
Gamma Spectrometry

Gamma Radionuclides
and X Ray
Spectrometry

Theremino System
Rev.2

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Radionuclides Gamma Spectrometry

Theory

Gamma-ray spectroscopy is the quantitative study of the energy spectra of gamma-ray sources, in such as the nuclear industry, geochemical investigation, and astrophysics.

Most radioactive sources produce gamma rays, which are of various energies and intensities. When these emissions are detected and analyzed with a spectroscopy system, a gamma-ray energy spectrum can be produced.

A detailed analysis of this spectrum is typically used to determine the identity and quantity of gamma emitters present in a gamma source, and is a vital tool in radiometric assay. The gamma spectrum is characteristic of the gamma-emitting nuclides contained in the source, just as in optical spectroscopy, the optical spectrum is characteristic of the material contained in a sample.

Gamma-ray characteristics

Gamma rays are the highest-energy form of electromagnetic radiation, being physically the same all other forms (e.g., X rays, visible light, infrared, radio) but having higher photon energy due to their shorter wavelength. Because of this, the energy of gamma-ray photons can be resolved individually, and a gamma-ray spectrometer can measure and display the energies of the gamma-ray photons detected.

Radioactive nuclei (radionuclides) commonly emit gamma rays in the energy range from a few keV to ~10 MeV, corresponding to the typical energy levels in nuclei with reasonably long lifetimes. Such sources typically produce gamma-ray "line spectra" (i.e., many photons emitted at discrete energies), whereas much higher energies (upwards of 1 TeV) may occur in the continuum spectra observed in astrophysics and elementary particle physics. The boundary between gamma rays and X rays is somewhat blurred, as X rays typically refer to the high energy electronic emission of atoms, which may extend to over 100 keV, whereas the lowest energy emissions of nuclei are typically termed gamma rays, even though their energies may be below 20 keV.

System components and principle of operation

The equipment used in gamma spectroscopy includes an energy-sensitive radiation detector, electronics to process detector signals produced by the detector, such as a pulse sorter (i.e., multichannel analyzer), and associated amplifiers and data readout devices to generate, display, and store the spectrum. Other components, such as rate meters and peak position stabilizers, may also be included.

The most common detectors include sodium iodide (NaI) scintillation counters and high-purity germanium detectors.

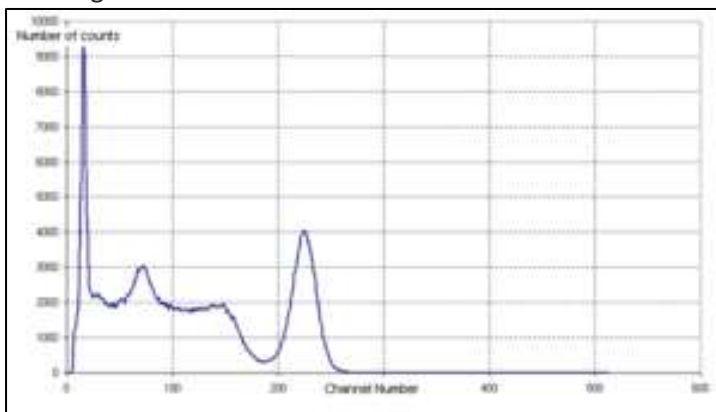
Gamma spectroscopy detectors are passive materials that wait for a gamma interaction to occur in the detector volume. The most important interaction mechanisms are the photoelectric effect, the Compton effect, and pair production. The photoelectric effect is preferred, as it absorbs all of the energy of the incident gamma ray. Full energy absorption is also possible when a series of these interaction mechanisms take place within the detector volume. When a gamma ray undergoes a Compton interaction or pair production, and a portion of the energy escapes from the detector volume without being absorbed, the background rate in the spectrum is increased by one count. This count will appear in a channel below the channel that corresponds to the full energy of the gamma ray. Larger detector volumes reduce this effect.

The voltage pulse produced by the detector (or by the photomultiplier in a scintillation counter) is shaped by a multichannel analyzer (MCA). The multichannel analyzer takes the very small voltage signal produced by the detector, reshapes it into a Gaussian or trapezoidal shape, and converts that signal into a digital signal. In some systems, the analog-to-digital conversion is performed before the peak is reshaped. The analog-to-digital converter (ADC) also sorts the pulses by their height. ADCs have specific numbers of "bins" into which the pulses can be sorted; these bins represent the channels in the spectrum. The number of channels can be changed in most modern gamma spectroscopy systems by modifying software or hardware

settings. The number of channels is typically a power of two; common values include 512, 1024, 2048, 4096, 8192, or 16384 channels. The choice of number of channels depends on the resolution of the system and the energy range being studied.

Scintillation Detectors

Scintillation detectors use crystals that emit light when gamma rays interact with the atoms in the crystals. The intensity of the light produced is proportional to the energy deposited in the crystal by the gamma ray. The detectors are joined to photomultipliers that convert the light into electrons and then amplify the electrical signal provided by those electrons. Common scintillators include thallium-doped sodium iodide (NaI(Tl))—often simplified to sodium iodide (NaI) detectors—and bismuth germanate (BGO). Because photomultipliers are also sensitive to ambient light, scintillators are encased in light-tight coverings.



Example of a NaI spectrum is the gamma spectrum of the caesium isotope ^{137}Cs shown in the figure aside. ^{137}Cs emits a single gamma line of 662 keV. It should be noted that the 662 keV line shown is actually produced by ^{137}mBa , the decay product of ^{137}Cs , which is in secular equilibrium with ^{137}Cs .

The spectrum in Figure was measured using a NaI-crystal (thallium activated (Tl)) on a photomultiplier, an amplifier, and a multichannel analyzer. The figure shows the

number of counts (within the measuring period) versus channel number. The spectrum indicates the following peaks (from left to right):

- low energy x radiation (due to internal conversion of the gamma ray)
- backscatter at the low energy end of the Compton distribution
- a photopeak (full energy peak) at an energy of 662 keV
-

The Compton distribution is a continuous distribution that is present up to channel 150 in Figure. The distribution arises because of primary gamma rays undergoing Compton scattering within the crystal: Depending on the scattering angle, the Compton electrons have different energies and hence produce pulses in different energy channels.

Calibration and Background radiation

If a gamma spectrometer is used for identifying samples of unknown composition, its energy scale must be calibrated first. Calibration is performed by using the peaks of a known source, such as caesium-137 or cobalt-60. Because the channel number is proportional to energy, the channel scale can then be converted to an energy scale. If the size of the detector crystal is known, one can also perform an intensity calibration, so that not only the energies but also the intensities of an unknown source—or the amount of a certain isotope in the source—can be determined.

Because some radioactivity is present everywhere (i.e., background radiation), the spectrum should be analyzed when no source is present. The background radiation must then be subtracted from the actual measurement. Lead absorbers can be placed around the measurement apparatus to reduce background radiation.

Equipment

Scintillation Probe Low Energy Gamma : Detector SEI RAP 47



Detector Alluminum
Length 19 cm, diameter 3,8 cm.

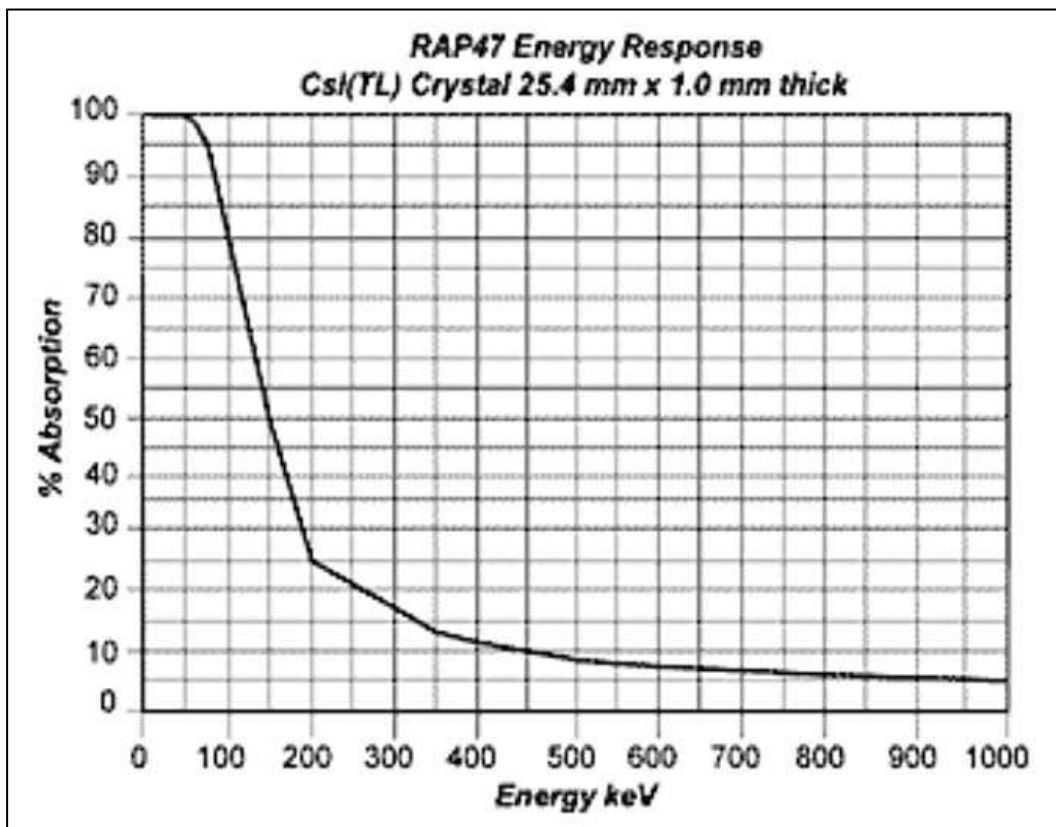
Temperature Range from -25°C to 40°C

Crystal Type Csl (Tl)

Crystal Dimensions
Diameter 25.4mm thickness 1.0mm

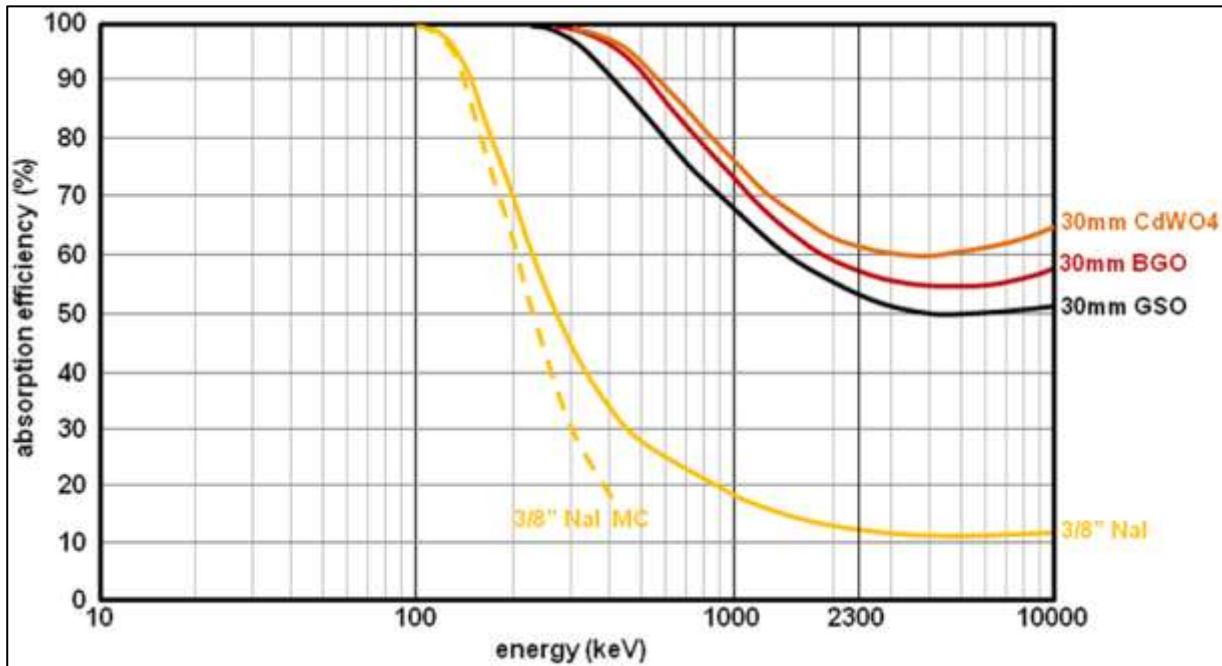
Energy from 8 keV to 1 MeV.

Absorption 100% a 47keV, 80% a 100 keV



CsI(Tl) Absorption Efficiency

Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal - PMT R6095 Hamamatsu



NaI(Tl) Absorption Efficiency



NaI(Tl) detector measurements setup with plastic well shielded with lead shots

Measurements Parameters

Measurements Time = more than 3600ses

Min Energy = 0

Integration Filter = 15%÷30%

Number of bins = X2

Base-line Test

Position = 50μsec

Width = 300 μsec

Max Slope = 20%

Max Noise = 20%

Resolution Compensation

Size = 20bins

Center = 30%

Left = 3%

Right = 7%

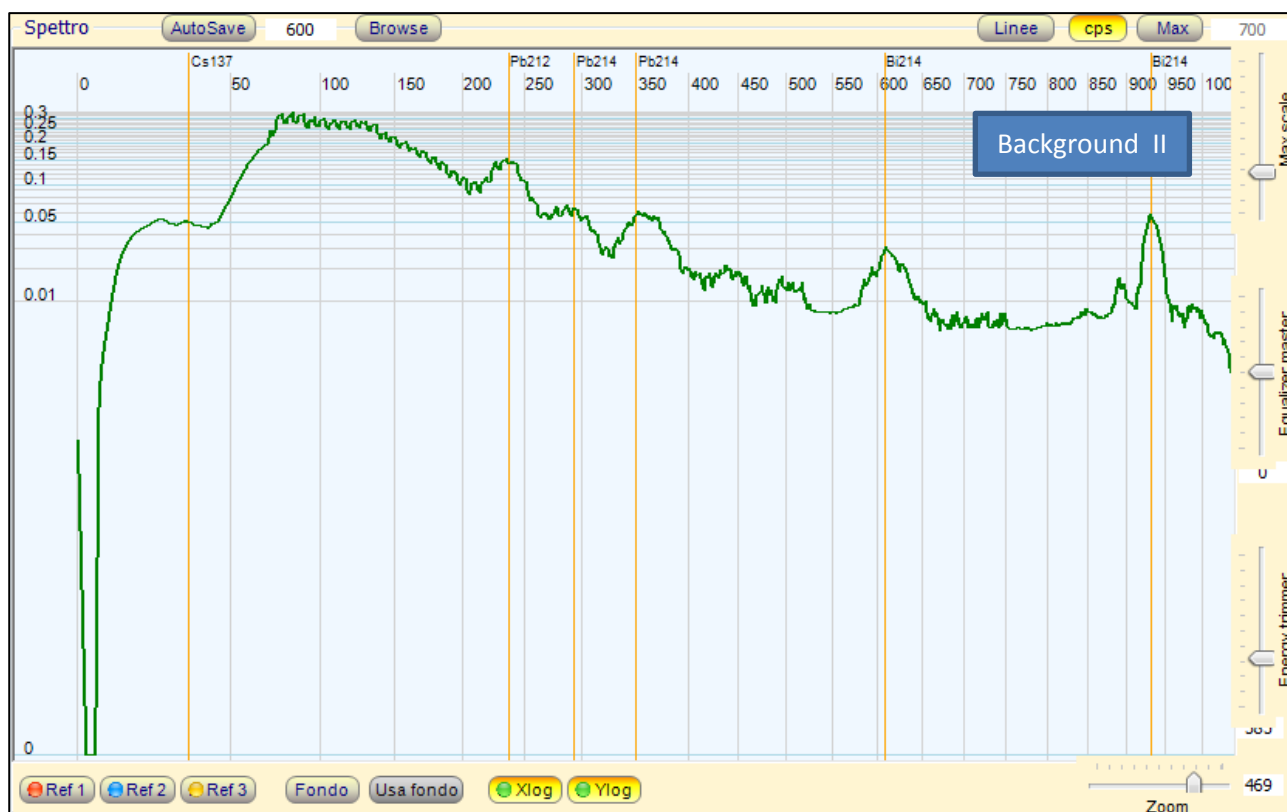
Background Radiation Inside Concrete Building

In the **Terrestrial Background Radiation**, the major radionuclides of concern are **potassium, uranium and thorium** and their **decay products**, some of which, like **radium** and **radon** are intensely radioactive but occur in low concentrations. Most of these sources have been decreasing, due to radioactive decay since the formation of the Earth, because there is no significant amount currently transported to the Earth. Thus, the present activity on earth from uranium-238 is only half as much as it originally was because of its 4.5 billion year half-life, and potassium-40 (half-life 1.25 billion years) is only at about 8% of original activity. In addition, many shorter half-life and thus more intensely radioactive isotopes have not decayed out of the terrestrial environment, however, because of natural on-going production of them. Examples of these are radium-226 (decay product of uranium-238) and radon-222 (a decay product of radium-226).

Thorium and uranium primarily undergo alpha and beta decay, and aren't easily detectable. However, many of their daughter products are strong gamma emitters. Thorium-232 is detectable via a 239 keV peak from lead-212, 511, 583 and 2614 keV from thallium-208, and 911 and 969 keV from actinium-228. Uranium-233 is similar but lacks the actinium-228 peak, which distinguishes it from thorium-232. Uranium-238 manifests as 609, 1120, and 1764 keV peaks of bismuth-214. Potassium-40 is detectable directly via its 1461 keV gamma peak.

Most of the **Atmospheric Background Radiation** is caused by radon and its decay products. **The gamma spectrum shows prominent peaks at 609, 1120, and 1764 keV, belonging to bismuth-214, a radon decay product.** The atmospheric background varies greatly with wind direction and meteorological conditions. Radon also can be released from the ground in bursts and then form "radon clouds" capable of traveling tens of kilometers.

The **cosmic radiation** at sea level usually manifests as **511 keV gamma rays from annihilation of positrons created by nuclear reactions of high energy particles and gamma rays.** The intensity of cosmic ray background increases rapidly with altitude, and at few kilometers above sea the cosmic rays dominate the spectrum and drown the other natural sources. At higher altitudes there is also the contribution of continuous bremsstrahlung spectrum.



Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu

Uranium



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). Uranium has the second highest atomic weight of the primordially occurring elements, lighter only than

plutonium. Its density is about 70% higher than that of lead, but slightly lower than that of gold or tungsten. It occurs naturally in low concentrations of a few parts per million in soil, rock and water, and is commercially extracted from uranium-bearing minerals such as uraninite.

In nature, uranium is found as **uranium-238** (99.2739 – 99.2752%), **uranium-235** (0.7198 – 0.7202%), and a very small amount of uranium-234 (0.0050–0.0059%). Uranium decays slowly by emitting an **alpha particle**. The half-life of uranium-238 is about 4.47 billion years and that of uranium-235 is 704 million years, making them useful in dating the age of the Earth.

Uranium-238

Uranium-238 is the most stable isotope of uranium, with a half-life of about 4.468×10^9 years, roughly the age of the Earth. **Uranium-235** has a half-life of about 7.13×10^8 years, and **uranium-234** has a half-life of about 2.48×10^5 years. For natural uranium, about 49% of its alpha rays are emitted by each of ^{238}U atom, and also 49% by ^{234}U (since the latter is formed from the former) and about 2.0% of them by the ^{235}U . When the Earth was young, probably about one-fifth of its uranium was uranium-235, but the percentage of ^{234}U was probably much lower than this.

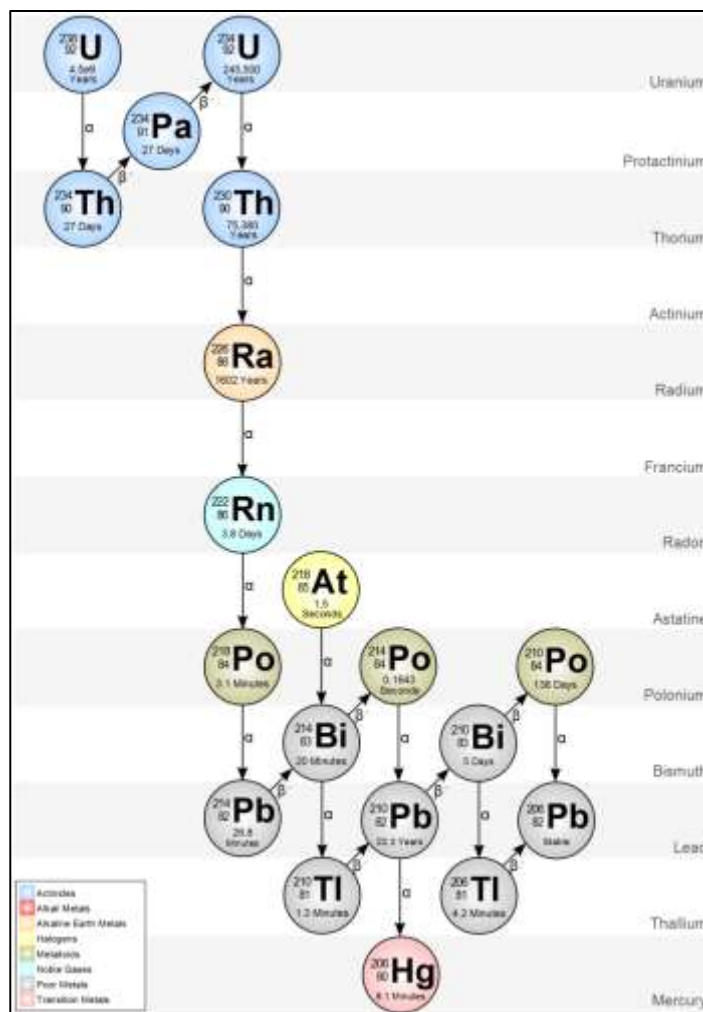
Uranium-238 is usually an α emitter (occasionally, it undergoes spontaneous fission), decaying through the "Uranium Series" of nuclear decay, which has 18 members, all of which eventually decay into lead-206, by a variety of different decay paths.

Uranium-238 is not fissile, but is a **fertile isotope**, because after neutron activation it can produce plutonium-239, another fissile isotope. Indeed, the ^{238}U nucleus can absorb one neutron to produce the radioactive isotope uranium-239. ^{239}U decays by beta emission to neptunium-239, also a beta-emitter, that decays in its turn, within a few days into plutonium-239. ^{239}Pu was used as fissile material in the first atomic bomb detonated in the "Trinity test" on 15 July 1945 in New Mexico.

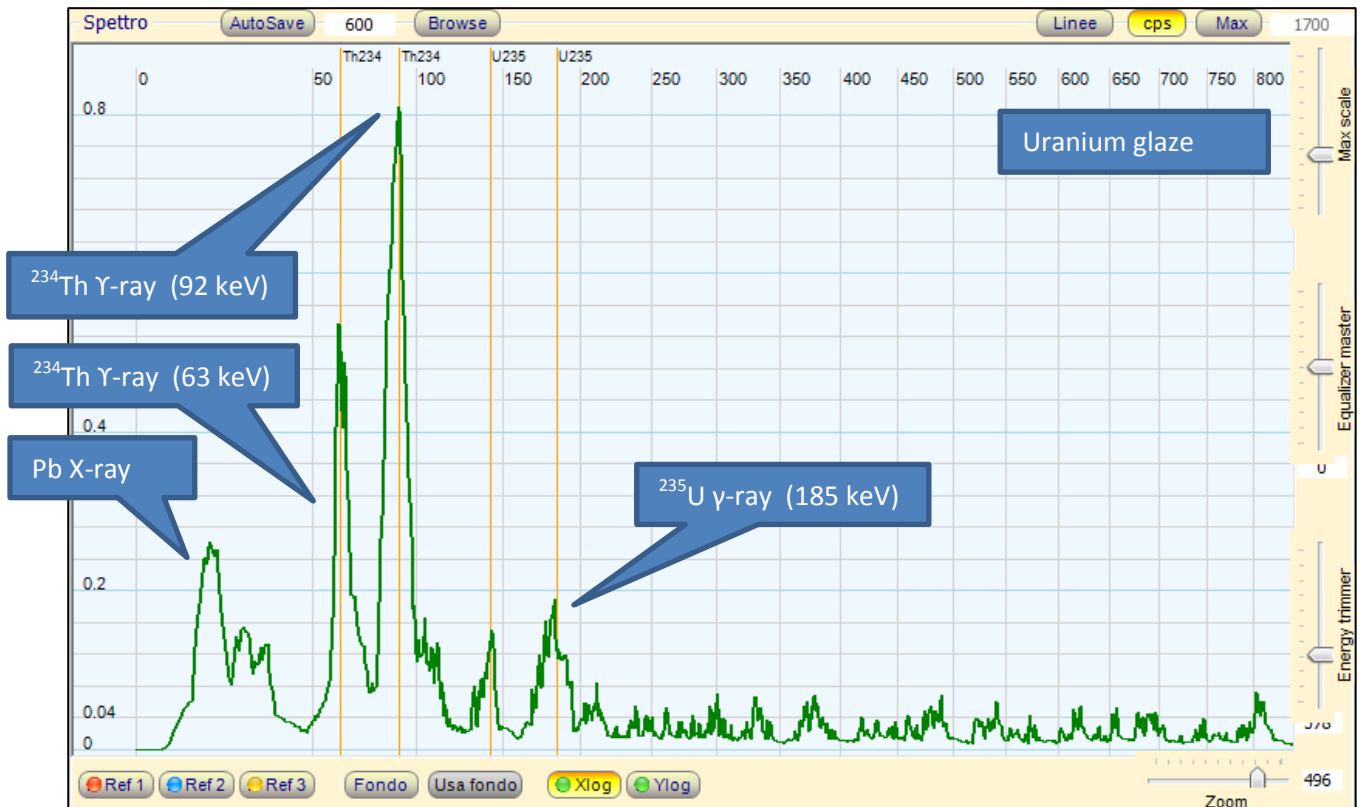
Uranium-235

Uranium-235 is an isotope of uranium making up about 0.72% of natural uranium. Unlike the predominant isotope **uranium-238**, it is fissile, i.e., it can sustain a fission chain reaction. It is the only fissile isotope that is a primordial nuclide or found in significant quantity in nature.

