Secondary gamma-ray detection a powerful technique for low nuclear cross section studies

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The experimental nuclear astrophysics program at the "Instituto de Física de la Universidad Nacional Autónoma de México" (IFUNAM) motivated the development of laboratory techniques: gamma detection, gamma-background reduction (cosmic and environmental) and the important summing correction. In this work the detection of gamma-rays as a secondary product of the reaction under study is presented in detail as a powerful technique for deducing reaction cross sections.

Keywords: Gamma detection; summing effect; nuclear reactions.

El programa de investigación en astrofísica nuclear de bajas energías del Instituto de Física de la UNAM ha motivado el desarrollo de instrumentación y protocolos experimentales para la detección de rayos gama, reducción de radiación ambiental de fondo (cósmico y de origen terrestre) y la correcta aplicación del efecto de suma para la medida de la eficiencia absoluta de detección. En este trabajo se presenta la técnica de detección de rayos gama secundarios como un poderoso método para medir secciones eficaces en reacciones nucleares.

Descriptores: Detección gama; efecto de suma; reacciones nucleares.

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1. Introduction

Anywhere in the world where experimental nuclear research is carried out, important infrastructure developments need to be accomplished before any significant scientific goals can be achieved. In some cases, technological breakthroughs are required to meet a particular experimental need; in others, local developments that do not represent new technologies are still required to make experiments possible. Even in the latter cases, the accumulation of local expertise in "old" or traditional technologies is of paramount importance as a step towards original developments and scientific discovery.

The scientific low energy nuclear physics program at the IFUNAM is the motivation behind a number of developments of instruments and procedures whose partial description is the object of the present work.

The program has been designed to run on low energy particle accelerators, mainly at IFUNAM's (3 MV) pelletron and ININ's EN-tandem (6 MV). The low energy beam condition imposes stringent limits also on the physics to be addressed. Two main fields of research in nuclear physics have been identified: nuclear astrophysics and the nuclear structure of light ions.

In this work we shall focus only on one of the many developments in infrastructure required for the nuclear astrophysics program at IFUNAM: the measurement of nuclear fusion cross-sections at very low energies.

We shall describe here a technique that is simple to implement in a laboratory with a low energy particle accelerator, with very a low budget, but that is, at the same time, a very powerful procedure for measuring nuclear cross-sections [1,2].

Gamma-ray detection is reviewed briefly in Sec. 2. In Section 3, we present the basic physics principles behind our technique, and a summary is offered in Sec. 4.

2. Gamma detection

Precise determination of gamma ray energy can at present be best achieved with Hyper-pure single germanium crystals, which are commercially available. Other materials (such as NaI or BaF crystals) have higher detection efficiency, but do not compete in energy resolution. In this section, the gamma detection procedure that we have implemented at the IFUNAM's Pelletron laboratory is presented.

2.1. Background

Gamma-background from earth-bound natural radioactive isotopes and cosmic-rays becomes a critical problem for any experiment involving gamma-ray detection and identification, especially those with low count rate. Lead, because of its large atomic number (absorption coefficient) and relative low cost, is the material most commonly used in shields. Its high density (11 g/cm^3) permits the design of rather compact shielding configurations. Large structures become quickly impractical because of their weight. Also, the secondary radiation produced by cosmic-rays on lead and the concentration of radioactive species (^{210}Pb, 22.3 years life time) set a practical limit on the thickness of the lead layer that can be used around a gamma-detector. A complete review on the subject of gamma-ray shielding can be found in Ref. 3.

Figure 1 shows the compact shielding configuration used in our nuclear astrophysics measurements. In the figure, the beam provided by the IFUNAM's pelletron accelerator is coming from the left into the reaction chamber, where the target is placed at the back end. The germanium detector sits just outside the water-cooled wall of the chamber. This configuration was used to minimize the distance from the detector to the target, optimizing the solid angle coverage for gamma rays produced in the reaction under study. Inside the beam line, an iron block 12 cm long, with an 8 mm diameter hole, provides shielding for the detector-chamber assembly from radiation coming from the beam pipe's direction. The assembly reaction-chamber-germanium-detector, is surrounded by a 9 cm thick lead layer inside iron containers. This configuration represents an improvement on other similar ones already successfully utilized in low gamma-ray counting experiments, just like those involved in nuclear reaction studies for astrophysics [4].

