EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/87-186

1 October 1987

**A RICH DETECTOR WITH A SODIUM FLUORIDE RADIATOR:
 π/K IDENTIFICATION UP TO 3 GeV/c**

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ABSTRACT

The use of a single crystal of sodium fluoride (NaF) as a Cherenkov radiator has been investigated. Its transparency has been measured and found to be good for photon energies below 9.8 eV. Data on its index of refraction are well fitted to a single-pole Sellmeier resonance formula. These data allow a realistic Monte Carlo simulation of a proximity-focused ring imaging Cherenkov (RICH) system. The photon detector is a multiwire proportional chamber (MWPC) with pad readout. The photosensitive gases considered are tetrakis(dimethylamine)ethylene (TMAE) and triethylamine (TEA). The simulation shows that a system having 10 cm radial thickness and 10% of a radiation length of material would identify pions and kaons below 3 GeV/c momentum. The pad dimensions required are about 5 mm $\times$ 5 mm.

Paper presented at the
London Conference on Position-Sensitive Detectors
London, 7-11 September 1987

1. INTRODUCTION

An important challenge when designing a detector for low-energy physics [the Low-Energy Antiproton Ring (LEAR) at CERN, $B\bar{B}$ factories, etc.] is π/K (and K/p) identification up to 3 GeV/c (5 GeV/c). A good solution is now available, namely, the ring-imaging Cherenkov (RICH) technique. It is reasonably well known [1], tested [2], and being used in different experiments (DELPHI, SLD, Omega, NA34 and others). At the Stanford Linear Collider (SLC) and the Large Electron-Positron Storage Ring (LEP) (where detectors with particle identification up to 30 GeV/c are required) a gas radiator (C_5F_{12}) covers the high-momentum region (25 GeV/c for π/K , 40 GeV/c for K/p) down to threshold (2.3 GeV/c π/K , 8 GeV/c K/p). To cover the low-momentum region an ultraviolet (UV) transparent liquid Cherenkov radiator was found (C_6F_{14} with a low refractive index of $n = 1.276$ at 6 eV), which gives particle identification up to 5 GeV/c π/K and 8 GeV/c K/p . This overlaps the gas radiator capability for π/K and just barely covers for K/p . An inconvenience and disadvantage of the liquid radiator is the need of a containment vessel with a quartz window, which increases the radiation length of the system and produces background photons. For lower energy applications (up to 3 GeV/c π/K) a solid crystal radiator sodium fluoride (NaF) is proposed, which simplifies the construction, reduces the radiation length, and has no containment window. In the following sections we propose a design for a RICH detector which could equip a LEAR detector (JETSET) or a $B\bar{B}$ factory detector at $\sqrt{s} = 10$ GeV. Results on transparency measurements and the variation of refractive index with photon energy are given. We then present a Monte Carlo calculation of the particle-identification capability of the proposed RICH detector.

2. DETECTOR DESIGN

The detector is shown in fig. 1. It uses a photosensitive gas to convert the Cherenkov photons emitted by the radiator medium (NaF). The photon detector is a standard multiwire proportional chamber (MWPC) filled with a mixture of methane, ethane, and the photosensitive gas tetrakis(dimethylamine)ethylene (TMAE). The wire spacing s is 5 mm and the photon conversion depth of 4 mm is separated from the 150 mm helium-filled (1 atm) gap by a 4 mm thick fused quartz window. Pad readout (5 mm $\times$ 5 mm) is shown in fig. 1 to cope with the high interaction rate of the JETSET experiment at LEAR. For lower luminosity e^+e^- colliders, conventional drift detectors [2] are sufficient. As the measurement of the depth coordinate is not foreseen, a very short photon mean free path (ℓ_0) is required (≈ 1 mm). This is obtained by heating the photon detector to about 85 °C. At this temperature the partial pressure of the TMAE is sufficiently high to obtain a 1 mm photon mean free path. The conversion depth of 4 mm is sufficient to absorb 98% of the incident photons in the detector gas. A short photon mean free path also resolves the photon feedback problem since the wire spacing $s \gg \ell_0$. The body of the detector is made of boron nitride (BN) machinable ceramic, and the wires are metallized quartz so as to give a very low or zero coefficient of thermal expansion.

3. SODIUM FLUORIDE

Single crystals have good transparency up to 9.8 eV. Our measurements of the transmission of an 11 mm thick sample are shown in fig. 2. Also shown, for comparison, are our measurements of

the transmission of a 5 mm thick calcium fluoride (CaF_2) crystal and 5 mm thick fused quartz. The quantum efficiencies of TMAE and triethylamine (TEA) are also given in fig. 2. The TEA quantum efficiency was measured in a predominantly methane-filled MWPC so the drop of efficiency beyond 8.4 eV is due to methane absorption. It does, however, represent a realistic value of the quantum efficiency: in order to achieve high single-electron counting efficiency (in an atmospheric pressure detector), methane is required. Two modes of operation are evident from fig. 2, namely TMAE with a quartz-window detector and TEA with a NaF or CaF_2 window. The latter is of great interest because the TEA partial pressure at 20 °C is 52 Torr, corresponding to a photon mean free path of 0.6 mm, thus allowing a room-temperature detector. This option is now under study.

