LETTER OF INTENT

FOR A STUDY OF HIGH ENERGY NEUTRINO INTERACTIONS USING A COUNTER SET-UP

CERN, Hamburg, Karlsruhe, Oxford
Rutherford Laboratory, Westfield College
Collaboration

CERN LIBRARIES, GENEVA
CM-P00059058
I. INTRODUCTION

The combination of a narrow band neutrino (antineutrino) beam and a large target mass counter detector (200 tons fiducial) provides a powerful facility to study inelastic neutrino and antineutrino interactions. We see three main advantages of the new, advanced designs\(^1\) of narrow band beams:

- precise energy definition (± 7% on the average for neutrino energies between 100 and 200 GeV)

- accurate flux determination (± 3%)

- purity of lepton type \(N(\overline{\nu})/N(\nu) \leq 10^{-4}\)

Combined with a counter set-up composed of an integrated target/hadron calorimeter and a muon filter and spectrometer it provides

- a muon trigger and reliable muon identification,

- an automatic analogue measurement of the total energy transferred to hadrons,

- a cross-check \(E_\nu = E_\mu + E_h\), event by event, for reliable energy calibration, and for safety against nonsense events (due e.g. to muon miss-identification, parent beam scraping the walls etc.),

- calibration for later running in high-band beams,

- high event rates in the energy range 100-200 GeV \((3 \times 10^5 \text{ for } 10^{19} \text{ incident protons})\).

The study envisaged would concentrate on exploiting these unique features to measure absolute total cross sections, and absolute differential inelastic cross sections (the \(q^2-\nu\) plot) and to search for lepton number non-conservation, for heavy leptons and for neutral hadronic currents.
We envisage a second stage in a medium band neutrino beam with enhanced flux (x 5 to x 10) to measure total cross sections on hydrogen and deuterium, and also the density in the \( q^2 - \nu \) plot for hydrogen and deuterium.

Further experiments with the calibrated apparatus (from narrow band running) would be of interest in a wide band or high-band beam (x 1000 to x 100 of narrow band intensity) to yield \( \sim 10^8 \) total events in order to search for rare or forbidden W.I. processes.

**II. PHYSICS**

**II.1 \( \sigma_T(\nu N) \) and \( \sigma_T(\bar{\nu}N) \)**

A 6 day exposure at \( 10^{13} \) ppp would give \( \sigma_T(\nu N) \) to \( \pm 3\% \) at 12 energies between 50 and 250 GeV. Deviations from a linear rise of \( \sigma_T \) with energy can be due to the propagator of the intermediate boson W (see figure 1). A boson of mass \( M_W = 30 \) GeV would produce a 5 standard deviation effect. \( \sigma_T(\bar{\nu}N) \) can be measured to \( \pm 10\% \) in a similar exposure, or \( \pm 5\% \) in a 24 day exposure.

**II.2 \( \frac{d^2\sigma}{dq^2d\nu}(the \ q^2-\nu \ plot) \)**

* a) **Locality**

A measurement of the energy dependence of the differential cross section at fixed values of \( q^2 \) and \( \nu \) provides a sensitive test of the current x current structure of the weak interaction with I = 1 vector and axial vector currents exchanged; this is referred to as the "locality" test. For this experiment it is important to know the neutrino flux accurately, as the test depends on the comparison of densities in the \( q^2 - \nu \) plot at different neutrino energies.

* b) **W propagator**

An exposure of \( 3 \cdot 10^{18} \) incident protons (30 day run at \( 10^{13} \) ppp) with neutrino energies between 100 and 200 GeV would be sensitive to deviations from scaling due to a boson of mass \( M_W = 75 \) GeV at a level of significance of about 5 standard deviations. We are not aware of any other test of comparable sensitivity to look for a propagator in the weak interaction.
c) **Scaling and the structure functions**

The strongly constrained kinematics of a narrow band beam experiment should remove potential sources of distortion of the $q^2-\nu$ plot, and together with the large events rate that can be expected would allow the separation of the 3 structure functions and an investigation of their scaling properties. We aim at a comparison with deep inelastic muon scattering.

**II.3 Lepton number conservation**

In conventional weak interactions theory it is assumed that there are two neutrino components, $\nu$ and $\bar{\nu}$, with mass zero; lepton number conservation then follows.