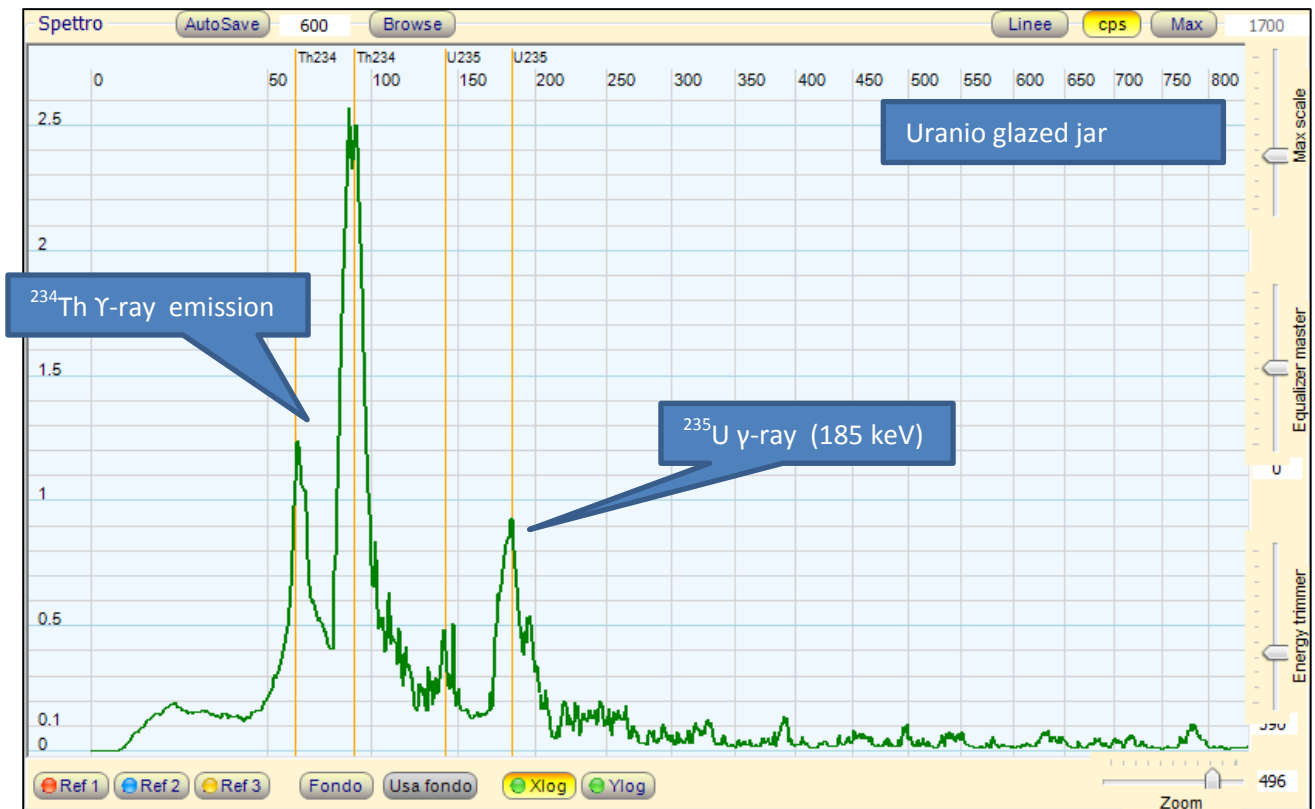
The decay series of ^{235}U , which is called the actinium series has 15 members, all of which eventually decay into lead-207. The constant rates of decay in these decay series makes the comparison of the ratios of parent to daughter elements useful in radiometric dating.



Uranium Oxide (Uranium Glaze)

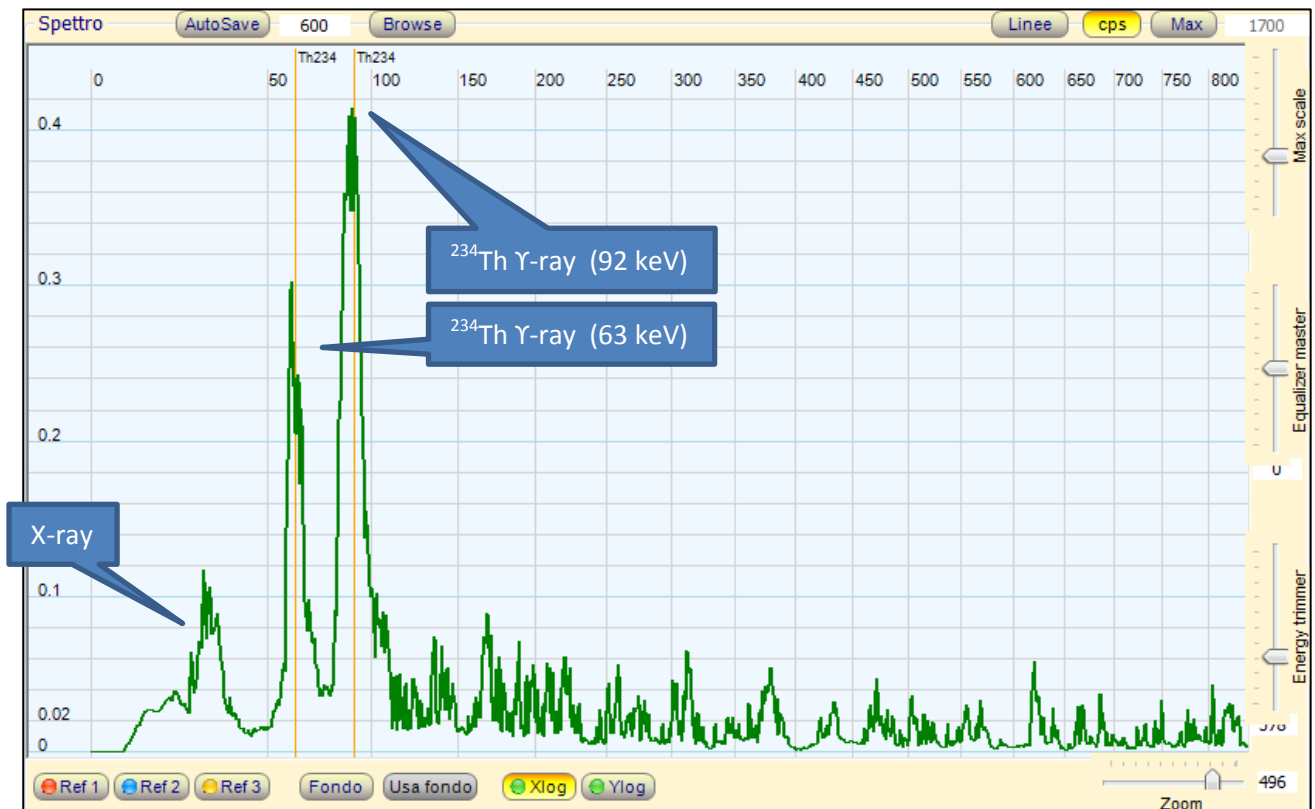


Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal - PMT R6095 Hamamatsu - Lead Shielded Measure



Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal - PMT R6095 Hamamatsu - Not Shielded Measure

Uranium Glass ("Vaseline Glass")



Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu - Lead Shielded Measure

The uranium contained in the glaze (previous page) and in the glass has been refined, so it does not contain all the products of the decay: from radio to the lead and bismuth. For this reason there is only the first isotope of the decay: thorium-234.

It should be noted in the spectra of the glaze the presence of isotope uranium-235. These photo peaks are sign that for these artifacts were used refined natural uranium and not depleted uranium. We can therefore deduce that the manufacturing period is probably before the Second World War because subsequently, for this kind of products, predominantly depleted uranium has been used.

Autunite (hydrated calcium uranyl phosphate)



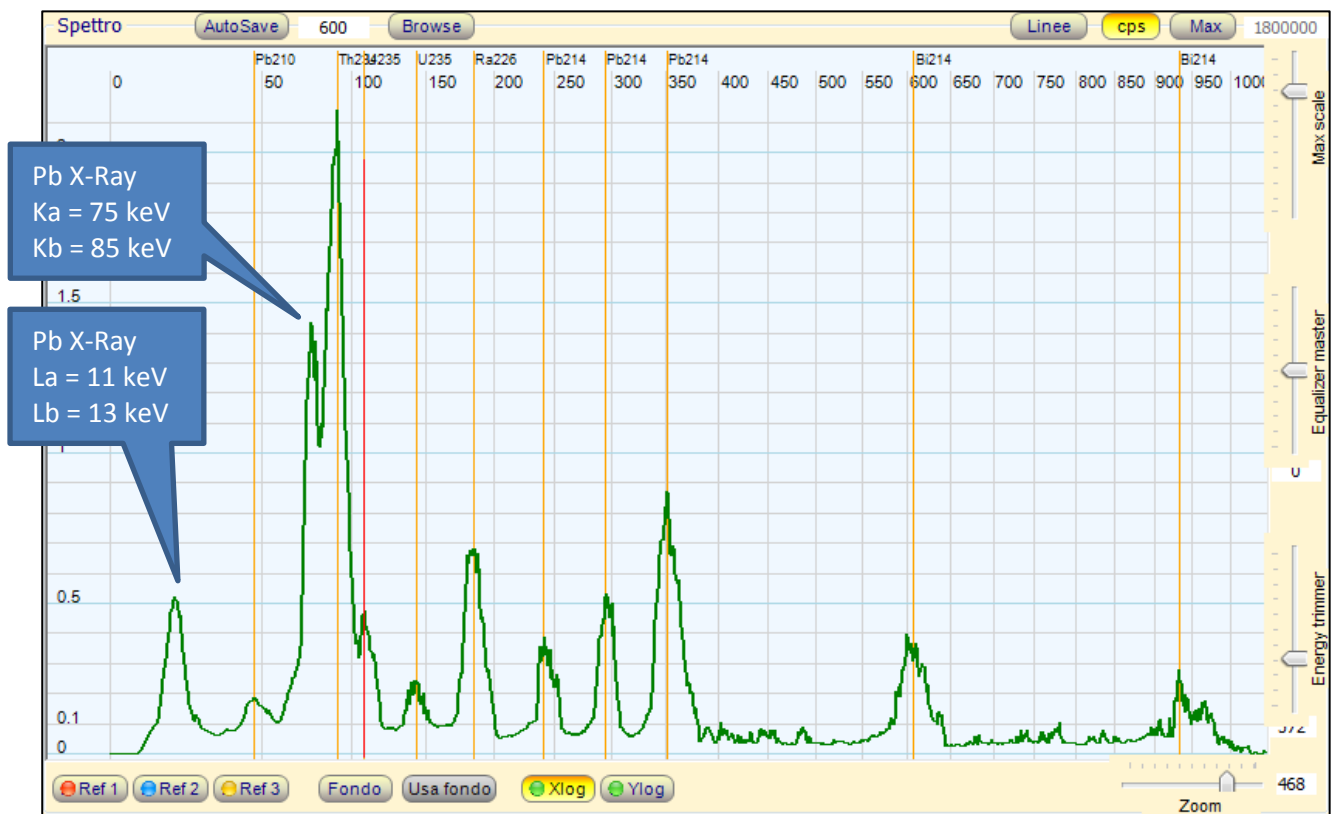
Autunite (hydrated calcium uranyl phosphate) with formula: $\text{Ca}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 10\text{-}12\text{H}_2\text{O}$.

Is a yellow - greenish fluorescent mineral with a hardness of 2 - 2½. Autunite crystallizes in the orthorhombic system and often occurs as tabular square crystals. Due to the moderate uranium content of 48.27% it is radioactive and also used as uranium ore. If the mineral dries out, it converts to meta-autunite-I, which can turn into meta-autunite-II after heating. These two subsequent minerals are very rare in nature. For scientific studies it is recommended to store the mineral in a sealed container to minimize the water loss. Museums are

known to have covered the mineral with lacquer to avoid drying of the mineral.

Autunite was discovered in 1852 near Autun, France. It occurs as an oxidation product of uranium minerals in granite pegmatites and hydrothermal deposits.

Associate minerals include metaautunite, torbernite, phosphuranylite, saleeite, uranophane and sabugalite.



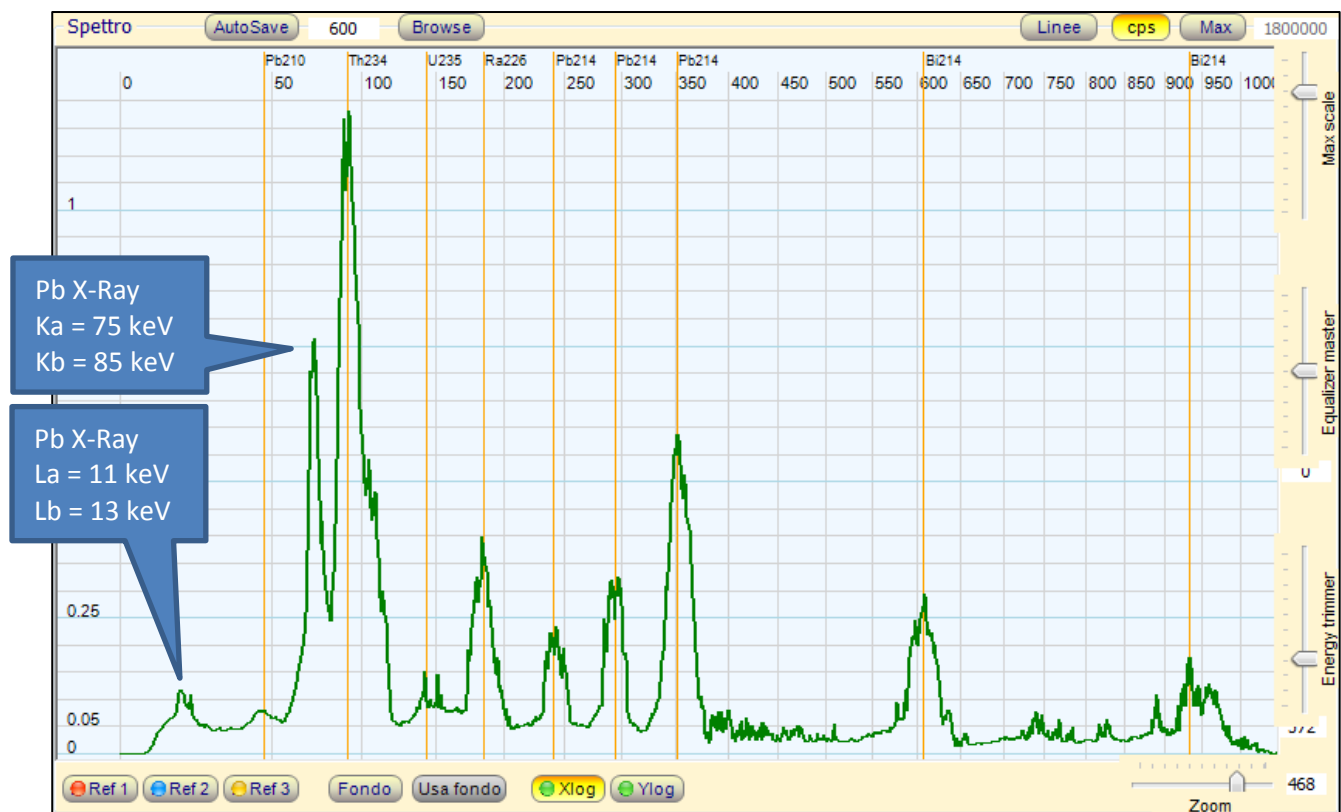
Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu - Lead Shielded Measure

Uraninite - Pitchblende (radioactive, uranium-rich mineral)



Uraninite is a radioactive, uranium-rich mineral and ore with a chemical composition that is largely UO_2 , but due to oxidation the mineral typically contains variable proportions of U_3O_8 . Additionally, due to radioactive decay, the ore also contains oxides of **lead** and trace amounts of **helium**. It may also contain **thorium**, and **rare earth elements**. It used to be known as **pitchblende** (from pitch, because of its black color, and blende, a term used by German miners to denote minerals whose density suggested metal content, but whose exploitation, at the time they were named, was either unknown, impossible or not economically feasible).

All uraninite minerals contain a small amount of **radium** as a radioactive decay product of uranium. Uraninite also always contains small amounts of the lead isotopes ^{206}Pb and ^{207}Pb , the end products of the decay series of the uranium isotopes ^{238}U and ^{235}U respectively. Small amounts of helium are also present in uraninite as a result of alpha decay. Helium was first found on Earth in uraninite after having been discovered spectroscopically in the Sun's atmosphere. The extremely rare elements technetium and promethium can be found in uraninite in very small quantities (about 200 pg/kg and 4 fg/kg respectively), produced by the spontaneous fission of uranium-238.



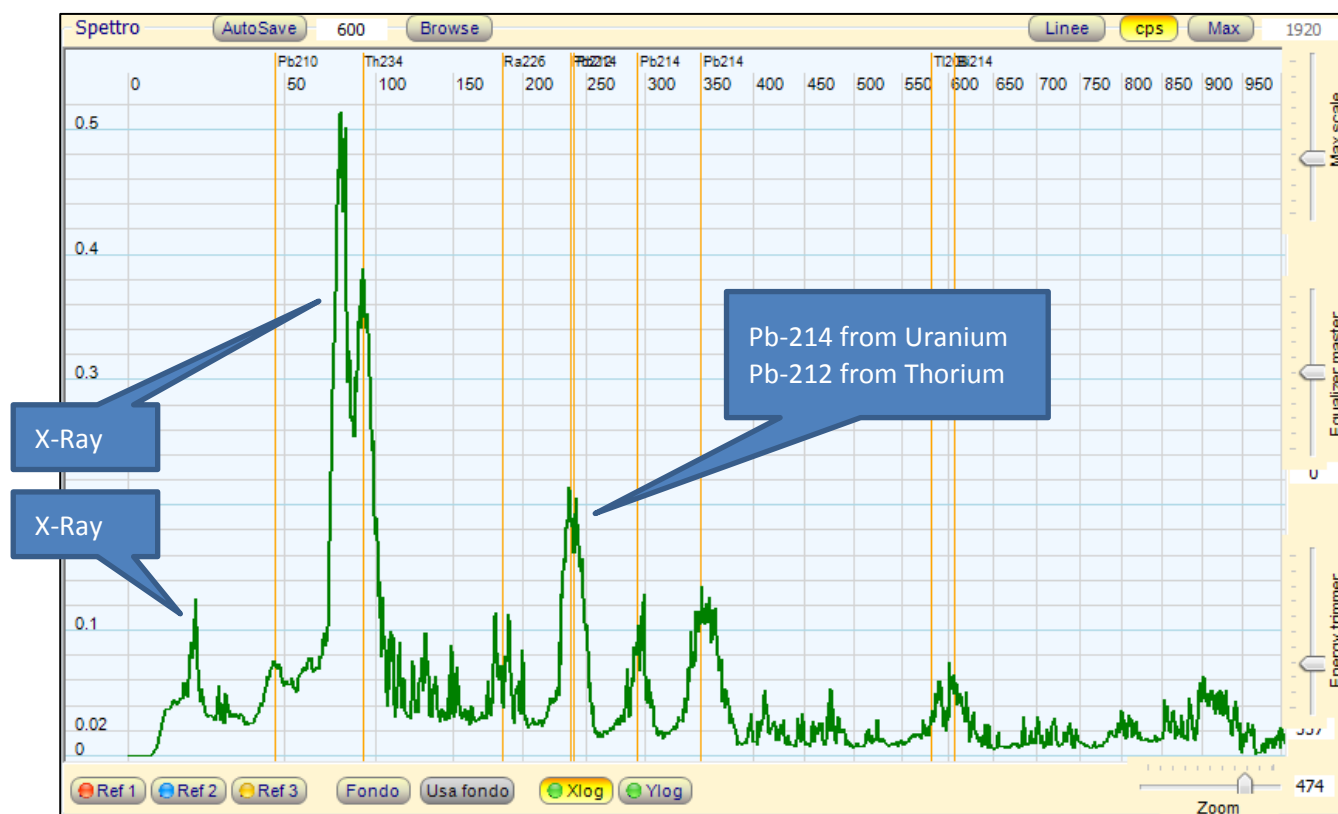
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Polycrase (radioactive, uranium-thorium rich mineral)



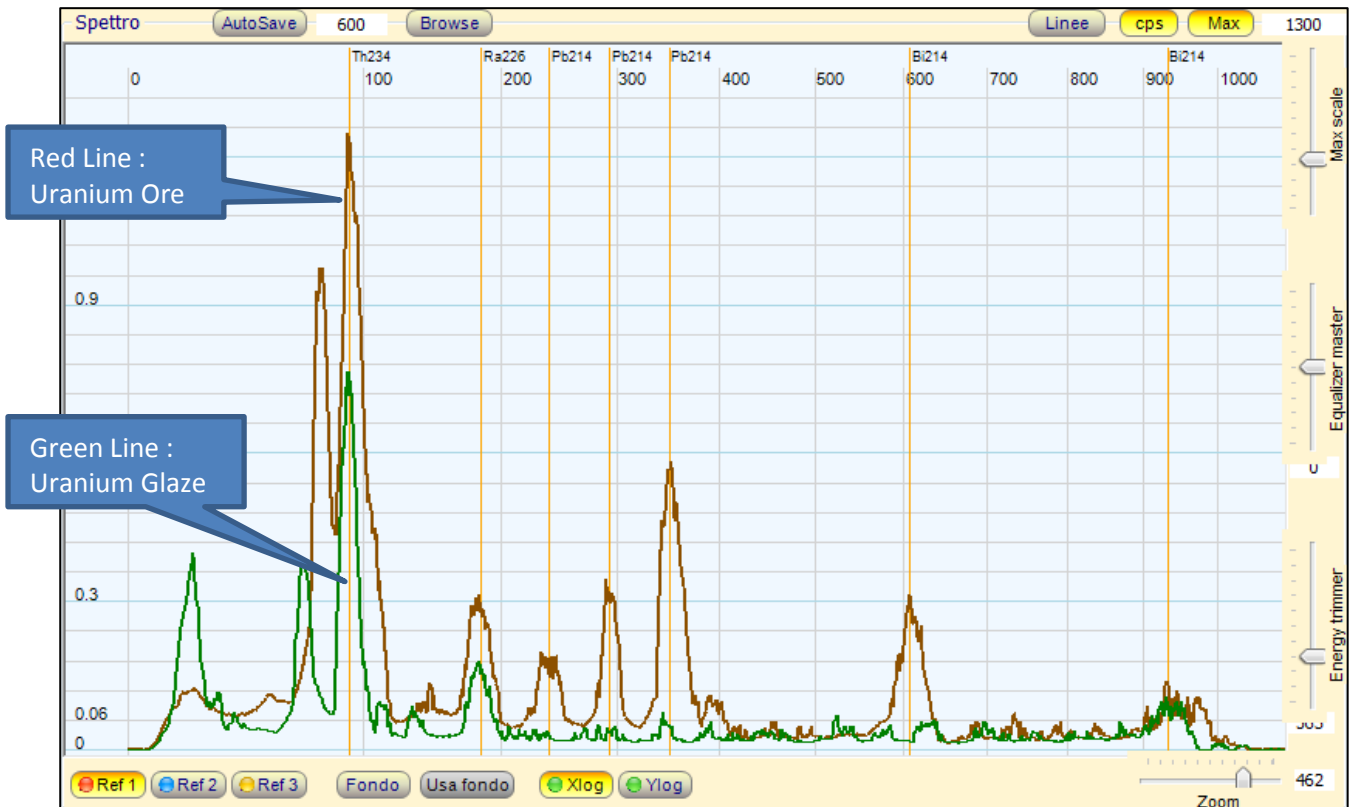
Polycrase or **polycrase-(Y)** is a black or brown metallic complex uranium yttrium oxide mineral with formula: $(Y,Ca,Ce,U,Th)_x(Ti,Nb,Ta)_2O_6$. It is amorphous. It has a Mohs hardness of 5 to 6 and a specific gravity of 5. It is radioactive due to its uranium content (around 6%). It occurs in granitic pegmatites.

Polycrase forms a continuous series with the niobium rich rare earth oxide euxenite.



Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu - Lead Shielded Measure

Uranium-238 Decay



The decay of uranium-238 could be divided in two parts :

- U-238 -> .. -> Ra-226 : Uranium-238 has half-life of millions of years
- Ra-226 -> .. -> Pb-206 : Radium-226 has half-life of 1600 years
-

In uranium ores all the decay chain isotopes are present because, during time, an equilibrium has been achieved, thus the activity is the same for all the isotopes.

In “modern” objects built with refined uranium the isotopes which comes from radium are absent because they had not enough time to be generated, particularly the following isotopes are absent : Ra-226, Pb-214 e Bi-214.

This feature is evident in the spectra shown in the image above.

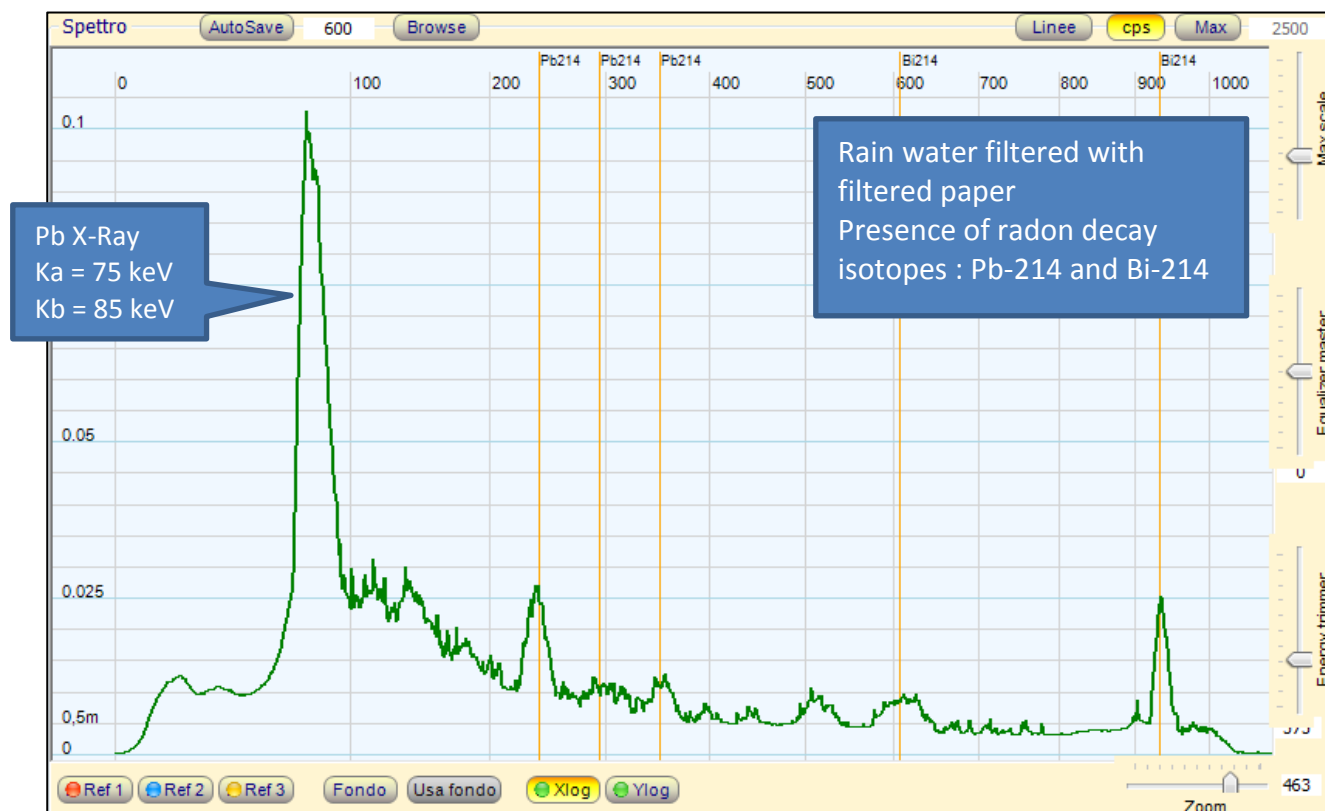
The red line is the gamma spectrum of a sample of the uranium ore uraninite, all the uranium decay chain isotopes shows their gamma photo peaks (at least the ones which are gamma emitters). The descendants of radium Ra-226 : Pb-214 and Bi-214 are present.

The green line is the gamma spectrum of uranium glaze (from fiestaware). The photo peaks of thorium-234 and uranium-235 are present, while the photo peaks of radium and its descendants are absent.

The photo peak near Ra-226 in the gamma spectrum of Uranium glaze is due to U-235.

