β DECAYS OF ^{92}Rb, $^{96\mathrm{gs}}$Y, AND ^{142}Cs MEASURED WITH THE MODULAR TOTAL ABSORPTION SPECTROMETER AND THE INFLUENCE OF γ MULTIPLICITY ON TOTAL ABSORPTION SPECTROMETRY MEASUREMENTS*

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Total absorption spectroscopy is a technique that helps obtain reliable β-feeding patterns of complex decays important for nuclear structure and astrophysics modeling as well as decay heat analysis in nuclear reactors. The need for improved measurements of β-feeding patterns from fission decay products has come to the forefront of experiments that use nuclear reactors as a source of antineutrinos. Here we present more detailed results, in particular the β-decay measurements of $^{96\mathrm{gs}}$Y, and demonstrate the impact of the β-delayed γ multiplicity on the overall efficiency of Modular Total Absorption Spectrometer used at Oak Ridge National Laboratory to study the decays of fission products abundant during a nuclear fuel cycle.

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1. Introduction

Total absorption spectrometry is a technique that can facilitate accurate measurements of β-feeding patterns in neutron-rich nuclei [1]. Such reliable β-decay characterization is needed to model the decays of fission products in nuclear reactors. Accurate β-decay feeding patterns also improve input data, such as half-lives and β-delayed neutron-emission fractions, needed for modeling of the r-process.

The β decay of fission products, where the decay schemes are incomplete or even incorrect, contribute substantially to the decay heat release during the nuclear fuel cycle [2]. It is the only source of heating nuclear fuel after planned or accidental reactor shut-down. Improved knowledge of the decay properties will help to analyze the energy release and, therefore, improve reactor operation efficiency as well as the safety of spent fuel transportation and storage. More recently, there is much interest in reactor-fission product decays from the high precision reactor antineutrino community. During nuclear reactor operations β decays are the only source of antineutrinos. The fission products most important for the decay heat analysis simultaneously play a crucial role in the evaluation of reactor antineutrino energy spectra.

Recently, results obtained with the Modular Total Absorption Spectrometer (MTAS) located at Oak Ridge National Laboratory on the three largest contributing nuclei to the high-energy part of the reactor $\bar{\nu}_e$ spectrum (^{92}Rb, $^{96\mathrm{gs}}$Y, and ^{142}Cs) pointed to large deficiencies in the earlier adopted β-decay properties of ^{142}Cs [3]. The β-transition intensities to low-energy levels in ^{142}Ba were shown to be largely overestimated. The MTAS-corrected decay pattern of a single nucleus, ^{142}Cs, has changed the overall calculated detectable antineutrino flux by 1%. This change reduces the reactor $\bar{\nu}_e$ anomaly while increasing the discrepancies in the high-energy portion of the $\bar{\nu}_e$ spectra ("shoulder") at $\bar{\nu}_e$ energies between 5 MeV and 7 MeV [4]. Also briefly reported was the validation of the $^{96\mathrm{gs}}$Y β decay. The explicit results and some further details of the $^{96\mathrm{gs}}$Y β decay are presented in these proceedings.

Evaluating β decays obtained through total absorption spectrometry requires relatively complicated procedures [5–8]. β-decay feedings are derived by measuring the γ rays that come from the decay of the β-fed level in the daughter nucleus. For lower lying energy levels, the decay paths often involve only 1 or 2 γ rays. But for higher lying energy levels, there are many lower lying energy levels accessible through E1, M1, and E2 γ transitions. There are usually many different decay paths possible, with most paths involving anywhere from 1 to 4 γ rays. Measuring and identifying multiple γ-ray decay paths, with the use of low-efficiency detectors, is challenging. It is not only time consuming, but in a case of many weak β-transitions to close-lying states, even high resolution HPGe detectors cannot resolve individual γ transitions and identify the decay path. Due to the low efficiency for detection of multi-γ cascades, the missed multi-γ decays from high energy levels have a large impact on the analyzed β-decay pattern.

