# Detecting Cherenkov radiation with a cellphone

Proposal for a new, cheaper and simpler method for
detection of Cherenkov radiation

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**Abstract**

Cherenkov radiation has multiple applications in the most prominent areas of modern research. It is the main contributor in the search for cosmic particles, as can be seen in the detector "Super-kamiokande" in Japan. It also enables optical scanning with the ability to potentially replace procedures such as PET and SPECT, which is of both economical and practical interest, as well as of relevance for medical aspects of space flight. The Cherenkov phenomenon is of great importance; however, very few are aware of its existence. This is only one example on how skew the amount of knowledge in particle physics is in comparison to its great importance. The objective of this project is therefore to begin the development of a method through which particle physics becomes easily accessible and suitable for classroom situated experiments, by investigating whether Cherenkov radiation can be detected with a cellphone.

The Cherenkov radiation was created by placing the radioactive isotope strontium-90 in a glass of water, in which the isotope emitted highly energetic B-particles upon its decay. Data was collected of both background- and Cherenkov light, analyzed in terms of blue photons and portrayed in histograms for comparisons and conclusions.

Through analysis of how circumstances such as insolation, radioactivity and camera settings affect the intensity of Cherenkov radiation that is to be detected, a system in which a cellphone can be used to detect the Cherenkov light was able to be constructed.

From the data collected one can draw the conclusion that the light can indeed be detected; however, it is a fragile system in need of further research to achieve its ultimate goal.

# Contents

## Abbrevations

CR - Cherenkov Radiation

PET - Positron Emission Tomography

SPECT - Single-Photon Emission Computed Tomography

CLI - Cherenkov Luminesensce Imaging

OI - Optical Imaging

PMT - Photo Multiplier Tube

# 1 Introductions

## 1.1 Background

Cherenkov radiation is created when a charged particle exceeds the speed of light in a dielectric medium, an electric isolator which can become polarized when exposed to an electric field, e.g. water, in which the speed of light is approximately 225 000 kilometers per second. A charged particle in movement at relativistic speeds induces a temporary electric field, and thus disrupts the structure of the medium which is equivalent to polarizing the atoms. As the medium regains its original structure and the electrons fall back to levels of lower energy, photons will be emitted with an energy corresponding to the energydisparity in the atom, according to eq. 1.

$$h = cf = \frac{hc}{\lambda} \quad (1)$$

For a particle whose velocity is no greater than the speed of light in the topical medium, the light waves interfere destructively; however, for a particle with a velocity larger than that of light in the medium, the waves interfere constructively, thus creating amplified waves of light distributing themselves spherically. The multiple spheres created as the particle moves through the medium sum up to a cone of light. This is what we call Cherenkov radiation (Olausson, 2012). As illustrated in figure 1, the edge of the cone travels i unity in the direction of the yellow arrow, which is dependant on the angle of distribution. The angle $\theta$ at which the radiation is diffracted is dependant on the velocity u as well as wavelength; it is described in eq. 2, assuming that $P_0$ is the momentum of the particle, c is the speed of light, $m_o$ is the rest mass of the particle, h is planck constant and $v = \frac{c}{n\lambda}$.

$$cos\theta = \frac{2(P_0^2c^2 + m_0^2c^4)^{\frac{1}{2}} + (n^2-1)hv}{2P_0cn} \quad (2)$$

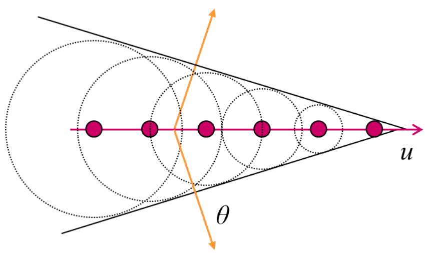


Figure 1: An illustration of the creation of CR. (Alaeian, 2014)

Since the distribution of light is dependant on the wavelength $\lambda$, light of shorter wavelengths will cause a higher value of cos $\theta$; the spectral distribution of shorter wavelengths is larger than that of longer ones. Blue light have shorter wavelengths than colours going towards the red part of the spectrum, and will therefore be at the edge of the cone, and thus hide the red photons. This is one reason as to why the CR appears blue (Cherenkov, 1958). It is also due to the number of photons created of different wavelengths. According to eq. 3, far more photons are created in the blue light spectra than in the green or red parts of the spectrum.

$$\frac{dN}{dx} = 2\pi\alpha(1 - \frac{1}{(\frac{v}{c})^2 n^2}) \int_{\lambda_2}^{\lambda_1} \frac{1}{\lambda^2} dy \tag{3}$$

Eq.3 assumes that $\alpha$ is the fine structure constant 1/137, n is the index of refraction of the material and $\lambda$ is the wave-length in the interval $\lambda_1$ to $\lambda_2$ (Boucher, Gill, Li and Mitchell, 2011).

CR is and has been of great importance in the search for neutrinos. In detectors such as Super-kamiokande in Japan and IceCube on Antarctica, large quantities of PMTs are distributed throughout the dielectric medium, which in these cases are water and ice respectively. The neutrinos interact with the medium and create charged leptons corresponding to the flavour of the neutrino (see table 1) in a process opposite to radioactive decay.

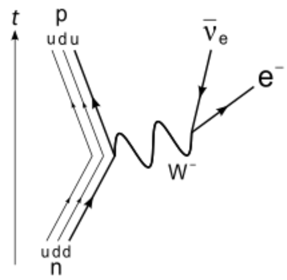


Figure 2: Schematic illustration of the beta-minus decay (wikipedia)

| Neutrino flavor | Lepton |
|---|---|
| Electron neutrino | Electron |
| Muon neutrino | Muon |
| Tau neutrino | Tau |

Table 1: The currently known neutrino flavors and their corresponding leptons

The charged leptons at relativistic speeds will generate CR as described. The PMTs in the detector will register the signals and due to the large quantity, high accuracy data on the properties of the light and thereby the particle can be obtained (Super-kamiokande, 2019).

The CR phenomenon also has numerous substantial applications in current medicinal research. In diagnosing cancer, methods such as Positron Emission Tomography, PET, and Single-Photon Emission computed tomography, SPECT, are used to locate tumors. In both cases, radioactive isotopes are injected into the patients body. The radioisotopes can be labelled with monoclonal antibodies that bind to specific receptors, as is done to achieve FDG, in which case the radioactive isotope Fluor-18 is attacthed to glucose, thus creating the molecule FDG which accumulates by tumors.

When performing PET, radionuclides which decay through beta plus decay are used. During decay, positrions are emitted, which will shortly annihilate with an electron in the tissue. The products of an annihilation is two opposing photons which create the illusion of a straight line. When using FDG or other specific tracers, the intersection of the lines will be at the spot of the tumor. SPECT on the other hand creates three-dimensional images of how the radionuclides are distributed (Ma, Wang and Cheng, 2014)

However, optical imaging, OI, is both easier and less expensive, but has before the discovery of CR been impossible due to the destruction of the light (Olausson, 2012). With CR, Cherenkov luminesensce imaging, CLI, seems to become a possible OI tool. Current research in CLI includes trying to investigate what levels of light intensity are achieveable, the accuracy of the methods and further optimizing of detectors. CLI provides painless, non-invasive examinations of living organisms with the aim of providing images which express the distribution of specific genes, cells and proteins (Boucher, Cherry, Gill, Li and Mitchell, 2011).

A video taken by a Samsung Galaxy S3 mini has its maximum frame rate at 30 frames per second (fps). The number of frames in a video with the length  minutes is determined with the following equation (DeviceSpecifications, 2019).

$$Numberofframes = 1800T \tag{4}$$

## 1.2 Rationale

Today's methods for detection of Cherenkov radiation are expensive, inaccessible and complicated. The lack of simpler detection methods creates an imbalance when in comparison to the demand of the phenomenon in modern research. The aim of the project is to start the development of an alternative method for detection of CR using cheaper equipment and suitable for lower levels of competence and education than what todays methods offer. This will make practical education within particle physics possible, as well as enable a larger quantity of CR related projects. A larger interest and enhanced appreciation might lay grounds for a faster development in the search for cosmic particles and treatments for tenacious diseases.

### 1.3 Question formulations

The main question that is to be examined is whether it is possible to detect CR using a cellphone.

This will be examined through investigation of the following problems:

- What circumstances and properties are necessary in a system suitable for detection of CR in a regular laboratory?
- If possible, what is required of the cellphone?

## 2 Hypothesis and limitations

The radioactive isotope used in this study is the strontium isotope 90-Sr. In decay, 90-Sr emitts electrons with sufficiently high kinetic energy, thus creating CR of higher intensity than what less energetic particles would provide. This is favorable since the sensitivity in the cellphone camera is thought to be quite low in comparison to other detection tools. Other radioactive elements and isotopes might in actuality be better suited; however, 90-Sr is considered energetic enough and has been shown previously successfull in investigations of CR. This study will therefore only examine the CR from this particular isotope.

