

AM 36

The Atomic Nucleus

In this laboratory you will become familiar with the properties of the atomic nucleus, in particular the radioactive decay processes and the emitted radiations. You will also learn how to detect the radiation and how it is absorbed in matter.

Introduction

The atomic nucleus consists of Z positively charged protons and N electrically neutral neutrons held together by the so-called strong or nuclear force. The range of this force is limited to the size of the nucleus, which is few $\times 10^{-15}$ meters. This can be compared to the size of an atom, which is few $\times 10^{-10}$ meters. The number of protons, Z, is called the atomic number and determines the place of the chemical element in the periodic system. In a neutral atom the number of electrons orbiting the atomic nucleus is the same as the number of protons in the nucleus. The atomic mass of the nucleus, A, is equal to Z+N. For given chemical element with atomic number Z, there can exist nuclei differing by the number of neutrons N. These are called isotopes. For example natural silver, Z=47, consists of two stable isotopes, ^{107}Ag and ^{109}Ag . Since Z, and hence also the number of electrons is the same for all isotopes of a given chemical element, the chemical properties will be the same. At present there are 118 known chemical elements whose discoveries have been confirmed, ranging from hydrogen (Z=1) to the heaviest recently discovered Z=118 and temporarily called **Ununoctium**. The first 94 elements are found naturally on Earth, and the rest are synthetic elements that have been produced artificially in particle accelerators or nuclear reactors. Elements 43 (technetium), 61 (promethium) and all

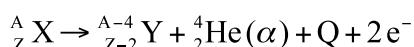
elements greater than 83 (Bismuth), beginning with 84 (Polonium) have no stable isotopes. Among the elements there are 255 stable and more than 3000 unstable isotopes. About 339 radioactive isotopes are known from nature i.e. they have been observed on Earth, and not as a consequence of man-made activities. Only few of the unstable isotopes are characterized by very long decay time (half life of order of 10^{9-10} years) and thus belong to the natural radioactivity on the earth. Most of the man-made radioactive isotopes are produced through nuclear reactions with a help of either particle accelerators or nuclear reactors.

The radioactive decay takes place through alpha (α), beta (β^- or β^+) decays or spontaneous fission. In most cases these processes are followed by emission of gamma rays.

Alpha decay

The alpha decay is due to emission of an α -particle, which is a stable entity identical to a helium nucleus - ${}^4\text{He}$. Alpha particles consist of two protons and two neutrons. Their rest mass is 4.0026 amu and their charge is +2 units. Because of their mass and charge, alpha particles are an intensely ionizing form of radiation and create serious radiation health hazards if inhaled or digested. Otherwise, alpha particles have low penetrating abilities and can thus easily be stopped by a sheet of paper. Alpha particles are emitted with discrete values of energy normally between 4 and 8 MeV. Alpha energies are characteristic of the nuclide which emits them.

Approximately 175 radionuclides have been identified which decay by alpha emission. Some common alpha emitters include ${}^{222}\text{Rn}$, ${}^{226}\text{Ra}$, ${}^{238}\text{U}$, ${}^{239}\text{Pu}$, and ${}^{241}\text{Am}$. Generally, atoms with large mass ($Z >> 82$) are capable of ejecting an alpha particle. In alpha decay, an atom with atomic number Z and mass number A produces a daughter product with an atomic number $Z-2$ and a mass number of $A-4$. In general form, this can be expressed as:

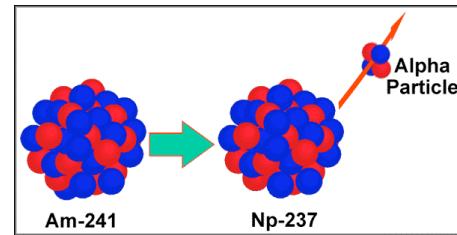
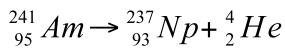
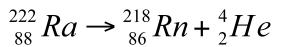


where :

X = the chemical symbol for the parent radionuclide

Y = the chemical symbol for the daughter nuclide.

