Kaon Production Off the Nucleon

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Abstract. We have studied the weak kaon production off the nucleon induced by neutrinos at the low and intermediate energies. The studied mechanisms are the main source of kaon production for neutrino energies up to 1.2 to 1.5 GeV for the various channels and the cross sections are large enough to be amenable to be measured by experiments such as MINERνA and T2K.

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INTRODUCTION

Neutrino energy region of a few GeV is quite sensitive to the precise determination of neutrino oscillation parameters and that is why experiments like MiniBooNE, SciBooNE, K2K, T2K, NOνA, etc. which have taken data or planned with, are in this energy range. In these experiments nuclear targets are being used and it has been realized that to understand the neutrino event rates, Monte Carlo generators which were being used for predicting the event rates in earlier experiments should be revisited and a reliable estimate of the cross section with proper theoretical understanding is a necessity.

Most of the theoretical calculations for inelastic process is confined to one pion production, however, in the energy range of 1-2 GeV, processes like kaon production, hyperon production, etc. may also become important for both ν and $\bar{\nu}$ induced processes. Kaon production is also an important background reaction in proton decay searches. Present limits on the proton's life time have been obtained by SuperK experiment,

$$\tau(p \rightarrow e^+\pi^0) \geq 5.4 \times 10^{33} yrs \;\; (90\%\, \mathrm{C.L}),$$
$$\tau(p \rightarrow K^+\bar{\nu}) \geq 2.3 \times 10^{33} yrs \;\; (90\%\, \mathrm{C.L}).$$

On the theoretical side non-supersymmetrical GUT theories and calculations with extra dimensions predict the dominant mode for proton decay with life time $\tau(p \rightarrow e^+\pi^0) \leq 1.4 \times 10^{36} yrs$ and $\sim 10^{35} yrs$ respectively. While, super-symmetric calculations predicted the dominant decay mode as $p \rightarrow K^+\bar{\nu}$ with estimated life time as $\tau \sim (0.3-3) \times 10^{34} yrs$ [1, 2]. For example experiments like LAGUNA plans to test physics at the GUT scale [3]. Nonetheless, in the coming years of precision neutrino physics, knowledge of weak kaon production could be relevant for the data analysis, apart from their own intrinsic interest related to the role played by the strange quarks in hadronic physics.

FORMALISM

The basic reaction for neutrino induced $\Delta S = 1$ kaon production is,

$$\nu_l(k) + N(p) \rightarrow l(k') + N'(p') + K(p_k), \qquad (1)$$

where $l = e, \mu$ and $N \& N'$=n,p. The expression for the differential cross section in the lab frame for the above process is given by,

$$\begin{aligned} d^9\sigma &= \frac{1}{4ME(2\pi)^5} \frac{d\vec{k}'}{(2E_l)} \frac{d\vec{p}\,'}{(2E_p')} \frac{d\vec{p}_k}{(2E_K)} \\ &\times \;\; \delta^4(k+p-k'-p'-p_k)\bar{\Sigma}\Sigma|\mathscr{M}|^2, \end{aligned} \qquad (2)$$

where $\vec{k}$ and $\vec{k}'$ are the 3-momenta of the incoming and outgoing leptons with energy E and E' respectively. The kaon 3-momentum is $\vec{p}_k$ having energy E_K, M is the nucleon mass, $\bar{\Sigma}\Sigma|\mathscr{M}|^2$ is the square of the transition amplitude matrix element averaged(summed) over spins of the initial(final) state. At low energies, amplitude is

$$\mathscr{M} = \frac{G_F}{\sqrt{2}} j_\mu^{(L)} J^{\mu\,(H)} = \frac{g}{2\sqrt{2}} j_\mu^{(L)} \frac{1}{M_W^2} \frac{g}{2\sqrt{2}} J^{\mu\,(H)}, \qquad (3)$$

where $j_\mu^{(L)}$ and $J^{\mu\,(H)}$ are the leptonic and hadronic currents respectively, $G_F = \sqrt{2}\frac{g^2}{8M_W^2}$ is the Fermi constant and g is the gauge coupling. The leptonic current can be readily obtained from the standard model Lagrangian coupling the W bosons to the leptons

$$\mathscr{L} = -\frac{g}{2\sqrt{2}} \left[j^\mu_{(L)} W_\mu^+ + h.c. \right]. \qquad (4)$$

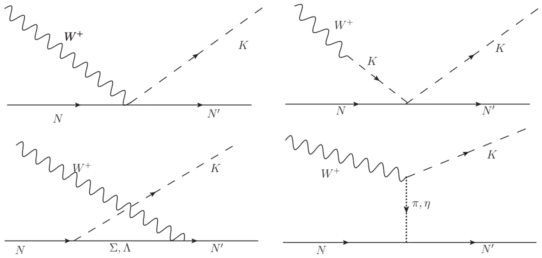

FIGURE 1. Feynman diagrams for the process $\nu N \rightarrow l N' K$. First row from left to right: contact term (labeled CT in the text), Kaon pole term (KP); second row: u-channel diagram ($Cr\Sigma$, $Cr\Lambda$) and Pion(Eta) in flight (πP, (ηP))

We consider four different channels that contribute to the hadronic current. They are depicted in Fig. 1. There is a contact term (CT), a kaon pole (KP) term, a u-channel process with a Σ or Λ hyperon in the intermediate state and finally a meson (π, η) exchange term.

