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Beta spectrum shape studies for the predictions of the antineutrino spectrum from reactors

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Abstract. Nuclear reactors antineutrino measurements at short baselines do not fully agree with model predictions calculated with the Conversion Method. An alternative method to calculate the antineutrino spectra is the Summation Method. Both methods require the shapes of beta spectra as inputs. For that reason a new setup to measure the shape of the beta spectrum of relevant fission products for the calculation of the antineutrino spectra of reactors has been developed. Some preliminary measurements performed at IGISOL with isotopically clean beams are presented in this contribution.

1 Introduction

Understanding the antineutrino ($\overline{\nu}_e$) spectrum from reactors has been a topic of great interest for the neutrino and nuclear physics communities. One objective of this research is dedicated to elucidate the properties of neutrinos taking advantage of their high production rate at nuclear reactor facilities [1]. Secondly it is also aimed at the development of methods for monitoring reactor neutrinos that may be used to help with the non-proliferation of nuclear weapons. [2].

In order to determine the $\overline{\nu}_e$ spectra from reactors, beta (β) decay electrons from reactors fuel byproducts are measured and the total $\overline{\nu}_e$ spectra are reconstructed from such measurements. For the reconstruction of the $\overline{\nu}_e$ spectra two main methods can be used: the Conversion Method (CM), and the Summation Method (SM).

The CM is based on the reconstruction of the $\overline{\nu}_e$ spectra from the main reactors' fuel isotopes (^{235,238}U and ^{239,241}Pu) cumulative β spectra. This method was first introduced by Schreckenbach et al. [3, 4]. Huber and Mueller (H.M.) [5, 6] have recently revisited this method, and they have used information from modern databases to improve the procedure of the CM. In particular, the approach of Mueller et al. [6] is a combined method, it starts from the SM and corrects the remaining discrepancies with the CM.

On the other hand, the reconstruction of $\overline{\nu}_e$ spectra with the SM is made by building such spectra from the contributions of the individual β decays of all of the fission products produced in reactors, then the $\overline{\nu}_e$ spectra can be obtained from these β decay spectra via the relation of conservation of energy [7]. To perform a SM calculations all β (or $\overline{\nu}_e$) spectra must be summed and weighted by their activities as

$$S_k = \sum_{i,b} A_{k,i}\, f_i^b\, s_{k,i}^b\ , \tag{1}$$

where S_k is the total β (or $\overline{\nu}_e$) spectrum of the k reactors' fissile isotopes, $A_{k,i}$ the i fission product activity, f_i^b is the β feeding to the b level β branch, and $s_{k,i}^b$ is the β (or $\overline{\nu}_e$) spectrum of the b level β branch.

The improvements in the models of the $\overline{\nu}_e$ spectra led to the identification of the Reactor Antineutrino Anomaly (RAA) at short baselines (a deficit of measured antineutrinos at distances shorter than 100 m), and to a "bump" in the $\overline{\nu}_e$ energy spectra around the 6 MeV region [1, 8].

Several explanations have been proposed to account for the RAA, like: physics beyond the standard model with the introduction of a fourth sterile neutrino, unidentified problems with the used $\overline{\nu}_e$ detectors (such as the presence of systematic errors in the detection or building materials), inaccuracies in reactor fuel descriptions, etc. Nonetheless, recent efforts have strongly indicated that the use of the SM as an alternative to the H.M. approach for the calculation of $\overline{\nu}_e$ spectra considerably reduces the RAA [7].

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In view of the favorable results of the SM, our collaboration (β-Shape) has developed electron detectors for measuring the β decay spectra of the most relevant contributors to the $\overline{\nu}_e$ spectra of reactors. Some of these decays are dominated by first forbidden transitions, and it has been suggested that these decays have a relevant role in explaining the differences between the measured and predicted $\overline{\nu}_e$ spectra of reactors [9, 10].

Even though it may be thought that the number of relevant nuclei to be included in the SM represents a daunting task due to the large number of fission products produced in reactors, not all of their β spectra contribute the same amount in all energy regions of the $\overline{\nu}_e$ spectra. For example, in the energy region of the "bump" approximately only 15 out of 280 β decaying levels contribute up to 75 % to the total $\overline{\nu}_e$ spectra [11]. Among these relatively few contributing fission products, the measurement of the β spectrum of ^{92}Rb has been of particular importance in our experimental campaign due to its relative high fission yield and contribution to the high energy part of the $\overline{\nu}_e$ spectra [12, 13].

