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Measurement of optical parameters of aerogel☆

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Abstract

The work is devoted to the measurement of optical parameters of aerogel which can be used as Cherenkov light radiator. The refractive index, the light scattering and absorption lengths, the variation of the refractive index inside an aerogel block were measured for the aerogel produced conjointly by the Institute of Catalysis and Institute of Nuclear Physics (Novosibirsk). Atomic and nuclear properties of the aerogel are presented.

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Keywords: Particle identification; Aerogel; Monte Carlo; Wavelength shifters

1. Introduction

Aerogel is used in Cherenkov counters for more than 20 years. During this period physicists were measuring optical parameters of aerogel since detector performance strongly depends on these parameters [1–7].

We measured the refractive index, the ratio of refractive index to density, local variations of the refractive index, light scattering and absorption lengths while developing aerogel Cherenkov counters for the KEDR detector [6,8,9]. Results and methods used in these measurements are presented in this paper.

2. Refractive index

For the refractive index measurement (Fig. 1) an aerogel block is positioned on the rotating table with the angle measurement. The light beam is directed through the corner of an aerogel block. The incidence angle α, the prism angle β, the outlet angle γ and the refractive index n are related by the formula:

$$\gamma = \alpha - \beta + \arcsin\left(n \cdot \sin\left(\beta - \arcsin\left(\frac{\sin(\alpha)}{n}\right)\right)\right).$$

We calculate n and β from two measurements of γ for different α.

The main error arises from the light spot size, the corresponding error σ_n is about 0.0005.

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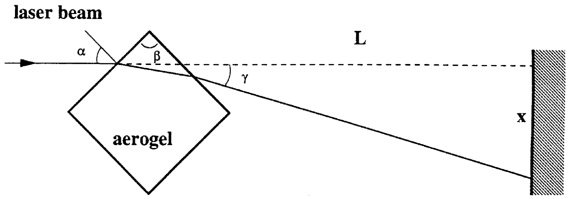

Fig. 1. The aerogel refractive index measurement.

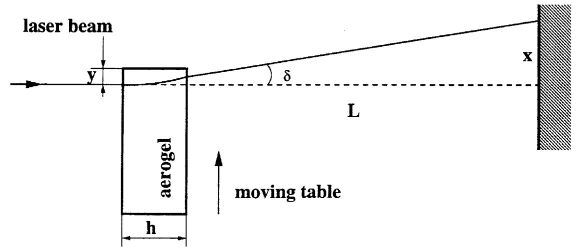

Fig. 2. The aerogel refractive index variation measurement.

A laser with $\lambda = 633$ nm was used in these measurements. Taking into account that the maximum of the spectrum of detected photons in Cherenkov counters is near 400 nm, measurements were corrected for aerogel dispersion. Since our aerogel is chemically identical to quartz, we calculate the correction coefficient from the quartz dispersion [10] $\frac{n(400)-1}{n(633)-1} = 1.0288$.

It is known that the aerogel refractive index value is proportional to its density. The coefficient of proportionality is determined as $n = 1 + k\rho$. In publications the variation of k is from 0.25 [1] to 0.21 [2–4]. The simple estimation based on data for the quartz density and refractive index gives [10]:

$$k = \frac{n_{SiO_2} - 1}{\rho_{SiO_2}} = \frac{0.470}{2.21} = 0.213.$$

The knowledge of this coefficient is necessary for the fast and simple refractive index control during the production.

Results of our measurement are $k = 0.199 \pm 0.003$ for $\rho = 0.1$ g/cm^3, $k = 0.206 \pm 0.003$ for $\rho = 0.2$–0.3 g/cm^3. The last number is consistent with the common number 0.21 [2–4], while for the light aerogel we have 5% difference.

There is a possibility of the refractive index correction by a sintering process. After 2 h of sintering at 820°C the refractive index was increased by $\Delta n = 0.009$ ($n \sim 1.05$). k did not change during sintering.

3. Variations of refractive index

Inhomogeneities may occur during the critical extraction phase of aerogel production. This leads to variations of the refractive index within monoliths of aerogel. Such variations can give a contribution to the accuracy of Cherenkov angle measurement in RICH counters. The method of refractive index variations measurement was taken from Ref. [4]. Light beam directed perpendicular to the flat aerogel plate can be deviated in the aerogel medium (Fig. 2). Deviation angle δ is proportional to the derivative of the refractive index variation: $\mathrm{d}n/\mathrm{d}y = n \cdot \delta/h$. Using the measurements of $\delta(y)$ the variation of n can be calculated:

$$\Delta n(y) = \frac{n}{h} \cdot \int_{y_0}^{y} \delta(y)\,\mathrm{d}y.$$

Measurements were performed with the aerogel of refractive index 1.05 and block dimensions of $53 \times 53 \times 24.5$ mm. Results are presented in Figs. 3 and 4. The edges of the block have the maximum of variations $\Delta n_{max} = 0.003$. This corresponds to $\Delta\rho_{max}/\rho = 6\%$.

