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Neutron Spectra Unfolding with Artificial Neural Networks

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Abstract — An artificial neural network has been designed to obtain the neutron spectra from the Bonner spheres spectrometer's count rates. The neural network was trained using a set of neutron spectra compiled by the International Atomic Energy Agency. These include spectra from isotopic neutron sources, reference and operational neutron spectra obtained from accelerators and nuclear reactors, and spectra obtained from mathematical functions. The spectra were transformed from lethargy to energy distribution and were re-binned to 31 energy groups using the MCNP 4C code. Re-binned spectra and UTA4 matrix were used to calculate the expected count rates in Bonner spheres spectrometer. These count rates were used as input and the respective spectrum was used as output during neural network training. After training, the network was tested with the Bonner spheres count rates produced by twelve neutron spectra, three were used during network training, three were obtained from mathematical functions and three were from actual situations.

Resumen — Se diseñó una red neuronal artificial para reconstruir los espectros de neutrones a partir de las tasas de conteo de un espectrómetro de Esferas de Bonner. La red neuronal se entrenó mediante un conjunto de espectros publicados por el Organismo Internacional de Energía Atómica. Los espectros incluyen fuentes isotópicas, espectros de referencia, operacionales, de aceleradores, reactores nucleares y de funciones matemáticas. Los espectros se transformaron de espectros por unidad de letargia a por unidad de energía y se estructuraron a 31 grupos de energía mediante el código MCNP 4C. Los espectros y la matriz de respuesta UTA4 se utilizaron para calcular las tasas de

conteo que cada espectro produce en un espectrómetro de Esferas de Bonner. Las tasas de conteo y los espectros se utilizaron para entrenar la red neuronal artificial. Después del entrenamiento la red se probó con doce espectros, tres se obtuvieron de los usados en el entrenamiento, tres se obtuvieron de funciones matemáticas y otros tres de espectros reales y no usados durante el entrenamiento.

Keywords — Artificial Neural Network, Unfolding, Neutron spectrum, Monte Carlo.

I. INTRODUCTION

I.1.- Neutron spectra unfolding

THE MONITORING of occupationala radiation exposure in neutron fields is mainly done with passive detection systems like track detectors, albedo dosimeters of film dosimeters with foil filters. [1, 2] These dosimetric systems have a response that strongly depends upon neutron energy. Thus, for low energy and thermal neutrons albedo dosimeters have a good response [3] while track detectors have good efficiency to fast neutrons [4].

At regular basis dosimeters are calibrated with a neutron field whose energy distribution is different to that where dosimeters are utilized resulting in wrong dose assessment [5]. Dose quantities like personal dose equivalent Hp(10), recommended by ICRP, requires of personal dosimeters with larger neutron detection efficiency. [6]

Neutron dosimeters are also utilized as multi-element systems where each element has a particular response to neutrons. Usually these dosimeters have better detection efficiency in a wider energy range allowing a better dose assessment. [2] This is achieved using the integral counts, obtained by the active detector, that are weighted by factors that belong to each element [7] or using the integral counts to unfold the neutron spectrum that is multiplied by neutron fluence-to-dose conversion coefficients. With the neutron spectrum information different dose quantities, like Hp(10), H*(10), can be estimated. [8]

With the Bonner spheres spectrometer (BSS), also known as multi-spheres spectrometer, neutron spectrum from thermal several MeV can be obtained, [9, 10] this is a thermal neutron detector that is located at the center of a high-density polyethylene sphere whose diameters are 2, 3, 5, 8, 10, 12, 16 and 18 inches. [11] To increase the BSS's response to neutrons with higher energies the moderating spheres are modified. [12-14]

The weight, time consuming procedure, the need to use an unfolding procedure and the low resolution spectrum are the BSS drawbacks. The BSS response matrix, the count rates and the neutron spectrum are related through the Fredholm integro-diferential equation, whose discrete version is. [15]

$$C_j = \sum_{i=1}^{N} R_{i,j} \; \Phi_i \qquad j = 1, 2, ..., m \tag{1}$$

where

C_j is j^{th} detector's count rate; $R_{i,j}$ is the j^{th} detector's response to neutrons at the i^{th} energy interval; Φ_i is the neutron fluence within the i^{th} energy interval and m is the number of spheres utilized.

Equation (1) is an ill-conditioned equations system with an infinite number of solutions. To unfold the neutron spectrum, Φ, several methods are used, Monte Carlo [16], regularization [17], parameterization and iterative procedures [18]. Each of them has difficulties that motivate the development of complementary procedures [15, 19, 20]. Recently methods based upon maximum entropy [21], genetic algorithms [22, 23] and artificial neural networks [2, 5, 24, 25] have been utilized. The application of artificial neural networks to unfold actual neutron spectra still has some problems and the need of more investigation has been suggested [24].

