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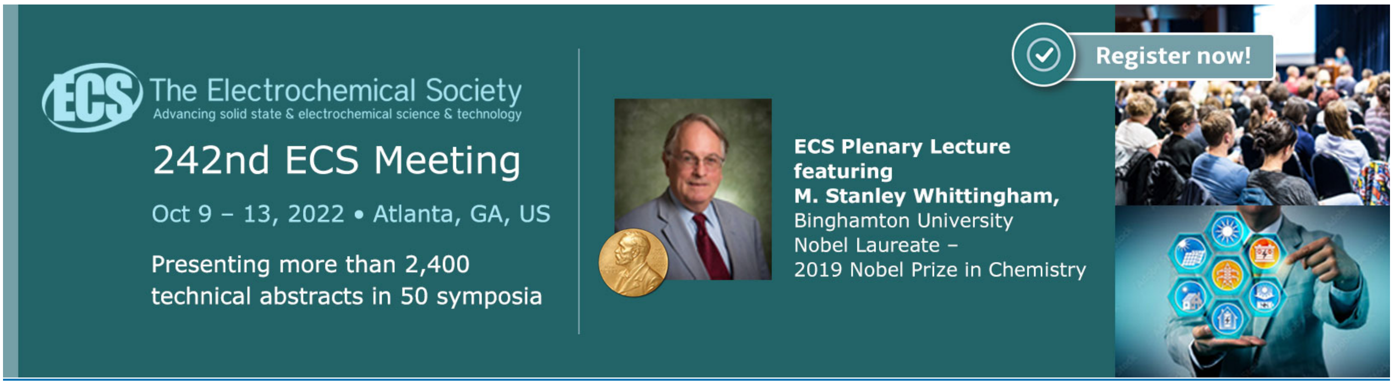

New spectrometer projects for challenging particle-gamma measurements of nuclear reactions

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Abstract. Two new gamma spectrometer projects are under development, both with some challenging technical characteristics in common, one for the investigation of weakly bound nuclear beam reactions at near barrier energies, and the other for the measurement of double charge exchange reactions in the 15-70 MeV per nucleon range. The first one is being developed and tested at the IFUSP, and the other is going to be built and installed at the LNS, INFN, under the NUMEN collaboration. The main characteristics of the two projects are presented and discussed.

1. Introduction

Under quite common situations charged particle detectors alone do not provide sufficient energy resolution for the measurement of reaction cross sections of specific nuclear states. In such cases the particle-gamma technique is an alternative which can adequately provide the required energy resolution to discriminate between nearby states. This technique has been implanted and tested at the *Instituto de Física da Universidade de São Paulo*, IFUSP [1,2], where the measurement of nuclear reactions with weakly bound stable beams have been performed. The beams were provided by the Pelletron Accelerator of the LAFN (*Laboratório Aberto de Física Nuclear*), DFN, IFUSP. For such measurements, the Saci-Perere spectrometer, originally developed for nuclear structure experiments

[3], was adapted with the insertion of collimator slits for the measurement of inelastic scattering and transfer angular distributions. The new project NC1 (*Nossa Caixa* phase 1) is being developed to improve the power and quality of the spectrometer for this type of measurement, and also for use with the RIBRAS [4] radioactive ion beam facility. With this system both stable and radioactive beams will be used to elucidate the complex reaction mechanisms with weakly bound nuclei at near barrier energies.

Another system in which the coincidence with gamma rays is required is the one to be used in the NUMEN project [5-8], under development at the *Laboratori Nazionali del Sud* (LNS), INFN, Italy. In this project, double charge exchange reactions are to be measured with the MAGNEX spectrometer [9-12], with beams provided by the CS (*Ciclotrone Supercondutore*) accelerator [12] in the 15-50 MeV per nucleon range. In some cases, particularly at transitional or strongly deformed mass regions, and also at the highest energies, the energy resolution is not sufficient to separate the ground state from the first excited state of the reaction products. A new gamma spectrometer array (GNUMEN) will be developed with the purpose of providing the necessary discrimination between these nearby energy states and allow for their separate cross section evaluation. With this system an extensive research program will be developed with the aim of helping to determine the nuclear matrix elements relevant to double beta decay physics. The characteristics of these new arrays will be presented in the next section.

