

Probing neutrino nature at Borexino detector with chromium neutrino source

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Abstract In this paper, we indicate a possibility of utilizing the intense chromium source (~ 370 PBq) in probing the neutrino nature in low energy neutrino experiments with the ultra-low threshold and background real-time Borexino detector located near the source (~ 8 m). We analyse the elastic scattering of electron neutrinos (Dirac or Majorana, respectively) on the unpolarised electrons in the relativistic neutrino limit. We assume that the incoming neutrino beam is the superposition of left–right chiral states produced by the chromium source. Left chiral neutrinos may be detected by the standard $V - A$ and non-standard scalar S_L , pseudoscalar P_L , tensor T_L interactions, while right chiral ones partake only in the exotic $V + A$ and S_R, P_R, T_R interactions. Our model-independent study is carried out for the flavour (current) neutrino eigenstates. We compute the expected event number for the standard $V - A$ interaction of the left chiral neutrinos using the current experimental values of standard couplings and in the case of left–right chiral superposition. We show that the significant decrement in the event number due to the interference terms between the standard and exotic interactions for the Majorana neutrinos may appear. We also demonstrate how the presence of the exotic couplings affects the energy spectrum of outgoing electrons, both for the Dirac and Majorana cases. The 90 % C.L. sensitivity contours in the planes of corresponding exotic couplings are found. The presence of interferences in the Majorana case gives the stronger constraints than for the Dirac neutrinos, even if the neutrino source is placed outside the detector.

1 Introduction

Possibility of utilizing various artificial neutrino sources (ANS) in the low energy neutrino (ν) experiments with the ultra-low background and threshold detectors to explore

the Lorentz structure of weak interactions and other non-standard ν properties has been discussed in many papers, e.g. [1–6]. The first concept of the use of the artificial neutrino source comes from Alvarez, who proposed to use ^{65}Zn [7]. The ^{51}Cr and ^{37}Ar ν sources were proposed by Raghavan [8] and Haxton [9]. As is well known there are essentially two types of ANS which can be used in the large liquid scintillator detectors: the monochromatic ν_e emitters (e.g. $^{51}\text{Cr}, ^{37}\text{Ar}, ^{49}\text{V}, ^{145}\text{Sm}$), and $\bar{\nu}_e$ sources with continuous β spectrum (e.g. $^{144}\text{Cs}-^{144}\text{Pr}, ^{106}\text{Ru}-^{106}\text{Rh}, ^{90}\text{Sr}-^{90}\text{Y}, ^{42}\text{Ar}-^{42}\text{K}$) [10, 11]. The ^{51}Cr sources (~ 66 PBq, ~ 18.5 PBq) as the dichromatic ν_e emitters with energies of 430 keV (10 %) and 750 keV (90 %), and a mean life time ($\tau \simeq 40$ days) have already been utilised to calibrate GALLEX and SAGE experiments [12–16], where a deficit in the rate of ν interactions has been found [17, 18]. The ^{37}Ar source (~ 14.8 PBq) has also been used by SAGE [19]. Presently, the ^{51}Cr emitter with activity of the order of ~ 370 PBq in the SOX experiment [20] (Short distance Oscillation with boreXino) with the Borexino detector will be used to search for the sterile ν_e 's [11, 21–27], to improve the current limits on the neutrino magnetic moment [28], and to reduce the uncertainty on the direct measurement of the standard couplings. The $^{144}\text{Cs}-^{144}\text{Pr}$ source with the deployment at the Borexino detector centre is also proposed to probe the non-standard $\bar{\nu}_e$ interactions. It is worth to remind that the extremely low background Borexino detector has precisely measured the low energy solar ν_e components (^7Be , pep) [29–31] and detected the geophysical $\bar{\nu}_e$'s [32].

This detector seems to be an appropriate tool to test the ν nature, i.e. whether ν 's are the Dirac or Majorana fermions. The problem of distinguishing between the Dirac and Majorana ν 's can be investigated in the context of non-vanishing ν mass and of standard vector–axial ($V - A$) weak interaction of the only left chiral (LCh) ν 's, using purely leptonic processes such as the polarised muon decay at rest or the mentioned neutrino–electron elastic scattering (NEES). Kayser

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[33] and Langacker [34] have proposed the first tests concerning the mass dependence, but it is worthwhile noting the other papers devoted to the various aspects of the nature of ν , e.g. [35–41]. It is necessary to point out that the current experiments regarding the discrimination between the Dirac and Majorana ν 's are mainly based on the searching for the neutrinoless double beta decay (NDBD) [42–44]; however, the low energy ν experiments with the intense ANS, very low background and threshold detector seem to have similar scientific opportunities, and may also shed some light on this problem. It is important to emphasise that there is also an alternative scenario within the relativistic ν limit, when one departs from the $V - A$ interaction and one admits the exotic scalar (S), tensor (T), pseudoscalar (P) and ($V + A$) weak interactions of the right chiral (RCh) ν 's (right-handed helicity when $m_\nu \rightarrow 0$) in the leptonic processes. The proper tests have been reported by Rosen [45] and Dass [46]. It is relevant to remark that the existing data still leaves a little space for the exotic couplings of the interacting RCh ν 's outside the SM [47–51]. Let us recall that the SM does not clarify the origin of parity violation (PV) at current energies. It is well known that the SM PV is incorporated in ad hoc way by assuming that gauge boson couples only to the left chiral currents. However, on the other hand, there is no experimental evidence of the parity conservation at higher energies so far. Moreover, the SM does not explain the observed baryon asymmetry of universe [52] through a single CP-violating phase of the Cabibbo–Kobayashi–Maskawa quark-mixing matrix (CKM) [53], the large hierarchy fermion masses, and other fundamental aspects. Consequently, a lot of non-standard schemes with the Majorana (and Dirac) ν 's, time reversal violation (TRV) exotic interactions, mechanisms explaining the origin of fermion generations, masses, mixing and smallness of ν mass appeared. They include a non-standard ν interactions (NSI) changing and conserving ν flavour [54–57], which may be generated by the mechanisms of massive neutrino models [58–62]. The NSI phenomenology has been extensively explored [63–77]. Concerning interacting RCh ν 's, the suitable non-standard models seem to be the left–right symmetric models (LRSM) [78–83], composite models (CM, where tensor and scalar interactions are generated by the exchange of constituents) [84–86], models with extra dimensions (MED) [87], the unparticle models (UP) [88–100]. In the MED the LCh standard particles live on the three-brane, while the RCh ν 's can move in the extra dimensions. This is the reason why the interactions of RCh ν 's with the LCh fermions are extremely tiny to be observed. Interestingly in the UP scheme the leptons with the different chiralities can couple to the spin-0 scalar, spin-1 vector, spin-2 tensor unparticle sectors. This means that the amplitude for NEES can have the form of the unparticle four-fermion contact interaction at low energies and contain the exotic contributions. Currently there is no unambiguous indication of a new non-standard

gauge model, because the experimental possibilities are still limited. There is a constant necessity of improvement of the precision of the present tests at low energies, and on the other hand, the precise measurements of new observables including the linear terms from the exotic couplings would be required. In this context the theoretically possible scenario of the measurement of the azimuthal asymmetry of recoil electrons as signature of the nature of ν has been considered [101]. The Hellaz [102–104] and Heron [105–107] proposals aiming at the measurement of recoil electron scattering angle and of azimuthal angle are worth to remind.

