PROCEEDINGS OF SCIENCE

RECH-1 neutron flux using neutron activation and Bayes' unfolding algorithms

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The Bayes' theorem of conditional probabilities is shown as an alternative to unfold the neutron flux energy distribution of experimental nuclear reactors, in particular to the RECH-1 reactor at CCHEN, from neutron activation measurements. This method has been tested assuming no knowledge of the neutron flux energy distribution. Experimental measurements for ^{nat}Cd foil, γ-spectroscopy and the respective saturation activity values are presented.

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1. Introduction

Obtaining neutron fluxes from neutron activation measurements is a standard procedure. Similar reactors worldwide [1–3] have used it in addition to iterative unfolding algorithms. Those algorithms need an initial input flux to start the iteration. In contrast, it is expected that [4] the Bayes unfolding algorithm does not need a previous knowledge of the neutron flux.

In this article two results are presented: a) Preliminary results of neutron activation experiments, in particular γ-spectroscopy of ^{nat}Cd foil after neutron activation at RECH-1, and b) tests on the Bayes algorithm assuming two different neutron flux initial distributions.

2. Method Description

When a foil of a certain material i is exposed into a neutron flux $\Phi(E)$, the daughter activity of the nuclei produced after the reaction will be determined by the reaction cross section $\sigma(E)$. If the sample is submitted during an infinite time to the same neutron flux, the saturation activity A_i^∞ is determined by

$$A_i^\infty = \int_0^\infty \sigma_i(E)\Phi(E)dE \qquad \rightarrow \qquad A_i^\infty = \sum_{j=1}^{n} \sigma_{ij}\Phi_j \tag{2.1}$$

The integral form of A_i^∞ has an infinite set of solutions for $\Phi(E)$, then it is convenient to use the discrete form, dividing the continuum functions $\Phi(E)$ and $\sigma(E)$ in n regions, where σ_{ij} is the corresponding neutron reaction cross section of sample i in the energy region j, and Φ_j is the neutron flux for the energy region j. Using the discrete form of A_i^∞, it is possible to obtain Φ_j inverting the σ_{ij} matrix. In summary one needs to solve the inverse problem $\Phi = \sigma^{-1}A^\infty$.

The matrix elements σ_{ij} can be obtained from standard nuclear data bases. The saturation activity can be obtained from γ-spectroscopy of the decaying daughter nuclei after the activation,

$$A^\infty = \frac{\lambda C}{\varepsilon_\gamma I_\gamma} \frac{e^{\lambda t_a}}{(1-e^{-\lambda t_w})(1-e^{-\lambda t_m})} \tag{2.2}$$

where C is the measured γ-transition number of counts, ε_γ and I_γ are the γ-efficiency and intensity respectively, λ is the decay probability of the daughter nuclei per unit of time, t_a, t_w and t_m are the activation, waiting and measuring time. All these values are obtained from experimental measurements, excepting I_γ and λ which are obtained from [5].

The Bayes' theorem relates causes with effects. Then it is possible to obtain an *a posteriori* probability $P(\Phi_j|A_i^\infty)$ given an *a priori* information or state of knowledge $P(\Phi_j)$, in addition to the evidence given by an experiment A_i^∞ [6]

$$P(\Phi_j|A_i^\infty) = \frac{P(A_i^\infty|\Phi_j)P(\Phi_j)}{\sum_{j=1}^{m} P(A_i^\infty|\Phi_j)P(\Phi_j)}, \tag{2.3}$$

where $P(A_i^\infty|\Phi_j)$ is the likelihood function which represents the probability of obtaining A_i^∞ due to Φ_j. In our case the likelihood function is equal to the neutron cross section σ_{ij}. Now, using a previously obtained *a posteriori* probability as an *a priori* information, it is possible to obtain an

Nuclear Reaction	Daughter Decay	$E_\gamma(keV)$	Saturation Activity (s^{-1})
$^{110}Cd(n,\gamma)^{111m}Cd$	IT	245.4	$(22.2 \pm 1.6) \times 10^{9}$
$^{114}Cd(n,\gamma)^{115m}Cd$	β^-	158.5	$(6.2 \pm 2.2) \times 10^{15}$
$^{116}Cd(n,\gamma)^{117m}Cd$	β^-	564.3	$(22.6 \pm 1.5) \times 10^{8}$

Table 1: Saturation activities Cd isotopes measured in neutron activation experiment.

