Spectral Monitoring with Cerenkov Photons

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This memo describes the possible use of Cerenkov photons as a light source with a stable spectral shape. The motivation for such a light source is to monitor the spectral response of a telescope. Compared to a lamp, the advantage of a Cerenkov light source is that it has no moving parts and no power supplies, thus making it a potentially stable device. For this initial study, I picked $^{106}_{45}$Rh (Rhodium) as a source of β^- with maximum kinetic energy of $T_e^{\max} = 3.541$ MeV. Its approximate energy spectrum is shown in Figure 1 using just phase space,

$$\frac{dN}{dT_e} \propto E_e P_e (T_e^{\max} - T_e)^2 \tag{1}$$

which is a rather marginal approximation for heavier elements.

Lucite is considered here as the Cerenkov radiator. This material is cheap, easy to machine, and does not produce scintillation light which may be more prone to spectral distortions as a function of temperature and other conditions. The index of refraction for Lucite is $n = 1.49$, which corresponds to a threshold of

$$T_{thr} = m_e \left[(1 - 1/n^2)^{-1/2} - 1 \right] = 0.178 \text{ MeV} \; . \tag{2}$$

Comparing with Figure 1, more than 98% of the β^- from $^{106}_{45}$Rh will generate Cerenkov photons. $^{106}_{45}$Rh is the daughter of $^{106}_{44}$Ru (Ruthenium) which has a half-life of 1.02 years. In addition to the spectrum in Figure 1, the parent $^{106}_{44}$Ru decay releases a β^- with $T_e^{\max} = 0.039$ MeV, which is well below the energy threshold for Cerenkov production.

To estimate the number of Cerenkov photons per decay, we start with the "PDG rule of thumb",

$$\frac{d^2 N_{\hat{C}}}{d\lambda dx} = \frac{4.6 \times 10^5}{(\lambda/\text{nm})^2} \left(1 - \frac{1}{\beta^2 n^2} \right) \text{nm}^{-1}\text{cm}^{-1} \tag{3}$$

where λ is in nm, and $\beta = v/c$ of the emitted beta is 0.67 at the Cerenkov energy threshold, but is usually closer to 1. The average distance traveled in Lucite by a β^- is about 0.5 cm before its energy drops below the Cerenkov threshold. The average value of $\beta = v/c$ is about 0.9, so that $(1 - 1/\beta^2 n^2) \sim 0.4$. The number of Cerenkov photons per nm wavelength band is

$$\frac{dN_{\hat{C}}}{d\lambda} = \frac{9 \times 10^4}{(\lambda/\text{nm})^2} \text{ nm}^{-1} \text{ per decay} \tag{4}$$