In the data collected when the CR-source is present, the intensity of photons in the blue light spectrum should evidentially be significantly higher than that of the background light. If shown through quantitative and qualitative collection and analysis of data that the intensity of blue photons is considerably higher when CR source is present than if not, a conclusion that the CR is detected can be drawn.

# 3 Methods

## 3.1 Construction of a functional system in a laboratory situation

In order to perform examinations with the sensitivity required for a cellphone, knowledge on how the prevailing external circumstances had to be adjusted for best possible results was imperative.

When investigating whether it is possible to detect any signals in the circumstancial conditions, studies on previously successful detection materials where done. A system was constructed as illustrated in figure 3; a sodium iodide crystal was attached to a photo multiplier tube, PMT, wired to a source of high voltage on one side and a computer software on the other. In front of the photo cathode a piece of Ceasium-137 was placed. The energy in the photons emitted in decay of 137-Cs is fairly high, 661,657 keV. In fact, it is too high to break loose any electrons in the photo cathode through photoelectric effect. Instead, the primary photons from the cesium-137 excited the sodium iodide crystals, which then deexcited and emitted secondary photons with an energy suitable for the PMT. The signal was then enhanced in the PMT and analyzed in the computer. The amplifier was set as illustrated in figure ?? in appendix A.

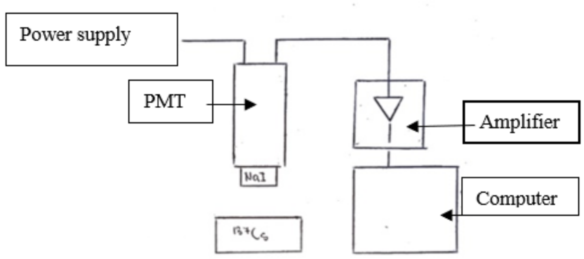


Figure 3: Expermental set-up.

The computer software used for collecting this data is a multi-channel analyzer by the brand Nucleus. It displayed variable diagrams with the channels (energy intervals) on the x-axis and number of photon counts in each channel on the y-axis, and could therefore be used to observe how many photons where detected and of what energy they where.

An identic set of measurements where then performed without the sodium iodide crystal. If they show less signals than those with the crystal, one can establish that a signal has been detected, and that the second set represent the

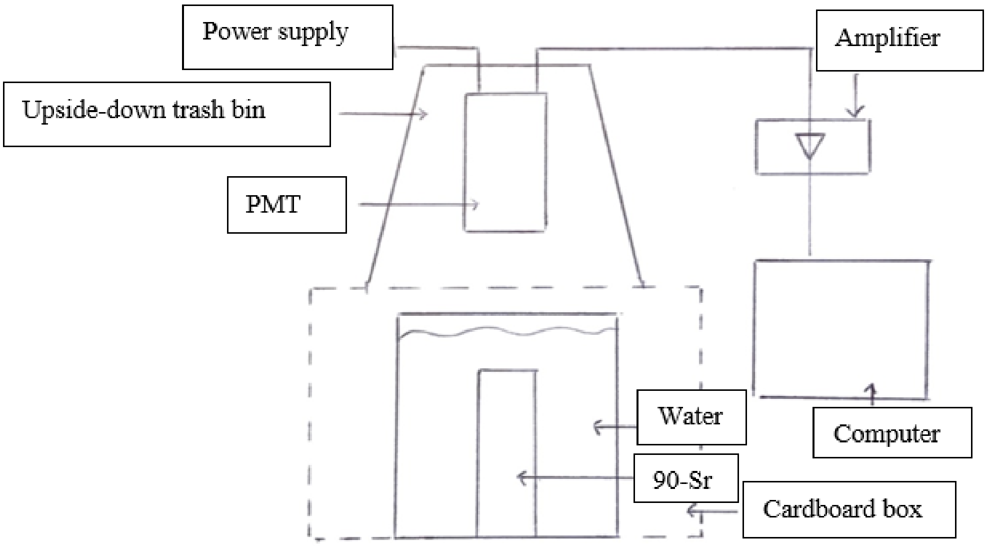


Figure 4: Experimental set-up.

background light.

With the calibration established, data was collected with the presence of the radioactive isotope Strontium-90 (90-Sr) placed in a glass of water, thus creating CR upon its decay. The system was now set up as seen in figure 4. The CR source (strontium-filled glass of water) was placed under a box with a circular hole above the glass. An upside-down trash bin was then positioned to cover the hole. At the top of bin, two small holes where cut big enough for some wires to be drawn through which were connected to the PMT placed inside of the trash bin with its photo cathode positioned towards the CR source. One wire was then connected to a power supply for high voltage, and the other to the computer software used previously through an amplifier.

Data was collected with and without the presence of 90-Sr and therefore CR source. If the intensity of photon counts is shown to be higher in those cases the CR source is present than in those when it is not, one can conclude that the excrescent signals have the CR as source.

While performing these studies, the system were darkened as invariable as possible to avoid differences in the background light. A large black tarpaulin-like blanket was therefore wrapped around the experimental set-up. To avoid any changes, a thread taped to the strontium created an elevator for the strontium. When pulled, the strontium no longer was in the water and could therefore not produce any Cherenkov light, thus allowing for studies on the total light without changing the amount of background light.

Once the system was set up and covered in the blanket, the voltage was turned on as well as the computer software. The software was then turned off after the predetermined time of 600 seconds. Data appeared in the first 200 channels, and these where collected and compiled into tables and diagrams for analysis, se results section.

## 3.2 Detecting the Cherenkov radiation with a cellphone

Once the circumstances required for a functional system set-up where identified, the PMT could be replaced with a cellphone, whose camera was positioned on the hole through which the cables where drawn in earlier experiments. A 6-minute-long video file was collected and then transferred to a computer and run through a program, see appendix A for full code. The program was optimized as the project went on.

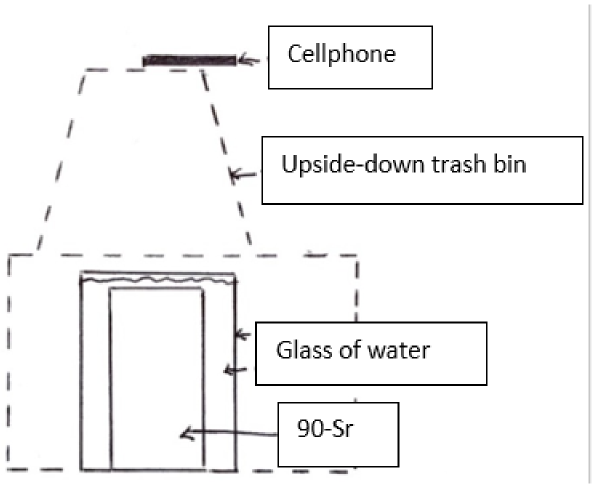


Figure 5: Experimental set-up.

Studies of different cellphones where performed with the aim of finding out which cellphone would work best for the purpose and produce results with the highest clarity. Of an iPhone 8+, Huawei Honor 7 and a Samsung Galaxy S3 mini, the latter seamed to be best suited and was therefore used primarily. A few further tests where done with the Honor 7.

The Samsung Galaxy S3 has several camera settings, and most combinations where tested. Since it became clear quite early which settings where most efficient, not all combinations where examined. For each combination examined, at least three videos where collected of both the light with CR-source present and exclusively the background light.

The video files were then run through a program to lay ground for analysis. Since the videos where only black frames to the human eye, they had to be analyzed by a computer before any results could be visible. The program split the video into its separate image frames and analyzed the intensity of blue light in each frame. This was then portrayed in a histogram with the intensity on the x-axis and number of frames with said intensity on the y-axis. An offset to the right in the histogram was therefore expected from videos taken with the presence of CR source, since this would indicate that the intensity of blue light is higher when the CR source is present than when it is not. Since the cellphone camera had to be turned on and off manually, the program skips the first and last 30 seconds of the film, since that is when the blanket over the system is not completely wrapped around the construction. 30 seconds represent approximately 900 picture frames according to eq. 4, and therefore, the following numbers where submitted to the program.

if count > 900 and count < 9900:

This is the start of a loop which then analyzes the intensity of blue light in each frame within the set interval.

As each video was turned into a histogram, manual analysis was possible.

# 4 Results

## 4.1 Construction of a functional system in a laboratory situation

This part of the study had to be done twice. In the first try, the radioactive activity in the strontium was 1 kBq, and the system was covered in a black blanket. No signals where detected beyond the background light. At the second try, the strontium instead had a radioactive activity at 45 kBq, and the blanket was folded twice before wrapped around the construction, thus creating a thicker barrier. These settings provided the following results.

The diagrams below portray channels, energy intervals, on the x-axis and number of photon counts in each channel on the y-axis. Figure 6-7 show results on the background light. Figure 8 shows the background light after data with the CR source was collected. Figure 9-10 show the results from measurements with the CR source present.