iterative method to unfold the neutron flux at bin j from the Eq.(2.1), (further details can be found in the analogue problem discused in [7]),

$$\Phi_j^{(s+1)} = \frac{1}{\sum_{i=1}^{m} \sigma_{ij}} \sum_{i=1}^{n} \frac{\sigma_{ij} \Phi_j^{(s)} A_i^{\infty}}{\sum_{k=1}^{n} \sigma_{ik} \Phi_k^{(s)}} \tag{2.4}$$

Bayes' algorithm is shown as a good method to solve the inverse problem mainly because an a priori knowledge of the neutron flux spectrum (in our case Φ_j^0) is not needed to converge to a final flux value, indeed the literature shows that it is possible to start iterating with an uniform distribution (Φ_j^0=constant) [4]. Furthermore this unfolding algorithm has been used recently to solve analogue problems in nuclear physics such obtaining feeding probabilities in total gamma spectroscopy beta decay measurements [7], and to obtain the neutron energy background at Canfranc Underground Laboratories using ^{3}He detectors embedded in individual polyethylene blocks of different sizes [8].
Using this algorithm to obtain the neutron energy spectrum from a nuclear reactor is a novel work, extending the applicability of the method.

3. Experimental Setup

The RECH-1 is a 5 MW pool-type research reactor using 20% enriched ^{235}U, being the only nuclear reactor operative in Chile [9]. Disks of 6 *mm* diameter and 127 to 250 μm width were placed at the end of the *dry tube* position inside RECH-1 pool located at 130 *cm* from the reactor core. A PTFE-teflon container was made to hold the sample avoiding the deformation of the flux energy distribution due to neutron absorption in the container. The activation time for each sample was 10 minutes with the reactor stable at 5 MW. The activation sample is stored until it is able to measured it with a GC2520 CANBERRA coaxial germanium detector and LINX digital signal analyser system. The γ-efficiency of the germanium detector was obtained experimentally measuring an ^{152}Eu standard source at the measuring distance (11 cm) and fitting a proper efficiency curve for germanium detector according to [10] (see Fig. 1). After the identification of γ-transitions from the γ-spectrum of the active nuclei, see Figs. 2 and 3, the saturation activity is calculated using Eq. 2.2 (see Table 1).

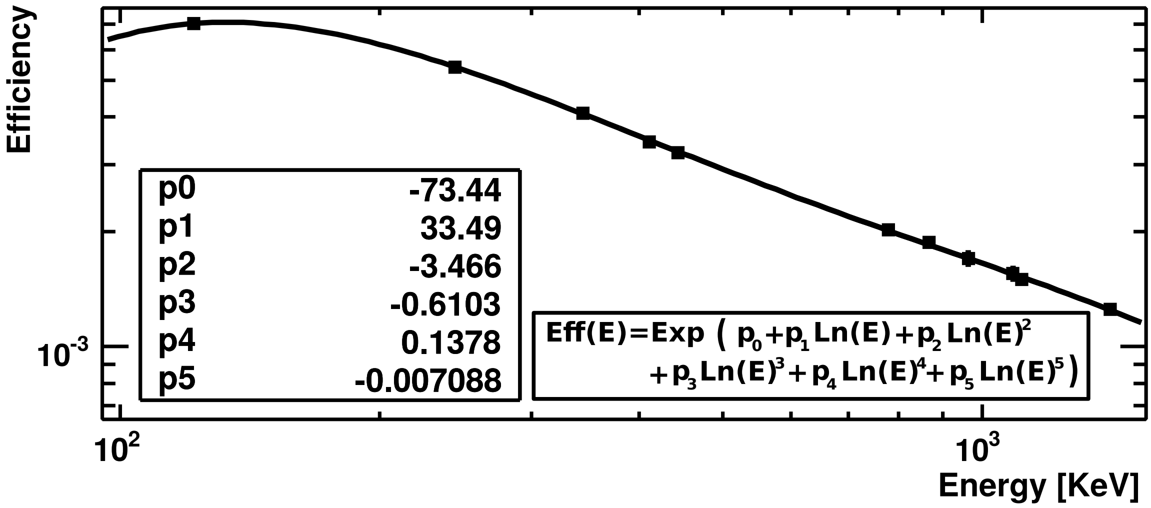

Figure 1: GC2520 CANBERRA coaxial Ge detector experimental absolute efficiency measurement using a ^{152}Eu γ-source and fitting the efficiency curve according to [10]. Error bars of the corresponding Eu peaks measured are smaller than marker size.