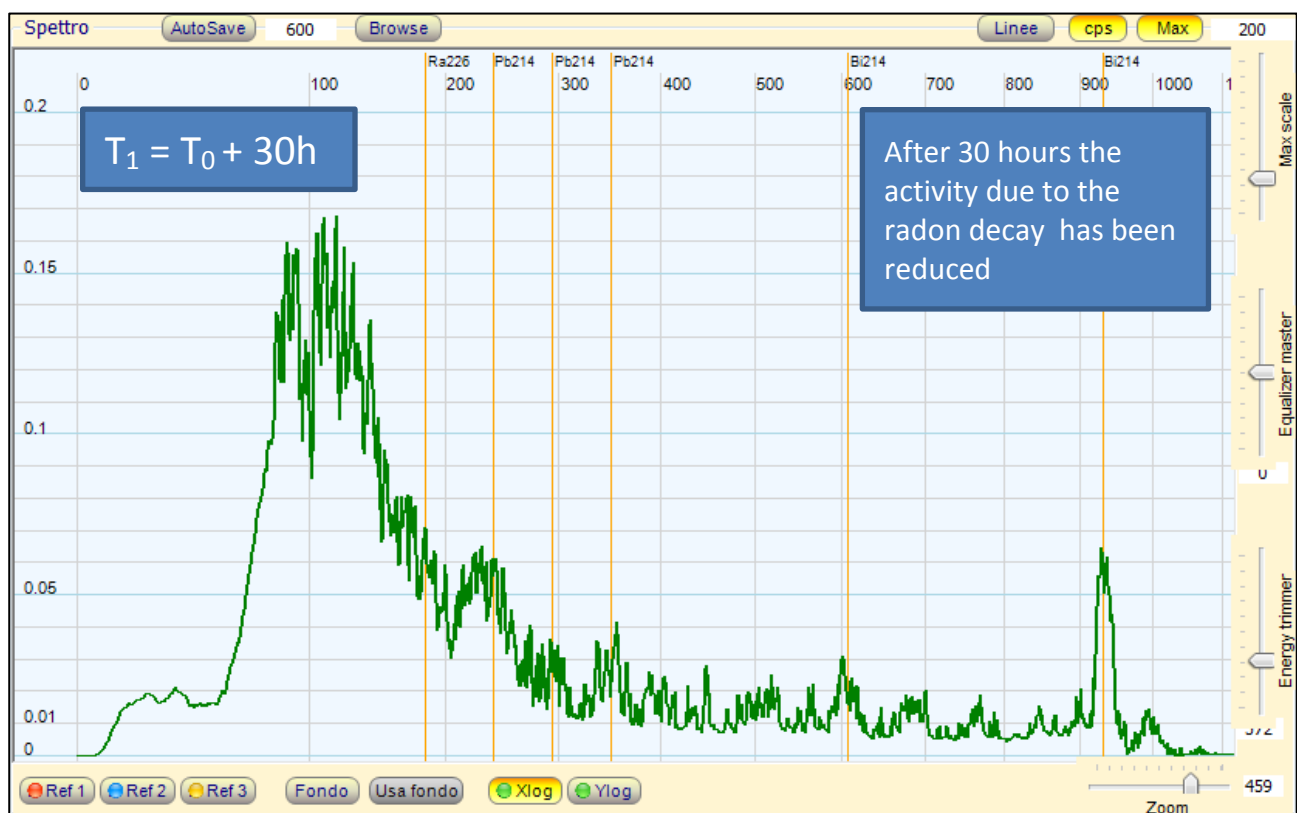
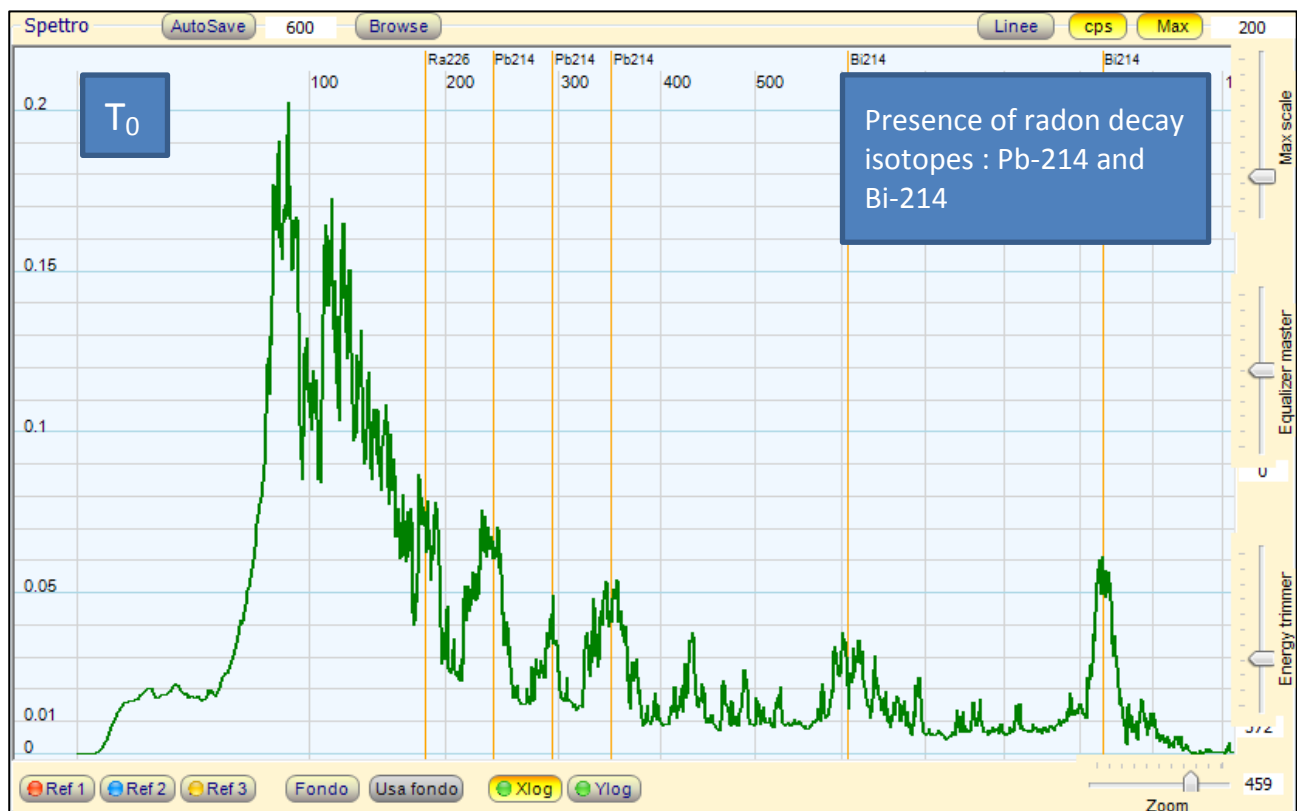
Rain Water

In the rain there are small amounts of radioactive substances. The main source of radioactivity is constituted by radon progeny like Pb-214 and Bi-214 which are incorporated into raindrops and dragged to the ground. To facilitate the measurement is preferable to concentrate the contents of these particles by boiling of collected rain or by filtration. In latter case the radioactive particles are retained by the filter.



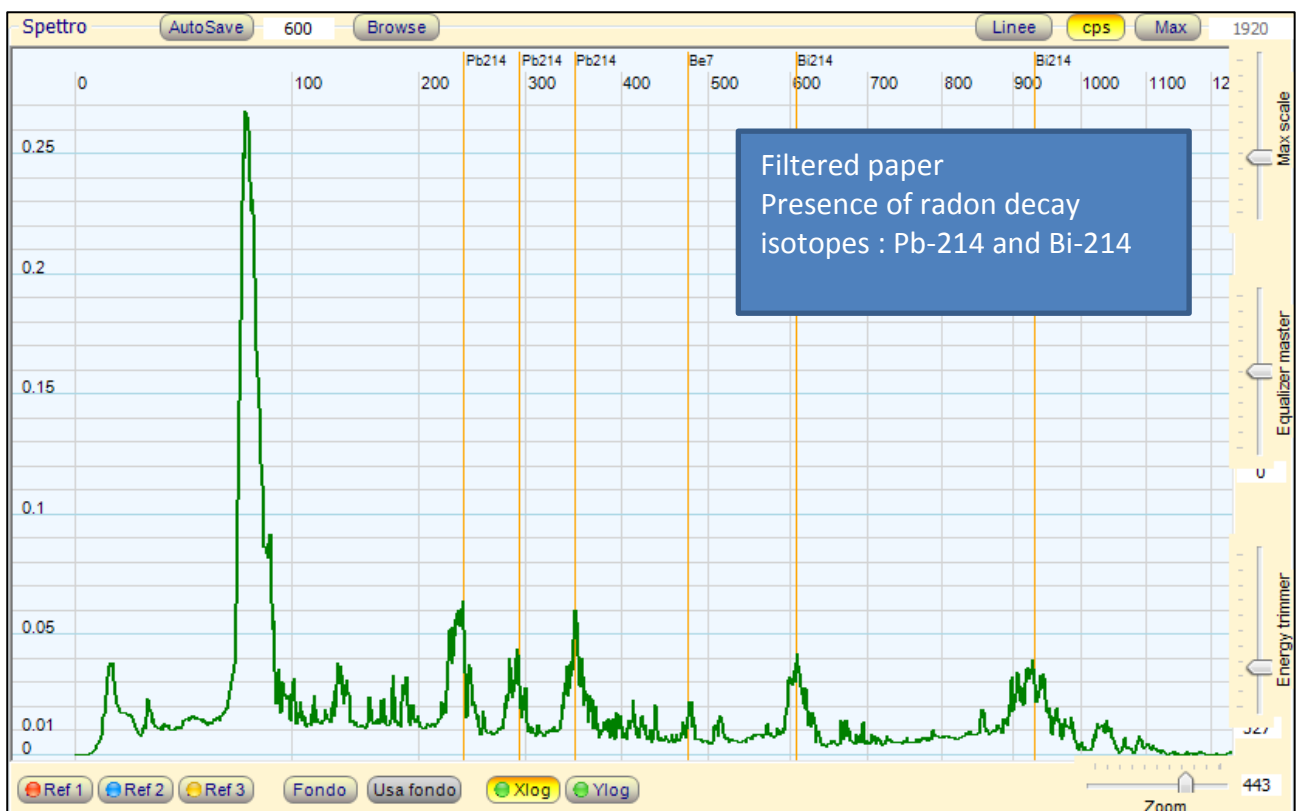
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Radon Decay in rain water



Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu - Lead Shielded Measure

Suspended in the air are small amounts of radioactive substances . The main source of radioactivity is constituted by radon progeny and then Pb-214 and Bi-214 . These particles are mainly present in the air indoors. To carry out sampling was used a fan powered at 12 V, inserted in a metal cylinder whose opening was covered with a filter paper. Activating the fan for a couple of hours indoors you can collect radioactive particles in measurable amount .



Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu - Lead Shielded Measure

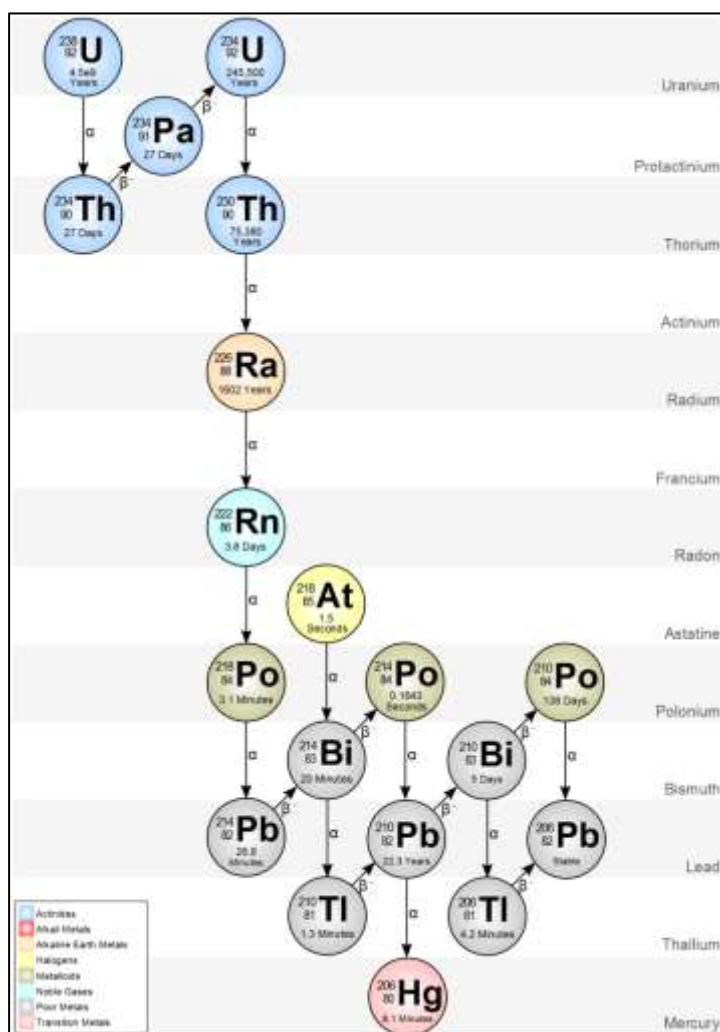
Filtering airborne particles outdoor

Radium (^{226}Ra)



Radium is a chemical element with symbol **Ra** and atomic number 88. It is the sixth element in group 2 of the periodic table, also known as the alkaline earth metals. The color of pure radium is almost pure white, but it readily oxidizes on exposure to air, becoming black in color. All isotopes of radium are highly radioactive, with the most stable isotope being **radium-226**, which has a half-life of 1600 years and decays into radon gas. When radium decays, ionizing radiation is a product, which can excite fluorescent chemicals and cause radio luminescence.

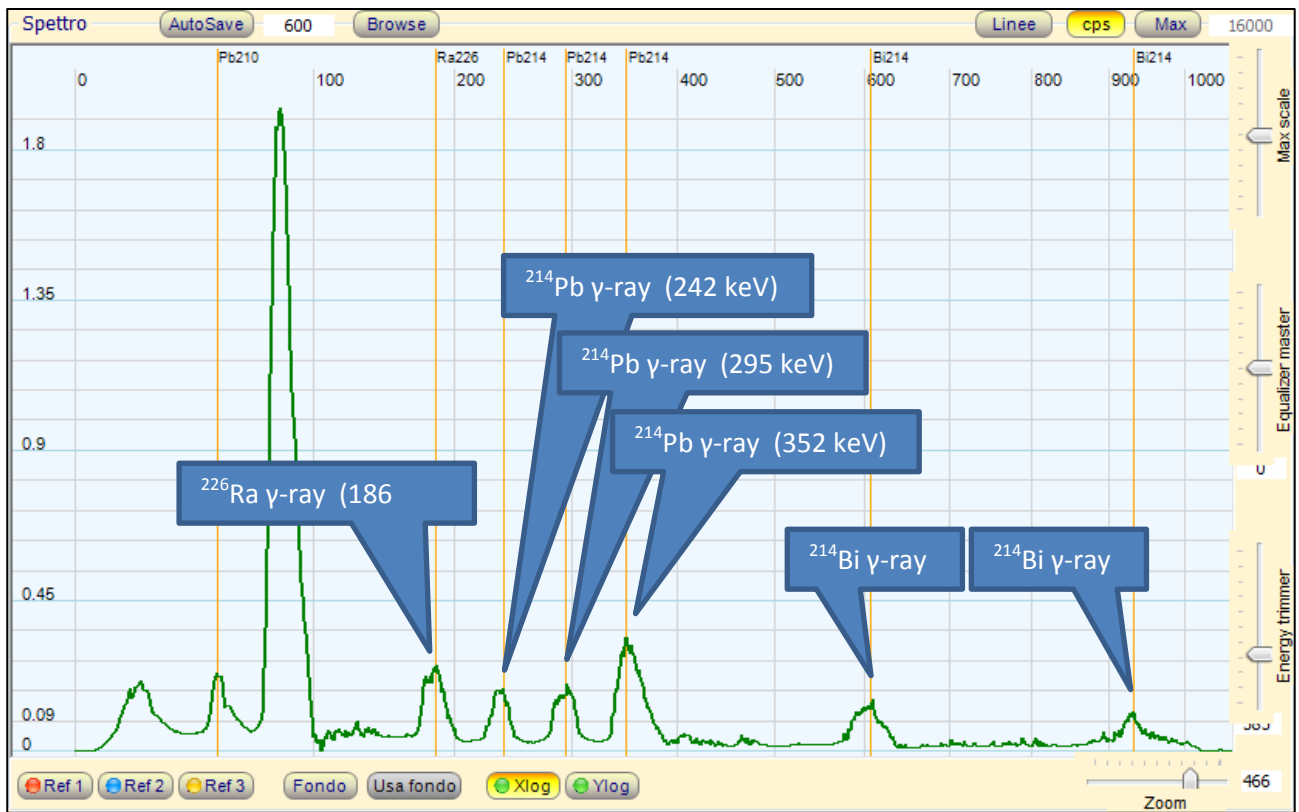
In nature, radium is found in uranium and thorium ores in trace amounts as small as a seventh of a gram per ton of uraninite.



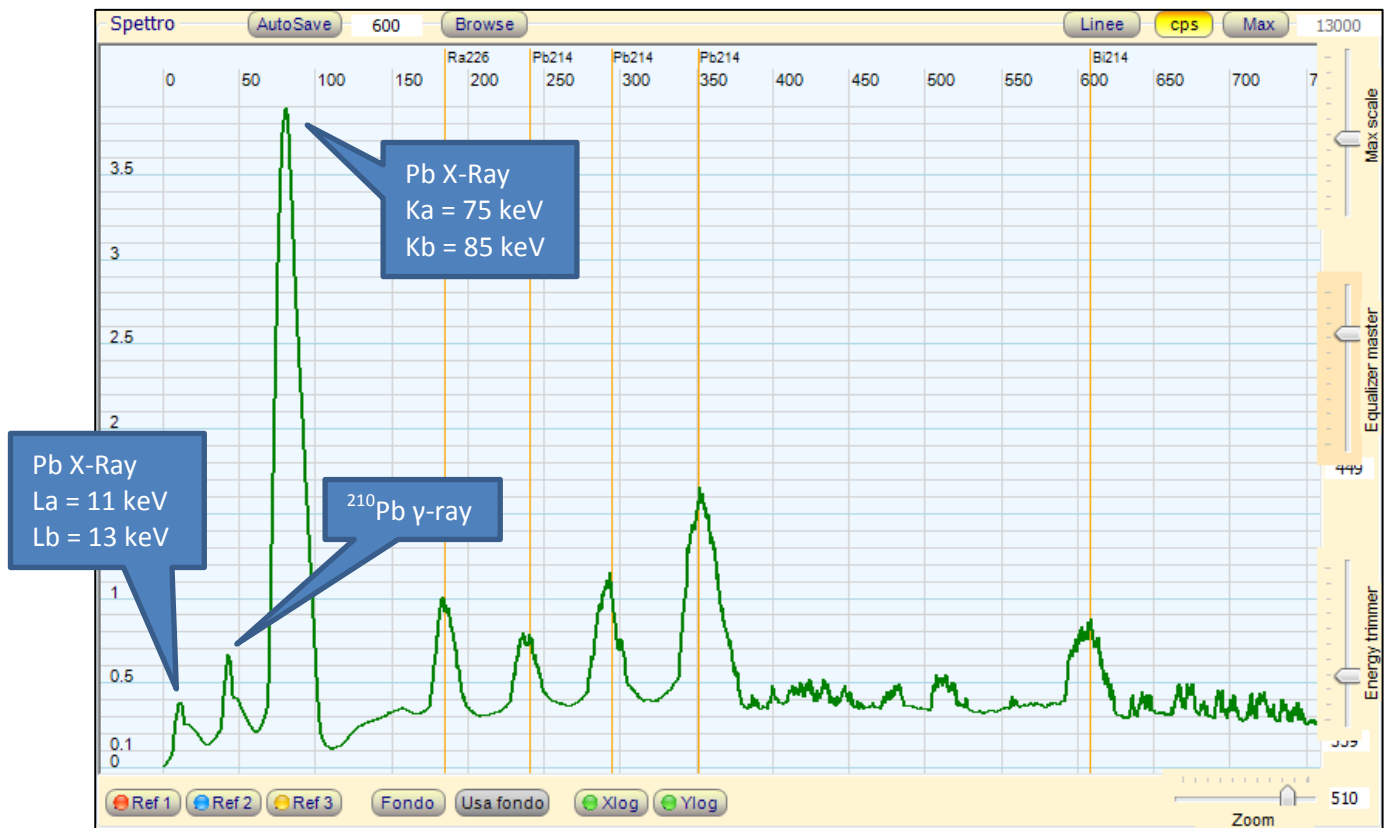
Radium has 33 known isotopes, with mass numbers from 202 to 234: all of them are radioactive. Four of these – ^{223}Ra (half-life 11.4 days), ^{224}Ra (3.64 days), ^{226}Ra (**1600 years**), and ^{228}Ra (5.75 years) – occur naturally in the decay chains of primordial **thorium-232**, **uranium-235**, and **uranium-238** (^{223}Ra from uranium-235, ^{226}Ra from **uranium-238**, and the other two from thorium-232). These isotopes nevertheless still have half-lives too short to be primordial radionuclides and only exist in nature from these decay chains. Together with the artificial ^{225}Ra (15 d), these are the five most stable isotopes of radium. All other known radium isotopes have half-lives under two hours, and the majority have half-lives under a minute. At least 12 nuclear isomers have been reported; the most stable of them is radium-205m, with a half-life of between 130 and 230 milliseconds, which is still shorter than thirty-four ground-state radium isotopes.

^{226}Ra is the most stable isotope of radium and is the last isotope in the $(4n + 2)$ decay chain of uranium-238 with a half-life of over a century. Its immediate decay product is the dense radioactive noble gas radon, which is responsible for much of the danger of environmental radium. It is 2.7 million times

more radioactive than the same molar amount of natural uranium (mostly uranium-238), due to its proportionally shorter half-life.



Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu - Lead Shielded Measure



Rap47 Scintillation Probe – CsI(Tl) 25.4 x 1.0mm crystal - Lead Shielded Measure

Thorium - Lantern Mantle (^{232}Th)

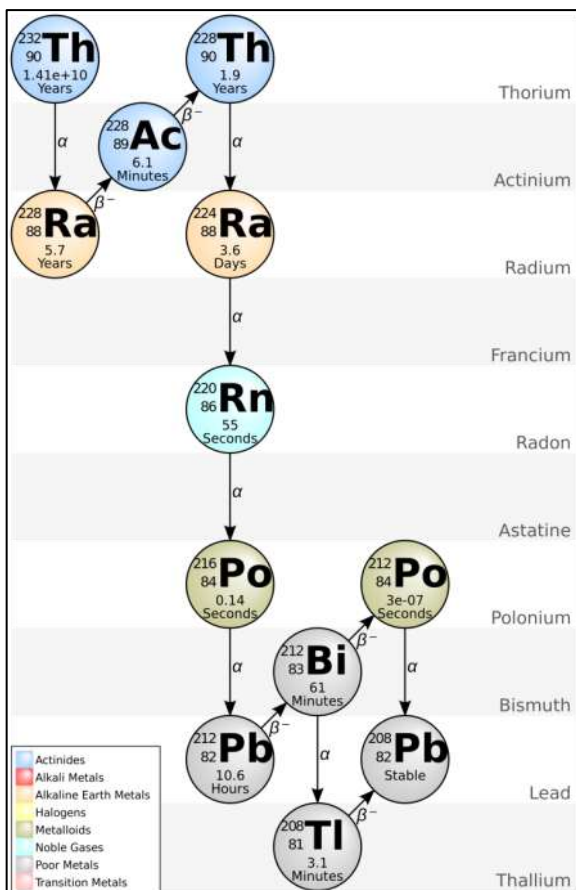


Thorium is a chemical element with symbol Th and atomic number 90. A radioactive actinide metal, thorium is one of only three radioactive elements that still occurs in quantity in nature as a primordial element (the other two being **bismuth** and **uranium**).

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. Thorium is weakly radioactive: all its known isotopes are unstable, with the six naturally occurring ones (thorium-227, 228, 230, 231, **232**, and 234) having half-lives between 25.52 hours and 14.05 billion years. **Thorium-232**, which has 142 neutrons, is the most stable isotope of thorium and accounts for

nearly all natural thorium, with the other five natural isotopes occurring only in traces: it decays very slowly through **alpha decay to radium-228**, starting a decay chain named the **thorium series** that ends at lead-208. 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.

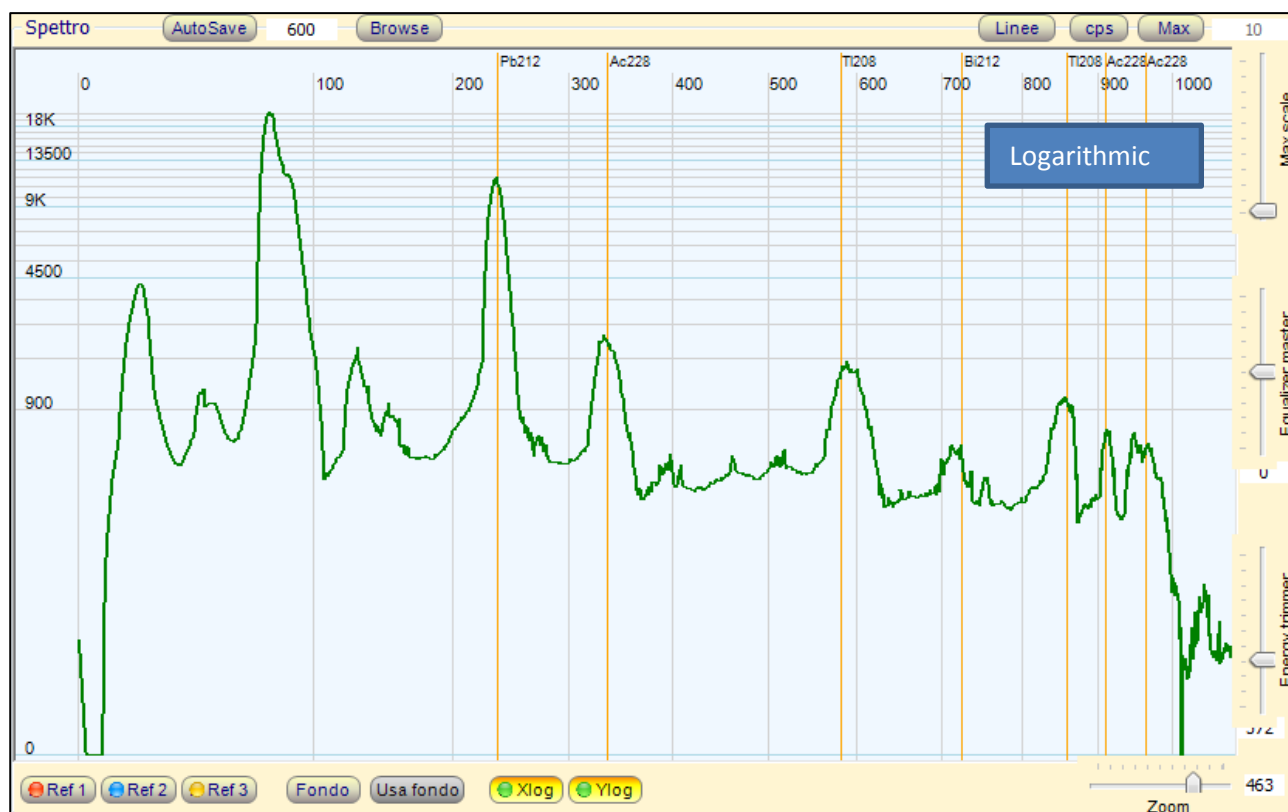
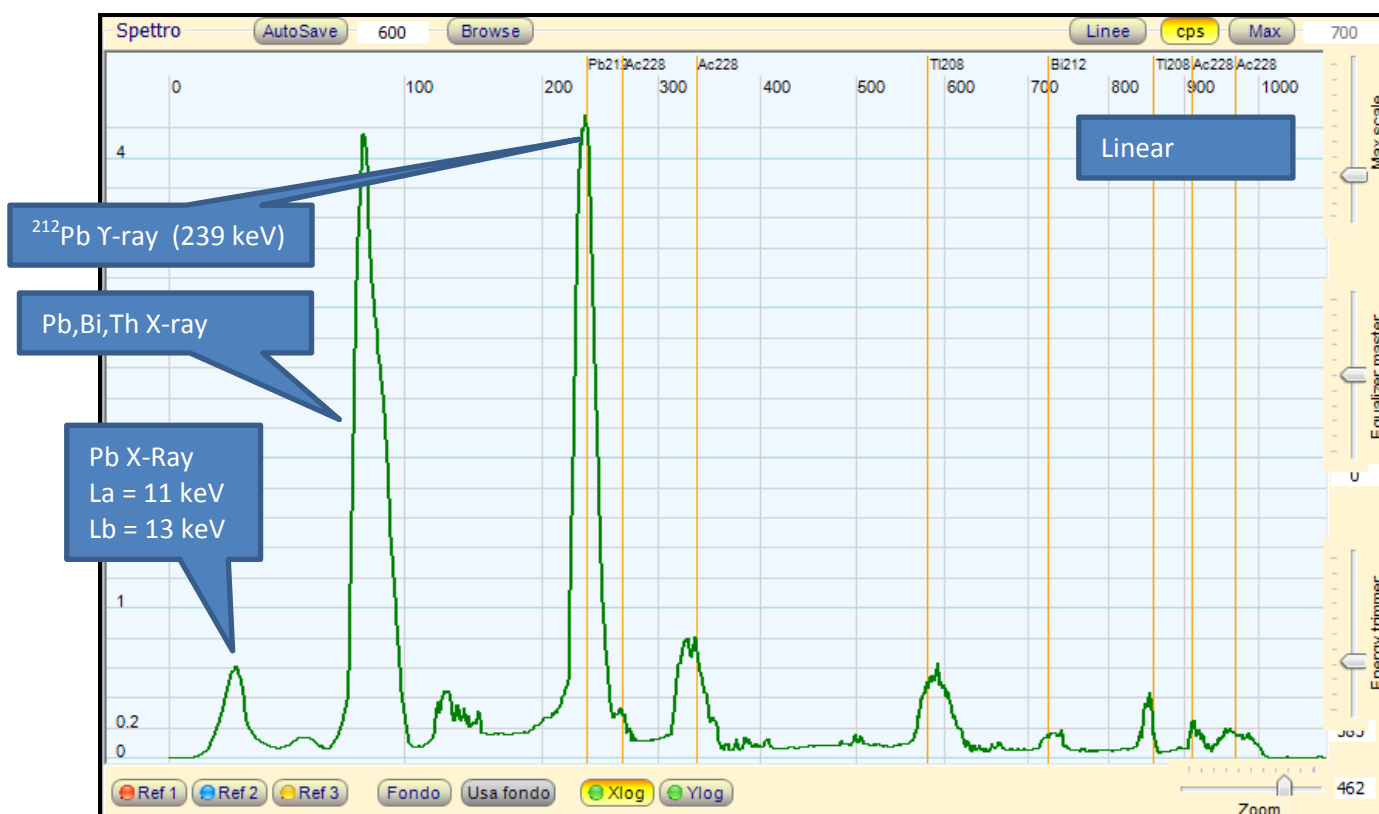
thorium-232 Decay Chain



The $4n$ chain of **Th-232** is commonly called the "thorium series" or "thorium cascade".

