Transparency variations and calibration in CMS electromagnetic calorimeter crystals: Monte-Carlo studies

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***Abstract*—The ageing of CMS electronic calorimeter scintillating crystals under radiation leads to a deterioration of their transparency, thus of their effective light yield and their calibration. The correlation between transparency variation, as measured by the fiber optic monitoring system, and the calibration variation depends on the optical properties of the scintillating material itself and of its environment. In previous studies, the possibility of light scattering within the bulk of the crystals was not taken into account.**

We present here the results of the simulation of this correlation for different types of CMS electronic calorimeter crystals using the program Litrani improved to allow light scattering in bulk. They show that scattering could explain the variation of correlation coefficients observed between within CMS/ECAL endcap and barrel crystals.

***Index Terms*—Calibration, electromagnetic calorimetry, Monte Carlo simulation, scintillation detectors.**

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I. INTRODUCTION

THE lead tungstate scintillating crystals of the CMS electromagnetic calorimeter (ECAL) will be exposed to an intense radiation throughout the accelerator operation, broken by quiet periods. The optical transmission of crystals, and consequently their light collection efficiency and calibration coefficients will fluctuate. In order to preserve the calibration precision of the instrument, both calibration with physical events, at a time scale of a few weeks, and continuous monitoring of the optical characteristics of the crystals, are required. This last technique is the purpose of the so-called laser monitoring system [1].

Previous papers [2,3,4] have shown that in general the correlation between variations of collection efficiencies for scintillation light (directly related to the calibration parameters) and monitoring light is dominated, for crystals of good optical quality, by the quality of light containment in crystals, that is by the properties of their surfaces and coating. The properties of the read-out device: surface, optical coupling, quantum efficiency versus wavelength…, are also important.

In CMS/ECAL, the situation is complicated by the fact that numerous cases are encountered: different crystal shapes, crystal origin, read-out devices etc.

In ECAL barrel, the crystals have 17 different truncated pyramidal shapes. One of their lateral faces is slightly depolished to correct for the non uniformity of the light collection induced by the pyramidal shape. They are placed in alveolas covered by a diffusive white coating, and read by two avalanche photodiodes (APDs) of surface $5 \times 5\ \mathrm{mm}^2$ each, glued on the rear (outer) face of the crystal. The monitoring light is injected by an optical fiber through the front (inner) face. All crystals have all been grown in Russia by the Bogoroditsk Techno Chemical Plant (BTCP).

In the ECAL endcaps, all the crystal have the same shape, 22 cm long by $3 \times 3\ \mathrm{cm}^2$, with all faces polished. They are read by vacuum phototriodes (VPTs), diameter 26.5 mm glued on the rear face, but during the research and development phase, some of them have been read by APD’s.. The monitoring light is injected by the same face. Part of the encap crystal has been grown in China by the Shanghai Institute of Ceramics (SIC), the remaining are from BTCP.

If one defines:

— R_0: signal of crystal under laser monitoring, before any radiation damage;
— R: signal of crystal under laser monitoring, after radiation damage;
— S_0: signal of crystal under electromagnetic shower, before any radiation damage; and
— S: signal of crystal under electromagnetic shower, after radiation damage;

it has been shown [5] that to a good approximation, one has:

$$\frac{S}{S_0} = \left(\frac{R}{R_0}\right)^{\alpha} \tag{1}$$

The correlation coefficient α is at least for small variation constant for a given crystal in a given optical environment.

Measurements of this coefficient have been done with sometimes puzzling results: Variations of α observed for crystals of the same shape and optical environment seem to indicate that internal parameters not taken into account up to now could play also an important role. In particular, the occurrence of light scattering in the bulk of the material has been proposed to explain some of the measurements.

We report here new simulation results obtained with Litrani [6], program of simulation of optical photons, in which the possibility of light scattering into materials has been added for the first time.

II. MEASUREMENTS

To our knowledge, no summary paper exists on the measurements of the α parameter done in CMS/ECAL. The content of this section is the result of a compilation from notes and presentations posted on CMS/ECAL web site, probably not complete. Please refer to the references quoted for more information on the way these measurements were taken. The mean values and standard déviations indicated herafter after computed from the data indicated in the references, weigthed by data errors when available.

