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LIST OF ACRONYMS AND ABBREVIATIONS

$LaBr_3$:Ce	A transparent scintillator material that offers the best energy resolution obtained so far. Hygroscopic, has to be encapsulated. Emission at 380 nm
$LaCl_3$:Ce	An alternative to $LaBr_3$, excellent for building Phoswich with $LaBr_3$ Hygroscopic, has to be encapsulated. Emission at 350 nm
BrilanCe	Brillance380 and Brillance350 is the trademark of Saint Gobain for $LaBr_3$ and $LaCl_3$ scintillators respectively.
CEPA4	Prototype detector: 4xPhoswich($LaBr_3$/$LaCl_3$) in one Al-encapsulation
PMT	Photo Multiplier Tube. Several different types have been tested; Hamamatsu R5380 standard 8 dynode-acceleration tube, very sensitive to external magnetic fields Hamamatsu R7600U-200 metal-package compact 10 dynode PMT, very reduced sensitivity to magnetic fields Hamamatsu R11187 metal package 8 dynode PMT
PM Base	Voltage divider to distribute the total voltage over the different dynodes to obtain the final amplification.
DT5730	CAEN pulse digitizer, converts analogue signals to digital numbers for further analysis (0.5 GHz sampling frequency)
DT5751	CAEN pulse digitizer, converts analogue signals to digital numbers for further analysis (1 GHz sampling frequency)

EXECUTIVE SUMMARY

Phoswich detectors are where two different scintillators are optically coupled. Typically, the scintillators are chosen so that the light output of the two materials has very different timing properties so that the energy deposited in the two parts of the phoswich can be extracted. Phoswich solutions are attractive for discriminating high-energy charged particles and gamma rays. They can also be a good solution for making economic use of novel scintillators to make detectors which have high energy resolution for low-energy gamma rays and high efficiency at the expense of resolution for high-energy gamma rays.

INTRODUCTION

The latest-generation phoswich detectors, composed of $LaBr_3$ and $LaCl_3$ scintillating crystals, offer ideal conditions for the detection of gamma radiation, as well as for charged particles at relativistic energies, with high efficiency, and excellent energy and time resolution [1-5]. This report focusses on research and development with a prototype, CEPA4, which has been tested with gamma radiation from sources, as well as with cosmic muons and protons in a recent experiment at the proton accelerator of the Institute of Nuclear Physics in Krakow, Poland. The goal of these studies is to determine the response of the prototype, consisting of four phoswich crystals. A particular challenge, especially for photo-multiplier tubes (PMTs) and read-out electronics, is the large dynamic range needed to cope with signals from gamma radiation and charged particles. Phoswich detectors are crucial for the investigation of reactions of radioactive beams at relativistic energies, where detection of all reaction products is required, e.g. to extract invariant mass spectra.

This milestone is related to the deliverable D9.4 of Task 2 Phoswich Detectors. The work presented has mainly been performed by the associated group CTH and the participating group of IEM and with considerate help from the collaboration especially IFJ PAN, TUM, TUD and USC.

SECTION 1 THE CEPA4 PROTOTYPE

The prototype used in this work, CEPA4, consists of 4 individual box-shaped phoswich crystals made of $LaBr_3$ and $LaCl_3$. Each crystal has an individual PMT for readout, connected to the $LaCl_3$ part of the phoswich crystals. In a first step, energy and time resolution were measured using gamma-ray sources and cosmic muons. A schematic drawing of CEPA4 is presented in Fig. 1. The PMTs were connected to commercial digitisers. Two models, CAEN DT5751 (1 GHz sampling frequency and a maximum input voltage of 1 V) and CAEN DT5730 (0.5 GHz sampling frequency and a maximum input voltage of 2 V) were tested, in order to investigate if the lower sampling frequency allowed for sufficient time resolution and to disentangle the signals of the two phoswich crystals. Different types of PMTs, were also tested with CEPA4. Originally Hamamatsu R5380 photomultipliers were used. Once the production of this model was discontinued, the performance of Hamamatsu R7600U-200 PMTs was evaluated.

