
Alpha Spectroscopy

Alpha Spectroscopy of Isotopes

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Preface

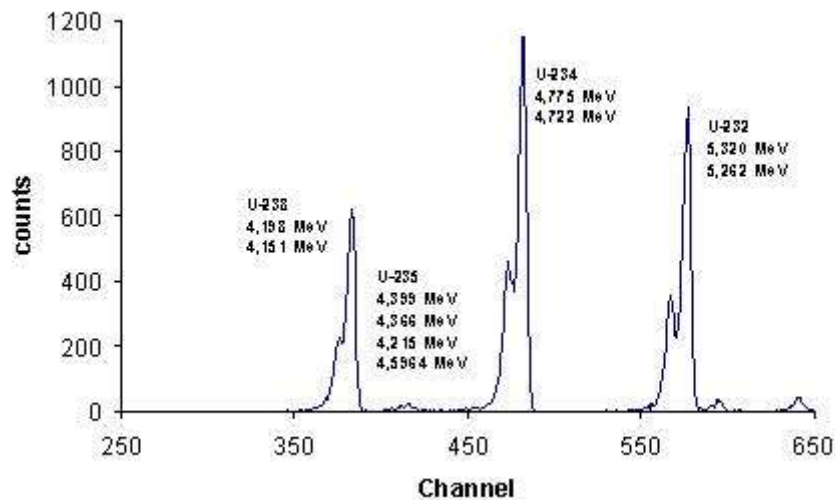


Alpha Spectrometry is a fascinating technique because it allows you to have accurate information about the radioactive decay of heavy nuclei and about the physics of the interaction of charged particles with matter. But this is a rather difficult technique, even more difficult than gamma spectrometry. The difficulties of this technique lie in the type of detector, usually a solid state silicon detector (rather expensive) that produces a very weak signal which requires, to be analyzed, very **low noise amplifiers**.

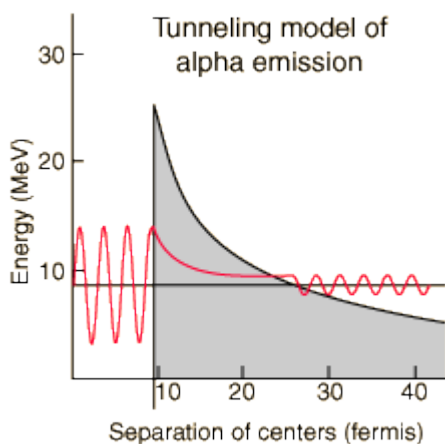
The measurement has to be made in **vacuum** conditions (however not high vacuum) so that the alpha particles are not shielded from the air. The sources that are measured have to be carefully prepared so as to have a layer as **thin and uniform** as possible so that alpha particles are not diffused and absorbed within the source itself.

Despite these difficulties it is possible, with a fair amount of work and patience, prepare a DIY instrument that can give a lot of satisfaction.

Introduction



The alpha radioactive nuclei (typically heavy nuclei) can decay by emitting alpha particles (helium nuclei) with energies of the order of a few MeV, with spectra with lines, corresponding to the energy levels of involved nuclei. In the figure aside it is an example of energy spectrum of alpha emissions of U-238. The alpha-active nuclei are heavy nuclei with atomic number greater than 82 (lead). Examples are Polonium, Radium, Thorium, Uranium, etc ...



The alpha decay has been explained theoretically by G. Gamow in the first half of the previous century making use of the tunnel effect in quantum mechanics. In the figure is a graph which shows the wave function of the alpha particle inside the nucleus and outside, beyond the Coulomb barrier. Although the alpha particle does not have enough energy to overcome the barrier it is seen as outside the nucleus the wave function is not zero and thus there is a non-zero probability that the alpha particle is ejected from the nucleus. Using this model it is possible to explain with good accuracy the characteristics of alpha decay.

Solid State Detector

In a semiconductor, the equivalent of the ionization energy is the **band-gap energy** to promote an electron from the valence to the conduction band. In **Si** at room temperature, $E_g = 1.1 \text{ eV}$, compared to $\sim 15 \text{ eV}$ to ionize a gas. A charged particle moving through Si therefore creates **more ionization** and a larger signal. When n-type and p-type silicon are put in contact, creating a p-n junction, the flow of the two different free charges across the boundary creates a **depletion zone**, an electrically neutral area near the junction where an internal electric field sweeps out any free charge.

By **reverse biasing** the junction, the depletion zone can be made large, $\sim$ hundreds of microns. If an energetic charged particle ranges out in the depletion zone, an amount of ionization proportional to the particle's initial energy will be created there, and swept out. By plating metallic ohmic contacts on the outer surfaces of the crystal, it is possible to both apply the bias and collect the free charge from the depletion zone, so that the whole assembly is a high gain, solid state version of the capacitive ionization chamber.



In our project we have used the detector shown in the image aside (thanks to Professor John Bland). It features the following technical data :

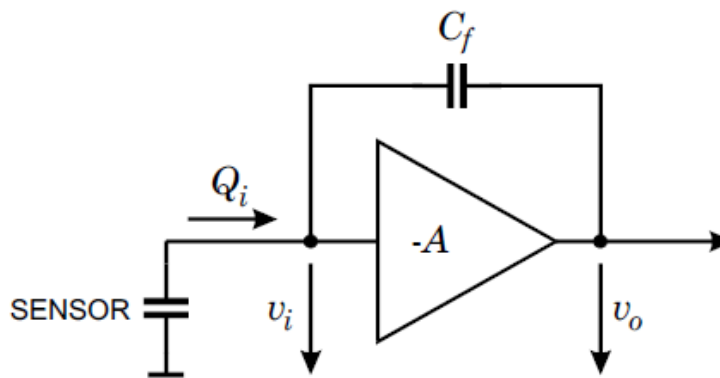
Canberra PIPS SPD-100-12 (partially depleted)

- Active Area = 100mm^2
- FWHM 12KeV at 5MeV
- Bias Voltage = 40V
- Thickness = $100\mu\text{m}$

Signal Processing

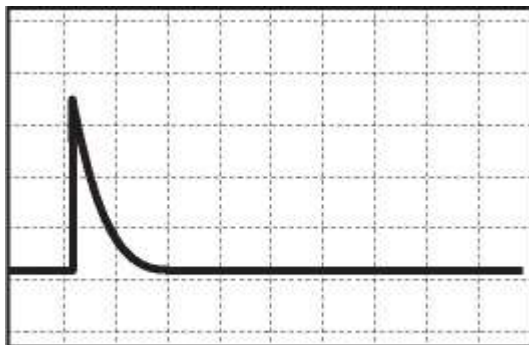
The signal produced by the detector has very low amplitude and therefore it requires an appropriate amplification. Given the very low level of the signal you must use very low noise amplifiers, also the bias voltage must be free of ripple, which is why we have adopted a power-based batteries. The preamplifier of the signal is based on a **charge sensitive preamplifier type (CSP)**: the current pulse generated by the detector is converted into a voltage pulse by means of the charge of a capacitor.

In the scheme below it is presented a basic diagram of a charge preamplifier :

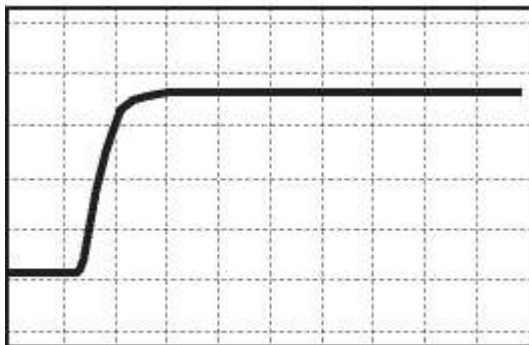


Basic configuration of a charge-sensitive amplifier

Response of a CSP amplifier



$i_d(t)$: detector current pulse: 10ns/div



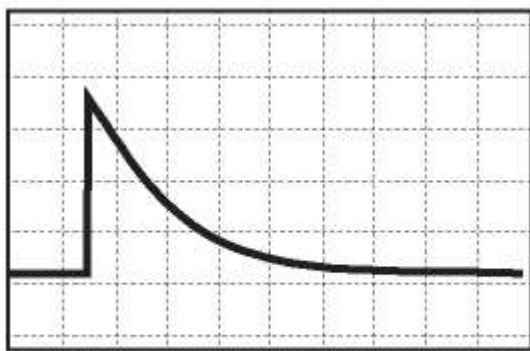
$V_{out}(t)$: CSP output pulse: 10ns/div

At time domains lasting up to a few microseconds, the CSP output is the time integral of the current pulse from the PIPS/Surface barrier detector. The output rise time is approximately equal to the duration of the current pulse, although the speed of the CSP sets a lower limit to this rise time.

Because the CSP Produces an output voltage step that is proportional to the time integral of the current input and remembering that :

$$V_{out}(t) \propto Q(t) = \int i_d d\tau$$

the CSP output is proportional to the total charge (Q) from the PIPS detector. At much longer time domains the response of a CSP to a fast current pulse from a PIPS detectors is in the form of a tail pulse.



CSP output pulse: 100 μ s/div

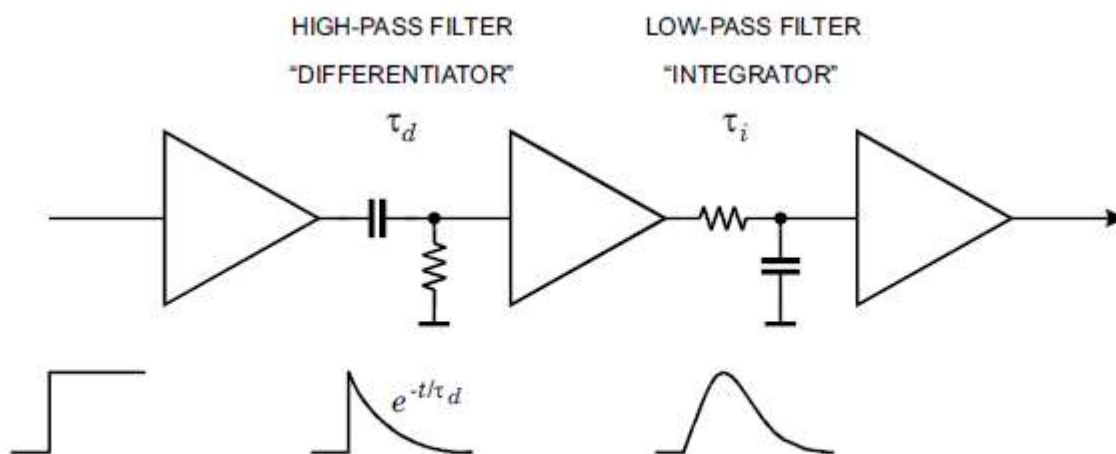
A tail pulse has a fast initial rise time followed by a very long exponential decay back to the baseline. A tail pulse response from a CSP module is shown below.

The reason for the exponential decay is the resistance that is placed in parallel to the feedback capacity. This solution is necessary so that the CSP can respond to subsequent pulses.

Shaping the Tail Pulse into a Gaussian Pulse

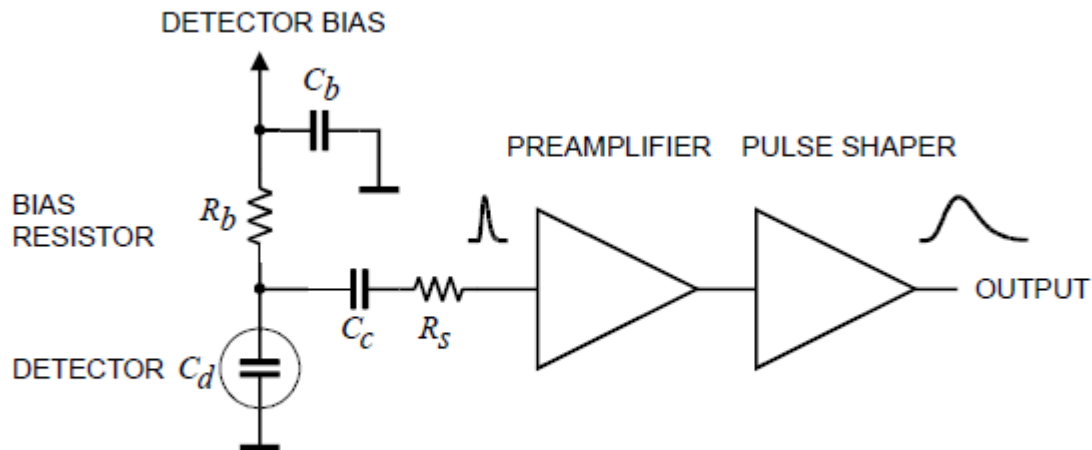
The output of the CSP (with its tail pulse signal shape) should only be considered to be an intermediary step in producing a measurable output. The long tail makes digitizing the pulse heights impractical, because pulses will often ride on top of the long tail of one or perhaps several preceding pulses. To quicken the decay time of the pulses we recommend routing the CSP output into a **shaping amplifier** internship which produces a symmetrical bell-shaped pulse. Another important feature of the shaping amplifier is that much of the noise is filtered, improving the signal to noise ratio considerably. Signals that may be buried in the noise of the CSP output become clearly above the noise after the shaping internship.

In the scheme below it is presented the basic diagram of a shaping amplifier:



A simple pulse shaper using a CR "differentiator" as a high-pass and an RC "integrator" as a low-pass filter.

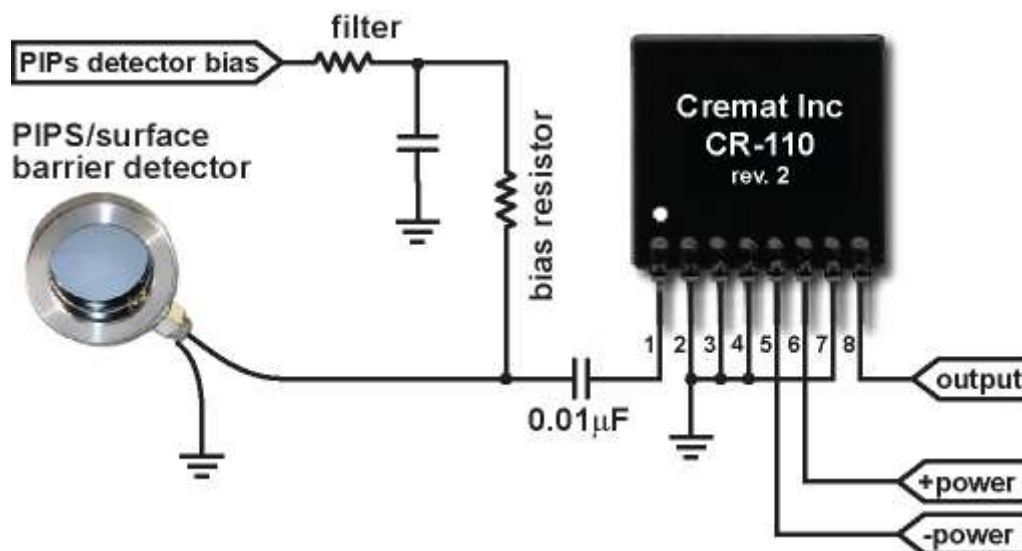
In following scheme the basic scheme of a signal processing chain is presented, it consists of bias, detector, CSP amplifier and pulse shaper :



