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Coupling a CLOVER detector array with the PRISMA magnetic spectrometer

Investigation of moderately neutron-rich nuclei populated by multinucleon transfer and deep inelastic collisions

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Abstract. Following the commissioning of the PRISMA large-acceptance spectrometer, installed at the Laboratori Nazionali di Legnaro (LNL), an international nuclear-structure collaboration has started to develop a large γ-ray setup to be installed in the target position of the spectrometer. The array is based on the EUROBALL composite CLOVER detectors. In this contribution the CLOVER detector array is described and its expected performance figures discussed. This new setup, by using the high-intensity heavy-ion beams provided by the LNL ALPI linac, will push the study of nuclear structure towards moderately neutron-rich nuclei by means of quasi-elastic and deep inelastic reactions.

PACS. 29.40.Wk Solid-state detectors – 29.30.Kv X- and γ-ray spectroscopy

1 Introduction

The coupling of an array of CLOVER germanium detectors [1] to the PRISMA [2,3] spectrometer will allow to study the nuclear structure of moderately neutron-rich nuclei, populated at relatively high angular momentum, by means of binary reactions such as multinucleon transfer and deep inelastic collisions.

PRISMA is a large-acceptance magnetic spectrometer for heavy ions, which is at present in the commissioning phase at LNL. It has been designed for the heavy-ion beams of the XTU Tandem-ALPI-PIAVE accelerator complex [4]. The most interesting features are its large angular acceptance of 80 msr; momentum acceptance ±10%; mass resolution 1/300 via TOF; energy resolution up to 1/1000 and rotation around the target in a large angular range ($-20° \leq \theta \leq 130°$).

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The above performances will be achieved by software reconstruction of the ion tracks using the position, time and energy signals from the entrance position-sensitive Micro-Channel-Plate and focal-plane detectors [5]. At the moment, the application of the spectrometer is limited to binary reactions but a program to develop the gas-filled working mode is in progress.

The use of the PRISMA spectrometer coupled to an array of Compton-suppressed γ-ray detectors marks a step forward with respect to the previous spectroscopy studies with deep inelastic or multinucleon transfer reactions. The high resolving power of PRISMA will give, for most of the reaction products, the full identification of mass and Z and will therefore lower the sensitivity limit in the measurements. This will allow to study excited states of nuclei away from stability produced with low cross-section.

In this project we have to optimize the sensitivity of the γ-ray detector array considering the boundary conditions imposed by PRISMA and by the nature of the binary reactions of deep inelastic scattering or multinucleon transfer, for which high γ-ray multiplicity (in deep inelastic scattering) can be expected with large product velocity. Therefore, a high granularity and a large Ge-crystal–to–target distance, to avoid Doppler broadening, are fundamental. On this basis the adopted solution has been to use the EUROBALL CLOVER detectors [1], taking advantage of the reduced dimensions of each of the four crystals composing the detector. The high granularity is guaranteed by the large number (25) of CLOVER detectors building up the array.

2 γ-spectroscopy studies of nuclei populated through multinucleon transfer and deep inelastic collisions

In the last few years, the use of binary reactions, quasi-elastic (multinucleon transfer) or deep inelastic scattering, combined with modern γ-ray arrays (GASP, GAMMASPHERE, EUROBALL, etc.) with or without efficient ancillary detectors, has increased substantially the amount of information available on the structure of previously inaccessible nuclei far from stability. A good example is the neutron-rich nucleus ^{68}Ni, where the investigation of its structure have revealed the doubly-magic–like character of $N = 40$, $Z = 28$ [6]. The neighbouring ^{71}Cu nucleus has also been studied, and its excited states interpreted by using experimental residual interactions extracted from the one- and two-valence particle nuclei with respect to the closed shell [7].

Deep inelastic collisions have also been used to populate the Sn isotopes with $N = 72$, 74 and 76, allowing the identification of the 10^+ isomeric states with $(\nu h_{11/2})^n$ configuration [8] in nuclei not accessible through the fission process.

In the region of doubly magic ^{208}Pb, the two-body neutron-neutron residual interaction and the neutron single-particle energies have been determined from the structure of the ^{210}Pb and ^{209}Pb nuclei [9,10], also populated in the aforementioned collisions. The information extracted on these nuclei is fundamental for the understanding of the states in nuclei with few valence neutrons above the shell closure at $N = 126$.