In this proceeding, we discuss the influence of γ-decay multiplicity on detector efficiency and the associated derived β-decay schemes. For the high-efficiency detector like MTAS, there are results that are somewhat non-intuitive when compared with well-known low-efficiency detectors. We will also discuss the influence on the $\bar{\nu}_e$ energy spectrum of anomalous decays that shift the $\bar{\nu}_e$ spectrum in the opposite direction as Pandemonium affected nuclei [1]. We use ^{92}Rb as an example to show the possible influence of other types of errors in the nuclear database on the $\bar{\nu}_e$ energy spectrum.

2. The β decay of $^{96\mathrm{gs}}$Y

As previously reported in [3], the β-feeding intensities for $^{96\mathrm{gs}}$Y are in line with the current ENSDF values [9]. In these proceedings, we provide further detail of the total absorption spectroscopy measurements of the β decay of $^{96\mathrm{gs}}$Y. The total fit of the simulated individual level decays to the total MTAS data for the $^{96\mathrm{gs}}$Y is shown in Fig. 1. The associated calculated β-feeding intensities are shown in Fig. 2. There are sev-

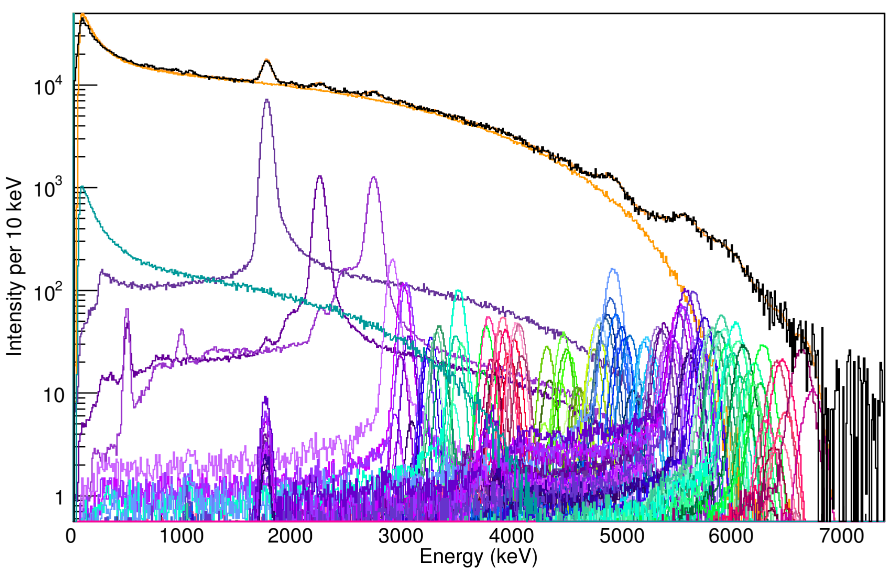

Fig. 1. (Color online) Fit of the individual level decays to the total extracted MTAS data for $^{96\mathrm{gs}}$Y (black). The ground state feeding (orange) and the feeding to the 1581 keV 0^+ excited state (blue–green) are the wide non-peaked distributions that increase at lower energies.

