iPhos, a new technique for the CALIFA CsI(Tl) calorimeter

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Abstract. Within this paper we will present an entirely new energy reconstruction method iPhos for charged particles detected in CsI(Tl) crystals. Based on pulse shape analysis of CsI(Tl) scintillation signals protons that cannot be stopped within the active detector material can be distinguished from those fully stopped. Due to a special signature of punch-through protons, they can be identified and their full energy is reconstructed from their specific energy loss. In a dedicated experiment at the Cyclotron Center Bronowice, Krakow the first proof of this method was achieved.

1. Introduction
The target region of the \(^{3}\)B experiment at the new accelerator facility FAIR (Darmstadt, Germany) will be surrounded by the large volume calorimeter CALIFA. This calorimeter consists of about 3000 CsI(Tl) crystals that are read out by large area avalanche photodiodes (LAAPD). It is a multipurpose detector that plays a key role in the realization of kinematically complete measurements. The main requirements are a high efficiency, a good energy resolution of 6\% at 662 keV \(\gamma\)-ray energy and a huge dynamic range that allows simultaneous measurement of \(\gamma\)-radiation of a few 100 keV up to scattered particles of several 100 MeV. In nuclear reactions with relativistic beam energies of up to 700 AMeV high energy secondary particles are emitted mainly in forward direction. For their detection the main feature of a calorimeter namely the stopping of these particles cannot be fulfilled due to geometrical constraints.

2. RPID
It is known for decades that CsI(Tl) scintillation light is dominated by two different components, a fast one with a decay time constant of \(\tau_f \approx 600\) ns and a slow one with \(\tau_s \approx 3.5\) \(\mu\)s. Evaluating these different scintillation amplitudes allows for a particle identification \([2, 3]\). This has already been performed in several experiments like CHIMERA \([4]\) and INDRA \([5]\). For the development of a simplified algorithm for this kind of particle identification (PID) that could be implemented in high density fast sampling ADC modules a first experiment in 2010 at the Maier-Leibnitz-Laboratorium (MLL) in Garching, Germany to produce \(\gamma\)-rays up to 15.1 MeV and protons in the energy region up to 21 MeV was performed. The experimental method, the detector...
and electronics setup as well as the implementation of the algorithm for PID of fully stopped particles are discussed in detail in [1].

For the separation of scattered protons and γ-rays the so called RPID algorithm [1] was used to extract the amplitudes of the fast component \( N_f \) and the slow component \( N_s \) of the CsI(Tl) signal from the traces of the preamplifier output signals. In that context \( N_f \) respectively \( N_s \) are the total amounts of emitted light in the particular component.

γ-rays and protons down to energies of about 1 MeV were clearly separated. The linear distribution of the amplitude of the fast component \( N_f \) versus the slow component \( N_s \) shows a constant and energy independent ratio for γ-rays.

In contrast the proton distribution at low energies differs considerably from the linear characteristics. For stopped protons an analytical relation between the amount of light emitted in the slow component and the fast component \( N_{s,p}(N_f) \), now with index \( p \) for protons, fitted the data very well.

\[
N_{s,p}(N_f) = a \left( e^{-bN_f} - 1 \right) + cN_f
\] (1)

As a byproduct also the pattern of protons not fully stopped \( N_{s,p,\text{frac}}(N_f) \) in the active detector material has been identified [1, p. 5].

3. Intrinsic phoswich - iPhos

Equation (1) shows that \( N_{s,p}(N_f) \) is a nonlinear function especially for low energy protons. It was shown in [6][7] that the total light output \( L \) for protons is in good approximation linear over a wide energy range

\[
L(E) \propto E = c_L \cdot E.
\] (2)

Additionally the assumption \( L = N_f + N_s \) is a good approximation for the light production in CsI(Tl). So it can be concluded that \( \frac{N_s}{N_f} \) is also nonlinear or the derivative \( \frac{dN_s}{dN_f} \) is not a constant. From experimental data described in the following section \( N_s(L) \) and \( N_f(L) \) can be extracted by fitting a similar function as Eq. (1) to the accessible energy range

\[
N_f(L) = a \left( e^{-bL} - 1 \right) + cL
\] (3)

