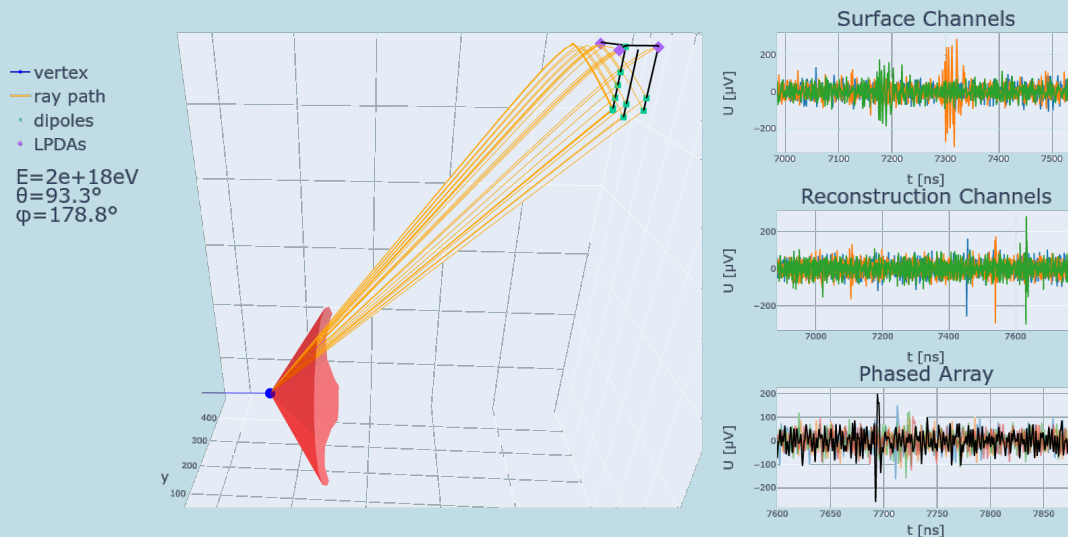


# Radio detection of high energy neutrinos in the Greenland icecap

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## CHAPTER

# 1

# NEUTRINOS

### 1.1 Discovery

### 1.2 Standard model

### 1.3 Outside sources

#### 1.3.1 Cosmic neutrinos

To estimate the temperature of the neutrinos who decoupled at the start of the universe, we can take a look at conservation of entropy [1] (...) The entropy before and after decoupling are:

$$s(a_1) = \frac{2\pi^2}{45} \left(2 + \frac{7}{8}(2 + 2 + 3 + 3)\right) T_1^3 \quad (1.1)$$

$$= \frac{2\pi^2}{45} \frac{86}{8} T_1^3 \quad (1.2)$$

$$s(a_2) = \frac{2\pi^2}{45} (2T_\gamma^3 + \frac{7}{8}(6)T_\nu^3) \quad (1.3)$$

$$(1.4)$$

Conservation of entropy:

$$s(a_1)a_1^3 = s(a_2)a_2^3 \quad (1.5)$$

$$\frac{86}{8}(T_1 a_1)^3 = \left( 2 \left( \frac{T_\gamma}{T_\nu} \right)^3 + \frac{42}{8} \right) (T_\nu a_2)^3 \quad (1.6)$$

$$\frac{86}{8} = 2 \left( \frac{T_\gamma}{T_\nu} \right)^3 + \frac{42}{8} \quad (1.7)$$

$$\frac{44}{16} = \left( \frac{T_\gamma}{T_\nu} \right)^3 \quad (1.8)$$

$$\left( \frac{T_\gamma}{T_\nu} \right) = \left( \frac{11}{4} \right)^{1/3} \quad (1.9)$$

i.e

$$T_\nu = \left( \frac{4}{11} \right)^{1/3} T_\gamma \quad (1.10)$$

$\Phi$

### 1.3.2 Oscillations

### 1.3.3 Majorana

## CHAPTER

# 2

## RADIO DETECTION

Here I'll first give a short overview of the equations governing radiation emitted by moving charges, more specifically of Cherenkov radiation. The reader who wants a thorough explanation and derivation is advised to check out *Chapter 14: Radiation by Moving Charges* from the book *Classical Electrodynamics* by Jackson.

### 2.1 Spectral distribution of radiation

We wish to know the emitted energy per elementary unit solid angle over a certain frequency interval for a moving charge far away from the source. For this we have that the vectorpotential  $\mathbf{A}$ , defined as

$$\mathbf{B} = \nabla \times \mathbf{A} \quad (2.1)$$

takes the form

$$\mathbf{A}(\omega) = \frac{q}{4\pi\sqrt{2\pi}} \sqrt{\frac{\mu}{\epsilon}} \frac{e^{ikr}}{r} \boldsymbol{\alpha} \quad (2.2)$$

with  $q$  the charge,  $r$  the distance from the charge to the observer and

$$\boldsymbol{\alpha} = \int_{-\infty}^{\infty} \boldsymbol{\beta}(t) e^{i\omega(t - \mathbf{e}_r \cdot \mathbf{r}_0(t)/c)} dt \quad (2.3)$$

