Quasi elastic scattering of $\bar{\nu}_\mu$ off ^{12}C

D. Grover[1], K. Saraswat[1], P. Kumar[1], P. Shukla[2,3], and V. Singh[1*]

[1]*Department of Physics, Institute of Science, Banaras Hindu University, Varanasi 221005, India*

[2]*Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai 400085, India and*

[3]*Homi Bhabha National Institute, Anushakti Nagar, Mumbai 400094, India*

Introduction

Neutrinos are elementary particles with no electric charge, no magnetic moment, half integral spin and a small but non-zero mass. Being electrically neutral, neutrinos rarely interact with matter via weak force. There are many neutrino scattering processes such as quasi elastic scattering (QES) [1], resonance pion production (RES) [2] and deep inelastic scattering (DIS) [3], at various neutrino energies. In charged current quasi elastic scattering, an (anti)neutrino interacts with a (proton)neutron producing a corresponding lepton and the (proton)neutron changes to (neutron)proton.

$$\nu_l + n \rightarrow l^- + p. \tag{1}$$
$$\bar{\nu}_l + p \rightarrow l^+ + n. \tag{2}$$

In this work, we study charged current antineutrino - nucleus (^{12}C) QES. To describe CCQES, we use the Llewellyn Smith (LS) model [4]. For incorporating the nuclear effects, we use the Fermi gas model along with Pauli suppression condition. We calculate $\bar{\nu}_\mu$−^{12}C CCQES differential and total cross sections for different values of axial mass M_A and compare the results with experimental data, with the goal of finding the most appropriate M_A value.

Formalism for Quasi Elastic $\bar{\nu} - A$ Scattering

The differential cross section per proton for anti-neutrino - nucleus quasi elastic scattering is defined as:

$$\begin{aligned}\frac{d\sigma^A(E_{\bar{\nu}}, Q^2)}{dQ^2} &= \frac{2V}{Z(2\pi)^3}\int_0^\infty 2\pi k_p^2 dk_p d(cos\theta)\\ &\quad f(\vec{k_p})S(\nu-\nu_{min})\\ &\quad \frac{d\sigma^N(E_{\bar{\nu}}^{eff}(E_{\bar{\nu}}, \vec{k_p}), Q^2)}{dQ^2},\end{aligned} \tag{3}$$

where the factor 2 accounts for the spin of the proton, V is the volume of the nucleus, k_p is the momentum of the proton, $\frac{d\sigma^N}{dQ^2}$ is the differential cross section of the anti-neutrino quasi elastic scattering off free proton and $E_{\bar{\nu}}^{eff}$ is the effective anti-neutrino energy in the presence of Fermi motion of nucleons defined as:

$$E_{\bar{\nu}}^{eff} = \frac{(s^{eff} - M_p^2)}{2M_p}. \tag{4}$$

Here, M_p is the proton mass and s^{eff} is defined as:

$$s^{eff} = M_p^2 + 2E_{\bar{\nu}}\left(E_p - k_p cos\theta\right). \tag{5}$$

Here, E_p is the proton energy.

The Fermi distribution function $f(\vec{k_p})$ is defined as:

$$f(\vec{k_p}) = \frac{1}{1 + exp(\frac{k_p - k_F}{a})}, \tag{6}$$

where $a = kT$ (= 0.020 GeV) is the diffuseness parameter. The Fermi momentum k_F for carbon nucleus is 0.221 GeV.

The Pauli suppression factor $S(\nu - \nu_{min})$ is defined as:

$$S(\nu - \nu_{min}) = \frac{1}{1 + exp(-\frac{(\nu - \nu_{min})}{a})}, \tag{7}$$