Beginning with naturally occurring **thorium-232**, this series includes the following elements : **actinium, bismuth, lead, polonium, radium, and radon**. All are present, at least transiently, in any natural thorium-containing sample, whether metal, compound, or mineral. The series terminates with **lead-208**.

The total energy released from thorium-232 to lead-208, including the energy lost to neutrinos, is 42.6 MeV.



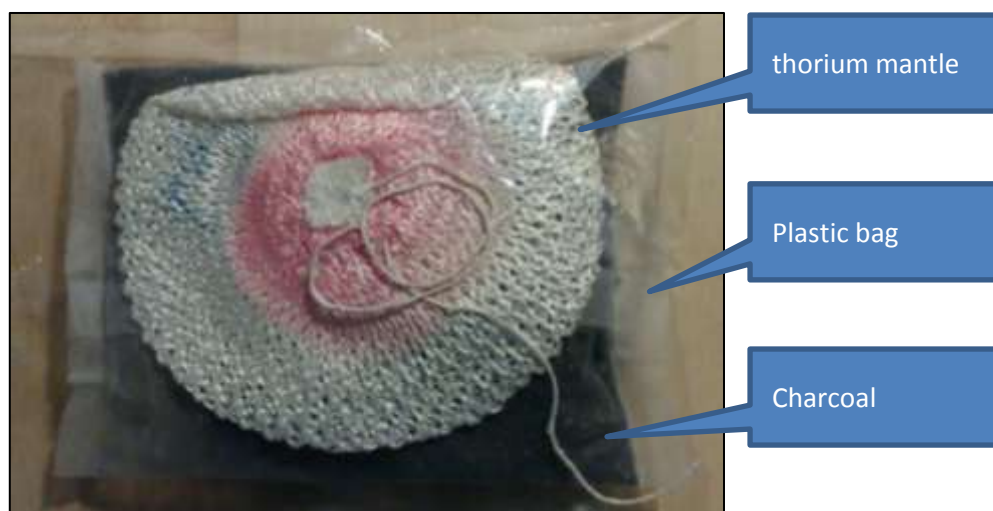
Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu - Lead Shielded Measure

“Thoron” decay (^{220}Rn)

Radon-220 (also known as thoron) is a short-lived isotope of radon and originates from thorium present in the earth's crust. The Rn-220 isotope is a natural decay product of the most stable thorium isotope (Th-232), and is commonly referred to as thoron. It has a half-life of 55.6 seconds and also emits alpha radiation.

In the thoron decay chain is evident the isotope **Pb-212**, with half-life of about 10 hours, this isotope generates the main gamma photo-peak at 239 keV, evident feature of the thorium gamma spectrum, shown in the gamma spectrum of the classic thorium gas mantle.

Other isotopes have shorter half-life and photo-peaks less evident, the main other isotopes which are present in the gamma spectrum are : Tl-208 and Bi-212. Isotope Ac-228 comes directly from thorium and thus, in the decay chain, it is generated before thoron.

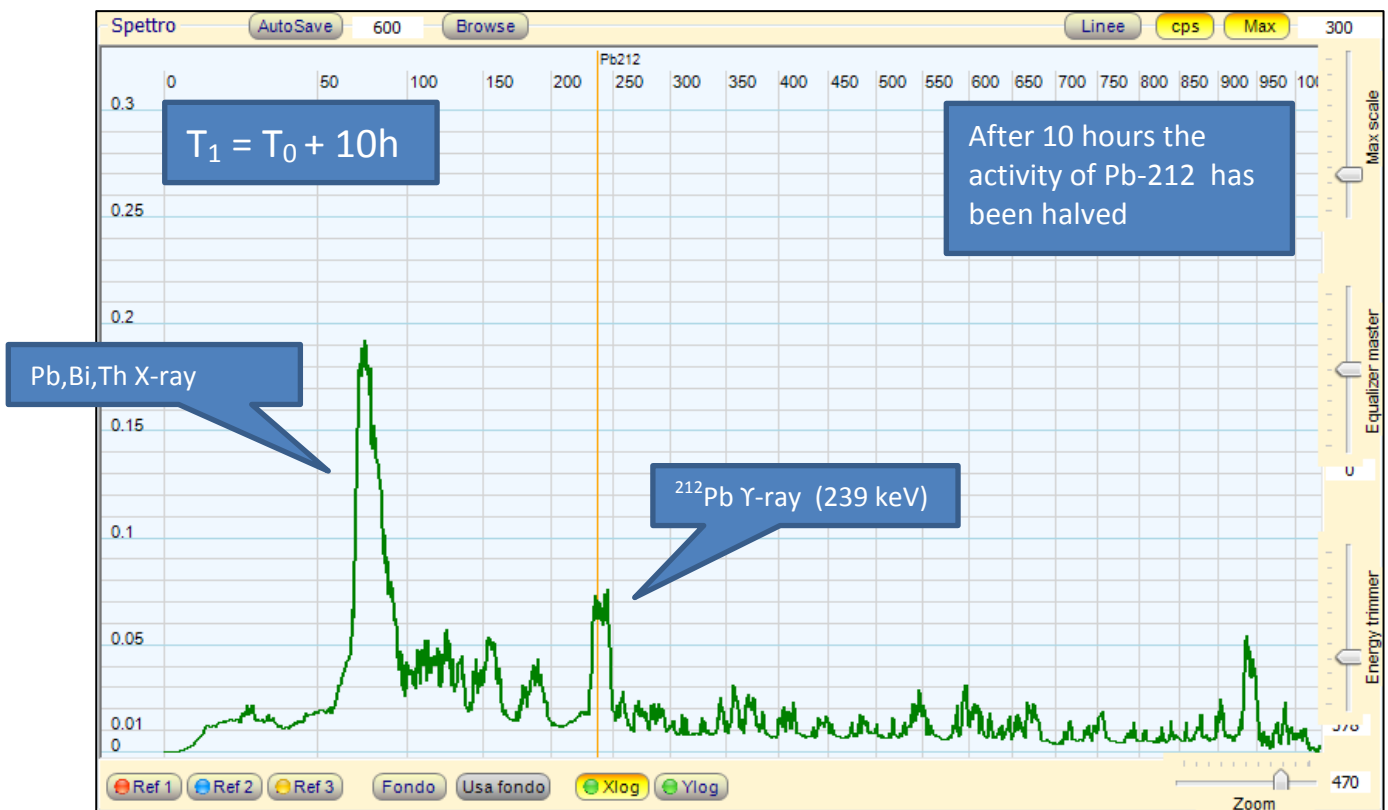
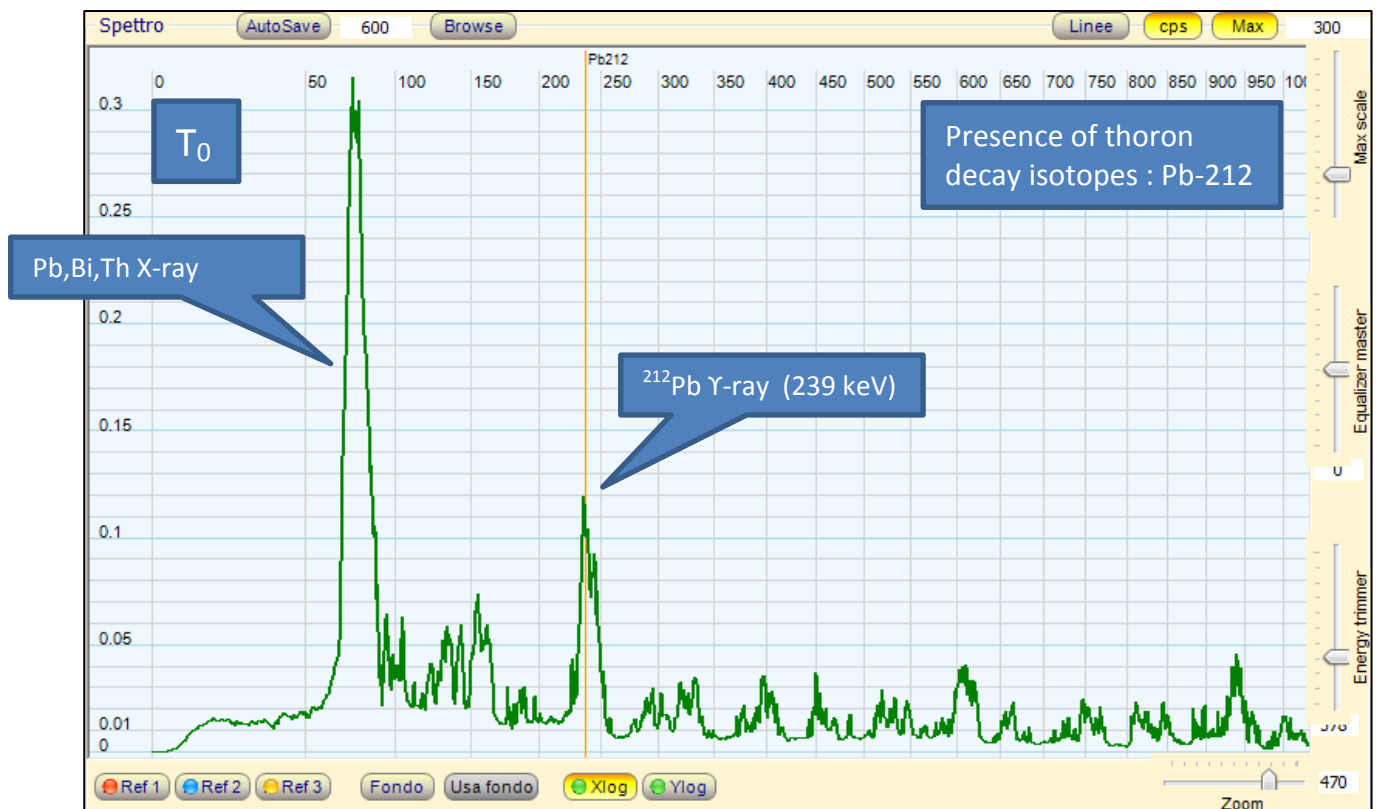


To make the measurement of the decay of the thoron we inserted in a plastic bag, a thorium gas mantle together with a bag of charcoal, the bag was placed in a warm place for about 24 hours.

During this time period the thoron has leaked from the mantle, also thanks to the heat, and has been absorbed by the charcoal filter. The process of decay of thoron was then also occurred inside the charcoal, producing his isotopes.

Finally the charcoal filter was extracted from the bag and was made the measurement of its gamma spectrum.

As expected we see the main peak of **Pb-212**, while others photopeaks are virtually absent. After a suitable period of time, about 10 hours, the peak of the Pb-212 has been much reduced, due to its decay.



Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu - Lead Shielded Measure
 Acquiring time 1000 sec

Monazite (radioactive ore containing thorium)

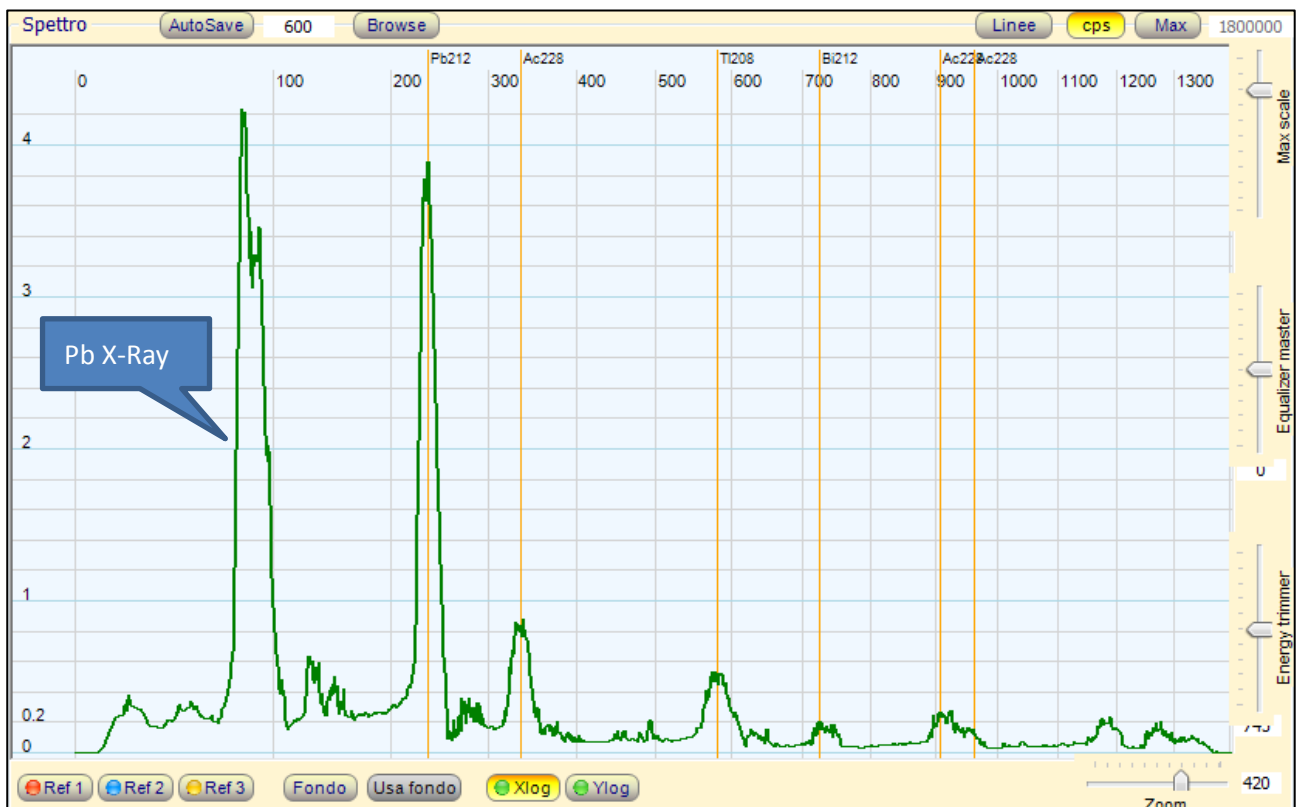


Monazite is a reddish phosphate mineral containing rare earth metals. It occurs usually in small isolated crystals. There are at least four different kinds of monazite, depending on relative elemental composition of the mineral:

- Monazite-(Ce), (Ce, La, Nd, Th)PO₄
- Monazite-(La), (La, Ce, Nd)PO₄
- Monazite-(Nd), (Nd, La, Ce)PO₄
- Monazite-(Sm), (Sm, Gd, Ce, Th)PO₄

The elements in parentheses are listed in the order of their relative proportion within the mineral: lanthanum is the most common rare earth element in monazite-(La), and so forth. Silica (SiO₂) is present in trace amounts, as well as small amounts of uranium and thorium. Due to the alpha decay of thorium and uranium, monazite contains a significant amount of helium, which can be extracted by heating.

Monazite is an important ore for thorium, lanthanum, and cerium. Monazite is radioactive due to the presence of thorium and, less commonly, uranium. Because of its radioactive nature, monazite is a useful for radiometric dating of geological events, such as crystallization, heating, or deformation of the rocks containing monazite.

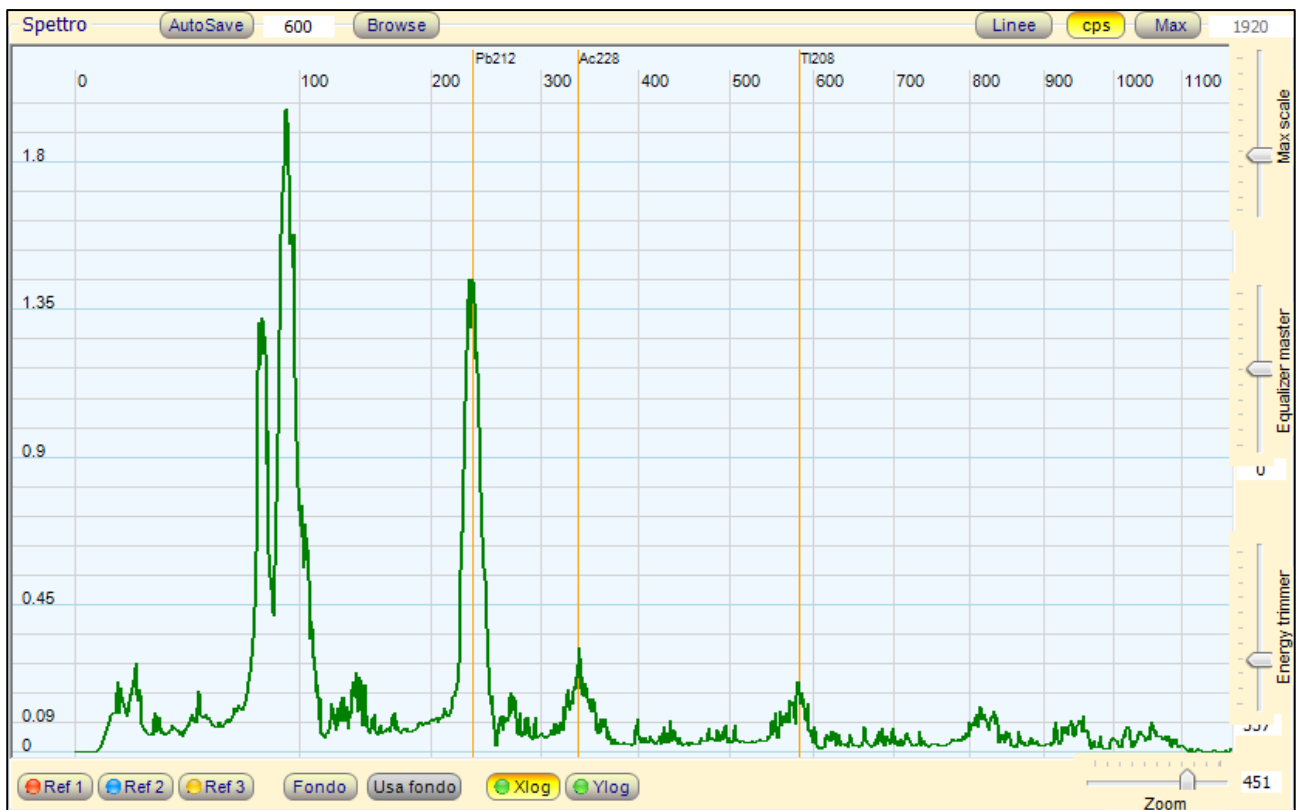


Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu - Lead Shielded Measure

Thorianite (radioactive ore containing thorium)



Thorianite is a rare thorium oxide mineral, ThO_2 . It was originally described by Ananda Coomaraswamy in 1904 as uraninite, but recognized as a new species by Wyndham R. Dunstan. It was so named on account of its high percentage of thorium; it contains oxides of uranium, lanthanum, cerium, praseodymium and neodymium. Helium is present, and the mineral is slightly less radioactive than pitchblende, but is harder to shield due to its high energy gamma rays. It is common in the alluvial gem-gravels of Sri Lanka, where it occurs mostly as water worn, small, heavy, black, cubic crystals.



Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu - Lead Shielded Measure

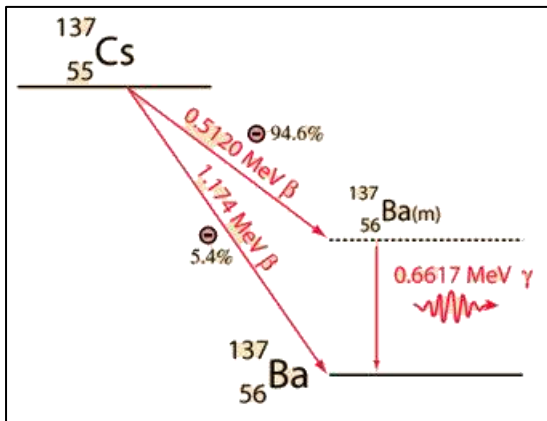
Caesium - Spark Gap (^{137}Cs)



Caesium-137 (Cs-137), cesium-137, or radiocesium, is a radioactive isotope of caesium which is formed as one of the more common fission products by the nuclear fission of uranium-235 and other fissionable isotopes in nuclear reactors and nuclear weapons. It is among the most problematic of the short-to-medium-lifetime fission products because it easily moves and spreads in nature due to the high water solubility of caesium's most common chemical compounds, which are salts.

Small amounts of **caesium-134** and **caesium-137** were released into the environment during nearly all nuclear weapon tests and some nuclear accidents, most notably the Goiânia accident, the Chernobyl disaster and the Fukushima Daiichi disaster.

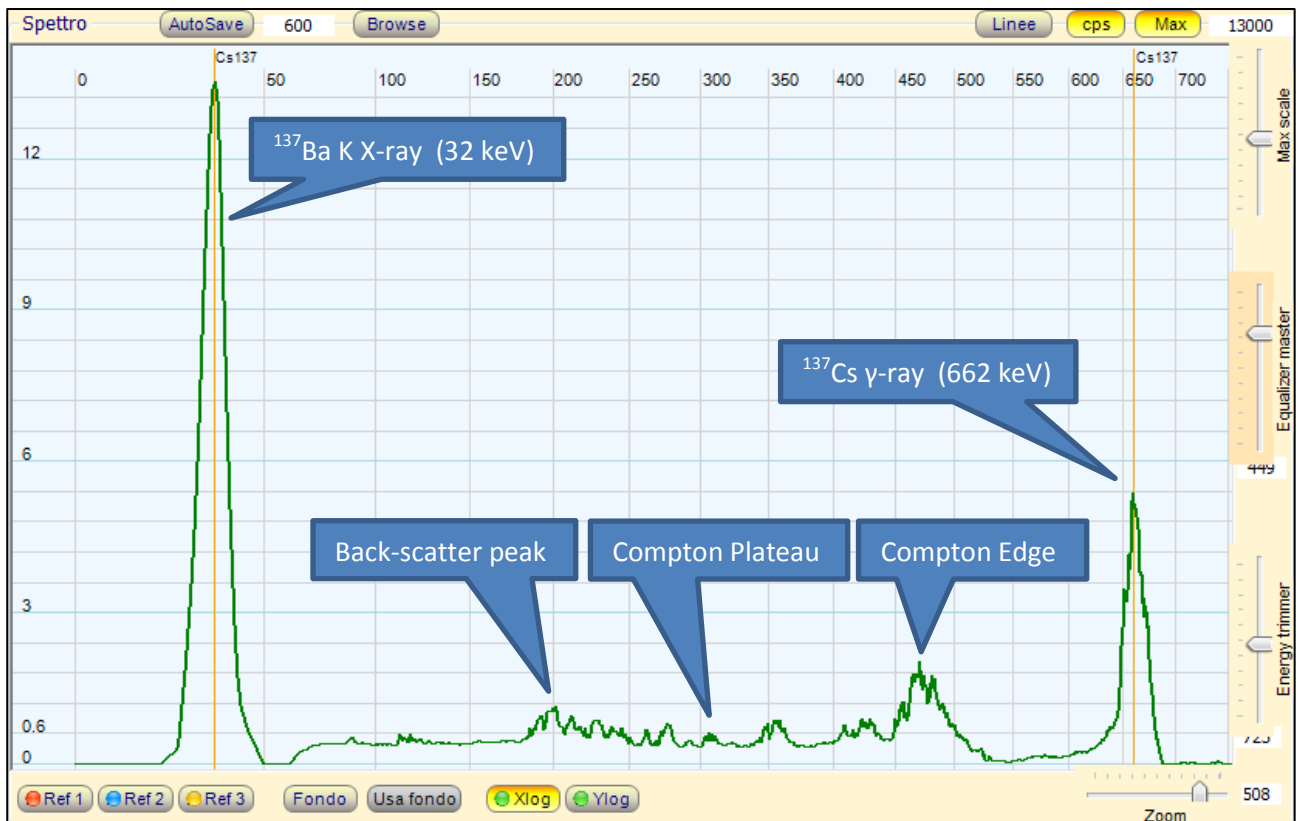
Caesium-137 Decay Chain



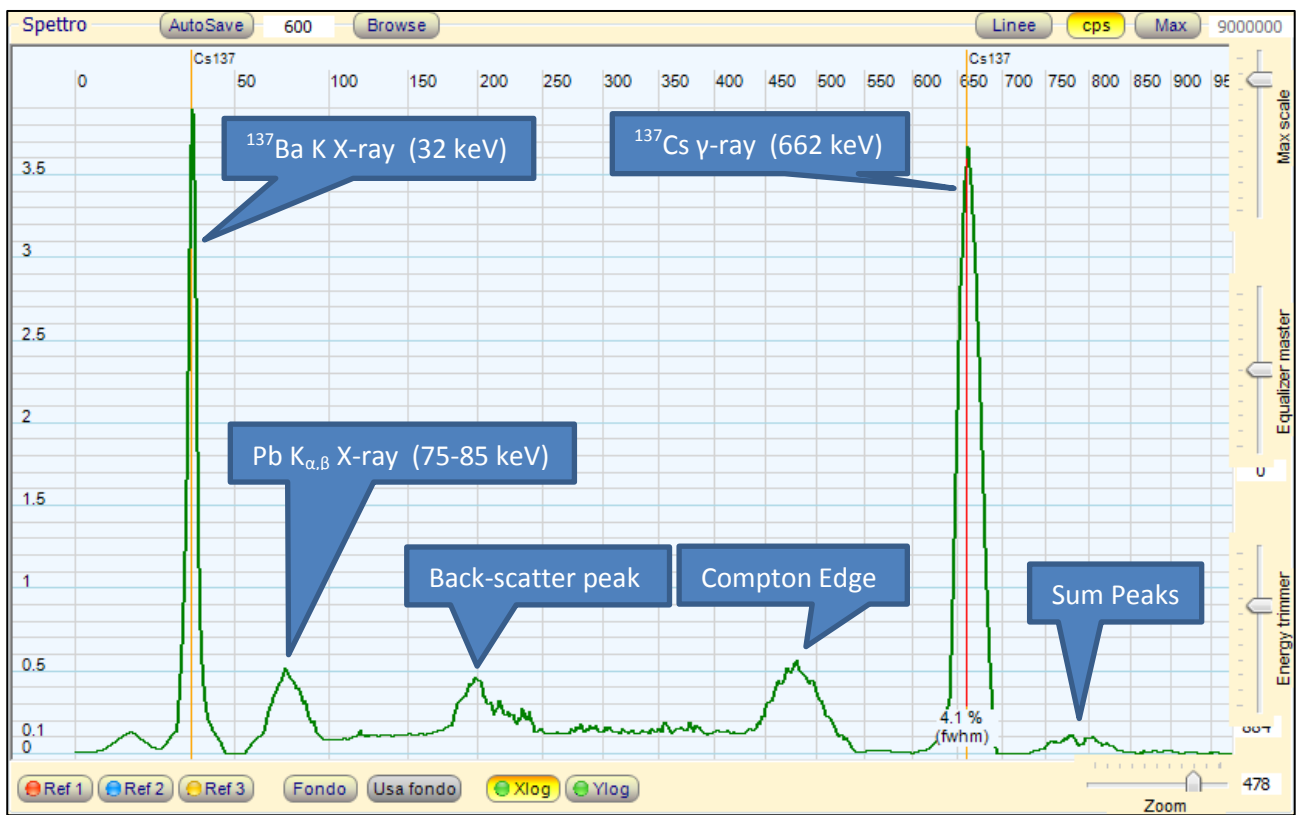
Caesium-137 has a half-life of about 30.17 years. About 95 percent decays by beta emission to a metastable nuclear isomer of barium: **barium-137m** (Ba-137m). The remainder directly populates the ground state of barium-137, which is stable. Ba-137m has a half-life of about 153 seconds, and is responsible for all of the emissions of gamma rays in samples of caesium-137.

