THEORETICAL QUESTIONS AND MEASUREMENTS OF NEUTRINO REACTIONS IN BUBBLE CHAMBERS

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ABSTRACT

This report will be divided into two sections, the first of which deals primarily with theoretical questions of interest in neutrino physics while the second describes the experimental aspects of these reactions in the NAL 15-ft bubble chamber. In both sections reactions are discussed in order of decreasing simplicity. A table is presented summarizing the capabilities of the 15-ft chamber with and without additional equipment.

I. THEORETICAL QUESTIONS

A. Two-Body Reactions

According to the currently accepted Cabibbo theory, the weak-interaction current consists of two terms, each of which is of the V-A form. The first has strangeness zero and transforms as the $I = 1$ $I_z = 1$ member of an SU(3) octet. The second transforms as the strangeness 1, $I = 1/2$, $I_z = 1/2$ member of the same octet. The allowed two-body reactions are therefore:

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

$$\bar{\nu} + p \rightarrow \mu^+ + B^0, \quad B^0 = n, \Lambda^0, \Sigma^0 .$$

The relative form factors and polarization correlations are all predicted by the theory and have been extensively discussed by Pais.[1] The final-state baryon polarization is more accessible experimentally than the muon polarization and is potentially of great importance. The Σ^0 production is especially interesting since the inverse process Σ^0 beta decay is not amenable to experiment due to the short lifetime of the Σ^0. The total cross sections for each of the two-body reactions is predicted to approach a constant value as the neutrino energy is increased. However, if the total inelastic cross-section levels out in the NAL energy range due to higher order weak effects, we might expect the quasi-elastic reactions above to fall with increasing E_ν.

In addition to the above, it will be interesting to search at high energy for the forbidden reactions with $\Delta S/\Delta Q = -1$ or $|\Delta S| = 2$. Similarly, one might look for second-class currents and/or CP violations becoming prominent at high energy.

B. Three-Body Reactions

These include single π production, N^* and Y^* production and the associated production processes. The electroproduction of N^* is related by CVC to the vector part of neutrino production of the same state and then by SU(3) to the Y^* neutrino production. In the N^* and Y^* regions simple tests are available of the $\Delta I = 1$ and $\Delta I = 1/2$ rule respectively. The three-body reactions allow the simplest test of the Adler relation[2] between neutrino and pion production of a general hadronic state F, namely,

$$\frac{d^2\sigma}{dq^2 d\nu}(\nu + N \to \mu^- + F) \underset{\theta_\mu \simeq 0}{=} \frac{G^2}{2\pi^2}\,\frac{f_\pi^2}{\nu}\,\sigma(\pi + N \to F)$$

$$\times\left[\frac{E_\mu}{E_\nu} - \frac{\nu}{E_\nu}\,\frac{m^2}{q^2+m_\pi^2} + \frac{\nu^2}{4E_\nu^2}\,\frac{q^2+m^2}{\left(q^2+m_\pi^2\right)^2}\right],$$

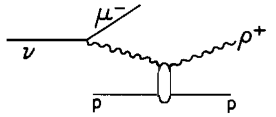
where f_π is the PCAC constant $\left(\partial_\mu A_\mu = f_\pi m_\pi^2 \phi_\pi\right)$ and m is the lepton mass.

The associated production (e.g., $\nu + p \to \mu^- \Sigma^+ K^+$) may yield a copious supply of hyperons whose polarization provides an easy test of T invariance through correlations such as $\sigma_\Sigma \cdot p_\mu \times p_\nu$.

C. Multiparticle Final States

1. Diffractive Production

Although simple vector-dominance models[3, 4] are in disagreement with newer electroproduction data, it is generally expected that diffractive processes will play an important role in high-energy electron and neutrino-induced reactions. The basic picture is that at high energies the weak-current diffractively dissociates (through "Pomeron" exchange with the target) into hadron states with the same quantum numbers as, for example, in the diagram below.



