Readout concepts for the suppression of the slow component of BaF$_2$ for the upgrade of the TAPS spectrometer at ELSA

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Abstract. For the measurement at extremely high interaction rates with fast scintillators, pile-up of consecutive events is a limiting factor. With a decay time of 600 ps of the fast cross-luminescence component, Barium Fluoride (BaF$_2$) is one of the fastest inorganic scintillators known today. However, the dominating slow component with a 3 orders of magnitude longer decay time of 630 ns limits the rate capability. To circumvent this limit, different approaches have been made in the past. The slow component can be suppressed for example by doping the crystals with rare earth ions like La$^{3+}$. The paper will give an overview over the various concepts investigated in the past and present the suppression via optical band pass filters. This method has been chosen for the upgrade of the BaF$_2$ crystals in the most forward region of the TAPS-spectrometer at ELSA in Bonn. It allows to reuse the existing crystals and to achieve a high degree of suppression of the slow component. The focus of the paper will be on the selection of the filters, the achievable rate capability and the energy resolution of the fast component.

1. Introduction

The Mini-TAPS, an hexagonally shaped forward wall of BaF$_2$ detector modules, is used together with the Crystal Barrel based on CsI(Tl) to operate as a nearly $4\pi$ electromagnetic calorimeter in experiments with real photons at the Electron Stretcher Accelerator (ELSA) at Bonn. Due to the high hit rates in the most forward region of the detector setup, an upgrade of the inner parts of the spectrometer will be performed to increase the rate capability, which is limited due to pileup of the slow component of BaF$_2$. The implementation of optical bandpass filters was chosen to suppress the slow component of BaF$_2$ peaking at an emission wavelength of 310 nm.

2. The CB-ELSA/TAPS Experiment

The CB-ELSA/TAPS Experiment [1] is used to investigate photonuclear reactions with energy marked photons of an energy up to 3.5 GeV, produced form a primary electron beam by tagging photons due to Bremsstrahlung. The experimental setup is shown schematically in Fig. 1. The photons interact with a fixed target in the center of the Crystal Barrel detector comprising 1380 CsI(Tl) crystals arranged in a barrel shape covering the angles between 12 and 168, respectively. Due to the kinematics of a fixed target experiment one needs a fast and efficient detector in the...
forward direction. This role is accomplished by the Mini-TAPS forward spectrometer covering the angles below 12°. It consists of 216 BaF$_2$ crystals with a length of 12 $X_0$, a hexagonal shape of 5.9 cm diameter and readout individually via photomultiplier tubes (2 inch diameter, Hamamatsu R2059-01 with fused silica window). The crystals are arranged annularly in 8 rings around the beam axis [2]. One removed single detector in the center allows the photon beam to pass.

2.1. The Scintillation Mechanism of BaF$_2$
Barium fluoride is among to the group of scintillator materials providing the fastest mechanism presently known. For illustration, Fig. 2 shows schematically the band model of BaF$_2$ explaining the origin of the two different luminescence processes. As an insulator, the conduction band is normally empty, while the valence band and the upper core band are nearly completely filled. In the excitation phase due to ionizing radiation, electrons are excited from the lower bands to the conduction band. Holes in the upper core band can relax very fast to the upper end of the core band and recombine via a core-to-valence transition with an electron from the valence band. This so called "cross luminescence", a special type of intrinsic luminescence within two bands with a decay time of 600 - 800 ps, is enhanced since the electron energy is not sufficient for excitation of Auger electrons from the valence band. The energy of the scintillation photons peaks at 195 nm and 220 nm, respectively, differing by the width of the valence band. The excited and slowly relaxed electrons in the conduction band can recombine via self trapped exciton formation with hole in the valence band. These luminescence processes are significantly slower at the level of 620 ns. However, this process has a much higher probability and dominates the emission spectrum. The emission spectrum of BaF$_2$ resulting from these two processes is shown in Fig. 2 with the maxima of the fast component at 195 nm and 220 nm and the slow component at 310 nm, which has in contrast to the fast component is strongly temperature quenched. Fig. 3 gives an overview over the most relevant parameters of BaF$_2$.

