NEUTRINO EXPERIMENTS AT A 10-20 TeV PROTONSYNCHROTRON

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1. Introduction

This is the report of the group working on the extrapolation of neutrino physics to the 10-20 TeV energy range. Within the general framework fixed at the beginning of the workshop, we have been mainly looking at the possibilities and the limitations of the existing and the foreseeable techniques, devoting little time to the physics that will be tackled at that time. However, we would like to list here a few miscellaneous points that, on top of the physics we are now doing with neutrinos, we consider relevant to this field of physics.

(i) It is probable that at energies and momentum transfers much larger than those available today, the problem of the universal coupling of the leptons and their inner structure will be a central one. One can foresee that experiments that compare the behaviour of leptons will be very important, so that in the neutrino field one must devise ways of producing and using beams not only of ν_μ's, but also of ν_e's, ν_τ's and of the other yet undiscovered neutrinos.

(ii) If quarks are liberated at large energy and momentum transfers, neutrino (and charged lepton) production will give rise to quarks that are more energetic in the laboratory than the ones produced in e^+e^- collisions. The study of the interactions of high energy quarks with matter will be specific to neutrino physics and in general to collisions of leptons with matter.

(iii) Very probably leptons will still be used as probes of matter (nucleons, quarks, constituents of quarks, etc.). For these kinds of studies the flux and the quality of the beams will be essential, so that ν_μ-beams will be needed. According to present views, at increasingly large momentum transfers a proton at rest will be a reasonably unbiased source of quark-antiquark pairs of high mass flavours or, more precisely, of any pair of high mass fermion-

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antifermion. Production of any new fermion through charged current interactions depends upon generalized Cabibbo angles that are not easily measured in high energy e^+e^- collisions. One can foresee that, while quark masses will be measured at e^+e^- beam machine, neutrino interactions will be important tools for determining the mixing angles.

(iv) Purely leptonic interactions of the type $\nu_\mu + e \rightarrow \nu_\mu + e$ will be studied at center-of-mass energies of the order of 4 GeV. These reactions, among the simplest ones, are inaccessible to e^+e^- colliding beam experiments and are unique for studying the effects of a possible lepton structure.

(v) Production of intermediate vector mesons and of new particles, will certainly be a large part of any physics program, together with the study of higher order effects in the electro-weak interaction. It is far too early to make any quantitative estimates of these effects, that will very probably be studied beforehand at e^+e^- colliding beam machines.

In summary there seems to be space for meaningful and unique experiments with neutrinos but one needs an assessment of the complementary roles of neutrino physics and of experiments performed with electron-proton colliding beams. If at these energies leptons still look pointlike and electron-muon universality holds true, neutrino experiments may become unnecessary. We are aware of the problem but have not tackled it for the moment. Our work has in fact concentrated on the technical problems connected with the scaling of the needed facilities from 0.5 TeV to the 10-20 TeV energy range.

2. Targets

At present targets of aluminium oxide are being bombarded with 10^{13} (30 GeV) protons per second and berylium oxide with 3×10^{13} (500 GeV) protons every eight seconds without any difficulty. These involve beam spills that are less than, or of the order of, 1 msec, which is also the characteristic time of heat transfer. It is anticipated that pure berylium targets and standard cooling methods are sufficient to handle 1 TeV protons with intensities of 5×10^{13} protons per pulse, again at the short spill (1 msec) domain. As such, one believes that there should be no difficulty in the viability of target at much higher energies, in that the multiplicity should rise logarithmically with energy and the intensities should be $\simeq$ few x 10^{13} per pulse for short spills, $\lesssim$ 1 msec. For higher intensities of protons, one will have to improve the cooling, or use multiple targeting and multiple ejection, or increase the spill length appreciably, beyond 1 second. This problem has to be looked at in detail.

3. Horns and other focussing systems

Present horn focussing devices with currents of 100-300 KAmps work reliably, achieving almost perfect focussing of charged secondary particles in producing wide band neutrino beams. The combination of the more forward collimation of charged particles as the energy is increased as well as the greater interest in the higher end of the energy spectrum, appears to make the horn problem easier at higher energies than at lower energies for horn designs of the type used at Fermilab. The flexibility of the relative positioning of target and horn, as well as the geometry of the horn angle, should be sufficient to allow for adequately focussing the pertinent charged particle in forming neutrino beams at high energies. Horn currents do not have to be increased because the average transverse momentum of the secondaries remains the same and the horns have to give a p_T kick which is energy independent, as in the approach adopted by Fermilab for the 1 TeV neutrino beam. In this case the distance between the target and the horns would increase in proportion to the proton momentum P.

