Quasielastic hyperon production in $\bar{\nu}_\mu$–Nucleus interactions

M. Rafi Alam, M. Sajjad Athar, S. Chauhan and S. K. Singh
Department of Physics, Aligarh Muslim University, Aligarh - 202 002, India
E-mail: sajatbar@gmail.com

Abstract. We have studied quasielastic charged current hyperon production induced by $\bar{\nu}_\mu$ on free nucleon and the nucleons bound inside the nucleus. The calculations are performed for several nuclear targets like $^{12}$C, $^{40}$Ar, $^{56}$Fe and $^{208}$Pb which are presently being used in various oscillation experiments using accelerator neutrinos. The inputs are the hyperon-nucleon transition form factors determined from neutrino-nucleon scattering as well as from semileptonic decays of neutron and hyperons using SU(3) symmetry. The calculations for the nuclear targets are done in local density approximation. The nuclear medium effects (NME) due to Fermi motion and final state interaction (FSI) effect due to hyperon-nucleon scattering have been taken into account.

PACS numbers: 13.15+g, 13.75.Ev, 14.20.Jn, 25.30.Pt

1. INTRODUCTION

The present day neutrino oscillation experiments are also providing cross section measurements of many quasielastic and inelastic processes induced by neutrinos and antineutrinos on nuclear targets which are being used in various Monte-Carlo neutrino generators. These recent cross section measurements are available mostly for $|\Delta S| = 0$ processes in nonstrange sector. In strange sector the results of older work available in literature on cross section measurements for $|\Delta S| = 0$ and $|\Delta S| = 1$ processes are used in these neutrino generators. The availability of high intensity neutrino and antineutrino beams in present generation neutrino oscillation experiments has opened up the possibility of experimentally studying, with better statistics, the weak production of strange particles through $|\Delta S| = 0$ and $|\Delta S| = 1$ processes induced by neutrinos and antineutrinos from nuclear targets. This has motivated many authors to perform new theoretical calculations of these processes [1] - [8]. In general the antineutrino - nucleus cross sections are not as well studied as the neutrino - nucleus cross sections specifically in the region of intermediate energies of $E_\nu \leq 2$GeV. In this energy region the dominant $|\Delta S| = 1$ process is the quasielastic production of hyperons induced by antineutrinos,
which are:
\[ \bar{\nu}_l + p \rightarrow l^+ + \Lambda \]
\[ \bar{\nu}_l + p \rightarrow l^+ + \Sigma^0 \]
\[ \bar{\nu}_l + n \rightarrow l^+ + \Sigma^- ; \ l = e, \mu . \] (1)

These processes are induced by $|\Delta S| = 1$ weak currents and are kinematically favored over $|\Delta S| = 0$ meson production processes. Generally, the processes like Eq. (1) are suppressed by a factor $\tan^2 \theta_C$, $\theta_C$ being the Cabibbo angle, as compared to the $|\Delta S| = 0$ associated production of hyperons. However, in the intermediate energy region of $E_\nu < 2$ GeV, the associated production of hyperons is kinematically suppressed by the phase space and the quasielastic production of hyperons shown in Eq. (1) may be important. Moreover, the experimental observation of quasielastic production of hyperons in antineutrino experiments where no charged leptons are seen in the final state will give evidence of Flavor Changing Neutral Current (FCNC) leading to study of physics beyond the Standard Model. These reactions have been earlier studied experimentally at CERN and Serpukhov using Gargamelle and SKAT Bubble Chambers filled with heavy liquid like Freon and/or Propane and at Brookhaven National Lab(BNL) and Fermi National Accelerator Lab(FNAL) using Hydrogen and Hydrogen-Neon targets [9] - [14]. These experiments have reported results for the cross sections($\sigma(E)$) and $Q^2$ distribution(i.e. $\frac{d\sigma}{dQ^2}$) which have large uncertainties due to poor statistics. It is proposed to study these reactions at MINER$\nu$A [15], MicroBooNE [16, 17] and ArgoNeuT [18, 19] experiments. They can also be studied at other neutrino oscillation experiments at SuperK [20], MiniBooNE [21], T2K [22] and NO$\nu$A [23]. Theoretically, these processes have been studied in past for nucleon targets either in quark model [24] or in Cabibbo theory [25] using SU(3)-symmetry of the weak hadronic currents [26] - [34]. No calculation has been made in past to study nuclear medium and final state interactions in these processes and it is only recently that some attempts have been made to study these effects [1, 2, 8] in view of the forthcoming experiments [15]-[19].

In this paper, we present the results of a study made for quasielastic production of $\Lambda$ and $\Sigma$ hyperons induced by antineutrinos on nuclear targets like $^{12}\text{C}$, $^{40}\text{Ar}$, $^{56}\text{Fe}$ and $^{208}\text{Pb}$ relevant for present neutrino oscillation experiments being done at MINER$\nu$A [15], MicroBooNE [16, 17], ArgoNeuT [18, 19], MiniBooNE [21] and T2K [22]. We also present an estimate of nuclear medium effects(NME) and final state interaction(FSI) effect when the reactions take place on bound nucleons in nuclei using the methods described in Ref. [1]. In Section-2, we briefly review the formalism and various assumptions used to calculate $|\Delta S| = 1$ quasielastic reactions and define various quantities used in this work. We describe the nuclear medium and final state interaction effects in Section-3 and present the numerical results for the total scattering cross sections and the differential cross sections relevant for various experiments where measurements of quasielastic hyperon production may be made in near future. In Section-4, we present a summary and future outlook of these processes in view of present antineutrino experiments.
2. QUASIELASTIC PRODUCTION OF HYPERONS