To perform the reconstructions of the $\overline{\nu}_e$ spectra with the SM, reliable β feedings of the fission products of interest must be available to model accurately the β decay schemes. For such applications experimental data free from the Pandemonium effect should be used [14]. Most of the β feedings in conventional data bases have been determined with Germanium detectors, and due to these detectors' low detection efficiencies for high energy γ rays, high energy γ transitions in daughter nuclei might not be detected, causing the β feedings to these high energy levels to be underestimated, and the low energy β feedings to be overestimated. Fortunately, the Total Absorption Gamma Spectroscopy (TAGS) technique can avoid the Pandemonium effect and give improved information on β feedings. TAGS detectors work as γ ray calorimeters. These detectors consist of a large volume of scintillating materials (e.g. NaI or BaF$_2$) that covers almost all the solid angle around the decaying isotopes. They possess a relatively large intrinsic γ detection efficiency, therefore γ transition information losses are minimized. TAGS β feedings in our collaboration are determined after solving the inverse problem with the response matrix of the detector with methods that have been developed by the Valencia group [15].

2 β-Shape experiment

For the measurement of the shapes of the β spectra of interest $\Delta E - E$ detectors were developed by our collaboration. These detectors are composed of a plastic scintillator (E) with a thin layer of silicon (ΔE) in front. The characteristics and dimensions of these detectors have been optimized to ensure the detection of electrons while the rejection of γ rays is maximized in the whole energy range of interest.

For this kind of experiment very clean isotopic radioactive beams of the fission fragments of interest are needed. It is essential to remove any source of contamination from the measured β spectra because the discrepancies in antineutrino spectra of reactors are of the order of a few units (RAA) to tens ("bump") of percentage, therefore, even small disturbances in the shape of these β spectra may impair our effort to try to find an explanation of these issues.

In view of this requirement the experiment was carried out at the IGISOL facility in the University of Jyväskylä, Finland. In our experiment a proton beam of 30 MeV collides with a natural Uranium target and induces fission. The fission fragments are transported to the beam line via a Helium gas jet. Then a preselection of the isotopes by their mass and charge is made in a dipole magnet, and finally the JYFLTRAP double penning trap performs an additional separation of the isotopes by their masses [16].

Thanks to the capability of the IGISOL facility to produce a clean radioactive beam of only one type of isotope, we were able to measure the β decay of ^{92}Rb with reduced contamination from the decays of other isobars. As pointed out by Zakari-Issoufou et al. [12], Sonzogni et al. [13] and Hayen et al. [10], the contribution of this isotope to the total $\overline{\nu}_e$ spectra of reactors is paramount because it has a high endpoint energy (8.1 MeV), its fission yield (4.8 %) is of the same order of the other fission fragments with high production rates, and its first forbidden ground state to ground state β transition dominates its decay. Therefore, it affects the $\overline{\nu}_e$ spectra in the whole energy region of the "bump" with a non-negligible contribution. In addition, the main β branch of this decay does not possess a regular allowed shape. The energy spectrum of the β decay of ^{92}Rb to ^{92}Sr measured at one $\Delta E - E$ detector is presented in Fig. 1.

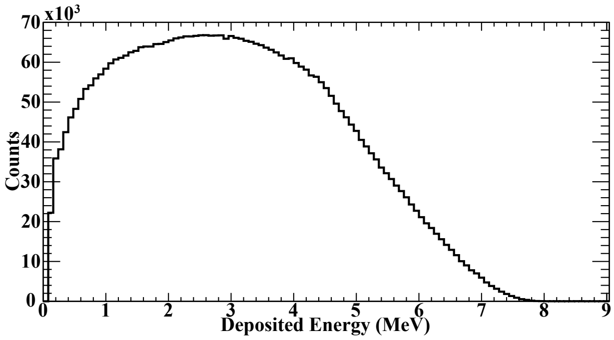

Figure 1. Measured $\Delta E - E$ coincidences spectrum for the decay of ^{92}Rb.

3 Comparisons to simulations

To obtain the actual energy distributions of β electrons it is necessary to deconvolute the measured β spectra. For this reason, first we need to validate the Monte Carlo simulation of the experiment to guarantee an appropriate determination of the response matrix of the detectors. To perform the validation, we need to show that the simulation spectra can properly reproduce experimental measurements whose β decay schemes are well known. The simulations for the validation have to take into account that the experimental data may suffer from the Pandemonium effect, and must reproduce the complexity of a nuclear decay with different decay channels open [14].