This material has the lowest refractive index ($n = 1.328$ at 3 eV) amongst solids. Its refractive index, in the 5.4 to 7.6 eV energy range (TMAE + quartz interval), is sufficiently small ($< \sqrt{2}$) for a large fraction of the Cherenkov photons to refract out of the crystal and not be trapped by total internal reflection. The variation of refractive index with photon energy as measured by Smakula [3] is shown in fig. 3. The fit uses the Sellmeier single-resonance formula:

$$(n^2 - 1)/(n^2 + 2) \approx F_A/(E_A^2 - E^2), \quad (1)$$

with the fit values $F_A = 48.76 \text{ eV}^2$, $E_A = 15.78 \text{ eV}$, and E the photon energy in eV. Our fit agrees well with that of Wemple [4], who uses the form

$$n^2 - 1 = G_A/(E_A^2 - E^2) \quad (2)$$

with $G_A = 169 \text{ eV}^2$ and $E_A = 15.1 \text{ eV}$. At $E = 6.5 \text{ eV}$ the refractive index is 1.387, corresponding to a Cherenkov threshold of $\beta = 0.72$ or $\gamma\beta = 1.04$ and a maximum Cherenkov angle ($\beta = 1$) of 766 mrad. The variation of Cherenkov angle with β is shown in fig. 4.

4. MONTE CARLO SIMULATION

We have performed a Monte Carlo simulation of the set-up shown in fig. 5. The RICH detector is made up of two parts: an end cap ($\theta < 45^\circ$) and a barrel part ($45^\circ < \theta < 90^\circ$) with symmetry about the $\theta = 90^\circ$ polar angle. The polar angle is measured from the beam axes as shown in fig. 5. Details of the NaF radiator and the MWPC detector are given in fig. 1. The resolution on position measurement was $\Delta x = \Delta z = 1.5 \text{ mm}$ (barrel) or $\Delta x = \Delta y = 1.5 \text{ mm}$ (end cap), corresponding to a $5 \text{ mm} \times 5 \text{ mm}$ pad size. The error in the photon-conversion depth in TMAE is $\Delta y = 1.5 \text{ mm}$ (barrel) or $\Delta z = 1.5 \text{ mm}$ (end cap). The resolutions on the incident-particle direction (θ, ϕ) are $\Delta\theta = 0.3/\sin\theta$ and $\Delta\phi = 0.4 \text{ mrad}$. Multiple scattering of the particle before radiating is included in the calculation. Photons are followed through the various media between the NaF radiator and the MWPC detector (see fig. 1). Reflection losses at boundaries and absorption loss in the bulk media are taken into account. The probability of conversion of photons (which arrive at the MWPC) into photoelectrons is given by the TMAE quantum efficiency curve of fig. 2. Finally an overall electron-counting efficiency of 0.8 has been assumed.

Figure 6 gives the number of photons detected as a function of θ_p , the angle of incidence of the particle (relative to the normal to the NaF radiator), where $\theta_p = \theta$ for the end cap and $\theta_p = \pi/2 - \theta$ for the barrel. The two curves of fig. 6 are for pions and protons of 2 GeV/c. The number is about 20 when $\theta_p = 0$ and descends to 10 or less when $\theta_p > 20^\circ$, corresponding to a loss due to total reflection in the radiator. Even in the worst case ($\theta_p = 40^\circ$) still 10 photoelectrons are detected for a 5 mm thick NaF radiator. Figure 7 presents the various contributions to the error $\Delta\theta_C$ on the reconstructed Cherenkov angle θ_C (for a single photoelectron) as a function of θ_p . The dominant error of 8 to 12 mrad comes from the energy spread of the photons (chromatic error). The error due to the photon emission distance ℓ in the radiator and that on the position measurement have the same feature, i.e. negligible at $\theta_p = 0^\circ$ and maximum at 45° (≈ 5 mrad).

The total error, obtained by adding the three sources in quadrature, is essentially constant: $\Delta\theta = 11$ mrad over the full range of θ_p . This corresponds to an error per particle track (≈ 10 photoelectrons) of $\Delta\theta = 3.5$ mrad on a Cherenkov angle of 766 mrad.