Figure 2 shows gamma-background measurements made with and without shielding in different conditions: exposed to natural radiation in Mexico City conditions just outside the laboratory, inside the laboratory building, inside a pit, below 20 m of solid rock and in the laboratory with the shield on. In all cases, but the last, the spectrum is dominated by gamma-rays produced by the decay of well known earth-bound, radioactive isotopes. When the shield is used, the spectrum is qualitatively different; a continuous, mostly featureless background from high energy cosmic-rays now dominates the spectrum.

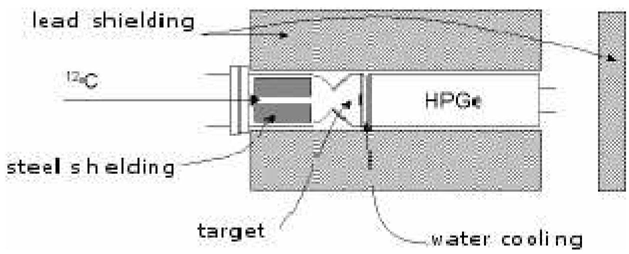

FIGURE 1. Schematic view of the experimental setup for the hyper-pure germanium gamma detector, the reaction chamber and the lead passive shielding.

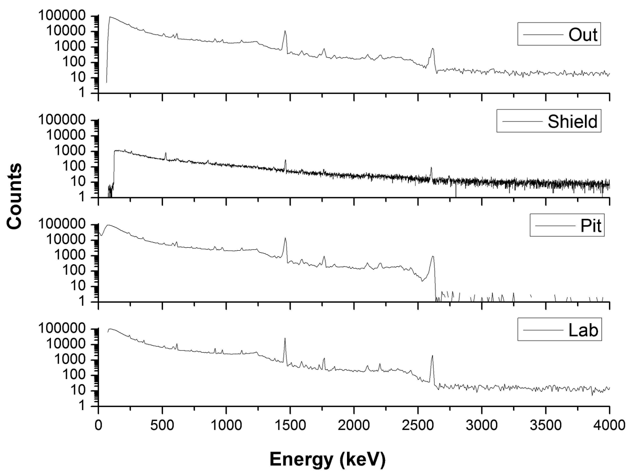

FIGURE 2. Gamma ray energy spectra taken by a Hyper-pure Germanium detector from background radiation in several different conditions see text.

In the high energy range, above the ^{208}Tl gamma peak (2.6 MeV), the reduction factor obtained with the lead shield is modest (10%). Inside the pit, under the rock, an order of magnitude or better is achieved, without any more shielding in the same energy region. This is the reason for the world wide interest in bringing accelerators underground where cosmic-ray flux is mostly nonexistent (see for instances details on the "LUNA" laboratory [5]). Unfortunately it is not always possible to have a laboratory underground. Our facility is on the surface at an altitude of 2100m, where cosmic ray contribution is important [3] and needs to be faced together with the earth-bound radiation. For medium energy gamma-rays, between 0.2 and 2 MeV, the natural gamma background with a well designed passive shielding can be drastically reduced. In our case, reduction factors from 50 to 20, depending on gamma energy, are attained.

3. Detection efficiency

The efficiency of a gamma-ray detector is the ratio of the number of gamma-rays detected to the total number that enter the detector. This quantity is a function of the gamma energy and is specific to each detector. It is normally measured with the help of a calibrated, radioactive source or a collection of them, providing a known number of photons of well-known energy. These are identified in the detector when its total energy is converted into the signal delivered by the detector. This is the photo-peak in scintillating or semiconductor counters.

The procedure is simple in principle, however most gamma sources are based on isotopes producing several gamma energies emitted in cascade. In this section we shall review in some detail the "Summing Effect", which is an important factor to take into account when accurate determination of the absolute detection efficiency is needed.

Summing correction is a term that has been used to describe the fact that, when a single nucleus decays by emitting more than one gamma-ray (cascade), the probability for more than one of them to reach a detector simultaneously is not zero. When this happens, the signal delivered by the detector corresponds to the sum of the signals generated by each ray, having the effect of reducing the strength of both photo-peaks, with the corresponding lost of information. Absolute efficiency measurements and cross-sections must be corrected by this effect.

It is well known [6-8], although most texts give little importance to this effect, that the relative angular distribution of consecutive gamma rays emitted in cascade from the same nucleus, has a well-defined form. It depends on the multipolarity of the second gamma emission. The more common gamma-gamma correlations to take into account are those arising from dipole and quadrupole transitions (electric and magnetic). The corresponding angular correlations follow the shape of the associated Legendre Polynomials of order one and two respectively and are shown in Fig. 3.