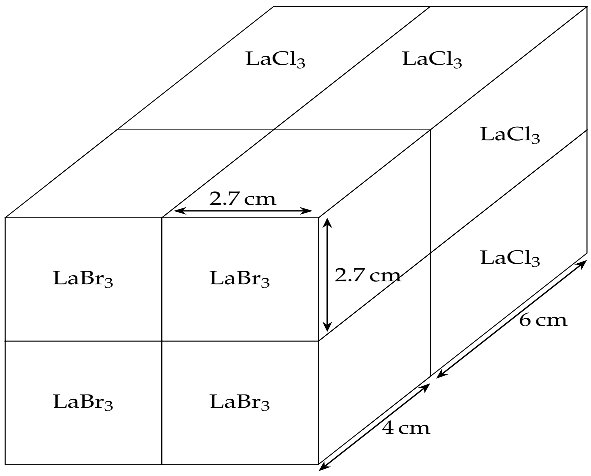

Fig. 1: Schematic of the CEPA4 prototype. The four $LaBr_3$/$LaCl_3$ crystals are optically isolated from each other. PMTs are mounted on the back of the $LaCl_3$ crystals.

Section 2 The Experiment

For protons, the punch-through energy for the $LaBr_3$ of CEPA4 is at about 120 MeV compared to the (full) gamma energies of interest, which are in the order of 1 - 20 MeV. Coping with the resulting factor of about 100 in dynamic range is a key challenge for the PMTs as well as the readout electronics. While it is relatively easy to obtain good energy resolution for either gamma rays or protons by selecting an appropriate bias voltage, it was not possible to find a bias voltage, which allowed for a good resolution for both, because the R7600U-200 PMTs displayed clear signs of saturation, see Fig. 2.

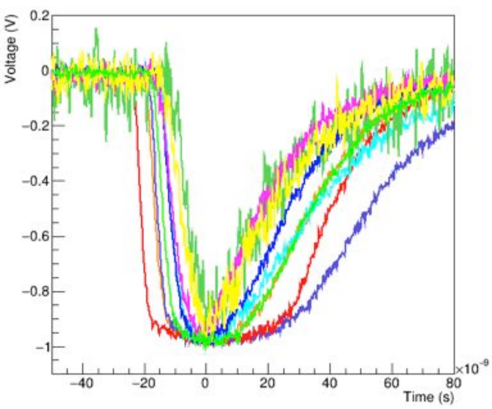

Fig. 2: Photomultiplier signals of cosmic muons traversing a $LaBr_3$ in CEPA4 at a bias voltage of -800 V. All pulses are normalized. The broadening of the pulses indicate the saturation of the PMT output signal.

In order to improve this situation, a new base was used for the R7600U-200 PMTs, providing in addition to an anode readout, also a second lower-gain signal from the last dynode. This new PMT assembly, called R7600U-200.mod1, was then tested not only with gamma rays and cosmic muons but also in an experiment (November 6 -12, 2017) at the Institute of Nuclear Physics in Krakow, Poland, which is capable of providing proton beams up to 225 MeV. The experimental setup is presented in Fig. 3. CEPA4 was mounted at an angle of 11° with respect to the beam axis. It detected beam particles after Rutherford scattering on target nuclei. During the experiment, not only CEPA4 but also other detectors, mostly arrays of CsI crystals, were tested.

