Interactions of the solar neutrinos with the deuterons

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1 Introduction

The semileptonic weak nuclear interaction has been studied for half a century. The cornerstones of this field of research are (i) the chiral symmetry, (ii) the conserved vector current and (iii) the partial conservation of the axial current (PCAC). In the formulation [1], the PCAC reads

\[ q_\mu \langle \Psi_f | j^{a}_\mu(q)|\Psi_i \rangle = i f_{\pi} m^{2}_\pi \Delta^T(q^2) \langle \Psi_f | m^{a}_\pi(q)|\Psi_i \rangle > , \]

where \( j^{a}_\mu(q) \) is the total weak axial isovector hadron current, \( m^{a}_\pi(q) \) is the pion source (the pion production/amplitude) and \( |\Psi_i, f > \) is the wave function describing the initial (i) or final (f) nuclear state. It has been recognized [2] in studying the triton beta decay

\[ ^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e , \]

and the muon capture [3]

\[ \mu^- + ^3\text{He} \rightarrow ^3\text{H} + \nu_\mu , \]

that in addition to the one–nucleon current, the effect of the space component of weak axial exchange currents (WAECs) enhances sensibly the Gamow–Teller matrix elements entering the transition rates. This suggests that the current \( j^{a}_\mu(q) \) can be understood for the system of \( A \) nucleons as the sum of the one- and two–nucleon components,

\[ j^{a}_\mu(q) = \sum_{i=1}^{A} j^{a}_{5\mu}(1,i,q_i) + \sum_{i<j}^{A} j^{a}_{5\mu}(2,i,j,q) . \]

Let us describe the nuclear system by the Schrödinger equation

\[ H|\Psi > = E|\Psi > , \quad H = T + V , \]

where \( H \) is the nuclear Hamiltonian, \( T \) is the kinetic energy and \( V \) is the nuclear potential describing the interaction between nucleon pairs. Taking for simplicity \( A = 2 \), we obtain from Eq. [1] in the operator form and from Eqs. [2] and [3] the following set of equations for the one- and two–nucleon components of the total axial current

\[ q_i \cdot j^{a}_{5}(1,q_1) = [ T_1, \rho^{a}_{5}(1,q_1) ] + i f_{\pi} m^{2}_\pi \Delta^T(q^2) \times m^{a}_\pi(1,q_1) , \quad i = 1,2 , \]

\[ q \cdot j^{a}_{5}(2,q) = [ T_1 + T_2, \rho^{a}_{5}(2,q) ] + ( | V , \rho^{a}_{5}(1,q) | + (1 \leftrightarrow 2)) + i f_{\pi} m^{2}_\pi \Delta^T(q^2) m^{a}_\pi(2,q) . \]
If the WAECs are constructed so that they satisfy Eq. (5), then the matrix element of the total current, sandwiched between solutions of the nuclear equation of motion (6), satisfies the PCAC (11).

It is known from the dimensional analysis (4), that the space component of the WAECs, \( J^5_{a}(2, q) \), is of the order \( \mathcal{O}(1/M^3) \). Being of a relativistic origin, it is model dependent. This component of the WAECs was derived by several authors in various models. In the standard nuclear physics approach (5,6,7,8,9), the model systems of strongly interacting particles contain various particles (effective degrees of freedom), such as \( N, \Delta(1236), \pi, \rho, \omega \) and other baryons and mesons. Using these effective degrees of freedom and chiral Lagrangians, it was possible to describe reasonably nuclear electroweak phenomena in the whole region of intermediate energies. In particular, the existence of mesonic degrees of freedom in nuclei, manifesting themselves via meson exchange currents, was proven to a high degree of reliability (8).

One of the employed Lagrangians is the one (5) containing the heavy meson fields \( p \) and \( a_1 \), taken as the Yang–Mills gauge fields (10). It reflects the \( SU(2)_L \times SU(2)_R \) local chiral symmetry. Another used Lagrangian has been built up (11) within the concept of hidden local symmetries (12,13). Besides possessing the chiral symmetry, our Lagrangians are characterized by the following properties: (i) They respect the vector dominance model, reproduce universality, KSFRI, FSFR2, (ii) they provide correct anomalous magnetic moment of the \( a_1 \) meson (iii) at the tree-level approximation, they correctly describe elementary processes in the whole region of intermediate energies (\( E < 1 \) GeV) and (iv) the current algebra prediction for the weak pion production amplitude is reproduced. Using such an approach, the exchange currents are constructed as follows. First, one derives the exchange amplitudes \( J^a_{5\mu}(2) \) as Feynman tree graphs. These amplitudes satisfy the PCAC equation

\[
q^\mu \ J^a_{5\mu}(2) = i f_\pi m_\pi^2 \Delta^\pi (q^2) M^a(2)
\]

where \( M^a(2) \) are the associated pion absorption/production amplitudes. The nuclear exchange currents are constructed from these amplitudes in conjunction with the equation, describing the nuclear states. Such exchange currents, combined with the one-nucleon currents, should satisfy Eq. (11).

