Consejo Superior de Investigaciones Científicas
Universitat de València
IFIC - INSTITUTO DE FISICA CORPUSCULAR

IFIC Preprint: 2000-11

Monte Carlo simulation of the response of a C_6D_6 total energy detector for neutron capture studies

J.L. Tain[1]
IFIC, C.S.I.C.-Univ. Valencia, E-46100 Burjassot, Spain

F. Gunsing
CEA/Saclay, DSM/DAPNIA/SPhN, F-91191 Gif-sur-Yvette, France

D. Cano-Ott
CIEMAT, E-28040 Madrid, Spain

[1] Tel. +34 963983497; fax +34 963963488; e-mail: Jose.Luis.Tain@ific.uv.es

1 Introduction

The cross-section of neutron capture (n,γ) reactions can be obtained by counting the number of γ-ray cascades generated after each capture process. This can be performed using a detector with 100 % cascade detection efficiency, which requires the use of a very large 4π detector. The same goal can be achieved using a detector with the property that the detection efficiency ε_γ for any individual γ-ray in the cascade is proportional to its energy E_γ:

$$\varepsilon_\gamma = kE_\gamma \tag{1}$$

If the γ-ray efficiency of such a detector is very small ($\varepsilon_\gamma \ll 1$), the detection efficiency of any cascade ε_c can be well approximated by the sum of the efficiencies of detecting the γ-rays in the cascade:

$$\varepsilon_c = 1 - \prod_j (1 - \varepsilon_{\gamma_j}) \approx \sum_j \varepsilon_{\gamma_j} \tag{2}$$

which is then proportional to the cascade energy E_c and thus independent of the cascade path:

$$\varepsilon_c \approx k \sum_j E_{\gamma_j} = kE_c \tag{3}$$

This type of detector is known as total energy detector. An elegant way (Maier-Leibnitz [1]) to achieve the proportionality of the detection efficiency with the energy is by *software* manipulation of the response function of the detector. This could be superior to the *hardware* solution due to Moxon and Rae [2] where the proportionality achieved is only approximate.

If R_{ij} represents the detector response distribution for a γ-ray of energy E_{γ_j}, verifying:

$$\sum_i R_{ij} = \varepsilon_{\gamma_j} \tag{4}$$

one needs to introduce a set of weighting factors W_i in order to fulfill the proportionality condition:

$$\sum_i W_i R_{ij} = kE_{\gamma_j} \tag{5}$$

It can be readily seen [3] that the weighting factors are a smooth function of energy and can be described by a polynomic function. Thus the weighting function can be obtained by least squares fit from a limited number of response distributions:

$$min \left(\sum_j \sum_i W_i R_{ij} - kE_{\gamma_j} \right)^2 \tag{6}$$

The use of a detector with a smooth response distribution reduces the systematic uncertainties in the procedure. Among several such detectors the C_6D_6 liquid scintillator has become a popular choice due to its low neutron sensitivity.

The application of the method requires the determination of a set of response distributions for γ-rays in the range of energies of interest, say up to 10 MeV. Since it is not easy to determine experimentally the R_{ij} in such a range, the solution adopted was to obtain them by Monte Carlo simulation. However, at some moment [4] it was realized that there existed a considerable discrepancy between the neutron width Γ_n obtained from transmission measurements and the one derived from capture measurements using the above mentioned technique for the 1.15 keV resonance in ^{56}Fe. A special task force was set-up to investigate this issue and it eventually became clear, mainly from the careful measurements of Corvi et al. [5], that the problem was originating in the Monte Carlo simulated response distributions.

It is the purpose of the present paper to discuss the present actual status of the technique and to report on new simulation results.

2 The measurements

As mentioned above, the measurements from Corvi et al. [5] (which will be referred as **1**) showed clearly that the response distributions calculated by the Monte Carlo method failed to reproduce the experimental ones. They also suggested that a possible explanation for the failure was the fact that the simulations included an over-simplified description of the set-up: only the active material was considered.

Recognizing the importance of the whole set-up in the detector response, a new measurement was performed by Corvi et al. [6] (which will be referred as **2**) with an arrangement common to the neutron capture measurements, so that the experimentally determined weighting functions could be employed in analyzing the capture data. They also provided a detailed description of the set-up in order to to encourage the investigation of the Monte Carlo simulations.

These are the data (mainly from reference **2**) with which we will compare the results of our simulations.

