INTRODUCTION

At present $M_W \gtrsim 2$ GeV from the CERN and Columbia-BNL spark-chamber neutrino experiment. It is possible that by NAL turn-on time the $W$-mass region will have been explored up to $\sim 3$ GeV by colliding $e^+e^-$ beams and up to $\sim 4$ GeV at Serpukhov. Certainly the region above 5 GeV will still provide an exciting prospect, and possibly even that above 2 GeV.

Searches for $W$'s using incident $\nu$'s, $\mu$'s, and p's all have special advantages and problems; the $\nu$-induced reactions $\nu (\nu \bar{\nu}) + A \rightarrow A + W + \mu^+\mu^-$, $W \rightarrow \mu^+\mu^- + \nu$ discussed here have the advantage of highly characteristic signatures (nothing in; $\mu\mu$, $\mu e$, or $ee$ out) but the disadvantage of having a geometrically and spectrally diffuse incident beam. The equipment for a $W$-search using neutrinos is also appropriate, with only small changes if necessary, for study of other high-energy neutrino interactions, e.g. the quasi-elastics $\nu + p(n) \rightarrow n(p) + \mu$.

Practically every idea discussed here was present in the CERN experiment.

SPECIAL FEATURES AT HIGH ENERGY

Intrinsic Focusing of $\nu$'s

The highest energy $\nu$'s will emerge with $p_\perp \lesssim 0.2$ GeV/c, mainly
from $K^+$'s. It is likely that the $K^+$'s will emerge with $p_\perp \lesssim 0.2 \text{ GeV/c}$ from $N^*$'s or $Y^*$'s which carry almost the full incident proton momentum, and that the $N^*$'s or $Y^*$'s themselves will have $p_\perp \lesssim 0.2 \text{ GeV/c}$. The result will very probably be that most $\nu$'s with $E_\nu \geq 50 \text{ GeV/c}$ will be contained within a cone of not more than 4 mrad (half) angle, and that those few $\nu$'s with $E_\nu \geq 100 \text{ GeV/c}$ will be contained within about 2 mrad. It is thus quite unlikely that focusing the $K$'s can increase the useful neutrino intensity of $E_\nu \geq 50 \text{ GeV}$ by even a factor of 4.

Since the probability of finding the $W$ as a function of its mass, the production spectrum of neutrinos, and the neutrino intensity needed to give an observable yield in the leptonic decay modes of the $W$ are all unknown, we are in no position to design an ideal experiment. Instead we must guess some characteristic neutrino beam divergence angle for design; $\pm 3 \text{ mrad}$ seems reasonable. The detector should therefore not have more than 1 m radius at 350 m from the target nor 2 m at 700 m. ("Radius" is used here as "half-width" if a square rather than circular cross section is taken, i.e. $\pi/4 = 1$ throughout).

**Signatures for Triggers**

In producing, say, an 8 GeV/c $^2$ mass $W$ from a 70 GeV $\nu$, the $\mu$ initially produced along with the $W$ will have a momentum from about zero up to about 20 GeV/c, and the $\mu$ or electron from the decay of the $W$ will have from about zero up to almost the full $W$ energy. Most of these $\mu$'s will have such a large range ($\sim 0.7 \text{ m/GeV in iron}$) that a coarse scintillation counter hodoscope triggering on them will give
strong rejection of cosmic rays and beam-associated backgrounds. An electron-initiated shower from such a high-energy electron also provides an exceptionally clear signature. In coincidence, perhaps even with a coarse common vertex requirement, such trigger signatures should allow a heavy flux (~ $10^5$ tracks/sec instantaneously) through spark chambers without triggering more than a few times per second. The tolerable level of background tracks can thus be increased by a factor of ~ $10^4$ over the level acceptable in a bubble chamber.

**Large-Aperture Momentum Analysis**

Magnetized iron provides a comparatively cheap and flexible method of getting large volume $B$-fields for momentum analysis of high-energy $\mu$'s. For $B = 15$ kG, the ratio of bending angle $\theta_B$ to rms coulomb scattering angle $\theta_{Sc}$ is $\sim 4 l^{1/2}$ in solid iron, where $l$ is in meters. Thus for $l = 5$ and $p_\mu = 40$ GeV/c we have $\theta_B \approx 0.06$ radians $\approx 10 \theta_{Sc}$, and the sagitta is ~4 cm. Scattering, rather than measurement accuracy, will therefore usually limit $\mu$-momentum measurement. For $W$-production, with two missing neutrinos, more precise measurement will not be very useful in any case.

