The CALIFA endcap

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The R^{3}B experiment (Reactions with Relativistic Radioactive Beams) at FAIR (Facility for Antiproton and Ion Research) is a versatile setup dedicated to the study of reactions induced by high-energy radioactive beams. It will provide kinematically complete measurements with high efficiency, acceptance and resolution, for reactions with relativistic heavy-ion beams up to 1 AGeV, allowing an intense and broad physics program with rare-isotopes.

One of the key detectors in this experiment, CALIFA (CALorimeter for In-Flight detection of γ rays and light charged pArticles), is a complex array of 2560 scintillation crystals, that will surround the R^{3}B target. To cope with the requirements of the R^{3}B program, CALIFA combines the detection of low energy γ rays from single-particle excitations and high-energy γ rays associated with different collective modes. Moreover, CALIFA should be able to detect high energy charged particles emitted from the reaction area.

CALIFA consists of two sections (see Figure 1), a cylindrical 'Barrel' spanning an angular range from 140 to 42 degrees and an 'Endcap' covering the angular range up to 7 degrees. The Barrel is formed by 1952 long CsI(Tl) coupled to APD devices and equipped with a digital readout system. The design of CALIFA Barrel was subject to a Technical Design Report accepted by FAIR management in January 2013 (see [1, 2, 3]) and is presently under construction. CALIFA Endcap has to provide the detection of the most energetic particles in an angular region strongly populated by the light reaction products and gammas (see Figure 1). Table 1 summarises the nominal specifications fixed for CALIFA.

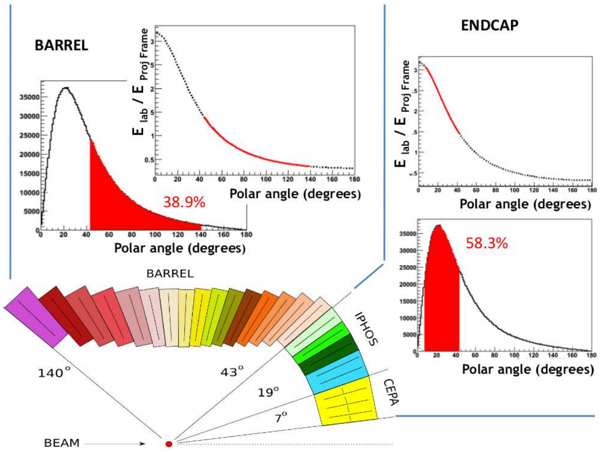

Figure 1: Schematic representation of the CALIFA detector profile. The portion of the angular distribution of emitted γ rays covered by each CALIFA section and the corresponding Doppler shift is highlighted in this figure for a fragment of 700 AMeV.

The CALIFA Endcap

The high-energy of the R^{3}B beams determined the conceptual design of the detector that has to accommodate a large Lorentz boost, particularly in the most forward region. Therefore, one main property of a calorimeter namely the complete kinematic reconstruction of emitted protons must be fulfilled within geometrical constraints, requiring sophisticated detector concepts to be employed.

To provide a feasible solution for the CALIFA Endcap two different detector concepts have been adopted (named the Phoswich and iPhos from now on) (see Figure 2). The Phoswich combines two very high intrinsic resolution scintillators (La_3Br:Ce and La_3Cl:Ce) optically coupled and

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Intrinsic photopeak efficiency	40 % (at E_γ=15 MeV projectile frame)
γ-ray sum energy resolution $\Delta(E_{sum})$/¡E_{sum}¿	<10 % for 5 γ-rays of 3 MeV
γ-ray Energy resolution	<6 % $\Delta E/E$ for 1 MeV γ-rays
Energy range for protons	Up to 700 MeV in Lab system
Energy resolution, protons stopped	<1 % $\Delta E_p/E_p$ $\frac{\sqrt{(100MeV)}}{\sqrt{E}}$
Energy resolution protons punch though	<7 % $\Delta E_p/E_p$ (at E_p=500 MeV)
Full energy peak efficiency for protons	>50 % (for all energies)
Proton-γ-ray separation	for 1 to 30 MeV

Table 1: Nominal specifications of the R^3B calorimeter (at β=0.82).

with a common readout, whereas the iPhos concept is composed by a monolithic CsI(Tl), similar to the most forward crystals of the CALIFA Barrel, that make use of the different decay times present in CsI(Tl) to identify particles. In both cases Pulse Shape Analysis (PSA) techniques are employed to separate punch-through protons from the fully stopped, providing a very good background suppression.

