Calibration and Monte-Carlo Simulation of the Detection System PTOLEMEOS

K. Spyrou, C. Chronidou, S. Harissopulos, E. Kossionides, T. Paradellis

Calibration and Monte-Carlo Simulation of the Detection System **PTOLEMEOS**

K. Spyrou, C. Chronidou, S. Harissopulos,
E. Kossionides, T. Paradellis.

Institute of Nuclear Physics, N.C.S.R. "Demokritos"
P.O.B. 60228, GR-153.10 Aghia Paraskevi, Athens, Greece

Abstract

Monte-Carlo simulation and efficiency calibration of the 4π NaI γ-ray detection system PTOLEMEOS is presented. This system is dedicated to the study of nuclear reactions of astrophysical interest. The simulation is evaluated with experimental data.

1 Intoduction

Capture reactions play a very important role in nuclear astrophysics. Their presence is crucial in stellar evolution, from hydrogen burning to the more complicated s,r and p -processes. These reactions are important in stellar processes because they all have positive Q-values (except for nuclei far of the valley of stability) and therefore contribute to the stellar energy production. Furthermore, these reactions,though slow, are very important in the synthesis of the elements [1].

One of the most important quantities in nuclear astrophysics is the reaction rate. From the point of view of nuclear physics one of the goals is the experimental determination of reaction rates of astrophysicaly interested reactions, as a function of temperature. The reaction rate in a stellar environment is given by r = $N_1 \cdot N_2 \cdot \langle \sigma \cdot v \rangle$ where N_1,N_2 the densities of the reacting nuclei (particles/cm^3) and

$$\langle \sigma \cdot v \rangle = \left(\frac{8}{\pi \cdot \mu} \right)^{1/2} \frac{1}{(K \cdot T)^{3/2}} \int_0^\infty \sigma (E) \cdot E \cdot e^{-E/KT} dE$$

is the reaction rate per particle pair.

It is obvious that the measurement of the total cross section of a nuclear reaction (going as low as possible in the energy range) is the necessary requirement for the evaluation of the reaction rate.

A nuclear capture reaction can proceed either via combound nucleus mechanism with resonant behavior or via direct capture. The result of such a reaction is the emission of γ-radiation -that is, the deexcitation can proceed through the emission of one or many photons (cascade).

Therefore, the determination of the efficiency of the detection system PTOLEMEOS, which is essential for the absolute measurement of the cross section, is not trivial and Monte Carlo simulation has to be performed.

2 Experimental setup

The detection system "PTOLEMEOS" consists of a NaI cylindrical crystal barel with 8 photomultiplier tubes (PMTs), 4 of which are situated in each base. There is a hole transversing the crystal barel, normal to the axis of the cylinder halfway along its height, where two extra NaI detectors (3×3") have been placed (figure 1). This configuration achieves 4π geometry.

The existence of a small cylindrical hole paralell to the axis of the cylinder combined with the possibility of moving the system on rails, allows the target holder to be placed in the middle of the detection system. Details concerning PTOLEMEOS have been presented in a previous publication [2].

The outputs from the ten PMTs sum over in groups of 5. The two group outputs are passed through two amplifiers and then they are sumed again to form the final summing signal which goes to the ADC and then to the computer for data acquitition. This is the reason why the crystal is called summing crystal, it gives information about what is detected simultaneously by all the detectors.