One gram of caesium-137 has an activity of 3.215 terabecquerel (TBq).

The photon energy of **Ba-137m** is 662 keV.



Rap47 Scintillation Probe – CsI(Tl) 25.4 x 1.0mm crystal

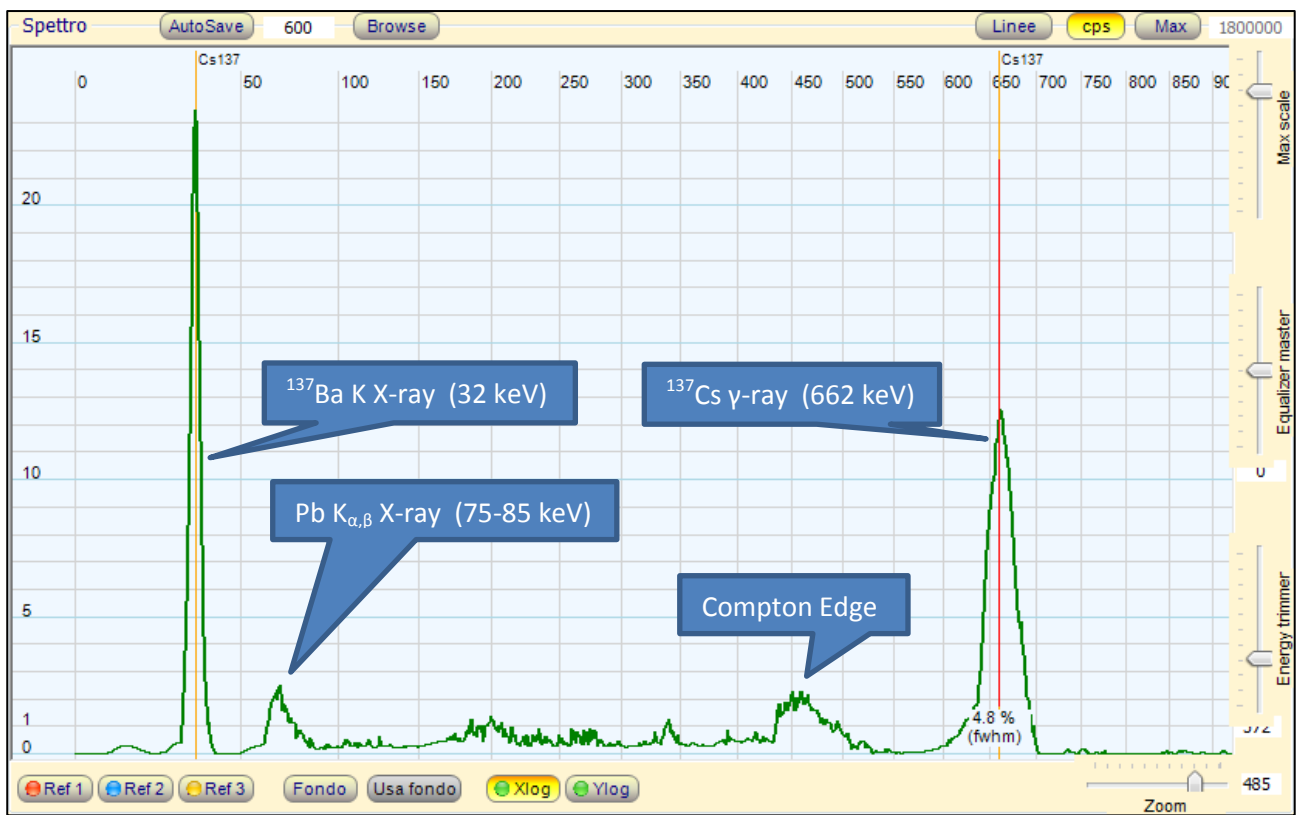


Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu
Lead Shielded Measure (Presence XRF from Pb K-L lines)

Cesium –Calibration Source (^{137}Cs)



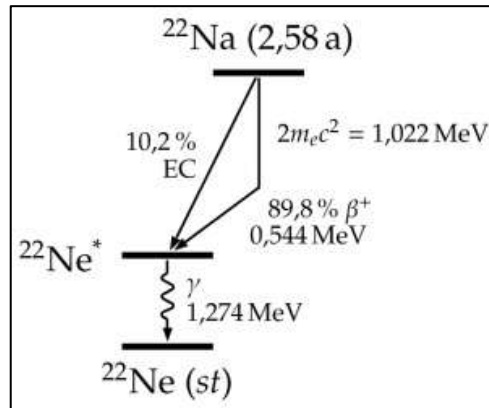
0,25 μCi isotope ^{137}Cs .



Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu

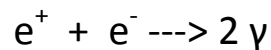
Lead Shielded Measure (Presence XRF from Pb K-L lines)

Sodium-22 –Calibration Source (^{22}Na)

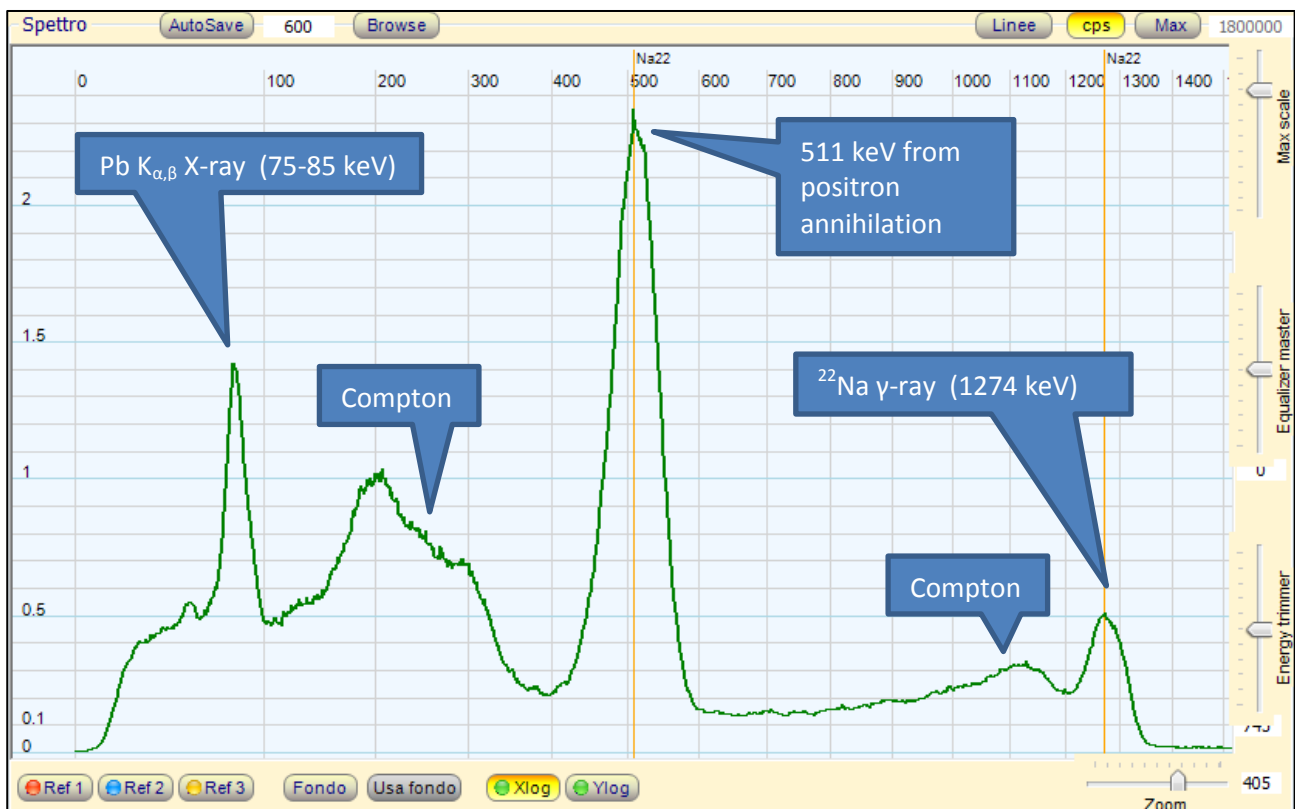


1 μCi isotope ^{22}Na and decay chain

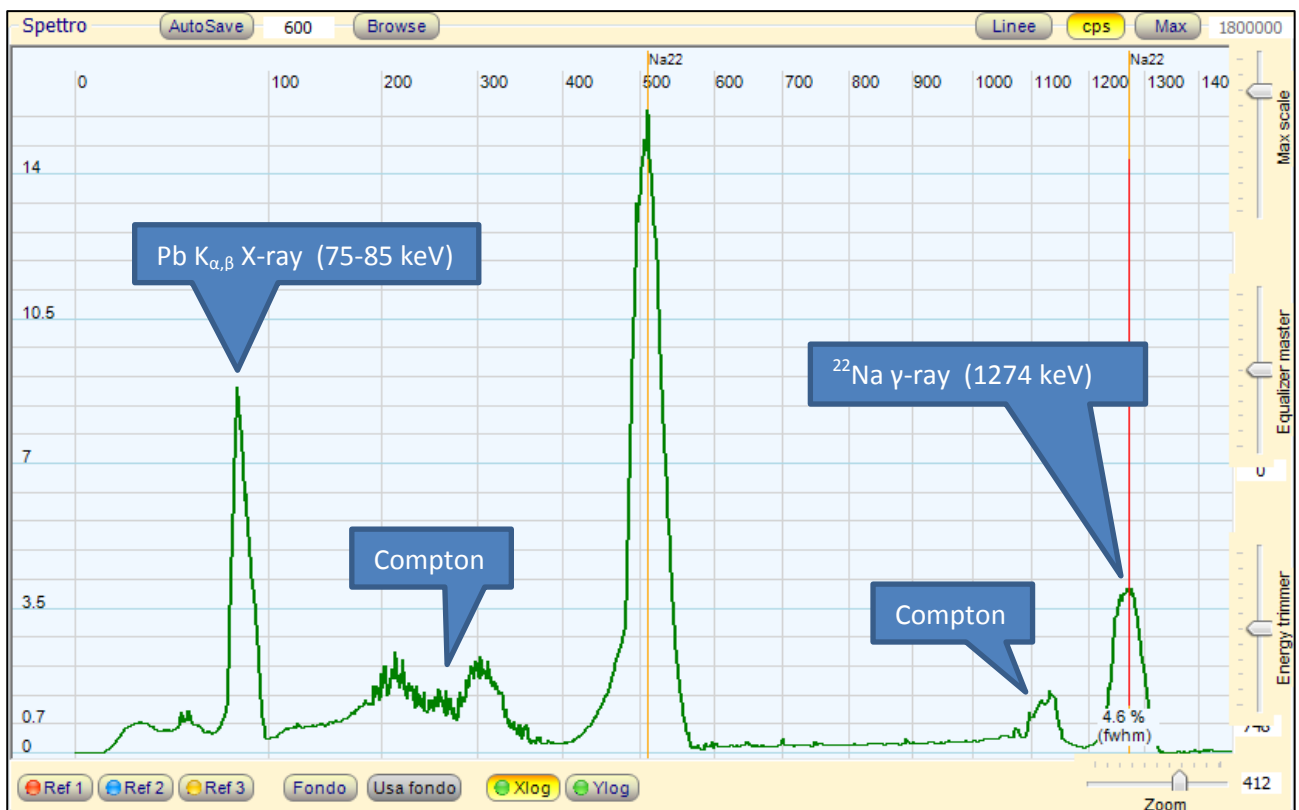
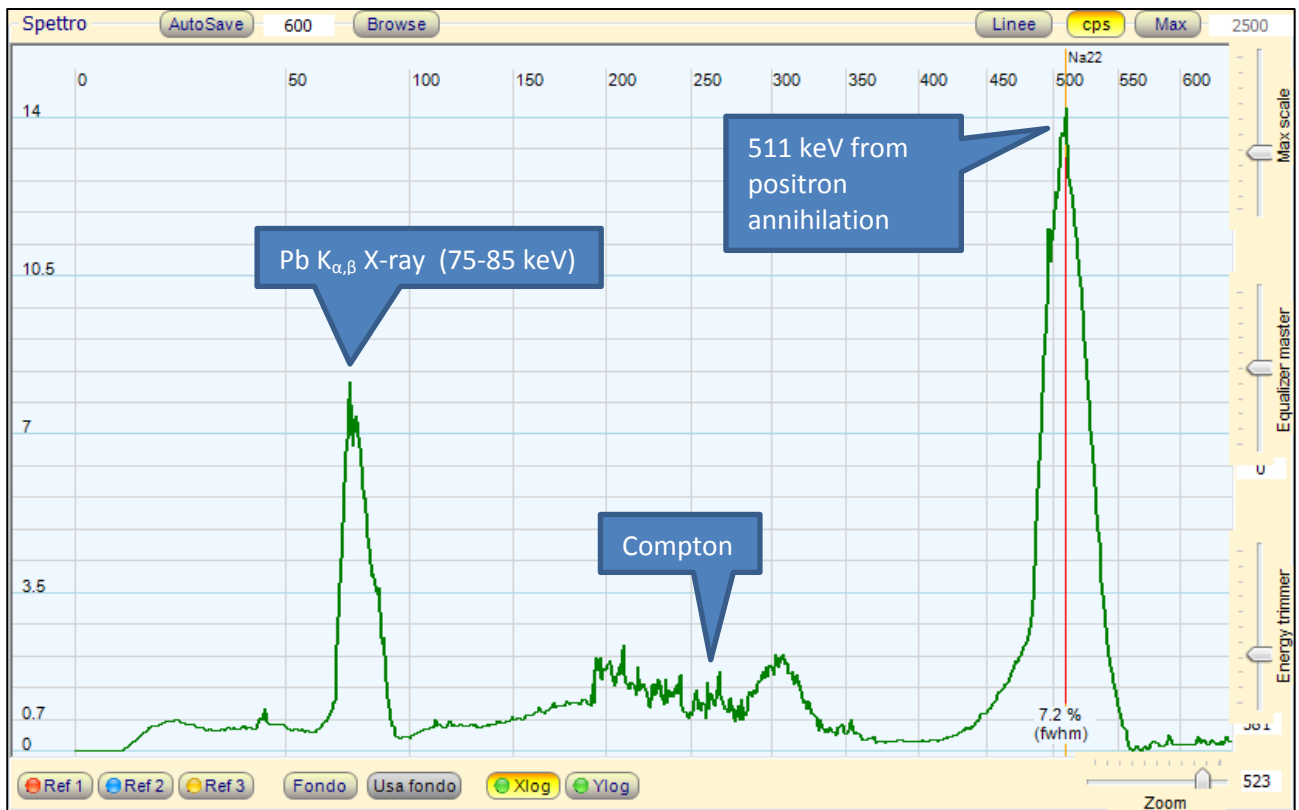
The isotope Na-22 decays (in 99.95% of cases) with a half-life of 2.6 years, by positron emission or electron capture to the first excited state of ^{22}Ne 1,274 MeV (which then relaxes by emitting gamma photon). The positrons emitted by the source annihilate inside the material that acts as a support to the source, producing two gamma photons of energy 0.511 MeV each, according to the process :



The two gamma photons to 0.511 MeV are issued at 180 degrees from each other. This allows measurements of correlation and coincidence.



Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu - Lead Shielded Measure
No broadening compensation



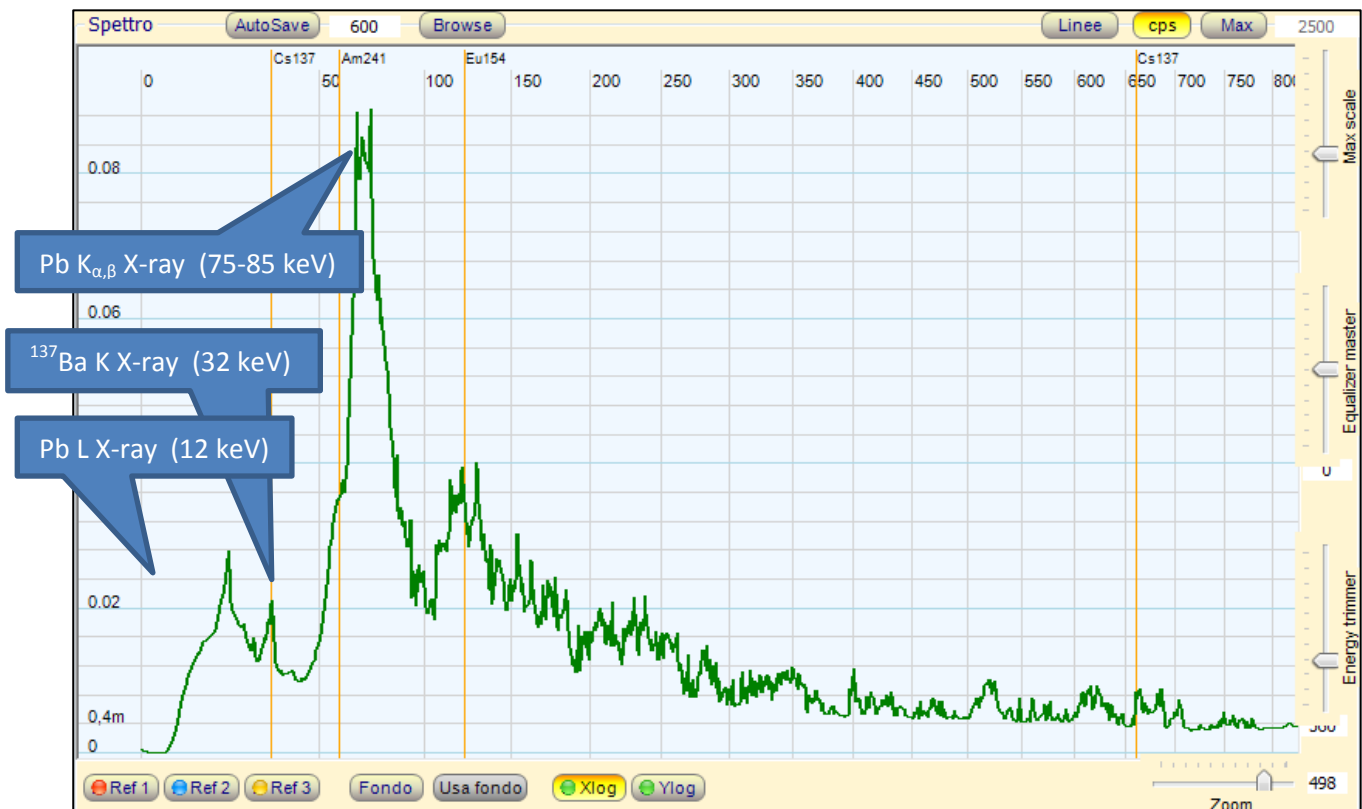
Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu - Lead Shielded Measure
With broadening compensation

Trinitite



Trinitite, also known as **atomsite** or **Alamogordo glass**, is the glassy residue left on the desert floor after the plutonium-based Trinity nuclear bomb test on July 16, 1945, near Alamogordo, New Mexico. The glass is primarily composed of arkosic sand composed of quartz grains and feldspar (both microcline and smaller amount of plagioclase with small amount of calcite, hornblende and augite in a matrix of sandy clay) that was melted by the atomic blast. It is usually a light green, although color can vary. It is mildly radioactive but safe to handle

There are many known fakes in circulation among collectors. These fakes use a variety of means to achieve the glassy green silica look as well as mild radioactivity, however, only trinitite from a nuclear explosion will contain certain neutron activation products that are not found in naturally radioactive ores and minerals. Gamma spectroscopy can narrow down the potential nuclear explosions from which the material formed.



Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu - Lead Shielded Measure



Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu - Lead Shielded Measure

The Trinitite sample has very low residual radioactivity. To obtain consistent data, adequate lead shielding must be used. From comparison of the spectrum of Trinitite sample with the spectrum of the background you can highlight the presence of the following isotopes from fission fragments and neutron activation:

- cesium-137
- americium-241
- europium-152 / europium-154

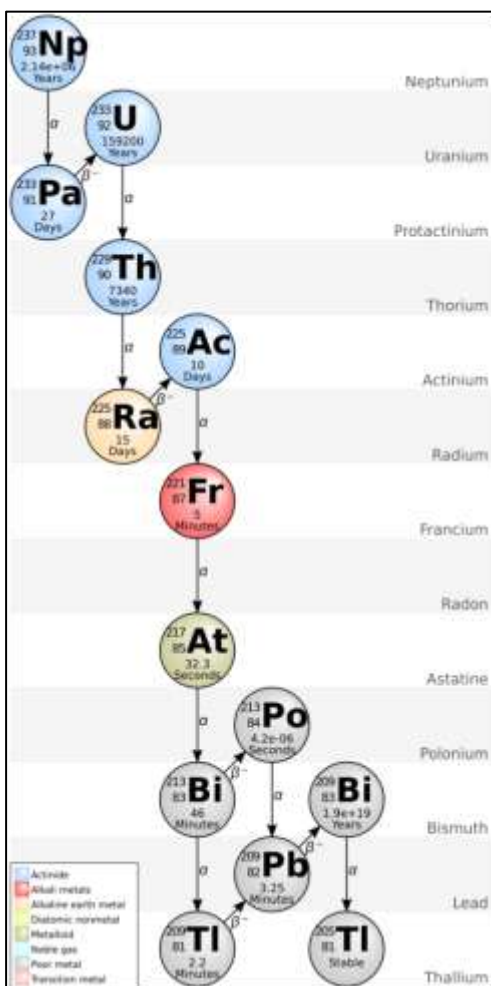
Americium (²⁴¹Am)



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-241 decay chain

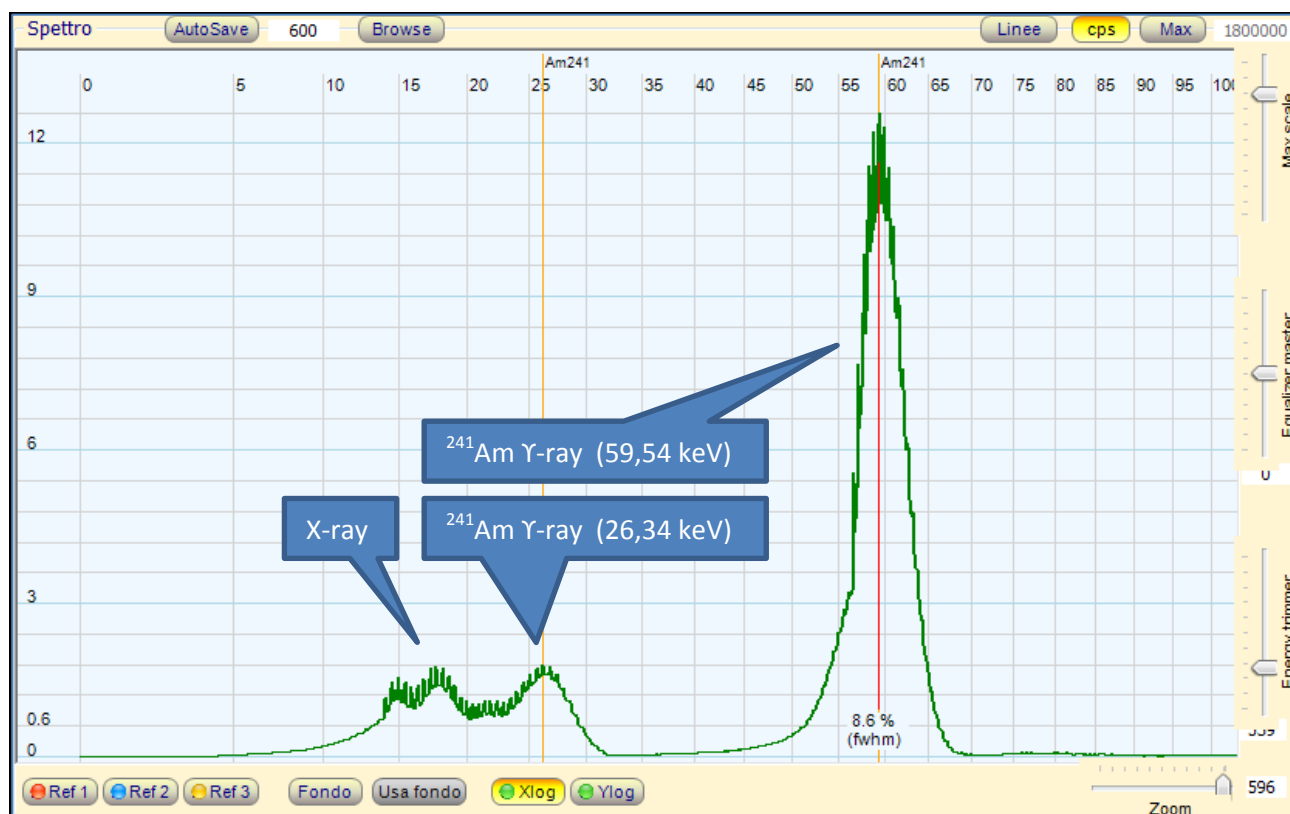
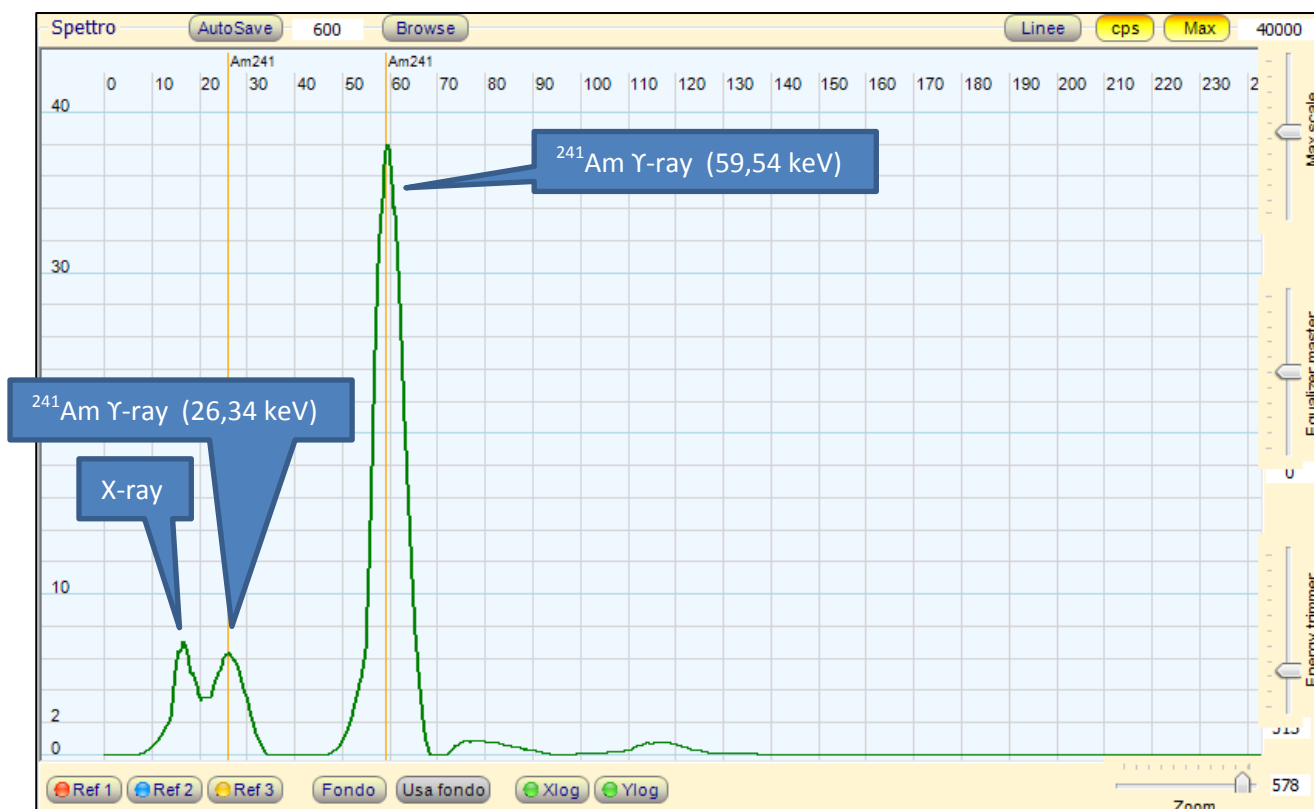


The $4n + 1$ chain of **Np-237** is commonly called the "neptunium series" or "neptunium cascade". In this series, only two of the isotopes involved are found naturally, namely the final two: bismuth-209 and thallium-205. A smoke

two: bismuth-209 and thallium-205. A smoke detector containing an americium-241 ionization chamber accumulates a significant amount of neptunium-237 as its americium decays.

