.

3. Nothing else.

The necessary features of the detection scheme are, therefore,

1. charge identification of the μ^+, μ^- or μ^-, e^+
2. momentum or energy analysis of the μ^-, μ^+.

Thus, thin plates are necessary.

One might consider measuring the wider angle muon (μ^+) energy by range with a block of solid material to provide a lower energy cut off and thinner plates to stop the μ^+. This could possibly be used to look at the decay angular distribution of the μ^+ to distinguish μ^+ from W^+ decay from μ^+ from π^+ decay.

For coherent production of W's, the signature becomes more constrained. The reaction is $\nu + Z \rightarrow Z + \mu^- + W^+$ where the momentum transfer to the nucleus must be insufficient for the ν to interact with only part of it, i. e., $q_{min} < 1/R$ where R is the nuclear radius. We see that the nuclear momentum transfer is

$(P_{Z_f} - P_{Z_i})^2 = (p_\nu - p_\mu - p_W) = q^2$ which can be shown to make q minimum when all angles are zero:

$$q_{min} \sim \frac{M_W{}^2}{2p_W} \approx \frac{M_W{}^2}{2E_\nu} .$$

The use of coherent production raises the possibility of other tricks to pin down the W^+ production more firmly. Not only can one think of doing an excitation curve of the events of interest to see the different energy dependence of W^+ production compared with various backgrounds but one can also study the relative importance of coherent and incoherent production of lepton pairs. Since coherent production varies as Z^2 one can think of using different materials for the W production chamber plates and comparing rates for different Z's. For coherent events the rate is also proportional to the density and this can be varied by changing the thickness of the Fe plates in one or more of the modules. These various possibilities have not yet been explored in any detail.

Background and Other Rates

An obvious process to consider is the direct four-fermion production of muon pairs. In Fig. 3 we have plotted the cross sections for coherent and incoherent production of $\nu + Z \rightarrow Z' + \mu^- + \mu^+ + \nu$ using the calculations of Czyz, Sheppey, and Walecka.[3] The cross section for this process integrated over the neutrino spectrum of interest is 6.5×10^{-34} cm^2/(Fe nucleus-m^2-10^{12} protons) which is quite small compared with any of the cross sections of Table I for the W mass range and is not a significant background for the W search. However, the process has intrinsic interest if it can be distinguished from backgrounds which simulate it.

There is, however, a large class of background which afflicts both the W search and, certainly, the four-fermion process. This consists of the inelastic processes induced by neutrinos. If one worries about all of the inelastic processes, the problem is quite severe since the cross section appears to be rising linearly with neutrino energy:

$$\sigma_{inel} = 0.6 \times E_\nu \text{ (GeV)} \times 10^{-38} \frac{\text{cm}^2}{\text{nucleon}} .$$

This cross section, integrated over the neutrino spectrum we have been considering, yields a result of 2.2×10^{-27} cm^2/(Fe nucleus-m^2-10^{12} protons). This is, of course, larger than any of the σ_W in Table I. The background comes from 1) our inability to distinguish π's and μ's (which is due to our use of thin plates and high energies) and by 2) $\pi \rightarrow \mu$ decay. Assuming we cannot detect kinks at all we are faced with a reduction factor given by the greater probability of π's to interact than to decay. In Fe, a pion collision length is 12 cm, which we must double to account for the gaps. A decay length, if we restrict our μ^+ to > 10 GeV, is > 550 m. This already yields a reduction factor of $25/55000 = 4.5 \times 10^{-4}$ so that the effective background cross section for comparison with Table I is 9.9×10^{-31} which appears significant only for searches for $M_W \geq 8$.

However the signal-to-noise situation is actually considerably better than this.

1. As shown in Table A.I of the appendix, the contribution to the W production cross section rises more rapidly than does the background. Thus, by cutting off the neutrino spectrum at 60 GeV the W^+ production cross section for $M_W = 8$ is only cut by 2% while the background above is cut by 96%.

2. Of greater significance is the lower energy cut on the μ^+. This makes the total inelastic cross section a gross overestimate for the background. The primary background is due to the single π production.

$$\nu + n \rightarrow \mu^- + \pi + n,$$

ignoring the fact that the dominance of $N^*_{3/2}$ implies that $\geq 20\%$ of the cross section for single π production is to π^0, we note that the cross section for single π seems to saturate at a value less than 2×10^{-38} cm^2/nucleon.