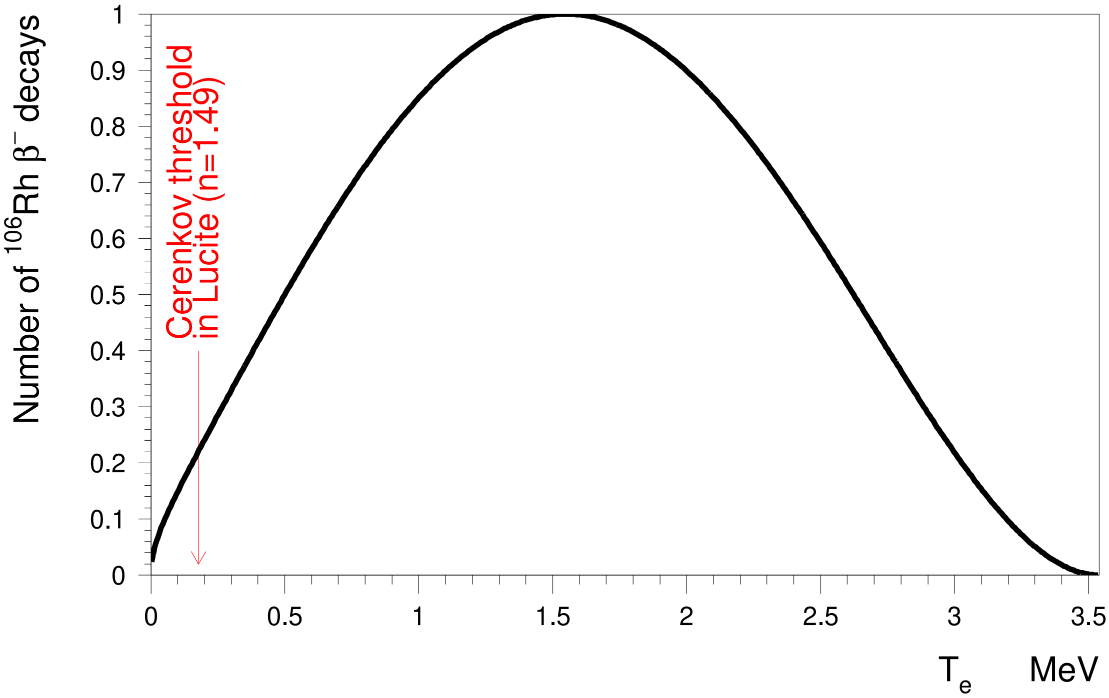

Figure 1: Approximate β^- kinetic energy spectrum for $^{106}_{45}$Rh based on phase space only. The arrow shows the Cerenkov energy threshold in Lucite.

As an example, the average number of Cerenkov photons in a 100 nm band, centered at 500 nm, is 36 per $^{106}_{45}$Rh decay.

Next we need to modify the phase space of the Cerenkov photons so that they appear to come from a point source. The emitted photons have well defined angle and large spatial spread; a cone-shaped Lucite radiator (Fig. ?) can in principle focus the light down to a point at the expense of spreading out the angular part of the phase space.

To estimate the amount of Cerenkov light available for calibration, consider the following parameters,

- 1 mC= 3.7×10^7 decays per second. This is a reasonable source that costs around 10^3 dollars
- distance from source to primary mirror is 10 meters.
- area of primary mirror is $\sim \pi$ m^2.

The number of Cerenkov photons that hit the mirror in one second is Eq. 4 multiplied by

$$\frac{(3 \times 10^7/s) \times \pi \ \mathrm{m}^2}{4\pi R^2} = 7.5 \times 10^4/s$$

which gives the rate at the primary mirror,

$$\frac{d^2N_{\rm mir}}{d\lambda dt} = \left[\frac{6.8\times 10^9}{(\lambda/{\rm nm})^2}\right] {\rm nm}^{-1}s^{-1} \tag{5}$$

The number of Cerenkov photons hitting the mirror is shown in Fig. 2. In the highest SNfactory wavelength band of 900-1000 nm, more than 7×10^5 Cerenkov photons will hit the mirror in one second.

The final step is to convert the number of photons hitting the mirror to the number of photons that hit the focal plane and the spectrograph. To get better throughput to the focal plane, I will assume that a Winston cone can be used in reverse to convert the point-like Cerenkov light source into light rays that are parallel to within the ± 5 arcmin (± 1.4 mrad) aperture of the telescope. The effort in preparing the optics will be a compromise between the cost of the Cerenkov defocussing optics vs. the cost (and hazard) of a stronger $^{106}_{45}$Rh source. To be conservative, assume that the Cerenkov defocussing optics is of poor quality such that only 1% of the Cerenkov light hitting the primary mirror will hit the focal plane. The Integral Field Spectrograph (SNIFS) has a $6'' \times 6''$ field of view, which is 4400 times smaller than the $4.7' \times 9.4'$ field of view of the telescope; therefore assume that the SNIFS see another $\times 4400$ reduction of the Cerenkov light flux. The number of Cerenkov photons that hit the focal plane and the SNIFS is

$$\frac{d^2N_{\rm foc}}{d\lambda dt} = \left[\frac{6.8\times 10^7}{(\lambda/{\rm nm})^2}\right] {\rm nm}^{-1}s^{-1} \qquad \frac{d^2N_{\rm SNIFS}}{d\lambda dt} = \left[\frac{1.5\times 10^4}{(\lambda/{\rm nm})^2}\right] {\rm nm}^{-1}s^{-1} \tag{6}$$

For example, within a 10 nm band centered at 400 nm (1000 nm), there are 56 (9) Cerenkov photons per minute that enter the SNIFS.