Comparisons between data in Figures 6-8 and 9-10 tell us that the intensity is remarkably higher when the CR source is present than when it is not, which implies that signals from some another source than the background light has been detected. See full set of diagrams in appendix C2, figures 17-23.

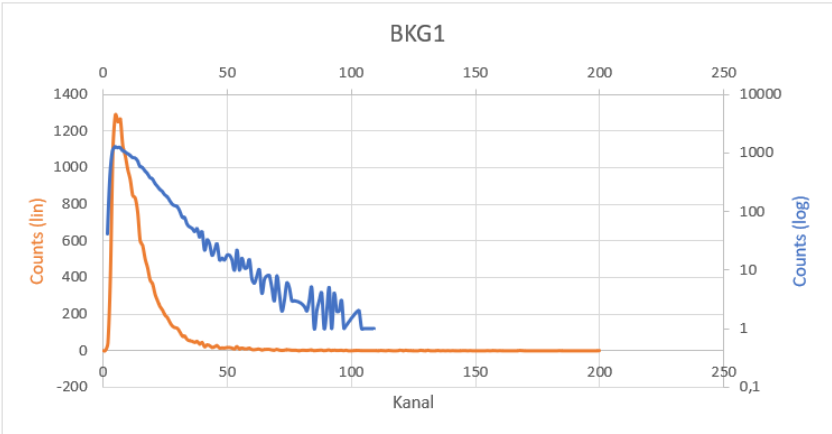


Figure 6: BKG1 was performed as the first one after the voltage was turned on. The strontium is not in the water, and no cherenkov light is therefore produced. The data therefore represent the background light.

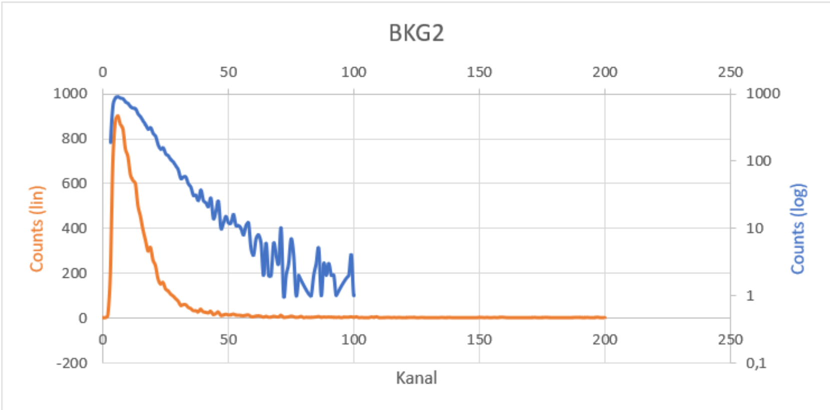


Figure 7: BKG2 was performed directly after BKG1 and is thereby the second one after the voltage was turned on. The strontium was not in the water, and could therefore not produce any cherenkov light. Fewer signals where collected than in BKG1.


Figure 8: BKG4 was performed after both BKG1-2 and SR1-2 to see if the background light changed during the study. This was the first one to be performed after the voltage was turned back on. The intensity detected was slightly higher than former ones.

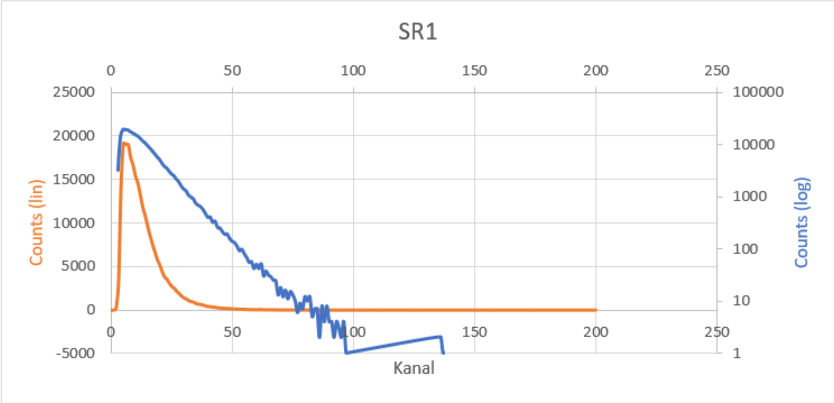


Figure 9: SR1 was performed directly after the voltage was turned back on. The strontium was in the water and could thereby produce cherenkov light. A remarkably higher intensity of light was detected.

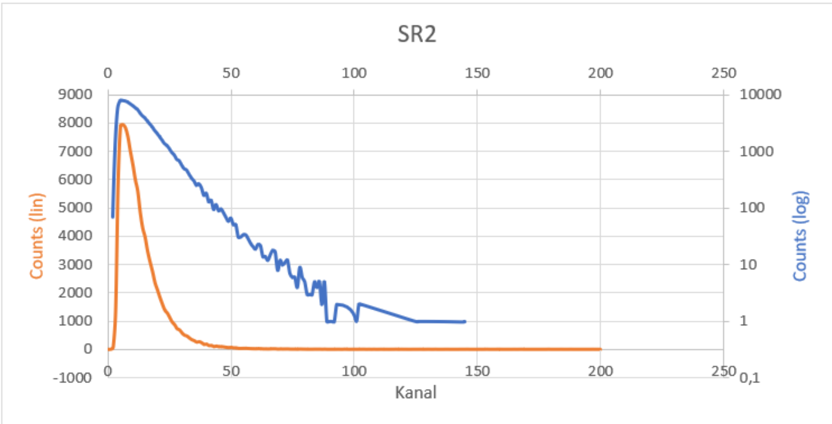


Figure 10: SR2 was performed directly after SR1 and is thereby the second one after the voltage was turned on. During SR2, the lights where turned off in the lab; however, sunlight still lit the room. The intensity detected was lower than SR1; nevertheless, it is still higher than those of the background.

Compilation of all data collected provided the number of detected photons that is shown in table 2. One can read from the table that the intensity of detected photons in the background were in the interval 12 099 to 17 931.

This number was calculated by integrating the photon counts in each channel, see appendix C1 for each channel's contents. In measuring the photons when the cherenkov light was installed, the interval was instead 79 963 to 256 164 photons.

| Diagram | Photon count |
|---|---|
| BKG1* | 17 931 |
| BKG2 | 12 437 |
| BKG3 | 12 099 |
| BKG4* | 14 155 |
| SR1* | 256 164 |
| SR2 | 106 316 |
| SR3 | 79 963 |

Table 2: Compilation of the photon count in each measurment. Measurments marked with a * are performed as the first in order after the voltage was turned on.

The voltage was turned off and turned back on before BKG1, SR1 and BKG4, which seem to have had some impact on the result, thus making the intervals quite wide. The time between the moment the voltage was turned on and when the computer started collecting data is in correlation with how many photons are detected, see appendix B2 for full set of diagrams. The intervals for the background is, however, still significantly lower than the cherenkov-interval.

## 4.2 Detecting the Cherenkov radiation with a cellphone

In testing different cellphones, the Samsung Galaxy S3 seemed to produce best results. The Honor 7 was also quite suitable; however, an iPhone calibrates the background light the program analyzes and is therefore not suitable.

From the data analysis the program provided, one can conclude that in most cases, the videos exposed to CR seem to have a higher intensity of blue light. The histograms produced with the intensity on the x-axis and number of photo frames with respective intensity on the y-axis show what intensity is the most prominent, and therefore most likely the intensity found in the background. If the answer to the question "can one detect Cherenkov light with a cellphone?" is to be "yes", the histogram from CR videos must be shifted to the right, which would imply that a higher number of photo frames have a higher intensity of blue light in them. This heightened intensity can then be expected to have the CR as its source, and it has then been detected with the cellphone.

Most combinations of cellphone settings were tested; however, it became clear quite quickly that if only the resolution was fairly high, the results did not suffer any impact of relevance. A lower resolution gave a higher unreliability; some diagrams where identical to those with higher resolution, where as some were completely different. All data presented below was therefore collected with high resolution. Other camera settings did not seem to matter.

The following histograms are colour-coded in such a way that those in the same shade of blue are from videos recorded on the same day, same cellphone and with the same set-up. More elaborate descriptions of each set of histograms will be provided throughout the following pages of data.

### 4.2.1 Samsung Galaxy S3 mini

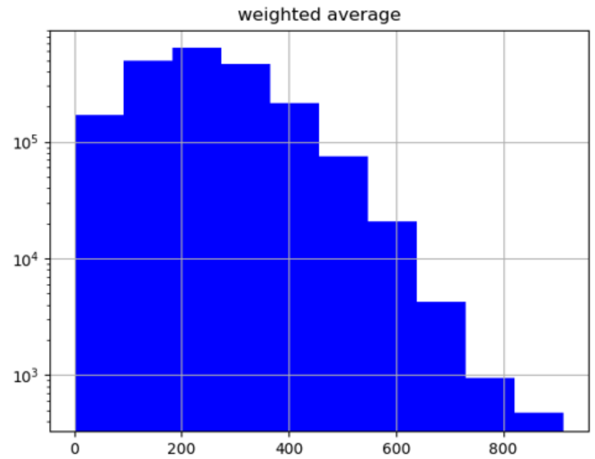


Figure 11: Dragram portraying the background light.

