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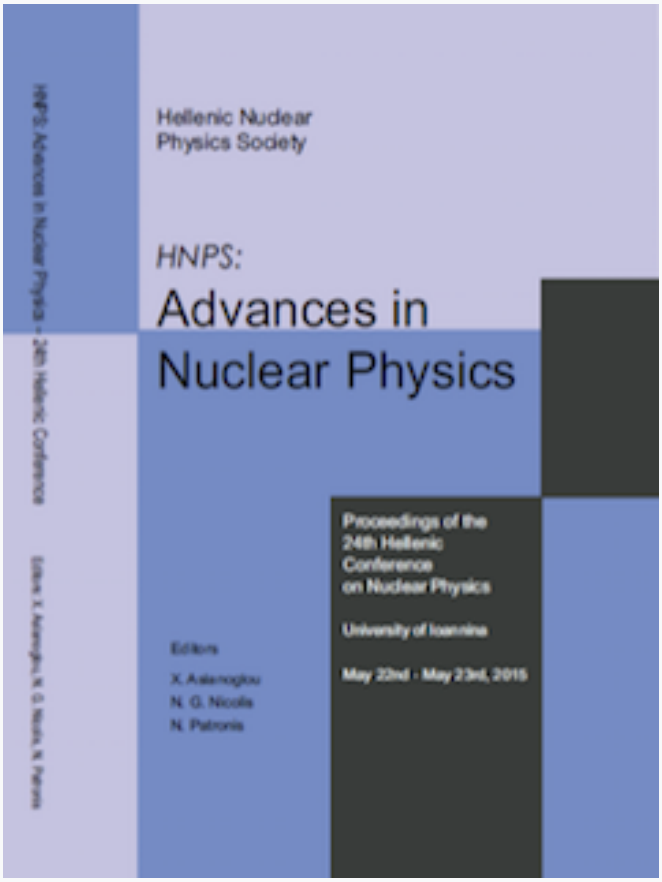
HNPS Advances in Nuclear Physics

Vol 23 (2015)

HNPS2015



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doi: 10.12681/hnps.1900

To cite this article:

Axiotis, M., Lagoyannis, A., Provatas, G., Foteinou, V., Karydas, A., Kantarelou, V., Bazzacco, D., Alvarez, C. R., Napoli, D. R., Menegazzo, R., & Harrisopulos, S. V. (2019). New Instruments for Nuclear Astrophysics. *HNPS Advances in Nuclear Physics*, *23*, 8–14. https://doi.org/10.12681/hnps.1900

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Proceedings of the 24th Syposium of the HNPS

New Instruments for Nuclear Astrophysics

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Abstract A major task in experimental nuclear astrophysics is the measurement of cross sections of capture reactions. In the last years, the astrophysics group of NCSR "Demokritos" developed and used a method for conducting this kind of research using a 4π NaI γ-detector [1]. Of great importance in this method is the determination of the efficiency of the detector, which depends on the average multiplicity of the γ-cascade de-exciting the entry state of the produced nucleus.

Two new experimental setups have been studied and are in course of installation at the Tandem Laboratory of the Institute of Nuclear and Particle Physics of NCSR "Demokritos", that will provide the possibility for conducting this kind of experiments inhouse. The first one is a new 14x14 inches NaI detector and the second is the BGO Ball of the GASP setup. These detector setups as well as their potential experimental use will be described in detail.

Keywords Nuclear Astrophysics, 4π NaI crystal, BGO Ball

INTRODUCTION

Stellar nucleosynthesis of elements above iron is known to proceed primarily by neutron capture reactions on already formed nuclides, which then decay by emitting electrons (β^- decay). As a result, the vast majority of the stable nuclei heavier than Fe are produced via the *s* and *r* processes that are comprehensively reviewed in [2-6]. Among the stable nuclei that are heavier than Fe, there exist 35 nuclei [7-9] which lie on the neutron-deficient side of the stability valley between ^{74}Se and ^{196}Hg. This group of stable nuclides, known as *p* nuclei, cannot be synthesized by either the *s* or the *r* process because stable isobars shield them from the β^- decay of more neutron-rich nuclei.

