LAPP-EXP 96-02
CPPM 96-02
ISN 96-10
LPC 96-05
Fevrier 1996

omparison of anti-neutrino reactor spectrum models with the Bugey 3 measurements

B.Achkar [b],R.Aleksan [e],M.Avenier [b],G.Bagieu [b],J.Bouchez[e],R.Brissot [b]
J.F.Cavaignac [b],J.Collot [b],M-C.Cousinou [c],J.P.Cussonneau [d],Y.Declais [a],Y.Dufour [d,†]
J.Favier [a],F.Garciaz [c], E.Kajfasz [c],H.de Kerret [d],D.H.Koang[b],B.Lefièvre [d]
E.Lesquoy [e],J.Mallet [e],A.Metref [a],E.Nagy [c], M.Obolensky [d],H.Pessard [a]
F.Pierre [e], A.Stutz [b], J.P.Wuthrick [d,†]

[a] *Laboratoire d'Annecy-le-Vieux de Physique des Particules, LAPP,*
IN2P3-CNRS, BP 110, F-74941 Annecy-le-Vieux, CEDEX, France

[b] *Institut des Sciences Nucléaires,*
IN2P3-CNRS, F-38026 Grenoble, CEDEX, France

[c] *Centre de Physique des Particules de Marseille,*
Faculté des Sciences de Luminy,
IN2P3-CNRS, F-91288 Marseille, CEDEX 09 France

[d] *Collège de France, Laboratoire de Physique Corpusculaire,*
IN2P3-CNRS, F-75231 Paris, CEDEX 05, France

[e] *CEA, DAPNIA, Service de Physique des Particules,*
CE Saclay, F-91191 Gif-sur-Yvette, CEDEX, France

(Submitted to Physics Letters B)

Abstract

The Bugey 3 neutrino oscillation experiment has provided high statistics neutrino energy spectra recorded at 15 and 40 meters from a nuclear reactor core. Assuming no oscillations, the measured spectra favor a model of reactor spectrum based on the beta spectra measured at ILL.

---

†*deceased*

1 Introduction

Since the discovery of the neutrino [1], nuclear reactors have been used as powerful sources of $\bar{\nu}_e$'s to study the properties of this particle, in particular the possible oscillations between leptonic flavors [2]. The energy of these $\bar{\nu}_e$'s, below 10 MeV, limits such oscillation experiments to the so-called "disappearance" method where a deficit of the initial flavor is searched for.

The simplest way to search for $\bar{\nu}_e$ disappearance is to measure the rate of the charged current reaction:

$$\bar{\nu}_e + p \longrightarrow e^+ + n \tag{1}$$

at a given distance of a reactor and compare it to the expectation. An improvement in sensitivity is achieved by measuring the energy spectrum of the detected neutrinos, as the neutrino deficit will vary with energy for oscillation lengths of the order of the source-to-detector distance.

Experiments are now able to register more than 10^5 neutrino interactions, but their sensitivity to oscillations, when measuring at a single location, is limited by the insufficient knowledge of the reactor spectrum rather than by statistical accuracy. Indeed, several predictions on reactor spectra can be found in the literature[2], but they differ by more than 10% above a few MeV. To overcome this limitation, most experiments have performed measurements at several distances, so that a comparison of these measurements, independent of the uncertainties on the initial spectrum, gives for the lower values of δm^2 a better sensitivity to oscillations than experiments performed at a single location (these comparisons are not sensitive to high δm^2 values for which the oscillations are washed out before reaching the detector).

It is clear that the high statistical accuracy reached by recent experiments can then be used to give constraints on the source spectrum which are more precise than the above-mentioned discrepancies, so that experiments can now discriminate between the various existing models for reactor neutrino spectra.

The Bugey 3 collaboration [3] has carried out a program of oscillation search near a 2800 MW Pressurized Water Reactor (PWR) of the French electricity company (EDF). With two shielded bunkers (15 meters and 40 meters away from a reactor core), we accumulated 120000 neutrino events at three distances. Three identical detectors using each 600 liters of ^6Li doped liquid scintillator [8] optically divided in 98 independent cells were built for this experiment. No oscillations have been found and we have substantially extended the previously excluded $\bar{\nu}_e \longrightarrow \bar{\nu}_x$ region in the $(sin^2 2\theta, \delta m^2)$ plane (reaching $10^{-2} eV^2$ in mass and 2.10^{-2} in mixing, 90% CL). Signal-to-noise ratios as large as 25 (15 m) and 2.2 (40 m) have been obtained. The experimental set-up and techniques have been described elsewhere [9].

