Identification of charged hadrons with CsI-RICH in HEP

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Fundamentals: the beginning

\[ \cos \theta = \frac{1}{n\beta} \]

\[ \theta_n = \sqrt{1 - \frac{1}{\gamma_n^2}} \]

The Editor of "NATURE" presents his compliments to Mr. P. A. Cherenkov and regrets he is unable to make use of the communication, returned herewith, entitled "VISIBLY RADIATION PRODUCED BY ELECTRONS MOVING IN A MEDIUM WITH VELOCITIES EXCEEDING THAT OF LIGHT".

P. Cherenkov
Nobel Prize 1958
A NEW TYPE OF ČERENKOV DETECTOR FOR THE ACCURATE MEASUREMENT
OF PARTICLE VELOCITY AND DIRECTION

ARTHUR ROBERTS
Department of Physics, University of Rochester

Received 22 June 1960

A new type of Čerenkov radiation detector is proposed, in which the light emitted by a single particle traversing a radiator is imaged, by means of a lens or mirror focused at infinity, on the cathode of an image-intensification tube. The image is a ring whose diameter measures accurately the Čerenkov cone angle, and thus the particle velocity. In addition to coordinates of the center of the Čerenkov image accurately indicate the orientation of the particle trajectory (though not its position). The sensitivity of presently available systems of cascaded image-intensifier tubes allows the photographic recording of the image produced by a single particle. The system is inherently insensitive to background noise. It can observe simultaneously several incident particles whose directions span a wide angle. It may be gated with microsecond coincidence resolving times. It can use cascaded gas Čerenkov radiators; with the former, chromatic dispersion is likely to limit the accuracy. For gas Čerenkov radiators, the attainable accuracy of velocity determination is estimated as \( \Delta v = \pm 0.0002 \) or better; the accuracy of track orientation \( \pm 0.001 \) radians. The range of velocity and orientation simultaneously observable depends on the angular field of view of the objective. Sources of error, their precision analysis, the design of practical systems and some possible applications are discussed.

A. Roberts never built a practical device…

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A. Roberts never built a practical device…

Particle identification based on:

\[
\cos \vartheta_c = \frac{1}{n(\lambda)\beta}
\]

\( \vartheta_c \) measured \( \Rightarrow \) \( \beta \) known

Particle momentum \( p \) measured

\[
m = \frac{p}{\beta \gamma} = p \sqrt{n^2 \cos^2 \vartheta_c - 1}
\]
The pioneers of Cherenkov light imaging

RICH = Ring Imaging CHerenkov

J. Seguinot and T. Ypsilantis

CERN, Geneva, Switzerland

Received 17 December 1976

We have investigated the photo-ionization process in gases and shown that single photon pulse counting in multiwire proportional chambers (MWPC) is possible with about 30% quantum efficiency for photons above 5.5 eV. An application of this technique to image the Cherenkov ultra-violet (UV) radiation is presented.

\[ \cos \vartheta_c = \frac{1}{n \beta} \Rightarrow \left( \frac{\sigma_\beta}{\beta} \right)^2 = \left( \tan \vartheta_c \sigma_\vartheta \right)^2 + \left( \frac{\Delta n}{n} \right)^2 \]

Separation power:

\[ \theta_2 - \theta_1 = n \sigma_{\vartheta c} \]

GOAL: detect the maximum number of photons with the best angular resolution

\[ \sigma_{\vartheta c}^2 = \sum \Delta \vartheta_i^2 \Rightarrow \sigma_{\vartheta c} = \frac{\sigma_\theta}{\sqrt{N_{p.e.}}} \]
Cherenkov angles and photon yields

\[ N_{ph} = 2 \pi LZ^2 \alpha \int_{\beta n>1} \left[ 1 - \left( \frac{\beta_t(\lambda)}{\beta} \right)^2 \right] d\lambda \frac{1}{\lambda^2} \]

\[ N_{ph}[cm^{-1}eV^{-1}]_{\beta=1} = 370 Z^2 \left( 1 - \frac{1}{n^2} \right) \]

\[ N_{p.e.} = 370L \int \sin^2 \vartheta_c(E) \cdot \prod \epsilon_i(E) dE \approx LN_o \sin^2 \vartheta_c \]

