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Neutrino Strange Particle Production at NuMI; Atmospheric ν Background in Nucleon Decay Searches

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Abstract

Neutrino interactions yielding strange particles are reviewed for the purpose of identifying exclusive channels amenable to high statistics investigation with the NuMI beam. As a case study of opportunity inherent with a fine-grained tracking calorimeter deployed in the NuMI near hall (e.g. the MINERνA proposal), we consider that strangeness production reactions are initiated by terrestrial atmospheric fluxes (ν_μ+ν_e+$\overline{\nu}_\mu$+$\overline{\nu}_e$) traversing underground detectors. These ν reactions present backgrounds to searches for nucleon decay modes favored by SUSY grand unification; uncertainties with rates for neutrino strangeness production reactions will complicate any nucleon decay search striving for sensitivities of $\tau_N \geq 10^{33-34}$ years. Specifically, $\Delta S = 0$ associated strangeness production by neutral currents, e.g. $\nu N \rightarrow \nu \Lambda \mathrm{K}^+$, will mimic all observable attributes of proton decay $\mathrm{p} \rightarrow \nu \mathrm{K}^+$ as the latter reaction would be recorded in a water Cherenkov detector. A fine-grained NuMI detector with ≈ 5 ns time resolution can address these uncertainties via precision measurement of selected ν strangeness production cross sections and their energy dependence.

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1 Neutrino Strangeness Production Reactions Near Threshold

In the threshold energy regime $1 \leq E_\nu \leq 6$ GeV, neutrino interactions involving strangeness production yield final states containing either one or two strange particles. Exclusive νN channels can be usefully divided into three categories, according to reaction type (charged current (CC) or neutral current (NC)) and to the $\Delta S = S_f - S_i$ of the hadronic system (either $\Delta S = 0$ or $\Delta S = 1$).

As illustrative of our first category, we consider charged current $\Delta S = 0$ reactions initiated by ν_μ neutrinos. These are associated production reactions in which a strangeness +1 meson (K^+ or K^0) is produced in conjunction with a strangeness -1 hyperon (Λ or $\Sigma^{\pm,0}$) or meson (K^- or $\overline{K}^0$). Reactions of this category which have been observed in bubble chamber experiments are the following:

$$\nu_\mu n \rightarrow \mu^- K^+ \Lambda^0 \tag{1}$$
$$\nu_\mu n \rightarrow \mu^- \pi^0 K^+ \Lambda^0 \tag{2}$$
$$\nu_\mu n \rightarrow \mu^- \pi^+ K^0 \Lambda^0 \tag{3}$$
$$\nu_\mu n \rightarrow \mu^- K^- K^+ p \tag{4}$$
$$\nu_\mu p \rightarrow \mu^- K^+ \overline{K}^0 \pi^0 p \tag{5}$$

Among CC $\Delta S = 0$ reactions, reaction (1) has the largest cross section. It has been suggested that this reaction, and reactions (2) and (3) as well, may proceed via N^* production followed by strong decay into KΛ.

Charged current $\Delta S = 1$ reactions comprise a second category. For neutrino reactions - but not $\overline{\nu}$ reactions - of this category, the produced final states contain single strange K-mesons. The reaction cross sections are Cabbibo-suppressed relative to $\Delta S = 0$ reactions involving similar hadronic masses. Here the $\Delta S = \Delta Q$ selection rule is operative and so the produced mesons are necessarily (K^+, K^0) and not (K^-, $\overline{K}^0$). Reactions of this category observed at threshold energies using ν_μ beams include

$$\nu_\mu p \rightarrow \mu^- K^+ p \tag{6}$$
$$\nu_\mu n \rightarrow \mu^- K^0 p \tag{7}$$
$$\nu_\mu n \rightarrow \mu^- \pi^+ K^0 n. \tag{8}$$

Additionally, $\Delta S = \Delta Q$ selection restricts $\Delta S = 1$ single hyperon production to $\overline{\nu}$ rather than ν reactions, e.g.

$$\overline{\nu}_\mu N \rightarrow \mu^+ + (\Lambda, \Sigma, Y^*). \tag{9}$$

Among the above, reaction (6) was observed by many experiments and likely has the largest cross section among $\Delta S = 1$ exclusive reactions.