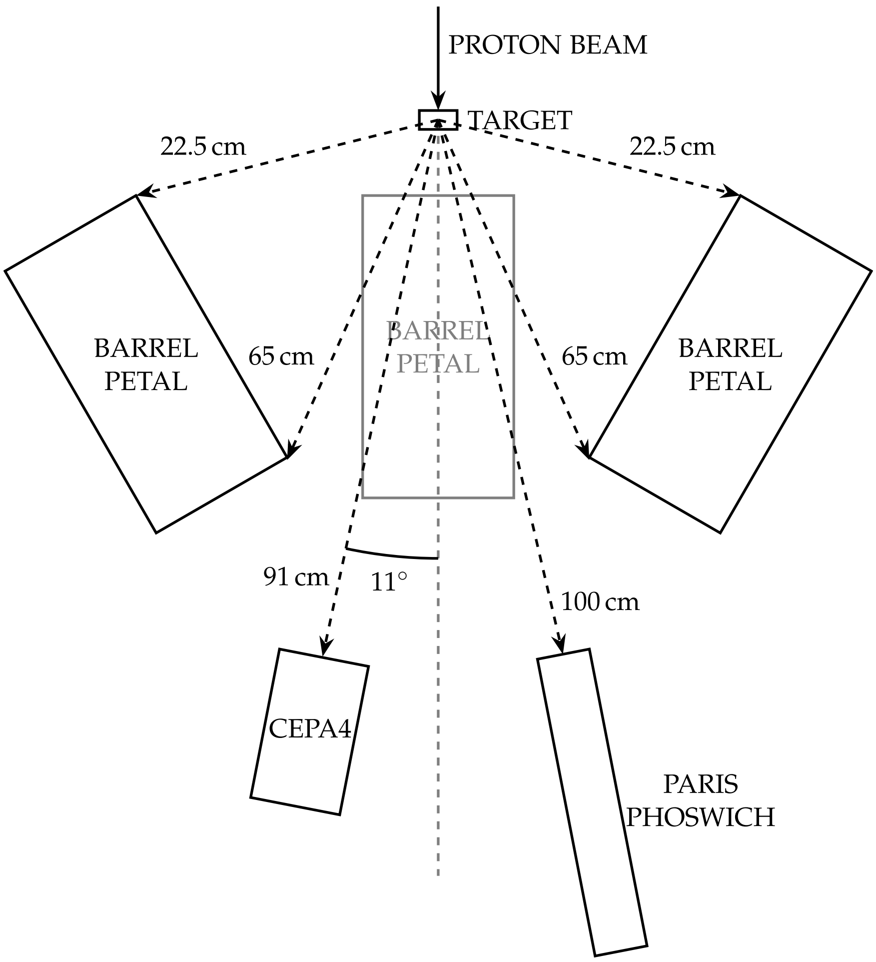

Fig.3: Schematic top view of the setup (not to scale) for the experiment at the Institute of Nuclear Physics in Krakow (IFJ PAN) with proton beams of energies between 70 and 225 MeV. In addition to CEPA4, three arrays of CsI crystals (one below the beam axis) of the CALIFA Barrel demonstrator (petals) and another phoswich detector of the PARIS detector were tested in the same experiment.

In the figure 4 a photograph of the experiment set-up at IFJ PAN is presented. During the beam time, targets of ^{208}Pb, $^{124,112}Sn$, graphite, plastic and H_2O were used at a wide range of beam energies. As the digitizers used for CEPA4 are able to self-trigger, CEPA4 was independent of the other detectors in the setup.