I.2.- Artificial neural networks

Neural networks are nonlinear black-box model structures than can be used with conventional parameter estimation methods. [1] Artificial neural networks are widely recognized as powerful modeling tools. [26] A neural network is a massively parallel distributed processor that has a natural propensity for storing experiential knowledge, previously acquired through a learning process, making it available for use [27]. A neural network simulates a highly interconnected, parallel computational structure with many individual processing elements, or neurons. It learns through an iterative process of adjustments applied to its synaptic weights and thresholds. A defined set of rules for the solution of a learning problem is the learning algorithm. [2, 24] In general a neural network consists of a set of input nodes that link directly to a series of output nodes or indirectly through one or more hidden layers [25].

The aim of this study was to use artificial neural networks to unfold neutron spectra from the count rates obtained from a Bonner spheres spectrometer.

II. MATERIALS AND METHODS

Using the Monte Carlo code MCNP 4C [28] one hundred thirty two neutron spectra were used as a point-like neutron source term in an empty space, neutrons were transported from the source to a detector located at 10 cm to modify its energy structure distribution. A group of spectra, originally defined from thermal to 435 MeV in 55 energy groups [29], other set of spectra defined from thermal to 630 MeV in sixty energy groups [30] were converted from thermal to 400 MeV in thirty one energy groups defined in the BUNKIUT unfolding code. Rebinned spectra were normalized to 1 neutron per second and the expected count rates in a Bonner sphere spectrometer were calculated using the UTA4 response matrix. [11, 19] The count rates were utilized as inputs in a neural network while the respective neutron spectrum was utilized as the network output during the neural network training.

The neural network was designed with four layers, the first one has 7 neurons to input data, second and third layers (hidden) have 56 neurons and the fourth layer has 31 outputs. This was designed using feed forward backpropagation. Training was carried using 132 spectra, 105 spectra have neutrons from thermal to 400 MeV, 27 spectra have single peaks: 16 spectra are monoenergetic, 3 have 2 peaks, 2 have 3 peaks, 3 have 4 peaks, 2 have 5 peaks and 1 has 6 peaks. The artificial neural network was trained until the error was reduced to 10^{-5}. The network was tested using twelve spectra, six were randomly selected form the set utilized during training and six were not. From this last group three belong to actual cases and three were the Watt's fission, Evaporation and Fusion spectra.

III. RESULTS AND DISCUSSION

From the set of neutron spectra utilized to test the network are shown six cases. In Figure 1 are the actual ^{241}AmF and the unfolded neutron spectrum using artificial neural networks (ANN), the χ^2 value is 3.5809E(-4). In Figure 2 are the ^{252}Cf/D_2O spectra, for these the χ^2 value is 0.0187. The probable explanation of such small values of χ^2 is because these two spectra were included in the set used to train the network.

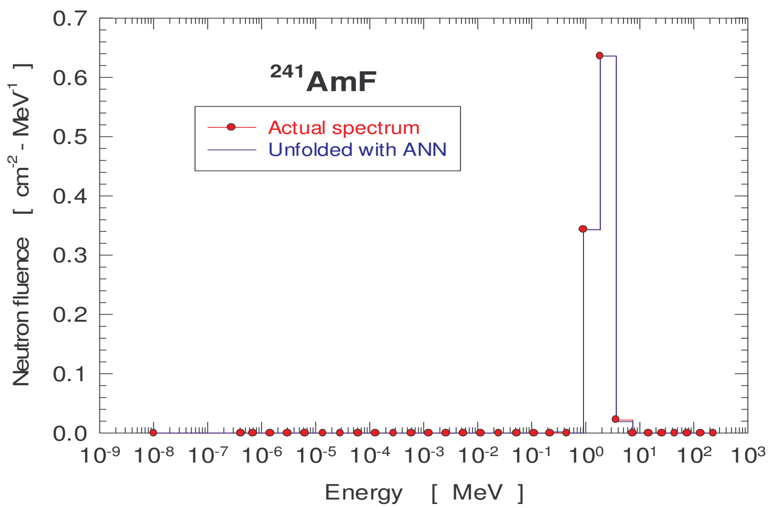

Figura 1. ^{241}AmF neutron spectrum.

In Figures 3 and 4 the Watt´s fission and Evaporation spectra are shown; here the differences between the actual and unfolded spectra are small whose χ^2 value is 0.1257 and 0.2666 respectively. The χ^2 here is also small even when these two spectra were no used in the training.

