РОССИЙСКАЯ АКАДЕМИЯ НАУК

Физический институт имени П.Н.Лебедева

ФИАН

E.G.DEVITSIN, V.A.KOZLOV, V.A.NEFEDOV, A.R.TERKULOV, B.I.ZADNEPROVSKI

PREPRINT

28

COLORLESS $NaBi(WO_4)_2$:In CHERENKOV CRYSTALS FOR ELECTROMAGNETIC CALORIMETRY

MOSCOW 2003

Colorless $NaBi(WO_4)_2$:In Cherenkov Crystals for Electromagnetic Calorimetry

V.A. Nefedov, B.I. Zadneprovski
All-Russia Research Institute of Synthesis of Mineral Raw Materials
Institutskaya st. 1, Alexandrov, Vladimir region, 601600 Russia

E.G. Devitsin, V.A. Kozlov, A.R. Terkulov.
Lebedev Physical Institute, Russian Academy of Sciences,
Leninskii prosp. 53, Moscow, 119991 Russia

Abstract

Colorless Cherenkov $NaBi(WO_4)_2$:In crystals have been developed. A reduction in the concentration of NBW yellow color centers provides a shift of the crystal optical transparency towards shorter wavelengths by about 50 nm in the UV range. Almost no deterioration in transmission properties of colorless NBW crystals was observed after irradiation with the dose of $3{\cdot}10^7$ rad.

The results of MC calculations for the energy resolution of electromagnetic calorimeters based on different NBW crystals are presented.

Аннотация

В данной работе были разработаны и исследованы бесцветные черенковские кристаллы $NaBi(WO_4)_2$:In. Уменьшение концентрации центров окраски обеспечивает смещение спектра оптического пропускания в кристаллах NBW на 50 нм в область коротких длин волн. При облучении этих кристаллов γ-квантами дозой $3{\cdot}10^7$ рад спектры оптического пропускания кристаллов остались практически прежними.

В работе так же обсуждается полученное с помощью вычислений методом Монте Карло энергетическое разрешение калориметров, изготовленных из кристаллов NBW различного состава.

Introduction

$NaBi(WO_4)_2$ single crystals previously known due to their acoustic, optical and laser properties were proposed in 1991 for a use in electromagnetic calorimetry [1,2]. The basic properties of NBW Cherenkov crystals are listed in Table 1.

Table 1

Property	**$NaBi(WO_4)_2$**
Growing method	Czochralski
Density, (g/cm^3)	7.57
Hardness, Moos	4.9
Index of refraction, n; (λ=450 nm)	2.31
Radiation length, X_0, (cm)	1.03
Moliere radius, R_m, (cm)	2.38
Critical energy, E_c, (MeV)	9.75
Optical transparency, nm	>380
Melting point, ^oC	920
Hygroscopic	no

For the first time, transparent light yellow color large-size NBW crystals were grown in All-Russia Research Institute of Synthesis of Mineral Raw Materials (Alexandrov) in 1990. The crystals were grown in ambient air by Czochralski method in platinum crucibles from the $Na_2O:Bi_2O_3:4WO_3$ charge mixture at the melting temperature of 940--980 ^oC. The crystal stretching and rotating rates were 4--5 mm/h and 30--32 min^{-1}, respectively.

The development of large-scale NBW crystal production gave rise to studies of NBW optical properties and radiation hardness [1,3,4]. According to [1], radiation damage of NBW crystals was negligible for the irradiation dose of 10^7 rad, which opened the way to use these crystals in hard radiation e-γ environment with annual rates of 10^7 rad and higher.

First beam tests of a calorimeter prototype based on NBW crystals were performed at the DESY electron beam in 1993. The goal was to study a possible use of the crystals in the HERMES (DESY, Hamburg) luminosity monitor [5].

Starting from 1995, NBW crystals are successfully used at the HERMES luminosity detector. Later on, the crystals began to employ at the HERMES longitudinal polarimeter, as well as for electron tagging with the H1 (DESY, Hamburg) luminosity detector.

The HERMES luminosity monitor and HERMES longitudinal polarimeter are working in radiation hard environment at a distance of several millimeters from the primary beam. Although NBW crystals are exploited in a stationary radiation environment, a possibility of excess radiation doses exists because of a sudden loss of electron beam along with a background from collimators in the case of poor beam tuning.

Besides that, recently in view of development of new generation of accelerators, a need occurred in radiation hard Cherenkov radiators capable of working close to a beam pipe. All arguments listed above induced a progress in NBW radiation hardness improvement.

