Impact of the Most Recent Total Absorption Gamma-ray Spectroscopy Data for Fission Fragments on Reactor Antineutrino Spectra and Comparison with the Daya Bay Results

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Abstract. The accurate determination of reactor antineutrino spectra is still a challenge. In 2017 the Daya Bay experiment has measured the evolution of the antineutrino flux with the fuel content of the reactor core. The observed deficit of the detected flux compared with the predictions of the conversion model was almost totally explained by the data arising from the fissions of $^{235}$U while the part dominated by the fission of $^{239}$Pu was in good agreement with the conversion model. The TAGS collaboration has carried out two experimental campaigns during the last decade at the JYFLTRAP of Jyväskylä (Finland) measuring a large set of data in order to improve the quality of the predictions of our summation method. These measurements allow the correction of the nuclear data for the Pandemonium effect, thus making an important contribution to calculating the antineutrino spectra. The impact of these ten years of measurement from our collaboration on the predicted antineutrino energy spectrum and flux are shown using our summation calculations. The results are compared with the Daya Bay measurements showing the best agreement in shape (in the antineutrino energy range 2 to 5 MeV) and in flux obtained so far with a model. The flux deficit observed by Daya Bay with respect to the summation method is now reduced to 1.9% leaving little room for the reactor anomaly. The shape anomaly between 5 and 7 MeV in antineutrino energy is still observed and remains unexplained.

1. Introduction and motivations

Nuclear reactors are the most intense and controlled sources of low-energy electron antineutrinos ($\bar{\nu}$). They derive their power from the fission of the 4 isotopes $^{235}$U, $^{239}$Pu, $^{241}$Pu and $^{238}$U. While the $^{238}$U constitutes the largest part of the fuel, it only contributes about 10% of the fissions. The dominant contribution of $^{235}$U to fission at the beginning of the cycle slowly decreases as it is burned in the core. The two other fissile nuclei are created, after the reactor starts, in...
capture/\beta-decay processes with more \textsuperscript{239}Pu being produced than \textsuperscript{241}Pu. The fission products (most of which are neutron-rich nuclei) undergo $\beta^-$ and $\beta$-n decays (about 6 per fission) and this is the origin of the large flux of antineutrinos produced in nuclear reactors. A knowledge of the antineutrino spectra and flux from nuclear power reactors is an important ingredient in the study of the neutrino oscillations. Over the last 40 years, many computations of the spectra have been developed and improved \cite{1, 2, 3, 4, 5, 6, 7, 8, 9, 10}. They rely on two different nuclear approaches tapping into either the electrons produced in the $\beta$ decay process or the gammas coming from the de-excitation of the $\beta$ decay daughter nucleus. In the former case, the calculation is based on the integral electron reference spectra measured by Schreckenbach et al. in the 1980s at the ILL reactor arising from the thermal fission of \textsuperscript{235}U, \textsuperscript{239}Pu and \textsuperscript{241}Pu\cite{1, 2, 3, 4}. The $\beta$ energy spectra then have to be converted into antineutrino spectra via a conversion model. In 2011, the conversion method was revisited and gave birth to the Huber-Mueller model (called H-M model hereinafter) \cite{4, 5}. In this approach, the reconstruction of the $\beta$ intensities and the end-points in the daughter nucleus\cite{9} gives access to the $\beta$ energy distribution of individual fission products. The summation method (called SM model hereinafter) consists in summing all the individual spectra of the fission products weighted by their associated fission yields \cite{4, 10}. This method which is the topic of the present work, is entirely dependent upon modern nuclear databases (NDB) and thus their potential biases \cite{10}. It will be presented in section 2.

