Physics Notebook - 2010 Steve Sekula's Analysis Notebook

Guest Lecture PHY 7361: Harnessing Cherenkov Radiation

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no tags

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Review of Cherenkov Radiation

You have already learned about Cherenkov Radiation in week 3 or 4. Here I will do a qualitative review of the topic. This is needed to motivate the principles of construction of a technology capable of exploiting Cherenkov Radiation for particle identification.

- Cherenkov Radiation occurs when a charged particle enters a medium with a larger index of refraction. If it has sufficient momentum, $\vec{p} = \gamma m \vec{\beta}$, it is possible for that particle to be traveling in excess of the speed of light in that material:

  $$c' = c/n$$

  (where n is the index of fraction of the material).
- The particle, traveling faster then the local speed of light, induces an asymmetric polarization of molecules in the material; this asymmetry induces the emission of radiation - Cherenkov light - with a well-defined relationship between the speed of the particle, the index of refraction, and the angle between $\vec{\beta}$ and the wave-front:

  $$\cos\theta = \frac{1}{|\vec{\beta}|n}$$

    - Let us go one step further. Let us relate momentum, mass, and Cherenkov angle. It is convenient to write

      $$\beta\gamma = \frac{\beta}{\sqrt{1-\beta^2}} = \left(\beta^{-2} - 1\right)^{1/2}.$$

We can then solve for β:

$$\beta = \left(m^2/p^2 + 1\right)^{-1/2}.$$

From this, we can solve for the Cherenkov angle in terms of n, p, and m:

$$\cos\theta_C = \frac{1}{n}\left(m^2/p^2 + 1\right)^{1/2}.$$

Let us tabulate some values of the Cherenkov angle for a 1GeV particle:

Particle	**Momentum (*GeV*)**	**Cherenkov Angle (mrad)**
Electron	2.5	825
Muon	2.5	824
Pion	2.5	823
Kaon	2.5	807
Proton	2.5	760

- The radiation spectrum has a character, given by the following formula:

$$\frac{dN}{d\lambda} = 2\pi\alpha L\frac{\sin^2\theta}{\lambda^2}$$

- You have to detect these photons if you want to use the radiation to characterize the particle. A typical detector relies on the conversion of photons into electrons (e.g. via the photoelectric effect). The average number of photo-electrons - electrons induced by the Cherenkov photons in some detector medium/technology, is given by the *Frank-Tamm* equation:

$$N_{pe} = 370L\int \varepsilon\sin^2\theta_C dE,$$

  where L is the path-length of the charged-particle trajectory in the radiator (in centimeters) and ε is the overall efficiency of collecting and observing these photons as photoelectrons.

Principles of Detection

Notes:

- a radiator material, with n>1
- transparency in the medium, to allow light propagation
- a detector device, with more sensitivity to the blue/uv end of the spectrum

Motivating Factors for Constructing a Detector

Particle identification plays a critical role in many experiments. My primary example today will be the *BaBar* experiment, although most collider experiments employ some system for particle ID (and a few of those use Cherenkov radiation). If there is time I will also discuss the *Super-Kamiokande* experiment, which is a relevant alternative approach to Cherenkov radiation.

The *BaBar* experiment is designed to detect the decay products of particles produced by the *PEP-II* collider. *PEP-II* operates at 10.58 *GeV* center-of-mass (CM) energy. It's primary design purpose was to measure precisely and accurately the decay properties of B mesons, in order to make possible measurements of CP symmetry violation in B mesons. See slides for a schematic of the process.

The key to unlocking this physics:

- precision position measurement (Δt)
- good momentum and energy resolution (distinction of particles and accurate measurement of their properties)
- particle identification - B decays contain many hadrons that need to be accurately sorted
  - examples: $K-\pi$ swapping between the signal and the "tag" B meson; golden modes such as $B\rightarrow\pi\pi$ and $B\rightarrow K\pi$ must be separated.

Energy loss (dE/dx) measurements in the tracking system are good UP to $p=700\ \mathrm{MeV}/c$, where the particle types are no longer separable (see slides). Kaons and pions from B meson decay have momenta up to $2\ \mathrm{GeV}/c$, with much of the momentum spectrum below $1\ \mathrm{GeV}/c$.