For a capture reaction $A(x,\gamma)B$ deexcitation may proceed via a cascade mode. Cascade photons are considered to be emitted simultaneously because of their small time scales, much smaller than the corresponding ones of the detector and electronics. Therefore there is a great possibility of summing all the photons, resulting in the appearence of the summing peak in the spectrum.
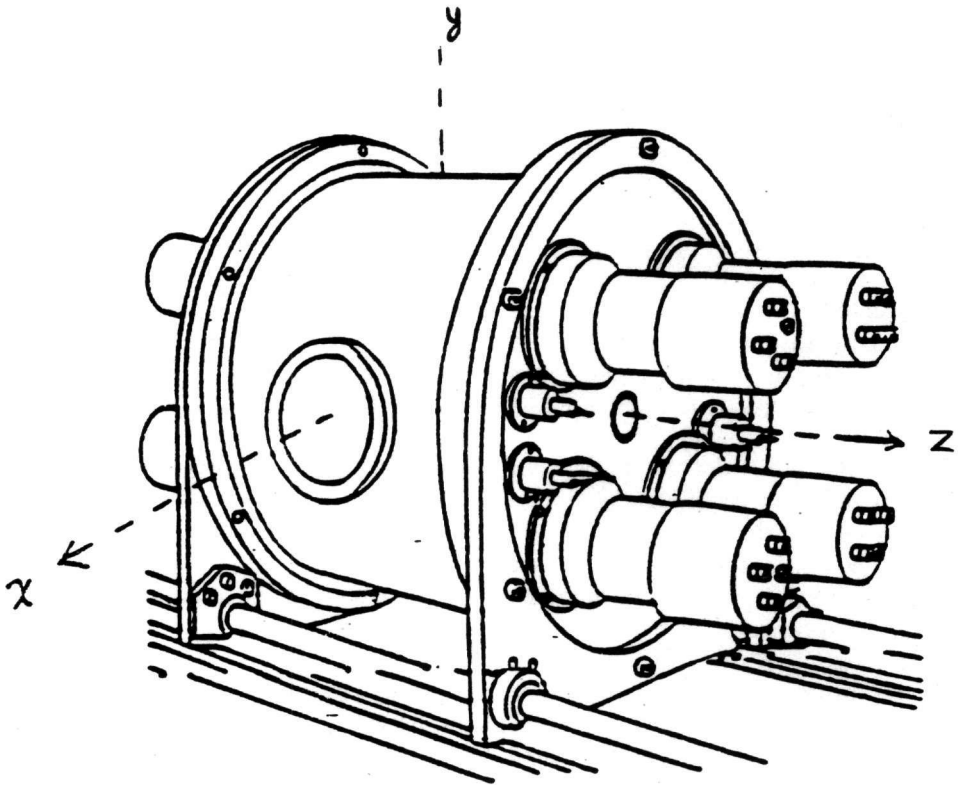
Fig.1 4π NaI γ-ray detection system PTOLEMEOS

154

The energy of the summing peak is equal to the excitation energy of the nucleus.

For example,in the case of a cascade which consists of two photons with energies E_1 and E_2, summing peak will appear at $E_s = E_1 + E_2$. The number of photons in the summing peak is generally given by :

$$N_{sum} = S \cdot \varepsilon_1 \cdot \varepsilon_2 \cdot y_1 \cdot y_2 \cdot \Omega^2 \cdot W(0°) \Rightarrow N_{sum} \sim \Omega^2$$

where S : number of deexcitations

Ω : solid angle of the detector and

$\varepsilon_1, \varepsilon_2, y_1, y_2$: efficiency and percentage per deexcitation of each photon respectively.

The above expression also indicates one of the major advantages of our system. The Ω^2 dependence of photon detection shows that our 4π solid angle coverage detection system is extremely efficient. Concequently its capabillity of measuring very low cross sections is enhanced. Another advantage of the system is its intrinsic angle integration property. That is, every measurement is angle integrated, due to the 4π solid angle of detection resulting in the direct measurement of the total cross section.

In figure 2, the summing effect (when all the detector signals are summed) is very impressive in the case of a ^{60}Co radioactive source which emmits two cascade photons of energy 1172 and 1332 keV.

In figure 3, a spectrum of a ^{22}Na source is shown. The summing peak here is the result of the summation of three photons which are emitted for every β^+ decay of ^{22}Na. Every positron leads to the emission of two 511 keV photons and the daughter nucleus deexcitates via the emission of one more photon.

