Theremino Particle Detector

Webcam Based Particle Detector

Lodovico Lappetito

Table of Contents

Introduction

The purpose of this document is to describe the use of a commercial webcam as a **particle detector**. We will show that, from an ordinary webcam, one can make a "low cost" detector can detect **beta particles, gamma radiation and cosmic rays**. The device can be used to make interesting experiments on radioactivity and make qualitative measurements of radioactive sources.

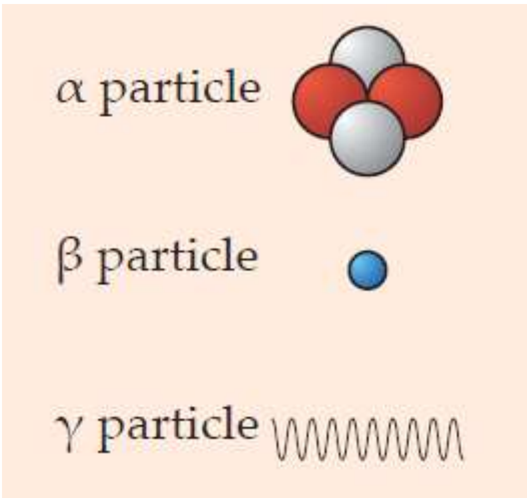
Radioactivity

Radioactivity is the phenomenon whereby some nuclei, not stable, are transformed into other emitting particles. Radioactivity was not invented by man, but on the contrary, man is exposed to radioactivity from the moment of its appearance on Earth. Radioactivity is as old as the universe and is present everywhere : in the Stars , the Earth and in our own bodies.

The isotopes occurring in nature are most stable. However, some natural isotopes, and almost all artificial isotopes, have unstable nuclei, due to an excess of protons and/or neutrons. Such instability causes the spontaneous transformation into other isotopes, and this transformation is accompanied by the emission of particles. These isotopes are called radioactive isotopes, or radioisotopes, or radionuclides.

The transformation of a radioactive atom leads to the production of another atom, which can also be radioactive or stable. It is called radioactive decay or disintegration. The average time it takes to wait for such a change could be extremely short or extremely long. It is said "average life" of the radioisotope, and can vary from fractions of a second to billions of years (for example, potassium-40 has an average life of 1.8 billion years). Another characteristic time of a radioisotope is the "half- time", ie the time required for half of the radioactive atoms initially present undergoes a spontaneous transformation.

There are three different types of radioactive decays , which differ from the type of particle emitted as a result of the decay : **Alpha particles, Beta particles and Gamma radiation**.



α Radioactivity

The **alpha particles**, alpha rays are a form of highly ionizing corpuscular radiation and with a low penetration due to the high cross section. Consisting of two protons and two neutrons bound together by the strong force, it is therefore 4He nuclei. From a chemical point of view they may also be identified by the symbol 4He++. The beta decay is mediated by the weak force, while the alpha decay is mediated by the **strong force**.
Alpha particles are typically emitted from radioactive nuclides of heavy elements, for example the isotopes of uranium, thorium, radium, etc .., In a process called alpha decay. Sometimes this decay is leaving the nuclei in an excited state, and consequently the excess energy can be removed with the emission of gamma rays.
Alpha rays, because of their electrical charge, strongly interact with matter and therefore are easily absorbed by materials and can travel for only few centimeters in the air.

β Radioactivity

Beta radiation is a form of ionizing radiation emitted by many radioactive nuclei types. This radiation is constituted by **beta particles** (β), which are high energy **electrons** or **positrons**, expelled by an atomic nuclei in a process known as **Beta Decay**. There are two types of beta decay, β− and β+, which emit an electron or a positron.
In the β− decay, one neutron is being converted in a proton, an electron and an electronic antineutrino (antiparticle of neutrino):

$$\mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^{-} + \bar{\nu}_e$$

In the β+ decay (in protons rich nuclei), one proton interacts with an electronic antineutrino to give a neutron and a positron (the direct decay of a proton in a positron has not been observed yet):

$$\mathrm{p} + \bar{\nu}_e \rightarrow \mathrm{n} + \mathrm{e}^{+}$$

Due to the presence of the neutrino, the atom and the beta particle do not normally recoil in opposite directions. The beta decay is mediated by the weak nuclear force. The interaction of beta particles with matter generally reach a length ten times, and ionizing power equal to one tenth compared to the interaction of alpha particles. They are completely blocked in a few millimeters of aluminum.

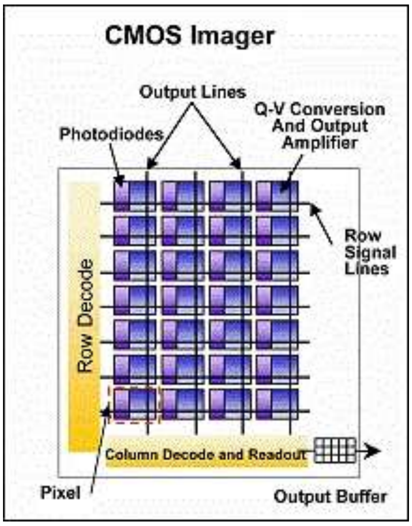
Y Radioactivity

In nuclear physics, **gamma rays** (often denoted by the corresponding lower case Greek letter γ) are a form of electromagnetic radiation at high energy, produced by decay or subatomic processes. The gamma rays are the most penetrating radiation produced by forms of decay, namely alpha decay and beta decay, because of the lower tendency to interact with the material.
Gamma rays are distinguished from X rays by their origin: gamma are produced by nuclear or other subatomic transitions, while X are produced by energy transitions due to fast-moving electrons in their quantized energy levels. Since it is possible for some electronic transitions exceed the energies of some nuclear transitions, high energetic x-rays overlap weaker gamma rays.

Webcam

We used the webcam Logitech C270, readily available at any computer store or online (eBay, Amazon) for about 20 Euros. In order to use it as a particle detectors, the webcam should be modified. With attention you can make the changes in a reversible manner so as to be able to restore the original functionality.

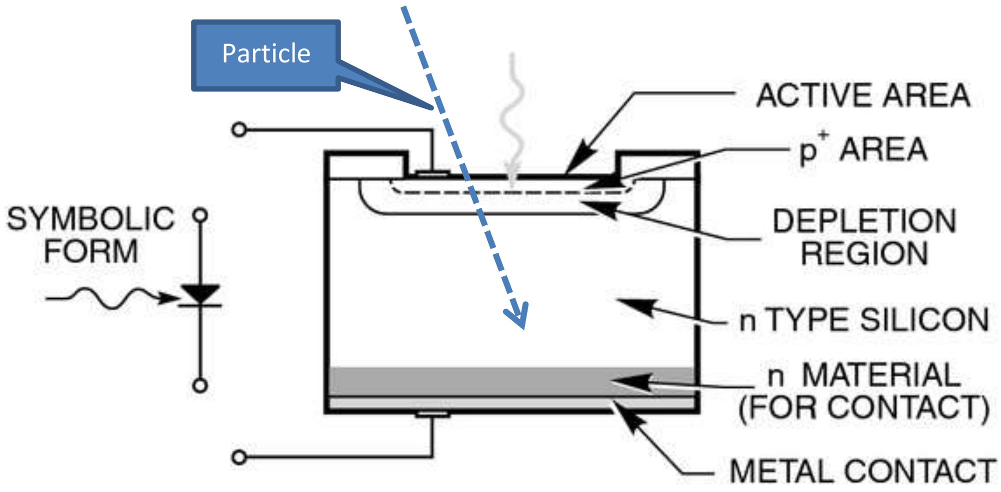
Original camera



Inside the webcam is present the CMOS sensor that is the light-sensitive element. The CMOS sensor is in practice constituted by a matrix of pixels. Each pixel includes a photodiode and a conversion circuit / amplifier that converts the charge originated in the photodiode into a voltage that is read, pixel by pixel, and subsequently digitized into a numerical value **ranging from 0 to 255**. To select the color a tiny color filter (red, green and blue) is positioned above each pixel, resulting in a "mosaic" of colored pixels, then the image is processed in a timely manner (interpolation) to reconstruct the original image.

The active element, sensitive to particles, is the photodiode, shown schematically in the image below. The ionizing particle enters into the sensitive area from the “top window” and produces in its passage several hundred electron / hole pairs which are collected by the cathode / anode of the diode and produce the signal that is subsequently digitized.
We give some data from the literature on solid state sensors :
Silicon Bang Gap = 1,115 eV
Couple Production Energy e/h (300°K) = 3,62 eV
Electron ionization power = 80 e/µm

As you can see from the data shown above, an electron which runs 10 µm produces about 1000 charge carriers, and thus an easily detectable signal, also because the electronic detection is local on the chip.



Actually the CMOS sensor is not optimized for the detection of the particles and therefore the detection efficiency is rather low, especially due to the fact that the sensitive region which is the depletion layer of the junction is very thin.
The alpha particles are not detected because the sensor is protected by a layer of glass (or other transparent material) that completely blocks the alpha particles.
Beta particles are partially absorbed by the surface protection but a high percentage reach the sensitive part and is detected.
Cosmic rays, which are high-energy muons, are detected practically 100 %.
For the gamma radiation the sensitivity is rather low and appears to be greater at low energies, this is also due to the small thickness of the sensitive region of the CMOS sensor.