A sensitive test of the assumptions can be made by searching for the process

$$K^+ \rightarrow \mu^+ \nu_\mu, \nu_\mu N \rightarrow \mu^+ + \text{hadrons}$$

which violates lepton number conservation. Narrow band neutrino beams have been shown\(^1\) to contain a background of antineutrinos of less than $10^{-4}$, contributing less than $3 \cdot 10^{-5}$ to the event rate.

**II.4 Search for heavy leptons**

Heavy leptons may be excited muons or may belong to a triplet\(^2\) ($M^+, \nu_\mu, \bar{\nu}_\mu$) in unified theories of weak and electromagnetic interactions. Their signature in the proposed narrow band experiment would be:

- missing energy in the balance $E_{\nu} = E_{h} + E_\mu$ (due to neutrino emission) for $\mu^*$ or $M^+$ production,

- apparent violation of lepton number conservation in the process

$$\nu_\mu + N \rightarrow M^+ + \text{hadrons}$$

Using the estimate of the branching ratio of $M^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\mu$ by Björken and Llewellyn-Smith\(^2\) and a model-independent lower bound on the cross section derived by Llewellyn-Smith\(^3\) an exposure to $3 \cdot 10^{18}$ incident protons is sensitive to $M^+$ of mass $M < 20$ GeV (see figure 2). The excitation curves of $M^+$ events against neutrino energy are plotted for several $M^+$ masses.
If an $M^+$ should be found then its mass can be deduced from the measured excitation curve.

II.5 Search for neutral hadronic currents

Theories of unified weak and electromagnetic interactions can resolve the problems of divergences in the conventional current $x$ current theory. They require the existence of neutral $\Delta S = 0$ hadron currents or heavy leptons or both. The envisaged experiment can decide if these ingredients exist in nature. The planned experiment with the combination of a narrow band beam and hadron calorimeter plus muon detector contains several valuable features which can be used to decide if neutral hadronic currents exist or not.

The process

$$\nu_\mu N + \nu_\mu \rightarrow \text{hadrons}$$

has a specific signature:

- missing muon track and also missing energy in the balance $E_\nu = E_h + E_\mu^*$, due to energy taken away by the outgoing $\nu_\mu$.

We intend to look for events with no apparent muon and with hadron energy $E_h$ lying between the two "peaks" of the narrow band beam spectrum (see figure 3).

$$E_\nu(\pi) < E_h < E_\nu(K)$$

(We expect a neutrino background of less than 3% in this energy range between the peaks). In this region background events with no muon track are due to

- neutrons produced by neutrinos in the high energy peak from kaon decay
- unidentified electron-neutrino events.

Background of the first type would be estimated from the depth distribution
of events. The beam contains 2% electron neutrinos in this region. This background can be estimated from identified electron events.

A search at a level of less than $10^{-2}$ seems feasible. If found, the details of the process can be studied: $\sigma_T$, $d\sigma/dq$, $d\sigma/dq^2$ and compared to charged current events.

II.6 Further possibilities

Upon completion of an exposure in a narrow band beam the apparatus has been calibrated for further work in a medium band beam of enhanced flux:

- hadron calorimeter and muon spectrometer are calibrated due to the cross check against $E_\nu$,
- a cross section, easily recognized in the envisaged detector, is measured as a function of $E_\nu$.

We would then attempt an exposure using a hydrogen- (or deuterium) filled dewar as a target in front of the calorimeter and measure:

$$\sigma_T(\nu p), \sigma_T(\bar{\nu} p), \sigma_T(\nu n), \sigma_T(\bar{\nu} n)$$

and some details of the differential cross section, $d^2\sigma/dq^2 d\nu$, to investigate hadron structure, test the sum rules measure some details of the final state and again compare with results from muon scattering. We believe that bubble chamber techniques have difficulties in determining the neutrino energy in hydrogen or deuterium.

A 15 day neutrino exposure at $10^{13}$ ppp incident on 2 tons of H$_2$ would give $\sigma_T$ to $\pm 3\%$ at 5 energies between 80 and 250 GeV. The enhanced flux could also be used to study rare processes, e.g. muon pair production.

