

Optical properties of RICH detectors ☆



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ABSTRACT

In this review article¹ we discuss the optical components in RICH detectors. In particular we mention transmission and refraction index in gases, liquids, solids, optical glues, matching gels and aerogel. We mention a few examples of mirror reflectivity in UV and visible region. We also discuss radiation damage, radio-luminescence, yellowing from light exposure, optical distortions in materials, and scintillation.

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1. Introduction

A beautiful thing about Cherenkov detectors is that their performance is basically determined by the refraction index, transparency of the medium, QE and angular resolution of photon detectors.

2. Refraction index

One deals with two refraction indices. The “phase refraction index” is defined by: $n \equiv n_{\text{phase}} = c/v_{\text{phase}}$, where v_{phase} is wave-form speed in the medium; it appeared first in Snell's law. The “group refraction index” is defined by: $n_{\text{group}} = c/v_{\text{group}} = (n_{\text{phase}} - \lambda dn/d\lambda)$, where v_{group} is propagation velocity of wave energy.²

Fig. 1 shows a typical wavelength-dependent difference between two indices for the fused silica; one can see that the energy propagates more slowly through a medium than the wave's phase, especially in far UV region. To determine the phase refraction index, one starts from the Lorentz–Lorenz equation:

$$\frac{(n^2 - 1)}{(n^2 + 1)} = \alpha f(E) \quad (1)$$

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¹ Invited talk at RICH 2013, December 4, Kamakura, Japan.

² Ibn Sahl was the first astronomer to use Snell's law accurately when building his lenses in Baghdad (940–1000 A.D.). The phase index was introduced by W. Snel van Royen (Willebrord Snellius), a Dutch astronomer (1580–1626). The group velocity concept was introduced ~200 years later by W. Hamilton, an Irish astronomer (1805–1865).

where $\alpha = 0.378 \text{ (cm}^3 \text{)} [\rho \text{ (g cm}^{-3} \text{)/M(g mole}^{-1} \text{)}]$ and $f(E)$ is the molar refractivity, usually fitted with two-pole Sellmeier function:

$$f(E) = \frac{F_A}{(E_A^2 - E^2)} + \frac{F_B}{(E_B^2 - E^2)} \quad (2)$$

Numerical values of F_A , F_B , E_A and E_B for typical Cherenkov detector materials can be found in these two references [1,2].

One can now calculate many quantities. For example, a transmission (Tr) of thin a window of thickness (L) can be calculated using these two equations:

$$R = \frac{(n-1)^2}{(n+1)^2}, \quad Tr = \frac{(1-R)^2 t}{1 + R^2 t^2}, \quad t = e^{-\mu L} \quad (3)$$

where (R) is reflectivity and (μ) is attenuation length.

Fig. 2 shows a history over past 30 years of a refraction index ($n-1$) of various radiators, transmission (Tr) of typical window materials and the photocathode quantum effectivity (QE) as a function of wavelength and photon energy. Generally one can say that there was a steady trend in change of operating point over the past ~30 years, going from very far UV region, represented by the HRS experiment with the Benzene photocathode, all the way to visible wavelengths, as represented by the BaBar DIRC [3] using the Bialkali photocathode. There are two main reasons: (a) operational difficulties were reduced substantially using commercial Bialkali photocathodes and (b) detectors had smaller chromatic errors.

An important group of radiator materials are Freon liquids $C_n F_{2n+2}$. Their refraction index can be described simply as $n = a + bE$, for photon energy range $5 \leq E \leq 7 \text{ eV}$, as shown in Fig. 3a [4]. During the ALICE experiment beam tests, a different slope was found for the $C_6 F_{14}$ liquid in the same energy interval: $n = 1.177 + 0.0172\lambda \text{ (Å)}$ [5].³ This was followed by more

³ Both STAR and ALICE experiments use this new parameterization.

