High-quality aerogel Cherenkov radiators recently developed in Japan

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Abstract. Around 1980, Japan's High Energy Accelerator Research Organization, also known as the KEK laboratory, began developing silica aerogels as a Cherenkov radiator. In 1996, the high energy physics group at Chiba University, Japan, began aerogel research and development in collaborating with KEK. The design of state-of-the-art Cherenkov detectors is enabled by improving aerogel transparency. Simultaneously, ultrahigh- and ultralow-refractive-index aerogels were developed to bridge the gap in the available indices for identifying low- and high-momentum particles, respectively. These are and will be employed in ongoing and future particle physics experiments all over the world. We report the latest results from the aerogel development and applications to threshold-type and ring-imaging Cherenkov detectors.

1. Introduction

Aerogel is one of the mesoporous materials with an internal structure in the order of ten nanometers. This solid-like medium has three-dimensional networks with constituent particle clusters, and the pores formed in the networks are filled with air. Among the aerogels, silica aerogel based on silicon dioxide (SiO_2) particles is transparent to visible light. Its refractive index is controllable by changing the silica–pore volume ratio during the production process. This leads to the fact that aerogel's index value ranges between gases and liquids or solids. The intermediate-index makes the silica aerogel an irreplaceable Cherenkov radiator for particle identification detectors in high energy physics experiments at the order of GeV/c. Precise control of aerogel's index while keeping high visible transparency is of particular interest in particle detector design study. In addition, large-area aerogel blocks with hydrophobic characteristics by applying chemical modifications are demanded building large-scale particle spectrometers with long-term operation stability. A mini-review on the basics of silica aerogels for use in Cherenkov radiators was given in the literature [1]. The present study focuses on recent applications of hydrophobic silica aerogels developed in Japan.

2. Aerogel applications to Cherenkov detectors

Around 1980, Japan's High Energy Accelerator Research Organization, also known as the KEK laboratory, began developing silica aerogels as a Cherenkov radiator. In 1996, the high energy physics group at Chiba University, Japan, began aerogel research and development in collaborating with KEK. The design of state-of-the-art ring-imaging Cherenkov (RICH) detectors is enabled by improving aerogel transparency. This study was first motivated by developing the high-refractive index ($n = 1.04$–1.06), a large-area radiator for the Belle-II Aerogel

Table 1. Aerogel specifications applied in physics experiments.

Experiment	Belle II (ARICH)	HELIX (RICH)	J-PARC E36 (AC)	EMPHATIC (Beam AC)	EMPHATIC (ARICH)
Facility	KEK (Japan)	Balloon (Polar region)	J-PARC (Japan)	Fermilab (USA)	Fermilab (USA)
Progress	Running	In preparation	Completed	In preparation	In preparation
Physics program	Particle/hadron	Cosmic-ray	Particle	Hadron/neutrino	Hadron/neutrino
Detector type	RICH	RICH	Threshold	Threshold	RICH
Particle identification target	π/K (up to 3.5 GeV/c)	Light isotopes (up to 4 GeV/nuc)	e/μ (0.24 GeV/c)	$\pi/K/p$ (4–12 GeV/c)	$\pi/K/p$ (above 2 GeV/c)
Refractive index	1.045 and 1.055	1.16	1.08	1.003, 1.007, and 1.026 (planned)	1.035 and 1.04 (planned)
Transmission length at 400 nm (mm)	47 and 36	33	20	15, 20, and 50	60 and 55
Original tile size (cm^3)	$18 \times 18 \times 2$	$11 \times 11 \times 1$	$18 \times 4.5 \times 2$	$10 \times 10 \times 2$	TBD
Number of tiles produced	450	100	45	Ongoing	Ongoing
Mass production period	2013–2014	2018	2014	Ongoing	Ongoing
Post-production processing	Water-jet cut	Water-jet cut	N/A	Water-jet cut or manual cut	Water-jet cut

RICH (ARICH) detector for identifying pions and kaons up to 3.5 GeV/c in the 2000s [2]. The ARICH detector being operated in the super B-factory experiment Belle II at KEK is the successor of the Aerogel Cherenkov Counter (ACC) system of the previous Belle detector, which successfully employed aerogels with low refractive indices (n = 1.01–1.03) in the 1990s. The aerogel technology is being transferred to the state-of-the-art RICH detectors in Japan and abroad. Simultaneously, ultrahigh- and ultralow-refractive-index aerogels were developed for filling the gap in available indices for the identifications of low- and high-momentum particles, respectively. These were and will be used in the ongoing and future particle and hadron/nuclear experiments, as well as cosmic-ray observations.