III. BEAMS AND EVENT RATES

The flux of a narrow band beam has been calculated for installation in the North Area (in coexistence with the muon beam) and in the West Area. Its spectrum for a 200 GeV/c parent beam is shown in figure 3. The results are similar and we quote here the North Area beam, sketched in figure 4. We have restricted the decay zone to a length of 300 m for better energy definition. The event rates are given in table 1.
### TABLE 1

Neutrino events per $3 \cdot 10^{18}$ incident protons

<table>
<thead>
<tr>
<th>Parent Momentum (GeV/c)</th>
<th>$K^+ \rightarrow \mu\nu$</th>
<th>$\pi^+ \rightarrow \mu\nu$</th>
<th>$K^- \rightarrow \mu\bar{\nu}$</th>
<th>$\pi^- \rightarrow \mu\bar{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>narrow band</td>
<td>medium band</td>
<td>narrow band</td>
<td>medium band</td>
</tr>
<tr>
<td></td>
<td>$r &lt; 0.75 m$</td>
<td>$r &lt; 1.5 m$</td>
<td>$r &lt; 1.5 m$</td>
<td>$r &lt; 1.5 m$</td>
</tr>
<tr>
<td>100</td>
<td>$10^5$</td>
<td>$2 \cdot 10^5$</td>
<td>$10^5$</td>
<td>$2 \cdot 10^5$</td>
</tr>
<tr>
<td>200</td>
<td>$10^5$</td>
<td>$1.8 \cdot 10^5$</td>
<td>$2 \cdot 10^5$</td>
<td>$4 \cdot 10^5$</td>
</tr>
<tr>
<td></td>
<td>$K^- \rightarrow \mu\bar{\nu}$</td>
<td>$\pi^- \rightarrow \mu\bar{\nu}$</td>
<td>$3 \cdot 10^4$</td>
<td>$6 \cdot 10^4$</td>
</tr>
<tr>
<td>100</td>
<td>$2 \cdot 10^3$</td>
<td>$3.5 \cdot 10^3$</td>
<td>$2 \cdot 10^4$</td>
<td>$4 \cdot 10^4$</td>
</tr>
<tr>
<td>200</td>
<td>$2 \cdot 10^3$</td>
<td>$3.5 \cdot 10^3$</td>
<td>$7 \cdot 10^3$</td>
<td>$2 \cdot 10^4$</td>
</tr>
</tbody>
</table>

It will be noted that event rates are of the order of $10^5$ for 30 days running with $10^{13}$ ppp for events produced by the upper peak of the dichromatic neutrino beam. This number is for neutrinos interacting in the "good energy definition" fiducial volume. At 200 GeV the "good region" is within a cylinder of radius 0.75 m. As the detector radius will be 1.75 m there will be additional events, about $10^5$ in number, in the outer regions of the calorimeter, which will have poorer definition of $E_\nu$ determined by the beam and hence a poorer energy cross check ($E_\nu = E_H + E_{\mu}$), and yet will still contain good physics. An additional bonus will be events from neutrinos in the lower peak (coming from $\pi$ decay). Taking a fiducial radius of 1.5 m (for shower containment) there will be $\sim 2 \times 10^5$ such events of about half peak energy. Although the definition of the beam neutrino energy is very poor (see fig.3) these events will
surely be of value.

The so called medium band mode of operation is an operation of the narrow band beam line with all the N.B. criteria relaxed:

- $\Delta p/p$ of the parent beam set at maximum
- decay zone increased from 300 to 600 m
- whole fiducial volume of calorimeter considered useful (up to a radius of 1.5 m)
- in the case of the North Area beam the FODO quadrupoles required for $\mu$ running may be switched on, thus making simultaneous $\mu$/medium band $\nu$ running possible.

In this mode of operation the neutrino energy is no longer defined (see fig.5) but event rates $\sim 10^6$/30 days are obtained. Interesting rates are also possible with 2 ton H$_2$ or D$_2$ targets.

We favour the installation in the North Area of a combined $\nu$-$\mu$ beam because of good scheduling possibilities. We would use the long spill or possibly an intermediate spill envisaged for this area. We would require a magnetized iron section for shielding against high energy muons. If the beam is operated for the muon experiment, we expect a medium band neutrino beam, with a spectrum as shown in fig.5; event rates are shown in table 1.

