The Beta Environmental Fine Structure (BEFS): The XAFS Nuclear Analogue

A. Monfardini[1], G. Benedek[2,3], O. Cremonesi[3,4], A. Filipponi[5], A. Nucciotti[3,4] and M. Sisti[3,4]

[1]ITC-IRST and INFN sez. Padova, Via Sommarive, 18 I-38050 Povo (TN), ITALY
[2] Dipartimento di Scienza dei Materiali dell'Università di Milano-Bicocca, Via Cozzi 53, I-20125 Milano, ITALY
[3]Istituto Nazionale di Fisica Nucleare (INFN) sez. Milano-Bicocca, Piazza delle Scienze 3, I-20126 Milano, ITALY
[4] Dipartimento di Fisica dell'Università di Milano-Bicocca, Piazza delle Scienze 3, I-20126 Milano, ITALY
[5]Dipartimento di Fisica dell'Università dell'Aquila, Via Vetoio, I-67010 Coppito di L'Aquila (AQ), ITALY

Abstract. The Beta Environmental Fine Structure (BEFS) effect is an oscillatory modulation on the otherwise smooth spectrum of electrons emitted by beta-decaying nuclei. The existence of this effect was theoretically proposed in 1991, for condensed emitters, in analogy with XAFS. In BEFS the electron, playing the role of the XAFS photoelectron, originates directly from the nucleus and an anti-neutrino is emitted at the same time. We present evidence for BEFS oscillations observed in Silver Perrhenate ($AgReO_4$) low-temperature (0.1K) microbolometers, together with a XAFS-like analysis that allowed for the first time a direct measurement of the anti-neutrino angular momentum [1]. We discuss the physical analogies and differences between BEFS and XAFS and the implications for the next generation experiments aimed at measuring the neutrino mass on purely kinematic grounds. Moreover, we briefly discuss the potential and the limits of BEFS-based techniques with respect to the classical XAFS.

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INTRODUCTION

In a large number of isotopes, as a consequence of a spontaneous nuclear transition, an electron-antineutrino pair is emitted. This reaction is the well-known beta decay, and occurs with a range of half-lifes ($T_{1/2}$) spanning at least 20 orders of magnitudes, from milliseconds to the Cosmological scale of 10^{10} years. The continuous nature of the electron energies spectrum led in 1930 to the famous postulate in which Pauli, as a "desperate remedy" to save the energy-momentum conservation laws, suggested the existence of a sterile, spin ½, low-mass particle then named "neutrino". Soon afterwards, Fermi elaborated the first theory of the so-called "Weak Interaction" realizing that the known forces couldn't account for the new evidences. After more than 20 years of inconclusive attempts, the elusive free neutrino was finally detected in 1953 [2]. This success boosted the experimental and theoretical efforts in the study of weak interactions. Recently, the evidence of non-zero mass, implied by the incontrovertible observation of atmospheric neutrino flavour oscillations [3], represented the first, and to date unique, evidence for Physics beyond the particle physics Standard Model. Among the open questions, with important implications in Fundamental Physics and Cosmology, the absolute value of the neutrino mass remains beyond experimental reach. The study of the beta spectrum shape is the most direct way of obtaining such information, not requiring other hypotheses on the neutrino properties.

An interesting "twist" in the beta spectrum, the Beta Environmental Fine Structure (BEFS), has been theoretically suggested in 1991 by Koonin [4] in analogy with XAFS. In BEFS the beta electron originating from the Nucleus plays the role of the photoelectron in XAFS. The result is that, due to the interference between the direct beta electron wave-function and the scattered waves by the neighboring atoms, the nuclear transition probability is perturbed in an oscillatory way. The residuals versus energy with respect to the smooth spectrum expected in case of an isolated atom are calculated in complete analogy with XAFS. The information contained in a calorimetric BEFS measurement allowed us to obtain interesting information on one peculiar beta transition.

LOW TEMPERATURE MICROCALORIMETERS

Low Temperature Detectors for single events studies are now extensively adopted in photon detection, neutrino mass experiments (single and double beta decay), dark matter and rare events searches [5]. The working principle is shown in figure.

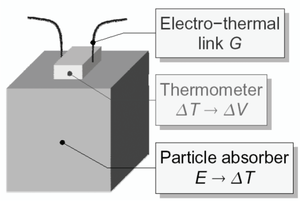

FIGURE 1. Low Temperature Microcalorimeter working scheme. A heat signal is internally generated and read-out by a thermometer linked to the cold finger of a proper refrigerator (T<0.1K).