4. Bayes' Unfolding Algorithm Preliminary Tests

Tests to the Bayes' unfolding algorithm, Eq.(2.4), were performed. For that purpose we have created seven different neutron cross sections, see Fig. 4, and a neutron flux distribution (Fig. 5). The cross sections and the neutron flux distributions were divided in 100 evenly spaced regions. The corresponding saturation activities were calculated using the corresponding cross sections and neutron flux distributions in Eq.(2.1). For the first test an uniform distribution is used as an initial input flux, $\Phi_j^{(0)}$, to start the iteration (see Fig. 6) and some differences between the invented flux distribution (in black) and the $\Phi_j^{(1000)}$ after 1000 iterations, mainly in those regions where the invented cross sections are higher. For the second test an *a priori* distribution similar to the invented flux is used as an initial input flux $\Phi_j^{(0)}$ (see Fig. 7) and the Bayes unfolding algorithm converges to the flux distribution (in black) even after the first iteration.

5. Conclusions

A method to obtain neutron flux energy distribution using neutron activation experiments and the Bayes unfolding algorithm have been shown. Detailed γ-spectroscopy of an natural Cd activated by the neutron flux of RECH-1 reactor was analyse to obtain the saturation activities of Cd isotopes after reaction.

The unfolding method test results suggest that previous knowledge on the neutron flux energy distribution is needed in order to use Bayes unfolding algorithm to obtain the neutron flux energy distribution from neutron activation experiments, probably from Montecarlo simulations.

This work is still in progress and further experimental measurement of different targets and Montecarlo simulations to obtain an *a priori* probability are needed.

