REPORT OF THE FIXED TARGET PROTON ACCELERATOR GROUP

Summarized by L. Pondrom

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I. Introduction

The fixed target proton accelerator group divided itself into two roughly equal parts. One sub-group concentrated on a high intensity (10^{14} protons/sec) moderate energy (30 GeV) machine while the other worked on a moderate intensity (5×10^{11} protons/sec) very high energy (20 TeV) machine. The proceedings of other workshops have been very helpful to both subgroups. Workshops concentrating on the proposed LAMPF II accelerator at Los Alamos[1] served as a framework for the deliberations of the first subgroup, whereas the studies by the International Committee for Future Accelerators were invaluable to the second[2].

Since accelerators have been operating in the 30 GeV energy range for years, it is possible to plan specific experiments for the high intensity version in detail. The subgroup was mainly interested in neutrino interactions and searches for rare decays of K mesons. A factor of ten increase in average intensity over the present Brookhaven AGS will provide significantly improved experiments in these and other instances.

The proposed 20 TeV machine would reach a maximum energy in the p-p center of mass of $\sqrt{s}$ = 190 GeV, less than half that currently available at the CERN $\bar{p}p$ collider, so it really is not practical to contemplate the construction of a fixed target machine to extend the available energy. For experiments where the total available energy is adequate, the fixed target option added to a $\bar{p}p$ 20 TeV collider ring has several attractive features: 1) High luminosity afforded by intense beams striking thick solid targets; 2) Secondary beams of hadrons, photons, and leptons; and 3) The versatility of a fixed target facility, where many experiments can be performed independently. The proposed experiments considered by the subgroup, including neutrino, photon, hadron, and very short lived particle beams were based both on scaled up versions of similar experiments proposed for Tevatron II at Fermilab and on the 400 GeV fixed target programs at Fermilab and CERN.

The experimental opportunities afforded by these new machines will be the subject of this summary. Construction techniques and cost estimates are covered in the report of the Accelerator Group in these proceedings.[3]

II. High Intensity Moderate Energy Proton Accelerator

The parameters chosen for this accelerator are:

$$E_p = 30 \text{ GeV}$$
$$I_p = 10^{14} \text{ protons/sec}$$
$$\text{duty factor} = 50\%$$

This is about a factor of 10 increase in intensity over the present Brookhaven AGS, which would allow either a corresponding increase in intensity of secondary beams, or improvement in the definition or purity of such beams, or both.

A. Neutrino Physics

The broad band neutrino beam at the AGS yields about 4.7×10^{17} ν_μ's per day, with half as many $\bar{\nu}_\mu$'s and less than 1% as many ν_e's.[4] The average energy is $\langle E_\nu \rangle = \langle E_{\bar{\nu}} \rangle$ = 1.4 GeV. The flux in a narrow band beam depends on the details of the design, but a factor of ten loss, or 4.7×10^{16} ν_μ's per day, seems to be a reasonable estimate. The new machine would therefore furnish a narrow band ν_μ beam with average intensity comparable to the present wide band beam.

A study of the differential cross sections for the neutral current reactions

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$
$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$$

becomes feasible in such a narrow band beam. In the Weinberg-Salam model the differential cross section is

$$\frac{d\sigma(\nu_\mu e^-)}{dy} = \frac{G^2 m_e E_\nu}{2\pi}\left\{(1-2\sin^2\theta_W)^2 + 4\sin^4\theta_W\,(1-y)^2\right\}$$

where $y = E_e/E_\nu$, and the constant and $(1-y)^2$ coefficients interchange for $\bar{\nu}_\mu e^-$ scattering. The narrow band beam is necessary because E_ν can be determined adequately from the transverse position of the event in the detector to allow a calculation of y from the measured electron energy. The total cross section for $(\nu_\mu e^-)$ is approximately

$$\sigma(\nu_\mu e^-) = \frac{G^2 m_e E_\nu}{6\pi} \sim 1.4 \times 10^{-42}\ E_\nu\ \mathrm{cm}^2/\mathrm{GeV}$$