The "spherical" correlation refers to the non-consecutive gamma emission, which does not involve a particular angular correlation between the two gammas; it also corresponds to the Legendre associated polynomial of zero order.

Because of the particular shape of these angular correlations, the probability for detecting two consecutive gamma rays simultaneously with the same detector, is very different from what it is for the non-correlated case, corresponding to a relative isotropic angular distribution.

The angle of detection and the solid angle coverage of the detector are important too. In the following discussion, we shall consider only the case where the detector is placed at zero degrees.

For very large solid angle coverage (approaching 2π) the probability for a double hit becomes large and independent of the particular multipolarity of the relative angular correlation. The largest dependence on multipolarity, as we shall show below, is encountered when the subtended solid angle is small, and for low gamma-ray energy.

In Fig. 4, the probability of a double hit has been calculated as a function of the second gamma energy, using Monte Carlo techniques for 5 cm tall cylinders of three different diameters (25, 5 and 1 cm) of a germanium crystal at a fixed distance from the gamma source corresponding to three different solid angle coverages (42, 18 and 2% off 4π, respectively).

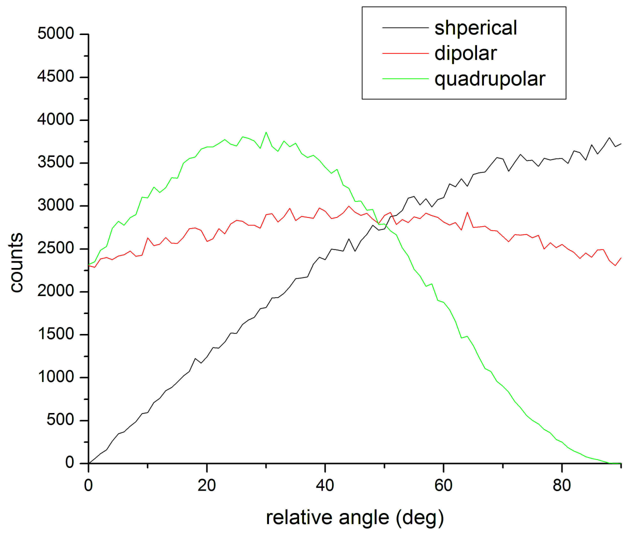

FIGURE 3. Angular correlation for consecutive gamma emissions from the same nucleus, depending on the polarity of the decay.

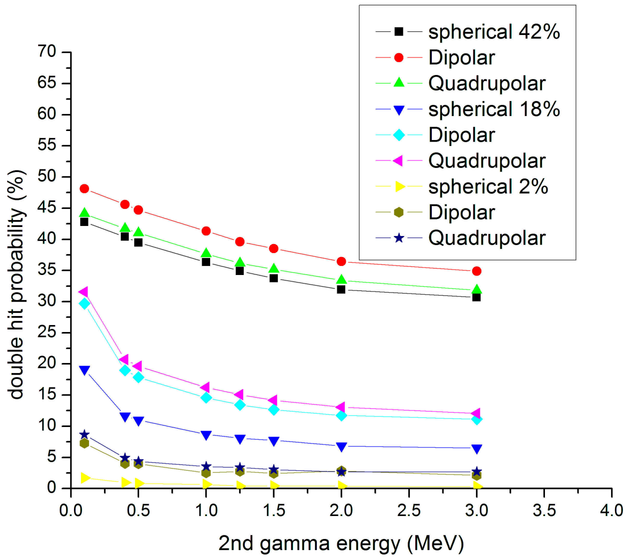

FIGURE 4. The probability for the detection of two consecutive correlated gamma rays emitted from the same nucleus in a cascade, according to the multipolarity of the decay and the solid angle coverage. Three cases are shown in the figure, spherical (no correlation) dipolar and quadrupolar for three different solid angle coverages (2, 18 and 42% of total).

