An idea for the future proton detection of (p,2p) reactions with the R^{3}B set-up at FAIR

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Abstract. The R^{3}B Collaboration has a long experience in probing exotic nuclei via quasi-free scattering reactions. To continue these studies a new array capable of detecting protons and gamma rays of high energy is currently being developed, the CALIFA (R^{3}B CALorimeter for In Flight γ arrays and high energy charged pArticles). This contribution reports on the current solution for the forward Endcap of the CALIFA detector and on the latest test results.

1. Quasi-Free Scattering reactions from GSI to FAIR

The R^{3}B Collaboration studies exotic nuclei using RIBs by means of quasi-free scattering (QFS) reactions as a tool to access the single particle properties in the nuclei. In this kind of reactions an incoming proton with medium-high energy (a few hundreds of MeV) knocks out a bound nucleon. Since the cross-section of the nucleon-nucleon interaction is small at these energies, the reaction can be interpreted with the impulse approximation (quasi-free). As both outgoing particles are nucleons of same mass, they are knocked out with an opening angle between 80° and 90° in the laboratory system. For a general review of QFS see [1][2][3].

In order to perform a complete kinematics analysis using QFS reaction, it is mandatory to detect the momentum vector of the outgoing nucleons and gammas from the de-excitation of the recoil nucleus. A new experimental setup (R3B) for this purpose is currently under design and construction for the future FAIR facility. One of the new systems is the gamma-ray and proton calorimeter-array CALIFA that will be surrounding the target position. This detector is composed of two sections: Barrel and EndCap (see figure 1). A Technical Design Report of its Barrel section has already been approved by the FAIR management board[4]. The inner section of the endcap will receive the highest energy gammas and protons, which typically means protons up to 400-700 MeV and gamma rays up to 30 MeV, this part will be covered by a $LaBr_3/LaCl_3$ Phoswich detector CEPA(CALIFA EndCap Phoswich Array).

2. The Phoswich approach

The collaboration sought for a solution able to fulfill the requirements and a phoswich array in the endcap section is the current answer. The first prototype was presented in [5]: two scintillators were optically coupled together as it is shown in the figure 2, using a common PMT as a readout. In order to choose the scintillator material several properties have to be taken into account; the first condition is that they must be optically compatible, meaning that the second crystal has to be transparent to the scintillation light produced by the first crystal. The

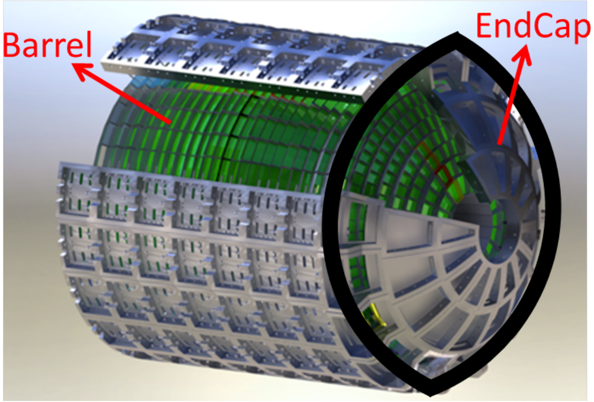


Figure 1. Model of the CALIFA detector, the barrel and Endcap section are visualised. The Barrel section will be surrounding the target position while the endcap corresponds to the most forward part of the detector, devoted to detect the higher-energy gamma rays and protons that continue in the beam direction.

second condition is to have low internal radioactivity. The materials $LaBr_3$ and $LaCl_3$ both fulfill previous conditions and have a set of good properties (see table 1): a resolution between 3-4% and a very good light output production of 63 and 49 photons/keV respectively. The difference in the decay time is a key parameter which opens the possibility of the pulse-shape analysis for doing Particle Identification and reconstructing the incident energy from the energy-loss measurement.

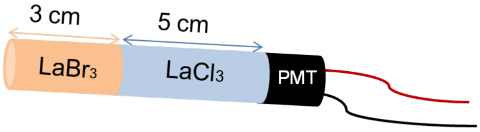


Figure 2. The first prototype was composed of a 3 cm $LaBr_3$ optically coupled to a 5 cm $LaCl_3$ crystal.

Table 1. Summary of the relevant properties of the scintillators for the phoswich array.

Material	Resolution at 662 keV	Light yield (photons/keV)	Decay Time (ns)	$\lambda_{emision}$(nm)
$LaBr_3$	2.9	63	16	380
$LaCl_3$	3.8	49	28	350

Coupling two different scintillator crystals together will produce two different light signals that are detected together in a common readout. The pulse can be carefully analysed by comparison of the integral of the whole signal against the tail. This tail depends on two parameters: the decay-time of the light emission in the material and the kind of interacting particle, thus it will allow us to separate the different light outputs from both crystals (see figure 3).