for $\sin^2\theta_W = 1/4$. If the "standard" detector is 2000 gm/cm^2 (20 meters of water equivalent), then the expected rate in the narrow band beam is R = 800 events/day for ν_μ and about half as many for $\bar{\nu}_\mu$. Even with some loss due to detection efficiency these rates are adequate to measure differential cross sections in a reasonable amount of running time. Because the two functions of $\sin^2\theta_W$ interchange with $\nu_\mu \to \bar{\nu}_\mu$, the ratio

$$\frac{d\sigma}{dy}(\nu_\mu e^-) \Big/ \frac{d\sigma}{dy}(\bar{\nu}_\mu e^-)$$

is particularly sensitive to $\sin^2\theta_W$ near y = 1. For example if $0.5 \le y \le 1.0$, $\sigma(\nu_\mu)/\sigma(\bar{\nu}_\mu) = 1.67$ if $\sin^2\theta_W = 0.2$, a ratio which inverts $\sigma(\nu_\mu)/\sigma(\bar{\nu}_\mu) = 0.60$ if $\sin^2\theta_W = 0.3$. If 10,000 events are obtained between $0.5 \le y \le 1.0$ for each sign of the neutrino beam, then from the ratio $\sigma(\nu_\mu)/\sigma(\bar{\nu}_\mu)$ a measurement $\sin^2\theta_W = 0.220 \pm 0.002$ should result.

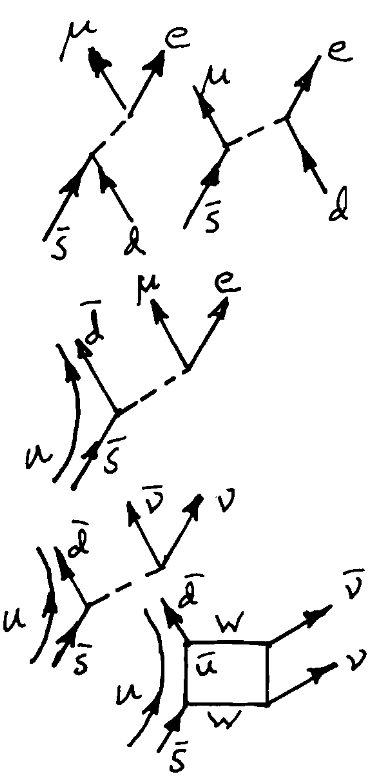
B. Rare K Decays

Recent theoretical speculations[5] have renewed interest in searching for rare decays which involve flavor changing neutral currents, or lepton number non-conservation, or both. In addition, the phenomenon of CP violation is a perennial puzzle. High intensity "K factories" make it possible to do more sensitive experiments on these subjects.

Representative decays are shown below, together with possible diagrams and present experimental limits. New neutral weak bosons which change quark flavor at one vertex and lepton flavor at the other, or lepto-quarks, which allow a quark to change into a lepton directly (and lead to a finite lifetime for the proton) are needed to make these reactions proceed. The third example, $K^+ \to \pi^+\nu\bar{\nu}$, is allowed in second order, as is shown schematically in the box diagram. In principle the rate for this second order process depends on the total number of $(\nu\bar{\nu})$ pairs accessible to the final state.[6]

RARE K DECAYS

DECAY MODE	DIAGRAMS	PRESENT LIMIT
$K_L^0 \to \mu^\pm e^\mp$		$<2\times10^{-9}$
$K^+ \to \pi^+\mu^\pm e^\mp$		$<5\times10^{-9}$
$K^+ \to \pi^+\nu\bar{\nu}$		$<1.4\times10^{-7}$



Searches for some of these decay modes with improved sensitivity are either in progress or proposed for existing machines at the present time. An order of magnitude intensity increase would aid these efforts. It is interesting to note that a selection rule which is not energy forbidden in a particular decay is in general much more sensitively tested by searching for the decay than by looking for a forbidden reaction in, for example e^+e^- colliding beams. The detailed argument is given in Ref. (5).