The lowest lying meson states with the quantum numbers of the weak current are π, ρ, A_1, K, K^*, K_A^*. It will be interesting to see, therefore, whether production of these states dominates over charge-exchange reactions such as ρ^0 production and over N^*-type events. It will be also interesting to see whether each diffractive reaction rises linearly with energy becoming a constant fraction of the total neutrino cross section. In this event we would have a parallel to diffractive ρ photoproduction which becomes a constant fraction ($\approx 1/6$) of the total photoabsorption cross section. Furthermore, in the diffractive region the contribution of the axial current to ρ production is expected to vanish yielding a direct test of CVC as noted in Ref. 4.

$$\frac{d^2\sigma(\nu \to \rho^+)}{dq^2 d\nu} = 4q^4 \frac{G^2}{e^4} \frac{d^2\sigma(e \to \rho^0)}{dq^2 d\nu} .$$

In the study of ρ^+ production, a good π^0 detection efficiency is imperative in order to make invariant-mass plots. In the case of A_1^+, one can either choose to study the $\pi^+\pi^+\pi^-$ decay mode which probably requires a muon identifier to avoid $\pi^- - \mu^-$ confusion or the equally frequent $\pi^+\pi^0\pi^0$ mode which requires observation of all four γ rays. Because of the coherent nature of these events, production in a heavy-liquid bubble chamber is most advantageous.

2. Multiplicity and Spectra of Particles Produced by Neutrinos

The simplest vector-dominance model would predict a particle multiplicity in neutrino reactions similar to that in hadronic reactions (perhaps rising logarithmically with c.m. energy). However, it is easy to conceive a more general diffractive model or a statistical model[5] in which the multiplicity might increase faster, perhaps as $\sqrt{E_\nu}$. The spectra of variously charged pions is also an item of theoretical interest. PCAC and current algebra imply the soft-pion theorems

$$\lim_{q_{\pi^0} \to 0} A(\nu + n \to \mu^- + \pi^0 + F) = \frac{2}{f_\pi} A(\nu + n \to \mu^- + F)$$

$$\lim_{q_{\pi^-} \to 0} A(\nu + n \to \mu^- + \pi^- + F') = 0,$$

where A is the amplitude for the indicated production process and F, F' are arbitrary hadronic states. It is likely that these theorems will produce marked differences between π^- and π^0 spectra in neutrino reactions. The π^+ spectrum should also be very different from the π^- spectrum. These differences should be reflected in the pion spectra from the "inclusive" reactions

$$\nu + N \to \mu^- + \pi^{\overset{\pm}{0}} + \text{anything}.$$

3. Current Algebra Sum Rules

Adler[6] has derived a current algebra relation between neutrino and antineutrino total differential cross sections. These read

$$\lim_{E_\nu \to \infty} \frac{d\sigma(\bar{\nu}p)}{dq^2} - \frac{d\sigma(\nu p)}{dq^2} = \frac{G^2}{\pi}\left(\cos^2\theta_c + 2\sin^2\theta_c\right)$$

$$\lim_{E_\nu \to \infty} \frac{d\sigma(\bar{\nu}n)}{dq^2} - \frac{d\sigma(\nu n)}{dq^2} = \frac{G^2}{\pi}\left(-\cos^2\theta_c + \sin^2\theta_c\right).$$

The interesting prediction here is that the difference in the differential cross sections becomes independent of q^2 for sufficiently large E_ν. To get some idea of the magnitude of the difference, let us assume that the sum rules saturate at some finite E_ν. Then we can integrate both sides of the Adler relation from $q^2 = 0$ to $2ME_\nu$. The result is

$$\sigma_t(\bar{\nu}p) - \sigma_t(\nu p) = \frac{2G^2ME_\nu}{\pi}\left(\cos^2\theta_c + 2\sin^2\theta_c\right).$$

This difference is greater than the average νp and νn cross section measured by CERN

$$\frac{1}{2}\left[\sigma_t(\nu p) + \sigma_t(\nu n)\right] = (0.6 \pm 0.15)\frac{G^2ME_\nu}{\pi};$$

in addition, the integrated sum rule violates the Pomeron-dominance prediction $\sigma_t(\bar{\nu}p) = \sigma_t(\nu p)$ discussed below. One can argue, of course, that the sum rule is saturated at higher and higher E_ν as q^2 is increased,[7] but it seems difficult to avoid ultimate conflict between the current-algebra predictions and popular Regge ideas. It must be noted, however, in warning, that a "no-subtraction" assumption as well as current algebra went into Adler's result.