Hence, we have created an event generator for the Monte Carlo simulations that can generate β decay spectra based on TAGS and ENSDF β feeding data with their corresponding γ cascades. Conversion electrons including E0 transitions and internal electron-positron pair production has been added when necessary. These inclusions are necessary to describe in great detail the decays of the nuclei of interest.

Another important feature of the event generator is the possibility to modify the shapes of the spectra of any branch of the β decay scheme according to the possible shape factors that affect the β transitions. This generator can use the output calculations of the Beta Spectrum Generator (BGS) code developed by Hayen & Severijns [17] for allowed β shapes with several nuclear and atomic corrections. First forbidden shape factors calculated by Hayen et al. [10] (or any other type of forbidden shape factor) may also be added to the corresponding decays when necessary.

Hayen's code [17] provides an extensive set of shape factor corrections for allowed decays that account for nuclear and atomic interactions that affect the energy distribution of the emitted β electrons. The weights of the contributions of these corrections to the spectra depend on the charge and mass of the isotopes and the kinetic and endpoint energy of the β electrons.

As a first approach, it was decided to only include allowed shape corrections that produce relative changes to the standard allowed shape (composed by the Phase Space factor plus the Fermi function (F_0)) of the order of the percentage level. Less important corrections may not be identified within the uncertainty of the measurements. The corrections selected were: the Nuclear Finite Size (L_0) and Radiative (R) correction, and the Atomic Exchange (X), Mismatch (r) and Screening (S). The Recoiling Nucleus (R_N) and Recoil Coulomb Distortion (Q) were also added, but these last two will be discarded in future analyses due to their limited effect on the shape of the spectra [17]. Moreover, a parametrized form of the Weak Magnetism correction (C_{WM}) for allowed Gamow-Teller transitions [5, 11] of the form

$$C_{WM}(W) = 1 + (0.67)(10^{-2})(0.511)W \tag{2}$$

was used when needed, where W is the β electron total energy in natural units. Therefore, the following relation

$$\begin{aligned} S^{b}_{k,i}(W) \propto\ & \eta W (W_0 - W)^2\, F_0(Z,W)\, L_0(Z,W) \\ & R(W,W_0)\, X(Z,W)\, r(Z,W)\, S(Z,W) \\ & R_N(W,W_0,M)\, Q(Z,W,M) \end{aligned} \tag{3}$$

was used as the corrected shape for allowed spectra (with Eq. (2) inserted when necessary), where η is the β electron momentum, W_0 is the endpoint energy of the decay, and Z and M are the daughter nucleus charge and mass respectively in natural units.

To validate the Monte Carlo model we will compare the results of the simulations with the experimental data. For this, a selection of the experimental spectrum has to be done carefully. During the β-Shape experimental campaign commonly used β sources and specific isotopes extracted from the JYFLTRAP (such as ^{90}Sr and ^{114}Ag) were measured for calibration purposes. Measurements using conventional β sources were done with a source holder in air, and the other sources produced in the facility were implanted on a movable magnetic tape under vacuum. The positions of the detectors with respect to the source holder and tape were kept identical.

To obtain a validation that can be extrapolated to other β spectra of the fission products of interest, this process has to be done with a spectrum measured in the same conditions as the measurements of the radioactive isotopes extracted from the trap. One possible case is the decay of ^{114}Ag which is dominated by allowed transitions. Since the production rate at IGISOL of ^{114}Ag is considerably lower than the production of ^{114}Pd, and due to the lower Q value of the latter with respect to the former, it was decided to produce ^{114}Ag through the decay chain of ^{114}Pd. This decay chain is represented by

$$^{114}\mathrm{Pd} \xrightarrow[\mathrm{Q\,=\,1.44\;MeV}]{\mathrm{t_{1/2}\,=\,2.42\;min}} {}^{114}\mathrm{Ag} \xrightarrow[\mathrm{Q\,=\,5.087\;MeV}]{\mathrm{t_{1/2}\,=\,4.6\;s}} {}^{114}\mathrm{Cd}\,.$$

The measurement of the combined decays of ^{114}Pd and ^{114}Ag only took a few hours to be completed with satisfactory statistics.

In the simulations performed for this case we need to include the full decay chain ($^{114}\mathrm{Pd} \rightarrow {}^{114}\mathrm{Ag} \rightarrow {}^{114}\mathrm{Cd}$). The ratio of the decays is 1:1 since the half-life of the ^{114}Pd (the parent) is much longer than the half-life of the ^{114}Ag (the daughter). Both decays are dominated by allowed transitions and by their ground state to ground state β branches (92 and 78 % respectively [18]). Therefore, it is expected that only with the corrected allowed shape plus the Weak-Magnetism term (Eqs. (3) and (2)), and using the β branches reported from high resolution spectroscopy experiments (ENSDF data), we should be able to obtain a satisfactory description of the experimental spectrum with the Monte Carlo simulation.

