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Technique for obtaining low resolution information on the beta delayed neutron energies with BELEN-like detectors

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BELEN is a detector-design aimed at measuring beta-delayed neutron emission probabilities of nuclides of interest in nuclear technology and nuclear physics. In a very simplistic way, it consists of a set of rings made of thermal neutron detectors (He-3) embedded in a High-Density Polyethylene (moderator) matrix.

The “Bonner spheres spectrometer” is a widely used technique for neutron energy-spectra measurement. From the hardware point of view, it consists of a set of polyethylene spheres of different diameters with a thermal neutron detector in their center. Due to the different moderator depths, each sphere is sensitive to a different neutron energy range. In order to have a good energy resolution, sets of 5-14 spheres of different diameters are usually used to determine the energy spectrum of neutron fields up to one GeV [1].

As a first approximation, each ring of a BELEN-like detector, can be considered equivalent to a Bonner sphere. Therefore, one would expect to extract spectrometric information from BELEN, by means of an adapted unfolding technique used in Bonner spheres spectrometers.

Bonner spheres technique

A given Bonner sphere, with a response function $R_i(E)$ exposed to a neutron field with spectral fluence $\phi(E)$, will produce a reading M_i. Mathematically, the reading is the folding of $R_i(E)$ with $\phi(E)$:

$$M_i = \int R_i(E)\phi(E) \qquad \text{Eq. 1}$$

When the spectral fluence is considered as a discrete function, $\mathrm{M_i} = \int \mathrm{R_i(E)\phi(E)}$ Eq. 1 could be approximated by:

$$M_i = \sum_{j=1}^{n} R_{ij}(E)\phi_j(E) \qquad \text{Eq. 2}$$

Where $\phi_j(E)$ is the fluence in group j extending from energy E_j to E_{j+1}, and, $R_{ij}(E)$ is $R_i(E)$ averaged over group j.

Even if the response function were known, the most common situation is that the sought solution, $\phi_j(E)$, cannot be attained in an analytical way. Usually, the problem is ill-defined and requires the use of iterative unfolding techniques.

In order to use the technique in BELEN-like detectors, a Bayesian unfolding method [2] was used to reconstruct the "measured" spectra. The algorithm is iterative and requires a priori information (initial spectrum guess).

Each ring of the BELEN-like detector acts as a Bonner sphere, and their response matrices are computed using Monte Carlo neutron transport (Geant4).

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BELEN

So far, the BELEN [3] [4] (BEta-deLayEd Neutron detector) concept has been used in several experimental campaigns at GSI[3], JYFL[4], and RIKEN[5], making use of a digital electronic trigger-less data acquisition system (Gasific). The design, construction and operation of the different version of BELEN have been done by UPC and IFIC.

All BELEN versions used so far have been designed and constructed with two main design criteria, namely: a) to attain the largest neutron detection efficiency compatible with, b) a flat energy-response in a predefine range of neutron energies. Therefore, each BELEN detector has been acting as a neutron-counter with a flat response to a given neutron energy range.

BELEN for RIKEN (BRIKEN)

Among the different versions of BELEN, only BRIKEN has more than three rings. Therefore, it is the only one that could be used to measure neutron energy spectra. It has been used in a long-lasting (2016-2021) experimental campaign at RIKEN. It is made of 140 He-3 detectors embedded in polyethylene using a seven "pseudo-ring" geometry (see Figure 1).

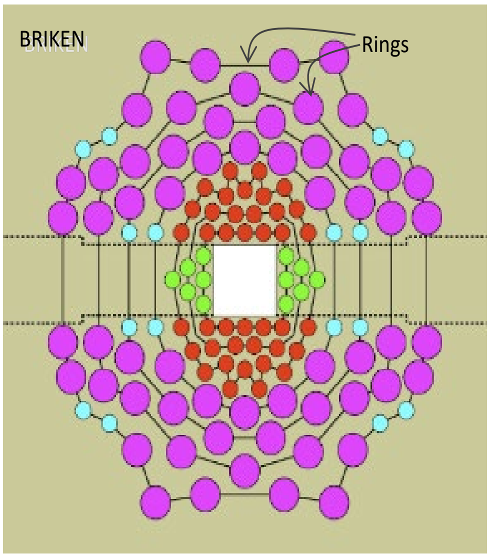

Figure 1. BRIKEN detector geometry.