In this letter we focus on the comparison of our data to the various reactor spectrum models introduced in section 2. Such a comparison requires a precise knowledge of the efficiency and the energy response of the detector to neutrino interactions: section 3 describes the energy calibration and monitoring of the Bugey detector, and the achieved performance. Section 4 describes how model spectra are compared to our data, and conclusions are drawn assuming that any possible oscillation is far away from our sensitivity domain.

2 The anti-neutrino reactor spectrum

It is well known that neutrinos are emitted through β-decays of unstable nuclei produced by the fission of the four main fissile elements present in the PWR fuel: ^{235}U, ^{239}Pu, ^{238}U and ^{241}Pu. For each of these 4 parents, hundreds of different nuclei are involved with their own Kurie distributions. The most rigorous way to evaluate these individual spectra would be to identify all the decay products and their production rates for one fission of the parent, then knowing their Kurie parameters, to deduce the summed anti-neutrino spectrum. Unfortunately many decay schemes are not known and have to be calculated. Differences between models appear in this part of calculation, depending on whether one just uses mean level densities for the daughter nuclei, or one takes into account more precise nuclear effects[12]. Another approach is purely phenomenological: measurements were performed at the high flux ILL neutron facility where small targets of ^{235}U,^{239}Pu,^{241}Pu were neutron activated, followed by a very accurate measurement of the overall β spectrum in the BILL high precision spectrometer [11]. From these β spectra, anti-neutrino spectra are deduced by a global fit of 30 arbitrary Kurie distributions. From now on we will use the definitions listed below:

- 'Model 1' is based on the calculated spectra of Klapdor and Metzinger who used in their work a detailed calculation of the level densities of the daughter nuclei involved in the beta transition probability of the unmeasured decay schemes[12].
- 'Model 2' uses the results of Tengblad et al. [10]; the authors have measured at CERN (ISOLDE) the beta spectra of 111 short-lived isotopes unknown before, which should contribute to the high energy part of the neutrino spectrum. They compute for each measured beta-decay electron spectrum the corresponding neutrino spectrum, and they add them all with the appropriate weights. We used for ^{241}Pu data the ILL measurement, since they did not calculate this element.
- 'Model 3 ' makes use of the ILL $\bar{\nu}_e$ spectra [11] for ^{235}U,^{239}Pu and ^{241}Pu ,while for ^{238}U, whose contribution to the total neutrino flux does not exceed 8 % (it has a fission threshold of 1 MeV and a low fission cross-section), we used the calculated spectrum of Klapdor and Metzinger [12]. In ref [11], the overall normalization accuracy is 1.9 %, while the precision of the neutrino spectrum extraction method which is not a bin-to-bin error but a global shape uncertainty, ranges from 1.34 % at 3 MeV (neutrino energy) to 9.2 % at 8 MeV.

The authors of model 1 and 2 can compare directly their computed β spectra to the ILL measurements. The best agreement is obtained with model 1 whose ratios stay around 1±0.05 in the 2 to 8 MeV range.

Time evolution of the neutrino spectrum

The neutrino spectra for each of the four parent fuel elements are different; during one annual cycle of electricity production their proportions in the core vary (burn-up effect), as can be seen in Fig.1(a), so does the total spectrum which changes appreciably with time (Fig. 1(b)). From EDF reactor surveys, we know the isotopic composition of the 157 fuel rods at the beginning and at the end of an annual cycle, and also their daily cumulated burn-ups. This information allows us to calculate for each day and each fuel rod the proportions of the four fissile elements. The radial and vertical power distributions are respectively deduced from these burn-up maps and from monthly internal neutron flux measurements taken along 50 instrumented rods. The precision on the vertical and radial neutrino source barycenter determination is a few centimeters and is a part of our global normalisation error[3]. We are thus able to compute the reactor neutrino spectrum for each day of data taking [13].

