Kaon Production in the MiniBooNE Detector

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July 25, 2002

1 Introduction

Neutrino interactions at MiniBooNE resulting in strange quarks are energetically disfavored compared to final states containing only nucleons and pions, but over the course of the run we should still see a significant number of kaons. A measurement of the exact rate of kaon production will be of particular interest to experiments looking for proton decay because these face an irreducible background from atmospheric neutrinos, many of which fall in an energy range comparable to MiniBooNE's. Some supersymmetric theories predict the possibility of a proton decaying into, for example, a kaon and a lepton at a very low rate, and this idea is being tested by a number of present and proposed nucleon decay experiments [1, 2, 3, 4, 5]. But atmospheric neutrinos interacting with protons could also produce kaons, thus mimicking the decay, and because these experiments cannot expect very large statistics, they need an especially solid understanding of their sources of systematic error.

2 Theoretical models

Table 1 shows a list of some of the major channels of kaon production at low energies, on the order of a few GeV. These are the possible interactions which result in a lepton, a kaon and a baryon. Final states containing multiple mesons are omitted. The first three channels in the charged-current column are flavor changing; the other final states all contain both an s quark and an $\bar{s}$.

This type of interaction has not been investigated from a theoretical standpoint in much depth in the past. Robert E. Shrock estimates rates for processes resulting in a K and a Λ in a 1975 paper [6] using a nonresonant Born model, but the results do not fit data very well and do not level off at high energies. Shrock has said that these calculations had as a goal only to give a rough idea of the rate [7]. He draws a parallel with analogous calculations of rates for neutrino-induced pion production, where again models were largely unpredicitive until they could be tuned by measurements. In the case of single K production, the absence of experimental results measuring cross-sections has made further development of theoretical models difficult.

Charged Current	Neutral Current
$\nu_\mu p \to \mu^- K^+ p$	$\nu_\mu p \to \nu_\mu K^+ \Lambda^0$
$\nu_\mu n \to \mu^- K^0 p$	$\nu_\mu n \to \nu_\mu K^0 \Lambda^0$
$\nu_\mu n \to \mu^- K^+ n$	$\nu_\mu p \to \nu_\mu K^+ \Sigma^0$
$\nu_\mu n \to \mu^- K^+ \Lambda^0$	$\nu_\mu p \to \nu_\mu K^0 \Sigma^+$
$\nu_\mu p \to \mu^- K^+ \Sigma^+$	$\nu_\mu n \to \nu_\mu K^- \Sigma^+$
$\nu_\mu n \to \mu^- K^+ \Sigma^0$	$\nu_\mu n \to \nu_\mu K^+ \Sigma^-$
$\nu_\mu n \to \mu^- K^0 \Sigma^+$	$\nu_\mu n \to \nu_\mu K^0 \Sigma^0$

Table 1: Channels of kaon production at MiniBooNE

A. A. Amer also calculates cross-sections for the production of $K^+\Lambda^0$ in a 1977 paper [8], but using a model of neutrino production of resonances based on a harmonic oscillator quark model, while Shrock assumes only associated (nonresonant) production. Amer estimates the cross-section to be between 1.35 and 2.65 $\times 10^{-41}$ cm^2, but this is more than an order of magnitude below the measured rate [9].

Using David Casper's cross-section calculating program nuance [10], currently being used in K2K, Sam Zeller obtained the plot in Figure 1.