Strange particle $\Delta S = 0$ associated production can also proceed via neutral current reactions, and these comprise our third category. Observed channels include

$$\nu_\mu p \rightarrow \nu K^+ \Lambda^0 \tag{10}$$

$$\nu_\mu \mathrm{n} \rightarrow \nu \mathrm{K}^0 \Lambda^0 \tag{11}$$
$$\nu_\mu \mathrm{n} \rightarrow \nu \pi^- \mathrm{K}^+ \Lambda^0 \tag{12}$$

As remarked concerning final states of (1) - (3), it is similarly plausible that the hadronic systems of (10) through (12) proceed via intermediate N^* states.

Notably absent from our list of categories are neutral current strangeness-changing reactions; these have never been observed. Their occurrence at rates accessible in NuMI would imply new physics beyond the Standard Model. Limits on NC $\Delta S = 1$ processes have been established in rare K decays. Clearly there are experimental difficulties with unambiguous identification of such processes in neutrino reactions. The possibility for a strangeness-changing NC search to be undertaken in the MINERνA experiment is under consideration [1].

2 Cross Section Measurements Using Bubble Chambers

Zeroth order cross sections for most of the above-listed reactions were obtained during the 1970's and '80s in experiments using large-volume bubble chambers exposed to accelerator neutrino beams. Principal experimental programs were the ν_μ and $\overline{\nu}_\mu$ exposures of the Gargamelle heavy liquid (C F^3 Br) bubble chamber at CERN [2, 3] and the $\nu_\mu \mathrm{D}_2$ exposures of the 12-foot diameter bubble chamber at Argonne [4] and of the 7-foot diameter bubble chamber at Brookhaven [5]. Typical measurements involved less than ten observed events per channel, and cross sections thereby inferred relate to one or few bins in E_ν. Contemporaneous theoretical/phenomenological treatments of reactions (1), (7), (8), (10), and (11) can be found in Refs. [7, 8, 9].

Cross section ratios obtained by the bubble chamber experiments provide rough characterizations of relative rates of occurrence among the strangeness reaction categories. For example, the frequency of strangeness versus non-strange hadronic final states in charged current reactions is indicated by [4]

$$\frac{\sigma(\nu \mathrm{N} \rightarrow \mu^- \Lambda \mathrm{K}^+ + \mu^- \mathrm{p\ K})}{\sigma(\nu \mathrm{N} \rightarrow \mu^- \mathrm{N} + \mathrm{pion(s)})} = 0.07 \pm 0.04 \tag{13}$$

The relative contribution of neutral current versus charged current reaction to threshold strangeness production is indicated by [5]

$$\frac{\sigma(\nu_\mu \mathrm{N} \rightarrow \nu_\mu \mathrm{V}^0 + \mathrm{anything})}{\sigma(\nu_\mu \mathrm{N} \rightarrow \mu^- \mathrm{V}^0 + \mathrm{anything})} = 0.22 \pm 0.14 \tag{14}$$

and

$$\frac{\sigma(\nu \mathrm{K}^+ \Lambda^0)}{\sigma(\mu^- \mathrm{K}^+ \Lambda) + \sigma(\mu^- \mathrm{K}^+ \Lambda X^0)} = 0.18 \pm 0.13 \tag{15}$$

Perhaps the most significant "find" arising from the bubble chamber survey experiments was the observation at Brookhaven of the first example of charmed baryon production in a CC

$\Delta S = 1$ final state [6]:

$$\nu_\mu \mathrm{p} \to \mu^- \quad \Sigma_c^{++} \tag{16}$$

$$\Sigma_c^{++} \quad \to \Lambda_c^+ \pi^+ \to \Lambda^0 \pi^+ \pi^+ \pi^- \tag{17}$$