As summarized in Table 1, for example, Aerogel Cherenkov (AC) counters equipped with high-index ($n = 1.08$) aerogels having sufficient transparency were employed for separating sub-GeV/c positrons from muons to test lepton universality using stopped kaon beams at J-PARC [3]. Ultrahigh-index ($n = 1.16$) aerogels with high transparency were developed for a RICH detector for use in the High Energy Light Isotope eXperiment (HELIX) supported by U.S. National Aeronautics and Space Administration [4]. The HELIX spectrometer is a balloon payload to observe galactic cosmic-ray light isotopes to be launched at polar regions. Experiment to Measure the Production of Hadrons At a Test beam In Chicagoland (EMPHATIC) is planned to run at U.S. Fermi National Accelerator Laboratory (Fermilab) for a better understanding of neutrino flux in long-baseline neutrino oscillation experiments and atmospheric neutrino

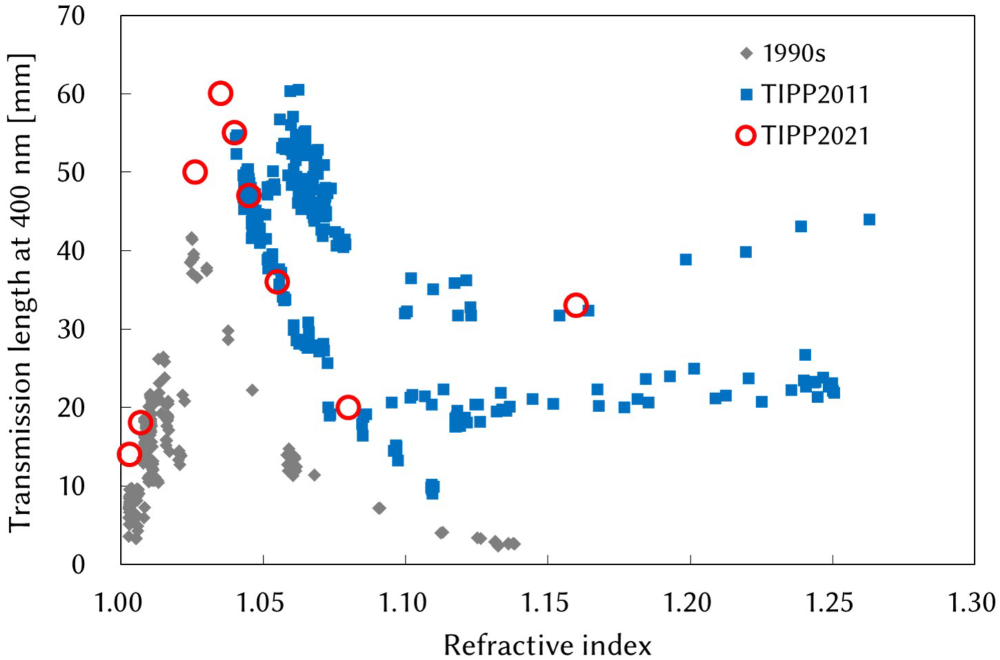

Figure 1. Transmission length measured at 400 nm wavelength versus the refractive index. The refractive index was measured with a 405 nm wavelength laser. Squares show individual aerogels experimentally produced, presented in the TIPP conference held in 2011. Circles show typical data of aerogels applied or to be applied in the experiments listed in Table 1.

experiments [5]. The EMPHATIC uses a beam AC counter array employing ultralow-index (down to $n = 1.003$) aerogels for identifying pions, kaons, and protons in beam particles with 4–12 GeV/c. In addition, scattered particles (pions, kaons, and protons) above 2 GeV/c will be identified by the EMPHATIC ARICH detector employing intermediate-index ($n = 1.03$–1.04) aerogels, which is modeled on the Belle-II ARICH detector. The optical properties (the transmission length versus the refractive index) of the above recently applied aerogels are shown in Fig. 1 while comparing with data presented in the previous international conference on Technology and Instrumentation in Particle Physics (TIPP) held in 2011 [6]. Highly transparent aerogels over a wide range of indices have been used in various physics experiments.

3. Summary

Made-in-Japan hydrophobic silica aerogels with high visible transparency and high-refractive indices ($n = 1.045$ and 1.055) are currently in operation in the ARICH detector for the super B-factory experiment Belle II at KEK. The ARICH detector is the successor of the ACC system of the Belle detector, which successfully employed aerogels with low indices ($n = 1.01$–1.03) in the 1990s. Low- and intermediate-index ($n = 1.003$–1.04) aerogels having further improved transparency will be used in the hadron production experiment EMPHATIC at Fermilab. High-index ($n = 1.08$) aerogels were also employed to test lepton universality at J-PARC. Specially developed ultrahigh-index ($n = 1.16$) aerogels with high transparency are ready for balloon-borne cosmic-ray experiment HELIX.

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