Charged current quasi-elastic scattering of $\bar{\nu}_\mu$ off $^{12}$C*

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Abstract: In this work, we study charged current quasi-elastic scattering (QES) of $\bar{\nu}_\mu$ off nucleon and nucleus using a formalism based on the Llewellyn Smith (LS) model. Parameterizations by Galster et al. are used for electric and magnetic Sach’s form factors of the nucleons. We use the Fermi gas model along with the Pauli suppression condition to take into account the nuclear effects in the anti-neutrino-nucleus QES. We calculate $\bar{\nu}_\mu-n$ and $\bar{\nu}_\mu-^{12}$C charged current quasi-elastic scattering differential and total cross sections for different values of axial mass $M_A$, and compare the results with data from the GGM, SKAT, BNL, NOMAD, MINER$\nu$A and MiniBooNE experiments. The present theoretical approach gives a good description of differential cross section data. The calculations with axial mass $M_A=0.979$ and 1.05 GeV are compatible with data from most of the experiments.

Keywords: cross section, quasi-elastic scattering, axial mass, form factors

PACS: 13.15.+g, 25.70.Bc, 96.40.Tv DOI: 10.1088/1674-1137/42/12/123104

1 Introduction

From their first postulation by Wolfgang Pauli in 1930, to explain the continuous energy spectra in the beta decay process, neutrinos have been a major field of research. Neutrinos exist in three flavors (electron, muon and tau neutrinos) along with their anti-particles, which are called anti-neutrinos. Searches for more neutrino flavors, called sterile neutrinos, are still underway. The standard model of particle physics assumes (anti)neutrinos to be massless. However, several (anti)neutrino oscillation experiments have confirmed small but non-zero (anti)neutrino masses [1–10]. Being neutral particles, (anti) neutrinos undergo only weak interactions (charged current, via exchange of $W^+/W^-$ bosons, and neutral current, via exchange of Z bosons) with matter, through scattering processes such as quasi-elastic scattering (QES), resonance pion production (RES) and deep inelastic scattering (DIS). For a review see Ref. [11]. In charged current (CC) quasi-elastic scattering (CCQES), an (anti)neutrino interacts with a (proton)neutron, producing a corresponding lepton, and the (proton)neutron changes to a (neutron)proton:

\[ \nu_e + n \to l^- + p, \]  
\[ \bar{\nu}_e + p \to l^+ + n, \]

Precise knowledge of (anti)neutrino CCQES is crucial to high energy physics experiments studying neutrino oscillations and hence extracting the neutrino mass hierarchy, mixing angles etc. [1–10]. Several experimental efforts, such as studies at Gargamelle (GGM) [12, 13], SKAT [14], Brookhaven National Laboratory (BNL) [15], Neutrino Oscillation Magnetic Detector (NOMAD) [16], Main Injector ExpeRiment for $\nu$ - A (MINER$\nu$A) [17] and Mini Booster Neutrino Experiment (MiniBooNE) [18] etc. have been performed to describe the quasi-elastic scattering of neutrinos and anti-neutrinos off various nuclear targets. GGM studied quasi-elastic reactions of neutrinos and anti-neutrinos on propane along with a freon target. SKAT bombarded a wide energy band neutrino/anti-neutrino beam onto a heavy freon (CF$_3$Br) target, BNL used hydrogen (H$_2$) as a target, NOMAD used carbon, MINER$\nu$A projected an anti-neutrino beam with average energy of 3.5 GeV onto a hydrocarbon target, and MiniBooNE used a mineral oil target. A global analysis of neutrino and anti-neutrino QES differential and total cross sections, along with the extraction of axial mass $M_A$, is presented in Ref. [19].

In this work, we study charged current anti-neutrino–nucleon and anti-neutrino–nucleus ($^{12}$C) QES. To describe CCQES, we use the Llewellyn Smith (LS) model [20] and parameterizations by Galster et al. [21]

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for the electric and magnetic Sach’s form factors of the nucleons. To incorporate the nuclear effects, in the case of $\bar{\nu}_p$ scattering off $^{12}$C, we use the Fermi gas model along with the Pauli suppression condition [19, 20, 22–24]. We calculate $\bar{\nu}_p-p$ and $\bar{\nu}_p-^{12}$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. This work does not include the contribution from the 2N2h (two nucleons two holes) effect in QES, where the interaction involves two nucleons producing two holes in the nucleus. Studies of the 2N2h effect in QES are presented in Refs. [25–29].