A further improvement in neutrino event rates may be desired at a later phase. A focussing device operating in the D.C. mode has been designed for this purpose. In connection with the FODO quadrupole channel of the $\mu$-beam it can provide neutrino beams of a great variety, from high-band to wide band. (see also D.Treille, F.Vanucci, ECFA 300 GeV Working Group, Vol.I(1972)p.153). An additional muon shield is required and another neutrino laboratory must be built behind such a shield. This extension can remain optional if provisions for another target are foreseen.
IV. APPARATUS REQUIRED

IV.1 The target-calorimeter assembly

We wish to obtain some 200 tons of target material over a radius of 1.25 m and with high density. This target material is part of a hadron ionisation calorimeter. A total radius of 1.75 m and length of 8 m are chosen to ensure containment of the hadron showers initiated by neutrino interactions. Experience by Engler et al\(^5\) indicates a total of 10 interaction lengths in the direction of the hadron shower (which coincides with the neutrino direction to within \(\pm 10^0\)) and 2.5 interaction lengths in the transverse direction to contain hadronic showers. We envisage to determine the total hadron energy by sampling the energy loss between plates of iron aiming for a resolution of \(\Delta E_h/E_h = \pm 5\%\), at \(E_h = 100\) GeV.

A series of tests has been started by members of the collaboration to design the sampling device; we are investigating

- sampling by liquid argon ionisation chambers as proposed by W. Willis\(^6\)
- sampling by scintillators as described by J. Engler et al\(^5\).

It is our aim to obtain an analogue signal for trigger purposes, and to ensure uniformity of response and stability over large volumes and long periods.

A device along the first line would be highly modular, composed of cells 50 x 50 x 50 cm\(^3\), of density \(\rho = 5\), in total about 900 elements. The modularity would allow some differentiation of final states. A sketch of the set-up is shown in fig.6.

A test cell of similar size to the unit specified is now under construction and we hope to make measurements on it in the coming months. The Willis detector, provided that there are no great problems in cryogenics and mechanical design, appears to be a very attractive contender for hadron calorimetry in neutrino experiments.

Additional space is required for a 8 m long \(\text{H}_2\) and \(\text{D}_2\) dewar in front of the calorimeter.
IV.2 Muon filter and spectrometer

The muon filter is required to reduce the ratio \( N(\pi)/N(\mu) \) to less than 1%; for an assumed average of \( \bar{n}^+ = 4 \), a minimum of 1290 gr/cm\(^2\) of Fe is required as a separation between target and muon spectrometer. Any particle going beyond this range is labelled "muon" for the purpose of the trigger; the corresponding threshold is 1.8 GeV. Part of this filter (860 gr/cm\(^2\)) is already contained in the calorimeter; the remaining (430 gr/cm\(^2\)) is to be added in front of the muon spectrometer (see figure 6).

The muon spectrometer has to have wide aperture in order to accept muons with angles up to \( \theta_{\mu,\nu} = 20^\circ \) from the target (corresponding to \( x \leq 1, y \leq 0.9 \), for \( E_\nu > 100 \) GeV). Its diameter is approaching 6 m. Good momentum resolution is required. Extrapolating experience of the Rutherford Laboratory with a magnetized iron core magnet of similar size at the ISR, we arrive at \( \Delta p/p = \pm 5\% \) with a modular construction composed of 5 blocks of ARMCO steel 1m thick each and interspersed track sampling devices (see fig.6). We estimate an average \( \Delta p_{T\mu} \sim 400 \) MeV/c, for an average \( \overline{p}_{T\mu} \sim 6 \) GeV/c at \( E_\nu = 200 \) GeV.

An air cored \( \mu \) spectrometer is also being considered and designs and costings are being made.

IV.3 Flexibility of design

We realize the danger that by the time that the experimental programme can start some interesting discoveries could have been made at NAL and the emphasis in the world of neutrino physics may well have changed. The best that we can hope to do in our planning is to design the most advanced beams and detectors that we know how, and to build into these designs as much flexibility as possible. With regard to the beam we believe that the design is very good and that one will have both good intensity and resolution and high purity of lepton type. For the detector we see the Willis calorimeter as having unique and advantageous qualities. There is some development work required, but the time scale is right for SPS. But other types of sampling devices may be technically simpler. We will hope to build all sections of the detector in modular form:
the calorimeter could be 16 modules each $3V_2 \times 3V_2 \times V_2 m^3$

the $\mu$ spectrometer may have 5 to 10 $lm$ or $V_2 m$ modules longitudinally and we may well split the $6m \times 6m$ tranverse extent into 4 $3m \times 3m$ blocks. Thus restacking would be possible if the physics interest changes and a change in layout is indicated!
V. COLLABORATION