Figure of merit \( N_o = 370 \cdot eV^{-1} \cdot cm^{-1} \cdot \langle \epsilon_{total} \rangle \Delta E \)

- The figure of merit is a measure of quality of the optical system and detector performance, limited mainly by photon detection efficiency (PDE 10-20%)
- \( N_o \sim 20 \text{ - } 100 \text{ cm}^{-1} \) typically

<table>
<thead>
<tr>
<th>Radiator</th>
<th>Refractive index</th>
<th>( \gamma_t )</th>
<th>( \theta_{max} )</th>
<th>( \Delta \theta_c = \theta_c(\pi) - \theta_c(K) ) [mrad]</th>
<th>( N_{ph}/(cm \text{ eV}) )</th>
<th>( N_{p.e.}/(cm \text{ eV}) ) (( N_o=50 \text{ &amp; } \beta=1 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Quartz (SiO(_2))</td>
<td>1.47</td>
<td>1.37</td>
<td>47.1(^\circ) (823 mrad)</td>
<td>6.5 @ 4 GeV/c</td>
<td>199</td>
<td>27</td>
</tr>
<tr>
<td>Liquid C(<em>6)F(</em>{14})</td>
<td>1.3</td>
<td>1.56</td>
<td>39.7(^\circ) (693 mrad)</td>
<td>8.4 @ 4 GeV/c</td>
<td>151</td>
<td>20</td>
</tr>
<tr>
<td>Aerogel (SiO(_2))</td>
<td>1.05</td>
<td>3.3</td>
<td>17.8(^\circ) (309 mrad)</td>
<td>22.8 @ 4 GeV/c</td>
<td>34.4</td>
<td>4.7</td>
</tr>
<tr>
<td>C(<em>4)F(</em>{10}) gas at 1 bar</td>
<td>1.0015</td>
<td>18.3</td>
<td>3.13(^\circ) (55 mrad)</td>
<td>29 @ 10 GeV/c</td>
<td>1.1</td>
<td>0.15</td>
</tr>
<tr>
<td>He gas at 1 bar</td>
<td>1.00004</td>
<td>111</td>
<td>0.5(^\circ) (8.9 mrad)</td>
<td>1.4 @ 100 GeV/c</td>
<td>0.03</td>
<td>0.004</td>
</tr>
</tbody>
</table>
RICH: the performance (and limits)

\[ \sigma_{\theta_c} (p.e.) = \sqrt{\sigma_{\theta_c}^2 (chromatic) + \sigma_{\theta_c}^2 (pixel) + \sigma_{\theta_c}^2 (imaging)} \]

- \( \sigma_{\theta_c} (chromatic) \): resolution broadening because of radiator dispersion \( n = n(\lambda) \)
- \( \sigma_{\theta_c} (pixel) \): resolution broadening due to final detector pixel size (spatial resolution)
- \( \sigma_{\theta_c} (imaging) \): effect of imaging method (lens, mirrors, …)

\[ \sigma_{\theta_c} (tot) = \frac{\sigma_{\theta_c} (p.e.)}{\sqrt{N_{p.e.}}} \oplus \sigma_{\theta_c} (track) \]

\[ \langle \sigma_{\theta_c} (chromatic) \rangle \propto E; \Delta E \]

For any combination of radiator and detection bandwidth there is an intrinsic (chromaticity) performance limit

**trend:** shift the detector bandwidth from UV to visible

Improved performance:  a) larger \( N_0 \)  b) higher rate capability
Wider range of materials for detector construction
RICH vs. other PID methods