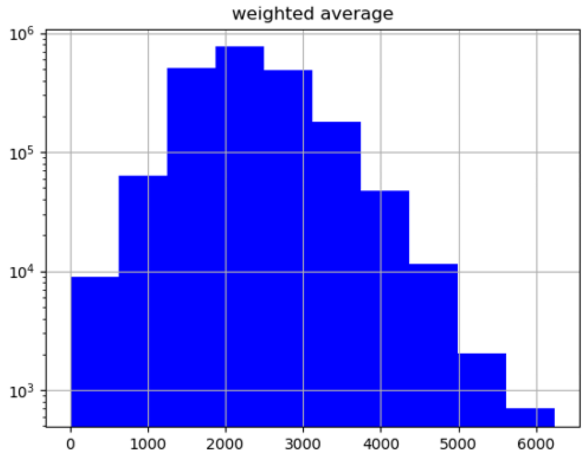


Figure 12: Video portraying the background light as well as the CR light.

Figure 11-12 show the blue light in two videos taken by the Samsung Galaxy S3 mini. Each video is between 6 to 6.5 minutes long. The first histogram is representative of the background light in the circumstantial situation, and the second is filmed with the previously described CR source installed. More histograms with similar results can be found in appendix D, fig 24-27.

Following two histograms show the light in videos filmed under much similar circumstances to figure 11 and 12; however, they were performed on a different day, and therefore show different results. More histograms from the same day can be found in appendix D, fig. 28-32.

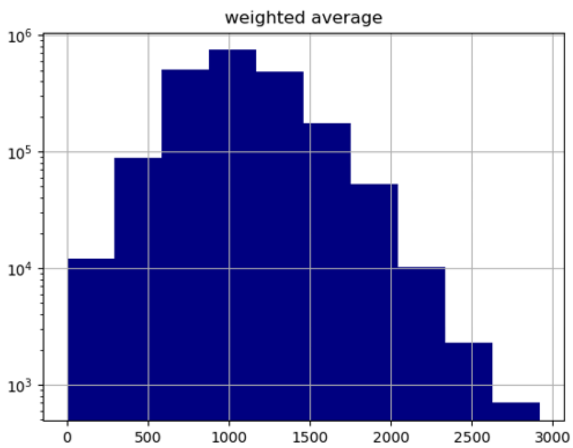


Figure 13: Dragram portraying the background light.

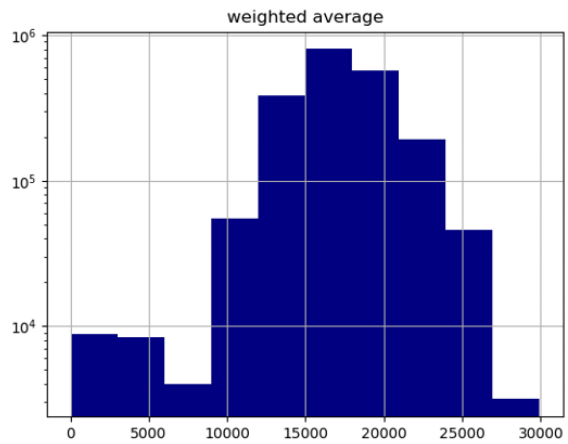


Figure 14: Video portraying the background light as well as the CR light.

As seen in figure 11-14, a much higher number of blue photons where detected when the camera was exposed to a source of CR than when not.

### 4.2.2 Huawei Honor 7

The two histograms below show the light from the exact same circumstances as figure 13-14. They were, however, recorded with a different cellphone, an Huawei Honor 7, which is a more modern type of cellphone, and produces videos of higher quality. It therefore calibrates some background light, which is why the intensity of the invisible blue light this program analyzes is remarkably lower than in videos recorded with the Samsung Galaxy S3. When analyzing these videos, a slight change was therefore required in the program code. The following row was altered so that the array “i” was squared.

Old: vikt.append(i*blue[i])

New: vikt.append(i*i*blue[i])

Full data is found in appendix D, fig 33-36.

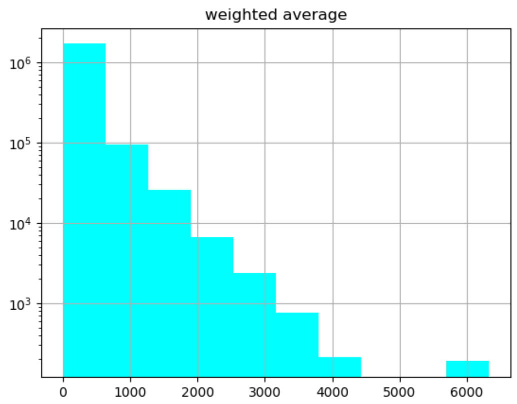


Figure 15: Dragram portraying the background light.

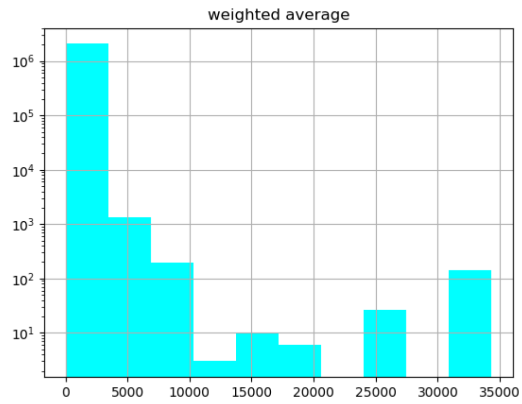


Figure 16: Video portraying the background light as well as the CR light.

# 5 Discussion and analysis

## 5.1 Analysis of result

### 5.1.1 Construction of a functional system in a laboratory situation

One can conclude from results that how well the system is covered in the blanket is in fact crucial. A poorly darkened system will catch too much of the background light, in which case the fairly weak CR signals will be unnoticeable. Above all it is of great importance to keep the darkness invariable throughout all data which is going to be compared to one another.

It also became clear that the power supply did infact have a significant impact on the results, and it is therefore important in further studies to let the power supply stabilize before any measurments. It is, however, not of utter importance since the power supply is not included in the experimental system with the cellphone.

#### 5.1.2 Detecting the Cherenkov radiation with a cellphone

From the histograms produced which correspond to the amount of blue light in each video, it is apparent that the intensity of blue light is in fact higher when a source of CR is present than when it is not, and it therefore seems as though CR can be detected with a cellphone. The system and method are not, however, very reliable. Small changes in the circumstantial conditions seem to obstruct positive results, which is not ideal, and the difference between background- and CR films are not in all cases very large. The small differences create an uncertainty in whether it is due to the CR source or simply smaller fluctuations in the background. Further research is required before the reliability in the method is fully established. The answer to whether Cherenkov radiation can be detected with a cellphone does nevertheless seem to be yes.

### 5.2 Sources of error

#### 5.2.1 Darkening the system

The particles examined in this study are all highly energetic and have a relatively short wave-length. It is therefore not possible to achieve a perfect darkness in the system; all data is contaminated with a significant amount of background light. A large part of the study has been to achieve as dark conditions as possible with the materials available; however, variations in the background have been shown in all data.

When performing studies with cellphone, the camera had to be turned on and off manually, which meant it was impossible to ensure the darkness would be completely invariable throughout all videos. This is the most dominant source of error. In further research, this would be the overriding issue to investigate, see section ”Future development and research”.

In adapting the program to the method, the first and last 900 frames where not analyzed, due to the issue described above. Since it is not known exactly how many frames where contaminated, signals in the removed intervals might have been missed.

### 5.2.2 Impact from power supply

As already discussed, the time between the moment on which the voltage was turned on until the data collection started seemed to have a direct impact on the results when studying the system with a photo multiplier tube. The data collected directly after it was tuned on showed much higher intensity of photons than the data collected afterwards. A higher certainty would be brought to the results through a more careful study of the impact it has and the reliability of the power supply.

### 5.2.3 Focal point of Cherenkov source

The glass in which the cherenkov radiation was created should have focal point above itself in which the photons emitted would congregate. In this specific point, it would be ideal to place the photo multiplier tube or the cellphone camera, thus ensuring that the maximum number of photons are detected. It is however a more complicated equation than one might think, since the photons emitted will bounce of the walls before leaving the water at random places. The transition from water to air also diverges the photon from its original path. The large number of unknown factors and lower level of relevance made it slightly omitted. It would be advantageous and interesting for future development to examine the relationship between the strontiums position and signals detected, and thereby investigate if there is a focal point in which the detector in question should be placed.

