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Silica aerogel Cherenkov counter for the KEK B-factory experiment

T. Sumiyoshi[a,*], I. Adachi[a], R. Enomoto[a], T. Iijima[a], R. Suda[a], C. Leonidopoulos[b], D.R. Marlow[b], E. Prebys[b], R. Kawabata[c], H. Kawai[c], T. Ooba[c], M. Nanao[c], K. Suzuki[c], S. Ogawa[d], A. Murakami[e], M.H.R. Khan[e]

[a] *High Energy Accelerator Research Organization (KEK) 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*

[b] *Princeton University, 381 Jadwin Hall, P.O. Box 708, Princeton, NJ 08544, USA*

[c] *Chiba University, 1-33, Yayoi, Inage, Chiba 263-8522, Japan*

[d] *Toho University, 2-2-1 Miyama, Funabashi, Chiba 274, Japan*

[e] *Saga University, 1 Honjo-machi, Saga 840, Japan*

Abstract

Low-refractive-index silica aerogel is a convenient radiator for threshold-type Cherenkov counters, which are used for particle identification in high-energy physics experiments. For the BELLE detector at the KEK B-Factory we have produced about 2 m^3 of hydrophobic silica aerogels of $n = 1.01$–1.03 using a new production method. The particle identification capability of the aerogel Cherenkov counters was tested and 3σ pion/proton separation has been achieved at 3.5 GeV/c. Radiation hardness of the aerogels was confirmed up to 9.8 Mrad. The Aerogel Cherenkov counter system (ACC) was successfully installed in the BELLE just before this conference.

1. Introduction

One of the most intriguing puzzles of nature is why the Universe is composed only of matter in contradiction with cosmological theory, which suggests that an equal amount of particles and antiparticles have been produced in the big-bang. A simple explanation of this phenomenon requires the violation of matter–antimatter symmetry (so-called CP symmetry). In order to elucidate this interesting physics, several B-Factories have been proposed and are being constructed around the world [1–5], where large numbers ($\sim 10^{7-8}$/year) of B-meson decays will be examined for the study of CP violation. In such B-Factories, separation of pions from kaons is vital for the identification of B or $\bar{\mathrm{B}}$ mesons and the selection of rare decays.

One method for such particle identification involves detection of the Cherenkov light emitted by charged particles passing through transparent materials. The simplest way is the so-called "threshold" type Cherenkov detector which identifies particle species according to whether Cherenkov light is emitted or not in the material. A material

* Corresponding author. Tel.: + 81-298-64-5333; fax: + 81-298-64-2580.

E-mail address: sumiyosh@kekvax.kek.jp (T. Sumiyoshi)

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having a refractive index less than 1.03 is necessary for pion/kaon separation at a few GeV/c region by a threshold-type Cherenkov detector. However, it is very difficult to attain such a low refractive index with most materials. For this reason, a large number of experiments [6] have used silica aerogels as the radiator for threshold-type Cherenkov counters.

Before the invention of the two-step method [7], it was very difficult to produce silica aerogels having a refractive index lower than 1.02. Recent B-physics experiments, however, require a good particle identification on the momentum range up to 4 GeV/c, and a low refractive index material ($n = 1.007$–1.03) becomes vital for such experiments. Thanks to the two-step method, silica aerogel with a very low refractive index can easily be produced.

The BELLE group (the experimental group for KEK B-Factory) has decided to use an array of silica aerogel Cherenkov counters (ACC) for such particle identification. In this article we will report on our production method and quality of silica aerogels prepared for the KEK B-factory experiment. The performance of ACC by beam test data and a Monte Carlo simulation is also presented.

2. Silica aerogel Cherenkov counter

2.1. BELLE aerogel Cherenkov counter system

Fig. 1 shows the configuration of the aerogel Cherenkov counter (ACC) in a central part of the BELLE detector [5]. The ACC consists of 960 counter modules for the barrel part and 228 modules for the end-cap part of the detector. In order to obtain good pion/kaon separation for the whole kinematical range, the refractive indices of aerogels are selected to be between 1.01 and 1.03, depending on their polar angle region. A typical single ACC module is as shown in Fig. 2. Five aerogel tiles are stacked in a thin (0.2 mm thickness) aluminum box of approximate dimensions $12 \times 12 \times 12$ cm^3. In order to detect the Cherenkov light effectively, one or two fine mesh-type photomultiplier tubes (FM-PMTs), which operate in a magnetic field of 1.5 T, are attached directly to the aerogels at the sides of the box. We use PMTs of three different diameters:

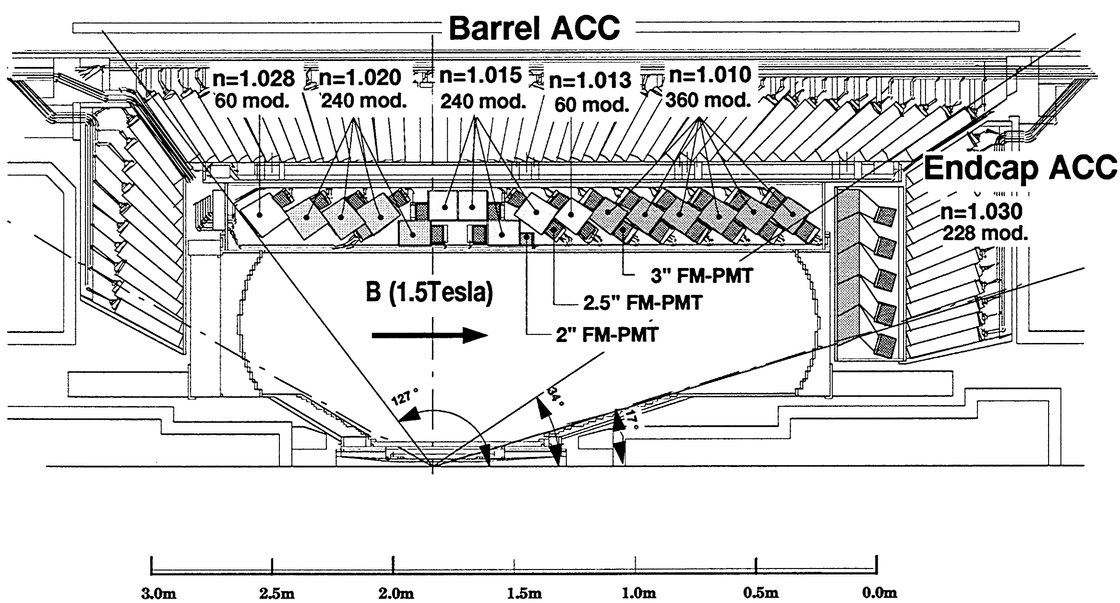

Fig. 1. The arrangement of the ACC at the central part of the BELLE detector.

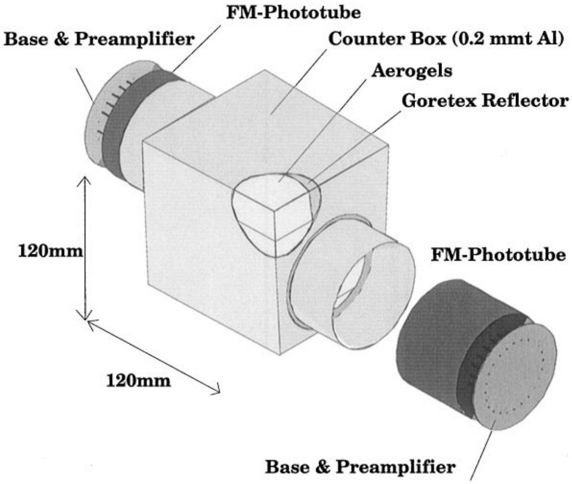

Fig. 2. Schematic drawing of a typical single ACC module: five aerogel tiles are contained in a thin aluminum box lined with a white reflector (Goretex sheet). They are viewed by two FM-PMTs.

3″ (R6683), 2.5″ (R6682) and 2″ (R6681) depending on the refractive indices. The inner surface of the box (except for the phototube windows) is lined with a diffuse reflector (Goretex sheet) to obtain a uniform response. The total volume of aerogel needed for the ACC is about 2.0 m^3.

2.2. Production of hydrophobic silica aerogels

We adopted the two-step method for the preparation of alcogels, in which we used a methyl-alkoxide oligomer as the precursor [8]. This oligomer is hydrolyzed and polymerized in a basic catalyst (NH_4OH) in a solution of methanol or ethanol. The average size of the alcogels is $120 \times 120 \times 24\ mm^3$ and they are formed in aluminum molds coated with a thin PTFE film. Typical gelation time ranges from a few minutes to 10 min depending on the densities.

Silica aerogels have been used in several experiments, however, their transparencies became worse within a few years of use [9]. This phenomenon may be attributed to the hydrophilic property of the silica aerogels. In order to prevent such effects, we have made our silica aerogels highly hydrophobic by changing the surface hydroxyl groups into trimethylsilyl groups [10]. This modification is applied before the drying. As a result of this treatment, our silica aerogels are still as transparent as they were when they were produced about two years ago.