3 The positron energy measurement

In the reaction (1), as the neutron carries a few tens of keV (taken into account in the analysis), we can relate the neutrino and positron energy by:

$$E_{\bar{\nu}} \simeq E_{e^+} + 1.8MeV \tag{2}$$

The amount of light emitted during the positron slowing-down in one cell is collected by two opposite photo-multipliers. The two recorded charges Q_{left} and Q_{right} have to be combined in order to extract the positron energy :

- *Correction of the z dependence.* The sum $Q_{left} + Q_{right}$ is an approximate parabolic function of the z position along the cell axis, with its minimum centered at the middle of the cell. We correct it for this variation using a function $F(Z_q)$, where :

  $$Z_q = \frac{Q_{left} - Q_{right}}{Q_{left} + Q_{right}} \tag{3}$$

  is our localization variable. The function $F(Z_q)$ is parameterized from our Monte-Carlo simulation of the cell response; the adequacy of this light collection simulation was verified by two sets of measurements: the backward Compton scattering of a collimated gamma source placed at different distances from the photo-multipliers [3, 9] and the neutron capture peak position dependence with Z_q obtained from monthly neutron calibration runs.

- *Energy calibration.* To convert charges into energy, the following calibration procedure has been elaborated: each cell of the 3 modules was monthly calibrated using a 4.4 MeV *Am-Be* gamma source. The Compton peak was enhanced including the other cells in an anti-multi-Compton trigger, as can be seen in Fig.2. The daily interpolation of our calibration coefficients was obtained with a 0.5% accuracy using a light pulser system[3, 6, 7, 9]. When averaged over the 98 cells of a detector, this becomes negligible compared to the systematical error described below. The mean amount of energy deposited in a cell in our Compton calibration procedure has been determined by two independent Monte-Carlo programs, taking care of edge effects, anti-multi Compton trigger, dead matter, light propagation, digitization, z dependence, gammas issued from neutrons of the $Am - Be$ source interactions with the liquid and the shielding, etc. Both programs agree within 0.2%.

- *Linearity.* The linearity of the detector has been measured with several gamma sources for which the Compton behavior within our detector and trigger have been simulated in the same way as for the monthly calibrations. Fig.2 shows the result; despite the nice behaviour, there is a small offset caused by a defect of linearity below 100 keV induced by non-linear physical effects. Defects in linearity above 4 MeV (limited at 4% for the end of the digitization window) have been measured with the help of the light pulser associated with optical grey filters; both low and high energy distortion effects are included in the analysis.

- *Systematical error on the energy scale.* The final systematical accuracy we claim on the positron energy scale is 34 keV at 4.3 MeV (0.8%); the uncertainty coming from the 511 keV annihilation gammas was estimated to 5 keV. We determined these errors in our Monte-Carlo by varying many detector and trigger parameters involved in the calibration process. The calibration errors, associated to the cell photo-statistics and Compton shape in the fitting procedure, are negligible when averaged on 98 cells[9]. The difference between electron and positron response is also simulated by Monte-Carlo as explained later.

4 Results and discussion

The comparison of neutrino data with those expected from the reactor model is done by generating Monte-Carlo events in the following way:

Neutrino emission,neutrino interaction and neutron capture simulation. As described in [3] and [13], neutrinos are generated with a time dependent distribution discussed previously, following the geometrical power map and the burn-up evolution of the reactor. Reaction (1) is simulated inside the detector and also in the hydrogen-rich matter surrounding it (veto counters); radiative corrections and neutron recoil effects on the cross-section are included [14]. The neutron thermalization is simulated as well as its final capture by a ^6Li or ^1H nucleus.

Positron simulation. The simulation of the positron range includes its energy deposition inside the detector material (slowing-down of the positron, the two-gamma positron annihilation in flight and at rest, wall effects), the light collection process, the digitization effects and the z dependant energy correction.

Experimental data. The same analysis cuts are applied to data and Monte-Carlo events and the ratio of spectra is performed. We used the experimental spectra, background substracted, published in ref[3]; moreover, the data at 15 and 40 meters are merged together, since we have assumed no oscillation. The total statistics represents 120000 neutrino events.

Results. Fig.3 shows the comparison of our data with the three reactor spectrum models previously described. The error bars given in the figures are statistical (data and Monte-Carlo). Systematic errors are represented by the area inside the dotted lines. They contain the deformation of the ratio when changing the energy scale by ±0.8% (one standard deviation), folded with the systematic errors quoted by the authors of the three models. [1]

Discussion.

