Bolometric Bounds on the Antineutrino Mass

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High statistics calorimetric measurements of the β spectrum of ^{187}Re are being performed with arrays of silver perrhenate crystals operated at low temperature. After a substantial modification of the experimental setup, a new measurement with ten silver perrhenate microbolometers has been running since July 2002. The crystals have masses around 300 μg and their average FWHM energy resolution is of 28.3 eV at the β end point. The Kurie plot collected during 4485 h $\times$ mg effective running time has an end-point energy of $2466.1 \pm 0.8_{\mathrm{stat}} \pm 1.5_{\mathrm{syst}}$ eV, while the half lifetime of the decay is found to be $43.2 \pm 0.2_{\mathrm{stat}} \pm 0.1_{\mathrm{syst}}$ Gy. These values are the most precise obtained so far for ^{187}Re. The best fit value for $m^2_{\overline{\nu}_e}$ is $147 \pm 237_{\mathrm{stat}} \pm 90_{\mathrm{syst}}$ eV^2, which corresponds to an upper limit for the electron antineutrino mass $m_{\overline{\nu}_e} \leq 21.7$ eV at 90% C.L.

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The interest in direct measurements of the neutrino mass m_ν from the β decay spectrum has been recently stimulated by the evidence of a nonzero value of Δm^2_ν detected in searches on solar and atmospheric neutrino oscillations [1–3].

Limits on direct measurements of m_ν have so far been obtained by experiments with electrostatic spectrometers investigating the β decay of tritium. Recent results [4,5] have set an upper limit of 2.2 eV at 90% C.L. These experiments are based on the measurement of the spectrum of the emitted electron. One cannot therefore exclude *a priori* that the decay could partially occur on an excited state of the daughter molecule. This and other systematic effects have given in the past years a negative value for m^2_ν. Even if now these problems seem to be almost completely solved, we think it is important to carry out a measurement with a different approach.

Calorimetric measurements, where all the energy released in the decay is recorded, appear therefore complementary to those carried out with spectrometers. In addition they allow the measurement of the entire β decay spectrum and can therefore test any possible distortion of the Kurie plot. A particularly suitable approach appears to be the bolometric one [6,7] in which detectors, operated at low temperature, include absorbers of a material containing the β active nucleus. If the absorbers are diamagnetic and dielectric crystals their heat capacity can be very low, since it is proportional to the cube of the operating temperature. As a consequence even the tiny energy delivered by a particle can give rise to a measurable pulse in a suitable thermal sensor.

The present experiment is carried out on the first forbidden unique decay:

$$^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os} + e^- + \overline{\nu}_e,$$

which is particularly promising [8] due to its low transition energy ($\sim$2.5 keV). In addition the large isotopic abundance of ^{187}Re (62.8%) allows the use of absorbers made with natural rhenium. We note also that a precise direct measurement of the half lifetime of this decay ($\sim$43 Gy) is of great interest in geochronology for the determination of the age of minerals and meteorites from their Re-Os abundance [9–13]. Measurements of the spectra of ^{187}Re have been reported by the Genova group [14] with single crystals of metallic rhenium and by our group [15] with an array of four crystals of silver perrhenate ($AgReO_4$), a dielectric compound of rhenium.

In this Letter we report on new high statistics measurements carried out in two successive runs with arrays of ten crystals of $AgReO_4$ with masses ranging from 250 to 350 μg. These crystals are thermally coupled to thermometers made of doped silicon chips implemented by the Istituto Trentino di Cultura (ITC-irst) in Trento and tested and calibrated at low temperature in Milano [16]. Special care is taken with the calibration of the energy scale and the monitoring of the stability and performance of all detectors. This is achieved by means of the 5.9 keV $K\alpha$ line of ^{55}Mn and the fluorescence $K\alpha$ lines produced