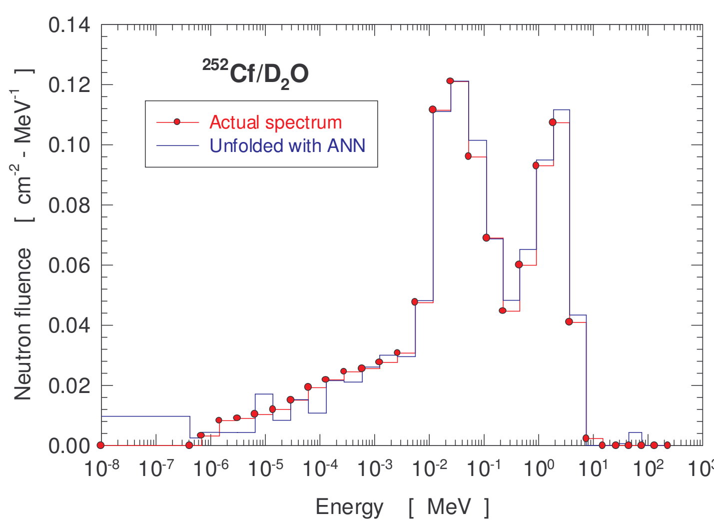

Figura 2. Heavy water moderated ^{252}Cf neutron spectrum

Caorso nuclear reactor and Microton accelerator spectra are shown in Figures 5 and 6, here the differences are also small. The χ^2 value for Caorso reactor is 0.3572 and 0.1055 for Microtron, this spectra were not used along the ANN training. For all spectra used to test the neural network the χ^2

value is small enough to assure that there is not difference statistically significative between actual and unfolded spectra. For monoenergetic spectra this network fails for the cases that contain one and two peaks, but it passes the test for spectra that have three peaks.

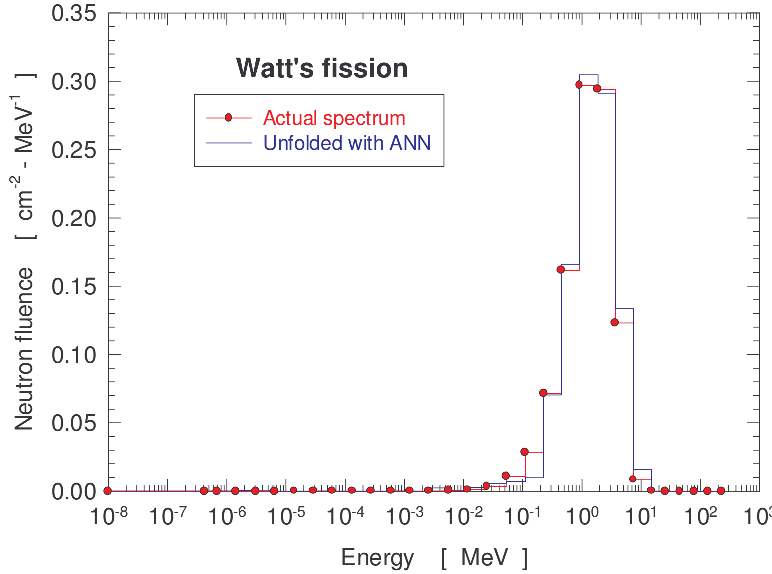

Figura 3. Watt´s fission neutron spectrum.

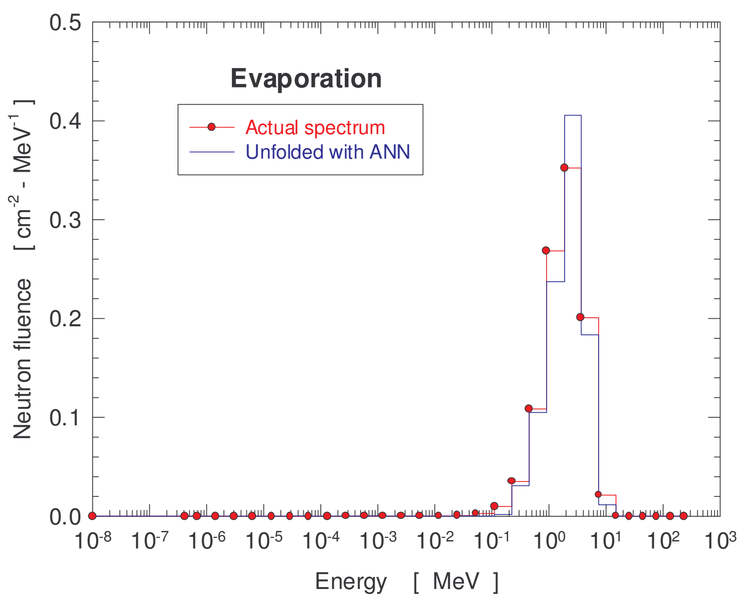

Figura 4. Evaporation neutron spectrum.