CMOS Sensor Data

The CMOS sensor in the Logitech C270 webcam features the following data :
Sensor Resolution = 1280 x 960
Pixel Dimension = 2,8 µm x 2,8 µm
Sensor Dimension = 3,5 mm x 2,7 mm
Sensor area = 9,45 mm^2
Image Resolution = 640 x 480
Image Pixel Dimension = 5,6 µm x 5,6 µm

Webcam Hacking

Modifying the Webcam is very simple. First, the front cover must be removed by levering with a screwdriver, then dismantle the underlying base by removing the three small screws. The open Webcam is shown in the image below :

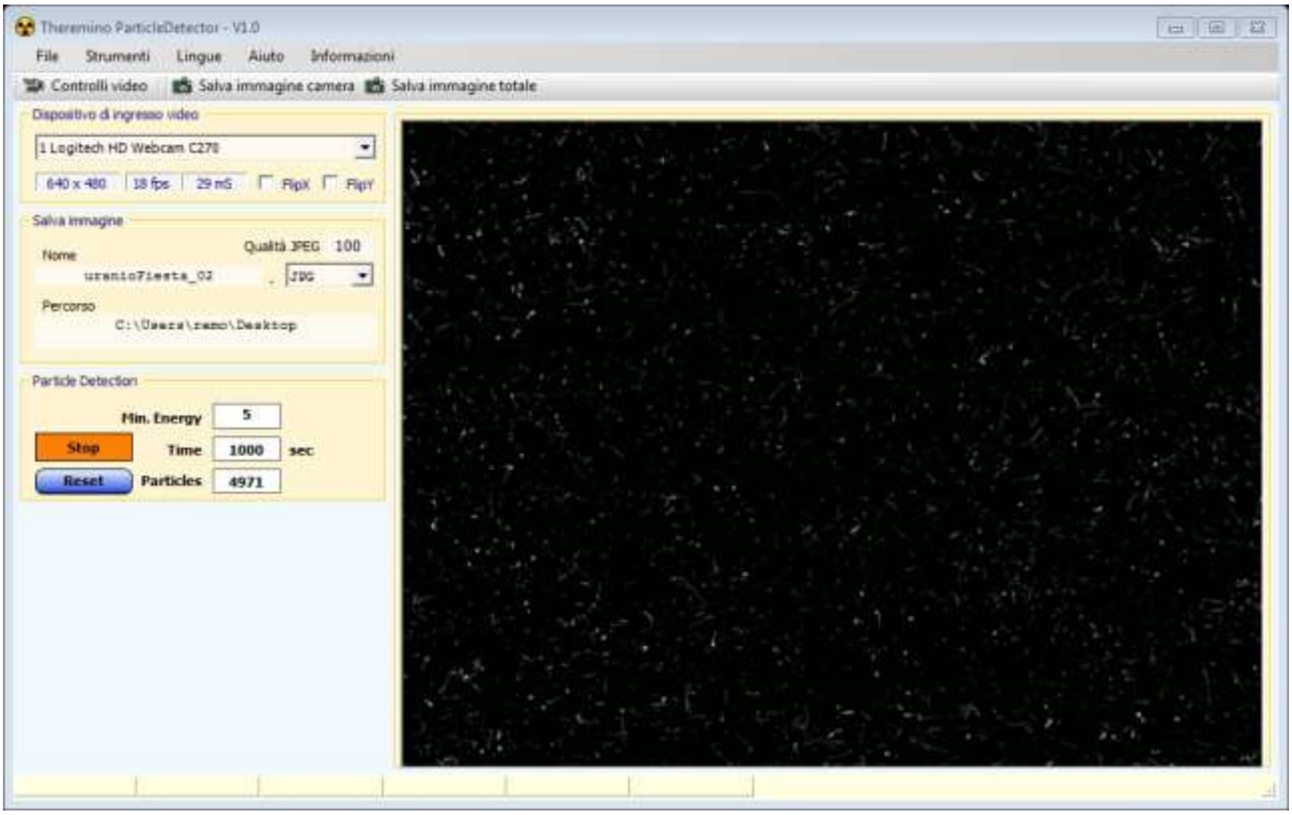
To prevent that the CMOS sensor is reached by LED light it is better to take it off with wire cutters or with solder. It should also be taken off even the webcam lens, as seen in the image below.

To avoid that the CMOS sensor is reached by the ambient light it is necessary to adequately shield it with an adhesive aluminum sheet, as shown in the figure below.

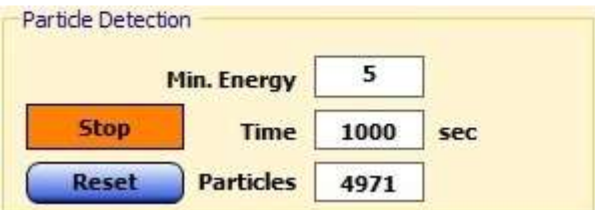
At the end the webcam can be mounted again using the covers previously removed.

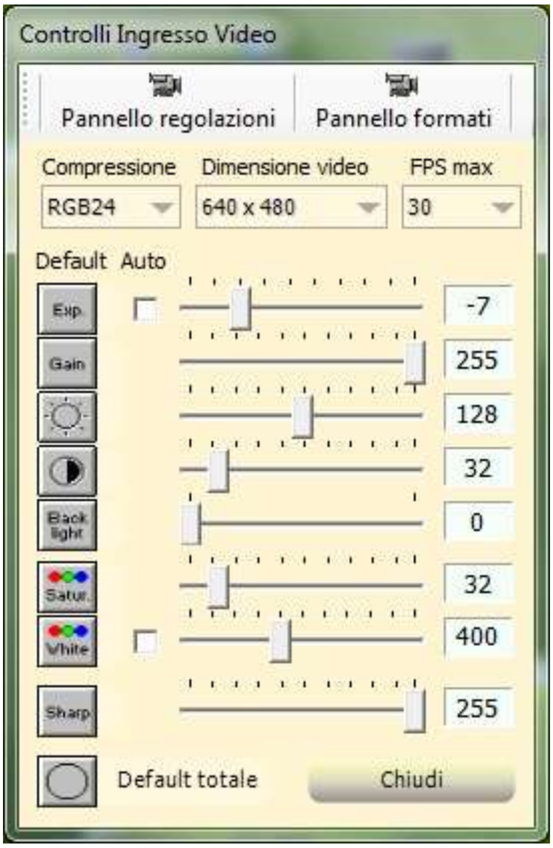
Theremino Particle Detector

To capture the images recorded with the webcam it has been realized the **Theremino ParticleDetector** software. This software simply performs the **integration of the images** so as to achieve a sort of "**long exposure**". In this way the particle tracks are not erased at every acquisition cycle but accumulate frame by frame. In the picture below an example of a recording is shown .



The application gives the possibility to set the **minimum energy (0 - 255**) in order not to count spurious events caused by the noise of CMOS sensor.
With the START / STOP control one can start and stop frame recording and events counting.
With the RESET control one can reset the integration time and the event counter.
During frame recording the events which are caused by a particle detection are counted and shown in the box “Particles”, the total recording time is shown in the box “Time”.
The ratio between these two values corresponds to the quantity “Counts per Seconds”, that is CPS.

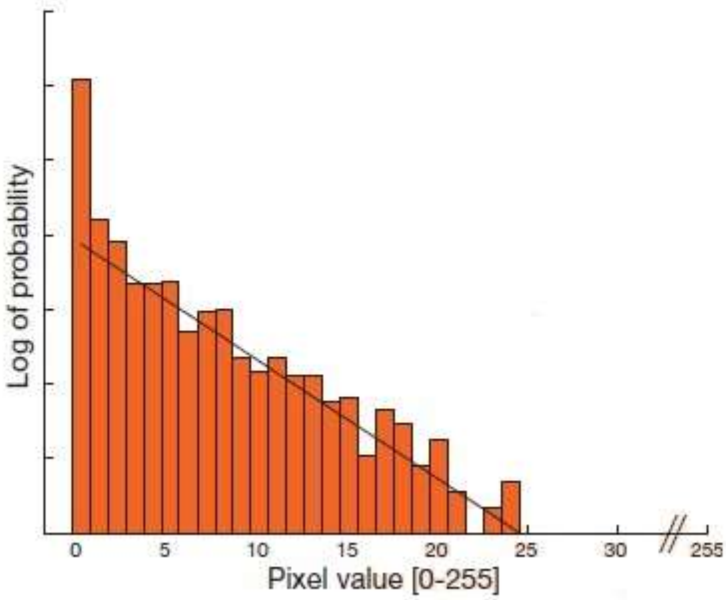




In order to obtain the best results it is advisable to set the Webcam with the parameters shown in the image aside. The following parameters are important :

Resolution = 640 x 480
Exposure = -7 (corresponding to 1/10 s)
Gain = 255
Sharp = 255

It should be also adjusted the "minimum energy" parameter, used to exclude from the survey the events due to the noise of the CMOS sensor. From studies in the literature the distribution of noise has an exponential trend, as seen in the semilog graph presented below. By setting this threshold to values comprised between 5 and 20 most of the noise can be canceled.



Noise distribution

Measurements

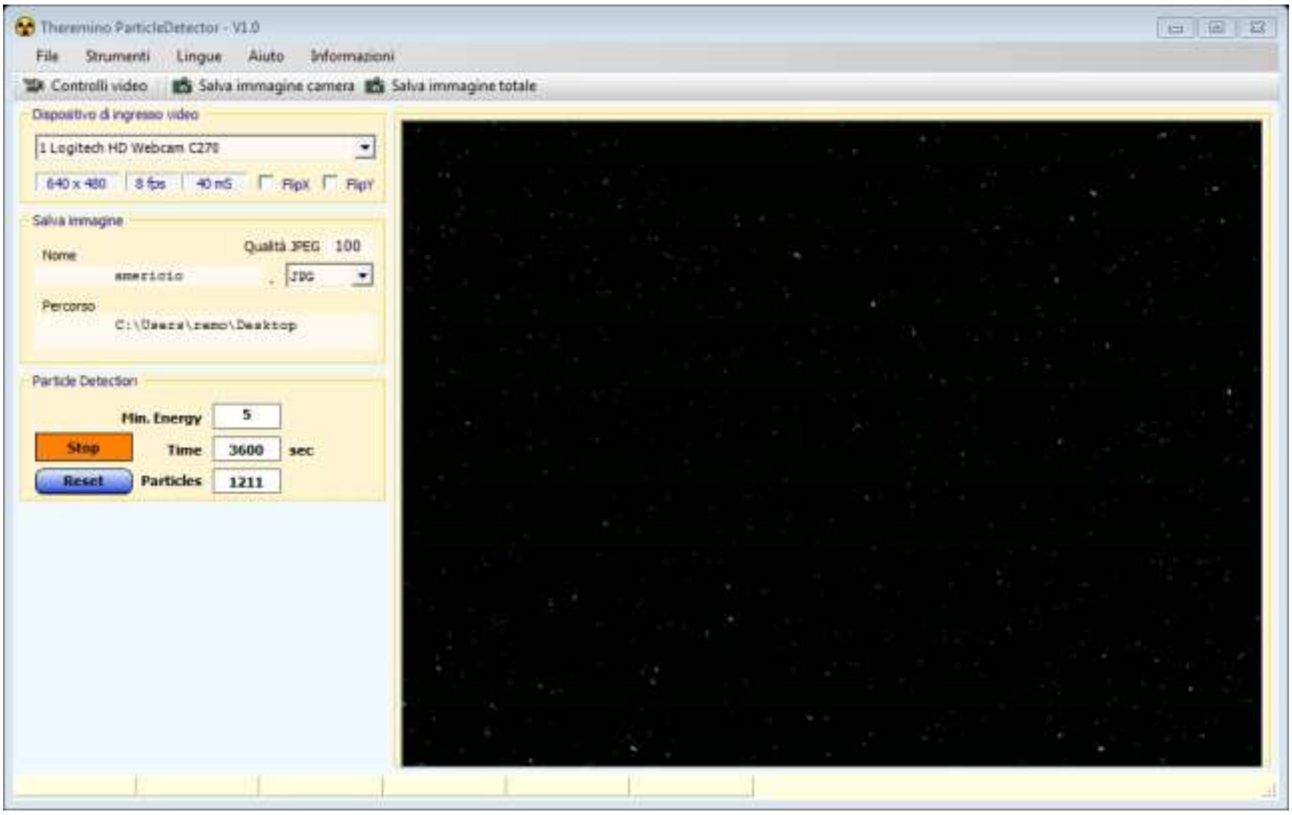
Measurements have been made by placing the source close to the Webcam, the figure below shows the typical setup used.