by two ^{55}Fe primary sources at 1.5, 2.6, 3.7, and 4.5 keV in Al, Cl, Ca, and Ti, respectively. During data acquisition all detectors are exposed to the fluorescence x rays produced by the sources for ~20 min every 2 h. Any system instabilities are then corrected off-line by fitting the time behavior of the higher energy x-ray peaks (Al and Cl peaks are never used for this procedure) and stabilizing them to straight lines [17]. Residual instabilities will result in a broadening of the x-ray peaks and are therefore included in the detector response function. They are estimated to contribute less than 0.2% to the peak broadening in the energy interval of interest. Figure 1 shows the result of the gain drift correction for a typical detector. After stabilization, the x-ray peak positions are used to calibrate the energy scale of the spectra. It turned out that all $AgReO_4$ detectors show x-ray peaks which are slightly asymmetric and whose shape can be satisfactorily reproduced only by fitting them with two symmetric Gaussians of equal width.

In a first run totaling 2354 mg × hours effective running time we have collected $\sim 1.4 \times 10^6$ counts from ^{187}Re decay above an energy threshold of 700 eV. The corresponding Kurie plot was fit with the spectrum calculated by Buhring [18], as described later in this Letter, and a preliminary upper limit of 31.9 eV at 90% C.L. could be set on the electron antineutrino mass. In this measurement the sensitivity to the antineutrino mass was mainly limited by the background of spurious counts, shown by the upper curve of Fig. 2. By means of a Monte Carlo simulation and of a dedicated measurement with the same setup, but without the ^{55}Fe primary sources, we found that the background was mainly caused by the internal bremsstrahlung accompanying the ^{55}Fe electron capture decay, with a branching ratio of $\sim 3.2 \times 10^{-3}$% [19]. Most of the peaks appearing in this spectrum are due to fluorescence in the copper of the detector holders and in a lead shield placed near the detectors.

As a consequence we substantially changed the calibrating setup with a new system which automatically moves the sources in a massive shield of Roman lead [20]. The resulting reduction of the background is shown by the lower curve of Fig. 2. The second run is being carried out in these improved conditions since July 2002 with a partially renewed array of ten $AgReO_4$ crystals, for a total mass of 2.683 mg. The data from two detectors, with poorer resolution, are not included in our statistics: the corresponding effective total mass is therefore of 2.174 mg. The present analysis refers to five months of continuous run totaling 4485 and 1070 h × mg of effective measurement and calibration times, respectively. The FWHM resolution of the eight detectors at 1.5 keV (the Al $K\alpha$ line) ranges from 21.2 to 28.7 eV with an average of 25.4 eV, while the FWHM resolution of the array extrapolated at the energy of the β end point (2.46 keV) is 28.4 eV. At this energy, the two symmetric Gaussians used to interpolate the x-ray peak shape are separated by 36 eV, the area ratio between the left and the right one being 3.7%. With this detector response function, the displacement of the Cl $K\alpha$ line from its nominal position is within 0.3 eV for all detectors. The 10% to 90% rise time of the detectors is in the range 340–680 μs with an average value of 492 μs.

The Kurie plot obtained from the sum of all eight detectors is shown in Fig. 3. It corresponds to $\sim 3.2 \times 10^6$ ^{187}Re decays above the common energy threshold of 700 eV. This Kurie plot was fit with the function $F = (f_{th} + f_{pup} + f_{bck}) \otimes f_{det}$, where f_{th} is the theoretical beta spectrum calculated by Buhring, f_{pup} is the pileup spectrum, f_{bck} is the unknown background, and f_{det} is the detector response function. The background is

