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The accurate determination of the emitted reactor antineutrino flux is still a major challenge for actual and future neutrino experiments at reactors, especially after the evidence of a disagreement between the measured antineutrino energy spectrum by Double Chooz, Daya Bay, and Reno and calculated antineutrino spectra obtained from the conversion of the unique integral beta spectra measured at the ILL reactor. Using nuclear data to compute reactor antineutrino spectra may help understanding this bias, with the study of the underlying nuclear physics. Summation calculations allow identifying a list of nuclei that contribute importantly to the antineutrino energy spectra emitted after the fission of ^{239,241}Pu and ^{235,238}U, and whose beta decay properties might deserve new measurements. Among these nuclei, ^{92}Rb exhausts by itself about 16% of of the antineutrino energy spectrum emitted by Pressurized Water Reactors in the 5 to 8 MeV range. In this Letter, we report new Total Absorption Spectroscopy (TAS) results for this important contributor. The obtained beta feeding from ^{92}Rb shows beta intensity unobserved before in the 4.5 to 5.5 MeV energy region and gives a ground state to ground state branch of 87.5 % $\pm$ 3%. These new data induce a dramatic change in recent summation calculations where a 51% GS to GS branch was considered for ^{92}Rb, increasing the summation antineutrino spectrum in the region nearby the observed bias. The new data still have an important impact on other summation calculations in which more recent data were considered.

Beta decay properties of fission products are at the origin of the antineutrino flux emitted by reactor cores. This flux has been used for decades as a source for reactor neutrino experiments, like the last ones Daya Bay, Double Chooz and Reno which have released recently their measurements of the mixing angle θ_{13} [1–3]. These results will allow the future search for the CP violation phase δ or the neutrino mass hierarchy with complementary experiments at reactors [4]. The accurate determination and understanding of the emitted reactor antineutrino flux is thus still a need for actual and future experiments. The recent re-estimate of reactor antineutrino energy spectra [5, 6] has led to the so-called "reactor anomaly" [7], at the origin of new experimental projects chasing short distance oscillations at research reactors [8]. These calculations are based on the conversion into antineutrinos of the integral beta energy spectra uniquely measured at the high neutron flux reactor ILL in Grenoble (France) [9]. The conversion method has been up to now considered as the most precise one by neutrino experiments. But lately, Hayes et al. [10] have shown that it is indeed dependent on the underlying nuclear physics and that the associated errors should be revised. In addition, very recent experimental results from [1–3] have shown an unexplained distortion in their measured energy spectra from Pressurized Water Reactors (PWR) between 4 and 8 MeV [11] w.r.t. converted spectra [5, 6]. In this context, new evaluations of the PWR antineutrino energy spectrum are mandatory.

An alternative calculation, independent from the ILL measurements, relies on the summation of the contributions of the fission product beta decay branches in order to obtain the antineutrino energy spectra. The necessity of the measurement of new nuclear physics properties of some major contributors was underlined in [12], especially using the Total Absorption Spec-

troscopy (TAS) technique in order to avoid the pandemonium effect [13] and improve the predictiveness of the summation method. The summation method is indeed the only one which allows predicting antineutrino spectra for which no integral beta measurement exists. This is required for instance in the context of the R&D of antineutrino detection as a tool for reactor monitoring [14].

All these recent findings reinforce the need for more exploration of the underlying nuclear physics at the origin of the reactor neutrino flux. In this Letter, the first results of an experimental campaign [15] aiming at measuring beta decay properties of important contributors to the reactor antineutrino energy spectrum emitted by PWR are presented. New results, obtained using the TAS technique, of beta decay properties of ^{92}Rb are discussed, ^{92}Rb being the major contributor to the reactor antineutrino flux in the energy range above 5 MeV. In the following, we present a short list of main contributors to the antineutrino energy spectrum above 4 MeV, obtained using the summation method presented in [12]. Then the previous experimental knowledge on beta decay properties of ^{92}Rb are summarised, and the TAS method, the used experimental setup and the data analysis performed are presented. Eventually we show the obtained beta feeding and present the impact of the new results on reactor antineutrino energy spectra.