There are many more examples of interesting experiments which became feasible with a high intensity 30 GeV machine. Such a facility would be a natural extension of existing accelerators, and would have unique advantages for the study of certain fundamental questions.

III. Moderate Intensity Very High Energy Proton Fixed Target Accelerator

The parameters chosen for this accelerator are:

E_p = 20 TeV
$\sqrt{s}$ = 190 GeV
$I_p = 4 \times 10^{11}$ protons/sec
(2×10^{14} protons/pulse)
Cycle Time 8 Minutes
Spill Length 2 minutes

A machine of this general type has been considered in great detail in Ref(2). The present report endorses and augments the ICFA study. Some of the results of that study are repeated here without much change for the sake of completeness.

A. Scaling Laws

The range of muons in condensed matter increases linearly with increasing energy up to a few hundred GeV. A rule of thumb is that the muon loses 1 GeV for every meter of iron traversed. Fortunately, for energies above 1 TeV this linearity no longer holds, because energy loss by radiative processes becomes important, and the muon range tends to saturate. By way of bremsstrahlung the muon pumps energy into γ rays and e^+e^- pairs which have a radiation length of 1.8 cm in iron. Hence about 1 km of Fe or 5 km of earth are adequate to range out 10 TeV muons.[7] Thus the shielding problem for a 20 TeV machine, although still formidable, is not absolutely overwhelming.

For focusing or bending of charged particle beams, one can assume constant magnetic field B and constant deflection X. For a dipole of length ℓ a distance L away, $X = B\ell L/p$, where p is the momentum in suitable units. If both the magnet length ℓ and the beam length L scale by $\sqrt{p}$, then X remains the same. This rule can be applied to spectrometers as well, so that the same drift chamber system will work with the same momentum resolution at 20 TeV as at 1 TeV as long as the magnet and the chamber system are both stretched longitudinally by $\sqrt{20} = 4.5$.

Any beam which depends on decays, muon or neutrino beams made by $\pi\to\mu\nu$ and $K\to\mu\nu$ for example, stretches linearly with p, since that is the way the decay length scales. The transverse momentum $p_\perp$ in the decay is invariant, however, so that the number, aperture, and excitation of the quadrupoles remain the same. They are merely placed further apart.

A large increase in laboratory momentum is especially advantageous for the study of very short lived particles, heavy flavors or new leptons, where the gain in flight path may be of considerable importance.

B. Neutrino and Muon Beams

Three neutrino beams were considered by Mori[7]: 1) A bare target beam with 10^{10} ν_μ's $E_\nu > 4$ TeV per 2×10^{14} protons; 2) A narrow band beam with $> 10^8$ ν_μ at $E_\nu \sim 10$ TeV; and 3) A prompt ν beam from a beam dump, with special interest in the flux of ν_τ's. Significant improvements over Mori's designs must await the experience to be gained at 1 TeV in the Tevatron II program at Fermilab.

A conventional muon beam can be scaled from the Tevatron II design.[8] The parameters of that beam are shown in the accompanying figure and table. The expected 20 TeV yields are the same numbers as those in Ref (8), scaled in momentum. The momentum p_μ is the central momentum for the transport system, which has a very broad acceptance. The hadron capture section of the beam line transmits all particles with momenta greater than 0.6 p.

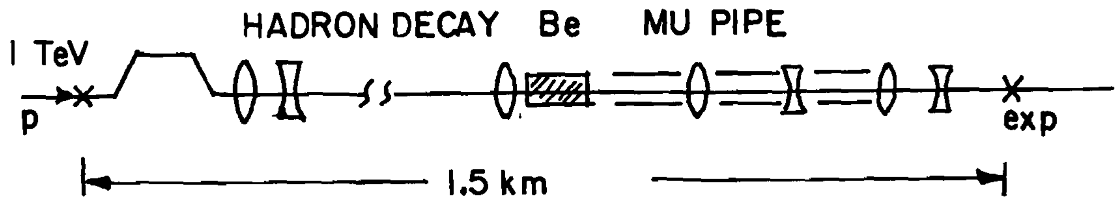


Fig. 1. Tevatron II muon beam design (Ref. 8).