In the present case, we describe the nuclear system by the Hamiltonian \( H = T + V \) and the nuclear states by the Schrödinger equation (9). The nuclear exchange currents are constructed within the extended S-matrix method, in analogy with the electromagnetic meson exchange currents (15), as the difference between the relativistic amplitudes \( J^a_{5\mu}(2) \) and the first Born iteration of the weak axial one–nucleon current contribution to the two–nucleon scattering amplitude, satisfying the Lippmann–Schwinger equation. This method has already been applied (10,17) to construct the space component of the WAECs of the pion range.

On the other hand, effective fields theories (EFTs) are being developed since early 90’s. In this approach, one starts from a general chiral invariant Lagrangian with heavy particle degrees of freedom integrated out and preserving \( N, \Delta(1236) \) and \( \pi \) (18), or \( N \) and \( \pi \) (19,20), or only nucleons (21,22). Such EFTs rely on systematic counting rules and on the existence of an expansion parameter, governing a perturbation scheme that converges reasonably fast. The expansion parameter is given as the ratio of the light and heavy scales.

In the pionless EFT (21,22), the heavy scale \( \Lambda \) is set to the pion mass \( m_\pi \). This choice restricts the application of the scheme to the processes taking place at threshold energies, such as the interaction of solar neutrinos with the deuterons (23). In the EFT with pions, the heavy scale is \( \Lambda \approx 4\pi f_\pi \approx 1 \) GeV, restricting the application of the EFT to low energies.

The goal of this study is twofold: (i) The construction of the WAECs of the heavy meson range, suitable in the standard nuclear physics calculations beyond the long–wave limit, with the nuclear wave functions generated from the Schrödinger equation using the one–boson exchange potentials (OBEPs). (ii) An application of the developed formalism to the description of the interaction of the low energy neutrinos with the deuterons,

\[
\nu_x + d \rightarrow \nu_x + n + p, \quad (10)
\]

\[
\overline{\nu}_x + d \rightarrow \overline{\nu}_x + n + p, \quad (11)
\]

\[
\nu_e + d \rightarrow e^- + p + p, \quad (12)
\]

\[
\overline{\nu}_e + d \rightarrow e^+ + n + n. \quad (13)
\]

where \( \nu_x \) refers to any active flavor of the neutrino. The reactions (10) and (12) are important for studying the solar neutrino oscillations, whereas the reactions (11) and (13) occur in experiments with reactor antineutrino beams. The cross sections for the reactions (10) and (12) are important for the analysis of the results obtained in the SNO detector (21,25,26). The standard nuclear physics calculations (27,28) generally differ (23) by 5%-10%, which provides a good motivation to make independent calculations aiming to reduce this uncertainty.

In Ref. (23), the effective cross sections for the reactions (10)–(13) are presented in the form

\[
\sigma_{EFT}(E_\nu) = a(E_\nu) + L_{1, \Lambda} b(E_\nu). \quad (14)
\]

The amplitudes \( a(E_\nu) \) and \( b(E_\nu) \) are tabulated in (23) for each of the reactions (10)–(13) from the lowest possible (anti)neutrino energy up to 20 MeV, with 1 MeV step. The constant \( L_{1, \Lambda} \) cannot be determined from reactions between elementary particles. Here we extract \( L_{1, \Lambda} \) from our cross sections calculated in the approximations of (23) only the \( 1S_0 \) wave is taken into account in the nucleon–nucleon final state and the nucleon variables are treated non-relativistically. The knowledge of \( L_{1, \Lambda} \) allows us to compare our cross sections with \( \sigma_{EFT}(E_\nu) \).