We now consider the scaling law for the focussing systems of a narrow band neutrino beam. Since the neutrino cross-sections increase with the neutrino momentum p_ν, one has the choice of scaling the beams at constant event rate or at constant neutrino flux. We feel the second choice is more reasonable, since high rates will certainly be needed for sophisticated experiments. We thus scale the focussing system by increasing the dimensions so that $\Delta p/p$ and $(p_T)_{max}$ remain constant. By keeping the topology of the focussing system fixed, one has

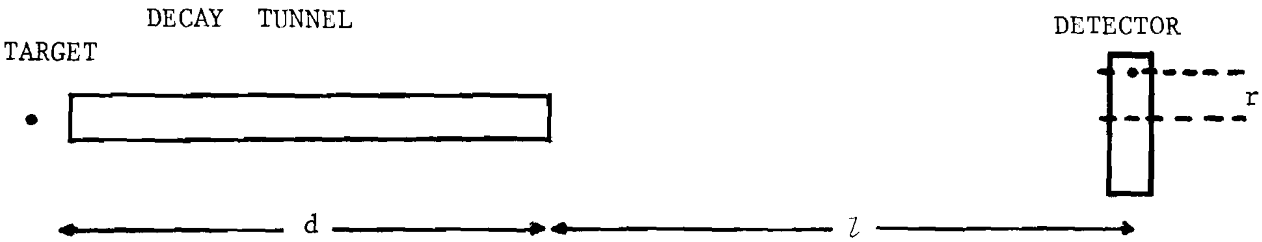
$$\frac{\Delta p}{p} \propto \frac{Sp}{B\ell L} \; ; \quad (p_T)_{max} \propto \lambda B, \tag{1}$$

where S is the source radius, ℓ the length of the system, L the length of the dipoles, and λ the length of the quadrupoles. Due to the heavy radiation fields we think normal temperature magnets will be used at these large energies also, and B has to remain constant. This implies that the length of the quadrupoles may remain constant. Since we suppose that the source transverse dimensions remain the same, we may scale the length of the system and of the bending magnets proportionally to $\sqrt{p}$ and keep $\Delta p/p$ constant. Then the aperture of the quadrupoles, $R \propto \ell\lambda B/p$, may even <u>decrease</u> proportionally to $1/\sqrt{p}$.

In conclusion, the focussing systems for neutrino beams do not limit the physics and their scaling laws are more favourable than the scaling laws of the accelerator itself.

4. Beams of ν_μ's and $\bar{\nu}_\mu$'s

The decay length d has to scale as the primary momentum P if one wishes to keep constant the fraction of pions decaying in muons. Certainly dichromatic beams will be used at these high energies and the next question has to be with the choice of the distance ℓ between the end of the main tunnel and the detector.



This length is determined by the fact that for events having vertex in the detector at a distance r from the center one likes to distinguish neutrinos produced by pions from neutrinos produced by kaons and compute the energy of the neutrinos from the measured value of r. The position uncertainty at the detector of a K-neutrino emitted at an angle θ_ν somewhere in the decay length d translates back to an angle uncertainty

$$\Delta\theta = \tfrac{1}{2}(\theta_{max} - \theta_{min}) = \tfrac{1}{2}\left(\frac{r}{\ell} - \frac{r}{\ell+d}\right)$$

which should be a small fraction η of the maximum θ_ν, thus

$$\Delta\theta = \eta\,\frac{P_{T\,max}}{P_\nu}$$

leading to a length ℓ

$$\ell = \frac{d}{2}\sqrt{1 + \frac{1}{\eta}\,\frac{2r}{d}\,\frac{P_\nu}{P_{T\,max}}} \qquad (2)$$

where P_ν is the neutrino momentum and $p_{T\,max}$ is the maximum transverse momentum in K-decay, i.e. 230 MeV/c.