$|\Delta S| = 1$ hyperon ($Y$) production processes induced by muon type antineutrinos which are presently being used in accelerator experiments are written as

\[ \bar{\nu}_\mu(k) + p(p) \rightarrow \mu^+(k') + \Lambda(p') \]
\[ \bar{\nu}_\mu(k) + p(p) \rightarrow \mu^+(k') + \Sigma^0(p') \]
\[ \bar{\nu}_\mu(k) + n(p) \rightarrow \mu^+(k') + \Sigma^-(p') \]

(2)

for which the differential scattering cross section in the laboratory frame is given by

\[ d\sigma = \frac{1}{(2\pi)^2} \frac{1}{4E_{p'}/M} \delta^4(k + p - k' - p') \frac{d^3k'}{2E_{k'}} \frac{d^3p'}{2E_{p'}} \sum |\mathcal{M}|^2, \]

(3)

where $M$ is the nucleon mass and $\mathcal{M}$ is the transition matrix element given by

\[ \mathcal{M} = \frac{G_F}{\sqrt{2}} \sin \theta_C l^\mu J_\mu. \]

(4)

In the above expression $l^\mu$ is the leptonic current ($\bar{\nu}(k')\gamma^\mu(1 + \gamma_5)v(k)$) and $J_\mu(|\Delta S| = 1)$ is the matrix element of strangeness changing hadronic current defined as

\[ J_\mu = \langle Y(p')|V_\mu - A_\mu|N(p)\rangle, \]

(5)

where coupling to the leptonic current $l^\mu$ is determined as $G_F \sin \theta_C / \sqrt{2}$ in terms Cabibbo angle $\theta_C$ using universality of weak interactions. In Eq. $[4]$ $Y(p')$ and $N(p)$ denote the final hyperon $Y$ and initial nucleon $N$ with momenta $p'$ and $p$, respectively and the matrix element of vector and axial vector currents are defined as

\[ \langle Y(p')|V_\mu|N(p)\rangle = \bar{u}_Y(p') \left[ \gamma_\mu f_1(q^2) + i\sigma_{\mu\nu} \frac{q^\nu}{M + M_Y} f_2(q^2) \right] u_N(p) \]
\[ + \frac{f_3(q^2)}{M + M_Y} q_\mu u_N(p) \]

(6)

and

\[ \langle Y(p')|A_\mu|N(p)\rangle = \bar{u}_Y(p') \left[ \gamma_\mu \gamma_5 g_1(q^2) + i\sigma_{\mu\nu} \gamma_5 \frac{q^\nu}{M + M_Y} g_2(q^2) \right] u_N(p) \]
\[ + \frac{g_3(q^2)}{M + M_Y} q_\mu \gamma_5 u_N(p), \]

(7)

where $q^2$ is the four momentum transfer square ($q^2 = -Q^2, Q^2 \geq 0$) and $M_Y$ is the mass of hyperon. In defining the matrix elements of vector and axial vector currents in Eqs. [6] and [7] we have followed the conventions used by Llewellyn Smith[27], while other conventions also exist in literature specially for the momentum dependent terms involving $f_2(q^2)$, $f_3(q^2)$, $g_2(q^2)$ and $g_3(q^2)$. This is discussed further in Section 2.1 when we determine them using symmetry properties of weak hadronic currents including SU(3) symmetry.

2.1. Form Factors

The six form factors $f_i(q^2)$ and $g_i(q^2)$ ($i = 1, 2, 3$) are determined using following assumptions about the weak vector and axial vector currents in weak interactions.
(a) The assumption of T invariance implies that all the form factors \( f_i(q^2) \) and \( g_i(q^2) \) are real.

(b) The assumption of SU(3) symmetry of weak hadronic currents implies that the vector and axial vector currents have definite transformation properties under SU(3) group of transformations. Assuming that \(|\Delta S| = 0\) and \(|\Delta S| = 1\) weak currents along with the electromagnetic currents transform as octet representation under SU(3) determine various couplings of these currents to initial and final baryons using SU(3) Clebsch-Gordan coefficients corresponding to the decomposition

\[
8 \otimes 8 = 1 \oplus 8^8 \oplus 8^A \oplus 10 \oplus 10 \oplus 27. \tag{8}
\]

Since initial and final baryons also belong to octet representation, each form factor \( f_i(q^2) \) \((g_i(q^2))\) occurring in the matrix element of vector(axial vector) current is written in terms of two functions \( D(q^2) \) and \( F(q^2) \) corresponding to symmetric octet(8\(^S\)) and antisymmetric octet(8\(^A\)) couplings of octets of vector(axial vector) currents. Specifically we write

\[
f_i(q^2) = a F_i^V(q^2) + b D_i^V(q^2) \]
\[
g_i(q^2) = a F_i^A(q^2) + b D_i^A(q^2), \tag{9}\]

where \( a \) and \( b \) are SU(3) Clebsch-Gordan coefficients given in Table-I. We find from the values of \( a \) and \( b \) given in Table-I that

\[
\frac{d\sigma}{dq^2}(\bar{\nu}_\mu n \to \mu^+ \Sigma^-) = \frac{1}{2} \frac{d\sigma}{dq^2}(\bar{\nu}_\mu p \to \mu^+ \Sigma^0). \tag{10}\]

(c) The assumption of SU(3) symmetry and G invariance together imply the absence of second class currents \[35\] leading to

\[
f_3(q^2) = 0. \tag{11}\]

(d) The assumption of Conserved Vector Current and SU(3) symmetry implies \( f_3(q^2) = 0 \) and leads to the determination of \( f_1(q^2) \) and \( f_2(q^2) \) in terms of electromagnetic form factors of nucleons \( f_1^N(q^2) \) and \( f_2^N(q^2); (N = p, n) \).