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Planned evolution of the collaboration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Laboratory</td>
</tr>
<tr>
<td>CERN</td>
<td></td>
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<tr>
<td>Hamburg</td>
<td></td>
</tr>
<tr>
<td>Karlsruhe</td>
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</tr>
<tr>
<td>Rutherford L.</td>
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</tr>
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<td>Westfield Col.</td>
<td></td>
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<tr>
<td>Oxford</td>
<td></td>
</tr>
</tbody>
</table>

Spokesmen for the collaboration: N.Lipman and K.Winter until 1.7.1974

The names of physicists and engineers involved now are:

CERN: F.Büsser, E.Friend, W.Schmidt-Parzefall, K.Winter

Hamburg: F.Niebergall


Westfield Col.: E.H.Bellamy, P.March

We are asking the laboratories for support and funding and could split up responsibilities for the various parts of the equipment as follows:
Hamburg and Karlsruhe:

Off-line computing facilities. On-line computers: Hewlett-Packard HP 2100, Telefunken TR 86, and CDC 1700, equipped with CAMAC interfacing; hadron calorimeter: design, electronics and part of manufacture. Beam monitoring.

Rutherford Lab., Westfield Coll., Oxford University:

Off-line computing facilities; muon spectrometer: design and manufacture, participation in calorimeter manufacture, and in track detector fabrication.

VI. EQUIPMENT REQUIRED FROM CERN

- The narrow band beam in the North Area
- The magnetized iron muon shield and hadron stopper
- Experimental area in zone 2 (see table 2)
- Possibility to create zone 3 at a later stage
- Some space in the West Area neutrino line for early tests from the start up of the SPS
- Cryogenics for liquid argon calorimeter (if adopted)
- Development and funding of large area track detectors
TABLE 2

Space requirements in zone 2

1) Detector:

<table>
<thead>
<tr>
<th>Item</th>
<th>Length</th>
<th>Width</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(_2)(D(_2)) dewar</td>
<td>8 m</td>
<td>3.5 m</td>
<td>10 t</td>
</tr>
<tr>
<td>Calorimeter</td>
<td>10 m</td>
<td>3.5 m</td>
<td>560 t</td>
</tr>
<tr>
<td>Muon filter</td>
<td>0.6 m</td>
<td>5 m</td>
<td>120 t</td>
</tr>
<tr>
<td>Muon spectrometer</td>
<td>6 m</td>
<td>5 m</td>
<td>1200 t</td>
</tr>
<tr>
<td>Free space</td>
<td>5.4 m</td>
<td>5 m</td>
<td></td>
</tr>
<tr>
<td>Free space behind</td>
<td>10 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>40 m</td>
<td>10 m</td>
<td>1690 t</td>
</tr>
</tbody>
</table>

Preferred beam height: 3.50 m

2) Service area:

<table>
<thead>
<tr>
<th>Item</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryogenics</td>
<td>200 m(^2)</td>
</tr>
<tr>
<td>Power supplies</td>
<td>50 m(^2)</td>
</tr>
<tr>
<td>Counting rooms and laboratory space</td>
<td>200 m(^2)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>450 m(^2)</td>
</tr>
</tbody>
</table>
REFERENCES

1) F. Büsser, N. Doble, N. Lipman, R. Orr, G. Petrucci and K. Winter
   "A New Design of Narrow Band Neutrino Beams", Nucl. Instr. and Meth.
   (to be published)

2) J. D. Bjorken and Ch. Llewellyn-Smith, Phys. Rev. D7, 887 (1973)


4) Report of the working party on neutrino beams for counter experiments
   CERN/SPSC/T73-4 (1973)

5) J. Engler et al., Nucl. Instr. and Meth. 106, 189 (1973)

6) W. Willis
   "A Liquid Argon Impactometer", ISRC (1972) and privtae communication
FIGURE CAPTIONS

Figure 1: Effect of propagator of an intermediate boson on total neutrino cross-section

Figure 2: Events rates expected for the production of heavy leptons of different masses

Figure 3: Spectrum of narrow band neutrino beam calculated for the proposed beam layout for the North Area at 200 GeV/c parent momentum

Figure 4: Proposed layout of narrow band beam

Figure 5: Neutrino spectrum expected in medium band mode tuned for 200 GeV/c parents

Figure 6: Sketch of envisaged detector for inelastic neutrino scattering
$\nu N \rightarrow \mu^- + \text{anything}$

$\nu N \rightarrow M^+ + \text{anything}$

400 GeV
$10^{18}$ protons
100 ton Fe

$v$ events per 10 GeV

$E_v$ vs. $v$ events per 10 GeV

FIG. 2