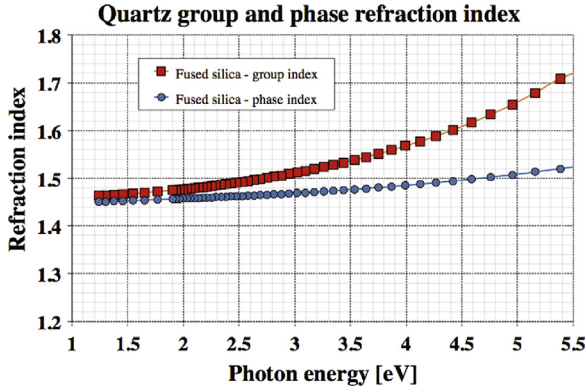


Fig. 1. Energy dependence of two refraction indices in the fused silica.

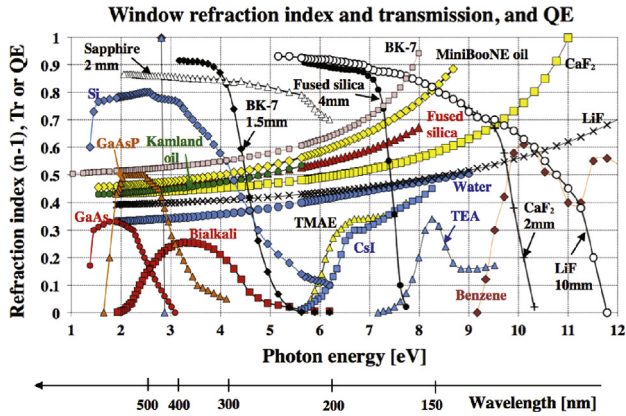


Fig. 2. Refraction index ($n-1$), transmission (Tr) and quantum efficiency (QE) of typical windows, radiators and photocathodes. **Benzene** was used by HRS; **TMAE** by DELPHI, SLD, OMEGA, CERES, JETSET and CAPRICE; **TEA** by CLEO; **Csl** by ALICE, ATLAS, COMPASS, HADES; and **BiAlkali** by HERA-B, DIRC, HERMES, Belle-II, CELEX detectors.

measurements, and a summary is shown in Fig. 3b.⁴ One can notice that the refraction index energy dependence is non-linear if a larger photon energy window is used.

Table 1 shows constants for the Sellmeier function Eq. (2) for noble gases [2]. Refraction index of gas and liquid phase are related through Eq. (4), where p is gas pressure, T is temperature, R is a gas constant, M is molecular weight and ρ is a liquid density.

$$\frac{n^2 - 1}{n^2 + 2} = \left(\frac{p}{RT}\right)_{\text{gas}} \left(\frac{M}{\rho}\right)_{\text{liq}} \left(\frac{n^2 - 1}{n^2 + 2}\right)_{\text{liq}} \quad (4)$$

A knowledge of the refraction index of various optical couplings between different materials is crucial for all optical designs as they influence the photon reflection, a phenomenon especially important at large incidence angles to glue/window interfaces. Fig. 4a shows examples of refraction indices of several coupling materials relative to the fused silica. For example, BaBar DIRC bars were glued together with the Epotek-301-2 epoxy, the 1-st FDIRC prototype used the Kamland oil to couple to fused silica (one can see that it is pretty good match to fused silica), final FDIRC prototype used Shin-Etsu RTV SES-403 to couple its optics to the DIRC bar boxes, Belle-II TOP counter is using Norland 61 epoxy, and Panda prototype used Marcol 82 mineral oil. Fig. 3b and c shows the measurement of the Epotek 301-2 optical epoxy and the Shin-Etsu SES-403 RTV. As one can see, some people use uncured