The contribution of the different terms can be obtained in a systematic manner using χPT. This allows to identify some terms that were missing in the approach of Ref. [5] which only included the u-channel diagrams in the calculation. The lowest-order SU(3) chiral Lagrangian describing the pseudoscalar mesons in the presence of an external current is,

$$\mathscr{L}_M^{(2)} = \frac{f_\pi^2}{4}\mathrm{Tr}[D_\mu U (D^\mu U)^\dagger] + \frac{f_\pi^2}{4}\mathrm{Tr}(\chi U^\dagger + U\chi^\dagger), \quad (5)$$

where the parameter $f_\pi = 92.4$MeV is the pion decay constant, $U(x) = \exp\left(i\frac{\phi(x)}{f_\pi}\right)$ is the SU(3) representation of the meson fields $\phi(x)$ and $D_\mu U$ is its covariant derivative

$$D_\mu U \quad \equiv \quad \partial_\mu U - i r_\mu U + i U l_\mu \,. \quad (6)$$

Here, l_μ and r_μ correspond to left and right handed currents, that for the CC case are given by

$$r_\mu = 0, \quad l_\mu = -\frac{g}{\sqrt{2}}(W_\mu^+ T_+ + W_\mu^- T_-), \quad (7)$$

with $W^\pm$ the W boson fields and

$$T_+ = \begin{pmatrix} 0 & V_{ud} & V_{us} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}; \quad T_- = \begin{pmatrix} 0 & 0 & 0 \\ V_{ud} & 0 & 0 \\ V_{us} & 0 & 0 \end{pmatrix}.$$

Here, V_{ij} are the elements of the Cabibbo-Kobayashi-Maskawa matrix. For detailed calculation see Ref. [4].

RESULTS AND DISCUSSION

We consider the following reactions:

$$\begin{array}{ll} \nu_l + p \rightarrow l^- + K^+ + p & (l = e,\ \mu) \\ \nu_l + n \rightarrow l^- + K^0 + p & \nu_l + n \rightarrow l^- + K^+ + n \end{array}$$

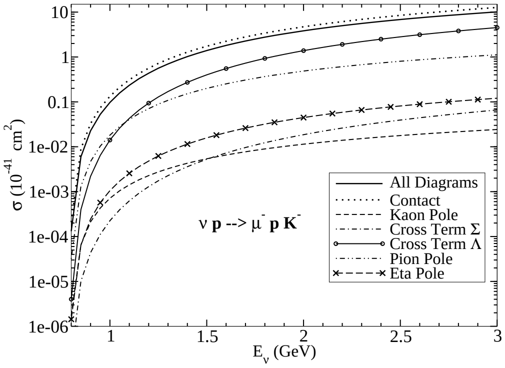

FIGURE 2. Contribution of the different terms to the total cross section for the $\nu_\mu p \rightarrow \mu^- K^+ p$ reaction.

The total scattering cross section σ has been obtained by using Eq. (2). In Fig. 2 the results from the contributions of the different diagrams to the total cross sections for $\nu_\mu p \rightarrow \mu^- K^+ p$ is presented. The kaon pole contributions are negligible at the studied energies. We observe the relevance of the contact term, not included in previous calculations, however, we find that the contact term is in fact dominant, followed by the u-channel diagram with a Λ intermediate state and the π exchange term. As observed by Dewan [5] the u-channel Σ contribution is much less important, basically because of the larger coupling ($NK\Lambda \gg NK\Sigma$) of the strong vertex. The curve labeled as All Diagrams has been calculated with a dipole form factor with a mass of ($M_A =$) 1 GeV. If M_A is varied by 10% the cross section changes by 10-12%. A similar effect is found in other channels. We have also checked that the cross section obtained without the contact term and after making the correction for the different parameters like Cabibbo angle and the Yukawa strong coupling, the results agree with the result of Fig. 7 of Ref. [5] at the energies of present interest. Higher energies are well beyond the scope of our model.