In Table I, the main contributors in 1 MeV bins from 4 to 8 MeV are listed , which were obtained with antineutrino energy spectra computed with the MURE code coupled with the list of nuclear data given in [12], emitted by ^{235}U, ^{239}Pu, ^{241}Pu and ^{238}U for a 450 day irradiation time. In order to obtain the main contributors to the antineutrino energy spectrum of a typical PWR, we have mixed the aforementioned four antineutrino spectra with the following proportions: 52%, 33%, 6% and 8.7% respectively. In our calculation, we have chosen to minimise the impact of the pandemonium effect on the antineutrino spectra and on the computed proportions of the nuclei per energy bin. To this purpose, we have used data from [16] for ^{92,93,94}Rb, ^{96}Y, ^{142}Cs, ^{135}Te and from [17] for ^{95}Sr and ^{90}Rb, because these two sets of data are likely to be pandemonium free (though they may suffer from other systematic errors). As they were not measured by [17] nor [16], data for ^{98m}Y and ^{100}Nb were taken from [18] and ^{104m}Nb from [19]. Indeed, a careful choice of datasets is needed, especially to select nuclei which would deserve new measurements, as is illustrated below with the case of ^{92}Rb.

^{92}Rb is the major contributor between 4 to 8 MeV, representing alone up to about 38 % of the 7 to 8 MeV bin and 16 % of the 5 to 8 MeV range. ^{92}Rb is quite controversial: the beta feeding to ground state of its daughter nucleus was fixed at 51% in the ENSDF data base [19] until two years ago, before including in the references the article from Lhersonneau et al. [20]. In this article, a new measurement of the $2^+ \rightarrow 0^+$ transition in ^{92}Sr shows a branching ratio of 0.032, in agreement with a previous measurement [21] rejected previously because leading to a too low log(ft) value for first forbidden transitions from the 0^- ground state of ^{92}Rb to the 0^+ and 2^+ states of ^{92}Sr. The authors conclude that the conflict could be solved assuming that close to half of the decay intensity, mostly high energy ground state transitions, is missing in the decay scheme. Following this reference the beta feeding to ground state for ^{92}Sr was changed recently to 95% in the ENSDF database [19].

The ^{92}Rb beta energy spectra has been measured by Rudstam *et al.* [16]. ^{92}Rb has a large Q_β value which makes it a good candidate to be a pandemonium nucleus. The pandemonium effect [13] arises from the difficulty encountered in building level schemes for complex beta decays using Germanium detectors, especially when beta transitions occur toward high-energy levels or in regions of high level density. This leads to an under-estimate of the corresponding beta branches of high energy leading to a distortion in the beta decay feeding called the pandemonium effect. In addition, ^{92}Rb has also been used as a critical example [22] to show how beta-decay strength calculations impact on the predictive power of models in reconstructing half-lives and beta delayed neutron emission probabilities of nuclei, whose properties are important in the simulation of astrophysical r-process. It is also on NEA/IAEA lists of important contributors to reactor decay heat [23].

A total absorption spectrometer is a calorimeter measuring the gamma cascades emitted by the de-excitation of the daughter nucleus after beta decay of the parent. The detection of the total energy allows deducing the feeding probability of excited levels populated during the beta decay. This quantity is calculated by solving the inverse problem as presented below. The beta feeding f gives direct access to the beta intensity $I_i = f_i/\Sigma_k f_k$ and then to the beta strength, a microscopic quantity

TABLE I. Main Contributors to a standard PWR antineutrino energy spectrum computed using the summation method described in [12].

	4 - 5 MeV	5 - 6 MeV	6 - 7 MeV	7 - 8 MeV
^{92}Rb	4.74%	11.49%	24.27%	37.98%
^{96}Y	5.56%	10.75%	14.10%	-
^{142}Cs	3.35%	6.02%	7.93%	3.52%
^{100}Nb	5.52%	6.03%	-	-
^{93}Rb	2.34%	4.17%	6.78%	4.21%
^{98m}Y	2.43%	3.16%	4.57%	4.95%
^{135}Te	4.01%	3.58%	-	-
^{104m}Nb	0.72%	1.82%	4.15%	7.76%
^{90}Rb	1.90%	2.59%	1.40%	-
^{95}Sr	2.65%	2.96%	-	-
^{94}Rb	1.32%	2.06%	2.84%	3.96%