The method employed to measure the mono-energetic γ-ray responses is the coincidence technique for two-gamma cascades populated in (p,γ) resonance reactions in light nuclei: ^{26}Mg, ^{30}Si and ^{34}S. A Ge detector is used to tag clean γ transitions and the absolute normalization is obtained from comparison of the number of counts in the singles (N_s) and coincidence (N_c) Ge spectra:

$$N_c = \varepsilon_{C_6D_6}\varepsilon_{Ge} n t \quad (7)$$

$$N_s = \varepsilon_{Ge} n t \quad (8)$$

$$\varepsilon_{C_6D_6} = \frac{N_c}{N_s} \quad (9)$$

where n is the rate of emission, t is the measuring time and $\varepsilon_{C_6D_6}$, ε_{Ge} are the detector efficiencies.

A number of corrections have to be applied in order to arrive to the correct result:

1. For the different dead time of singles and coincidence acquisition systems

2. For the anisotropy of the intensity distribution within the solid angle of the detectors due to the angular correlations

3. For contaminant gamma cascades parallel to the main transition

In order to perform correction 2) the knowledge of the multipolarity of the transitions and the multipole mixing ratios is required. Correction 3) demands the complete knowledge of the level scheme connecting the two levels of interest. The corrections were applied either from the known literature values or from new measurements which were done whenever the authors felt that the previous knowledge was not accurate enough.

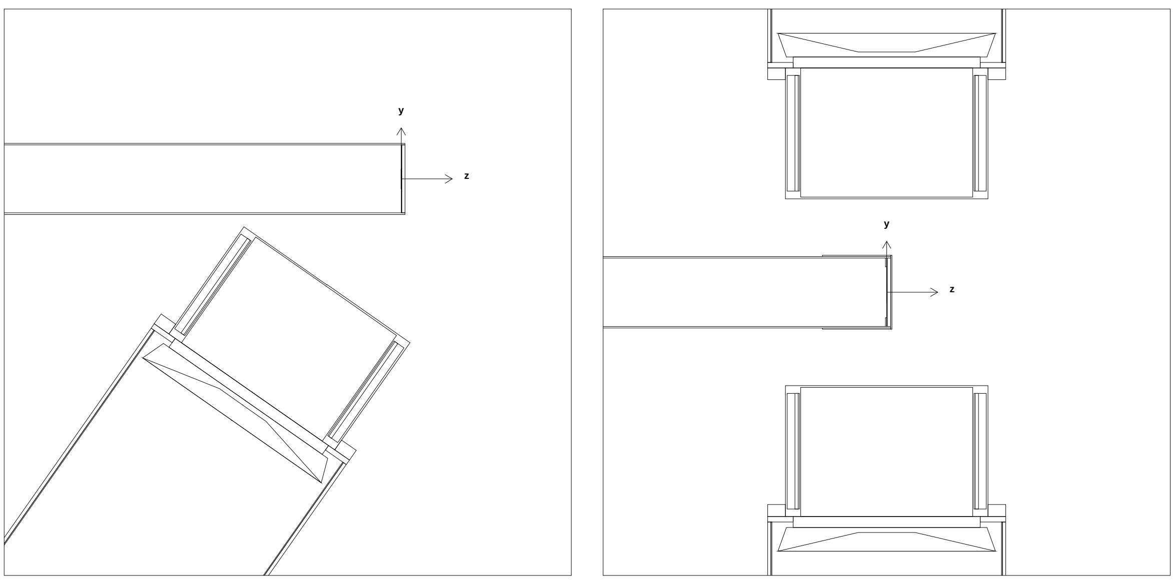

Figure 1: Geometry employed in the GEANT3 simulations for both set-ups

In reference **1** a ⌀10.2cm × 7.6cm C_6D_6 detector was placed at 125° with respect to the beam direction (in order to minimize the angular distribution corrections) and in reference **2**, two detectors in sum mode were placed at 90° (see Fig. 1). In both cases, the Ge detector was placed at 0°. The target material is deposited on a 0.3 mm thick water cooled Ta disk glued at the end of the Al beam pipe. Further details on the geometry can be found in both references.