After three weeks of aging including the surface modification, the alcogels are dried by super critical drying method of CO_2. This drying process takes 47 h. The volume of extractor is 140 l and we can produce about 38 l of silica aerogel in one batch. After seven months of operation (two batches/week), we have produced about 2 m^3 of silica aerogels.

2.3. Quality of the aerogels

All the aerogel tiles thus produced have been checked for optical transparency, transmittance of unscattered light, refractive index, density, size, etc. Fig. 3 shows a typical transmittance curve obtained by a photo-spectrometer for aerogels of four different refractive indices. The $n = 1.028$ aerogels have better transmittance than the others. Their average transmission length (Λ) at 400 nm is 46 mm, while others are around 25 mm. Here we define Λ as: $T/T_0 = \exp(-d/\Lambda)$, where T/T_0 is the transmittance defined as (1 − Absorption and diffuse scattering), and d is the thickness of the aerogels. These

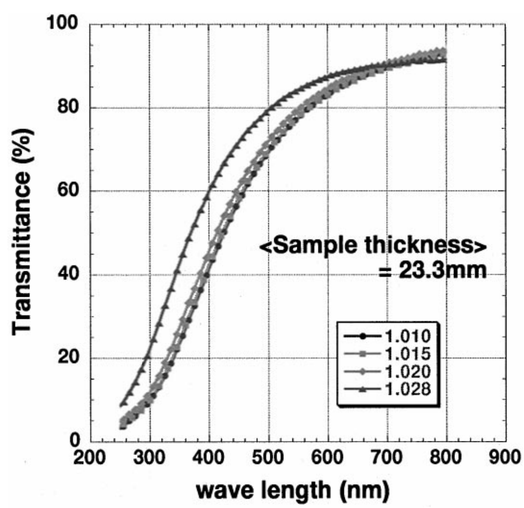

Fig. 3. Light transmittance spectra for the silica aerogels (thickness = 23.3 mm) of $n = 1.01$, 1.015, 1.02 and 1.028. The silica aerogels of $n = 1.028$, which were prepared by using methanol as the preparation solvent, have shown best transmittance.

aerogels were produced from the alcogel which was prepared by using methanol as the solution.

The refractive indices are well controlled as $\Delta n/(n-1) \sim 3\%$ for all the produced aerogel tiles, which is almost the same as the measurement error of the refractive index determined by measuring a deflection angle of laser light (He–Ne: 543.5 nm) at a corner of each aerogel tile.

We carried out a test to ensure the radiation hardness of aerogels by placing them in high-intensity γ-rays from a ^{60}Co source [11]. Transparencies and refractive indices of aerogels were measured at several irradiation stages. Up to 9.8 Mrad, which corresponds to more than 10 years of running at the KEK B-Factory, no deterioration on the transparency and no change in the refractive indices were observed.

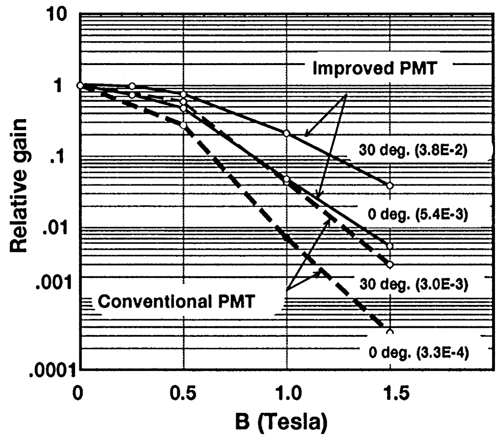

Fig. 4. Relative gains of FM-PMTs (conventional and improved ones) in a magnetic field when they are placed parallel (0°) or tilted by 30° w.r.t. the field direction.

3. Fine mesh photomultiplier tubes

Since ACC is placed in a high magnetic field of 1.5 T in the BELLE detector, we decided to use fine-mesh (FM) PMTs for the detection of the Cherenkov photons, because of its large effective area and high gain [12]. Other candidate photosensors such as HAPD, MCP-PMT were still at R&D stages or extremely expensive when this decision was made.

3.1. Gain

The FM-PMTs have 19 dynode stages of fine mesh, which ensures high gain ($\sim 10^8$) with moderate HV values (< 2500 V). The gain of FM-PMT decreases as a function of field strength as shown in Fig. 4. The gain reduction is $\sim 10^{-3}$ for the PMTs placed parallel to the direction of magnetic field and slightly recovers when they are tilted. A recent production of FM-PMTs by "Hamamatsu Photonics" which use finer meshes than conventional ones have more than 10 times better gain.