The large-volume bubble chambers were remarkable detectors for neutrino event imaging, providing millimeter spatial resolution with magnetic tracking. That good spatial resolution is prerequisite for examination of neutrino strangeness reactions, is illustrated by the bubble chamber event of Fig. 1. The Figure shows a tracing of a magnified photographic image recorded by one of four separate camera views of this ν_μn interaction. The event shown is the first example of NC associated strangeness production via reaction (11) obtained using the deuterium-filled 12-ft diameter bubble chamber at ANL. Within the final state, the flight paths of the K_s^0 and and Λ^0 from the primary vertex to their respective vee decay points are 8.0 cm and 5.5 cm respectively [4]. Fortunately it may be possible, with a lattice of triangular cell scintillator tracking elements of a fine-grained detector, to achieve spatial resolutions comparable to bubble chamber resolution. Capability of this type, together with dE/dx ionization imaging and momentum determination by ranging and by external magnetic tracking, would enable a NuMI experiment in the near hall to explore exclusive strangenss production processes.

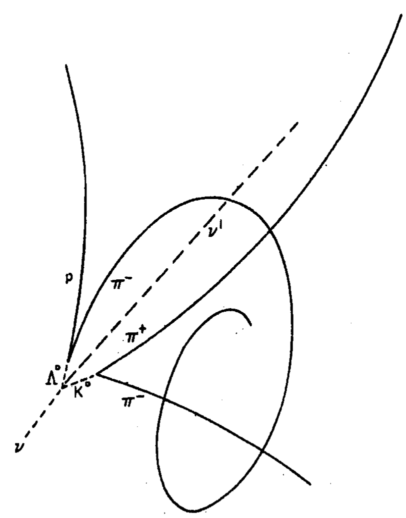


Figure 1: Trace of photograph from the ANL 12-ft diameter bubble chamber, of a neutrino neutral current interaction in liquid deuterium yielding NC associated production $\nu \mathrm{K}\Lambda$. Flight paths to the vee decays of the two strange particles in the event are 8.0 cm and 5.5 cm in real space.

For the proposed neutrino scattering experiment MINERνA, we envisage pursuit of a few selected topics among neutrino strangeness processes. Motivation and general outline for one specific undertaking are described in paragraphs below.

3 Proton Decay Search; Background from Atmospheric Neutrinos

An attractive framework for physics beyond the Standard Model is provided by grand unified theories invoking SU(5) or SO(10) as the fundamental gauge group and including supersymmetry. Notable features of SUSY GUTs include aesthetic and useful classification of fermions into fundamental representations, unification of the strong, electromagnetic, and weak couplings at high mass scale, and accomodation of the seesaw mechanism yielding small neutrino masses. The unification of quarks and leptons in this approach necessarily entails their mutual inclusion in the same supermultiplets. This allows transitions of quarks into leptons to be mediated, with the consequence that protons and (bound) neutrons may be inherently unstable. Therein lies a prediction for nucleon decay which has not been verified, in spite of dedicated searches by two generations of underground experiments. However current experimental limits, while having ruled out non-SUSY SU(5) GUTs and having disproved predictions of nucleon decay with lifetimes $\tau_{BR} \leq 10^{32}$ years suggested by mininal SUSY GUTs models, have not diminished hopes for the eventual success of SUSY grand unification. Consequently there is strong motivation to proceed with more ambitious experimental searches. For the near future, improved searches for nucleon decay will be carried out by SuperKamiokande. Eventually these will be taken up by a next generation of underground detectors, e.g. by megaton-scale water Cherenkov experiments such as HyperKamiokande and/or UNO [10].

Continued progress, either with improving limits to 10^{33} - 10^{34} year lifetimes or with discovery of proton decay, hinges upon improved knowledge of certain neutrino interactions which, when initiated by atmospheric ν fluxes, can imitate nucleon decay signals. The most problematic of background ν reactions arises with neutral current associated production of strangeness at threshold energies, as we describe below.