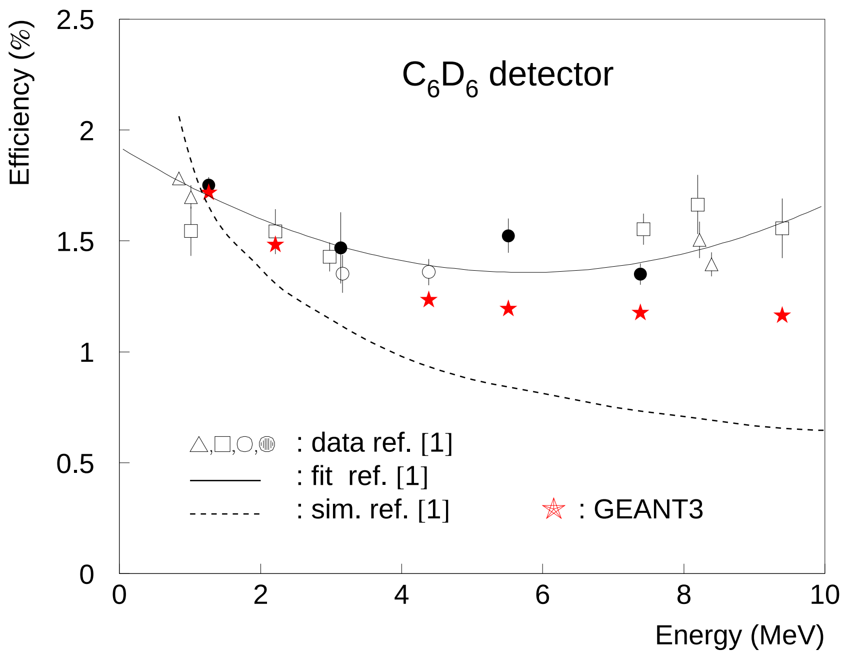

Figure 2: Comparison of measured and simulated detection efficiencies for set-up 1.

3 The simulations

The simulations were performed using the GEANT3 package [7]. The geometry employed tries to reproduce as far as possible the geometrical set-up described in both references. In Fig. 1 it is shown the geometry as depicted by the simulation program for both set-ups. The description of the C_6D_6 detector is taken from reference **2** and includes the quartz window of the photomultiplier tube. It is assumed that in reference **1** the same detector description applies. The γ-rays are generated randomly within a disk of ⊘4mm in the very thin layer ($\approx 0.2\mu$m) of target material. The Ge detector is not included in the simulation since by the very principle of the coincidence technique its influence must be negligible.

We start by considering the simulation results obtained for the total efficiency with a detection threshold of 100 keV. Fig. 2 compares this results with the measurements for the the first set-up (reference **1**). The solid line represents a fit to the experimental values (dark symbols) while the dashed line is the result they obtained from a Monte Carlo simulation which considered only the active volume of C_6D_6. As can be seen the efficiency measured at the higher energies is more than a factor 2 larger than the efficiency they calculated. The red stars represent our GEANT3 result. A much better agreement is now obtained, particularly at the lower energies. Nevertheless the agreement of the total efficiency (integral value) is not really indicative of the accuracy achieved. The comparison with the whole response distribution is needed. Since we could only get the measured

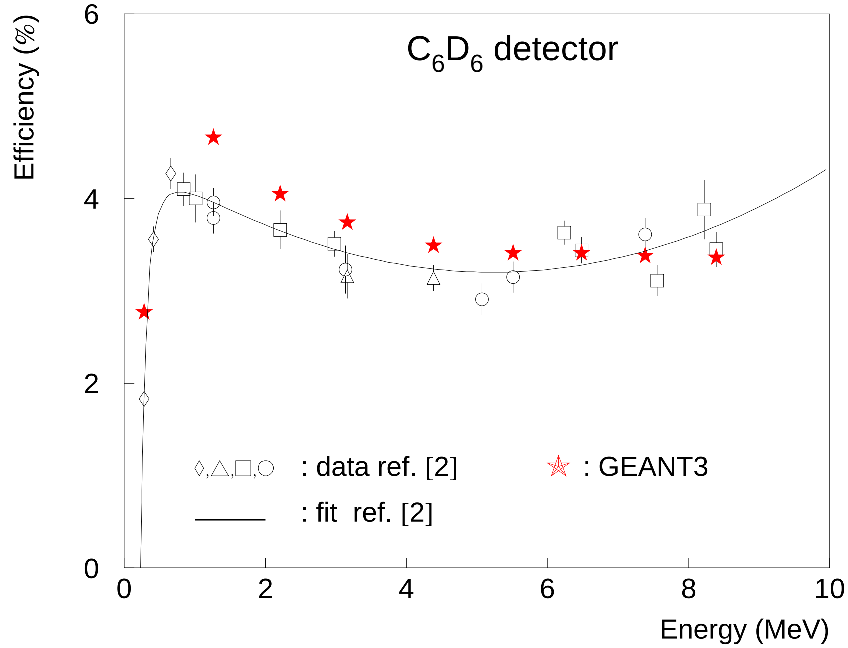

Figure 3: Comparison of measured and simulated detection efficiencies for set-up 2.