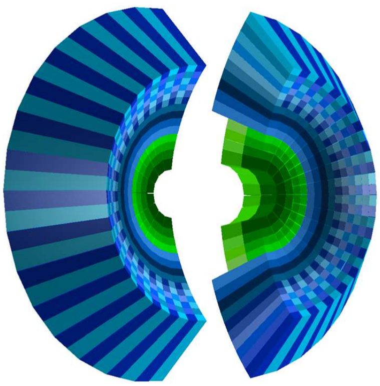

Figure 2: Artistic drawing of the two halves of the CALIFA Endcap. The four inner rings will consist of $LaBr_3/LaCl_3$ phoswich detectors, while the ten outer rings will be provided with the new iPhos detector concept.

The most forward angles up to about 20 deg are covered by Phoswich detectors. In this angular region the lower Doppler dependence on the angle allows for a broader-segmentation. The remaining angular range is covered by iPhos detectors. The granularity of CALIFA has been optimised in a manner to ensure that the final resolution is not dominated by Doppler broadening, but close to the intrinsic resolution of the scintillation material. While aiding energy resolution, an excessively high segmentation would be at the expense of calorimetric properties, consequently the optimum compromise between these factors has been determined. Figure 3 summarises the selected angular aperture for the CALIFA Endcap detectors that would guarantee a γ ray energy resolution between 4-6%, for projectile velocity β=0.82 all over the Endcap angular range.

We will underline the main technical characteristics inherent to this versatile device.

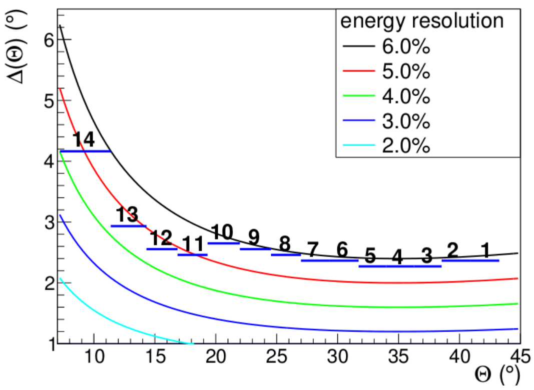

Figure 3: Graphic representation of the polar angular aperture needed as a function of the polar angle for a given projectile velocity (at β=0.82). The coloured lines correspond to different values for the maximum contribution to the energy uncertainty due to Doppler broadening, ranging form 2 to 6 %. Each blue line corresponds to the angular range covered by a crystal ring. Rings 1-10 correspond to the region covered by the iPhos section while rings 11-14 are covered by CEPA.

The Phoswich concept: CEPA

The inner section of the CALIFA Endcap, CEPA will be built as an array of individual phoswich modules (sectors) based on the optical coupling of 7 cm of $LaBr_3$(Ce) with 8 cm of $LaCl_3$(Ce) and readout by metal package PM of Hamamatsu R7600U-200 with E5996 Voltage divider. CEPA is divided into 4 rings divided into 8 sectors. $LaBr_3$(Ce) and $LaCl_3$(Ce) both are very hygroscopic materials that need to be encapsulated. The sectors will be formed by 0.20 mm thick cans of Aluminium. The can holds a 4 mm thick glass exit window, this window divided so that each readout is optically isolated. Each sector will contain 12 crystals; the inner two rings with 2 crystals followed by 2 consecutive rings of 4 crystal in each ring. CEPA comprises 96 double crystals, leading to a total weight of 42 kg and a volume of 9.5 dm^3 .