Figures 8, 9, and 10 give the e/π , π/K , and K/p separation at $\theta_p = 0^\circ$ and $\theta_p = 40^\circ$, as a function of particle momentum. The quantity plotted as ordinate is N_σ , the difference between the π and the K Cherenkov angle (at momentum p) divided by the error $\Delta\theta$ (per photon) and multiplied by the square root of the number of converted photons. It is seen that e/π identification extends to 0.9 GeV/c (4.2 σ corresponds to 1% misidentification), π/K extends to 3 GeV/c and K/p up to 5.2 GeV/c.

The geometry has not been varied so as to optimize the resolution. It is clear that by tilting the radiators so that θ_p is always between 0° and 20° several advantages accrue. Firstly, the position and depth errors are small (≈ 1.5 mrad), hence larger pad dimensions will be possible with a saving in the number of electronic channels. Secondly the number of detected photons is larger (≈ 15), which increases precision.

5. CONCLUSION

A Monte Carlo simulation of the RICH detector of fig. 1 with a NaF radiator has shown that π/K particle identification up to 3 GeV/c is possible. The number of photoelectrons in the image varies between 10 and 20 for a 5 mm thick crystal. The material shown in fig. 1 represents 10% of a radiation length. The simulation used $D = 150$ mm as the distance between the radiator and the quartz window, but this can surely be decreased (by a factor of 2) because of the dominance of chromatic errors. Tilting the NaF radiator plates so that θ_p is always between 0° and 20° will reduce the position error (also the emission distance error) to 1.5 mrad, which is negligible compared to the 11 mrad chromatic error. Reducing D to 75 mm and increasing the pad size to 10 mm $\times$ 10 mm brings the position error to 6 mrad, which is still small compared to the chromatic one. This extremely advantageous reduction of position and emission point errors occurs at near normal incidence because n^2 approaches 2. This can be seen from the analytically derived formulae for a plane radiator and a parallel, plane detector (at $\theta_p = 0^\circ$ and $\beta = 1$):

i) Chromatic

$$\partial\theta_C/\partial n = n/\sqrt{n^2 - 1}.$$

ii) Position x

$$\partial\theta_C/\partial x = (2 - n^2)^{3/2}/D .$$

iii) Emission distance ℓ

$$\partial\theta_C/\partial\ell = [(2 - n^2)^{3/2}\sqrt{n^2 - 1}]/D .$$

iv) Conversion depth z

$$\partial\theta_C/\partial z = (2 - n^2)^{3/2}/D .$$

Thus, a RICH design with 100 mm overall radial thickness, 10% of a radiation length, and π/K identification up to 3 GeV/c, has been demonstrated. In addition, the pad (pixel) size need only be 10 mm $\times$ 10 mm.

Finally, the use of TEA as a photoionizing gas looks quite promising. Even though the domain of operation of a TEA detector is high ($E = 8.2$ eV), where NaF has an index of refraction of about 1.45, a simulation has shown that for incident angles between 10° and 30° one gets 18 and 22 photoelectrons, respectively, from a 10 mm thick NaF crystal with the TEA quantum efficiency as in fig. 2. At 0° incidence no photoelectron is seen because of total internal reflection. More surprisingly, the index of refraction and its variance is 1.447 ± 0.01 , thus giving a chromatic error of 8 to 12 mrad which is not worse than that for TMAE. As stated before, the advantage of TEA lies in its high room-temperature vapour pressure, which will simplify construction and operation of the detector since no heating is needed.

Scintillation of NaF is possible and must be investigated as this could lead to background photoelectrons.

Acknowledgements

We wish to thank P. Pavlopoulos and F. Montanet for the loan of the NaF crystal on which the transmission measurements were made, and C. Nichols of CERN for polishing it.

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Figure captions

- Fig. 1** Geometry of the RICH system used for the Monte Carlo simulation.
- Fig. 2** Transmission (T) of NaF (11 mm thick), CaF₂ (5 mm), and fused quartz (5 mm) and the quantum efficiencies QE of TMAE and TEA versus photon energy E (eV).
- Fig. 3** The refractive index of a single crystal of sodium fluoride versus photon energy E. The points are experimental and the curve is the fit of Eq. (1) (see text for parameters).
- Fig. 4** The variation of Cherenkov angle θ_c with particle velocity β for a single-crystal NaF radiator at E = 6.5 eV.
- Fig. 5** Geometry of the barrel and the end caps in the simulation and the definition of coordinates and polar angle θ .
- Fig. 6** Results of a simulation for the number of photoelectrons versus θ_p (see text), for pions and protons of 2 GeV/c.
- Fig. 7** Results of a simulation for the r.m.s. errors (chromatic, position, and radiator thickness) versus θ_p .
- Fig. 8** Results of a simulation for the e/π identification capability as the number of standard deviations N_σ versus particle momentum for 0° and 40° θ_p (p_π is the pion threshold momentum).
- Fig. 9** Same as fig. 8 but for π/K identification.
- Fig. 10** Same as fig. 8 but for K/p identification.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10