We assume that the pion and kaon spectra are functions of $x = p/P$, where P is the proton momentum and p the secondary momentum, while their average p_T remains roughly constant. As shown in the previous section, one can scale the length of the focussing system proportionally to $\sqrt{p}$ and maintain the same neutrino fluxes. In fact we increase somewhat the neutrino flux because of the energy dependence of the secondary multiplicity. As in present neutrino experiments at CERN and Fermilab, we take d = 300 m for P_ν = 0.3 TeV. If the detector dimensions are kept constant with $r \lesssim 1$ m and one chooses $\eta \simeq 0.15$, Eq. 2 implies $\ell \simeq 3$ d. By taking for the narrow band beam $P_\nu^K \simeq 0.7$ P, we finally come to a target-detector distance:

$$(d+\ell)_{km} \simeq 3\,P_{TeV}\ ;\ \frac{\ell}{d} \simeq 3\ . \qquad (3)$$

At large energies muons radiate and the thickness of shielding material needed to range them out does not increase proportionally to the energy. The energy and the straggling of high energy muons have been computed by R.R. Wilson$^{1)}$. The <u>average</u> ranges in various materials have been calculated by D. Theriot and S. Mori by taking into account all the losses and appear in the Table together with the ratio of the bremsstrahlung and collision losses at the indicated energies.

E Muon energy (TeV)	Iron Av. Range $\bar{R}$ (km)	Iron $\left[\frac{(\Delta E\ brem)}{(\Delta E\ coll)}\right]$	Earth Av. Range $\bar{R}$ (km)	Earth $\left[\frac{(\Delta E\ brem)}{(\Delta E\ coll)}\right]$
1	0.25	1.5	1.6	0.6
5	0.50	8.3	3.0	3.3
10	0.60	17.3	3.8	6.5

Wilson has shown that (i) the fluctuations in the radiation process decrease by a factor ℓn2 the range and (ii) the fluctuations on the ranges of individual tracks (straggling) are smaller than might be expected intuitively. Wilson computed the r.m.s. fractional straggling $S/\bar{R}$ and found that it is practically constant between 1 and 10 TeV and is of the order of 0.5. By taking as a safe value 4 r.m.s. value from the average range, one can then estimate the needed thickness of shielding:

$$(\text{shielding thickness}) \simeq \frac{\bar{R}}{\ell n 2}\left(1 + \frac{4S}{\bar{R}}\right) \simeq 2\bar{R} .$$

Comparing the entries of the table with eq. 3 we conclude that for proton momenta larger than ≃ 2 TeV there is no need of iron shielding. If the path ℓ required to obtain a reasonable dichromatic beam is under earth, the muons would be ranged out by this natural shielding.

In conclusion a good narrow band neutrino beam of $P_\nu^K \simeq 10$ TeV could be obtained from a 15 TeV proton beam with $d \simeq 15$ km and $\ell \simeq 45$ km. These 45 km should not all be in earth since about 15 km of earth would be sufficient to shield the detectors from the muons: a hilly countryside is suitable for siting a 10 TeV neutrino beam. Since the muons in the shielding are in equilibrium with neutrinos, the increased muon range will produce a larger background than in present neutrino beams. The background flux scales as $\sigma_\nu \cdot \bar{R}$, i.e. roughly as $P_\nu \cdot \bar{R}$. Since in passing from 0.5 TeV to 10 TeV the flux increases by a factor ∿ 80, the background of muons may cause some problems to bubble chambers, but should be acceptable to electronics experiments.

5. Production of ν beams, other than ν_μ's

In the ν_μ beams presently in use the ν_e's are a small contamination. In order to enhance the ν_e content, pion decay should be suppressed, for instance by shortening the beams. Two ideas have been around, K_L beams and a muon storage ring, and at least one of them will presumably be implemented in the next years around the SPS or in FNAL.