The Lorentz boost applied to the in-flight emitted γ rays in CEPA can reach a value $\approx$ 3 (a 10 MeV γ ray

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could correspond to 30 MeV depending upon the emission angle). At such a high energy, the interaction of γ rays with matter is dominated by pair production. Montecarlo simulations show that, about half of the γ rays of 20 MeV undergo pair production within the first 5 cm of a $LaBr_3$(Ce) crystal, depositing most of their energy in and around the first interaction. Having two layers of different crystals and being able to distinguish between the energy deposited in both, will allow us to implement intelligent add-back algorithms in which, by imposing conditions on one or the other layer (veto or coincidence), one can obtain information about the physical processes and even reconstruct part of the energy lost.

Protons, contrary to γ rays, interact with matter by a continuous deceleration, leaving part of their energy along the track, but they will deposit most of their energy in the final absorption process (Bragg peak). This also favours the use of two layers. Instead of using one very long crystal; it is possible to determine the initial energy by the energy loss in two shorter crystals, and thus avoid the reactions of very high energy protons ($>$200 MeV) where a major part of the energy may be lost due to production of neutral particles (pions or neutrons).
Figure 4 shows an example of proton identification using a CEPA prototype consisting of four 4 cm long $LaBr_3$(Ce)and a 6 cm long $LaCl_3$(Ce) packages. It corresponds to data recorded at the IFJ PAN Kraków cyclotron that can accelerate protons with energies ranging from 70 to 230 MeV. We distinguish in the two-dimensional ΔE-E plot three areas. Protons with energies comprised between 70 - 130 MeV are fully stopped in the first crystal ($LaBr_3$(Ce)) of the phoswich (line A), protons with energies between 130-200 MeV pass through the first crystal but are fully stopped in the second one ($LaCl_3$(Ce)) (line B), whereas the most energetic protons have to be detected by the partial energy deposited in both crystals (line C). The final resolution can be very different as a function of the proton energy and can range from 2 to 7% (for the largest energy in this experiment 230 MeV).

The iPhos concept

The ten outer rings of CALIFA Endcap will consist of monolithic CsI(Tl) crystals using the new iPhos method for the reconstruction of high-energy particles and described in [4]. The crystals are arranged in carbon fibre alveoli filled with four crystals each. The outer 6 rings include two different crystal geometries that are mirror images and follow identical geometrical configuration to Barrel crystals.They provide a smooth gap free transition between Barrel and the most inner 4 rings. Here one alveolus covers 4 crystals in a row to provide the best mechanical stability. The system amounts for 512 crystals of 22 cm long, filling an approximate volume of 90 dm^3 and a weight of 408 kg.

As part of the development of the iPhos concept for the CALIFA Endcap, a beam test at TRIUMF, Vancouver was

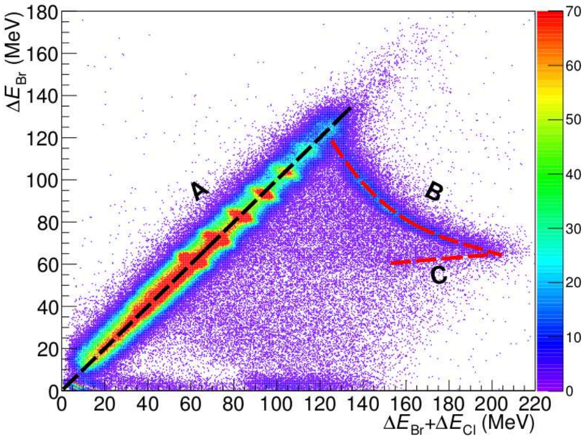

Figure 4: Two-dimensional ΔE-E plot for the runs included in the resolution analysis (protons of 70 - 230 MeV. The 2D histogram has been later projected onto the three lines: A, B and C for the determination of the energy resolution (see text).

performed. The TRIUMF H^- cyclotron provides a proton beam with intensities down to 100 particles per second and energies of 355 MeV and 480 MeV. The detector setup consisted of 12 CsI(Tl) crystals with a length of 15 cm and read out by LAAPDs. To modify the incoming beam energies and access a large set of different energies, an active degrader array with 4 cm and 3 cm long CsI(Tl) crystals was used in front of detector. It was shown that the RPID algorithm [5] preserves up to an energy of 480 MeV a nearly constant separation for stopped and punch-through protons, which is N = 13 times larger than the width of the correlation of fast and slow component of the light emission. This favours the use of the iPhos method up to these energy regions.