2. General characteristics of the new spectrometers

Both spectrometers have in common that a moderate gamma energy resolution is sufficient for the discrimination of the relatively simple gamma spectra expected after coincidence with the charged particles, while high count rates and intense neutron radiation will have to be tolerated. For this reason, inorganic scintillators were chosen as the gamma-sensitive material. In principle LYSO(Ce) or LuAG(Ce) crystals will be used, but other possible materials are under consideration, such as GAGG(Ce), $LaBr_3$(Ce) or $CsBr_3$.

2.1. The NC1 project

The NC1 project comprises both the particle and gamma arrays. The particle detector system will be an array of plastic *phoswich* ΔE-E telescopes, similar to the *Saci* [3] ones, whose scintillation will be detected with 4×4 pixel SiPM (Silicon Photomultipliers) devices, for position discrimination, allowing kinematic coincidences. Only a few units will be used in phase 1, but a more complete array is under consideration, covering a large fraction of the solid angle of a sphere in advanced phases. With *phoswich* detectors, a high count rate per detector and radiation tolerance can be achieved. The energy resolution of these detectors is not very high, while sufficient for the identification of the atomic number Z of the particle, and the identification of the channel and state will be done essentially by the characteristic gamma rays which are detected in coincidence. Separate measurements with high particle energy resolution Silicon detectors are required for obtaining the elastic angular distributions, such as in [13].

The NC1 gamma array consists of 4 modules of 3×3 LYSO(Ce) scintillator crystals. Each crystal has a length of 40 mm and a cross section of 12.4×12.4 mm². The scintillation photons from each crystal are converted into electric pulses by 2×2 SiPM devices with about the same total area as the crystal cross section. Additional modules will be incorporated in advanced phases. These modules will operate in vacuum at a close packed geometry in order to maximize the geometrical efficiency. The use of SiPM allows for the operation of the array in the strong magnetic fields of the superconducting solenoid of the RIBRAS radioactive beam facility. For the stable beam experiments high resolution GeHP detectors can also be used.

2.2. The GNUMEN project

For the advanced phases of the NUMEN project [5-8], several improvements will be required with respect to the present system, among which an increase in magnetic field intensity of MAGNEX, replacement of the focal plane detectors (FPD), and a dramatic increase in beam intensity (by 2 or 3 orders of magnitude from the presently available) after the CS upgrade, which will also require cooling of the target and the construction of a bunker to suppress the gamma and neutron radiation from the beam dump. This will allow for the measurement of very low DCE cross sections and detailed angular distribution measurements of the moderately low ones. The uncorrelated gamma count rate expected from a typical experiment could be of the order of 1 GHz or more. The system should have, therefore, a large granularity in order to avoid the pile up of signals in each detector, and to keep the count rate per electronic channel manageable. The preliminary design of the array would consist of 2000 or more scintillator crystals covering 60% or more of the 4π solid angle of a sphere with a inner radius of about 25 cm. The crystals would be combined in 3×3 modules similarly to the NC1 ones, but with about two times larger volume crystals.

3. Preliminary tests

3.1. Gamma spectra with radioactive sources

Figure 1 shows typical gamma spectra from a ^{60}Co radioactive calibration source obtained with the single crystals of the NC1 project. The relative energy resolution (7.4% and 5.8% at 1.33MeV) of both types of scintillation crystals (LYSO(Ce) and GAGG(Ce), respectively) is compatible with what is expected for the respective material compositions. Further tests indicated that, while the LYSO(Ce) crystal spectra maintain the expected performance in resolution down to at least 30 keV gamma-ray energy (at least when the cross section of the SiPM is close to that of the crystal, granting a good light collection efficiency), the GAGG(Ce) measurements have shown a degradation of the timing and energy resolutions for gamma ray energies below about 200 keV, which is certainly due to the self absorption of the scintillation in this type of crystal. Further tests are planned with SiPM devices coupled at both sides of the crystal in order to increase the light collection and also obtain detection position information along the axis of the crystal. The energy and timing resolution performances at low energies are expected to be significantly improved with this approach.