We observe that, due to the difference between the energy thresholds, single kaon production for the $\nu_\mu p \rightarrow \mu^- p K^+$ is dominant below 1.5 GeV. We compare our results with the values for the associated production obtained by means of the GENIE Monte Carlo program in Fig. 3. Also at higher energies the Associated kaon production dominance is well established experimentally Ref. [7, 8]. However, for the other two channels associated production becomes comparable at lower energies. Still, single K^0 production off neutrons is larger than the associated production up to 1.3 GeV and even the much smaller K^+ production off neutrons is larger than the associated production up to 1.1 GeV. The consideration of these $\Delta S = 1$ channels is therefore important for the description of strangeness production for all low energy neutrino spectra and should be incorporated in the exper-

TABLE 1. Cross sections averaged over the neutrino flux at different laboratories in units of 10^{-41} cm^2. Theoretical uncertainties correspond to a 10% variation of the form factor mass.

Process	ANL	MiniBooNE	T2K
$\nu_\mu n \to \mu^- K^+ n$	0.06(1)	0.07(1)	0.09(1)
$\nu_\mu p \to \mu^- K^+ p$	0.28(5)	0.32(5)	0.43(8)
$\nu_\mu n \to \mu^- K^0 p$	0.17(3)	0.20(3)	0.25(5)

imental analysis.

In Table 1 we show the total cross section results for the three channels averaged over the ANL [9], the MiniBooNE [10] and the off-axis (2.5 degrees) T2K [11] muon neutrino fluxes, all of them peaking at around 0.6 GeV. After normalization of the neutrino flux ϕ we have

$$\bar{\sigma} = \int_{E_{\rm th}}^{E_{\rm high}} dE\, \phi(E)\sigma(E), \tag{8}$$

where $E_{\rm th}$ is the threshold energy for each process and $E_{\rm high}$ is the maximum neutrino energy. As discussed previously, in these three cases, the neutrino energies are low enough for single kaon production to be relevant as compared to associated kaon production. Also the invariant mass of the hadronic system and the transferred momentum only reach the relatively small values where our model is more reliable.

We show the Q^2 distribution in Fig. 4 for the three studied channels at a neutrino energy $E_\nu = 1.5$ GeV. The forward peaking of the reactions shows the small momentum transfer at low energies. We also found the dependence of the cross section on the mass of the final lepton that reduces the cross section at low Q^2.

It is expected that in the neutrino induced kaon production, nuclear effects will be much smaller, because there is no kaon absorption and the final state interaction is reduced to a repulsive potential, and hence is small when compared with the typical kaon energies. Also there is no resonant channels in the production processes. However, in the case of antineutrinos, resonant diagrams like Σ^* would also contribute, as well as resonances like $\Lambda(1405)$ may also become important. Therefore, $\bar{\nu}$ induced kaon productions from nuclei would be more challenging.

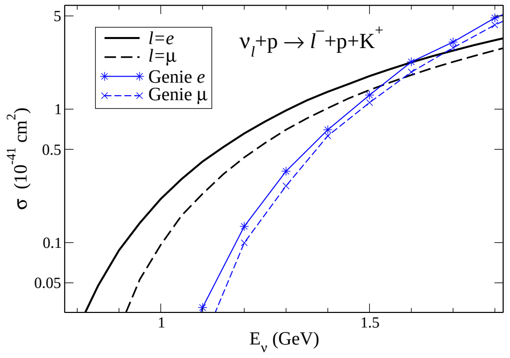

FIGURE 3. Cross sections as a function of the neutrino energy for single kaon production vs. associated production obtained with GENIE [6].

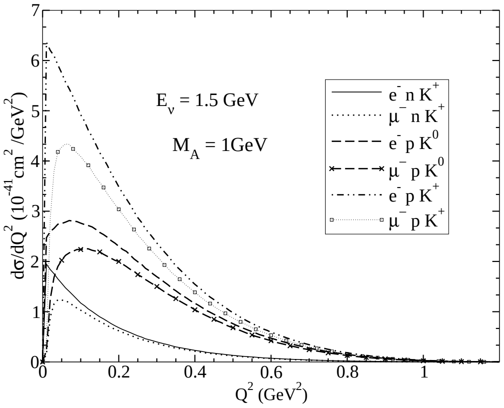

FIGURE 4. $\frac{d\sigma}{dQ^2}$ at $E_\nu = 1.5 GeV$ with $M_A = 1 GeV$ for single kaon production induced by neutrinos. The curves are labeled according to the final state of the process.

To conclude, we have studied neutrino induced kaon production from the nucleons and obtained cross sections that are around 2 orders of magnitude smaller than for pion production for neutrino spectra such as those of ANL or MiniBooNE. Nonetheless, the cross sections are large enough to be measured, for instance, with the expected MINERνA and T2K fluxes and could have been well measured at MiniBooNE. We have also found that, due to the higher threshold of the associated kaon production, the reactions we have studied are the dominant source of kaons for a wide range of energies, and thus their study is important for some low energy experiments and for the atmospheric neutrino flux.

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