Another disadvantage of NBW crystals is a low light yield of Cherenkov photons (about 30% of the total light yield). Because of the crystal's high refraction index (n = 2.31 at λ = 450 nm), a significant number of the photons undergo the internal reflection and remain inside the crystal. In addition, NBW crystals are transparent only at wavelengths above 380 nm and, therefore, turn out insufficiently transparent for Cherenkov light.

The energy resolution of NBW-based electromagnetic calorimeters, which was measured at the DESY test beam, is about $9\%/\sqrt{E}$ [6]. Further improvement of the NBW-based calorimeter energy resolution is apparently associated with more transparent optical crystals. The number of Cherenkov photons leaving an NBW crystal can be increased by expanding the crystal's optical transmission region toward the UV range, where the intensity of Cherenkov radiation sharply rises.

The improvement of optical properties and radiation hardness of NBW crystals was attained in the framework of a special program. Effects of doping with various raw materials, of changes in the crystal stoichiometry, and of different additives on the crystal's performance were studied.

Analysis of data obtained previously in [7,8] showed that the shift of absorption spectra toward longer wavelengths, the existence of yellow color centers, and radiation hardness of NBW crystals are correlated with the intensity of the absorption band around 350—420 nm. It was shown that this absorption band is associated with tungsten vacancies and bismuth cations located at sodium sites.

Apparently, the presence of such defects leads to the formation of deep bands of acceptor and donor levels in the forbidden zone. Transitions between these levels and conduction or valence bands determine the observed shift of the crystal absorption spectra towards the long-wave region. Doping the crystals with certain additives, i.e., with scandium, as well as surplus of tungsten in the process of crystal growth allowed us to partly compensate the effect of these defects and to improve the crystal transmission in the near UV region together with increasing the radiation hardness of the crystals [7,8].

As a result of the tests using a number of various dopants, it was established that Indium was the most efficient among them. Ignoring details of physico-chemical nature of the effect under study, we note that this effect can be associated with the occupation of low-energy levels in the conduction band. In this case, the self-absorption because of transitions onto these levels is impossible, which causes a shift of the absorption spectra toward higher energies, and, correspondingly, the attenuation or disappearance of the band around 350—420 nm.

Doping crystals with indium was performed in the form of In_2O_3 introduced into the melt. The concentration of In_2O_3 was varied in the range 0.1—2% (by mass). The visible effect of doping was expressed as attenuation right up to disappearing the crystal yellow color. In crystal transmission spectra, doping with indium was accompanied by a shift of the absorption toward the UV range by about 50 nm (see Fig. 1). No other additional absorption bands were observed.

The radiation hardness of NBW(pure) and NBW(In) samples was studied with a radioactive ^{60}Co source at the dose rate of 200 rad/s. Each NBW sample was irradiated with the dose of $3 \cdot 10^7$ rad. Optical transmission spectra before and after the irradiation for NBW(pure) and NBW(In) crystals are shown in Fig. 2

It is evident, that irradiated NBW(In) crystals have almost no reduction in the transmission spectrum.

Simulation of energy resolution of NBW crystal matrix

Monte Carlo simulation of the energy resolution for a matrix composed of NBW crystals was performed using LITRANI code recently developed by F. Gentit (CMS collaboration) [9]. The motivation of the LITRANI code was to simulate the emission collection and detection of light in experimental facilities widely used in high-energy physics experiments.

3×3 crystal matrix, with $22\times22\times200$ mm^3 NBW crystals was used in the simulation. The crystals were wrapped with aluminized mylar. Optical grease having the reflection index n = 1.45 was used for optical coupling PMTs with the crystals.

The Hamamatsu R4125Q PMTs having quartz window 15 mm in diameter were used as photodetectors. The spectral sensitivity of their bialkaline photocatodes lies within the wavelength range from 160 to 650 nm and has a maximum yield of 90 mA/W at 420 nm. The quantum efficiency of the R4125Q PMT is shown in Fig. 3

The light attenuation length, calculated according to the formula [10]

$$L_{\mathrm{att}} = \frac{l}{\ln[T(1-T_S)^2/(\sqrt{4T_S^4 + T^2(1-T_S^2)^2} - 2T_S^2)]}, \quad (1)$$

was used in simulations, where l is the crystal length, T is the measured longitudinal transmittance, and T_s is the ideal transmittance limited only by light losses at two end surfaces of the crystal, and

$$T_S = \frac{1-R}{1+R}, \quad (2)$$

with

$$R = \frac{(n - n_{\mathrm{air}})^2}{(n + n_{\mathrm{air}})^2}. \quad (3)$$

Here, n and n_{air} are wavelength-dependent refraction indexes of NBW and air, respectively.