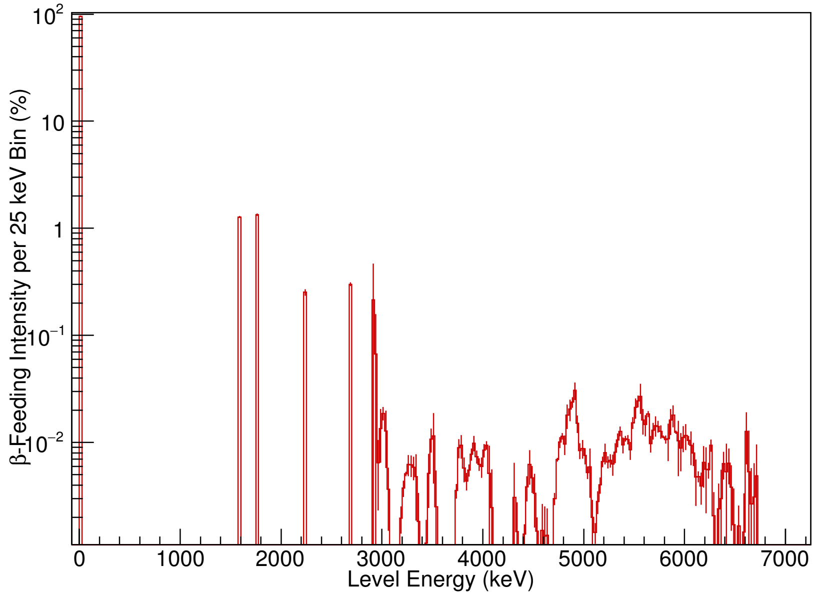

Fig. 2. Calculated β-feeding intensities for the $^{96\mathrm{gs}}$Y. Above 6600 keV, the intensities are consistent with zero. The large uncertainty just below 3000 keV comes from varying the end point and this type of effect is described in [10].

eral challenges associated with the $^{96\mathrm{gs}}$Y β-decay analysis. First, there are two different states of ^{96}Y produced by nuclear fission of heavy elements, the ground state, $^{96\mathrm{gs}}$Y ($T_{1/2} = 5.34$ s, 0^-), and the isomeric state, ^{96m}Y ($T_{1/2} = 9.6$ s, 1140 keV, 8^+). The ratios of these two states produced by nuclear fission are not well-known [11]. In our experimental setup, the isomer ^{96m}Y is not extracted directly from the ion source, nor is it produced from the decay of ^{96}Sr, due to its high spin (8^+), hence we did not study the decay of the isomeric state ^{96m}Y.

Another difficulty with the $^{96\mathrm{gs}}$Y analysis is the existence of a $0^+ \to 0^+$ transition from the first excited state 1581 keV. This is the lowest excited state in ^{96}Zr and hence only decays via an E0 decay to the ground state in ^{96}Zr. This E0 decay is mostly via conversion electrons but there is a branching via electron–positron pair production. As can be seen in Fig. 1, the signal from this decay in MTAS is similar in shape to a β decay to this level. This is because of the low efficiency for MTAS to detect conversion electrons of 1500 keV. We were unable to detect these electrons in the auxiliary detectors because these electrons are too energetic to produce a clear peak in 1 mm thick silicon detectors. Due to the inefficiency of MTAS to clearly detect the conversion electrons, we assume the β intensity of 1.26% reported for the 1581 keV level are correct [12, 13].

3. MTAS Efficiency as a function of γ multiplicity

For a total absorption spectrometer (TAS), there are two important efficiencies to consider, full energy efficiency and total efficiency. Full energy efficiency is when the entire energy of a γ ray is detected by a TAS and total efficiency is when any amount of energy from a γ ray is detected by a TAS.

The single γ-ray peak efficiency for MTAS (with auxiliary β detectors) is a flat 81% from 300 to 800 keV, and then the peak efficiency decreases smoothly to 71% at 6 MeV as shown in [7]. The MTAS single γ-ray efficiency is the black curve shown in Fig. 3. It is worth noting that the MTAS peak efficiency curve is relatively flat, with an approximate decrease of only 11% going from 300 keV to 5 MeV.

