Solar Neutrinos, Tritium Background, and Dark Matter in XENON1T

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Introduction

The XENON1T experiment is a liquid xenon dual-phase time-projection chamber located in Laboratori Nazionali del Gran Sasso. It is primarily designed for the search of the so-called WIMPS (weakly interacting massive particles) — one of the most popular dark matter candidates. WIMPs are detected via the coherent elastic scattering on nuclei (CEνNS) but the experiment is also capable of detecting particles via the elastic scattering on electrons. It is also expected to be sensitive to solar neutrinos from the ^{8}B reaction via CEνNS on Xe nuclei. In 2020, the collaboration published their electron recoil spectrum featuring an excess of events in the 1–7 keV region [1].

1 Objectives

Properties:

- Detector mass: 1.04 ton
- Exposure time: 0.62 year
- Dark matter density: 0.3 $\frac{\text{GeV}}{\text{cm}^3}$
- Dark matter velocity: 220 $\frac{\text{km}}{\text{s}}$

Tasks:

1. Look up the flux and energy spectrum of ^{8}B solar neutrinos. Define the relevant energy range for elastic scattering with electrons and Xe nuclei.
2. Estimate the number of events due to $\nu-$e and ν-Xe coherent scattering.
3. Plot the differential energy spectra for both electron and nuclear recoils from solar neutrinos. Discuss the spectral shape and relevant features (e.g., recoil energy range, endpoint).
4. Use the XENON1T data (electron recoil spectrum) showing a slight excess at low energies. Assuming it is due to ^{3}H ($\tau_{1/2}$ = 13.2 years, Q = 18 keV), estimate total number of ^{3}H atoms in the detector.
5. For DM of mass 100 GeV/c^2, and cross section 10^{-42} cm^2, assuming a standard local DM density and velocity, estimate the expected number of DM-Xe scattering events.

2 Sensitivity to ^{8}B solar neutrinos

Coherent elastic scattering of solar neutrinos from the ^{8}B reaction is a possible source of irreducible background for dark matter detectors. Among the other neutrino sources it is the closest one to the sensitivity range of modern DM experiments.

The energy spectrum of the ^{8}B neutrinos is available at [2].

As neutrinos are practically massless compared to electrons and nuclei, their elastic scattering process is compton-like with the maximal recoil energy

$$T_{\max}(E_\nu) = \frac{1}{1+\frac{M}{2E_\nu}}, \tag{1}$$

where M is the mass of the electron/nucleus and E_ν is the neutrino energy. As the endpoint of the ^{8}B neutrino spectra is 16.56 MeV, the recoil spectrum endpoint is 16.31 MeV for electrons and 4.49 keV for nuclei, respectively.

2.1 Electron recoil

The differential cross section of the $\nu - e$ elastic scattering is:

$$\frac{d\sigma(E_\nu, T)}{dT} = \frac{2}{\pi} G_F^2 m_e \left[g_L^2 + g_R^2 \left(1 - \frac{T}{E_\nu}\right) - g_L g_R m_e \frac{T}{E_\nu^2} \right], \tag{2}$$

where G_F is the Fermi constant, m_e is the electron mass, g_L and g_R are coupling constants:

$$g_L = \begin{cases} \frac{1}{2} + \sin^2(\theta_W) & \text{for } \nu_e \\ -\frac{1}{2} + \sin^2(\theta_W) & \text{for } \nu_\mu \text{ and } \nu_\tau \end{cases} \tag{3}$$

$$g_R = \sin^2(\theta_W), \tag{4}$$

and θ_W is the Weinberg angle.

Solar neutrinos are emitted as electron neutrinos but experience neutrino oscillations on their way to the detector and thus are detected as a mixture of flavors. Moreover, they experience the matter effect (Mikheyev–Smirnov–Wolfenstein (MSW) effect) while propagating in the Sun, so the survival probability of electron neutrinos gains energy dependence. We considered the MSW-LMA solution [3] for the survival probability of solar neutrinos and applied it to our estimation of the event rate. As the cross section of non-electron neutrinos is smaller than that of ν_e, we expect less events with respect to the non-oscillated signal model.