3.2. Resolution

Single-photon spectrum of the FM-PMT cannot have comfortable peak as a normal box and grid-type PMT. Because of its amplification mechanism, FM-PMT has exponential distribution for a single-photon response. Hence the obtained multi-photon spectrum is worse than what was expected from Poisson distribution. This means even if 20 photoelectrons are emitted from the photocathode, the effective number of photoelectrons ($\mu_{\rm eff}$), which is determined by the spectrum using the equation, $\mu_{\rm eff} = [\langle {\rm ADC} \rangle/\sigma]^2$, is less than 20. The excess noise factor ENF $= N_{\rm pe}/\mu_{\rm eff}$ for FM-PMT is about two in general. This ENF is further enhanced in a strong magnetic field of 1.5 T, even though Cherenkov photons from aerogel radiators are well observed by the FM-PMTs as discussed in the next section.

4. The performance of the ACC

4.1. Performance of the single counter modules

The performance of single ACC modules has been tested using a 3.5 GeV/c negative pion beam at KEK PS (π2 beam line). The number of photoelectrons obtained for 3.5 GeV/c pions are 18.2, 20.3 and 20.3 for $n = 1.01$, 1.015 and 1.02 silica aerogels, respectively. Typical pulse-height distributions for 3.5 GeV/c pions and protons observed by an aerogel counter ($n = 1.015$ with two 2.5″ PMTs) are shown in Fig. 5(a). Pions (above

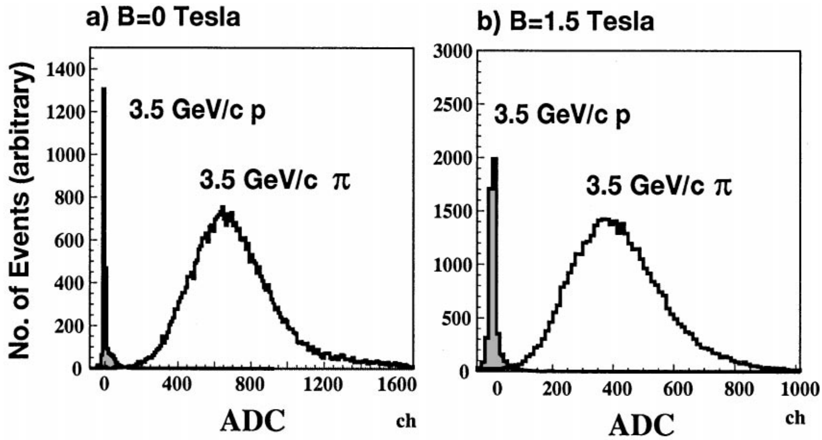

Fig. 5. Pulse-height spectra for 3.5 GeV/c pions (above threshold) and protons (below threshold) obtained by a single module of ACC in non-magnetic field (a) and in a high magnetic fileld ($B = 1.5$ T) (b), in which $n = 1.015$ silica aerogels were stacked.