In the following tables, resolution and efficiency measurements for the detection system with several radioactive sources are presented.
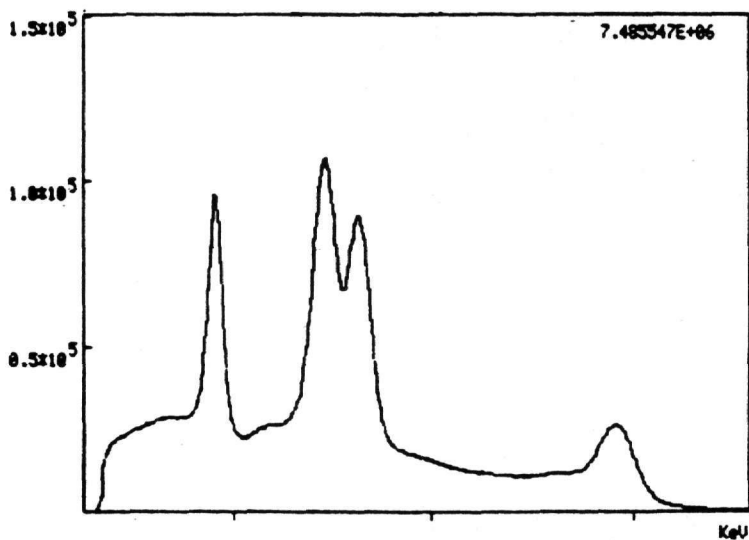
Fig. 2a Spectrum of ^{137}Cs and ^{60}Co sources taken with only 5 of the detectors active
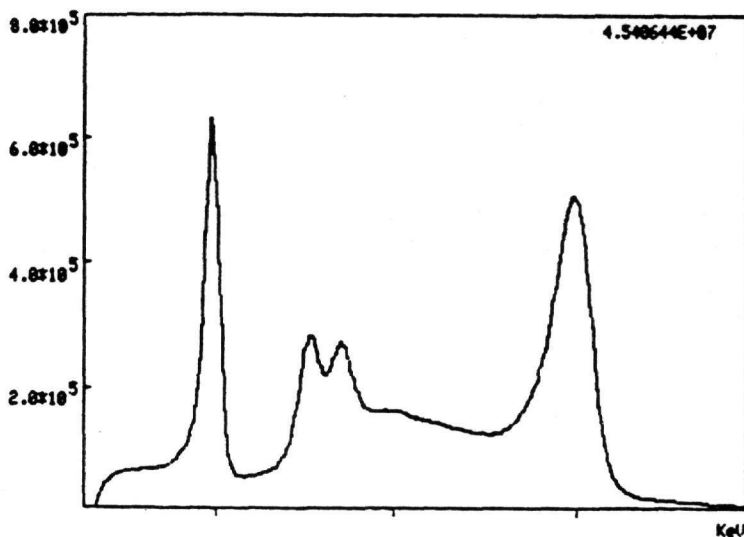

Fig. 2b Spectrum of ^{137}Cs and ^{60}Co sources taken with all the detectors active. Summing peak is highly increased.
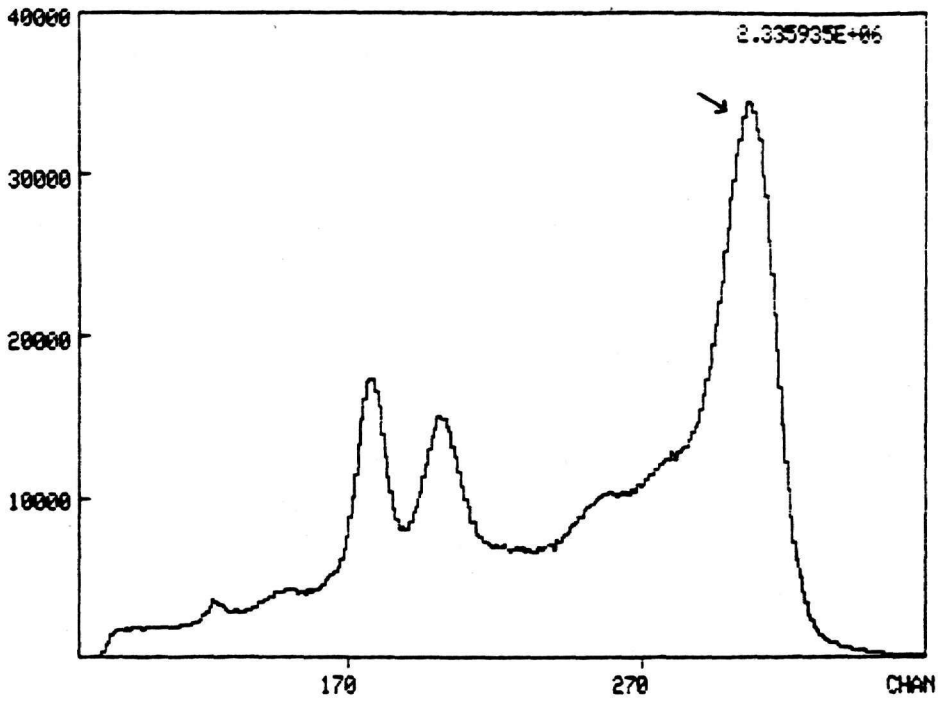
Fig. 3 Sum spectrum of a ^{22}Na radioactive source