BRIKEN basic neutron-energy capabilities

Several radionuclides and a neutron source were used for testing, experimentally, the neutron energy sensitivity per ring. These nuclides were selected due to the differences in their neutron energy spectrum (see Table 1).

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[4] Accelerator Laboratory, University of Jyväskylä, Finland

[5] Radioactive Isotope Beam Factory (RIBF), Nishina Center for Accelerator-Based Science, Wako, Japan

Nuclide	$Q_{\beta 1}$, MeV	Mean Energy, MeV
Ge-85	4.66	0.69
Cu-77	5.61	0.79
Cu-78	6.22	0.80
Ga-83	8.09	1.01
Cf-252	-	2.13

Table 1. BRIKEN. Magnitudes of neutron spectra for selected nuclides.

Each ring shows a different response to the neutron spectrum's mean and end-point (~$Q_{\beta 1}$) energies (see Figure 2). Rings are ordered using their radius, ring number 1 is the one located closest to the center of the detector. Even though BRIKEN has not been designed with spectrometric response in mind, it shows sensitivity to neutron energy spectra.

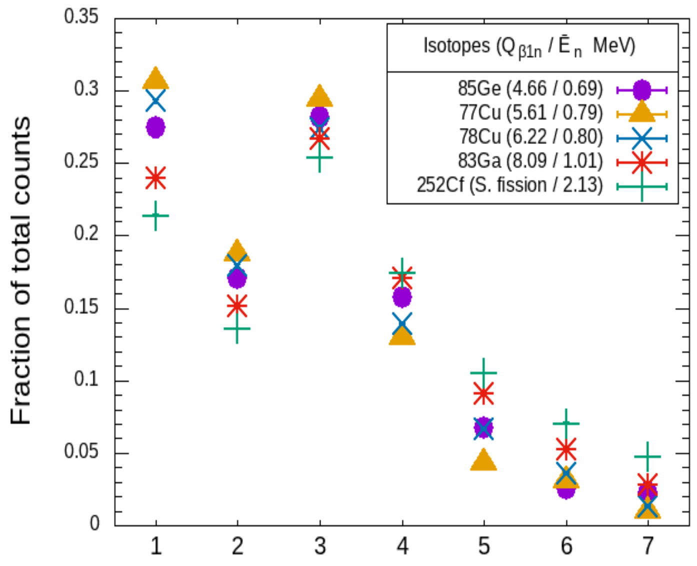

Figure 2. Normalized counts. BRIKEN energy sensitivity per ring for selected radionuclides.

Data for the selected nuclides is now under analysis. In addition to half-lives and delayed neutron emission probabilities, we expect that basic neutron-energy parameters, as well as low-resolution spectra, could be obtained.

Cf-252 neutron-energy spectrum from BRIKEN

During the experimental campaign at RIKEN, efficiency calibrations were performed using a Cf-252 source. Several of these calibration runs were selected to test the Bonner sphere technique using BRIKEN.

BRIKEN's response matrix (see Figure 3) was computed using MC (Geant4 v10.0.1), using neutrons emitted from a point source located in the center of the detector. The maximum statistical uncertainty per bin is 0.8%.

A Maxwellian energy spectrum was used as the initial guess for a Bayesian unfolding code. In order to benchmark the results, the unfolded spectra were compared to the Manhart evaluation [5].

As can be seen in Figure 4, unfolded spectra show a good agreement with the Manhart one. It is worth to mention that the unfolding method, based on the experimental measurement with BRIKEN, is able to provide a good reconstruction starting from a much more harder neutron spectrum guess.

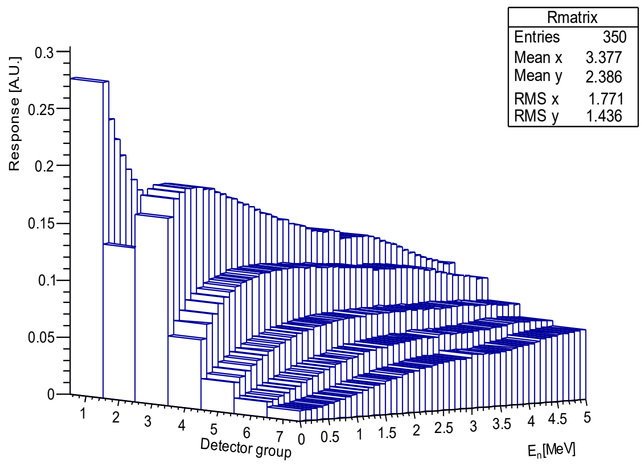

Figure 4. BRIKEN's response matrix computed with Geant4.