Fig. 4 shows n_{NBW} as a function of the wavelength. The data were obtained by interpolation of the results of [11,12].

The dependencies of light attenuation length L_{att} on the wavelength for NBW(pure) and NBW(In) are presented in Fig. 5. This figure shows the induced attenuation length (L'_{att}) for NBW(pure) crystals irradiated by the dose of $3 \cdot 10^7$ rad.

An NBW crystal placed in the center of 3×3 matrix was exposed to electrons of different energies (2, 5, 10, 15, and 20 GeV). Photons and electrons of electromagnetic showers having energies lower than 10 keV were ignored in the calculations.

For the available statistics of the electron-beam particles, the distribution of a number of photoelectrons was obtained. This distribution has a Gaussian shape and is characterized by the parameters σ and E. The energy resolution of the crystal matrix was determined as $\sigma(E)/E$. The calculated values of the energy resolution were fitted by the formula:

$$\frac{\sigma(E)}{E} = \frac{b}{\sqrt{E}} \oplus c, \quad (4)$$

where $\oplus$ implies quadratic summation.

Initially, the energy resolution for NBW(pure) crystals, which is presently used in the HERMES experiment was calculated (see Fig. 6). The results of the fit are the following:

$$\frac{\sigma(E)}{E} = \frac{(9.6 \pm 0.4)\%}{\sqrt{E(\mathrm{GeV})}} \oplus (1.4 \pm 0.3)\%.$$

It should be reminded, that first experimental studies of 3×3 matrix of NBW(pure) crystals have been carried out at the DESY electron beam in 1995 [5,6]. The following result was obtained:

$$\frac{\sigma(E)}{E} = \frac{(4.3 \pm 0.8)\%}{E(\mathrm{GeV})} \oplus \frac{(9.3 \pm 0.4)\%}{\sqrt{E(\mathrm{GeV})}} \oplus (0.3 \pm 1.4)\%.$$

We note that experimental results are in good agreement with Monte Carlo calculations.

We also interested in deterioration of the energy resolution of an electromagnetic calorimeter based on NBW(pure) crystals after the irradiation by a dose comparable to radiation environment near the beam pipe.

The calculations of $\sigma(E)/E$ for NBW matrix irradiated with the dose of $3 \cdot 10^7$ rad are shown in Fig. 6. Table 2 presents the fitted parameters for NBW(pure) matrix before and after the irradiation.

Table 2

Parameter	Before irradiation	After irradiation
b, %	9.6±0.4	12.0±0.5
c, %	1.4±0.3	1.5±0.4

Thus, the decrease in transmission of NBW(pure) crystal for about 7-8% after irradiation leads to deterioration of the energy resolution of the matrix by about 25%.

The calculated dependence of the energy resolution for 3×3 matrix assembled of colorless NBW(In) crystals is shown in same Fig. 6. The fitted parameters are: b=(7.6±0.4)%, and c=(1.0±0.2)%.

Conclusions

New colorless Cherenkov $NaBi(WO_4)_2$(In) crystals were developed and studied. Introducing indium ions made it possible a shift of the crystal's optical transmission spectrum towards shorter wavelengths for about 50 nm compared to NBW(pure) crystal. This shift increased the yield of Cherenkov photons in the crystal, and, therefore, improved the energy resolution of an electromagnetic calorimeter based on NBW(In) crystals. The stochastic terms *b* are 7.6% and 9.6% for NBW(In) and NBW(pure) based calorimeters, respectively.

The radiation hardness of new $NaBi(WO_4)_2$(In) crystals was significantly improved. No radiation damage of the crystal was observed at the irradiation dose of $3{\cdot}10^7$ rad.

We note that these results were obtained by the choice of an adequate dopant on the basis of commonly used initial raw materials. Such an approach aimed at the improvement of crystal property seems to be very promising.