In the first case$^{2)}$ all charged particles are swept out immediately after the production target (for a 15 TeV beam one needs 10^3 Tm). This is to be followed by a weaker sweeping magnet, to sweep away the pions produced in the decays of K_S and hyperons, thus reducing the ν_μ background (one needs $2 \cdot 10^3$ Tm). For an optimum ν_e flux the decay tunnel should have a length similar to one for ν_μ's from π and K decay, since $\gamma c t$ is similar. With the same decay path of the previous section one should obtain a ν_e-flux which is about two orders of magnitude less than the flux of ν_μ's from K decay. In case the detector is a bubble chamber, the K_L decay region probably has to be followed by a muon absorber. The beam consists of roughly equal amounts of ν_μ, $\bar{\nu}_\mu$, ν_e and $\bar{\nu}_e$, from $K_L^0 \to \pi\mu(e)\nu$, in the form of a wide band spectrum. Also ν_μ and ν_e from charmed particle decay will be present in a comparable amount. To determine the ν energy and type, a tagging system would be needed, the size and complexity of which will probably defy attempts to make it feasible economically. At best one can hope that a detailed study will result in a design of a beam much shorter than optimum for intensity, that could be equipped with a tagging system and still have rates that are interesting. A tagged $K^\pm$ beam should then also be considered, since it might become competitive with a shortened K_L beam, despite the 5% branching ratio $K^\pm \to \nu_e$. A shortened decay tunnel also has the advantage of a smaller radius since the production angle of the particles goes as 1/P.

The second idea is to build a racetrack-like storage ring. Initially π and K decays would deliver ν_μ's and at a later time muon decay would give equal amounts of ν_e and ν_μ; finally (anti) protons would be left in the ring.[3)] Tagging would not be useful. For 2 TeV muons the radius of curvature would be larger than 2 km.

The solution is certainly very expensive, but one could envisage using the same large acceptance ring for something else. For instance to collide pions and muons with the main ring or to produce $\mu^+\mu^-$ annihilations at large energies and very small luminosities. We think that the next workshop should devote some thoughts to these wild ideas.

Other neutrinos, like ν_τ from τ decay, will have to be produced in beam dumps, as the parents do not live long enough to make beams of them. In the dump the particles with decay distances $\gamma c \tau$ longer than their strong interaction absorption length λ will be prevented from decaying, but instead transfer their energy into a shower of which the last generation particles will finally be captured or decay and give low energy muons. Of the strongly interacting particles only charmed particles and heavy flavours with lifetimes < 10^{-12} sec, will decay before interacting, for energies of 1 TeV and below. The charmed particles decay into $\mu\nu_\mu$ and $e\nu_e$, the heavy flavours also in $\tau\nu_\tau$. There is not enough known about production cross section in a new energy domain to guess something about the ν_τ fraction of events. Tagging will presumably be impossible but variations of target thickness might vary the relative neutrino mix. Also the p_t dependence of the various neutrino components is presumably different and might be helpful in enhancing a particular component.

6. A hybrid bubble chamber for neutrino physics in the TeV range

A large cryogenic bubble chamber equipped with external as well as internal hybridisation is well suited to many aspects of a future neutrino physics program. The technology is well developed and extrapolated performance features can be predicted with some confidence. A zeroth order approximation considered here is a cylindrical chamber about 5 metres long and 2 metres diameter equipped with a modest field of about 30 Kgauss. The volume ($\sim$ 15 m^3) is about one half of BEBC or the 15 ft FNAL chamber. The chamber would be equipped with a track sensitive target of approximately 3 x 1.5 x 1.5 m^3 (comparable in volume with that operated this year in BEBC). The chamber could then be used either as a pure hydrogen or deuterium chamber or as a pure heavy liquid neon or neon-hydrogen chamber or as an internal hybrid with two sections: a TST (hydrogen or deuterium) followed by heavy liquid (of variable radiation length 40-1000 cm). External hybridisation would include a hadron calorimeter and a muon identifier as minimal components.

We consider here only general features of the set up and clearly no detailed optimization has been included nor have alternative schemes such as the argon chamber proposed for the energy doubler been looked into.

The obvious advantages of the chamber based system are:

Excellent resolution and track measurement precision which allows together

1. Track counting before secondary interaction confuse the situation
2. Precise measurements of charged particle momenta including electrons in hydrogen and muons before they leave the chamber

3. Precise angle measurements
4. Excellent electron identification in neon hydrogen
5. Some visible gamma conversions to monitor the start of the hadron calorimetry
6. Strange particle detection and identification (K^0, Λ^0's) when they decay in the chamber

For a cross-section $\sigma \sim 0.8\ E_{GeV}\ 10^{-38}\ cm^2$ a 3 metre hydrogen filled TST will have $\sim$ 1 event per pulse for 10^{13} protons on the target ($10^{10}\nu$/pulse). The chamber could easily cycle at 1 per second taking 10 pictures, i.e. 10 events, per flat top.