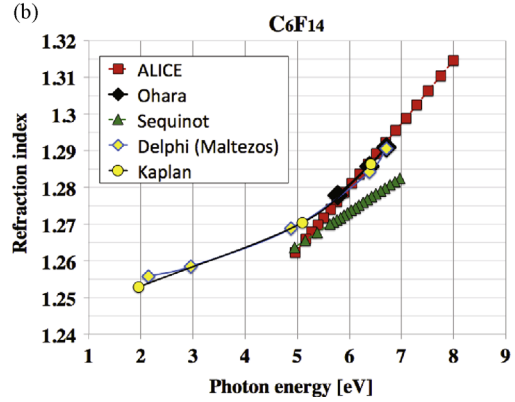
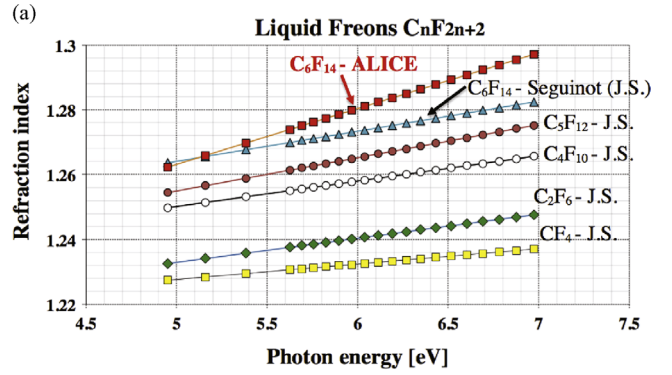


Fig. 3. (a) Refraction indices of various Freon liquids as measured by DELPHI [3] and ALICE [4]. (b) Summary of all measurements for the C_6F_{14} liquid for a larger energy range. The refraction index does not follow a simple linear relationship if a larger photon energy window is used [4–7].

epoxy; cured epoxy is made in a form of a wedge to enable laser-based deflection measurements.

Fig. 5 shows the refraction index of the K_2CsSb BiAlkali photocathode, which can also influence reflection and absorption [9]. Its real part (n) describes the phase refraction index, and the imaginary part (k) describes the absorption.

The refraction index is influencing the chromatic broadening of the Cherenkov angle, which is typically limiting the performance. The chromatic error contribution to the Cherenkov angle σ_{θ_c} is calculated by differentiating equations “ $\cos \theta_c = 1/\beta n(E)$ ”, and the Lorentz-Lorenz Eq. (1) [1]:

$$\sigma_{\theta_c} = \frac{\partial \theta}{\partial n} \frac{dn}{dE} \sigma_E = \left(\frac{1}{n \tan \theta}\right) \left(\alpha \frac{(n^2 + 2)^2}{6n} \frac{df}{dE}\right) \sigma_E \quad (5)$$

The chromatic error is reduced by reducing dn/dE and σ_E . A decreasing σ_E results in a decreased number of photoelectrons. The best way to reduce the chromatic error is by choosing a detector with a longer wavelength response. The error σ_E is determined by the detector overall response. For example, Fig. 6 shows energy response of FWHM ~ 1 eV for the 1-st FDIRC prototype [10], and Eq. (5) gives $\sigma_{\theta_c} \sim 4.5$ mrad.

New fast DIRC-like RICH detectors can correct the chromatic error using timing – see Fig. 7. This idea was pioneered for the first time by the 1-st FDIRC prototype [10]. Fig. 7a and b shows the principle. The red photon is faster than the blue photon and their time of arrival to a given pixel can be measured with a fast detector. One can determine a correlation between $d\theta = \theta(\lambda) - \theta(\lambda_{\text{ref}})$ and $d\text{TOP}/L_{\text{path}} = \text{TOP}/L_{\text{path}}(\lambda) - \text{TOP}/L_{\text{path}}(\lambda_{\text{ref}})$, where TOP is time of propagation in quartz, L_{path} is photon path length and λ_{ref} is a reference wavelength, taken in the middle of acceptance. If the Cherenkov angle is measured well ($\sigma(\theta_c) \sim 10$ mrad) with timing

⁴ ALICE group asked Ohara Co. to measure the C_6F_{14} refraction index. Their values were found to be consistent with data of Maltezos [6] and Kaplan [7].

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