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EXPERIMENTAL RESULTS, METHODS, AND FACILITIES

# New Phase of the $^{116}$Cd 2β-Decay Experiment with $^{116}CdWO_4$ Scintillators*

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**Abstract**—A new step of the $^{116}$Cd 2β-decay experiment is in progress at the Solotvina Underground Laboratory. The upgraded setup consists of four enriched $^{116}CdWO_4$ crystal scintillators of total mass 339 g. As an active shield, 15 $CdWO_4$ crystals (20.6 kg) are used. The background rate (in the energy interval 2.7–2.9 MeV) is 0.06 count/(yr kg keV), one order of magnitude lower than in the previous apparatus. Combined with results of preceding measurements, the half-life limit for the neutrinoless 2β decay of $^{116}$Cd to the ground state of $^{116}$Sn is determined as $T_{1/2}(0\nu) \geq 5.1 \times 10^{22}$ yr with 90% C.L. The limits on $T_{1/2}$ for transitions to the excited $2_1^+$ and $0_1^+$ levels of $^{116}$Sn are $8.6 \times 10^{21}$ and $4.1 \times 10^{21}$ yr, respectively (at a 90% C.L.). For 0ν2β decay accompanied by the emission of one and two Majorons, the constraints on the half-life are $T_{1/2}(0\nu M1) \geq 1.4 \times 10^{21}$ yr and $T_{1/2}(0\nu M2) \geq 4.1 \times 10^{20}$ yr (at a 90% C.L.). The corresponding constraints on the neutrino mass and the neutrino–Majoron coupling constant are $\langle m_\nu \rangle \leq 3.1$ eV and $\langle g_M \rangle \leq 1.9 \times 10^{-4}$, respectively. © *2000 MAIK "Nauka/Interperiodica".*

## 1. INTRODUCTION

With the aim of extending the number of 2β-decay candidate nuclides studied at a sensitivity comparable with that for $^{76}$Ge and $^{136}$Xe (a neutrino-mass limit of 1–3 eV [1]), scintillators made of cadmium tungstate crystal and enriched in $^{116}$Cd to 83% were used in $^{116}$Cd research [2, 3]. The measurements were performed in the Solotvina Underground Laboratory (SUL) in a salt mine 430 m below sea level (about 1000 mwe) [4]. The $^{116}CdWO_4$ crystal (15.2 cm$^3$) viewed by a FEU-110 photomultiplier tube (PMT) through a light guide 51 cm long was placed inside a plastic scintillator (∅38 × 115 cm) that served as a veto detector. Passive shield of high-purity copper (5 cm), lead (23 cm), and polyethylene (16 cm) surrounded the plastic counter with the main detector. The detector background rate in the vicinity of energy release in the 2β decay of $^{116}$Cd ($Q_{2\beta}$ = 2805(4) keV [5]) was reduced to a level of 0.6 count/(yr kg keV) [2, 3]. On the basis of total statistics collected over 19175 h ($Nt = 3.63 \times 10^{23}$ nucleus yr, where $N$ is the number of $^{116}$Cd nuclei and $t$ is the measurement time), the half-life limit for the neutrinoless 2β decay of $^{116}$Cd was found to be given by $T_{1/2}(0\nu) \geq 3.2 \times 10^{22}$ yr (at a 90% C.L.) [3]. Calculations revealed that [6] this value corresponds to the following limits on the neutrino mass and right-handed admixtures in weak interaction: $\langle m_\nu \rangle \leq 4.4$ eV, $\langle \eta \rangle \leq 5.7 \times 10^{-8}$, and $\langle \lambda \rangle \leq 5.0 \times 10^{-6}$; neglecting the right-handed contribution, we arrive at $\langle m_\nu \rangle \leq 3.9$ eV. The calculations from [7] lead to a similar result: $\langle m_\nu \rangle \leq 3.5$ eV. In accordance with [8], the *R*-parity-violating parameter of the minimal SUSY Standard Model is restricted by our $T_{1/2}$ limit as $\varepsilon \leq 1.1 \times 10^{-3}$. Also, limits on 0ν2β-decay modes involving the emission of one (M1) or two (M2) Majorons were established: $T_{1/2}(0\nu M1) \geq 1.2 \times 10^{21}$ yr and $T_{1/2}(0\nu M2) \geq 2.6 \times 10^{20}$ yr (at a 90% C.L.) [9]. By using the calculated nuclear matrix elements and the phase-space integral for $^{116}$Cd [10], the limit on the Majoron–neutrino coupling constant was determined as $\langle g_M \rangle \leq 2.1 \times 10^{-4}$, at a level compared with the best results obtained for other nuclei [1].

## 2. NEW SETUP WITH FOUR $^{116}CdWO_4$ DETECTORS

### *2.1. New Setup and Measurements*

In order to enhance the sensitivity of the $^{116}$Cd experiment, the following improvements were scheduled: an increase in the number of $^{116}$Cd nuclei, a reduction of the background, and an advance in the data taking and processing [3]. With this aim, the upgraded setup with four enriched $^{116}CdWO_4$ crystals (total mass of 339 g) was mounted at the SUL in August 1998. All the materials used in the apparatus were previously tested and selected for low radioactive impurities in order to avoid their contributions to the background.

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In the new apparatus, enriched crystals were viewed by the PMT (EMI9390KFLB53) through a light guide 10 cm in diameter and 55 cm long, which is composed of two glued parts: quartz 25 cm long and plastic scintillator (Bicron BC-412) 30 cm long. The enriched crystals are surrounded by an active shield made from fifteen natural $CdWO_4$ scintillators of large volume (about 200 $cm^3$ each) with a total mass of 20.6 kg. This active shield provides an effective suppression of background in the energy region of interest owing to the large density (8 $g/cm^3$) and the high purity of $CdWO_4$ crystals [11]. The later are viewed by a low-background PMT (FEU-125) through an active plastic light guide (17 cm in diameter and 49 cm long). In turn, the entire array of $CdWO_4$ detectors is placed within the additional active shield made from polystyrene-based plastic scintillator of dimensions $40 \times 40 \times 95$ $cm^3$. Together with active light guides (connected to enriched and natural $CdWO_4$ crystals), a complete $4\pi$ active shield of the main $^{116}CdWO_4$ detectors is therefore provided.