Figs. 2 and 3 show preliminary comparisons of the experimental spectrum of the decay chain of ^{114}Pd measured with one of the β-Shape detectors compared with simulations using β branches reported by ENSDF [18]. Simulations were done employing allowed shapes. The blue line was calculated only with the Fermi function in all β branches of both isotopes, and the red line was obtained by adding all Hayen's corrections for allowed β spectra plus the parametrized form of the Weak Magnetism term in all Gamow-Teller transitions. A measured background was added to the simulations.

Fig. 2 shows that the simulations describe relatively well the experimental β distribution despite the presence of a small discrepancy with respect to the experimental spectrum between 1 and 2 MeV, and at the high energy region of the decay of ^{114}Ag. It must be highlighted that the values of χ^2/df from the simulations with only the Fermi function (blue line) and Hayen's corrections plus the Weak Magnetism (red line), (22.1 and 49.8 respectively for a binning of 80 keV per channel), favor the prediction of the

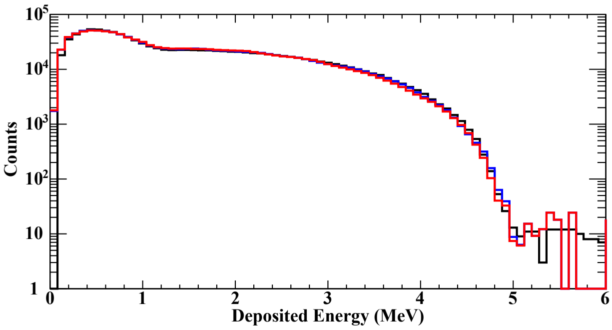

Figure 2. Measured ^{114}Pd decay chain $\Delta E-E$ coincidences spectrum (black line) compared with simulations with the Fermi function (blue line) and including Hayen's corrections plus the Weak Magnetism term (red line).

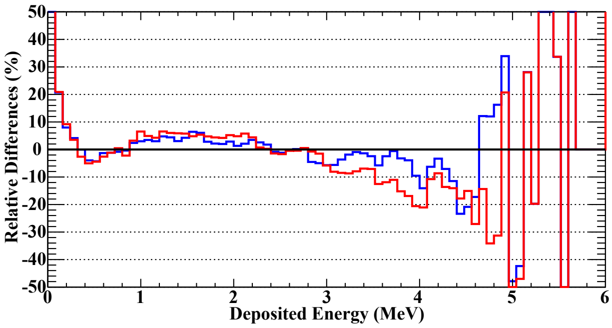

Figure 3. Relative differences of simulations with respect to the measured spectrum from Fig. 2.

first spectrum over the second one. This is an unexpected preliminary result that we are still trying to understand. This can also be noticed in Fig. 3 where it can be seen that the β spectrum without any corrections describes better the experimental data in the whole energy range of the decay chain. Relative differences are between 5 and 20 %. Work is still ongoing related to the interpretation of these differences. Possible sources of these discrepancies can be an incomplete knowledge of the decay scheme of ^{114}Ag, and/or a poor knowledge of the Q value of the decay of ^{114}Ag.

4 Conclusions

We have carried out a first experimental campaign aimed to determine the shape of the β spectra of important contributors to the $\overline{\nu}_e$ spectra of reactors. In the experiment we performed tests of the detectors under the expected experimental conditions to verify their functionalities, obtain calibrations, and measure cases for the validation of the Monte Carlo. A satisfactory amount of data of some of the isotopes of interest was gathered, including measurements of the decay of ^{92}Rb which is an important case for understanding the $\overline{\nu}_e$ spectra of reactors [10, 13].

To further improve the Monte Carlo model of the experiment and its validation, we still need to carefully check the impact of certain aspects of the Monte Carlo such as the shapes and materials of the simulated setup, and the dependence of the results on the position of the implantation of the isotopes in the tape. These issues are especially important because the movement and energy loss of electrons are greatly affected by their surroundings.

Another point to be clarified is the effect of the corrections to the shapes of the β spectra, and to what extent they have to be included in the simulations of the experimental data. This question arose due to the preliminary results we have presented in Fig. 3 where the shape of the spectrum with only the Fermi function (blue line) leads to a smaller χ^2/df value. Once these concerns have been resolved, we will continue with the determination of the response matrix of the detectors and the subsequent deconvolution of the measured spectra.

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