---

[1] Notice that in ref.[11], model 3, errors are 90 % C.L; we use in this letter errors for 68.3 % C.L. Furthermore, a 1.9 % quoted normalization error has been unfolded. Some small residual bin-to-bin errors coming from the extraction of the neutrino spectrum from a beta decay spectrum , quoted in our previous publication, are neglected here.

One can see the excellent agreement between our data and the model 3 expectation while differences appear for model 1 and model 2. Fitting the ratio with model 3 by a constant gives the value 0.99 (χ^2 of 9.23/11), in perfect agreement as well in absolute normalization for the neutrino flux (normalization and related errors are discussed in detail in ref[3]). The apparent "oscillatory" shape of the ratios with model 1 or 2 is already present in earlier direct comparisons with the beta spectra of ILL[11],[10] and reflect only their differences.

An error on the energy calibration constant (energy scale) would result in a distortion of the ratio spectrum, mainly in the high energy bins. For instance, a modification by 1% of this calibration constant induces a fall (or a rise) in the 6 MeV positron energy region of about 10%. This is clearly illustrated in the lower part of Fig.4 where we have modified the energy scale by 0.4%, which is half the systematical error we claim for the absolute energy scale constant. One can see that the ratio (data/model 3) becomes remarkably flat, with a χ^2 of 4.3/11. Of course the slight negative slope seen in the upper part of Fig.4 can be explained also by a difference between the model and the reality. Nevertheless, the result of this correction is worth mentionning.

5 Conclusion

The high statistics Bugey 3 oscillation search experiment shows an excellent agreement between the measured reactor neutrino spectrum and the model 3 based on the ILL measured beta spectra of neutron activated fissile elements. Our results allow us to state that both the absolute flux [2] and the shape of a PWR reactor neutrino spectrum are accurately modelised. This result is in contradiction with those of ref [15] which disagree with model 3 by 10% in shape.

It is a pleasure to thank the EDF staff at Bugey for their hospitality and technical help, as well as for the financial support of this company.

References

[1] F. Reines and C.L. Cowan, Physical Review 92 (1953) 830

[2] see for instance: F. Boehm and P. Vogel, " Physics of Massive Neutrinos ", 2nd ed., Cambridge University Press (1992)

[3] B.Achkar *et al.*, Nucl. Phys. B534 (1995) 503

[4] see for instance: E.Pasierb *et al.* Phys. Rev. Lett. 43 (1979) 96
G.S Vidyakin *et al.* J. Moscow Phys. Soc. 1 (1991) 85

[5] Y. Declais *et al.*, Phys. Lett. B 338 (1994) 383

[6] P. Besson, doctorat thesis, LAPP (Annecy), 1989.

[7] J. Berger *et al.*, Nucl. Instr. and Methods A279 (1989) 343

[8] S. Ait-Boubker *et al.*, Nucl. Instr. and Methods A277 (1989) 461.

---

[2] A more precise flux determination has been performed at Bugey [5] with an integral detector made of water and proportional ^3He tubes; their measured rate is also in very good agreement with model 3

[9] To be published in Nucl. Instr.anu Methods.
preprint: LAPP-EXP 95-07, CPPM 95-02, ISN 95-108, LPC 95-51

[10] O.Tengblad *et al.*, Nucl. Phys. A503 (1989) 136

[11] K. Schreckenbach *et al.*, Phys. Lett. B160 (1985) 325
A.A. Hahn *et al.*, Phys. Lett. B218 (1989) 365.

[12] H.V Klapdor and J. Metzinger, Phys. Lett. B112 (1982) 22
H.V Klapdor and J. Metzinger, Phys.Rev. Lett. 48 (1982) 127
H.V Klapdor, J. Metzinger, Private communication.

[13] F. Garciaz, Recherche des oscillations de neutrinos auprès d'un réacteur nucléaire, Thèse pour obtenir le titre de Docteur de l'Université de Provence, Marseille, 1992.

[14] P. Vogel, Phys. Rev. D29 (1984) 1918.