2 Formalism for quasi-elastic $\bar{\nu}-N$ and $\bar{\nu}-A$ scattering

The Llewelyn Smith model describes (anti)neutrino scattering using a plane wave impulse approximation and calculates the QES cross sections. The anti-neutrino-nucleon charged current quasi-elastic differential cross section for a free nucleon at rest is given as [20]:

$$\frac{d\sigma}{dQ^2} = \frac{M_N^2 G_F^2 \cos^2 \theta_c}{8\pi E_n^2} \times \left[ A(Q^2) + \frac{B(Q^2)(s-u)}{M_N^2} + \frac{C(Q^2)(s-u)}{M_N^4} \right],$$

where $M_N$ is the nucleon mass, $G_F = 1.16 \times 10^{-5}$ GeV$^{-2}$ is the Fermi coupling constant, $\cos \theta_c = 0.97425$ is the Cabibbo angle, and $E_n$ is the anti-neutrino energy. In terms of the Mandelstam variables $s$ and $u$, the relation $s-u=4M_N^2E_n-Q^2-m_n^2$; where $Q^2$ is the square of momentum transfer from the anti-neutrino to the outgoing lepton and $m_n$ is the mass of the outgoing lepton.

The functions $A(Q^2)$, $B(Q^2)$ and $C(Q^2)$ are defined as [11, 20, 23]:

$$A(Q^2) = \frac{m_n^2+Q^2}{4M_N^2} \left[ (1+\tau)F_A^2-(1-\tau)(F_Y^V)^2 \right. $$

$$+\tau(1-\tau)(F_Y^P)^2 + 4\tau F_Y^V F_Y^P \right],$$

$$B(Q^2) = \frac{Q^2}{M_N^2} F_A (F_Y^V + F_Y^P),$$

$$C(Q^2) = \frac{1}{4} \left[ F_A^2 + (F_Y^V)^2 + \tau(F_Y^P)^2 \right],$$

where $\tau = \frac{Q^2}{4M_N^2}$. $F_A$ is the axial form factor, $F_Y^V$ is the pseudoscalar form factor and $F_Y^P$, $F_Y^V$ are the vector form factors.

The axial form factor $F_A$ is defined in the dipole form as [30]:

$$F_A(Q^2) = \frac{g_A}{\left(1+\frac{Q^2}{M_A^2}\right)^2},$$

where $g_A = -1.267$ is the axial vector constant and $M_A$ is the axial mass.

The pseudoscalar form factor $F_Y$ is defined in terms of the axial form factor $F_A$ as [31]:

$$F_Y(Q^2) = \frac{2}{Q^2+m_n^2} F_A(Q^2),$$

where $m_n$ is the mass of the pion.

The vector form factors $F_Y^V$ and $F_Y^P$ are defined as [30, 32]:

$$F_Y^V(Q^2) = \frac{1}{1+\tau} \left[ G_E^p(Q^2)-G_M^p(Q^2) \right]$$

$$+ \tau \left[ G_M^p(Q^2)-G_M^n(Q^2) \right],$$

$$F_Y^P(Q^2) = \frac{1}{1+\tau} \left[ G_M^p(Q^2)-G_M^n(Q^2) \right]$$

$$- \left[ G_E^p(Q^2)-G_E^n(Q^2) \right],$$

where $G_E^p$ is the electric Sach’s form factor of the proton, $G_M^p$ is the electric Sach’s form factor of the neutron, $G_M^n$ is the magnetic Sach’s form factor of the proton and $G_M^n$ is the magnetic Sach’s form factor of the neutron. Several groups such as Galster et al. [21], Budd et al. [33], Bradford et al. [34], Bosted [35] and Alberico et al. [36] provide parameterizations of these form factors by fitting the electron scattering data. For the present calculations, we are using Galster et al.’s parameterizations of these form factors.