3.1 Nucleon decay lifetime limits

Impressive lifetime lower limits for proton decay into two-body final states have been obtained by SuperKamiokande. The most restrictive partial lifetime limit is

$$\tau(\mathrm{p} \to \mathrm{e}^+\pi^0) \leq 5.4 \times 10^{33} \text{ years [11].} \tag{18}$$

Limits well-exceeding 10^{32} year lifetimes have also been reported for modes p $\to \mu^+\pi^0$, $\mathrm{e}^+\eta^0$, $\mu^+\eta^0$, and n $\to \nu\eta^0$ [12]. Searches in these modes appear to be devoid of atmospheric backgrounds at present, and continued progress is anticipated. In SUSY GUTs these modes are mediated by exchange of the supersymmetric version of X and Y lepto-quark bosons. Unfortunately the mass requirements for the GUT-scale leptoquark bosons generally preclude nucleon decay into these modes with τ/B of less than 10^{36} years. However, other processes involving particle loops with supersymmetric particles arise in these theories which can also mediate nucleon decay. Diagrams for these virtual processes generally integrate to zero unless the transitions involve intergenerational mixing. As a result, final states containing strange mesons are to be expected, with lifetimes which are possibly accessible, e.g. 10^{33} - 10^{35} years.

Specifically, SUSY GUTs predicts the following nucleon decay modes to be relatively 'fast':

$$\mathrm{p} \rightarrow \nu \mathrm{K}^+ \quad (19)$$
$$\mathrm{n} \rightarrow \nu \mathrm{K}^0 \quad (20)$$

and possibly

$$\mathrm{p} \rightarrow \mu^+ \mathrm{K}^0 \quad (21)$$
$$\mathrm{p} \rightarrow \mathrm{e}^+ \mathrm{K}^0 \quad (22)$$

From the SUSY GUTs perspective, decay modes (19) and (20) hold particular promise for first observation of baryon instability. Mode (19) has received considerable attention by SuperK and a stringent lifetime lower limit has been established. At 90% confidence level,

$$\tau(\mathrm{p} \rightarrow \nu \mathrm{K}^+) \; > \; 2.2 \times 10^{33} \text{ years [11].} \quad (23)$$

At the current search sensitivity of SuperK, backgrounds for mode (19) arising from atmospheric neutrino reactions appear to be negligible, and so this mode can be usefully pursued experimentally for the near term. It is likely that a similar situation exists with searches investigating mode (21).

For a number of other nucleon decay modes however, the possibility for background-free searching may already be precluded. In particular, for neutron decay mode (20) - the isospin companion to proton decay mode (19) - searches probing $\geq 10^{32}$ years may be background-limited to such an extent that discovery capability is effectively voided.

By way of illustrating the latter situation, we show some data from the 5.9 kiloton-year exposure of Soudan 2. Fig. 2 shows the final state invariant mass versus net momentum for contained events having two charged tracks whose ionization dE/dx identifies them as $\pi^\pm$ or $\mu^\pm$. The events have been reconstructed as muon-pion pairs (the muon is the longest non-scattering track) under the assumption that they represent charged current single pion production,

$$\nu \mathrm{N} \rightarrow \mu^\pm \pi^\pm + (\mathrm{N}'). \quad (24)$$

Events are plotted according to their "coordinates" in invariant mass versus net momentum. In a subset of events, a recoil proton is observed as a third track from the primary vertex; these events are indicated with solid circles. Such events are highly unlikely as nucleon decay and are instances of reactions (24) most assuredly. Superposed in Fig. 2 is a rectangular search region for mode (20) (and also one for $\mathrm{n} \rightarrow \mu^+\pi^-$). It is an approximation to the more restrictive elliptical region which was actually used [13]. An occurrence of $\Delta B = 1$ decay (20) of a bound neutron would yield a K^0_s which could subsequently decay into $\pi^+\pi^-$ and give rise to an open-circle event within the dot-dash region.