A knowledge of the $\bar{\nu}$ spectrum has been essential for the last 20 years for short baseline neutrino experiments as it constituted their reference \cite{11}. It also played an important role for the next generation Double-Chooz \cite{12}, Daya Bay (DB) \cite{13} and Reno \cite{14} experiments. But even for modern multi-baseline experiments which are designed to be independent of a precise knowledge of flux and reactor spectrum \cite{15, 16, 17, 18, 19}, a good theoretical or phenomenological knowledge of the spectrum allows for its full understanding as well as the understanding of the associated uncertainties. The efforts devoted in 2011 to improve the conversion model, taking account of a revision of the neutron lifetime and off-equilibrium effects, led to a new normalisation of the predicted antineutrino flux lying some 6\% above the detected flux at short distances from reactors \cite{11}. This reactor anomaly (RAA) has triggered considerable experimental activity across the world, chasing sterile neutrinos close to experimental reactors. At the same time, the three large reactor experiments Double Chooz, Daya Bay and Reno have released their measurements of the shape of the reactor antineutrino spectrum close to Pressurized Water Reactors. It turned out that the comparison between the converted spectra and the measured spectra, apart from the normalisation which confirmed the reactor anomaly, exhibited a large distortion of the data with respect to the model between 5 and 7 MeV in $\bar{\nu}$ energy \cite{12, 13, 14}.

These two findings raised questions about the antineutrino predictions based on the H-M model and its systematic uncertainties associated with several nuclear effects \cite{5, 20, 21, 22}.

This context evolved a bit more by the end of 2017 when Daya Bay published for the first time the evolution of the antineutrino flux \cite{23}. Overall the slope of the evolution of the flux with an increasing percentage of fissions from \textsuperscript{239}Pu is rather well reproduced by the model, but it is still 6\% higher in its absolute magnitude. Moreover Daya Bay disentangled the contributions to the antineutrino flux from \textsuperscript{235}U and \textsuperscript{239}Pu fission and highlighted that their deficit in flux essentially arises from the fission of \textsuperscript{235}U. These results were confirmed recently by both DB and Reno \cite{24, 25} with improved statistics.

All in all, the \textsuperscript{235}U predicted spectrum is under question and the recently improved summation method, as presented in sub-section 3.1, should be considered as an alternative to the H-M model. In sub-section 3.2, we present a comparison of our updated SM model with some of the most

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\footnote{Thanks to the measurement of the $\gamma$\textsubscript{7s} emitted from its deexcitation.}
Figure 1. Left: Illustration of the Pandemonium effect on the $^{104}$Tc nucleus $\bar{\nu}$ energy spectrum present in the JEFF3.1.1 database and corrected in the TAS data. Right: The ratio between two summation spectra for $^{239}$Pu, namely the spectrum built with the SM-2012 over the spectrum from the same model but the 7 nuclei measured by the TAS collaboration in 2005 as explained in sub-section 3.1.

recent DB results and we find that there is even less room for the reactor anomaly.

2. Impact of the Pandemonium bias on the SM model

2.1. Pandemonium bias in NDB

High resolution gamma ray spectroscopy was commonly used before the 90s for the measurement of gamma-rays. Despite the excellent resolution they offer, germanium detectors have an efficiency which decreases strongly at high energy, thus higher energy levels may not be detected. Hence, there is a danger of overlooking the existence of $\beta$-feeding into the high energy levels of daughter nuclei. An illustration of such bias is shown in the left hand panel of Fig. 1 where the expected $\bar{\nu}$ spectrum from the $\beta$-decay of the $^{104}$Tc nucleus is extracted from a measurement with Ge detectors based on the JEFF3.1.1 nuclear database (dashed line) and compared with a TAGS measurement that is Pandemonium free (solid line) (see next section for more detail on the technique of measurement). The Pandemonium effect [26] affects some of the measurements included in the NDB. Consequently it affects the summation calculations of the antineutrino spectra which are overestimated at higher energies.