A typical detector front-end circuit

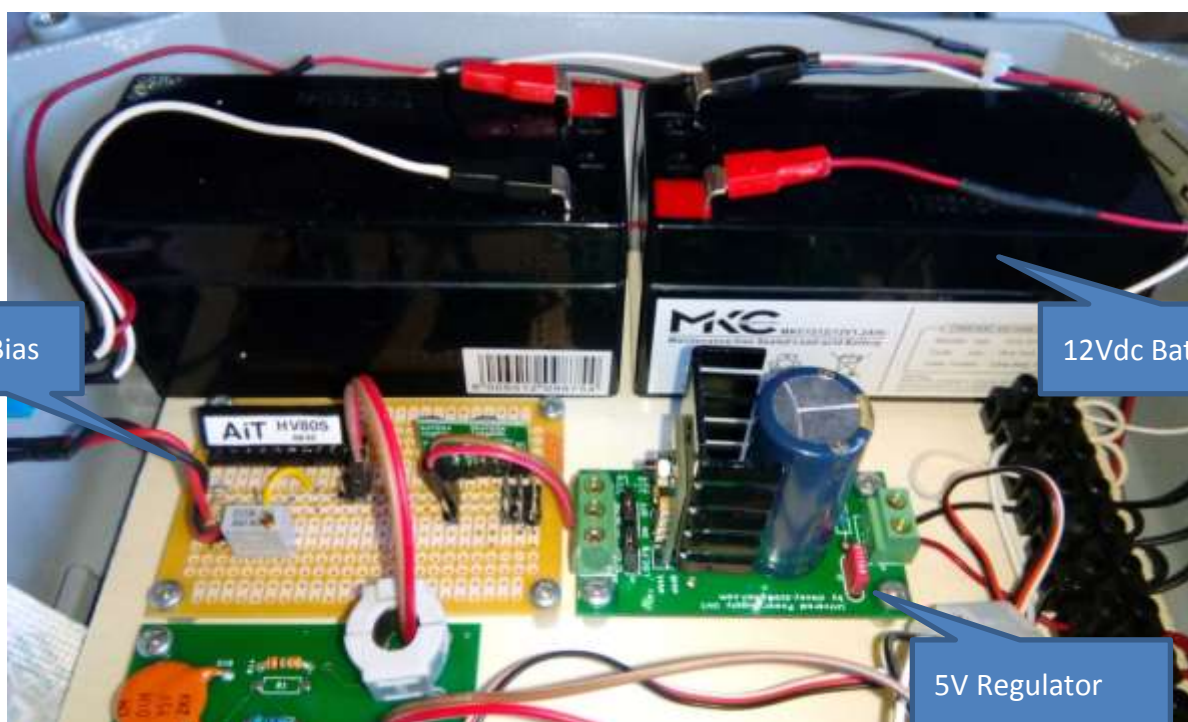
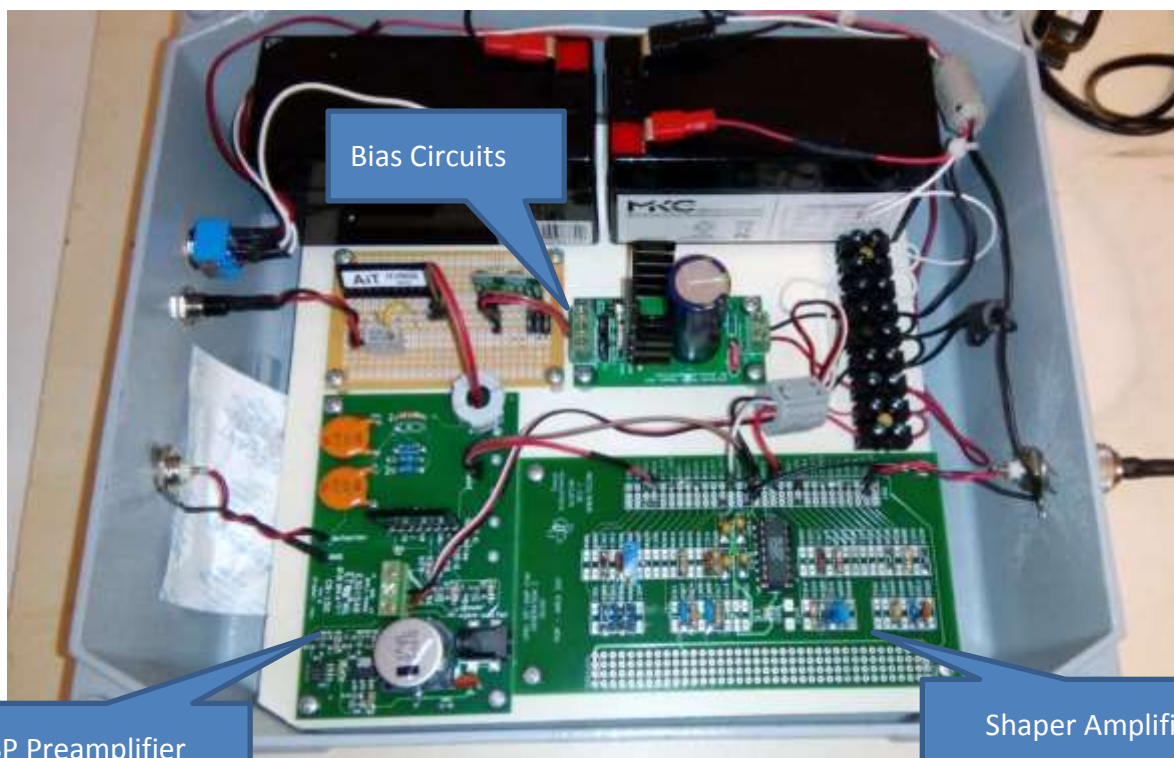
Amplifier Construction

For our alpha spectrometer we decided to use a **commercial CSP**, the model CR-110 made by Cremat. It is a hybrid CSP preamplifier with a feedback capacity of 1.4 pF and a feedback resistance of 100 M Ω , the time constant of the amplifier is **140 μ s**. We decided to adopt a commercial component (it is not expensive) because the CSP is a critical component and the functioning of the system depends greatly on the good performance of the CSP in terms of gain and low noise. The diagram below shows the connections of the component:



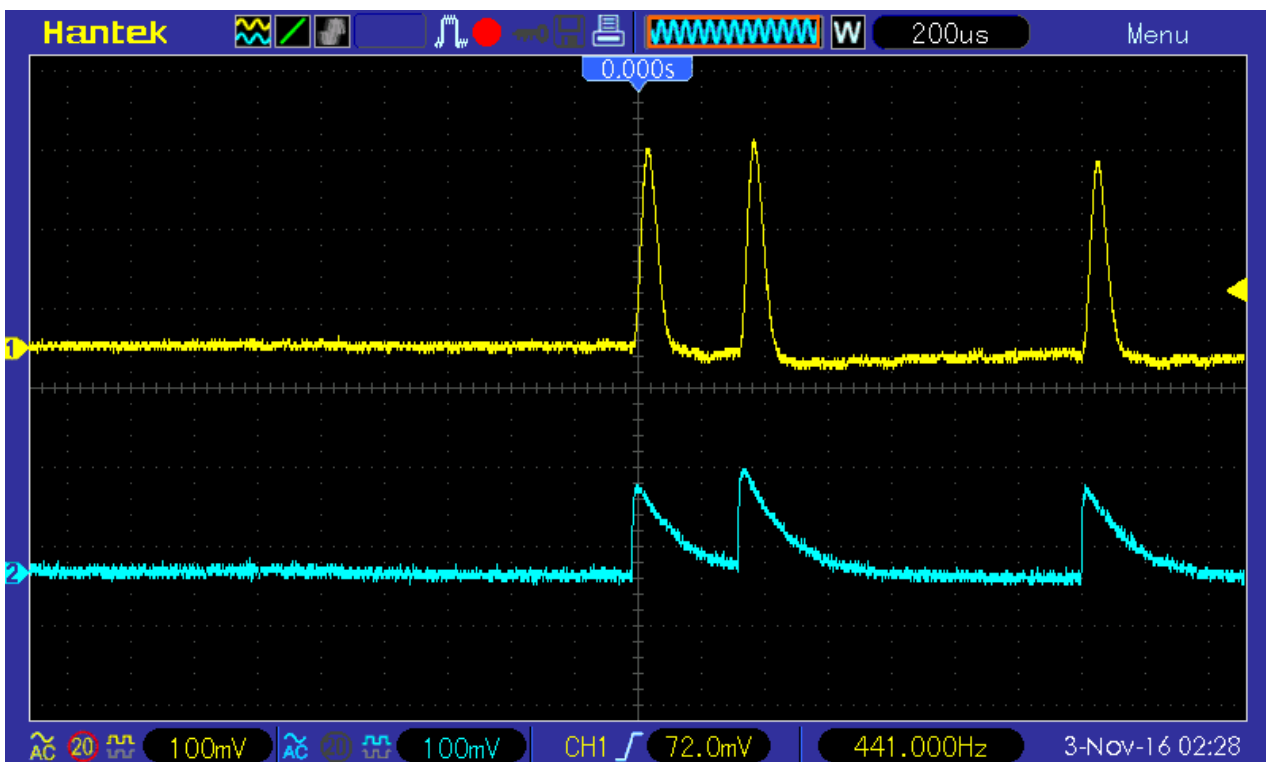
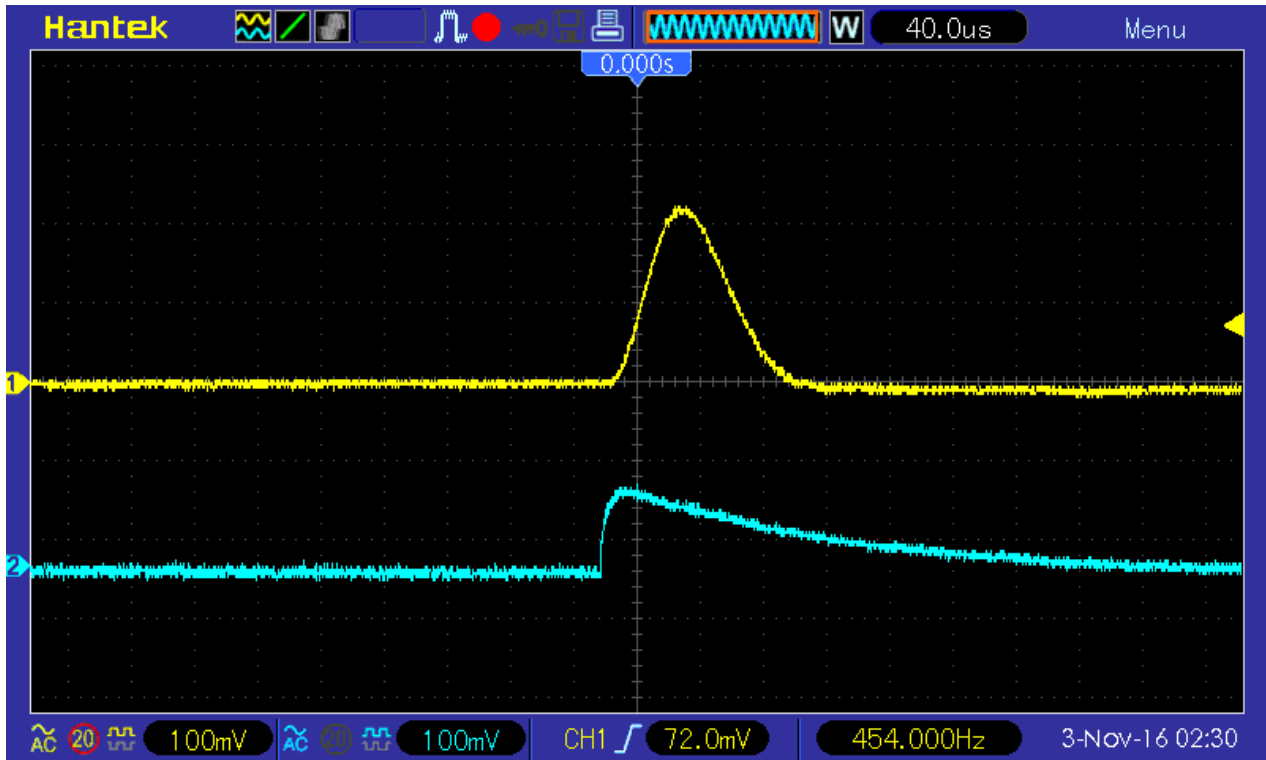
In particular the bias resistance and filter resistance were chosen of 10 M Ω . These values, taking into account a dark current of less than 100nA, guarantee a good compromise between the need to limit the drop in the bias voltage and that of having an adequate amplitude signal on the coupling condenser towards the CSP.

The shaping amplifier instead was "homebrew", as already described in the post [PMT Pulse Processing](#). The images below show the finished circuits inside a metal box that constitutes a shield against RF interference.



Pulses

The images below shows the paths of the output signals at the shaper (in yellow) and at the CSP output (in blue). You can see how the pulse produced by the shaper has a **Gaussian** shape, with amplitude of about 200mV and a duration of approximately **80 μ s**. The pulse produced by CSP has instead an **exponential** decay with a much longer duration: **300 μ s**.

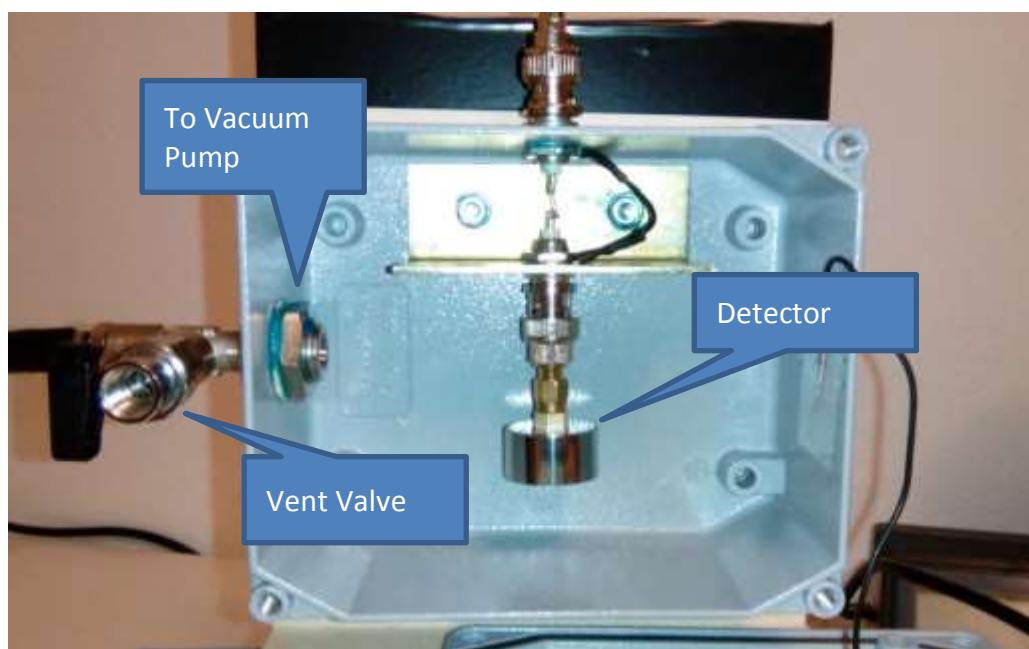


Vacuum and Chamber Setup

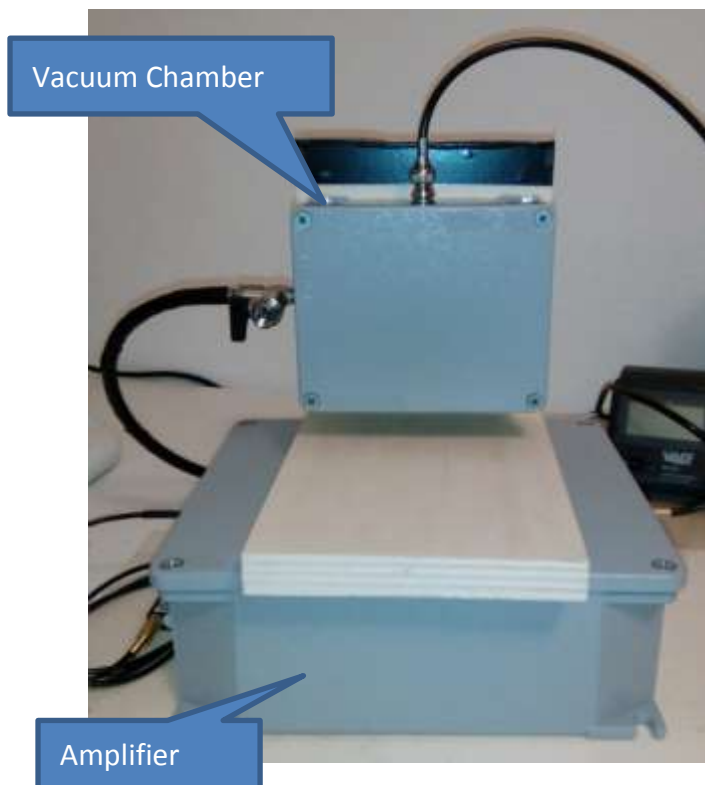


The first solution that we tried in order to achieve the alpha spectrometer has been an old system no longer used (found on eBay ..): the famous "Nucleus", image on side. It is an apparatus which includes a small vacuum chamber along with all the necessary electronics for the biasing the sensor and for processing the signal. But the evidence shows the old electronics proved not to be very reliable so we decided to remake both the vacuum chamber that all the electronics.

For the vacuum chamber we used a sealed die-cast aluminum container, drilled for the BNC connector and for through-connection for the pipe from the vacuum pump. In the picture below you can see the "new vacuum chamber" :



In the images below instead you see the overall setup of the apparatus and the vacuum pump, two-stage rotary pump.