In this study, we focus on the application of ^{51}Cr electron neutrino (ν_e) source deployed at 8.25 m from the centre of the Borexino detector to find the allowed limits on the exotic S , P , T , $V + A$ couplings in the relativistic ν_e limit, when the incoming ν_e beam is the superposition of left–right chiral states and has Dirac or Majorana nature. We analyse the elastic scattering of ν_e beam off the unpolarised electron target as the detection process of possible exotic signals. In the experiment the scintillator detector does not allow one to observe the directionality of the recoil electrons, so all the interference terms between the standard and exotic couplings in the differential cross section vanish for the Dirac ν_e 's, and only the contributions from the squares of exotic couplings of the RCh ν 's and of non-standard couplings of LCh ones (and at most the interferences within exotic couplings) may generate a possible effect. The situation is different for the Majorana ν 's, where some linear terms coming from the exotic couplings after the integration over the azimuthal angle of outgoing electron momentum may occur. One of the goals is to show how the expected event number for the standard $V - A$ interaction depends on the precision of measurement of the standard couplings. Next, we calculate in a model-independent way, the predicted event number coming from the admixture of exotic interactions both for the Dirac and Majorana ν_e 's. It is also interesting to demonstrate how the spectrum of outgoing electrons depends on the various combinations of exotic interactions, taking into account the detector resolution function. Finally, we find the 90 % C.L. sensitivity contours in the planes of proper exotic couplings for both scenarios.

2 Elastic scattering of Dirac electron neutrinos off unpolarised electrons

We assume that the incoming monochromatic Dirac ν_e beam comes from the electron capture by ^{51}Cr ($e^- + ^{51}\text{Cr} \rightarrow \nu_e + ^{51}\text{V}$) and is the superposition of left–right chiral states. To give an illustration, let us refer to Ref. [108], where the muon capture by proton as the production process of left–right chiral superposition has been considered. The formula for the longitudinal component of the ν polarisation contains

the terms from the LCh ν 's produced in the $V - A$ interaction and RCh ones generated in the exotic $(S, T, P)_R$ interactions. There are also the interferences between the $V - A$ and $(S, T, P)_R$ interactions, but they are strongly suppressed by the ν mass. It is noteworthy that when the admixture of RCh ν 's in addition to the LCh ones is admitted in the polarised ν source and the production plane is assigned, the ν polarisation vector may acquire the transversal components, both T-even and T-odd. The transversal ν polarisations consist only of the interferences between the $V - A$ and $(S, T, P)_R$ couplings and do not vanish in the relativistic ν limit.

LCh ν_e 's are mainly detected by the standard $V - A$ interaction, while RCh ones are detected only by the exotic scalar S , pseudoscalar P , tensor T , $V + A$ interactions in the elastic scattering on the unpolarised electrons; $\nu_e + e^- \rightarrow \nu_e + e^-$. The considered scenario admits also the detection of ν_e 's with left-handed chirality by the non-standard $(S, T, P)_L$ interactions. It is important to emphasise that our analysis is carried out for the flavour (current) ν_e eigenstates. The amplitude for the $\nu_e e^-$ scattering at low energies takes the form

$$M_{\nu_e e^-}^D = \frac{G_F}{\sqrt{2}} \{ (\bar{u}_{e'} \gamma^\alpha (c_V^L - c_A^L \gamma_5) u_e) (\bar{u}_{\nu_e'} \gamma_\alpha (1 - \gamma_5) u_{\nu_e}) + (\bar{u}_{e'} \gamma^\alpha (c_V^R + c_A^R \gamma_5) u_e) (\bar{u}_{\nu_e'} \gamma_\alpha (1 + \gamma_5) u_{\nu_e}) + c_S^R (\bar{u}_{e'} u_e) (\bar{u}_{\nu_e'} (1 + \gamma_5) u_{\nu_e}) + c_P^R (\bar{u}_{e'} \gamma_5 u_e) (\bar{u}_{\nu_e'} \gamma_5 (1 + \gamma_5) u_{\nu_e}) + \frac{1}{2} c_T^R (\bar{u}_{e'} \sigma^{\alpha\beta} u_e) (\bar{u}_{\nu_e'} \sigma_{\alpha\beta} (1 + \gamma_5) u_{\nu_e}) + c_S^L (\bar{u}_{e'} u_e) (\bar{u}_{\nu_e'} (1 - \gamma_5) u_{\nu_e}) + c_P^L (\bar{u}_{e'} \gamma_5 u_e) (\bar{u}_{\nu_e'} \gamma_5 (1 - \gamma_5) u_{\nu_e}) + \frac{1}{2} c_T^L (\bar{u}_{e'} \sigma^{\alpha\beta} u_e) (\bar{u}_{\nu_e'} \sigma_{\alpha\beta} (1 - \gamma_5) u_{\nu_e}) \}, \quad (1)$$

where $G_F = 1.1663788(7) \times 10^{-5} \text{ GeV}^{-2} (0.6 \text{ ppm})$ [109] is the Fermi constant. The coupling constants are denoted with the superscripts L and R as $c_{V,A}^{L,R}, c_{S,T,P}^{R,L}, c_{S,T,P}^{R,L}$, respectively, to the incoming ν_e of left- and right-handed chirality. Because we take into account the TRV, all the coupling constants are complex. Let us recall that we probe the case when the outgoing electron direction is not observed, so the laboratory differential cross section is presented after integration over the azimuthal angle ϕ_e of the recoil electron momentum. The obtained formula, in the relativistic limit, does not contain the interference terms between the standard $c_{V,A}^L$ and exotic $c_{S,T,P}^L, c_{V,A}^R$ couplings. We also assume the relations between the coupling constants, $c_{S,T,P}^R = c_{S,T,P}^{*L}$, which appear at the level of interaction lagrangian. As a result the contributions coming from the S, T, P interactions do not depend on $\hat{\eta}_\nu \cdot \hat{\mathbf{q}}$:

$$\frac{d\sigma}{dy_e} = \left(\frac{d\sigma}{dy_e} \right)_{(V-A)} + \left(\frac{d\sigma}{dy_e} \right)_{(V+A)} + \left(\frac{d\sigma}{dy_e} \right)_{(S,P,T)}, \quad (2)$$