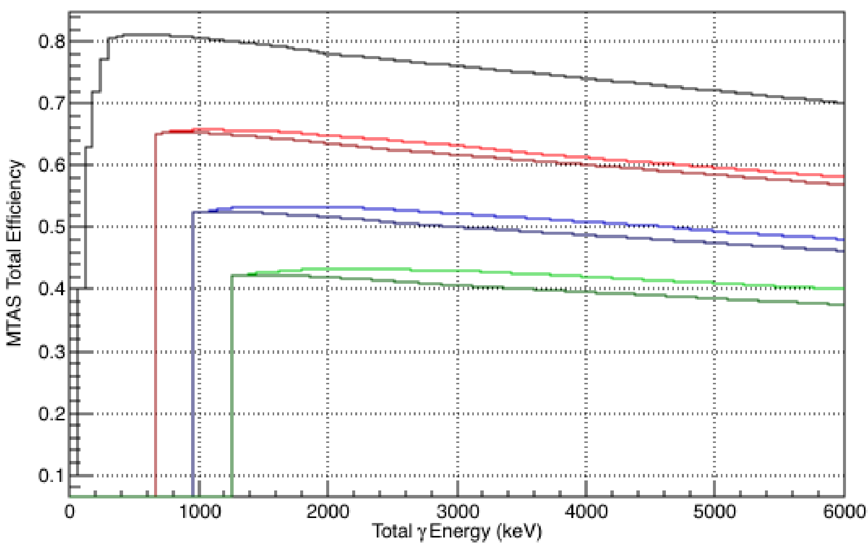

Fig. 3. (Color online) Plot of the range of MTAS (including auxiliary detectors) total efficiencies for 1 γ ray (top, black), 2 γ rays (second from top, red), 3 γ rays (third from top, blue), and 4 γ rays (fourth from top, green). The total γ energy is the sum of all γ rays considered. The range in efficiencies for each number of γ rays represents the uncertainty based on not knowing the energies of the individual γ rays. The sharp drops at 600, 900, and 1200 keV are due to the 300 keV cut on individual γ ray energy in the calculation.

By convoluting the efficiency curve with itself, the range of MTAS peak efficiencies for two γ rays of with a total energy, $E_{\mathrm{Total}} = E_{\gamma_1} + E_{\gamma_2}$, can be obtained. By convolving the single γ-efficiency curve with itself three times, with a total energy, $E_{\mathrm{Total}} = E_{\gamma_1} + E_{\gamma_2} + E_{\gamma_3}$, the range of MTAS peak efficiencies for three γ rays can be calculated. The same process can be extended to four (or more) γ-ray multiplicity decays. The MTAS peak efficiencies for total energy as a function of the γ-ray multiplicity is shown in Fig. 3.

We have simulated various four γ decays to validate the convolution method described above. The simulated total MTAS efficiencies for 4 different energy γ rays, with a summed energy of 4 MeV, varies from 0.394 to 0.418, which is identical to Fig. 3. This demonstrates that the total MTAS efficiency, for a given number of γ rays, is relatively insensitive to the energies of the individual γ rays.

The other interesting observation about the MTAS peak efficiency is that when compared to other detectors, the efficiency as a function of the number of γ rays does not change radically. An ideal detector's peak efficiency would not depend on the number of γ rays emitted. To make this observation clear, we compare the efficiencies of various detectors for detecting a single 4 MeV γ ray to the efficiency of detecting four 1 MeV γ rays *i.e.* compare two extreme different decay paths from a 4 MeV level. For MTAS, the peak efficiency of a 4 MeV γ is 0.74 and the efficiency to detect all the energy of four 1 MeV γ rays is $0.80^4 = 0.41$. The ratio of these efficiencies is $R = \epsilon_{1\gamma}/\epsilon_{4\gamma} \sim 1.8$. This ratio is less than 2.0 for MTAS over all the energies appropriate for measuring β decays. At first glance, a ratio of less than 2.0 may seem large, but it is, in fact, quite small when compared to other low-efficiency detectors. For example, Gammasphere, which is a modular HPGe (with BGO suppression) detector, has a 4.2% peak efficiency at 4 MeV and a 10.5% peak efficiency at 1 MeV, so that the ratio is given by $R = \epsilon_{1\gamma}/\epsilon_{4\gamma} \sim 0.042/0.105^4 = 346$ [14]. When compared with other high-efficiency detectors, the ratio of 1 and 4 γ ray efficiencies for MTAS are also closer to the ideal of 1.0, due to MTAS's much larger size. For the Lucrecia detector (including auxiliary detectors), a 50% peak efficiency at 4 MeV and a 63% peak efficiency at 1 MeV [15] the ratio is given approximately by $R = \epsilon_{1\gamma}/\epsilon_{4\gamma} \sim 0.5/0.63^4 = 3.2$. This minimization of the sensitivity of efficiency to the number of γ rays leads to improved estimates of β feeding to higher energy levels. Given that the ideal ratio of one 4.0 MeV γ ray peak efficiency to the efficiency of four different γ rays with 4.0 MeV total energy peak efficiency is 1.0, demonstrates that MTAS is much closer to this ideal than low-efficiency detectors.

