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CEPA: A $LaBr_3$ (Ce)/$LaCl_3$ (Ce) PHOSWICH ARRAY FOR SIMULTANEOUS DETECTION OF PROTONS AND GAMMA RADIATION EMITTED IN REACTIONS AT RELATIVISTIC ENERGIES

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A sophisticated design of 750 $LaBr_3$(Ce):$LaCl_3$(Ce) phoswich crystals (CEPA10) with a segmentation determined by the Doppler correction and an energy resolution of 5% at 1 MeV is presented. Monte Carlo simulations have been performed for high energy protons (50–500 MeV) and gamma radiation (0.5–30 MeV) to determine the length and shape of the crystals for optimum performance of the detector. In the case of protons, the two-layer detector can be used as a ΔE_{LaBr3} – E_{Tot} telescope or, for very high energies, as a double energy loss detector (ΔE_{LaBr3} + ΔE_{LaCl3}), in order to determine the initial energy. In addition, an experimental test with high energy protons (70–230 MeV) was performed at the cyclotron center in Krakow, Poland with a first prototype of 2 x 2 phoswich rectangular crystals (CEPA4) packed in an aluminum can (0.5 mm case). To simulate CEPA10 efficiencies and resolutions, optical pulses detected in CEPA4 by photomultiplier tubes with a DAQ system were used as energy input functions in Monte Carlo simulations.

Keywords: Phoswich; scintillators; protons and gamma radiation.

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1. Introduction

Detectors made of fast scintillator materials, properly segmented for Doppler correction and adapted to a high level of electronics and mechanical integration, are increasingly needed to study nuclear reactions at relativistic energies. Satisfying these demands, an array of $LaBr_3$(Ce):$LaCl_3$(Ce) phoswich crystals (CEPA10), optimized to be placed 50 cm from the reaction-target where it will cover the region from 7º to 43º, is presented.[1]

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In an attempt to complete the CEPA10 final design, we have used Monte Carlo simulations to establish the proper shape and length of the crystals for the most efficient high energy proton and gamma radiation detection. A very realistic simulation of CEPA10 was performed when the photomultiplier (PM) pulses detected with a first prototype of 2 x 2 phoswich rectangular crystals (CEPA4) of 10 cm length (4 cm of $LaBr_3$ + 6 cm of $LaCl_3$) packed in one can made of Al (0.5 mm case) were included in R3BRoot simulation package.[2] This detector was tested with protons in the energy range between 70 MeV and 230 MeV at the cyclotron in Krakow.

2. CEPA4 and CEPA10 design

The prototype CEPA4 is an array of 2 x 2 rectangular phoswich crystals (4 cm $LaBr_3$ + 6 cm $LaCl_3$) packed in an aluminum can (0.5 mm case), each crystal having an entrance surface of 27 x 27 mm^2. Each crystal is coupled to a Hamamatsu R830 PM tube. A MSX25-500 (Micron Semiconductor) double-sided silicon strip detector (DSSSD) is positioned on the front with the purpose of obtaining position data of the proton events (see Fig. 1).

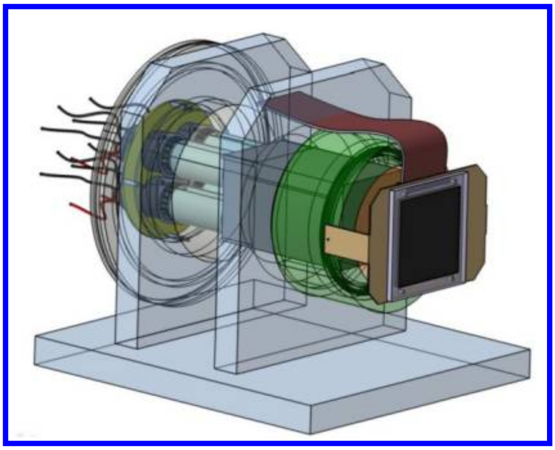

Fig. 1. CEPA4 experimental design with the DSSSD and the mechanical structure.

A proton response test was performed with CEPA4 in March, 2013 for proton energies ranging from 70 MeV to 230 MeV at the Bronowice Cyclotron Center at the Henryk Niewodniczanski Institute of Nuclear Physics in Krakow, Poland. The protons were scattered to an angle of 17.8° on the 50 µm thick titanium foil of the beam-line exit window to reach the detector.[3]

The CEPA10 detector design[4] is shown in Fig. 2. It is divided into 10 petals of 5 alveoli each, which are in turn sub-divided into 15 alveoli to hold individual phoswich crystals. Each phoswich unit consists of a 4 cm long $LaBr_3$ crystal optically coupled to a 6 cm long $LaCl_3$ crystal. In total, there are 750 individual crystals in the form of truncated pyramids. Each phoswich crystal is wrapped in 0.5 mm of Teflon and the alveoli are enclosed in 0.8 mm of Al. The petals are separated by two 5 mm thick Al plates (1 cm total separation). CEPA10 was implemented in R3BRoot[2] (Fig. 2, right) without the mechanical configuration (i.e., 750 phoswich units with 0.5 mm of Teflon wrapping).