To date, the prediction of the solar-system abundances of the *p* nuclei is one of the major puzzles of all models of *p*-process nucleosynthesis [9]: although the latter are capable of reproducing these abundances within a factor of 3, they fail in the case of some light *p* nuclei around A≈90, with ^{92}Mo and ^{94}Mo being the most striking cases, and a number of heavier ones. Although, these discrepancies could be attributed to uncertainties in the pure astrophysical modelling, nuclear physics uncertainties also need to be considered. This is because astrophysical abundance calculations make an extensive use of the Hauser-Feshbach (HF) theory [10] to obtain a vast number of cross sections and from those the reaction rates of more than 20000 reactions of an extended reaction network involving almost 2000 nuclei heavier than iron. Nuclear physics input, such as ground state (g.s.) properties, level densities, *γ*-ray strength functions, and optical model potentials are

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needed for these calculations. This input can be determined, tested, and improved by laboratory cross-section measurements of capture reactions to finally obtain robust and reliable model predictions for these parameters. It is, hereby, worth noting that the vast majority of these reactions involves unstable target nuclei far off stability that are hardly reachable, even with the latest developments in the production and acceleration of radioactive ion beams.

In the present paper, a brief description of a method developed by the astrophysics group of the NCSR "Demokritos" will be given, and in addition the new experimental setups of the Tandem Accelerator Laboratory will be presented.

THE 4π γ-SUMMING METHOD

A major task in experimental nuclear astrophysics is the measurement of cross sections of capture reactions. In such in-beam experiments, the total cross section σ_T is derived from the total reaction yield Y by using

$$\sigma_T = \frac{A}{N_A}\frac{Y}{\xi}$$

where A is the atomic weight in *amu* of the target used, N_A is the Avogadro number and ξ is the target thickness. The total reaction yield is obtained from the absolute efficiency corrected A_0 coefficients of the corresponding angular distributions of all the transitions depopulating the entry state (transitions γ_0, γ_1 and γ_2 of left panel of Fig.1). The same quantity can also equivalently be derived from all the transitions feeding the ground state (transitions γ_0, $\gamma_{1,0}$ and $\gamma_{2,0}$ of left panel of Fig.1) using

$$Y = \sum_{i}^{N} A_0^i$$

where N is the total number of transitions to be considered. Obviously, the determination

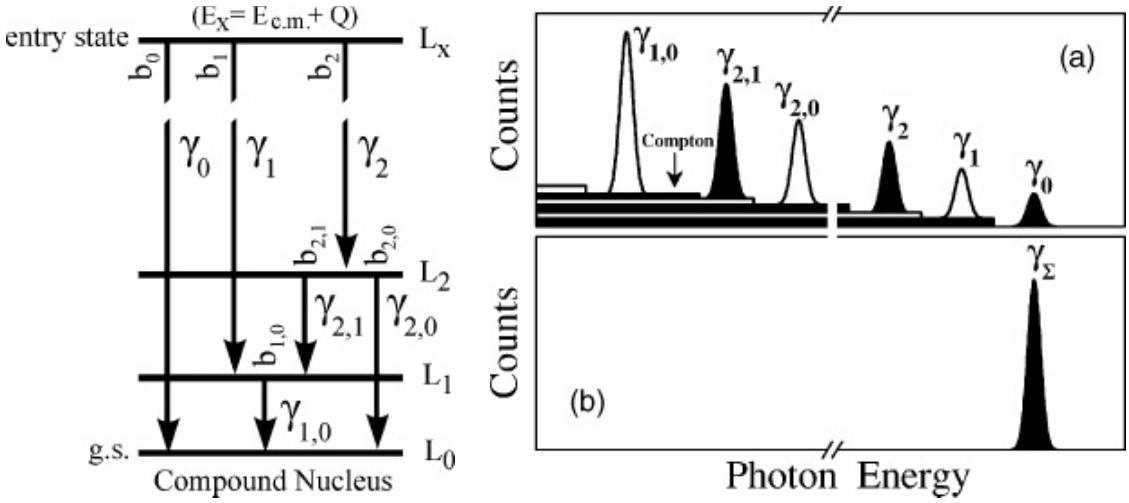

Fig. 1. ***Left panel***: Simplified decay scheme of a compound nucleus produced in a capture reaction at an excited (entry) state with energy E_X. ***Right panel***: Typical γ spectra for the de-excitation of the compound nucleus illustrated on the right by using (a) a small-size NaI(Tl) crystal and (b) a large volume 4π NaI(Tl) summing detector.

of cross sections from γ-angular distribution measurements can become very time

consuming with increasing number *N* of γ transitions, since spectra for each transition at every energy and for several angles have to be analyzed.

