Limits on the Existence of Heavy Neutrinos in the Range 50–1000 eV from the Study of the ^{187}Re Beta Decay

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We analyzed the spectrum of the ^{187}Re beta decay, obtained with a cryogenic microcalorimeter, searching for heavy neutrinos in the mass range 50–1000 eV. No evidence has been found for them and the upper limits on the mixing angle with a zero-mass neutrino are reported. Upper limits of 9×10^{-3} at 1000 eV/c^2, 1.2×10^{-2} at 500 eV/c^2, 4.4×10^{-2} at 200 eV/c^2, and 0.116 at 100 eV/c^2 at 95% C.L. have been obtained. These upper limits are a factor of 2 to 4 lower than the current limits reported in the literature.

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The search for neutrino oscillations is a very sensitive tool to test light neutrino admixture. This includes atmospheric neutrinos, solar neutrinos, experiments at accelerators, and nuclear power reactors. However, to test the assumption of heavy neutrino admixture, experimental methods investigating weak decays or looking directly for neutrino decay are more favorable [1]. In particular, for neutrino masses above some tens of eV and below ca. 1 MeV, beta decay experiments searching for kinks in the energy spectra of the emitted electron are most sensitive. Experiments of this kind have been performed on ^{3}H, ^{35}S, ^{63}Ni, and ^{64}Cu [2–9]. We report here the results of such a search made studying the beta decay spectrum of ^{187}Re obtained with a cryogenic microcalorimeter.

In five months of data taking, about 6 000 000 ^{187}Re beta-decay events from the energy threshold of 420 eV to the end-point energy have been acquired with an energy resolution of 40.8 eV rms (see Fig. 1) [10,11]. The low end-point energy of the ^{187}Re decay (2470 ± 5 eV [11]) and the good performances of the detector, especially in terms of energy resolution and detector response, allow significantly improved limits on the mixing angle of heavy mass neutrino in the mass interval between 50 and 1000 eV, which has been rarely investigated before [3,4].

The calorimetric experiment measures not only the beta energy, but all the detectable energy released in the process (the electron energy and the excitation energy of the residual system) provided that the energy is fully thermalized. The measured spectrum is therefore well suited for neutrino mass investigations because it is complementary to the neutrino energy spectrum and is unaffected by the final state distribution or by secondary interactions of emitted electrons.

The operating principles of microcalorimeters as particle detectors have already been reported in detail by many authors [12]. A microcalorimeter is composed of three parts: an absorber that converts the energy of the decay into heat, a thermometer (sensor) that detects the temperature variations of the absorber, and a weak thermal link between the detector and a heat sink. When energy is absorbed, it is converted to thermal phonons and the temperature of the detector first rises and then returns to its original value due to the weak thermal link with the heat sink. The temperature change is proportional to the energy and is detected by the sensor. The sensor is generally a resistor whose resistance has a strong dependence on the temperature at the working point. Although the amount of energy deposited in the absorber could be very small (down to about 200 eV in this experiment), the increase in temperature is not negligible (in the range of μK) due to the extremely small heat capacity of the microcalorimeter at the working temperature.

In this experiment we used a superconducting rhenium single crystal of mass 1.572 mg both as absorber and beta source, with an activity of about 1.1 Bq. The sensor is a neutron transmutation doped (NTD) germanium thermistor (230 μm × 100 μm × 100 μm). Sensor and absorber are connected with a drop of epoxy (Epotek H301-2) and the microcalorimeter is suspended by two ultrasonic-bonded Al wires 15 μm in diameter, which also provide the electrical connection and the weak thermal connection to the heat sink. The heat sink is a ^{3}He-^{4}He dilution refrigerator working at a base temperature of 60 mK.

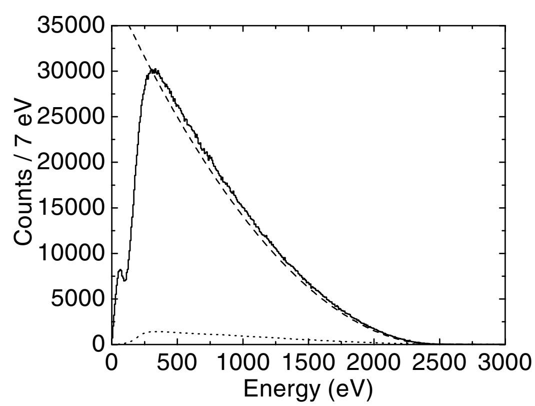

FIG. 1. Energy spectrum of the ^{187}Re beta decay (continuous line) and fit result decomposed in the β spectrum and the unidentified pileup (dashed and dotted lines).