A. Barrel BTCP crystals with APDs

20 BTCP crystals of the barrel have been measured in a dedicated test beam during summer 2002 [7]. The result was: $\alpha = 1.532 \pm 0.021$ (20 crystals).

B. Barrel SIC crystals with APDs

No measurements exist for these crystals.

C. Endcap BTCP crystals with APDs

Two sets of measurement on SC04 exist, coming from the H4 test beam of 2004. The first measurements [8] give: $\alpha = 1.25 \pm 0.11$ (4 crystals), and the second [9]: $\alpha = 1.21 \pm 0.07$ (5 crystals).

D. Endcap BTCP crystals with VPTs

Two sets of measurements on SC03 exist, coming from the H4 test beams of 2004 [10]: $\alpha = 1.565 \pm 0.021$ (2 crystals). and 2007 [11]: $\alpha = 1.525 \pm 0.305$ (29 crystals)

E. Endcap SIC crystals with APDs

Ten measurements exist, coming from the H4 2004 test beam [9]: $\alpha = 0.79 \pm 0.08$ (10 crystals).

F. Endcap SIC crystals with VPTs

Two sets of measurements on SC03 exist, coming from the H4 test beams of 2004 [10]: $\alpha = 0.986 \pm 0.065$ (9 crystals), and 2007 [11]: $\alpha = 1.07 \pm 0.32$ (12 crystals)

G. Comments

At few exceptions, barrel crystals, all grown at the same place, present a correlation coefficient a with little variation around 1.53, despite of the differences in geometrical shape. At the contrary, endcap crystals, identical in shape but of different origin and read-out, show large variations. It is understandable that VPT's and APD's read-out lead to different α parameters, the surface covered by photodetectors and their refractive indexes and quantum efficiencies being different, but the dispersion of parameters and the differences of their mean between Russian and Chinese crystals could only be due to variations in the optical properties of the crystals themselves. Among the possible causes of α variation, the presence of light scattering centers in the crystal bulk has often been supposed.

III. SIMULATIONS

A. Generalities

1) Modelisation

The characteristics of the generation are the following:

— The geometry is simulated exactly, without any approximation: shape of crystals, of APDs or of VPTs.

— The characteristics of all wrappings or alveola used are also simulated very precisely using measurements done: presence or not of a slice of air, proportion of scattering versus reflection, albedo. In particular, for the endcaps the alveola is described as a totally black wrapping, but with a slice of air, so that total reflection remains possible, whereas for the barrel the alveola is described as partly reflective and diffusive.

— The characteristics of the glue were also simulated exactly using data from the producer.

— Precise description of the characteristics of the APDs including the description of the optical thin slice of the front window.

— Precise description of the characteristics of the VPTs: quantum efficiency versus wavelength of photon, index of reflection versus wavelength of entrance window, and so on.

— The light injection was modelled precisely: there is a gap of air between fibre and crystal and the angular distribution of light from the fibre is the one measured at Saclay.

— Formula (1) implying a logarithmic dependence, it is necessary to generate a very high number of photons in order to get statistically significant results (some 45 10^9 photons for the second simulation quoted in this paper). In order to speed up the calculations (by a factor of about 4), $PbWO_4$ is treated as isotropic, not birefringent.

2) Absorption data

The absorption length of the $PbWO_4$ crystal is simulated exactly, with a wavelength dependence corresponding to the measurement done on a real crystal, n° 8981 in CMS data base, which is a BTCP crystal. The variation of this absorption length with irradiation has also been simulated exactly, using measurements done under 6 various irradiations for this crystal. The crystal has been irradiated by ^{60}Co gamma rays in the installation Cocase [12] up to the equivalent of 514 Gy in air. The crystal was placed transversally to the direction of the source. The parameters of irradiation are reported in table I. At each step the longitudinal optical absorption of the crystal was measured using the apparatus and method previously described in [13], and the attenuation coefficient calculated after correction the surface refraction using the optical indices given in [14]. Fig. 1 shows the values of the mean absorption coefficient versus wavelength of this crystal, before irradiation and after two last steps of irradiation.