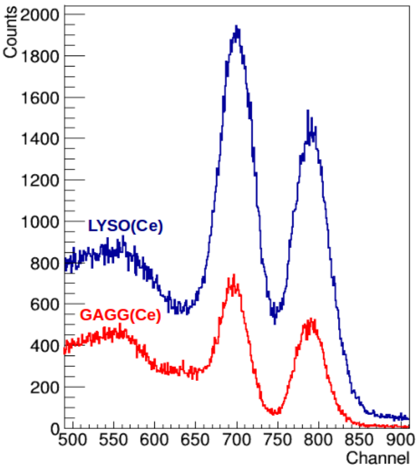

Figure 1. *Typical ^{60}Co source gamma spectra of LYSO(Ce) (upper line, in blue) and GAGG(Ce) (lower line, in red) scintillators of the NC1 project.*

3.2. In-beam timing and gamma spectrum

Figure 2 presents the random-background subtracted time spectrum (gamma pulse on start, beam bunch 20 MHz radio-frequency pulse on stop) of the ^{20}Ne +^{116}Cd reaction at 15 MeV/nucleon (from the LNS CS) taken with a 16×16×50 mm³ LYSO(Ce) crystal, outside the MAGNEX scattering chamber. The radiation from the Faraday cup (~18 cm downstream) was partially shielded with a Lead brick, and both time peaks, one from the 1.46 mg/cm² target related events, and the other from the thick Faraday cup events are clearly visible. The time-of flight difference between gamma rays generated in these separate sites (4.0 ns), is consistent with the measured time separation between the two peaks. A FWHM resolution of about 1.4 ns could be determined for these peaks. The time spectra is gated by the gamma-ray energy between 900 keV and 1060 keV. The energy and timing resolutions below about 300 keV are progressively degraded. This is due to poor light collection since the SiPM used for the scintillation signal conversion was only 6 mm wide. Indeed tests with larger SiPM devices and radioactive sources have shown a much better energy and timing resolution at low energy.

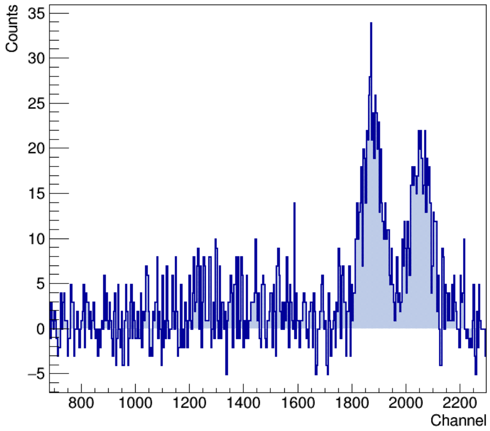

Figure 2. *In-beam time spectrum (23 ps/channel) from the ^{20}Ne experiment showing time peaks from target (right) and from the Faraday cup (left) reactions*
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4. GEANT4 simulations of the detector modules

The performance of the detection modules was studied with GEANT4 [14] simulations. Figure 3 (Left) shows the perspective view of a 3×3 scintillator crystal module and (Right) simulation of 500 keV gamma rays hitting the central crystal and eventually scattering into the surrounding units.

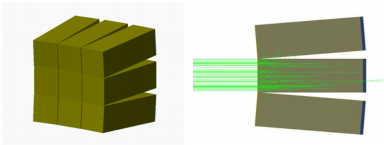

Figure 3. *Detector modules with 3 × 3 pixel LYSO crystals. Left: perspective view. Right: section view illustrating the GEANT4 simulations of the scattering of 500 keV gamma rays hitting the central pixel.*

The simulated photopeak efficiency and peak-to-total ratios after summation of surrounding first neighbours of each crystal approaches that of a monolithic one with the same total volume, at low energies. At 500 keV the intrinsic efficiency decreases from about 75% to 71%, and the peak to total ratio (P/T) from 86% to 84% for the 16 mm wide crystals, and also a few percent less for 12.4 mm crystals. With the full array of closely packed units the intrinsic efficiency could rise to 93% and P/T to 94%, but some form of gamma ray tracking will be necessary to properly recover the full energy of the gamma rays. Detailed simulations are under way towards the evaluation and optimization of this procedure.

