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NEUTRINO-INDUCED KAON PRODUCTION

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Abstract

A formalism is presented for the description of neutrino-induced kaon and associated hypernucleus production. It is shown that the cross section can be written as the contraction of a leptonic and hadronic tensor if the interaction is modelled as a quasifree process. The hadronic tensor is written in a model-independent way in terms of thirteen nuclear structure functions. A Born-term model is used to describe the underlying elementary hyperon and kaon production process. The bound state wave functions of the hyperon and nucleon are calculated within a relativistic mean field approximation. Preliminary results are discussed.

1 Introduction

The main motivation for this work is the realization that kaons and hypernuclei are likely products of weak neutrino-nucleus reactions. The role of neutrinos and strange hadrons in the behaviour of supernovae is also a contemporary research topic. Other phenomena that can be illuminated by the study of weak strangeness production is neutrino oscillations (a spontaneous change in neutrino flavour). Currently experiments to detect these events are underway at Fermilab (BooNe) and JPARC. Neutrino-induced kaon production is especially important since kaons produced by the interactions of atmospheric neutrinos with nuclei can mimic the signals of kaons arising from proton-decay predicted by supersymmetric theories (see Ref. [1]).

Our model is the first attempt at describing the weak production of hypernuclei and kaons. It is a fully relativistic treatment of this problem since

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both relativistic kinematics and dynamics are used. Refs. [2] and [3] give descriptions of the elementary neutrino-nucleon scattering process in terms of Born s, t and u channels and Ref. [4] discusses a formalism for the description of neutrino-induced associated production. Our work is based on a general scattering formalism developed in Refs. [5] and [6].

2 Our Model

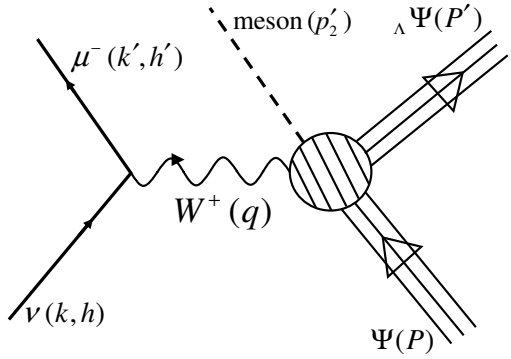


Figure 1: General charged current neutrino scattering process resulting in production of a hypernucleus and a kaon.

Figure 1 shows the general type of scattering process we describe. A more complete discussion of the model can be found in Ref. [7]. The cross section is written as

$$d\sigma = \frac{1}{2\,(2\pi)^5\,E_{p_2'}}\,\delta^4\left(k+P-k'-p_2'-P'\right)\,d^3\mathbf{k}'\,d^3\mathbf{p}_2'\,d^3\mathbf{P}'\,|\mathcal{M}|^2\,. \quad (1)$$

The invariant matrix element squared is written as the contraction of a leptonic and a hadronic tensor

$$|\mathcal{M}|^2 = \frac{G_F^2}{2}\cos^2\theta_C\,\ell_{\mu\nu}W^{\mu\nu}, \quad (2)$$

where θ_C is the Cabibbo angle and G_F is the Fermi-constant for beta-decay. These tensors describe the relativistic dynamics of the projectile and the nucleus. The leptonic tensor is derived using a conventional relativistic approach of Dirac planewave spinors and the weak leptonic current operator.

The hadronic tensor is parametrised in a model-independent basis using 13 structure functions. Eq. (2) then gives

$$\begin{aligned}\ell_{\mu\nu}W^{\mu\nu} &= \frac{4}{E_kE_{k'}}\left[(-W_1(k\cdot K')+W_2f_1(q)+W_3f_1(P)+W_4f_1(p_2')\right.\\ &+ W_5f_2(P,q)+W_6f_2(q,p_2')+W_7f_2(P,p_2'))+i\left(W_{10}\epsilon_{\mu\nu\alpha\beta}P^\mu p_2'^\nu k^\alpha K'^\beta\right.\\ &+ \left.W_{11}f_3(q,P)+W_{12}f_3(q,p_2')+W_{13}f_3(P,p_2'))\right], \quad (3)\end{aligned}$$