The energy calibration is provided by a removable fluorescence source of Cl, Ca, and Va K-α and K-β x rays, excited by an ^{55}Fe x-ray source also used for the calibration. When the fluorescence source is removed for low background measurements, the calibration is provided by low rate ^{55}Fe x rays [11].

Previous analyses [10,11,13] have already led to an estimate of the end-point energy and half-life of the decay and to the discovery of the influence of crystalline structure on beta decays. This latter effect, called beta environmental fine structure (BEFS), was postulated in 1991 [14] and corresponds to an oscillatory modulation of the beta spectrum amplitude of the order of 1%. The parameters depend on the crystalline structure and the details of the effect are reported by Galeazzi [10] and Gatti *et al.* [13].

The experimental setup and data reduction procedure have already been described in detail [10,11]. In particular, since this was the first high statistics measurement on ^{187}Re with microcalorimeters, the reduction and interpretation of the data have been carefully tested. The detector characteristics turn out to be relatively simple and well understood and the experimental spectrum follows the expected beta distribution over the full energy range of the detector [10,11]. Experimental behaviors considered in the interpretation of the data, and that have been analyzed in detail, include the detector response function, the detector energy resolution, the energy calibration and detector linearity, the effect of unidentified pileup, the possible distortion of the spectrum due to electron escape, the effect of the data reduction and, in particular, of cuts in the pulse shape analysis, and the goodness of the theoretical spectral shape.

The detector response has been evaluated using the ^{55}Fe K_α line and it is in good agreement with a Gaussian distribution (see Fig. 2). Any low-energy or high-energy tail, if present, contributes less than 0.1% to the total counts and is negligible with respect to the statistical uncertainties [11]. The spectrum obtained with the fluorescence source has been used to investigate the possible energy dependence of the resolution and the detector nonlinearity. The energy resolution does not show any measurable dependence on the energy: $\Delta\sigma/\sigma < 0.02 \pm 0.04$ in the whole spectrum [11]. The data show a detector nonlinearity well described by a parabolic distribution of the energy versus the pulse amplitude. The pulse amplitude is about 0.16% low in the region of the end point and about 0.5% low for the ^{55}Fe K_α line [11]. In order to avoid any possible contamination of the β spectrum, the lowest peak of the calibration source is above the ^{187}Re end-point energy. Therefore we studied the source of the energy resolution and energy nonlinearity in order to be able to extend the considerations reported above to the ^{187}Re energy spectrum without introducing any appreciable systematic effect. The energy resolution is completely determined by the ratio between the pulse amplitude and the noise in the detector. The detector noise is due to phonon noise from the thermal link, Johnson noise from the sensor, and amplifier noise [15]. All these terms are energy independent; therefore the energy resolution is also expected to be independent on the energy. As a check, we repeated our fits varying the energy resolution by up to 50% around the expected value: the results changed by less than 0.2%, indicating that they depend very little on the energy resolution. The energy nonlinearity of the detector is due to the temperature dependence of the detector heat capacity, thermal conductivity, and sensitivity. These are well known properties of the detector that we studied in detail, concluding that any difference from our assumed parabolic distribution is completely negligible with respect to other uncertainties. The effect of an external calibration source in a microcalorimeter has been studied in detail by Porter *et al.* [16]. The effect is the presence of a low-energy tail in the calibration lines that adds to the detector background (but, as reported above, it is negligible in the high-Z material used in this experiment), while no difference in the peak position is expected.

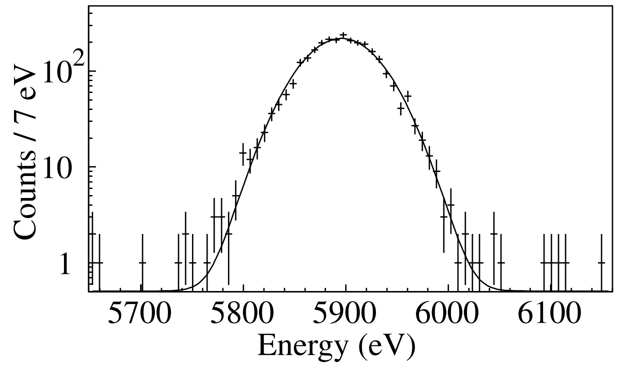

FIG. 2. ^{55}Fe calibration line in logarithmic scale and Gaussian fit. The energy resolution is 40.8 eV rms. Any low-energy or high-energy tail, if present, contributes less than 0.1% to the total counts.