The 4π γ-summing method described here in brief and presented in detail in [1] is based on the use of a large-volume NaI(Tl) detector, covering a solid angle of almost 4π for photons emitted at its center. Because of the large volume of the detector and the large decay time of the crystal (typically ≥ 250 ns), the detector absorbs fully all the photons and additionally it "sums" the energy of the photons of each cascade. The spectra from the two different methods are depicted in the right panel of Fig.1. It is clear from the discussion that for each energy it is necessary to acquire only one "angle integrated" spectrum to analyze. In this case, the total reaction yield needed for the determination of the cross section is obtained by

$$Y = \frac{I_\Sigma}{N_b \varepsilon_\Sigma}$$

where I_Σ is the intensity of the sum peak, N_b is the number of beam particles and ε_Σ is the sum-peak efficiency. The problem that arises is the determination of the ε_Σ. The method was introduced and tested with the 12x12 inch NaI(Tl) detector at the Dynamitron Tandem Laboratory of the University of Bochum, Germany (see Fig.2). The specific setup was

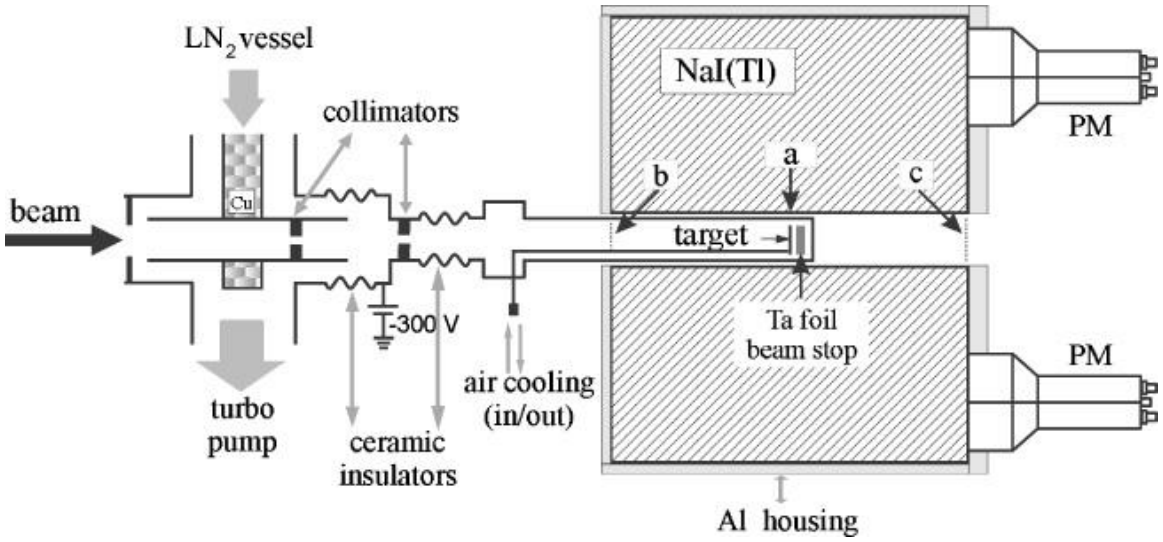

Fig. 2. Experimental setup at the Bochum university consisting of a 12x12 inch NaI(Tl) detector. The arrows marked with "a", "b" and "c" indicate target positions.

