On lepton charge conservation in the double β decay of ^{130}Te

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It has been established that the upper limit of the lepton charge nonconservation parameter does not exceed $(2–5)\times 10^{-4}$. This value was obtained on the basis of a direct experimental study of the double β decay of ^{130}Te $T_{1/2} > 1.2 \times 10^{21}$ years.

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It is known that the double β decay, which is a source of valuable information about the fundamental properties of neutrinos, the weak interaction, and the resonances in nuclei is one of the most sensitive methods of verifying the lepton charge conservation law.[1]

Our group has recently completed an experimental study of the 2β decay of ^{130}Te.[2] The experiment was performed by using the previously described[3] apparatus whose sketch is shown in Fig. 1. The main detector (ϕ 145×185 mm) was assembled from 14, 10-mm-thick scintillation (polystyrene) plates. The mass of ^{130}Te, which was arranged in a uniform layer (160 mg/cm^2) between the plates, was 342.82 g. The detector was connected to a photomultiplier by means of a polymethylmethacrylate lightguide (ϕ 145×60 mm).

To effectively suppress the background in the apparatus, we used a complex system consisting of an inner mercury shield, an "active" scintillation shield against anticoincidences, and a multilayer outer shield (steel, lead, polyethylene). In addition, to eliminate the effect of the radioactivity of air, we enclosed the main detector and the scintillators of the "active" shield in a sealed chamber that was purged with purified gas. The apparatus was placed on the ground surface.

Figure 2 shows the spectra recorded in an experiment with a 3300-hour "live" time. The lower curve represents the background spectrum (1000 hours) and the upper spectrum was collected from ^{130}Te (2300 hours).

The spectrum in Fig. 3 shows the background excess due to the sample. We can see that there are no peaks in the region of the neutrino-free 2β decay of ^{130}Te (1.8–3.0 MeV). The background rise is apparently due to the presence of trace amounts of uranium, thorium, and their decay products in the sample.

The average background level in the region 2.1–2.76 MeV amounts to $(8.9 \pm 0.08) \times 10^{-3}$ keV^{-1} hour^{-1}, according to Fig. 3. The overall recording efficiency, calculated with allowance for self-absorption in the sample and for the energy resolution of the detector, is 49%. On the basis of these data and the sample mass we established that the lower limit of the half-life of ^{130}Te with respect to the neutrino-free 2β decay is equal to 1.2×10^{21} years (at a 68% confidence level). This value is approximately 10^5 times higher than the half-life limit for ^{130}Te obtained in the previous direct experi-

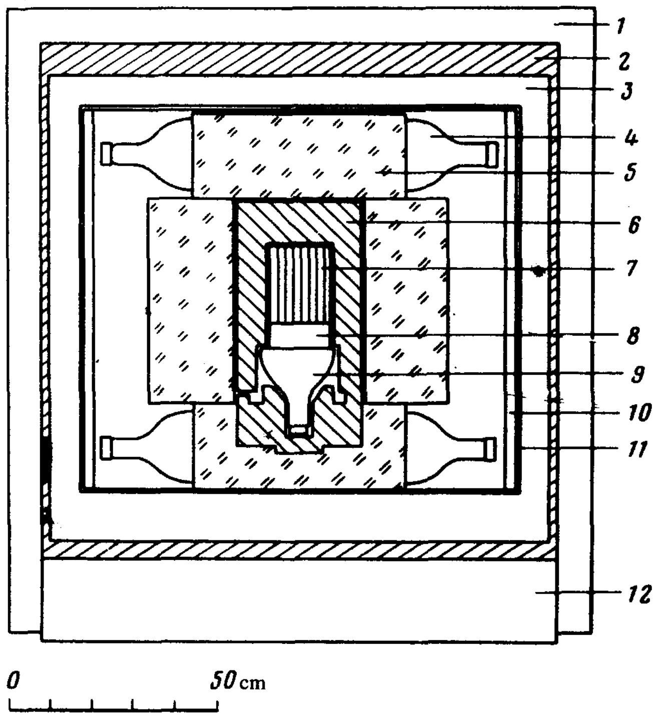

FIG. 1. Schematic of the apparatus: 1, polyethylene; 2, lead; 3, steel; 4, PM of the "active" shield; 5, scintillators of the "active" shield; 6, mercury; 7, "sandwich" consisting of scintillator plates and ^{130}Te layers; 8, lightguide; 9, PM of the main detector; 10, stainless steel; 11, sealed chamber; 12, plastic.

ment[4] using photoemulsion.