TABLE I
PARAMETERS OF THE IRRADIATION OF CRYSTAL CMS 8981

step	duration	dose rate (Gy/h)	cumulated dose (Gy)
1	30h 40mn	0.092	6.8
2	117h 41mn	0.143	44.0
3	146h 25mn	0.25	90.7
4	45h 31mn	1.0	137
5	184h 43mn	2.0	514

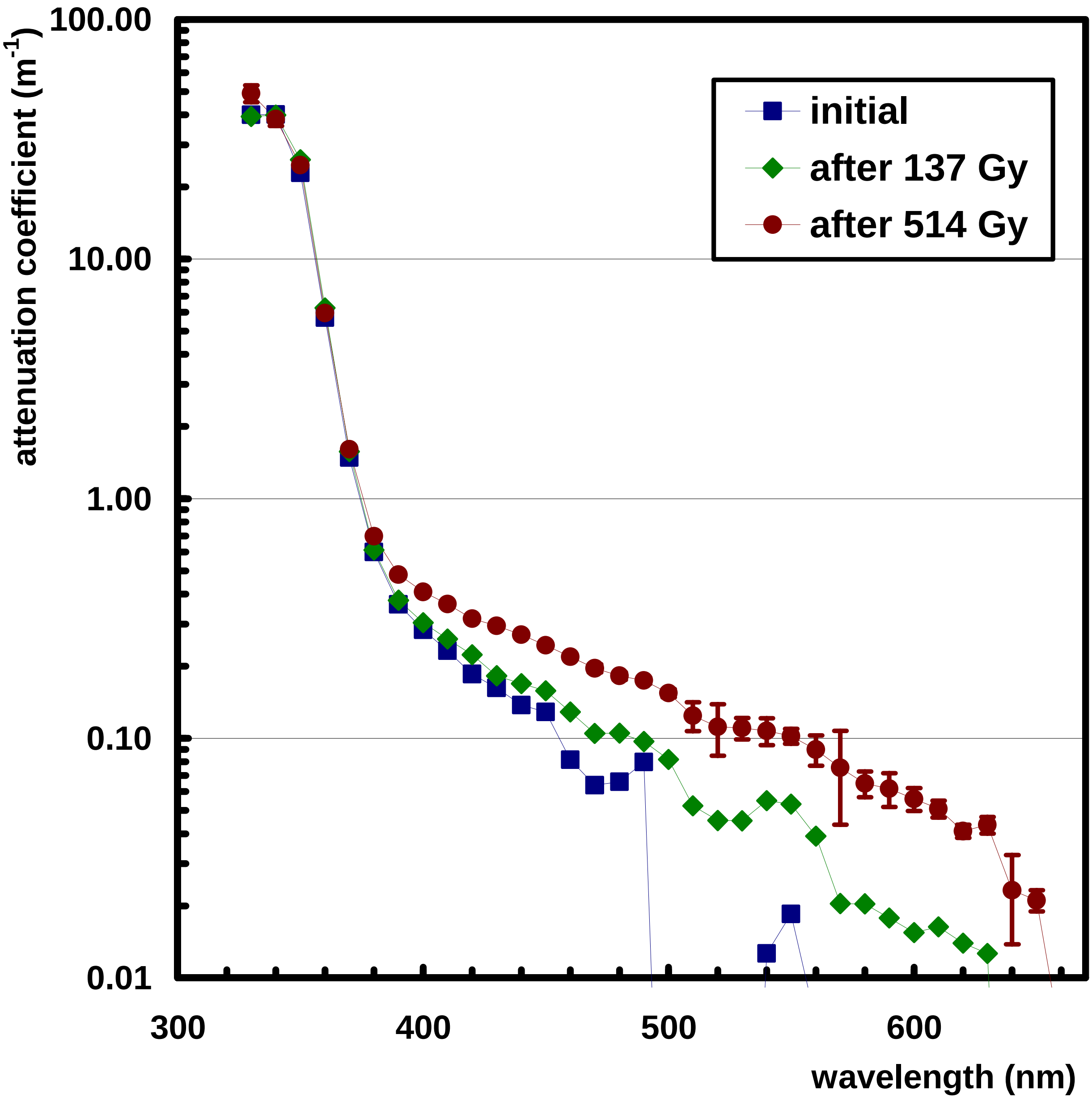

Fig. 1. Attenuation coefficient versus wavelength for crystal 8981 before irradiation and after the two last steps of irradiation.

