Weak quasielastic production of hyperons at the atmospheric neutrino energies

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Introduction

We have presented the results for the antineutrino induced quasielastic hyperon production from nucleons and nuclear targets at the atmospheric neutrino energies. The inputs are the nucleon-hyperon $(N-Y)$ transition form factors [1, 2] determined from the analysis of neutrino-nucleon scattering and the semileptonic decays of neutron and hyperons using SU(3) symmetry. The calculations for the nuclear targets are done in the local density approximation. The nuclear medium effects (NME) like Fermi motion, Pauli blocking and final state interaction (FSI) effects due to hyperon-nucleon scattering have been taken into account [3, 4, 5]. The hyperons giving rise to pions through weak decays also contribute significantly to the weak pion production in the energy region of $<$ 0.7 GeV in addition to the Δ excitation mechanism. The results for the pions coming from the hyperons are compared with the results coming from the delta excitations. Also, we have presented the results for the polarized hyperons which indepedently give information about the $N-Y$ transition form factors.

In Nucleon
$\sigma_\Lambda(\pi^-) \sim 10\%$ of $\sigma_\Delta(\pi^-)$ at $E_{\bar\nu_\mu}$ = 700 MeV, and
$\sigma_\Lambda(\pi^0) \sim 28\%$ of $\sigma_\Delta(\pi^0)$ at $E_{\bar\nu_\mu}$ = 700 MeV.

In the Carbon Nucleus
$\sigma_\Lambda(\pi^-) \sim 26\%$ of $\sigma_\Delta(\pi^-)$ at $E_{\bar\nu_\mu}$ = 700 MeV, and
$\sigma_\Lambda(\pi^0) \sim 73\%$ of $\sigma_\Delta(\pi^0)$ at $E_{\bar\nu_\mu}$ = 700 MeV.

Quasielastic production of hyperons

The quasielastic hyperon production processes are

$$\bar\nu_\mu(k) + N(p) \rightarrow \mu^+(k') + Y(p'), \quad N = p, n, \quad Y = \Lambda, \Sigma.$$

for which the transition matrix element $\mathcal{M}$ is given by

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} \sin\theta_c\, l^\mu\, J_\mu.$$

The leptonic (l^μ) and the hadronic (J_μ) currents are defined as

$$\begin{aligned} l^\mu &= \bar u(k')\gamma^\mu(1+\gamma_5)u(k) \\ J_\mu &= \bar u(p')\left[\gamma_\mu f_1(Q^2) + i\sigma_{\mu\nu}\frac{q^\nu}{M+M_Y} f_2(Q^2) + \frac{2q_\mu}{M+M_Y} f_3(Q^2) \right. \\ &\quad \left. - \left(\gamma_\mu\gamma_5 g_1(Q^2) + i\sigma_{\mu\nu}\gamma_5\frac{q^\nu}{M+M_Y} g_2(Q^2) + \frac{2q_\mu\gamma_5}{M+M_Y} g_3(Q^2)\right)\right] u(p). \end{aligned}$$

$f_1(Q^2)$, $f_2(Q^2)$, $g_1(Q^2)$ and $g_3(Q^2)$ are the first class currents while $f_3(Q^2)$ and $g_2(Q^2)$ are the second class currents. The vector form factors $f_{1,2}(Q^2)$ are expressed in terms of the experimentally determined Sach's electric and magnetic form factors. The axial vector and the weak electric form factors $g_{1,2}(Q^2)$ are determined in terms of $g_{A,2}(Q^2)$, which are parameterized in the dipole form as

$$g_i(Q^2) = g_i(0)\,\left[1 + \frac{Q^2}{M_i^2}\right]^{-2}; \quad i = A, 2$$

with $g_A(0) = 1.267$, $g_2(0) = g_2^R(0) + i g_2^I(0)$ and $M_A = M_2 = 1.026$ GeV. Using the above definitions, the Q^2 distribution and the flux averaged Q^2 distribution are written as

$$\frac{d\sigma}{dQ^2} = \frac{G_F^2\,\sin^2\theta_c}{8\pi M^2 E_{\bar\nu_\mu}^2}\mathcal{L}_{\mu\nu}\mathcal{J}^{\mu\nu}, \qquad \left\langle\frac{d\sigma}{dQ^2}\right\rangle = \frac{\int_0^\infty \frac{d\sigma}{dQ^2}\phi(E_{\bar\nu_\mu})dE_{\bar\nu_\mu}}{\int_0^\infty \phi(E_{\bar\nu_\mu})dE_{\bar\nu_\mu}}.$$