The effect of unidentified pulse pileup was a major concern in the data reduction; therefore three different methods have been used to evaluate it. 10 000 000 events reproducing the microcalorimeter characteristics have been generated in a Monte Carlo simulation, in a format compatible with the analysis procedure [17]. The simulation allows verification of the analysis program and construction of a “spectrum of pileup,” composed of pulses classified as good pulses by the analysis program, while really composed of multiple events. The spectrum of pileup is then added to the theoretical spectral shape in the fit procedure. The pileup spectrum has also been theoretically calculated assuming an energy dependence of the pileup compatible with the experiment. The result of the theoretical calculation is in good agreement with the spectrum of pileup obtained using the Monte Carlo simulation. The experimental results have also been compared with the data from a second microcalorimeter, with lower activity and therefore smaller influence of the pileup (the unidentified pileup in the second microcalorimeter is estimated to be about 1/3 of that in the first one). The results from the two microcalorimeters are in perfect agreement, indicating that the analysis of unidentified pileup does not introduce any systematic effect on the physical results of the experiment [11].

The absorber is a rhenium crystal; therefore the radiation source is uniformly distributed in it. If a beta decay occurs in a nucleus close enough to the surface of the crystal, the emitted electron could escape from the surface or could produce an x ray that escapes from the surface. This effect has been investigated and the conclusion is that it affects only a very thin layer near the surface of the crystal, equal to less than 0.01% of the total volume. The distortion introduced by the escape is therefore completely negligible with respect to the statistical uncertainties.

To test the effect of the pulse shape analysis procedure used to remove spurious pulses from the data set [17], two spectra have been obtained using two different sets of cuts [10,11], and the analysis has been performed on both. No systematic difference in the results has been found. Moreover, the complete data reduction procedure has been performed independently by two members of the team, and the results show no evidence of a systematic difference.

^{187}Re decays through beta emission to ^{187}Os. The decay is first order unique forbidden ($\Delta J = 2, \Delta\pi = 1$ [18]) and the theoretical energy spectrum of the emitted electrons is represented by

$$N_\beta(E,Z,m) \propto \sum_i A_i F(Z,E) S(E) E p_e (E_0^i - E)^2 \times \sqrt{1 - \frac{m^2}{(E_0^i - E)^2}}\,, \qquad (1)$$

where the sum is over all the final atomic states i of ^{187}Os, E and p_e are, respectively, the energy and the momentum of the β electron, m is the neutrino mass, and E_0^i is the end-point energy related to the atomic state i (i.e., the total energy of the nuclear decay minus the energy of the atomic state), and A_i is the probability of the decay to the atomic state i ($\sum_i A_i = 1$). The primary correction factors to the β spectrum include $F(Z,E)$, the Fermi function, and $S(E)$, the Shape factor, which have been calculated explicitly for the ^{187}Re isotope by Bühring [19] and which are described in [10,11,17].

In our calorimetric experiment the measured quantity is $W = E + E^i$, where E^i is the excitation energy of the residual atomic system. Equation (1) can be written as

$$N(W,Z,m) \propto \sum_i A_i F(Z, W - E^i) S(W - E^i)(W - E^i) \times p_e (W_0 - W)^2 \sqrt{1 - \frac{m^2}{(W_0 - W)^2}}\,, \qquad (2)$$

where W_0 is the total end-point energy of the decay. The decays of ^{187}Re to ^{187}Os atomic excited states with not negligible energy are forbidden by the conservation of quantum numbers. The quantity E^i is then expected to be very small, in the range of tens of eV. Moreover, the factor $F(Z,E)S(E)\,(E)p_e$ is very slowly dependent on the energy E; therefore it is possible to use W instead of $(W - E^i)$ in Eq. (2) [10,11]. Therefore, the theoretical expression of the ^{187}Re β decay becomes

$$N(W,Z,m) \propto F(Z,W) S(W) W p_e \times (W_0 - W)^2 \sqrt{1 - \frac{m^2}{(W_0 - W)^2}}\,. \qquad (3)$$

This theoretical calculation has been compared with the experimental spectrum from the energy threshold of 420 eV to the end-point energy and the result shows good agreement between the two [11]. An oscillatory factor, $K(E)$, should also be added to the spectral shape to take into account the effect of the BEFS. This effect, after folding with the detector energy resolution of 40.8 eV is of the order of 1% below 2 keV and it decreases at higher energies [10,13].