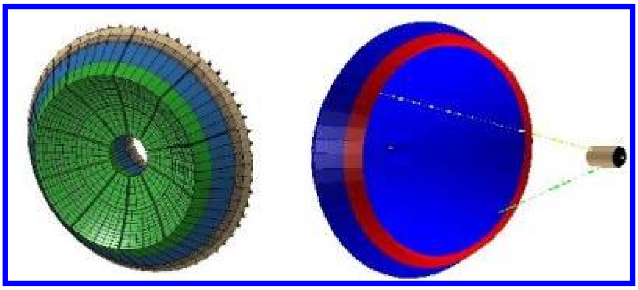

Fig. 2. Left: CEPA10 mechanical design. Right: CEPA10 design implemented in R3BRoot.

3. Simulations with CEPA10

The response to high energy gamma radiation (0.5–30 MeV) and protons up to 500 MeV was simulated to analyze CEPA10 efficiency and resolution as a function of crystal dimensions. The goal of these simulations was to design the most efficient detector for protons and gamma radiation with geometry and dimensions compatible with the segmentation needed to correct for the Lorentz boost and Doppler effect that will occur when studying nuclear reactions at relativistic energies (R3B@FAIR).[5]

It was determined that the optimum crystal length is 10 cm, which is evident from Fig. 3 where it can be seen that proton and gamma efficiencies increase by only 5% with a 2 cm increase in phoswich unit length. This small improvement would be at a considerable increase in cost.

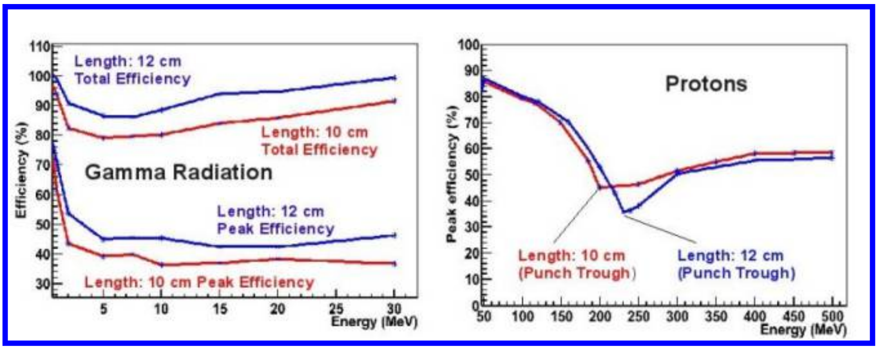

Fig. 3. Gamma (left) and proton (right) total and peak efficiency for crystals of 10 cm and 12 cm length. The punch through is shown for the different crystal lengths (10 cm: 200 MeV, 12 cm: 230 MeV).

3.1. *Simulations with CEPA10 as a $\Delta E_{LaBr3} - E_{Tot}$ telescope*

CEPA10 is a two-layer detector that can be used as a $\Delta E_{LaBr3} - E_{Tot}$ telescope or, for very high energies, as a double energy loss detector ($\Delta E_{LaBr3} + \Delta E_{LaCl3}$) in order to determine the initial energy. The energy deposited in the first crystals of the detector vs. the energy deposited in all of them is plotted in Fig. 4. Primary proton energies up to 500 MeV are also indicated in the plot.

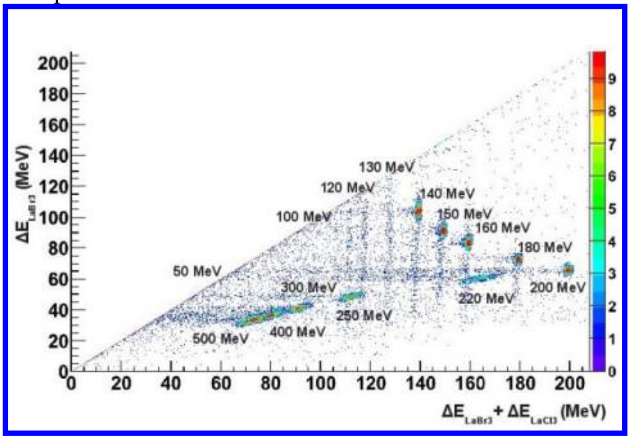

Fig. 4. Bidimensional plot of energy deposited in the first crystals vs. energy deposited in all of them. The right hand scale corresponds to the Z-axis and indicates with colors the relative number of protons for each energy.