*Electronic address: `venkaz@yahoo.com`

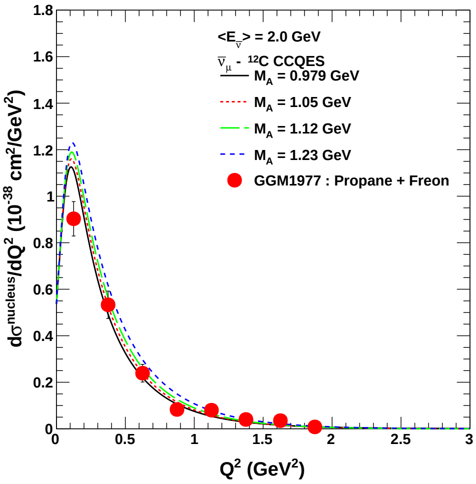

FIG. 1: $\frac{d\sigma}{dQ^2}$ per proton for $\bar{\nu}_\mu-^{12}$C CCQES as a function of Q^2, for different values of axial mass M_A and for $< E_{\bar{\nu}} > = 2$ GeV compared with GGM data.

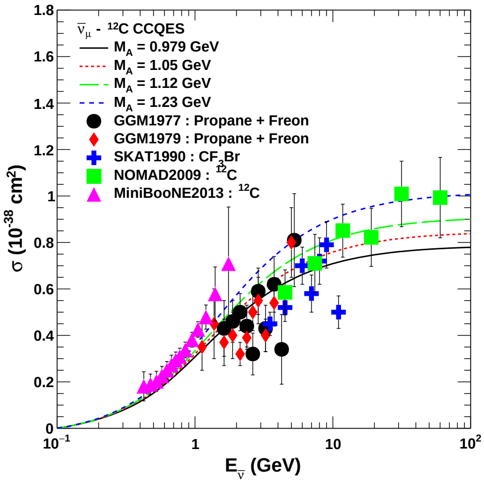

FIG. 2: σ per proton for $\bar{\nu}_\mu-^{12}$C CCQES as a function of $E_{\bar{\nu}}$, for different values of axial mass M_A compared with GGM(1977), GGM(1979), SKAT, NOMAD and MiniBooNE data.

where ν is the energy transfer in the interaction and ν_{min} is defined as:

$$\nu_{min} = \sqrt{k_F^2 + M_n^2} - \sqrt{k_p^2 + M_p^2} + E_B. \quad (8)$$

Here, M_n is the final state neutron mass and E_B is the binding energy. Complete formalism and references can be found in Ref. [1].

Results and Discussions

Fig. 1 shows $\frac{d\sigma}{dQ^2}$ per proton for $\bar{\nu}_\mu-^{12}$C CCQES as a function of Q^2, for different values of axial mass (M_A = 0.979, 1.05, 1.12 and 1.23 GeV) and for $< E_{\bar{\nu}} > = 2$ GeV. The results obtained are compared with data from Gargamelle (GGM), studying quasi elastic reactions of neutrinos and antineutrinos on propane plus freon target. The calculations with axial mass M_A = 0.979 and 1.05 GeV are compatible with data.

Fig. 2 shows σ per proton for $\bar{\nu}_\mu-^{12}$C CCQES as a function of $E_{\bar{\nu}}$, for different values of axial mass (M_A = 0.979, 1.05, 1.12 and 1.23 GeV). The results obtained are compared with data from GGM(1977), GGM(1979), SKAT, NOMAD and MiniBooNE experiments. The calculations with axial mass M_A = 0.979 and 1.05 GeV are compatible with GGM(1977), GGM(1979) and SKAT data, though the calculations overestimate the data at low anti-neutrino energies. The calculation with axial mass M_A = 1.05 GeV is compatible with NOMAD data and the calculation with axial mass M_A = 1.23 GeV is compatible with MiniBooNE data.

Acknowledgements

The authors D. Grover and P. Kumar are thankful to the DST and UGC, New Delhi for their financial support.

References

[1] D. Grover *et al.*, arXiv:1807.08911 [hep-ph]; Chinese Physics C (In Press 2018).

[2] K. Saraswat, P. Shukla, V. Kumar and V. Singh, Phys. Rev. C **93**, 035504 (2016).

[3] D. Grover *et al.*, arXiv:1808.00287 [hep-ph]; Phys. Rev. C (Accepted 2018).

[4] C. H. Llewellyn Smith, Phys. Rept. **3**, 261 (1972).