The following common sources have been used :

- Thoriated gas mantle
- Uranium glaze (FiestaWare)
- Radium watch hands
- Uraninite
- Isotope Americium 241 from smoke sensor
- Isotope Cesium 137 – license exempt small quantitative
- Isotope Sodium 22 - license exempt small quantitative
- Isotope Strontium 90 - license exempt small quantitative

Americium 241

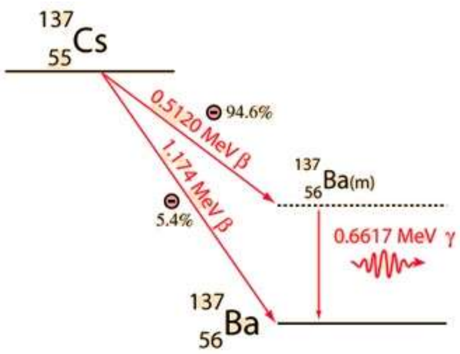
Americium is a chemical element with atomic number 95. Its symbol is Am. Americium is a synthetic metallic element of the actinide family, obtained by bombarding plutonium with neutrons. It decays alpha in Neptunium - 237 with a half-life of about 400 years, in its decay also emits gamma radiation at about **59keV and 26keV**.



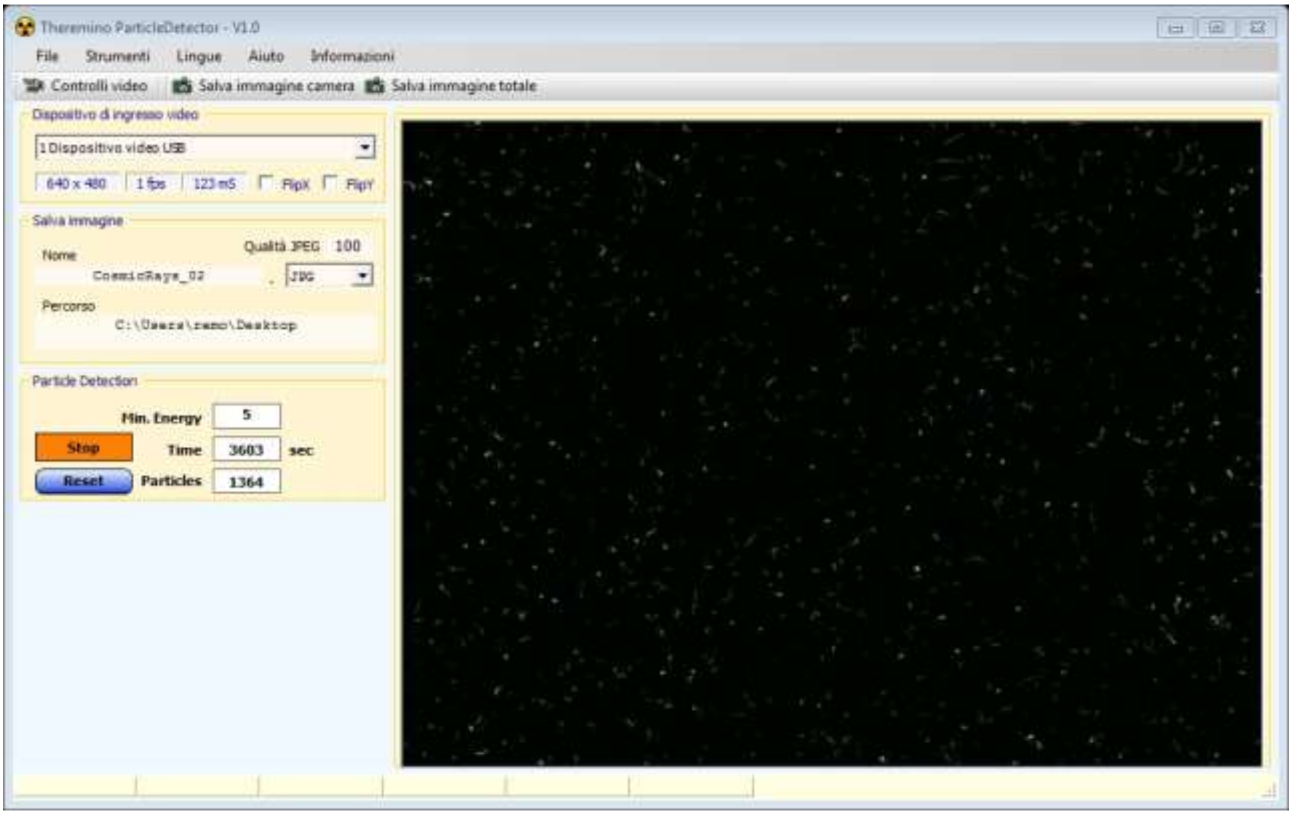
Source = Americium (^{241}Am) 1µCi
Time = 3600s
Particles = 1211
CPS = 0,336

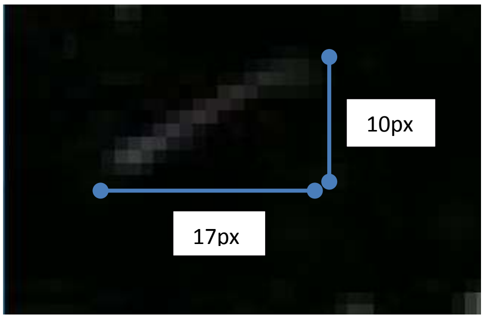
The CMOS sensor does not detect alpha particles, so the points that you see in the image are due to gamma rays emitted by 1µCi americium source or by secondary electrons.

Cesium 137



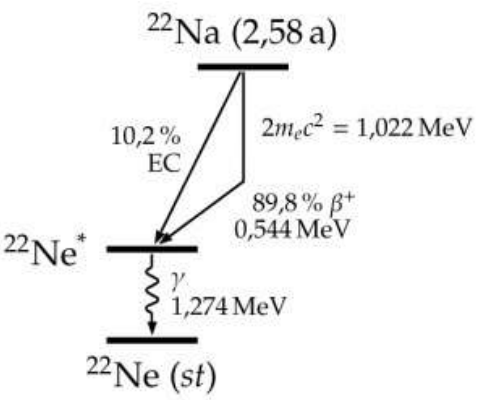
Cesium-137 has a half-life of about 30.17 years. About 95 percent decays by beta emission to a metastable nuclear isomer of barium: **barium-137m** (Ba-137m).
Beta electrons have maximum energy of **512keV for 94% and of 1,174MeV for 5,4%, there is a gamma photon at 662keV**.