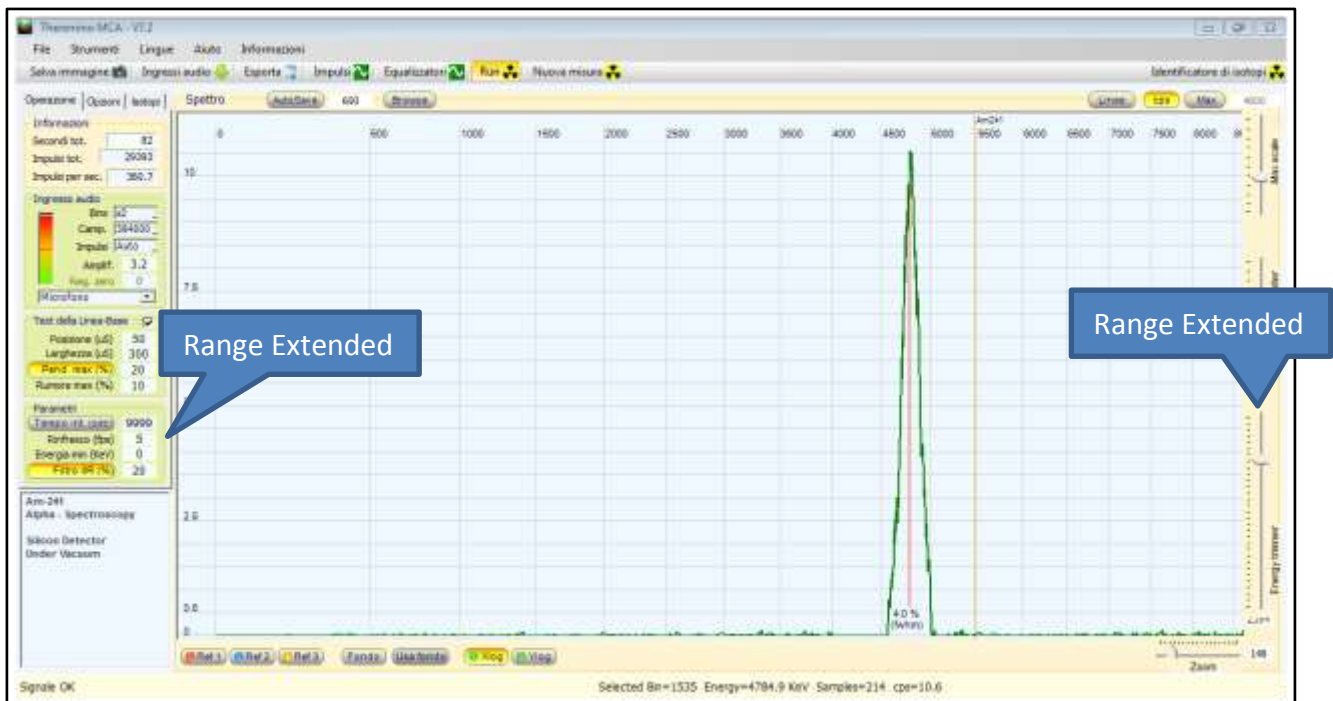


Multichannel Analyzer

After the hardware now we deal with software. The pulses generated by the shaper are acquired by [MCA Theremino](#) software through a USB sound card. Theremino MCA is the software that we have extensively used in gamma spectroscopy studies, widely reported on this blog. In [Theremino](#) web site there is a whole section on this application, with a rich set of documentation.

The version that we used is **7.2**. This version has been specially modified to enable the usage also for alpha spectroscopy. In particular has been expanded the scale of energies up to 10 MeV, it has also been expanded adjustment range of MinEnergy and EnergyTrimmer parameters.

In the image below we show the alpha spectrum of Americium source Am241 (from smoke detector) which emits at about 5,5 MeV.



Because of the source shielding, alpha particles have an energy a little bit smaller than the real one and so the peak is shifted at about 4800 MeV. This source, easily available, can still be used for a first **calibration** of the software. The **amplification** parameter and the energy trimmer cursor must be adjusted so as to bring down the peak at about 4800 MeV. If acting on these adjustments it cannot place the peak adequately, then it is necessary to act on the amplification **shaper**, up or down, so as to fall within the range of expected energies.

Operazione Opzioni Isotopi		
Nome	Energia	
☐ Nd144	1830.00	
☐ Gd152	2140.00	
☐ Sm147	2230.00	
☐ Sm146	2460.00	
☐ Hf174	2500.00	
☐ Gd150	2730.00	
☐ Gd148	3180.00	
☐ Pt190	3180.00	
☐ Th232	3950.00	
☐ Th232	4011.00	
☐ U238	4150.00	
☐ U238	4200.00	
☐ U235	4366.00	
☐ U235	4396.00	
☐ U235	4415.00	
☐ U236	4440.00	
☐ U236	4493.00	
☐ U235	4556.00	
☐ Bi210	4570.00	
☐ U235	4597.00	
☐ Ra226	4599.00	
Deseleziona tutte le righe		
Estendi le righe abilitate		
Estendi isotopo selezionato		
Select sample		
Modifica il file delle righe		

In order to have readily available the main alpha emitters isotopes it has been prepared a new file of the isotopes energies, comprising only alpha emitters with energies from 1.5 to 9 MeV.

The new **Isotopes_Energy.txt** ([isotopes energy](#)) files must be replaced to the existing file in **Theremino_MCA/Extra** folder (you should make a copy of the original file). The list of the isotopes will appear as shown in the image aside.

Operating Procedure

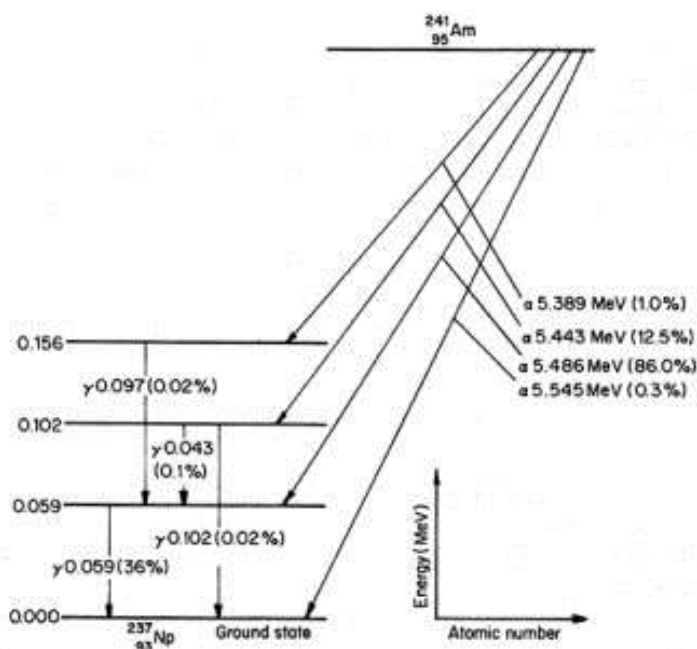
To take a measurement it is necessary to insert the source inside the vacuum chamber, activate the vacuum pump and when the pressure has dropped to the minimum, give voltage to the detector. The detector should never be biased at atmospheric pressure and should never be exposed to light when powered otherwise be damaged. The detector is very sensitive and its active area must never be touched, if you need to remove dust you could use a breath of air, also maximum working voltage must not be exceeded. Another care that must be followed is that of not leaving alpha sources within the vacuum chamber for too long, this is because the sensor is slowly damaged by the particles themselves. It is also important to be careful to not "contaminate" the measuring chamber with residues of samples, this can be easily done using a disposable aluminum foil as a source of support.

Some Alpha Spectra

With the help of the spectrometer for alpha particles, described in the post [DIY Alpha Spectrometer](#), we looked at some isotopes and radioactive substances. The main difficulty of the alpha spectroscopy is the preparation of the source: to obtain net lines and good resolutions it is necessary that the active layer is very thin (ideally only a few atoms) and homogeneous. Of course this is quite hard to get, so we will content ourselves of the sources that can be prepared in a "home" laboratory.

Spectrum α Americium (^{241}Am)

Americium-241 was directly obtained from plutonium upon absorption of one neutron. It decays by emission of a α -particle to ^{237}Np ; the half-life of this decay was first determined as 510 ± 20 years but then corrected to 432.2 years. Americium is the only synthetic element to have found its way into the household, where one common type of smoke detector uses ^{241}Am in the form of americium dioxide as its source of ionizing radiation. This isotope is preferred over ^{226}Ra because it emits 5 times more alpha particles and relatively little harmful gamma radiation. The amount of americium in a typical new smoke detector is **1 microcurie (1 μCi , 37 kBq) or 0.28 microgram**. This amount declines slowly as the americium decays into **neptunium-237**, a different transuranic element with a much longer half-life (about 2.14 million years). With its half-life of 432.2 years, the americium in a smoke detector includes about 3% neptunium after 19 years, and about 5% after 32 years.

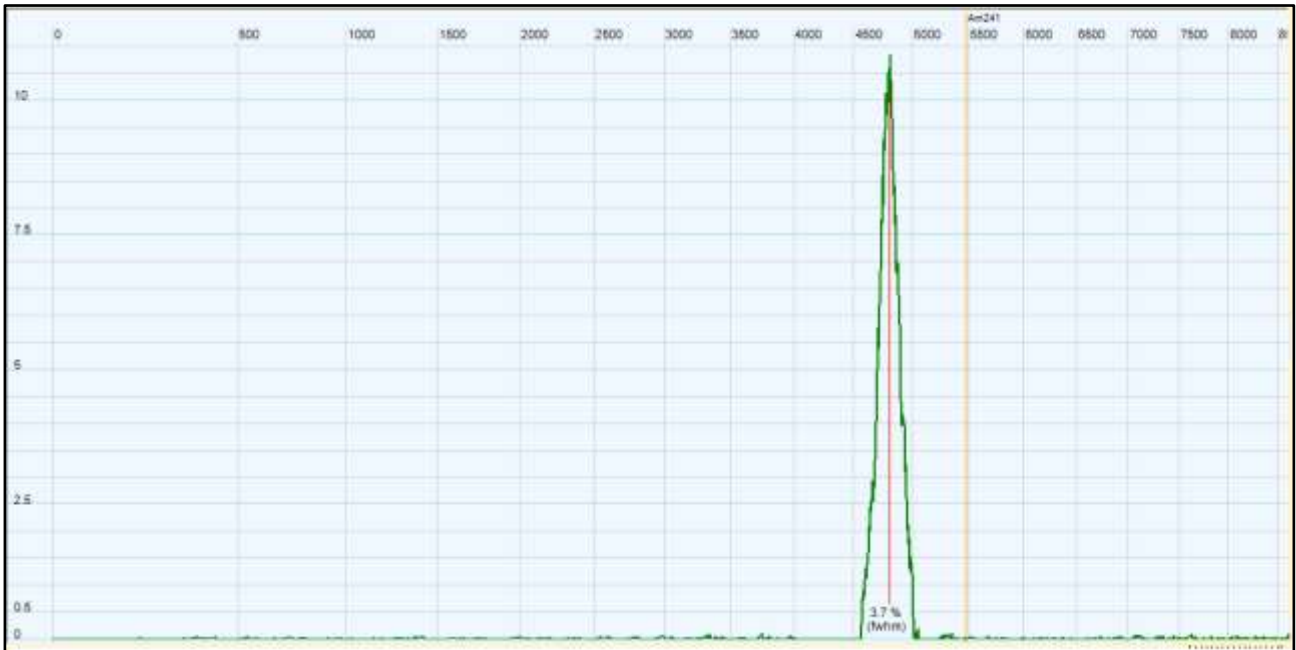


Americium decays by means of the $4n + 1$ chain of **Np-237** is commonly called the “neptunium series” or “neptunium cascade”. The americium decay takes place by means of **emission of alpha particles with energy of 5443 KeV and 5486 KeV**.

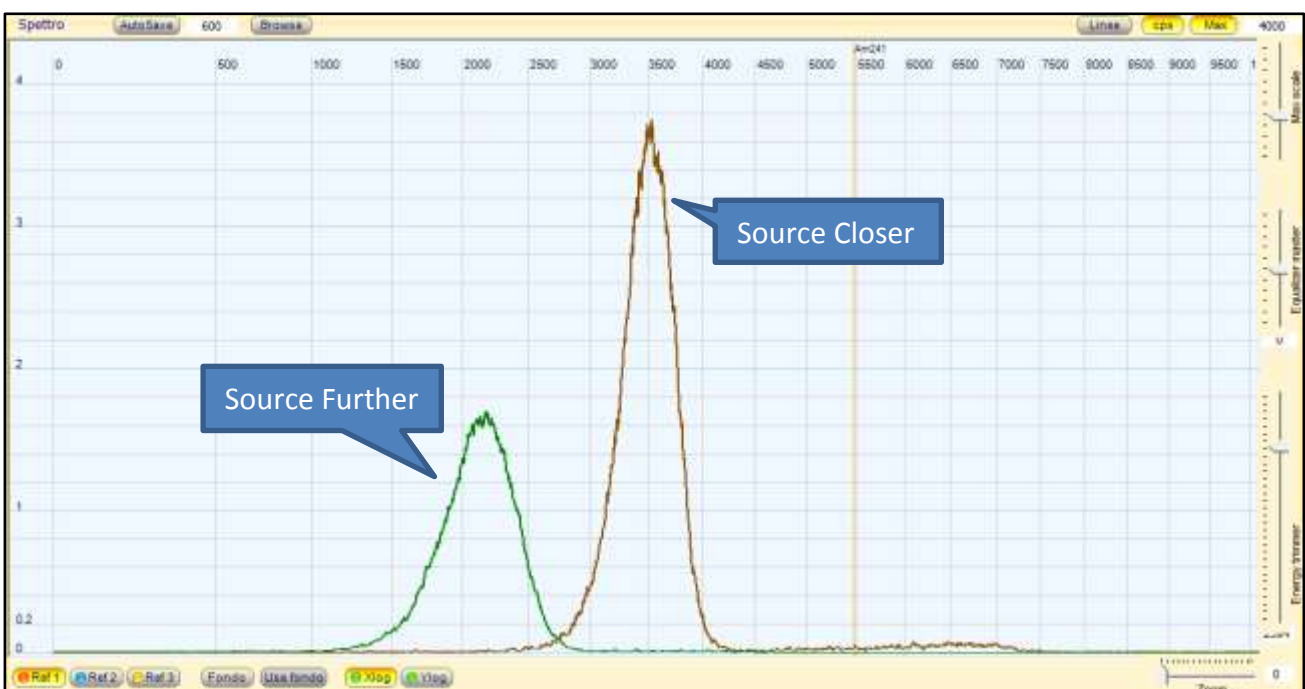
For our test we used a americium capsule contained in a smoke detector. Keep in mind that the active element is deposited on a support protected by a very thin golden plate, as seen in the image above, this has the effect of lowering a bit the energy of alpha particles and enlarge the line

emission decreasing the resolution.

In the diagram below you can see the alpha spectrum of americium emission : a line centered at about 4800 keV with a FWHM of about 4%.



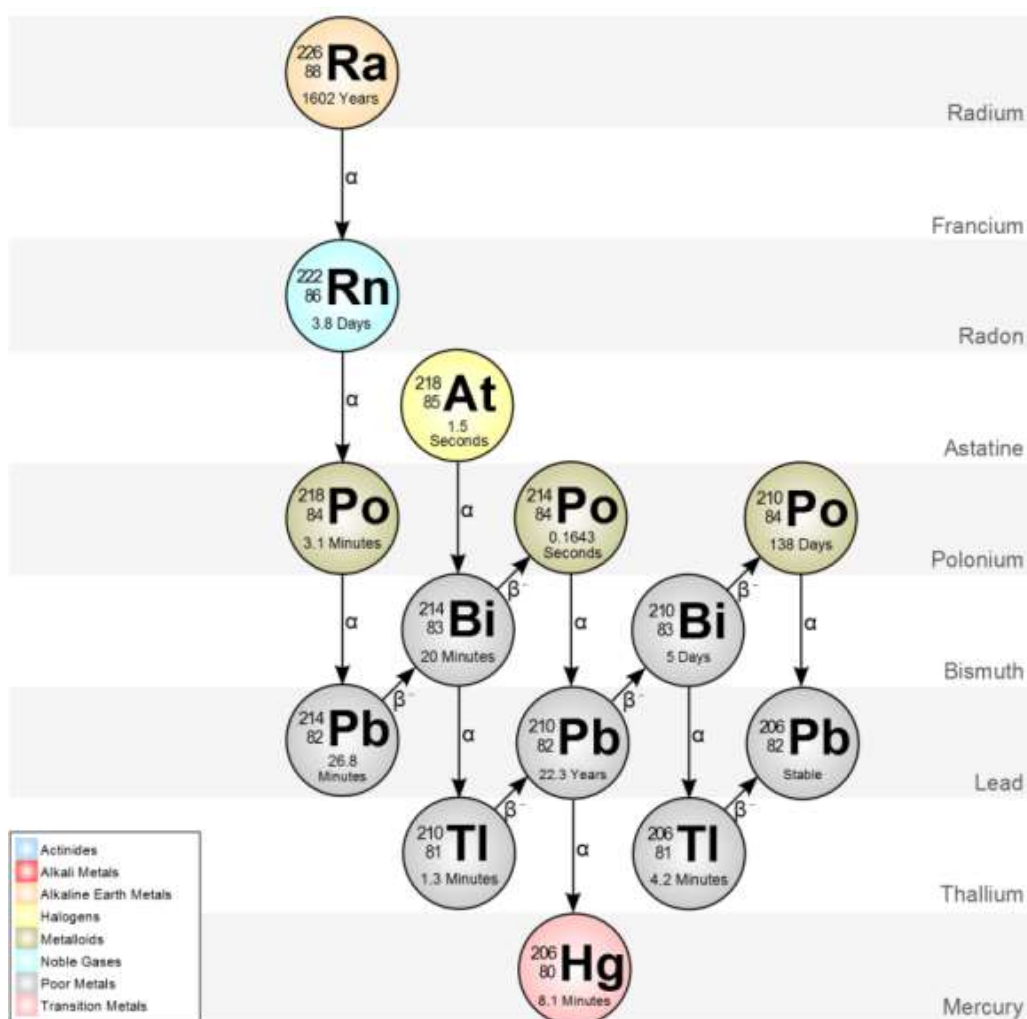
The measurement of the americium spectrum displayed above was made in a vacuum, if no air is evacuated from the measuring chamber the result that is obtained is different because the air has the effect of slowing the alpha particles and dispersing their energy. The chart below shows two spectra of americium alpha taken with the source at two different distances from the detector without evacuating the chamber. You can see that how the lowest peak, corresponding to a greater distance from the sensor, has lower energy and greater line width than the largest peak, taken at a shorter distance, this effect is known as **energy straggling**.