Braga and Dias [24] did use neural network to unfold neutron spectra, along the training monoenergetic neutron spectra were included. They do report good results for spectrum with 8 peaks; here we have good results for spectra with three peaks.

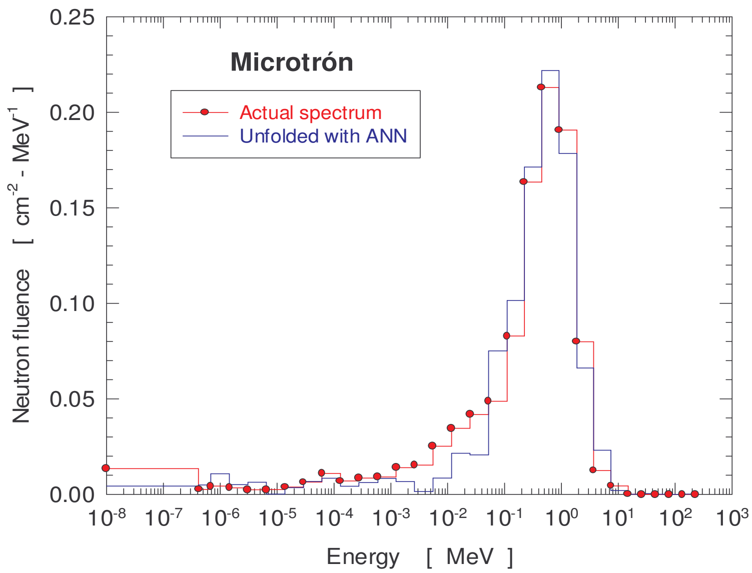

Figura 5. Microtron neutron spectrum.

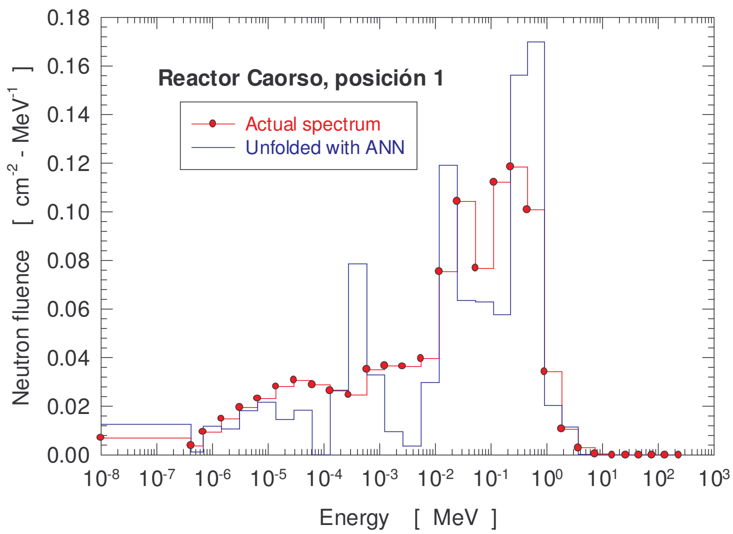

Figura 6. BWR Caorso nuclear reactor spectrum.

When our results are compared with those reported by Fehrenbacher et al., [2] and Cordes et al., [5] our results are similar, even when they used a different neural network but the features of neutron spectra used during training are similar to ours.

Kardan et al., [25] reports good agreement between actual and unfolded spectra using ANN, but they use 6, 8 and 10 energy groups to unfold the neutron spectra, here we used 31 energy groups and the agreement we have reached is good.

Neutron spectra unfolded with artificial neural networks technology are in better agreement to those unfolded using Genetic algorithms. [22, 23].

IV. CONCLUSIONS

Artificial neural networks technology has been utilized to unfold the neutron spectra from Bonner spheres spectrometer count rates. One hundred thirty two spectra and their count rates were used during the network's training. The trained network was tested with twelve neutron spectra; during testing, network performance was compared with the few results reported in literature where different networks are used.

The set of neutron spectra used during training have the strongest influence in the unfolded spectra's quality. However, a secondary factor is the network topology, in order to have more solid conclusions it is mandatory to perform more extensive studies.

The success of Artificial Neural Networks technology in the unfolding neutron spectra, using only the Bonner spectrometer count rates as input in the trained network will overcome all the problems associated with the solution of such ill-conditioned problem.

The results here reported are encouraging. The use of this technology in neutron spectroscopy and, eventually in neutron dosimetry is becoming a promising tool.

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