3.2. *Simulations with CEPA10 optical pulses*

Optical pulses generated by protons were simulated at specific energies and used as input functions in R3BRoot to simulate the CEPA10 response with protons. Great advantages arise from managing these realistic pulses because they have all the information coming from the scintillator (optical properties like time decay response of the crystals, percentage of absorption, light yield, *etc.*) and from the electronics (any kind of electronic signal distortion that widens the pulses or delays the signals) that are really difficult to simulate with Monte Carlo programs.

The optical pulses used to simulate the CEPA10 proton response were generated based on the optical pulses detected with the DAQ from the CEPA4 PM tube. For this reason, the detector was turned 90º so that the crystals were facing the beam and protons would deposit energy either in the $LaBr_3$ or $LaCl_3$ units. The highest pulse amplitudes corresponded to protons that deposited energy in the $LaBr_3$ crystals and the lowest ones in the $LaCl_3$. They were de-noised, background subtracted and fit with energy-dependent exponential functions in order to be used as input functions in R3BRoot.[6]

4. Analysis of the Simulations

In order to calculate CEPA10 proton efficiencies and resolutions, an analysis of the $\Delta E_{LaBr3} - E_{Tot}$ plot was performed. In the case of protons, the primary energy was determined from the energy loss in the crystals. Proton efficiency was calculated by projecting the bi-dimensional plot $\Delta E_{LaBr3} - E_{Tot}$ onto the E_{Tot} axis and calculating the area under the same Gaussian fit function (with a width of 2.3σ) for each energy. Resolutions were calculated as well with the same procedure.

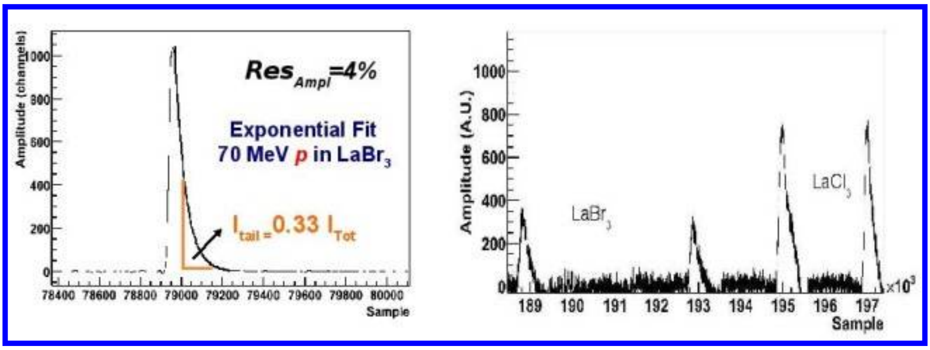

Fig. 5. Exponential function fit for the 70 MeV proton pulse shape when CEPA4 was turned 90º to the beam.

On the other hand, gamma and proton energy reconstruction can be performed using the hit finder and first neighbor clusterization addback algorithms included in R3BRoot. With the hit finder algorithm, gamma and proton initial energy can be reconstructed from the position (polar, azimuthal angle and radius) of the hit. The neighbor clusterization addback algorithm adds the energy contributions (spread of energy) of neighboring crystals that have been exposed and fall inside a user-defined square window. Protons efficiencies using these algorithms and $\Delta E_{LaBr3} - E_{Tot}$ plots give very similar results.

4.1. *The phoswich configuration to reconstruct the energy of the protons*

The CEPA10 phoswich configuration makes it possible to reconstruct proton energies greater than the punch through, and thus the detector can be calibrated for any energy. The proton punch through for CEPA10 is 200 MeV, meaning that protons with higher energies are not stopped in the detector (see the energy area of Fig. 4 for values higher than 200 MeV). In order to calibrate CEPA10 for energies beyond the punch through, this region has to be specially treated since not all of the energy is deposited in the crystals. The fifth order non-linear function given in Eq. (1) has been proposed for this purpose:

$$E_{Rec} = 3739 - 96.5\, xE + 1.11\, x\, E^2 - 65xE^3 + 2.05x10^{-5}xE^4 - 2.5x10^{-8}xE^5, \qquad (1)$$

where E_{Rec} is the reconstructed primary energy and E is the sum of energies deposited. Figure 6 shows a CEPA10 proton energy calibration generated using this algorithm for primary energies beyond the punch through, along with an example of energy reconstruction.