[15] Yu. V. Klimov *et al.*, Sov. J. Nucl. Phys. 52 (6) (1990) 994

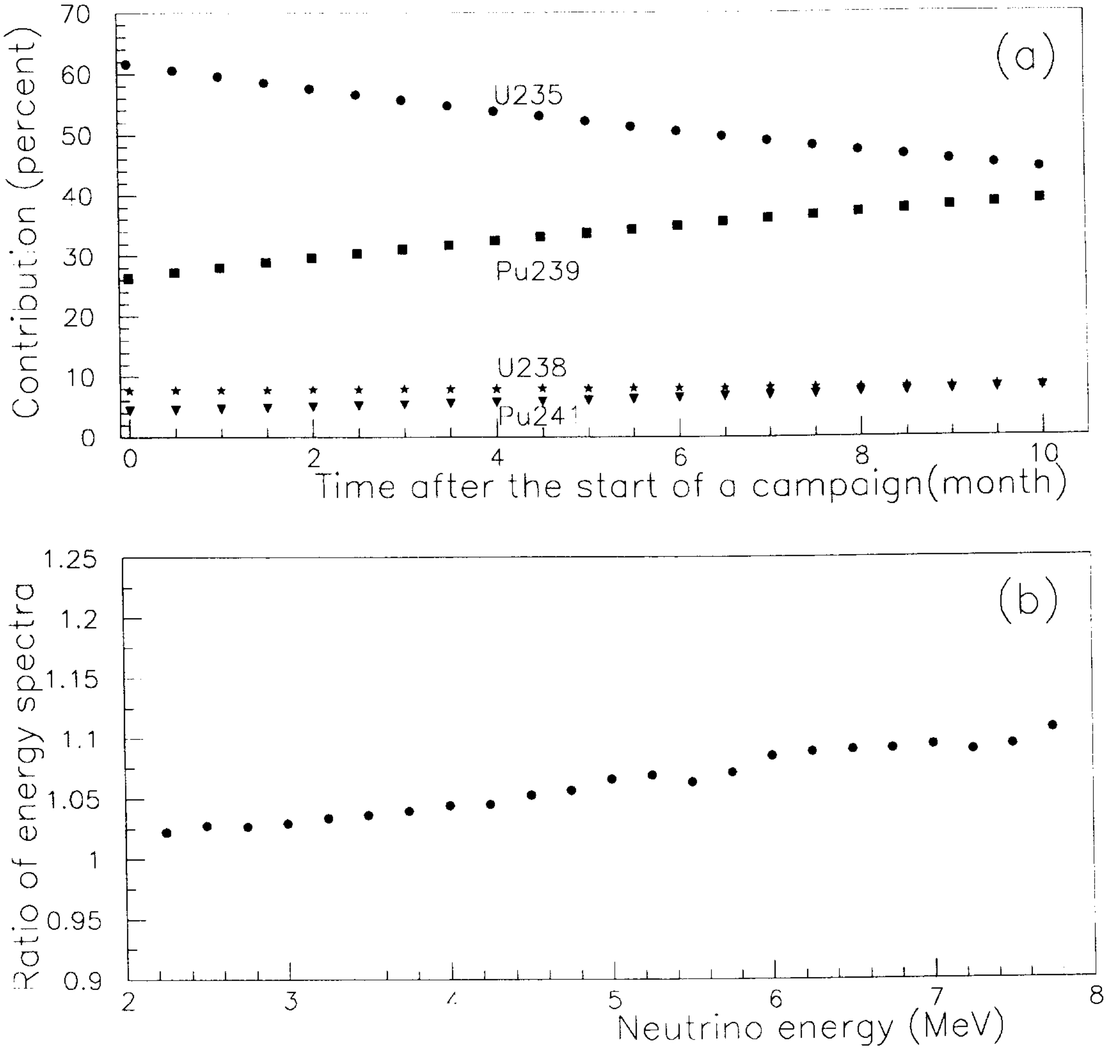

Figure 1: The contribution of the four fissile elements to the number of fissions as a function of the burnup time (a) and the ratio of the neutrino spectra calculated at the beginning and at the end of an annual cycle (b).