2 Weak axial nuclear exchange currents

The starting quantities of our construction are the relativistic Feynman amplitudes \( J^a_{5\mu,B}(2) \) of the range \( B \),

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1 We refer the reader for more details to Ref. (14).
with the cross sections of Refs. \[27,28\]. Our WAECs contain the following components \[14\]: the pair terms \(j_{5p, B}^0(p\text{air})\) \((B = \pi, \rho, \omega, a_1)\), the non–potential exchange currents \(j_{5p, \perp}^0(\rho\pi)\), \(j_{5p, \perp}^0(a_1)\) and the \(\Delta\) excitation terms \(j_{5p, \perp}^0(\Delta)\) \((B = \pi, \rho)\).

The pion exchange part of our model WAECs is similar to the one employed in \[27\]. The representative cross sections, presented in table I of Ref. \[27\], are calculated using the AV18 potential \[33\], that is another high quality second generation potential\(^2\) and the \(S\)- and \(P\)-waves are taken into account in the nucleon–nucleon final states.

We also compare our results with those reported in table I of Ref. \[28\], where the calculation were performed (i) with the Paris potential \[34\]; (ii) with the currents taken in the impulse approximation; (iii) with the \(S\)- and \(P\)-waves taken into account in the nucleon–nucleon final states.

### 3 Numerical results

Using the technique developed in Refs. \[35,36\] one obtains the equations for the cross sections \(\sigma_{pot}(E_\nu)\) that can be found in \[14\]. The equations are the same as those of Ref. \[27\], but we treat the nucleon variables in the phase space non-relativistically. In Ref. \[23\], the bounds on the phase space are defined in the neutral channel by

\[
0 \leq E_\nu' \leq E_\nu - \nu - 2M_r + 2 [M_r(M_r - |\epsilon_B|)]^{1/2},
\]

\[
\max\left[-1, \frac{E_\nu^2 + E_\nu'^2 + 4M_r(\epsilon_B - q_0)}{2E_\nu E_\nu'}\right] \leq \cos \theta \leq 1,
\]

where \(M_r\) is the reduced mass of the neutron–proton system and \(\epsilon_B = -2.2245\) MeV is the deuteron binding energy.

We have found that it is more effective to integrate numerically within the bounds

\[
-1 \leq \cos \theta \leq 1,
\]

\[
0 \leq E_\nu' \leq E_\nu \cos \theta - 2M_r + [4M_r^2 + 4M_r(\epsilon_B - q_0) - \epsilon_B^2(1 - \cos^2 \theta) - 4M_rE_\nu \cos \theta]^{1/2}.
\]

For the charged channel, the momentum of the final lepton is restricted by

\[
0 \leq p_l \leq p_{l,max},
\]

where \(p_{l,max}\) is the solution of the equation

\[
(E_\nu - p_l^2)^2 + 4M_r(E_l) + 4M_r(\Delta - E_\nu) = 0.
\]

Here \(E_l(p_l) = (p_l^2 + m_\chi^2)^{1/2}\) and

\[
\Delta = M_n - M_p + |\epsilon_B|, \quad M_r = M_p, \quad \nu e^-,
\]

\[
\Delta = M_n - M_p + |\epsilon_B|, \quad M_r = M_n, \quad \bar{\nu} e^+.
\]

\(^2\) However, its short range part is not an OBEP.
Table 1. Values of the constant $L_{1,A}$ obtained by the fit to the cross sections of the reactions (10)-(13) calculated using the Nijm1, Nijm93 and OBEPQG potentials and by the fit (NSGK) to the cross sections of table I of Ref. [27].

| reaction | NijmI | Nijm93 | OBEPQG | NSGK |
|----------|-------|--------|--------|------|
| (10)     | $L_{1,A}$ | 4.6 | 5.2 | 4.8 | 5.4 |
| S        | 1.001 | 1.001 | 1.001 | 1.000 |
| (11)     | $L_{1,A}$ | 4.9 | 5.5 | 1.0 | 5.5 |
| S        | 1.001 | 1.001 | 1.001 | 1.000 |
| (12)     | $L_{1,A}$ | 4.1 | 5.0 | - | 6.0 |
| S        | 1.001 | 1.001 | - | 1.002 |
| (13)     | $L_{1,A}$ | 4.5 | 5.4 | 6.9 | 5.6 |
| S        | 1.001 | 1.000 | 0.9996 | 0.9997 |