2.2. Total Absorption Gamma-ray Spectroscopy as a solution

The use of the Total Absorption Gamma-ray Spectroscopy (TAGS) technique [27] allows one to correct for these systematic uncertainties. A TAS is a calorimeter of crystals covering $4\pi$ enabling the absorption of the full energy released by the gamma cascades in the $\beta$-decay process instead of detecting the individual gamma rays. The correction of the Pandemonium effect reduces the branching to low-lying states and shifts the predicted antineutrino energy spectrum to lower energy. An illustration of the impact of 7 nuclei measured initially for their importance on decay heat calculations [28] is shown in the right hand panel of Fig. 1 [10]. The ratio of the neutrino spectrum obtained from a summation calculation including these 7 nuclei over the same $\bar{\nu}$ spectrum calculation but including the data for these 7 nuclei from high resolution spectroscopy measurements is presented for $^{239}$Pu. This relative representation highlights the typical spectral distortion due to the inclusion of data affected by the Pandemonium effect: it increases the spectrum below 2-3 MeV and decreases it above. Given the dependence of the Inverse Beta Decay (IBD) cross-section on the energy, this clearly reduces the predicted IBD yield as well. We would like to emphasize that this effect is the major bias in the determination of the antineutrino spectrum with the SM, much larger than the effect of forbidden non-unique...
transitions [20, 21, 22]. Correcting for most of the data affected by Pandemonium is thus an essential pre-requisite for the calculation of the associated uncertainties of the spectra. The TAGS collaboration performed two experimental campaigns in 2009 and 2014 at the IGISOL facility in Jyväskylä on nuclei from a list of nuclei of priority interest for the antineutrino spectrum.

3. Comparison with recent Daya Bay results

3.1. Ingredients of our updated SM Model

In 2012, we first published a revision of our summation calculations where the main ingredients can be summarized in the following way [10]. Firstly independent yields from the JEFF-3.1 database were used as input to the Bateman equations which are solved with an evolution code (MCNP Utility for Reactor Evolution) coupled with the Monte Carlo N-Particle neutron transport code. Secondly Pandemonium-free data - those coming from Total Absorption Gamma-ray Spectroscopy (TAGS) measurements and from [29] - were selected in priority even if they are not included in evaluated decay databases. Thirdly when no decay data exist but the independent yield exists, beta decay properties were taken from models. In 2019, our model has been updated in two essential aspects summarized in [30], the main one being the inclusion of the 15 nuclei analyzed and published so far from the TAGS campaigns presented above. Depending on the list of nuclei included in the calculations, we call our model SM-2012 (after the inclusion of $^{102,104,105,106,107}$Tc, $^{105}$Mo and $^{101}$Nb [28, 10]), SM-2015 (after the inclusion of $^{92,94}$Rb and $^{87,88}$Br [31, 32]), SM-2017 (after including $^{91}$Rb, $^{86}$Br [33]) and SM-2018 (with $^{100,100m,102,102m}$Nb included [34]) hereinafter.

3.2. Results less in favour of a reactor anomaly

The summation calculations of the full antineutrino energy spectrum had never been published previously without any renormalisation and compared with published experimental data. We performed such study for the first time and the result compared to the Daya Bay measurement is presented in Fig. 2 [30, 35]. In the top panel of the figure, the ratios of the DB spectrum over the SM-2017 spectrum (dashed line), the SM-2018 spectrum (continuous line) and the H-M model spectrum (open diamonds) are compared. The global shape of the DB over SM ratios are similar to that of DB over H-M, but closer to one. The inclusion of the TAGS data for the
niobium isotopes improves the situation above 3 MeV, extending the good shape agreement with the Daya Bay spectrum up to 5 MeV. This observation is of great significance as the 2 to 5 MeV energy region dominates the detected flux. The lower panel of the figure compares our 2017 and 2018 calculations with H-M shows that we also get closer to H-M in shape above 5 MeV, a region sensitive to the Pandemonium effect. The bump previously measured by neutrino experiments w.r.t. H-M between 5 and 7 MeV is thus also present in the comparison of the Daya Bay spectrum with our SM-2018 calculations, but its amplitude is reduced by the inclusion of the new data which improve the agreement globally.