3) *Simulations*

Using these seven sets of data, 14 runs of simulation, for each value of scattering length, were done: 7 runs for laser pulses (“laser”), and 7 runs for 120 GeV electromagnetic showers (“beam”). To simulate electromagnetic showers, Litrani uses the simplified formulae proposed in the “Review of Particle physics” [15]. More details are available in [16]. α is then determined by the slope of the linear fit of normalised data “beam” versus “laser”.

4) *Scattering length*

In the second simulation described in this paper, it has been considered that a scattering length could play a role in the measured results. The possibility of the presence of optical scattering in addition to absorption has been added in Litrani, by the introduction of a scattering length defined as the mean distance after which a photon is stopped and reemitted with the same wavelength in any direction, chosen isotropically on 4π. In this first stage, no dependence of scattering length upon wavelength of photon was introduced.

B. Dependency of α on the shape of the barrel crystals

This first simulation with Litrani was done in 2003/2004 to study the eventual effect of the 17 different shapes of the barrel crystals on the α parameter. In this study no scattering length was added in the simulation. Data were fitted to the formula (1) for the 17 different shapes.

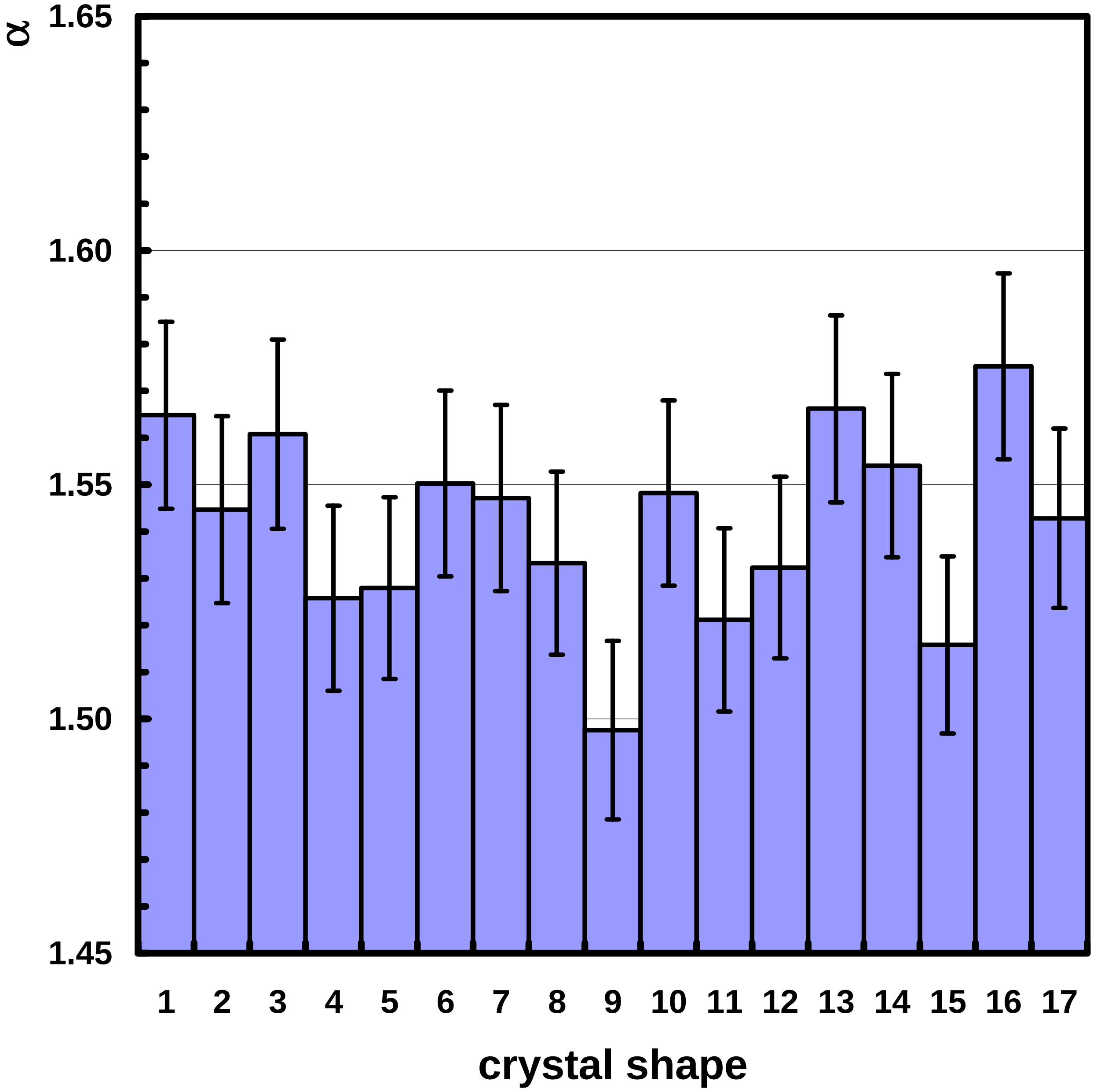

Fig. 2. Correlation coefficient α simulated by Litrani as function of the shape of CMS/ECAL barrel crystals.

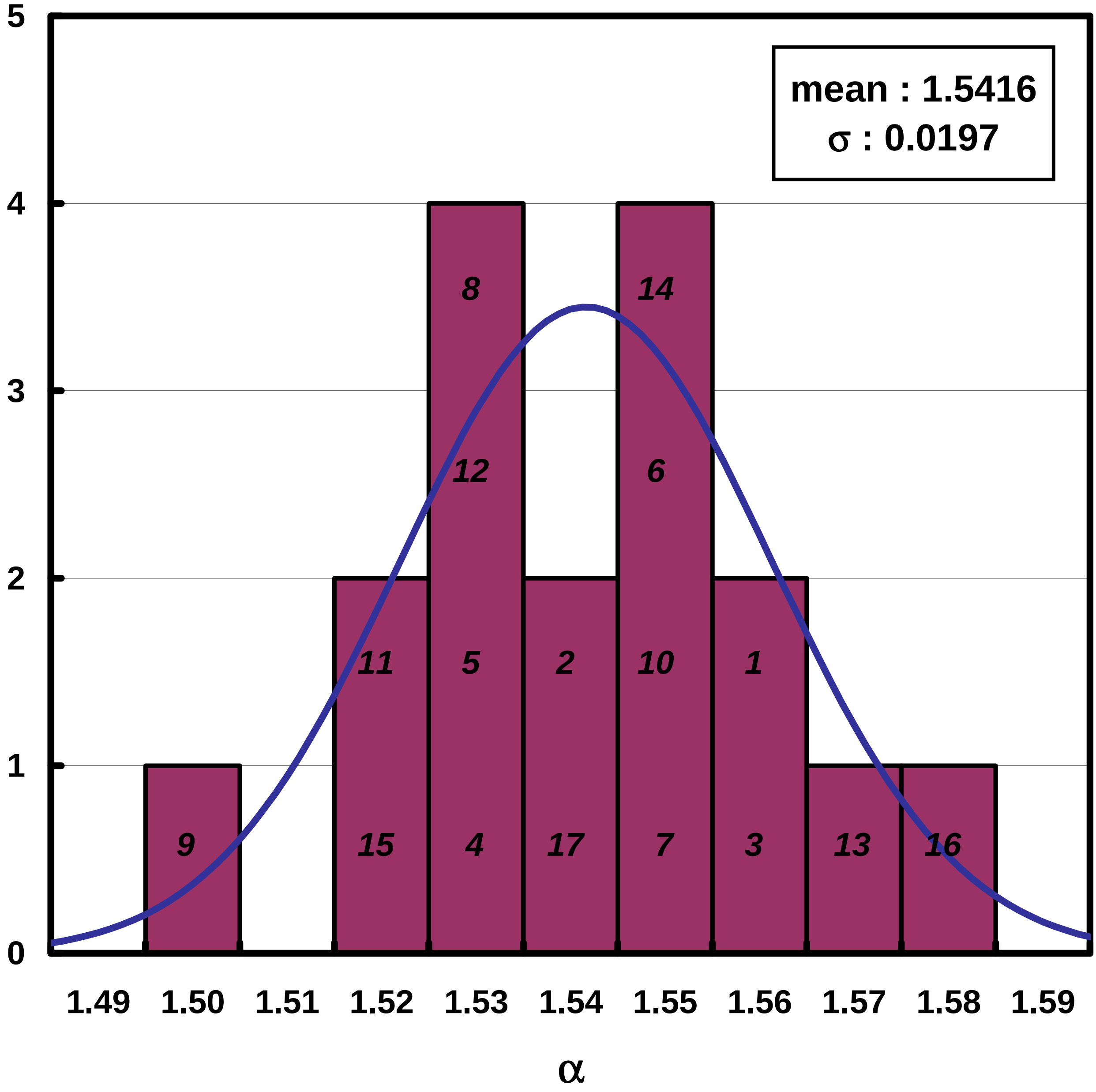

Fig. 3. Distribution of the α parameter simulated by Litrani for CMS/ECAL barrel crystals (the numbers shown in the histogram are those of the crystal shapes).