Another feature of the iPhos method, also shared by the Phoswich concept, is the discrimination and suppression of nuclear reactions inside the active detector material [4]. In 22 cm long CsI(Tl) crystals used in the CALIFA Endcap, nearly 50 % of protons above 300 MeV cause a non-negligible amount of nuclear reactions and have to be suppressed.

Figure 5 shows a full energy loss spectrum of 500 MeV protons in 250 mm of CsI(Tl). If we assume a (p,2p) experiment at an incoming beam energy of 700 AMeV different cuts can be applied based on the kinematics constraints smeared by the Fermi momentum distribution of the knocked-out proton inside the nucleus. This cut in the RPID parameter space reduces the amount of nuclear reactions dramatically (see Figure 5, red). All events that interact predominantly electromagnetically are located inside the energy loss peak and therefore in good approximation in the energy interval 185 MeV $< E_p <$ 220 MeV. The ratio between all events in the cleaned spectrum to all simulated events defines the efficiency of the detector at 500 MeV. The ratio of events of the cleaned spectrum in-

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side that interval to all events in that spectrum is a measure for the purity of the selection. If not constrained by any kinematics a pure proton cut in the RPID still cleans very efficiently. The characteristic numbers for both cases are shown in table 2.

	Purity	**Efficiency**
(p, 2p)	98,7 %	52,1 %
proton cut	90,5 %	58,1 %

Table 2: Summary of the two characteristic numbers purity and efficiency for (p,2p) reactions and a proton only cut for comparison.

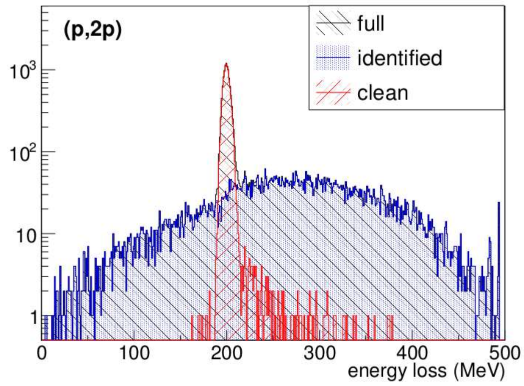

Figure 5: Energy loss spectrum from a GEANT4 simulation for single protons reaching the detector at $E_{kin} = 500\,\mathrm{MeV}$ (black). Events selected by the minimum bias (p,2p) kinematics cut in the RPID parameter space are shown in red. Events excluded by the iPhos method are shown in blue (from [6]).

The QFS Physics case

The full system has been simulated for a number of realistic physics cases; demonstrating that the detector performance meets the R^3B physics program requirements.

We will use as example the quasi-free reaction (p,2p) induced by a ^{18}O beam at 700 AMeV on a proton target to demonstrate the performance of the CALIFA Endcap. For this kind of experiment CALIFA has the challenging role of detecting the energy of the two protons plus the coincident γ rays from the de-excitation of the recoiling heavy fragments, covering a huge dynamical range. By measuring the energy as well as the momentum direction of both outgoing protons and knowing the incoming beam, the four-momentum vectors in the laboratory frame can be reconstructed.

The simulated excited states for the resulting fragment, ^{17}N, are below the particle separation threshold, so only electromagnetic transitions will occur. In this simulation we allow only the equal population of the ground state and the first two excited states (1373.9 and 1849.6 MeV respectively).

The application of missing mass spectroscopy [8, 9], allows for the reconstruction of the excitation energy independently of the actual measurement of the decay γ rays.

We have made use of the R3BRoot simulation package to evaluate the achievable missing mass resolution ΔM. This quantity depends on the energy resolution of both protons and was evaluated starting from an angular resolution of $\Delta\ \Theta$ = 1 mrad. If the energy of one of the protons is measured precisely, the energy resolution of the second is of lesser importance. For example with one proton energy resolution of 1% and the other 7% an invariant mass resolution of ΔM = 2.5MeV can still be achieved.

We show in Figure 6 the spectrum of the reconstructed missing mass of the ground state and the first excited $1/2^+$ state in ^{17}N. The excitation energy peak of the 1850 keV state is clearly shifted. This kind of measurement is a essential part of the R^3B and would contribute to study the role of final state interactions in exotic nuclei.