In 2017, Hayes et al. first compared their IBD yield predictions with the data published by the Daya Bay collaboration. Even if they obtained a discrepancy with the experimental value lower than the H-M model, they still obtained a deviation in flux of 3.5% which could not discount the RAA [36]. We performed the same IBD yield comparison with our updated model comparing step by step the effect of the inclusion of the 15 Pandemonium nuclei in the calculation as described in section 3.1 on the global antineutrino flux. The result of this study is shown in Fig. 3 where the IBD yield is presented as a function of the fraction of fissions from $^{239}$Pu ($F_{239}$) and compared with a SM calculation using only the TAGS data from Greenwood et al. [29]. This is taken as a reference as it corresponds more or less to the H-M predictions and to the state of the art of the summation method in 2011 (when the H-M was revisited as well).

A clear systematic trend is obtained from the SM-2012 calculation to SM-2018: the higher the number of Pandemonium free data included, the smaller the discrepancy in flux with the Daya Bay measurement (open diamonds) [23]. So far, with the SM-2018, the remaining discrepancy with the Daya Bay flux is reduced to just 1.9% compared with the ~6% discrepancy of the H-M model. In the absence of associated error bars, due to the lack of knowledge of the decay data covariance matrices, the robustness of the IBD yield obtained with the SM has been tested studying the range of variation of the predicted spectrum and flux depending on different choices of decay data. The energy region most robust is from 2 to 3.5 MeV with a maximal impact of 2%. This region puts a stringent constraint on the global normalisation of the SM spectrum. The higher energy region, above 5 MeV, still contains data potentially affected by the Pandemonium effect.

Lastly, table 1 summarizes the four IBD yields corresponding to the individual contributions to the fissions of $^{235}$U, $^{238}$U, $^{239}$Pu and $^{241}$Pu obtained with SM-2018 and compared with DB and the H-M model. The SM-2018 IBD yields differ respectively by 1.8, 3.5, 0.4 and 3.1% from the Daya Bay individual IBD yields. The situation is in contrast with the IBD yields provided by the H-M model, in which $\sigma_5$ carries most of the flux discrepancy.

**Figure 3.** IBD yields as a function of the $^{239}$Pu fission fractions for different versions of the SM as explained in section 3.1. The open diamonds are the data points from DB [23].
Table 1. Contributions to the IDB yield from individual actinides measured by the Daya Bay collaboration (second column) or computed with the SM-2018 (third column) or with the H-M model (fourth column). The labels 5, 9, 8 and 4 stand for $^{235}$U, $^{239}$Pu, $^{238}$U and $^{241}$Pu respectively.

|       | DB                  | SM-2018             | H-M                |
|-------|---------------------|---------------------|--------------------|
| $\sigma_5$ ($10^{-43}$ cm$^2$) | 6.17 ± 0.17         | 6.28                | 6.69 ± 0.15        |
| $\sigma_9$ ($10^{-43}$ cm$^2$) | 4.27 ± 0.26         | 4.42                | 4.36 ± 0.11        |
| $\sigma_8$ ($10^{-43}$ cm$^2$) | 10.1 ± 1.0          | 10.14               | 10.1 ± 1.0         |
| $\sigma_4$ ($10^{-43}$ cm$^2$) | 6.04 ± 0.6          | 6.23                | 6.04 ± 0.6         |

4. Conclusion

In these proceedings, our summation method revisited with a new cocktail of decay data has been presented. The TAGS measurements of our collaboration performed during the last decade, now including 15 nuclei corrected for the Pandemonium effect, have been taken as first priority in the cocktail resulting in a systematic reduction of the predicted antineutrino flux. We have shown that the inclusion of corrections for this effect is essential to improve the predictions of summation calculations and to determine their associated uncertainties. With our new model the remaining discrepancy between our predicted IBD yield with that of Daya Bay amounts to only 1.9%, which should be reduced even further with the addition of forthcoming Pandemonium free data in the calculation. In view of these results, the progress made by the nuclear data during the last decade leaves little room for the RAA, while it still cannot explain the shape anomaly.

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