Measurement of the p to s Wave Branching Ratio of ^{187}Re β Decay from Beta Environmental Fine Structure

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(Received 9 March 2005; revised manuscript received 15 November 2005; published 31 January 2006)

The mixed occurrence of s-wave and p-wave contributions in a first forbidden unique Gamow-Teller β decay has been investigated for the first time by measuring the beta environmental fine structure (BEFS) in a ^{187}Re crystalline compound. The experiment has been carried out with an array of eight $AgReO_4$ thermal detectors operating at a temperature of $\sim$100 mK. A fit of the observed BEFS spectrum indicates the p-wave electron emission as the dominant channel. The complete understanding of the BEFS distortion of the ^{187}Re β decay spectrum is crucial for future experiments aiming at the precise calorimetric measurement of the antineutrino mass.

DOI: 10.1103/PhysRevLett.96.042503 PACS numbers: 23.40.−s, 14.60.Pq, 61.10.Ht, 61.18.−j

Recent evidence of neutrino oscillations [1] has further stimulated interest in precise measurements of the absolute value of the neutrino mass (m_ν). Direct measurements of m_ν are studying tiny distortions close to the end point of the spectra of electrons emitted in a low energy β decay. Up to a few years ago these measurements were carried out only on the β decay spectrum of ^{3}H, with a transition energy of $\sim$18.6 keV. The most stringent constraint on m_ν (about 2 eV at 95% C.L.) has recently been achieved by experiments studying the β spectrum of ^{3}H with electrostatic spectrometers [2]. Motivated by the controversial reports by Simpson [3] and Sur *et al.* [4] on the observation of a kink below the end point of the ^{3}H spectrum (which at that time was interpreted as an indication of the existence of a neutrino with a mass of 17 keV), Koonin [5] in 1991 suggested that a β spectrum could be deformed by an effect similar to the extended x-ray absorption fine structure (EXAFS). The EXAFS is the oscillatory pattern observed in x-ray absorption spectra just above the absorption edges as an effect of the interference between the direct wave of the ejected photoelectron and the wave scattered by the neighboring atoms. These oscillations depend on the interatomic distance, while their amplitude is tied to the electron-atom scattering cross section. An analogous effect is expected when the electron emitted by a nucleus is reflected by the neighboring atoms of a molecule or of a crystal, where the emitting nucleus is embedded. As Koonin himself suggested, this effect, called BEFS for beta environmental fine structure, could be of interest for the study of materials. It could be detected in the low energy region of a β spectrum, which is generally more populated when the transition energy is low. Koonin had theoretically evaluated the oscillatory patterns expected for implanted ^{3}H and ^{14}C, as well as for molecular tritium. BEFS has not been searched for in these nuclei, but the effect has been detected in metallic rhenium [6] in the β decay of ^{187}Re, which has the lowest known transition energy ($\sim$2.5 keV) [7]. In this Letter we report the first experimental evidence for BEFS in a rhenium compound, silver perrhenate ($AgReO_4$), and obtain through a fit of the observed BEFS spectrum a first determination of the p- to s-wave branching ratio for the β decay of ^{187}Re. This is possible also thanks to the peculiar lattice structure of the $AgReO_4$ crystal.

The present experiment is based on the relatively new technique of thermal detectors (or calorimeters) [8]. The heat capacity of a sufficiently cold dielectric and diamagnetic crystal is proportional to the cube of the ratio between the operating and Debye temperatures. As a consequence, it can become so small that even the tiny energy released by a charged particle inside this crystal, acting as *absorber,* can produce a detectable temperature increase, which can be measured by a suitable thermal sensor (*thermometer*). In principle, any material with a sufficiently high Debye temperature can be used as a detector absorber. In particular, for a neutrino mass experiment, one can choose a crystal containing a β active isotope. This approach to the direct measurement of m_ν, with the β source embedded in the detector, has several advantages because, being calorimetric, it allows the measurement of the entire energy emitted in a decay, except that carried away by the neutrino. Moreover, the very low energy threshold and excellent energy resolution (down to 3 eV FWHM [8]) of thermal detectors make them a valuable choice for this kind of application.