The following elements are also present in it, at least transiently, as decay products of the neptunium: actinium, astatine, bismuth, francium, lead, polonium, protactinium, radium, thallium, thorium, and uranium. Since this series was only studied more recently, its nuclides do not have historic names. One unique trait of this decay chain is that it does not include the noble-gas radon, and thus does not migrate through rock nearly as much as the other three decay chains.

The total energy released from californium-249 to thallium-205, including the energy lost to neutrinos, is 66.8 MeV.



Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu - Lead Shielded Measure

Tritium (^3H)



Tritium, (symbol T, ^3H or H-3 also known as hydrogen-3) is a radioactive isotope of hydrogen. The nucleus of tritium (sometimes called a triton) contains one proton and two neutrons, whereas the nucleus of protium (by far the most abundant hydrogen isotope) contains one proton and no neutrons. Naturally occurring tritium is extremely rare on Earth, where trace amounts are formed by the interaction of the atmosphere with cosmic rays. The name of this isotope is formed from the Greek word "tritōs" meaning "third".

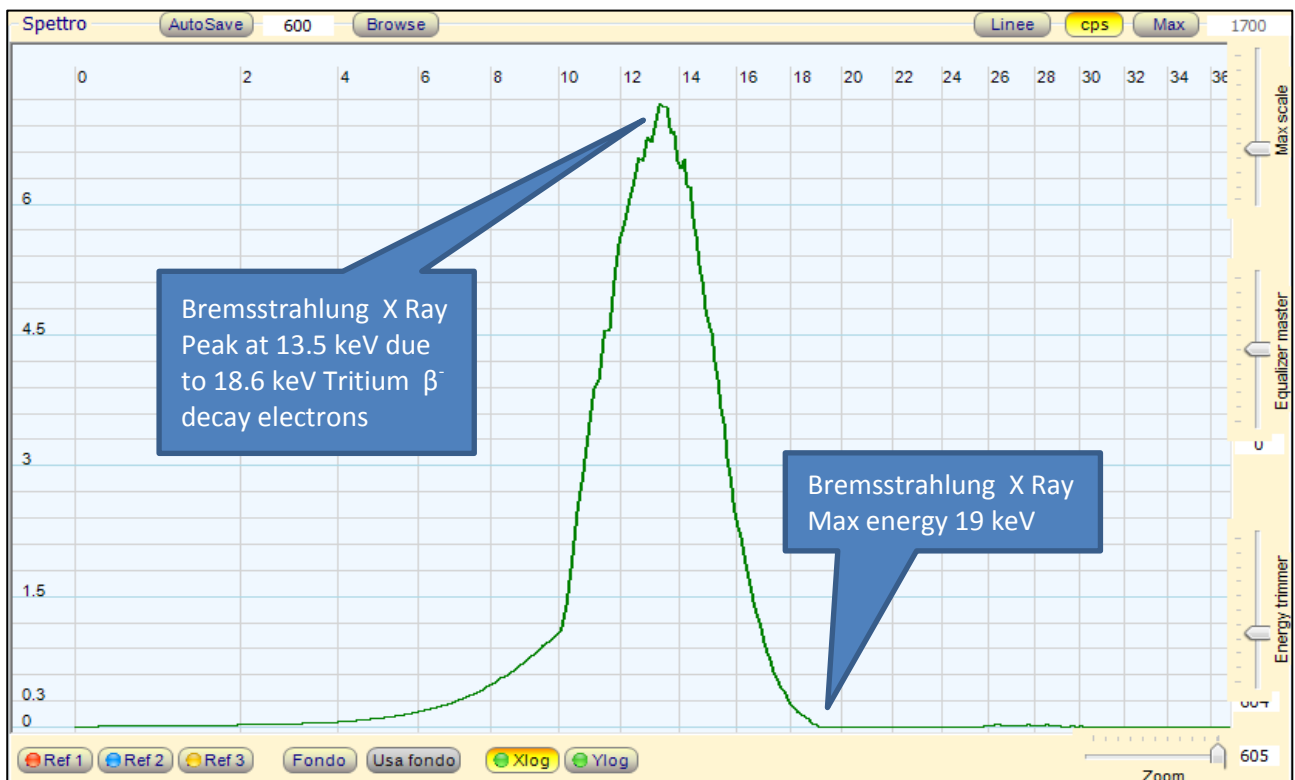
Tritium Decay Chain

While tritium has several different experimentally determined values of its half-life, the National Institute of Standards and Technology lists $4,500 \pm 8$ days (12.32 ± 0.02 years). It decays into helium-3 by beta decay as in this nuclear equation:



and it releases **18.6 keV** of energy in the process. The electron's kinetic energy varies, with an average of 5.7 keV, while the remaining energy is carried off by the nearly undetectable electron antineutrino. Beta particles from tritium can penetrate only about 6.0 mm of air, and they are incapable of passing through the dead outermost layer of human skin. The unusually low energy released in the tritium beta decay makes the decay (along with that of rhenium-187) appropriate for absolute neutrino mass measurements in the laboratory (the most recent experiment being KATRIN).

The low energy of tritium's radiation makes it difficult to detect tritium-labeled compounds except by using liquid scintillation counting.



Rap47 Scintillation Probe – CsI(Tl) 25.4 x 1.0mm crystal

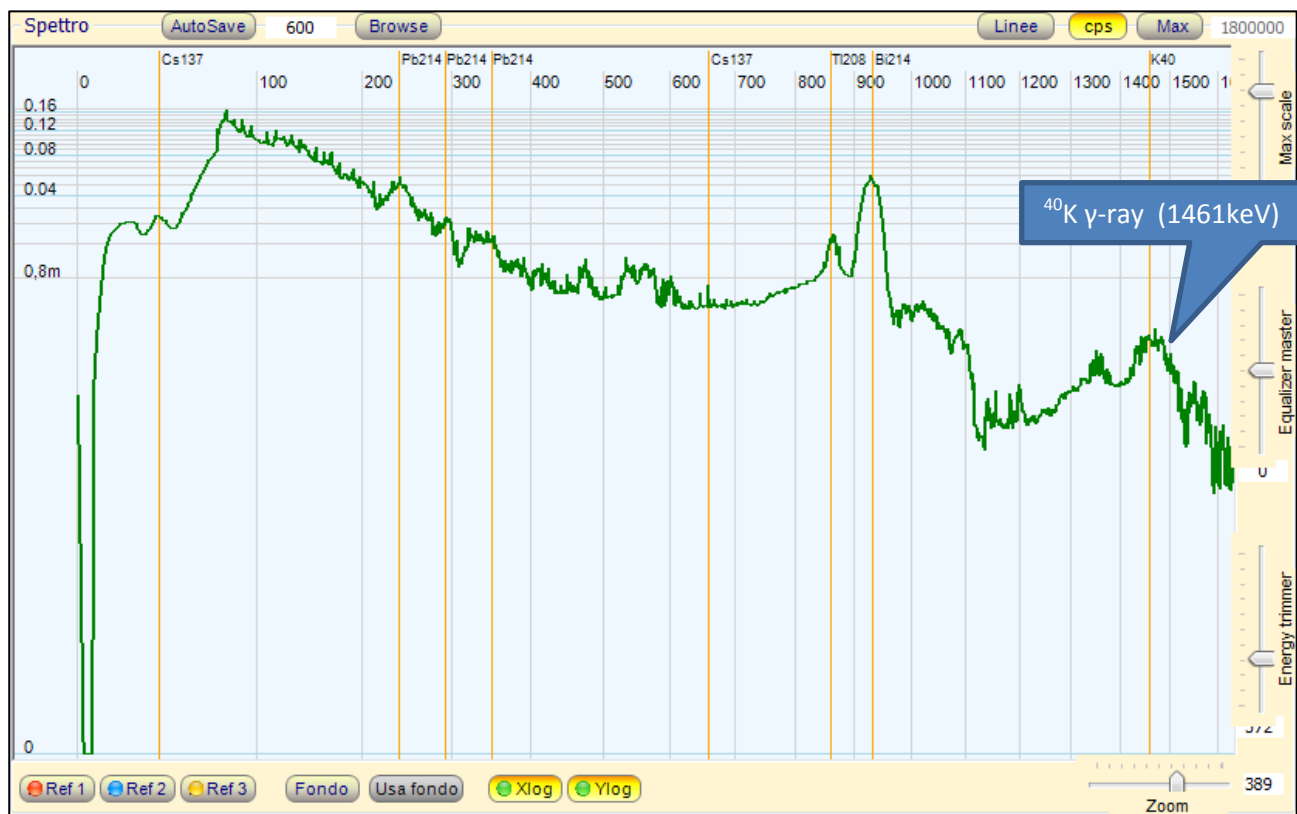
Potassium ^{40}K



Potassium-40 (^{40}K) is a radioactive isotope of potassium which has a very long half-life of 1.251×10^9 years. It makes up 0.012% (120 ppm) of the total amount of potassium found in nature.

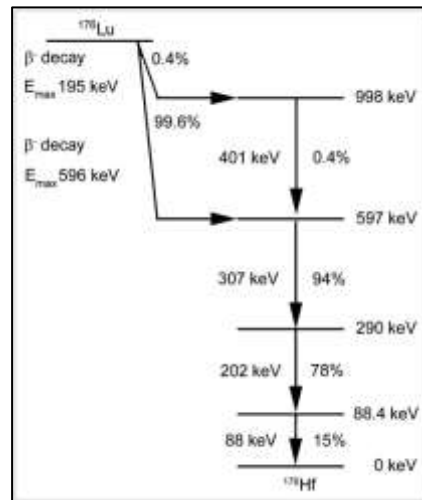
Potassium-40 is a rare example of an isotope that undergoes all three types of beta decay. About 89.28% of the time, it decays to calcium-40 (^{40}Ca) with emission of a beta particle (β^- , an electron) with a maximum energy of 1.33 MeV and an antineutrino. About 10.72% of the time it decays to argon-40 (^{40}Ar) by electron capture, with the emission of a **1.460 MeV gamma ray** and a neutrino. The radioactive decay of this particular isotope explains the fact that argon is the cheapest totally inert gas available. Very rarely (0.001% of the time) it will decay to ^{40}Ar by emitting a positron (β^+) and a neutrino.

A Marinelli beaker has been used for the measure of a potassium salt. The measure last several hours. In the gamma spectrum, in addition to the ^{40}K emission, the emission peaks of Pb, Bi, Tl and Cs are evident, all of them belong to the background radiation.

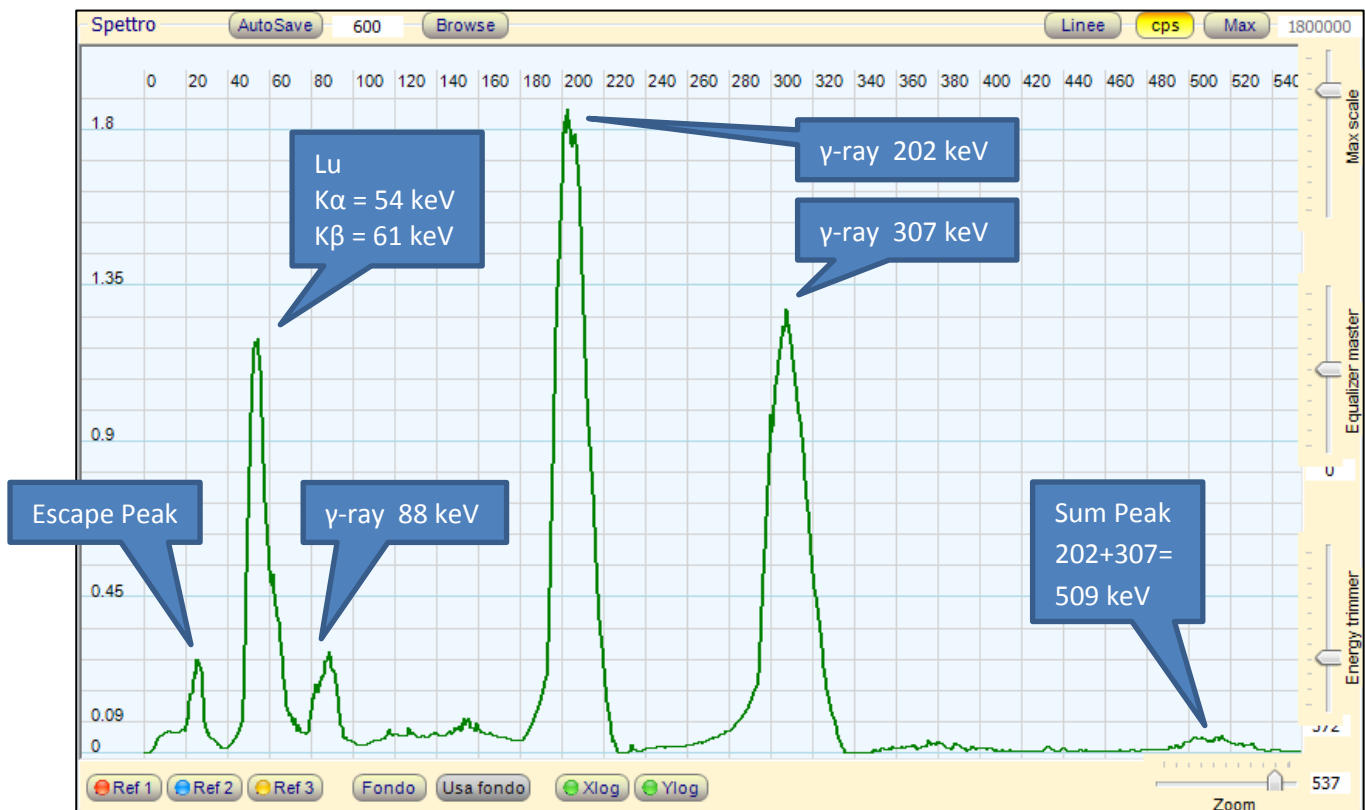


Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu - Lead Shielded Measure

Lutetium ¹⁷⁶Lu



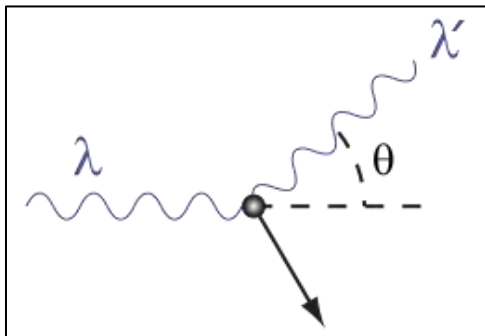
Lutetium occurs on the Earth in form of two isotopes: lutetium-175 and lutetium-176. Out of these two, only the former is stable, making the element monoisotopic. The latter one, lutetium-176, decays via beta decay with a half-life of 3.78×10^{10} years; it makes up about 2.5% of natural lutetium. In the image above the sample is shown with the decay chain of ¹⁷⁶Lu.



Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu - Lead Shielded Measure

Compton Scattering

Compton scattering is the inelastic scattering of a photon by a quasi-free charged particle, usually an electron. It results in a decrease in energy (increase in wavelength) of the photon (which may be an X-ray or gamma ray photon), called the **Compton effect**. Part of the energy of the photon is transferred to the recoiling electron.

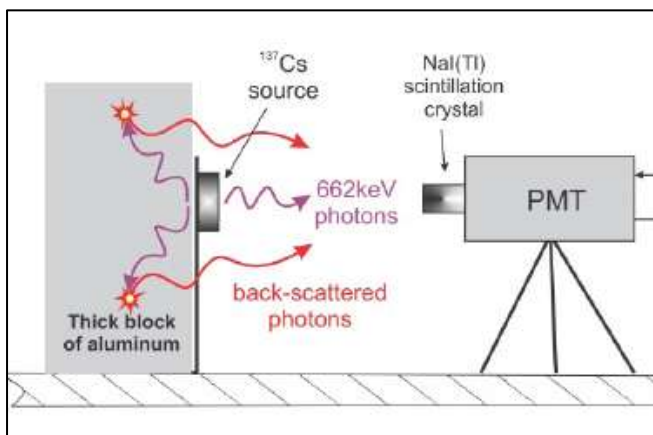


A photon of wavelength λ comes in from the left, collides with a target at rest, and a new photon of wavelength λ' emerges at an angle θ .

Because the mass-energy and momentum of a system must both be conserved, it is not generally possible for the electron simply to move in the direction of the incident photon. The interaction between electrons and high energy photons (comparable to the rest energy of the electron, 511 keV) results in the electron being given part of the energy (making it recoil), and a photon containing the remaining energy being emitted in

a **different direction** from the original, so that the overall momentum of the system is conserved.

The Compton effect could be seen in the gamma spectrum of cesium-137. Where it can be seen a Compton edge at about **490 keV**, a plateau and a Compton backscatter peak at about **170 keV**. The latter is due to the backscatter photons which are Compton scattered at an angle of 180° .

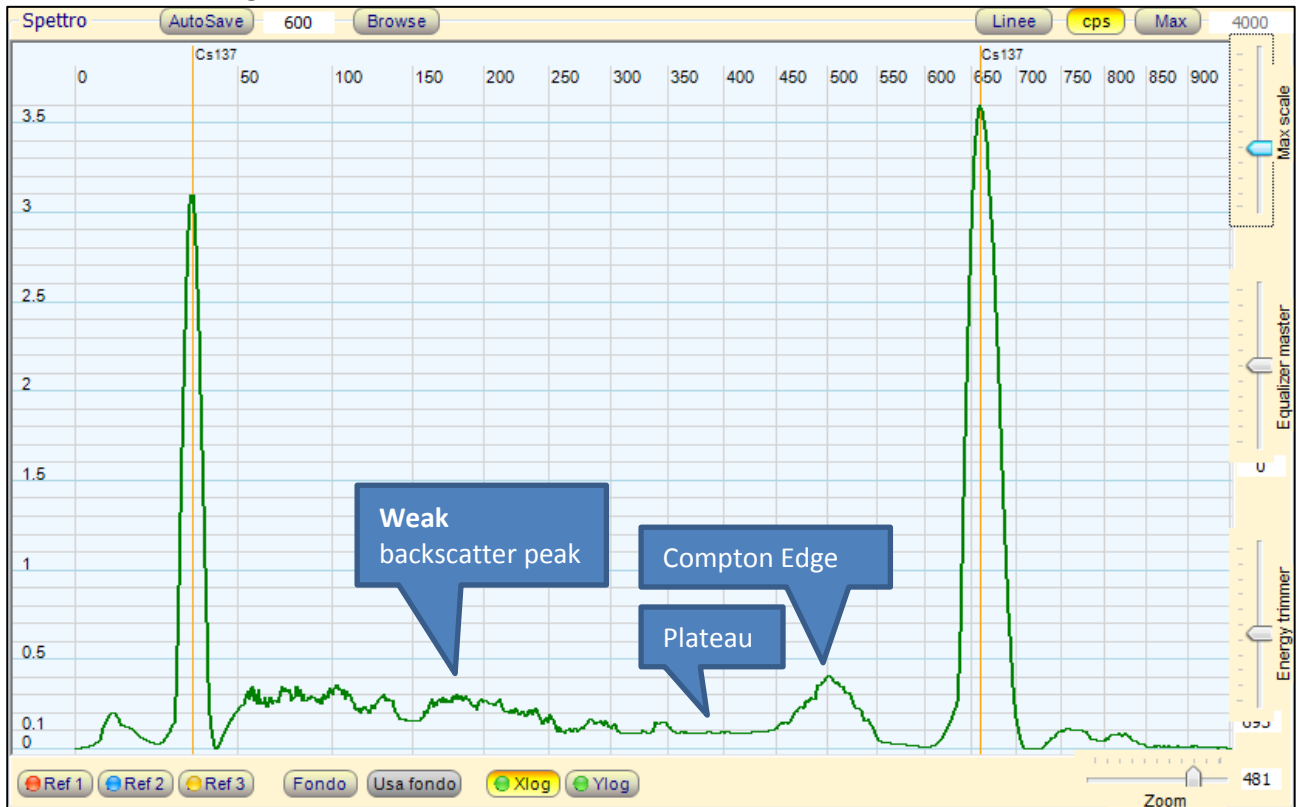


Putting a metal background behind the radioactive source it is as if it has been put a source of free electrons which can act as Compton scattering centers. So we expect an increase in the height of the backscatter peak when we put the metal background behind the cesium radioactive source.

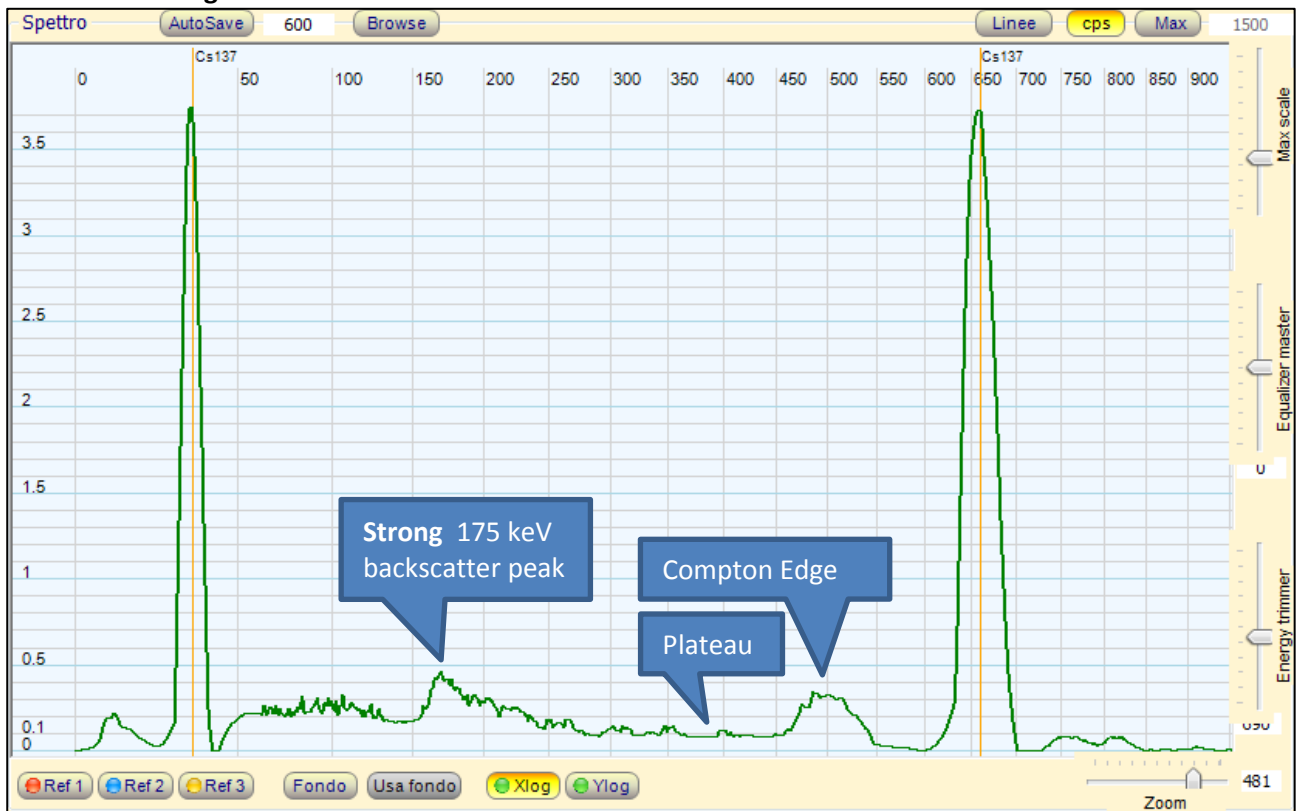


Experiment setup : the first measure is done without background, the second one is done with thick metal background

Without metal background



With metal background



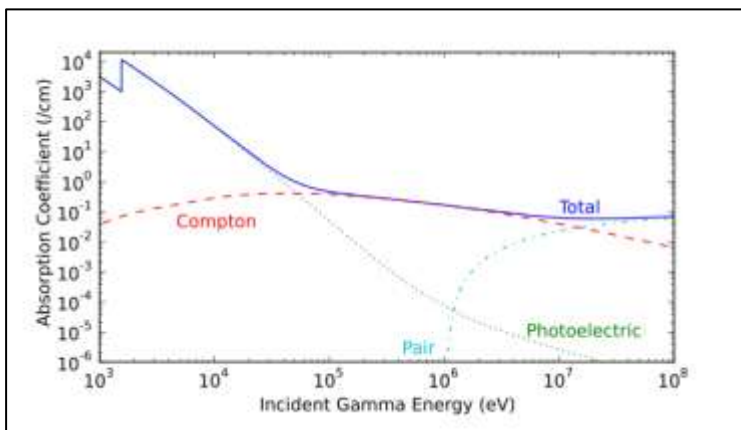
Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu

Gamma Radiation Absorption

When a gamma ray passes through matter, the probability for absorption is proportional to the **thickness** of the layer, the **density** of the material, and the **absorption cross section** of the material. The total absorption shows an exponential decrease of intensity with distance from the incident surface:

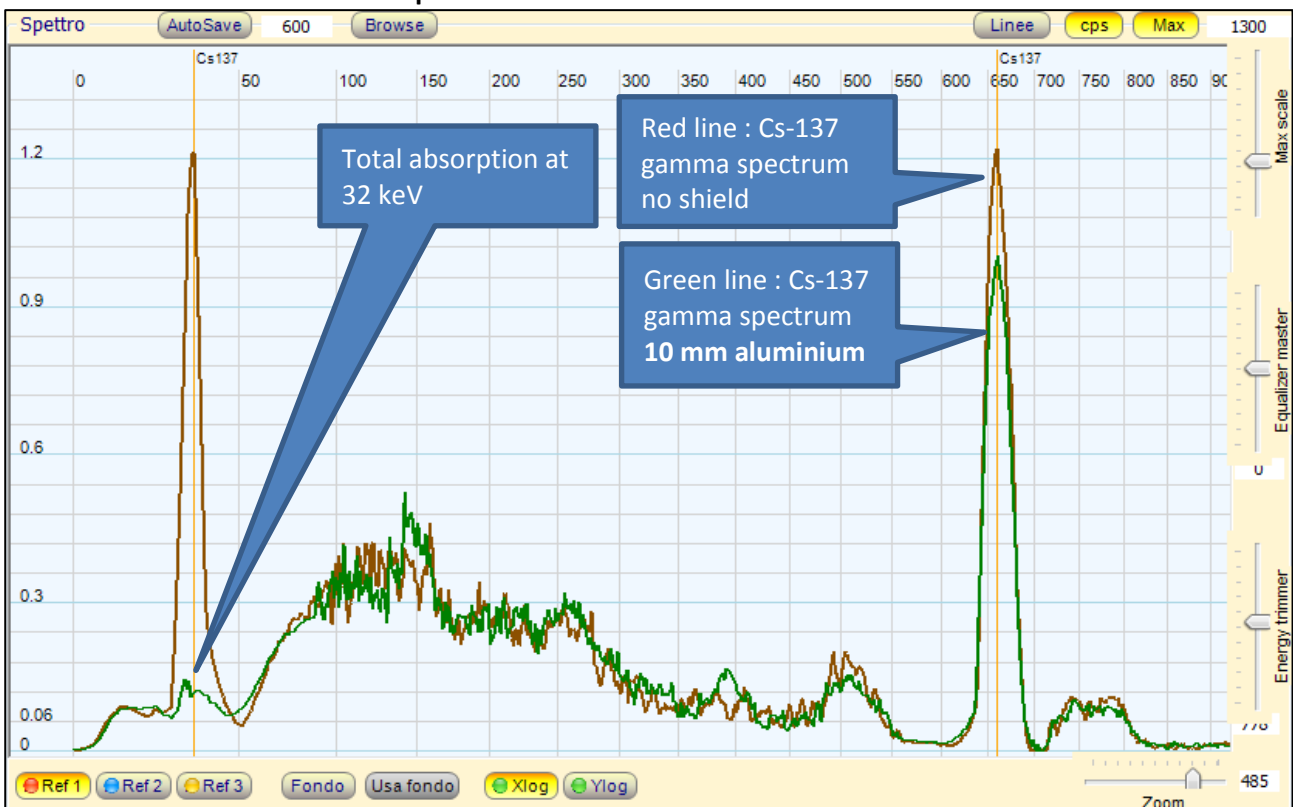
$$I(x) = I_0 \cdot e^{-\mu x}$$

where x is the distance from the incident surface, $\mu = n\sigma$ is the **absorption coefficient**, measured in cm^{-1} , n the number of atoms per cm^3 of the material (atomic density) and σ the absorption cross section in cm^2 . As it passes through matter, gamma radiation ionizes via three processes: the photoelectric effect, Compton scattering, and pair production.