The outer passive shield surrounds plastic scintillators and consists of high-purity copper (thickness 3–6 cm), lead (22.5–30 cm), and polyethylene (16 cm). Two plastic scintillators ($120 \times 130 \times 3$ $cm^3$) are installed above the passive shield to ensure cosmic-muon veto. Because the air in the SUL contains radon (about 30 $Bq/m^3$), the setup is isolated carefully to avoid any penetration of the air into the detectors. All cavities inside the shield were filled with pieces of Plexiglas, and a high-purity Cu shield was sealed with the aid of silicon glue and enclosed inside a tight Mylar envelope.

The new event-by-event data acquisition is based on two IBM PCs and a CAMAC crate with electronic units. The system allows one to carry out measurements with up to 16 independent channels. For each event, the following information is stored on the hard disk of the first computer: the amplitude (energy) of a signal, its arrival time, and additional tags (coincidence between different detectors and signal of a radionoise-detection system; and triggers for the light-emitting diode and the pulse-shape digitizer). The second computer allows one to record the pulse shape of the $^{116}CdWO_4$ scintillators in the energy range 0.25–5 MeV. This complementary system is developed on the basis of a fast 12-bit ADC (Analog Devices AD9022) and is connected to a computer by a parallel digital I/O board (PC-DIO-24 from National Instruments) [12]. Two additional PC-DIO-24 boards are used to link both computers and to establish (with the aid of the corresponding software) a one-to-one dependence between information stored in the first PC and the pulse-shape data recorded by the second computer.

The energy calibration is performed weekly by using a $^{207}Bi$ source ($\gamma$ rays with energies of 570, 1064, and 1770 keV) and once per two weeks by using $^{232}Th$ (2615 keV). The resolution of the main detector (four enriched crystals taken as a whole) was 14.5% at 1064 keV and 11% at 2615 keV. During measurements, the dead time of the spectrometer and data acquisition is monitored permanently with the aid of a light-emitting diode optically connected to the PMT of the enriched $^{116}CdWO_4$ scintillators. The background spectrum of the four $^{116}CdWO_4$ crystals measured over 4056 h in the new apparatus is shown in Fig. 1, which also displays, for the sake of comparison, the data obtained with the old apparatus using one $^{116}CdWO_4$ crystal of mass 121 g. As can be seen from this figure, the background is decreased over the entire energy range owing to the improved shielding and the pulse-shape analysis of the data (see below). The only exception is the $\beta$ spectrum of $^{113}Cd$ ($Q_\beta = 316$ keV), which is present in the $^{116}CdWO_4$ crystals with an abundance of 2.15% [2]. The background rate in the energy region of interest (2.7–2.9 MeV), where we expect the peak corresponding to the $0\nu2\beta$ decay of $^{116}Cd$, is reduced to 0.06 count/(yr kg keV) (2 events over 4056 h), which is one order of magnitude lower than that in the previous apparatus.

### 2.2. Time–Amplitude Analysis

As was shown previously [13], information about the arrival time for each event can be used to analyze and select some decay chains in $^{232}Th$, $^{235}U$, and $^{238}U$ families like $^{214}Bi$ ($Q_\beta$ = 3.3 MeV) $\longrightarrow$ $^{214}Po$ ($Q_\alpha$ = 7.8 MeV, $T_{1/2}$ = 164.3 μs) $\longrightarrow$ $^{210}Pb$ or $^{220}Rn$ ($Q_\alpha$ = 6.4 MeV) $\longrightarrow$ $^{216}Po$ ($Q_\alpha$ = 6.9 MeV, $T_{1/2}$ = 0.145 s) $\longrightarrow$ $^{212}Pb$. The energies of the first and second decays and the time interval between events are used to enhance sensitivity and to reach higher accuracy in determining the trace radioactive contaminants in the detector. By way of example (important in the following for the analysis of the background in the region of the $0\nu2\beta$ decay of $^{116}Cd$), the events in the decay chain $^{220}Rn \longrightarrow {}^{216}Po \longrightarrow {}^{212}Pb$, which were selected from a 2822.7-h run, are shown in Fig. 2. Taking into account the contribution from accidental coincidences (4 pairs from 107 selected), we found that the activity of $^{228}Ac$ ($^{232}Th$ family) inside the $^{116}CdWO_4$ crystals is as low as 39(4) μBq/kg.

The relative light yield for $\alpha$ and $\beta$ particles and the energy resolution of the detector for $\alpha$ particles were also determined from the time–amplitude analysis. The results are $\alpha/\beta = 0.148 + 0.0072E_\alpha$ ($E_\alpha$ is measured in MeV) and $\mathrm{FWHM}_\alpha(E_\alpha) = 0.0444E_\alpha$.

### 2.3. Pulse-Shape Discrimination

The shape of the pulse in the $^{116}CdWO_4$ scintillators in the energy region 0.25–5 MeV is digitized by the 12-bit ADC and stored in 2048 channels with a channel width of 50 ns. On the basis of the optimal digital filter, the method of pulse-shape (PS) discrimination was developed [12] to process scintillation pulses from the