4. Comparison of σ_{tot} in νp, νn, $\bar{\nu}p$, $\bar{\nu}n$ Collisions

(α) Isotopic spin symmetry and the Cabibbo theory of the weak currents imply $d\sigma_t(\nu p) = d\sigma_t(\bar{\nu}n)$, where we have written $d\sigma_t$ for $d^2\sigma_t/dq^2d\nu$. Regge arguments based on Pomeron dominance[8] predict for large ν

$$d\sigma_t(\nu p) = d\sigma_t(\bar{\nu}p), \quad d\sigma_t(\nu n) = d\sigma_t(\bar{\nu}n).$$

Thus, the combination of isotopic-spin symmetry with Pomeron dominance predicts the equality of all four neutrino-nucleon cross sections.

$$d\sigma_t(\nu p) = d\sigma_t(\bar{\nu}p) = d\sigma_t(\nu n) = d\sigma_t(\bar{\nu}n).$$

(β) One can also argue from the point of view of the quark model[9] that at high q^2 the weak current interacts incoherently with the quarks in the nucleon. Since the neutron has two n-type quarks and one p-type while the proton has two p-type and one n-type, one expects

$$d\sigma_t(\nu n) = 2\, d\sigma_t(\nu p)$$
$$d\sigma_t(\bar{\nu} p) = 2\, d\sigma_t(\bar{\nu} n)\,.$$

(γ) Finally, we might mention the predictions of the recent field-theoretical parton model[10] in the region $2M_\nu >> q^2$

$$d\sigma_t(\nu p) = 3\, d\sigma_t(\bar{\nu} n)$$
$$d\sigma_t(\nu n) = 3\, d\sigma_t(\bar{\nu} p)\,.$$

5. σ_t Verses E_ν

The behavior of the total neutrino cross section as a function of E_ν is a quantity of great theoretical interest. It has been shown[11] that if the lepton current is local, if there is no W boson, and if the structure function νW_2 scales, then σ_t rises linearly with lab energy. Unitarity, however, requires the cross section to turn over eventually. If the turnover is due to a W boson, one can factor the W propagator out of the differential cross section (in the same way that the photon propagator is factored out of electroproduction) and ask whether the remaining structure functions scale.

6. Tests of Lepton Locality

There are two tests proposed for the common assumption that the lepton current acts at a point (lepton locality). Any contribution from Feynman diagrams involving internal lepton lines such as higher-order weak effects or final-state electromagnetic lepton-hadron interactions can cause deviations from the predicted behavior.

The first test[12] requires that any neutrino cross section be of the form

$$\frac{d^2\sigma}{dq^2 d\nu} = \frac{A}{E_\nu^2} + \frac{B}{E_\nu} + C,$$

where A, B, and C are in general functions of q^2 and ν.

The second test[1] is a restriction on the possible correlations between the lepton plane and any suitably defined hadron plane. For example, let ϕ be the angle between the lepton plane and the $p' - y^+$ plane in the reaction

$$\nu + p \to \mu^- + p' + y^+,$$

where y^+ is a single or multiparticle hadron state. Then the most general form of the cross-section dependance on ϕ, consistent with lepton locality, is

$$\frac{d\sigma}{d\phi} = a + b \sin\phi + c\cos\phi + d \sin 2\phi + e\cos 2\phi.$$