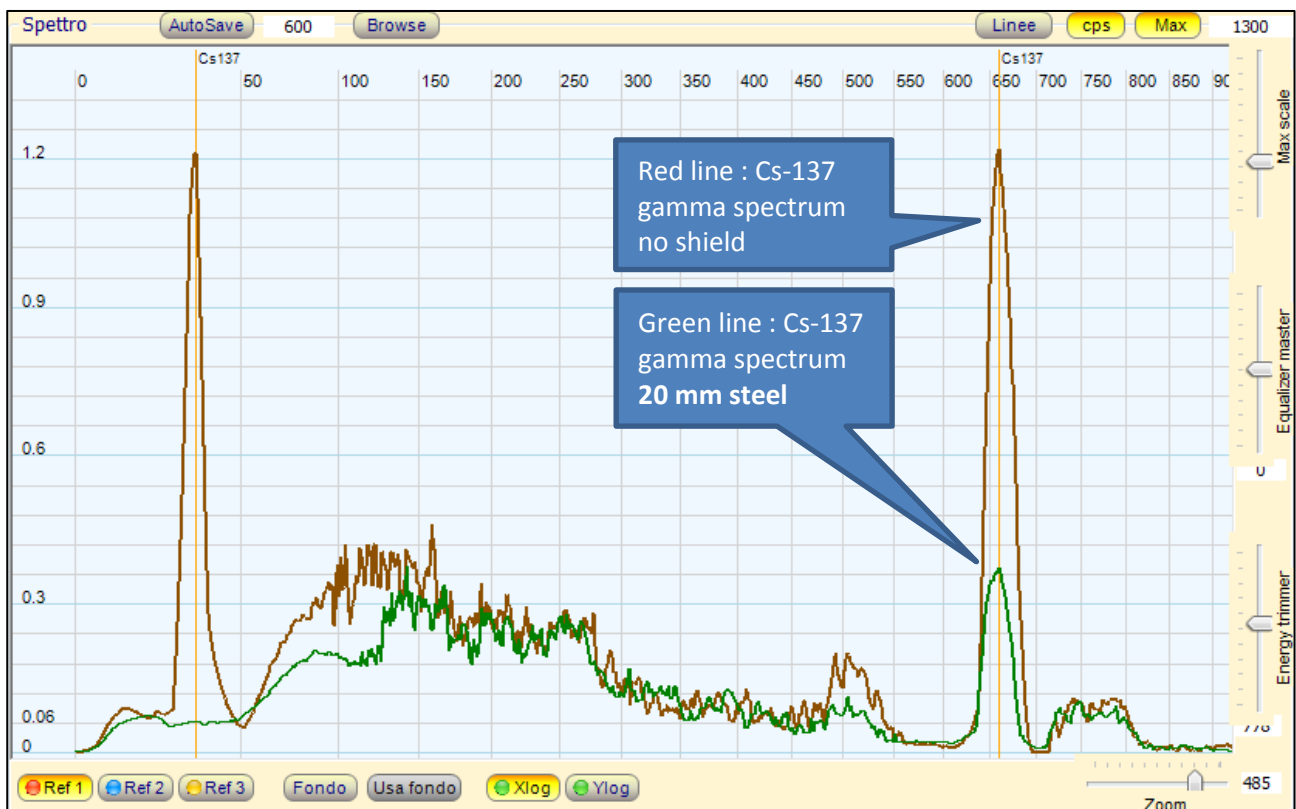
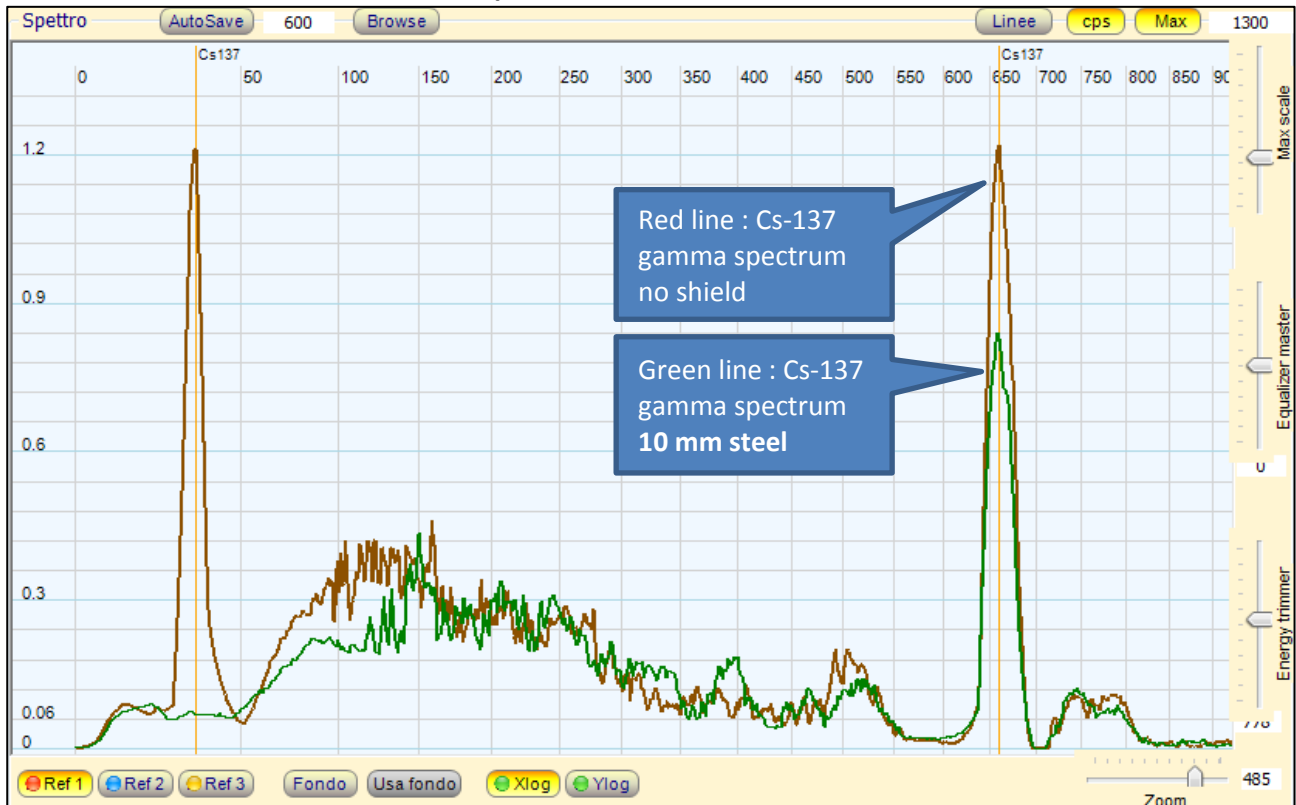
The total absorption coefficient of aluminium (atomic number 13) for gamma rays, plotted versus gamma energy, and the contributions by the three effects. As is usual, the photoelectric effect is largest at low energies, Compton scattering dominates at intermediate energies, and pair production dominates at high energies.

Aluminum 10 mm thickness absorption



Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu

Steel 10 mm and 20 mm thickness absorption

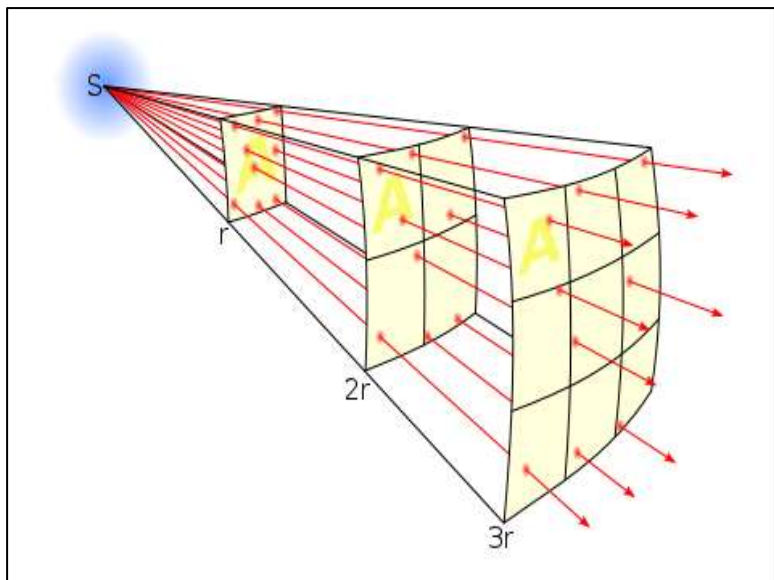


Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal - PMT R6095 Hamamatsu

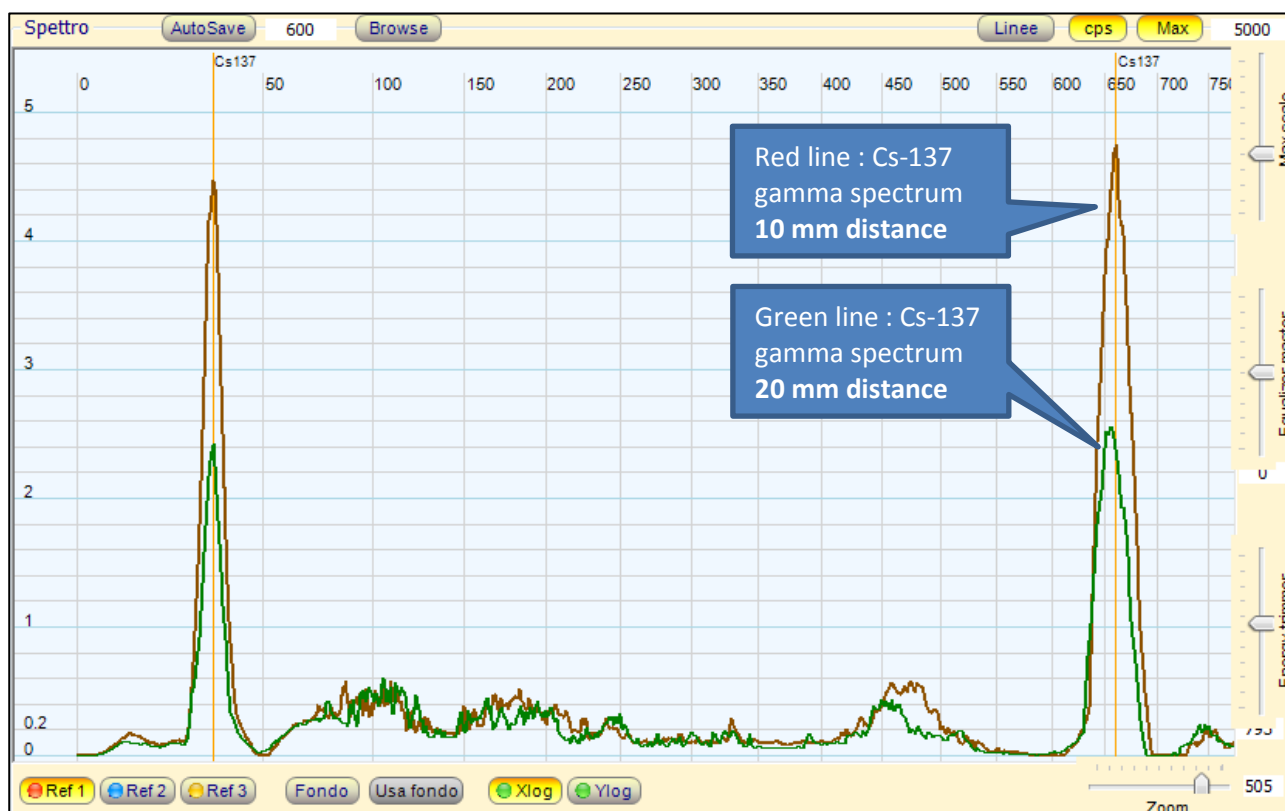
Analyzing the two gamma spectrum with 10 mm and 20 mm thick steel plate as a shield it is clear that the intensity reduction is not linear, an exponential law gives better fit.

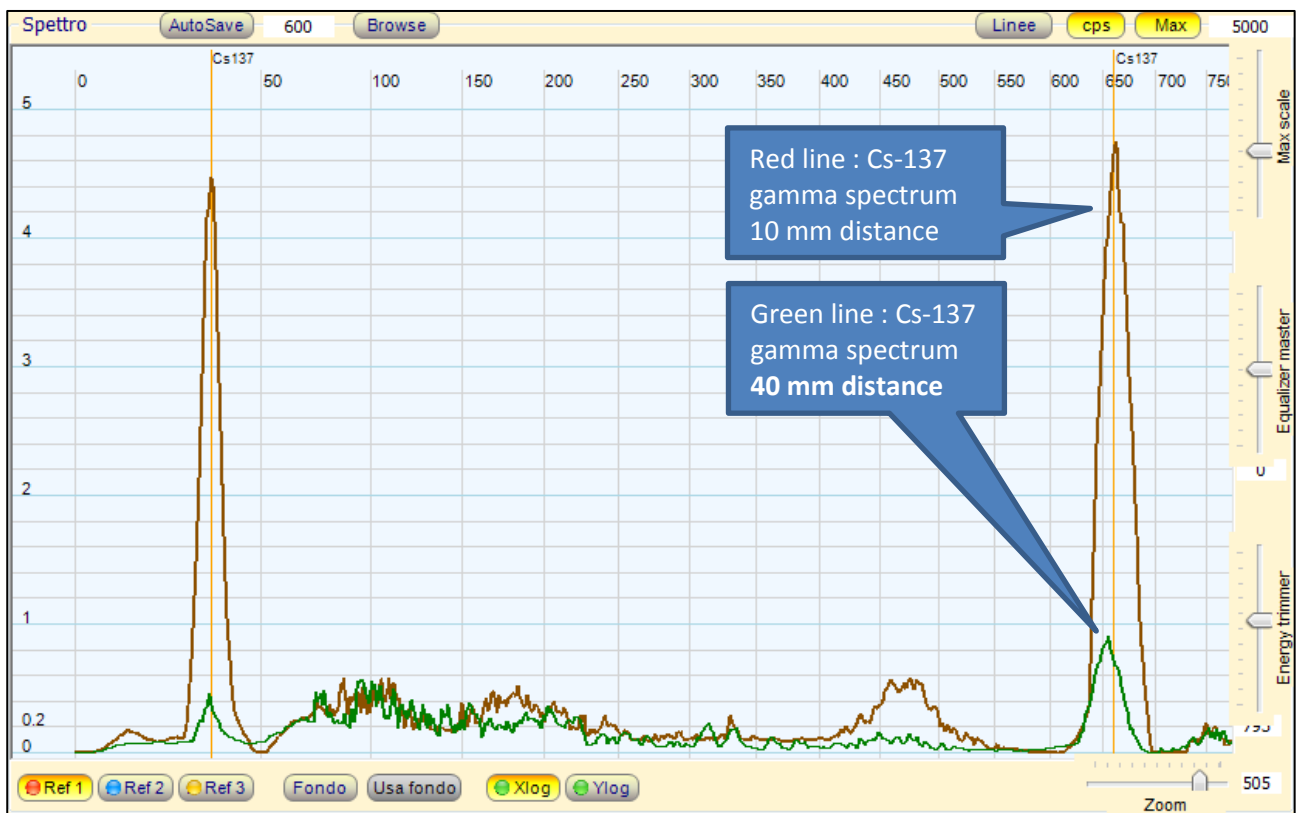
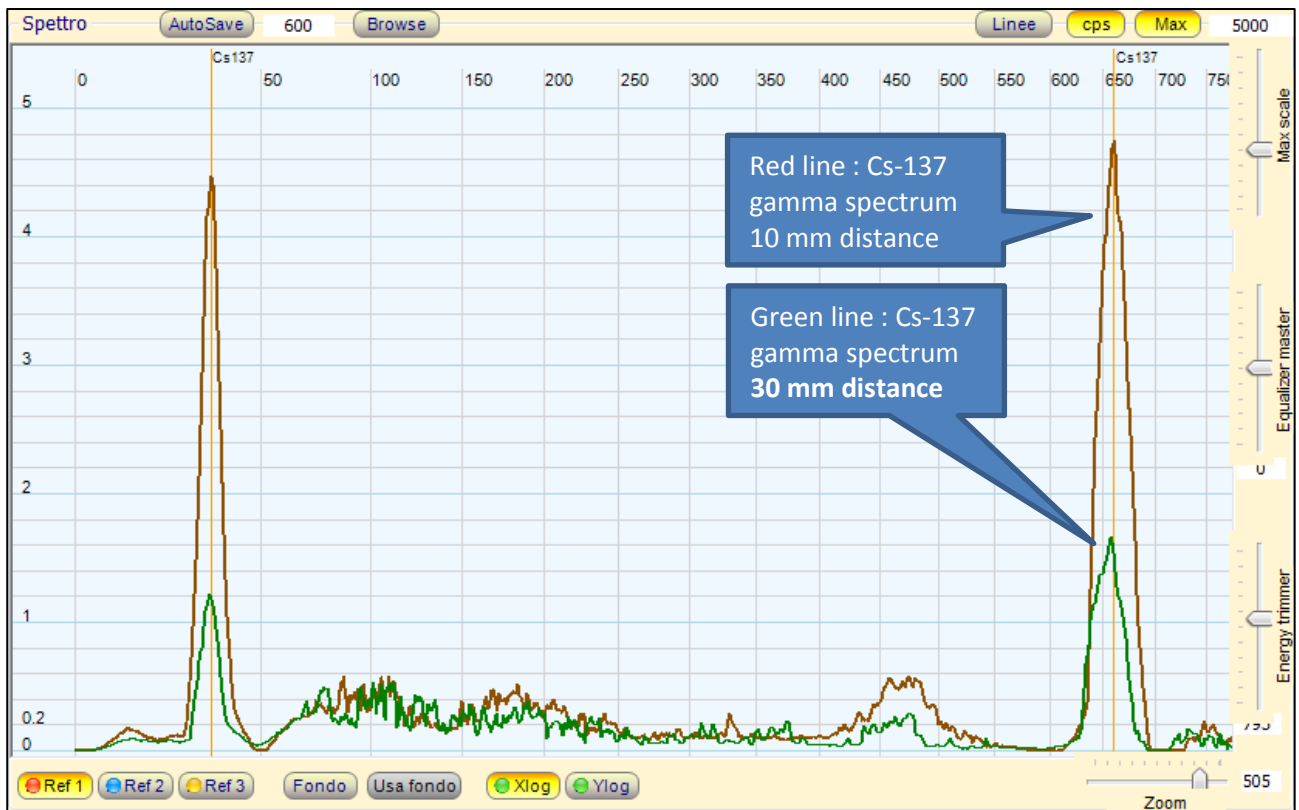
Inverse Square Law

The attenuation with a screen comes in addition to the **solid angle effect**, which is purely **geometrical** and states that the number of photons hitting a target in vacuum drops as the square of the distance to the source.



The inverse-square law generally applies when some force, energy, or other conserved quantity is evenly radiated outward from a **point source in three-dimensional space**. Since the surface area of a sphere (which is $4\pi r^2$) is proportional to the square of the radius, as the emitted radiation gets farther from the source, it is spread out over an area that is increasing in proportion to the square of the distance from the source. Hence, the intensity of radiation passing through any unit area (directly facing the point source) is inversely proportional to the square of the distance from the point source.





The inverse square law is respected only partially because the Cs-137 source is not a point source but it is rather a little surface. Thus the diminishing rate is not exactly proportionally to the square of the distance.

Energy Resolution

The absorption of the gamma ray inside the scintillation crystal and the production of photo-electrons inside the PMT are essentially random processes, thus the Poisson and Gaussian statistical distribution could be applied to explain the broadening of the lines.

The energy resolution is measured as the full width at half maximum (**FWHM**). To a first approximation the gamma ray line width (FWHM) is **2.35 σ** , where **σ** is the standard deviation of the Gaussian distribution related to the statistical fluctuations in the number of photo-electrons, **Ne**, that are collected from the photocathode of the phototube.

From the Gaussian distribution we have :

$$\sigma = \sqrt{Ne}$$

$$FWHM = 2.35 * \sqrt{Ne}$$

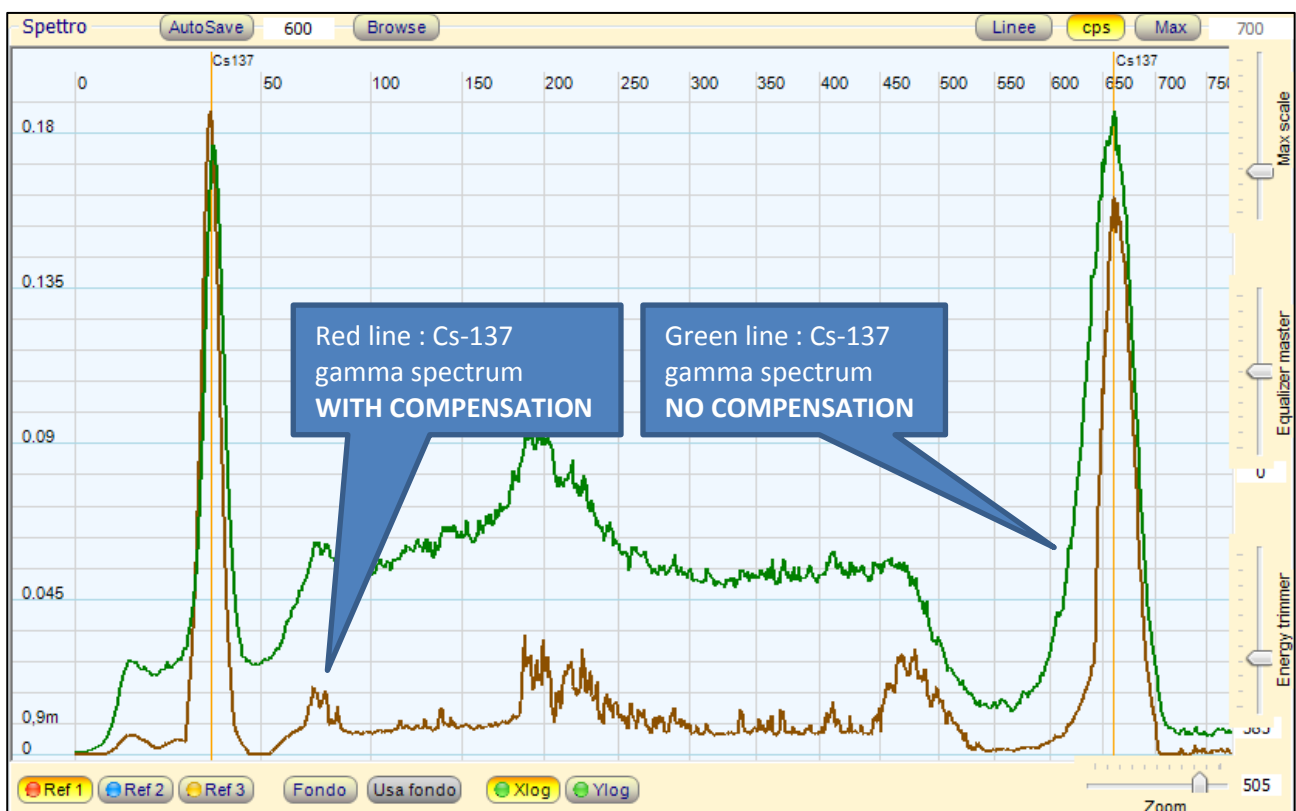
The number of photo-electrons **Ne** is proportional to the gamma energy: **E γ** , thus we can have for the resolution R

$$R = \frac{FWHM}{E_{\gamma}} = k \sqrt{E_{\gamma}} / E_{\gamma} = k / \sqrt{E_{\gamma}}$$