Tantalizingly, eight candidates for mode (20) appear in the search box. Note that a water Cherenkov detector would not record low momentum recoil protons and might include an additional four solid-circle events as candidates. In any case solid-circle events in the search region serve as a warning that neutrino reactions (24) are a background. To gauge the extent of the problem, we consider corresponding diplots from a NEUGEN-based full detector

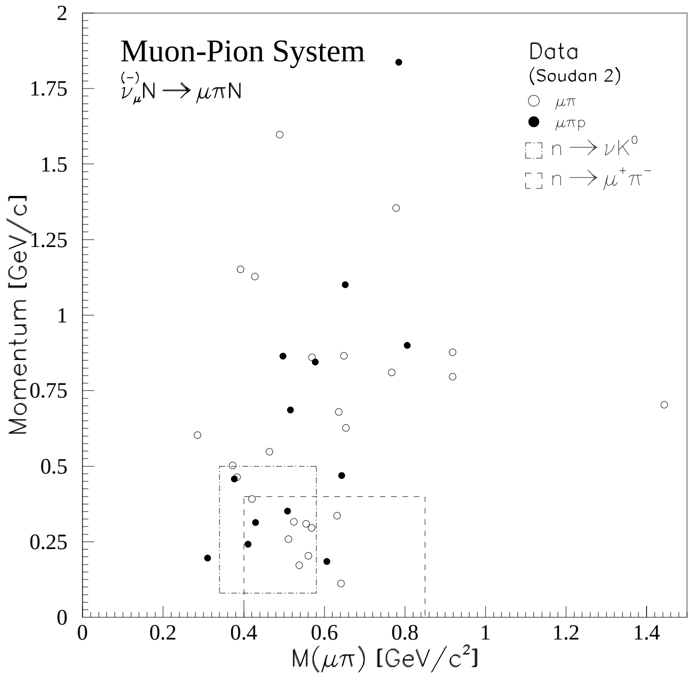


Figure 2: Invariant mass versus momentum for muon-pion systems from Soudan 2 data events assigned to CC single pion reactions. Regions enclosed by dot-dash and dash-dash boundaries are search regions for neutron decays n→ νK^0 and n→ $\mu^+\pi^-$ respectively.

simulation of the Soudan 2 experiment [14], or else from constrained fits to CC reactions (24) from exposure of the ANL 12-ft diameter bubble chamber to an accelerator ν_μ beam. These diplots are shown in Figs. 3a and 3b respectively; the samples displayed represent extrapolations to Soudan 2 exposures exceeding 36 fiducial kiloton years. The dense volley of candidate events in the search regions of Fig. 3 shows that the search for SUSY-GUT favored neutron decay (20) would become background-limited in the fine-grained Soudan tracking calorimeter at exposures of few kiloton-decades.

3.2 Search for p $\rightarrow \nu$K$^+$ in SuperK

The reigning nucleon decay search experiment for the next decade (and probably longer) will be SuperKamiokande. Its successor is also likely to be an underground water Cherenkov detector with similar resolutions but with a monitored water volume approaching megaton scale (the SuperK fiducial volume is 22.5 kilotons). Consequently the strategies developed by SuperK for mode (19) searching may remain in use for a very long time. As currently invoked by SuperK, the search for proton decay (19) is carried out using three different methods. The motivations for these are readily understood by keeping in mind the specific final state sequence which is sought:

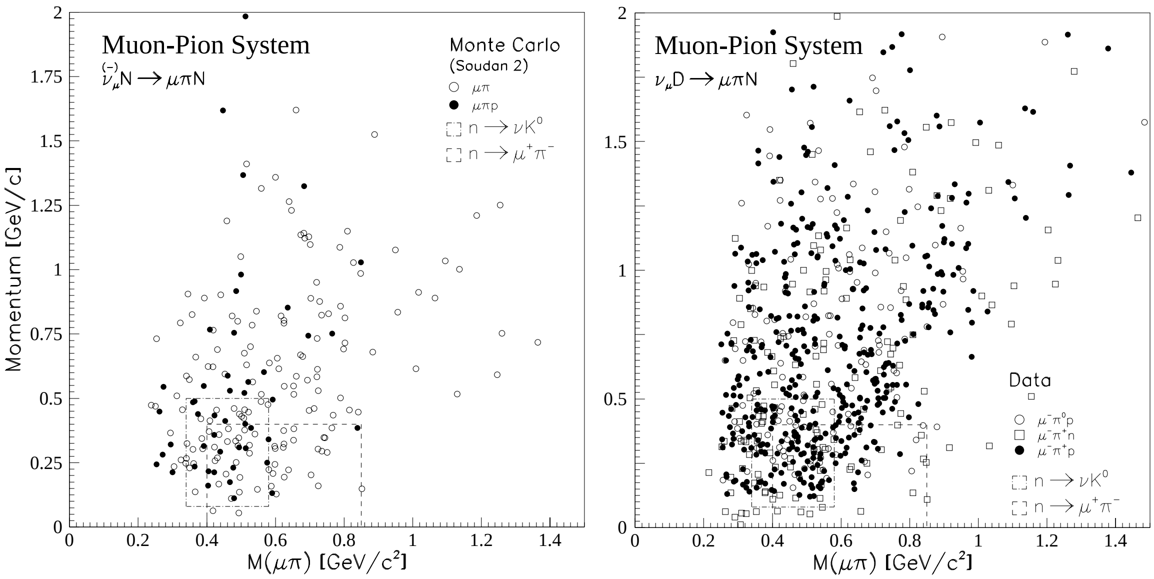
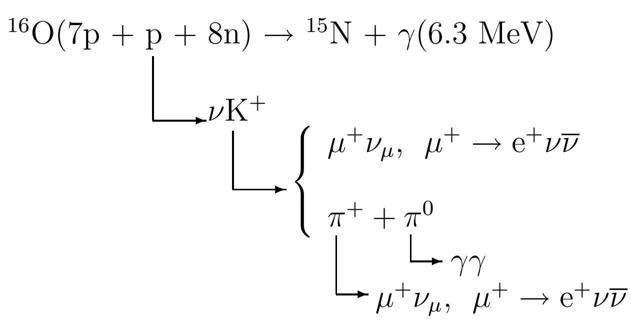


Figure 3: Invariant mass versus momentum for muon-pion systems of *a)* atmospheric ν MC events in Soudan 2 reconstructed as CC single pion production reactions, and of *b)* neutrino events with best fits to ν_μ-CC reactions (24) recorded in $\nu_\mu D_2$ exposures of the ANL 12-foot diam. bubble chamber. The plots indicate that nucleon decay searches for mode (20) become neutrino background limited in underground exposures of few tens of kiloton years.



The three SuperK approaches to finding proton decay (19) are:

i) $K^+ \rightarrow \mu^+\nu$ spectrum search: One looks for an excess of single μ-like ring events for which the reconstructed momenta p_μ match that of two-body K^+ decay at rest and the prompt rings accompanied by subsequent $\mu \rightarrow e$ decay showers.

ii) $K^+ \rightarrow \mu^+\nu$ gamma search: A candidate event has a signature 6.3 MeV gamma emitted by the parent nucleus together with a single μ-like ring having p_μ of a stopped K^+ and accompanied by $\mu \rightarrow e$ decay.

iii) $K^+ \to \pi^+\pi^0$ search: Candidates have three rings compatible with $\pi^+\pi^0$ with $\pi^0 \to \gamma\gamma$ from a stopped K^+ and with a subsequent $\mu \to e$ decay signal.

The requirement of a prompt γ tag as in method *ii)* is found to be especially useful for stringent limit setting.

The projected partial lifetime sensitivity for mode (19) in a search conducted with a next generation megaton-scale water Cherenkov detector [12] is shown in Fig. 4. The combined sensitivity that could be achieved using all three methods is $\approx 3 \times 10^{34}$ years, with the proviso that neutrino-induced backgrounds can be kept to a minimum.