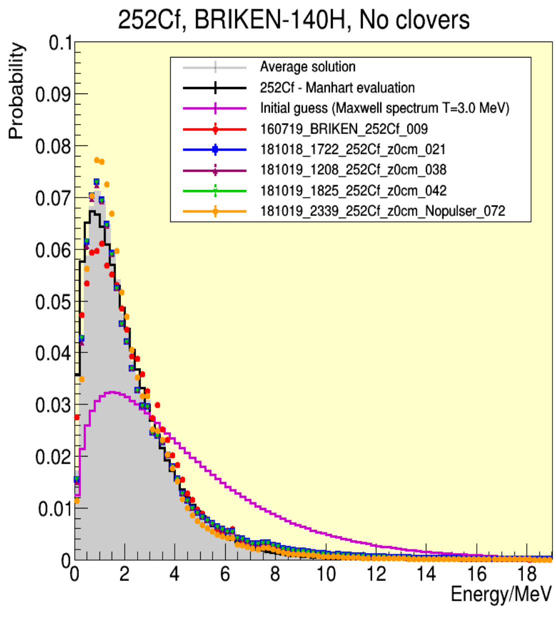

Figure 3. Cf-252 spectra obtained with BRIKEN.

BELEN-62

In the framework of this project (Work package 1, task 1.1.2), we have developed a new BELEN design with some spectrometric capabilities. Instead of the flat response criterion mentioned above, we prioritized the number of rings. With a set of 62 tubes distributed in 6 rings, BELEN-62, (See Figure 5 and Table 2), a good compromise between energy response (Figure 6) and total efficiency (Figure 7) is reached.

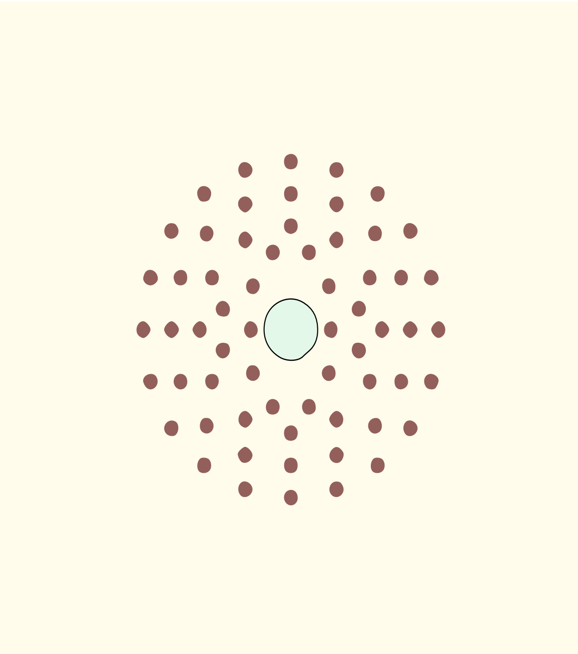

Figure 5. BELEN-62 detector geometry.

Table 2. BELEN-62 rings properties.

Ring	Tubes	R, cm
1	2	6.38
2	4	8.58
3	8	11.20
4	12	14.50
5	16	19.00
6	20	23.50

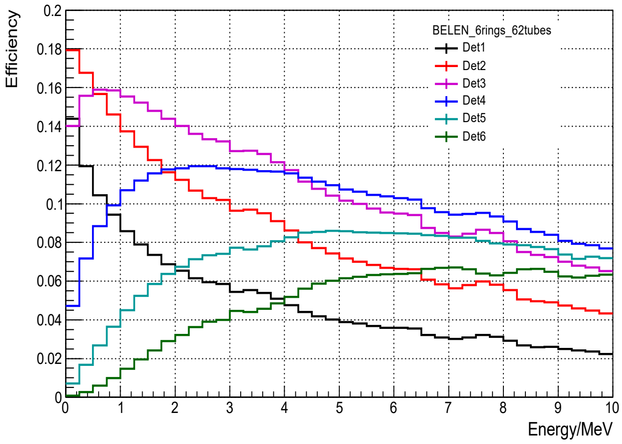

Figure 6. BELEN-62 energy response.