<table>
<thead>
<tr>
<th>Material</th>
<th>Refractive index @ 600 nm</th>
<th>$p_{\text{threshold}}$ [GeV/c]</th>
<th>$\lambda_{\text{cutoff}}$ [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>1.000035</td>
<td>$\pi$ 16.68, $K$ 59.01, $p$ 112.14</td>
<td>112</td>
</tr>
<tr>
<td>Ar</td>
<td>1.000283</td>
<td>$\pi$ 5.87, $K$ 20.75, $p$ 39.44</td>
<td>124</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>1.000449</td>
<td>$\pi$ 4.66, $K$ 16.47, $p$ 21.48</td>
<td>175</td>
</tr>
<tr>
<td>C$<em>4$F$</em>{10}$</td>
<td>1.0015</td>
<td>$\pi$ 2.5, $K$ 9.0, $p$ 17</td>
<td>136</td>
</tr>
<tr>
<td>Aerogel</td>
<td>1.03</td>
<td>$\pi$ 0.6, $K$ 2.0, $p$ 3.8</td>
<td>300</td>
</tr>
<tr>
<td>C$<em>6$F$</em>{14}$</td>
<td>1.3 (@170nm)</td>
<td>$\pi$ 0.174, $K$ 0.614, $p$ 1.168</td>
<td>165</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>1.33</td>
<td>$\pi$ 0.158, $K$ 0.56, $p$ 1.065</td>
<td>190</td>
</tr>
<tr>
<td>NaF</td>
<td>1.33</td>
<td>$\pi$ 0.161, $K$ 0.567, $p$ 1.079</td>
<td>125</td>
</tr>
<tr>
<td>LiF</td>
<td>1.39</td>
<td>$\pi$ 0.144, $K$ 0.509, $p$ 0.969</td>
<td>105</td>
</tr>
<tr>
<td>quartz</td>
<td>1.46</td>
<td>$\pi$ 0.132, $K$ 0.465, $p$ 0.884</td>
<td>158</td>
</tr>
<tr>
<td>Technique/detectors</td>
<td>$\gamma$ range</td>
<td>comment</td>
<td></td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>----------------</td>
<td>----------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Cont. Cerenkov ed Areogel</td>
<td>$\gamma &gt; 2$</td>
<td>$\pi/K @ \gamma = 6$ (m.i.p.)</td>
<td></td>
</tr>
<tr>
<td>Energy loss multiple ionizations</td>
<td>$\gamma &lt; 6$</td>
<td>$dE/dx = 1/\beta^2$, good discrim. with modest resol. in $dE/dx$</td>
<td></td>
</tr>
<tr>
<td>T.O.F.</td>
<td>$\gamma &lt; 6$</td>
<td>$\sigma = 300$ ps (scintill.) $\sigma &lt; 100$ ps (RPC)</td>
<td></td>
</tr>
<tr>
<td>Cherenkov gas counter</td>
<td>$\gamma &gt; 10$</td>
<td>Not for $4\pi$ acceptance</td>
<td></td>
</tr>
<tr>
<td>Energy loss multiple ionizations</td>
<td>$2 &lt; \gamma &lt; 50$</td>
<td>$s = 2-3%$ required</td>
<td></td>
</tr>
<tr>
<td>RICH</td>
<td>$2 &lt; \gamma &lt; 200$</td>
<td>UV light, acceptance</td>
<td></td>
</tr>
<tr>
<td>TRD</td>
<td>$\gamma &gt; 1000$</td>
<td>Compatti, per discrim. e/h, $\pi/K$, $\pi/K$, $\pi/K$</td>
<td></td>
</tr>
</tbody>
</table>
RICH vs. other PID methods

- TOF & dE/dx cover the lowest momentum range
- For a given Cherenkov radiator several options exist for the photon detector and the choice depends mainly from experimental conditions (and cost…)
- Availability of commercial devices with time resolution of a few 10 ps is pushing the mixing of TOF and RICH techniques (FDIRC, TOP, TORCH, …) for all high luminosity future systems
- Interesting developments are ongoing in the field of micropattern gaseous photon counters (CsI+GEM, TGEM, …) which represent still the most cost-effective solution for large photosensitive surface (> 1 m²)
## RICH design in HEP experiment