$$\left(\frac{d\sigma}{dy_e} \right)_{(V-A)} = B \left\{ (1 - \hat{\eta}_\nu \cdot \hat{\mathbf{q}}) \left[|c_V^L + c_A^L|^2 + |c_V^L - c_A^L|^2 (1 - y_e)^2 - \frac{m_e y_e}{E_\nu} (|c_V^L|^2 - |c_A^L|^2) \right] \right\}, \quad (3)$$

$$\left(\frac{d\sigma}{dy_e} \right)_{(V+A)} = B \left\{ (1 + \hat{\eta}_\nu \cdot \hat{\mathbf{q}}) \left[|c_V^R + c_A^R|^2 + |c_V^R - c_A^R|^2 (1 - y_e)^2 - \frac{m_e y_e}{E_\nu} (|c_V^R|^2 - |c_A^R|^2) \right] \right\}, \quad (4)$$

$$\left(\frac{d\sigma}{dy_e} \right)_{(S,P,T)} = 2B \left\{ \frac{1}{2} y_e \left(y_e + 2 \frac{m_e}{E_\nu} \right) |c_S^L|^2 + \left((2 - y_e)^2 - \frac{m_e}{E_\nu} y_e \right) |c_T^L|^2 + y_e (y_e - 2) \text{Re}(c_S^L c_T^{*L}) + \frac{1}{2} y_e^2 |c_P^L|^2 + y_e (y_e - 2) \text{Re}(c_P^L c_T^{*L}) \right\}, \quad (5)$$

where

$$y_e \equiv \frac{T_e}{E_\nu} = \frac{m_e}{E_\nu} \frac{2 \cos^2 \theta_e}{\left(1 + \frac{m_e}{E_\nu} \right)^2 - \cos^2 \theta_e} \quad (6)$$

is the ratio of the kinetic energy of the recoil electron T_e to the incoming ν_e energy E_ν ; θ_e is the angle between the direction of the outgoing electron momentum $\hat{\mathbf{p}}_e$ and ν_e LAB momentum unit vector $\hat{\mathbf{q}}$ (recoil electron scattering angle); m_e is the electron mass; $B \equiv (E_\nu m_e / 2\pi) (G_F^2 / 2)$; $\hat{\eta}_\nu$ is the unit 3-vector of ν_e spin polarisation in its rest frame; $(\hat{\eta}_\nu \cdot \hat{\mathbf{q}}) \hat{\mathbf{q}}$ is the longitudinal component of ν_e spin polarisation; $|\hat{\eta}_\nu \cdot \hat{\mathbf{q}}| = |1 - 2Q_L^y|$, where Q_L^y is the probability of producing the LCh ν_e .

It can be noticed that there are only the contributions from the T-even longitudinal component of the ν_e spin polarisation, and no linear terms from the exotic couplings in the relativistic limit appear. The formula for the number of events for the standard and non-standard interactions is similar to [3]:

$$N = N_t \cdot \Phi_0 \cdot \Gamma(t_{tr}, t_{ex}) \cdot F \left(\frac{R}{D} \right) \cdot \int_{250 \text{ keV}}^{700 \text{ keV}} dT_e^m \cdot \left[0.81 \int_0^{T_e^{\max}(E_\nu=746 \text{ keV})} dT_e R(T_e^m, T_e) \frac{d\sigma}{dT_e} \Big|_{E_\nu=746 \text{ keV}} + 0.09 \int_0^{T_e^{\max}(E_\nu=751 \text{ keV})} dT_e R(T_e^m, T_e) \frac{d\sigma}{dT_e} \Big|_{E_\nu=751 \text{ keV}} \right]. \quad (7)$$

In order to compute the expected event number for the standard $V - A$ interaction, we use the experimental values

of standard couplings: $c_V^L = 1 + (-0.04 \pm 0.015)$, $c_A^L = 1 + (-0.507 \pm 0.014)$ [110]. Assumptions concerning the technical setup are analogical as in [3] except the stronger source activity. $N_e = 3.3 \cdot 10^{32}$ is the number of electrons calculated for 100 tons of spherical fiducial volume ($R = 3$) m of the detector; $D = 8.25$ m is the distance between the chromium source and detector centre; $\Phi_0 = (I_0/4\pi D^2)$; $I_0 = 370 \text{ PBq} = 10 \text{ MCi}$ is the intensity of the source at the end of bombardment; $F(h) = (3/2h^3)\{h - [(1 - h^2)/2] \ln[(1 + h)/(1 - h)]\} \simeq 1.028$ is the factor taking into account the geometry of the system; $\Gamma(t_{tr}, t_{ex}) = \tau \exp(-t_{tr}/\tau)[1 - \exp(-t_{ex}\tau)]$; $\tau = (T_{1/2}/\ln 2) \simeq 39.97$ days; $t_{tr} = 5$ days and $t_{ex} = 60$ days define the exposure time. We have

$$R(T_e^m, T_e) = \frac{1}{\sqrt{2\pi}\delta(T_e)} \exp\left[-\frac{(T_e^m - T_e)^2}{2\delta^2(T_e)}\right] \quad (8)$$

is the detector resolution function; $\delta(T_e)/\text{keV} = 48\sqrt{T_e/\text{MeV}}$ is the electron energy resolution; $T_e^m \in [250, 700]$ keV is the energy window for the reconstructed recoil electron kinetic energy.

Figure 1 shows how the uncertainty on the measurement of standard $c_{V,A}^L$ couplings affects the expected event number. In this case we assume a pure LCh ν_e beam with $\hat{\eta}_\nu \cdot \hat{\mathbf{q}} = -1$. Figure 2 illustrates the dependence of the event number on $\hat{\eta}_\nu \cdot \hat{\mathbf{q}} \in [-1, 1]$ for the standard interaction (solid thick line) and various combinations of exotic couplings (other lines). Upper and lower plots of Fig. 3 demonstrate the predicted event number coming from the superposition of left–right chiral ν_e 's for two chosen scenarios $(c_V^L, c_A^L, c_V^R, c_A^R)$, $(c_V^L, c_A^L, c_V^R, c_P^L)$. Middle plot is for the pure LCh ν_e beam. We use the experimental values for the standard couplings $c_V^L = 1 - 0.04$, $c_A^L = 1 - 0.507$ and probe the interval $[-0.6, 0.6]$ of all the exotic couplings. We stress that for the left–right chiral superposition of ν_e states $\hat{\eta}_\nu \cdot \hat{\mathbf{q}} \neq -1$ is admitted. To illustrate the effects from the exotic interactions of RCh ν_e 's we assume $\hat{\eta}_\nu \cdot \hat{\mathbf{q}} = -0.9$ corresponding to $P_L = 0.95$. For the scenario with only LCh ν_e 's participating both in the standard $V - A$ and non-standard (S_L, T_L, P_L) interactions we take $\hat{\eta}_\nu \cdot \hat{\mathbf{q}} = -1$.