In the case of gamma radiation, one can include the Doppler factor correction (β=0.87 for our simulated R3B experiments) to correct the Doppler and Lorentz boost effect at relativistic fragment energies. Efficiencies and resolutions (Fig. 7) have been simulated using this method. Otherwise β=0 was used for protons.

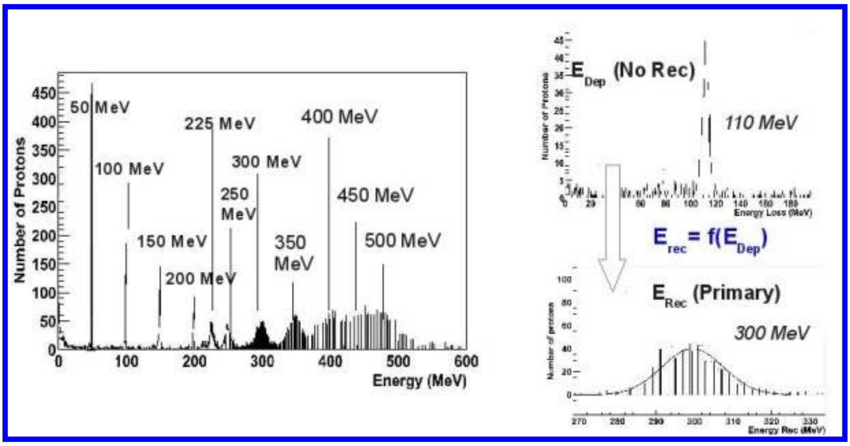

Fig. 6. (Left) Reconstructed primary energy for 50–500 MeV protons in CEPA10 using the hit finder and first neighbor clusterization addback algorithm; Eq. (1) has been used for energies>200 MeV. (Right) Example of energy reconstruction for a deposited energy of 110 MeV and incoming energy of 300 MeV.

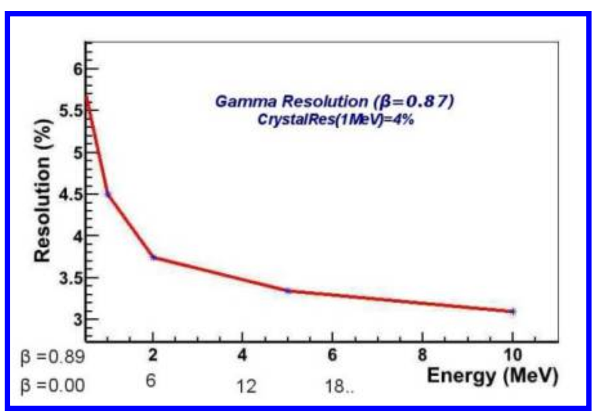

Fig. 7. Resolution using the reconstructed primary energy for 0.5–10 MeV gamma radiation in CEPA10 in the fragment reference frame with the hit finder and first neighbor clusterization addback algorithm.

4.2. *Pulse shape analysis using realistic pulses obtained from the PM tube*

This method is described in Ref. 4 and is based on finding the solutions of a system of equations that involves the analytical exponential fit function properties of the pulse. Proton pulses of 70 MeV (Fig. 5, left) were analyzed to obtain the pure fit function of the pulses attributed to protons that deposited all of their energy in the $LaBr_3$ crystals or in the $LaCl_3$ crystals that were facing the beam (CEPA4 turned 90 degrees). These fits are dependent on the energy deposited in the crystals so that proton pulses for any energy can be simulated in R3BRoot and used in CEPA10 simulations. The amplitudes of the lowest and highest CEPA4 pulses for energies lower than 150 MeV (CEPA4 sides of 5 cm wide mark the new distance for the new punch through) were histogrammed and fit to a Gaussian function, so that the mean value of the amplitude and the resolution of CEPA10 for such energies were calculated and are in agreement with Fig. 9 (right).

Primary energy reconstruction was obtained by plotting the tail intensity versus the total intensity (I_{Tail} vs. I_{Total}) of the simulated pulses for different proton energies the same as their amplitude vs. their total intensity (Amplitude vs. I_{Total}), or as the pulses' total intensity obtained from protons that deposit their energy only in the $LaBr_3$ crystals versus the ones that deposit energy in both of them (I_{LaBr3} vs. I_{Tot}) (Fig. 8). This latter plot was used to determine the CEPA10 peak efficiencies and resolutions shown in Fig. 9. In the case of I_{Tail} vs. I_{Total} plots, the break off energy (i.e., the energy at which the protons begin to deposit energy in the second crystals) is shown and depends on the amount of the tail area of the pulse selected. Experimental resolutions are on average 1% higher than the simulated ones. The main reason is due to the fact that CEPA10 is an idealistic detector in which some experimental characteristics like electronics or optical properties were only considered for the experimental pulses detected at a fixed energy (70 MeV).