response distributions for the second set-up, we will restrict ourselves in what follows to the data of reference **2**. Even so, we have to say that we could only obtain [8] the scanned response distributions from old figures, since the original data are lost. We start also by comparing the integrated efficiency in Fig. 3. As it can be observed a rather surprising result is obtained, namely the calculated efficiencies are larger than the experimental ones at the lower energies (18 % at 1266 keV) and agree at the higher energies.

In Fig. 4 we compare the response distributions for three γ-ray energies: 1266, 4386 and 7383 keV. The calculated responses have been widened by an instrumental Gaussian response, with variance given by $\sigma^2 = 3E$ (in keV^2) which seems adequate. The dark points represent the data, the red stars represent the simulation. Each distribution is independently normalized: the measured one to the experimental efficiency and the simulated one to the calculated efficiency. For the 1266 keV γ-ray we find that the whole response is over-estimated. In fact if we normalize both distributions to each other a good reproduction of the shape is obtained. We turn now to the 7383 keV data. Contrary to the previous case (which corresponds to a transition from the first excited state to the ground state) the 7383 keV response is contaminated with other higher multiplicity cascades connecting the same levels. The violet points represent the distribution obtained for a 7383 keV γ-ray, while the red points include the contribution from the known [9, 10] contaminant cascades. As can be observed a very good agreement is reached. This really indicates that a a better agreement is obtained at the higher γ-ray energies. For the

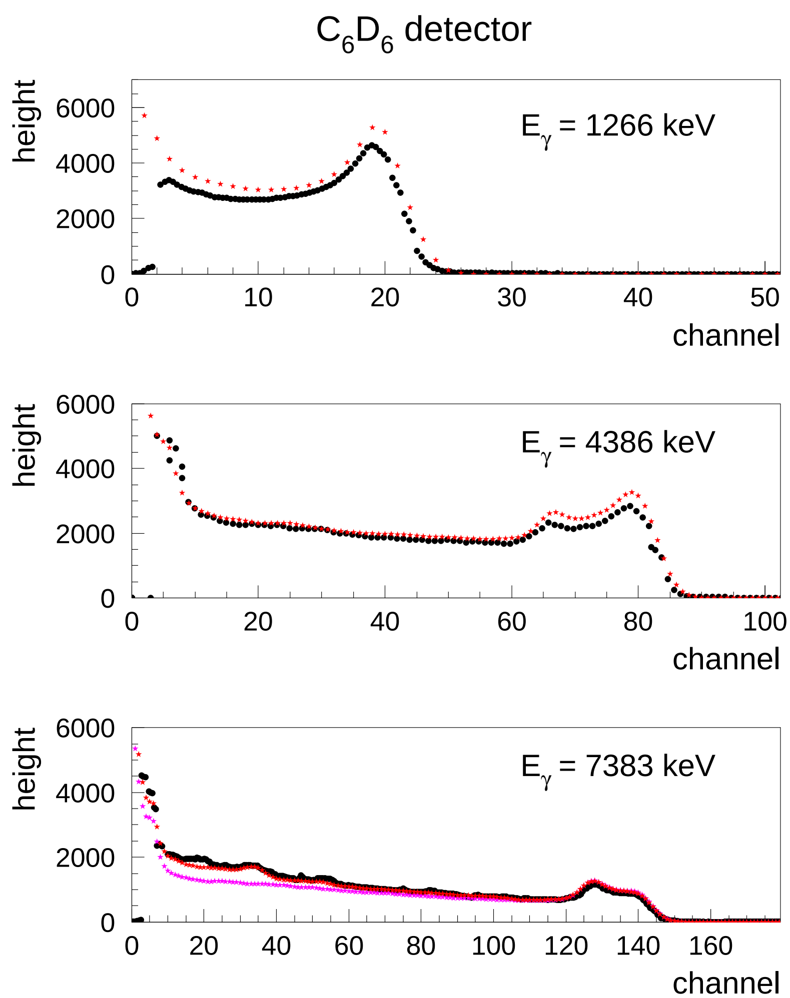

Figure 4: Comparison of measured and simulated response distributions for set-up 2.