In order to do this, we write electromagnetic current in terms of its SU(3) content as

\[
V_{\mu}^{em} = V_\mu^3 + \frac{1}{\sqrt{3}} V_\mu^8, \tag{12}\]

where the superscript 3 and 8 denote SU(3) indices. We define the matrix element of the electromagnetic current between nucleon states in terms of electromagnetic form factors of nucleons \( f_1^N(q^2) \) and \( f_2^N(q^2) \) as

\[
\langle N(p')|V_{\mu}^{em}|N(p)\rangle = \bar{u}_N(p') \left[ \gamma_\mu f_1^N(q^2) + i\sigma_\mu \frac{q_\nu}{2M} f_2^N(q^2) \right] u_N(p). \tag{13}\]

Evaluating Eq. \[13\] between nucleon states, we find

\[
\begin{align*}
  f_1^p(q^2) &= F_1^V(q^2) + \frac{1}{3} D_1^V(q^2), \\
  f_1^n(q^2) &= -\frac{2}{3} D_1^V(q^2), \\
  f_2^p(q^2) &= 0, \\
  f_2^n(q^2) &= 0; \\
\end{align*} \tag{14}\]

\( i = 1, 2 \)
which determines the functions $D^V_i(q^2)$ and $F^V_i(q^2)$ corresponding to the non-vanishing form factors $f_i(q^2) \ (i = 1, 2)$ in terms of the electromagnetic form factors of nucleons. This along with the Clebsch-Gordan coefficients $a$ and $b$ given in Table 1, completely determine all the vector form factors and are given in Table 2. It may be noted that we have implemented the SU(3) symmetry at the level of form factor $f_2(q^2)$ and not at the level of $f_2(q^2)/M_Y$ as done by Cabibbo et al.[36, 37] in the analysis of semileptonic decays.

(e) In the axial vector sector, the form factor $g_2(q^2)$ vanishes due to G invariance and SU(3) symmetry. The contribution of $g_3(q^2)$ is very small as it is proportional to the lepton mass in the matrix element and is generally neglected in the case of $|\Delta S| = 0$ reactions. We neglect it here in the case of $|\Delta S| = 1$ reactions. Thus the only non-vanishing form factor is therefore $g_1(q^2)$ which is determined in terms of the two functions $D^A_1(q^2) = D(q^2)$ and $F^A_1(q^2) = F(q^2)$. With the values of Clebsch-Gordan coefficients $a$ and $b$ given in Table 1, we tabulate them in Table 2 for the reactions studied in this paper. It should be emphasized that the determination of various vector(axial vector) form factors $f_i(q^2)(g_i(q^2)) \ (i = 1, 2, 3)$ depends very crucially on SU(3) symmetry which is known to work well in the analysis of semileptonic decays of hyperons provided the physical masses for hyperons are used in the analysis. But the question of SU(3) symmetry in $|\Delta S| = 1$ reactions induced by anti(neutrinos) is yet to be studied and should be investigated specially when there are indications of non-zero $g_2(q^2)$ in the analysis of semileptonic hyperon decays. With antineutrino beam of high intensity, the study of strange particle production through $|\Delta S| = 1$ reactions shall provide an opportunity to study SU(3) breaking effects as well as G invariance in the strangeness sector.

2.2. $q^2$ dependence of form factors

(i) Vector form factors

The vector transition form factors for $p \rightarrow \Lambda$ and $p \rightarrow \Sigma^0$ transitions given in terms of the electromagnetic form factors of neutrons and protons as shown in Table 2 are written in terms of Sach’s form factors $G^{p,n}_E(q^2)$ and $G^{p,n}_M(q^2)$ as

$$f_1^{p,n}(q^2) = \frac{1}{1 - \frac{q^2}{4M^2}} \left[ G^{p,n}_E(q^2) - \frac{q^2}{4M^2} G^{p,n}_M(q^2) \right]$$

$$f_2^{p,n}(q^2) = \frac{1}{1 - \frac{q^2}{4M^2}} \left[ G^{p,n}_M(q^2) - G^{p,n}_E(q^2) \right]. \quad (15)$$

The Sach’s form factors $G^{p,n}_E(q^2)$ and $G^{p,n}_M(q^2)$ are parameterized as

$$G^{p}_E(q^2) = \left( 1 - \frac{q^2}{M_Y^2} \right)^{-2},$$

$$G^{p}_M(q^2) = (1 + \mu_p) G^{p}_E(q^2),$$

$$G^{n}_M(q^2) = \mu_n G^{p}_E(q^2),$$
\[ G^n_E(q^2) = \frac{q^2}{4M^2\mu_n G^n_E(q^2)} \xi_n; \]  