A particular application is the direct (kinematic) measurement of the neutrino mass based on the following beta reaction:

$$^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os} + \overline{\nu}_e + e^- . \qquad (1)$$

The neutrino mass determines a slight deformation of the electron energy spectrum near the end-point, where the spectrum itself is asymptotically zero. The isotopic abundance of ^{187}Re in natural rhenium is 62.8%. The end-point is only of the order of 2.5keV; the sensitivity to a rest mass of the electron antineutrino is thus maximized. In the transition the nuclear spin changes from $5/2^+$ to $1/2^-$, and as a consequence the antineutrino-electron pair must carry at least one fundamental unit of orbital angular momentum. The ^{187}Re beta decay is then by definition "first-forbidden", and a large half-life is expected. Adopting metallic rhenium microcalorimeters $T_{1/2}$ = $(4.12\pm0.11)\cdot10^{10}$ yr. has been determined [6]. The extremely long lifetime of the ^{187}Re nucleus allows the Re-Os abundances ratio to be used for Cosmochronology determinations [7].

In our case, namely the experiment MIBETA, the microcalorimeters are made of Silver Perrhenate ($AgReO_4$) dielectric absorbers ($m_{abs}\approx300\mu g$) coupled to heavily doped/compensated Silicon thermistors [8]. The array is run at about 0.1K in a dilution refrigerator and calibrated via an external X-ray fluorescence source. A one year long measurement has been carried out with a eight detectors array, resulting in the best limit on the neutrino mass ever obtained with the calorimetric technique: $15eV/c^2$ [9]. The average energy resolution of the detectors at the end-point was ΔE_{FWHM}=23eV. A new challenging experiment, MARE (Microcalorimeters Arrays for a Rhenium Experiment), based on the same technique but with thousands of channels, has been recently proposed to break into the more interesting sub-eV/c^2 range of sensitivities [10].

THE BEFS EFFECT

In the original paper, Koonin had evaluated the effect in case of ^{3}H and ^{14}C. Both the beta decays considered are "allowed", meaning that the electron is emitted with spherical symmetry (s-wave, l=0). As already anticipated, the ^{187}Re nucleus is such that the beta electron can carry orbital angular momentum. In [11] we extended the Koonin theory to include this first forbidden beta transition. Almost at the same time, the BEFS effect was observed for the first time by means of a metallic rhenium microcalorimeter [12]. In 2001, the MIBETA array was first operated for a large statistics measurement. The final beta spectrum, consisting of about $6\cdot10^6$ events above the common low energy threshold of 350eV, is reported in figure 2.

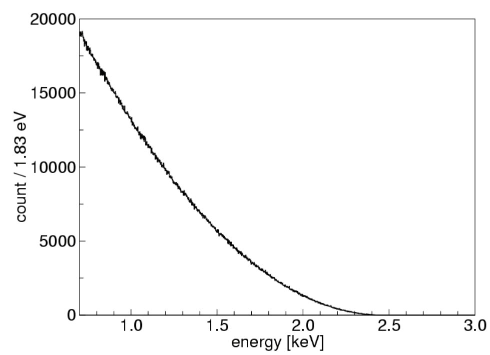

FIGURE 2. MIBETA final ^{187}Re beta spectrum.

As expected, the BEFS oscillations superimposed to an otherwise well-fitted continuous spectrum are evident. The residuals with respect to the theoretical spectrum shape of an isolated atom are shown in figure 3 together with a full curved-wave, multiscattering XAFS-like fit based on the GNXAS [13] software. Atoms within 6Å of the decaying nucleus have been considered in the calculations. The Debye-Waller attenuating factor, at this very low operating temperature, is essentially due to the zero-point energy of the bonded atoms. As evident in figure 3, and despite the large statistical errors, the BEFS nature of the deviations is not debatable.

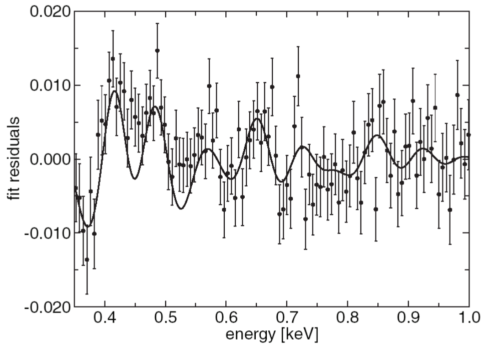

FIGURE 3. Fit residuals fitted with a realistic BEFS model. Above 1keV the error bars become too large, and the analysis is restricted to the interval [350eV:1000eV].