PARAMETER	1 TEV	20 TEV
Decay length	1 km	20 km
Beryllium absorber	11 m	15 m
Mu pipe (4"ID,6"OD		
Iron magnetized to 15 kg)	300 m	1.3 km
Quadrupoles	4Q120,2.7kg/inch	Same
Number of Quads	20	20
Distance between quads	64 m	1280 m
Total beam length	1.5 km	30 km

Expected Yields for 20 TeV Protons

p_μ TeV/c	$\mu^+/2 \times 10^{14}$	halo (3m x 3m)
4.4	6×10^{10}	8%
8.8	1.5×10^{10}	5%
15.0	2×10^{9}	4%

The 15 TeV muon beam has an average intensity of 2×10^6 μ's/sec and corresponds to kinematic variables in the μ-p center of mass of E* = 170 GeV, $Q^2{}_{max} = 3 \times 10^4$ GeV^2, nearly the same as in an e(10 GeV) x p(1 TeV) collider.[9]

The equivalent luminosity of the muon beam is 10^{32} cm^{-2}sec^{-1} in a 10 m liquid hydrogen target, or 6×10^{33} cm^{-2}sec^{-1} in a 5000 gm/cm^2 iron target.

The muon helicity is naturally backwards for the weak interactions, that is forward μ^- from $\pi^- \to \mu^-$ decay are right handed. The backward μ^- are left handed, but have about 60% of the energy and much less favorable solid angle. Helicity flip could be accomplished by tuning the muon line to 8 TeV, say, and using 8 TeV π's for forward μ's, but 13 TeV π's for backward μ's. The μ spin flip is certainly possible, but costs both in flux and in maximum muon energy.

It is intriguing to consider the possibility of constructing a tagged neutrino beam-that is one in which both the charged lepton and the neutrino are detected in coincidence.[10] Tagging unambiguously gives the flavor of the neutrino (ν_μ, ν_e, $\bar{\nu}_\mu$, $\bar{\nu}_e$) as well as E_ν. For muon neutrinos this same information is available in a dichromatic beam, but for electron neutrinos tagging may be the only method of positive identification. Tagging is hard to do because of the large number of charged leptons that must be recorded to get one neutrino detected. The probability of detecting a neutrino in 5000 gm/cm^2 is $P = 2 \times 10^{-11}$ E_ν (GeV) which becomes $P = 2 \times 10^{-8}$ for E_ν = 1 TeV. At this energy 5×10^7 e's must be counted for every ν_e event, which might actually be feasible.

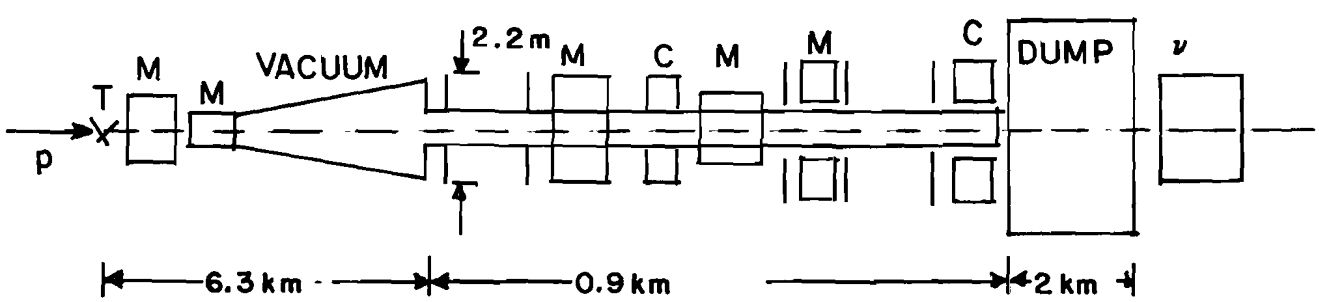


Fig. 2. Tagged ν beam from $K_L^0 \to \pi e\nu$, $\pi\mu\nu$. T is the target, M's are magnets, C's are e.m. and hadronic calorimeters for $e\mu\pi$ identification.