Taking the entire ν spectrum we have been using (and, again, we would gain greatly in signal-to-noise by cutting out $E_\nu \leq 40$ GeV), we get a cross section for single pion production in our situation of

$$\sigma_{1\pi} = 2.9 \times 10^{-28} \frac{\text{cm}^2}{\text{Fe nucleus-m}^2\text{-}10^{12}\text{ protons}},$$

which, again, is attenuated by 4.5×10^{-4} for (π decay/π absorption) in Fe to

$$\sigma_{1\pi} = 1.31 \times 10^{-31} \frac{\text{cm}^2}{\text{Fe nucleus-m}^2\text{-}10^{12}\text{ protons}}.$$

This cursory look indicates that the W search with spark chambers is far from being uninteresting and should be investigated in considerably more detail.

Electron Decay Mode

The following remarks concerning the electronic decay mode are due to Dave Frisch.

The $W^+ \rightarrow e^+ + \nu$ decay mode should have practically the same branching ratio as the $W^+ \rightarrow \mu^+ + \nu$ mode. The e mode probably should not stand out quite as well as the μ mode from the background. The background in both cases probably will come primarily from N^* production, but for the e mode through π^0's, giving gammas and thence showers, rather than from π^+'s. The same cross section for $N^{*+} \rightarrow \pi^+ + n$ will presumably apply in N^* production to π^0 production, after multiplication by the appropriate ratio of C-G coefficients. As with the π^+ background, there is reason to expect that the strong-interaction form factors will cut the very high energy π^0 background way down.

If each plate has a thickness t, the chance per plate of converting at least one of the γ's is about $2d/X_0$ where X_0 is the conversion length. For 1/4 in. iron or 1 in. aluminum plates, for example, more than half of the π^0's make showers with only none, one, or two gaps missed, so that a missing gap criterion to differentiate electron-induced from γ-induced showers will be of only limited use. Some further small help may be got from the rejection of those events which show by their structure a common origin for two γ-induced showers.

The shower size--by spark counting or spatial structure or both--will give a stronger handle, probably allowing energy selection to $\pm 40\%$. This should allow a rough plot of angle vs energy, and the distribution should be the same in absolute number and angular dependence as for the μ's.

Thus if there is production by neutrinos of high-energy leptons with larger momentum transfers than expected from a point interaction it should be observable in both leptonic modes, provided the very high energy π^0 background is quite small. Along with anomalous absorption of neutrinos into large momentum transfer events if a W is produced, there should be an anomalous dispersion around the W-threshold into the same modes but with low internal momentum transfers, i.e., anomalous 4-fermion form factors showing in the forward production of $\mu^-\mu^+$ and $\mu^- e\nu$ events. Experiments should therefore aim to separate forward angle events from the background at as high an energy as the flux will allow. Here the sensitivity to neutrino flux measurements is greater than in the large-momentum-transfer search, and the importance of a well-understood high-pass neutrino beam becomes even greater.

REFERENCES

[1] A. C. T. Wu, University of Michigan, private communication.

[2] D. Frisch, Beam and Spark-Chamber Detector for Search for W's Produced by Neutrinos, National Accelerator Laboratory 1968 Summer Study Report B. 1-68-66, Vol. III, p. 235.

[3] Czyz, Sheppey, and Walecka, Nuovo Cimento 34, 404 (1964).

APPENDIX

Table A. I

E_ν, GeV	M_W, GeV/c^2	Contribution of E_ν to σ_W	M_W	Contribution of E_ν to σ_W
20	3	40%	5	6.9%
30		17		18.4
40		12.6		24.1
40		11.3		21.9
60		8.3		14.7
70		5.5		7.6
80		2.9		3.8
90		1.4		1.7
100		0.7		1.0
110		0.4		
50	8	1.6	10	3.0
60		9.3		7.9
70		24.5		22.2
80		24.4		28.5
90		19.6		38.3
100		12.0		
110		8.6		

The need for more high-E_ν neutrinos and the advantage (for signal-to-noise) of fewer low-E_ν neutrinos is obvious.