DISCUSSION: where do you want to put a dedicated PID system?
GUIDE: PID requires stronger or more frequent interactions with material, but you cannot disturb tracking.

A separate PID system is therefore a requirement of the experiment. The PID system cannot be located before the tracking system and it cannot be located after the calorimeter. It needs to lie between them, and this places physical constraints on its design:

- thin: it cannot have too many radiation lengths or it will distort the energy resolution of the calorimeter.
- uniform: the material cannot be non-uniform or again it disturbs energy resolution
- fast: *PEP-II* collides at 250 *MHz* and there are typically 10 or more charged particles per collision in this environment. The system must be fast, both to handle collision rate and overlapping information. It should be tolerant of high background rates.

The decision was made to choose a Cherenkov-based system, and the final design is the one I'll discuss today. It illustrates key considerations in the construction of a Cherenkov detector.

The DIRC is a subtype of a larger class of PID detectors called RICH: *Ring-Imaging* Cherenkov devices. A typical RICH uses TRANSMITTED Cherenkov radiation to do the detection. What distinguishes the DIRC is that is uses INTERNALLY REFLECTED Cherenkov radiation to perform detection.

The major components of the DIRC are illustrated on the slides:

- A radiator material with $n_1 > 1$
- highly polished surfaces which enhance total internal reflection of the light
- A second material at the end of the radiator to expand the Cherenkov light trajectory $(n_3 > n_1)$
- A detector system to collect the light

Realities of Detection

The reality of constructing such a system provides design considerations, as well as inherent limitations in the precision of the instrument. Let's discuss some of these:

- chromatic aberration/optical dispersion
  - material properties or non-uniformity can cause different colors to travel at slightly different angles, rather than the single $theta_C$ we assume in the simplistic view of Cherenkov radiation (see slides for an illustration).
  - this makes the index of refraction a function of frequency ($n = n(\nu)$). This also means that we cannot treat the light as traveling at the phase velocity, but rather at the group velocity (which is the speed at which ENERGY propagates in a dispersive medium). Thus the time taken for light to travel the radiator is

    $$t_p = L_p n_g / c$$

    where L_p is the path length of the photon.
- losses due to reflection or attenuation (loss in intensity through the medium)
  - photons will be scattered by the bulk of the material
  - photons will be slightly transmitted out of the radiator when they encounter the surface of the radiator. Each of these will cause a small transmission probability. That means losses of photons due to attenuation or reflection. The DIRC radiator material was designed to be highly transparent, with an internal reflection coefficient of 0.99992. This gives 80% efficiency for light undergoing up to 280 reflections along the radiator.
- radiation hardness
  - susceptibility of the material to radiation damage can affect transmission of blue and uv frequencies. Selection of material requires attention to this detail, especially in modern colliders which usually contain an intense radiation environment.
- space considerations (has to come after momentum measurement but before calorimetry)
- radiation lengths for charged particles
  - see material contribution on slides
- multiple particles passing through radiator material at nearly the same time - separation of signals in time (time resolution)
- detection efficiency
  - the light detection system will naturally have inefficiencies. In fact, in the case of the

DIRC this is the leading cause of efficiency loss.
- unique to the DIRC design: ambiguities, since photons traveling away from the detector are reflected back and arrive at a later time.

The Babar "DIRC" - Detector of Internally Reflected Cherenkov light

Describe the key ingredients in the DIRC:

- radiator material: spectrasil, a manufactured quartz substitute ($< n(\nu) >= 1.473$), with high radiation tolerance, excellent uniformity and index of refraction. Can be polished to a high surface uniformity to achieve the desired coefficient of internal reflection. (see slides for image of spectrasil bar and total internal reflection of blue laser light). Natural quartz is bi-refringent - it has two indices of refraction - and is unsuitable to this purpose.
- mirror on the front end of each bar to reflect light back to the rear of the bar
- an epoxied wedge on the back end of each bar to connect the bar to the water tank. The wedge allows the light exiting the bar at different angles to
- a water tank of de-ionized, recycled water, in which the Cherenkov cone is expanded for readout by the phototubes
- Photomultiplier tubes (more on these later): 11,000 of these, arrayed in a "fly's eye" configuration, each with a light collector to catch and focus photons that otherwise would miss the face of the PMT.