It is probably not worth the trouble to magnetize iron spark-chamber plates themselves, since the ranges of typical proton recoils are too small to analyze for plates of any practical thickness in very large mass chambers.

**SIZE**

The $\mu$'s from heavy $W$'s will stand out at angles $\sim \sqrt{2m_p/E_\nu} \approx 1/5$, 

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so that if they are to be measured in a 5-meter long block of magnetized iron, this analyzer block should have 1-m radius even if the W-production takes place on the axis of the spark chamber and analyzer. For a spark chamber of ~1-m radius, the analyzer should have ~2-m radius. This is already fairly large, since wire or visual spark chambers must be put in every half meter or so in order to measure curvatures, and 4-m diameter is about as big as one would make a single spark chamber. If we take 2-m radius for the analyzer, and 1-m radius for the (comparatively) thin plate spark chamber in which the W's are created, the spark chamber should not be longer than about 5 m. The module shown in Fig. 1 incorporates these choices.

As discussed above, a 1-m radius detector suggests ~300 m as the natural decay space for the K's. Insofar as modules can be stacked one behind another on a scale small compared with 300 m, for a given total detector mass a maximum in total rate will be reached at this distance even for K's with a longer mean free path.

A schematic of such a layout with four modules is shown in Fig. 2. Such a setup should produce over a hundred times more W's than the 25-ft chamber. It would probably cost about $1 million.

One reservation about this choice of module is that if the spark chamber were larger diameter, the relative size of the magnetized iron analyzer behind it could be smaller, e.g. a 4-m diameter spark chamber followed by a 6-m diameter analyzer would use only 9/16 as much analyzer volume per spark-chamber volume. The difference in
cost between 4 units of the type in Fig. 1 and a single unit with a chamber 4 m × 4 m × 5 m long and a 6 m × 6 m × 5 m-long analyzer would be between $100,000 and $200,000. Against this must be put the inefficiency per unit mass for subtending neutrinos if their angular distribution is as estimated above, and the greater clumsiness of the large spark-chamber arrays. In addition, μ's from the quasi-elastic reactions \( \nu + p(n) \rightarrow n(p) + \mu \) will go almost dead forward with very high energy, so that for these reactions the momentum analyzer can be thin and will need to be very long; a given total volume will be better utilized in a long series of thinner modules. Finally, unless the μ-shielding is part of, or somehow charged off to, another experiment, the cost of making the shielding say 6 m × 6 m rather than 4 m × 4 m in cross section will be of the order of $1 million. (We shall return to this question of the diameter of the shield below). We conclude that the module of Fig. 1 is large enough.

**NEUTRINO INTENSITY**

S. L. Meyer has suggested that an appropriate place for this kind of spark-chamber setup might be in the BC neutrino beam at the beginning of, or within, the main earth shielding, and has kindly calculated the flux of neutrinos within 1-m radius from a pencil beam of K's with 300-m drift space. Figure 3 shows his calculations. The "1/10 Trilling" yield of \( 2 \times 10^{-4} \) neutrinos of 70 GeV and above traversing the spark chambers per interacting proton is probably a high upper limit. A lower limit might be set by a guess at coherent N*(1700)
production is $1/10$ millibarn per nucleus with a $10^{-2}$ branching ratio into $K^+ \Lambda^0$, giving $10^{-7}$ useful $\nu$'s per interacting proton. $W$'s of mass $8$ GeV/c$^2$ could just be detected even with this lowest intensity, while if the Trilling yields are correct $12$ GeV/c $W$'s from $140$ GeV $\nu$'s could just be detected, all with the setup of Fig. 2. (The drift space there is $250$ rather than Meyer's $300$ meters, a negligible difference in view of the uncertainties of estimation). We have used the $W$ production cross sections calculated by A. C. T. Wu et al. and given by T. D. Lee in a NAL report, based on zero anomalous moment, and have assumed that the $\mu\nu$ mode accounts for about half the total $W$ decay rate.