7. Structure Functions of the Nucleon in the Deeply Inelastic Region

Assuming the conventional local lepton current, the inelastic differential cross section for scattering of neutrinos (antineutrinos) from nucleons is

$$\frac{d^2\sigma}{d\Omega_\mu dE_\mu} = \frac{G^2 E_\mu^{\;2}}{2\pi^2} \left[\cos^2 \frac{\theta_\mu}{2} W_2^{\pm}(q^2, \nu) + 2 \sin^2 \frac{\theta_\mu}{2} W_1^{\pm}(q^2, \nu) \mp \frac{E_\nu + E_\mu}{M_N} \sin^2 \frac{\theta_\mu}{2} W_3^{\pm}(q^2, \nu) \right],$$

where one has, in principle, different W's for neutron and proton. In a parton model W_1, νW_2, and W_3 are expected to become functions of the scale-invariant parameter $\omega = q^2/2M_\nu$. W_3 is a measure of the strength of the V, A interference.

9. Four-Fermion Interaction

This class of experiments includes the scattering of neutrinos from the atomic electrons[13]

$$\nu_\mu + e \to \mu^- + \nu_e,$$

and the lepton-pair production[14] in the Coulomb field of a heavy nucleus

$$\nu_\mu + Z \to \nu_\mu \mu^- \mu^+ Z \quad \text{or} \quad \nu_\mu + Z \to \nu_e \mu^- e^+ Z.$$

The muon-pair production is an example of the "diagonal" interaction between lepton currents.

10. W Search

If the W boson exists it can be produced with a relatively model-independent cross section in the reaction

$$\begin{array}{l} \nu_\mu + Z \to \mu^- + W^+ + Z \\ \qquad\qquad\qquad\quad\;\; \llcorner\!\!\to \mu^+ \nu_\mu \\ \qquad\qquad\qquad\quad\;\; \llcorner\!\!\to e^+ \nu_e \\ \qquad\qquad\qquad\quad\;\; \llcorner\!\!\to \text{hadronic states.} \end{array}$$

Simple theories of the W boson do not remove renormalization difficulties of weak-interaction theory. Nevertheless, there are some shaky reasons to believe in a W boson (or some equivalent weak interaction cutoff) in the mass region 4 to 10 BeV. If such an object is found, there will be great interest in observing its various decay modes in a heavy-liquid bubble chamber.

11. Miscellaneous Topics

(α) Neutral Currents

At low energy there are no indications of the existence of neutral currents coupled to leptons, e.g.,[15]

$$\frac{\Gamma(K^+ \to \pi^+ \nu \nu)}{\Gamma(K^+ \to \text{all})} < 1.2 \times 10^{-6}.$$

However, it is a valid question to ask whether such currents exist, perhaps even with a strength comparable to the charged currents at high momentum transfer. In a bubble chamber one might look, for instance, for the muonless interaction

$$\nu_\mu + Z \to \nu_\mu + \text{hadrons}.$$

In a bubble chamber one might avoid background from neutrons by asking for a uniform distribution of events across the chamber or by requiring the hadronic state to have one unit of strangeness.

(β) Heavy leptons

These hypothetical particles might appear in either of two species. The first would be an excited state of the muon (or electron) decaying electromagnetically into $\mu + \gamma$ or $e + \gamma$. The second would be a new lepton with its own neutrino. The latter would be forbidden by lepton conservation to decay electromagnetically and would, therefore, disintegrate through a weak interaction such as

$$\ell^- \to \pi^- \nu_\ell .$$

II. EXPERIMENTAL ASPECTS OF NEUTRINO PHYSICS IN THE NAL 15-FT BUBBLE CHAMBER

The experimental investigation of ν reactions in the NAL 15-ft bubble chamber (BC) is summarized using essentially the corresponding NAL proposals (until July 1970). Typical processes are mentioned which allow the study of the various theoretical questions discussed in Section I.

The cross section for ν interactions and the target mass of the BC are small. One exposes the BC to a broad-band ν beam and takes advantage of the full flux. Hence the ν energy is unknown. In a process

$$\nu + N \to \mu + \text{hadrons},$$

the μ has to be identified among the final-state particles, and the total energy of the hadrons has to be measured in order to get the ν energy.