The calculated correlation coefficients and their distribution are shown in Fig. 2 and 3. The mean value of the α parameter is 1.542 ± 0.020, to be compared to the measurements quoted in II.A. Within statistical errors, no obvious variation with the crystal shape is observed.

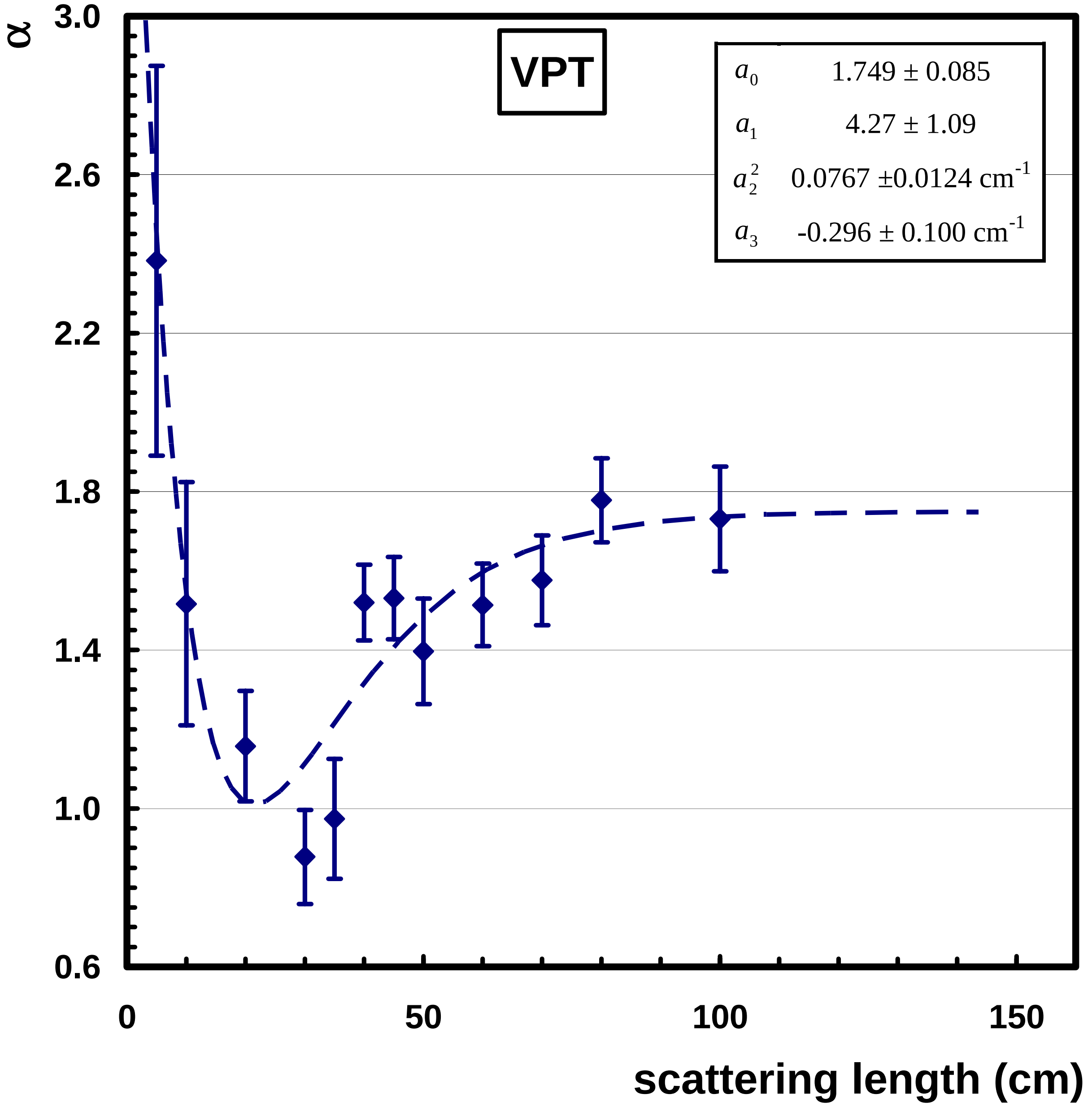

Fig. 4. α parameters calculated with Litrani for an endcap crystal with VPTs read-out in function of the light scattering length in crystal, and fit (see text).