### 5.2.4 Amount of data

A higher reliability could be brought to the study through a higher quantity of data to analyze. This will, however, always be a fact. A quite high number of data has been collected, and the conclusion is therefore quite reliable. In developing the method to achieve a laboration suitable for a classroom situation, a much higher number must be performed.

## 5.3 Future development and research

This project offers a wide range of aspects to develop and perform further research on. All sources of error discussed are examinable. Specifying what circumstances are required for the experiment to be fully functional and reliable is crucial in order for it be performed as a classroom lab, which is the ultimate goal.

The method is for now only operative with two certain cellphone models, the Samsung Galaxy S3 mini and the Honor 7. For other models, the program must be adjusted, and for most models the method does not work at all. Further optimizing is therefore requisite before it can become a classroom lab. However, since this is not part of the problem investigated in this study, which is to answer whether the CR can be detected at all, it is not of higher relevance for the project. It is furthermore the next step in developing the lab.

Further, it would be of highest interest to investigate what results could be achieved with better darkening, a clearer picture of how the positioning affects the intensity, better knowledge on the effect of the power supply and with different radioactive isotopes. Out of these, the darkening is of highest significance, since it is the most prominent reason for unreliability when collecting data with the cellphone. It would be ideal if a way through which the darkness could be held intact throughout all the data, since it is rather the differences between different videos that is of relevance than the intensity itself. Despite the fact that a darker system increases reliability, even more accuracy would be brought by keeping this factor invariable.

If given the oppurtunity, what I would primarily investigate is the darkening. One proposition is to mimic the elevator for the strontium used in the PMT experiments and incorporate a similar construction in the cellphone experiments, and thereafter adapt the program to analyse two different parts of one video separately. This would allow for collection of both background - and CR data under identical circumstances and not needing to turn the camera on and off between them. One large source of error is then completely eliminated.

Due to its simplicity, it would be of interest to further optimize the sensitivity of the method and thus perhaps develop a cancer identification method with a frugality suitable for space flight. To identify tumors early on in an environment in which astronauts are exposed to high doses of radiation is imperative when working towards exploring further out in space, since the health of the astronauts is a crucial factor in the success of the mission.

## 6 Acknowledgements

I deeply thank prof. Richard Brenner for initially bringing the exciting concept of Cherenkov radiation to my attention and guiding me through this project, and Uppsala University for premises and required equipment. I also express thanks to the Swedish Astronomical Youth Association for the financial support without which the project would not be possible. I further thank Anders Crona and Kitas Gymnasium for helpful assistance and believing in

my project.

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# 8 Appendices

## Appendix A

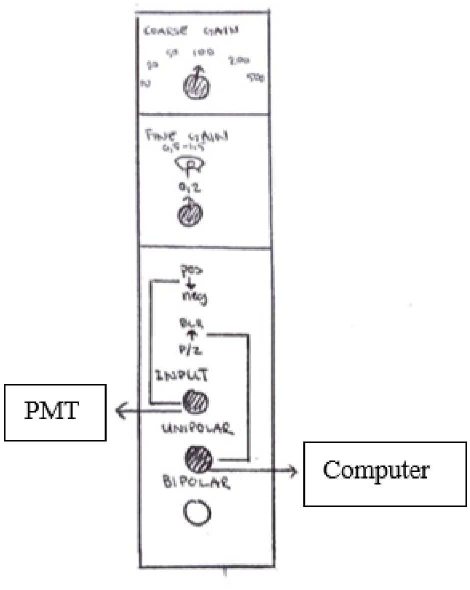


Figure 17: Settings on amplifier

## Appendix B

The code which analyzed the videos. The algorithm splits the video into its picture frames, analyzes the amount of blue light in each picture and portrays in histograms.

```
import cv2
import os
import sys
from PIL import Image
from matplotlib import pylab
import numpy
import glob
import csv
import os.path
import time
import math
import matplotlib.mlab as mlab
import matplotlib.pyplot as plt
print(cv2.__version__)
#Get current path
path = os.getcwd()
#Open result files
resultFile = open("Signal.csv",'wb')
wr = csv.writer(resultFile, dialect='excel')
resultFile = open("Background.csv",'wb')
bg = csv.writer(resultFile, dialect='excel')
resultFile=open("RawImage.csv",'wb')
rw =csv.writer(resultFile, dialect='excel')
#Open film
```

```
vidcap = cv2.VideoCapture('film.mp4')
print "File open?     ",vidcap.isOpened()
success,image = vidcap.read()
count=0 #counter for frames, amount of pictures in film
rcount=0 #counter for raw frames
scount = 0 #counter for signal frames, pictures with signal
bcount = 0 #conter for background frames, pictures with no signal
#print(success)
success = True
VMhist=[]
#Read frame and write frame
while success:
 success,image = vidcap.read()
 if success==True:
   count += 1
 # Write frame to image
   cv2.imwrite("frame.jpg", image)
 #  Read image from file
   im = Image.open("frame.jpg") #image file created
 # First a option to skip the first part of the film that may be contaminated by light
   if count > 1200 and count < 9900:
 # Do the discrimination calculating the if count > 1200 and count < 9900:signal and applying a
   threshold
    pixels = im.load() # colors are added to variabel pixel
    hist = im.histogram() # colorpixels added to histagram
    blue = hist[529:768] # color blue is chosen, may vary with cellphone
    if rcount<10:
     rw.writerow(hist)
```

```
     rcount+=1
#   signal=sum(blue)
    signal=0 # signal is defined as 0
    vikt=[] # a vector
    for i in range (len(blue)):
      vikt.append(i*blue[i])  # every position in the array is the array index multiplied by the array
      value in areay with the name "blue". For some cellphones, \i" might need to be squared
      signal=signal+vikt[i] # signal is the sum of array with the name vikt
      VMhist.append(signal)
 # Define as signal if over treshold . Write data of events to excel file and store 10 first signal
   frames.
    if signal >=4000:
       wr.writerow(blue)
       if scount<10:
         print "signal frame: ", count
         cv2.imwrite("signal%d.jpg" % scount, image)     # save frame as JPEG file
         scount += 1
  # Otherwise background. Write data of events to excel file and store 10 first background frames.
       else:
        bg.writerow(blue)
        if bcount<10:
         cv2.imwrite("background%d.jpg" % bcount, image) # save frame as JPEG file
         bcount += 1
 else:
  # Plot histogram
  plt.hist(VMhist, facecolor='blue')#blue can be changed to arbitrary color
  plt.title('weighted average')
  plt.grid(True)
```

```
plt.yscale('log')
plt.show()
 #Print quick statistics
print 'Frames analysed:              ', count
print 'Signal frames found:          ', scount
print 'Background frames found::     ', bcount
```

## Appendix C1

Number of photon counts in each channel when collecting data with photo multiplier tube. Left number describes number of channel; value on the right are the photon counts in respective channel.

| | | | | | |
|---|---|---|---|---|---|
| BKG1 | 15 602 | 31 103 | 47 15 | 63 10 | 79 0 |
| 0 0 | 16 576 | 32 81 | 48 16 | 64 4 | 80 3 |
| 1 2 | 17 503 | 33 79 | 49 15 | 65 7 | 81 3 |
| 2 42 | 18 454 | 34 61 | 50 18 | 66 8 | 82 2 |
| 3 411 | 19 388 | 35 55 | 51 18 | 67 8 | 83 3 |
| 4 1095 | 20 367 | 36 52 | 52 15 | 68 5 | 84 5 |
| 5 1289 | 21 310 | 37 46 | 53 10 | 69 3 | 85 1 |
| 6 1252 | 22 274 | 38 51 | 54 22 | 70 8 | 86 2 |
| 7 1266 | 23 242 | 39 37 | 55 10 | 71 4 | 87 3 |
| 8 1121 | 24 223 | 40 45 | 56 16 | 72 2 | 88 4 |
| 9 1067 | 25 195 | 41 22 | 57 11 | 73 3 | 89 1 |
| 10 992 | 26 181 | 42 33 | 58 11 | 74 6 | 90 2 |
| 11 937 | 27 155 | 43 28 | 59 15 | 75 5 | 91 5 |
| 12 850 | 28 135 | 44 18 | 60 7 | 76 3 | 92 1 |
| 13 836 | 29 127 | 45 22 | 61 6 | 77 3 | 93 4 |
| 14 758 | 30 123 | 46 28 | 62 8 | 78 3 | 94 2 |