5. Expected performance and observational limit

With the detector granularity proposed for the GNUMEN array, the pile-up probability is expected to remain well below 10% for beam intensities up to 5×10^{12} particles/s (or about 100 times the presently available one), and can be neglected in a preliminary evaluation of the performance. At such high beam intensities, however, the probability of a second nuclear reaction, besides the DCE, with production of gamma rays in a given beam bunch can be quite significant (typical total reaction cross sections are of the order of a few barns). These gamma rays will be detected within the 2 ns time window of the prompt peak and cannot be resolved. They constitute unavoidable chance coincidences. Due to that fact, the main source of background (BG) in the DCE measurement of the cross sections populating the ground state (*gs*) and first excited state (2^+) of the exit channel is expected to be the accidental detection of one of these uncorrelated gamma rays which happen to have an energy within the energy gate around the first excited state transition. The $2^+\rightarrow 0^+$ transition gamma-gated FPD DCE reaction energy spectrum will present in general two peaks (partially resolved or unresolved), one corresponding to *gs* state in accidental coincidence with the BG gamma rays, and the other to the 2^+ state in true or accidental coincidence. Similarly, the spectra in anti-coincidence with the $2^+\rightarrow 0^+$ transition gamma-ray energy will have two superimposed contributions, from the *gs* state peak, and from the 2^+ excited state when the corresponding transition is not detected due to the less than 100% efficiency of the array. Two main parameters control the proportion of these different contributions: the total photopeak efficiency and the probability of production of a gamma signal within the 2^+ excited state, and which is approximately proportional to the width of the energy gate and, therefore, to the energy resolution of the array. From Poisson statistics it is possible to predict analytically the *observational limit* of the array: the minimum ratio of DCE to total reaction cross section which can be measured with a specified statistical uncertainty (such as 20%). Figure 4 presents the “reduced” observational limit (B, a number proportional to the observational limit but independent of the time duration of the experiment), as a function of the average number of reactions per beam bunch $\bar{k}$ (which is proportional to the beam luminosity). The curves apply to both the *gs* and 2^+ excited state measurement since in these calculations an equal cross section was assumed for both. The probability that a spurious reaction (not the DCE) produces a gamma ray signal within the $2^+\rightarrow 0^+$ transition energy gate was assumed to be close to 50%. This is appropriate for high gamma-ray multiplicity reactions and relatively poor energy resolutions such as for LYSO(Ce) scintillators. As it can be seen, the observational limit decreases rapidly with $\bar{k}$ up to values of the order of $\bar{k}$=1. The curves with the presence of BG go through a minimum which defines the optimum $\bar{k}$ and the absolute reduced observational limit (B = 3 at $\bar{k}$=2.8 in the 50% efficiency case, roughly corresponding to an observational limit of 6×10^{-12}, or 20pb in 3b total cross section, for a one week data taking time). Note that even in the ideal case of 100% efficiency the improvement in observational limit is not very dramatic, and the limiting factor is the growing contribution of the BG at high luminosities.

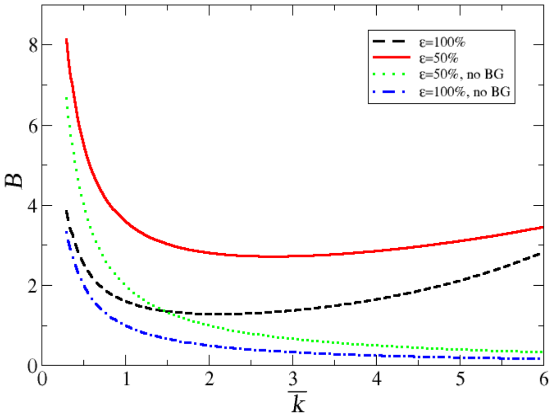

Figure 4. *Reduced observational limit as a function of $\bar{k}$ for 50% efficiency with BG (solid), and no BG (dot), and 100% efficiency with BG (dot) and no BG (dot-dash).*

6. Final considerations

According to these preliminary tests and analyses, a sufficient sensitivity can be obtained with the proposed gamma arrays to fulfil the experimental requirements. Further detailed simulations and experimental tests are planned for definition of the the details of the final design. The most difficult parameter to evaluate is the random coincidence BG which will be generated during the real experiments. For this it will be necessary to perform test experiments of the specific reactions to be measured and validate detailed simulations of the array response. The tolerance to the high neutron flux of the detectors and electronic equipment will also have to be experimentally evaluated in the near future.

Acknowledgments

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