Before using $^{106}_{45}$Rh as a source of Cerenkov photons for calibration, the flux and spectral stability must be checked. I am not aware of studies that check the λ^{-2} dependence, nor the stability of the spectrum. Obvious concerns are temperature, pressure, atmospheric conditions, and degradation of the Lucite material which could modify the Cerenkov spectrum. A rough plan for how to develop this technique is as follows:

1. Measure Cerenkov light output with small $^{106}_{45}$Rh source, and compare with calculations. A nano-Curie should be sufficient, and is small enough to avoid any serious handling problems. A PMT and oscilloscope are sufficient to check the rate, but the PMT will have to have an absolute gain calibration. To avoid electron backscattering out of the Lucite, the source should be placed in a small hole bored into the Lucite.

2. The next step is to check the stability of the spectral output. This can be done with two PMTs, each with a different filter that selects a different part of the spectrum. At this point, we do not know the absolute ratio between the two wavelength bands, but the relative ratio can be monitored very accurately. Stability should be studied as a function of temperature, mechanical shock (i.e., shipping), humidity, and any other conditions that it might experience at an observing sight.

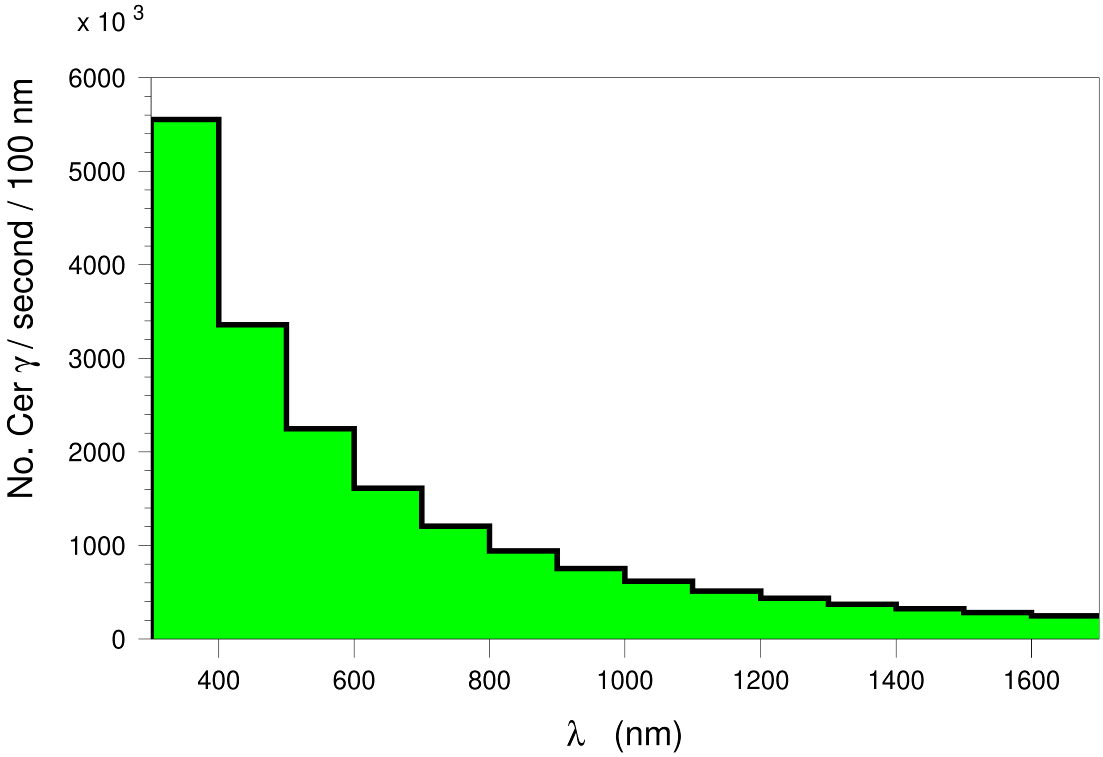

Figure 2: Number of Cerenkov photons per second, and per 100 nm wavelength band, hitting a π m^2 primary mirror located 10 meters from the $^{106}_{45}$Rh source.

3. If the $^{106}_{45}$Rh source has sufficient light output, and its spectral response is stable, then a large source will have to be purchased and encased in a Lucite box that is surrounded by metal. The maximum β^- range from $^{106}_{45}$Rh decay is 2 cm in Lucite, so several cm of Lucite with metal casing should provide sufficient protection. A one mC source is considered a radioactive hazard, and telescope operators may not like having such a thing on their site. This means that a box must be built that will not break, even under extreme shocks such as dropping it from the ceiling.