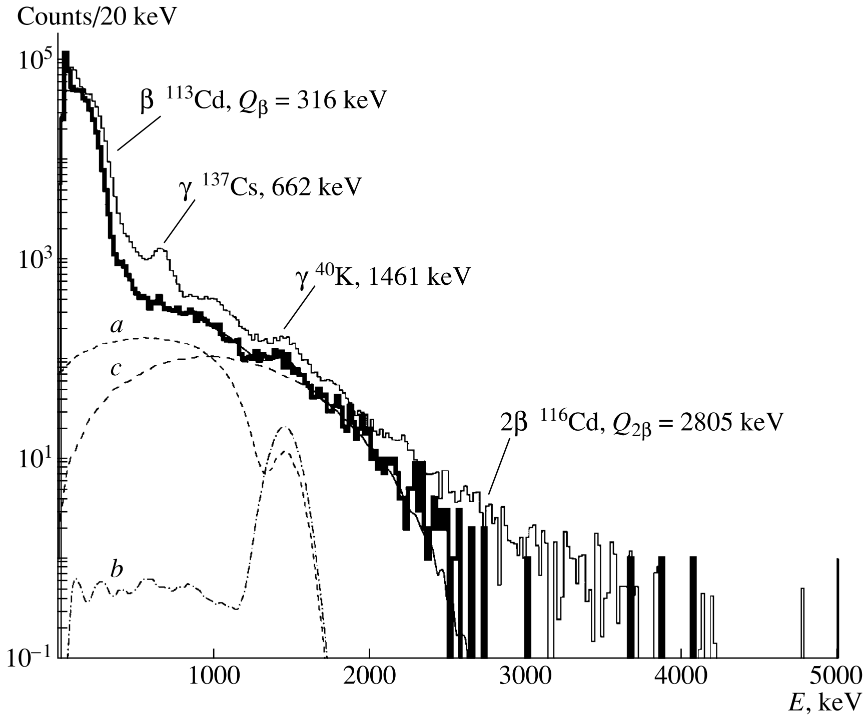


**Fig. 1.** Background spectrum of $^{116}CdWO_4$ detectors (339 g) measured in the new setup over 4056 h (thick histogram). The old data obtained with 121-g $^{116}CdWO_4$ crystal over 19986 h are shown for the sake of comparison (thin histogram; the data are normalized to the time of measurements and the mass of the new detector). The background components used for fitting in the energy region 950–2900 keV are (curve *a*) $^{40}$K inside the $^{116}CdWO_4$ detector [activity value from the fit is 1.7(2) mBq/kg], (curve *b*) $^{40}$K in the shielding of $CdWO_4$ crystals [1.7(4) mBq/kg], and (curve *c*) 2ν2β decay of $^{116}$Cd ($T_{1/2}(2\nu2\beta) = 2.3(2) \times 10^{19}$ yr].

$CdWO_4$ crystals. Owing to the different shapes of the scintillation signals for different kinds of sources (α particles, protons, photons, and cosmic muons were investigated), a clear discrimination between γ rays and γ particles was achieved [12]. A numerical characteristic of the shape (shape indicator, further abbreviated as SI) has a slight dependence on the particle energy (with the slope of about –1%/1 MeV) and lies in the region $SI_\gamma = 20.0 \pm 2.8$ for photons and $SI_\alpha = 28.5 \pm 3.2$ for α particles (the values are given for 0.9-MeV photons and 4.8-MeV α particles). The technique of pulse-shape selection ensures the very important possibility of discriminating "illegal" events, such as double pulses and α events, and thereby suppressing the background. The example of a double pulse is shown in Fig. 3*a*. The value of the shape indicator for the full signal is SI = 12.0; for the first pulse, it is $SI_1 = 20.2$ (hence, it corresponds to a γ or a β particle). For the second pulse, we have $SI_2 = 27.8$ (α particle). The energy release is 2.99 MeV, and, without a PS analysis, it would be a candidate event for the 0ν2β decay of $^{116}$Cd. By way of illustration, Fig. 4 displays the spectra of the $^{116}CdWO_4$ scintillators in the energy region 1.2–5 MeV that were collected over 4056 h in anticoincidence with the active shield. Figure 4*a* presents the initial spectrum without pulse-shape selection, while Fig. 4*b* shows this spectrum after a PS selection of events whose SI lies in the interval $SI_\gamma \pm 2.58\sigma$ ($SI_\gamma$) (it contains 99% of γ/β events). From these figures, the background reduction due to pulse-shape analysis is obvious. Further, Fig. 4*c* shows the distribution of events with $SI \geq SI_\gamma + 2.58\sigma(SI_\gamma)$. These events, at least for energies in excess of 2 MeV, can be produced by the $^{228}$Ac activity from the intrinsic contamination of the $^{116}CdWO_4$ crystals (measured by the time–amplitude analysis as described above). Indeed, two decays in the fast chain $^{212}$Bi ($Q_\beta$ = 2.3 MeV) $\longrightarrow$ $^{212}$Po ($Q_\alpha$ = 9.0 MeV, $T_{1/2}$ = 0.3 μs) $\longrightarrow$ $^{208}$Pb cannot be time-resolved in the $CdWO_4$ scintillator (decay time is about 15 μs [11, 12]) and will result in one event. The response function of the $^{116}CdWO_4$ detectors for the $^{228}$Ac chain was simulated with the aid of the GEANT3.21 package [14]; the initial kinematics of events (how many particles are emitted, their types, energies, and directions and times of emission) was determined with the event generator DECAY4 [15]. One can see from Fig. 4*c* that the high-energy tail of the experimental spectrum is well reproduced by the expected response for $^{212}$Bi $\longrightarrow$ $^{212}$Po $\longrightarrow$ $^{208}$Pb decays. The corresponding activity of $^{228}$Ac inside the $^{116}CdWO_4$ crystals, as obtained from the fit in the energy range between 2.6 and 3.6 MeV, is 34(5) μBq/kg, in