Angular momentum conservation allows for two possible lepton states: $\{e(s_{1/2}), \bar{\nu}(p_{3/2})\}$ (s-wave electron) and $\{e(p_{3/2}), \bar{\nu}(s_{1/2})\}$ (p-wave electron). The case in which the two leptons have opposite spins would require two units of orbital angular momentum to be carried away, and is thus cinematically suppressed to the second order. The s-wave electron case is analogous to the $l-1$ channel in the L_3 edge XAFS, while the K edge is similar to the p-wave electron situation. The latter is possible only in beta forbidden transitions. Considering the final effect as an incoherent superposition of the two quoted states, we were able to estimate the fraction of p-wave electron decays. If F_p is the fraction of such events, from the residuals fit we estimate: $F_p=0.84\pm0.30$. This represent to our knowledge the first direct measurement of the electron (antineutrino) orbital angular momentum, confirming the qualitative expectations based on purely kinematical arguments [14]. This measurement, which is possible thanks to the existence of an EXAFS-like phenomenon, has fundamental implications in Nuclear Physics [1]. The large error associated to the F_p parameter is mainly determined by the poor measurement statistics. The silver perrhenate crystal is a scheelite-type tetragonal (a=b≠c) structure with $I4_1/a$ space group. The reticular parameters obtained in the same BEFS fit are: a=b=5.344±0.006Å, c=11.704±0.037Å. These are in agreement with the expected values, extrapolated back to the operating temperature T=0.1K.

IMPLICATIONS FOR NEUTRINO MASS MEASUREMENTS

So far, neutrino mass experiments based on calorimetric technique had barely the statistics to see the BEFS effect in the low energy part of the spectrum (E<1keV). The past experiments were based on a statistics of about 10^7 beta decays. No deviations are seen or expected at the energies of interest for the neutrino mass. The second generation experiments, with a statistics of about 10^{10} events and aimed at constraining m_ν down to $2eV/c^2$, will soon allow a precise study of BEFS with unprecedented detail. However, according to Montecarlo simulations, the main science goal (m_ν) shouldn't be affected by solid-state effects. Even if not included in the fit, BEFS will not play a significant role down to those limits [15]. The third generation experiment, MARE, on the other hand, with an ambitious goal of at least 10^{14} decays and ultimate sensitivity of 0.2 eV/c^2, will definitely need a precise BEFS understanding to safely isolate the kinematical distortion related to the neutrino mass. Our studies of the BEFS effect in case of ^{187}Re forbidden transition represent a good starting point, and we are confident that the effect will be fully understood with the 2nd generation data in hand.

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REFERENCES

1. Arnaboldi, C., et al., *Physical Review Letters* **96**, 042503 (2006).
2. Reines, F., and Cowan, C.L., *Physical Review* **92**, Issue 3, 830-831 (1953).
3. Fukuda, Y., et al., *Physical Review Letters* **81**, Issue 8, 1562-1567 (1998).
4. Koonin, S.E., *Nature* **354**, 468-470 (1991).
5. Nucciotti, A., *Nuclear Instruments and Methods in Physics Research A* **559**, Issue 2 , 334-336 (2006).
6. Galeazzi, M., Fontanelli, F., Gatti, F. and Vitale, S., *Physical Review C* **63**, Issue 1, 014302 (2001).
7. A. Monfardini, "Microbolometri per lo studio della massa del neutrino", Ph.D. Thesis (in italian), Università degli Studi di Milano, 2000.
8. Alessandrello, A., et al., *Physics Letters B* **457**, Issue 1-3, 253-260 (1999).
9. Sisti, M., et al., *Nuclear Instruments and Methods in Physics Research A* **520**, Issue 1-3, 125-131 (2004).
10. Monfardini, A., et al., *Nuclear Instruments and Methods in Physics Research A* **559**, Issue 2, 346-348 (2006).
11. Benedek, G., et al., *Nuclear Instruments and Methods in Physics Research A* **426**, 147-155 (1999).
12. Gatti, F., et al., *Nature* **397**, 137-139 (1999).
13. Filipponi, A., et al., *Physics Review B* **52**, 15122 (1995).
14. Williams, R.D., et al., *The Astrophysical Journal* **281**, 363-366 (1984).
15. Monfardini, A., et al., *Nuclear Instruments and Methods in Physics Research A* **559**, Issue 2, 364-366 (2006).