studied and simulated with Geant4 [11] and the procedure proposed for the calculation of the sum-peak efficiency is the following. The efficiency strongly depends on the multiplicity of the cascade and the energy of the sum peak. By Geant4 simulations and experimental measurements it was demonstrated that by acquiring a spectrum at two different positions of the setup, i.e. the "in" position indicated by "a" in Fig.2 and the "out" position indicated by "b" and "c" in Fig.2, the ratio *R* can be calculated by the formula

$$R = \frac{I_\Sigma^{in}}{I_\Sigma^{out}}$$

where I_Σ^{in} and I_Σ^{out} are the corresponding intensities of the sum peak. The "averagemultiplicity" <*M*> of the cascade is deduced by the relation $R = 2.48(3)^{<M>}$. In the left part of Fig.3 two representative "in" and "out" spectra along with their Geant4 simulations are presented, while in the right part the dependence of the ratio *R* to the

average multiplicity <*M*> is given for several sources and reactions. Once the average multiplicity is calculated and since the energy of the sum peak is known from the spectra,

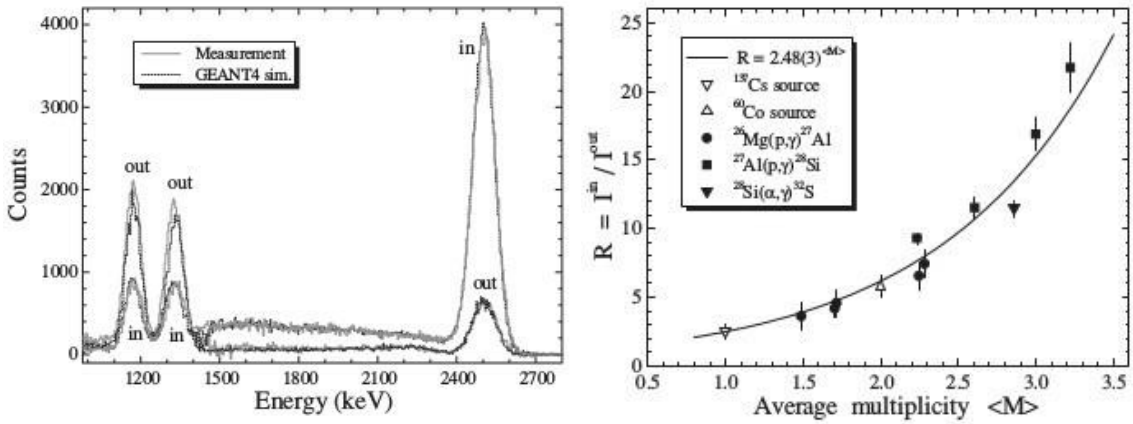

Fig. 3. ***Left panel***: γ spectra of a 60Co source at the "in" and "out" position, along with the corresponding Geant4 simulations. ***Right panel***: Measured dependence of the ratio *R* to <*M*> for several sources and reactions along with the calculated arithmetic relation.

by the use of the "map" given in Fig.4 the efficiency ε_Σ for the specific setup can be deduced.

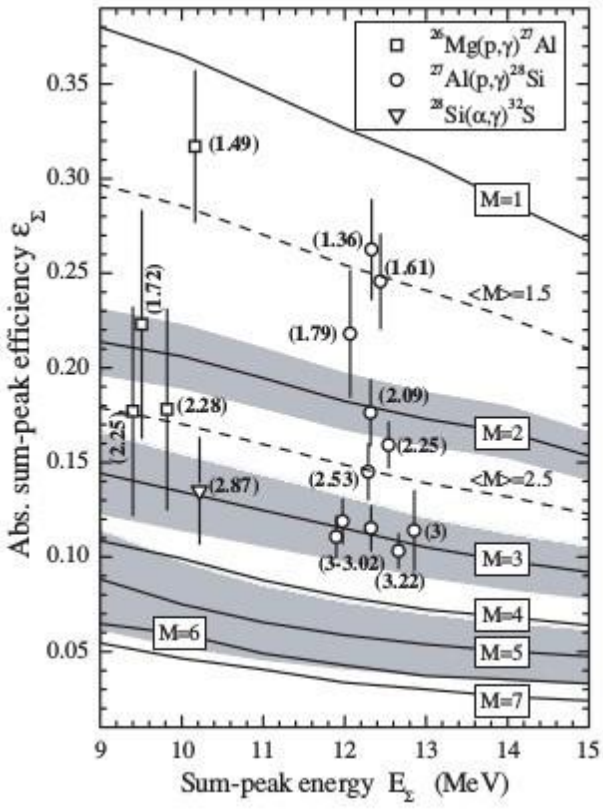

Fig. 4. Experimental and simulated sum-peak efficiencies for different sum-peak energies E_Σ and multiplicities <*M*>, determined for the resonances of the three reactions listed in the legend.