A tagged K_L^0 beam was designed to detect charged $\pi^{\pm}\mu^{\mp}$ downstream of a 6.3 km decay path. With the neutrino vertex the reconstruction of the event is a 2C fit. The tagger is shown schematically in Fig (2). The device could also be used to search for rare K_L^0 decays like $K_L^0 \rightarrow \mu^{\pm}e^{\mp}$.

The energy E_ν ranges from 0.5 to 2 TeV, known to ±6% from the tag. The average tag counting rate is 10^7/sec (50% good). The estimated charged current rate per year per 5000 gm/cm^2 detector is:

RATE PER YEAR

	ν	$\bar{\nu}$
e	1.2×10^5	4×10^4
μ	8×10^4	3×10^4

C. Photon Beams

Several methods were considered for constructing a photon beam. Perhaps the most novel, also discussed in Ref (2), employs synchrotron radiation energy loss to separate e^- from π^- and K^-. The fractional energy loss for a charged particle with mass m is

$$\frac{\Delta E}{E} = 8.6 \times 10^{-20} \frac{B^2 L p}{m^4} \qquad \frac{T^2 \text{ meters GeV}}{(\text{GeV})^4}$$

Hence in a 2T field extending over 6 m a 5 TeV e^- becomes a 4 TeV e^-. The spatially separated electrons could then be used to make a tagged photon beam. A broad band γ beam could be made by passing a neutral beam through a low Z hadron filter. A conventional tagged photon beam could be made by converting γ's, bending the resulting electrons around, and reconverting. These three methods are summarized in Figure 3.

A fourth method was to use neutral strange particle decay as a source of γ rays. A decay pipe 1 km long would be used, and γ rays from $K_S^0 \rightarrow \pi^0\pi^0$ and $\Lambda \rightarrow n\pi^0$ would be collected in a ring aperture subtending 10 μrad to 30 μrad at the upstream end of the decay region. The γ ray spectra so obtained are shown in Fig. 4. The advantages of such a beam are that it has no low energy bremsstrahlung peak, and that it contains no hadrons. The characteristics of the photon beams are summarized in the table.

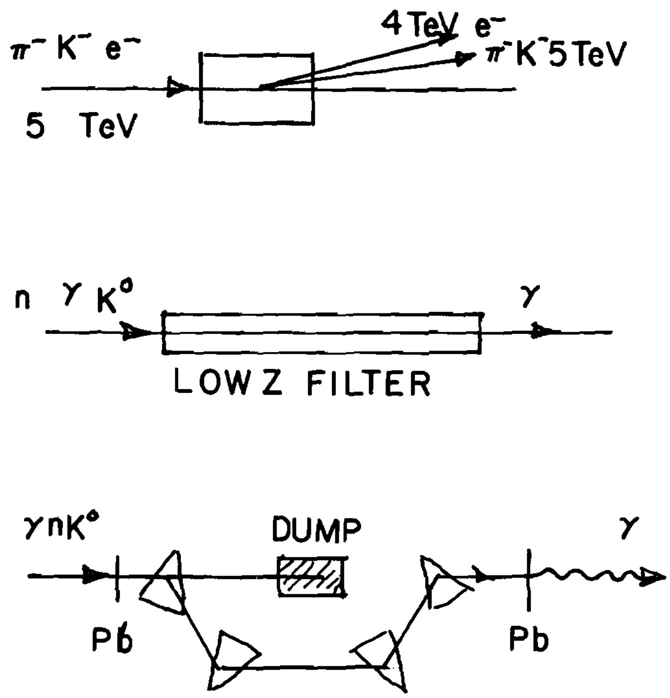


Fig. 3. Photon beams by synchrotron radiation separation, hadronic filtering, and $\gamma \rightarrow e \rightarrow \gamma$ conversion.