Figure 4 illustrates 90 % C.L. sensitivity contours in the planes (c_V^R, c_A^R) , (c_S^L, c_T^L) , (c_V^R, c_P^L) , respectively. It should be noticed that we consider five degrees of freedom and then carry out the projection onto the appropriate plane of couplings. The proper contours are calculated with the use of inequality taken from [3]:

$$\left| \frac{N}{N_{SM}} - 1 \right| \geq \epsilon_{90} = 3.039 \frac{\delta N_{SM}}{N_{SM}}, \quad (9)$$

where $\delta N_{SM} = \sqrt{N_B + N_{SM}(1 + N_{SM}\delta_A^2)}$ is the total 1σ uncertainty of the signal; $\delta_A = 0.01$ is the uncertainty of source activity. We assume that the number of background

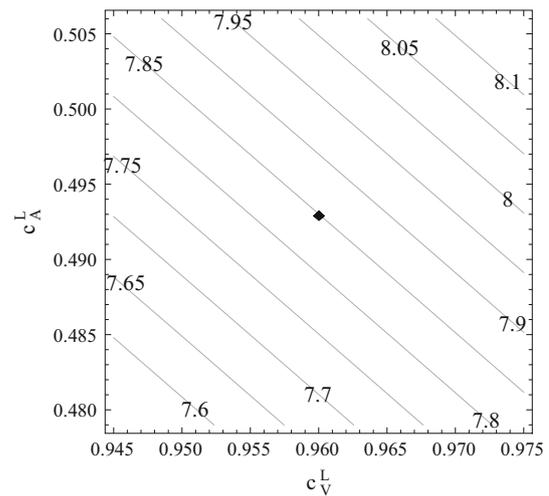


Fig. 1 Dirac ν_e . Dependence of the event number $N/10^3$ on the errors of the experimental values of the standard c_V^L, c_A^L couplings

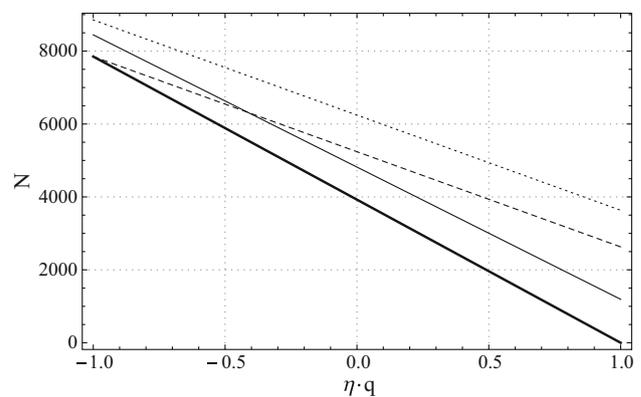


Fig. 2 Dirac ν_e . Dependence of the event number on $(\hat{\eta}_\nu \cdot \hat{\mathbf{q}}) \in [-1, 1]$. Solid thick line for the pure standard $V - A$ interaction; dashed line, dotted line and thin line for combinations of the standard $V - A$ interaction together with contributions from $(c_V^R = c_A^R = 0.4, c_S^L = c_T^L = c_P^L = 0)$, $(c_V^R = c_A^R = c_S^L = c_T^L = 0.4, c_P^L = 0)$ and $(c_V^R = -0.4, c_A^R = c_S^L = c_T^L = c_P^L = 0.4)$, respectively

events is $N_B = 4380$ as in [3]. Figure 5 shows how the energy spectrum of recoil electrons depends on the various scenarios with the exotic couplings. The departure from the standard expectation (dotted line) for the outgoing electrons with $T_e^m \in [0.25, 0.5]$ MeV is seen.

Equation (7) shows that the number of events depends on the geometry of the experimental setup only through the numerical factor independently of the nature of the interactions, and can easily be taken into account on the plots of Figs. 2, 3 and 5. On the other hand the number of events competes with the background, and thus the geometry (together with uncertainty of the source activity and assumed number of degrees of freedom) influences the C.L. sensitivity contours on Fig. 4. Let us further remark that in the complete model-independent analysis of the experiment non-standard

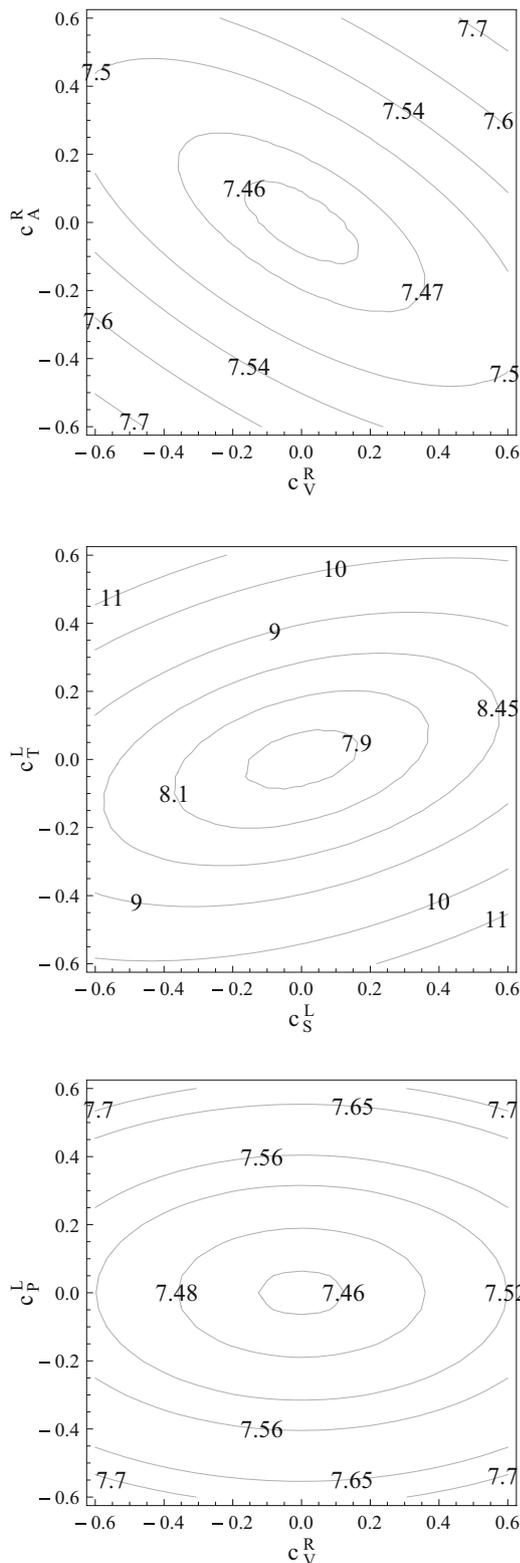


Fig. 3 Dirac ν_e . Upper and lower plots show the predicted event number $N/10^3$ coming from the superposition of left–right chiral ν_e 's for two scenarios $(c_V^L, c_A^L, c_V^R, c_A^R)$, $(c_V^L, c_A^L, c_V^R, c_P^L)$ with $\hat{\eta}_\nu \cdot \hat{q} = -0.9$, respectively. Middle plot concerns $(c_V^L, c_A^L, c_S^L, c_T^L)$ interactions of LCh ν_e 's with $\hat{\eta}_\nu \cdot \hat{q} = -1$