Polarization of the hyperon

The polarization 4-vector (ξ^τ) of the hyperon produced in the quasielastic reaction is written as:

$$\xi^\tau = \left(g^{\tau\sigma} - \frac{p'^\tau p'^\sigma}{M_Y^2}\right)\frac{\mathcal{L}^{\alpha\beta}\mathrm{Tr}\left[\gamma_\sigma\gamma_5\Lambda(p')J_\alpha\Lambda(p)\tilde J_\beta\right]}{\mathcal{L}^{\alpha\beta}\mathrm{Tr}\left[\Lambda(p')J_\alpha\Lambda(p)\tilde J_\beta\right]}.$$

One may write the polarization vector as

$$\vec\xi = \xi_P\vec e_P + \xi_L\vec e_L + +\xi_T\vec e_T,$$

where $\vec e_P$, $\vec e_L$ and $\vec e_T$ are the unit vectors corresponding to the perpendicular, longitudinal and transverse directions along the momentum of the hyperon and are given as

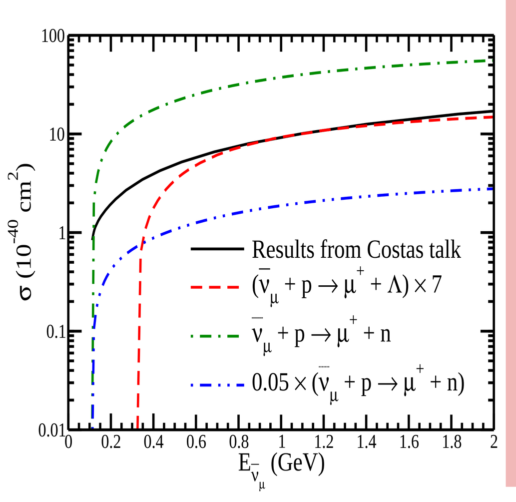
$$\vec e_L = \frac{\vec p'}{|\vec p'|}, \quad \vec e_P = \vec e_L \times \vec e_T, \quad \vec e_T = \frac{\vec p' \times \vec k}{|\vec p' \times \vec k|}; \quad \text{with} \quad \xi_{P,L,T}(Q^2) = \vec\xi\cdot\vec e_{P,L,T}.$$

The longitudinal $P_L(Q^2)$, perpendicular $P_P(Q^2)$ and transverse $P_T(Q^2)$ components of the polarization vector are obtained as:

$$\begin{aligned} P_L(Q^2) &= \frac{M_Y}{E_{p'}}\xi_L(Q^2) = \frac{M_Y}{E_{p'}}\frac{A(Q^2)\vec k.\vec p' + B(Q^2)|\vec p'|^2}{N(Q^2)\,|\vec p'|}, \\ P_P(Q^2) &= \xi_P(Q^2) = \frac{A(Q^2)[(\vec k.\vec p')^2 - |\vec k|^2|\vec p'|^2]}{N(Q^2)\,|\vec p'|\,|\vec p' \times \vec k|}, \\ P_T(Q^2) &= \xi_T(Q^2) = \frac{C(Q^2)M[(\vec k.\vec p')^2 - |\vec k|^2|\vec p'|^2]}{N(Q^2)\,|\vec p' \times \vec k|}. \end{aligned}$$

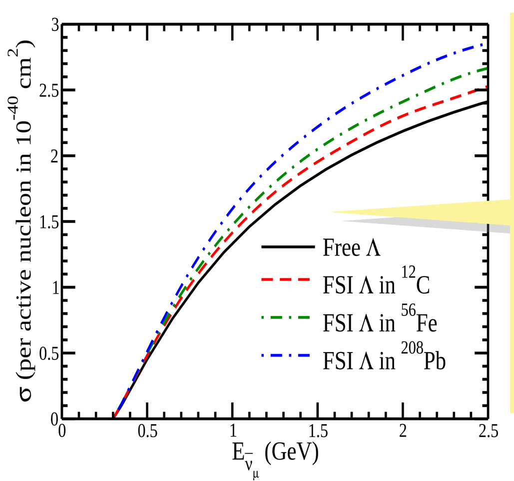
The expressions of $A(Q^2)$, $B(Q^2)$, $C(Q^2)$ and $N(Q^2)$ are given in Ref. [1].
The real value of $g_2(0)$ gives G-violation while conserving T-invariance. In this case, the transverse component of polarization, which arises due to the interference terms of the first and the second class current, vanishes. The imaginary value of $g_2(0)$ gives G-violation as well as T-violation.

