Electromagnetic Calorimetry with $PbWO_4$ in the Energy Regime below 1 GeV[1]

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Abstract

The study of the performance and application of $PbWO_4$ in electromagnetic calorimetry at energies far below 1GeV has been continued. The significantly improved optical and scintillation properties of 15cm long Nb/La-doped crystals, optimized for the ECAL/CMS calorimeter, are documented. The lineshape, energy and time response of a 5x5 matrix are tested with monoenergetic photons up to 790MeV energy and compared to previous measurements. First attempts have been made to enhance the scintillation yield by suitable dopants (Mo, Tb) for applications at very low photon energies.

As a first large scale project at medium energies, the proposed concept for a compact photon spectrometer to be implemented into the ANKE magnetic spectrometer at COSY (KFA Jülich) is illustrated.

I. INTRODUCTION

$PbWO_4$ has been selected as the most appropriate material for the new generation of homogeneous high energy electromagnetic calorimeters as under construction for CMS or ALICE, detectors at the future LHC [1,2]. Due to the thermal quenching at room temperature, one has to cope with a very fast scintillator material but in principle with low light output. However, in a series of previous experiments with electrons [3] and energy marked photons [4] between 50 and 855MeV energy, respectively, the applicability of $PbWO_4$ at much lower energies has been proven by very promising energy and time resolutions ($\sigma/E = 1.54\%/\sqrt{E[GeV]} + 0.30\%$, $\sigma_t < 200ps$). The results have been obtained with a 5x5 detector matrix consisting of 15cm long crystals even with large inhomogeneities and not optimum optical and scintillation quality. The response function shows that the achievable energy resolutions below 200MeV photon energy are significantly limited by the low photon statistics of $PbWO_4$. Therefore, any further improvements will strongly rely on scintillator crystals with high optical transparency and an enhanced luminescence yield, either optimized by the crystal growth conditions or the use of suitable dopants. In this paper we will report on the properties of Nb/La-doped crystals, optimized for the ECAL/CMS calorimeter, and the first results on Mo- and Tb-doped samples. Finally, the proposed concept for a compact photon spectrometer to be implemented into the ANKE magnetic spectrometer at COSY (KFA Jülich) will be introduced.

II. THE NEW $PbWO_4$-CRYSTALS

A. Optical Performance of Nb/La-doped Crystals

Nb/La-doped crystals of slightly tapered shape have been manufactured and preselected by RI&NC (Minsk, Belarus) and Bogoroditsk Techno-Chemical Plant (Russia). The optically polished crystals of 150mm length (~ 17 radiation length X_0) have a quadratic front face ($20.5x20.5mm^2$) and a tapering angle of ~0.4°.

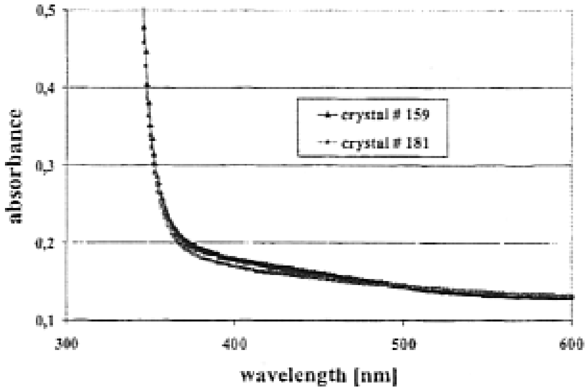

Figure 1: Optical absorbance as a function of wavelength for two typical tapered Nb/La-doped $PbWO_4$ samples measured perpendicular to the crystal axis (thickness d=20.5mm).

The homogeneity of the optical quality is determined by measuring the transmission perpendicular to the crystal axis at various positions within the relevant wavelength regime. Figure 1 illustrates the absorbance for two typical samples. In some cases a weak absorption band near λ~420nm becomes still visible. The transparency region near the natural absoprtion edge can be characterized by the wavelength λ_{50} where the transmission drops down to T=50%. The mean

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value amounts to $<\lambda_{50}>$ = 350.9nm with a variation $\Delta\lambda_{50}$<2nm along the crystal axis.

B. The Luminescence Yield

Exploiting the excellent single photo-electron response of hybrid photodiode tubes (HPD) the scintillation yield has been measured using a low energy γ-source (^{60}Co). The optically polished crystals are wrapped in PTFE-foil. The mean number of detected photo-electrons is determined to characterize the crystal quality. Figure 2 shows on a logarithmic scale the spectrum of the observed light-output for a high quality crystal. The number of photo-electrons (PE) can be counted directly.