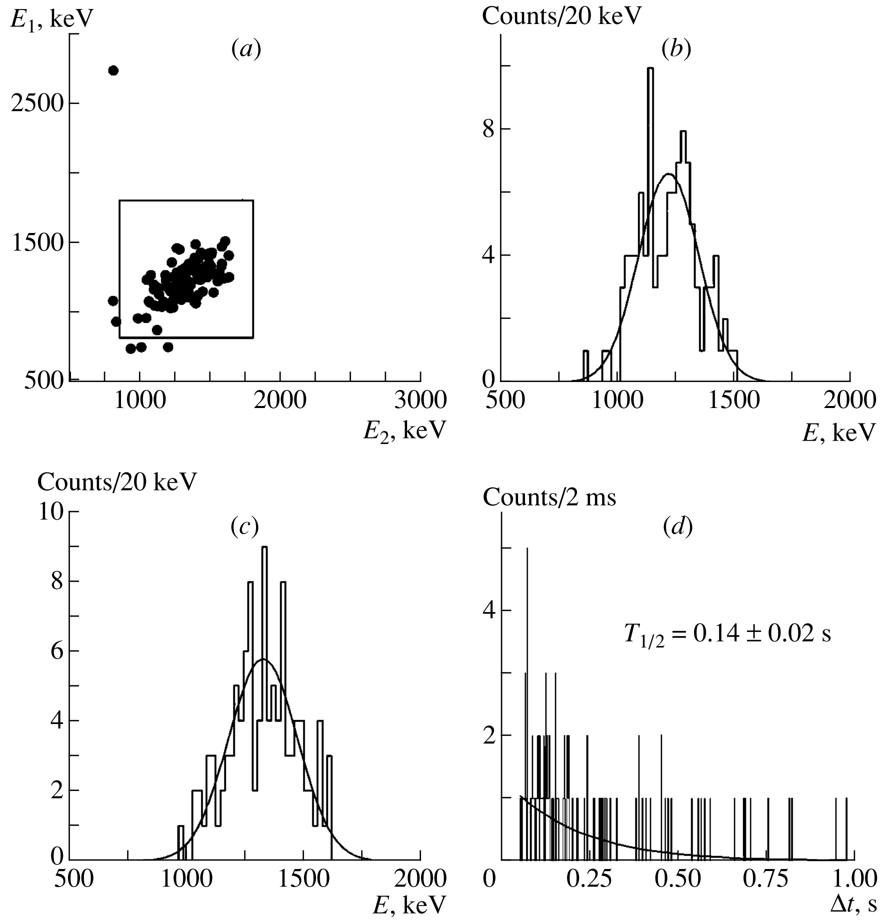


**Fig. 2.** (*a*) Two-dimensional and (*b* and *c*) one-dimensional energy spectra of first and second α particles in the decay chain $^{220}$Rn ($Q_\alpha = 6.4$ MeV) ⟶ $^{216}$Po ($Q_\alpha = 6.9$ MeV, $T_{1/2} = 0.145$ s) ⟶ $^{212}$Pb ($^{116}CdWO_4$ 339 g, 2822.7 h). Because α/β ratio is less than unity, the equivalent energy on the scale of photon energies is nearly 5 times smaller. The inset in Fig 2 *a* shows events used for a further analysis. (*d*) Distribution of times between the first and second events, together with the fitting exponent. The fitted value of $T_{1/2} = 0.14 \pm 0.02$ s is in agreement with the tabular value of $T_{1/2} = 0.145(2)$ s from [17].

good agreement with the value determined by the time–amplitude analysis.

Apart from the shape indicator, which characterizes the full signal, it is also useful to examine the pulse front edge (Fig. 3*b*). By way of example, we indicate that, from the analysis of 42 events with energies 2.0–3.8 MeV presented in Fig. 4*c*, the half-life of the second part of the signal was determined as $T_{1/2} = 0.29(7)$ μs, in agreement with the tabular value for $^{212}$Po $T_{1/2} =$ 0.299(2) μs [17].

## 3.RESULTS AND DISCUSSION

### *3.1. Two-Neutrino Double-Beta Decay of $^{116}$Cd*

In order to determine the half-life of $^{116}$Cd with respect to its two-neutrino 2β decay, the background in the energy interval 950–2900 keV was simulated with the aid of the GEANT3.21 package [14] and the event generator DECAY4 [15]. Only three components were used to construct the background model: a $^{40}$K contamination of the enriched and natural $CdWO_4$ scintillators, whose activity limits of less than 4 mBq/kg were established earlier [11], and the two-neutrino 2β decay of $^{116}$Cd. This simple background model describes experimental data in the chosen energy interval 950–2900 keV reasonably well ($\chi^2 = 1.4$) and yields the following results: the activities of $^{40}$K inside the enriched and natural $CdWO_4$ crystals are, respectively, 1.7(2) and 1.7(4) mBq/kg (only statistical uncertainties are given); the half-life of $^{116}$Cd with respect to two-neutrino 2β decay is $T_{1/2}(2\nu2\beta) = 2.3(2) \times 10^{19}$ yr. These components are depicted in Fig. 1.

The 2ν2β Curie plot determined as $K(\varepsilon) = [S(\varepsilon)/((\varepsilon^4 + 10\varepsilon^3 + 40\varepsilon^2 + 60\varepsilon + 30)\varepsilon)]^{1/5}$, where $S$ is the number of events in the experimental spectrum with energy ε (in electron-mass units) is presented in Fig. 5*a*. For actual 2ν2β-decay events, the Curie plot should be the straight line $K(\varepsilon) \sim Q_{2\beta} - \varepsilon$, where $Q_{2\beta}$ is the energy release in the 2β decay of $^{116}$Cd. From Fig. 5*a*, one can see that, in the region 1.6–2.4 MeV (it is chosen to avoid the

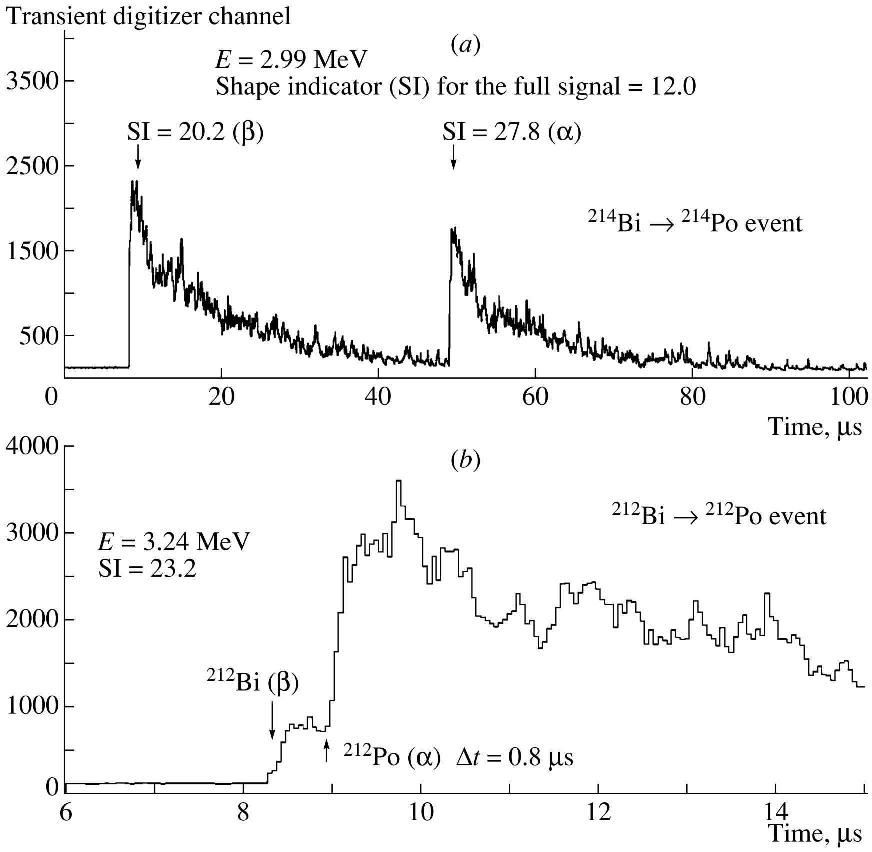


**Fig. 3.** (*a*) Example of a double pulse with the energy release in the region of $^{116}$Cd 0ν2β decay ($E$ = 2.99 MeV). The shape indicators for the full signal and separately for its first and second parts are $SI_{full}$ = 12.0, $SI_1$ = 20.2 (close to $SI_\gamma$), and $SI_2$ = 27.8 (close to $SI_\alpha$). Most probably, it is the event of the successive decays $^{214}$Bi (β) ⟶ $^{214}$Po (α; $T_{1/2}$ = 164.3 μs) ⟶ $^{210}$Pb. (*b*) Probable event of the chain $^{212}$Bi (β) ⟶ $^{212}$Po (α; $T_{1/2}$ = 0.3 μs) ⟶ $^{208}$Pb.