E(keV)	Δ E(keV)	$\frac{\Delta E}{E}(\%)$
662	89.0	13.5
835	99.2	11.9
1173	130	11.0
1332	139	10.5
2505	222	9.2

Table 1 : Resolution for various energies.

Photon source	Total detection efficiency (%)	Sum peak efficiency (%)
$^{137}Cs(662keV)$	88.7 ± 6.4	
$^{54}Mn(835keV)$	78 ± 5	
$^{60}Co(1173keV)$ (1332keV)	97.1 ± 5.3	27 ± 2

Table 2 : Efficiency for various sources

3 Monte Carlo simulation and calculated efficiency of the detector

For an absolute measurement of the total cross section of a nuclear reaction, the knowledge of the detection efficiency is mandatory. The total efficiency of a detection system is the percentage of the total number of events detected by the system.

In the case of PTOLEMEOS where capture reactions are involved, the evaluatation of the efficiency is not trivial due to the emission of high energy cascade photons. In this case the total efficiency depends on the mode of deexcitation process of the compound or product nucleus. Different cascades, that is diferent sets of emitted photons of the same total energy, have remarkably different total detection efficiencies. The total efficiency also depends on the region of spectrum integration. So different integration windows yield to different efficiencies.

The above mentioned arguments indicate that experimental determination of the total efficiency is unapplicable and Monte-Carlo simulation has to be

performed.

The Monte Carlo simulation procedure was based on the GEANT package (version 3.20) [3]. GEANT is a system of detector description and simulation tools. The user's supplied code consists of the main program and six subroutines, all of them in FORTAN programming language. This code is subsequently compiled with more than 1500 subroutines from GEANT library.

One of the user supplied subroutines concerns the description of the geometrical setup. For the description of PTOLEMEOS over 70 different volumes of varius shapes and materials were simul.

For every initial 'event', that is, the simulation of the emission of one or more photons from the center of the system, all the possible interactions and tracks in every defined volume are simulated and recorded.The deposited energy in the crystal from every track, initial or secondary, is computed. The output of the program is a histogram spectrum showing the number of events versus the deposited energy in the simulated NaI crystal.

The output drawing of the program with all the simulated volumes of the detection system is displayed in figure 4, while the simulation of 500 photons is shown in figure 5. A typical simulation procedure includes 100000 initial events.

The procedure described above, concerns the simulation of the physical processes which take place in the detection system. Thus, the output histogram is not the simulation of the real spectrum because the effects of the PMTs and the electronics are not included.

In order to account for the above mentioned effects, the output histogram spectrum h(E) is convolved with an appropriate responce function g(E,E') considered to be a gaussian.

$$f(E) = \int h(E') \cdot g(E, E') \, dE'$$

where
$$g(E, E') = \frac{1}{\sqrt{2\pi}\,\sigma} \, e^{-(E-E')^2/2\sigma^2}$$

and σ : standard deviation of the responce function, experimentaly determined from the resolution of the detector.