Due to the linear response of the material, it is possible to correlate the total integral directly with the tail integral as follows:

$$I_{Cl}^{tail} = a_{Cl} I_{Cl}^{total} \tag{1}$$

$$I_{Br}^{tail} = a_{Br} I_{Br}^{total} \tag{2}$$

$$I = I_{Cl} + I_{Br} \tag{3}$$

Using these three equations it is easy to solve the system of equations:

$$I_{Br}^{total} = \frac{I^{tail} - a_{Cl} I^{total}}{a_{Br} - a_{Cl}} \tag{4}$$

$$I_{Cl}^{total} = \frac{a_{Br} I^{total} - I^{tail}}{a_{Br} - a_{Cl}} \tag{5}$$

This allows the full separation of the two different contributions, and an energy calibration can be performed. The energy is directly proportional to the signal integral $I = \beta E$ where the constant is dependent on the material, thus it can be calibrated using data from previously known energies.

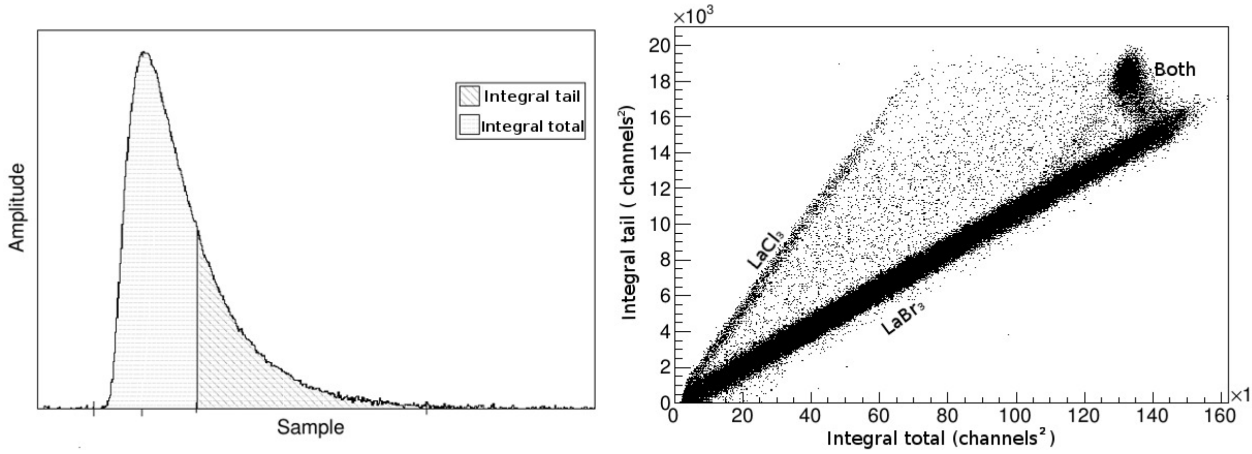


Figure 3.
Left: Typical sampled pulse signal from the photomultiplier, the total integral and the integral of the tail are indicated. The tail threshold must be calibrated in every experiment in order to optimise the separation of the signals.
Right: Integral Total *vs* Integral tail for 150 MeV protons. The two straight lines corresponds to the signals coming from only one of the scintillators, the slope difference can be easily appreciated, thus fitting to the lines gives us the needed parameters to solve the equations 4 and 5. The blob corresponds to the 150 MeV protons that loss the full energy within the phoswich, punching through the $LaBr_3$ crystal and producing the Bragg peak inside the $LaCl_3$.

3. Current prototype: CEPA4

The next step towards the final CALIFA design was to produce a small phoswich array called CEPA4, composed of four phoswich units of 4 cm of $LaBr_3$ and 6 cm of $LaCl_3$ with a common readout. The crystals are optically insulated from each other by a 1 mm of teflon reflector and packed together in an aluminium case 0.2 mm thick (see figure 4). The characterisation of the prototype and its response to high-energy protons was recently published [6].