The derivative then describes the amount of fast component that is emitted within an infinitesimal amount of light production or path length of a proton through the active material

\[
\frac{dN_f}{dL}(L) = -ab e^{-bL} + c
\] (4)

Knowing the energy loss in the detector material the amount of \( N_f \) can now be calculated by integration

\[
\int_{L_1}^{L_0} \frac{dN_f}{dL}(L) dL = \int_{L(E_1)}^{L(E_0)} \frac{dN_f}{dL}(L) dL
\] (5)
Here $L_0$ corresponds to the total amount of light that would be produced if the incoming proton is stopped. Due to Eq. (2) this can be described in terms of the energy $E_0$ of the incoming proton. If the crystal is not long enough to stop the proton, $E_1$ corresponds to its energy when leaving the crystal and $L_1$ would be the total amount of light produced by stopped proton of this energy. For stopped protons ($E_1 = 0$) the integration starts at $L(0) = 0$ for punch-through protons at $L(E_1) \neq 0$. The amplitude of the slow component $N_s$ is treated accordingly.

If we assume a detector with a fixed thickness of the CsI(Tl) crystals, the integration limits for punch-through protons are correlated due to the dependence of the energy loss within the crystal on the incoming energy.

$$E_1 = E_0 - \Delta E = E_0 - f(E_0)$$

where $\Delta E$ is the energy loss in the CsI(Tl) crystal. The function $f$ is analytically not accessible. To overcome this problem the energy loss calculation and the integration is done numerically within the simulation package GEANT4[8]. In that way the behaviour of the punch-through protons in the $N_s$ vs. $N_f$ plot can be nicely reproduced.

4. Experimental verification

To verify this finding and to define the potential use of this effect, an experiment to explore the “intrinsic phoswich properties” of CsI(Tl) was performed in spring 2013 at the Cyclotron Center Bronowice at the Henryk Niewodniczański Institute of Nuclear Physics[9] (IFJ PAN) in Krakow, Poland. The proton cyclotron “Proteus C-235” is used for different purposes like nuclear physics experiments and radiation therapy for cancer patients. The accelerator facility allows for protons with energies from 70 MeV up to 226 MeV using a fast and easy energy and intensity adjustment for efficient use. To cope for the minimum beam intensity of about 1 pnA and to allow for a synchronous measurement in several different experimental setups, scattered protons from a 50 µm thick titanium target which also acted as an exit window of the vacuum beam pipe were used.

4.1. Experimental setup

The detector setup for this experiment was placed in a distance of about 2 m and an angle of $\Theta = 10^\circ$ with respect to the beam axis. It consisted of the prototype detector DemoZero[10] of the CALIFA Barrel that is equipped with 32 CsI(Tl) trapezoidal-conical shaped crystals. The crystal shapes and sizes correspond to the forward part of the CALIFA Barrel between $55.5^\circ < \Theta < 70.4^\circ$ (see[11, p. 15]). Each crystal was wrapped in one layer of high reflective foil[1] (see Fig. 1, left bottom) and four of these were grouped within one carbon fibre alveolus. The scintillation light was read out by Hamamatsu S8664-1020 LAAPDs[12]. The LAAPD signals were preamplified by a 32-channel Mesytec[2] MPRB preamplifier at a dynamic range of 30 pC.

The detector was placed vertically to the incoming particles (see Fig. 1, left top). To limit the scattering angles of the protons, but also the hit position along the crystals most of the active volume was covered by a massive lead shielding. Protons could reach the active volume only through a vertical slit of $d = 1$ cm. Here the average thickness of the crystal layers were between 13.0 mm and 15.3 mm (see Fig. 1, right).

For a systematic investigation of the proposed effect eight different beam energies (90 MeV, 100 MeV, 105 MeV, 110 MeV, 120 MeV, 130 MeV, 155 MeV and 180 MeV were used. In the following only the first crystal row with an effective thickness of 15.3 mm of active detector material is used for the energy reconstruction.

1 Vikuiti™ Enhanced Specular Reflector by 3M
2 http://www.mesytec.com
Figure 1. The detector setup consisted of 32 CsI(Tl) crystals that were wrapped with high reflective foil and read out by two 10x10 mm² LAAPDs (bottom left). Four of these crystals were grouped within one carbon fibre alveolus and surrounded by a 2 mm thick Pertinax housing (top left). More details can be found in [10]. A detailed schematic drawing of the setup is shown on the right. The effective thickness of the first two crystals is about 15.3 mm and is decreasing for those following.