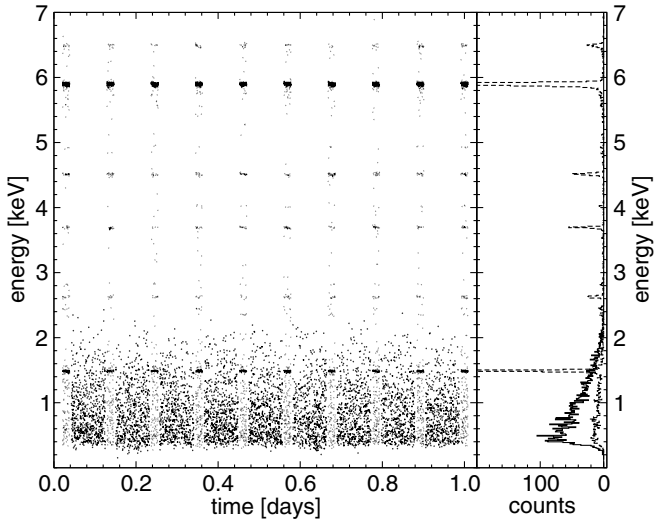

FIG. 1. A sample one day measurement, after gain stability correction, showing the periodical exposure to the calibration source.

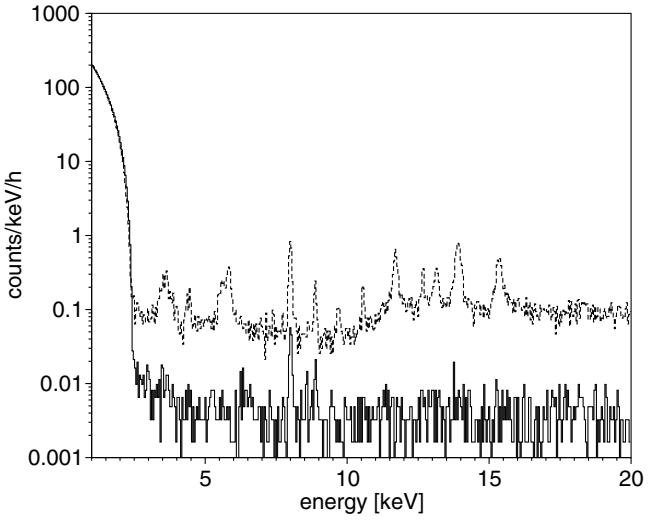

FIG. 2. Background in the high energy region with (continuous line) and without (dashed line) source shielding. The peak at 8 keV is the Cu $K\alpha$ line.

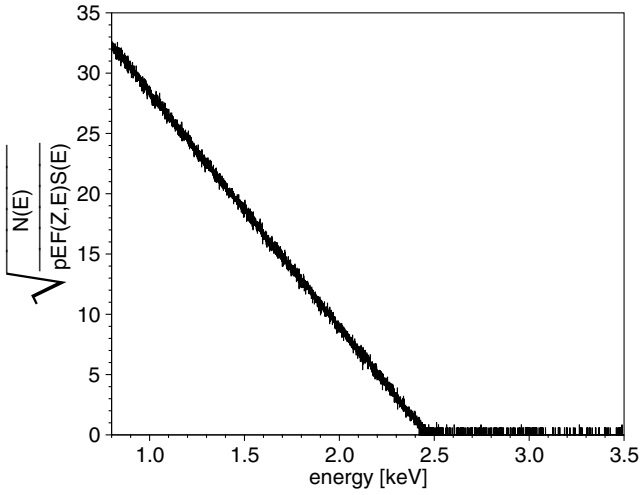

FIG. 3. Kurie plot obtained, in the second run, from the sum of all eight detectors, where p is the electron momentum, E is the electron kinetic energy, $F(Z, E)$ is the Coulomb factor, and $S(E)$ is the shape factor.