Spectrum α Radium (^{226}Ra)

Radium is a chemical element with atomic number 88. Its symbol is **Ra**. The word radioactivity is derived from the name of this element (for historical reasons) even if it is not the element with the highest known radioactivity. White, black on exposure to air. It is an alkaline – earth metal present in trace amounts in uranium minerals. Its most stable isotope, Ra 226, has a half-life of 1602 years and decays into radon. Radium 226 belongs to the decay chain $4n+2$ of U-238 called the “**uranium series**” or “uranium cascade”.

Beginning with naturally occurring **uranium-238**, this series includes the elements: **astatine**, **bismuth**, **lead**, **polonium**, **protactinium**, **radium**, **radon**, **thallium**, and **thorium**. All are present, at least transiently, in any natural uranium-containing sample, whether metal, compound, or mineral. The series terminates with **lead-206**. The image below shows the radium section of the decay chain.



As you see there are many alpha decays that should leave their mark on the alpha spectrum of a radio source. In the following table the main radium decays are reported, highlighting the alpha decays and the corresponding energies.

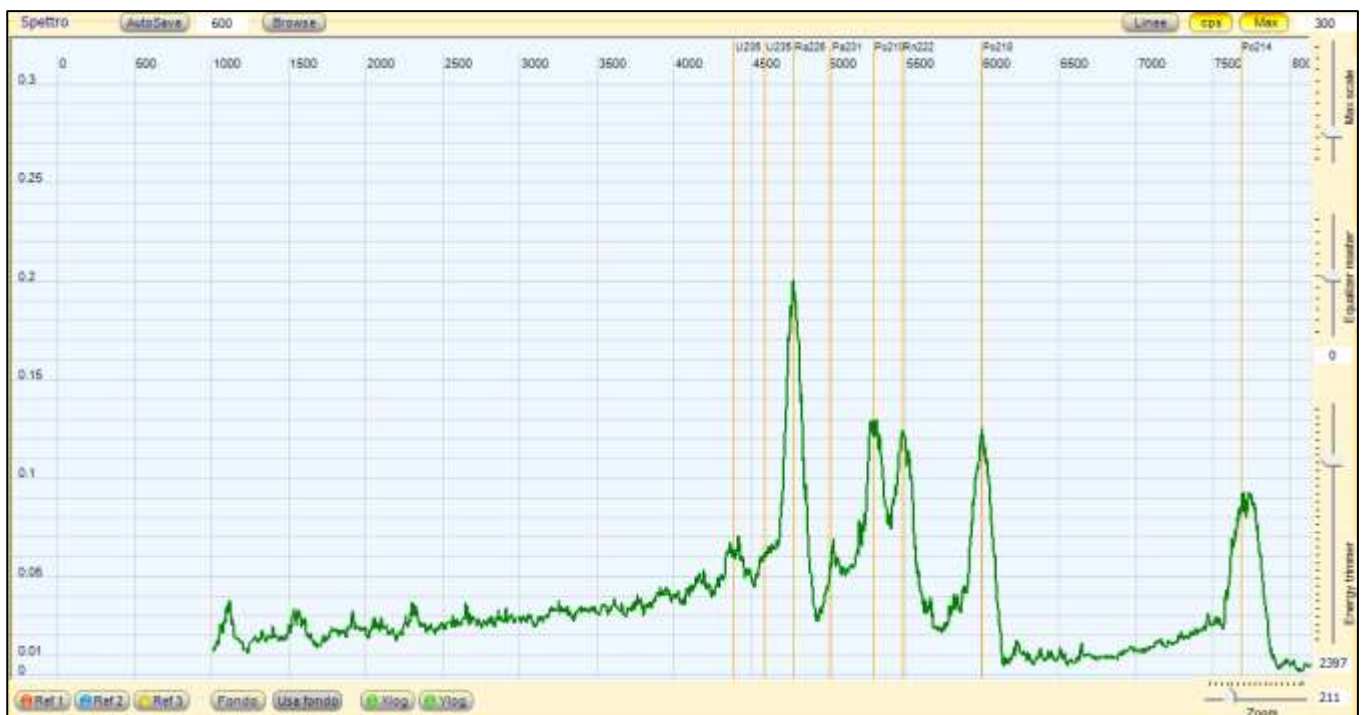
Decay process	Half-life
$^{226}\text{Ra} \rightarrow ^{222}\text{Rn} + \alpha(4784.34 \text{ keV})$	1600 year
$^{222}\text{Rn} \rightarrow ^{218}\text{Po} + \alpha(5489.48 \text{ keV})$	3.8232 day
$^{218}\text{Po} \rightarrow ^{214}\text{Pb} + \alpha(6002.35 \text{ keV})$	3.071 min
$^{214}\text{Pb} \rightarrow ^{214}\text{Bi} + e^- + \tilde{\nu}$	26.916 min
$^{214}\text{Bi} \rightarrow ^{214}\text{Po} + e^- + \tilde{\nu}$	19.8 min
$^{214}\text{Po} \rightarrow ^{210}\text{Pb} + \alpha(7686.82 \text{ keV})$	162.3 μs
$^{210}\text{Pb} \rightarrow ^{210}\text{Bi} + e^- + \tilde{\nu}$	22.23 year
$^{210}\text{Bi} \rightarrow ^{210}\text{Po} + e^- + \tilde{\nu}$	5.012 day
$^{210}\text{Po} \rightarrow ^{206}\text{Pb} + \alpha(5304.33 \text{ keV})$	138.3763 day

Table Energy of principal α particles emitted by ^{226}Ra source.

For our test we used two watch hands with radium luminous paint, the level of radioactivity is low, but the layer of paint is very thin and this facilitates the formation of emission peaks.



In the image below we report the spectra obtained. The first spectrum without line broadening compensation, the second with this algorithm applied (it is for gamma spectroscopy but applicable also in this case) in order to make the energy peaks more visible.

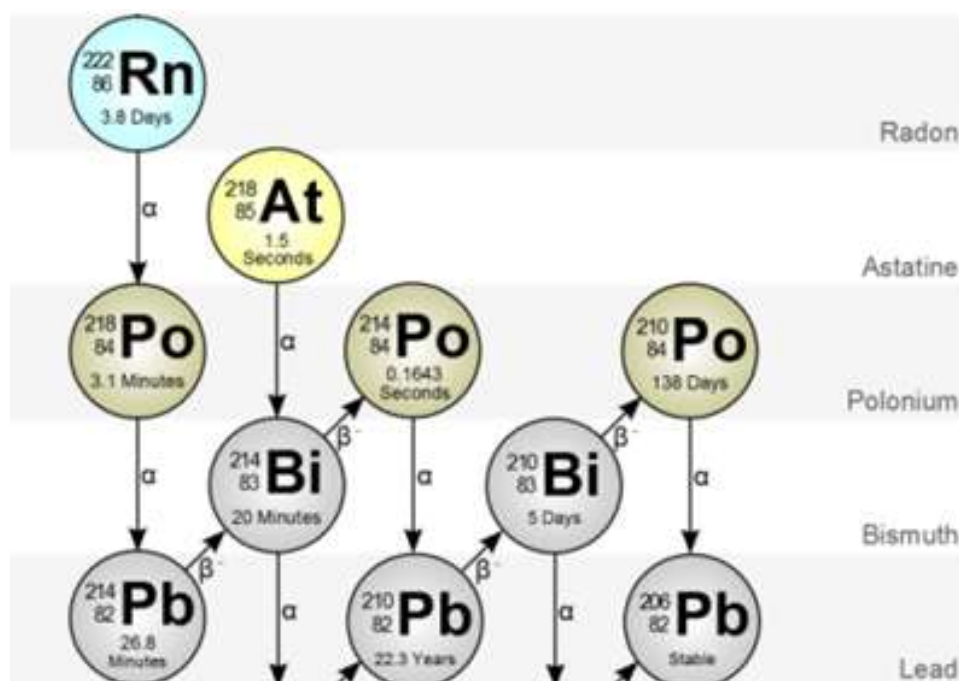


In the spectrum we recognize the emission peaks of **Radium 226** (4782 KeV), of **Polonium 210** (5305 KeV), **Radon 222** (5490 KeV), **Polonium 218** (6002 KeV) and **Polonium 214** (7687 KeV). There is also a peak at around 5000 keV, which corresponds to isotope **Protactinium 231** and emission peaks which could be correspond to **Uranium 235** emission.

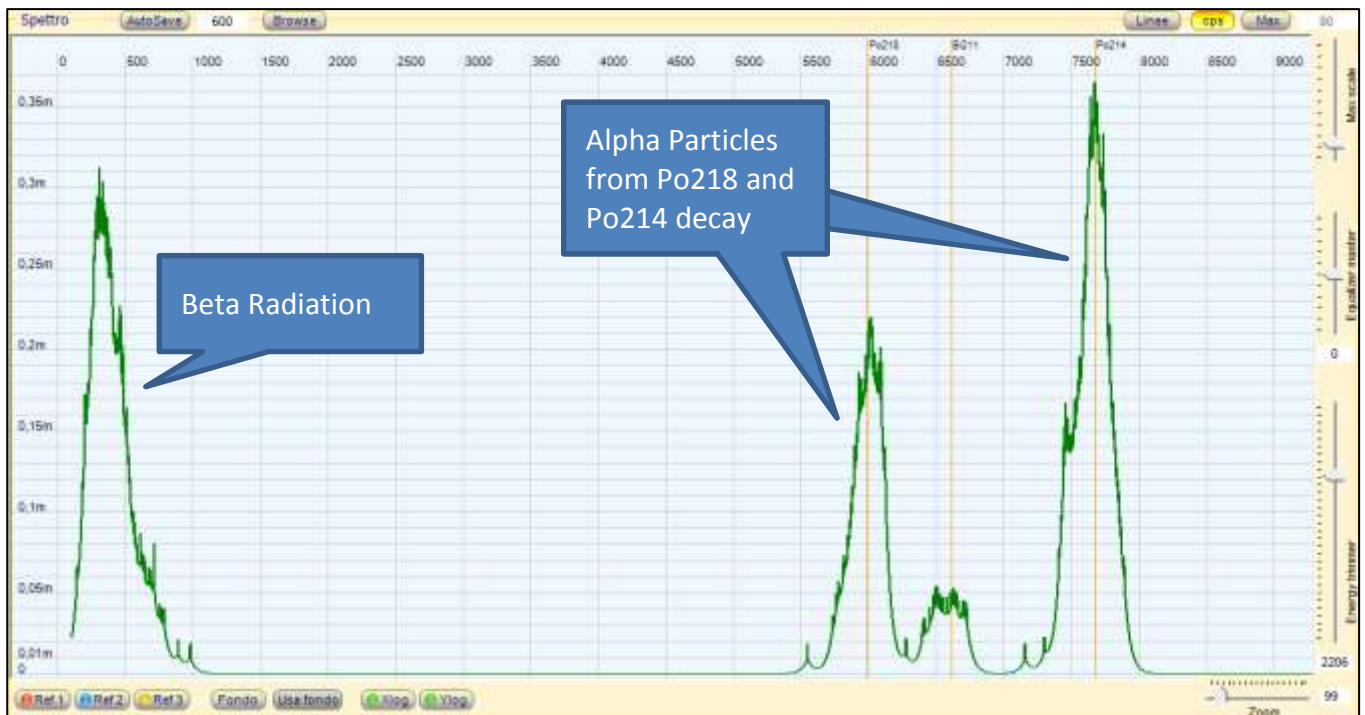
Spectrum α Radon-222 Daughters



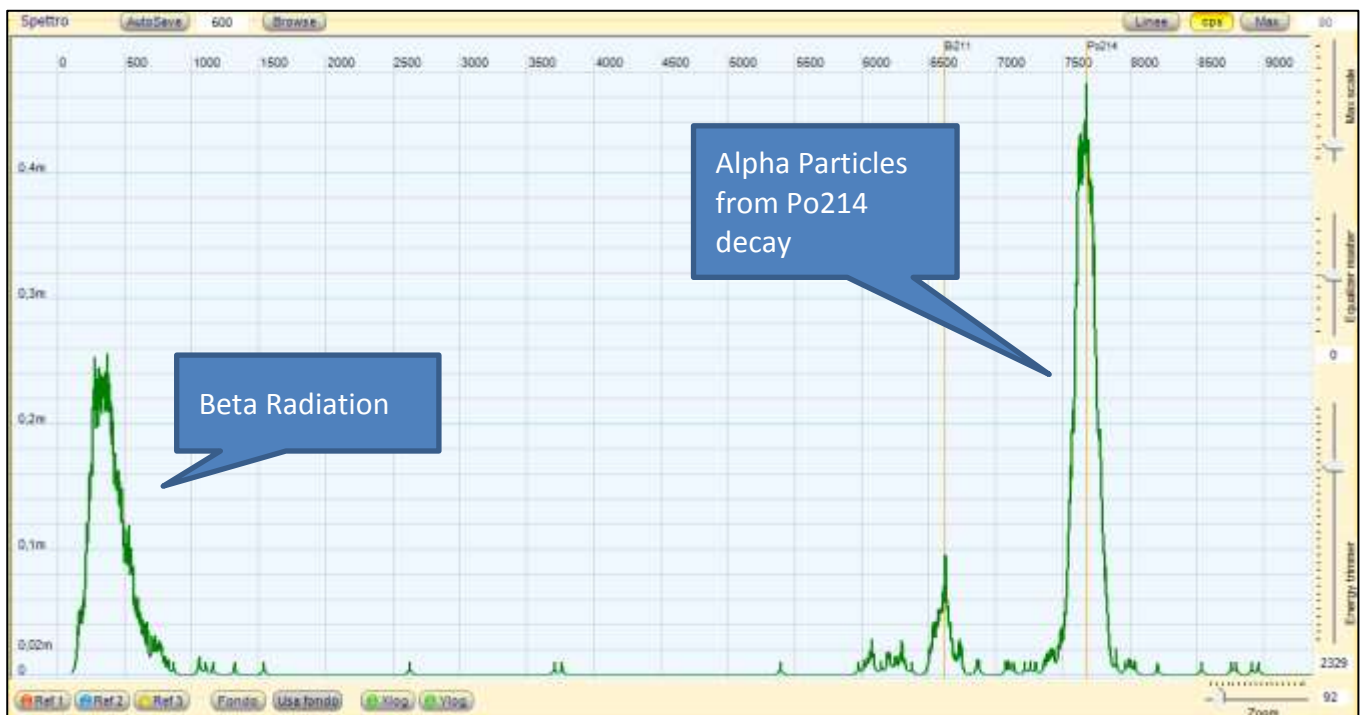
Adopting the setup shown in the images above you can make the spectrometry of some isotopes of Radon progeny. A uraninite sample is placed inside a sealed pouch with a piece of paper. Radon emitted from the ore with his daughters (in particular **Po²¹⁸**, **Pb²¹⁴**, **Bi²¹⁴** and **Po²¹⁴**) settles in part on the surface of the paper and can be detected by the alpha spectrometer.