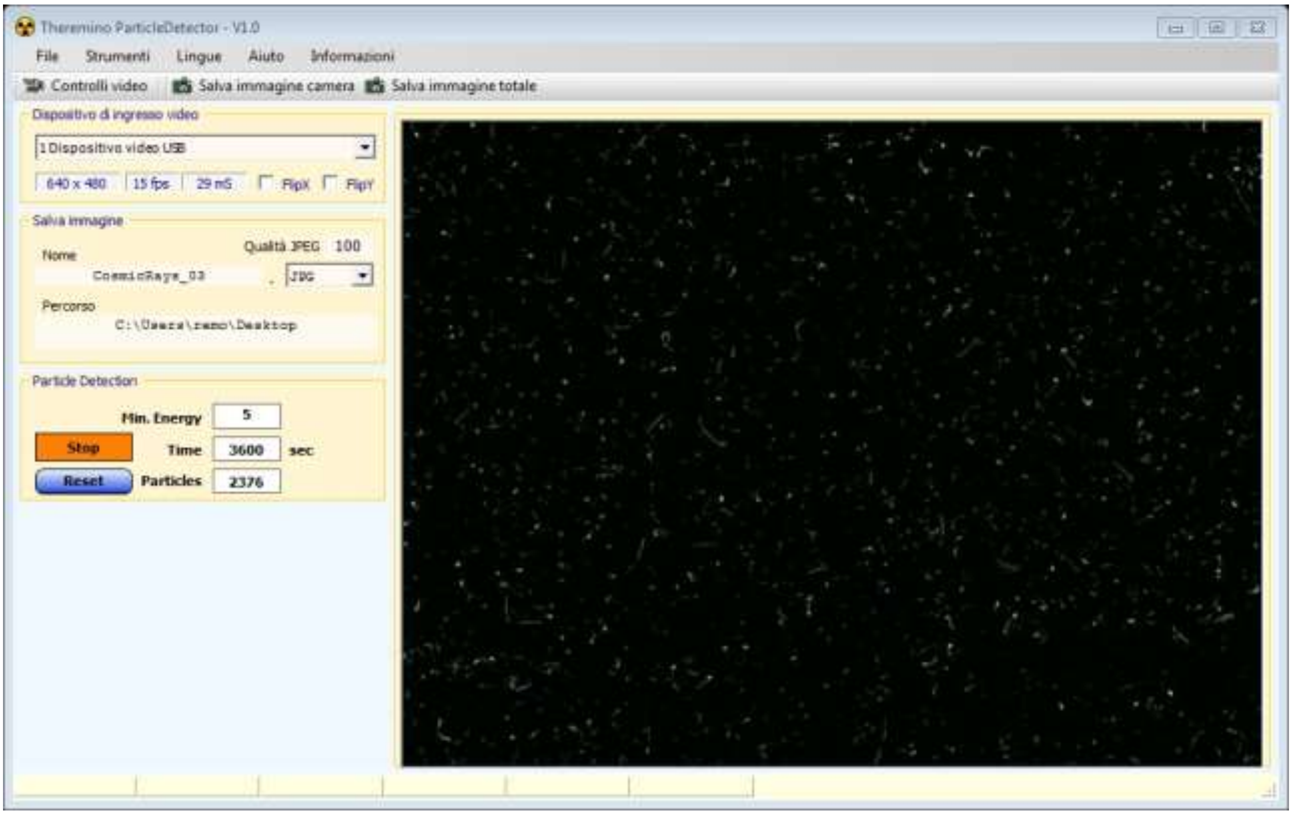


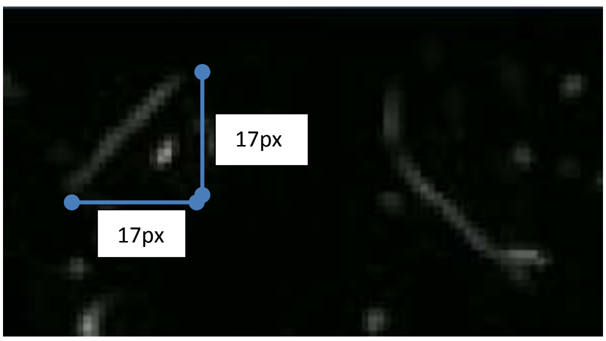
Source = Cesium (^{137}Cs) 0,25µCi
Time = 3600s
Particles = 1364
CPS = 0,379
Trace Length = 20px * 6µm = 120 µm
The CMOS sensor detects the beta radiation emitted by the decay of cesium.
In the picture aside you see the magnified image of the track of an electron.

Sodium 22



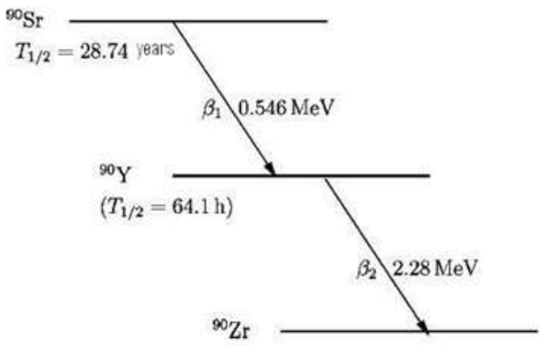
The isotope **Na-22** decays (in 99.95% of cases) with a half-life of 2.6 years, by positron emission or electron capture to the first excited state of 22Ne 1,274 MeV (which then relaxes by emitting gamma photon). **The positrons are emitted by the source at an energy of 544keV**. When they annihilate, they produce two gamma photons of energy 0.511 MeV each.



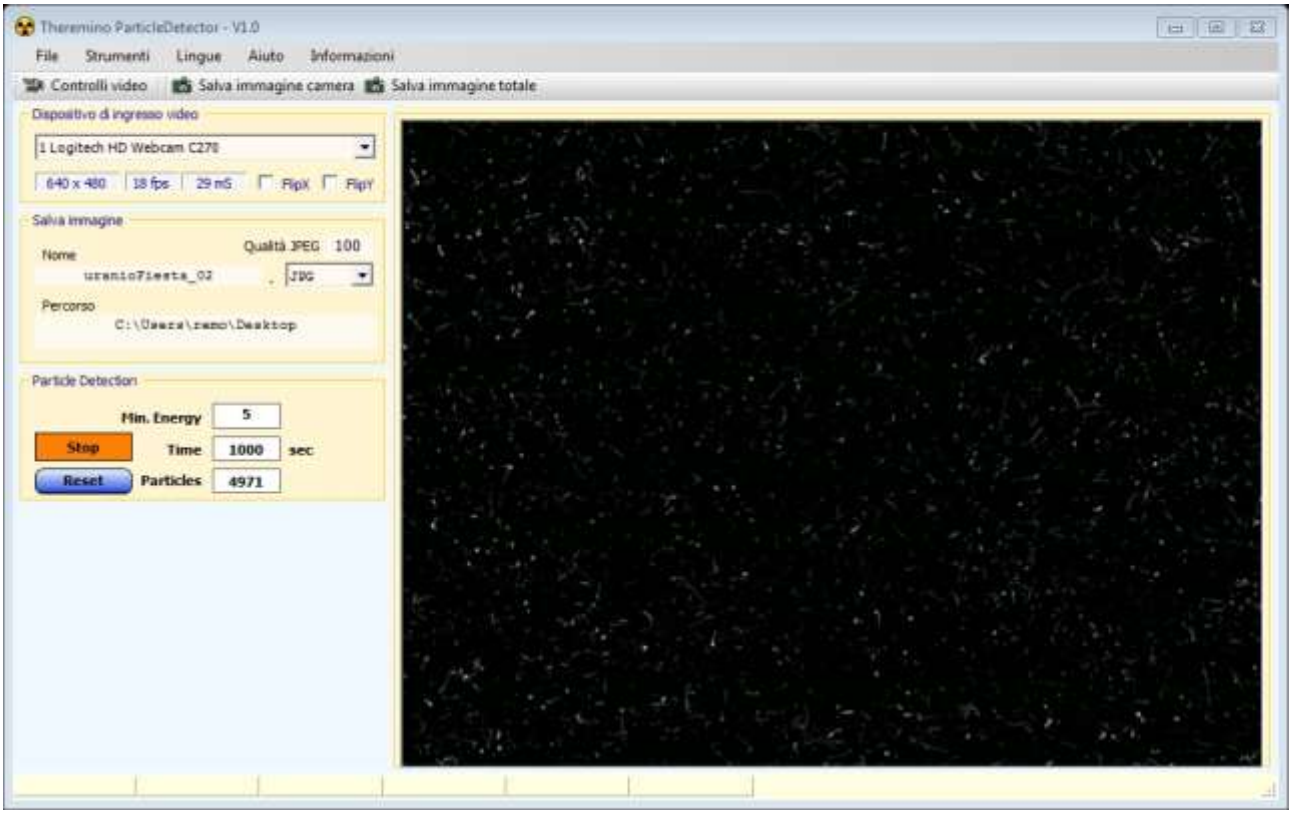


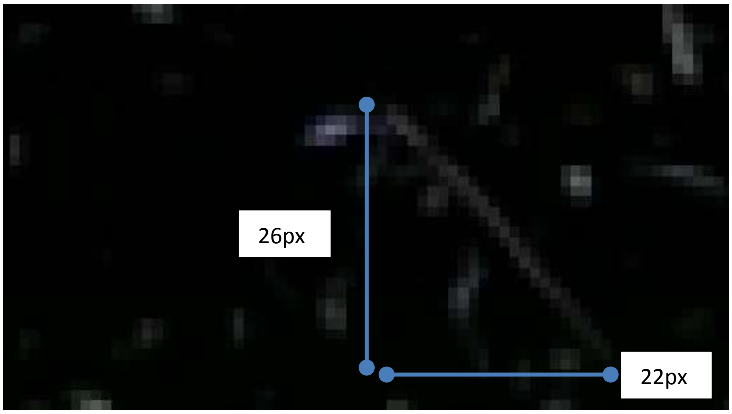
Source = Sodium (^{22}Na) 1µCi
Time = 3600s
Particles = 2376
CPS = 0,66
Trace Length = 24px * 6µm = 144 µm
The CMOS sensor detects the beta radiation (positrons) emitted by the decay of sodium.
In the picture aside you see the magnified image of the track of a positron.

Strontium 90



Strontium-90 is an isotope of strontium produced by the nuclear fission of uranium, having a radioactive half-life of 28.8 years. It undergoes β-decay transformed into yttrium-90 , with an energy of 0.546 MeV decay. the **beta decay of strontium 90 gives rise to the emission of beta particles with maximum energy of 0,546MeV and 2,28Mev.**

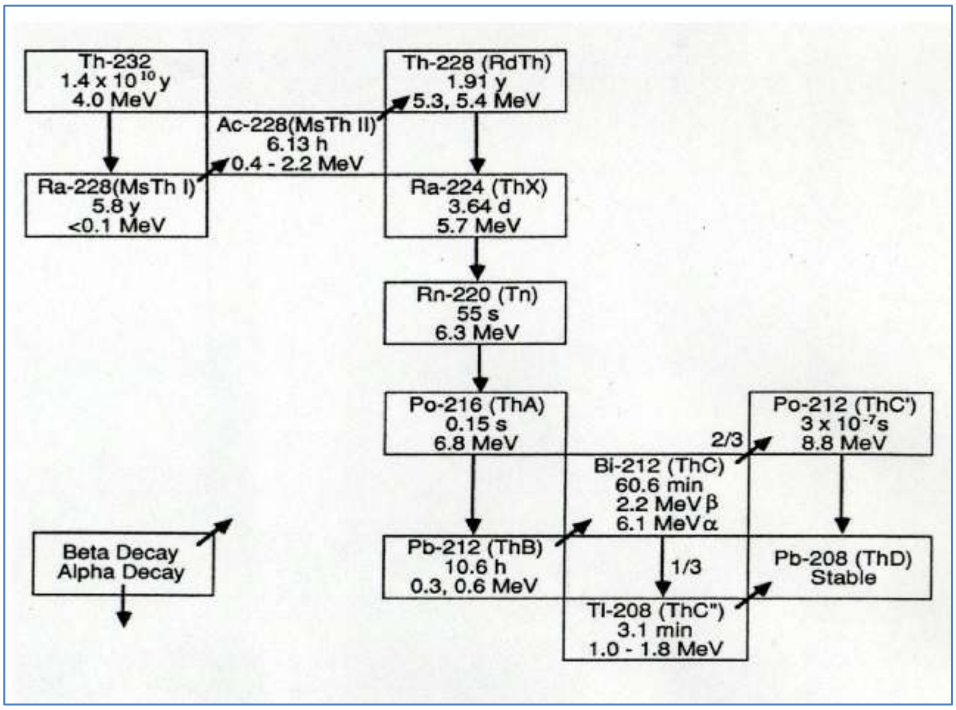




Source = Strontium (^{90}Sr) 0,1µCi
Time = 3600s
Particles = 4971
CPS = 1,38
Trace Length = 33px * 6µm = 198 µm
The CMOS sensor detects the beta radiation emitted by the decay of strontium.
In the picture aside you see the magnified image of the track of an electron.