**Mirror focusing high momenta**

**Proximity focusing low momenta**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Radiator (n)/L</th>
<th>Photon detector (photosensitive area)</th>
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</thead>
<tbody>
<tr>
<td>ALICE @ CERN/LHC</td>
<td>Proximity focusing</td>
<td>C$<em>6$F$</em>{14}$ (1.029)/1.5 cm</td>
<td>CsI-MWPC (11 m$^2$)</td>
</tr>
<tr>
<td>COMPASS @ CERN/SPS</td>
<td>Mirror focusing</td>
<td>C$<em>4$F$</em>{10}$ (1.0014)/3 m</td>
<td>CsI-MWPC + MAPMT (6 m$^2$)</td>
</tr>
<tr>
<td>PHENIX @ RHIC</td>
<td>Proximity focusing</td>
<td>CF$_4$ (1.0005) / 50 cm</td>
<td>CsI-GEM (1.5 m$^2$)</td>
</tr>
<tr>
<td>LHCb @ CERN/LHC</td>
<td>Mirror focusing</td>
<td>Aerogel (1.03)/ 5 cm C$<em>4$F$</em>{10}$ (1.0014)/80 cm CF$_4$ (1.0005) / 200 cm</td>
<td>HPD (3.3 m$^2$)</td>
</tr>
<tr>
<td>NA62 @ CERN/SPS</td>
<td>Mirror focusing</td>
<td>Ne (1.000063) / 18 m</td>
<td>PMT (0.4 m$^2$)</td>
</tr>
</tbody>
</table>
Proximity focusing RICH
RICH detectors in HEP experiments

- Hadron physics (COMPASS, PANDA….)
- Flavour physics and CP violation studies (BABAR, BELLE, NA62, LHCb,…)
- Nucleon structure (HERMES, COMPASS, TJLAB…)
- Heavy ion physics (PHENIX, STAR, ALICE…)

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</tr>
<tr>
<td>LHCb @ CERN/LHC</td>
<td>Mirror focusing</td>
<td>Aerogel (1.03)/5 cm $C_4F_{10} (1.0014)/$ 80 cm</td>
<td>HPD (3.3 m²)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$CF_4 (1.0005)/200$ cm</td>
<td></td>
</tr>
<tr>
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<td>Mirror focusing</td>
<td>$Ne (1.000063)/18$ m</td>
<td>PMT (0.4 m²)</td>
</tr>
</tbody>
</table>
**RICH detectors in HEP experiments**

**LHCb: RICH1 & RICH2**

Photon detectors: 484 HPDs developed in collaboration with industry (Photonis):
- quartz window with S20 photocathode;
- cross-focusing optics;
- space resolution 2.5 x 2.5 mm$^2$;
- low noise (dark co. rate < 5 kHz/cm$^2$);
- 0.5 Mchannels
RICH detectors in HEP experiments

Two RICHs for $\pi/K$ separation from 1 to 100 GeV/c

LHCb: RICH1 & RICH2

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Direct CP Violation in $B^0$ decays

B $\rightarrow$ hh signal without RICH PID

B $\rightarrow$ hh signal using RICH PID

Asymmetry

Entries / 0.5 ps

$B^0 \rightarrow J/\psi K^0$

$q=+1$

$q=-1$
CsI: a revolution in Cherenkov photon converters

- RD26 (F. Pieu et al., R&D for the development of large area CsI photocathodes, 1992): readout electronics with long integration time (1.2 µs) → low gas gain (6-8 $10^4$)
- Photoelectrons are extracted isochronously → “Fast RICH detectors” (STAR/BNL, HADES/GsI, COMPASS/CERN, JLAB-HALL A, ALICE/CERN)

- CsI processing, QE enhancement (substrate layout and cleaning, slow deposition rate 1 nm/s, thermal treatment at 60 °C for 8 h, in situ encapsulation and dry Ar, in situ measurement of PC response, mounting in glove-box)
- Stable operation under gas (read-out electronics with long integration time (1 µs) → low gas gain ~ $5 \times 10^4$)
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CsI deposition plant at CERN

- Slow deposition rate (~1 nm/s)
- Min. CsI dissociation
- Little or no reaction with residual gases

- Thermal treatment during and after CsI deposition (~8 hrs at 60°C)
- In situ encapsulation under dry Argon before the implementation in the MWPC

In situ QE evaluation under vacuum
ALICE-HMPID at LHC

High Momentum Particle Identification Detector

$\pi/K$: 1-3 GeV/c  
$K/p$: 1.5-5 GeV/c

analogue pad readout (∼160 k channels)
the largest scale (11 m$^2$) application of CsI photocathodes
ALICE-HMPID at LHC