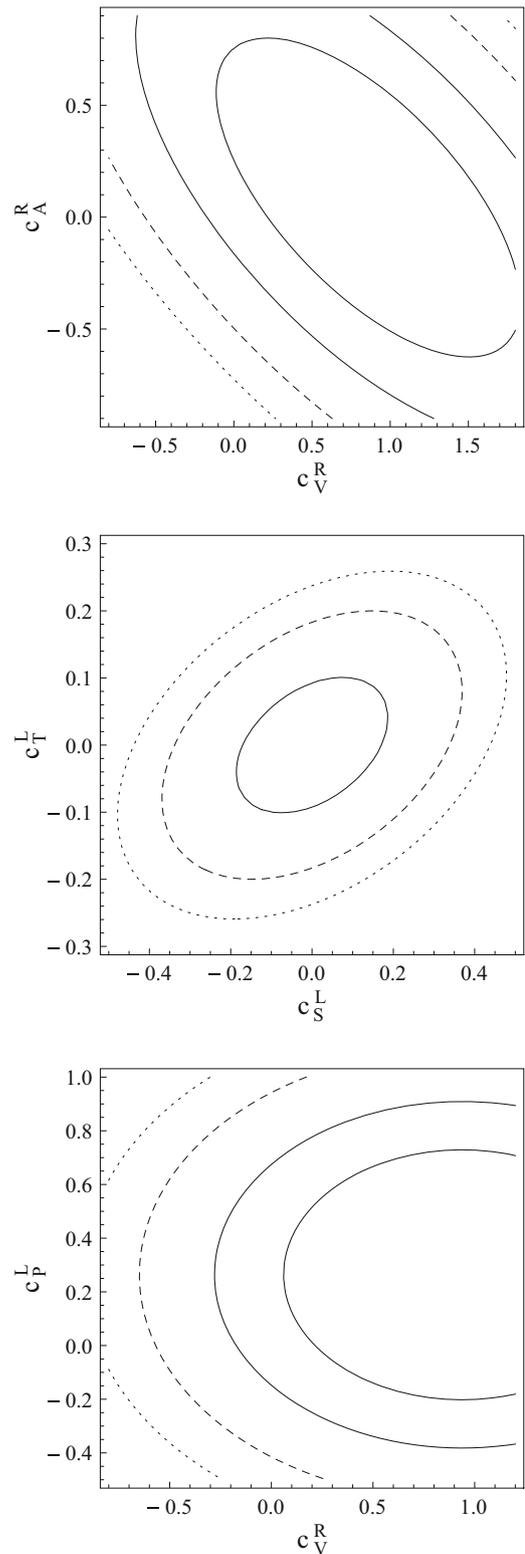


Fig. 4 Dirac ν_e . Upper and lower plots concern 90% C.L. sensitivity contours in the planes (c_V^R, c_A^R) , (c_V^R, c_P^L) for $\hat{\eta}_\nu \cdot \hat{q} = -0.9$, while middle plot is in the plane (c_S^L, c_T^L) with $\hat{\eta}_\nu \cdot \hat{q} = -1$, respectively. Solid line of each plot is for the source located at the detector centre and for $\delta_A = 0.001$. Dashed line is for $\delta_A = 0.01$ and the chromium source at the detector centre. Dotted line is for $D = 8.25$ m and $\delta_A = 0.01$

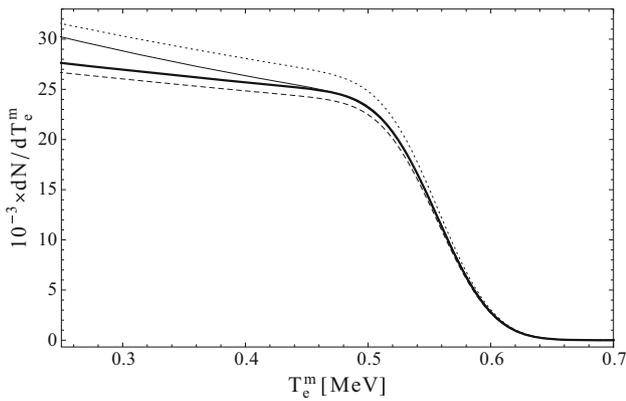


Fig. 5 Dirac ν_e . Dependence (dN/dT_e^m) on T_e^m . *Solid thick line* for the standard $V - A$ interaction with $\hat{\eta}_\nu \cdot \hat{\mathbf{q}} = -1$; *dashed line* for $(c_V^R = c_A^R = 0.4, c_S^L = c_T^L = c_P^L = 0)$ with $\hat{\eta}_\nu \cdot \hat{\mathbf{q}} = -0.9$; *dotted line* for $(c_V^R = c_A^R = c_S^L = c_T^L = 0.4, c_P^L = 0)$ with $\hat{\eta}_\nu \cdot \hat{\mathbf{q}} = -0.9$; *thin line* for $(c_V^R = -0.4, c_A^R = c_S^L = c_T^L = c_P^L = 0.4)$ with $\hat{\eta}_\nu \cdot \hat{\mathbf{q}} = -0.9$

interactions of the production process should also be taken into account. This in general would modify the dependence of the event number on the exotic couplings and would introduce new ones (cf. [108]) enlarging the number of degrees of freedom. This issue requires thorough follow-up studies.