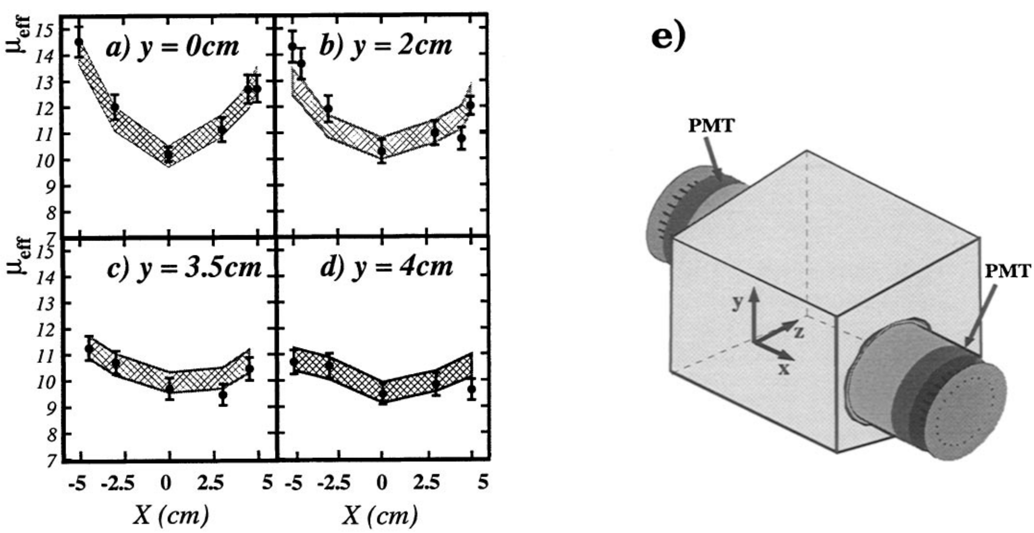

Fig. 6. Incident position dependence of the light yield (μ_{eff}): (a) $y = 0$ cm, (b) $y = 2$ cm, (c) $y = 3.5$ cm and (d) $y = 4$ cm. The points with error bars are the experimental data and the hatched areas are the Monte Carlo predictions. The coordinate is defined as (e), and the beam direction is parallel to the z-axis.

threshold) and protons (below threshold) are clearly separated by more than 3σ. This separation is maintained even in a high magnetic field (1.5 T) as shown in Fig. 5(b), where we used a preamplifier and applied a higher HV to get almost same gain as that without a magnetic field. We also found that cracks in the aerogel do not make a difference in the light yield.

4.2. Monte Carlo simulation

In order to arrive at a better understanding of the performance of the aerogel counters, a Monte Carlo program [13] has been developed to simulate the behavior of Cherenkov photons in the aerogel as realistically as possible. All considerable effects such as Rayleigh scattering, absorption by the aerogel, reflection by the Goretex walls, absorption by the wall, and the response of the PMTs are taken into account as a function of wavelength. The only unknown factor is the absorption in the aerogel, which we have treated as a free parameter and later determined by comparing the results from the simulation with the test beam data. As shown in Fig. 6, incident position dependence of the pulse height is well reproduced by the simulation. The absorption length thus determined is about 7 m at $\lambda = 400$ nm and increases almost exponentially as a function of λ.

This simulator is implemented in a BELLE standard detector simulator based on the GEANT 3. Performance of a pion/kaon separation by ACC can be demonstrated in the selection of two reactions; $B \to K\pi/\pi\pi$, which are very important for the CP physics in the B-Factory. Fig. 7 shows the distributions of energy imbalance ΔE, which is defined as $\Delta E = E_1 + E_2 - E_{Beam}$, where E_1 and E_2 are energies of particles calculated by assuming both to be pions, and E_{Beam} is the beam energy. Fig. 7(a) shows that for generated $B \to K\pi/\pi\pi$ events in the whole solid angle, and Fig. 7(b) and (c) those for the selected $B \to \pi\pi$ and $K\pi$ events, respectively, where $B \to K\pi$ and $\pi\pi$ are considered to be background and eliminated by only the ACC information (a dE/dX information by the central drift chamber can further eliminate the background). The ACC is very effective for the separation of K/π.

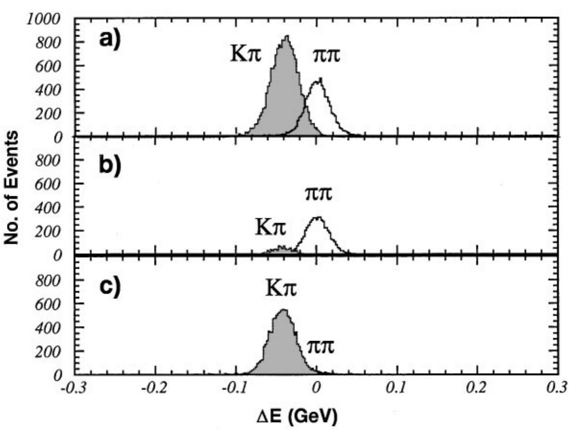

Fig. 7. The energy imbalance (ΔE) distribution for $B \to \pi\pi$ and $B \to K\pi$ events: (a) Generated, (b) after ACC cut for $B \to \pi\pi$, and (c) for $B \to K\pi$.

5. Conclusion

For the BELLE detector at KEK B-Factory we have produced about $2\,m^3$ of silica aerogels of $n = 1.01$–1.03 using a new production method. The particle identification capability of the aerogel Cherenkov counters was tested by using real beams. Pion/proton separation of three standard deviations has been achieved. Radiation hardness of aerogels was tested up to 9.8 Mrad. Neither deterioration of transparency nor change in the refractive index was observed, which gives us confidence in particle identification with aerogels in a high-radiation environment. The FM-PMTs show an excellent performance even in a strong magnetic field of 1.5 T for the detection of Cherenkov photons from aerogels.

The ACC was successfully installed in the BELLE detector at the beginning of November 1998, just before this conference. The BELLE will be ready in December 1998 and will be rolled in March 1999.

Acknowledgements

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