The present experiment has been performed with an array of 8 microcalorimeters, where the absorbers are crystals of $AgReO_4$, for a total mass of 2.174 mg. They are glued to doped silicon chip thermometers and operated

at temperatures around 100 mK in a dilution refrigerator. $AgReO_4$ is a dielectric compound of rhenium with a natural fraction of ^{187}Re of about 0.32 giving a β-decay rate of about 5.4×10^{-4} Hz/μg. Details of the experimental setup, data analysis, and results are given in [7,9]. The β spectrum of ^{187}Re has been measured for almost one year, determining the most precise values of the end-point energy and of the half lifetime, the latter one having important implications in geochronology and nucleosynthesis [10]. From the fit of the final Kurie plot, shown in Fig. 1, corresponding to 2168 h $\times$ mg, a preliminary upper limit of 15 eV on m_ν has been set [9] at 90% C.L. This indicates the potentiality of this relatively new technique. The fit residuals in the energy interval between 350 eV (the common energy threshold for half of the detectors of the array) and 1 keV clearly show an oscillatory modulation of the data (see Fig. 2), corresponding to the BEFS oscillations.

While the decays of ^{3}H and ^{14}C are allowed, that of ^{187}Re to ^{187}Os is a $5/2^+ \rightarrow 1/2^-$ first forbidden unique transition. The Koonin theory was therefore extended to correctly consider the electron final states for forbidden β decays [11]. The nuclear angular momentum change, $\Delta I = -2$, implies a Gamow-Teller process. Consistently with the selection rules, the (vector) sum of electron and antineutrino orbital angular momenta ($l_e + l_{\bar\nu}$) must be as low as possible in order not to centrifugally suppress the overall transition rate. This implies two possible final states, according to whether the residual angular momentum is carried away by the antineutrino (s-wave electron emission, $\{e(s_{1/2}), \bar\nu(p_{3/2})\}$) or by the electron ($p$-wave electron emission, $\{e(p_{3/2}), \bar\nu(s_{1/2})\}$) [10].

As suggested in [5,6,11], the BEFS correction ΔP to the probability P that an electron with a wave number k (or, equivalently, an energy E) is emitted in the decay process, can be derived in complete analogy with the EXAFS description [12–14]. In this analogy the outgoing electron plays the role of the photoelectron. The BEFS effect

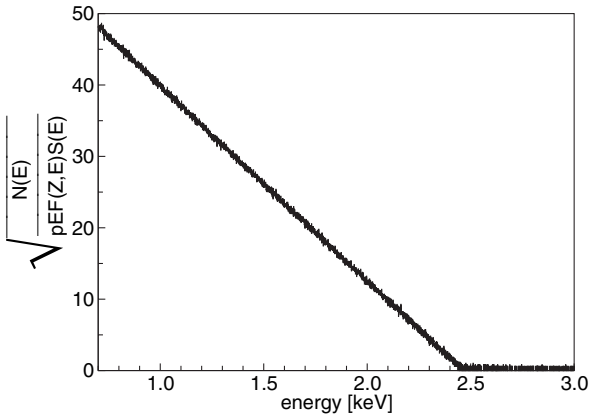

FIG. 1. Kurie plot obtained from the sum of all 8 detectors, where p is the electron momentum, E is the electron kinetic energy, $F(Z, E)$ is the Coulomb factor, and $S(E)$ is the shape factor.

$\chi_{\mathrm{BEFS}} \equiv \Delta P/P$ is obtained considering the perturbation to the final state electron wave function for a free atom due to the presence of the neighboring atoms. As in EXAFS, the resulting effect χ is proportional to the scattered electron wave function at $r = 0$. Whereas in EXAFS this comes from the strong localization of the tightly bound core electron in the initial state, in the BEFS case it is due to the electroweak interaction short range. Thanks to this analogy one can write

$$\chi_{\mathrm{BEFS}}(k_e) = F_s \chi^{l=0}_{\mathrm{EXAFS}}(k_e) + F_p \chi^{l=1}_{\mathrm{EXAFS}}(k_e), \qquad (1a)$$