We extracted $L_{1,A}$ by comparing the cross section $\sigma_{EFT}(E_\nu)$ with our cross sections $\sigma_{pot}(E_\nu)$ using the least square fit and also considering an average value of $L_{1,A}$

$$\bar{L}_{1,A} = \frac{\sum_{i=1}^{N} L_{1,A}(i)}{N},$$

where

$$L_{1,A}(i) = \frac{\sigma_{pot,i} - a_i}{b_i}.$$

We estimated the quality of the fit by the quantity $S$ defined as

$$S = \frac{1}{N} \sum_{i=1}^{N} \frac{\sigma_{EFT,i}}{\sigma_{pot,i}}.$$

It was found that the fit providing the average value $\bar{L}_{1,A}$ results in better agreement between $\sigma_{EFT}(E_\nu)$ and $\sigma_{pot}(E_\nu)$ and we present the results in table 1 only for this fitting procedure. We also applied this fit to the cross sections of table I of [27] (cf. the column NSGK).

In table 2 we present the scattering lengths and the effective ranges, obtained from the Nijm1, Nijm93, OBEPQG and AV18 potentials and also the values used in the EFT calculations [23]. For the generation of the final state nucleon–nucleon wave functions from the Nijm1 and Nijm93 potentials, we used the program COCHASE [14]. The program solves the Schrödinger equation using the fourth-order Runge–Kutta method. This can provide low–energy scattering parameters that slightly differ from those obtained from the Nijmegen group, employing the modified Numerov method [12]. Some refit was necessary, in order to get the correct low–energy scattering parameters in the neutron–proton and neutron–neutron $^1S_0$ states.

Shall we now present the results for the reactions (10)-(13). In comparing our results with [23] we use in our calculations their values $G_F = 1.166 \times 10^{-5} GeV^{-2}$ and $g_A = -1.26$. Instead we use the value $g_A = -1.254$, as employed in [27] and [28], when comparing our results with these works. In the cross sections for the charged channel reactions (12) and (13) the value $\cos \theta_C = 0.975$ is taken for the Cabibbo angle.

Table 3. Cross section and the differences in % between cross sections for the reaction (10). In the first column, $E_\nu$ [MeV] is the neutrino energy, in the second column, $\sigma_{Nijm1}$ (in $10^{-42} \times cm^2$) is the cross section calculated with the Nijm1 nuclear wave functions. Column 3 reports the differences between $\sigma_{Nijm1}$ (Nijm1) and the EFT cross section $\sigma_{EFT}$, calculated with the corresponding constant $L_{1,A}$ from table 1. The differences between $\sigma_{NSGK}$ (22) and $\sigma_{EFT}$ are reported in column 4. Further, $\Delta_1(2)$ is the difference between the cross sections $\sigma_{Nijm1}$ ($\sigma_{Nijm93}$) and $\sigma_{NSGK}$; $\Delta_3$ is the difference between the cross sections $\sigma_{Nijm1}$ and $\sigma_{Y HH}$, where the cross section $\sigma_{Y HH}$ is from [28] in table I.

| $E_\nu$ [MeV] | $\sigma_{Nijm1}$ | $\sigma_{NSGK}$ | $\Delta_1$ | $\Delta_2$ | $\Delta_3$ |
|-------------|------------------|----------------|------------|------------|------------|
| 3           | 0.00335          | 1.2            | -1.1       | -0.5       | -          |
| 4           | 0.0306           | 1.3            | -0.8       | -0.2       | 12.0       |
| 5           | 0.0948           | 1.3            | -0.9       | -0.2       | 5.0        |
| 6           | 0.201            | 1.1            | -1.0       | -0.3       | 10.2       |
| 7           | 0.353            | 1.0            | -1.1       | -0.4       | 8.1        |
| 8           | 0.551            | 1.0            | -1.3       | -0.5       | 10.1       |
| 9           | 0.798            | 1.0            | -1.5       | -0.7       | 8.9        |
| 10          | 1.093            | 0.4            | -0.1       | -0.6       | 7.6        |
| 11          | 1.437            | 0.8            | -1.6       | -1.0       | 9.4        |
| 12          | 1.831            | -0.1           | -0.3       | -2.1       | -1.2       |
| 13          | 2.274            | -0.1           | 0.0        | -2.3       | -1.4       |
| 14          | 2.767            | -0.4           | 0.0        | -2.6       | -1.7       |
| 15          | 3.308            | -0.8           | -0.1       | -2.9       | -2.0       |
| 16          | 3.898            | -1.2           | -0.3       | -3.2       | -2.2       |
| 17          | 4.537            | -1.6           | -0.4       | -3.5       | -2.5       |
| 18          | 5.223            | -1.9           | -0.3       | -3.9       | -2.9       |
| 19          | 5.957            | -2.3           | -0.4       | -4.2       | -3.2       |
| 20          | 6.738            | -2.9           | -0.6       | -4.6       | -3.6       |

3.1 Reaction $\nu_x + d \rightarrow \nu'_x + n + p$.

In Table 3 we present the difference in %, between the cross sections, obtained with the Nijm1 and AV18 potentials models and the EFT cross sections, calculated with the corresponding $L_{1,A}$ from table 1. Besides, we give the differences between the cross sections, computed with the wave functions of various potential models.