4386 keV data we deal also wit the case of a non-pure transition, although in this case the known [11, 10] contamination is rather small (1.4 %). The red points include this contribution. As it can be observed the agreement in shape is not as good as before. The height of the Compton edge and double escape peak bumps is larger than the measured ones.

Irrespective of the discrepancies, it will be of prime interest to investigate the contribution of dead materials, i.e. materials other than the active volume of C_6D_6, to the simulated response distributions. In the left pannels of Fig. 5 we represent for two γ-ray energies (1266 and 7383 keV) the simulated response distributions when all materials are considered (red line), when no dead materials belonging to the detector are included (green line) and when no dead material at all is included (dark line). The distributions, with a bin size of 50 keV, have not been widened by the instrumental resolution. It is to

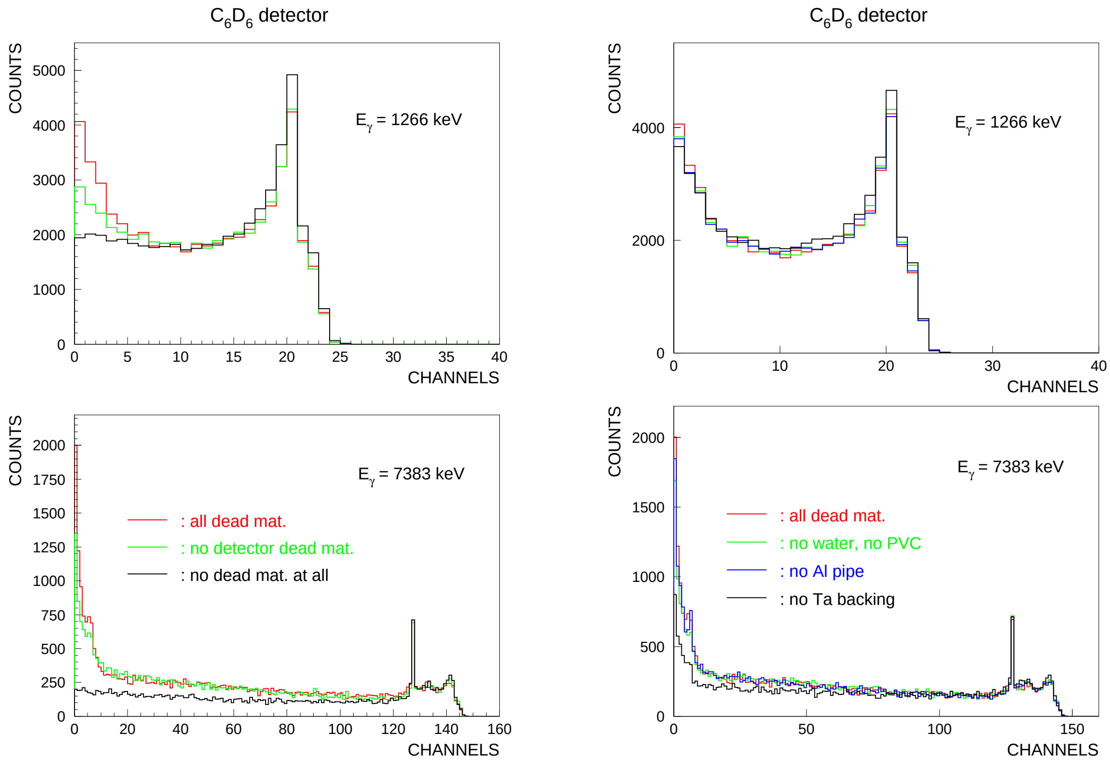

Figure 5: Effect of dead materials in the detector response.

be noticed that at low energies the effect of dead materials is small, while at high energies the increment in detection efficiency is not due to the extra material belonging to the detector but rather to the material surrounding the source. This is further investigated in the right pannels of Fig. 5 where we selectively remove the dead material around the source: the water and PVC cap of the cooling system (green), the Aluminium beam pipe (blue) and the Tantalum backing (black). As can be observed it is the Ta backing (with high Z and close to the source) the one producing most of the extra radiation (secondary electron/positrons or they bremsstrahlung) which enters into the active volume of the detector and contributes to its efficiency.

4 Discussion and Conclusions

We do not have at present any convincing explanation for the discrepancy between measured and calculated response distributions, which is mostly an overall normalization problem dependent on the energy. It is hard to understand why, for example, the simulation should fail to reproduce the absolute efficiency at 1266 keV, and a normalization problem in the data should not be excluded.