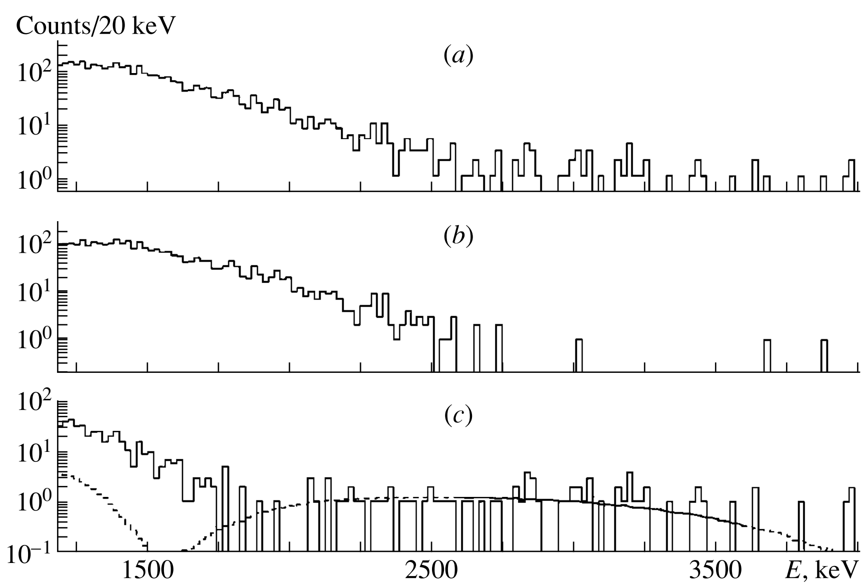


**Fig. 4.** (*a*) Initial spectrum of the $^{116}CdWO_4$ crystals (339 g, 4056 h) in anticoincidence with shielding detectors without pulse-shape discrimination; (*b*) pulse-shape-selected γ events with SI = $SI_\gamma \pm 2.58\sigma(SI_\gamma)$; (*c*) events with SI ≥ $SI_\gamma + 2.58\sigma$ ($SI_\gamma$), together with the fit by the response function for the $^{212}$Bi ⟶ $^{212}$Po ⟶ $^{208}$Pb decay chain. The fitted (in the range 2.6–3.6 MeV) activity of $^{228}$Ac inside the $^{116}CdWO_4$ crystals is 34(5) μBq/kg.

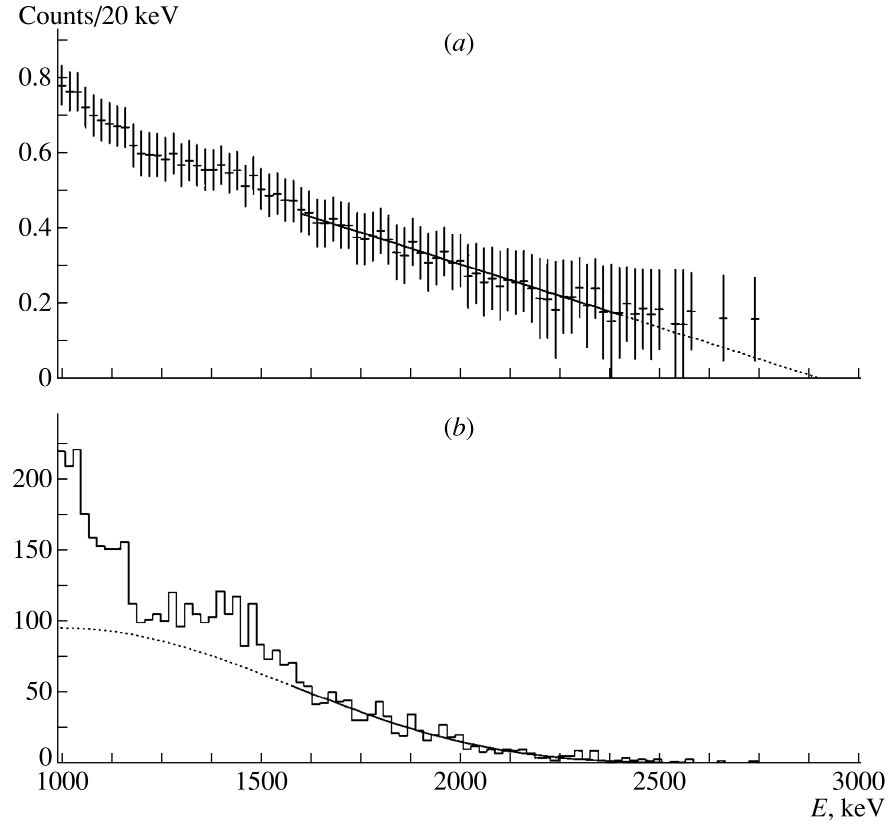


**Fig. 5.** (*a*) $2\nu2\beta$-decay Curie plot and its fit by a straight line in the range 1600–2400 keV; (*b*) experimental spectrum of the $^{116}CdWO_4$ scintillators (339 g, 4056 h, anticoincidence with the shielding detectors) and its fit by the convolution of the theoretical $2\nu2\beta$ distribution with the detector resolution function.

influence of $^{40}K$), the experimental Curie plot is well fitted by the straight line with $Q_{2\beta} = 2908(211)$ keV (the latter is in reasonable agreement with the theoretical value of $Q_{2\beta} = 2805(4)$ keV [5]). In this approach, however, the energy resolution of the $^{116}CdWO_4$ scintillators was not taken into account; the latter does not distort significantly the continuous $2\nu2\beta$ curve but effectively shifts it to higher energies (recall that, for four $^{116}CdWO_4$ crystals, FWHM $\simeq 290$ keV at the energy 2615 keV) and results in an overestimated $Q_{2\beta}$ value. To take into account this effect, the experimental spectrum was fitted to the convolution of the theoretical $2\nu2\beta$ distribution $\rho(\varepsilon) = A\varepsilon(\varepsilon^4 + 10\varepsilon^3 + 40\varepsilon^2 + 60\varepsilon + 30)(Q_{2\beta\nu} - \varepsilon)^5$ [1] with the detector resolution function (a Gaussian function with a FWHM determined in the measurements with calibration sources as $\mathrm{FWHM}(E) = \sqrt{-226.0 + 16.6E + 6.42 \times 10^{-3}E^2}$, energy $E$ and FWHM being given in keV). The amplitude $A$ of the theoretical distribution and the $Q_{2\beta}$ value are the parameters of the fit. The result of the fit in the energy region 1.6–3.0 MeV is shown in Fig. 5*b*. The resulting value of $Q_{2\beta} = 2807(29)$ keV is in a good agreement with the theoretical result $Q_{2\beta} = 2805(4)$ keV [5], thus justifying greatly our assumption that experimental data in the region above 1.6 MeV are associated primarily with the $2\nu2\beta$ decay of $^{116}Cd$. The amplitude $A$ corresponds to the half-life of $T_{1/2}(2\nu2\beta) = 2.4 \times 10^{19}$ yr.