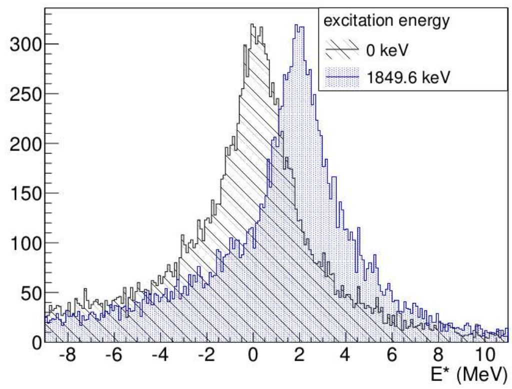

Figure 6: Simulation of the reconstructed excitation energy in ^{18}O(p,2p)17N for the ground state and first excited state at 1849.6 keV.

The detection of γ-rays corresponding to single state is also possible with CALIFA. Figure 7 shows the reconstructed γ ray spectrum after a Doppler correction with respect to the emitting fragment. The final energy resolution achieved with CALIFA nicely allows to separate the full energy peak at 1370 keV and 1850 keV and also the decay branch between these two states at around 480 keV.

Electronics and Trigger Logic

The CALIFA performances could not be achieved without an intelligent and dedicated data acquisition system and trigger logic.

Besides a synchronized trigger mode, in which all channels are read out at the same time in a common deadtime domain, CALIFA will feature a free-running mode, in which channels are self-triggered and record data independently. This trigger mode was successfully tested in a recent experiment performed at GSI in October 2014 in

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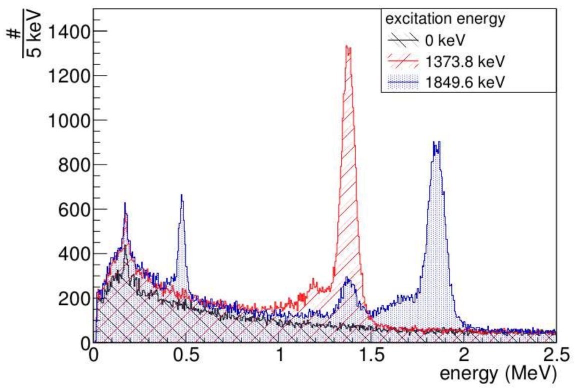

Figure 7: Simulation of the γ-spectrum corresponding to the population of the ground state (black) and the first two excited states of ^{17}N after Doppler reconstruction.

which the R^3B event reconstruction was accomplished with the White Rabbit time stamp system which in turn was distributed to the different branches.

In the future, a better event selection at high event rates will be accomplished by complex triggers involving the full information of the calorimeter read out by 200 FEBEX modules. Based on the total energy sum, the event multiplicity or the geometrical distribution of hits, different reaction topologies will be selected. To achieve this, a new concept called the trigger transfer tree protocol (T^3P) will combine the trigger data from all 2560 channels in a hierarchical tree structure.

On the channel level, the slope of the detector response is used to get a quick ($\Delta t < 1\,\mu$s) energy estimate to generate crystal triggers. On the cluster level, the energy sum and multiplicity for 16 channels within one FEBEX module is calculated. The cluster level information is sent using a serial protocol over 12 LVDS pairs to a R-FAB (Receiver FEBEX Add-on Board), which is currently under development. The R-FAB combines up to eight of these channels to a single output sent to the next level. The signal will be aggregated in two more tree levels before a global trigger decision is made.

The R-FAB will feature a dedicated FPGA/CPLD hybrid for very fast, "on the fly" calculation. By implementing the trigger modules as FEBEX addon boards, it will furthermore be possible to insert trigger information directly into the MBS data stream for online monitoring.

The development of CALIFA is rather advanced. The CALIFA Barrel is presently under construction. The commissioning of the CALIFA Demonstrator was done in conjunction with other R^3B detectors in October 2014. CALIFA Endcap Technical Design Report was endorsed by FAIR for evaluation in November 2014. According to our schedule, the complete CALIFA could be installed and operational in the R^3B cave by the end of 2017 ready to accommodate Day 0 experiments.

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