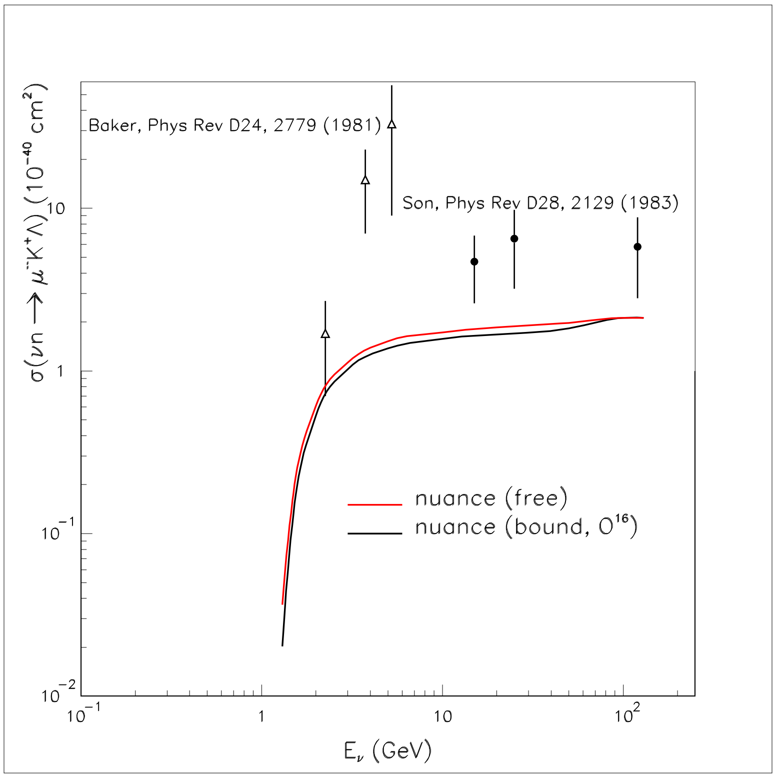

Figure 1: Data points with Nuance theoretical estimate for the channel $\nu_\mu n \to \mu^- K^+ \Lambda^0$

This estimate misses the data points by a factor of four and has an overall χ^2 of around 11/6, but the program includes only resonant kaon production based on the Rein and Sehgal models for pion production [11, 12]. Table 2 lists the various resonances included in the model which can result in $K^+\Lambda^0$ final states, as well as the branching ratios both from the program [10] and from the Particle Data Guide [13].

Resonance	Branching Ratio	
	Nuance Program	Particle Data Guide
$N(1650)$	8%	3–11%
$N(1675)$	0%	<1%
$N(1700)$	0%	<3%
$N(1710)$	15%	5–25%
$N(1720)$	5%	1–15%
$N(1970)$	10%	resonance not listed

Table 2: Resonances with branching ratios for final state $K^+\Lambda^0$

So perhaps this indicates that around one fourth of the production is resonant. Also it is encouraging that the cross-sections on free and bound nucleons are approximately equal. However, each of the models underestimates the cross-section significantly when compared to experimental results.

3 Preliminary cross-section estimates

Most experimental information about these cross-sections in our energy range dates back to bubble chamber experiments from the 70s and 80s [9, 14, 15]. As a result the most studied channel has been $\nu_\mu n \to \mu^- K^+\Lambda^0$ because it is the easiest way to produce a Λ^0 and these particles are easily recognized in a bubble chamber. Because of the disparities between the different theoretical models available for this type of process, in order to make a preliminary estimate of the number of events that will occur in MiniBooNE I fitted a curve to a plot of data points from older measurements (see Figure 2). The curve is an error function modified to give a threshold of 1.1 GeV while passing through the first data point and asymptotically approaching an appropriate level. It has a χ^2 value of 3.81/6.

This is the most investigated channel, and I approximated the cross-sections for other channels using the same basic shape for the curve, multiplying by appropriate scaling factors to get the relative rates right, and then shifting the curve over to adjust the thresholds.

The cross-section for $\nu_\mu n \to \mu^- K^+\Lambda^0$ levels off at around 6×10^{-40} cm^2. The equivalent neutral current interactions ($\nu_\mu n \to \nu_\mu K^0\Lambda^0$ and $\nu_\mu p \to \nu_\mu K^+\Lambda^0$) resulting in Λ^0s should each have about one quarter that cross-section. Because these last two interactions are so similar, their cross-sections should be approximately equal [2, 6, 14]. Similarly the three flavor changing charged current interactions which result in nucleons should all have about the same cross section. Each of these processes can be realized in two basic ways, either by scattering off of a $\bar{u}$ quark in the sea or else by scattering off an s quark in the sea. The Cabibbo