3 Elastic scattering of Majorana electron neutrinos off unpolarised electrons

The amplitude for the elastic scattering of the Majorana ν_e 's on the unpolarised electrons at low energies has the form (one assumes the flavour ν_e eigenstates similarly to the Dirac case):

$$\begin{aligned}
 M_{\nu_e e^-}^M &= \frac{2G_F}{\sqrt{2}} \{ -(\bar{u}_{e'} \gamma^\alpha (c_V - c_A \gamma_5) u_e) (\bar{u}_{\nu_e'} \gamma_\alpha \gamma_5 u_{\nu_e}) \\
 &+ (\bar{u}_{e'} \gamma^\alpha (\tilde{c}_V + \tilde{c}_A \gamma_5) u_e) (\bar{u}_{\nu_e'} \gamma_\alpha \gamma_5 u_{\nu_e}) \\
 &+ (\bar{u}_{e'} u_e) [c_S^L (\bar{u}_{\nu_e'} (1 - \gamma_5) u_{\nu_e}) + c_S^R (\bar{u}_{\nu_e'} (1 + \gamma_5) u_{\nu_e})] \\
 &+ (\bar{u}_{e'} \gamma_5 u_e) [c_P^L (\bar{u}_{\nu_e'} \gamma_5 (1 - \gamma_5) u_{\nu_e}) \\
 &+ c_P^R (\bar{u}_{\nu_e'} \gamma_5 (1 + \gamma_5) u_{\nu_e})] \}. \tag{10}
 \end{aligned}$$

As is well known, the neutrino part of the amplitude for the Majorana ν_e 's is of the form $\sim (\bar{u}_{\nu_e'} \Gamma (1 \pm \gamma_5) u_{\nu_e}) - (\bar{\nu}_{\nu_e} \Gamma (1 \pm \gamma_5) \nu_{\nu_e'})$, where $\Gamma = \gamma_\alpha, \gamma_\alpha \gamma_5, \mathbf{1}, \gamma_5, \sigma_{\alpha\beta}$. This is a direct consequence of the (u, ν) -mode decomposition of the Majorana field. As a result of the Majorana condition, $\nu_{\nu_e} = i\gamma_2 u_{\nu_e}^*$, one gets $(\bar{\nu}_{\nu_e} \Gamma \nu_{\nu_e'}) = -(\bar{u}_{\nu_e'} \Gamma u_{\nu_e})$ for $\Gamma = \gamma_\alpha \gamma_5, \mathbf{1}, \gamma_5$, and $(\bar{\nu}_{\nu_e} \Gamma \nu_{\nu_e'}) = (\bar{u}_{\nu_e'} \Gamma u_{\nu_e})$ for $\Gamma = \gamma_\alpha, \sigma_{\alpha\beta}$. Consequently, the above amplitude does not contain the contribution from the V and T interactions in contrast to the Dirac case, where both terms partake. The $V + A$ interaction is also admitted. Moreover, due to the above relations the A and S contributions are multiplied by the factor of 2. The indices L (R)

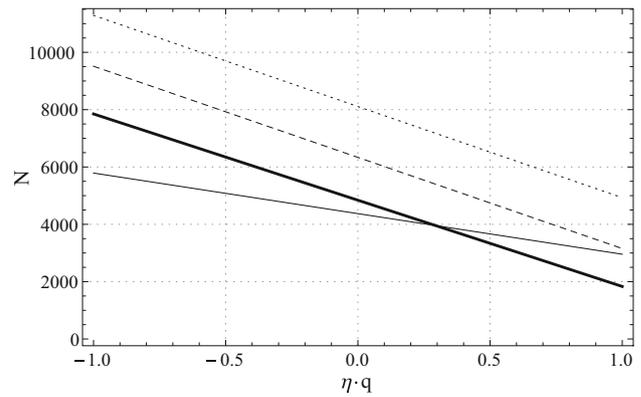


Fig. 6 Majorana ν_e . Dependence of the event number on $(\hat{\eta}_\nu \cdot \hat{\mathbf{q}}) \in [-1, 1]$. *Solid thick line* for the pure standard $V - A$ interaction; *dashed line, dotted line and thin line* for combinations of the standard $V - A$ interaction with $(\tilde{c}_V = \tilde{c}_A = 0.4, c_S^L = c_P^L = 0)$, $(\tilde{c}_V = \tilde{c}_A = c_S^L = c_P^L = 0.4)$ and $(\tilde{c}_V = 0.2, \tilde{c}_A = -0.2, c_S^L = c_P^L = 0.4)$, respectively

for c_V, c_A (\tilde{c}_V, \tilde{c}_A) couplings are omitted. It means that both LCh and RCh ν_e 's may participate in the standard A and non-standard \tilde{A} interactions of Majorana ν_e 's off the electron target. The exotic S, P coupling constants are denoted with the superscripts L and R as $c_{S,P}^{L,R}$ respectively to the incoming ν_e of left- and right-handed chirality. All the couplings are assumed to be complex numbers as for the Dirac case. It is necessary to take into account the relations between the couplings, $c_{S,P}^R = c_{S,P}^{*L}$. The differential cross section for the elastic scattering of Majorana current ν_e 's on the unpolarised electrons in the relativistic limit has the form

$$\begin{aligned}
 \frac{d\sigma}{dy_e} &= \left(\frac{d\sigma}{dy_e} \right)_{(V-A)} + \left(\frac{d\sigma}{dy_e} \right)_{(\tilde{V}+\tilde{A})} \\
 &+ \left(\frac{d\sigma}{dy_e} \right)_{(V-A)(\tilde{V}+\tilde{A})} + \left(\frac{d\sigma}{dy_e} \right)_{(S)} + \left(\frac{d\sigma}{dy_e} \right)_{(P)}, \tag{11}
 \end{aligned}$$

$$\begin{aligned}
 \left(\frac{d\sigma}{dy_e} \right)_{(V-A)} &= B \left\{ -\frac{2m_e y_e}{E_\nu} (|c_V|^2 - |c_A|^2) \right. \\
 &+ |c_V + c_A|^2 (2 + (1 + \hat{\eta}_\nu \cdot \hat{\mathbf{q}})(y_e - 2)y_e) \\
 &+ |c_V - c_A|^2 (2 + (1 - \hat{\eta}_\nu \cdot \hat{\mathbf{q}})(y_e - 2)y_e) \left. \right\}, \tag{12}
 \end{aligned}$$

$$\begin{aligned}
 \left(\frac{d\sigma}{dy_e} \right)_{(\tilde{V}+\tilde{A})} &= B \left\{ -\frac{2m_e y_e}{E_\nu} (|\tilde{c}_V|^2 - |\tilde{c}_A|^2) \right. \\
 &+ |\tilde{c}_V - \tilde{c}_A|^2 (2 + (1 + \hat{\eta}_\nu \cdot \hat{\mathbf{q}})(y_e - 2)y_e) \\
 &+ |\tilde{c}_V + \tilde{c}_A|^2 (2 + (1 - \hat{\eta}_\nu \cdot \hat{\mathbf{q}})(y_e - 2)y_e) \left. \right\}, \tag{13}
 \end{aligned}$$

$$\begin{aligned}
 \left(\frac{d\sigma}{dy_e} \right)_{(V-A)(\tilde{V}+\tilde{A})} &= 4B \left\{ Re(c_A \tilde{c}_A^*) \left(2 + (y_e - 2)y_e + \frac{m_e y_e}{E_\nu} \right) \right.
 \end{aligned}$$