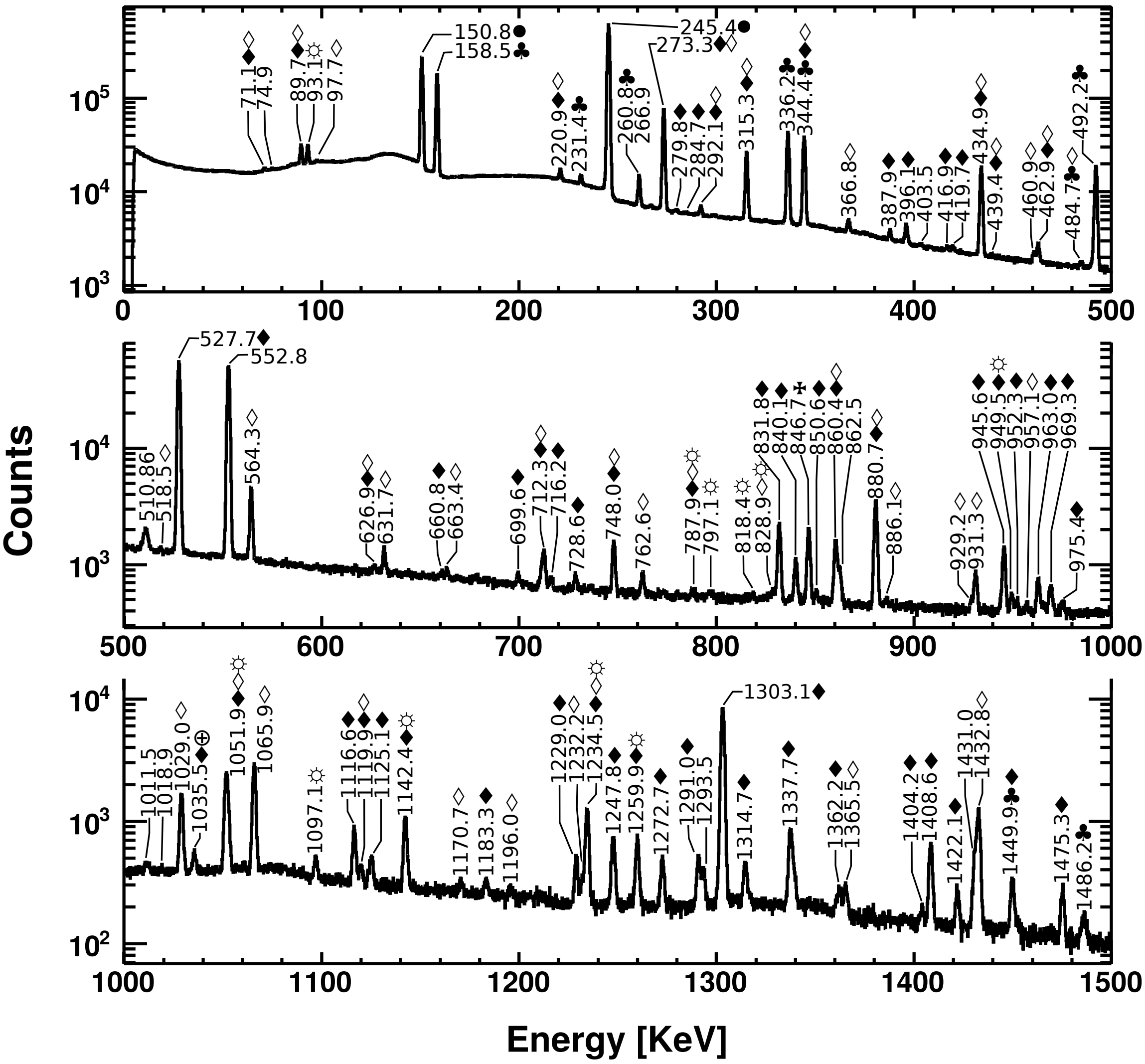

Figure 2: Natural Cd γ-spectrum, from 0-1500 keV, after neutron activation. The γ-lines from the ^{111m}Cd IT decay are marked with •. The γ-lines from the ^{115m}Cd β^- decay are marked with ♣. The γ-lines from the ^{117m}Cd β^- decay is marked with ♢. The γ-lines from the ^{117}Cd β^- decay is marked with ♦. The γ-lines from the ^{107}Cd EC decay is marked with ☼. The γ-lines from the ^{56}Mn β^- decay (trace) is marked with ✢.

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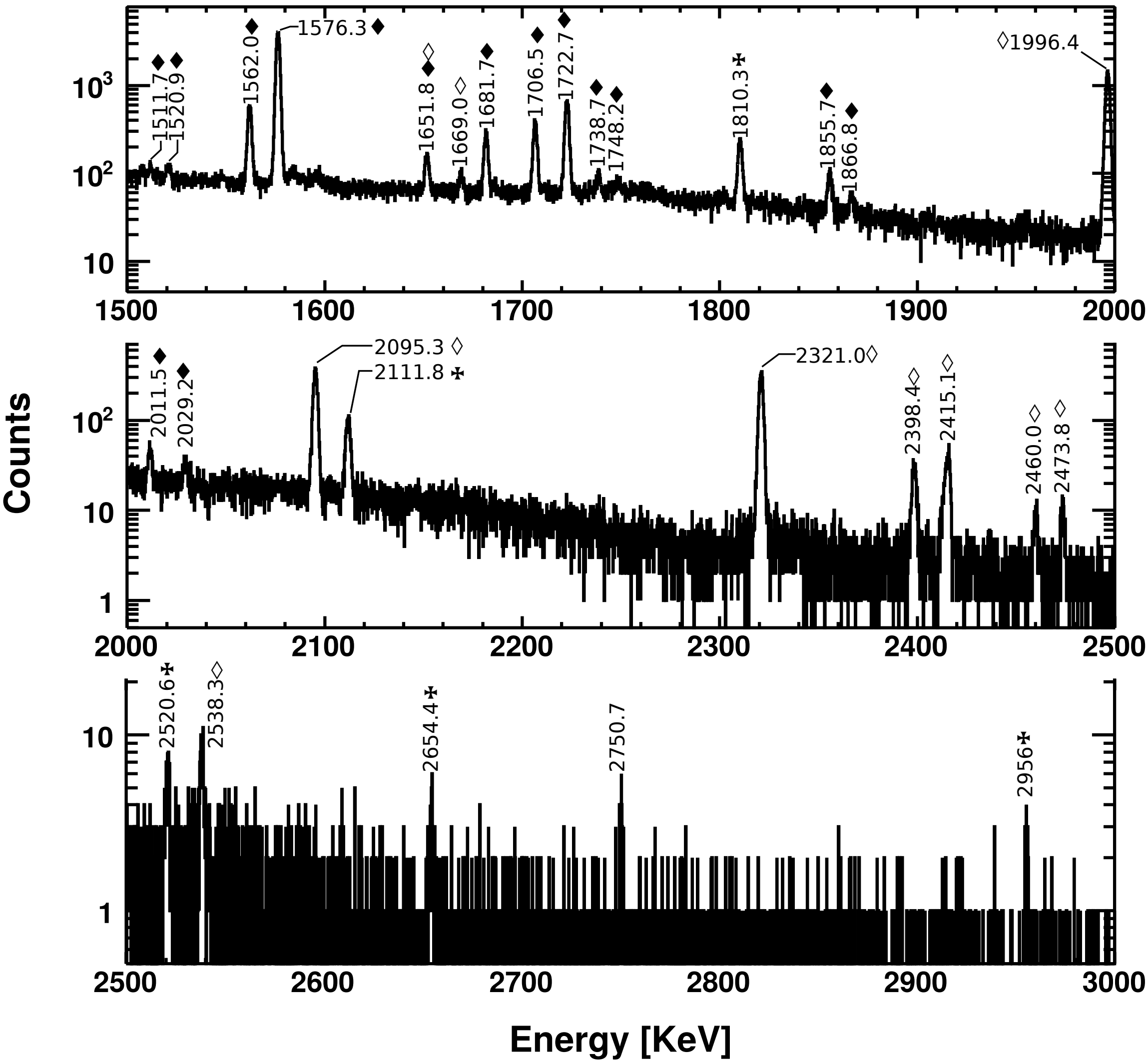