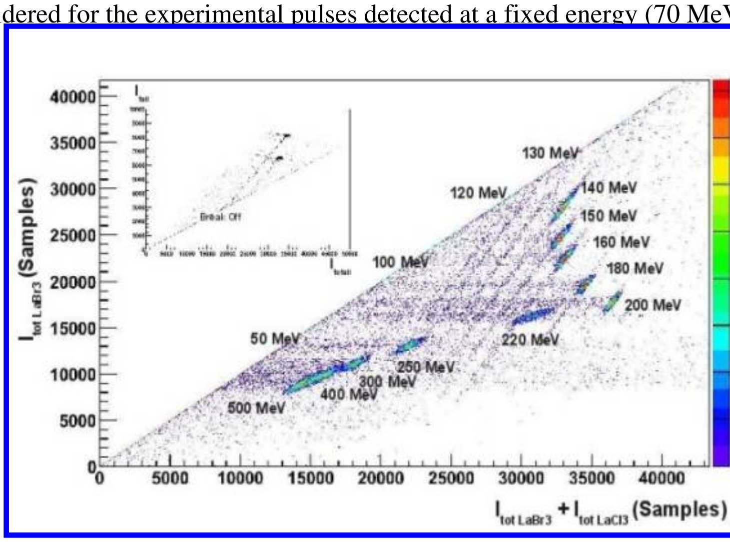

Fig. 8. CEPA10 Total Intensity of the pulses in LaBr3 crystals versus Total Intensity of the simulated pulses of the protons that deposit energy in all of the crystals. The small plot shows CEPA10 Tail to Total Intensity (I_{Tail} vs. I_{Total}).

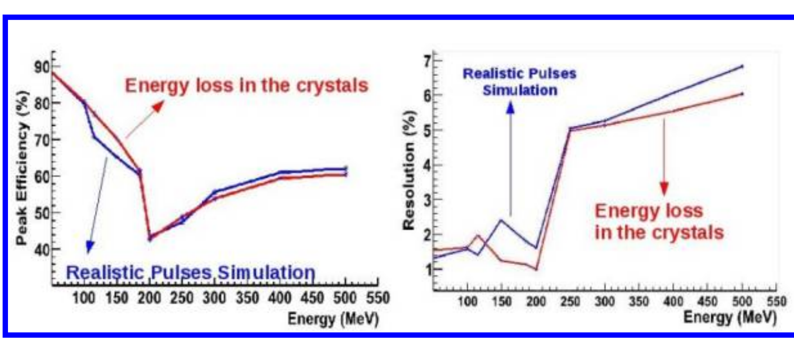

Fig. 9. CEPA10 efficiencies (left) and energy resolutions (right) calculated with the plots obtained with the simulated optical pulses and with only the proton energy loss in the crystals.

The high energy resolution and high peak efficiency of CEPA10 for protons and gamma radiation is remarkable. The high resolution, even for energies greater than the punch through, is due mainly to the excellent properties of $LaBr_3$ and $LaCl_3$ as scintillator materials. The phoswich configuration makes this detector compact but still valid to determine primary proton energies up to 500 MeV with high efficiency through the use of energy reconstruction algorithms. Thus it is ideal for use as a spectrometer and calorimeter in R3B experiments.

5. Conclusions

We have presented a sophisticated design of a 750 $LaBr_3$(Ce):$LaCl_3$(Ce) phoswich crystal detector (CEPA10) with a high energy resolution and efficiency for protons and gamma radiation. A prototype 2 x 2 array of rectangular phoswich crystals (4 cm $LaBr_3$ + 6 cm $LaCl_3$) was tested for protons in the energy range from 70 to 230 MeV. CEPA10 proton (50–500 MeV) and gamma radiation (0.5–30 MeV) peak to total efficiencies and resolutions were simulated using the experimental pulses detected with the CEPA4 PM tube and used as input parameters for the simulations. Energy reconstruction algorithms were used to determine the primary energy of the protons or gamma radiation and obtain the simulated resolutions and efficiencies.

Furthermore, a CEPA10 proton energy calibration was simulated and a fifth-order polynomial algorithm was used to reconstruct energies higher than the punch through. Pulse shape analysis has also been performed. The results indicate that CEPA10 would have an excellent resolution and could be used as a high efficiency spectrometer and calorimeter in R3B experiments.

Acknowledgments

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