In nuclear systems with large quadrupole deformation the coherent addition of the excitation induced by multinucleon transfer or deep inelastic collisions and Coulomb excitation process, populates very high-angular-momentum states. Some examples of this phenomenon are revealed in studies of the rotational bands and of the $(\nu h_{11/2})$ pairs alignment in the ^{100}Mo region [11], or the investigation of rotational structures in the neutron-rich Dy, Yb and Sm isotopes [12–14].

The region of light actinides is probably the only part of the whole chart of the nuclei where we expect to find cases of static quadrupole-octupole deformation. This area extends to neutron-rich isotopes and the fingerprint of such deformation consists of pairs of rotational bands (quadrupole collectivity) of opposite parity (parity doublets) connected by electric-dipole transitions. Observation of opposite-parity bands up to $J \approx 30\hbar$ in such nuclei has been possible only through multinucleon transfer reactions [15].

3 The CLOVER array

The CLOVER detectors are composed of four Ge-HP crystals, each with a diameter of ≈ 50 mm, mounted in a single cryostat. Anti-Compton shields surrounding the detector are used to improve the peak-to-background ratio. As we mentioned already, the geometry of the array is strongly conditioned by the PRISMA spectrometer. The large angular acceptance requires a reduced target-to-entrance quadrupole and only $\approx 3\pi$ sr of the total solid angle can be used to place CLOVER detectors. In addition, the relatively large velocity of the products in the proposed reactions has prevented the placement of all the detectors at angles close to $\theta = 90°$. Under these conditions, the solution we have adopted is to distribute the CLOVER detectors in a hemisphere opposite to PRISMA with most of the Ge crystals placed at large azimuthal angles, between $\theta = 104°$ and 180°, with respect to the entrance direction of the spectrometer.

The detector system, installed on a mobile platform, will rotate together with the spectrometer, in such a way that reaction products detected in the spectrometer focal plane, in coincidence with the γ-rays, will have a forward trajectory with respect to the array. The PRISMA Micro-Channel-Plate start detector (MCP) [16] allows to determine the trajectory of the products with an angular resolution $\Delta\theta < 1°$. Because of the high accuracy in the direction of the nuclei emitting the γ-rays, the final Doppler broadening will be due only to the angular aperture of the Ge crystals.

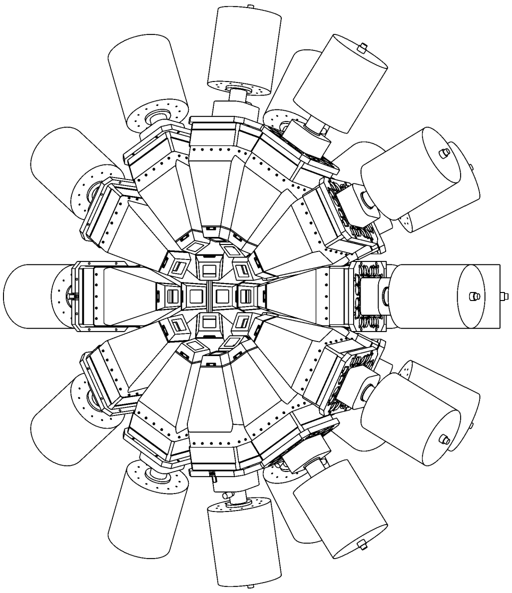

Fig. 1. Proposed configuration for the CLOVER detector array.

4 Performance figures

To estimate the performance of this array based on CLOVER detectors, Monte Carlo simulations have been performed. The CERN detector design and simulation tool GEANT3 [17] library has been used. The simulation of the interaction of γ-rays with the detectors has been carried out including all relevant physics processes, taking into account the kinematic conditions expected when measuring with PRISMA, and with the geometry shown in fig. 1.

In the CLOVER detectors the energy signals from the four crystals are acquired independently and, since one γ-ray can interact with more than one crystal, add-back algorithms are used to determine the γ-ray energy. These algorithms have been included in the evaluation routines for the simulated data. A threshold of 20 keV for the Ge crystals and of 50 keV for the anti-Compton BGO shield have been introduced to simulate the response of detectors and electronics.

The performance figures obtained in the calculation are: total photo-peak efficiency $\approx 3.3\%$, peak/total (P/T) ratio $\approx 48\%$, energy resolution ≈ 10 keV for a product velocity (v/c) of 10%.

The efficiency of the array as a function of the γ-ray energy and γ-ray cascade multiplicity is shown in fig. 2. The efficiency of the setup for relatively high γ-ray energies improves when using add-back. Due to the large granularity of the array (100 crystals), the peak efficiency is not very much affected by large cascades of γ-rays, and only at very high multiplicities ($M_\gamma \approx 30$) we have efficiency losses of the order of 20%.