A plate of several interaction-lengths thickness inside[16] or outside[17] the BC will identify the μ by range.

With a heavy-liquid BC filling (e.g., Ne), one has about 20 times the target mass of the H_2 BC. By restricting the analysis to a small fiducial volume upstream in the BC, one leaves, say, about three interaction lengths for the final state hadrons, enough to detect 95 percent of them including the n's. A statistical separation of π's from μ's should be possible.[18] Also, most of the γ rays from π^0 decay would be detected. One should be able to determine the total energy of the final-state hadrons to 10-20 percent.[19]

A track-sensitive D_2 target (TST) inserted in the BC filled with Ne[20] has characteristics similar to the Ne-filled BC. It has the advantage of a "pure" nucleon target although for only one-sixth of the full BC volume.

A proportional wire chamber quantameter next to the chamber body[21] detects the π^0 decays and with a hadrometer behind the BC[22], one will be able to identify the μ's and measure the hadron energy including the n's with an accuracy of about 5 percent. In such a hybrid system one uses the full BC as target.

The two-and three-body final states, however, can be identified without any additional equipment in a H_2 or D_2 BC[23]. Using a charge-separated beam and neglecting the small ($\bar{\nu}$, ν) contamination at low energies (a few percent in the region $E_\nu \lesssim 50$ GeV where the bulk of the BC events occur) one identifies the μ by its charge. Missing n's can be identified (for about 20 percent of the events in the 15-ft BC with H_2) by associated p recoils giving 3c fits which eliminate the background.[24] But even in multiparticle final states, one will be able to study gross features of the reactions: for example, in the reaction

$$\nu\, p \rightarrow \underbrace{\mu^-}\, p\, \pi^+\, \pi^+ \underbrace{\pi^-} ,$$

one cannot distinguish between the μ^- and the π^-. One might expect to pick up in many cases the μ^- by taking the fastest forward-going negative particle. The behavior of the μ^- can be studied with the subset of events where the π^- interacts in the chamber. Studying events with a final-state n interacting, investigating the behavior of final-state protons and in addition by taking one-half of the visible $\pi^\pm$ energy for the missing π^0 energy, one should be able to estimate the total hadron energy in an inelastic reaction to 20-30 percent.

This would allow one to distinguish, for example, between theoretical predictions for cross sections (see Section I)

$$\sigma(\nu n) = \sigma(\nu p) = \sigma(\bar{\nu} p),$$

or

$$\sigma(\nu n) = 2\, \sigma(\nu p),$$

or

$$\sigma(\nu n) = 3\, \sigma(\bar{\nu} p).$$

With a rough determination of the energy dependence of the average charged multiplicity $< n_c >$, it would be possible to decide whether

$$< n_c > \sim \ln E_\nu$$

or

$$< n_c > \sim \sqrt{E_\nu}.$$

A H_2 or D_2 bubble chamber without additional equipment for μ identification and π^o and n detection is already quite a powerful tool. It allows even in the high multiplicity final states the study of gross features in the cross-section behavior and enables one to find new phenomena.

However, for an accurate study of the energy dependence of the total cross section, especially in regions where the ν spectrum falls off very sharply, an accurate comparison between ν and $\bar{\nu}$ reactions with p's and n's, and for the detailed study of the structure functions in the deeply inelastic region, the mentioned hybrid system clearly does the best. Although it is event-rate limited to lower ν energies ($E_\nu \lesssim 120$ GeV) due to its relatively small target mass (compared with counter experiments), it has the virtue of a pure nucleon target and of a good measurement of the ν energy (experiments using a high A target will always have to measure how the A dependence varies with the ν energy and extrapolate to the nucleon).