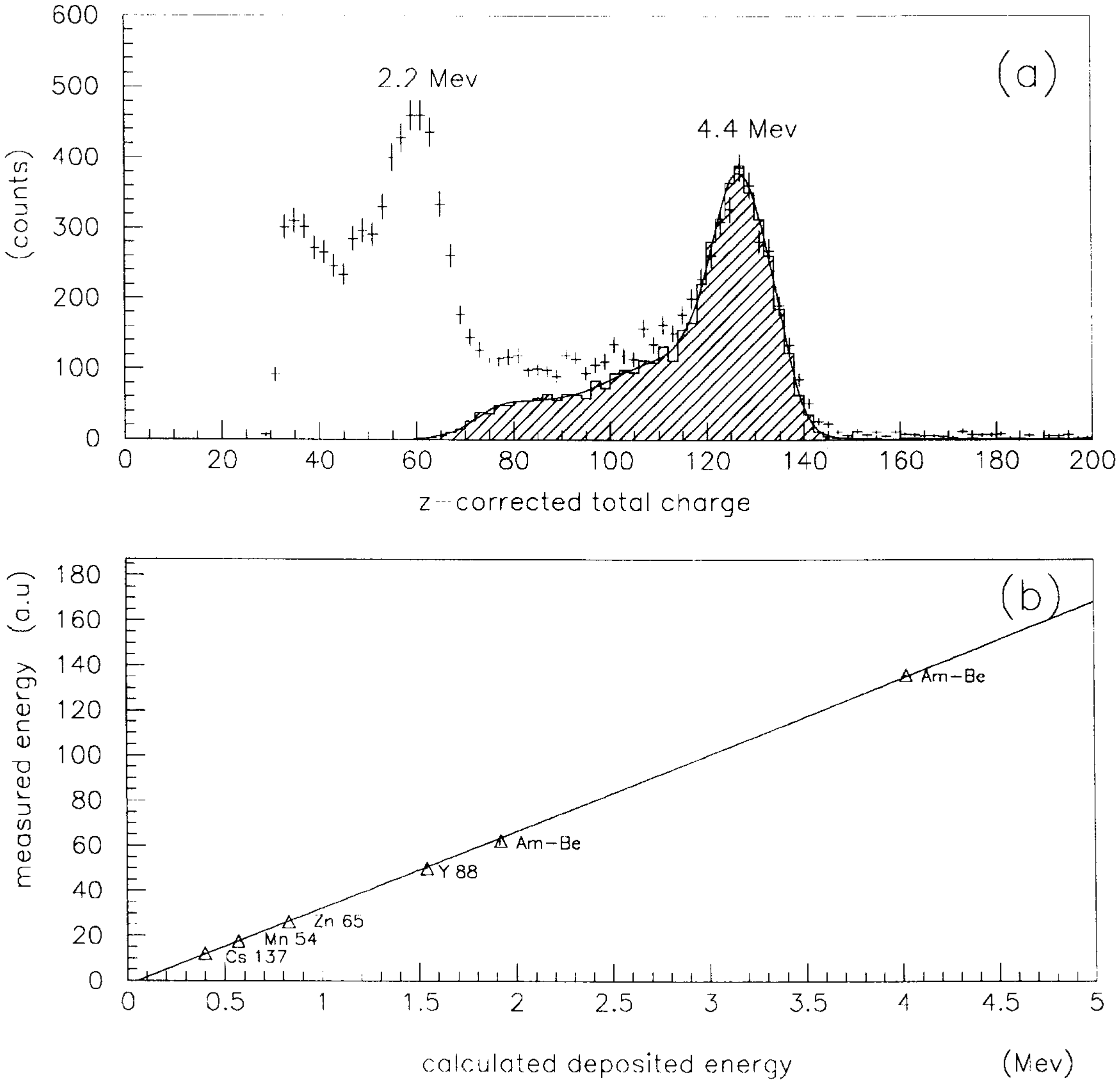

Figure 2: (a) The Compton edge of the $4.4 MeV$ photon obtained with an *Am-Be* source. The solid line is the Monte Carlo simulation (including the threshold effect of the calibration run). The peak near 2 MeV corresponds to gammas from the capture of neutrons in hydrogen not included in the simulation. (b) The total charge measured at the end of the opto-electronic chain as a function of the deposited energy calculated by Monte Carlo for different gamma sources. The error bars are smaller than the symbols except at the 2 MeV peak which corresponds to the neutron capture in hydrogen.