The electric and magnetic Sach’s form factors of the nucleons are defined as [21]:

$$G_E^p(Q^2) = G_D(Q^2),$$

$$G_M^p(Q^2) = \mu_p \frac{G_D(Q^2)}{},$$

$$G_M^n(Q^2) = \mu_n \frac{G_D(Q^2)}{},$$

We define the electric Sach’s form factor of the neutron using the Krutov and Troitsky [37] parameterization as:

$$G_E^n(Q^2) = -\mu_n \frac{0.942 \tau}{(1+4.61 \tau)} G_D(Q^2),$$

where $\mu_p = 2.793$ is the magnetic moment of the proton, and $\mu_n = -1.913$ is the magnetic moment of the neutron.
and $G_D(Q^2)$ is the dipole form factor, defined as [30]:

$$G_D(Q^2) = \frac{1}{\left(1 + \frac{Q^2}{M^2_s}\right)^2},$$  \hspace{1cm} (15)

where $M^2_s = 0.71$ GeV$^2$.

The total cross section of anti-neutrino–nucleon (free) quasi-elastic scattering is obtained by integrating the differential cross section, defined by Eq. (3), over $Q^2$ as [23]:

$$\sigma_{\text{free}}(E_\bar{\nu}) = \int_{Q^2_{\text{min}}}^{Q^2_{\text{max}}} dQ^2 \frac{d\sigma_{\text{free}}(E_\bar{\nu}, Q^2)}{dQ^2},$$  \hspace{1cm} (16)

where $Q^2_{\text{min}}$ and $Q^2_{\text{max}}$ are defined as:

$$Q^2_{\text{min}} = -m^2 + 2E_\bar{\nu}(E_\bar{\nu} - \mid \vec{k} \mid),$$

$$= \frac{2E^2_\bar{\nu}M_N - M_Nm^2 - E_\bar{\nu}m^2 - E_Q}{2E_\bar{\nu} + M_N},$$  \hspace{1cm} (17)

$$Q^2_{\text{max}} = -m^2 + 2E_\bar{\nu}(E_\bar{\nu} + \mid \vec{k} \mid),$$

$$= \frac{2E^2_\bar{\nu}M_N - M_Nm^2 + E_\bar{\nu}m^2 + E_Q}{2E_\bar{\nu} + M_N}.$$

Here, $E_\bar{\nu}$ and $\vec{k}$ are the energy and momentum of the outgoing lepton, and $E_Q$ is defined as:

$$E_Q = E_\bar{\nu}\sqrt{(s-m^2)/2(s+m^2)}M^2_N + M^2_s.$$

where $s = M^2_N + 2M_N E_\bar{\nu}$.

3 Nuclear modifications

For studying anti-neutrino–nucleus quasi-elastic scattering, the nucleus can be treated as a Fermi gas [19, 20, 22–24], where the nucleons move independently within the nuclear volume in an average binding potential generated by all nucleons. The Pauli suppression condition is applied for the nuclear modifications, which implies that the cross section for all the interactions leading to a final state nucleon with a momentum smaller than the Fermi momentum $k_F$ is equal to zero.

The differential cross section per proton for anti-neutrino–nucleus quasi-elastic scattering is defined as [23, 24]:

$$\frac{d\sigma_{\text{nuclear}}(E_\bar{\nu}, Q^2)}{dQ^2} = \frac{2V}{Z(2\pi)^3} \int_0^{\infty} 2\pi k_F^2 \frac{dk_F d(cos \theta)}{d \omega} f(k_F) S(\nu - \nu_{\text{min}})$$

$$\times \frac{d\sigma_{\text{free}}(E_\bar{\nu}, k_F, Q^2)}{dQ^2},$$  \hspace{1cm} (20)

where the factor 2 accounts for the spin of the proton, $V$ is the volume of the nucleus, $k_F$ is the momentum of the proton, $d\sigma_{\text{free}}$ is the differential cross section of the anti-neutrino quasi-elastic scattering off a free proton as defined by Eq. (3), and $E_{\nu_{\text{eff}}}$ is the effective anti-neutrino energy in the presence of Fermi motion of nucleons. $E_{\nu_{\text{eff}}}$ is defined as [23]:

$$E_{\nu_{\text{eff}}} = \frac{(s_{\text{eff}} - M^2_p)}{2M_p}.$$

Here, $M_p$ is the proton mass and $s_{\text{eff}}$ is defined as [23]:

$$s_{\text{eff}} = M^2_p + 2E_\nu(E_p - k_F \cos \theta),$$

where $E_p$ is the proton energy, defined as:

$$E_p = \sqrt{k_F^2 + M^2_p}.$$

The Fermi distribution function $f(k_F)$ is defined as:

$$f(k_F) = \frac{1}{1 + \exp \left(\frac{k_F - k_F}{a}\right)},$$  \hspace{1cm} (24)

where $a = kT = 0.020$ GeV is the diffuseness parameter [24]. The Fermi momentum $k_F$ for the carbon nucleus is 0.221 GeV [38].

The Pauli suppression factor $S(\nu - \nu_{\text{min}})$ is defined as [23, 24]:

$$S(\nu - \nu_{\text{min}}) = \frac{1}{1 + \exp \left(\frac{\nu - \nu_{\text{min}}}{a}\right)},$$  \hspace{1cm} (25)

where $\nu$ is the energy transfer in the interaction, defined as:

$$\nu = (Q^2 + M^2_n - M^2_p)/(2M_p),$$

and $\nu_{\text{min}}$ is defined as:

$$\nu_{\text{min}} = \sqrt{k_F^2 + M^2_n} - \sqrt{k_F^2 + M^2_p + E_B}.$$

Here, $M_n$ is the final state neutron mass and $E_B$ is the binding energy. For the carbon nucleus, $E_B = 10$ MeV [24].

The total cross section of anti-neutrino–nucleus quasi-elastic scattering is obtained by integrating the differential cross section, as defined by Eq. (20), over $Q^2$, where $Q^2$ ranges from $Q^2_{\text{min}}$ to $Q^2_{\text{max}}$ defined by Eqs. (17) and (18), calculated with $E_{\nu_{\text{eff}}}$ instead of $E_{\nu_{\text{eff}}}$.

4 Results and discussion

We calculated the charged current $\bar{\nu} - N$ and $\bar{\nu} - A$ quasi-elastic differential scattering cross sections. Figure 1 shows the present calculations of $\bar{\nu}_\mu - p$ charged current quasi-elastic differential scattering cross section $d\sigma_{\text{CC}}$ as a function of the square of momentum transfer $Q^2$, for different values of axial mass ($M_A = 0.979, 1.05, 1.12$ and 1.23 GeV) and for anti-neutrino energy $E_{\nu_{\text{eff}}} = 2$ GeV. The value of differential cross section increases with increasing axial mass.
$Q^2$ due to nuclear effects. The cross sections gradually drop to zero with increasing value of $Q^2$.

We compared the present calculations of $\nu_\mu^{-12}\text{C}$ charged current quasi-elastic differential cross section with experimental data from several collaborations. Figure 3 shows the flux-integrated differential cross section $\frac{d\sigma}{dQ^2}$ per proton for anti-neutrino–carbon CCQES as a function of the square of momentum transfer $Q^2$ corresponding to the MiniBooNE data [18], measuring the muon anti-neutrino CCQES cross section off a mineral oil (carbon) target. The calculations are performed for different values of axial mass ($M_A = 0.979, 1.05, 1.12$ and $1.23$ GeV). The average anti-neutrino energy $<E_{\bar{\nu}}> = 665$ MeV. The calculations with axial mass $M_A=0.979$ and 1.05 GeV are compatible with data.

Figure 4 shows the differential cross section $\frac{d\sigma}{dQ^2}$ per proton for anti-neutrino–carbon CCQES as a function of the square of momentum transfer $Q^2$, for different values of axial mass ($M_A = 0.979, 1.05, 1.12$ and $1.23$ GeV) and for average anti-neutrino energy $<E_{\bar{\nu}}> = 2$ GeV. The results obtained are compared with data from Gargamelle (GGM) [12], which studied quasi-elastic reactions of neutrinos and antineutrinos on a propane plus freon target.
The calculations with axial mass $M_A = 0.979$ and 1.05 GeV are compatible with data.