The numerical values of various parameters are taken as,

\[ \xi_n = \frac{1}{1 - \lambda_n \frac{q^2}{4M^2}}, \]
\[ \mu_p = 1.792847, \]
\[ \mu_n = -1.913043, \]
\[ M_V = 0.84 \text{GeV} \text{ and } \lambda_n = 5.6 \] (17)

(ii) Axial vector form factors

With \( g_2(q^2) = 0 \) and the contribution of \( g_3(q^2) \) being negligible, only \( g_1(q^2) \) contributes to the cross section for reactions considered in this paper. \( g_1(q^2) \) is described in terms of two functions \( F(q^2) \) and \( D(q^2) \) for all reactions in |\( \Delta S \)| = 1 sector. There is a priori no reason to assume same \( q^2 \) dependence for \( F(q^2) \) and \( D(q^2) \); but if we do that then all the transitions are determined in terms of one function for the \( g_1(q^2) \) form factor which is chosen to be \( F(q^2) + D(q^2) (= g_{n\rightarrow p}(q^2)) \) and is determined from |\( \Delta S \)| = 0, neutrino (antineutrino) reactions on nucleons and a constant term \( x \) given by:

\[ x = \frac{F(q^2)}{F(q^2) + D(q^2)} = \frac{F(0)}{F(0) + D(0)} \] (18)

The above relation given by Eq. 18 is valid, if the same \( q^2 \) dependence is assumed for \( F(q^2) \) and \( D(q^2) \). For numerical calculations we take \( F(0) = 0.463 \) and \( D(0) = 0.804 \) [36].

With these assumptions, \( g_1(q^2) \) form factor for various transitions in Table-2 are given as

\[ g_1^{p\rightarrow n}(q^2) = -\sqrt{\frac{3}{2}} \frac{1 + 2x}{3} g_A(q^2) \]
\[ g_1^{p\rightarrow \Sigma^0}(q^2) = \sqrt{\frac{1}{2}} (1 - 2x) g_A(q^2) \] (19)

where

\[ g_A(q^2) = g_A(0) \left( 1 - \frac{q^2}{M_A^2} \right)^{-2}. \] (20)

We use \( g_A(0) = 1.267 \) [36] and \( M_A = 1.03 \text{GeV} \) [38] for the numerical calculations.

2.3. Nuclear Effects

When the reactions shown in Eq. 2 take place on nucleons which are bound in the nucleus, Fermi motion and Pauli blocking effects of initial nucleon is to be considered. In the final state the produced hyperon is affected by the final state interactions with the nucleons inside the nucleus through the hyperon nucleon quasielastic and charge exchange scattering processes. The Fermi motion effect is calculated in a local Fermi
Transitions | a | b  
---|---|---
\(p \to \Lambda\) | \(-\sqrt{\frac{3}{2}}\) | \(-\sqrt{\frac{1}{6}}\)  
\(n \to \Sigma^-\) | \(-1\) | \(1\)  
\(p \to \Sigma^0\) | \(-\frac{1}{\sqrt{2}}\) | \(\frac{1}{\sqrt{2}}\)

Table 1. Values of the coefficients \(a\) and \(b\) of the form factors given in Eq. 9.

Gas model and the cross section is evaluated as a function of local Fermi momentum, \(p_F(r)\) and integrated over the whole nucleus. In a nucleus, the neutrino scatters from a neutron or a proton whose local density in the medium is \(\rho_n(r)\) or \(\rho_p(r)\), respectively. The corresponding local Fermi momentum for neutrons and protons are given as

\[
p_{F_n} = \left[3\pi^2 \rho_n(r)\right]^{1/3}; p_{F_p} = \left[3\pi^2 \rho_p(r)\right]^{1/3}.
\quad (21)
\]

The differential scattering cross section for the scattering of antineutrinos from nucleons in the nucleus is then given as

\[
\frac{d\sigma}{d\Omega dE_l} = 2 \int d^3r \int \frac{d^3p}{(2\pi)^3} n_N(p,r) \left[\frac{d\sigma}{d\Omega dE_l}\right]_{\text{free}}
\quad (22)
\]

where \(/
\frac{d\sigma}{d\Omega dE_l}\)/_{\text{free}} is the differential cross section for free antineutrino nucleon scattering given in Eq. 3 and \(n_N(p,r)\) is local occupation number of the initial nucleon of momentum \(p\) at a radius \(r\) in the nucleus, which is 1 for \(p < p_{F_N}\) and 0 otherwise.

2.4. Final State Interactions

For the final state interaction of hyperons we have followed Ref. [1]. In this prescription an initial hyperon produced at a position \(r\) within the nucleus interacts with a nucleon to produce a new hyperon state within a short distance \(dl\) with a probability \(P = P_Y dl\), where \(P_Y\) is probability per unit length given by

\[
P_Y = \sigma_{Y+n \to f}(E) \rho_n(r) + \sigma_{Y+p \to f}(E) \rho_p(r),
\]

where \(f\) denotes a possible final hyperon-nucleon \((Y_f(\Sigma \text{ or } \Lambda) + N(n \text{ or } p))\) state with energy \(E\) in the hyperon-nucleon CM system, \(\rho_n(r)\) is the local density of neutron(proton) in the nucleus and \(\sigma\) is the total cross section for charged current channel like \(Y(\Sigma \text{ or } \Lambda) + N(n \text{ or } p) \to f\) [1]. Now a particular channel is selected giving rise to a hyperon \(Y_f\) in the final state with the probability \(P\). For the selected channel Pauli blocking effect is taken into account by first randomly selecting a nucleon in the local Fermi sea. Then a random scattering angle is generated in the hyperon-nucleon CM system assuming the cross sections to be isotropic. Using this information hyperon and nucleon momenta are calculated and Lorentz boosted to lab frame. If the nucleon in
Table 2. Form factors of Eqs. 6 and 7. $f_1^N(q^2), i = 1, 2, N = n, p$ are defined in Eq. 15 and $g_A(q^2)$ is defined in Eq. 20. The parameters $F$ and $D$ are determined from the semileptonic decays which for the present work are taken as 0.463 and 0.804 respectively.