The systematic uncertainties in the determined $T_{1/2}(2\nu2\beta)$ value were estimated in a way similar to that adopted [2]. The result, $T_{1/2}(2\nu2\beta) = [2.3 \pm 0.2(\mathrm{stat.})^{+1.0}_{-0.3}(\mathrm{syst.})] \times 10^{19}$ yr is in a good agreement with the measured half-lives of $T_{1/2}(2\nu2\beta) = 2.6^{+0.9}_{-0.5} \times 10^{19}$ yr [16] and $T_{1/2}(2\nu2\beta) = 2.7^{+0.5}_{-0.4}(\mathrm{stat.})^{+0.9}_{-0.6}(\mathrm{syst.}) \times 10^{19}$ yr [2] and disagrees to some extent with the value of $T_{1/2}(2\nu2\beta) = [3.75 \pm 0.35(\mathrm{stat.}) \pm 0.21(\mathrm{syst.})] \times 10^{19}$ yr [7]. It should be noted, however, that, in the last experiment, the detection efficiency $\eta$ was quite small ($\eta = 0.0173$) and was only calculated by the Monte Carlo method (without experimental verification); therefore, the systematic error could be significantly higher than the quoted value.

In addition to the determined value of $T_{1/2}(2\nu2\beta)$, it seems useful (for comparison with theoretical predictions) to set a lower limit on the $^{116}Cd$ $2\nu2\beta$ half-life from our data. It could be obtained in the simplest and very conservative way by just demanding that, in any energy region, the theoretical $2\nu2\beta$ distribution not

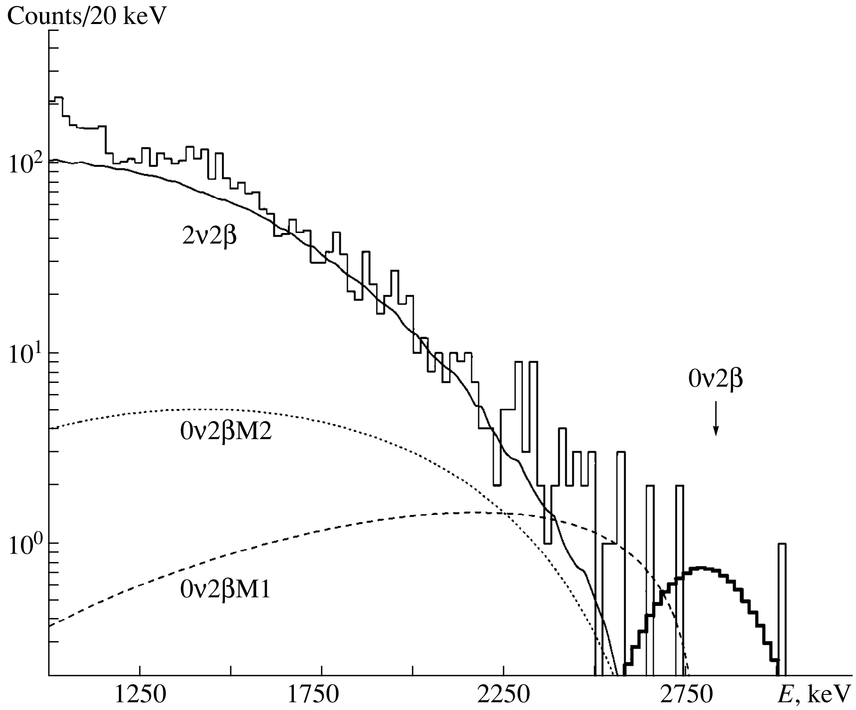


**Fig. 6.** Section of the experimental spectrum of the $^{116}CdWO_4$ detectors measured over 4056 h (histogram), together with the fit by 2ν2β contribution ($T_{1/2}(2\nu) = 2.3 \times 10^{19}$ yr) and excluded (at a 90% C.L.) distributions of 0νM1 and 0νM2 decays of $^{116}$Cd with $T_{1/2}(0\nu M1) = 1.4 \times 10^{21}$ yr and $T_{1/2}(0\nu M2) = 4.1 \times 10^{20}$ yr, respectively. Expected distribution from $^{116}$Cd 0ν2β decay with $T_{1/2}(0\nu) = 1.0 \times 10^{22}$ yr is also shown.

exceed the experimental spectrum. There are 729 events in the region 1600–2200 keV, which gives a 99.5% C.L. limit for the number of events $S \le 7562$ under the full 2ν2β curve. Using the relation $T_{1/2} = N\eta t \ln 2/S$, where $N$ is number of $^{116}$Cd nuclei ($N = 4.66 \times 10^{23}$), $t$ is the time of the measurements ($t = 4056$ h), and $\eta$ is efficiency for 2η2β decay in anticoincidence with the shielding detectors ($\eta = 0.962$), we obtain $T_{1/2}(2\nu2\beta) \ge 1.9 \times 10^{19}$ yr at a 99.5% C.L.