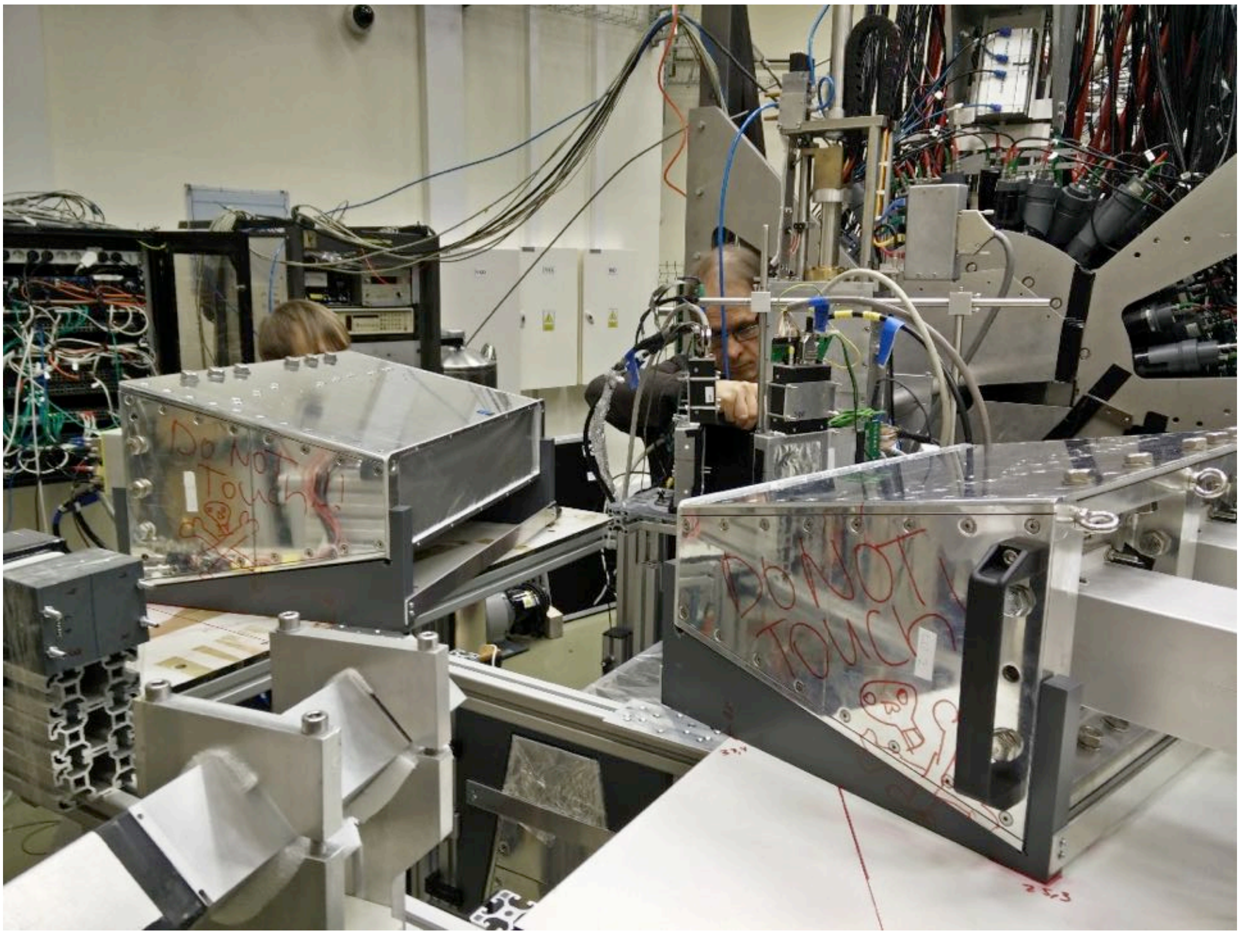

Fig. 4: Photograph of the setup while preparing the liquid water target. CEPA4 is oriented perpendicular to the beam axis at the far left of the picture. It is protected by a grey plastic cover.

The different targets and beam energies were motivated by different physics cases for the CALIFA detector. For example, the H_2O target is ideal to study (p,2p) reactions on protons, as well as quasi-free scattering on ^{nat}O, which provides also gamma rays that can be used for calibration. In order to study the direct interaction of protons with the $LaBr_3$ and the $LaCl_3$ crystals separately, CEPA4 was, for part of the beamtime, rotated to be perpendicular to the axis of the (scattered) beam.

SECTION 3 RESULTS AND DISCUSSION

The digitized PMT output, or trace, can be used to obtain in a first step the energy of the signal, while it can also be used to extract timing information and perform pulse-shape analysis to disentangle the signals of the $LaBr_3$ and the $LaCl_3$ crystals. In order to obtain an energy signal, two approaches, illustrated in Fig. 5, are possible. Either the maximum amplitude or the integrated area of the peak can be used. Raw energy spectra of CEPA4 obtained from the maximum amplitude of the signals from the high- and the low-gain output, are presented in Fig. 6.