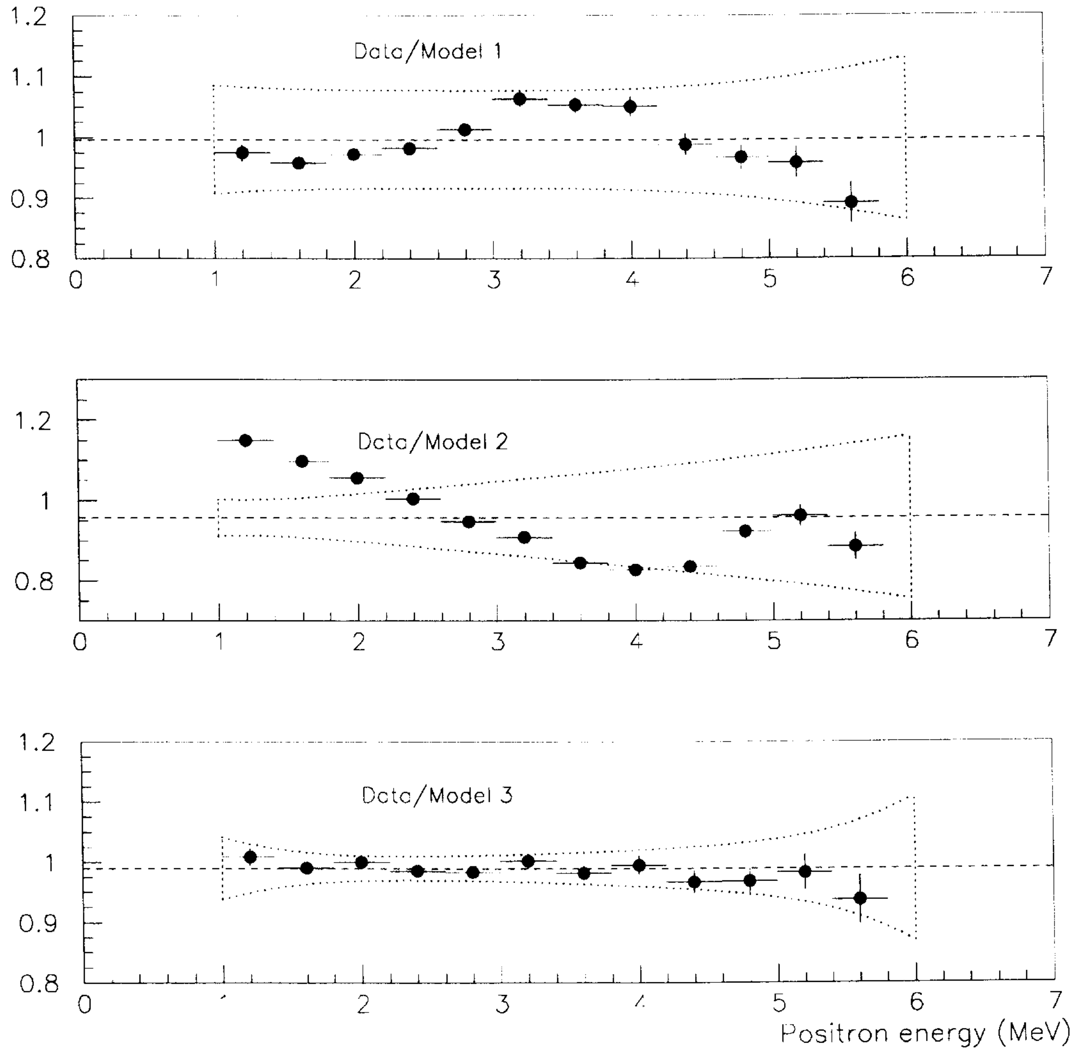

Figure 3: The ratios data/model for the three different reactor spectrum models. Model 1 uses the calculated spectra of Klapdor and Metzinger [11]. Model 2 is based on the work of Tengblad et al.[9] which includes Isolde measurements. The model 3 is made from the ILL beta spectra measurements of Schreckenbach et al.[10]. The dashed lines are the quadratic sum of the quoted errors of the models and the effect of deformation when the energy scale is modified by one standard deviation (0.8%).