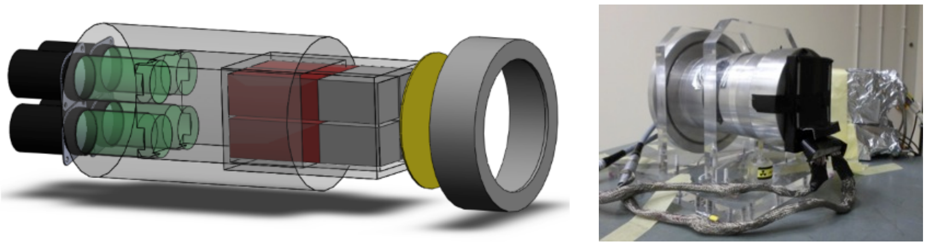
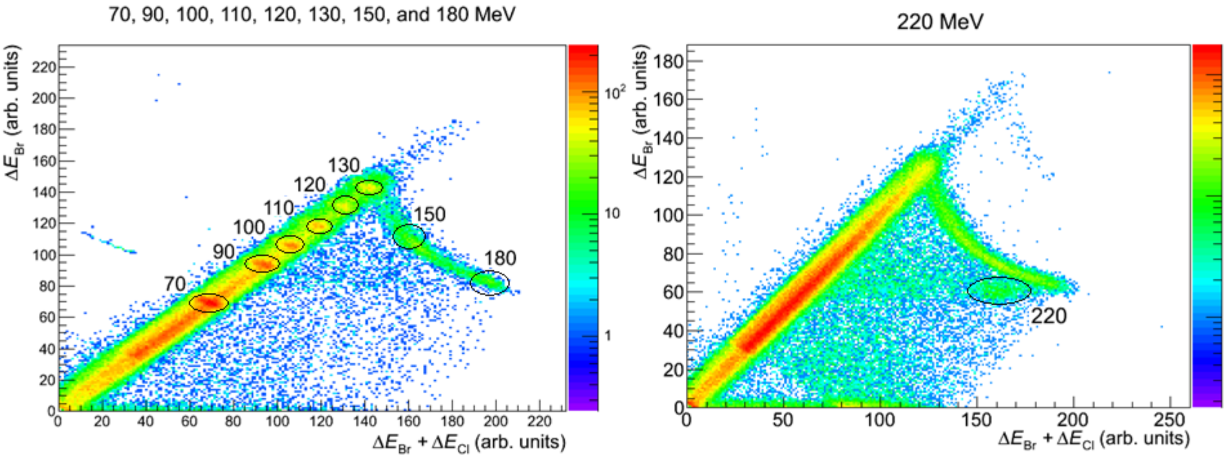


Figure 4.
Left: Scheme of CEPA4 with the four phoswich units (grey-LaBr$_3$ and red-LaCl$_3$) the PMTs are painted in green. The LaBr$_3$ faced the beam direction in the test beam.
Right: A picture of CEPA4 in a test experiment.

The CEPA4 proton response has been tested at the Bronowice Cyclotron Centre(CCB) in Krakow which provided a proton beam with energies from 70 to 235 MeV, allowing us to test the prototype in a broad energy range. At this beam test we were seeking protons with high energy that punch-through the whole phoswich, this was expected to happen around 200 MeV. Thus following the same procedure explained in the previous section the two different signals where separated and their contributions calibrated to produce the figure 5.



70, 90, 100, 110, 120, 130, 150, and 180 MeV

220 MeV

Figure 5. Calibrated Total Energy vs Energy Loss in the first crystal (LaBr$_3$).
Left (a): From 70 to 180 MeV the different blobs along the line corresponds to the Bragg peaks of the different beam energies. Up to 130 MeV are protons stopped in the first crystal(LaBr$_3$) and from 140 MeV up to around 200 MeV are stopped in the second crystal (LaCl$_3$).
Right (b): The 220 MeV protons punch-through the whole phoswich, thus leaving energy in both crystals without any Bragg peak.

Protons that do not leave the Bragg peak within our detector are losing less energy on both crystals, thus the signal produced is smaller and as we are plotting two contributions in a two dimensional plot that difference can be observed. As a further proof of the goodness of the method, the higher energy protons blob has been displayed in figure 6 in order to check the good separation between the different contributions. The measured energy resolution is 7% [6] for 220 MeV protons.

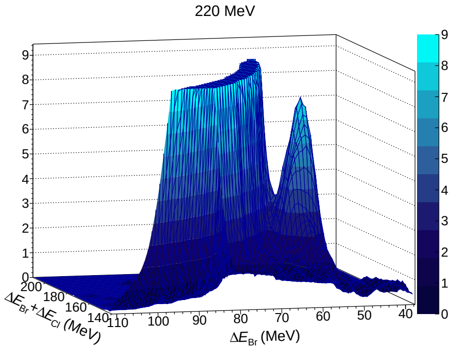


Figure 6. Three dimensional representation of the right graph of the figure 5b and zoomed close to the 220 MeV spot.

4. Conclusions

It has been described a solution that is being tested for the CALIFA EndCap. The results using the prototype CEPA4 were presented while introducing the potential of this system to separate protons that do not loose full energy within the detector.

Acknowledgments

This work was partly financed by the Spanish Research Funding Agency CICYT under Project FPA2012-32443. Further Guillermo Ribeiro acknowledges his FPI-MICINN grant.

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