4. Light scattering length in aerogel

Because the light scattering length in aerogel is much smaller than the absorption length, the scattering length in aerogel can be measured through the transmittance:

$$T = \frac{I}{I_0} = A \cdot \exp \frac{-d}{L_{sc} \cdot (\lambda/400)^4} = A \cdot \exp \frac{-C \cdot d}{\lambda^4},$$

d – thickness of a sample, λ – wavelength in nanometers, L_{sc} – scattering length at 400 nm, A – surface scattering coefficient. Sometimes, clarity coefficient C is used instead of L_{sc}. The results for aerogel with $n = 1.05$ are presented in Fig. 5, $L_{sc} = 5.4$ cm ($C = 0.0047$ μm^4/cm), $A = 0.93$.

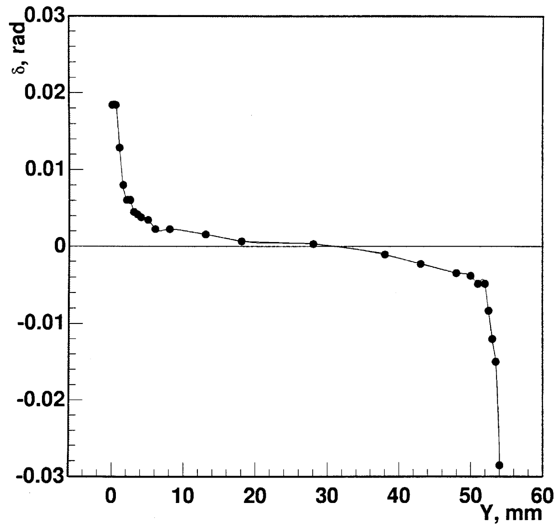

Fig. 3. The dependence of the deviation angle over the coordinate.

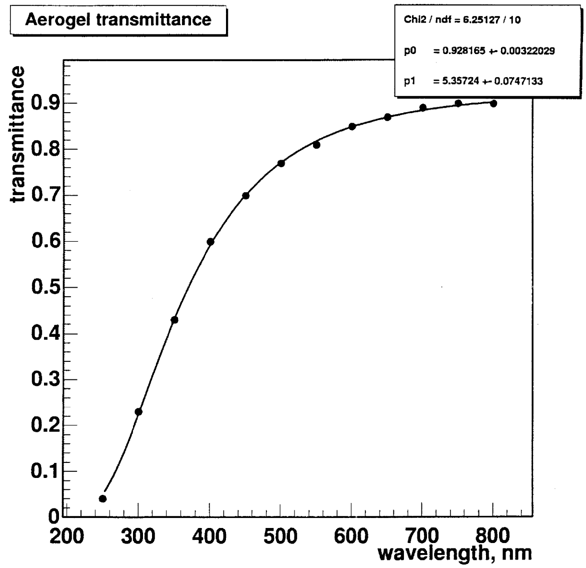

Fig. 5. The transmittance of the aerogel block. The thickness is 2.4 cm.

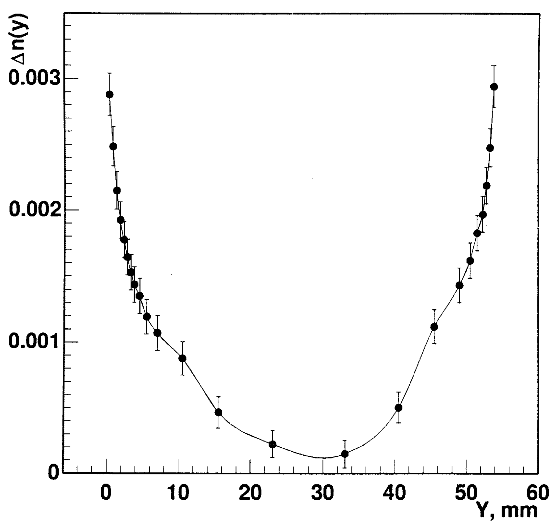

Fig. 4. The refractive index variation in the aerogel block.

5. Light absorption length in aerogel

The information about the light absorption length in the aerogel is very important for the aerogel threshold Cherenkov counters (ATC). The lack of data on this parameter leads to the complex procedure of elaboration for optimization of the ATC counters.

The method of measurement of the light absorption length in the aerogel was developed in our group [5,6].

The idea is to measure the light collection in the box with and without the aerogel, and then using the known light scattering length in this aerogel, the light reflection coefficient on the walls, and the box configuration to reconstruct the absorption length in the aerogel with the help of the special Monte Carlo code. The box was wrapped by multi layers of PTFE film which has high reflectivity [12]. A special scattering cavity is connected to the box to produce the homogeneous light angle distribution at its entrance. The light is detected by a photomultiplier working as a photodiode.