that can be directly compared with models [24]. The decay detector used in the measurement of the ^{92}Rb is composed of 12 crystals of BaF_2 arranged in a compact geometry [25]. Each crystal is observed by a photomultiplier tube converting the scintillation light in an electrical signal directly proportional to the detected energy. The gamma detection efficiency was about $\sim$ 80 % at 5 MeV. This spectrometer was coupled with a Silicon detector placed in the center, in front of the source implantation zone, to tag the beta emission. This allows reducing the background by making coincidence between the beta event and the following gamma emission from daughter de-excitation.
The measurements have been performed at the IGISOL facility of the Jyväskylä University (Finland) [26] which is equipped with a double Penning trap system (JYFLTRAP) [27]. The latter achieves a mass resolution reaching a $\delta M/M$ of 10^{-6}, allowing a very precise selection of fission products. This level of purification of the beam is necessary in TAS experiments in order to reduce systematic uncertainties related to the purity of the beam.

As stated above the main observable of a TAS measurement is the beta feeding to the energy levels of the daughter nucleus which is contained in the measured gamma spectrum convoluted with the detector response. To obtain this information we have to solve the so called "inverse problem". It consists in solving the equation $d_i = R_{ij}^{(B)} \times f_j$, where $R_{ij}^{(B)}$ is the response matrix of the detector to an assumed decay level scheme (B). R_{ij} connects feeding to level j (f_j) to counts in the bin i of the "measured" TAS spectrum (d_i). The analysis procedure has been described in previous publications [24, 28] and is well under control.

To perform this analysis, very clean data d are required. To this purpose, possible contaminations from the daughter nuclei and pileup signals are subtracted from the raw data.The shape of the pile-up spectrum has been computed by summing in the ADC time window two events randomly extracted from the raw data. The absolute normalisation of the pileup was performed using the data counting rate and the ADC time window in which random coincidences can occur [29, 30]. The shape of the spectrum from the daughter nucleus ^{92}Sr has been simulated using its known level scheme from ENSDF [19] and the detector response. The normalisation factor has been obtained solving the Bateman equations for ^{92}Rb decay in realistic experiment conditions, i.e. considering the experimental time for implantation and measuring cycles. The obtained contamination from ^{92}Sr represents 0.08 % of the total ^{92}Rb acquired data. The response matrix R is calculated by simulating the detector response to beta and gamma cascades emitted during the decay with a dedicated GEANT4 [31] Monte Carlo simulation. The latter one has been tuned using measurements performed with known sources in order to reproduce the detector response in great details [29, 32, 33]. The inverse problem is solved by using a maximisation expectation algorithm based on the Bayes theorem and combined with a χ^2 minimisation [34]. It consists in an iterative method to find the final feeding distribution which minimises the difference between the experimental data and the spectrum recreated by the iteration. The analysis starts with a first guess of feeding values extracted from literature, or an equally probable feeding distribution if the nucleus is poorly known, and stops when the χ^2 value between the two spectra is minimal.

The starting point of the resolution of the inverse problem is the construction of the branching ratio matrix (B) of the decay. For that, known levels from high resolution measurements are considered up to 1778 keV in the daughter nucleus ^{92}Sr [19]. The remaining energy range is divided in energy bins of 40 keV up to the Q_β value.

A required input is the level density of the daughter nucleus in the full Q_β window. While we consider experimental values of the level density in the low energy part, in the high energy range we have to rely on semi-empirical models. Different models were tested: Back-Shifted-Fermi-Gas (BSFG), Constant-Temperature and Gilbert-Cameron models, the latter one being a combination of the two previous ones. The Gilbert-Cameron formulation was chosen because it better reproduces experimental data at low energies.The needed gamma strengths have been modelled with a Lorentz function using the parameters from [35]. As regards the β-feeding distribution to each level, it is possible to fix or let free the feeding associated to each level/energy bin. In our analysis of ^{92}Rb we have chosen to forbid (fix to zero) the feeding to the 1673.3 keV level because its probable spin parity is 4^+ and it has never been reported to be populated in beta decay measurements [21, 36]. The impact of allowing/forbidding the feeding to the other levels in the discrete zone which are all assigned 2^+ has been studied. It was found that the algorithm cannot converge if the access to these levels is set to zero because it means forbidding all the feeding between 0 and 1778 keV.