Charged hadrons are measured within the TST (i.e. before secondary interactions become too serious) with precision

$$\left(\frac{\Delta p}{p}\right) \simeq 5\left(\frac{p}{100\ GeV}\right)\ \%$$

Muons are measured with improved accuracy

$$\left(\frac{\Delta p}{p}\right) \simeq 2\left(\frac{p}{100\ GeV}\right)\ \%$$

Electrons are identified by bremmstrahlung in the neon-hydrogen 100% efficiency. Electron measurements are made in hydrogen with an optimum length and precision which are only slowly varying with momentum ($\ell = 20\ p_{GeV}^{0.4}$cm) so that

$$\left(\frac{\Delta p}{p}\right) \simeq 7\ p_{GeV}^{0.2}\ \%$$

Angle errors for electrons are always in the range 0.1 - 0.4 mrad. Externally it would be useful to have a hadron calorimeter followed by a muon identifier. The muon identifier should be instrumented to give as good a momentum measurement as possible and help in correlating the tracks between the chamber and the EMI.

To allow photography of the full chamber depth of 2 metres the resolution is limited to 600 μm. The decay length of a particle of mass M is $\delta \sim (\frac{p}{M})$ 30 n μm where $\tau = n \cdot 10^{-13}$ s. For $\frac{p}{M} \sim 100$ $\delta \sim 3$ n mm. Thus in a clean production situation, the normal resolution will allow clear longitudinal separation of vertices. Laterally the separation of decay vertices from neighbouring tracks will be $\sim$ 30 n μm and is not feasible. However, in the "dirty" situation, i.e. many produced particles one of which is a new flavour, it should be possible to find the decay vertices by measurement and fitting. At a loss of rate of a factor less than 10 a slice of the chamber could be viewed with about 100 μm resolution.

In summary a first look indicates that reasonably conventional bubble chamber neutrino experiments will be viable and very interesting at high energies and could form a major part of the physics program at a multi TeV machine. More ambitious solutions such as the ARGONAUT system clearly also have attractions and should be considered alongside that considered here. Equally pure electronic experiments will certainly play a role. The short time available did not allow any serious consideration of the possible developments of these kinds of detectors.

7. Unconventional use of neutrino beams

The opening angle of the beam is so small that reasonable counting rates would be obtained at large distances from the decay tunnel. For instance, a detector of 20 x 20 x 25 m^3, containing 10^4 tons of material and placed at 3000 km from the target, would see one neutrino event for every 10^{13} protons on target. One can thus envisage directing the neutrino beam towards a far away detector. The possible uses of such a scheme have been listed by P. Koster et al. in a proposal recently presented to Fermilab.4) For the time being we leave this open as an interesting possibility.

8. Conclusions

In scaling up by a factor 10-20 of present day neutrino physics we have not found sharp limitations. However, we see many areas of potential problems. In particular the targets and the background flux of muons produced in the shielding have to be studied in more detail. Beams of unusual neutrinos call for new solutions, among which we consider the muon storage ring very attractive; especially if the same ring can find some other interesting utilization. It seems that bubble chambers will still be useful instruments, but the development of new devices, such as the argon time projection chamber, has to be followed in the next years.

A physics question dominates the whole development of neutrino physics: will electron-proton colliders make neutrino beams useless? The answer depends on what nature is still hiding from us, but still the problem is worth investigating on the basis of possible scenarios and we believe that this could be one of the main topics in the lepton working group of the next ICFA workshop.

We are grateful to S. Mori and D. Theriot for very informative discussions and for providing us with the data appearing in the Table.

References

1) R.R. Wilson, Evolution of particle physics, M. Conversi ed., Academic Press, 1970, p. 294.

2) Studies for a K_L beam have been made by Baltay et al., FNAL proposal 296 (1974). Mori, FNAL technical note 78 TM 769 (1978). See also Cline, Mori, Stefanski, FNAL technical note TM 802 (1978).

3) A muon storage ring has been considered by Koshkarev, CERN report ISR DI 74-62, 16 December 1974.

A comparison of various schemes has been made by Wojcicki, FNAL preprint (1978).

4) P. Koster, Some experiments with long terrestrial neutrino beam lines, 1978.