Radiator:
15 mm C₆F₁₄ – n=1.3 @ 170 nm

Photon detector:
- MWPC, CH₄ at atm. P, 8x8.4 mm² pad segmented cathode coated with 300 nm CsI layer
- multiplexed analogue pad readout, ~160K channels
Physics with HMPID in ALICE

Identified particle spectra

Nuclear modification factor

(anti)deuterons

Deuterons vs. centrality
RICH pattern recognition
Pattern recognition with RICH (in STAR at BNL)

The Hough Transform Method (HTM) represents an efficient implementation of a generalized *template matching* strategy for detecting complex patterns in binary images (looking for local maxima in a *feature parameter* space)

\[(x,y) \rightarrow ((x_p,y_p,\theta_p,\phi_p), \eta_c)\]

- cluster coordinate
- photon Cherenkov angle
- impact track parameter
- solution in one dimensional mapping space \(\eta_c\)

RICH in STAR was 1/3 of a module of ALICE-HMPID
COMPASS RICH: High rates

- Hadron PID from 3 to 60 GeV/c
- Photosensitive area ~ 6 m²
- Trigger rates: up to ~30 kHz, beam rates up to ~40 MHz
- RICH in operation since 2002, upgraded in 2006 with Hamamatsu R7600-03-M16 MaPMTs on 25% of active area

MWPC+Csl operation at large rates induces photocathode ageing and/or instability owing to charging up effects and ion bombardment

CsI + GEMs

- fast signals [1-10 ns]
- high gain $[>10^5]$  
- operation in noble gases (mixtures)
- high 2D precision
- largely reduced photon feedback compared to “open” geometry

R. Chechik and A. Breskin
NIM A 595 (2008) 116

Micro-hole + Flipped reverse-bias strip plates: ions are trapped by negatively biased cathode strips

- no ion feedback
- high rate capability $(>10^6 \text{ particles/mm}^2)$
Hadron Blind Detector in PHENIX at RHIC

- Hadron Blind Detector, 50 cm CF\textsubscript{4} gas radiator, proximity focusing, photon blobs imaging by CsI/3-GEM operated with same CF\textsubscript{4} (windowless detector, record $N_0 \sim 300$ cm\textsuperscript{-1})
- Reverse bias in drift region for “hadron blindness”, detect only e+/e-
Thicker Gas Electron Multiplier (THGEM)

**Standard GEM**

Typical parameters:
- 50µm Kapton
- Ø 60µm holes
- 100-200µm pitch
- $10^3$-$10^4$ gain

**THGEM**

- Thickness 0.2~0.5 mm
- Ø 0.2 -1mm holes
- 0.5-1 mm pitch
- $10^5$ gain in single THGEM

F. Sauli NIM A 433 (1997) 531

Periale et al., NIM A478 (2002) 377
Thicker Gas Electron Multiplier (THGEM)

Standard GEM

Typical parameters:
- 50µm Kapton
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THGEM

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- Ø 0.2 -1mm holes
- 0.5-1 mm pitch
- 10⁵ gain in single THGEM

Resistive TGEMs (RETGEM)
- resistive instead of metallic electrodes, providing additional protection against sparks

THGEM and spark-protected RETGEM are robust and cost effective solution for large area RICH applications (COMPASS and ALICE RICH upgrades)

F. Sauli NIM A 433 (1997) 531

V. Peskov et al., NIM A576 (2007), 362

Periale et al., NIM A478 (2002) 377
ALICE & COMPASS RDs on CsI-THGEM counters

**Effective gain:** $0.91 \times 10^6$

**Ar/CH$_4$:** 50/50
Conclusion

Cherenkov light imaging is

- very fertile and versatile technique;
- “gold standard” for hadron ID;
- For a given Cherenkov radiator several options exist for the photon detector and the choice will depend mainly from experimental conditions (and cost…)
- Interesting developments are ongoing in the field of micropattern gaseous photon counters (CsI+GEM, TGEM, …) which represent still the most cost-effective solution for large photosensitive surface (> 1 m²)

Thank you