In case of a γ-ray interacting with more than one crystal, it is possible with simple algorithms to determine, the crystal where the first interaction happened, in $\approx 80\%$ of the fully absorbed γ-rays. This information can be used to measure angular distributions with with $\theta \approx 13°$ accuracy.

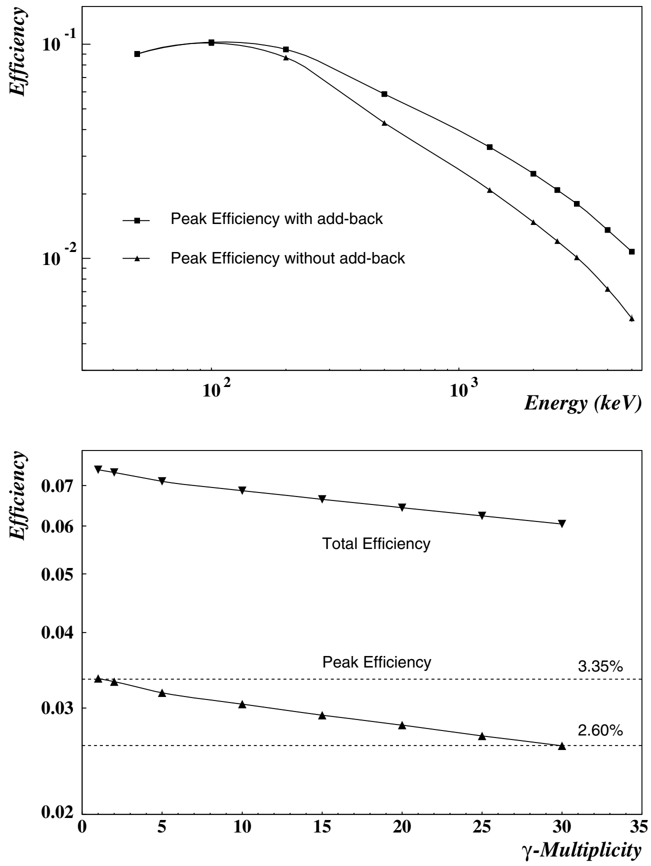

Fig. 2. Upper panel: simulated peak efficiency as a function of the γ-ray energy with and without the add-back (sum of the energy released in the four crystals of the CLOVER detector). Lower panel: simulated peak and total efficiency of the array as a function of the γ-ray multiplicity of the cascade. In both pictures the simulated points are represented by the symbols, while the continuous line is only to guide the eye.

Two performance figures characterising γ-ray arrays, together with the total peak efficiency and peak-to-total ratio, are very important for the discussion of the quality of the detection system *i.e.* the resolving power (R) and the sensitivity limit (α) [18,19]. The resolving power is proportional to the average separation energy of the γ-rays in a cascade and to the peak-to-total ratio and inversely proportional to the γ-ray detection resolution (ΔE_γ).

$$R \propto \left(\frac{\langle E_\gamma - E'_\gamma \rangle}{\Delta E_\gamma} \right) \frac{P}{T} \,. \tag{1}$$

The average separation energy depends on the structure of the nuclei to be studied, while the peak-to-total ratio is a construction characteristic of the detector, mainly defined by the anti-Compton shielding. The γ-ray resolution depends on the characteristics of the detector (intrinsic resolution) but is also affected by the experimental conditions. It has a contribution from the solid angle covered by the single crystal (Doppler broadening) and also from the indetermination of the trajectory and energy of the reaction products (kinematic broadening). In

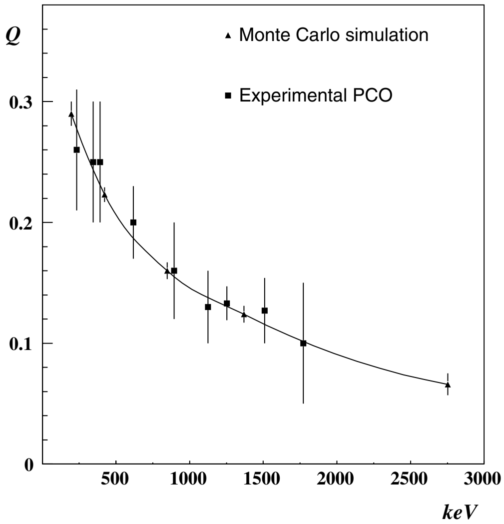

Fig. 3. Polarization sensitivity of a CLOVER detector, experimental and calculated by Monte Carlo simulation [21].