where the nature of the decay final states is included in the parameters F_p and $F_s = 1 - F_p$, which indicate the fractions of p-wave ($l = 1$) and s-wave ($l = 0$) electron emission, respectively. $\chi^{l=0}_{\mathrm{EXAFS}}$ and $\chi^{l=1}_{\mathrm{EXAFS}}$ are the EXAFS signals for the L3 (s channel) and K edge absorptions, respectively, and are given by

$$\chi^{l}_{\mathrm{EXAFS}}(k_e) = (-1)^l \sum_{n=1}^{N} B_{nl}(k_e, R_n) e^{-2k_e^2\sigma_n^2} \times \sin(2k_e R_n + 2\delta_{0l} + \delta_{nl}). \qquad (1b)$$

The index n runs over the atoms neighboring the central emitting nucleus, R_n being their distance from the center. The truncation at the Nth neighbor is justified by the finite mean free path of the electron for elastic scattering. k_e is the emitted electron wave number (expressed in Å^{-1}), and R_n directly determines the oscillation frequency generated by the nth atom in k space. $B_{nl}(k_e, R_n) \equiv |f_{nl}(\pi)|/k_e R_n^2$, where in the curved-wave scheme adopted for the present analysis $f_{nl}(\pi)$ is an effective complex backscattering amplitude that is a function of k_e and R_n [14]. $\delta_{0l} = \delta_{0l}(k_e)$ and δ_{nl}, with $\delta_{nl} = \delta_{nl}(k_e, R_n) \equiv \arg[f_{nl}(\pi)]$, are the phase shifts due to the central atom and to the nth

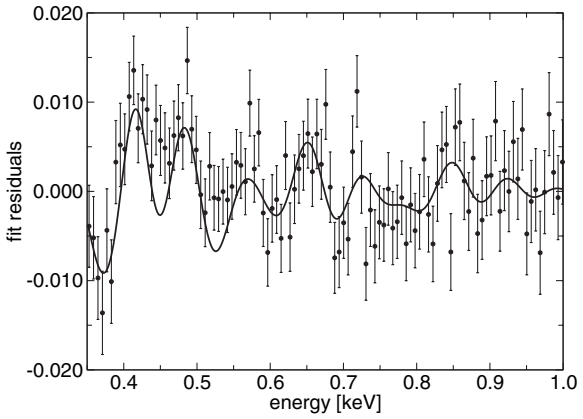

FIG. 2. The filled circles are the experimental fit residuals derived as the difference between the theoretical ^{187}Re β spectrum for free rhenium atoms and the measured one, as explained in the text. The BEFS oscillations appearing in the experimental residuals are fitted by using (1) with the backscattering amplitudes and phase shifts calculated with the Filipponi *et al.* theory [16] (solid line).

surrounding atoms, respectively. The exponential factor gives the Debye-Waller attenuation due to the thermal mean square displacement $\sigma_n^2(T)$ of the nth neighbor atom with respect to the central atom. In the case of our detectors, which work at temperatures below 1 K, the only non-negligible contribution to the Debye-Waller term arises from the zero-point energy.

$AgReO_4$ crystallizes in the scheelite-type tetragonal structure ($a = b \neq c$) with space group $I4_1/a$. While Ag and Re ions are fixed at the corners of the tetragonal unit cell, oxygen ions surround Re ions with almost tetrahedral symmetry at a distance of about 1.7 Å. The cell values have been recently determined by single crystal x-ray diffraction at two different temperatures [15]: at $T = 298$ K, $a = b = 5.3742$ Å and $c = 11.792$ Å, while at $T = 95$ K, $a = b = 5.3585$ Å and $c = 11.722$ Å. No other experimental values below room temperature exist in the literature.