NEW EXPERIMENTAL SETUPS AT TANDEM ACCELERATOR LABORATORY

4π NaI DETECTOR

In the context of the LIBRA EU project and in order to be able to measure cross sections in house, it was foreseen the equipment of the Tandem Accelerator Laboratory of the NCSR "Demokritos" with a large 4π NaI detector at. After extensive Geant4 simulations of different setups (see Fig.5) the concluded design was the 14x14 inch detector segmented

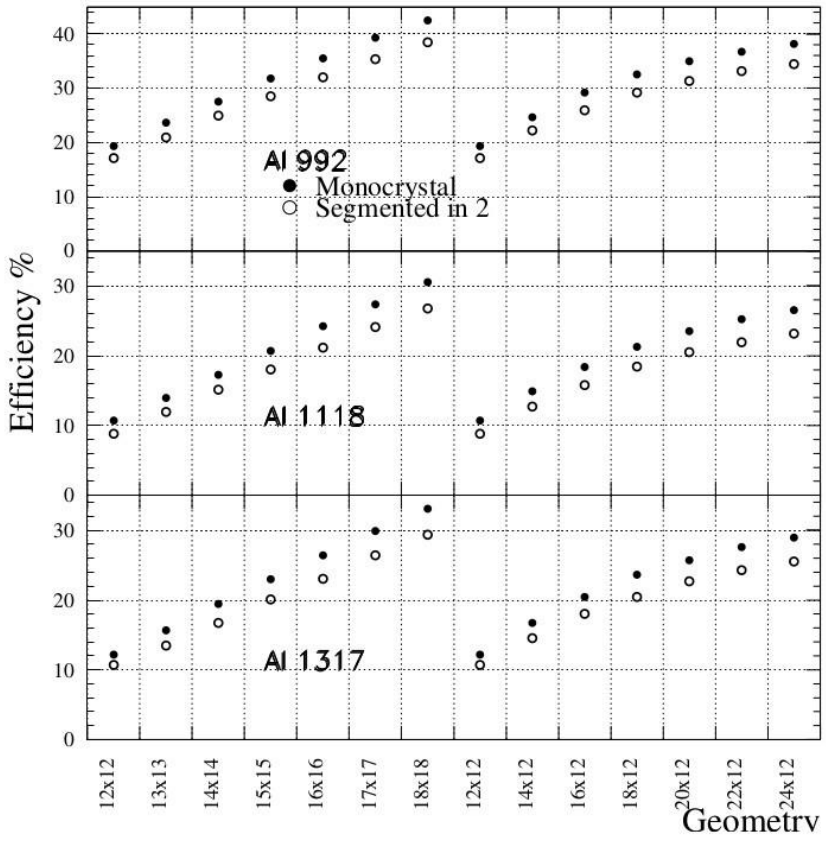

Fig. 5. Simulated sum-peak efficiencies for different detector geometries. On the geometry axis, the first number refers to the diameter of the detector and the second to its length, both measurements are given in inches. Full circle marks are for monocrystal detector, while the open circle ones correspond to a detector segmented in two parts.

in two parts, i.e. "up" and "down". The first advantage of the proposed setup, is the larger volume of the detector in comparison to the one of the University of Bochum, thus resulting at a greater efficiency, which in some cases reaches 45%. This feature will enable the group to measure reactions of lower cross section or reduce the measurement time of the experiment. The second advantage of the detector acquired by the group is its segmentation. In the case of the monocrystal setup of Bochum, in order to calculate the average multiplicity of the reaction, two separate measurements at a given energy are needed, i.e. one with the target at the "in" position and one at the "out" position. In the case of the segmented detector, by placing the target at the center of the setup three separate spectra can be acquired simultaneously, i.e. one from the top segment, one from

the bottom segment and the sum of the two. This feature will also greatly reduce the experimental measurement time, as for each beam energy only one measurement is required instead of two.
A drawing of the newly acquired detector along with a photo of one of its segments is given in Fig.6.