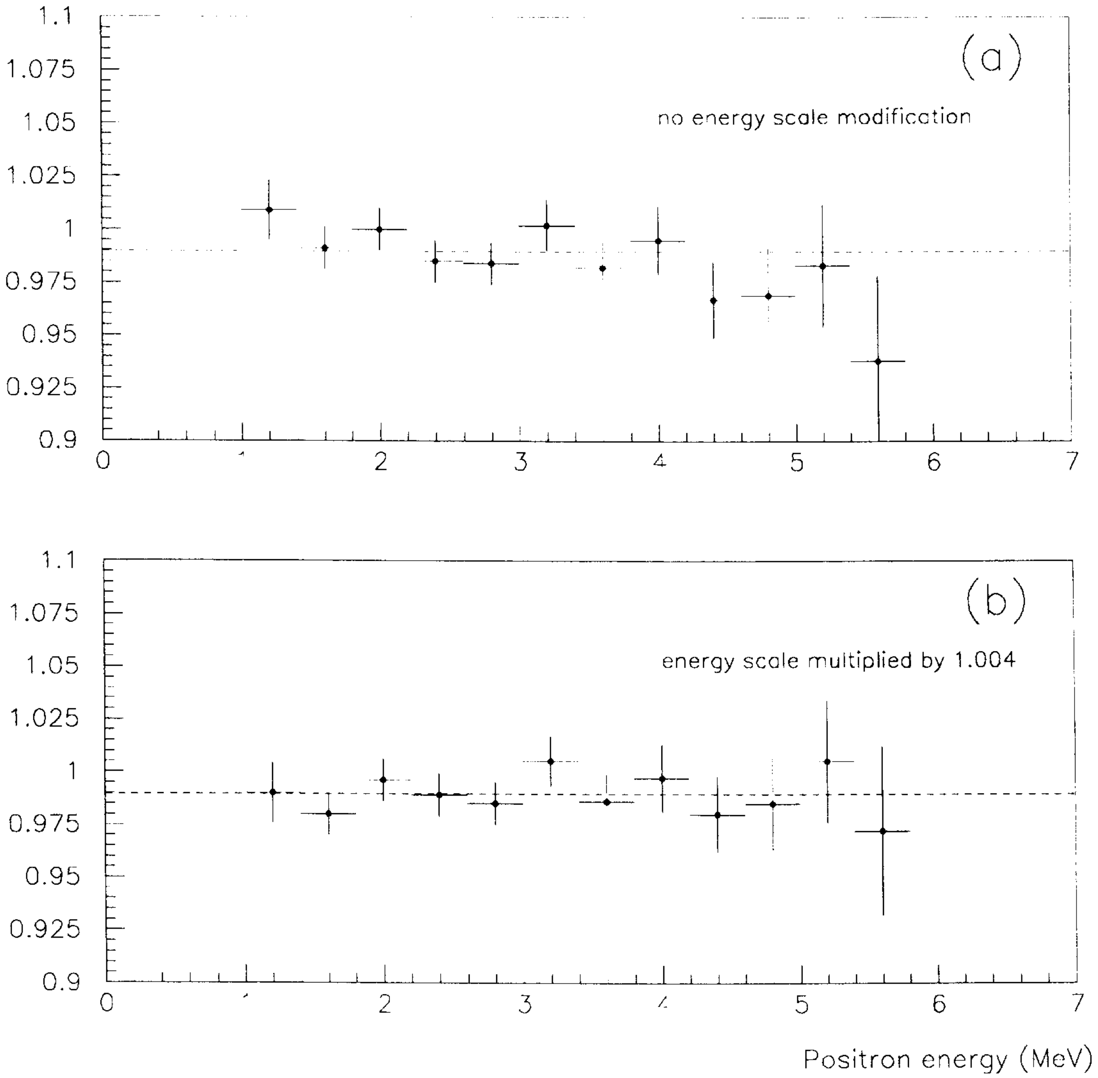

Figure 4: (a) Ratio of the data spectrum by the Monte-Carlo predicted positron spectrum using the reactor spectrum model 3; the dashed line is the fit of a constant which gives a χ^2 of 9.2 for 11 d.o.f. (b) The same plot with the energy scale modified by 0.4% (1/2 of our energy scale systematic error); the agreement with a constant is very good, the χ^2 being 4.3/11.