In heavy neutrino investigations it is useful to assume that the electron neutrino ν_e is a linear combination of two mass eigenstates ν_1 and ν_2, of masses m_1 and m_2:

$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta\,; \qquad (4)$$

then the beta spectral shape can be written

$$N_\beta(W,Z,m_1,m_2,\theta) = N_\beta(W,Z,m_1)\cos^2\theta + N_\beta(W,Z,m_2)\sin^2\theta\,. \qquad (5)$$

In order to investigate the existence of a heavy neutrino mixed with a light one we assume a zero-mass light neutrino ($m_1 = 0$) and we investigate the rhenium spectrum using Eq. (5) with m_2 and $\sin^2\theta$ as free parameters. The theoretical distribution used in our investigation also includes a flat background and a contribution due to uniden-

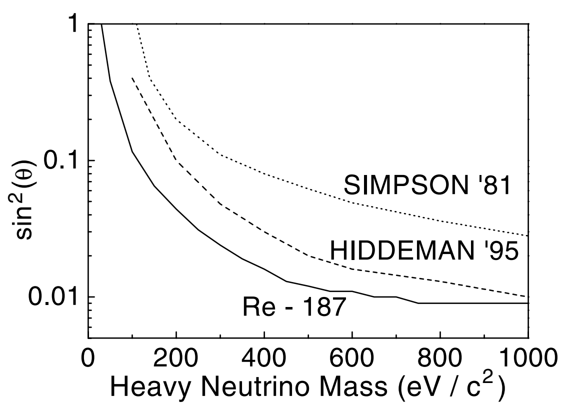

FIG. 3. Upper limits at 95% C.L. on the mixing angle of a heavy neutrino with a massless one versus the heavy neutrino mass in the range 0–1000 eV. The comparison is between our result (Re-187) and the previous measurements with tritium by Hiddeman *et al.* (HIDDEMAN 95, [3]) and Simpson (SIMPSON 81, [4]).

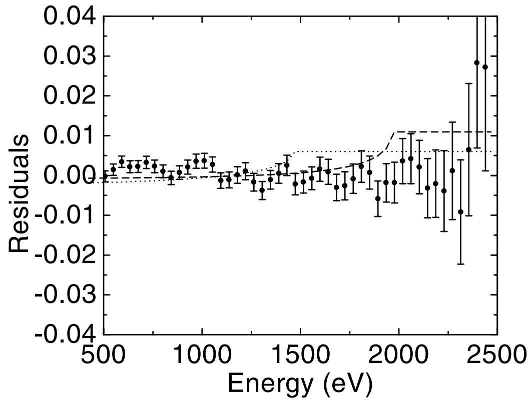

FIG. 4. Residuals of the best fit of the experimental spectrum with the theoretical distribution assuming a zero-mass light neutrino and no mixing (data points). The expected curves due to a 500 eV/c^2 and a 1000 eV/c^2 heavy neutrino with mixing of 1.2×10^{-2} and 9×10^{-3}, respectively, are also reported (dashed and dotted lines).

tified pileup obtained with Monte Carlo simulation. The ratio between the unidentified pileup and the total number of counts resulting from the fit is $P = 0.0628 \pm 0.0017$, while the flat background is compatible with zero. This is due to the fact that the background, in the whole energy interval of the fit, is dominated either by the spectrum or by the unidentified pileup. Figure 1 reports the measured spectrum and its decomposition in the ^{187}Re β spectrum and unidentified pileup using the result of the fit. We do not include the effect of BEFS, because its theoretical behavior is not yet sufficiently well known over the whole energy spectrum. This fact limits the sensitivity to the mixing angle that can be achieved to the level of the BEFS oscillations, i.e., to about 1% [10,13]. Even though our statistics would allow us to reach better limits, especially for heavier neutrinos, we do not want to introduce possible artifacts in our analysis due to an incorrect estimate of the BEFS effect. Since the energy threshold of the detector is about 400 eV and the end-point energy is 2470 eV, with this experiment it is possible in principle to investigate neutrino masses up to about 2 keV, but it is in the mass range 50–1000 eV that we have measurably improved the current limits.

We analyzed the data using the unified approach proposed by Feldman and Cousins [20] and accepted by the Particle Data Group [21]. No evidence of a heavy mass neutrino in the range 50–1000 eV has been found, and the upper limits at 95% C.L. of the mixing angle $\sin^2\theta$ as a function of the neutrino mass in the range 0–1000 eV are reported in Fig. 3. The existing previous limits obtained by studying the ^{3}H beta decay by Hiddeman *et al.* [3] and Simpson [4] are also reported in the figure for comparison. Limits of 9×10^{-3} at 1000 eV/c^2, 1.2×10^{-2} at 500 eV/c^2, 4.4×10^{-2} at 200 eV/c^2, and 0.116 at 100 eV/c^2 at 95% C.L. have been obtained. Figure 4 reports the residual of the fit assuming that there is no heavy neutrino mixing. The expected curve due to the presence of a 500 eV/c^2 and a 1000 eV/c^2 neutrino with mixing angles equal to our sensitivity are also reported. The result of this experiment sets new limits in an energy range almost uninvestigated before. These limits are a factor of 2–4 lower than the best results currently available in the literature [3,4]. These constraints may be helpful in the discussion about possible scenarios concerning hot or mixed dark matter. Improvements of the limits reported in this paper require a new experiment dedicated to the study of BEFS.

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