Figure 3: Natural Cd γ-spectrum, from 1500-3000 keV, after neutron activation. The γ-lines from the ^{111m}Cd IT decay are marked with •. The γ-lines from the ^{115m}Cd β^- decay are marked with ♣. The γ-lines from the ^{117m}Cd β^- decay is marked with ♢. The γ-lines from the ^{117}Cd β^- decay is marked with ♦. The γ-lines from the ^{107}Cd EC decay is marked with ☼. The γ-lines from the ^{56}Mn β^- decay (trace) is marked with ✠.

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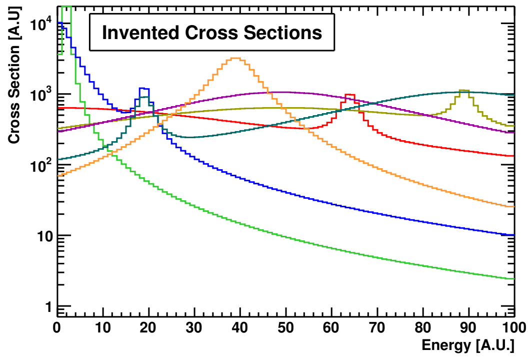

Figure 4: Cross sections used for testing purposes (color on-line)

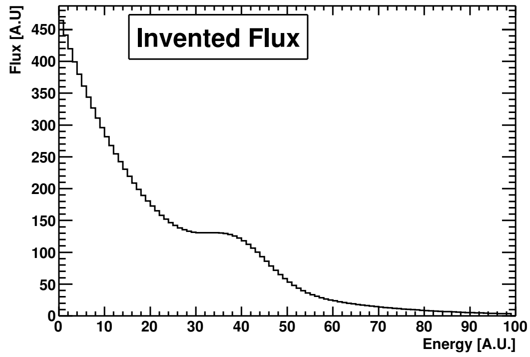

Figure 5: Neutron flux distribution, for testing purposes

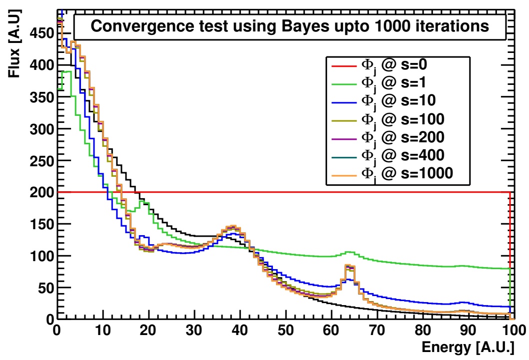

Figure 6: Bayes' unfolding algorithm tested using an uniform *a priori* probability, in red (color on-line), to start the iteration.

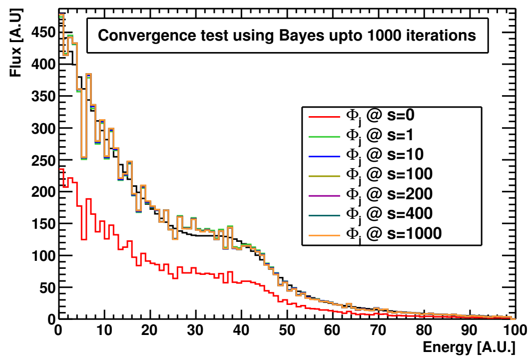

Figure 7: Bayes' unfolding algorithm tested using an *a priori* distribution probability, in red (color on-line), similar to the invented flux, in black, to start the iteration.