95 2
96 3
97 1
98 3
99 0
100 0

BKG2
0 0
1 0
2 10
3 190
4 695
5 878
6 901
7 863
8 844
9 754
10 720
11 639
12 613
13 598
14 500
15 453
16 393
17 346
18 298
19 313
20 257
21 232
22 173
23 150
24 157
25 128
26 120
27 105
28 97
29 85
30 74
31 55
32 58
33 58
34 46
35 41
36 31
37 31
38 26
39 37
40 26
41 24
42 21
43 28
44 14
45 18
46 25
47 10
48 12
49 15
50 12
51 12
52 16
53 11
54 11
55 10
56 8
57 11
58 12
59 5
60 4
61 7
62 8
63 6
64 2
65 6
66 2
67 2
68 6
69 4
70 3
71 10
72 1
73 2
74 3
75 7
76 4
77 1
78 2
79 6
80 0
81 2
82 1
83 1
84 2
85 3
86 5
87 1
88 3
89 2
90 3
91 2
92 2
93 1
94 2
95 0
96 2
97 2
98 2
99 4
0 1

BKG3
0 0
1 1
2 9
3 146
4 693
5 906
6 846
7 847
8 809
9 753
10 662
11 650
12 572
13 520
14 489
15 431
16 376
17 368
18 280
19 293
20 221
21 230
22 207
23 176
24 133
25 125
26 129
27 111
28 102
29 69
30 69
31 73
32 58
33 52
34 50
35 36
36 38
37 41
38 43
39 27
40 28
41 22
42 23
43 25
44 14
45 15
46 23
47 18
48 14
49 18
50 11
51 17
52 9
53 15
54 11
55 6
56 8

57 9
58 4
59 6
60 6
61 9
62 4
63 1
64 3
65 4
66 4
67 3
68 7
69 5
70 5
71 7
72 4
73 5
74 1
75 4
76 4
77 4
78 4
79 2
80 3
81 2
82 2
83 1
84 0
85 1
86 2
87 3
88 0
89 3
90 5
91 1
92 3
93 2
94 2
95 0
96 1
97 1
98 1
99 0
100 1

BKG4
0 0
1 0
2 15
3 261
4 1074
5 1514
6 1598
7 1520
8 1475
9 1343
10 1216
11 1162
12 1099
13 1006
14 832
15 772
16 678
17 625
18 530
19 478
20 429
21 362
22 335
23 281
24 255
25 229
26 196
27 158
28 160
29 143
30 123
31 98
32 121
33 89
34 69
35 64
36 67
37 58
38 52
39 42
40 32
41 41
42 43
43 28
44 23
45 30
46 25
47 28
48 22
49 19
50 18
51 26
52 20
53 13
54 7
55 7
56 16
57 10
58 14
59 7
60 10
61 15
62 6
63 7
64 3
65 1
66 7
67 4
68 5
69 2
70 3
71 4
72 3
73 1
74 6
75 2
76 1
77 1
78 1
79 2
80 0
81 2
82 0
83 2
84 5
85 2
86 2
87 2
88 4
89 2
90 2
91 3
92 1
93 0
94 5
95 2
96 1
97 0
98 1
99 0
100 0

SR1
0 0
1 0
2 218
3 3219
4 14044
5 19098
6 18989
7 18949
8 17474
9 16599
10 15331
11 14511
12 13182
13 11795
14 10807
15 9632
16 8526
17 7551
18 6681

19 5779
20 5192
21 4419
22 3799
23 3537
24 3057
25 2713
26 2486
27 2152
28 1916
29 1599
30 1391
31 1288
32 1063
33 979
34 901
35 743
36 682
37 639
38 564
39 471
40 401
41 402
42 321
43 335
44 256
45 248
46 212
47 189
48 189
49 156
50 139
51 131
52 112
53 92
54 97
55 80
56 68
57 55
58 56
59 42
60 50
61 42
62 51
63 30
64 37
65 31
66 29
67 25
68 24
69 13
70 18
71 12
72 16
73 11
74 15
75 13
76 10
77 6
78 9
79 7
80 12
81 10
82 12
83 5
84 7
85 7
86 2
87 8
88 4
89 8
90 4
91 4
92 2
93 4
94 3
95 2
96 4
97 1
98 3
99 0
100 1

SR2

0 0
1 1
2 70
3 1349
4 5853
5 7916
6 7948
7 7840
8 7519
9 7002
10 6542
11 6005
12 5597
13 4850
14 4295
15 3964
16 3472
17 3092
18 2753
19 2359
20 2105
21 1839
22 1601
23 1386
24 1286
25 1126
26 963
27 870
28 730
29 688
30 576
31 499
32 471
33 397
34 340
35 303
36 254
37 269
38 231
39 169
40 183
41 130
42 137
43 95
44 115
45 90
46 97
47 83
48 69
49 59
50 67
51 51
52 51
53 31
54 31
55 34
56 34
57 29
58 24
59 21
60 19
61 23
62 22
63 14
64 14
65 12
66 15
67 18
68 17
69 8
70 12
71 10
72 11
73 12
74 7
75 6
76 6
77 4
78 9
79 6
80 5
81 3
82 3
83 3

84 5
85 4
86 5
87 2
88 5
89 1
90 1
91 1
92 1
93 2
94 2
95 0
96 4
97 2
98 0
99 1
100 2

SR3
0 0
1 1
2 43
3 967
4 4325
5 6045
6 6169
7 6014
8 5663
9 5226
10 4802
11 4562
12 4058
13 3619
14 3258
15 2882
16 2663
17 2325
18 2014
19 1802
20 1576
21 1399
22 1209
23 1072
24 918
25 827
26 725
27 670
28 550
29 486
30 401
31 413
32 332
33 294
34 259
35 225
36 213
37 179
38 159
39 151
40 132
41 108
42 113
43 104
44 96
45 82
46 72
47 60
48 59
49 57
50 50
51 42
52 46
53 37
54 33
55 27
56 18
57 18
58 21
59 17
60 19
61 23
62 14
63 7
64 14
65 12
66 18
67 4
68 7
69 6
70 5
71 6
72 8
73 7
74 5
75 2
76 3
77 5
78 3
79 5
80 4
81 2
82 8
83 3
84 0
85 7
86 5
87 4
88 1
89 3
90 2
91 0
92 1
93 2
94 1
95 1
96 1
97 0
98 1
99 1
100 6

## Appendix C2

All data from appendix B1 compiled into diagrams.

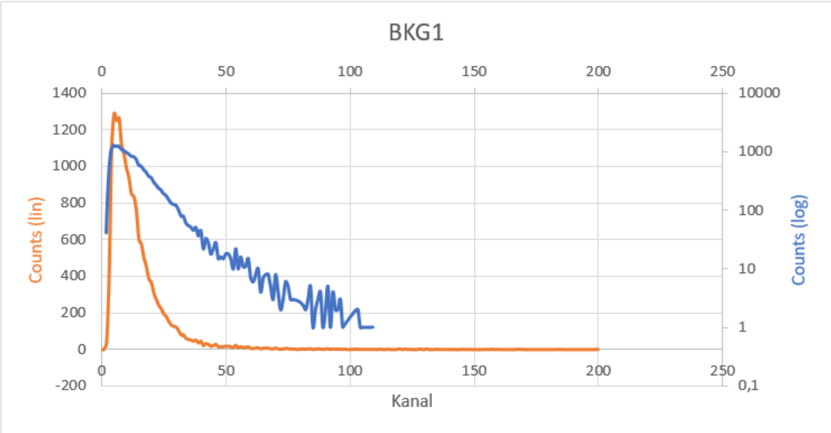


Figure 18: BKG1 was performed as the first one after the voltage was turned on. The strontium is not in the water, and no cherenkov light is therefore produced. The data therefore portrays the background light.

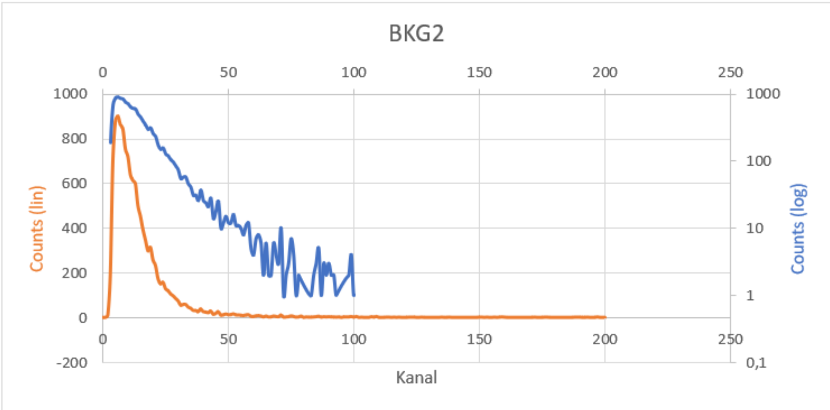


Figure 19: BKG2 was performed directly after BKG1 and is thereby the second one after the voltage was turned on. The strontium was not in the water, and could therefore not produce any cherenkov light. Fewer signals where collected than in BKG1.