References

1. G.I. Britvich, et al., Preprint IHEP 91-134(1991), Protvino, Russia; Nucl. Instr. and Meth. A321(1992)64.
2. V.A. Nefedov, et al., “Cherenkov detector”, 1991, USSR Patent №1817932 (in Russian).
3. V.G. Baryshevsky, et al., Nucl. Instr. and Meth. A322(1992)231.
4. V. Samsonov, Proc. of the Workshop “Crystal 2000”, Chamonix, France, (1993)383.
5. K. Ackerstaff, et al., “HERMES Spectrometer”, Nucl. Instr. and Meth., A417(1998)230.
6. T. Benisch, et al., Nucl. Instr. and Meth., A471(2001)314.
7. V.A. Nefedov, et al., Radiation measurements 33(2001)597.
8. B.I. Zadneprovski, et al., Nucl. Instr. and Meth., A486(2002)355.
9. F.X. Gentit, CMS Note 2001/044.
10. D.A. Ma and R.Y. Zhu, Nucl. Instr. and Meth., A333(1993)422.
11. V.A. Nefedov, et al., Proc. Intern. Workshop on Tungstate Crystals, Universita La Sapienza, Roma (1999)83.
12. A.A. Kaminskii, et al., Phys. Stat. Sol.(A), 144(1989)713.