The essentially four different BC configurations of the NAL proposals (July 1970) for ν-BC experiments are briefly outlined in Table I.[25] Columns 1 to 4 give beam particle, target, number of pictures requested, and physics emphasized. In Column 5 the BC configuration is sketched. Column 6 gives an estimate of the error on the total hadron energy in an inelastic reaction, and Column 7 mentions technical problems with the additional equipment or exotic BC filling proposed.

For the discussion of the measurements relevant to the theoretical questions asked in Section I, the different ν and $\bar{\nu}$ reactions and the quantities to be measured are listed in Table II.

The processes which can be studied completely in a H_2 or D_2 BC without additional equipment are listed first. Scanning down the table, one encounters more need for additional equipment to identify the ν and the N and π^o, or at least the need for heavier liquid (Ne).

This order in the table is purely experimentally oriented. It is not a judgment of the relative importance of the physics questions mentioned! The first column of Table II divides the processes into two-body, three-body, and multiparticle final states and gives examples for reactions to be studied. The second column mentions the interesting quantities to be measured.

For the study of specific two- and three-body final states, a relative figure of merit for the pure $H_2(D_2)$, TST, and the hybrid system is:

$$\left\{ \frac{\text{target volume}}{\text{useful target volume of the full BC}} \right\} \times \left\{ \begin{matrix} \text{detection efficiency for the} \\ \text{final state neutrals} \end{matrix} \right\}.$$

The variation of the ν flux across the BC has been neglected. For the TST about one-third of the useful BC volume was taken and ~ two radiation lengths and ~ one interaction length in Ne were used. For the hybrid system ~ 0.9 for the solid-angle detected[22] and ~ 100% electronic detection efficiency were used, the useful target volume being the same as in the "simple" H_2, D_2 configuration.

For the multiparticle final states the error on the ν energy for the different configurations is given as a figure of merit.

Column 3 indicates whether additional equipment for μ identification is needed. Column 4 mentions π^o, n detection, and kinematics. In Column 5 the theoretical questions outlined in Section I are listed.

Some remarks about event rates: An extension of the 300-m Fe shield to about a 1400-m soil shield seems realistic for financial reasons. Event rates calculated for a 200-GeV p operation for constant cross sections would drop by ~ one-third, for linearly-rising cross sections by ~ three-fourths. If previously calculated for a 500-GeV p operation, the corresponding factors are ~ one-sixth and ~ one-third. One should also keep in mind that a 10^6 picture exposure in a 400-GeV p operation lasts about 2-1/2 months without any breakdown (7 sec repetition rate of the accelerator). Actually, a realistic estimate of the first year's output of the NAL 15-ft chamber is ~ 10^6 pictures.[26]

The above estimates are, of course, only correct if the total cross section keeps rising linearly and doesn't turn over at, say, $E_\nu = 10$ GeV already.

Additionally, it must be mentioned that the event rates in the ν energy region from ~ 5-15 GeV are reduced by more than a factor of 10 due to the shield extension mentioned.[27] This leaves a big gap in the ν spectrum from the different accelerators in this energy region.[28]

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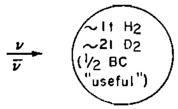
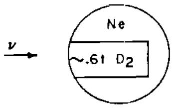
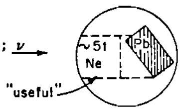
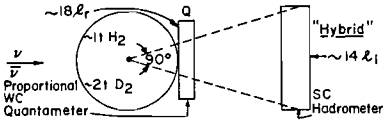
Table I. NAL ν - BC Proposals (July 1970).