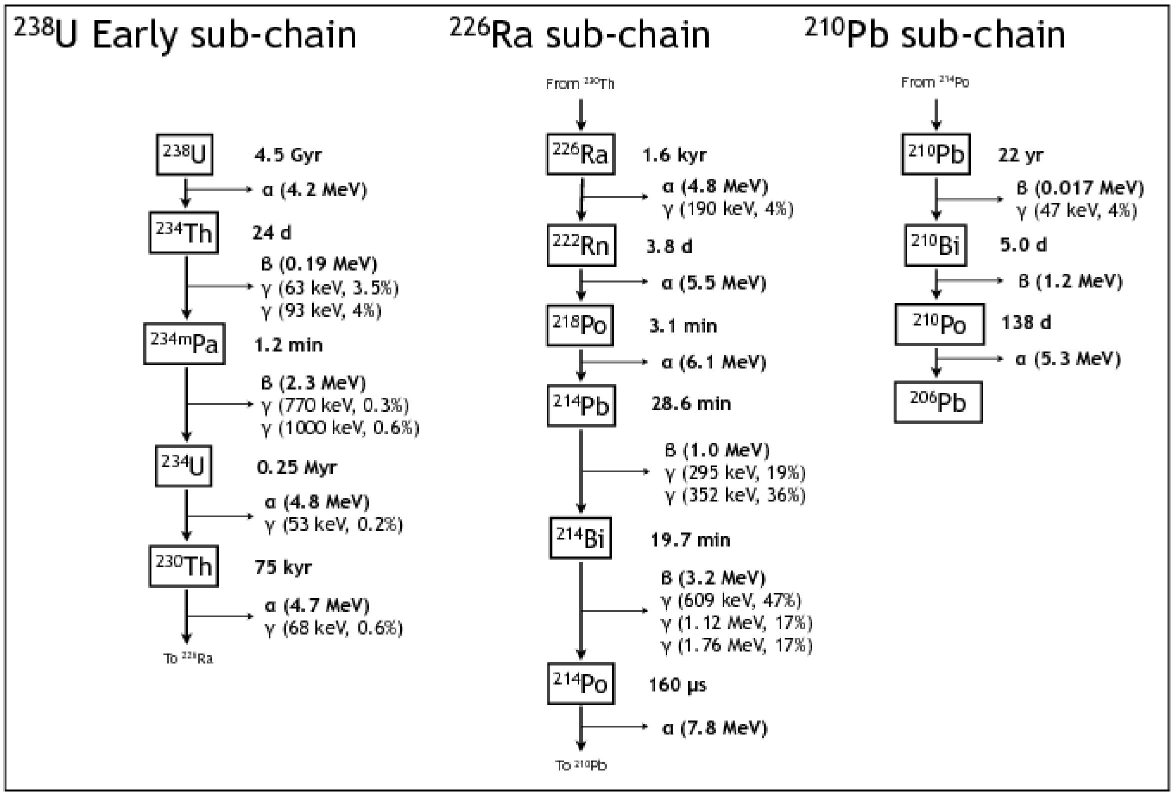
Thorium Decay

Thorium 232 decay chain with energies of alpha and beta particles.



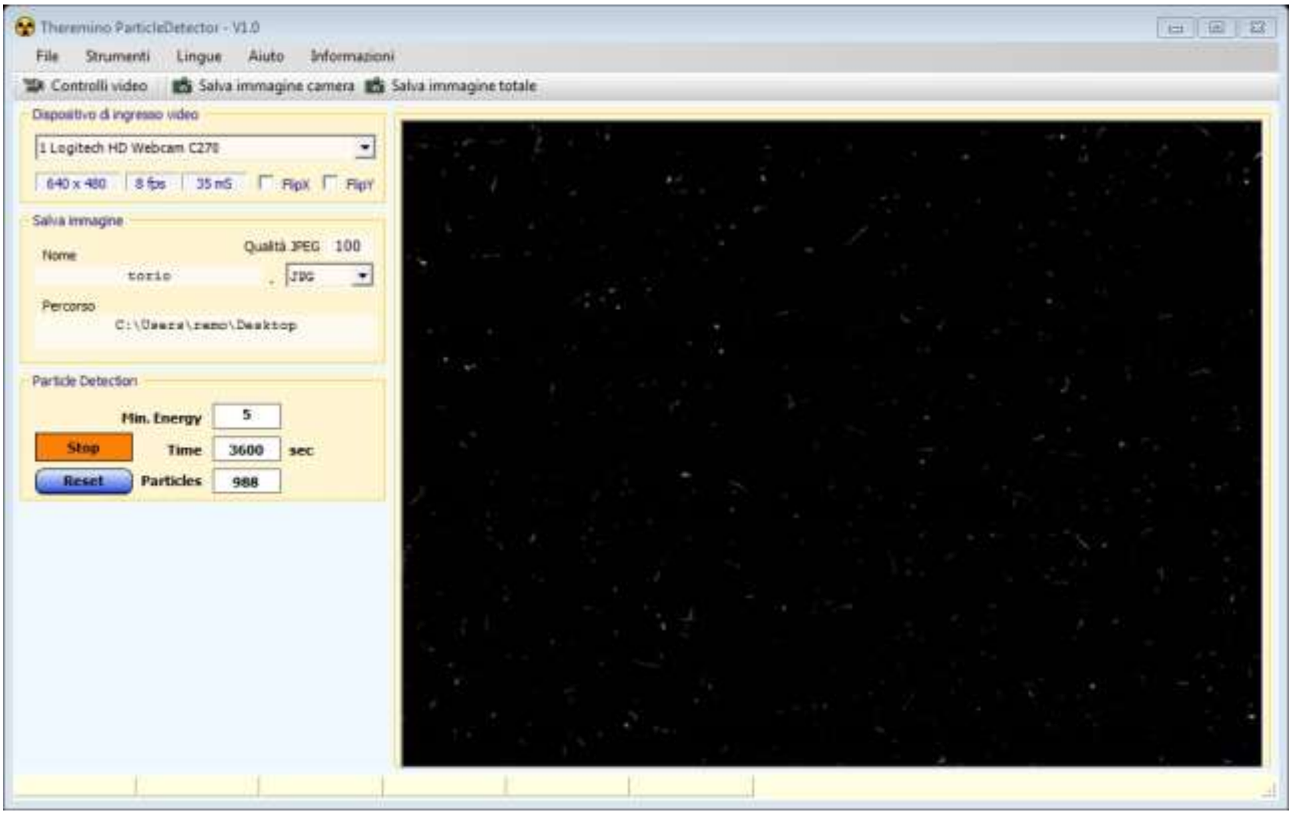
Uranium Decay

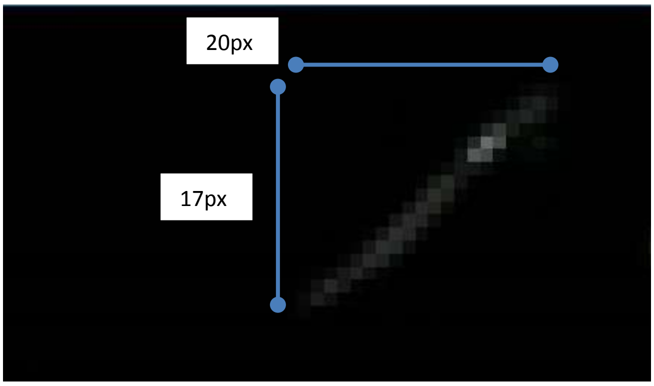
Uranium 238 decay chain with energies of alpha and beta particles.



Thorium

Thorium is a chemical element with symbol Th and atomic number 90. A radioactive actinide metal, thorium is one of only three radioactive elements that still occurs in quantity in nature as a primordial element (the other two being **bismuth** and **uranium**).
The decay chain of thorium produces alpha particles, beta particles and gamma radiation. In particular, the **emitted beta particles are characterized by quite high energy**.