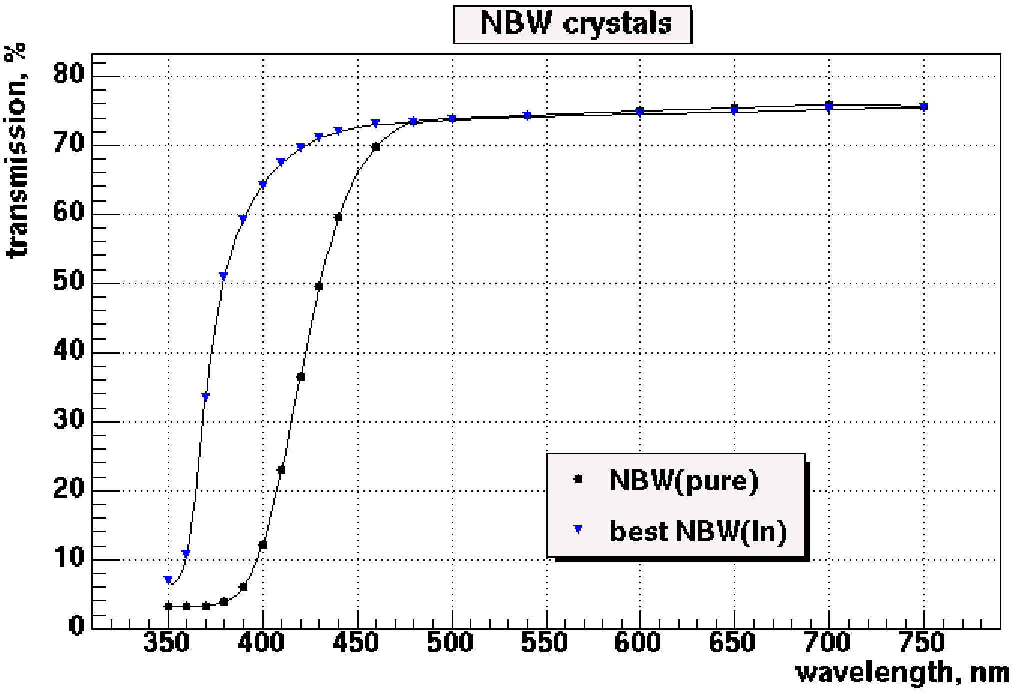

Fig. 1 *Optical transmission of different NBW crystals before irradiation*

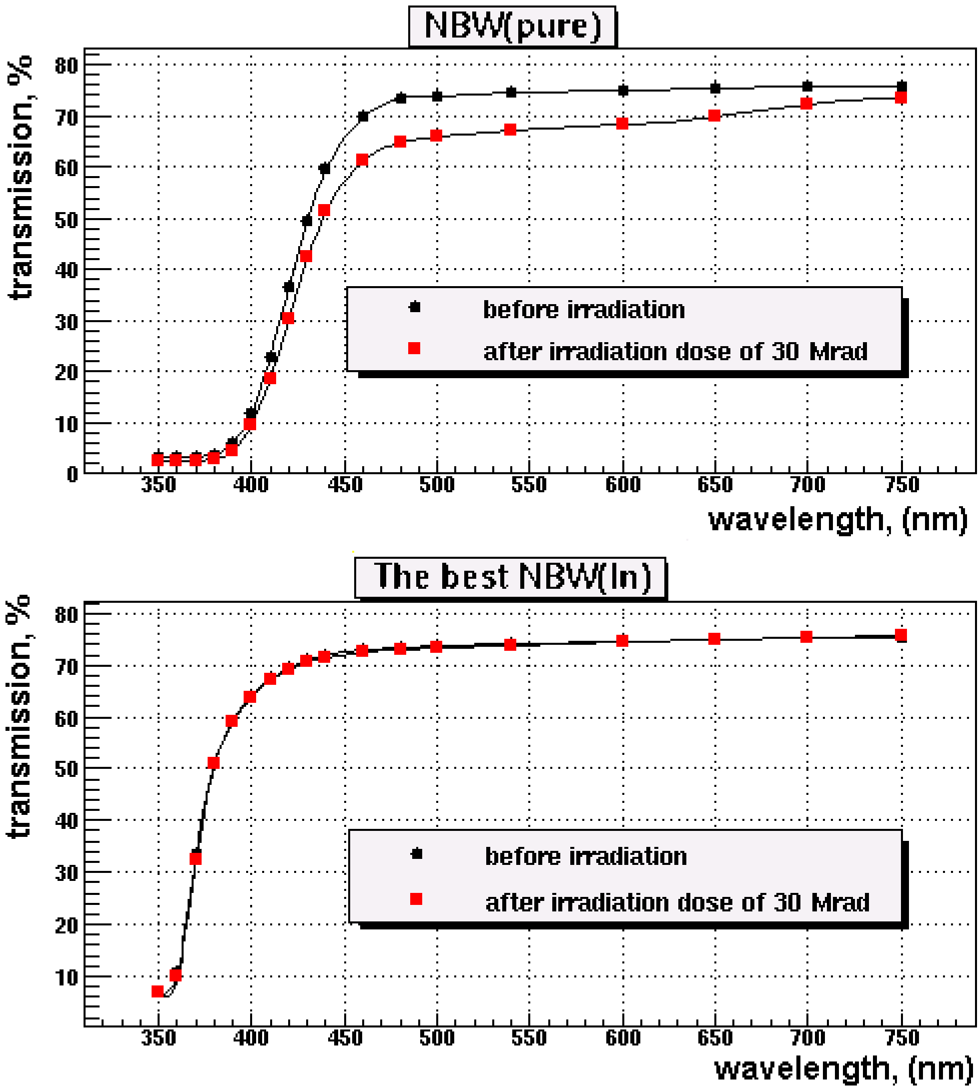