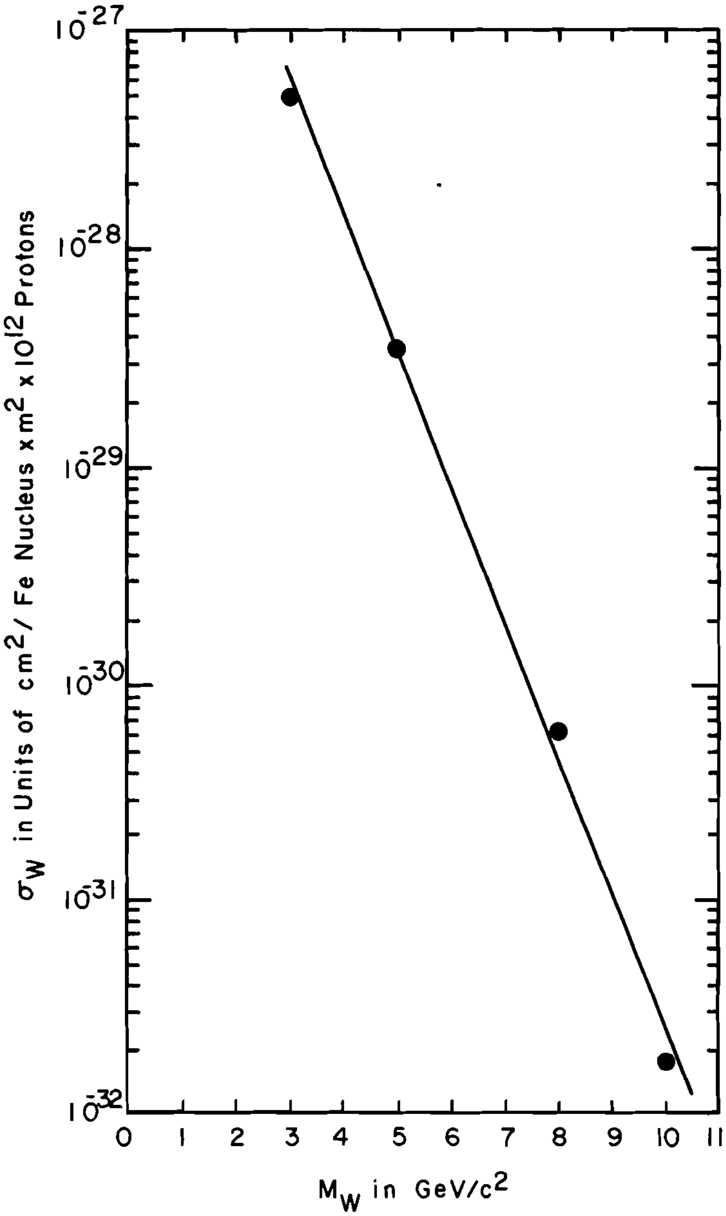

Fig. 1. Cross section for W production by neutrinos versus W mass.