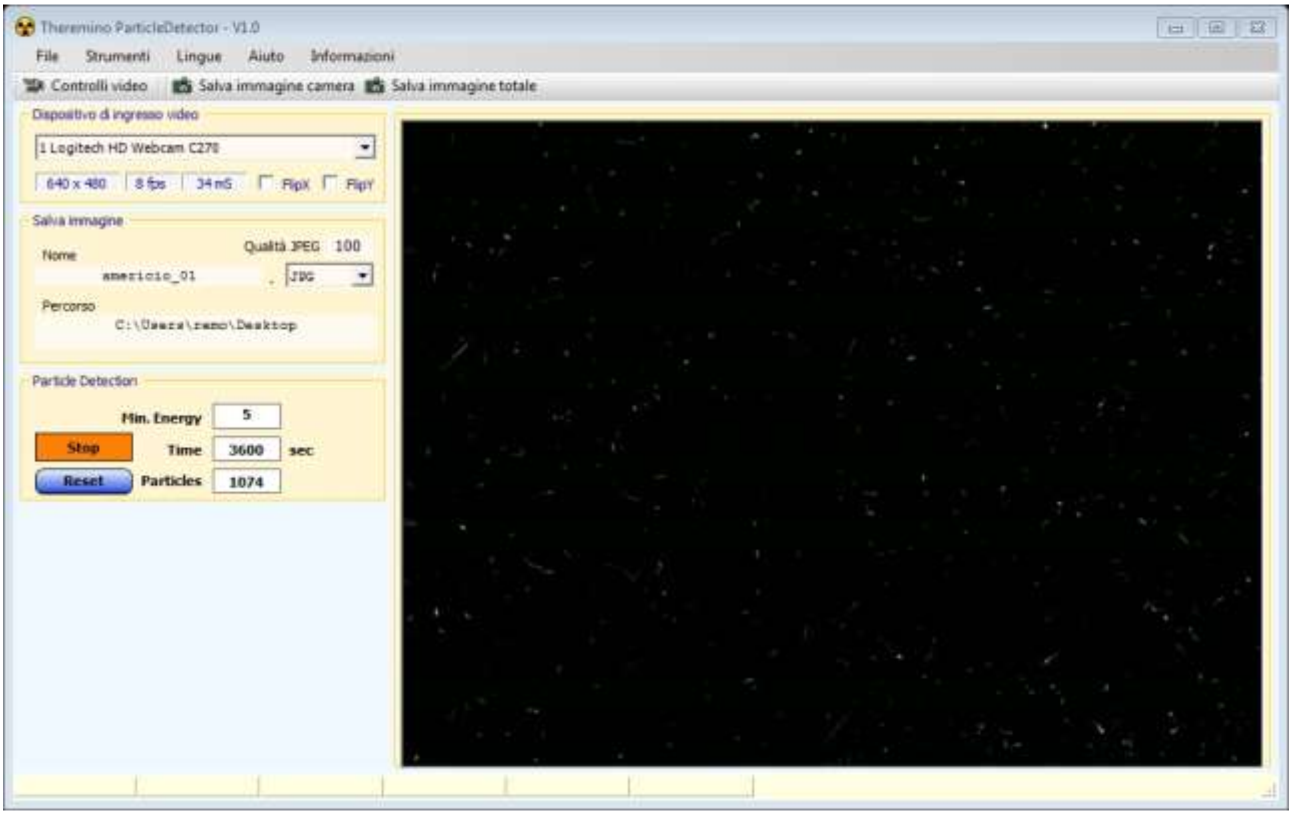


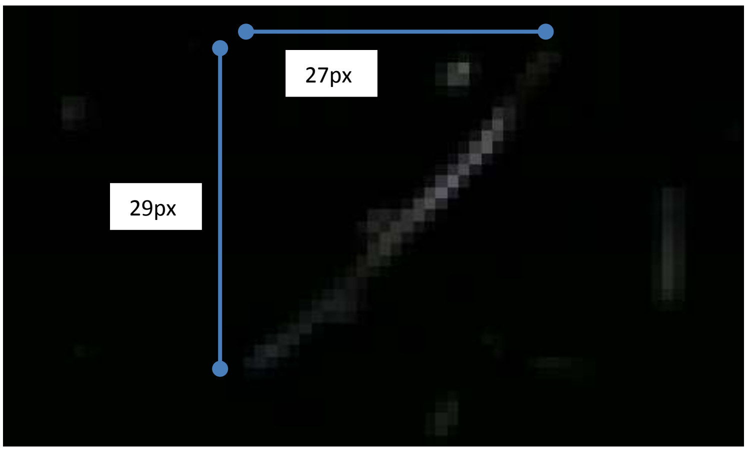


Source = Thorium (gas mantle)
Time = 3600s
Particles = 988
CPS = 0,274
Trace Length = 26px * 6µm = 156 µm
The CMOS sensor detects the beta radiation emitted by the decay of thorium.
In the picture aside you see the magnified image of the track of an electron.

Uranium - Uraninite

Uranium is a chemical element with symbol U and atomic number 92. It is a silvery-white metal in the actinide series of the periodic table. A uranium atom has 92 protons and 92 electrons, of which 6 are valence electrons. Uranium is weakly radioactive because all its isotopes are unstable (with half-lives of the 6 naturally known isotopes, uranium-233 to uranium-238, varying between 69 years and 4.5 billion years). The most common isotopes of uranium are **uranium-238** (which has 146 neutrons and accounts for almost 99.3% of the uranium found in nature) and **uranium-235** (which has 143 neutrons, accounting for 0.7% of the element found naturally).
Uraninite or **Pitchblende** is a highly radioactive ore, one of the main sources of uranium.

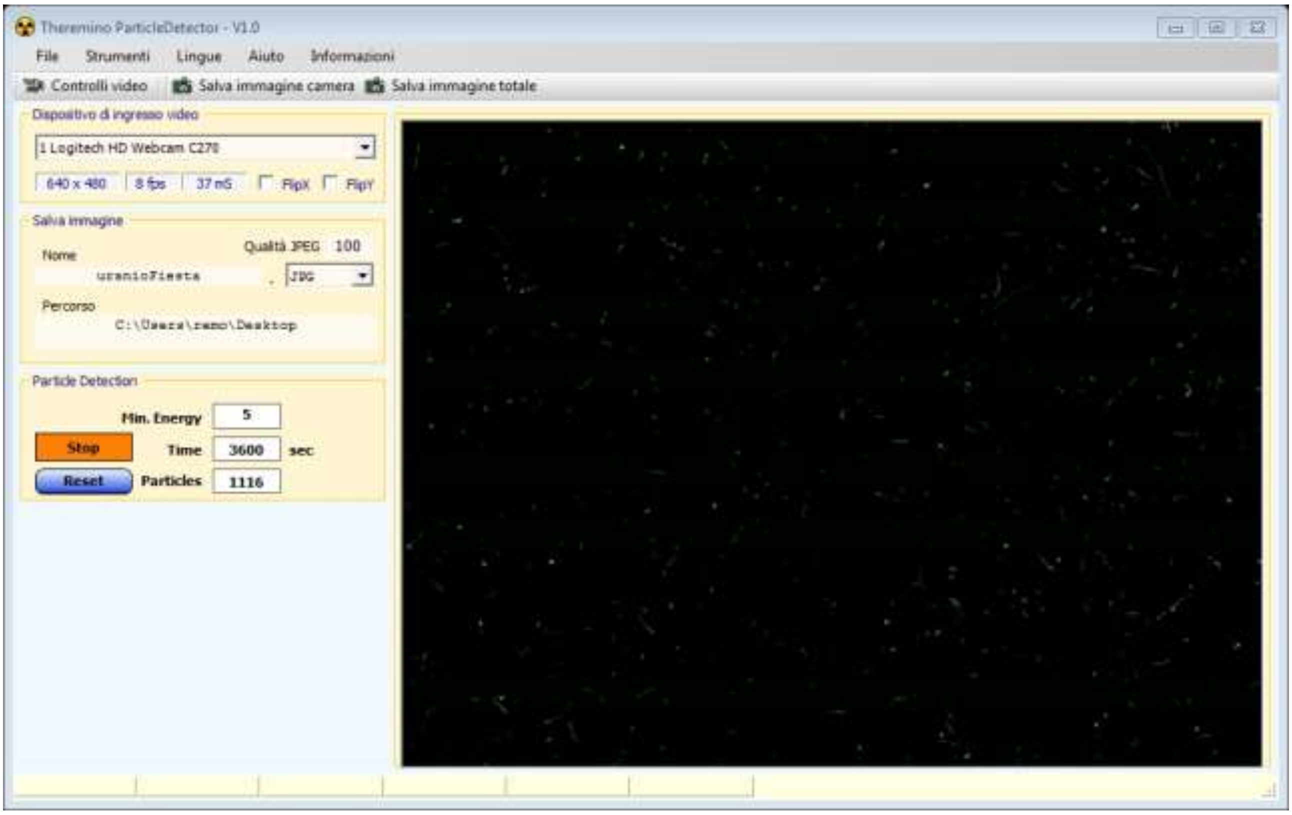


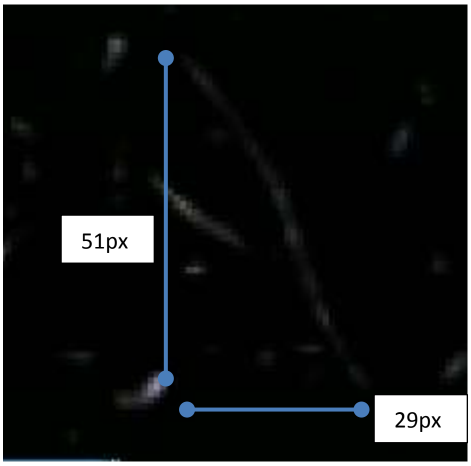


Source = Uranium Oxide (Uraninite)
Time = 3600s
Particles = 1074
CPS = 0,298
Trace Length = 40px * 6µm = 240 µm
The CMOS sensor detects the beta radiation emitted by the decay of uranium. In the picture aside you see the magnified image of the track of an electron.

Uranium – FiestaWare

Uranium was used in the past to give a bright color to ceramic glazes. The uranium content in the glaze has the distinction of being refined, so it does not contain all its decay products from radium to lead and bismuth. For this reason the isotopes from Radium onwards are present only in small part.