Fig. 2 *Optical transmission of NBW crystals before and after irradiation*

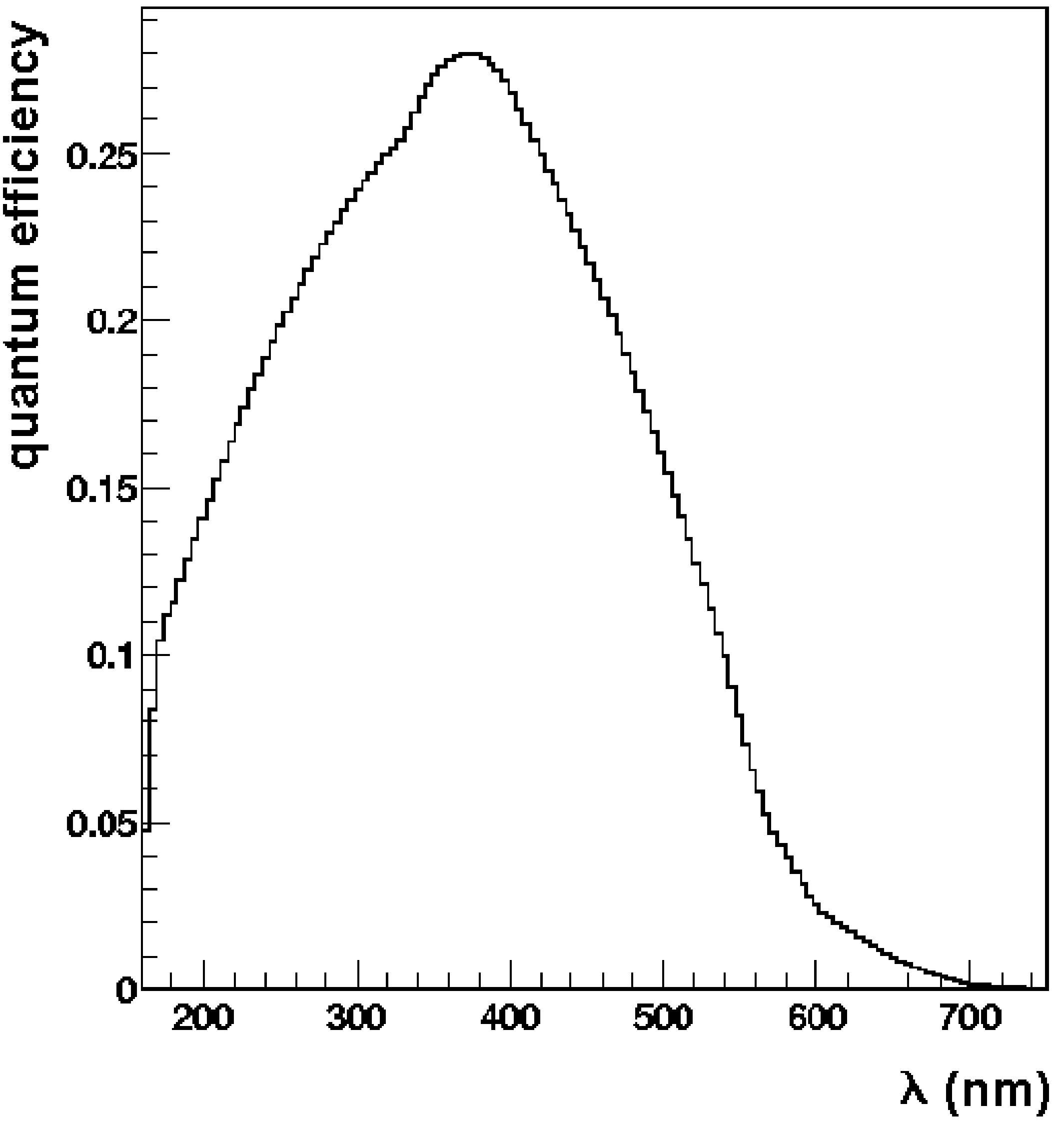

Fig. 3 *Quantum efficiency of* *Hamamatsu R4125Q PMT*

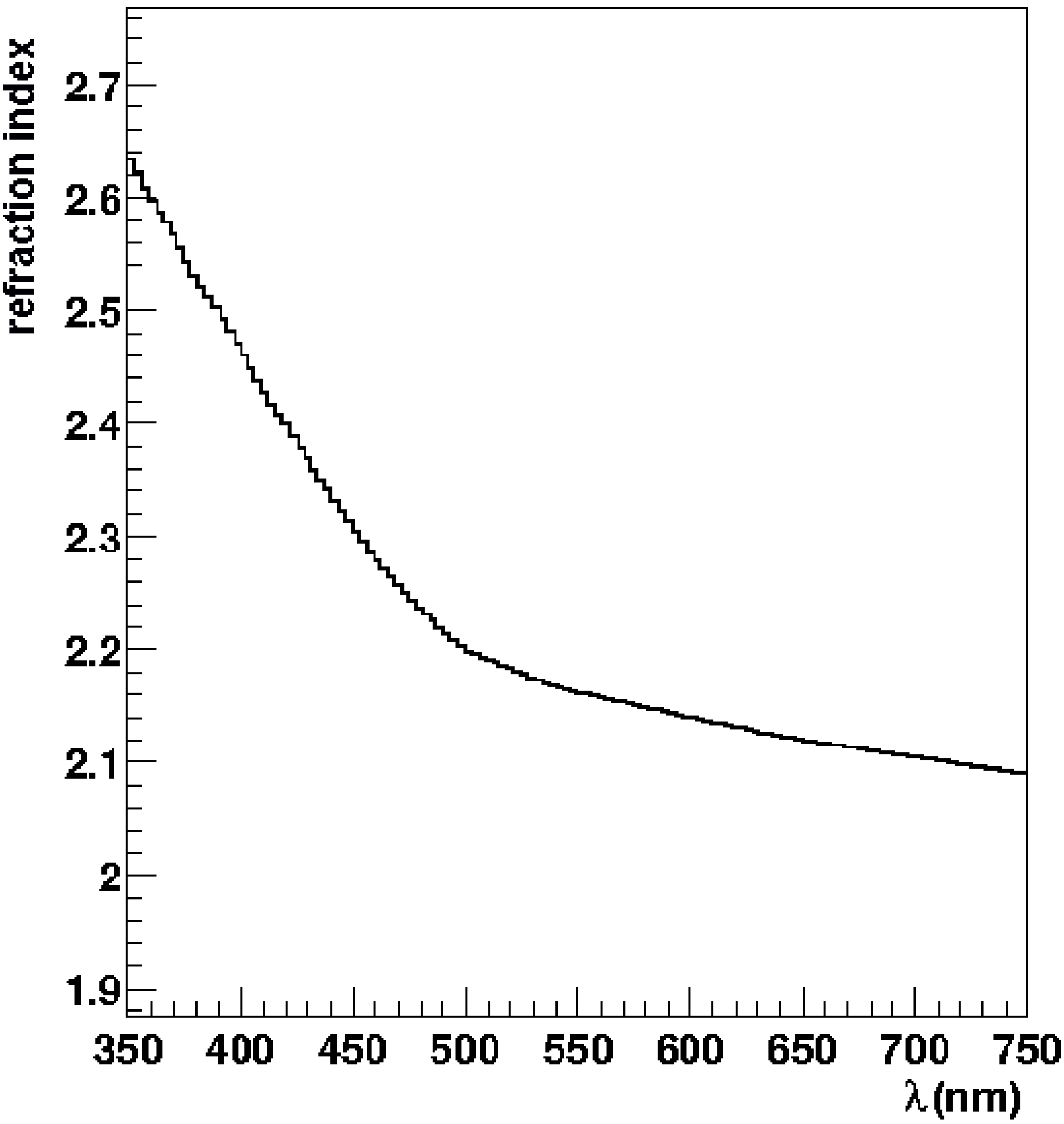