4. Estimating γ multiplicity in MTAS

By gating on total energy and looking at the energy deposit in the different modules of MTAS, we can estimate the decay paths from β feedings in the energy gate. This tells us the average number of γ rays emitted in addition to identifying the major decay paths. For clear peaks, the decay paths can be identified explicitly, but for very high multiplicity γ decays coming from a smooth continuum, this becomes more challenging. However, as demonstrated above, as long as we can estimate the various number of γ rays in the decay paths, identifying the exact energies of the individual γ rays does not matter strongly. This is useful in the case of a low statistics measurement, where we detect a clear β-fed level but with not enough statistics to extract all of the decay paths. Further information on using the modularity of MTAS to identify the decay paths can be found in [8, 16].

5. Correction of $\bar{\nu}_e$ energy spectrum with respect to previous ^{92}Rb data

There is some belief that all corrections to the $\bar{\nu}_e$ spectrum relative to ENSDF data are biased in one direction. This bias is based on assuming that the Pandemonium effect is the only correction important to TAS corrected β-decay measurements [1]. This is not necessarily the case. Many of the calculations of the $\bar{\nu}_e$ energy spectrum were based on ^{92}Rb data that had a 50% feeding to the ground state of ^{92}Sr [17, 18]. The data were not corrected until 2012 [19]. The ratio of these data to the calculated MTAS spectra is shown in Fig. 4. This results in large changes to the high-energy part of the expected $\bar{\nu}_e$ spectrum. While the influence of the Pandemonium effect may be the dominant correction to current nuclear data, other types of corrections must always be entertained as a possibility. In other words, only a proper total absorption measurement can yield a reliable β-decay pattern for complex β decays.

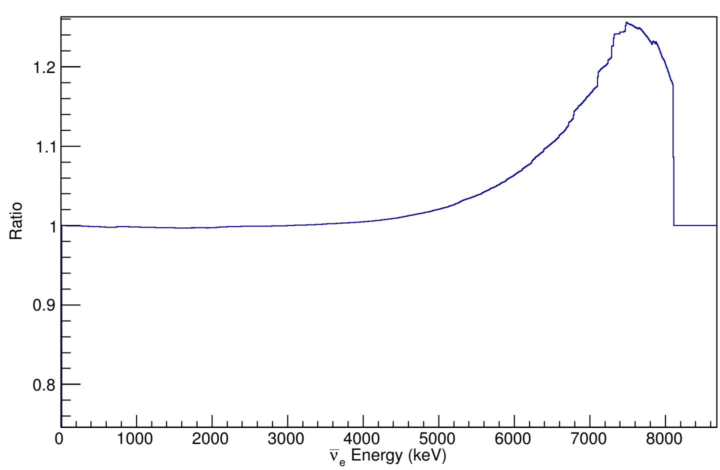

Fig. 4. Ratio of the calculated MTAS data to the 2007 ENSDF data of the $\bar{\nu}_e$ flux as a function of energy for ^{235}U fuel for ^{92}Rb. This correction is in the opposite direction to reductions in ground state to ground state feedings based on nuclei affected by the Pandemonium effect.

6. Summary

We show the fit to the MTAS singles energy spectrum and the calculated β-feeding intensity for $^{96\mathrm{gs}}$Y. This validates the current ENSDF decay scheme for this nucleus. With the latest set of total absorption spectrometers, and MTAS in particular, we are approaching an ideal total absorption spectrometer. This is shown by the small change in the peak efficiency as a function of the of γ-ray multiplicity. It is also demonstrated by the minimal dependence of the MTAS peak efficiency on the individual energies of γ rays of a given decay with a particular multiplicity (less than 3% for 4 γ rays with a total energy of 4 MeV). With an estimate of the MTAS peak efficiency averaged over γ multiplicity, we can quickly estimate an average β feeding. While we do not use this property directly during the full analysis, we can use this information during online analysis to identify the possible incompleteness of each measured β-decay feeding intensity. This quickly and accurately demonstrates where new β-feeding corrections are required. Lastly, we show the case of ^{92}Rb as a warning about other possible influences on the $\bar{\nu}_e$ energy spectra of incomplete nuclear data.

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