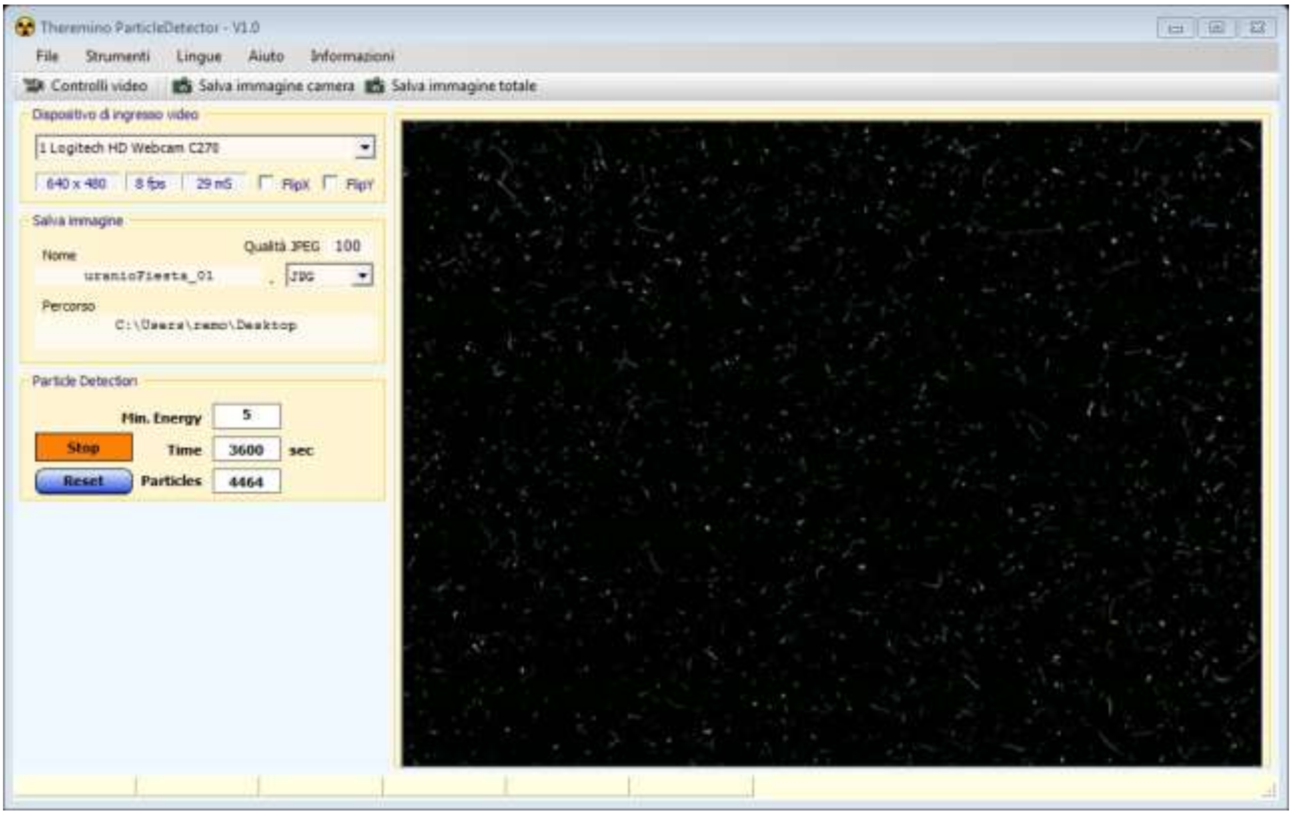


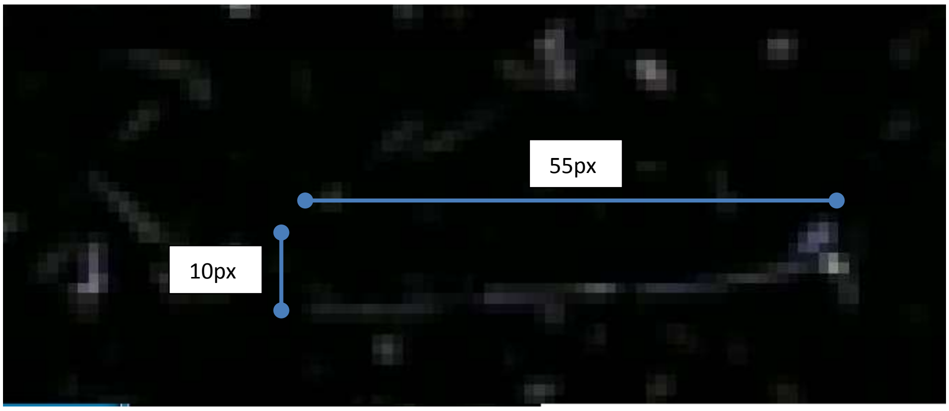


Source = Uranium glaze
Time = 3600s
Particles = 1116
CPS = 0,31
Trace Length = 59px * 6µm = 354 µm
The CMOS sensor detects the beta radiation emitted by the decay of uranium.
In the picture aside you see the magnified image of the track of an electron.

Radium

Radium is a chemical element with symbol **Ra** and atomic number **88**. It is the sixth element in the group 2 of the periodic table, also known as the alkaline earth metals. The pure radium color is almost pure white, but oxidizes easily when exposed to air and becomes black. All of the radio isotopes are highly radioactive, the more stable is the radio - isotope 226, which has a half-life of 1600 years, and decays into radon.

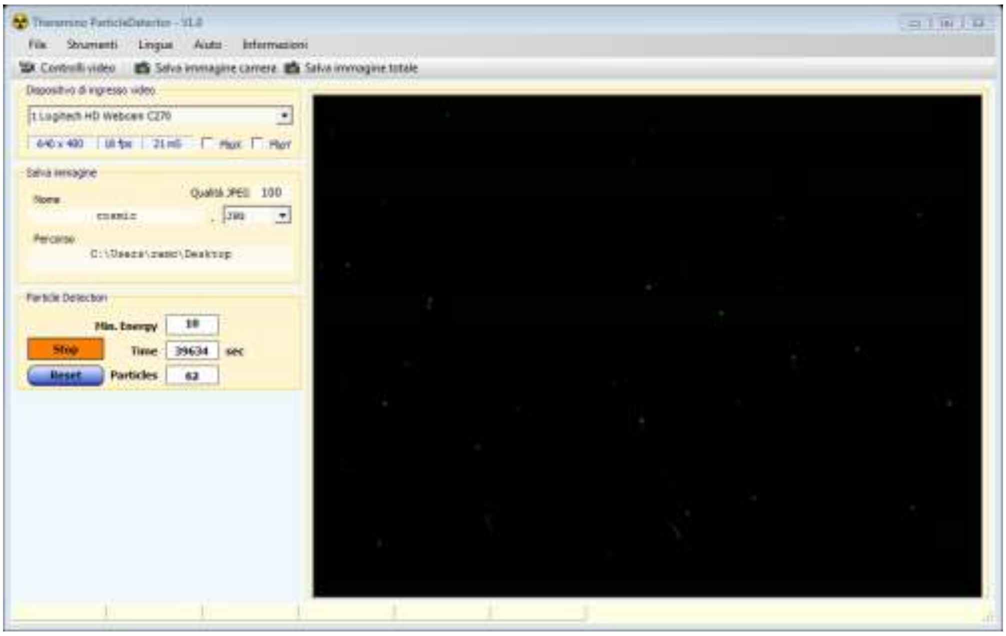


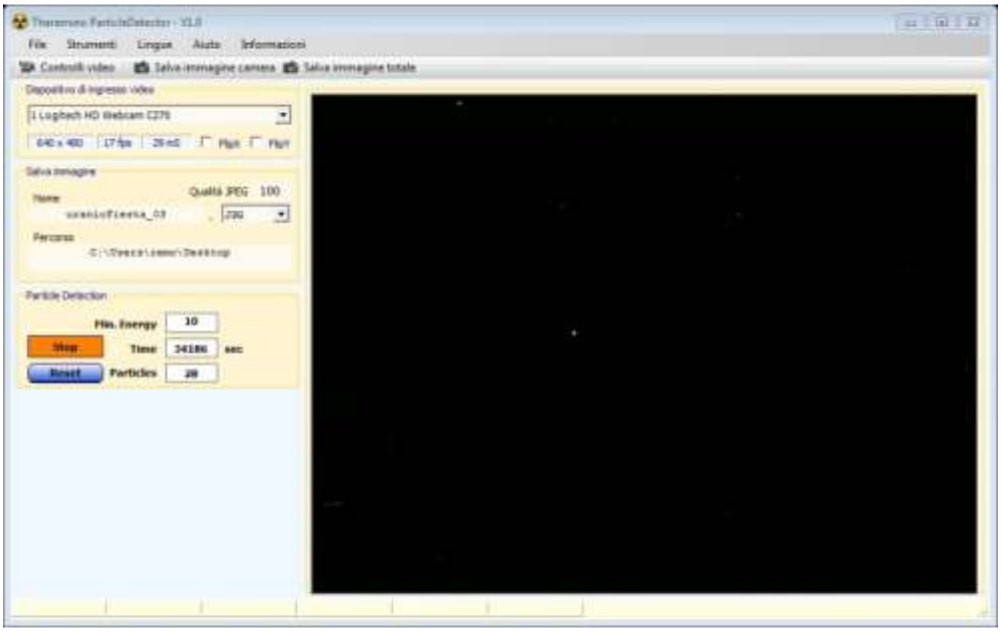


Source = Radium watch hands
Time = 3600s
Particles = 4464
CPS = 1,24
Trace Length = 56px * 6µm = 336 µm
The CMOS sensor detects the beta radiation emitted by the decay of radium.
In the picture above you see the magnified image of the track of an electron.

Cosmic Rays

With the Webcam sensor can be carried out surveys of cosmic muons. Just put it horizontal so as to maximize the sensitive surface and take an exposure lasting many hours. The two images below are relative to two measurements :