Fig. 4 *Wavelength dependence of NBW refraction index*

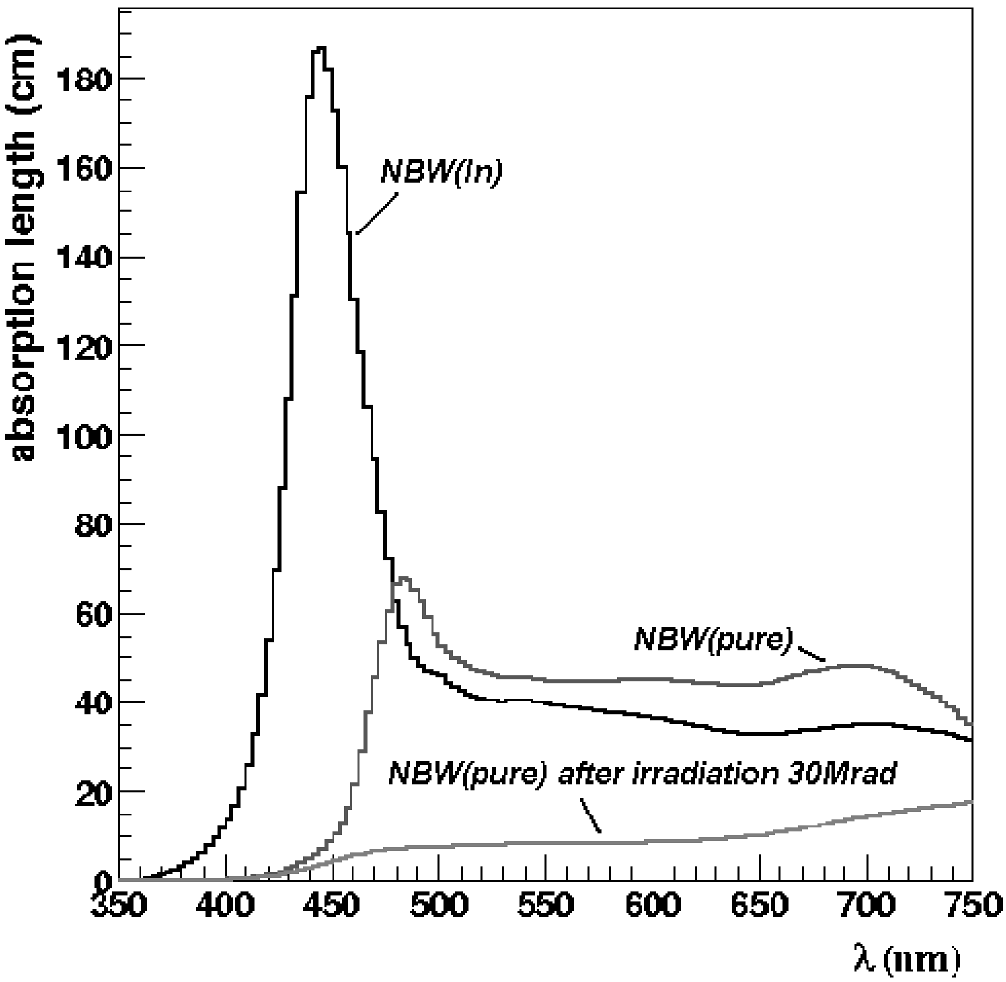

Fig. 5 *Wavelength dependencies of light attenuation length for different NBW crystals*