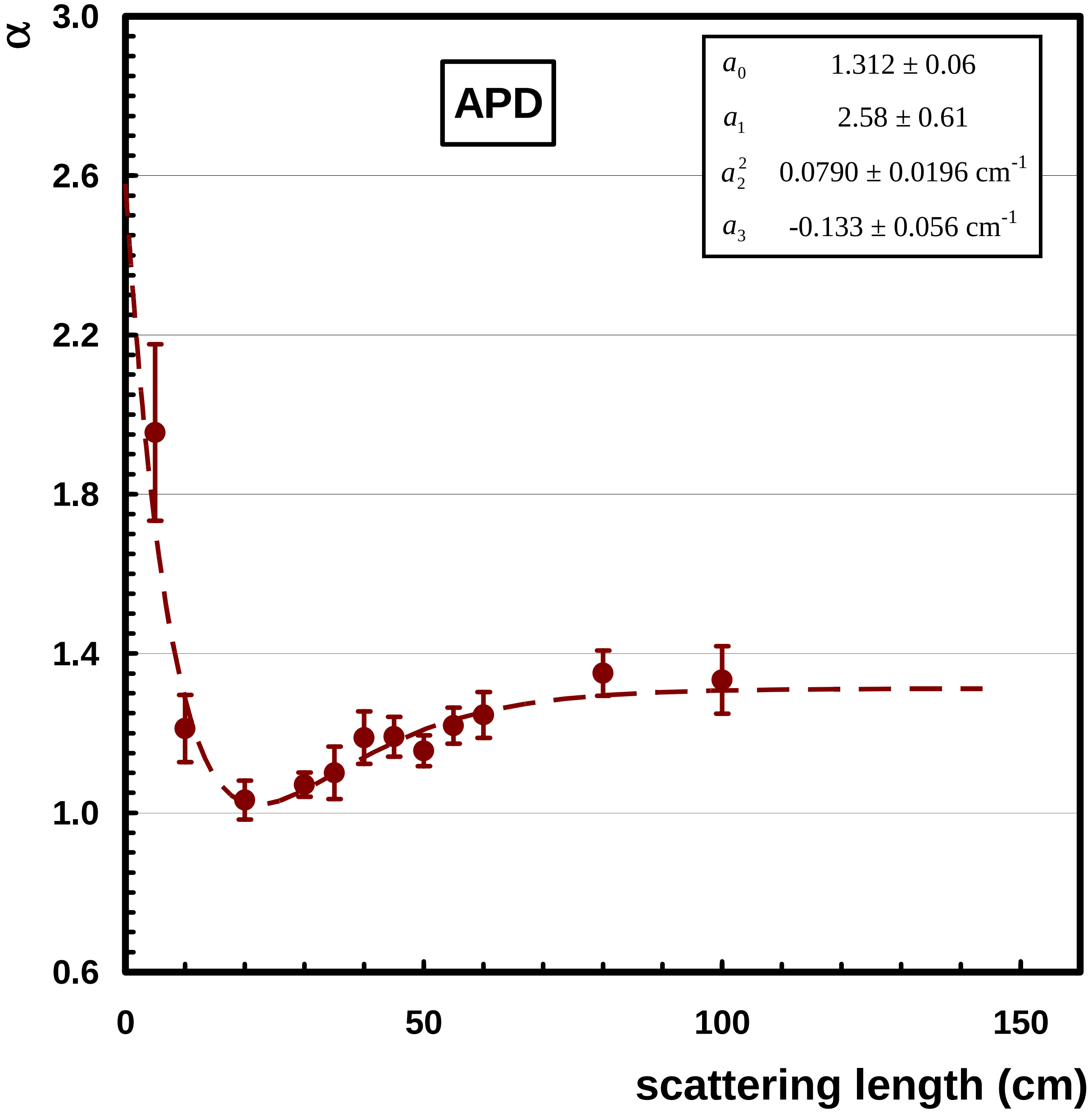

Fig. 5. α parameters calculated with Litrani for an endcap crystal with APDs read-out in function of the light scattering length in crystal, and fit (see text).