The rate of neutrino interactions is then calculated as follows:

$$R = N_e \Phi_\nu \int dE_\nu \frac{d\lambda_\nu}{dE_\nu} \int_0^{T_{\max}} \left[\frac{d\sigma_e(E_\nu, T)}{dT} P_{ee}(E_\nu) + \frac{d\sigma_{\nu,\tau}(E_\nu, T)}{dT} (1 - P_{ee}(E_\nu)) \right] dT, \tag{5}$$

where $N_e = 2.58 \cdot 10^{29}$ is the total number of electrons in the detector, Φ_ν is the total neutrino flux, $\frac{d\lambda_\nu}{dE_\nu}$ is the differential neutrino spectrum, P_{ee} is the survival probability of electron neutrinos.

The electron recoil sprectum can be calculated from equation (5) if we integrate only over E_ν. The comparison of the initial neutrino spectrum and the electron recoil spectra with and without neutrino oscillations is shown in Fig. 1.

Integrating equation (5), taking into account the exposure time and assuming zero detection threshold, we get the next estimation for the number of electron recoils due to solar neutrinos: 0.94 ± 0.11 events in the non-oscillation case and 0.74 ± 0.09 events in the case of MSW-LMA neutrino mixing. In this estimation we considered the ^{8}B flux predicted by the Standard Solar Model with high metallicity (GS98) $\Phi_\nu = 5.46(1 \pm 0.12) \times 10^6$ cm^{-2}s^{-1} [4].

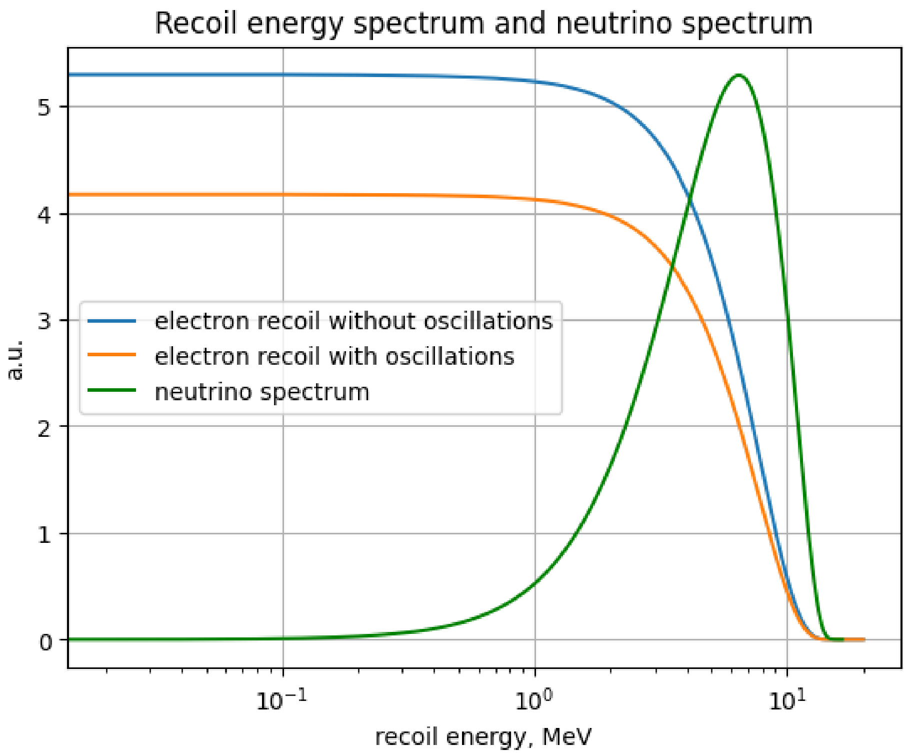

Figure 1: Energy spectrum of ^{8}B solar neutrinos and electron recoil spectra with and without oscillations.

2.2 Nuclear recoil

The differential cross section of coherent elastic neutrino-nucleon scattering is [5]:

$$\frac{d\sigma(E_\nu, T)}{T} = \frac{G_F^2 M}{2\pi} Q_W^2 F^2(Q)(2 - \frac{MT}{E_\nu^2}), \tag{6}$$

where M is the nuclear mass, $Q_W = N - (1 - 4\sin^2\theta_W)Z$ is the weak nuclear charge, N and Z are the numbers of neutrons and protons in the nucleus, respectively, $F(Q)$ is the nuclear form factor as a function of the momentum transfer Q. In this estimation we consider full coherence and $F(Q) = 1$.