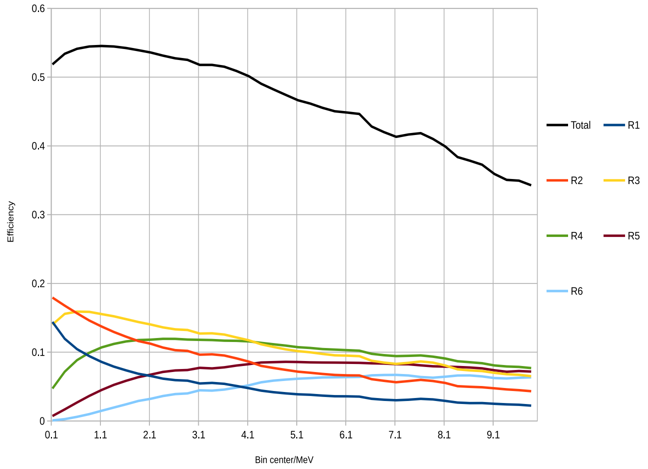

Figure 7. BELEN-62 neutron detection efficiency.

BELEN-62 basic spectrometric performance

In order to verify the spectral capacities of BELEN-62 Montecarlo-based tests were carried out.

A set of radionuclides, selected among the standards recommended in literature [6], and a neutron source (see Table 3) were used to test the energy response of the new design. The energy spectra of each radionuclide were taken from ENDF/B-VIII.0 [7]. Counts on each He-3 tube were obtained using Geant4.

Nuclide	$Q_{\beta n}$, MeV	<E>, MeV
Cf-252	---	2.13
Br-88	1.922	0.2515
Rb-94	3.452	0.4424
Rb-95	4.883	0.5295
I-137	2.001	0.6298

Table 3. BELEN-62. Neutron spectrum magnitudes of selected nuclides.

As we did for BRIKEN, counts-per-ring are used as a first indicator of the spectrometric capabilities of the detector. The new design presents a good energy sensitivity per ring (see Figure 8).

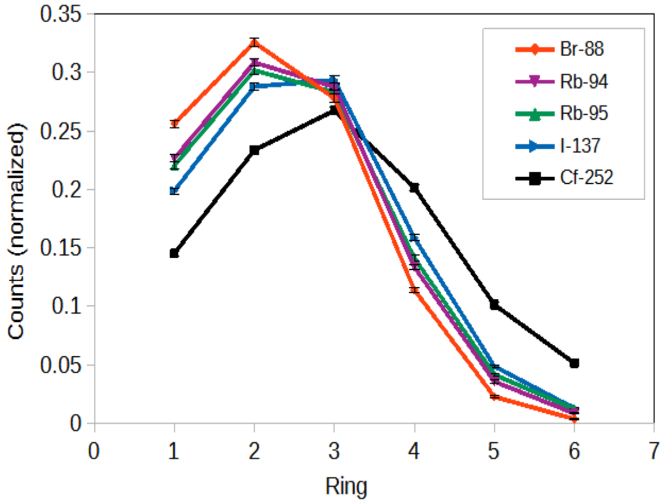

Figure 8. BELEN-62 energy sensitivity per ring for selected radionuclides.

Neutron-energy spectra with BELEN-62

Energy spectra were obtained by unfolding the detector's counts per ring. A Bayesian unfolding method was used to reconstruct the spectra. As initial educated guesses, a Maxwellian spectrum was used for Cf-252, while a simple constant beta-strength spectrum was used for the beta-delayed neutron emitters.

A good agreement is found between the unfolded spectra and the expected ones (see Figure 9 to Figure 13, and Table 4).