C. α parameter for the endcap crystals, influence of read out and light scattering

Fig. 4 and 5 show the variation of α versus scattering length, as explained in III.A.4, for resp. VPT's and APD's read-out.

To allow more quantitative analysis, the data have been fitted to a function of the form:

$$\alpha(l_{scat}) = a_0 + \left(a_1 - a_0 + \frac{a_3}{l_{scat}} \right) \exp\left(\frac{-a_2^2}{l_{scat}} \right) \tag{2}$$

where the fitted parameters a_0, a_1, a_2 and a_3 are:

a_0 asymptotic value of α without light scattering;

a_1 asymptotic value of α for large light scattering;

$-a_2^2$ factor of l_{scat}^{-1} in exponential;

a_3 factor of l_{scat}^{-1} in polynomial.

The values of the fitted parameter are reported in table II.

The increase of α for small scattering length (fit parameter a_1) is due to the geometry of monitoring in endcap crystals, for which light is injected through the same face as the photodetector. Thus, for long scattering length, the monitoring light travel through twice the crystal length, whereas for strong scattering it is shortly retro diffused toward the photodetectors.

TABLE II

VALUES AND ERRORS OF THE PARAMETERS OF THE FIT OF $\alpha(l_{scat})$° BY THE FUNCTION $\alpha(x) = a_0 + (a_1 - a_0 + a_3 x)\exp(-a_2^2 x)$

	VPT		APD	
parameter	value	error	value	error
a_0	1.749	0.085	1.312	0.060
a_1	4.27	1.09	2.58	0.61
a_2^2 (cm^{-1})	0.0767	0.0124	0.0790	0.0196
a_3 (cm^{-1})	-0.296	0.0997	-0.133	0.0558

Litrani reproduces correctly the increase of the α parameters when switching from APDs to VPTs read-out for Russian endcap crystals for which simulations are in good agreement with experimental data. Without light scattering: we calculate $\alpha = 1.749 \pm 0.085$ for VPTs read-out and 1.312 ± 0.060 for APD's, to be compared with resp. 1.525 ± 0.305 and 1.28 ± 0.03 (cf II.C and II.D). The best agreement is found for a scattering length of about 60 cm (more exactly 55 cm for APDs and 61 cm for VPTs, statistically compatible).

A strong light scattering (about 20 to 30 cm for l_{scat}) lowers α values down to approximatively 1. However, even lower α values are measured in SIC crystals in which $\alpha \approx 0.8$ for VPT's and ≈ 1.0 for APD's (cf II.E and II.F).

However one should first note that the present simulation have been done using spectral, transparency and irradiation data measured on a BTCP crystal, and it is known that crystals of the two origins do not have exactly the same properties.

Secondly the approximations taken for the light scattering model: no wavelength dependance, isotropic re-emission of photons…, are certainly too crude to represent in detail the real behaviour of photons in crystals. Thus these simulations are only an indication that ligth scattering, as suggested many times, can explain the low values of α observed in Chinese crystals. The lack of experimental data on the light scattering forgive us for the moment to give more precise and quantitative predictions. It would be extremely interesting to measure the proportion of scattering versus absorption for BTCP and SIC crystals, using for example the new "Monte-Carlo refractive index matching technique" method proposed by David Wahl [17].

CONCLUSION

It is shown here that the correlation between scintillation light and laser monitoring light signals variations,or in other worlds, the correction parameter of the calibration coefficients, the so-called α or S/R parameter, is well reproduced by our simulation with the program Litrani for CMS/ECAL barrel crystals. The influence of the crystal's shape remains below the statistical and experimentals dispersions.

For endcap crystals, Litrani, completed by the introduction of a crude model of light scattering in material bulk, simulation agreed less precisely with measurements, but suggests strongly that ligth scattering within chinese crystal could be at least part of the reason for the low values of the measured correlation coefficients and for their dispersion. More experimental data, on optical and irradiation parameters of these cristals would be necessary to conclude more quantitavely.

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