To make a comparison with our experimental data, we have calculated the expected BEFS modulation (1) for $AgReO_4$ in the energy domain, and then convolved it with the detector response—a Gaussian function with a FWHM energy resolution of 23 eV (the average FWHM resolution of our detector array below 1 keV). The effective complex backscattering amplitudes $f_{nl}(\pi)$ have been evaluated with the help of the GNXAS data-analysis code for x-ray absorption spectroscopy from Filipponi *et al.* [16]. For the central atom phase shift δ_{0l} we used the osmium atom values. The theoretical framework underlying GNXAS includes both a full curved-wave treatment and a multiple scattering analysis. The experimental atomic distances at $T = 95$ K have been used as a first guess to determine the neighbor contributions and their first derivative. A first order Taylor expansion was then applied during the fit. This is fully justified by the smallness of the reticular parameter variations. The BEFS calculation was performed for all the atoms contained in a sphere of $\sim$12 Å of diameter centered on the decaying nucleus—the sum truncation in (1). The Debye-Waller factor $e^{-2k_e^2\sigma_n^2}$ has been calculated as in [11].

The experimental data have been obtained as fit residuals of the ^{187}Re β spectrum measured with our microbolometer detector array. First the spectrum is fitted with the theoretical beta shape calculated for the decay without BEFS [7]; then the fit function is compared to the experimental data, and the difference between the two is plotted as a function of the energy of the emitted electron. Since the 8 detectors of our array had different β thresholds (due to different sensitivities to microphonic noise), we divided the fit residual data in energy windows: each energy window contains the fit residuals obtained from the sum β spectrum of the detectors with an energy threshold equal to or lower than the lower limit of the window. In this way we exploit the lower threshold of some detectors without losing statistics at higher energies. The adopted energy windows are four: 350 to 400 eV, 400 to 470 eV, 470 to 750 eV, and 750 to 1000 eV. The four windows contain the residuals obtained from sum spectra of 4, 6, 7, and 8 detectors, respectively. For each of these four spectra a fit with the theoretical function has been performed, and the difference between the fit and the data has been calculated in the proper energy window. The so obtained fit residual subsets have then been composed in one single data set extending from 350 eV to 1 keV, in order to maximize statistics in every energy bin. The final fit residual plot is shown in Fig. 2. Above 1 keV the oscillatory modulation of the present data fit residuals is not statistically significant, due to both the need of more statistics and the fading off of the BEFS effect related to the zero-point energy (Debye-Waller factor). The experimental data were then fitted with the theoretical BEFS modulation (1) calculated as explained above. Free parameters of the fit are F_p and the cell values a and c.

The results are shown as a solid line in Fig. 2. The best fit yields $F_p = 0.84 \pm 0.30$, $a = b = 5.344 \pm 0.006$ Å, $c = 11.704 \pm 0.037$ Å, with a corresponding χ^2/DOF of 0.67. More statistics in the experimental data would be needed to reduce the fit errors but the obtained results indicate the p-wave electron emission final states in ^{187}Re β decay as the dominant contribution. This is in accordance with theoretical considerations [10]. To our knowledge, this is the first time that such a parameter is determined experimentally. It should also be noted that the comparatively large error on F_p is basically due to the small difference between the $l = 0$ and $l = 1$ signal components. This difference, however, would be enhanced in systems where the p-wave degeneracy is lifted by a reduction of the point symmetry around the β emitter. The cell values a and c obtained from the fit agree with the ones extrapolated to the detector operating temperature $T = 100$ mK from the literature data reported above, assuming a rigid cell contraction below 95 K, with no distortion or phase transformations.

More sensitive calorimetric neutrino mass experiments will require higher statistics and improved energy resolution [17]. In these conditions the BEFS modulation over the entire ^{187}Re β spectrum may be detectable, and it would be possible to extend and test the BEFS calculation up to the ^{187}Re β end point. A more complete evaluation of the BEFS effect over the entire energy range will also allow one to estimate eventual systematic uncertainties induced in the m_ν determination. However Monte Carlo simulations show that the BEFS modulation in $AgReO_4$ can be neglected in experiments with m_ν sensitivities down to about 1 eV.

As already suggested [5,11], the BEFS effect could be a useful tool for structural studies of compounds containing a β-emitting isotope. Cryogenic calorimeters can be made with many different absorbers, so they are the ideal detectors for the study of different crystals and molecules. However, this work also demonstrates how the study of a

subtle condensed matter effect can provide important insight into a nuclear physics process.

This work is supported in part by the Commission of European Communities under Contract No. HPRN-CT-2002-00322. Other information can be found at http://crio.mib.infn.it/wig/.

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