### *3.2. New Limit for 0ν2β Decay of $^{116}$Cd to the Ground State of $^{116}$Sn*

To estimate the half-life limit for the neutrinoless decay mode, the simple background model was used. In fact, only two background contributions are important for the 0ν2β-decay energy region: the tail of the 2ν2β spectrum and the expected distribution from the $^{212}\mathrm{Bi} \longrightarrow {}^{212}\mathrm{Po} \longrightarrow {}^{208}\mathrm{Pb}$ decay ($^{228}$Ac chain). As was shown above, two decays in the fast chain $^{212}\mathrm{Bi} \longrightarrow {}^{212}\mathrm{Po} \longrightarrow {}^{208}\mathrm{Pb}$ create the background in the region of 0ν2β decay (Fig. 4*c*). For the activity of $^{228}$Ac inside the $^{116}CdWO_4$ crystals, two values were obtained: 39(4) μBq/kg (time–amplitude method) and 34(5) μBq/kg (pulse-shape analysis). Hence, we can conclude that, with the current code used for the pulse-shape analysis, there is a residual $^{228}$Ac activity of 5(6) μBq/kg in our resulting pulse-shape-selected spectrum (Fig. 4*b*). The experimental data are in agreement with this calculation: for example, five events presented in the region 2600–3600 keV of the pulse-shape-selected spectrum correspond to 3.8 μBq/kg of $^{228}$Ac.

The high-energy part of the experimental spectrum of $^{116}CdWO_4$ crystals (339 g, 4056 h) measured in anticoincidence with the shielding detectors and after the pulse-shape discrimination is shown in Fig. 6. The peak of 0ν2β decay is absent, and the data were used to obtain a lower limit on the half-life: $\lim T_{1/2} = N\eta t \ln 2/\lim S$, where $N = 4.66 \times 10^{23}$ is the number of $^{116}$Cd nuclei, $t = 4056$ h, and $\lim S$ is the number of events in the peak that can be excluded at a given confidence level. The value of $\eta = 0.828$ was calculated by the DECAY4 [15] and GEANT3.21 [14] codes. To obtain the value of $\lim S$, the section of the spectrum in region 1.9–3.8 MeV was fitted in terms of the sum of three functions: the 2ν2β tail and the expected distribution from the $^{212}\mathrm{Bi} \longrightarrow {}^{212}\mathrm{Po} \longrightarrow {}^{208}\mathrm{Pb}$ decay, which represent the background, and the simulated $^{116}$Cd 0ν2β peak. This procedure yields the value of $S = -2.0 \pm 2.5$ and, thus, $\lim S = 3.1$ at a 90% C.L. It corresponds to $T_{1/2}(0\nu2\beta) \ge 4.0 \times 10^{22}$ yr (at a 90% C.L.), which is higher than the value of $3.2 \times 10^{22}$ yr obtained in the previous experiment with one $^{116}CdWO_4$ crystal over 19986 h [3].

Using the calculations from [6], we can obtain the following limits on the neutrino mass and the right-handed admixtures in the weak interaction: $\langle m_\nu \rangle \le 3.9$ eV, $\langle \eta \rangle \le 5.1 \times 10^{-8}$, and $\langle \lambda \rangle \le 4.5 \times 10^{-6}$; neglecting the right-handed contribution, we have $\langle m_\nu \rangle \le 3.5$ eV.

Finally, the limits obtained in the previous experiment (with one crystal) and current measurements (with four crystals) can be combined in the following way: $\lim T_{1/2} = \ln 2 \sum_{i=1}^{2} N_i \eta_i t_i / \lim S$. To derive the value of combined $\lim S$, the numbers of events in the $0\nu 2\beta$ peak have been simply added: $S = S_1 + S_2$; their error were added quadratically: $\sigma^2 = \sigma_1^2 + \sigma_2^2$. With $S_1 = -5.0 \pm 5.5$ (previous result) and $S_2 = -2.0 \pm 2.5$, we arrive at $S = -7.0 \pm 6.2$; thus, we have $\lim S = 6.8$ at a 90% C.L. Considering that $N_1 = 1.66 \times 10^{23}$, $t_1 = 19986$ h, and $\eta_1 = 0.835$, we obtain the combined limit $T_{1/2}(0\nu 2\beta) \ge 5.1 \times 10^{22}$ yr (at a 90% C.L.). The corresponding constraints on the neutrino mass and right-handed admixtures are $\langle m_\nu \rangle \le 3.5$ eV, $\eta \le 4.5 \times 10^{-8}$, and $\lambda \le 3.9 \times 10^{-6}$; neglecting the right-handed contribution, we obtain $\langle m_\nu \rangle \le 3.1$ eV.

### *3.3. $0\nu 2\beta$ Decay of $^{116}Cd$ to Excited Levels of $^{116}Sn$*

Not only ground state (g.s.) but also excited levels of $^{116}$Sn with $E_{\text{lev}} \le Q_{2\beta}$ can be populated in the $^{116}$Cd $2\beta$ decay. In this case, one or a few photons, conversion electrons, and $e^+e^-$ pairs will be emitted in a deexcitation process, in addition to two electrons emitted in the $2\beta$-decay process. The response functions of the $^{116}CdWO_4$ detectors for $^{116}$Cd $0\nu 2\beta$ decay to the first and second excited levels of $^{116}$Sn ($2_1^+$ with $E_{\text{lev}} = 1294$ keV and $0_1^+$ with $E_{\text{lev}} = 1757$ keV) were simulated with the aid of the DECAY4 and GEANT3.21 codes. The full absorption of all emitted particles should result in the peak at $E = Q_{2\beta}$ (the same peak as that which is expected for the $0\nu 2\beta$ decay of $^{116}$Cd to the g.s. of $^{116}$Sn). The calculated full peak efficiencies are $\eta(2_1^+) = 0.137$ and $\eta(0_1^+) = 0.065$. These numbers and the value of $\lim S = 3.1$ (determined for the g.s. $\longrightarrow$ g.s. transition) give the following restrictions on $T_{1/2}$ of $^{116}$Cd with respect to $0\nu 2\beta$ decay to the excited levels of $^{116}$Sn: $T_{1/2}(0\nu 2\beta$, g.s. $\longrightarrow 2_1^+) \ge 6.6 \times 10^{21}$ yr and $T_{1/2}(0\nu 2\beta$, g.s. $\longrightarrow 0_1^+) \ge 3.1 \times 10^{21}$ yr at a 90% C.L.

These limits can be slightly improved by combining them with the old data, as was described above for the g.s. $\longrightarrow$ g.s. transition. Taking into account the efficiency values for the 121-g $^{116}CdWO_4$ crystal used in the previous run [$\eta(2_1^+) = 0.144$ and $\eta(0_1^+) = 0.069$] and using the already determined combined value of $\lim S = 6.8$, we arrive at $T_{1/2}(0\nu 2\beta$, g.s. $\longrightarrow 2_1^+) \ge 8.6 \times 10^{21}$ yr and $T_{1/2}(0\nu 2\beta$, g.s. $\longrightarrow 0_1^+) \ge 4.1 \times 10^{21}$ yr (at a 90% C.L.).