Figure 5 shows the differential cross section $\frac{d\sigma}{dQ}$ per proton for anti-neutrino–carbon CCQES as a function of the square of momentum transfer $Q^2$, for different values of axial mass ($M_A = 0.979, 1.05, 1.12$ and 1.23 GeV) and for average anti-neutrino energy $<E_{\bar{\nu}}>$ = 3 GeV. The results obtained are compared with SKAT data [14] studying the cross sections of neutrino and anti-neutrino quasi elastic interactions using a wide energy band (3 - 30 GeV) neutrino/anti-neutrino beam on a heavy freon (CF$_4$Br) target. The calculations with axial mass $M_A = 0.979$ and 1.05 GeV are compatible with data.

Figure 6 shows the differential cross section $\frac{d\sigma}{dQ}$ per proton for anti-neutrino–carbon CCQES as a function of the square of momentum transfer $Q^2$, for different values of axial mass ($M_A = 0.979, 1.05, 1.12$ and 1.23 GeV). The results obtained are compared with MINERvA data [17] measuring muon anti-neutrino quasi-elastic scattering on a hydrocarbon target at $<E_{\bar{\nu}}>$ = 3.5 GeV. The calculation with axial mass $M_A = 0.979$ GeV is compatible with data.

We calculated the total cross section for charged current $\nu-N$ and $\bar{\nu}-A$ quasi elastic scattering and compared the present results with data from several experiments. Figure 7 shows the present calculations of the total cross section $\sigma$ for anti-neutrino–proton CCQES as a function of the anti-neutrino energy $E_{\bar{\nu}}$, for different values of axial mass ($M_A = 0.979, 1.05, 1.12$ and 1.23 GeV). The
value of total cross section increases with increasing axial mass. We compared the obtained results with data from the BNL [15] and NOMAD [16] experiments. The calculation with axial mass $M_A = 1.05$ GeV is compatible with data.

Figure 8 shows the total cross section $\sigma$ for $\bar{\nu}_e - p$ and $\bar{\nu}_e - ^{12}$C charged current QES as a function of the anti-neutrino energy $E_{\bar{\nu}}$, with axial mass $M_A = 1.05$ GeV. The nuclear effects reduce the anti-neutrino–carbon cross section compared to the anti-neutrino–proton cross section.

Figure 9 shows the total cross section $\sigma$ per proton for $\bar{\nu}_e - ^{12}$C charged current QES as a function of the anti-neutrino energy $E_{\bar{\nu}}$, 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 the GGM(1977) [12], GGM(1979) [13], SKAT [14], NOMAD [16] and MiniBooNE [18] experiments. The calculations with axial mass $M_A = 0.979$ and 1.05 GeV are compatible with the GGM(1977), GGM(1979) and SKAT data, though the calculations overestimate the data at low anti-neutrino energies. The approach parameterizing axial mass $M_A$ as a function of anti-neutrino energy, presented in Ref. [39], can be used to get a better agreement with 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.

5 Conclusion

We have presented a study on charged current anti-neutrino–nucleon and anti-neutrino–nucleus (carbon) quasi-elastic scattering using the Llewellyn Smith
(LS) model. For the electric and magnetic Sach’s form factors of nucleons, we used Galster et al.’s parameterizations. The Fermi gas model, along with the Pauli suppression condition, has been used to incorporate the nuclear effects in anti-neutrino–nucleus QES. We calculated $\bar{\nu}_\mu^{-p}$ and $\bar{\nu}_\mu^{-^{12}C}$ charged current quasi-elastic differential and total scattering cross sections for different values of axial mass $M_A$ and compared the obtained results with data from the GGM, SKAT, BNL, NOMAD, MINERvA and MiniBooNE experiments. The present theoretical approach gives a good description of differential cross section data. The calculations with axial mass $M_A = 0.979$ and 1.05 GeV are compatible with data from most of the experiments.

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