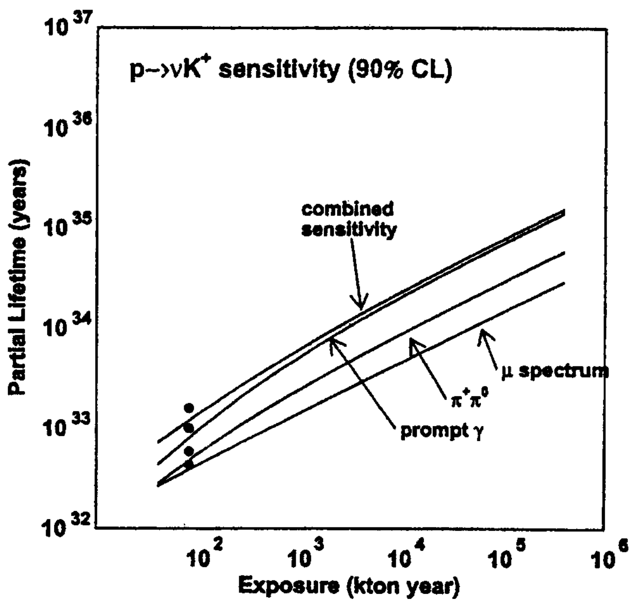


Figure 4: Estimated sensitivity of a search using the proposed water Cherenkov detector UNO, for the partial lifetime of protons to decay via the mode $p \to \nu K^+$. Background to this mode from ν p→ $\nu\Lambda K^+$ enters with exposures approaching 1 Megaton-year.

3.3 Neutrino background for p→ $K^+\nu$

As indicated in Fig. 4, the combined search sensitivity for p→ νK^+ is dominated by the prompt gamma method for which detection of a 6.3 MeV gamma from the nuclear de-excitation chain is crucial. Assuming this capability will be retained by next generation underground water Cherenkov detectors, there is but one atmospheric neutrino reaction which may become a limiting background for the search of this mode, and that is the neutral current associated strangeness production reaction (10). That is, in an underground water Cherenkov detector, an atmospheric neutrino of ν_μ or ν_e flavor may interact with a proton bound in an oxygen nucleus, producing a K^+ meson together with a Λ hyperon and an (invisible) outgoing neutrino. Subsequently, the ^{15}N nucleus which is the remnant of the struck ^{16}O, de-excites producing the 6 MeV signature gamma. The final state Λ is a target fragment and will most always have low momentum. When it decays into $\mathrm{p}\pi^-$ as will happen in two-thirds of reaction (10) occurrences, the daughter tracks will usually be below Cherenkov threshold and hence invisible to a search experiment. The final state K^+ will subsequently decay, usually at rest, to yield a μ^+ or $\pi^+\pi^0$ signature. Consequently the detection sequence in a water Cherenkov experiment indicated above for proton decay (20) is perfectly mimicked:

$$\nu + {}^{16}\mathrm{O} \rightarrow \nu + \mathrm{K}^+ + \Lambda^0 + {}^{15}\mathrm{N} + \gamma(6.3\ \mathrm{MeV})$$

$$\Lambda^0 \rightarrow \mathrm{p}\pi^-\ \text{(below Č threshold)}$$

$$\mathrm{K}^+ \rightarrow \begin{cases} \mu^+\nu_\mu, \quad \mu^+ \rightarrow \mathrm{e}^+\nu\overline{\nu} \\ \pi^+ + \pi^0 \end{cases}$$

$$\pi^0 \rightarrow \gamma\gamma$$

$$\pi^+ \rightarrow \mu^+\nu_\mu, \quad \mu^+ \rightarrow \mathrm{e}^+\nu\overline{\nu}$$

The rate of occurrence of the latter reaction in an underground detector can only be estimated roughly at this time and is of order one event per Megaton-year of fiducial exposure. It is important for future and for ongoing proton decay searches as well, that neutrino background poised by (10) and by other neutrino strangeness production reactions be quantitatively understood. We propose that relevant neutrino strangeness production cross sections including their E_ν dependence be precisely measured using a high resolution NuMI Near Detector as envisaged in the MINERνA proposal.

4 Precision Measurement of $\sigma(\nu\Lambda\mathrm{K}^+)$

The intense neutrino fluxes which will be available in the NuMI near hall, incident upon a fine-grained tracking calorimeter comprised of extruded solid scintillator elements, will allow a precision determination of the exclusive $\Delta S = 0$ neutral current channel

$$\frac{d\sigma}{dE_\nu}(\nu_\mu \mathrm{p} \rightarrow \nu_\mu \mathrm{K}^+\Lambda). \tag{25}$$