The extent to which the result[2] limits the lepton charge nonconservation parameter η can be determined on the basis of one of the currently proposed theoretical models for a two-nucleon or resonance double β decay mechanism.[5] We shall initially examine the first model. To do this, we shall use the theoretical equations of Rosen and Primakoff[5] expressing the dependence of the half-life ($T^{0\nu}_{1/2}$ is the neutrino-free channel and $T^{2\nu}_{1/2}$ is the two-neutrino channel) on the nuclear matrix elements ME of the transition:

$$T^{0\nu}_{1/2} = \frac{f_2}{\eta^2} \quad \frac{1}{|\mathrm{ME}|^2} \tag{1}$$

$$T^{2\nu}_{1/2} = \frac{f_4}{|\mathrm{ME}|^2}, \tag{2}$$

where f_2 and f_4 are the effective phase volumes for the final states with two and four

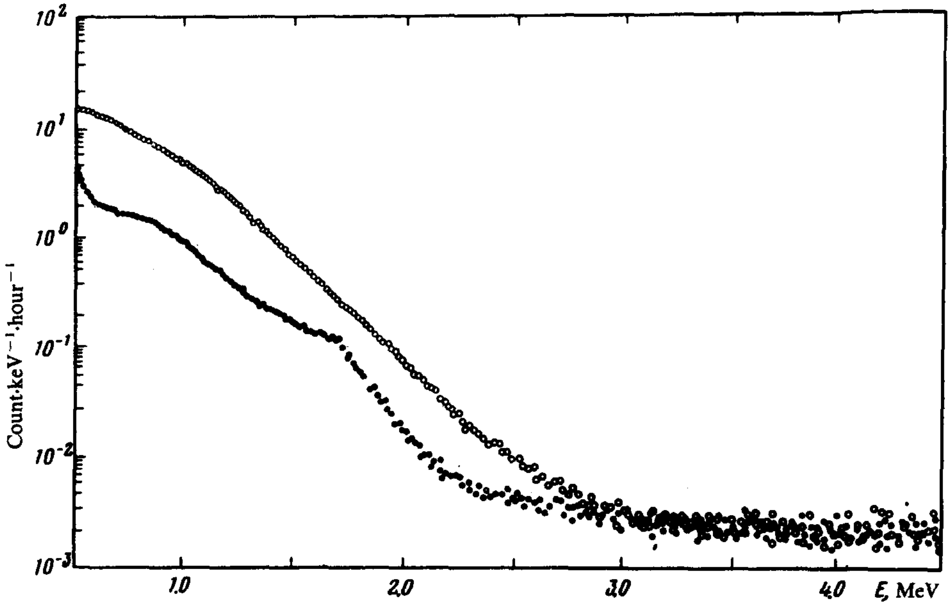

FIG. 2. Background spectra obtained in the experiment: the upper spectrum was obtained from ^{130}Te; the lower spectrum represents the detector background.

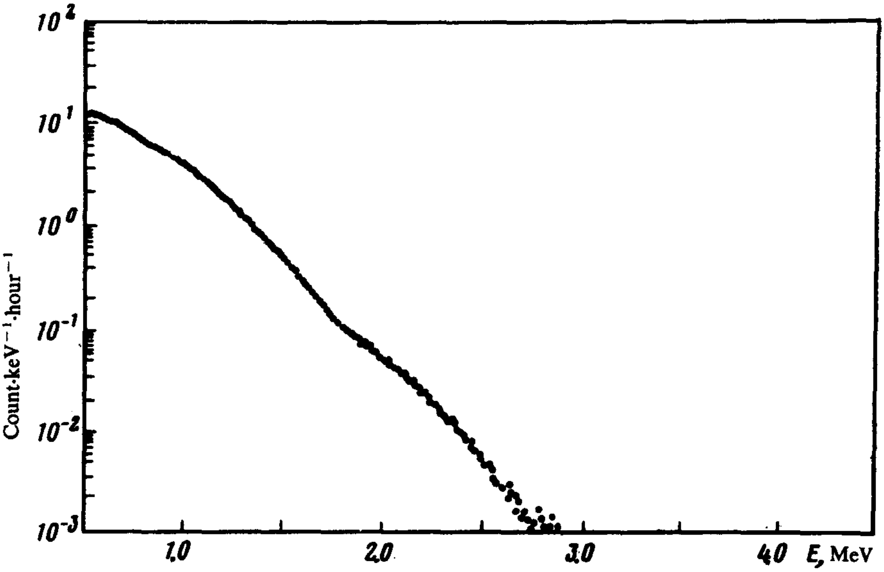

FIG. 3. Background excess due to ^{130}Te.