Coherent neutrino-nucleus scattering is a flavor-blind process, and equation (5) is reduced to

$$R = N_{\mathrm{Xe}} \Phi_\nu \int dE_\nu \frac{d\lambda_\nu}{dE_\nu} \int_0^{T_{\max}} \frac{d\sigma(E_\nu, T)}{dT} dT, \tag{7}$$

where $N_{\mathrm{Xe}} = 4.78 \cdot 10^{27}$ is the number of nuclei in the detector. Given the $^{131}_{54}\mathrm{Xe}$ properties, the total number of nuclear recoil events during the exposure time is 132.01 ± 16.14 under the assumption of zero detection threshold. The recoil spectrum is much less energetic with respect to the electron recoil (see Fig. 2), so in a real case the event rate would be suppressed due to the trigger efficiency of the detector at low energies.

^{8}B recoil type	Number of events
ER (non-ocs)	0.94 ± 0.11
ER (MSV-LMA)	0.74 ± 0.09
NR	132.01 ± 16.14

Table 1: Expected events in 1.04 ton $\times$ 0.62 yr exposure

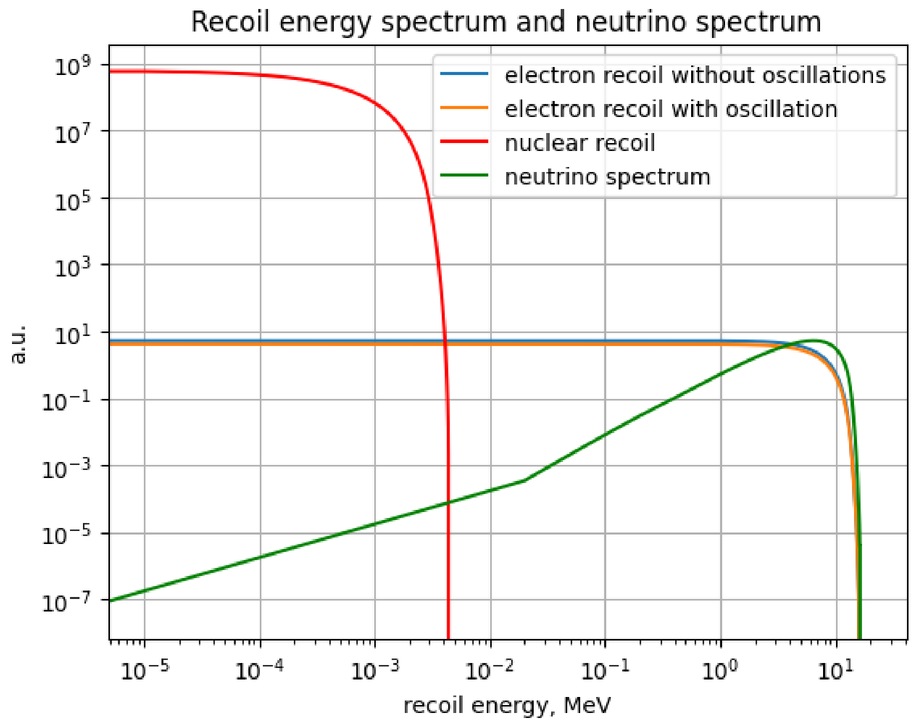

Figure 2: Comparison of electron and nuclear recoil spectra for the same exposure. Normalization of the initial neutrino spectra is arbitrary.

3 Low-energy event excess and the tritium background

3.1 Fit of the electron recoil spectrum

To study the tritium background hypothesis as a possible explanation of the low-energy excess in the electron recoil spectrum we performed a binned likelihood fit of the data spectrum with the sum of the standard background $f_B(T)$ and the tritium β-decay spectrum $f_{\mathrm{Tr}}(T)$:

$$f(T) = R_B \cdot f_B(T) + R_{\mathrm{Tr}} \cdot f_{\mathrm{Tr}}(T), \tag{8}$$

where event rates R_B and R_{Tr} are free parameters. The rate of tritium events from the fit is 158.38 ± 51.98 events/t/y, or 102.13 ± 33.52 events during the exposure time. The fit example is shown in Fig. 3.

3.2 Number of tritium atoms in the detector

From the number of decays during the exposure time T_{exp} one can obtain the total number of tritium atoms in the detector. For isotopes with mean lifetime τ it reads

$$N_{\mathrm{total}} = \frac{N_{\mathrm{decays}}}{1 - \exp^{(-T_{\mathrm{exp}}/\tau)}} \tag{9}$$

For the mean lifetime of tritium $\tau = -\log(2) \cdot \tau_{1/2} = 17.75$ years, the total number of tritium atoms from the fit is 2974.31 ± 976.12.