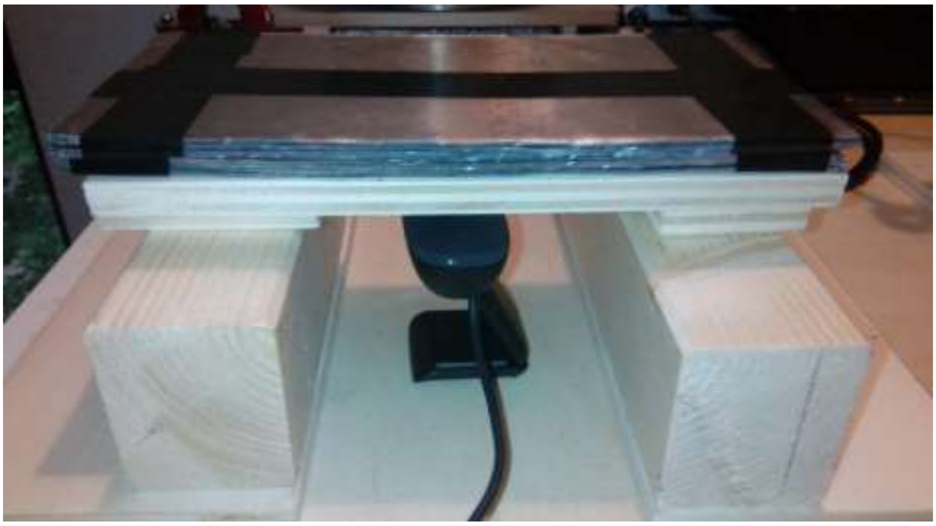


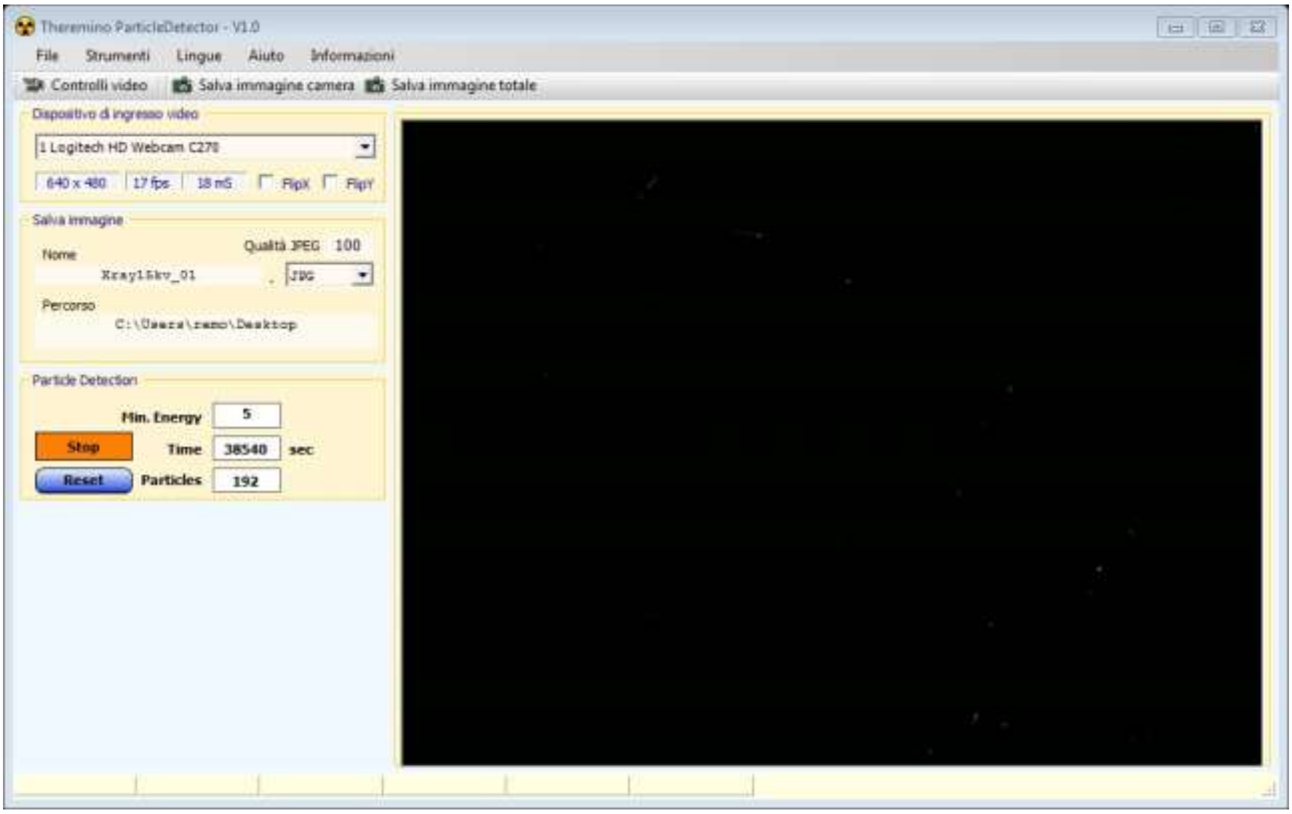
First measurement : 0,00156 CPS = **0,0939 CPM**
Second measurement : 0,00082 CPS = **0,0492 CPM**

The two measurements agree with each other. The theoretical flow to the surface of **9,45 mm^2**, taking into account the fact that the “normal“ flow is of 1 CPM for an area of 1cm^2, is about **0,0945 CPM**. The measures are little lower than "theoretical" value due to the fact that the sensitive surface of the CMOS sensor is significantly less than the "geometric value".

Electromagnetic Cascades

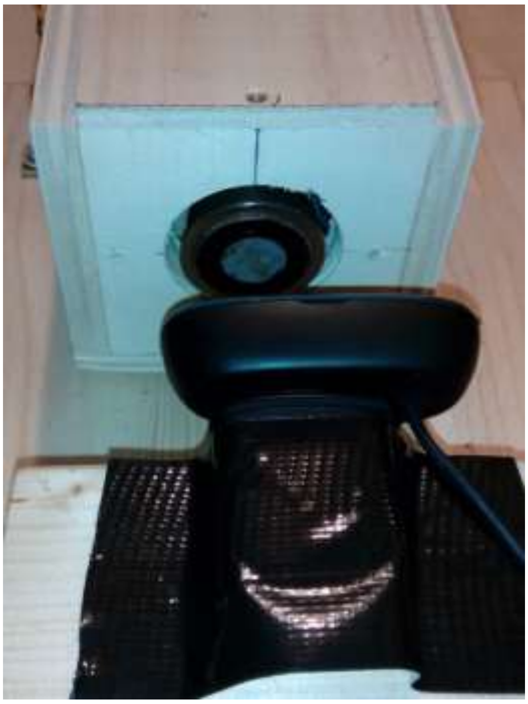
With the Webcam sensor you can make measurements on electromagnetic cascades generated in high density materials, such as lead. The image below shows the setup of the experience : the webcam is placed under sheets of lead with thickness of about 2cm. The "soft" component of cosmic rays interacting with the lead, generates secondary particles, electrons and positrons, which are detected by the webcam.



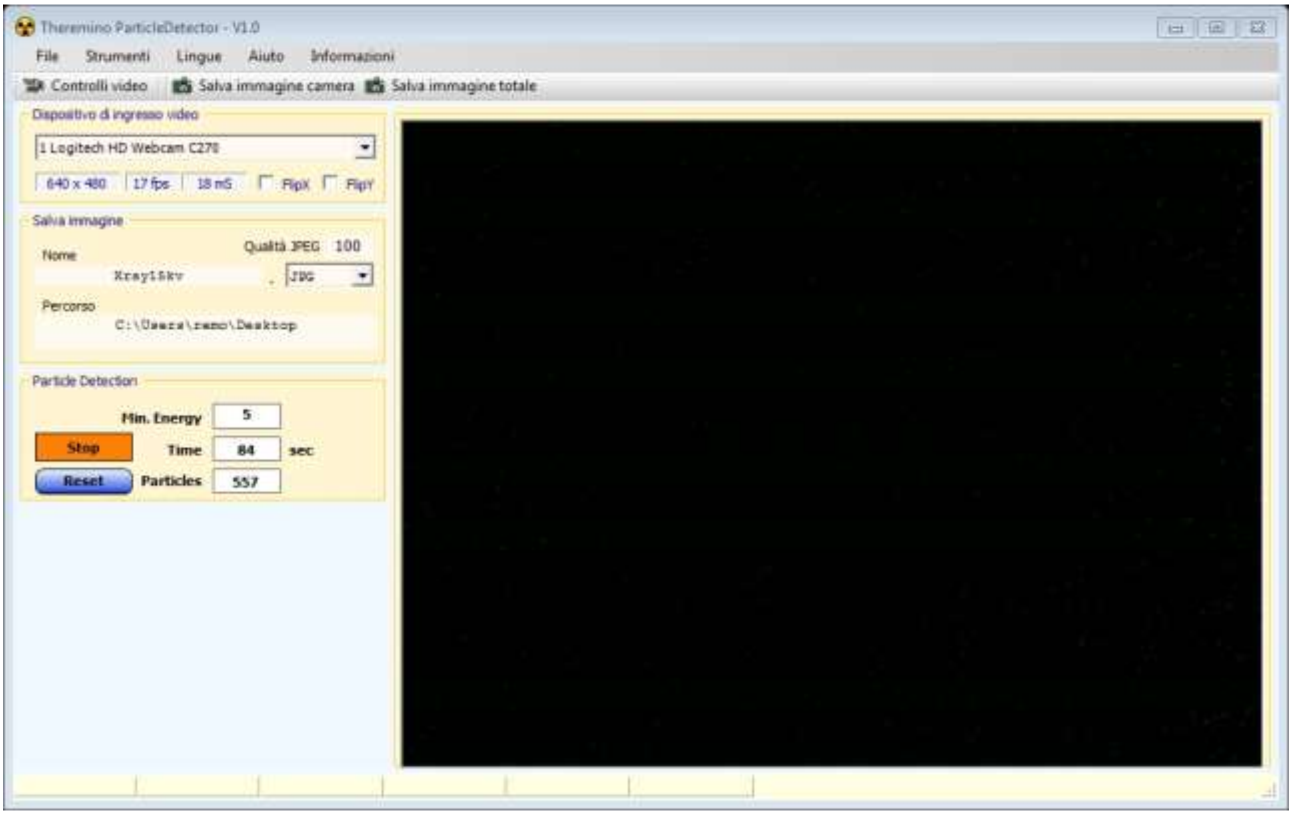


Time = 38540s
Particles = 192
CPS = 0,00498 – Higher than the value obtained without lead sheets

X Rays



We used the Webcam sensor to do a test with a **15kV X-ray** generator. In the figure we see the detail of the Cam positioned in front of the front window (beryllium) of the tube. The Cam is sensitive, even if with low efficiency, to the X-ray. Below you see the detail of some pixels activated by X photons. The pixel brightness is low due to the low X photon energy.



Time = 84s
Particles = 557
CPS = 6,6

Conclusions

Tests have shown that a commercial webcam can be used as a simple "low cost" particles detector.

The sensitivity to alpha particles, however, is severely limited by the transparent protective layer of the CMOS sensor. Remove this protection would make the webcam sensitive also to alpha radiation, but it is a difficult operation which easily leads to the sensor break.

The webcam features a good sensitivity to the more penetrating beta radiation, the estimate of the length of the traces left by electrons detected by the sensor, can give rough information on the energy of the particles.

Source Type	Max Traces Length	Max β Emission Energy
Cesium 137	**120 µm**	**512 keV**
Sodium 22	**144 µm**	**544 keV**
Strontium 90	**198 µm**	**546 keV – 2,280 MeV**
Thorium	**156 µm**	**>1MeV**
Uranium – Uraninite	**240 µm**	**>2MeV**
Uranium – Fiestaware	**354 µm**	**>2MeV**
Radium	**336 µm**	**>2MeV**

From the above table it can be seen that cesium and sodium emit beta electrons with energy of about 500 keV which give rise to traces significantly shorter than strontium, uranium, radium that emit beta electrons with energies even higher than 2-3MeV.
Of course it is only purely qualitative estimates.

The webcam is also sensitive to cosmic particles such as muons, however the little surface of the sensor, limits the possibility of extensive use.

The sensitivity of the webcam to gamma radiation is limited, likely due to the small probability of interaction within the sensitive area of the CMOS sensor. Tests were made both with gamma radiation at low energy (americium 241) and both with "soft" X-rays at 15keV. From an initial analysis it appears that the CMOS sensor responds better to low energy gamma radiation (< 100keV).