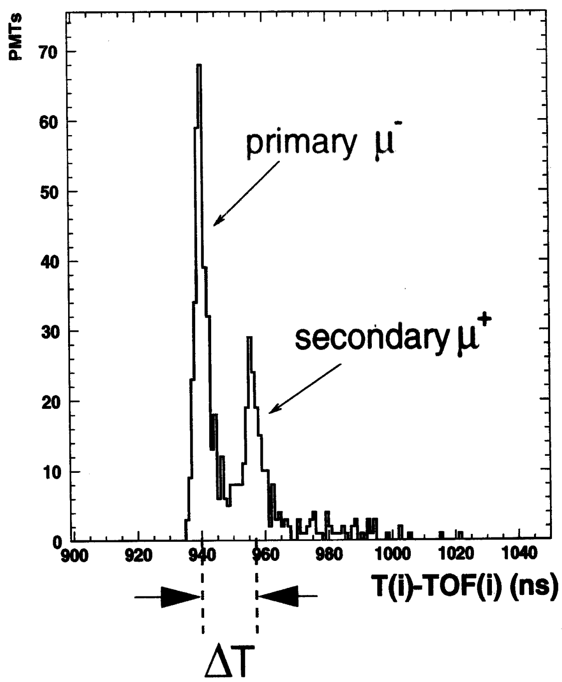


Figure 5: Time distribution from a neutrino interaction candidate for $\nu n \rightarrow \mu^- \Lambda K^+$, $K^+ \rightarrow \mu^+ \nu$ recorded using the 1 kiloton water Cherenkov detector (1KT) at KEK. Two peaks, separated in time by a few tens of nanoseconds, signal the occurrence of a K^+ decay subsequent to the primary charged current interaction.

We propose to measure this cross section, from its threshold at $\approx$ 1 GeV through its rise and leveling off to an energy-independent value at E_ν between 10-15 GeV. For purposes of comparison and as a valuable check on systematics[15], we will simultaneously measure the the $\Delta S = 0$ companion charged current reaction

$$\frac{d\sigma}{dE_\nu}(\nu_\mu \mathrm{p} \rightarrow \mu^- \mathrm{K}^+ \Lambda). \tag{26}$$

The off-line selections required to isolate reactions (35) and (36) are straightforward. Assuming final state Λ decays into p π^- for these reactions, they share the following topological attributes:

i) The reactions have relatively low charged particle multiplicities from the primary vertex region. Reaction (35) has three charged prongs, including the two daughter tracks from Λ decay; reaction (36) has four charged prongs.

ii) The proton track of Λ decay will appear as a short, heavily ionizing track from the vertex region which ranges to stopping.

iii) The final state K^+ mesons will decay at rest or nearly at rest, consequently large-angle μ^+ tracks may result.

The most distinctive signature, however, arises with the time sequence for light emission in scintillator elements from these events. For reaction (35) there arises a "prompt" signal from the two-body decay of the Λ into charged tracks; in reaction (36) the prompt burst is enhanced by the presence of the charged current μ^- in the final state. The prompt signal is followed by a second signal, delayed by some few tens of nanoseconds, which arises from two-body decay of the K^+, assuming the latter also occurs within scintillator of the detector. This timing signature, taken in conjunction with the three topology attributes above, should yield clean samples of reactions (35) and (36).

We note that accumulation of candidate samples for these reactions is currently underway using the K2K near detectors at KEK exposed to a low energy ν_μ beam. The feasibility of exploiting the signature afforded by the signal time profile of these reactions is illustrated in Fig. 5. The Figure shows the time distribution from Cherenkov light from a candidate event for reaction (36), where the occurrence of two PMT peaks separated by approx. 16 nanoseconds is readily seen [11]. At K2K however the effective energy reach of the KEK neutrino beam restricts cross section measurements to $E_\nu \leq 3$ GeV. The atmospheric neutrino flux on the other hand extends to higher energies. Thus the NuMI ν_μ beam operated in the "low energy" configuration will enable a complete picture of $\sigma(E_\nu)$ for reactions (35) and (36) to be obtained, providing an observational basis for future proton decay searches to discover or set improved lifetime lower limits on decay modes favored by SUSY grand unification models.

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