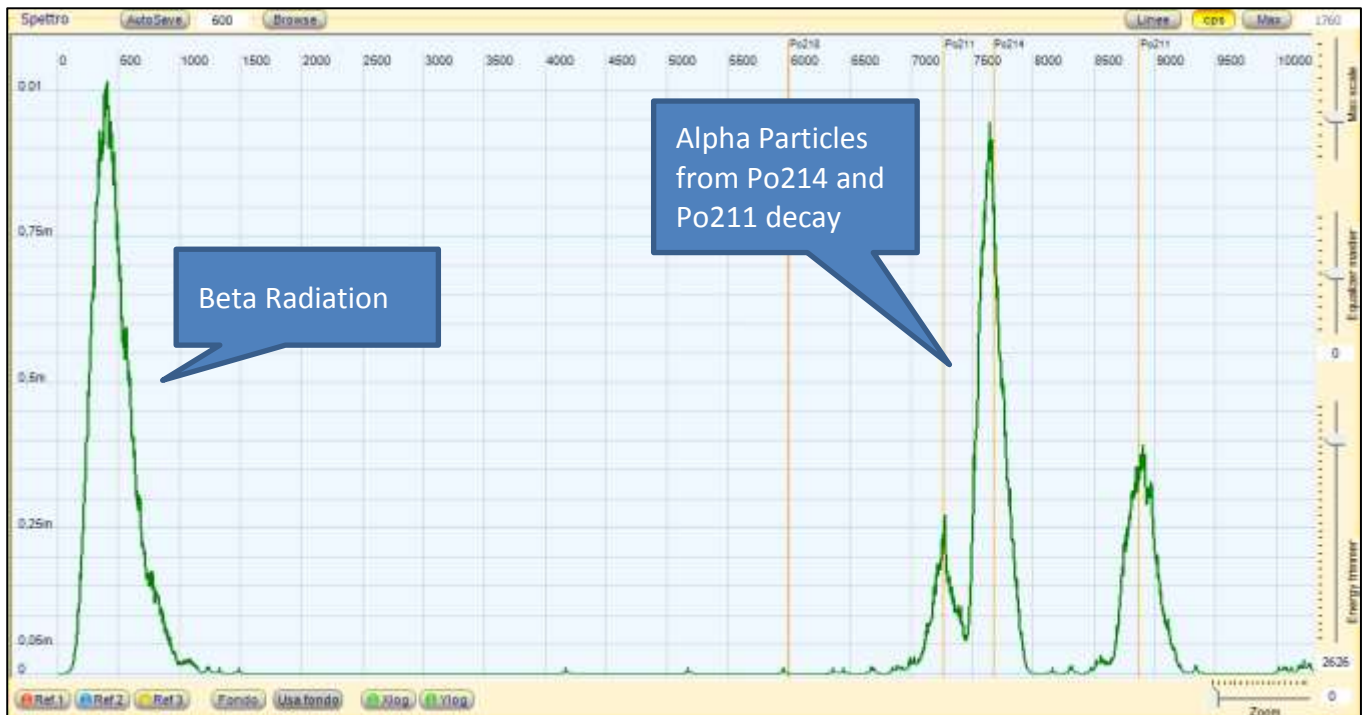
In the graph below you can see after few minutes the peaks of **Po218** at **6000 KeV** and **Po214** at **7687 KeV**.



In the chart below you can see how after several minutes remained only the peak of **Po214** due to the fact the **Po218** has a decay time of **3 minutes**. Note the presence of an emission peak in correspondence isotope **Bi211**, product of the decay of uranium 235 through the Radon 223.



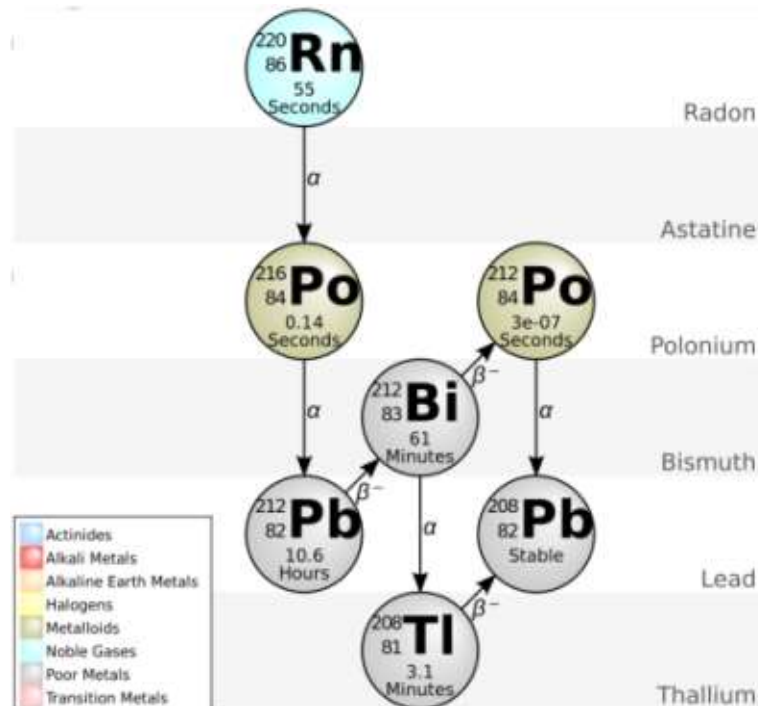
Using the electrostatic trap that will be described in the following paragraph has been acquired an additional spectrum of radon progeny. The electrostatic trap allows for selectivity and concentration of the positive ions produced by radon decay.



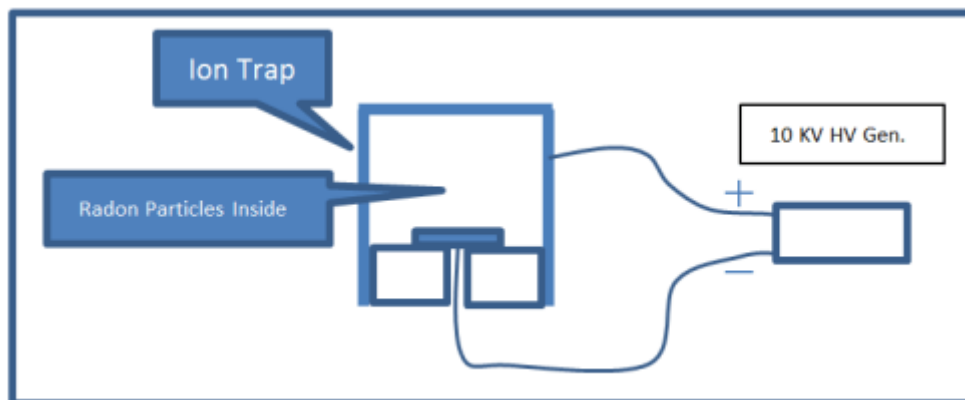
We note the presence of the isotope Po211 product of the decay of uranium 235 through 223 Radon.

Spectrum α Radon-220 (Thoron) Daughters

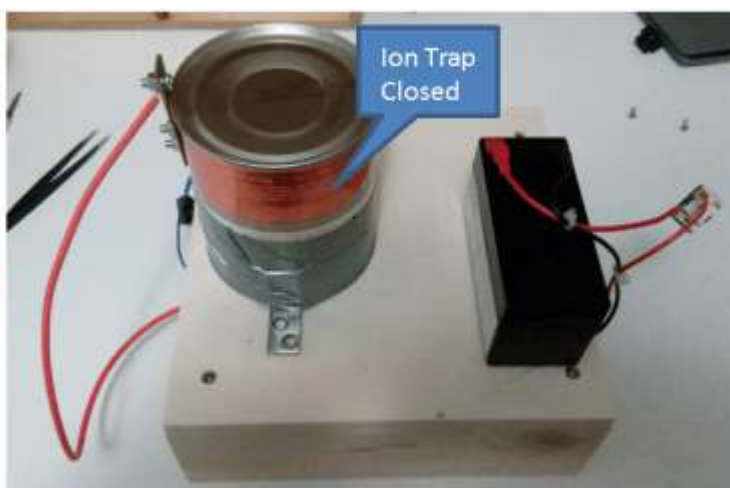
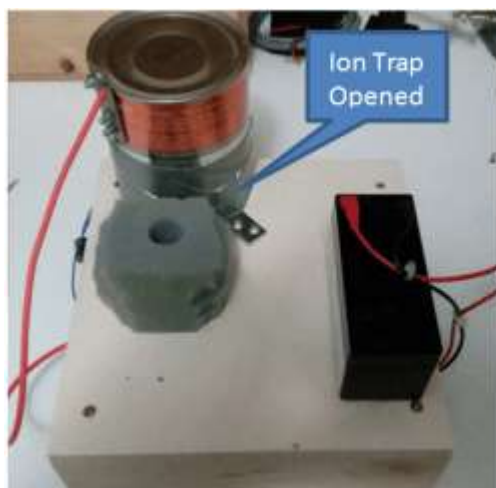
"**Thoron**" is the name that identifies the radon isotope with atomic weight 220. This radioactive isotope is produced in the decay chain of thorium and its decay time is about **55 seconds**.



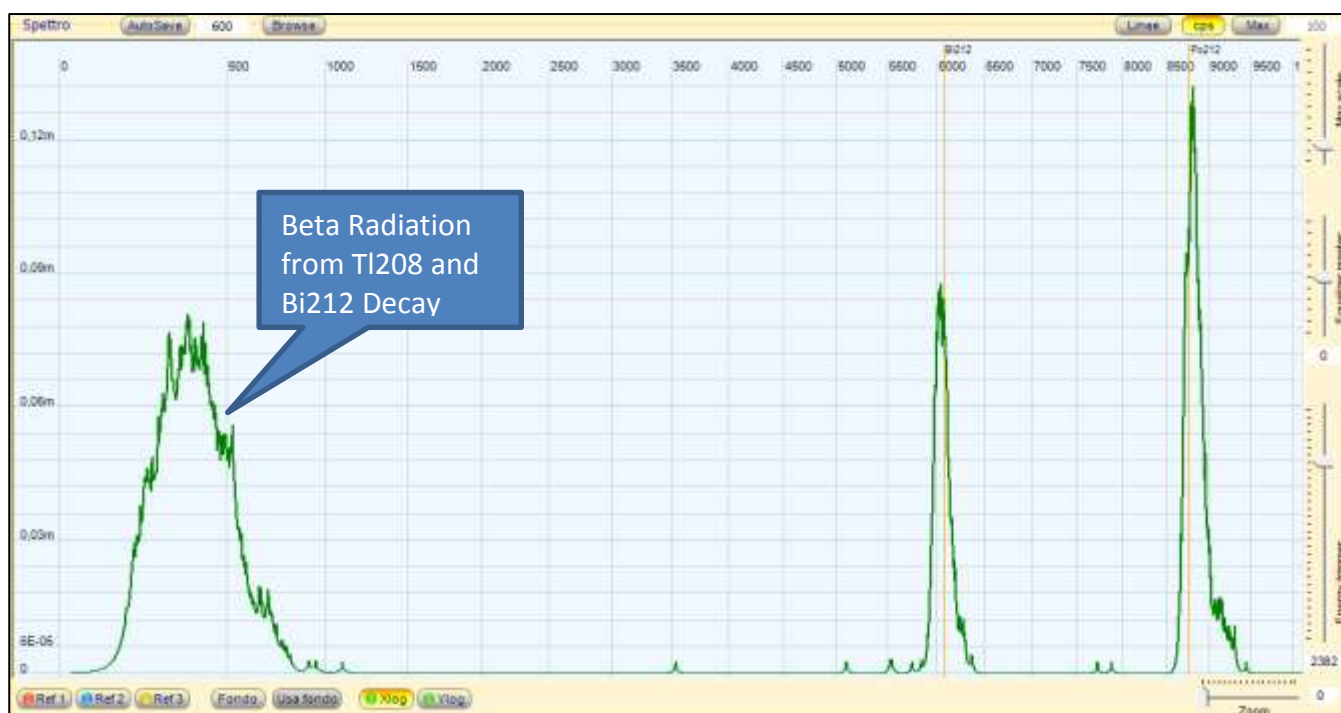
In the thoron decay chain highlights the **Pb-212** isotope, with a half-life of approximately 10 hours, with the 239 keV main gamma peak. In the field of alpha radiation important are the **Bi-212** and **Po-212** isotopes. The image on the left shows a part of the decay chain from radon 220 onwards. As thoron source were used the classical thorium mantles. To capture the progeny of thoron an "**electrostatic ion trap**" has been used to capture and concentrate the isotopes on a metal plate, the positive ions produced by the beta decay of Pb-212 : **Bi-212** and **Po-212**, both of them alpha emitters.



The ion trap is shown schematically in the drawing shown below : it is a metal container that is positively charged with respect to a metal plate placed inside at a center position. Inside is introduced (or generated directly inside) Radon gas, which in turn decays and produces positively ionized isotopes that are rejected by the external walls and attracted toward the plate by the electrostatic field. The images below show the device.



With this method it was possible to concentrate the two isotopes and obtain the alpha spectrum shown below, in which are seen, the emission peaks of the Bi212 and the Po212 with the corresponding beta emission.

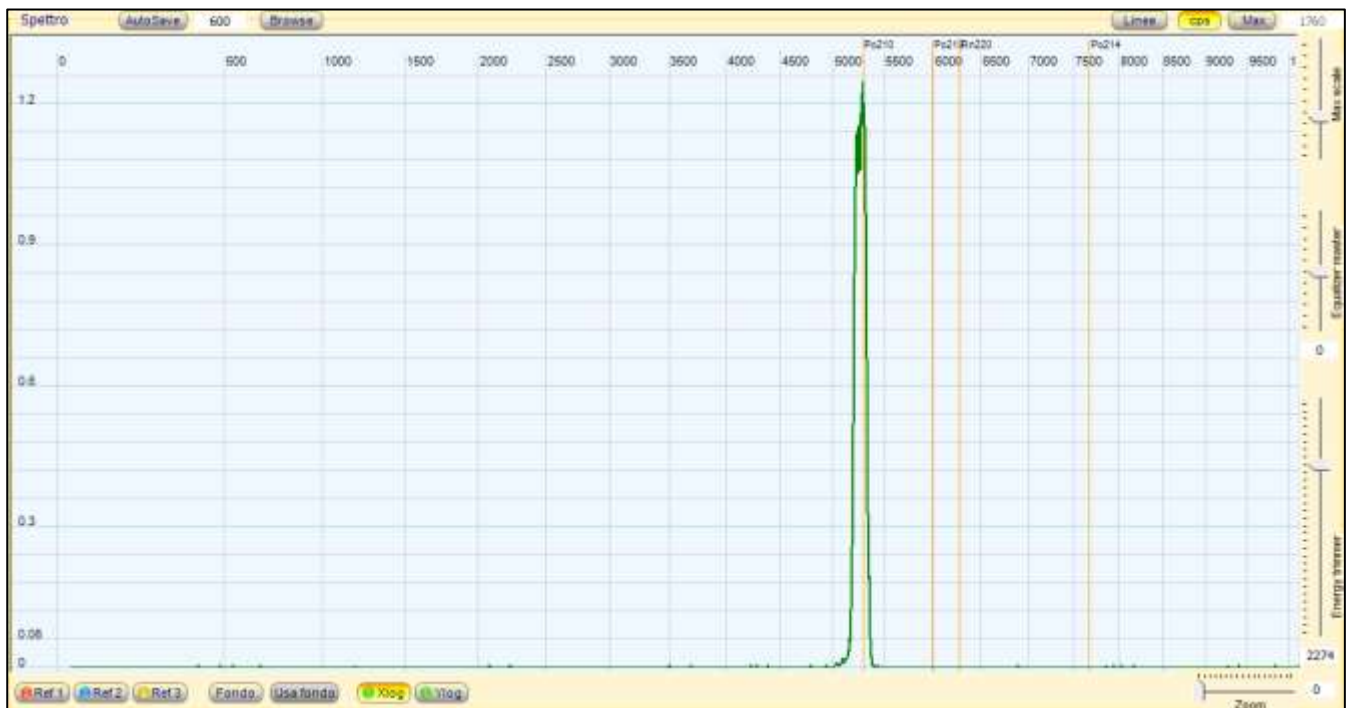


Spectrum α Polonium (^{210}Po)

This isotope of polonium is an alpha emitter with a half-life of 138.39 days. One milligram of this metalloid emits the same number of alpha particles of 5 grams of the radio. The decay of this element also releases a large amount of energy: half a gram of polonium-210, if it is thermally isolated from the environment, it can quickly reach temperatures of about 500°C , and develop about 140 W/g into thermal energy. A few curies (giga Becquerel) of

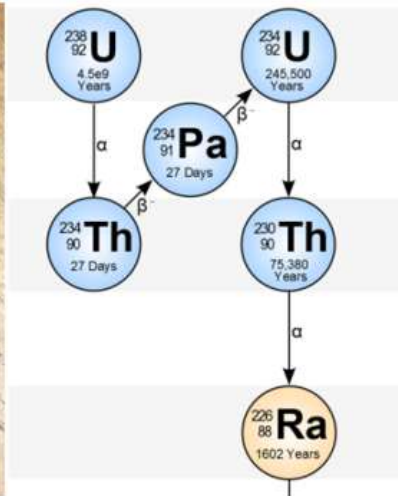
polonium-210 emits a blue luminescence due to excitation of the surrounding air for Compton effect. Infinitesimal quantity of this isotope can be used as **alpha source sample** for energy calibration in the alpha spectrometer. It should be handled with great care since the source is open and this isotope is highly toxic. In the images below shows the source and its location inside the instrument.