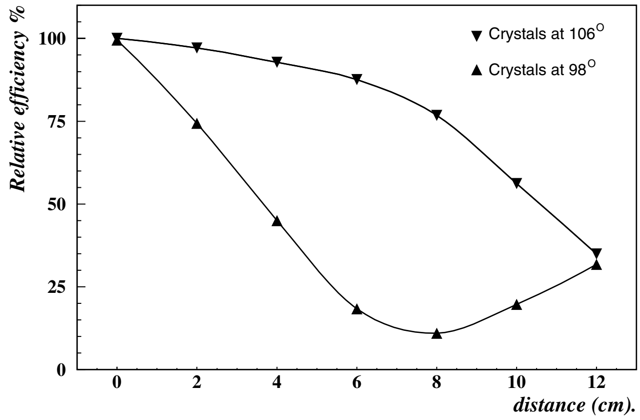

Fig. 4. Simulation for the CLOVER array of the relative efficiency, for 1.332 MeV γ-ray, as a function of the distance between the emission point and the target. The values are relative to the efficiency for 1.332 MeV γ-radiation emitted at the target position. Results of the simulation for crystals at 106° and 98° are shown for several distances and therefore emission delays. The lifetime measurement is done by comparing the measured intensity at these two angles.

the CLOVER array the Doppler broadening is reduced to ≈ 0.01 for products with large velocities $\beta \approx 0.1$. The kinematic broadening will be very much reduced when the energy and the trajectory are determined by the PRISMA spectrometer.

The sensitivity limit α depends on the total peak efficiency and on the resolving power, and it represents the minimum fraction of total cross-section that can be measured with the γ-array. For modern stand-alone arrays of Ge detectors the limit for large fold events is of the order of $\alpha \approx 10^{-3}$ to 10^{-4}. This limit can be largely improved by using complementary detectors as the PRISMA spectrometers [20] and in particular it opens the possibility of using low γ-ray multiplicity with no loss of sensitivity.

5 Linear-polarization measurements

The CLOVER detectors can be used as Compton polarimeters giving the possibility to measure the degree of linear polarization of the γ-rays emitted by the products. The CLOVER composite detectors have an excellent sensitivity for Compton polarization measurements [21] (see fig. 3). In nuclear reactions where the outgoing products have a preferential direction for the alignment of the angular momentum, the polarization coincidence measurements in oriented nuclei (PCO), together with the angular distributions or correlation (DCO) information, allows one to determine the character and multipolarity of the electromagnetic transitions and thus to obtain fundamental information on the angular momentum and parity of excited states.

6 Lifetime measurements

The combination of the CLOVER array setup with the PRISMA spectrometer allows to perform lifetime measurements with several techniques. For short lifetimes, below ≈ 1 ps, a technique based on the lineshape analysis can be used. This technique, developed at the EUROBALL Recoil Filter Detector [22], is based on the straggling of the ions in the target. Since the PRISMA start MCP detector can give an accurate trajectory of the outcoming ion and therefore a precise Doppler correction, it is possible to distinguish between the fraction of events emitted in the target where the ion can still change the trajectory (imprecise Doppler correction) and the fraction emitted outside the target for which the Doppler correction works. The lifetime range covered by this technique goes from ≈ 50 fs to ≈ 0.5 ps using different target thicknesses.

A lifetime technique covering the range from ≈ 1 ps to ≈ 1 ns can be based on a differential recoil distance method where the velocity of the outgoing products is changed at a certain distance from the target by a degrader foil.

Finally, for long lifetimes, the Recoil Shadow Method, developed at EUROBALL with the CLOVER detectors [23], can measure up to several ns depending on the product velocity. This technique is based on the shadowing of the CLOVER detector crystals by the collimator. It allows to measure the average distance from the target to the point where the radiation has been emitted. The simulation of this technique for the detector ring at 108° of the CLOVER array is shown in fig. 4.

7 Conclusions

Moderately neutron-rich nuclei can be populated at relatively high angular momentum, by means of binary reactions such as multinucleon transfer and deep inelastic collisions. The use of these reactions, where possible, has the advantage that the outgoing reaction products have relatively low velocity, in contrast to the products of fragmentation reactions. Consequently, their use is compatible with the characteristics of the present generation of gamma arrays. The use of the CLOVER γ-array coupled to the PRISMA spectrometer marks a step forward with respect to previous spectroscopy studies using these mechanisms. The physical topics covered by this setup will complement studies performed with current radioactive-beam facilities, at least until the second generation of such facilities like SPES, SPIRAL II, SIRIUS or RIA, are fully operating.

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