Photon Beams

5×10^{11}/sec 20 TeV protons on target assumed. (25% duty factor)

	BROAD BAND	TAGGED	Λ, K_S^0 DECAY
	Hadrons in Beam		
E_γ	< 12 TeV max <7.5 TeV useful	$\leq$ 7.5 TeV	0.5 TeV - 10 TeV
AVG E N_γ/sec.	2.5×10^7	2.5×10^6	1.5×10^6

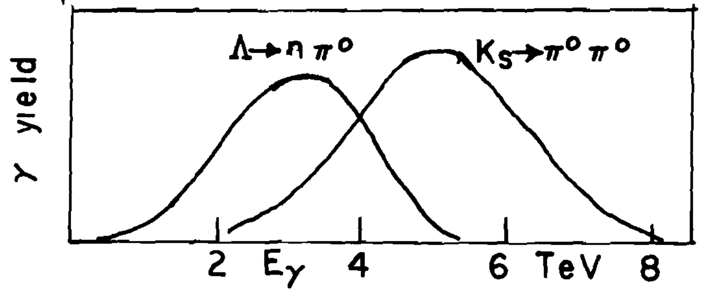


Fig. 4. Spectra of γ's from decay of neutrals.

PRODUCTION OF HEAVY FLAVORS

	PHOTOPRODUCTION		HADROPRODUCTION	
	$\sigma_{\gamma N}(\sqrt{s} = 60$ GeV)	σ_T fraction	$\sigma_{pp}(\sqrt{s} = 300$ GeV)	σ_T fraction
σ_{TOT}	150 μb	1	50 mb	1
$c\bar{c}X$	2 μb	.013	500 μb	.01
$b\bar{b}X$	70 nb	4.4×10^{-4}	3 μb	6×10^{-5}
$t\bar{t}X$ (m_t = 20 GeV)	$\lesssim$ 15 nb	$\leq 10^{-4}$	2 nb	4×10^{-8}

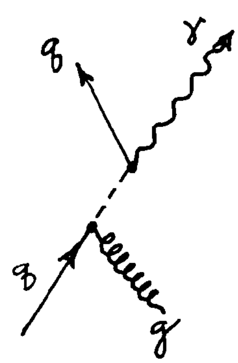
A major application of a multi-TeV photon beam would be the photoproduction of new (and old) flavors. Photon-gluon fusion competes favorably with gluon-gluon pair production and the three gluon vertex, as is shown in the table above. The signal to noise ratio should increase dramatically for $b\bar{b}$ and $t\bar{t}$ production by photons. The pair production of new leptons also competes very favorably with the hadronic Drell-Yan process.

D. Hadron Beams

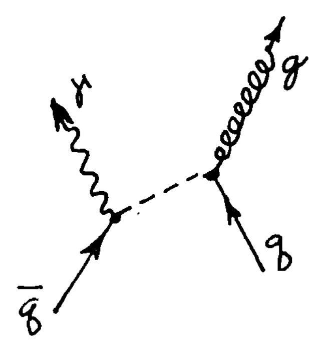
The ability to send an intense hadron beam into a beam dump is a unique feature of a fixed target machine. Dumps have been briefly mentioned in Section B in connection with τ neutrinos. Such passive dumps might also be the best way to look for new heavy neutral leptons.[11] An instrumented beam dump, in which the total electromagnetic and hadronic energy is measured, could be used to search for new non-interacting particles, albeit at a reduced luminosity.

The experimental feasibility of such a search depends on three factors: 1) The energy resolution function of the instrumented dump; 2) The energy carried off by the unobserved neutrino-like particle; and 3) The probability of producing the particle per interaction. Suppose the resolution of the calorimeter is $\Delta E = 0.7 \sqrt{E}$ GeV. The tails are probably not gaussian, but assume that they are. Then the energy of the beam into the dump can be optimized to search for a given amount of missing energy with a certain probability. For example if E (missing) = 100 GeV and E_{TOT} = 1 TeV, then the missing energy is about 4σ away from E_{TOT}, meaning that if the new particle is made about $\sim 10^{-3}$ per interaction, it would be observable. To eliminate "ordinary" neutrinos, the accompanying $\mu^{\pm}$ or $e^{\pm}$ would have to be observed as well. Decays like $\tau \to$ hadrons + ν_τ would form a background.