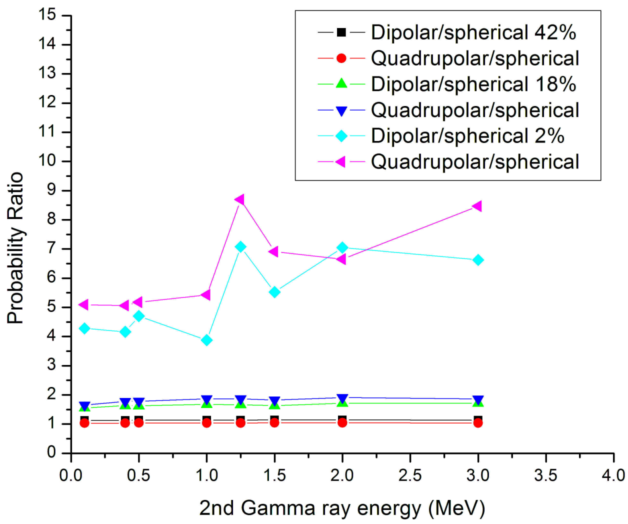

FIGURE 5. As a function of the energy of the correlated gamma, this plot shows the importance of taking into account explicitly the multipolarity of the second gamma detected in the cascade. The plot shows the ratio of the actual summing effect to the non-correlated case (spherical angular correlation).

These results show that the summing effect is very important and the factor needed to correct an absolute efficiency measurement can reach 50% when the solid angle subtended is large. Strikingly, a potential larger error is involved in the opposite case, the limit of very small solid angle coverage, contrary to common opinion. There the KNOWLEDGE of the correct multipolarity of the second gamma emission is critical, as illustrated in Fig. 5. Where the probability for the detection of the second gamma ray, assuming a dipolar or quadrupolar angular correlation is divided by that of an isotropic angular correlation for three different solid angles. The "small" solid angle coverage yields a far larger dependence on the specific shape of the angular correlation.

So, when it is known that a particular pair of gamma-rays are emitted consecutively within a cascade from a nucleus, this summing effect must be taken into account to correct for the number of photo-peak events lost. Such is also the case when one uses commonly available gamma sources like ^{60}Co, ^{152}Eu (this has over 200 known gamma transitions, and several cascades [9]) for absolute efficiency determinations.

It is worth stressing that this summing effect is NOT related to or a consequence of a high count rate, which leads to a totally different phenomenon known as pile-up [7,8].

4. The secondary gamma detection technique

Once the gamma-ray background has been suppressed (reduced), and the absolute detection efficiency of the detector has been obtained, nuclear reaction (like fusion) cross sections can be measured through the so called "Secondary gamma emission technique". A number of works have taken advantage of this technique [10-13].

In this section we shall describe only the physical principle behind the method, and offer an example of its application.

Its principle is simple: the compound nucleus formed after a nuclear reaction (for instance fusion) induced by a combination of projectile and target at a given bombarding energy, cools by particle emission (mainly neutron, alpha and proton), until the excitation energy left in the Evaporation Residue (ER) is smaller than all particle emission thresholds. This still excited, but now bound system, will lose any energy excess by the slower electromagnetic process: gamma decay. These transitions occur among the lower lying states of that particular ER, in a cascade of gamma emissions until the whole excitation energy is exhausted. The energies of the emitted gamma-rays are known so they can be identified upon detection. Under certain conditions, the number of gamma-rays emitted (detected) can be related to the primary process that eventually led to the secondary decay by the excited ER.