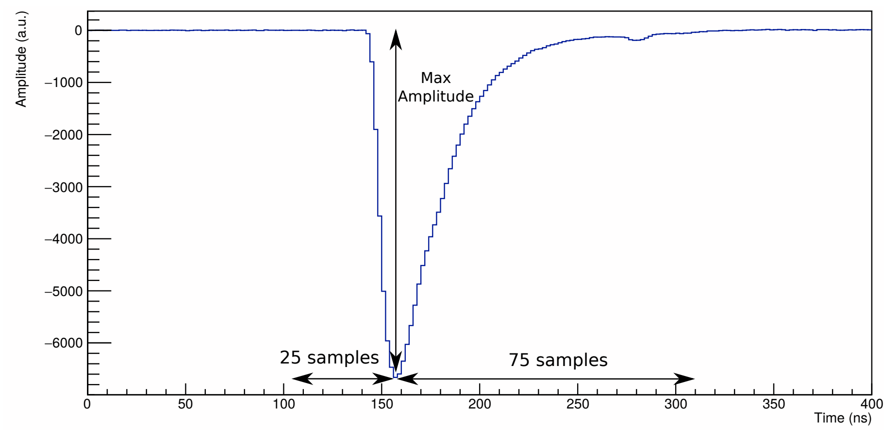

Fig. 5: Digitized PMT signal of a CEPA4 crystal. Indicated are the amplitude and the window (100 samples) that can be used to determine the energy of the signal.

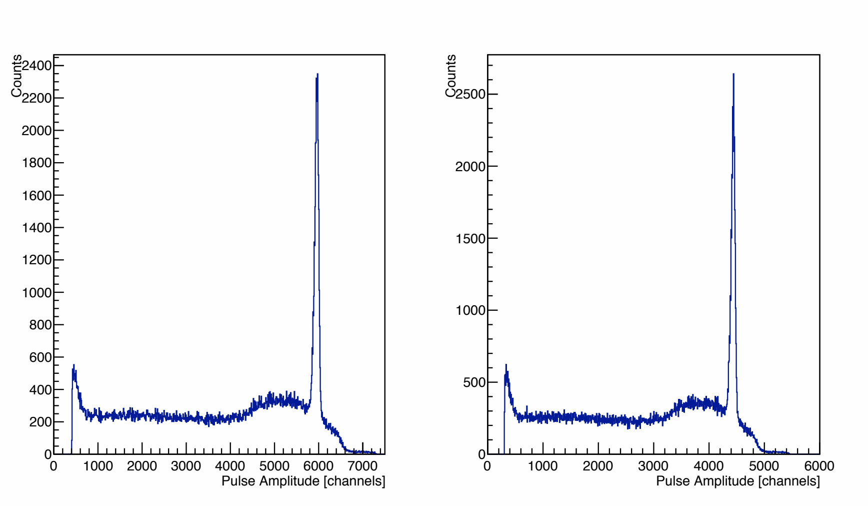

Fig. 6: Histograms of the maximum amplitude of a PMT signal for the high-gain (left) and the low-gain (right) outputs of crystal 1 of CEPA4 for protons at a beam energy of 200 MeV, scattering on a liquid H_2O target. The PMT bias was -500 V.

By plotting the energy signal obtained from integration over 100 digitizer samples (see Fig. 5) versus the signal amplitude, structures emerge (Fig. 7). The reason for this is that protons deposit energy in the $LaBr_3$ and the $LaCl_3$ parts of CEPA4, which have, however, different decay time constants (16 ns and 28 ns, respectively [6]).