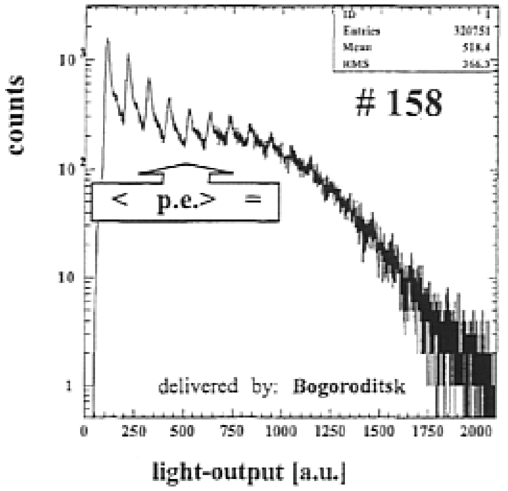

Figure 2: Response of a $PbWO_4$ crystal to a ^{60}Co γ-source measured with a HPD. The mean number of photo-electrons is indicated.

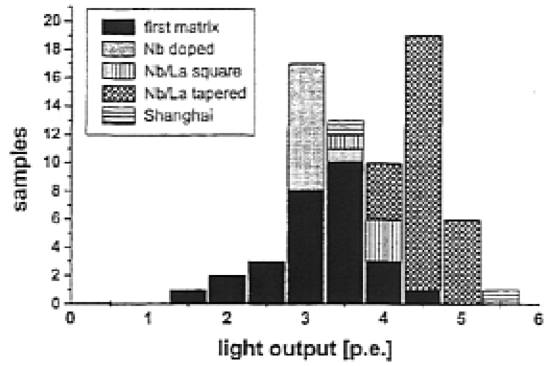

Figure 3: Distribution of the mean number of photo-electrons measured for ^{60}Co using a HPD. The quality of the present Nb/La-doped samples is compared to those from previous deliveries and two selected crystals provided by SICCAS.

The significant improvement in the scintillation performance of 150mm long crystals is illustrated in Figure 3 in a comparison to the measured light-output of samples used in previous experiments. The obtained mean light-output of the new generation crystals of ~4.6PE corresponds to an increase of 33% with respect to the value obtained before. In addition, the narrow distribution reflects the improved reproducibility in crystal production. By coupling sample #158 to a photomultiplier tube (Hamamatsu R2059-01), energy resolutions of σ/E=30% and σ/E=25% have been obtained for the photopeak of ^{137}Cs (E_γ=662keV) and ^{60}Co (E_γ~1.25MeV) γ-sources, respectively.

III. FIRST TB- AND MO-DOPED CRYSTALS

The technology to produce radiation hard, high quality Nb/La-doped crystals, optimized for high energy applications, has made significant progress as illustrated in Figure 3. However, the recent developments indicate that a maximum in light yield has been reached. Photon measurements with $PbWO_4$ at energies far below 100MeV would become only attractive and competitive with other much less compact scintillator materials if an even further enhancement of the luminescence yield could be achieved. Therefore, a new approach has been started by controlled doping.

Several large size $PbWO_4$ single crystals have been grown at the Bogoroditsk Techno-Chemical Plant doped with Mo, Mo + La and Tb, respectively. Small samples (volume ~5 to 8cm^3) of the ingots have been investigated with respect to optical and scintillation properties. First results can be shown.

A. The Measured Quality

The optical transmission curves of a Mo- and a Tb-doped crystal, respectively, are compared to the performance of a Nb/La-doped crystal, which fulfills the CMS/ECAL specifications, as a reference. Figure 4 shows the measured spectra normalized to equal crystal thickness.

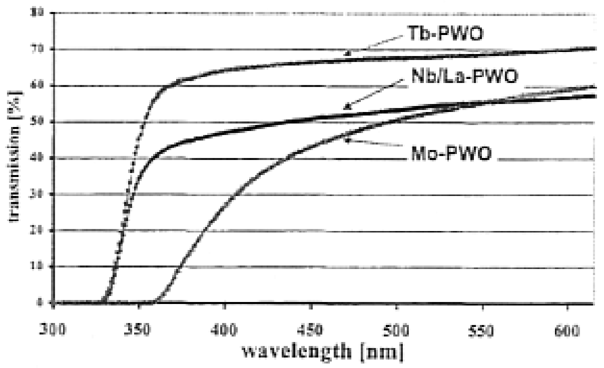

Figure 4: Optical transmission of two doped samples compared to a standard $PbWO_4$ crystal (Nb/La-doped) as a reference.