With  $\boldsymbol{\beta} := \mathbf{u}/c$  and  $\mathbf{u}$  the speed of the particle, the integration is along the path of the moving charged particle. The energy emitted per unit solid angle is given by

$$\frac{d\mathcal{P}}{d\Omega} = R'^2 \mathbf{S}(t) \cdot \mathbf{n}' \quad (2.4)$$

Defining  $\mathcal{E}$  to be the time integral of this, we can reformulate this into (standard practice to integrate over the frequencies)

$$\frac{d\mathcal{E}}{d\Omega} = r^2 \int_{-\infty}^{\infty} d\omega (\mathbf{E}(\omega) \times \mathbf{H}(-\omega)) \cdot \mathbf{e}_r = \int_0^{\infty} \frac{d^2 \mathcal{J}(\omega)}{d\omega d\Omega} \quad (2.5)$$

i.e.  $\frac{d^2 \mathcal{J}}{d\omega d\Omega}$  is the energy radiated per elementary unit solid angle and per elementary unit frequency interval, re-writing gives

$$\frac{d^2 \mathcal{J}(\omega)}{d\omega d\Omega} = 2r^2 \Re\{\mathbf{E}(\omega) \times \mathbf{H}^*(\omega)\} \cdot \mathbf{e}_r \quad (2.6)$$

up to  $\mathcal{O}(r^{-2})$  we get

$$\frac{d^2 \mathcal{J}(\omega)}{d\omega d\Omega} = \frac{q^2 \omega^2}{16\pi^3} \sqrt{\frac{\mu}{\epsilon}} |\mathbf{e}_r \times (\mathbf{e}_r \times \boldsymbol{\alpha})|^2 \quad (2.7)$$

## 2.2 Cherenkov radiation

Cherenkov radiation is like the elektromagnetic equivalent of a sonic boom, a sonic boom happens when something goes faster than the sounds speed in the medium; A particle emits Cherenkov radiation if it goes faster than the light speed in the medium. Choosing the particle trajectory to lie along the z axis we can approximate equation 2.7 as

$$\frac{d^2 \mathcal{J}(\omega)}{d\omega d\Omega} = \frac{q^2}{4\pi} \sqrt{\frac{\mu}{\epsilon}} \beta^2 \omega^2 \delta^2[\omega(1 - \beta \mathbf{e}_r \cdot \mathbf{e}_z)] |\mathbf{e}_r \times \mathbf{e}_z|^2 \quad (2.8)$$

or, in spherical coordinates,  $1 - \beta \mathbf{e}_r \cdot \mathbf{e}_z = 1 - \beta \cos(\theta_c)$  in the delta function. We thus only expect radiation if

$$\cos(\theta_c) = \frac{1}{\beta} = \frac{c}{u} \quad (2.9)$$

I.e if  $u > c$  Cherenkov radiation will be emitted along a cone surface with half angle  $\frac{\pi}{2} - \theta_c$  as illustrated in figure 2.2. Integrating equation 2.8 over the solid angle and formally deviding by the time interval we get:

$$\frac{d^2 \mathcal{J}}{d\omega dt} = \frac{q^2}{4\pi} \sqrt{\frac{\mu}{\epsilon}} \beta \omega \left(1 - \frac{1}{\beta^2}\right) \quad (2.10)$$

We see that the energy is proportional to  $\omega$ , so we expect that most radiation will be emitted "in blue", as seen in figure 2.1.

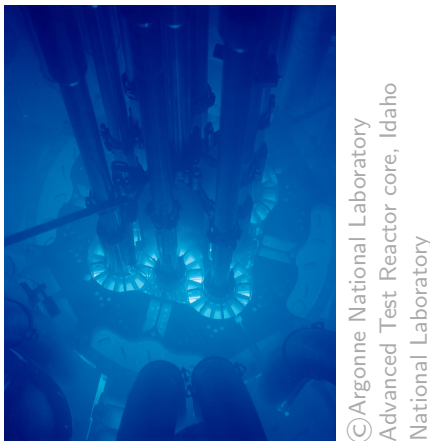


Figure 2.1: Cherenkov radiation in a nuclear reactor

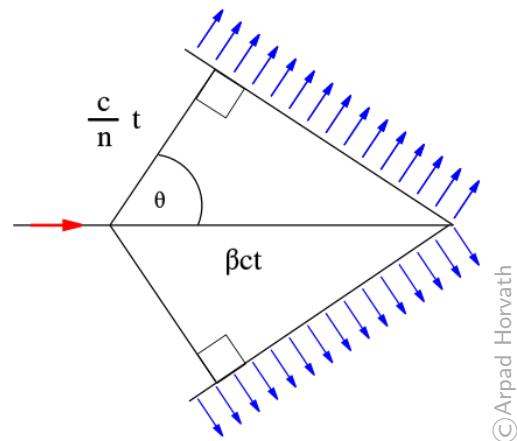


Figure 2.2: Diagrammatic representation of Cherenkov radiation

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- [1] Scott Dodelson. Modern Cosmology. Academic Press, Amsterdam, 2003.