Proposal Number	Target	No. of Pictures (10^6)	Physics Emphasized	Configuration (ℓ_r = rad length; ℓ_i = int. length)[a]	$\frac{\Delta E_\nu}{E_\nu}$[b]	Problems with Additional Equipment[c]
(1) 20 ν	D_2	1/4	elastic events; Y prod.; 1π prod.; gross features of inelastic reactions ($E_\nu \lesssim$ 70 GeV)	 simple = no additional equipment ~.2 ℓ_r ~.2 ℓ_i	20-30%	
31 $\bar{\nu}$	H_2	1				
45 ν	H_2	1/2				
(2) 42 ν	D_2 (Ne)	1	As (1); more final states (π^0, n ident.) ($E_\nu \lesssim$ 70 GeV)	 D_2 - TST in Ne ~2 ℓ_r ~2 ℓ_i	~20%	large TST not yet run, accuracy? Ne?; γ pointing: distorted lenses, shower ("overcount")
44 ν	D_2 (Ne)	1/2				
(3) 28 ν	Ne	1	diffractive processes; deeply inelastic processes; σ_{tot}; W search; ($E_\nu \lesssim$ 150 GeV)	 No. 28) simple ~8 ℓ_r ~3 ℓ_i	~10%	plate = 30 t weight; lose μ < 2 GeV (by range)
53 ν	Ne (30% D_2 for flux)	1		No: 53 Pb plate ~6 ℓ_i Pb ~4 ℓ_r Ne, 1 1/2 ℓ_i Ne	~20%	
(4) 9 $\frac{\nu}{\nu}$	H_2	1	as (1); deeply inelastic and σ_{tot} accurately ($\Delta E_h/E_h$ ~5%); nucleon target ($E_\nu \lesssim$ 120 GeV)		~5%	Trigger: interactions in coils; γ shower pointing in Q; lose $\mu \lesssim$ 4 GeV (bent off by field)
	D_2					

[a] All proposals use a charge-separated broad band ν ($\bar{\nu}$) beam and would welcome additional μ identification.

[b] Estimate of the error on the total hadron energy $\Delta E_h = \Delta E_\nu$ in $\nu + N \rightarrow \mu$ + hadrons.

[c] Technical details of TST, Pb plate, quantameter, and hadrometer are discussed in SS-202, 201, 185, 186, and Proposal 9 respectively.

Table II. ν - Reactions in the NAL 15-ft BC.

Final State	Process	Measurements	μ Ident. Equipment	n, π^o Detection Kinematics	Physics (See Section I)
2 body elastic	$\nu n \to \mu^- p$	$\sigma(E_\nu)$; $d\sigma/dq^2$;	—	—	
	$\bar{\nu} p \to \mu^+ n$	N polarization[a]	—	3c fit: np → np ~20% H_2 TST ~90% hybr.	Form factors; Y production ? ($\Delta S = \Delta Q$)
Y production	$\bar{\nu} p \to \mu^+ \Lambda$	$\sigma(E_\nu)$; $d\sigma/dq^2$;	—	—	
	$\mu^+ \Sigma^o$	Λ polarization easy[a]	—	$P_\perp$ imbalance (Σ^o slow) 3c: γ ~20% H_2 ~30% TST ~90% hybr.	Form factors; $\frac{\Delta S = 1}{\Delta S = 0}$; no Σ^o leptonic decay
	$\bar{\nu} n \to \mu^+ \Sigma^-$		—	—	
3 body $\Delta S = 0$	$\nu p \to \mu^- p \pi^+$		—	—	
	$\mu^- n \pi^+$	$\sigma(E_\nu)$;	—	3c: np → np ~20% H_2 TST ~90% hybr.	$\Delta I = 1$ rule: N^* ratios; compare with N^* electroprod.; Adler test; locality test: angle ϕ between (ν, μ) - and (N, π) plane[b]
	$\mu^- p \pi^o$	$d\sigma/dq^2$;	—	3c: π^o ~25% TST ~90% hybr.	
	$\bar{\nu} p \to \mu^+ p \pi^-$	N^* production		—	
	$\bar{\nu} n \to \mu^+ n \pi^-$		—	3c: np → np ~20% H_2 TST ~90% hybr.	
	$\nu p \to \mu^- \Sigma^+ K^+$		—	—	
	$\nu n \to \mu^- \Lambda K^+$	$\sigma(E_\nu)$;	—	—	If strongly produced:
	$\bar{\nu} p \to \mu^+ \Sigma^- K^+$	$\left.\begin{matrix}\Sigma^+ \\ \Lambda\end{matrix}\right\}$ polarization[a]	—	—	$\vec{\sigma}_Y \cdot \left(\vec{P}_\mu \times \vec{P}_\nu \right)$
	$\bar{\nu} n \to \mu^+ \Sigma^- K^o$		—	—	T invariance test
$\Delta S = -1$	$\bar{\nu} p \to \mu^+ \Sigma^\pm \pi^\mp$		($\Sigma^- \pi^+$)	—	
	$\mu^+ p K^-$	$\sigma(E_\nu)$;	—	—	
	$\mu^+ \Lambda \pi^o$	$d\sigma/dq^2$;	—	3c: π^o ~25% TST ~90% hybr.	$\Delta I = 1/2$ rule: Y^* ratios; compare with N^* production
	$\bar{\nu} n \to \mu^+ \Lambda \pi^-$	Y^* production	—	—	