The output of the above procedure is the simulation of the real spectrum.
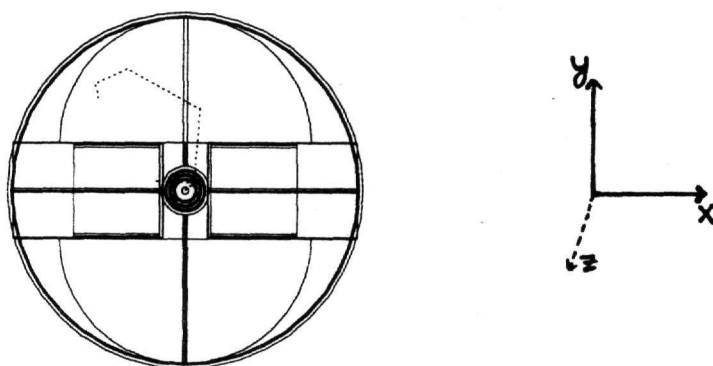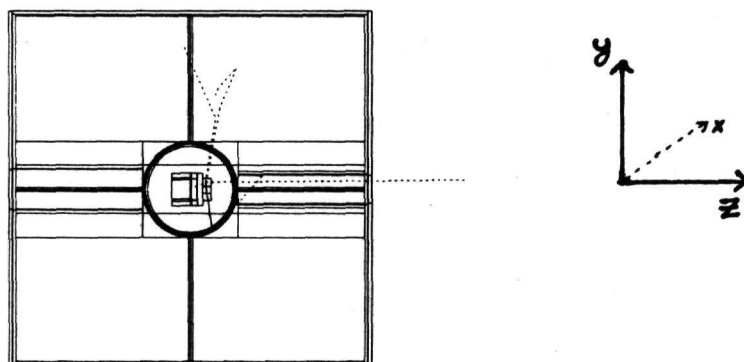
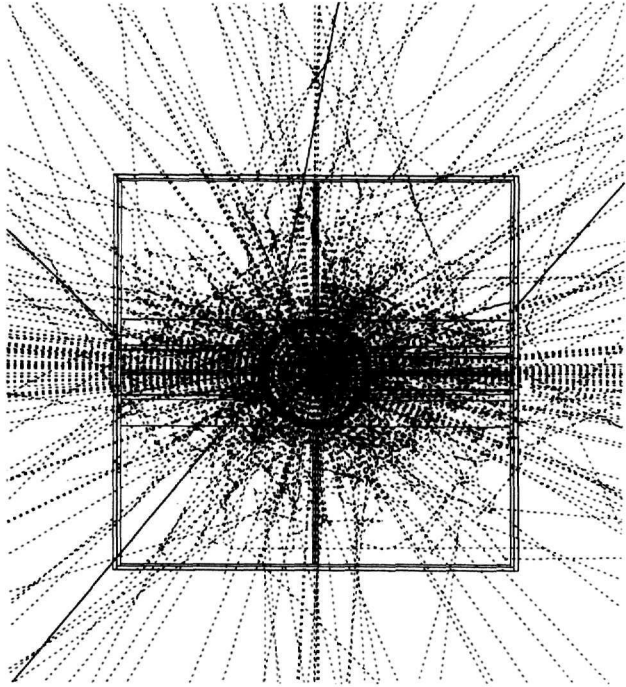Fig.4 Simulated geometrical setup of the detection system showed in two different planes

Fig.5 Simulation of 500 photons of 835 keV

The total efficiency for a specific case is derived by integrating the simulated spectrum for the desired integration window. The total efficiency of PTOLE-MEOS vs energy for monoenergetic photons is shown in figure 6.

The results of efficiency measurements and efficiency calculations from Monte Carlo simulation for three radioactive $\gamma-$ ray sources are summarised in table 3. Two of the sources (^{137}Cs and ^{54}Mn) emit monoenergetic photons while the ^{60}Co source emits two cascade photons.

Photon source	Experimental total efficiency (%)	M - C calculated efficiency (%)
$^{137}Cs(662keV)$	88.7 ± 6.4	81.0
$^{54}Mn(835keV)$	78 ± 5	79.5
$^{60}Co(1173keV)$ $(1332keV)$	97.1 ± 5.3	94.9

Table 3.

It is evident that the efficiency depends strongly on the number of photons which are emitted. This is obvious in the case of the ^{60}Co source. For a single photon with energy 2505 keV the efficiency of the detection system would be about 0.71 (see fig.6). However, the fact that we have two photons with total energy $E_{\gamma_1} + E_{\gamma_2} = 2505$ keV instead of one, increases the efficiency to 0.95. Thus, the deexcitation mode of combound nucleus (via the emission of either a single photon or through a cascade) has a great impact on the efficiency.