The graph below shows the spectrum of the source, it is a specially prepared source (thin and uniform layer), so you can reach a good resolution: **FWHM = 2%**

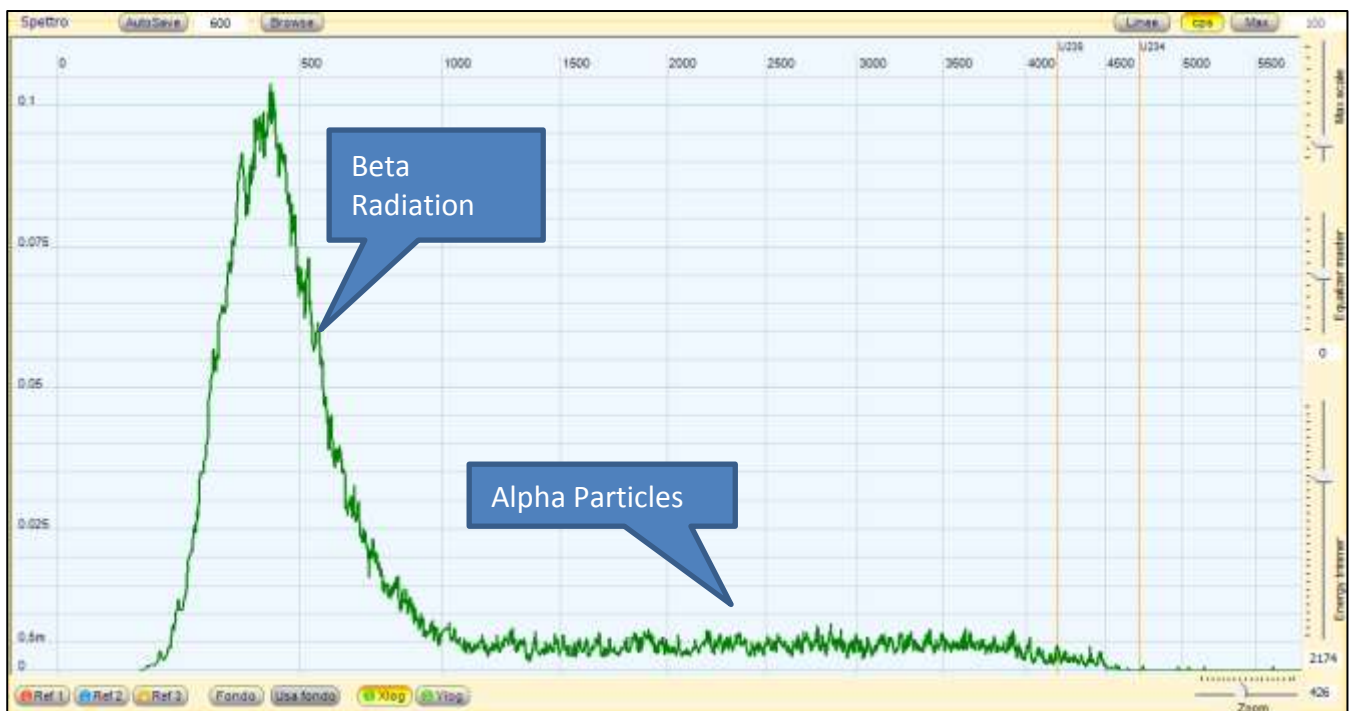


Spectrum α Uranium from “Fiestaware”

Fiesta ware was the largest selling dish line in American history – 200 million dishes were shipped since 1936. The red/orange color glaze contains **uranium**. The government seized the company's uranium supply in 1943 out of fear it could be used to make a bomb. A single plate contains about **4.5 grams of uranium, mostly U-238**. Production resumed in 1959 with depleted uranium (depleted of U-



235) and continued until 1972 when it was discontinued out of concerns about uranium and lead leaching out of the glaze. Because it had not time to be produced, the glaze does not contain radium, it contains only uranium and some of its daughter isotopes : The radioactivity comes mainly from U238 and U234 for alpha particles and from Th234 and Pa234 for beta particles. We tested a piece of this glaze with the our alpha spectrometer. The chart below shows the result :



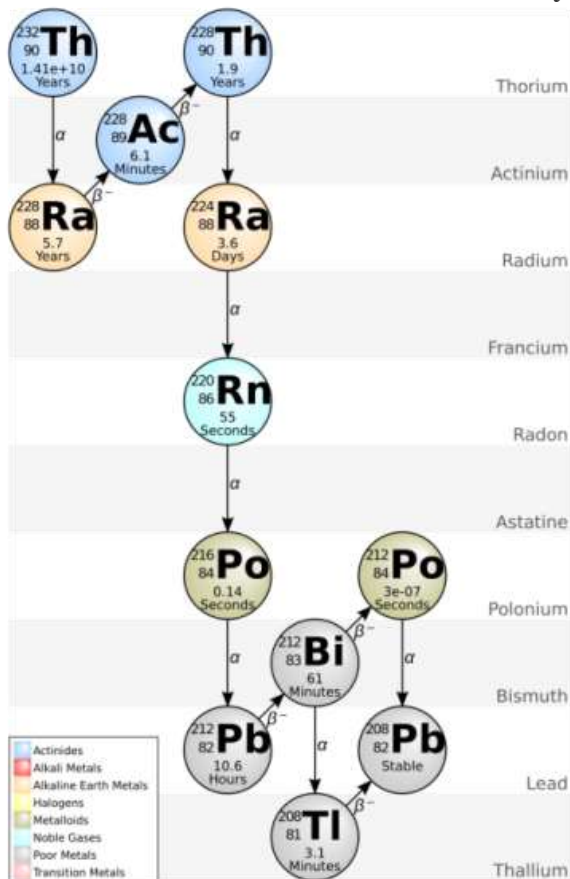
The glaze does not permit to have clear alpha peaks but instead we have a large "blob" that starts from 1MeV and goes till the energy of U238 and U2354 emissions. Below 1MeV it is also evident the spectrum of beta emission.

The graph below shows the alpha spectrum obtained from a fragment of FiestaWare. There is low resolution due to auto absorption of alpha particles. There are still some peaks and steps in correspondence at the energy of main alpha emitters of uranium chain : U 238 and U 234. There is also the peak for the isotope U 235.



Spectrum α Thorium from “Gas Mantles”

Thorium is a chemical element with symbol **Th** and atomic number 90. A radioactive actinide metal, thorium is one of only two significantly radioactive elements that still occur naturally in large quantities as a primordial element (the other being uranium).



A thorium atom has 90 protons and therefore 90 electrons, of which four are valence electrons. Thorium metal is silvery and tarnishes black when exposed to air, forming the dioxide. Thorium is weakly radioactive: all its known isotopes are unstable. Thorium-232 (^{232}Th), which has 142 neutrons, is the most stable isotope of thorium and accounts for nearly all natural thorium, with six other natural isotopes occurring only as trace radioisotopes. Thorium has the longest half-life of all the significantly radioactive elements, 14.05 billion years, or about the age of the universe; it decays very slowly through alpha decay to radium-228 (^{228}Ra), starting a decay chain named the thorium series that ends at stable lead-208 (^{208}Pb). Thorium is



estimated to be about three to four times more abundant than uranium in the Earth's crust, and is chiefly refined from monazite sands as a by-product of extracting rare earth metals.

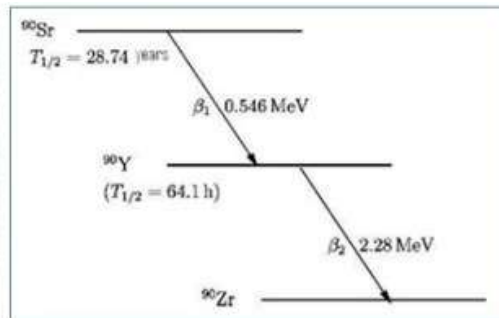
In the past, thorium was commonly used as a source of light in Auer mantles and as a material for metal alloys, but these applications declined because of concerns about its radioactivity.

The graph below shows the alpha spectrum obtained from a fragment of gas mantle. There is low resolution due to auto absorption of alpha particles. There are still some peaks and steps in correspondence at the energy of main alpha emitters of thorium chain.



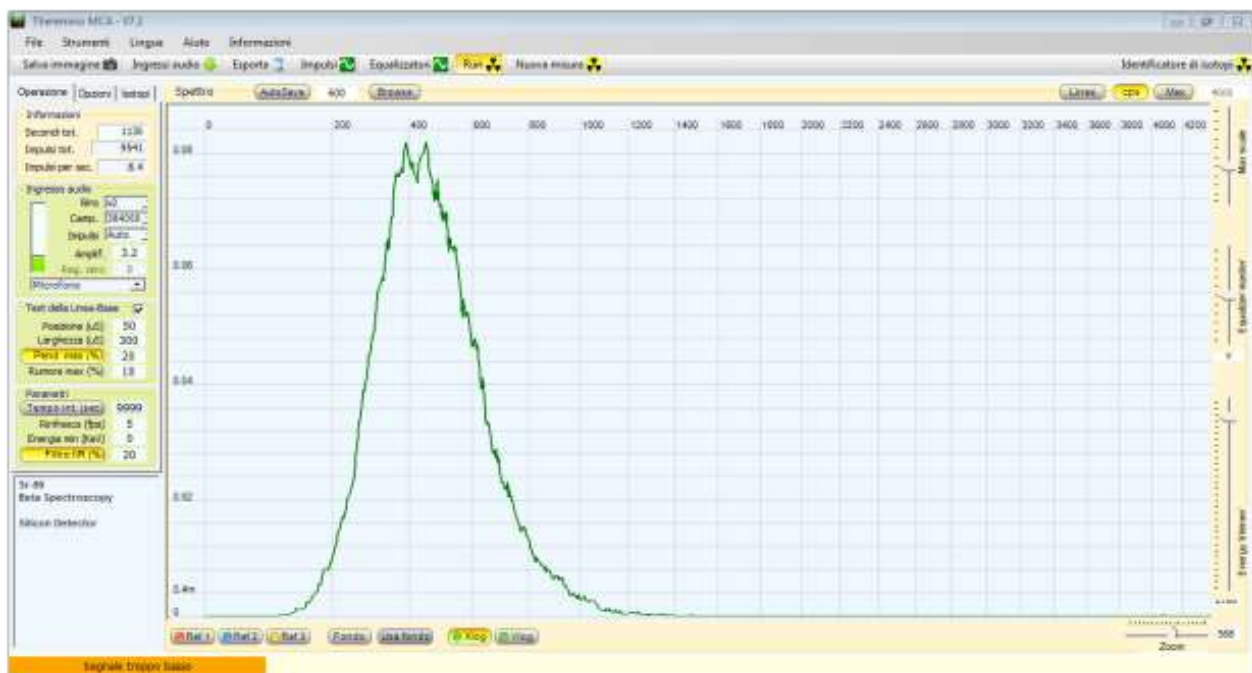
Spectrum β Strontium 90 (^{90}Sr)

Strontium-90 is a radioactive isotope of strontium produced by nuclear fission, with a half-life of 28.8 years. It undergoes β -decay into yttrium-90, with a decay energy of 0.546 MeV. Strontium-90 has applications in medicine and industry and is an isotope of concern in fallout from nuclear weapons and accidents.



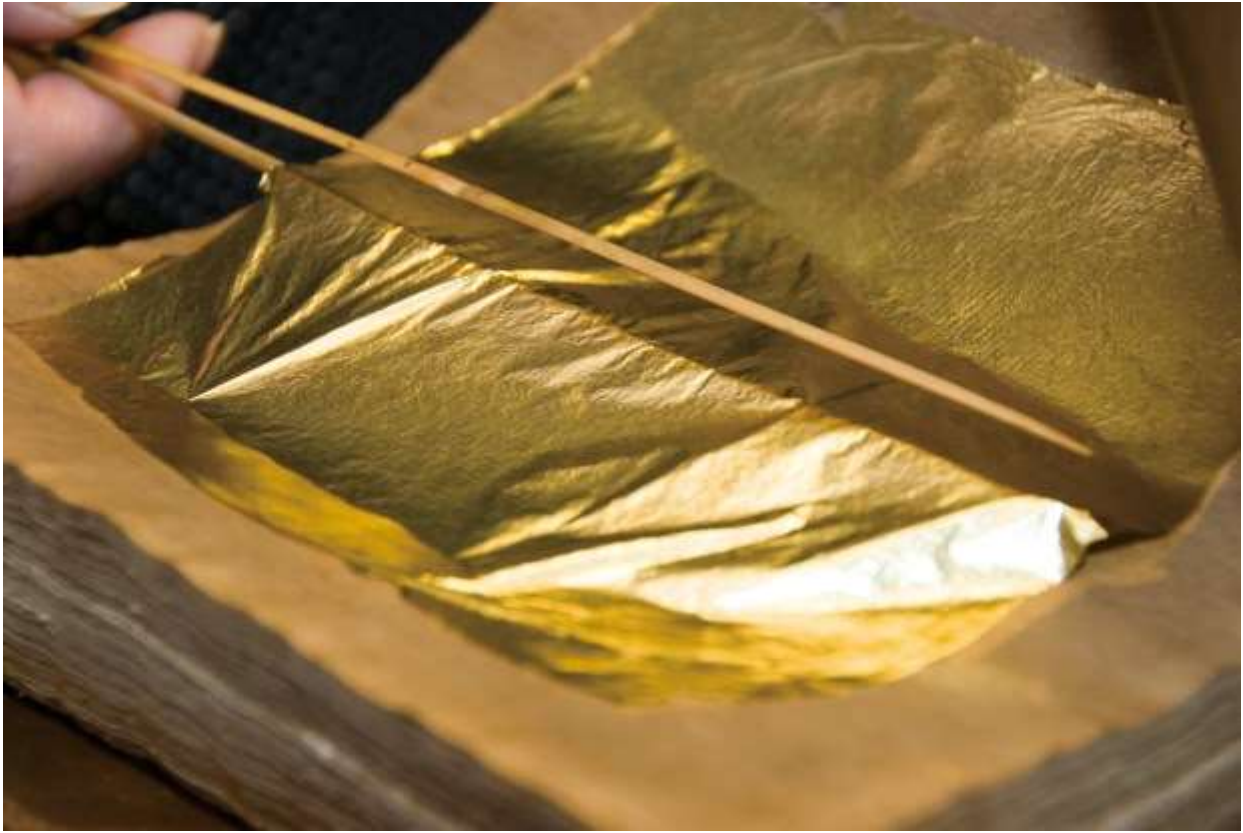
Naturally occurring strontium is nonradioactive and nontoxic at levels normally found in the environment, but ^{90}Sr is a radiation hazard. ^{90}Sr undergoes β^- decay with a half-life of 28.79 years and a decay energy of 0.546 MeV distributed to an electron, an anti-neutrino, and the yttrium isotope ^{90}Y , which in turn undergoes β^- decay with half-life of 64 hours and decay energy 2.28 MeV distributed to an electron, an anti-neutrino, and ^{90}Zr (zirconium), which is stable. Note that $^{90}\text{Sr}/\text{Y}$ is almost a pure beta particle source; the gamma photon emission from the decay of ^{90}Y is so infrequent that it can normally be ignored.

The alpha spectrometer can also be used for the measurements of beta particles, even if the electrons are more penetrating, and then the stopping power of the detector is lower; this means that the more energetic electrons can pass through the sensitive layer of the detector releasing only a part of their energy. Below, the spectrum obtained from a sample source to 0,1 μCi .



As it can be seen the maximum detected energy is about 1200 KeV due to the fact that the more energetic electrons escape from the detector. The measure is therefore reliable only for the part relative to the beta emission of the Sr-90, while the more energetic emission of Y-90 is detected only partially.