Fig. 6. ***Left panel***: A drawing of the 14x14 inch segmented NaI detector of the Tandem Accelerator Laboratory. ***Right panel***: A photo of one of the two segments of the detector.

BGO BALL

At the beginning of the 90's, at the Laboratori Nazionali di Legnaro the GASP spectrometer was commissioned. The setup consisted of 40 Compton suppressed Hyper-pure high efficiency n-type germanium detectors (HPGe) and a 4π calorimeter of 80 BGO crystals. In the mid 00's the setup was decommissioned, and while the HPGe detectors were used in different projects, the BGO calorimeter was not.
Lately, the BGO calorimeter and its supporting structure was lent to the Tandem Accelerator Laboratory. The setup (shown in Fig.7) consistes of 80 BGO crystalls, each

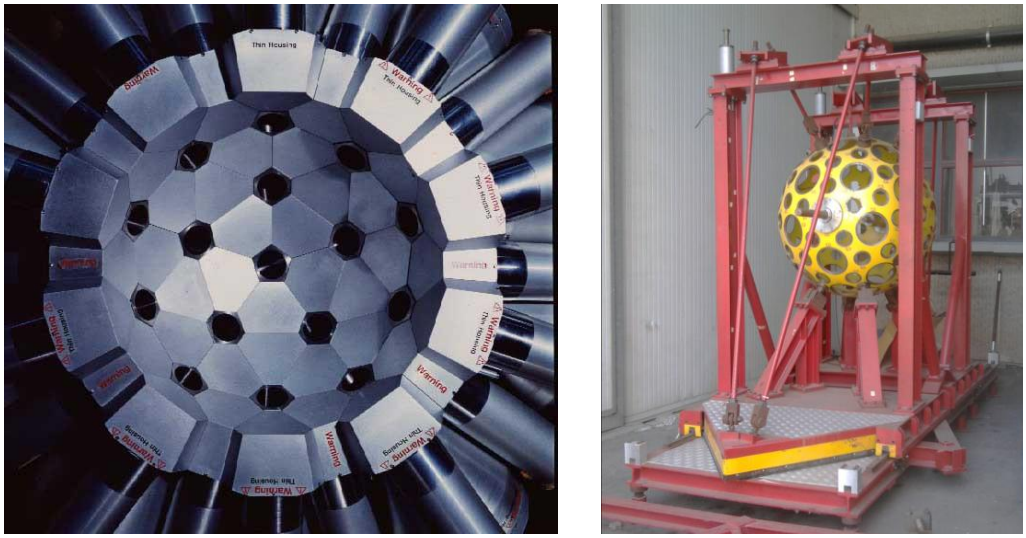

Fig. 7. ***Left panel***: A picture of the BGO Ball installed at the Laboratori Nazionali di Legnaro. ***Right panel***: A photo of the supporting frame.

having an efficiency of ≈95% for a 1.0 MeV γ transition. The total solid angle coverage of the setup is ≈80% of 4π and the total efficiency for a 1.0 MeV γ ray is of ≈70%.
The idea of installing the BGO Ball at the Tandem Accelerator Laboratory is to acquire a complementary means of determining the average multiplicity of the deexcitation of a produced nucleus during capture reactions. The great granularity of the system along with its high efficiency is expected to give results that can lead to the multiplicity of the cascades with high accuracy.

FUTURE PLANS

In the present paper two new experimental setups of the Tandem Accelerator Laboratory were presented. Both of the setups are delivered at the NCSR "Demokritos". In the case of the new 4π NaI detector, a new support frame has to be designed and constructed in order for the detector to be placed at a beamline, namely the old Ptolemeos one. In the case of the BGO Ball, the first thing to be done is to be inserted to the "Green" experimental hall. In order to accomplish this, the supporting frame has to be disassembled and maintained from rust. Once inside the hall, it will be installed at a new beamline at 15°. Furthermore, the detectors and their electronics modules, that were also given together, have to be tested in order to determine their performance after all these years of measurements.

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