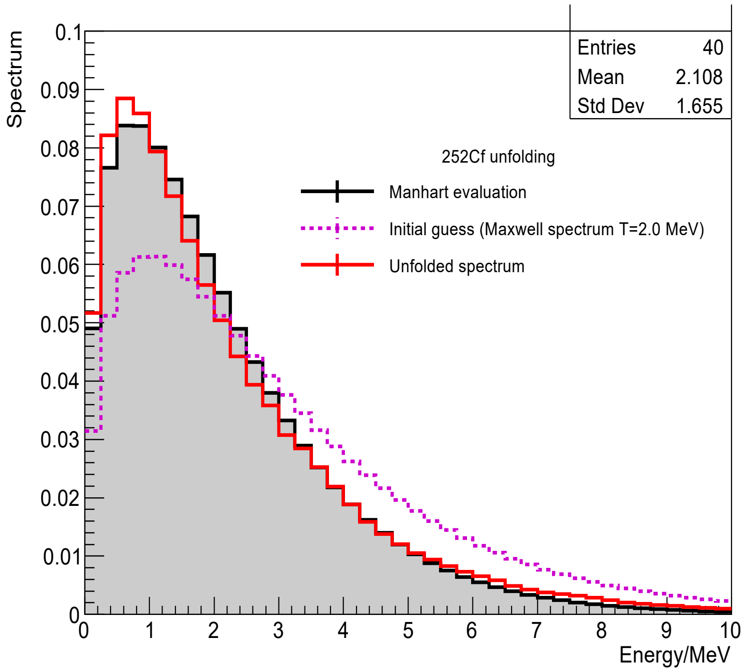

Figure 9. BELEN-62. Cf-252 spectrum.

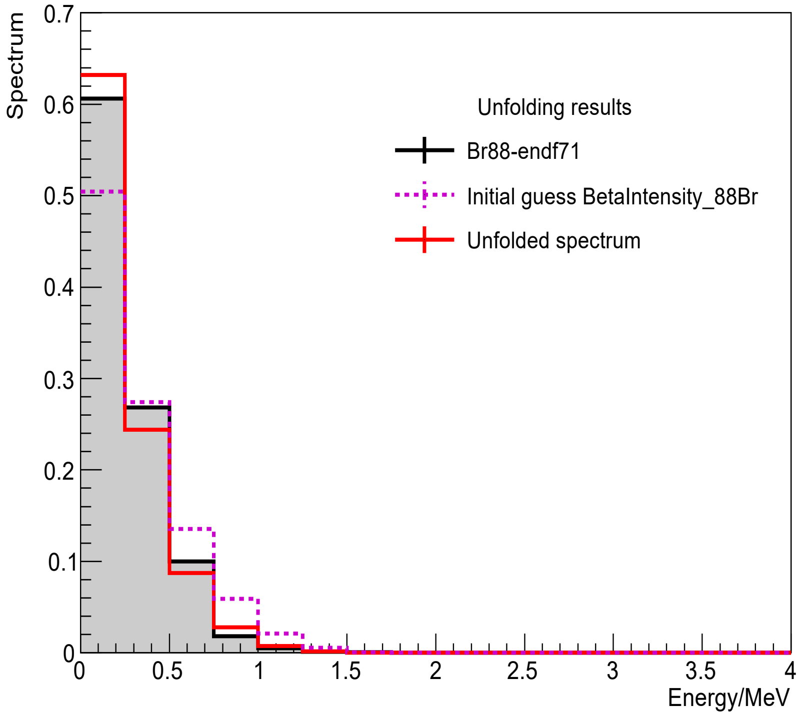

Figure 10. BELEN-62. Br-88 unfolded spectrum.

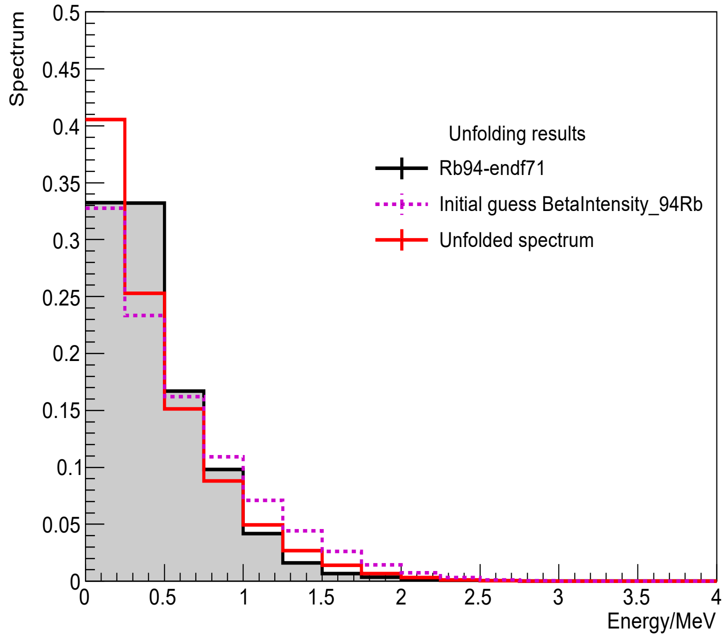

Figure 11. BELEN-62. Rb-94 unfolded spectrum.