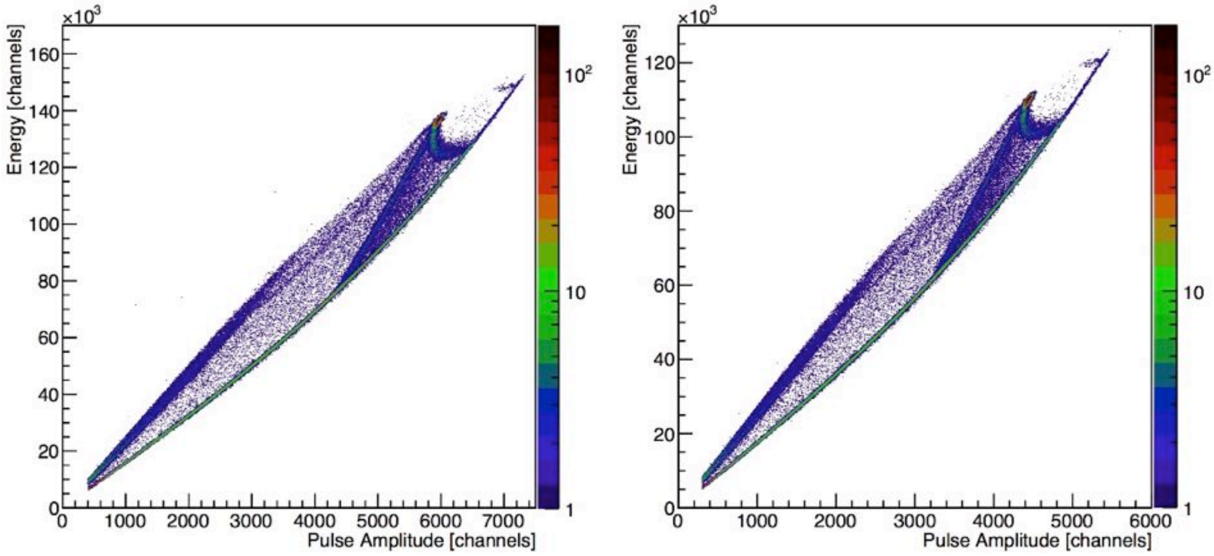

Fig. 7: Histograms of a pulse energy, measured in the window integrated over 100 samples (see Fig.6) versus the maximum amplitude of a PMT signal. Both, high-gain (left) and the low-gain (right) outputs of crystal 1 of CEPA4 for protons at beam energy of 200 MeV, scattering off a liquid H_2O target. The PMT bias was -500 V.

Another important observation is that the relation between the two observables is not linear (see lower limit of the two areas). This is a clear sign that the saturation of the PMT signal persists also for the low-gain output. A measurement of the gain difference gave only a factor of about 2.5 in gain between the two outputs. The observation of saturation is consistent with this low gain difference and indicates, that the PMT used in the experiment is not suited for a final detector. Note that laboratory tests with a new PMT, Hamamatsu R11187, delivered only in mid-January 2018, are in progress to overcome this limitation.

While the analysis of the data measured in the Krakow experiment is ongoing, some sample spectra look promising, concerning our ability to perform pulse-shape analysis. The difference in the decay times of the two parts of the phoswich crystals becomes clearer in Fig. 8. Punch-through of the protons at higher beam energy are clearly visible.

In a final test, CEPA4 has been rotated by 90° with respect to the scattered protons. That way it was possible to expose also the $LaCl_3$ crystals directly to protons, as presented in Fig. 9. Depending on which crystal is hit, an almost linear relation (the non-linearity is caused by PMT saturation) between the integrated tail area and the total integrated area can be seen. This is expected for signals from either the $LaBr_3$ or the $LaCl_3$ crystal. The line connecting the two originates from protons that cross the optical connection between the crystals and deposit energy in both crystals. Small losses due to imperfect optical coupling can be observed.