where

$$\begin{aligned} f_1(x) &= (k\cdot x)(K'\cdot x) - x^2/2(k\cdot K'), \\ f_2(x,y) &= (k\cdot x)(K'\cdot y) + (k\cdot y)(K'\cdot x) - (x\cdot y)(k\cdot K'), \\ f_3(x,y) &= (k\cdot y)(K'\cdot x) - (k\cdot x)(K'\cdot y), \end{aligned} \tag{4}$$

and

$$K' \equiv \frac{1}{2}(k' - h' m_{k'} s) \xrightarrow[m=0]{} k'\delta_{h',-1}\ , \tag{5}$$

$$s^{\mu}(\mathbf{k}') \equiv \frac{1}{m}\left(|\mathbf{k}'|\,, E_{k'}\hat{\mathbf{k}}'\right). \tag{6}$$

2.1 Model-dependent evaluation of the hadronic vertex

We make use of the quasifree approximation for the hadronic vertex. A Born-term model (s, t and u-channels) is used to construct the current of the elementary hadronic process (see Ref. [2]). The form of the elementary currents is extended to the quasifree case by integrating over the momentum of the bound nucleon

$$h^{\mu} = \int d^3\mathbf{p}_1\, \overline{\mathcal{U}}_Y(\mathbf{q}+\mathbf{p}_1-\mathbf{p}_2')J^{\mu}\mathcal{U}(\mathbf{p}_1). \tag{7}$$

The bound state wave functions we use are calculated using a relativistic mean-field formalism (FSUGold for neutron and NLSH for hyperon). The model-dependent hadronic tensor is then given by

$$(W^{\mu\nu})_{\text{model}} = \sum_{m_N, m_Y} h^{\mu}\,(h^{\nu})^*\,, \tag{8}$$

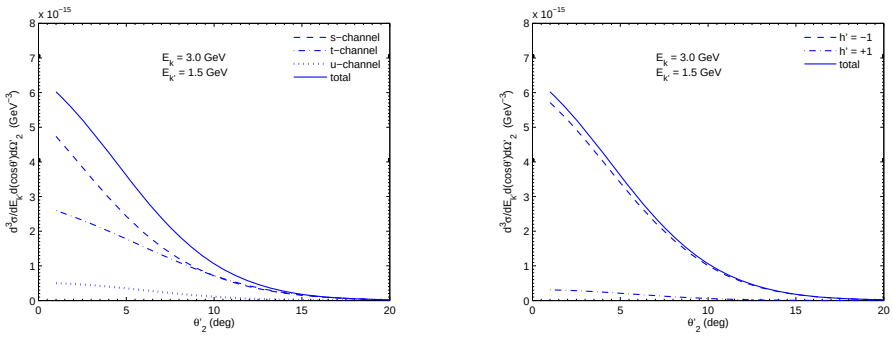
where m_N and m_Y refer to the projections of the total angular momentum of the nucleon and hyperon. The structure functions are extracted from the model-dependent hadronic tensor as described in Ref. [7] and inserted into Eq. (3).

3 Results

An example calculation was done for a 3 GeV neutrino projectile and a 1.5 GeV ejectile muon for the reaction $\nu + {}^{12}\mathrm{C} \rightarrow \mu^- + K^+ + {}^{12}_{\Lambda}\mathrm{C}$ (elementary process: $\nu + n \rightarrow \mu^- + K^+ + \Lambda$) . Fig. 2 (a) shows that the largest channel-contributions to the differential cross section come from the s and t-channels

for which exact phenomenological form factors were used. The u-channel, for which we assumed an exact SU(3) symmetry which lead to approximate form factors in the baryon octet, delivers only a small contribution.

Fig. 2 (b) shows the contribution of the different helicity states of the ejectile muon to the total differential cross section. The contribution of the negative helicity muon clearly far exceeds that of the positive helicity one. This can be ascribed to the fact the muon mass is so small in comparison to its energy that the helicity of the neutrino ($h = -1$) is largely conserved in the reaction.



(a) Born channels and total (b) Contributions of different muons.

Figure 2: Differential cross section of the $1p^{3/2}$ neutron to $1s^{1/2}$ hyperon transition.

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