Results

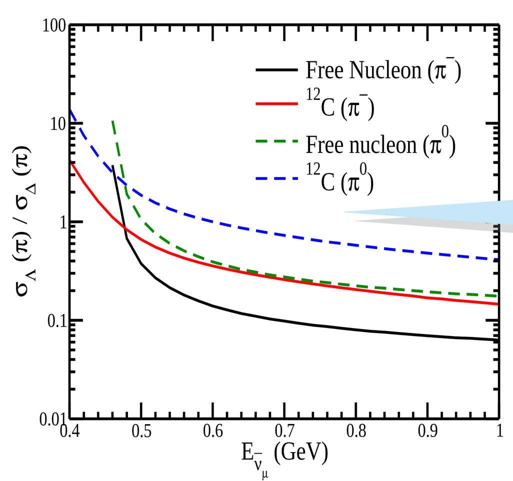


Our results (scaled by a factor of 7) for the Λ production cross section are compared with the results presented by Costas [6] generator. Also we have presented the results for the QE neutron production and for

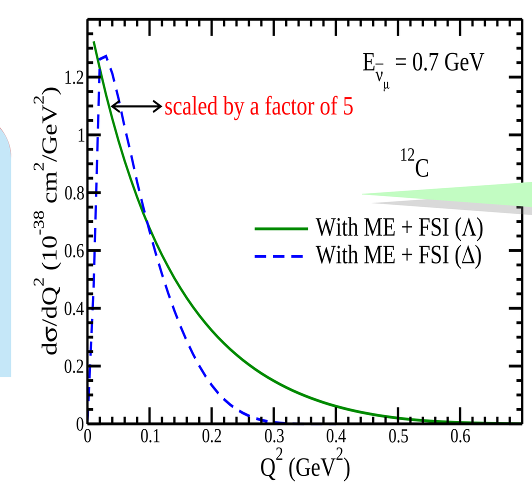
$$\sigma_{\Delta S} \approx \tan^2\theta_c\sigma_{QE} = 0.05\sigma_{QE}.$$



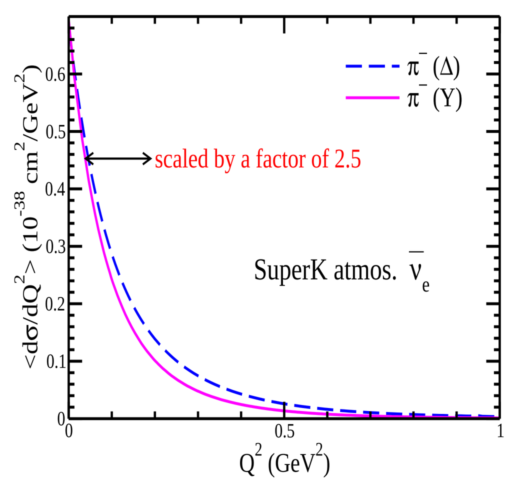
Results for the Λ production cross section off the nucleon and the nuclear targets are presented. The σ/nucleon increases with the increase in A.

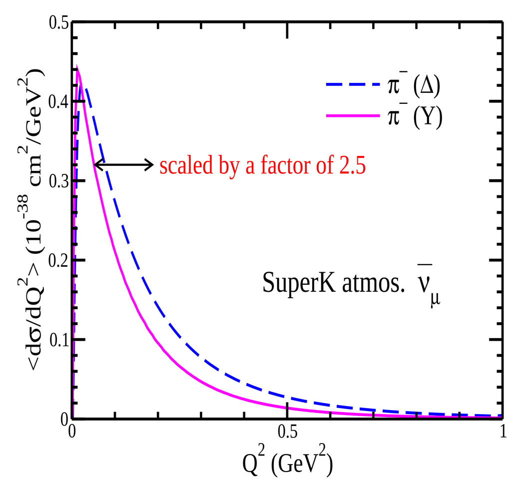


Ratio of Λ to Δ production cross section leading to π^-/π^0 in the final state for the free nucleon case and the ^{12}C target.