We have calculated the weighting function (degree 4 polynomial) for the (p,γ) set-up

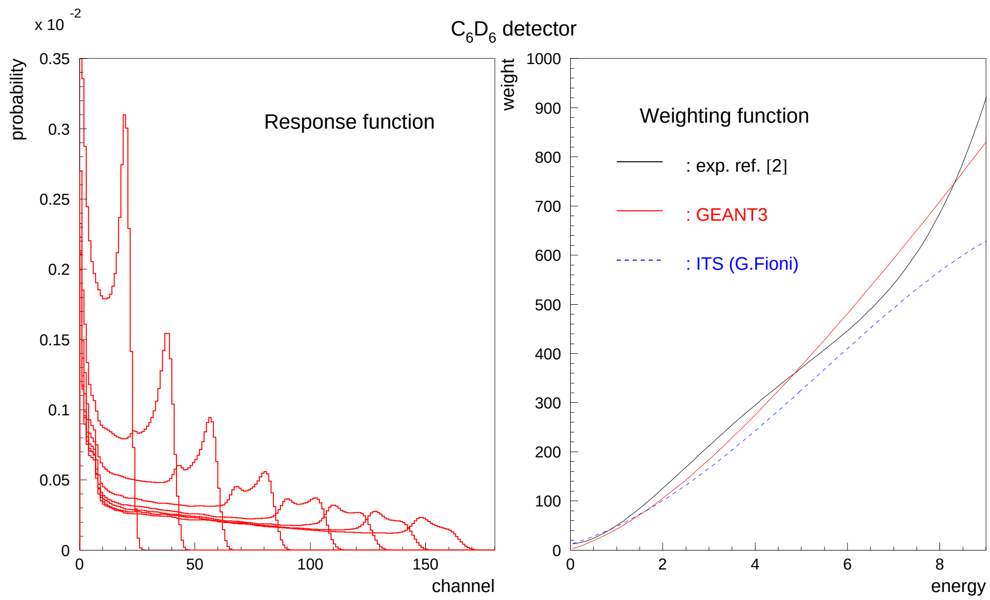

Figure 6: Comparison of measured and simulated weighting functions for set-up 2.

from the set of simulated distributions (energies: 1266, 2209, 3163, 4386, 5515, 6483, 7383 and 8392 keV) which are shown in the left pannel of Fig. 6, and compare them with the experimental weighting function obtained in reference **2** in the right pannel of the Figure. The experimental curve (in black) shows an oscillation which is not present in the simulated curve (in red), but there is an overall agreement. Unfortunately we cannot check the effect of the new curve on the cross-section results since this would imply to reanalyze the capture data. We include also (dashed blue line) in the right pannel of the Figure the weighting function derived from previous Monte Carlo simulations [12] performed using the ETRAN based code ITS [13], which as can be observed lies consistently lower. It is interesting to notice that they obtain a similar but stronger over-prediction of total efficiencies at the lower energies, as compared to our results. Since the response distributions themselves are not shown, neither the geometry employed is fully described, it is difficult to arrive to any conclusion from the comparison. Finally we would like to comment that there has been also an attempt [6] by the Oak Ridge group to calculate the response distributions for the (p,γ) set-up using the EGS4 Monte Carlo [14] code with apparently limited success.

One should not forget anyhow that the reproduction of the response distributions measured with (p,γ) reactions is not the goal but just a check on the reliability of the simulations. It is the (n,γ) set-up which has to be simulated and the derived weighting functions proved. Furthermore as we have shown, the most important contribution to the detection efficiency comes in the (p,γ) set-up from the target backing, and analogously one should expect in the (n,γ) set-up that the most important contribution comes from the sample. Therefore, the use of the experimentally determined weighting function from the (p,γ) set-up to analyze capture data may introduce a systematic error in the results. The only practical way to take into account the different measuring conditions (samples) in different experiments will be to use Monte Carlo derived weighting functions. The accuracy of these weighting functions has to be checked by (n,γ) measurements. For example, by measuring resonances with very simple decay schemes (^{207}Pb, light nuclei,...) which allow a direct check of the response distributions, or by performing systematic studies of cross-sections for several sample thicknesses (for example in ^{56}Fe).

5 Acknowledgments

We would like to thank Paolo Mutti who made available to us the (p,γ) response distributions. This work was supported by C.I.C.Y.T. (Spain) under project AEN96-1662.

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