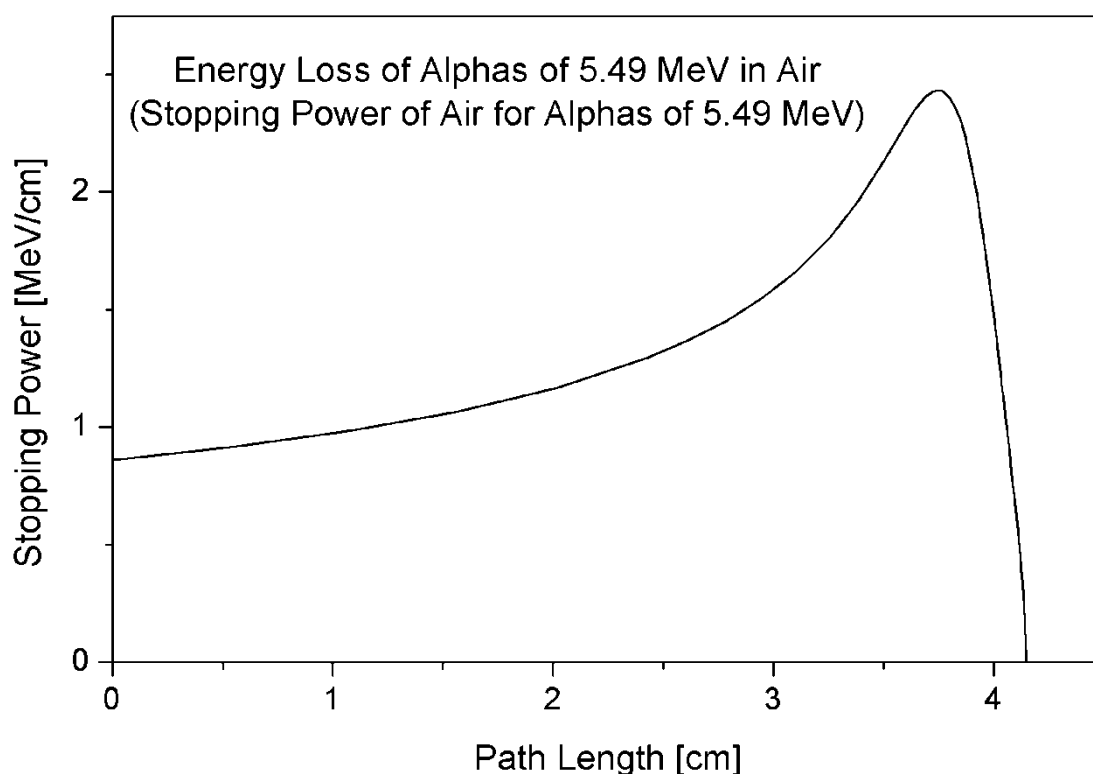
Gold Leaf Thickness with Alpha Spectrometry



With the knowledge of the theory of the interaction of alpha particles with matter it is possible to measure with precision the thickness of a very thin gold foil. In this experiment the principal concern will be the specific ionization and rate of energy loss, dE/dx , of an alpha particle as it passes through matter, particularly we deal with alpha particles passing through thin gold foil.

Theory

Alphas from natural sources typically have energies in the range of 3 to 8 MeV. The alpha is a relatively massive nuclear particle compared with the electron (about 8000 times the mass of the electron). When an alpha particle goes through matter it loses energy primarily by ionization and excitation. Since the alpha particle is much larger than the electron with which it is interacting, it travels through matter in a straight line. The energy required to strip one electron from a gas typically lies between 25 and 40 eV. For air, the accepted average ionization potential is 32.5 eV. The number of ion pairs that are theoretically possible can therefore be calculated easily.



Specific ionization is defined as the number of ion pairs produced per unit of path length. Specific ionization is energy dependent. The reason for this energy dependence is that it affects the rate of travel through the material that is being ionized; lower energy alpha particles spend more time per unit of path length than do the higher energy particles.

The image shows a typical **Bragg curve** for alpha particles in air.

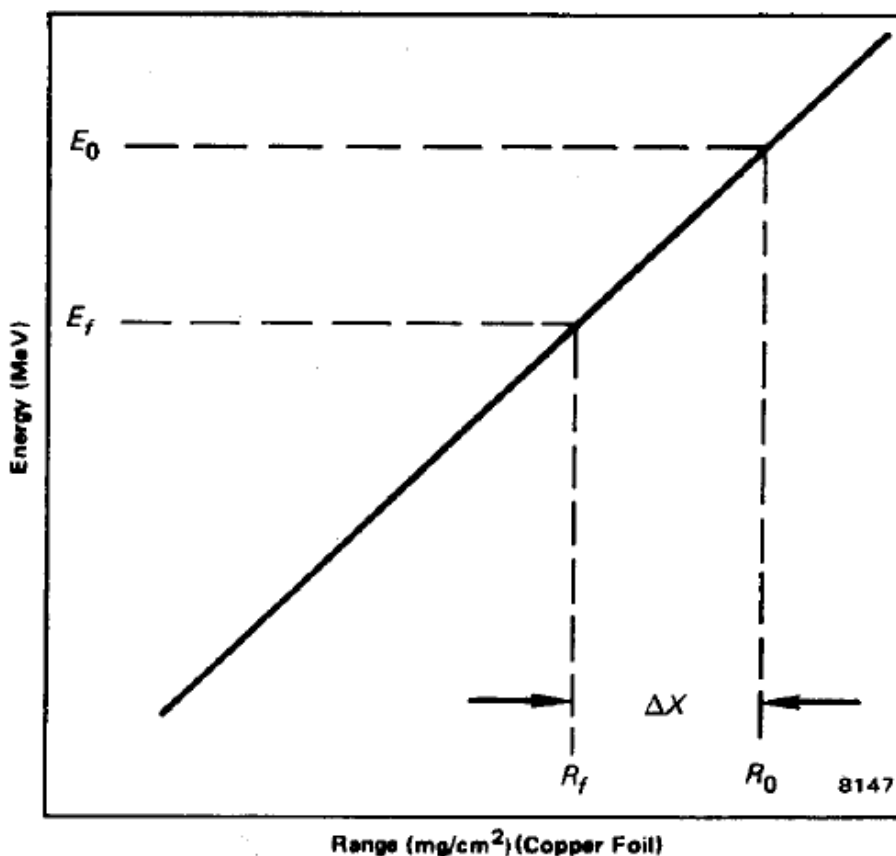
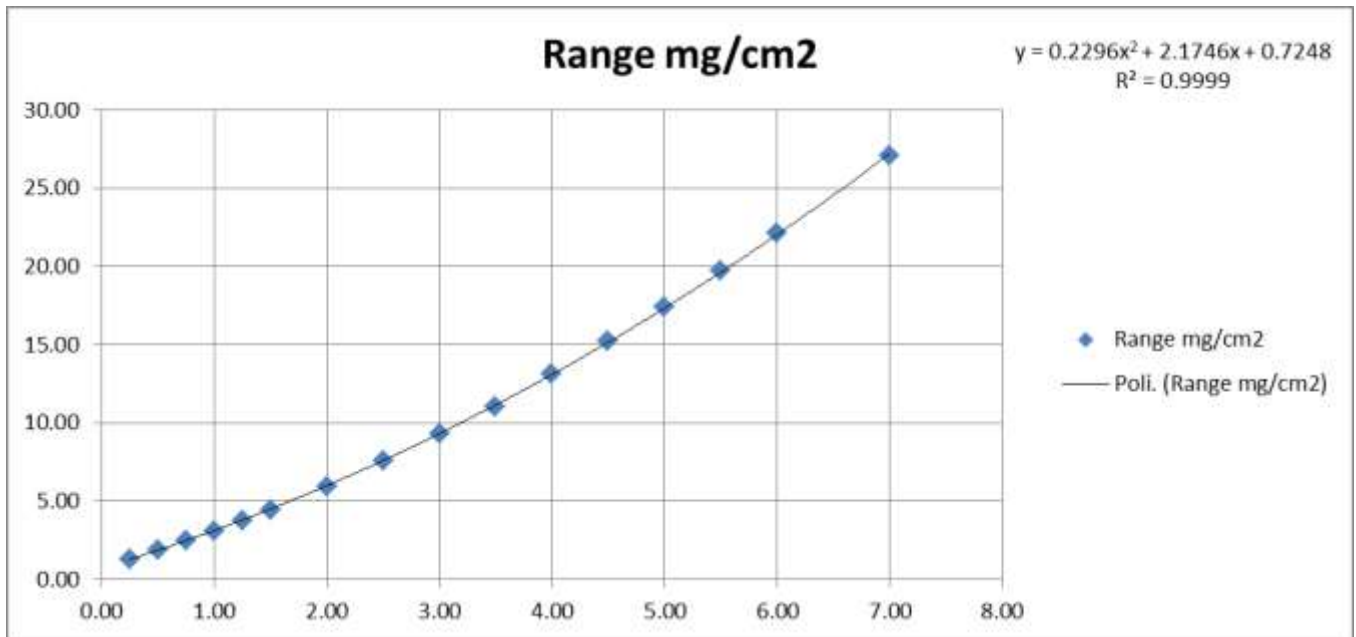
The **Bragg peak** is a pronounced peak on the *Bragg curve* which plots the energy loss of ionizing radiation during its travel through matter. For protons, α -rays, and other ion rays, the peak occurs immediately before the particles come to rest. This is called Bragg peak, after William Henry Bragg who discovered it in 1903. When a fast charged particle moves through matter, it **ionizes atoms** of the material and deposits a dose along its path. A peak occurs because the interaction **cross section increases** as the charged particle's energy **decreases**. Energy lost by charged particles is inversely proportional to the square of their velocity, which explains the peak occurring just before the particle comes to a complete stop. In the upper figure, it is the peak for alpha particles of 5.49 MeV moving through air.

The phenomenon is exploited in particle therapy of cancer, to concentrate the effect of light ion beams on the tumor being treated while minimizing the effect on the surrounding healthy tissue.

Table 5.1. Range-Energy Values for Alpha Particles in Various Absorbers*

E_0 (MeV)	Ranges (mg/cm ²)			
	Copper	Nickel	Gold	Helium
0.25	0.79	0.74	1.31	0.181
0.50	1.09	1.02	1.90	0.245
0.75	1.38	1.29	2.50	0.316
1.00	1.69	1.58	3.12	0.399
1.25	2.01	1.88	3.79	0.490
1.50	2.36	2.21	4.47	0.601
2.00	3.11	2.91	5.97	0.850
2.50	3.93	3.68	7.59	1.14
3.00	4.82	4.50	9.34	1.48
3.50	5.80	5.44	11.0	1.86
4.00	6.81	6.39	13.1	2.29
4.50	7.9	7.40	15.2	2.76
5.00	9.1	8.51	17.4	3.27
5.50	10.3	9.66	19.7	3.82
6.00	11.6	10.87	22.1	4.41
7.00	14.3	13.46	27.1	5.70

The range of alpha particles that pass within a material therefore depends on its initial energy. The **Bethe-Bloch formula** provides the theoretical description of the interaction of alpha particles with matter and allows to calculate the theoretical expected range in function of the initial energy of the particle and as a function of the type of material. The table on the side shows the range of alpha particles (expressed in mg/cm²) for Copper, Nickel and Gold and for the helium gas, as a function of the energy of the particle. In the case of gold, we have included the tabular data into an Excel chart and we have obtained the polynomial function that gives the fitting. The image below shows the graph with the equation of the curve fitting.



From these theoretical data and measuring the energy of the alpha particles before and after their passage through a layer of material it is possible to obtain easily the thickness of the material crossed by the particles layer. The figure shows graphically the process, you have to make the measurement without the material layer, then repeat the measurement interposing between the source and the detector a layer of thickness dx (for example nickel, copper, gold).

Graphically or with the fitting equation you can obtain the ranges corresponding to the two measured energies. From the difference of the values it is obtained the thickness of the material layer : $dx = R_0 - R_f$

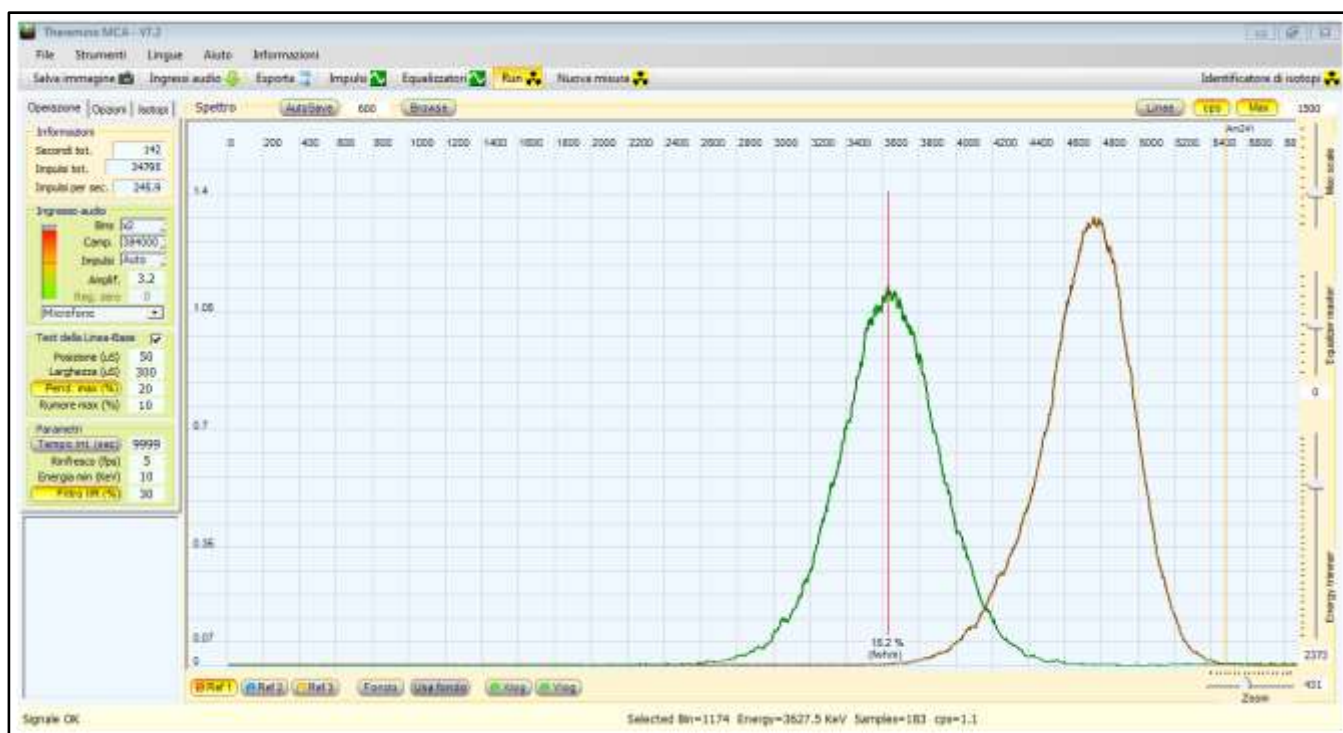
Measures



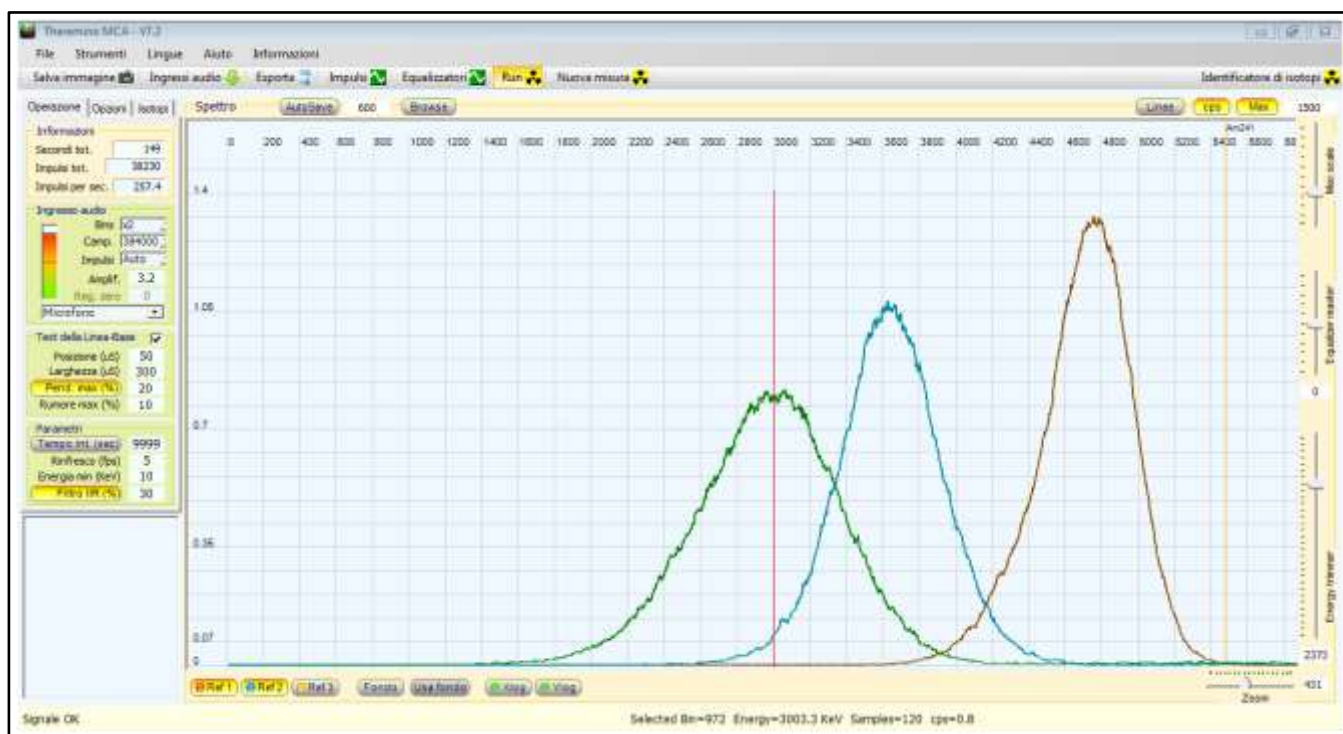
In the images above you can see the gold leaf used for thickness measurements. This is the gold leaf used for decorations, it is extremely thin and should be handled with great care otherwise very easily torn, turned against light appears almost transparent. Three measurements were made. In the first was acquired the alpha spectrum of americium source, in the second was acquired the alpha spectrum interposing between the source and the detector four layers of gold leaf, in the third were interposed six gold leaf layers. In the figure to the right you see the detector with americium source and the gold leaf placed on the source. The graphs below show the results of the three measures.