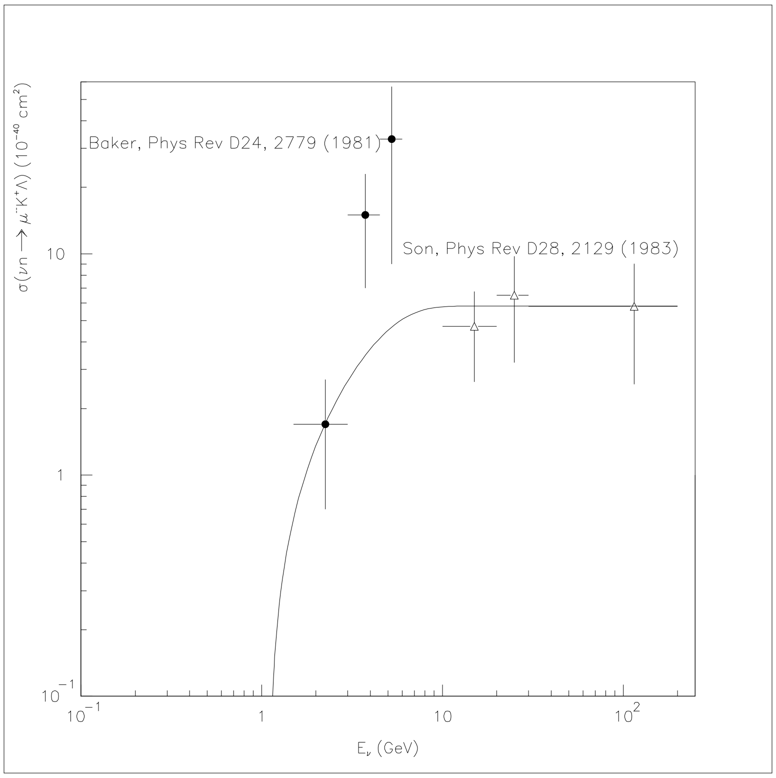

Figure 2: Data points with fitted curve for the channel $\nu_\mu n \to \mu^- K^+ \Lambda^0$

suppression factor associated with the process $d \to u$ in the interaction $\nu_\mu p \to \mu^- \pi^+ p$ is .9754, while the factor for the processes $\bar{u} \to \bar{s}$ and $s \to u$ in the flavor changing channels is .2205. The pion production channel has been extensively measured and that cross section levels off at around 70×10^{40} cm^2 [16]. This suggests that the three flavor changing channels should each have a cross-section of about 5.5% of that for $\nu_\mu p \to \mu^- \pi^+ p$ for both the $s \to d$ and $\bar{u} \to \bar{s}$. This latter channel is further suppressed by helicity considerations, making its cross-section one third that of the former one. Furthermore pion production is dominated by resonant production, while there are no known resonances which can result in a kaon and a nucleon [13]. The ratio of the rates for $\nu_\mu p \to \mu^- K^+ p$ to $\nu_\mu p \to \mu^- \pi^+ p$ has been measured to be around 1.7% [17]. So the actual ratio is smaller than one would expect from Cabibbo considerations alone, but this is largely because of the fact that resonances dominate the pion production channels but not the kaon production channels. So the cross-sections for these flavor changing processes should each be about equal and level off at 1.2×10^{-40} cm^2. Figure 3 shows a plot of each of these rates around MiniBooNE's energy range.

4 Event rates at MiniBooNE

Convoluting this with the GEANT flux estimate (Figure 4) and assuming a fiducial detector of 450 tons (4.04×10^8 grams) I obtained the event rates shown in Table 3. These are all assuming 5×10^{20} protons on target (expected after a year of running) and a detection efficiency of 100%. One bubble chamber experiment using a somewhat similar neutrino energy

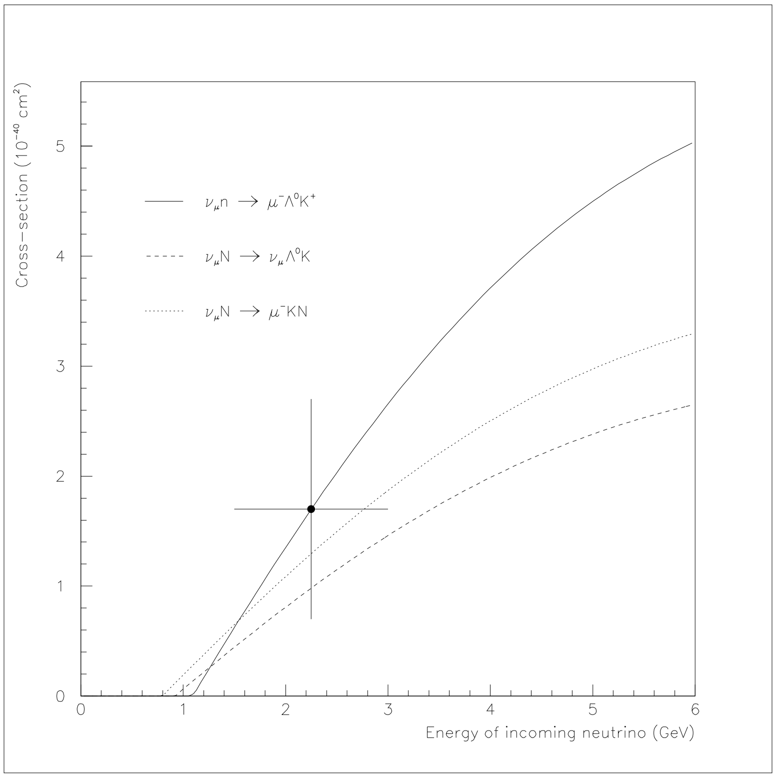

Figure 3: Estimated cross-sections for probable neutrino-nucleon interactions. Data point is from N. J. Baker *et al.*, Phys. Rev. D **24**, 2779 (1981).

spectrum cites event rates for the processes $\nu_\mu n \to \mu^- K^+ \Lambda^0$ and $\nu_\mu p \to \mu^- K^+ p$ which are comparable, whereas according to my estimates the $K^+\Lambda^0$ is expected to dominate, but their results are quoted with large errors, so it is difficult to be sure [2].