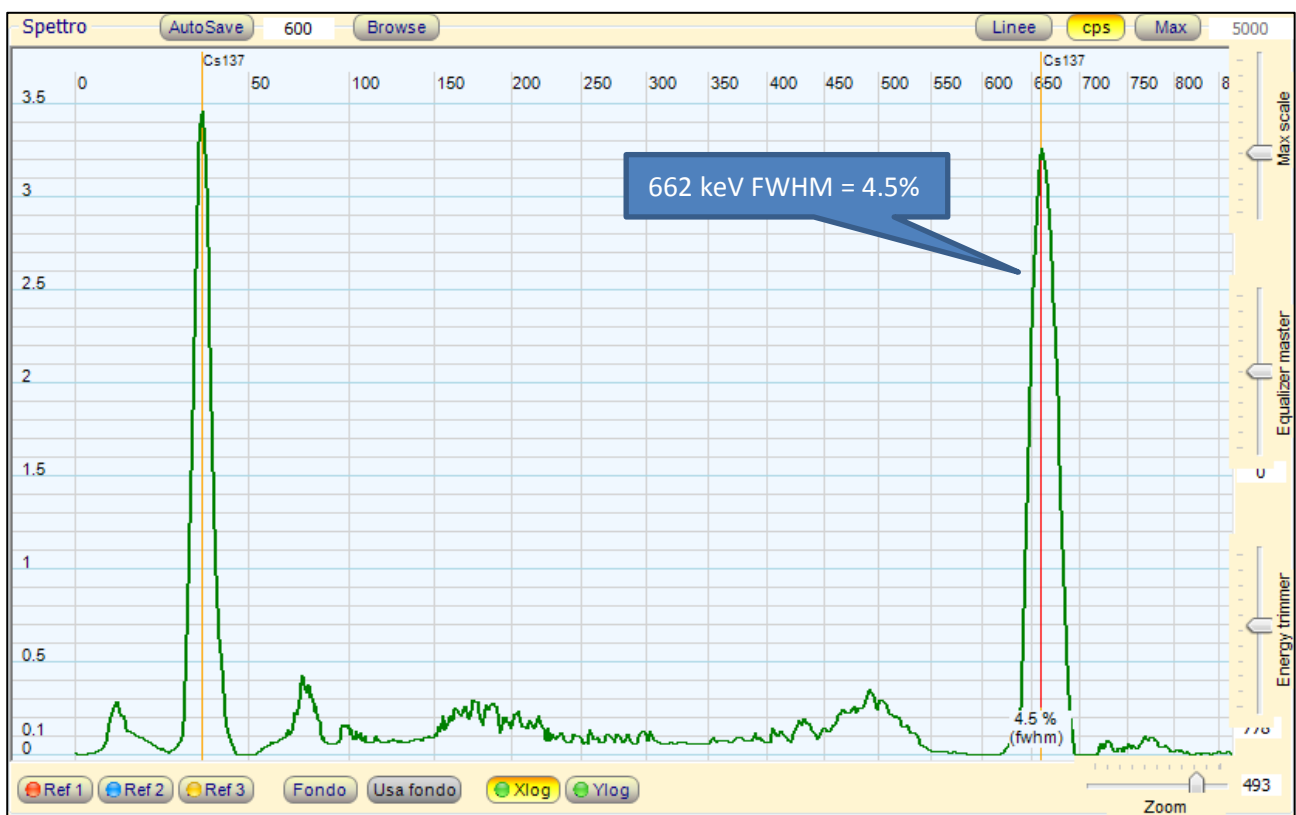
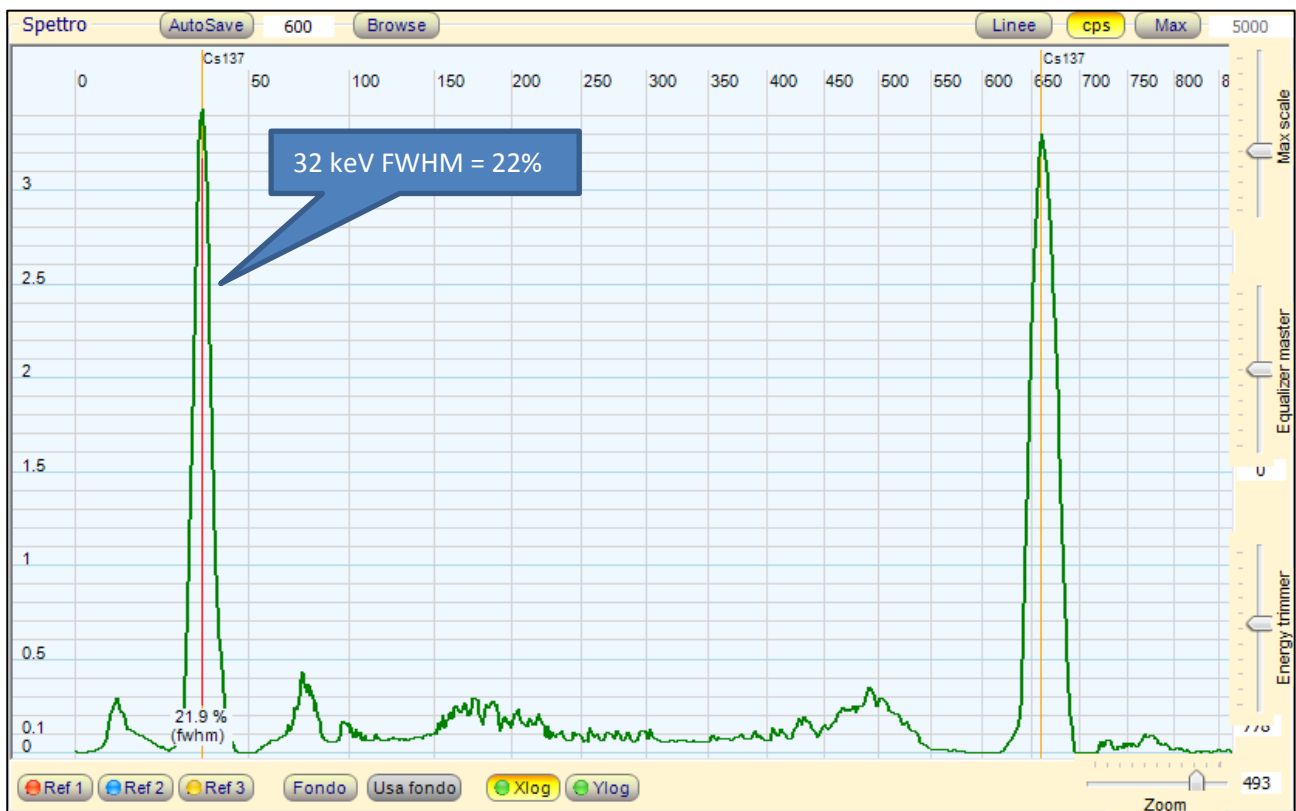
So the energy resolution should be inversely proportional to the square-root of the gamma ray energy.

The energy resolution improves as the gamma ray energy is increased.

For the NaI(Tl) scintillation crystals the energy resolution is about from 5% to 10% but could be improved with software algorithm which can partially compensate the crystal broadening.



Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu - Lead Shielded Measure

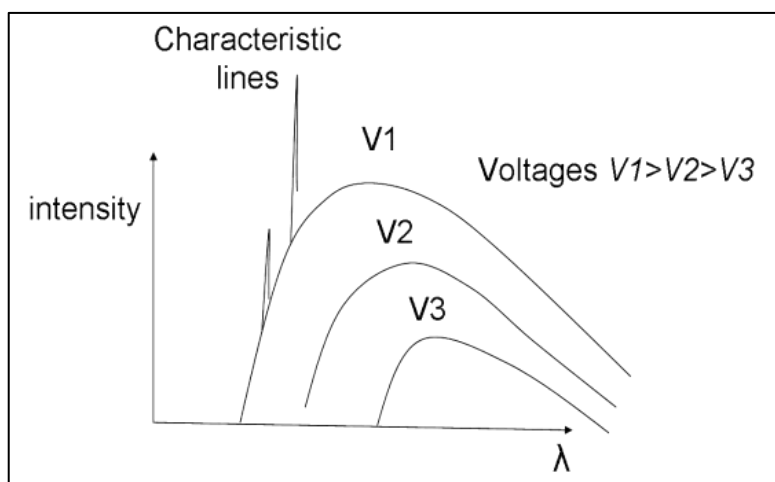


Scintillation Probe – NaI(Tl) 25.4 x 25.4mm crystal -PMT R6095 Hamamatsu - Lead Shielded Measure

X Ray Sources Spectrometry

Theory

An X-ray tube is a vacuum tube that produces X-rays. They are used in X-ray generators. X-rays are part of the electromagnetic spectrum, an ionizing radiation with wavelengths shorter than ultraviolet light. X-ray tubes evolved from experimental Crookes tubes with which X-rays were first discovered in the late 19th century, by Wilhelm Roentgen and the availability of this controllable source of X-rays created the field of radiography, the imaging of opaque objects with penetrating radiation. X-ray tubes are also used in CAT scanners, airport luggage scanners, X-ray crystallography, and for industrial inspection.



As with any vacuum tube, there is a cathode, which emits electrons into the vacuum and an anode to collect the electrons, thus establishing a flow of electrical current, known as the beam, through the tube. A high voltage power source, for example 30 to 150 kilovolts (kV), is connected across cathode and anode to accelerate the electrons. The X-ray spectrum depends on the anode material and the accelerating voltage.

In many applications, the current flow (typically in the range 1 mA to 1 A) is

able to be pulsed on for between about 1 ms to 1 s. This enables consistent doses of X-rays, and taking snapshots of motion. Until the late 1980s, X-ray generators were merely high-voltage, AC to DC variable power supplies. In the late 1980s a different method of control was emerging, called high speed switching. This followed the electronics technology of switching power supplies (aka switch mode power supply), and allowed for more accurate control of the X-ray unit, higher quality results, and reduced X-ray exposures.

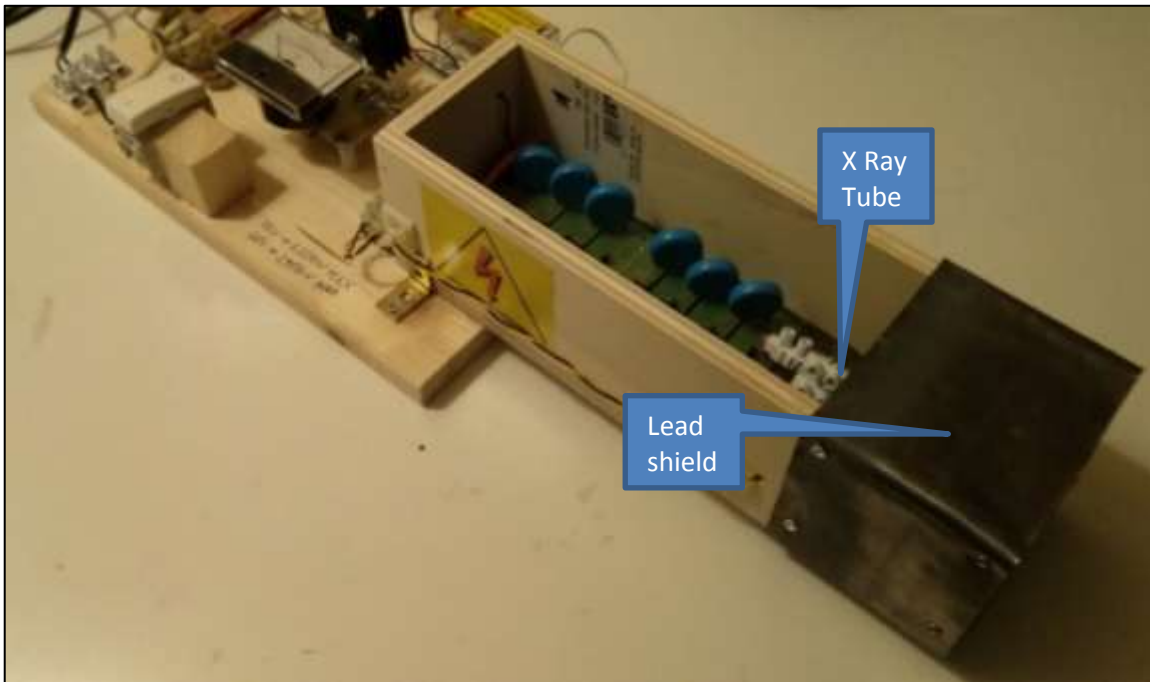
Electrons from the cathode collide with the anode material, usually tungsten, molybdenum or copper, and accelerate other electrons, ions and nuclei within the anode material. About 1% of the energy generated is emitted/radiated, usually perpendicular to the path of the electron beam, as X-rays. The rest of the energy is released as heat. Over time, tungsten will be deposited from the target onto the interior surface of the tube, including the glass surface. This will slowly darken the tube and was thought to degrade the quality of the X-ray beam, but research has suggested there is no effect.[5] Eventually, the tungsten deposit may become sufficiently conductive that at high enough voltages, arcing occurs. The arc will jump from the cathode to the tungsten deposit, and then to the anode. This arcing causes an effect called "crazing" on the interior glass of the X-ray window. As time goes on, the tube becomes unstable even at lower voltages, and must be replaced. At this point, the tube assembly (also called the "tube head") is removed from the X-ray system, and replaced with a new tube assembly. The old tube assembly is shipped to a company that reloads it with a new X-ray tube.

The X-ray photon-generating effect is generally called the Bremsstrahlung effect, a contraction of the German bremsen for braking, and strahlung for radiation.

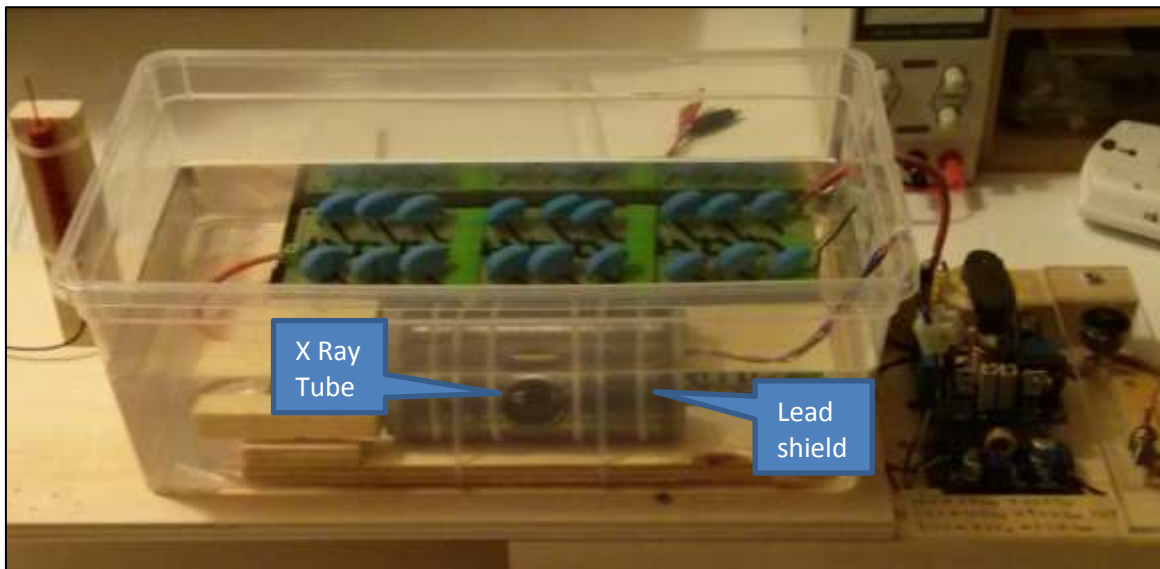
The range of photonic energies emitted by the system can be adjusted by changing the applied voltage, and installing aluminum filters of varying thicknesses. Aluminum filters are installed in the path of the X-ray beam to remove "soft" (non-penetrating) radiation. The number of emitted X-ray photons, or dose, are adjusted by controlling the current flow and exposure time.

Equipment

15 kV X Ray Generator

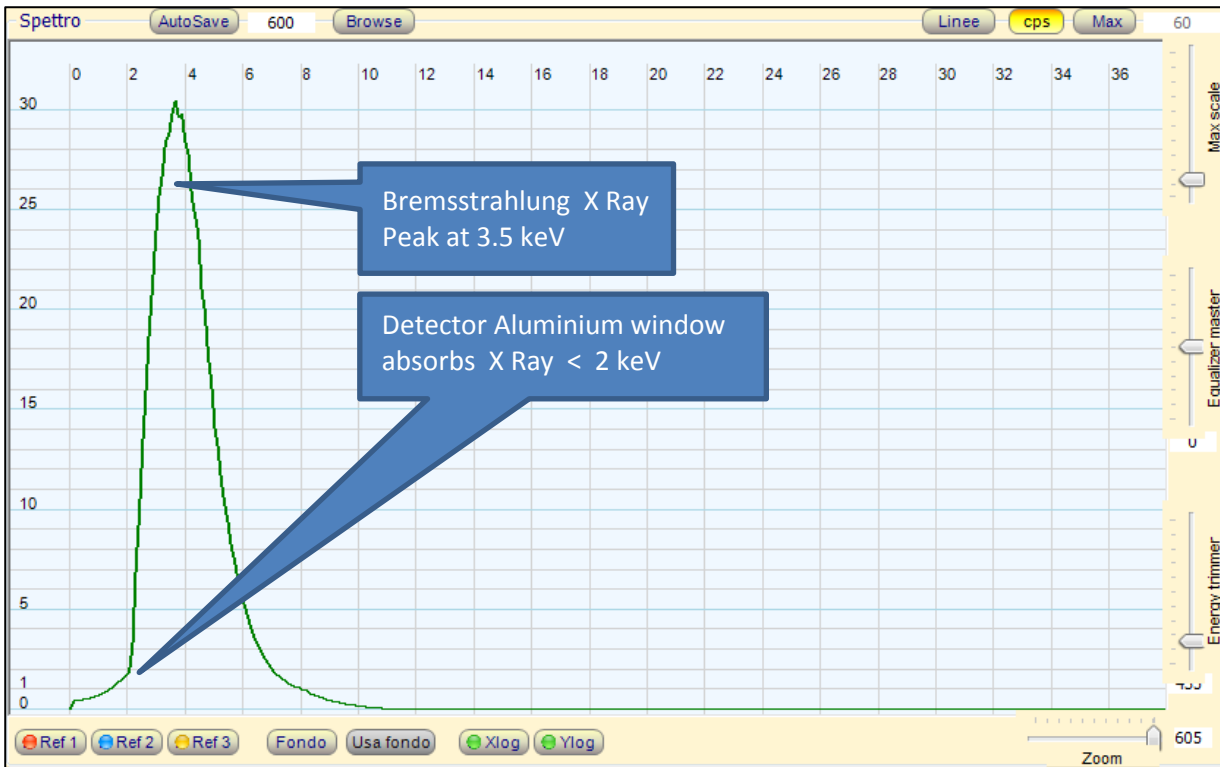


75 kV X Ray Generator

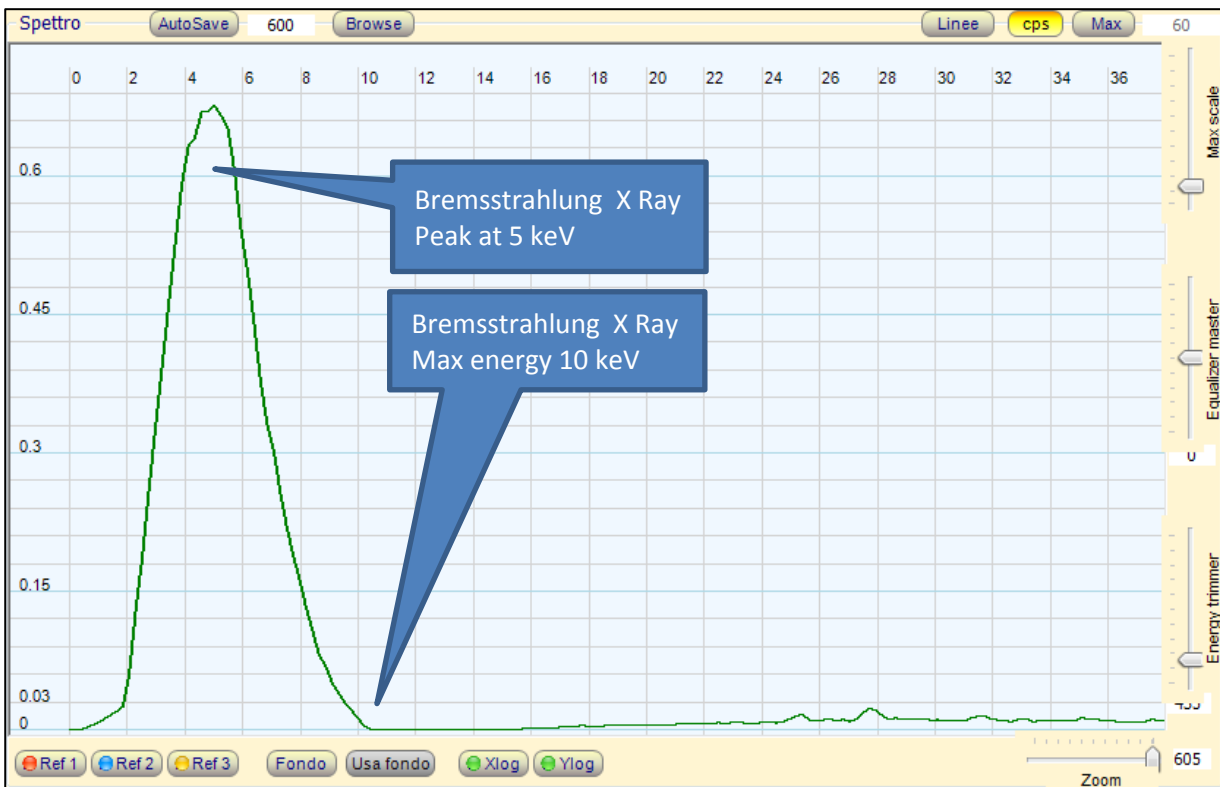


X Ray Source 15 kV (beryllium window – tungsten Cathode)

V ~ 10 kV



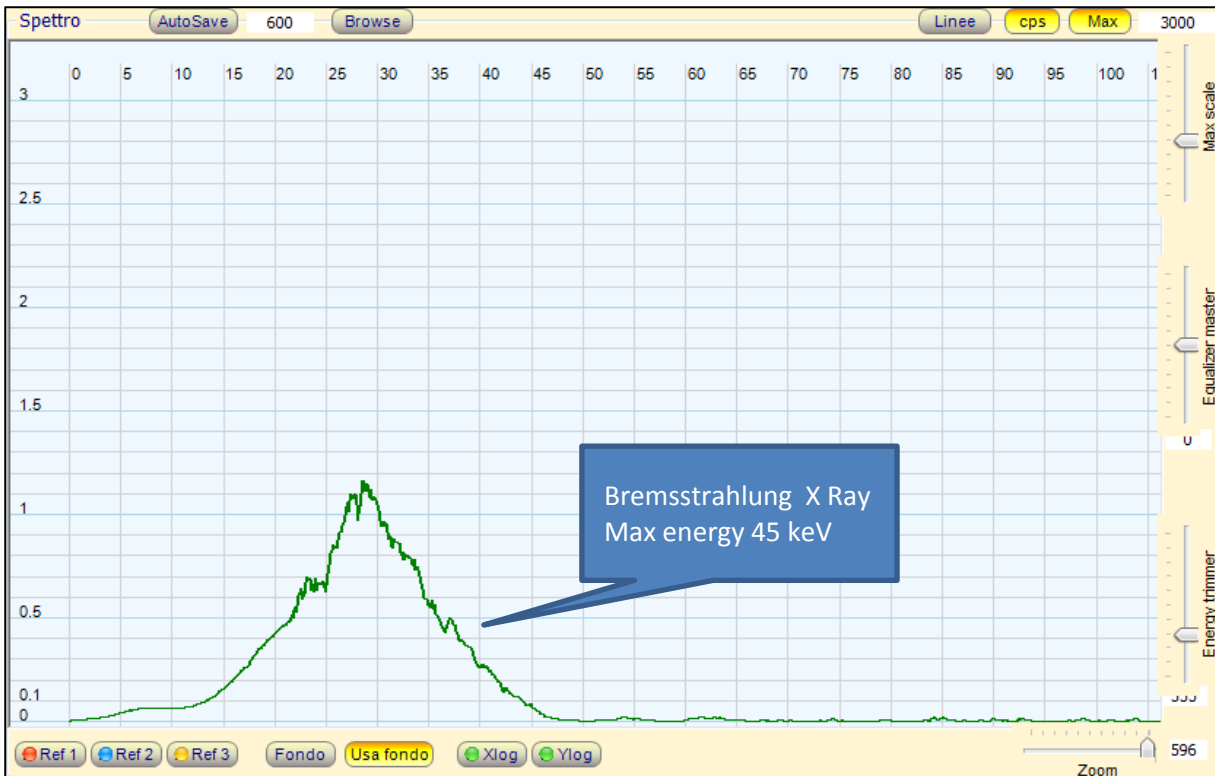
V ~ 15 kV



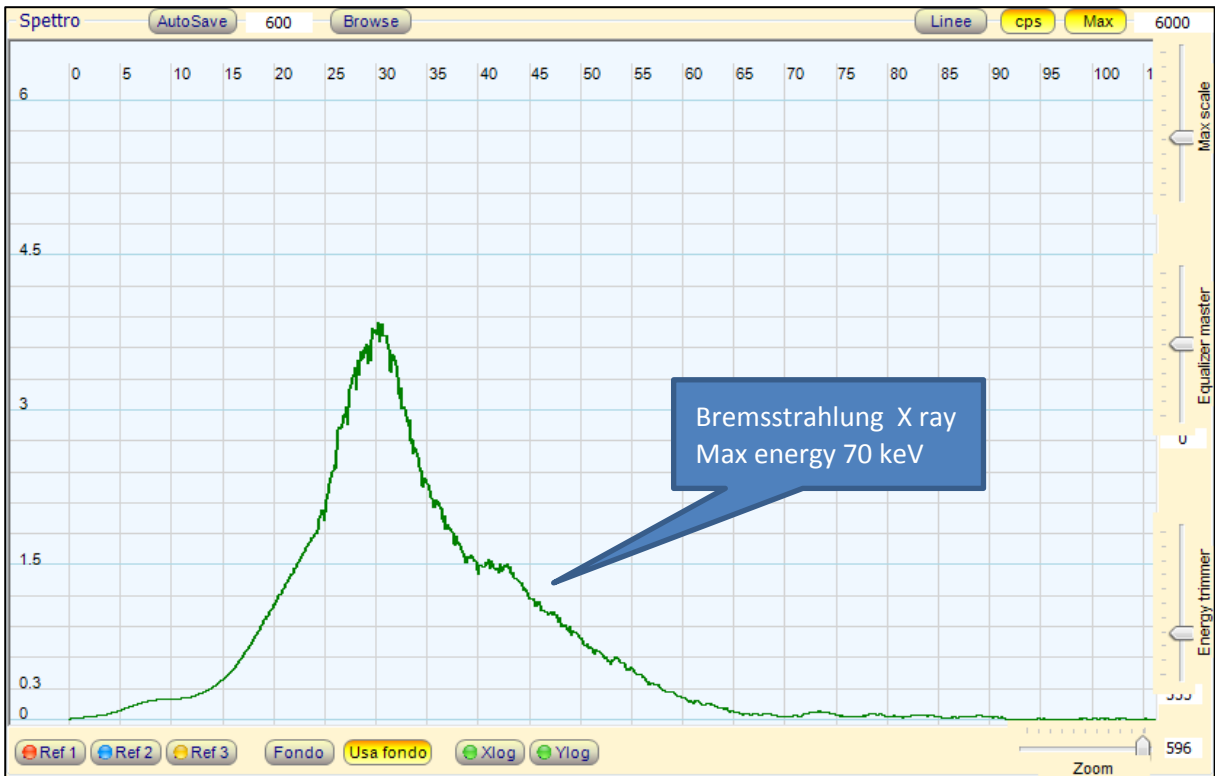
Rap47 Scintillation Probe – CsI(Tl) 25.4 x 1.0mm crystal

X Ray Source 75 kV (glass tube – tungsten Cathode)

V ~ 45 kV



V ~ 70 kV



Rap47 Scintillation Probe – CsI(Tl) 25.4 x 1.0mm crystal

V ~ 100 kV



Rap47 Scintillation Probe – CsI(Tl) 25.4 x 1.0mm crystal
Measure done with lead collimator to reduce the counting rate

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.

IMPORTANT NOTICE:

The only purpose of this paper is to illustrate, for educational purposes, the techniques of gamma spectrometry of Theremino’ device. The Theremino team disclaims any civil and criminal liability for improper use of the notions contained in this document, such as damage to property of any kind, injuries and poisoning of people and animals caused by electrical discharges and improper use of chemical and radioactive’ material; radioactive contamination of people and animals, places more or less extensive, public or private, any incident occurring in order to replicate any example reproduced or simply mentioned in this document; all the harmful consequences of any entity involving accidents with chemical, electrical and radioactive material.