### *3.4. Neutrinoless $2\beta$ Decay with Majoron(s) Emission*

Because it is obvious that the contributions of $^{40}$K are negligible above the energy of 1600 keV, the fitting procedure to obtain half-life limits for $0\nu 2\beta$ decay with the emission of one (two) Majoron(s) was performed as follows. The data were fitted in the energy range 1600–2500 keV by using only two theoretical distributions: the two-neutrino $2\beta$ decay of $^{116}$Cd as a background, and $0\nu 2\beta$ decay with the emission of one (two) Majoron(s) as the effect. The $\chi^2$ value was equal to 1.1 both for $0\nu$M1 and for $0\nu$M2 fits. As a result, the number of events under the theoretical $0\nu$M1 curve was determined to be $47 \pm 35$, giving no statistical evidence for the effect. It leads to an upper limit of 94 events, which corresponds to the following half-life limit of $0\nu$M1 $2\beta$ decay of $^{116}$Cd: $T_{1/2}(0\nu\text{M1}) \ge 1.4 \times 10^{21}$ yr at a 90% C.L. (the efficiency in anticoincidence mode is $\eta = 0.905$). A similar procedure for $0\nu 2\beta$ decay accompanied by the emission of two Majorons leads to $T_{1/2}(0\nu\text{M2}) \ge 4.1 \times 10^{20}$ yr (at a 90% C.L.). A section of the experimental spectrum with the excluded $0\nu$M1 and $0\nu$M2 distributions is shown in Fig. 6. Either of the half-life limits presented above is better than that established in the previous experiment over 19986 h [9] and in the NEMO experiment [7].

The probability of $2\beta$ decay with Majoron emission is $T_{1/2}^{-1}(0\nu\text{M1}) = \langle g_M \rangle^2 |\text{NME}|^2 G$, where $\langle g_M \rangle$ is the effective Majoron–neutrino coupling constant, NME is the nuclear matrix element, and $G$ is a kinematical factor. By using our result $T_{1/2}(0\nu\text{M1}) \ge 1.4 \times 10^{21}$ yr and the $G$ and NME values as calculated within the model relying on the quasiparticle random-phase approximation and taking into account proton–neutron pairing [10], we obtain $\langle g_M \rangle \le 1.9 \times 10^{-4}$ (in the approach used in [7], $\langle g_M \rangle \le 1.1 \times 10^{-4}$), which is one of the most stringent constraints obtained so far in direct $2\beta$-decay experiments [1].

## 4. CONCLUSION

The experiment to seek for $^{116}$Cd $2\beta$ decay with enriched $^{116}CdWO_4$ scintillators entered into a new phase, now in collaboration with the group from the University of Firenze and INFN (Firenze). A new setup with four $^{116}CdWO_4$ crystals (339 g) has been running since October 1998. In addition to the active shield of plastic scintillators, a new active shield made from fifteen pure $^{nat}CdWO_4$ crystals (full weight of 20.6 kg) was installed. The passive shield was improved too. The new data-acquisition system makes it possible to apply the time–amplitude analysis and pulse-shape discrimination to experimental data. All these measures resulted in reducing the background in the range 2.7–2.9 MeV to 0.06 count/(yr kg keV), which is nearly one order of magnitude less than that in the previous apparatus.

Together with increased number of $^{116}$Cd nuclei (by a factor of 3), this leads to a substantial improvement of the sensitivity of the $^{116}$Cd experiment by about one order of magnitude. In the first run of duration 4056 h, the half-life of $^{116}$Cd with the respect to 2ν2β decay was determined to be $T_{1/2}(2\nu2\beta) = [2.3 \pm 0.2(\text{stat.})^{+1.0}_{-0.3}(\text{syst.})] \times 10^{19}$ yr, and improved limits for neutrinoless modes of 2β decays were obtained to be $T_{1/2}(0\nu2\beta) \geq 4.0 \times 10^{22}$ yr, $T_{1/2}(0\nu M1) \geq 1.4 \times 10^{21}$ yr, and $T_{1/2}(0\nu M2) \geq 4.1 \times 10^{20}$ yr (all at a 90% C.L.). The combined (with old data) constraint for 0ν2β decay was also derived: $T_{1/2}(0\nu2\beta) \geq 5.1 \times 10^{22}$ yr (at a 90% C.L.). The half-life limits for 2β transitions to first two excited levels of $^{116}$Sn were determined: $T_{1/2}(0\nu2\beta, \text{g.s.} \longrightarrow 2^+_1) \geq 8.6 \times 10^{21}$ yr and $T_{1/2}(0\nu2\beta, \text{g.s.} \longrightarrow 0^+_1) \geq 4.1 \times 10^{21}$ yr (at a 90% C.L.). The following constraints on the neutrino mass, the right-handed admixtures in the weak current, and the Majoron–neutrino coupling constant were calculated: $\langle m_\nu \rangle \leq 3.5$ eV, $\langle \eta \rangle \leq 4.5 \times 10^{-8}$, $\langle \lambda \rangle \leq 3.9 \times 10^{-6}$ (neglecting the right-handed contribution, we have $\langle m_\nu \rangle \leq 3.1$ eV), and $\langle g_M \rangle \leq 1.9 \times 10^{-4}$.

In August 1999, one of $^{116}CdWO_4$ crystals used (with the poorest spectrometric characteristics) was additionally annealed (for about 100 h at high temperature), and its light output was improved on about 13%. The PMT of the main $^{116}CdWO_4$ detectors was replaced by a special low-background EMI tube (5 inches in diameter) with an RbCs photocathode, whose spectral response better fits the $CdWO_4$ scintillation light. As a result, spectrometric parameters of four crystals taken as a whole were improved. In particular, the energy resolution of the main detector is equal now 11.4% at 1064 keV and 8.6% at 2615 keV (Those before upgrading were 14.5 and 11%, respectively).

It is expected that, after approximately three years of measurements, the limit $T_{1/2}(0\nu2\beta) \geq 2 \times 10^{23}$ yr will be reached, which corresponds to $\langle m_\nu \rangle \leq 1.5$ eV. The $T_{1/2}$ limits for neutrinoless modes of $^{116}$Cd 2β decay accompanied by Majoron emission; 2β transitions to the excited levels of $^{116}$Sn; and 2β processes in $^{106}$Cd, $^{108}$Cd, $^{114}$Cd, $^{180}$W, and $^{186}$W can also be improved.

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