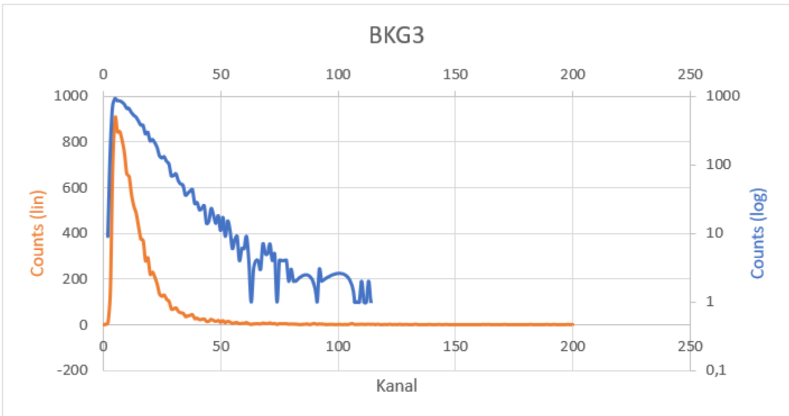


Figure 20: BKG3 was performed directly after BKG2 and is thereby the third one after the voltage was turned on. The strontium was not in the water and could therefore not produce any cherenkov light. Fewer signals where detected than in both BKG1 and BKG2.


Figure 21: BKG4 was performed after both BKG1-3 and SR1-3 to see if the background light changed during the study. This was the first one to be performed after the voltage was turned back on. The intensity detected was slightly higher than former ones.

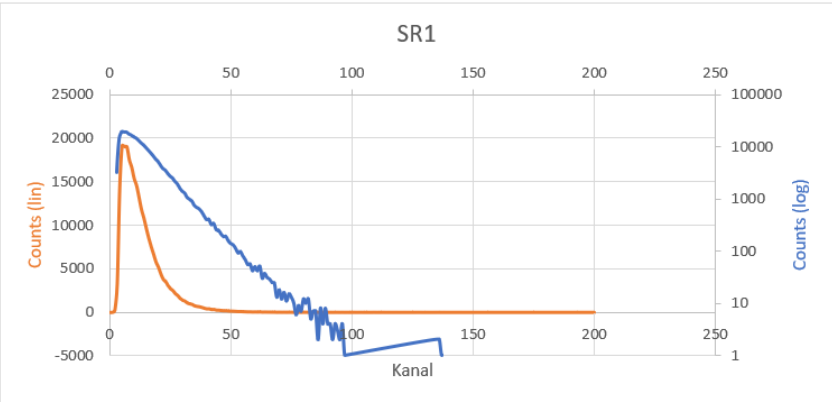


Figure 22: SR1 was performed directly after the voltage was turned back on. The strontium was in the water and could thereby produce cherenkov light. A remarkably higher intensity of light was detected.

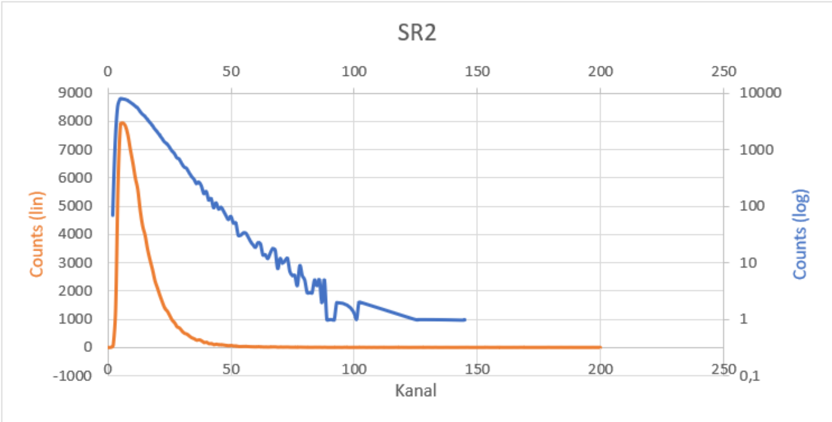


Figure 23: SR2 was performed directly after SR1, and is thereby the second one after the voltage was turned on. During SR2, the lights where turned off in the lab; however, sunlight still lit the room. The intensity detected was lower than SR1; nevertheless, it is still higher than those of the background.

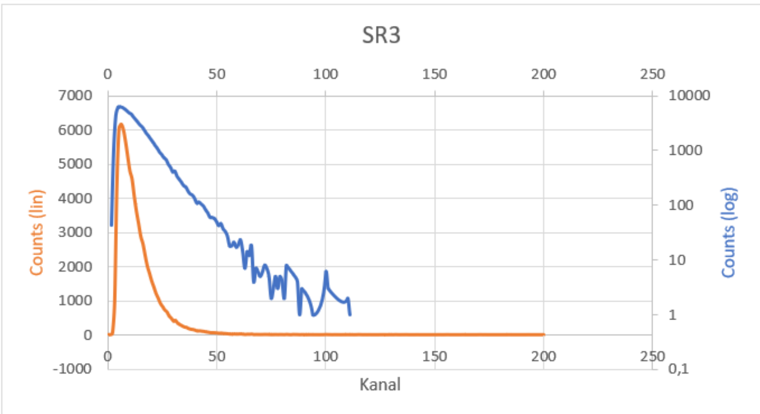


Figure 24: SR3 was performed directly after SR2 and is thereby the third one after the voltage was turned on. The strontium was in the water and could therefore produce cherenkov light. The intensity detected was lower than SR1 and SR2 but still higher than those of the background.

## Appendix D

Each diagram represents one video of either the background light or the light when a source of cherenkov light is present. Diagrams in the same shade of blue portray videos recorded with same cellphone and on the same day.