leptons. Their values and those of the matrix element ME for the double β decay of ^{130}Te were calculated elsewhere[6]:

$$f_2 = 3.16 \times 10^{13} \text{ years}$$

$$f_4 = 6.64 \times 10^{20} \text{ years}$$

$$|\mathrm{ME}| = 0.496 .$$

After substituting in Eq. (1) the experimental lower limit of $T^{0\nu}_{1/2}$ (Ref. 2) and the theoretical values of f_2 and $|\mathrm{ME}|$, we can see that

$$\eta < 3.2 \times 10^{-4}.$$

Since the nuclear matrix elements are difficult to calculate and the initial theoretical assumptions[1,5,6] greatly affect their results, we can calculate the parameter η by using a method that does not depend explicitly on the ME values. With this goal in mind, first we shall determine the branching ratio R, which is equal to the ratio of the neutrino-free 2β decay rate to the total 2β-decay rate

$$R = \lambda_{0\nu}/\lambda_{2\beta}.$$

Assuming that the ME for the 0ν and 2ν-decay channels are approximately equal, we obtain from Eqs. (1) and (2)

$$T^{2\nu}_{1/2} / T^{0\nu}_{1/2} \approx \eta^2 f_4 / f_2 . \tag{3}$$

Taking into account that

$$T^{2\nu}_{1/2} / T^{0\nu}_{1/2} = R / (1 - R), \tag{4}$$

we transform Eq. (3) to the following form:

$$\eta^2 \leqslant \frac{R}{1-R} \; \frac{f_2}{f_4}. \tag{5}$$

Let us assume that the total 2β-decay rate of ^{130}Te corresponds to the value measured in a recent mass-spectrometer experiment[7]:

$$\lambda_{2\beta} = \ln 2 \times 10^{-21} \text{ year}^{-1} .$$

In this case, $R_{\mathrm{exp}} \leqslant 0.83$ and it follows from Eq. (5) that

$$\eta \leqslant 4.8 \cdot 10^{-4}.$$

We shall now estimate the lepton nonconservation within the context of a resonance mechanism for the 2β decay. On its basis the following expression was obtained[5] for $T^{0\nu}_{1/2}$:

$$T^{0\nu}_{1/2} \approx \frac{10^{17.5}}{\eta^2 \, g(E_0)} \cdot \left[\frac{1 - \exp(-2\pi a Z)}{2\pi a Z}\right]^2 \frac{1}{P(\Delta) \, |\langle \Phi_f \mid \Phi_i \rangle|^2}, \tag{6}$$

where $g(E_0) = E_0^2(E_0^5 + 14E_0^4 + 81E_0^3 + 221E_0^2 + 228E_0 + 140)$, E_0 is the energy (in units of electron mass) achieved in the 2β decay, $P(\Delta)$ is the probability of finding the Δ (1232) resonance in the nucleus, and $\langle\Phi_f|\Phi_i\rangle$ is the overlap factor of the wave functions of the initial and final states of a nucleus. If we assume, as in Refs. 1 and 5, that $P(\Delta)$ and $|\langle\Phi_f|\Phi_i\rangle^2$ have values of 10^{-2} and 10^{-1}, respectively, then with allowance for the experimental result,[2] it follows from Eq. (6) that

$$\eta \lesssim 2.3\times 10^{-4}.$$

Since the values of $P(\Delta)$ and $\langle\Phi_f|\Phi_i\rangle$ were estimated rather arbitrarily, we calculate η from the ratio R_{exp}. Picciotto theoretically calculated $T_{1/2}^{2\nu}$ for the resonance mechanism[8]:

$$T_{1/2}^{2\nu} \approx \frac{5\times 10^{19}}{f(E_0)}\left[\frac{1-\exp(-2\pi a Z)}{2\pi a Z}\right]^2 \frac{1}{P(\Delta)\,|<\Phi_f\,|\,\Phi_i>|^2}, \tag{7}$$

where

$$f(E_0) = 2E_0^7(1 + E_0/2 + E_0^2/9 + E_0^3/90 + E_0^4/1980)/[8!(E_0+2)].$$

We obtain from Eqs. (6) and (7)

$$T_{1/2}^{2\nu}/T_{1/2}^{0\nu} = 158\,\eta^2\, g(E_0)//f(E_0).$$

At $R_{\text{exp}} \leqslant 0.83$ and taking into account Eq. (4), we can see that $\eta \leqslant 4.4\times 10^{-4}$.

Thus, the experimental value[2] limits the lepton charge nonconservation parameter to $(2\text{–}5)\times 10^{-4}$, regardless of the theoretical model used.

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