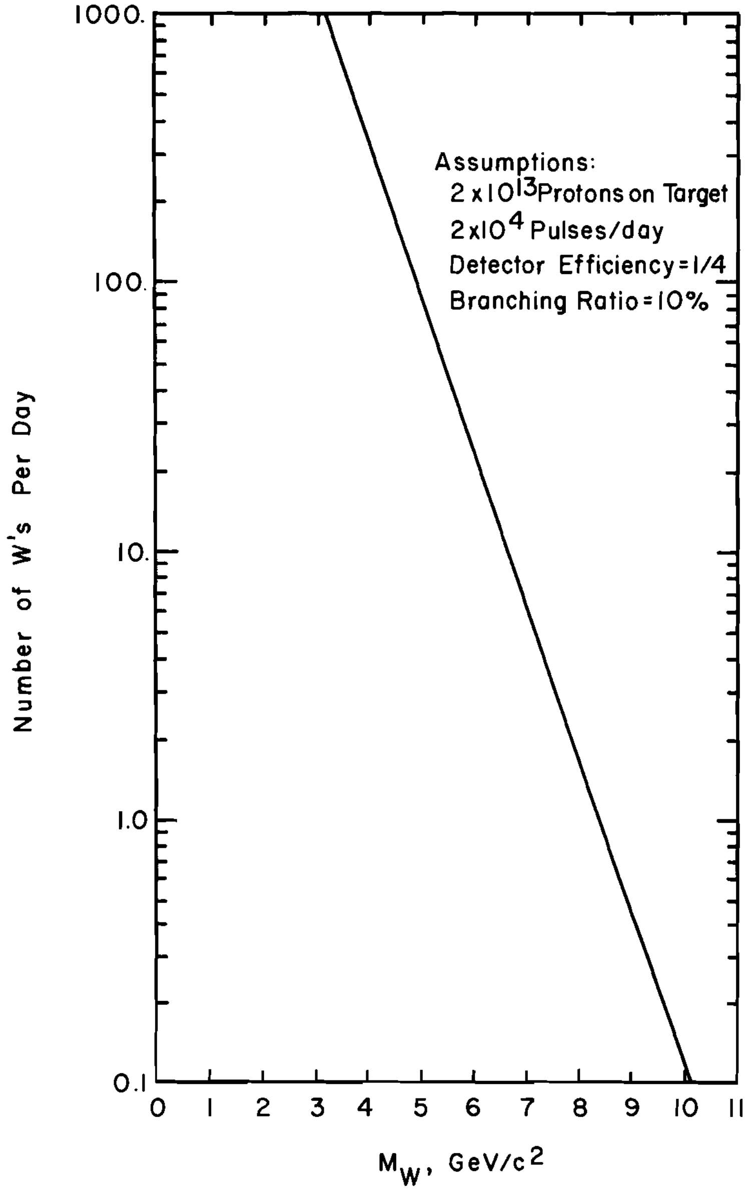

Fig. 2. Rate of W production per day plotted against W mass for the conditions statec for the incident neutrino spectrum of SS-146, Fig. 24.

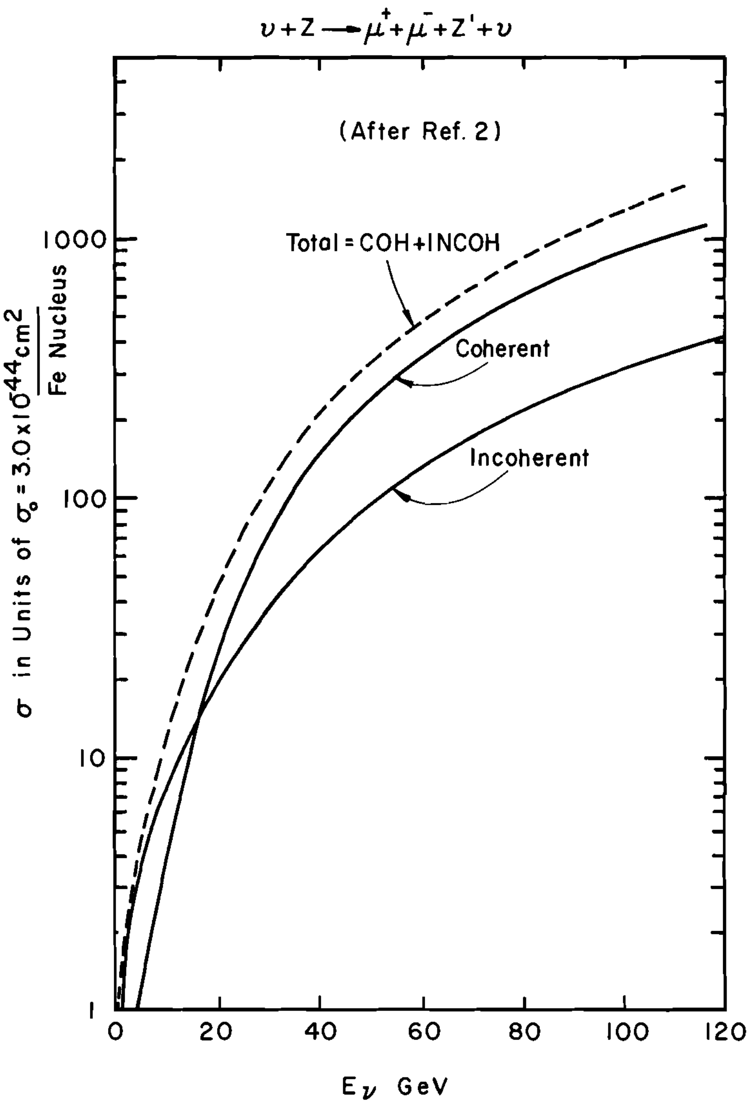

Fig. 3. Plot of the production of muon pairs versus neutrino energy according to the calculations of Ref. 2.