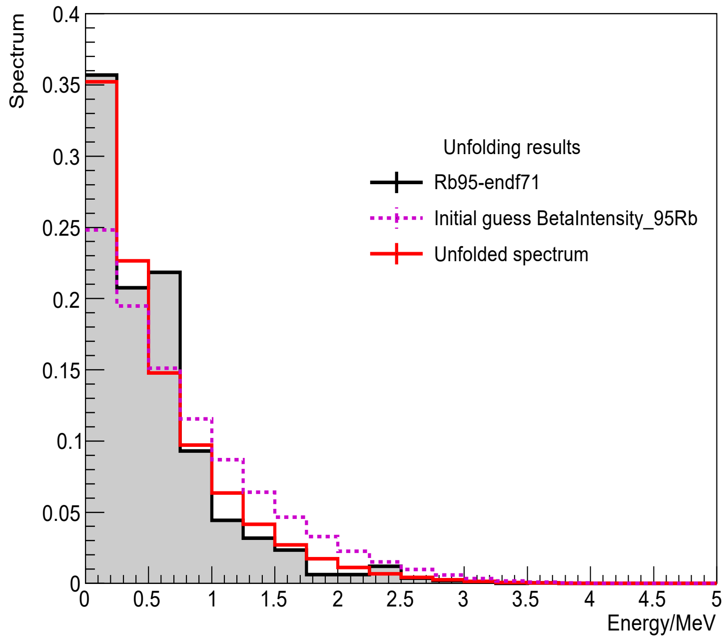

Figure 12. BELEN-62. Rb-95 unfolded spectrum.

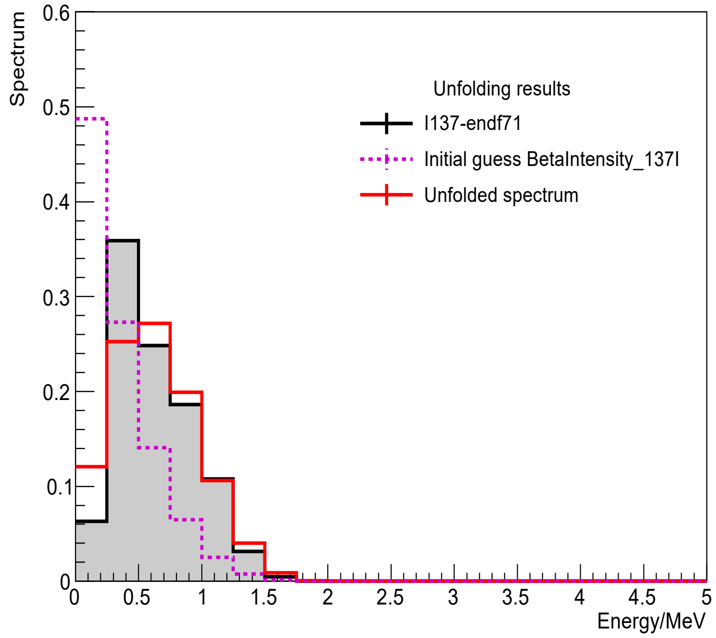

Figure 13. BELEN-62. I-137 unfolded spectrum.

Nuclide	Ratio <E>
Cf-252	1.019
Br-88	1.033
Rb-94	1.032
Rb-95	1.091
I-137	1.023

Table 4. Ratio of expected to unfolded mean energies.

Both, data and response matrix have been computed using Montecarlo. Further investigation on the "goodness" of the Montecarlo is required. Experimental demonstration is required.

Concluding remarks

Iterative unfolding methods can be used to obtain basic spectral data from beta delayed neutron emitters from BELEN-like detectors.

BELEN-like neutron detectors can be used to measure low-resolution neutron energy spectra of beta-delayed emitters and Cf-252 neutron source.

A new device, BELEN-62, for precise study of fission products and their decay for future measurements has been designed.

BELEN-62 has a mean neutron detection efficiency larger than 50% for neutron energies up to 5 MeV. For neutron energies up to 2.5 MeV, the efficiency has a flatter behavior than BELEN-48.

BELEN-62 offers good spectrometric capabilities. The mean energies seem to be well reproduced and the unfolded spectra are a good smoothed representation of the expected ones.

Experimental data is required to fully verify BELEN-62 performance.

Further investigation on the physics goodness of the Montecarlo codes need to be carried on.

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