Americium Source – Emax = 4800 KeV



Four Layers – Emax = 3630 KeV



Six Layers – Emax = 3000 KeV

In the following table the results of the three measures are summarized:

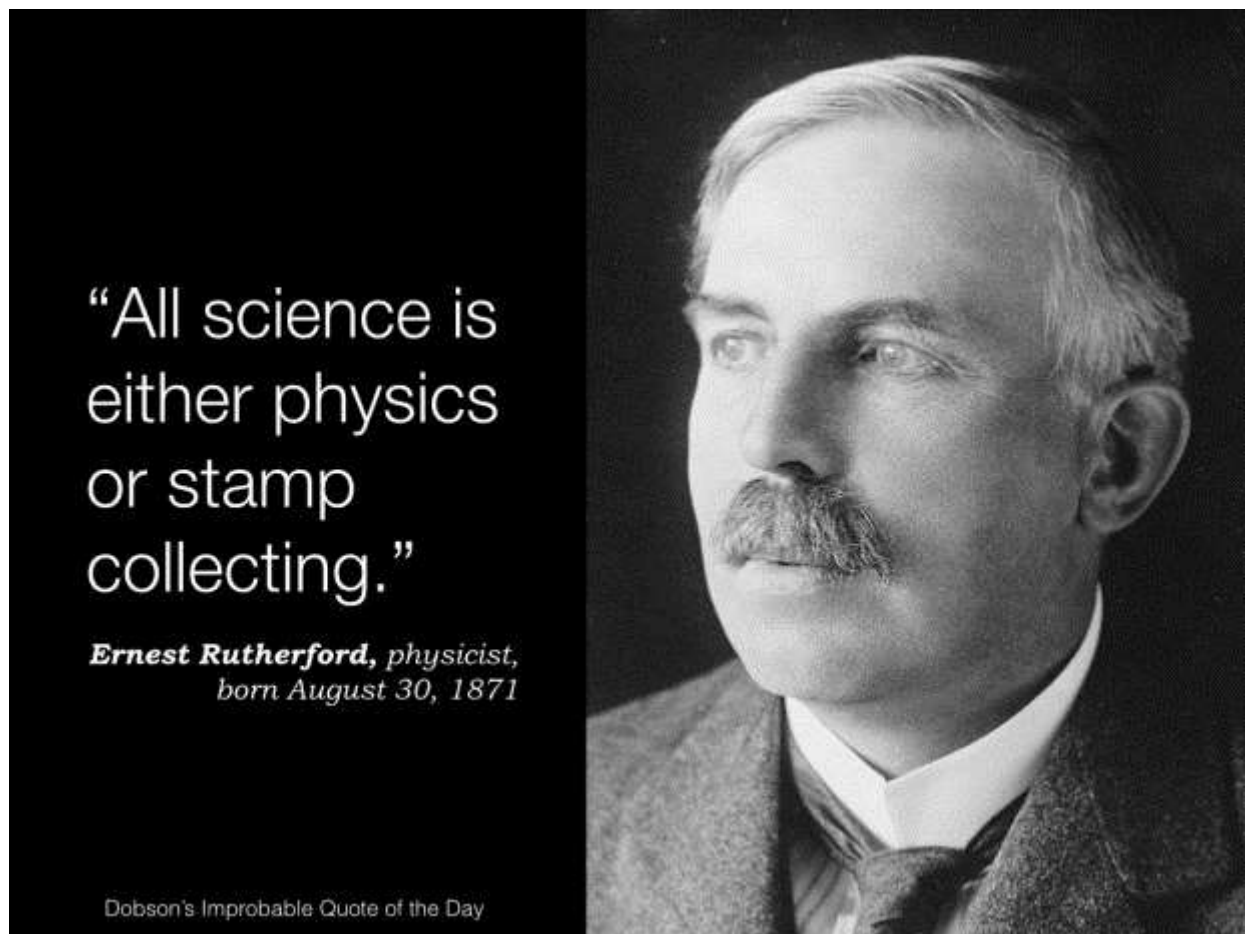
Energy (KeV)	Range (mg/cm ²)	dx (mg/cm ²)	Thickness layer (mg/cm ²)
4800	16.45	0.00 (0 layer)	0
3630	11.64	4.81 (4 layer)	1.20
3000	9.32	2.33 (2 layer)	1.16

It is apparent that the thickness of the gold leaf is equal to **1.20 mg/cm²**

Taking into account that the gold density is equal to **19.3 mg/cm³** we calculate a thickness of **0.62 μ m**.

Taking into account that the gold atom radius is **0.144 nm**, this thickness corresponds to only **2000 atoms** !

Rutherford Scattering

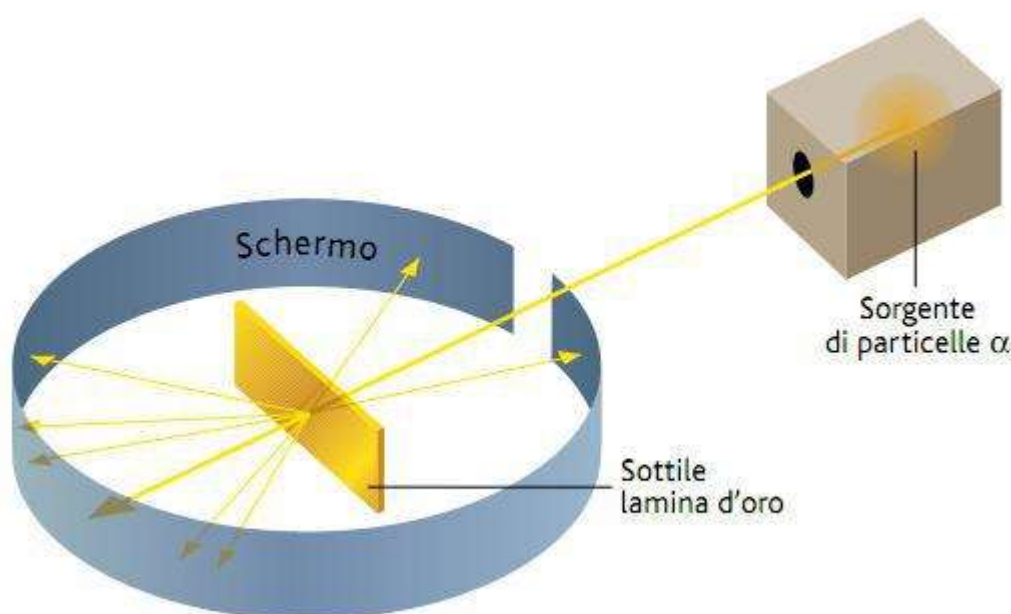


Rutherford scattering is the elastic scattering of charged particles by the Coulomb interaction. It is a physical phenomenon explained by Ernest Rutherford in 1911 that led to the development of the planetary Rutherford model of the atom and eventually the Bohr model. It is now exploited by the materials analytical technique Rutherford backscattering. Rutherford scattering was first referred to as **Coulomb scattering** because it relies only upon static electric (Coulomb) forces, and the minimal distance between particles is set only by this potential. The classical Rutherford scattering of alpha particles against gold nuclei is an example of "elastic scattering" because the energy and velocity of the outgoing scattered particle is the same as that with which it began.

The initial discovery was made by Hans Geiger and Ernest Marsden in 1909 when they performed the gold foil experiment in collaboration with Rutherford, in which they fired a beam of alpha particles (helium nuclei) at layers of gold leaf only a few atoms thick. At the time of the experiment, the atom was thought to be analogous to a plum pudding (as proposed by J. J. Thomson), with the negative charges (the plums) found throughout a positive sphere (the pudding). If the plum-pudding model were correct, the positive "pudding", being more spread out than in the current model of a concentrated nucleus, would not be able to exert such large columbic forces, and the alpha particles should only be deflected by small angles as they pass through.

However, the intriguing results showed that around 1 in 8000 alpha particles were deflected by very large angles (over 90°), while the rest passed straight through with little or no deflection. From this, Rutherford concluded that the majority of the mass was concentrated in a minute, positively charged region (the nucleus/ central charge) surrounded by electrons. When a (positive) alpha particle approached sufficiently close to the nucleus, it was repelled strongly enough to rebound at high angles. The small size of the nucleus explained the small number of alpha particles that were repelled in this way. Rutherford showed, using the method below, that the size of the nucleus was less than about 10^{-14}m (how *much* less than this size, Rutherford could not tell from this experiment alone; see more below on this problem of lowest possible size).

The image below shows the layout of the famous Rutherford - Geiger - Marsden experiment on the scattering of alpha particles by a thin gold foil.



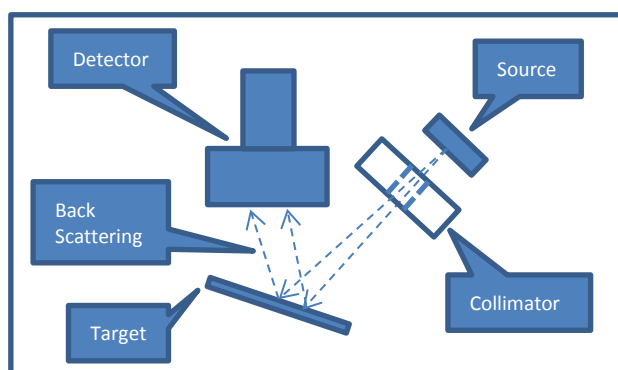
Experiment

With the DIY alpha spectrometer we tried to replicate, in a qualitative way, the famous Rutherford experiment on the scattering of alpha particle. In particular we have tried to make the detection of back scattering, that is, those alpha particles that are spread to angles greater than 90° , in practice bounce backwards.

In the image below is presented the experiment setup: the alpha source of americium, collimated through a wooden screen, is placed in the upper part of the vacuum chamber and is directed toward the target, in our case a lead plate, the target is placed directly below the detector.

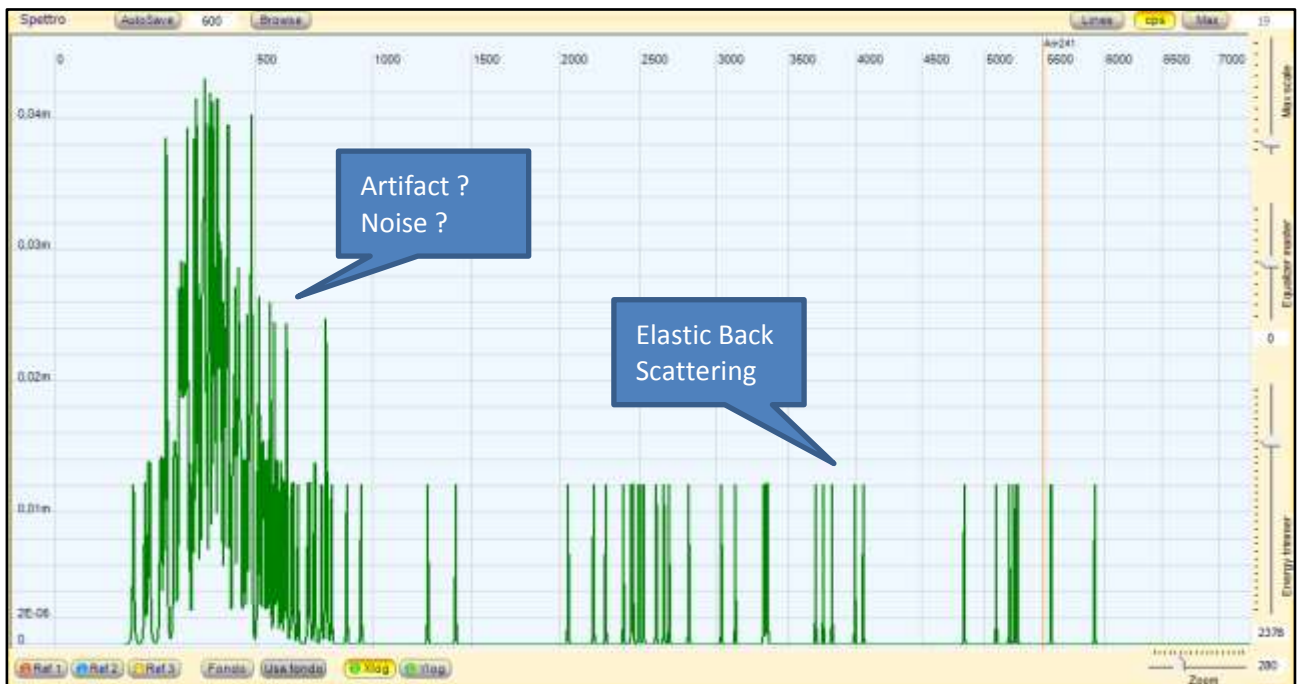


In the picture below you see the basic diagram of the experimental setup.



Results

The alpha spectrometer was run for about an hour, and it has obtained the following spectrum :



In the energy range from 2,000 KeV to 5500 KeV we note about 30 pulses which can be attributed with reasonable certainty to the same number of **back scattering events** originated from the lead target, the energy variation depends on the depth within the target where the alpha particle has been scattered. There is then a maximum of events around the energy of 500 keV, the interpretation of which has yet to be analyzed.

Disclaimer and Safety Warning

- **Before using any radioactive sources:** local, national, and international regulations may restrict the purchase, storage, transport, use or disposal of radioactive sources. Please consult your local regulations to ensure your compliance before you manage any radioactive sources.
- **Never** tamper with an ionization smoke detector or attempt to remove the radioactive source. **Do not dismantle** smoke detector. **Do not remove** the radioactive material from any object.
- The experiments shown in this document are intended for **educational purposes** and for **testing** the measuring instruments and **should never be replicated without** proper knowledge and without the compliance with regulations.

Precautions with Radioactive Sources

Time: The simplest way to reduce exposure is to keep the time spent around a radioactive source to a minimum. If time is cut in half, so is the exposure, with all the other factors remaining constant.

Distance: Distance is another effective means to reduce radiation exposure. A formula known as the “inverse square law” relates the exposure rate to distance. Doubling the distance from a radioactive source reduces the exposure to one-fourth its original value. If the distance is tripled, the exposure is reduced by a factor of nine.

Shielding: Shielding is any material used to reduce the radiation reaching the user from a radioactive source. While a single sheet of paper may stop some types of radiation such as alpha particles, other radiation such as neutrons and photons require much more shielding. Dense materials, such as lead or steel, are used to shield photons. Materials containing large amounts of hydrogen, such as polyethylene, are used to shield neutrons.

Never wear the same rubber gloves while operating your counting instrument, as any contamination on the glove could be transferred to the instrument.

No food or drink is ever to be permitted in a radioactive laboratory.

Another good habit to acquire is **never allowing the hands to touch** any other part of the body, or another individual, while working with liquid sources.