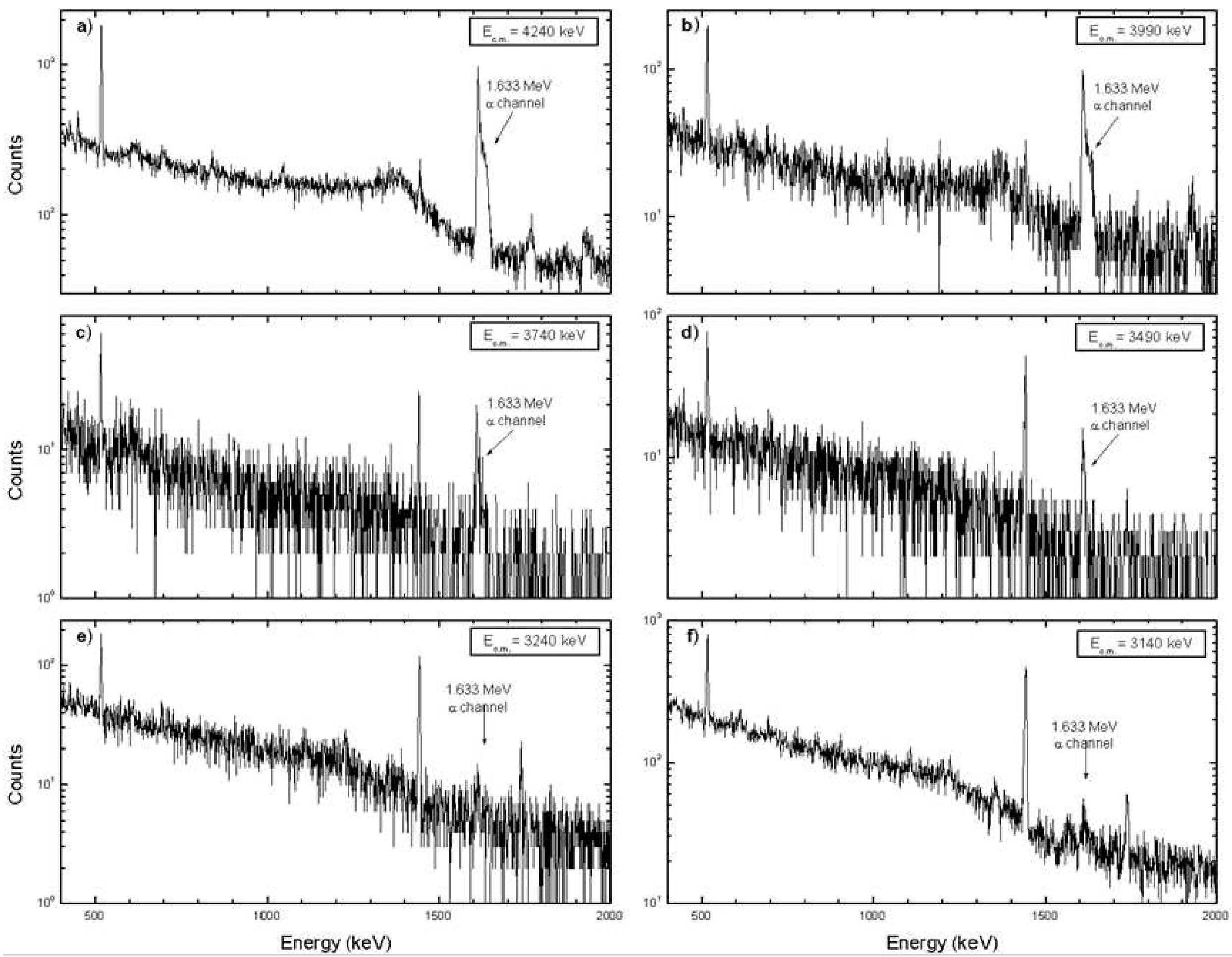

FIGURE 6. Gamma energy spectra from the $^{12}C+^{12}$ C system at different bombarding energies. The peak at 1.633 MeV corresponds to the photo-peak of the detection of gamma-rays from the decay of ^{20}Ne from its first excited state. ^{20}Ne being the Evaporation Residue left after alpha emission from the compound ^{24}Mg.

Perhaps the main advantage of this procedure is the fact that the signature of the nuclear reaction under study is precisely the presence of specific gamma-rays of known energies corresponding to the transitions among states in the ERs. What changes with bombarding energy is the relative intensities of the lines.

Figure 6 shows a collection of gamma-ray spectra taken with a Hyperpure-Germanium Detector from $^{12}C+^{12}C$ fusion reactions. Center of mass energies are given in the figure.

As can be seen, the information about the fusion reaction in study lies always in the same place, the same photo-peak energy, regardless of the beam energy.

If the experiment is carried out on a target thin enough for the energy loss of the beam particle's being small, typically a few keV, the integral of the background subtracted peak (yield) is just proportional to the fusion cross section at the beam energy. On the other hand, if the target is thicker, as in the case of figure 6 where the beam was stopped in the target itself, a de-convolution procedure must be followed to relate to the cross section see Refs. 10 and 14 for a more detailed description of such procedures.

5. Summary

Detection of gamma-rays from the decay of the excited remnants (Evaporation Residues) of a nuclear reaction, can be used as a signature to identify the primary nuclear process responsible for the ultimate (secondary) gamma-decay.

Under certain conditions the yield of these gamma-rays can be related to the cross section of the primary process.

Correct gamma detection becomes then a key issue. Once care is taken in facing the omnipresent gamma-ray background, and absolute detection efficiency of the detector in use, the technique allows a surprisingly simple method to measure nuclear reaction cross sections.

The $^{12}C+^{12}C$ system has been used throughout this article to exemplify the performance of this simple but powerful technique.

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