2.2. Hit Rate Distribution for TAPS
To illustrate the rate limitation of TAPS, Fig. 4 shows the hit rate distribution for the different regions of the TAPS spectrometer in a typical photonuclear reaction with a fixed target. The figure clearly shows, that the rates are significantly enhanced in the central region and peaking at the first and second ring leading to an increase by a factor of 3 to 5. To avoid pile-up of the slow component, which requires on average an integration time of 2µs, the single crystal rate has to be limited to $\sim$ 100 kHz, which has a strong impact on the detection efficiency of weak processes. As a solution, the suppression of the slow component at least in the inner 2 to 3 rings could exclude the rate limitation due to the scintillator itself.
3. Concepts for the Suppression of the Slow Scintillation Component

In the past several concepts have been investigated to suppress the slow component of BaF$_2$. Several attempts have been made to change the scintillation process by appropriate co-doping. Alternative approaches are based on a selective sensitivity of photo sensors or the use of optical filters, which has been chosen for the upgrade of the TAPS modules.

3.1. Use of Doped Crystals

The doping of BaF$_2$ crystals, especially with rare earth elements like La$^{3+}$ ions was studied in detail by Schottanus et al. [3]. Fig. 5 shows the impact of different La$^{3+}$ concentrations on the emission spectra of BaF$_2$. The created color centers lead to a strong but not sufficient suppression primarily of the slow component. However, even for the largest concentration (13.3 mol%, both components are nearly of similar intensity, since the fast component is reduced to a level of around 50 % in parallel.

3.2. Use of Special Photo Sensors

Another possibility to suppress the slow component would be the use of photo sensors which are insensitive in the spectral range of the slow component. Solar blind PMTs, such as the (Hamamatsu R4679), exploit a CsTe photocathode with a peaking quantum efficiency at 225 nm and a sensitivity above 300 nm reduced by almost 3 orders of magnitude. Fig. 6 (left) shows the quantum efficiency of such a PMT (Hamamatsu R3197) in comparison to the actually used Hamamatsu R2059-01 PMTs and compared to the emission spectrum of BaF$_2$. Test measurements showed, that the finally detected light consists of 50 % fast and 50 % slow component which can be explained by the quantum efficiency (QE) in Fig. 6 and the relative intensity of the two luminescence components. A second better adapted possibility is the use of diamond photo sensors, which were developed for astrophysical applications [5]. Due to the
3.3. Use of Optical Filters

The use of optical filters became the most promising and finally chosen concept for the upgrade of the existing TAPS setup with the advantage that all existing components can be reused. Fig. 7 (middle) illustrates schematically the position of the filter within an existing TAPS module consisting of a BaF$_2$ crystal, a PMT and a voltage divider base. The main requirements for an optical filter are a high transmittance for the fast component and at the same time a high grade of suppression for the slow component. An ideal filter would be a short pass filter with a sharp edge between 230 nm and 235 nm. Fig 7 (left) shows a theoretically calculated transmission performed with a special simulation program provided by LOT-Oriel. However, there are no practical experiences in producing such filters and a costly development would be required.

Finally, standard optical band pass filters consisting of hard coated quartz glass, as shown in Fig. 7, will be used after an optimization of the most probable wavelength. As a remaining disadvantage, a small but tolerable part of the tail of the slow component towards short
wavelengths causes a $\text{LY}_{\text{fast}} / \text{LY}_{\text{slow}}$ ratio $> 5$. Since the remaining slow component is emitted with a significantly longer decay constant of 620 ns, only a small background contribution will be left over underneath setting a short integration gate of typically 20 ns.

### 4. Response Measurements Using Optical Band Pass Filters
To verify the applicability of the optical filters, different response tests have been performed.

#### 4.1. Quality Control of the Filters
For the upgrade 40 filters have been delivered from Princeton Instruments. Fig. 8 (left) shows the overlay of the measured transmission curves and a picture of a typical filter. The Gaussian transmission distribution peak is on average at a wavelength of $214 \pm 3$ nm with an absolute transmission value for $\lambda_{\text{max}}$ between 36% and 42%, respectively. Under the assumption of the spectral distribution of the emission spectrum, as shown in Fig. 7 (right), the contributions to both scintillation components have been calculated for each of the measured transmission curves of the available filters considering in addition the quantum efficiency of the photomultiplier R2059-01 and the transmission of the crystal. However, the kinetics of the luminescence processes has been ignored. The two correlations shown in Fig. 8 (right) relate the normalized intensity of the slow component to the fast component or the integral light yield collected after the filter, respectively. Unfortunately, both figures illustrate the consequence from the nearly identical transmission shape of the filters that a small shift of the transmission curve to higher wavelengths increases the total light yield after the filter but allows also a larger contribution from the slow scintillation component.