4 Dark matter search

Dark matter flux can be expressed in terms of the standard dark matter properties as:

$$\Phi_{\mathrm{DM}} = n_{\mathrm{DM}} \cdot v_{\mathrm{DM}} = \frac{\rho_{\mathrm{DM}}}{M} \cdot v_{\mathrm{DM}}, \tag{10}$$

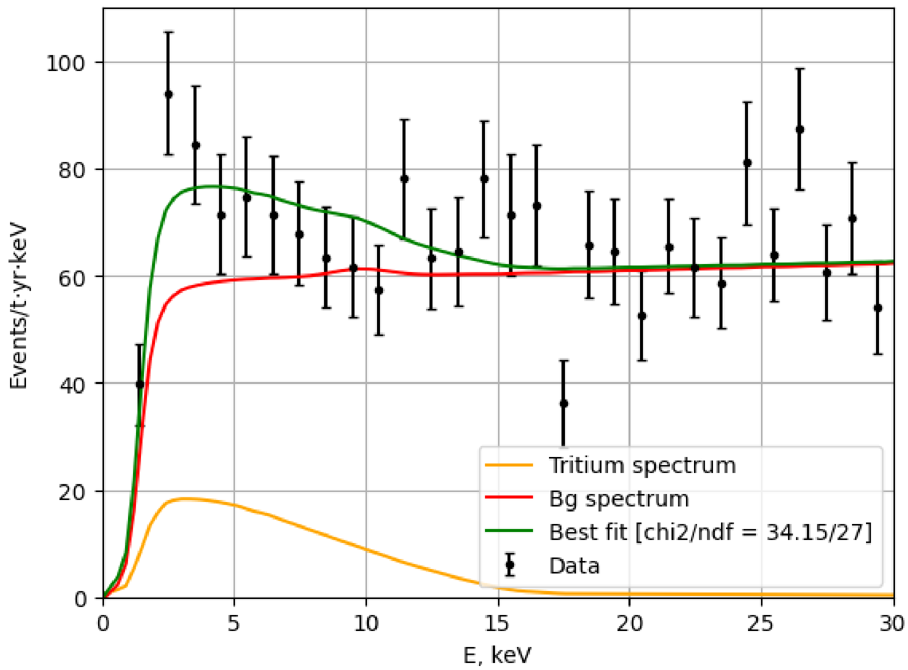

Figure 3: Fit example. Resulting χ^2 value corresponds to p-value=0.16.

where ρ_{DM} and v_{DM} are the standard energy density and velocity of DM particles and M is the WIMP mass. WIMP interaction rate is then

$$R_{\mathrm{DM}} = N_{\mathrm{Xe}} \cdot \Phi_{\mathrm{DM}} \cdot \sigma \tag{11}$$

For DM of mass 100 GeV/c^2, and cross section 10^{-42} cm^2, one can get the rate of 0.01 event per year or 0.006 events during the exposure time.

5 Summary

As a result of the project, the following results were obtained:

- The data for the energy spectrum and flux of ^{8}B solar neutrinos were established. The relevant energy rages for or elastic scattering with electrons and Xe nuclei are $E_{ER} \in [0, 16.31]$ MeV and $E_{NR} \in [0, 4.49]$ keV respectively.
- The number of events due to ν-e and ν-Xe coherent scatterings were calculated. For ν-e scattering neutrino oscillations were been taking in account: $N_{ER}^{\text{non-ocs}} = 0.94 \pm 0.11$ and $N_{ER}^{\text{MSV-LMA}} = 0.74 \pm 0.09$. For nuclear recoils $N_{NR} = 132.01 \pm 16.14$.
- The differential energy specutra for both electron and nuclear recoils from solar neutrinos were plotted (Fig. 1, Fig. 2).
- The fits to XENON1T data under hypothesis of tritium nature of excess was prodused. The rate of tritium events from the fit is 102.13 ± 33.52 events during the exposure time. The $\chi^2/ndf = 34.15/27$ means that assumption that exceed is due to ^{3}H is too approximate.
- for DM mass 100 GeV/c^2, andcross section 10^{-42} cm^2, assuming a standart local DM density and velocity (ρ_{DM} =0.3 GeV/c^2, v_{DM}=220 km/s), the expected number of DM-Xe scattering events were estimated: 0.006 events during the exposure time.

References

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