The reconstructed spectrum (blue line) calculated using the feeding distribution obtained from this analysis is compared with the clean decay data (black) of ^{92}Rb in the upper panel of figure 1 [29]. The lower panel shows the residues between these two curves. The beta intensity obtained from the solution of the inverse problem for ^{92}Rb is shown in figure 2 in blue, while the red lines are the intensities for ^{92}Rb from ENSDF [19] database. As the ground state feeding is very important in the case of ^{92}Rb decay, we have estimated the main errors impacting this reconstruction [29]. They are: error on the thickness of the beta silicon detector, statistical error, error induced by pile-up subtraction, errors on the detector

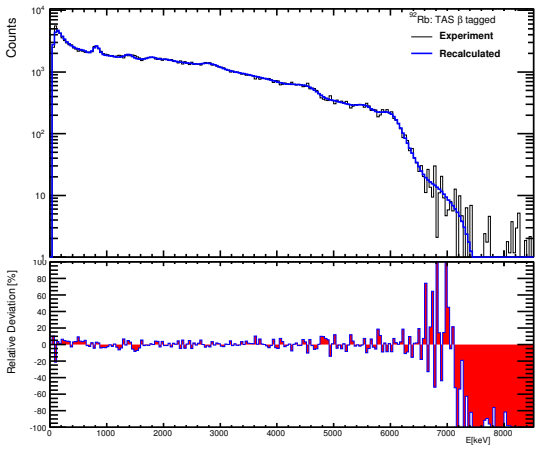

FIG. 1. Upper panel: Comparison between measured spectrum (black) and reconstructed one (blue) with the feeding obtained from TAS data analysis, lower panel: residues between the two curve reported in the upper panel.

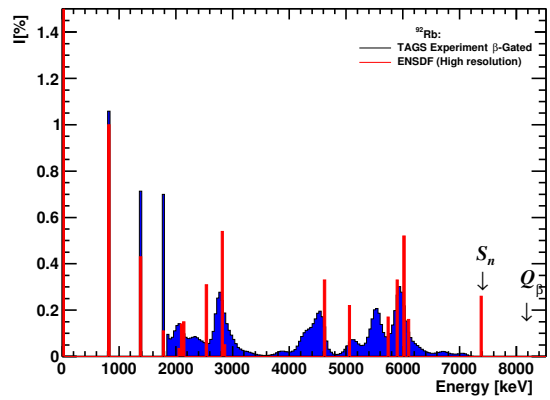

FIG. 2. Beta intensity for the decay of ^{92}Rb obtained with TAS measurements.

energy calibration and resolution used in the calculation of the response matrix R and the errors obtained by testing different input parameters for R calculation and inverse problem resolution. A sum in quadrature of all the systematic and statistical errors quoted above gives a 3 % error on the ground state feeding. This result is conservative, as we have voluntarily adopted large values of the main errors which are associated with the thickness of the beta detector and with the choice of model for the level density. The TAS results show some beta intensity around 4 and 5 MeV which was not detected before. The intensity to the ground state obtained from our analysis is 87.5 %. This value can be obtained from data analysis because the TAS detector also measures the penetration of the betas generated in the decay of the parent nucleus. These events are in the low energy part of the measured spectrum and, since they are considered in the response matrix R, they contribute to the reconstruction of the spectrum and, then, in the calculation of beta feeding. The selected ground state feeding is the one which minimises our data over reconstructed spectrum difference. If we fix the ground state feeding to 95 % as reported in ENSDF data base our analysis converge with a χ^2 value of 2048 which is much larger than the minimum one (630) and completely excludes this hypothesis.

The antineutrino energy spectrum emitted by ^{92}Rb beta decay has been computed using the fore-presented beta feeding. The GS to GS transition is first-forbidden non-unique (0^-). Different spectral shapes were assumed for this transition, considering the different possibilities listed in [10] ; an allowed shape, a first forbidden non-unique shape due to the GT operator and a first forbidden non-unique shape due to the ρ_A operator. It was also assumed that the remaining transitions were of allowed or first forbidden unique type. The various combinations of these options were computed and the obtained shapes were very similar, so that no significant impact is awaited arising from the uncertainty of the shape of the first forbidden non-unique 0^- GS to GS transition. As it is not possible to know which operator should be used, we chose to adopt an allowed shape for the GS to GS transition and first forbidden unique shapes for the remaining branches due to the spins and parities of the known transitions in this nucleus.