To describe the processes of light collection and propagation we used a special code developed in our institute [5,11–13]. This code simulates the following processes: Rayleigh scattering inside the aerogel, Lambert angular distribution of the reflected light, Fresnel refraction on the boundary of two media, light absorption inside the aerogel and on the walls.

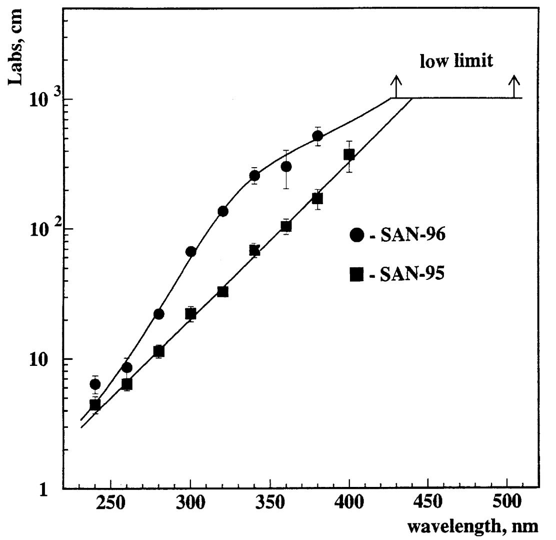

Fig. 6. The light absorption length in the SAN-95 and the SAN-96 aerogels.

Results of the measurement of the SAN-95 (aerogel produced in 1995) and the SAN-96 (aerogel produced since 1996) are presented in Fig. 6. The accuracy of the method for the high quality aerogel is about 10% in the region 240–260 nm, about 3% in the region 280–320 nm, 15% in the region 340–380 nm. In the region > 400 nm we present only the low limit for the light absorption length.

Data on the aerogel absorption and scattering lengths are intensively used by our group for the Monte Carlo simulation of the light collection in aerogel Cherenkov counters. The Monte Carlo predictions are in good agreement with the measurements on prototypes for the BaBar detector [14,15] and the KEDR detector [12].

6. Atomic and nuclear properties of aerogel

Chemical structure of the ordinary aerogel is SiO_2 with small 1–5% contamination of the water depending on the backing procedure [2,3]. Thus, atomic and nuclear properties of aerogels are almost the same as for quartz (chemical formula – SiO_2). Using recommendations from PDG [16] we calculate the following numbers for aerogel with 3% of water.

- $\langle Z/A \rangle$:

$$\langle Z/A\rangle_{\mathrm{aer}} = 0.97\langle Z/A\rangle_{\mathrm{SiO_2}} + 0.03\langle Z/A\rangle_{\mathrm{H_2O}} = 0.50093;$$

- nuclear collision length $\lambda_{\mathrm{T}}\{\mathrm{g/cm^2}\}$:

$$1/\lambda_{\mathrm{T}} = 0.97/\lambda_{\mathrm{T}}(\mathrm{SiO_2}) + 0.03/\lambda_{\mathrm{T}}(\mathrm{H_2O}),\ \lambda_{\mathrm{T}} = 66.3;$$

- nuclear interaction length $\lambda_{\mathrm{I}}\{\mathrm{g/cm^2}\}$:

$$1/\lambda_{\mathrm{I}} = 0.97/\lambda_{\mathrm{I}}(\mathrm{SiO_2}) + 0.03/\lambda_{\mathrm{I}}(\mathrm{H_2O}),\ \lambda_{\mathrm{I}} = 96.9;$$

- $\mathrm{d}E/\mathrm{d}x \left\{\dfrac{\mathrm{MeV}}{\mathrm{g/cm^2}}\right\}$:

$$\mathrm{d}E/\mathrm{d}x = 0.97\ \mathrm{d}E/\mathrm{d}x(\mathrm{SiO_2}) + 0.03\ \mathrm{d}E/\mathrm{d}x(\mathrm{H_2O}) = 1.71;$$

- radiation length $X_0\{\mathrm{g/cm^2}\}$:

$$1/X_0 = 0.97/X_0(\mathrm{SiO_2}) + 0.03/X_0(\mathrm{H_2O}),$$

$$X_0 = 27.25.$$

In the table of nuclear properties of materials presented by Particle Data Group [17] the values of those quantities for aerogel are notably different from those for quartz. This can be explained by an incorrect consideration that aerogel is a mixture of $n(SiO_2) + 2n(H_2O)$, which means the SiO_2 mass content is 62.5% and H_2O 37.5%. This is in dramatic contradiction with the real structure of the aerogel mentioned above.

7. Conclusion

The refractive index, the ratio of refractive index to density, the variation of the refractive index inside the aerogel block, the light scattering and absorption lengths were measured for the aerogel produced conjointly by the Institute of Catalysis and Institute of Nuclear Physics (Novosibirsk).

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