Comparing the columns Nijm1 and NSGK of table 3 we can see that the NSGK cross section is closer to the EFT cross section. This means that the standard approach and the pionless EFT differ, since the approximations, made in our calculations and in EFT, coincide: the nucleon–nucleon final state is restricted to the $^1S_0$ wave and the nucleon variables are treated non-relativistically. Besides, the inspection of columns $\Delta_1$ and $\Delta_2$ shows that our cross sections closely follow the NSGK cross section up to the energies when the $P$- waves in the nucleon–nucleon final state start to contribute. On the other hand, as it follows from column $\Delta_3$, it is difficult to understand the behavior of the cross section $\sigma_{Y HH}$ in the whole interval of the considered neutrino energies.

3.2 Reaction $\bar{\nu}_x + d \rightarrow \bar{\nu}'_x + n + p$.

In analogy with section 3.1, we present in table 4 a comparative analysis for the reaction (11).
Table 2. Scattering length and effective range (in fm) for the nucleon–nucleon system in the $^1S_0$ state, corresponding to the NijmI, Nijm93 [9], OBEPQG [24], AV18 [53] potentials and as used in the EFT calculations [23], and their experimental values.

| $\sigma_{pp}$ | $r_{pp}$ | $\sigma_{np}$ | $r_{np}$ |
|---------------|----------|---------------|----------|
| Nijm | -23.72 | 2.65 | -23.74 | 2.73 |
| Nijm93 | -23.73 | 2.70 | -23.73 | 2.70 |
| OBEPQG | -23.74 | 2.70 | -23.74 | 2.70 |
| AV18 | -7.82 | -7.82 | -7.82 | -7.82 |
| EFT | -18.49 | -18.49 | -18.49 | -18.49 |
| exp. | -18.59±0.40 | -18.59±0.40 | -18.59±0.40 | -18.59±0.40 |

Table 4. Cross section and the differences in % between cross sections for the reaction $^1P_1$. For notations, see table 3. For instead of $E_\nu$, now $E_\bar{\nu}$ is the antineutrino energy in MeV.

| $E_\bar{\nu}$ | $\sigma_{NijmI}$ | $\sigma_{NSGK}$ | $\Delta_1$ | $\Delta_2$ |
|---------------|-----------------|-----------------|-----------|
| 3  | 0.00332 | 0.6  | 0.1  | -1.1 | -0.5 |
| 4  | 0.0302 | 1.0  | 0.2  | -0.8 | -0.1 |
| 5  | 0.0928 | 1.0  | 0.1  | -0.8 | -0.1 |
| 6  | 0.196 | 1.1  | 0.3  | -0.9 | -0.1 |
| 7  | 0.342 | 0.8  | 0.1  | -1.0 | -0.2 |
| 8  | 0.531 | 1.4  | 0.8  | -1.1 | -0.3 |
| 9  | 0.765 | 0.8  | 0.2  | -1.2 | -0.4 |
| 10 | 1.043 | 0.6  | 0.2  | -1.4 | -0.5 |
| 11 | 1.364 | 0.1  | -0.2 | -1.6 | -0.7 |
| 12 | 1.729 | -0.2 | -0.4 | -1.7 | -0.8 |
| 13 | 2.136 | -0.3 | -0.2 | -1.2 | -2.2 |
| 14 | 2.585 | -0.5 | -0.2 | -2.1 | -2.4 |
| 15 | 3.074 | -0.2 | -0.7 | -2.1 | -2.4 |
| 16 | 3.604 | -0.9 | -0.1 | -2.6 | -1.7 |
| 17 | 4.173 | -1.2 | -0.2 | -2.9 | -1.9 |
| 18 | 4.779 | -1.6 | -0.3 | -3.3 | -2.2 |
| 19 | 5.422 | -1.9 | -0.3 | -3.6 | -2.5 |
| 20 | 6.101 | -2.2 | -0.2 | -3.9 | -2.9 |

Clearly, our cross sections are closer to $\sigma_{EFT}$ and also to the cross section $\sigma_{NSGK}$, than in the neutrino-deuteron case of table 2. The behavior of the cross section $\sigma_{YHH}$ is as little understandable as for the reaction 10.