![Figure 8. Measured transmission spectra of 40 band pass filters and a picture of a typical band pass filter (left). Correlations between the calculated intensity of the slow component and the fast component (middle) and the total light yield detected after the filter (right), respectively. The assumptions are explained in the text.](image)

#### 4.2. Signal Shapes with and without a Filter
Fig. 9 shows the measured signal shape for a low energy $\gamma$-source of a BaF$_2$ detector, read out with a R2059-01 PMT with and without an optical band pass filter in between, recorded with a digital oscilloscope at high sampling rate. Without a filter, the slow component is dominating after 10 ns with a significant contribution up to 2.5 $\mu$s. Using a filter, there remains nearly no visible contribution of the slow component. Only on a larger scale one can identify a small contribution of the remaining slow component slightly above the baseline in the first 50 ns. However, the contribution underneath the fast component is well below 10%. From this observations, a rate capability of at least 1-2 MHz can be estimated for the modified detector modules without major limitations due to any pile-up. In contrast to this, with an ideal short pass filter rates of 10 MHz should be possible.
4.3. Response to Low Energetic Gamma Rays and Cosmic Muons

To get a first estimate for the light yield and the energy resolution using optical band pass filters, measurements with radioactive gamma sources ($^{137}$Cs, $^{22}$Na, $^{60}$Co) and cosmic muons have been performed. Fig. 10 (left) shows that a broad photo peak can be clearly distinguished above the noise threshold and a linear response is confirmed. In these tests, a light yield of 20-25 pe/MeV and a time resolution of $\sigma_t = 400$-500 ps have been obtained. Based on the calibration with low energy photons the most probable energy deposition for passing cosmic muons is shown Fig. 10 (right). The detector was placed horizontally and the diameter between two opposite sides of the hexagonal cross section amounts to 5.9 cm. The measured most probable energy loss comes close to the energy deposition of minimum ionizing particles of 37.6 MeV for 5.9 cm BaF$_2$. The TAPS calorimeter is used for reconstructing electromagnetic showers up to 3.5 GeV energy. The obtained individual detector threshold well below 500 keV will not limit the achievable energy resolution of the inner detectors relying on the fast light component only.

4.4. Response Expected for High Energy Photons

To get an estimate for the overall energy resolution for electromagnetic showers up to several GeV energy equipping the detectors with optical band pass filters, a calculation was made based on the known energy resolution of the TAPS calorimeter measured for the total light output as well as the fast component separately by A. Gabler et al. [6]. The contribution of the scintillation light of the fast component was obtained by charge integration of the photomultiplier signal within an integration gate of 50 ns. Assuming an optical transmittance of the UV-filters of 30 - 35 % and considering an additional light loss of 10-20 % due to the missing slow component within the first 50 ns, an energy resolution given by $\sigma/E = (1.41\% - 1.61\%)/\sqrt{E} + 1.80\%$ can be estimated, which is comparable to the energy resolution of the target calorimeter of the
Figure 11. Energy resolution of a matrix of 19 BaF$_2$ scintillation detector in TAPS geometry read out with a PMT with bialkali photocathode. The emission light in total was collected within an integration time of 2 µs (solid line) and the fast component was extracted separately by integrating over the first 50 ns only (dotted line) [6]. For comparison, the expected energy resolution using a filter with reduced transmittance is indicated by the dashed area.

future PANDA detector at FAIR based on lead tungstate when operating at room temperature. The measured and expected energy resolutions, respectively, are compared in Fig. 11.

5. Discussion and Outlook

The fast component of BaF$_2$ represents the fastest scintillation mechanism in inorganic scintillators, presently known. Therefore, the selective readout of the fast component only (10 times faster kinetics than PWO) would enable very high rate capabilities without giving up the required energy resolution for electromagnetic showers in the energy range between a 50 MeV and 3.5 GeV, respectively. Even commercially available optical band pass filters provide a high grade of suppression of the slow component and the reduced photon statistics is still sufficient to guarantee a high resolution electromagnetic calorimeter. Presently, only the most forward part of the TAPS-wall is considered to be modified. However, there is one serious drawback in the applicability of BaF$_2$. Due to the very different origin of the two luminescence components, the line shape of a BaF$_2$-detector allows particle/photon separation via pulse shape analysis exploiting the ratio of the two components. For highly ionizing charged particles appears the fast component significantly reduced compared to electron/positrons generated in the electromagnetic shower. Therefore, the modified detector modules will provide only information on energy and timing. A direct proof of the energy resolution of a sub-matrix of modified detectors is scheduled in summer 2014 using energy marked photons up to 800 MeV at the tagging facility at MAMI, Mainz (Germany).

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