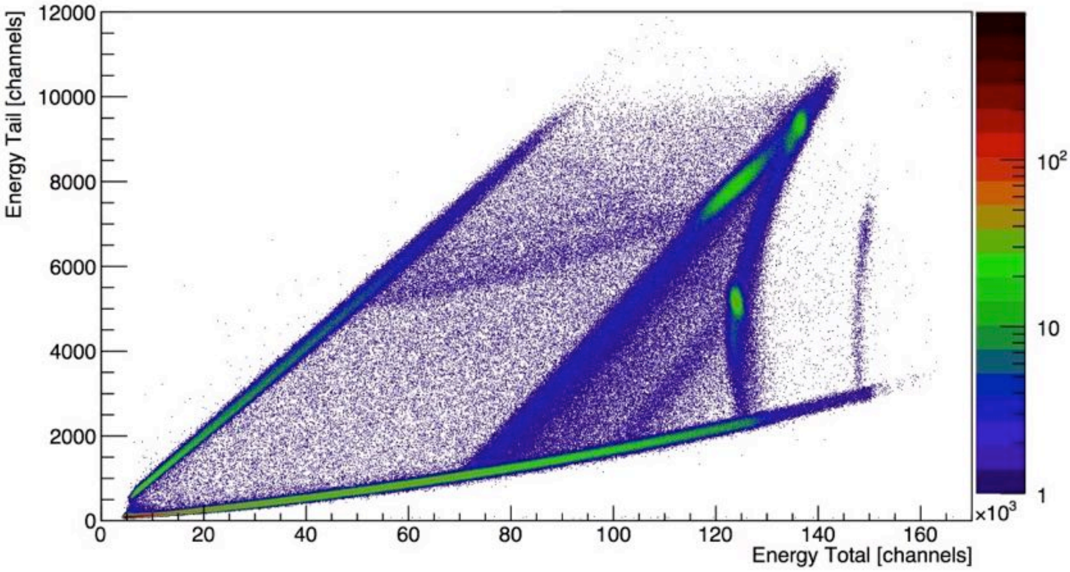

Fig. 8: Histogram of the tail of the signal (35 samples), which is dominated by the slower $LaCl_3$ signals, versus the total energy (window with 100 samples, see Fig. 6) from the high-gain output of crystal 1 of CEPA4 for protons at beam energy of 70, 150, 200, 220 and 225 MeV, scattering off a plastic target. The PMT bias was -500 V. The upper limit is given by the output of the $LaCl_3$ crystal, while the lower one represents the output of the $LaBr_3$ part of the detector.

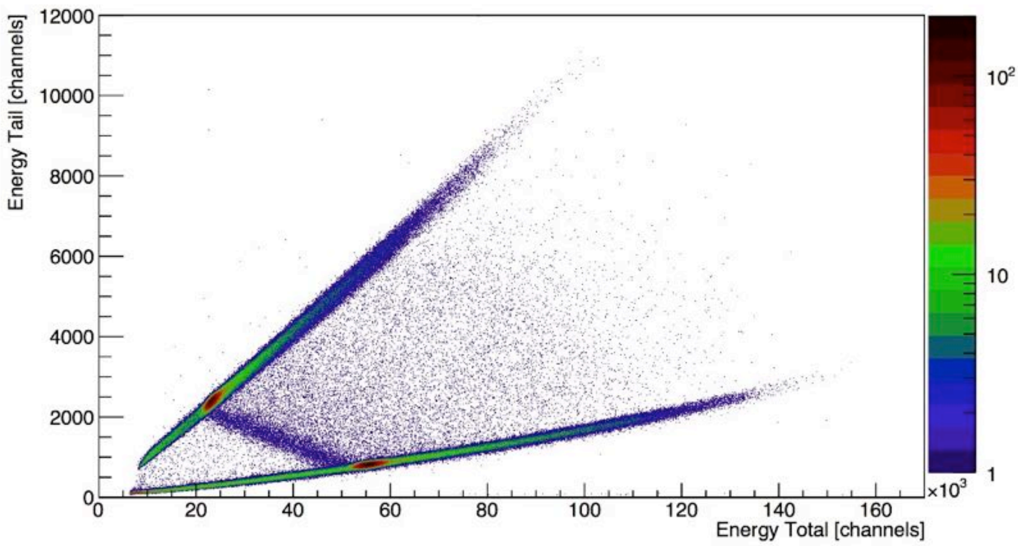

Fig. 9: Histogram similar to Fig. 8 but with the CEPA4 rotated by 90° with respect to the scattered protons. Signals from the high-gain output of crystal 1 of CEPA4 for a proton energy of 200 MeV on plastic at a PMT bias of 500 V are presented. As in Fig. 8, the upper and lower limits in the spectrum are given by the outputs of the $LaCl_3$ and $LaBr_3$ parts of the detector, respectively.

Section 3 Summary

The CEPA4 crystal has been tested in the lab with gamma rays from sources and cosmic muons as well as in an experiment with protons at energies between 70 and 225 MeV. The results indicate that the phoswich approach works well. The data processing is under control, but that the PMTs tested up to now limit the pulse-shape analysis over the full dynamic energy range due to saturation of the maximal output signal. This problem is currently being addressed by testing a third PMT type (Hamamatsu R11187 metal package 8 dynode) with less dynodes and thus less multiplication factor. Further, different voltage dividers, taking the output signal not only form the anode but also from one or two of the earlier dynodes, are to be tested. The features of this phoswich array and especially the data processing to obtain the wanted pulse identification will be further investigated within the PASPAG project.