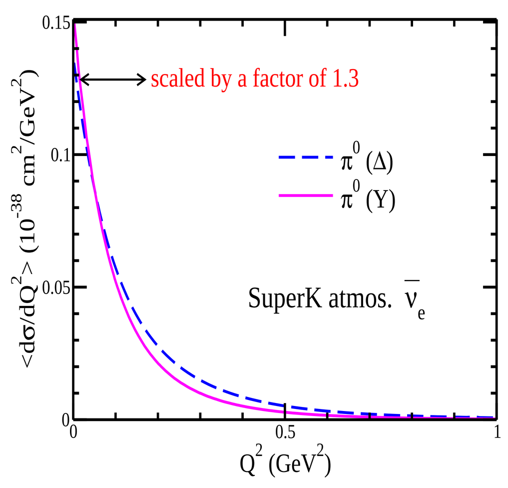


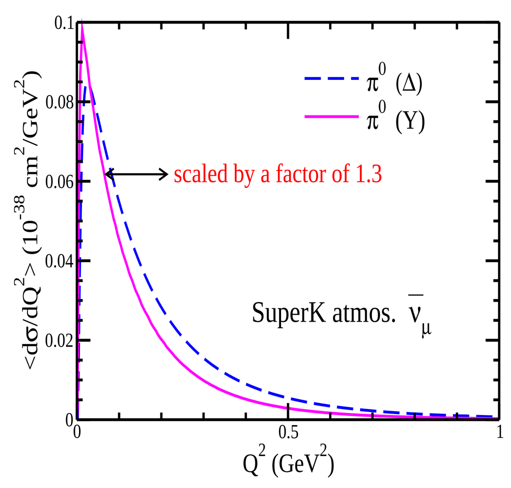
Q^2 distribution for the Λ and Δ produced in the quasielastic process off the ^{12}C target. The Λ production is $\sim$ 20% of the Δ production cross section.



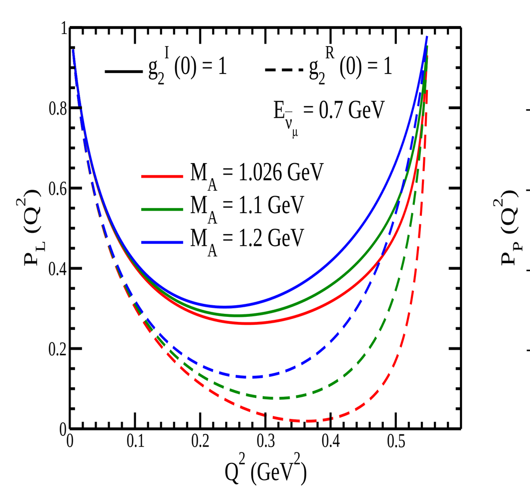


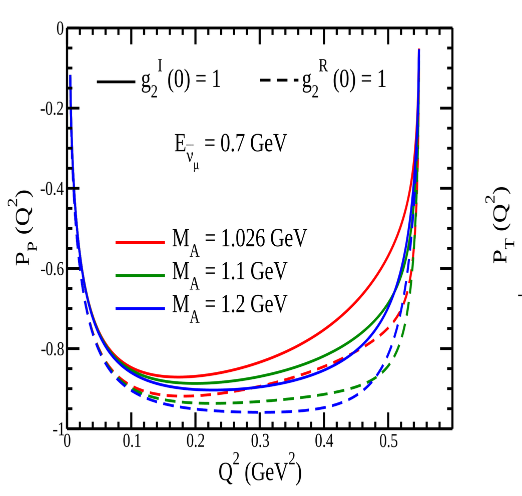
The results for the Q^2 distribution of the π^- produced through the decays of Δ and hyperons, averaged over the Super-K atmospheric neutrino flux are presented. The π^- production from the hyperon is $\sim$ 40% of the π^- coming from Δ.