Reconstruction of the Cherenkov Cone

There are a few main ingredients in how DIRC information is used in the reconstruction:

- momentum information from the tracking system (where and at what angle the track enters the DIRC)
- timing information from the tracking system (when the track enters the DIRC).
- spatial information about the bar through which the track passed
- Photons within 300ns of the event trigger are treated as correlated with that event (the trigger occurs some time after the actual crossing of the electron and positron bunches)
- the emission angle and timing of the photons' arrival at the *PMTs*.

Goals of the Reconstruction:

- assign photons to the track that created them
- measure the Cherenkov angle track by track
- perform particle identification

Reconstruction:

- The photons are assigned vectors in 3-D, from the center of the phototube to the center of the face of the radiator bar. The radiator bar dimensions are small compared to the size of the stand-off box (water tank)
- Snell's Law is used to extrapolate the trajectory of the photon in the radiator bar, before

it exited into the water tank.

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

- Together with the track direction, this yields the Cherenkov angle, up to a 16-fold ambiguity that is determined by:
  - the last vertical reflection from the top or bottom of the bar
  - the last horizontal reflection from the left or right side of the bar
  - the last reflection from the top side of the wedge (or not)
  - reflection from the forward mirror (or not)
- a timing cut (within 8ns of the expected arrival time from a track) helps reduce these ambiguities from 16 to 2-3.

Backgrounds:

- background photons arise from the electron and positron beams (synchrotron radiation, etc.) and PMT noise.
- there are 50-300 Cherenkov photons per event, and an order-of-magnitude more background photons (in the trigger window)

Checking the Reconstruction

- Simulation is used to check the reconstruction. The reconstructed Cherenkov angle is compared to the one that was generated in the simulation (the simulation uses theoretical physics and previous measurements of Cherenkov radiation to predict outcomes in the DIRC). The *resolution* is defined as follows

$$\Delta\theta_{C,\gamma} \equiv \theta_{C,\gamma}^{reco.} - \theta_{C,\gamma}^{sim.}$$

***PMTs*: operational information and experimental considerations**

PMTs have a fairly standard configuration:

- a window on the front allows photons to enter the tube
- the window is coated with a thin layer of metal - the cathode. This is typically the part of the tube at the highest negative voltage
- electrons are produced by the photoelectric effect in the cathode and focused into the body of the tube by an accelerating electric field
- a series of dynodes, each at different voltages, leads to an avalanche of electrons. The photo-electrons strike the first dynode, freeing more electrons, which are accelerated up to speed by the next dynode, etc. until the electrons reach the anode.
- The current in the phototube is proportional to the number of photons that entered the tube in the first place.

Features of phototubes:

- system needs to be light-tight, or backgrounds are easily induced
- "dark noise" - fakes resulting from thermal photons, typically produced from the cathode
- magnetic fields can disrupt the phototube: the tubes need to be magnetically shielded.

- gain (the amount of signal amplification) can be adjusted by adjusting the voltages.
- in low-background situations (e.g. dark matter searches), the inherent radioactivity in the GLASS (largely from radioactive potassium) is a limiting factor, inducing fake signals in the PMT

The Superkamiokande Detector

Notes:

- use this as a discussion piece. Engage students on what will happen, what signals will look like, etc.
- Discuss the layout - water, *PMTs*
- Discuss what electron neutrino interactions and muon neutrino interactions will look like
  - electrons and muons have MeV energies.
  - electrons have a "fuzzy" Cherenkov ring, due to the EM showering of the electron as it travels through the water
  - muons have a crisper ring structure

Conclusions

- Cherenkov theory will get you relatively far with detectors
- Detector realities - non-uniformity (aberration/distortion), attenuation, losses due to reflection - need to be strongly considered
- Choose a material wisely: radiation hardness, PMT design, chemical environment
- Simulation is key to understanding the material, but back it up with data
- Think about how fundamental physics will manifest as a detector signature