![Figure 1](image-url)

**Figure 1.** $\sigma$ vs $E_{\nu\mu}$, for $\bar{\nu}_\mu + p \rightarrow \mu^+ + \Lambda$ process. Experimental results (triangle right [9], square [10], circle [13], triangle up [11], circle [13], triangle down [14]) are shown with error bars, Theoretical curves are of Kuzmin and Naumov [2](double dashed-dotted line), Brunner et al. [13](dashed line), Erriquez et al. [10](dashed-double dotted line) obtained using Cabibbo theory with axial vector dipole mass as 0.999GeV, 1.1 GeV and 1 GeV, respectively, while the results of Wu et al. [5](dotted line) and Finjord and Ravndal [24](dashed dotted line) are obtained using quark model. The results of present calculation are shown with solid line. Notice that we have multiplied the results of Wu et al. [5] by 3 to plot on the same scale.

the final state has momenta above the Fermi momenta we have a new hyperon type($Y_f$) and/or a new direction and energy of the initial hyperon($Y_i$). This process is continued until the hyperon gets out of the nucleus. As the decay modes of hyperons to pions are highly suppressed in the nuclear medium [26] making them live long enough to pass through the nucleus and decay outside the nuclear medium, therefore, the produced pions are less affected by the strong interaction of nuclear field and their FSI have not been taken into account.
3. Results and Discussion

The numerical results for the quasielastic production of $\Sigma^0$, $\Sigma^-$ and $\Lambda$ hyperons induced by antineutrinos from the nucleon targets have been presented using Eqs. 3 and 4 with the vector and axial vector form factors given by Eqs. 15 and 20. The results have been then applied to calculate the hyperon production in nuclear targets like $^{12}C$, $^{40}Ar$, $^{56}Fe$ and $^{208}Pb$ where nuclear medium effects and final state interaction effect due to hyperon-nucleon interaction in the nuclear medium have been considered. The numerical results for the $Q^2$ distribution have also been presented. In the case of free nucleon the results for $\bar{\nu}_\mu + p \rightarrow \mu^+ + \Lambda$ and $\bar{\nu}_\mu + p \rightarrow \mu^+ + \Sigma^0$ have been presented. The cross sections
Figure 4. $\sigma$ vs $E_{\bar{\nu}_\mu}$ in $^{40}$Ar, for quasielastic hyperon production. Curves here have the same meaning as in Fig.3.

Figure 5. $\sigma$ vs $E_{\bar{\nu}_\mu}$ in $^{56}$Fe, for quasielastic hyperon production. Curves here have the same meaning as in Fig.3.

Figure 6. $\sigma$ vs $E_{\bar{\nu}_\mu}$ in $^{208}$Pb, for quasielastic hyperon production. Curves have the same meaning as in Fig.3.
Figure 7. Ratio of $\frac{\sigma(\Sigma^0) - \frac{1}{2}\sigma(\Sigma^-)}{\sigma(\Sigma^0)}$ for $\bar{\nu}_\mu$ induced interactions in nuclei with Final State Interaction (FSI) effect. Solid line is the result in $^{12}\text{C}$, dotted is the result in $^{40}\text{Ar}$, dashed line is the result in $^{56}\text{Fe}$ and dashed-dotted line is the result in $^{208}\text{Pb}$.

Figure 8. $\sigma$ vs $E_{\bar{\nu}_\mu}$, for $\Sigma^+$ production arising due to final state interaction effect of $\Lambda$ and $\Sigma^0$ hyperons in nuclei. Solid line is the result in $^{12}\text{C}$, dotted is the result in $^{40}\text{Ar}$, dashed line is the result in $^{56}\text{Fe}$ and dashed-dotted line is the result in $^{208}\text{Pb}$.

for $\bar{\nu}_\mu + n \rightarrow \mu^+ + \Sigma^-$ are related to $\bar{\nu}_\mu + p \rightarrow \mu^+ + \Sigma^0$ by a simple relation which is modified due to final state interaction in the medium and has been discussed in some detail. Similarly, $\Sigma^+$ is not produced from a free nucleon but can be produced through the final state interactions for which results have been presented.

3.1. Total Cross Section

In Fig. 1 we have presented the results for $\bar{\nu}_\mu$ induced $\Lambda$ production from free proton in the energy region of $E_{\bar{\nu}_\mu} < 10\text{GeV}$ and compared them with the quark model calculations of Wu et al.\textsuperscript{5} and Finjord and Ravndal\textsuperscript{24} as well as with the experimental results from Gargamelle bubble chamber at CERN\textsuperscript{9-11} using Propane with a small admixture of Freon and from Serpukhov SKAT Bubble Chambers\textsuperscript{13} using Freon and results from
Figure 9. $\frac{d\sigma}{dQ^2}$ vs $Q^2$ for $\bar{\nu}_\mu + p \to \mu^+ + \Lambda$ process at $E_{\bar{\nu}_\mu} = 2\text{GeV}$. Solid line is the result with the present model and the dashed line is the result of Finjord and Ravndal [24].