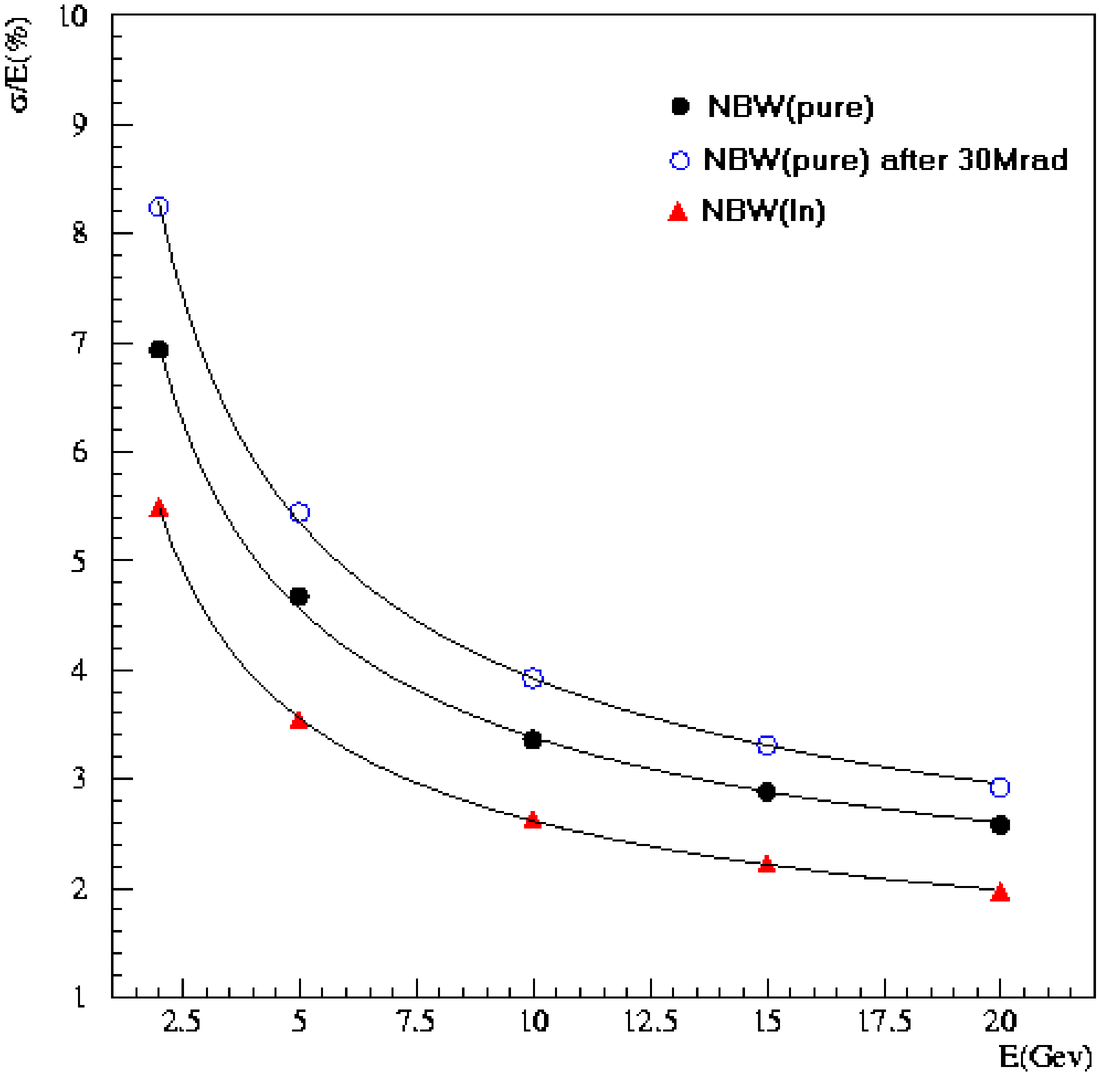

Fig. 6 *Energy resolution of EM calorimeters on the basis of different NBW crystals*