The scintillation properties have been tested by comparing the response to low energy γ-sources (^{137}Cs [662keV]). Figure 5 shows the obtained pulse height spectra (integration gate 2.5μs). A significant increase of light output and improvement in resolution due to photon statistics can be observed for the samples doped with Tb and Mo. An energy resolution of σ/E~20% can be even achieved for the latter crystal. In order to compare the primary light yields, a scaling factor of 1.8 has to be considered to correct for the reduced quantum efficiency of the photocathode at the Mo emission wavelength, which is shifted to λ~500nm compared to λ~420nm of standard crystals.

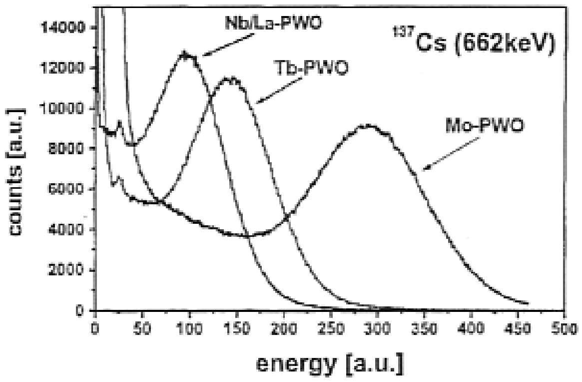

Figure 5: Response to low energy photons measured for Tb- and Mo-doped $PbWO_4$-samples in comparison to a crystal which fulfills CMC/ECAL specifications (Nb/La-PWO).

Figure 6 illustrates the difference in light output and decay time by comparing the measured position of the photopeak of the ^{137}Cs [662keV] source as a function of the width of the integration gate. Whereas almost the full light yield is collected within less than 500ns in case of the reference and the Tb-doped $PbWO_4$, the Mo-doped scintillator requires an integration over several microseconds. Therefore, future applications of PWO:Mo have to cope with limited count-rate capabilities to avoid pile-up, but for the advantage of a very compact scintillator with light yield hopefully sufficient for applications at low energies.

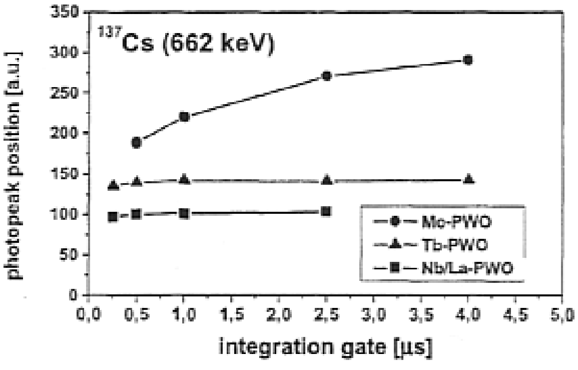

Figure 6: Measured position of the photopeak of the ^{137}Cs [662keV] source as a function of the integration width for the three samples used in Fig. 4.

IV. Response to High Energy Photons

According to the specification tests reported above a sufficient number of excellent crystals was available to set-up a new matrix of 5x5 detectors in order to repeat the measurement of the response to energy-marked photons between 66 and 790MeV energy at the tagging facility of MAMI, University of Mainz. The crystals, individually wrapped in PTFE-foil, are coupled with optical grease to fast photomultiplier tubes (Hamamatsu R3478, base: E2253-06, ∅=19mm – covers 35% of the crystal endface) and stacked into a light-tight box, which was temperature stabilized at t=5.5°C. The detector block can be moved by remote control to illuminate directly each crystal with the collimated photon beam (<10mm$^{\varnothing}$) for calibration purposes. A plastic scintillator in front of the crystal matrix serves as a charged particle veto. The detector signals are transfered via long coaxial cables (~50m RG58) to the data acquisition system to deduce energy and time information by means of commercial electronics.