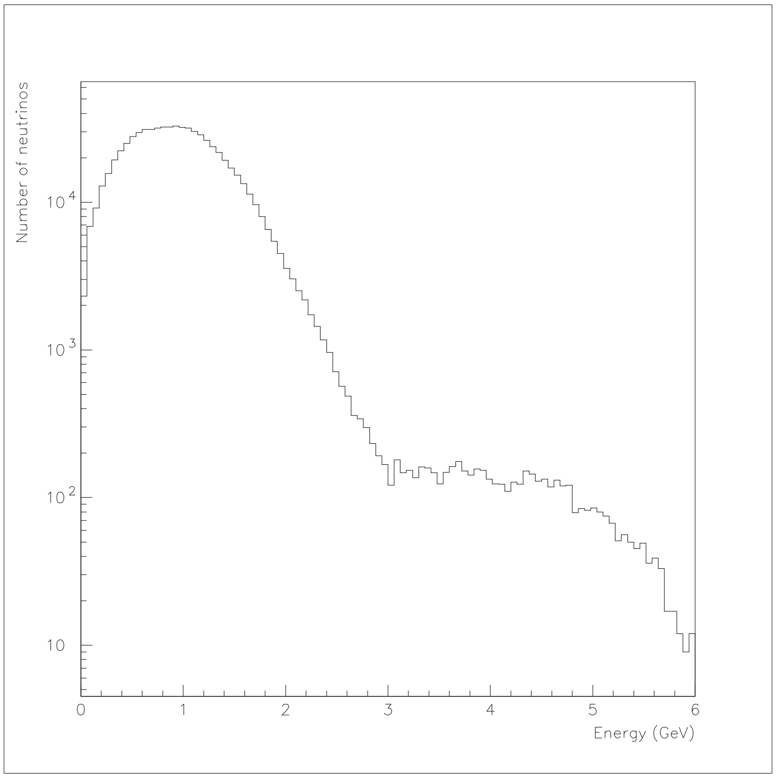

Figure 4: GEANT ν_μ flux estimate for 1 billion protons on target

Channel	Events
$\nu_\mu n \to \mu^- K^+ \Lambda^0$	1095
$\nu_\mu p \to \mu^- K^+ p$	565
$\nu_\mu n \to \mu^- K^0 p$	424
$\nu_\mu n \to \mu^- K^+ n$	424
$\nu_\mu p \to \nu_\mu K^+ \Lambda^0$	545
$\nu_\mu n \to \nu_\mu K^0 \Lambda^0$	408

Table 3: Estimated event rates for major kaon-production channels assuming 100% efficiency and GEANT flux model

Altogether there will be about 2629 K^+s produced and 832 K^0s, not counting events which result in Σ baryons or events which result in multiple mesons. These channels have not been investigated in much detail in the past, but they are suppressed in our energy range and will in any case only add events. By comparison the bubble chamber experiments from the 70s and 80s had event rates on the order of a few dozen at most. It is also possible that these cross-sections are too optimistic. The fit for $\nu_\mu n \to \mu^- K^+ \Lambda^0$ is almost linear between the threshold and the first data point, which is at 2.25 GeV, but most of the events at MiniBooNE will be at lower and relatively uncharted energies, and this point itself has large statistical and systematic errors associated with it. Perhaps mass suppression effects will cause the cross section to increase a great deal more slowly than anticipated, but we should see events even if this effect is of two orders of magnitude.

It should be emphasized that overall there is very little theoretical or experimental guidance for estimating these cross-sections, so the event rates listed here are necessarily only rough estimates about what MiniBooNE can hope to see.

5 Detection of charged and neutral kaons

Not all of the particles produced will be detected. A K^+ decays 63.5% of the time to $\mu^+\nu_\mu$ and 21.2% of the time to $\pi^+\pi^0$, while a K^0 decays to $\pi^+\pi^-$ 68.6% of the time and to $\pi^0\pi^0$ 31.4% of the time [13]. Because most kaon production will occur near threshold, the majority of the K^+s will have low kinetic energies and will come to a stop by interacting electromagnetically before they decay. The resultant two body decays will then produce a monoenergetic stream of μ^+s which can be seen by the detector [18].

Separating individual channels of K^+ production will probably be difficult. It will certainly be possible to distinguish charged current and neutral current events, but identifying the accompanying baryons is likely to prove more problematic Λ baryons decay 63.9% of the time to $p\pi^-$, and 35.8% of the time to $n\pi^0$. π^-s in our detector will be practically invisible, because they will generally be captured quickly by nearby nuclei, but it may be possible to see the π^0s [18].

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