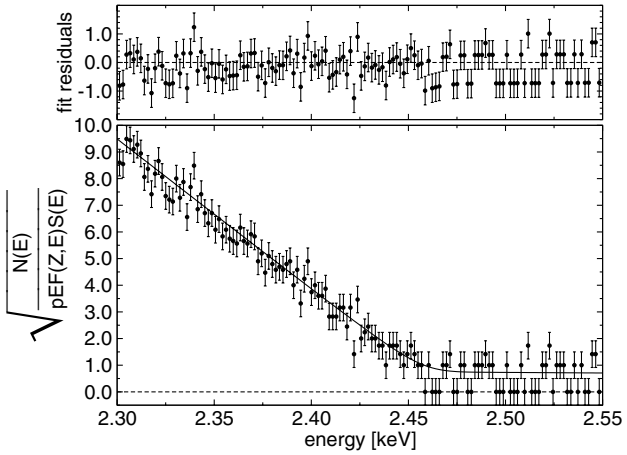

FIG. 4. Fit residuals and fit function F (see text) superimposed to the experimental data in the energy region around the β end point.

typically supposed to be constant, as it appears to be above 5 keV, where the contribution from the pileup spectrum is not present. Less satisfactory agreement with the data has been obtained by allowing the presence of a linear component in the background shape. The beta end point, the beta and pileup spectrum normalizations, the background level, and the squared electron antineutrino mass $m^2_{\bar{\nu}_e}$ are all free parameters of the fit. In order to check our hypotheses we perfomed fits varying both the upper—between 3 and 5 keV—and the lower—between 0.7 and 2.1 keV—limits of the fitting interval: the results obtained for the five fit parameters are stable within the errors, thus confirming the good description of the data given by the function F. The results reported here are obtained for the fitting interval 0.8–4 keV and a blowup of the region around the β end point is shown in Fig. 4. In the 30 eV below the end point the ratio between the β decay signal and the background fluctuations is 8.6. We find no deviation from the above mentioned calculation of Buhring for the spectrum expected in the absence of the neutrino mass. The χ^2/DOF of the fit is 1.004. With the present statistics we also find no evidence for deformations of the spectrum as a consequence of atomic and environmental effects. This beta environmental fine structure had been detected for metallic rhenium by the Genoa group [21]. A much reduced effect is, however, expected in our experiment because the distance among the rhenium and silver nuclei is quite larger and the cross section for this effect on oxygen nuclei much weaker [22]. The measured value for the end point is $2466.1 \pm 0.8(\text{stat}) \pm 1.5(\text{syst})$ eV. The systematic error is determined by the uncertainties in the energy resolution, in the detector response function, in the shape of the background below the beta spectrum, and in the theoretical spectral shape for the ^{187}Re beta decay. Because of the substantial absence of spurious counts we could precisely determine the effective decay rate from the distribution of the time intervals between two successive β decays. The half lifetime is thus found to be $[43.2 \pm 0.2(\text{stat}) \pm 0.1(\text{syst})] \times 10^9$ yr, where the statistical error is due to the uncertainties in the measurement of the mass of the absorbers and the systematic error is due to the uncertainties in the pileup discrimination. The values for the end-point energy and for the half lifetime are the most precise existing in the literature. The latter, as noted before, has considerable impact in geocronology.

The squared electron antineutrino mass $m^2_{\bar{\nu}_e}$ is $147 \pm 237(\text{stat}) \pm 90(\text{syst})$ eV^2, where the systematic error has the same origin as for the end-point energy quoted above. The 90% C.L. upper limit to the electron antineutrino mass is 21.7 eV. This result is in agreement with the expected sensitivity deduced from a Monte Carlo simulation of an experiment with the same statistical significance as our present data set. The limit on the electron antineutrino mass is not improved by a combined analysis of the two runs because of the substantial improvements in the new run, both on the statistics and on the background.

This result, even if not yet competitive with those obtained with spectrometers, has to be considered, in our opinion, complementary to them and shows the potential of future bolometric measurements of the neutrino mass. As pointed out before, it measures the total released energy and not only that of the electron. In addition, it allows the investigation of all possible deviations from the standard theory of beta decay over the entire energy range. The measurement is still presently running, but improvements are planned, based on the use of better and more massive crystals and improved thermal coupling between them and the thermistors. A new experiment is planned based on a larger array and different and faster thermal sensors.

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