One can also conclude from the differences given in the columns NijmI, NSGK, $\Delta_1$ and $\Delta_2$ of tables 3 and 4 that the cross sections for the reactions 10 and 11 are described by both the potential models and the pionless EFT with an accuracy better than 3%.

### 3.3 Reaction $\nu_e + d \rightarrow e^- + p + p$.

The comparison of the columns NijmI, NSGK, $\Delta_1$ and $\Delta_2$ of table 3 shows that, disregarding the cross sections for $E_\nu = 2$ MeV, the cross sections for the important reaction 12 are described with an accuracy of 3.3%. However, while our cross sections and the cross section 27 are smooth functions of the neutrino energy, the EFT cross section exhibits abrupt changes in the region $7 < E_\nu < 12$ MeV. In our opinion, the reason can be an incorrect treatment of the Coulomb interaction between protons in the EFT calculations. We have verified that the non-relativistic approximation for the Fermi function, employed in 23, is valid with a good accuracy in the whole interval of the solar neutrino energies.

Inspecting the difference of the cross sections $\Delta_3$ shows that the cross section 28 is of the correct size in this case.

### 3.4 Reaction $\bar{\nu}_e + n \rightarrow e^- + n + n$.

It follows from table 6 that our cross sections for the reaction 13 are in a very good agreement with the EFT 23 and 27 calculations. This confirms our conjecture that the treatment of the Coulomb interaction between protons 23 in the reaction 12 is not correct.

The calculations 28 provide too a small cross section. The most probable reason for this large difference is that the Paris potential does not describe the neutron–neutron interaction correctly.
Table 6. Cross section and the differences in % between cross sections for the reaction NSGK. For notations, see table 3

| E0  | | | | | | |
|-----|---------|---------|---------|---------|---------|---------|
| 5   | 0.0274  | -1.3    | -0.9    | -2.4    | -1.3    | 9.0     |
| 6   | 0.116   | 0.1     | -1.1    | -1.1    | 8.1     |
| 7   | 0.277   | 0.2     | -0.2    | -1.8    | 0.7     |
| 8   | 0.514   | 0.5     | -0.1    | -1.7    | 7.1     |
| 9   | 0.829   | 0.4     | -0.2    | -1.7    | 6.9     |
| 10  | 1.224   | 0.9     | 0.4     | -1.7    | 6.8     |
| 11  | 1.697   | 0.7     | 0.2     | -1.9    | 6.0     |
| 12  | 2.249   | 0.6     | 0.1     | -2.0    | 6.1     |
| 13  | 2.876   | 0.4     | 0.0     | -2.2    | 6.0     |
| 14  | 3.578   | 0.4     | 0.2     | -2.3    | 5.2     |
| 15  | 4.335   | 0.0     | 0.0     | -2.6    | 4.9     |
| 16  | 5.200   | -0.2    | 0.1     | -2.8    | 4.6     |
| 17  | 6.115   | -0.3    | 0.2     | -3.1    | 3.5     |
| 18  | 7.097   | -0.5    | 0.4     | -3.4    | 2.1     |
| 19  | 8.143   | -0.9    | 0.2     | -3.8    | 2.8     |
| 20  | 9.251   | -1.2    | 0.3     | -4.1    | 2.4     |

4 Conclusions

We calculated here the cross sections for the reactions of the solar neutrinos with the deuterons, NSGK, within the standard nuclear physics approach. We took into account the weak axial exchange currents of the OBE type, satisfying the nuclear continuity equation [3]. These currents were constructed from the Lagrangians, possessing the chiral local SU(2)L × SU(2)R symmetry, in the tree approximation. Using the OBE potentials NijmI, Nijm93 and OBEPQG, we made consistent calculations. We took into account the nucleon–nucleon interaction in the 1S0 final state and we treated non-relativistically the nucleon variables.

Our cross sections for the reactions NSGK agree with the EFT cross sections and also with the cross sections within an accuracy better than 3 %. The agreement for the reaction NSGK is within 3.3 %. In our opinion, the agreement for the reaction is in % can be improved by paying more attention to the treatment of the Coulomb interaction between the protons in the final state in the pionless EFT calculations.

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