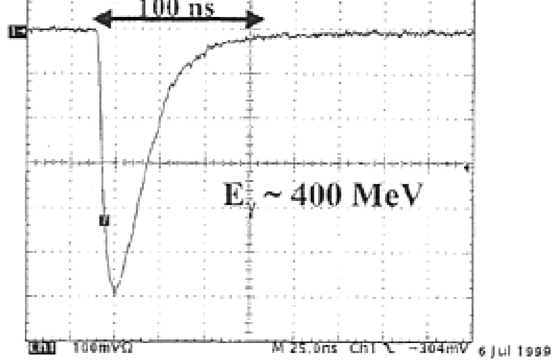

Figure 7: Lineshape of a Nb/La-doped single crystals induced by 400MeV photons measured with a digital scope (TDS 744).

As shown in Figure 7, the inspection of the lineshape by means of a digital scope indicates no significant slow scintillation components in agreement to measurements, provided by the supplier, that more than 96.5% of the total light output (1µs integration width) are emitted within the first 100ns.

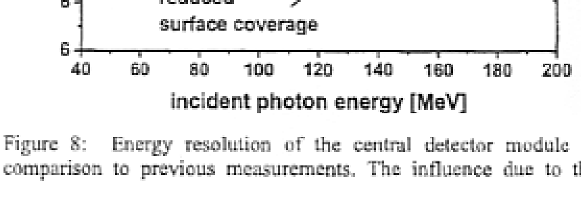

Figure 8: Energy resolution of the central detector module in comparison to previous measurements. The influence due to the

reduced coverage of the crystal endface by the photomultiplier is indicated.

Affected by the chosen photomultiplier/base combination an unexptected non-linear energy calibration had to be applied to correct for saturation effects, which has limited, in particular at the higher photon energies, the finally achieved resolution after the reconstruction of the electromagnetic shower deposited within the detector array. However, the response of the central detector below 200MeV incident photon energy documents the improved quality of a single crystal. The effect becomes more obvious if one applies a correction for the reduced surface coverage of the photmultiplier, due to the larger endface of the tapered crystals. The energy resolution of the central detector in comparison to previous measurements is shown in Figure 8. The shown experimental values are not corrected for the energy width of the incident photons given by the selected tagger channel, which varies between 1.2 and 2.5MeV, respectively, in the covered energy range.

V. CONCLUSIONS AND OUTLOOK

Based on the obtained optical and scintillation properties of the present generation of 150mm long Nb/La-doped crystals an optimum quality appears to be reached. In spite of the unexpected electronical read-out limitations, the improved performance can be confirmed in general by measurements with high energy photons.

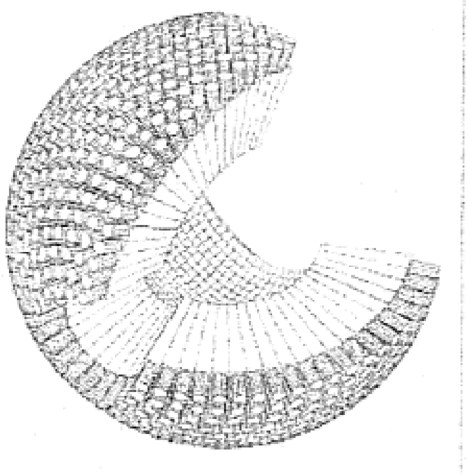

Figure 9: Schematic view of the proposed photon detector for ANKE at COSY (KFA Jülich).

In a new approach, controlled doping of $PbWO_4$ with Tb- or Mo-ions has delivered crystal samples with significantly enhanced light yield. The first results, in particular with Mo are very promising. The observed increase of the decay time might not in general impose a severe limiting factor on nuclear physics experiments at low and intermediate energies.

Initiated by the achieved performance so far, a first technical proposal for a detector system to be operated at intermediate energies is in preparation. A compact photon detector with nearly 4π-coverage in solid angle has been suggested as an upgrade of the charged particle magnetic spectrometer ANKE – Apparatus for studies of Nulceon and Kaon Ejectiles – at the synchrotron COSY (KFA Jülich, Germany).

The physics program, which is concentrating on charged meson production in nucleon-nucleon and nucleon-nucleus collisions, could be completed by the direct identification of neutral mesons emitted in coincidence based on an invariant mass analysis of the detected decay photons. Due to geometrical constraints (∅~60-70cm) a very compact spherical arrangement with high granularity (~1000 scintillator elements), sufficient time and energy resolution is needed. Due to the strong strayfield of the magnetic spectrometer a fast read-out in a magnetic field (<0.5T) has to be realized. Figure 9 gives a first impression of the envisaged geometry. At the moment, $PbWO_4$ appears to be the only material to fulfill all the essential experimental requirements.

VI. REFERENCES

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