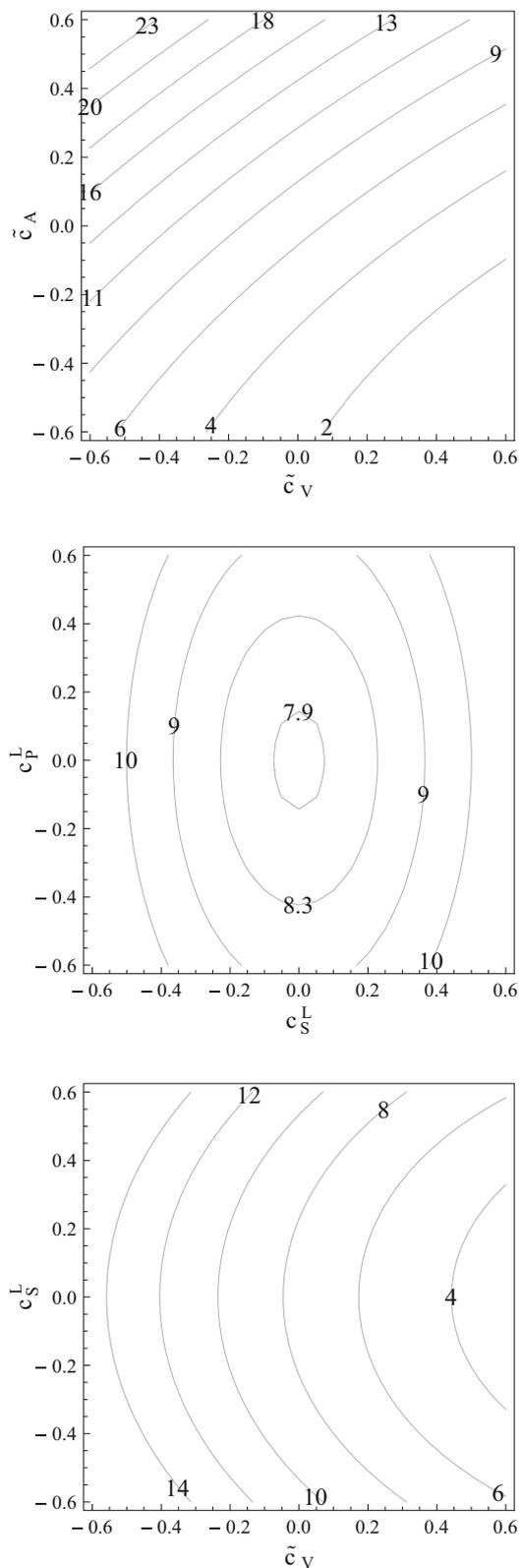


Fig. 7 Majorana ν_e . Upper and lower plots show the expected event number $N/10^3$ for two scenarios $(c_V, c_A, \tilde{c}_V, \tilde{c}_A)$, $(c_V, c_A, \tilde{c}_V, c_S^L)$, respectively, with $\hat{\eta}_\nu \cdot \hat{q} = -0.9$; the interferences between (c_V, c_A) and $(\tilde{c}_V, \tilde{c}_A)$ can significantly decrease the event number. Middle plot concerns (c_V, c_A, c_S^L, c_P^L) interactions of LCh ν_e 's with $\hat{\eta}_\nu \cdot \hat{q} = -1$

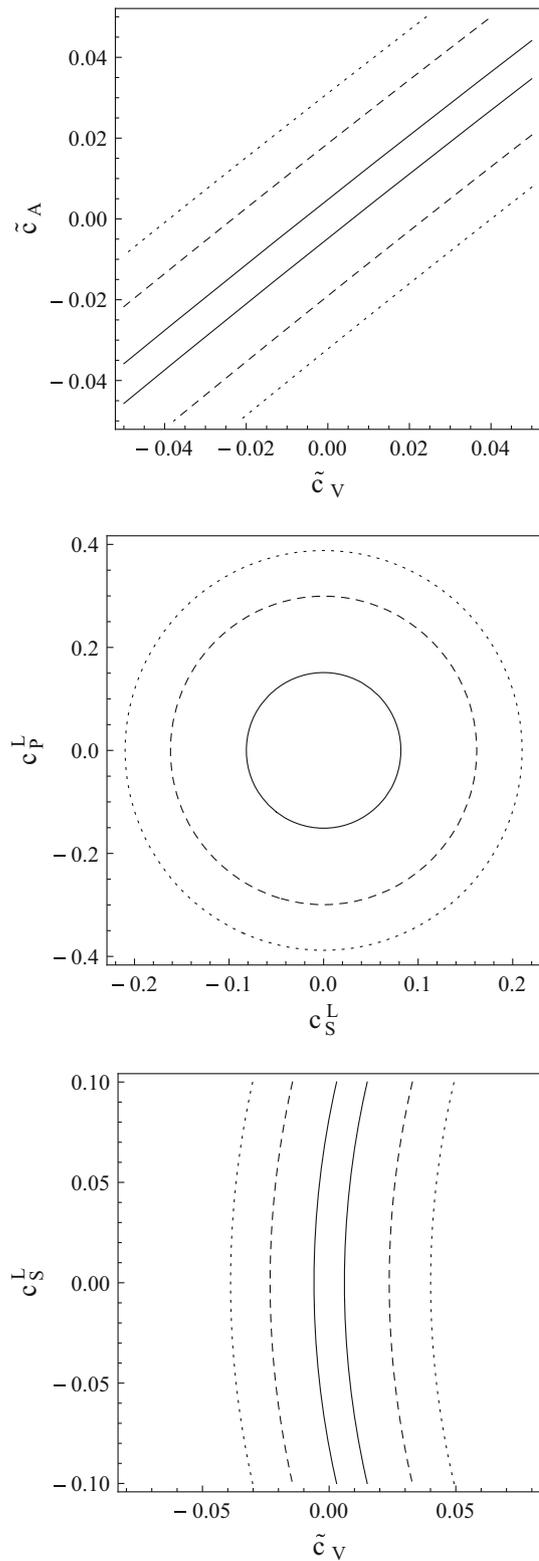


Fig. 8 Majorana ν_e . Upper and lower plots show 90 % C.L. sensitivity contours in the planes $(\tilde{c}_V, \tilde{c}_A)$, (\tilde{c}_V, c_S^L) with $\hat{\eta}_\nu \cdot \hat{q} = -0.9$, respectively. Middle plot is in the plane (c_S^L, c_P^L) with $\hat{\eta}_\nu \cdot \hat{q} = -1$. Solid line of each plot is for the source located at the detector centre and for $\delta_A = 0.001$. Dashed line is for $\delta_A = 0.01$ and the chromium source at the detector centre. Dotted line is for $D = 8.25$ m and $\delta_A = 0.01$