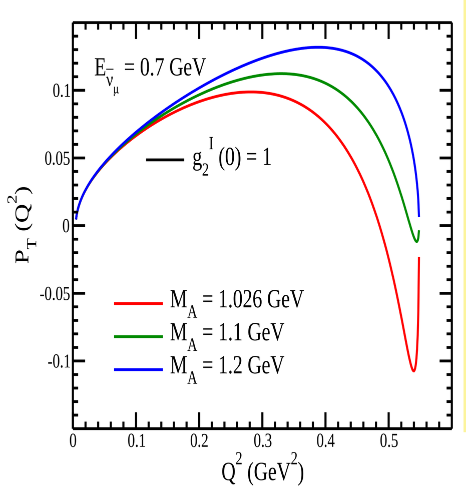




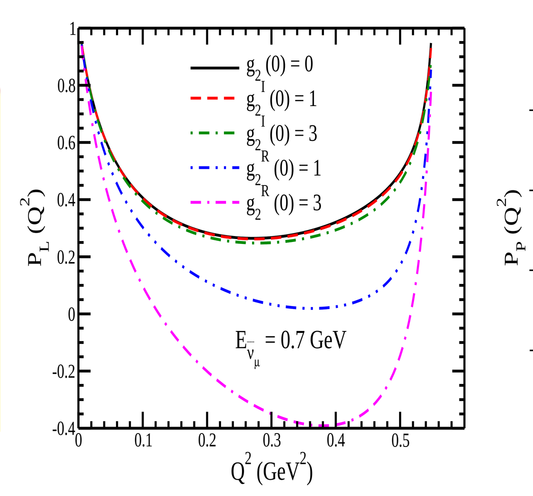
The results for the Q^2 distribution of the π^0 produced through the decays of Δ and hyperons, averaged over the Super-K atmospheric neutrino flux are presented. The π^0 production from the hyperon is $\sim$ 75% of the π^0 coming from Δ.

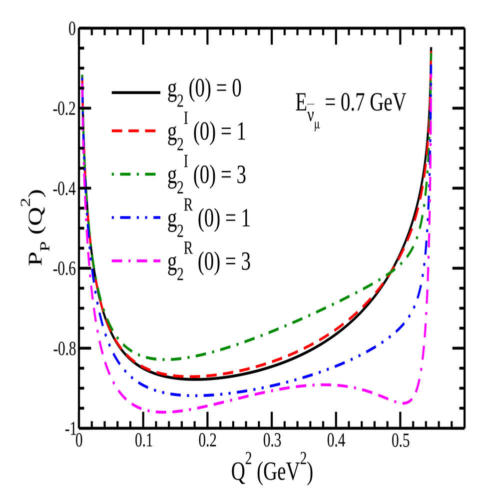


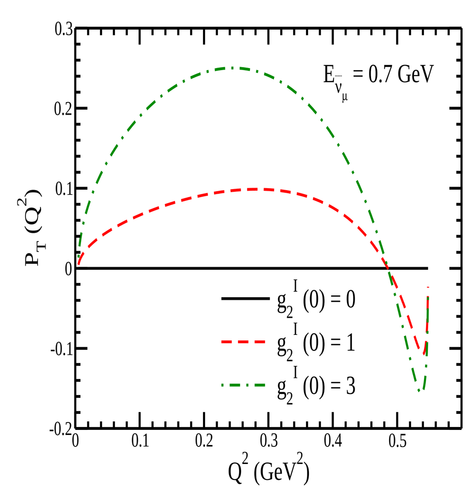




The results are presented for the polarization observables for the polarized Λ when M_A is varied in the range 1.026–1.2 GeV while taking indepedently $g_2^I(0) = 1$ and $g_2^R(0) = 1$.







The results are presented for the polarization observables for the polarized Λ with the different values of $g_2(0)$ and M_A = 1.026 GeV at the atmospheric antineutrino energies.

Conclusions

There exists a discrepancy between the theoretical results obtained by us and the results quoted in Ref. [6]. Our results are atleast a factor of 7 smaller than the results quoted in Ref. [6].

There is large suppression for the pions coming from Δ, as Δ is renormalized in the nuclear medium and its mass and width get modified to give a reduced cross section. Furthermore, Δ decays instantly, and the pions undergo absorption and rescattering due to FSI before coming out of the nucleus. This gives a further reduction in the pion yields.

The produced hyperon has negligible nuclear effects of Fermi motion and Pauli blocking, and has only FSI effect with the residual nucleus. Due to FSI, the Σ hyperon also gives Λ through the processes $\Sigma^0 \rightarrow \Lambda + \gamma$, which results in an enhancement in the Λ production and reduction in the Σ production. The hyperons being long lived when decay to pions, the pions are assumed to have almost negligible FSI. Pion absorption due to FSI is not considered for the pions produced from the Λ.

The experimental observation of the transverse component of polarization may give direct information about T-violation.

References

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