Figure 10. $\frac{d\sigma}{dQ^2}$ vs $Q^2$ for $\bar{\nu}_\mu + p \to \mu^+ + \Sigma^0$ process at $E_{\bar{\nu}_\mu} = 2\text{GeV}$. Solid line is the result with the present model and the dashed line is the result of Finjord and Ravndal [24].

BNL experiment using Hydrogen target [14].

The results of theoretical calculations performed by Erriquez et al. [10], Brunner et al. [13] and Kuzmin and Naumov [2] are based on the prediction from Cabibbo theory using axial vector dipole mass as 1.1 GeV, 1 GeV and 0.999 GeV, respectively. Finjord and Ravndal [24] have used relativistic quark model. Theoretical results of Wu et al. [5] are based on non-relativistic quark model. It may be noted from the figure that quark model calculations underestimate the experimental data while Cabibbo theory with SU(3) symmetry can reproduce the data well if the dipole mass of the axial vector form factor is chosen properly. In Fig. 1 we have used the currently favored value of $M_A = 1.03\text{GeV}$. On the other hand Erriquez et al. [10] have used $M_A = 0.883\text{GeV}$ and Brunner et al. [13] have used $M_A = 1.0\text{GeV}$ and obtained slightly smaller values of the total cross sections in better agreement with the experimental
Figure 11. $\frac{d\sigma}{dQ^2}$ vs $Q^2$ in $^{40}$Ar corresponding to the reaction given in Eq. 1 at $E_{\bar{\nu}_\mu} = 0.65$ GeV (left panel) and 3.0 GeV (right panel). The results are presented with nuclear medium and final state interaction effects.

Figure 12. $\frac{d\sigma}{dQ^2}$ vs $Q^2$ in $^{56}$Fe corresponding to the reaction given in Eq. 1 at $E_{\bar{\nu}_\mu} = 1.5$ GeV (left panel) and 3.0 GeV (right panel). The results are presented with nuclear medium and final state interaction effects.

results. In a recent calculation Kuzmin and Naumov [2] have used $M_A = 0.999$ GeV with the BBBA [39] parameterization of the vector form factors to obtain a good agreement with the experimental results. While determining the vector form factors in connection with $|\Delta S|=1$ reaction as well as semi leptonic decay of hyperons, it is worth mentioning the suggestion of Gaillard and Sauvage [37] that a rescaled value of $M_V = 0.97$ GeV instead of $M_V = 0.84$ GeV should be used while implementing the SU(3) symmetry. A larger value of $M_V$ will make the agreement with the experimental results worse.

The magnetic form factor $f_2(q^2)$ is determined using SU(3) symmetry for calculations and is given by (see Table 2)

$$f_2^{p\rightarrow \Lambda}(q^2) = -\sqrt{3}\frac{1}{2}f_2^p(q^2)$$  

(23)
However, instead of Eq. 23, if we choose to implement the SU(3) symmetry at the level of $f_2(q^2)$ as done by Cabibbo et al. [36], we would obtain with our definitions of matrix element defined in Eq. 4

\[
\frac{f_{p \rightarrow \Lambda}(q^2)}{M_\Lambda + M} = -\sqrt{3} \frac{f_N^p(q^2)}{2 M_n + M_p}
\]  

leading to

\[
f_{p \rightarrow \Lambda}(q^2) = -\sqrt{3} \frac{M_\Lambda + M}{2 M_n + M_p} f_N^p(q^2)
\]  

and similarly

\[
f_{p \rightarrow \Sigma^0}(q^2) = -\frac{M_\Sigma + M}{\sqrt{2} M_n + M_p} (f_N^p(q^2) + 2 f_N^n(q^2))
\]  

This implies a 10-15 % variation in the values of the form factor $f_2(q^2)$. We find that the total cross sections are not affected by this variation in the $f_2(q^2)$ form factor. This is consistent with the results of Dworkin et al. [40] who have analyzed the semileptonic decay of $\Lambda$ hyperons using SU(3) symmetry and took two different values for weak-magnetism coupling $\omega (= \frac{f_2(0)}{f_1(0)})$ viz. $\omega = 0.15$ and $\omega = 0.97$, and find that the decay rates are not affected. Note that their definition of the transition matrix element involving the $f_2(q^2)$ term is slightly different from ours.

In Fig. 2, we present our results for the reaction $\bar{\nu}_\mu + p \rightarrow \mu^+ + \Sigma^0$ and compare our results with the results of Wu et al. [5] and Finjord and Ravndal [24]. We have also shown the experimental result obtained in the bubble chamber Gargamelle experiment by Erriquez et al. [10].