4.2. Identification and reconstruction of punch-through protons
The results of the RPID pulse shape analysis, which separates the two components $N_f$ and $N_s$ are shown in Fig. 2.

In that two dimensional spectrum three different distributions (1-3 in Fig. 2) can be identified clearly. The structure marked with (2) corresponds to the low energy protons that are stopped within the crystals. For increasing energies and therefore protons that punch through the crystal, this line is strongly bent in the distribution (1). Due to angular uncertainties and therefore slightly varying effective detector thickness and also due to multiple scattering, the distribution of the stopped protons exceeds the punch-through energy in some cases. So in descending order the four peaks from 90 MeV to 180 MeV can be identified in the distribution (1), which corresponds to the reduced light output due to a reduced energy loss for punch-through protons. A simulation of the reaction in TALYS™ showed that deuterons are also produced in the reaction $^{48}$Ti(p,d)$^{47}$Ti with a cross section of about 10% compared to $^{48}$Ti(p,p')$^{48}$Ti. They can be found in the RPID histogram marked as (3).

The function $N_{s,ipho}(N_f)$ in Fig. 3 (drawn in black) shows the expected signal distribution of the punch-through protons. As first step of the reconstruction of the full energy all the events that are identified as punch-through protons are projected on this function to reduce

3 http://www.talys.eu
Figure 2. Result of the RPID pulse shape analysis for one crystal and 90 MeV protons. The different distributions correspond to punch-through protons (1), stopped protons (2) and deuterons (3).

Figure 3. Result of the RPID pulse shape analysis for one crystal and the four energies 90 MeV, 105 MeV, 130 MeV and 180 MeV. The black drawn function is the projection function for punch-through protons. More explanations can be found in the text.

Figure 4. Energy loss of protons with 90 MeV, 105 MeV, 130 MeV and 180 MeV in 15.3 mm of CsI(Tl) (left). The energy loss is extracted from the projected events of the RPID. The least energy loss corresponds to the highest energy and vice versa. The reconstructed proton energies of these four energies are shown on the right.

The last step is a standard evaluation of the full energy from the measured energy loss. This could be done numerically with the help of energy loss calculators like ATIMA or LISE++

\[ \Delta E = N_f + N_s \]  

\[ \text{http://web-docs.gsi.de/~weick/atima/} \]
\[ \text{http://lise.nscl.msu.edu/lise.html} \]
For the present data the full energy is known from the accelerator setting with a precision of \( \Delta E < 1\% \) and is used for calibration.

After the reconstructed full energy is plotted in a 1D histogram (see Fig. [3]). While protons with an incoming energy of 90 MeV can be reconstructed with a resolution of \( \frac{\Delta E}{E} = 4.9 \% \), it is decreasing for 180 MeV to \( \frac{\Delta E}{E} = 13.0 \% \). All evaluated energy resolutions can be found in Table [1]. For comparison the energy straggling (FWHM), calculated by LISE++, divided by the energy loss is summarized in the right column. From Table [1] we conclude that the resolution of the reconstructed energy is dominated by the energy straggling inside the material, which is expanded by the extrapolation between \( \Delta E \) and \( E_{iPhos} \). For energies near the punch-through energy of about 60 MeV the iPhos energy reconstruction provides a resolution close to the straggling limit. For increasing energies the extrapolation leads to a degradation of the achieved resolution.

| E       | Resolution (FWHM) | Energy straggling (FWHM) |
|---------|------------------|--------------------------|
| 90 MeV  | 4.9 %            | 4.3 %                    |
| 100 MeV | 6.3 %            | 4.4 %                    |
| 105 MeV | 5.6 %            | 4.5 %                    |
| 110 MeV | 7.2 %            | 4.7 %                    |
| 120 MeV | 7.8 %            | 4.9 %                    |
| 130 MeV | 8.9 %            | 5.2 %                    |
| 155 MeV | 9.6 %            | 5.9 %                    |
| 180 MeV | 13.0 %           | 6.5 %                    |

Table 1. Energy resolution of the iPhos reconstruction technique using 15.3 mm CsI(Tl) crystals in comparison to the relative energy straggling.

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