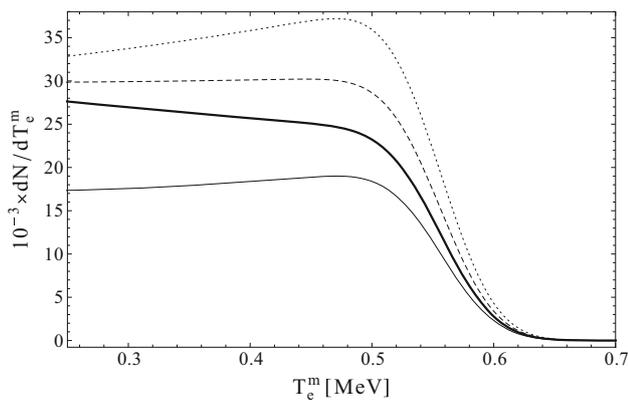


Fig. 9 Majorana ν_e . Dependence (dN/dT_e^m) on T_e^m . *Solid thick line* for the standard $V - A$ interaction with $\hat{\eta}_\nu \cdot \hat{\mathbf{q}} = -1$; *dashed line* for $(\tilde{c}_V = \tilde{c}_A = 0.4, c_S^L = c_P^L = 0)$ with $\hat{\eta}_\nu \cdot \hat{\mathbf{q}} = -0.9$; *dotted line* for $(\tilde{c}_V = \tilde{c}_A = c_S^L = c_P^L = 0.4)$ with $\hat{\eta}_\nu \cdot \hat{\mathbf{q}} = -0.9$; *thin line* for $(\tilde{c}_V = 0.2, \tilde{c}_A = -0.2, c_S^L = c_P^L = 0.4)$ with $\hat{\eta}_\nu \cdot \hat{\mathbf{q}} = -0.9$

$$\begin{aligned}
 &+ \left(\text{Re}(c_V \tilde{c}_A^*) - \text{Re}(c_A \tilde{c}_V^*) \right) (y_e - 2) y_e \hat{\eta}_\nu \cdot \hat{\mathbf{q}} \\
 &+ \text{Re}(c_V \tilde{c}_V^*) \left(-2 - (y_e - 2) y_e + \frac{m_e y_e}{E_\nu} \right) \Big\}, \quad (14)
 \end{aligned}$$

$$\left(\frac{d\sigma}{dy_e} \right)_{(S)} = 4B y_e \left(y_e + 2 \frac{m_e}{E_\nu} \right) |c_S^L|^2, \quad (15)$$

$$\left(\frac{d\sigma}{dy_e} \right)_{(P)} = 4B y_e^2 |c_P^L|^2. \quad (16)$$

We see that the interference terms between (c_V, c_A) and $(\tilde{c}_V, \tilde{c}_A)$ couplings appear in contrast to the Dirac case, where such contributions annihilate. It can also be noticed that the differential cross section does not contain T -odd observables similarly as for the Dirac ν_e 's. It is obvious that the predicted event number for the pure $V - A$ interaction in the Majorana case is the same as for the Dirac ν_e 's. However, if one departs from the standard couplings and allows for the exotic interactions, the possibility of distinguishing between the Dirac and Majorana ν 's in the limit of vanishing ν_e mass due to the interferences appears. Figure 6 shows how the event number depends on $\hat{\eta}_\nu \cdot \hat{\mathbf{q}} \in [-1, 1]$ in the standard case and for the exotic interactions. It is noteworthy that the presence of interference terms may cause a decrease of event number (thin line) in contrast to the Dirac scenario, where such a regularity is impossible. Figure 7 illustrates the predicted event number for the superposition of left–right chiral ν_e 's in the case of various scenarios. Upper and lower plots show clearly the impact of the interferences between (c_V, c_A) and $(\tilde{c}_V, \tilde{c}_A)$ on the event number for given $\hat{\eta}_\nu \cdot \hat{\mathbf{q}} = -0.9$. The significant decrement (increment) in the event number in comparison with the Dirac case can be noticed.

Figure 8 demonstrates 90 % C.L. sensitivity contours in the planes $(\tilde{c}_V, \tilde{c}_A)$, (\tilde{c}_V, c_S^L) with $\hat{\eta}_\nu \cdot \hat{\mathbf{q}} = -0.9$ and in the plane (c_S^L, c_P^L) with $\hat{\eta}_\nu \cdot \hat{\mathbf{q}} = -1$, respectively. In the present

case we admit fourth degrees of freedom for the Majorana ν_e 's (inequality (9) with $\epsilon_{90} = 2.789(\delta N_{SM}/N_{SM})$) and then carry out the projection onto the appropriate plane of exotic couplings. One can see the qualitative difference due to the interferences in comparison with the Dirac case, even when the source is placed at $D = 8.25$ m with $\delta_A = 0.01$ (dotted line). Figure 9 illustrates how the energy spectrum of recoil electrons depends on the various scenarios with the exotic couplings. The departure from the standard $V - A$ prediction in comparison with the Dirac ν_e 's for the outgoing electrons with the measured energies $T_e^m \in [0.25, 0.5]$ MeV is more noticeable (thin and dotted lines).

4 Conclusions

We have shown that the high-precision low-energy experiment with the intense ^{51}Cr ν_e source located at near distance from the ultra-low threshold Borexino detector centre may be useful tool to test the problem of the nature of ν in the limit of relativistic ν . It is important to stress that the interference terms between $c_{V,A}$ and $\tilde{c}_{V,A}$ couplings for the Majorana ν_e 's do not vanish. This means that even if the intense ^{51}Cr source is deployed outside the Borexino detector, the significant decrement (increment) in the event number caused by the interferences may occur. The 90 % C.L. sensitivity contours in the planes $(\tilde{c}_V, \tilde{c}_A)$, (\tilde{c}_V, c_S^L) with $\hat{\eta}_\nu \cdot \hat{\mathbf{q}} = -0.9$ give the stronger constraints than for the Dirac case (no linear contributions from the exotic couplings survive). In addition, the energy spectrum of recoil electrons is more sensitive to the exotic couplings in the Majorana case than for the Dirac ν_e 's. Although the chromium source cannot be placed at the detector centre, such a location would allow more sensitive tests of the exotic couplings and of the nature of ν , provided that the errors on the activity source could be considerably reduced. As is well known the beta emitter ^{144}Cs – ^{144}Pr with the deployment at the detector centre is considered as well, so the combined analysis for both sources would further constrain the allowed region on the exotic couplings and shed more light on the fundamental question of the nature of ν .

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