Table II. (Continued).

Final State	Process	Measurements	μ Ident. Equipment	n, π^0 Detection Kinematics	Physics (See Section I)
Diffractive	$\nu A \to A\mu^-\rho^+(A_1^+)$ $\rho^+ \to \pi^+\pi^0$ $A_1^+ \to \pi^+\pi^+\pi^-$ $\pi^+\pi^0\pi^0$	Low q^2 - invariant mass plots	—	best in Ne - BC (high A)	$\pi^+/\rho^+/A_1^+$; diffractive constant fraction of σ_{tot}? Compare e.g., with ρ - photoproduction.
Multibody	Inclusive type: $\nu p \to \mu^- + \pi^{\overset{\pm}{0}} + \ldots$	π momentum distribution (low momentum)	—	—	Soft π theorems
		$\langle n_c \rangle$: average charged multiplicity vs E_ν	—	—	$\langle n_c \rangle \sim \ln E_\nu$ or $\sim \sqrt{E_\nu}$?
		$\frac{d\sigma}{dq^2}(\nu p) - \frac{d\sigma}{dq^2}(\nu p)$ comparison of $\sigma(\nu p)$, (νn), $(\bar{\nu} p)$, $(\bar{\nu} n)$	(Yes)[c]	$\Delta E_\nu / E_\nu$ ~20-30% D_2, H_2 ~20% TST ~10-20% Ne BC ~5% hybr.	Current algebra sum rules; various models: predictions differ by factors 1...3.
		σ_{tot} vs E_ν	Yes	Figure of merit as above	linear rise, turnover (scaling, W)
	$\nu_\mu + e \to \mu^- \nu_e$ $\nu_\mu + Z \to Z\,\mu^-\mu^+\nu_\mu$		Yes	High Z: Ne - BC[d]	Purely leptonic interaction "Diagonal" coupling
	Deeply Inelastic	$\frac{d^2\sigma}{dq^2 d\nu}$	(Yes)	Ne - BC; hybrid best, nucleon target	Structure functions: W_1, W_2, W_3; E_ν dependence of $d^2\sigma/dq^2 d\nu$
	W production	Electronic decay hadronic decay	Yes	Ne-BC (hybrid: low target mass)	
	Heavy lepton production	$\ell^- \to \pi^- \nu_\ell$		Ne - BC	

[a] Some event rates as calculated in the proposals have to be reduced by a factor of ~1/6 if the 300 m (Fe) shield in Area I is extended to ~1400 m (soil). The measurement of the baryon polarization becomes then statistically inaccurate (see SS-198 and SS-200).

[b] This test is applicable to the general case with any hadron state instead of the π. But one has to identify the particles in the hadron state when defining the hadron plane. Even then the test is statistically not very significant since one has 5 parameters to fit the φ distribution (see Section I).

[c] As described in the text, one can study gross features here "guessing" the μ on a statistical basis the goodness of which is also indicated by the error on the estimate of the ν energy.

[d] Event rates in the proposals are very low already and have to be reduced by a factor of ~1/3 due to the "realistic" μ shield length.