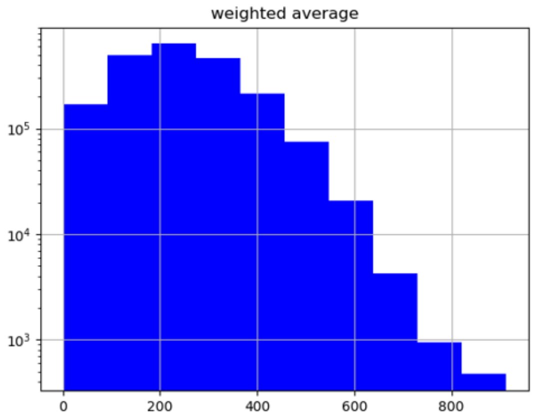


Figure 25: Background with Samsung Galaxy S3

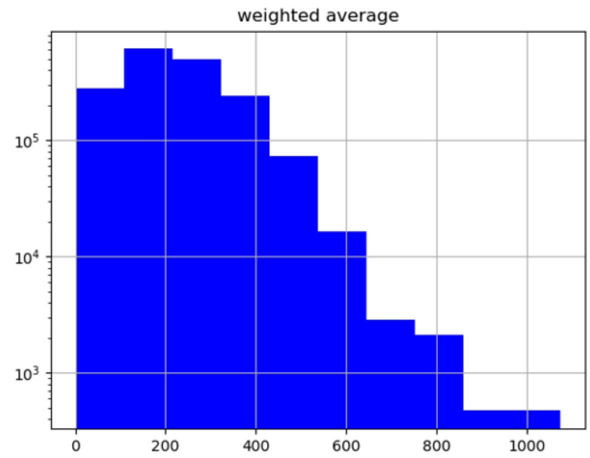


Figure 26: Background with Samsung Galaxy S3

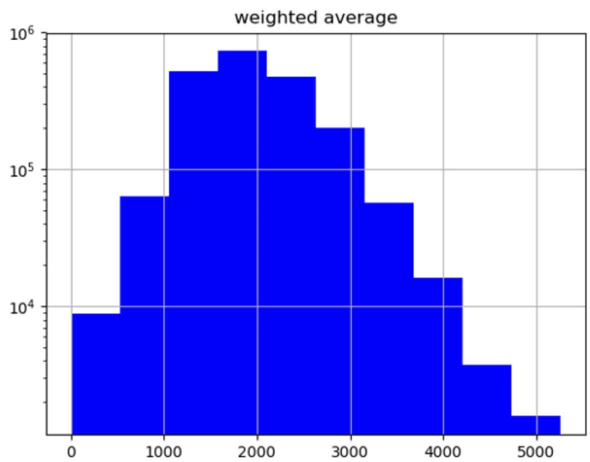


Figure 27: Cherenkov light with Samsung Galaxy S3

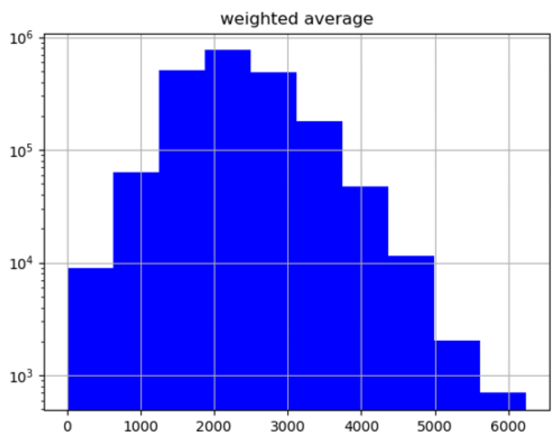


Figure 28: Cherenkov light with Samsung Galaxy S3

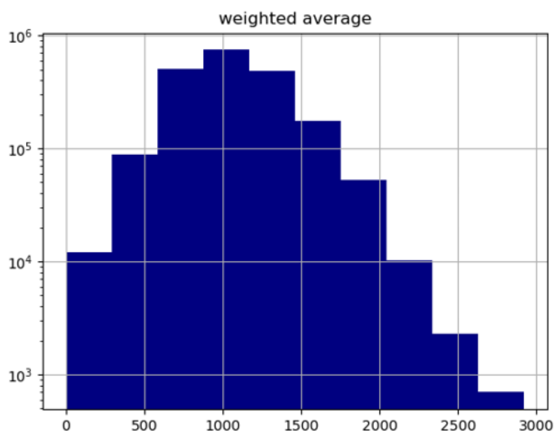


Figure 29: Background with Samsung Galaxy S3

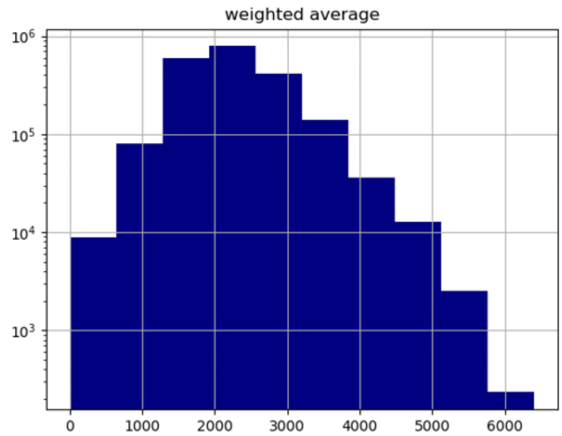


Figure 30: Background with Samsung Galaxy S3

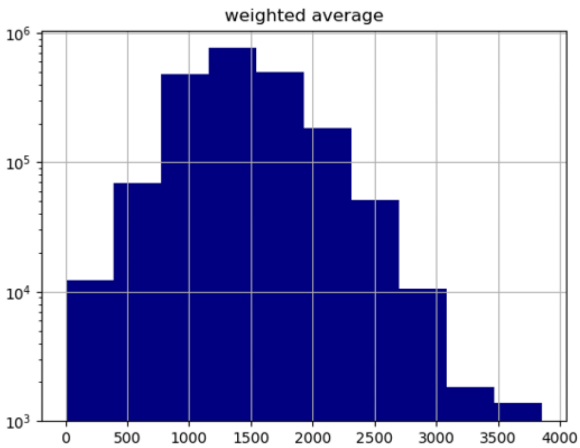


Figure 31: Background with Samsung Galaxy S3

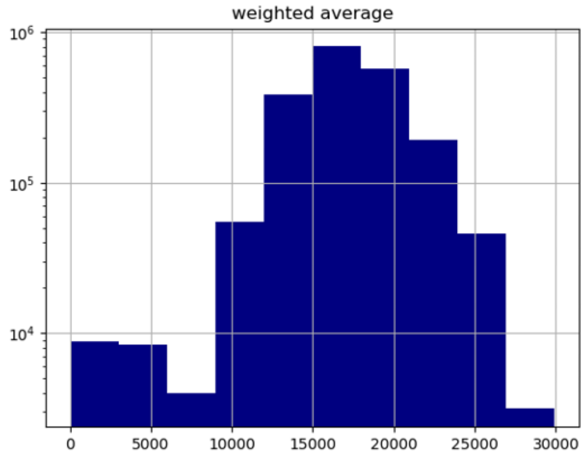


Figure 32: Cherenkov light with Samsung Galaxy S3

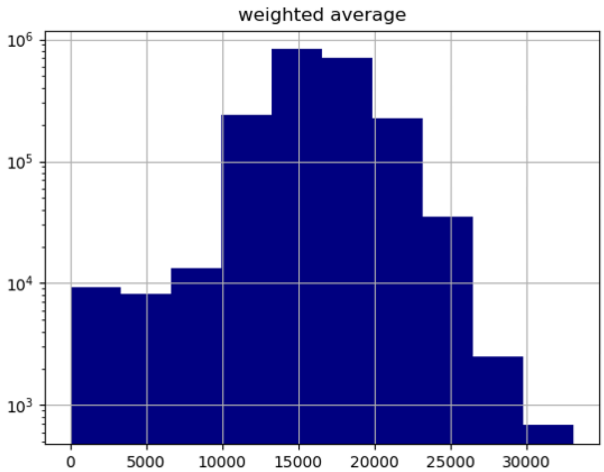


Figure 33: Cherenkov light with Samsung Galaxy S3

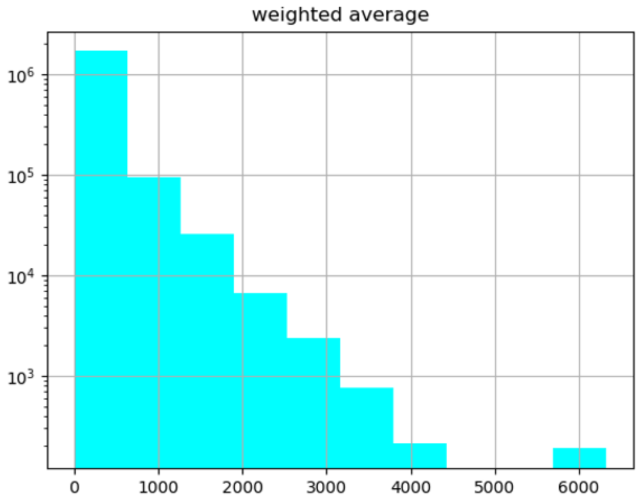


Figure 34: Background with Honor 7

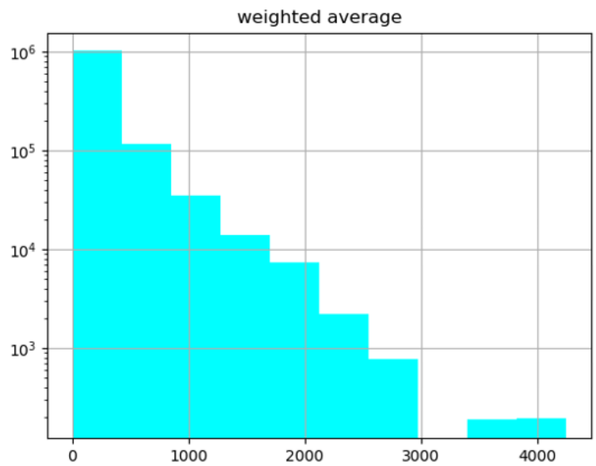


Figure 35: Background with Honor 7

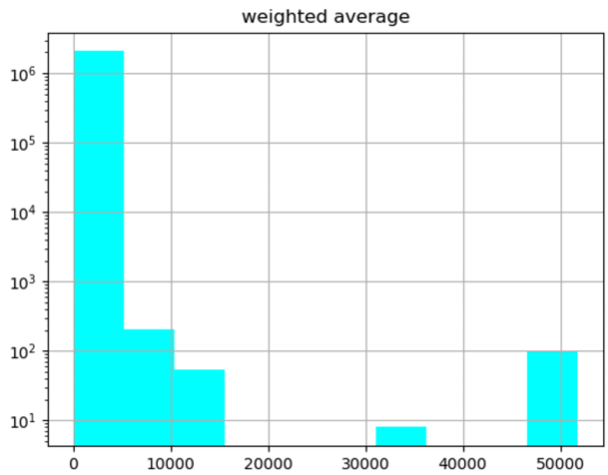


Figure 36: Cherenkov light with Honor 7

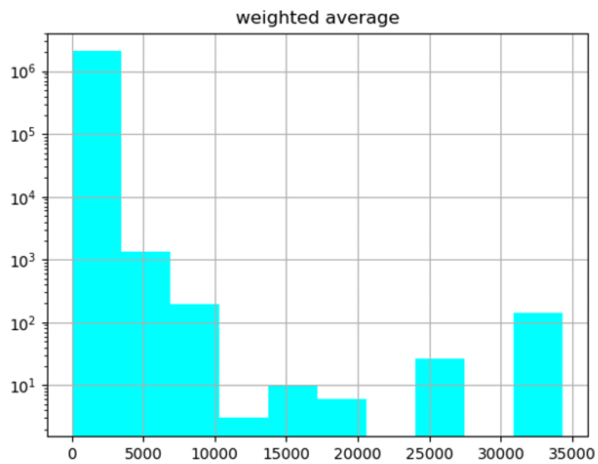


Figure 37: Cherenkov light with Honor 7