Pion beams offer advantages in the study of the Drell-Yan process, the production of quark and gluon jets, and the production of single γ rays. For example, a comparison of $\pi^+(u\bar{d})$ and $\pi^-(d\bar{u})$ on an I = 0 (u = d) target can be used in principle to study gluon jets. The argument involves the separation of two single γ ray production diagrams, the compton and the annihilation. The second



Compton



Annihilation

diagram will be proportional to the square of the $(\bar{q}q)$ charge, and hence larger in $\pi^- \to$ jet + γ than in $\pi^+ \to$ jet + γ.

An appealing feature of a 20 TeV fixed target accelerator is the possibility of producing "beams" of very short lived particles. A 5 TeV Λ_c^+ has a mean flight path of about 15 cm, while a τ lepton of the same energy goes about 20 cm. One can think of several applications where these distances would be useful. For example, the magnetic moments of these particles might be measurable. The Λ_c^+ moment is expected to be about 0.3 nm (g/2 = 0.7), while that of the τ is 0.5 nm (g/2 = 1). It is difficult to use conventional high field magnet techniques. The Λ_c^+ spin would precess only 7° in 15 cm in a 20T magnet. The channeling of particles along planes in a bent crystal, however, produces very strong equivalent magnetic fields, $B_{eff} \sim 1000$ T, so that if a substantial number of polarized high energy Λ_c^+'s or τ^+'s could be captured by a crystal, high sensitivity to (g/2 - 1) could be achieved.[12] Presumably forward production $p \rightarrow \Lambda_c^+$ would be the best way to produce polarized charmed baryons, relying on the process which works so well at lower energies for $p \rightarrow \Lambda$. The decay $F^+ \rightarrow \tau^+\nu_\tau$ gives polarized τ's directly. Perhaps photoproduction would be the best way to make F's. Both F's and τ's would have to channel in the bent crystal in this case. The Λ_c^+ spin direction could be measured in a final state which involves a Λ. Leptonic decays of the τ indicate the spin direction just like μ decay. Nothing to it.

IV. Conclusions

Two types of fixed target machines have been discussed in this report. Each can make fundamental contributions to high energy physics which are complimentary to the colliders. If a 20 TeV "Desertron" collider is constructed in the future, the fixed target option should be seriously considered.

References

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2) Workshop on Possibilities and Limitations of Accelerators and Detectors; 2nd held at Les Diablerets, Switzerland, 1979. Ed. Ugo Amaldi, CERN (1980).

3) Report of the Accelerator Study Group, these proceedings.

4) The authors wish to thank Dr. R. Lanou for data on AGS neutrino beams.

5) See the Report of Beyond the Standard Model Group, these proceedings.

6) This calculation is difficult to perform because of unknown quark mixing angles and other complications. This was pointed out by Dr. R. Schrock.

7) See the article by Shigeki Mori in Ref (2).

8) "Design Study for a High Energy Muon Beam" by R. Evans, T. Kirk, et al, Fermilab Technical Memorandum TM-754, 1977 (unpublished).

9) The physics capability of such an ep facility is discussed in detail in the "Cheer Feasibility Report" Canadian Institute of Particle Physics, 1980. (unpublished)

10) This possibility is discussed for the UNK machine by S.P. Denisov, et al, Report of the Institute for High Energy Physics IFVE 81-98, Serpukhov, 1981 (unpublished). Various Fermilab proposals have also looked into neutrino tagging.

11) This possibility is discussed by M. Perl in the Report of Beyond the Standard Model Group, these proceedings.

12) R.A. Carrigan, et al, Nucl. Instr. & Meth. 194, 205 (1982).