We have also obtained the results for the total cross section $\sigma(E_{\bar{\nu}_\mu})$ vs $E_{\bar{\nu}_\mu}$ for various nuclei of interest like $^{12}$C, $^{40}$Ar, $^{56}$Fe and $^{208}$Pb relevant to ongoing neutrino experiments at T2K, MicroBooNE and MINERvA. The results for $\Lambda$ and $\Sigma^-$ production...
are shown for $^{12}C$, $^{40}Ar$, $^{56}Fe$ and $^{208}Pb$ in Figs. 3-6. We find that nuclear medium effects are very small. However, the final state interactions due to $\Sigma - N$ and $\Lambda - N$ interactions in various channels tend to increase the $\Lambda$ production and decrease the $\Sigma^-$ production. $\Sigma^-$ and $\Sigma^0$ production are separately affected and the relation $\sigma(\bar{\nu}_\mu + p \to \mu^+ + \Sigma^0) = \frac{1}{2} \sigma(\bar{\nu}_\mu + n \to \mu^+ + \Sigma^-)$ is modified in the nucleus due to the presence of other nucleons.

In Fig. 7, we show $R = \frac{\sigma(\Sigma^0)}{\frac{1}{2}\sigma(\Sigma^-)}$ as a function of energy in $^{12}C$, $^{40}Ar$, $^{56}Fe$ and $^{208}Pb$. We also see appearance of $\Sigma^+$ due to final state interaction processes like $\Lambda p \to \Sigma^+ n$ and $\Sigma^0 p \to \Sigma^+ n$. In Fig. 8, we present the results for the cross section for $\Sigma^+$ production as a function of antineutrino energy in various nuclei.

In Figs. 9-10, we show $\frac{d\sigma}{dQ^2}$ for $\bar{\nu}_\mu + p \to \mu^+ + \Lambda$ and $\bar{\nu}_\mu + p \to \mu^+ + \Sigma^0$ processes at $E_{\bar{\nu}} = 2$ GeV and compare the results with the quark model calculation of Finjord and Ravndal [24].

In Figs. 11-13, we have presented the results for $\frac{d\sigma}{dQ^2}$ per nucleon vs $Q^2$ respectively in $^{40}Ar$, $^{56}Fe$ and $^{208}Pb$. These results are presented with nuclear medium and final state interaction effects. The results in $^{40}Ar$ are at the $E_{\bar{\nu}}$ energies of 0.65 GeV and 3.6 GeV corresponding to the average energies of MicroBooNE [16, 17] and ArgoNeut [18, 19] experiments. In $^{56}Fe$ and $^{208}Pb$, the results are presented at $E_{\bar{\nu}}=1.5$ GeV and 3 GeV corresponding to the low energy spectrum of MINERνA [15] experiment and also the results in $^{56}Fe$ would be relevant for the atmospheric neutrino/antineutrino experiment proposed at India Neutrino Observatory (INO) [41].

4. Summary and Outlook

In this paper, we have studied quasielastic production of $\Sigma$ and $\Lambda$ hyperons from nucleons and nuclear targets induced by antineutrinos through $|\Delta S| = 1$ weak charged currents. The calculations have been done using Cabibbo theory along with the symmetry properties of weak $|\Delta S| = 1$ hadronic currents and various transition form factors have been determined using SU(3) symmetry, G-invariance and conserved vector current. Some SU(3) breaking effects are included through the use of physical masses for all the hadrons belonging to SU(3) octet. There is some indication of nuclear medium effects in the work of Errriquez et al. [10, 11] where they quote the results for the cross sections separately for free and bound (including free) nucleons which shows a reduction due to the nuclear medium effects though consistent with no medium effects within the statistical errors. On the other hand the experimental analysis of Eichten et al. [9] implies an increase of about 5% in Lambda production. In view of these results and future experiments to be performed at low and medium energies it is important to study the nuclear medium effects in quasi elastic production of hyperons.

The results for the total cross section and $Q^2$-distribution would be relevant for the experiments like MINERνA [15], MicroBooNE [16, 17], ArgoNeut [18, 19], INO [41], etc. Therefore, we have presented the results for $\bar{\nu}_\mu + p \to \mu^+ + \Lambda$, $\bar{\nu}_\mu + p \to \mu^+ + \Sigma^0$ and $\bar{\nu}_\mu + n \to \mu^+ + \Sigma^-$ processes on nuclear targets like $^{12}C$, $^{40}Ar$, $^{56}Fe$ and $^{208}Pb$ which are
being used in the present and proposed experiments. The theoretical results have been compared with predictions of quark model calculations where available. A comparison with old experimental results from Gargamelle\[?\] and SKAT\[13\] collaborations has been presented. The nuclear medium effects and final state interaction effect due to hyperon nucleon interactions in the presence of other nucleons in the nuclear medium have been included. The deviation from SU(3) symmetric predictions for $\Sigma^-$ and $\Sigma^0$ production and appearance of $\Sigma^+$ production due to final state interactions have been studied using Monte-Carlo simulation of final state interactions using experimental hyperon-nucleon scattering cross sections. While the nuclear medium effects are small, the final state interactions lead to an increase of $\Lambda$ production and decrease of $\Sigma^-$ and $\Sigma^0$ productions and appearance of $\Sigma^+$, which is only produced in the final state interaction.

SU(3) symmetry seems to work quite well in analyzing the semileptonic hyperon decays where symmetry breaking effects are shown to be small in decay rates but play important role in explaining the observed asymmetries. There are some ambiguities in implementing the SU(3) symmetry in determining the weak form factors $f_2(q^2)$ and $g_3(q^2)$ in $|\Delta S| = 1$ sector. SU(3) violating effects in the case of weak hyperon production and hyperon semileptonic decays are also related with the existence of second class currents in $|\Delta S| = 1$ sector. The quasielastic production of hyperons induced by antineutrinos provides a unique opportunity to study these effects.