The U and Pu isotope antineutrino energy spectra were calculated with the summation method described in [12]. In [12] the data adopted for ^{92}Rb were extracted from [16]. In principle, these measurements should not suffer from the pandemonium effect, nor from lack of knowledge of the types of the beta transitions, unfortunately the error bars are quite large. In figure 3 is displayed with a continuous black line the ratio between the antineutrino spectra of ^{239,241}Pu and ^{235,238}U from [12] and the ones obtained using our new results for ^{92}Rb. As expected the main effect is in the 4 to 8 MeV energy range and amounts to 4.5% for ^{235}U, 3.5% for ^{239}Pu, 2% for ^{241}Pu and 1.5% for ^{238}U. These discrepancies are due to the difference in the shapes of the antineutrino spectra built with the newly measured beta feedings w.r.t. the antineutrino spectra converted from Rudstam's measurements. The sharp drop of the ratio, in one single bin located at the Q value of the ^{92}Rb, is due to a different value of the latter quantity between [16] and [19], that we have used to reconstruct the antineutrino spectrum. Such an impact is akin to affect the comparison of measured antineutrino energy spectra by reactor neutrino experiments with the summation method spectra in the 4 to 8 MeV range. The comparison would be very similar if we would have used the latest ENSDF [19] data for ^{92}Rb in our summation calculations, as was done in [37]. The ratio is displayed as well in Fig. 3 with dashed lines, and is nearly superposed with the ratio built when using Rudstam data in the first place. The change becomes

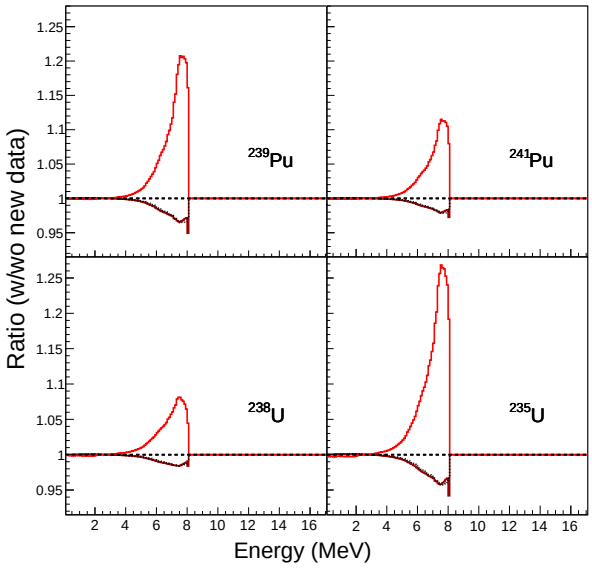

FIG. 3. Ratio between the antineutrino spectra calculated including the results presented in this paper and the one calculated with the data on ^{92}Rb decay used in [12] (black continuous line), in [37] (dotted line) and in [38] (red Line).

dramatic if one compares with summation method spectra in which an older version of the ENSDF data was used, like in [38]. The corresponding ratio is plotted in red continuous lines in figure 3.
We have compared the newly obtained energy spectra with converted spectra from [6]. The overall agreement is improved in the 4 to 8 MeV range except in the case of ^{235}U for which the summation method spectrum is always below the converted spectrum.

In this Letter, have been presented the results of new measurements performed with the TAS technique of the beta decay properties of ^{92}Rb. This nucleus is indeed among the most important contributors to the emitted antineutrino flux by standard thermal reactors in the energy region above 5 MeV. Total Absorption Spectroscopy provides beta intensities free from the pandemonium effect. The experiment has been performed at the Jyväskylä facility using the total absorption spectrometer from [25]. The obtained beta feeding of ^{92}Sr states is displayed. ^{92}Rb exhibits a 87.5% GS to GS branch, and extra-feeding to states located between 4 and 6 MeV unobserved before in previous high resolution spectroscopy experiments. A first conservative estimate of the systematic error associated to this GS feeding gives a $\pm 3\%$ systematic error. The resulting beta and antineutrino energy spectra associated to ^{92}Rb beta decay are computed. The impact of the new results on the antineutrino energy spectra of the main Uranium and Plutonium isotopes built with the summation method is assessed in the cases of three published calculations [12, 37, 38]. The change is specially striking in the case of [38] in the 5 to 8 MeV range, which overlaps the energy region in which reactor neutrino experiments have evidenced a spectral distorsion [11] w.r.t. converted spectra [5, 6].

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