**SHIELDING**

Since $\mu$-yields from $\pi$'s will presumably dominate, the $\mu$'s may be as many as $3$ times the $\nu$'s given in Fig. 3. To get the muons from $10^{13}$ interacting protons per pulse down to $10^5$ $\mu$'s by range absorption we would then need about $90$ meters of iron. If the iron shield is $4$ m $\times$ $4$ m in cross section, to shield the analyzer as well as the spark chamber in the module shown in Fig. 1, at $90$ meters length if would cost something like $2$ million at $150$/ton.

There is, however, the possibility of using a much shorter length of magnetized iron to throw out the high-energy $\mu$'s rather than stop them. For example $30$ m of iron at $15$ kG will bend a $140$-GeV $\mu$ through approximately $1/10$ radian, so that after a comparatively short drift space --say $30$ meters-- the modules of Fig. 1 should be protected to the $10^5 \mu$/sec level. This would bring down the cost of the shield to about $2/3$ million dollars.
In the overall optimization of costs it might be better to sacrifice a factor of several in the area of the analyzer, and hence in analyzable events, to keep the shield narrow. For example, a magnetized shield 2 m x 2 m x 30 m long would cost only about $150,000, but it could be used only with an analyzer only 2 m x 2 m square, the same size as the spark chamber. This setup is shown in Fig. 4.

It is assumed throughout that concrete and/or dirt shielding will delimit the radius of the decay region to that of the shielding, and that $\leq 10^5 \mu s$ per pulse will be scattered in from the dirt; this latter assumption has not been checked by detailed calculation.

**EXPERIMENTAL HALL**

Also shown in Figs. 2 and 4 is a room 50 m long x 20 m wide; it should be 10 m high and have an access ramp. Blockhouse shielding for people within it may also be necessary, especially if the shorter shield is used. At $50/ft^2$, the Experimental Hall will cost $0.5 million.

**BEAM**

As discussed above, the bubble-chamber neutrino beam might be suitable. The bubble-chamber beam will presumably have the advantages of sign selection and focusing, but since it is pulsed it requires more massive shielding than contemplated here. Also, if the beam is long compared with about 500 m, intensity in the 50-70 GeV region will begin to drop seriously.

An alternative is to modify the bubble-chamber neutrino beam, bringing it farther downstream before hitting the target (as shown in
Fig. 2), foregoing sign selection and focusing unless separate magnets are installed for these spark-chamber experiments. If the mechanisms of high-energy π and K production are mainly N^{**} and Y^{**} production, positive sign should dominate sufficiently that toroidally magnetized blocks defocusing positive μ's will not gather too many high-energy negative μ's, and a beam formed without sign selection may be tolerable. If so, a succession of targets can be used, as shown in Fig. 4, to pick up a factor of 3 or so more than the bubble-chamber beam yield. Multiple targets are possible because a 200-GeV proton beam scatters only ~0.1 mrad in ~30% of an interaction length in a low-Z material, and most of the ≥ 50 GeV K's produced are expected to spread out over several mrad, so they clear the next proton target, and soon.

CONCLUSION

For about $2 million in facilities from NAL, and for about $1 million in new equipment an extremely sensitive search for the W and other ν-induced reactions can be performed by using techniques available at these ultra-high energies.
5 Meter Long, 500 Gap
Fe (or CH₂) Spark Chambers
with Scintillators Every Half
Meter

5 Meter Long Toroidally Magnetized Iron
with Spark Chambers Every Half Meter
and Scintillators Every Meter

Scale: 0 1 2 3
Meters

Fig. 1. Spark chamber and analyzer unit.
Fig. 2. Schematic layout. Drift space may be increased to 500 m, with sign selection as shown in Fig. 1 of NAL Summer Study Report B.1-68-82.
Proton Energy = 200 GeV
Decay Space = 300 meters
Shield Length = 50 meters
Detector Radius = 1 meter

Fig. 3. Integral neutrino spectra, as calculated from data of NAL Summer Study Report B.1-68-82.
Targets:

First Target is 1 cm. Diameter with ~30% Absorption

2nd Target Subtends 1 m rad at 1st., But K's Go Out UP to ~3 m rad

3rd. Target Ditto w.r.t. 2nd.

Shielding & Detector:

30 m Magnetized Iron Shield

Fig. 4. Alternative targeting, shielding, and detector layouts.