4 Discussion

The comparison between experimental and calculated efficiency shows excellent agreement. A nuclear capture reaction may procceed via many different deexcitation modes of the combound nucleus, with a different propability for each one. In such a case, simulation and efficiency computation for each independent mode has to be performed.
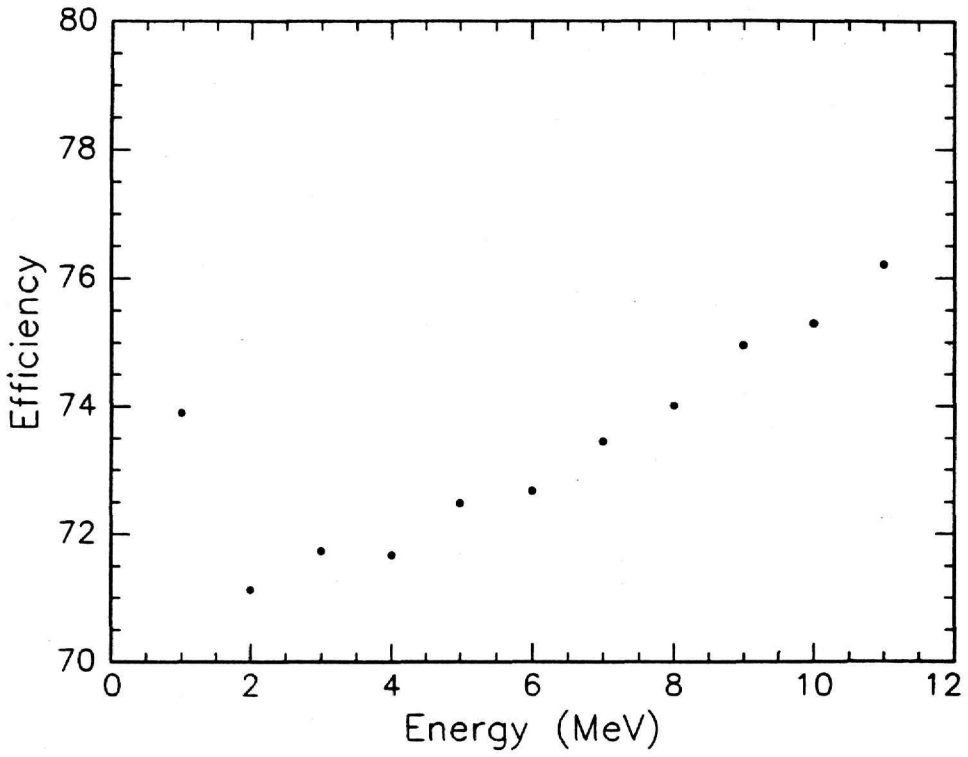
Fig.6 Efficiency of 'PTOLEMEOS' vs energy for monoenergetic photons

The total efficiency of the detection system will be the linear combination of all the different weighted efficiencies $n_i w_i$.

$$n = w_1 n_1 + w_2 n_2 + ... + w_N n_N = \sum_{i=1}^{N} w_i n_i$$

where N : total number of deexcitation modes (cascades).

The main deexcitation modes for a given reaction can be found in literature or in the case where there is lack of information, they can be estimated experimentally. The procedure for this estimation is to take a spectrum from one of the detectors of the system, simultaneously with the summing spectrum. The observed photon peaks would yield the main deexcitation modes which are involved in the specific interaction.

Apparently, the fact that the uniqueness of every nuclear reaction is taken into account when calculating the efficiency of the system, makes the whole procedure reliable and very sensitive, although time consuming.

Nevertheless, the effort for a reliable efficiency calibration is not completed. The whole procedure has to be tested using known nuclear reactions, a process through which the overall error bars of our calculated efficiency will be extracted.

References

[1] C. Rolfs and W. Rodney, " Cauldrons in the Cosmos ", The University of Chicago Press (1988)

[2] S. Harissopulos et al, Proceedings of the European Workshop on Heavy Element nucleosynthesis, Budapest, Hungary, March 9-11,1994,ed. Somorjai and Z. Fulop (published by the Institute of Nuclear Research of the Hungarian Academy of sciences, 1994) p. 74

[3] GEANT-Detector Description and Simulation Tool, (CERN, Geneva 1993)