The observation of quasielastic weak production of hyperons induced by antineutrinos and experimental data on total cross sections and differential cross section would provide very useful information on weak form factors of nucleon-hyperon transition giving valuable information on various symmetry properties of weak hadronic currents like, SU(3) symmetry, $G$-invariance and CVC in $|\Delta S| = 1$ sector.

5. Acknowledgements

M. S. A. is thankful to Department of Science and Technology(DST), Government of India for providing financial assistance under Grant No. SR/S2/HEP-18/2012.

References

[1] Singh S K and Vicente Vacas M J 2006 Phys. Rev. D 74 053009.
[2] Kuzmin K S and Naumov V A Phys. Atom. Nucl. 72, 1501 (2009) [Yad. Fiz. 72, 1555 (2009)].
[3] Adera G B, Van Der Ventel B I S, van Niekerk D D and Mart T 2010 Phys. Rev. C 82 025501.
[4] Mintz S L and Wen L L 2006 Nucl. Phys. A 766 219.
Mintz S L and Wen L L 2007 Eur. Phys. J. A 33 299.
[5] Wu J J and Zou B S arXiv:1307.0574 [hep-ph].
[6] Alam Rafi M, Simo Ruiz I, Athar Sajjad M and Vicente Vacas M J 2010 Phys. Rev. D 82 033001.
[7] Alam Rafi M, Simo Ruiz I, Athar Sajjad M and Vicente Vacas M J 2012 Phys. Rev. D 85 013014.
[8] Alam Rafi M, Chauhan S, Athar Sajjad M and Singh S K 2013 Phys. Rev. D 88 077301.
[9] Eichten T et al., 1972 Phys. Lett. B 40, 593.
[10] Erriquez O et al., 1978 Nucl. Phys. B 140, 123.
[11] Erriquez O et al., 1977 Phys. Lett. B 70, 383.
[12] Ammosov V V et al 1989 Sov. J. Nucl. Phys. 50 67, JETP Lett. 43, 716 (1986).
[13] Brunner J et al [SKAT Collaboration] 1990 Z. Phys. C 45 551.
[14] Fanourakis G et al., 1980 Phys. Rev. D 21, 562.
[15] Fields L et al. [MINERvA Collaboration] 2013 Phys. Rev. Lett. 111 022501; http://minerva.fnal.gov/
[16] Ignarra C M [MicroBooNE Collaboration] arXiv:1110.1604 [physics.ins-det]
[17] Karagiorgi G [MicroBooNE Collaboration] 2012 J. Phys. Conf. Ser. 375 042067.
[18] Anderson C et al [ArgoNeuT Collaboration] 2012 Phys. Rev. Lett. 108 161802; http://t962.fnal.gov/
[19] R. Acciarri et al. [ArgoNeuT Collaboration]. arXiv:1404.4809 [hep-ex].
[20] Ashie Y et al. [Super-Kamiokande Collaboration] 2005 Phys. Rev. D 71 112005;
http://www-sk.icrr.u-tokyo.ac.jp/sk
[21] Aguilar-Arevalo A A et al. [MiniBooNE Collaboration] 2013 Phys. Rev. D 88 032001;
http://www-boone.fnal.gov/
[22] Abe K et al. [T2K Collaboration] 2011 Nucl. Instrum. Meth. A 659 106;
http://t2k-experiment.org/
[23] Habig A [NOvA Collaboration] 2012 Nucl. Phys. Proc. Suppl. 229-232 460;
http://www-nova.fnal.gov/
[24] Finjord J and Ravndal F 1976 Nucl. Phys. B 106 228.
[25] Cabibbo N and Chilton F 1965 Phys. Rev. 137 B1628; Cabibbo N 1963 Phys. Rev. Lett. 10 531.
[26] Oset E et al. 1990 Phys. Rept. 188 79.
[27] Llewellyn Smith C H 1972 Phys. Rept. 3 261.
[28] Adler S L 1963 Nuovo Cimento 30 1020.
[29] Egardt L 1963 Nuovo Cimento 29 954.
[30] Ketley I J 1965 Nuovo Cimento 38 302.
[31] Pais A 1971 Annals of Phys. 63 311; ibid. 1972 69 604.
[32] Marshak R E, Riazuddin and Ryan C P Theory of Weak Interactions in Particle Physics(Wiley-Interscience, 1969).
[33] Bell J S and Berman S M 1962 Nuovo Cim. 25 404.
[34] Block M M et al. 1964 Phys. Rev. Lett. 12 262.
[35] Weinberg S 1958 Phys. Rev. 112 1375.
[36] Cabibbo N, Swallow E C and Winston R 2003 Ann. Rev. Nucl. Part. Sci. 53 39.
[37] Gaillard J M and Sauvage G 1984 Ann. Rev. Nucl. Part. Sci. 34 351.
[38] V. Bernard, L. Elouadrhiri and U. G. Meissner, J. Phys. G 28, R1 (2002).
[39] A. Bodek, S. Avvakumov, R. Bradford and H. S. Budd, Eur. Phys. J. C 53, 349 (2008).
[40] Dworkin J et al. 1990 Phys. Rev. D 41 780.
[41] N. K. Mondal [INO Collaboration], Pramana 79, 1003 (2012).