All alpha emissions follow this general form. A specific examples are:



The alpha particle may carry all of the decay energy between the parent and the daughter or the daughter may be left in an excited state. If an excited state remains it subsequently will de-excite, normally by gamma emission. Figure 1 shows an example of an alpha decay

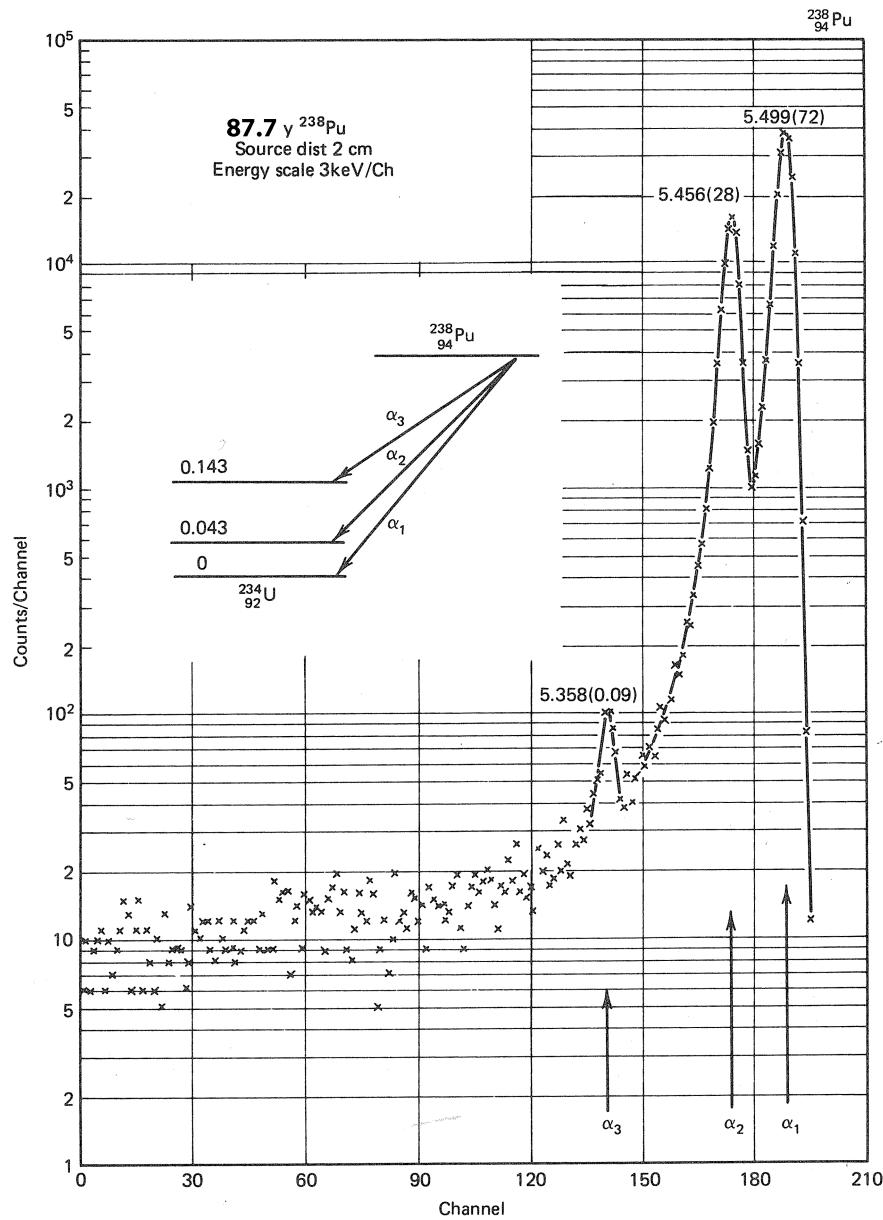
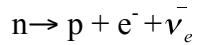


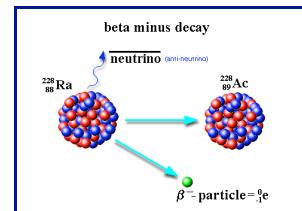
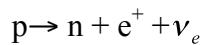
Figure 1: Alpha particle groups produced in the decay of ^{238}Pu . The spectrum shows the three groups as measured by a charged particle detector (silicon detector). Each peak is identified by its energy in MeV and percent abundance (in parentheses). The insert shows the decay scheme.

Beta decay

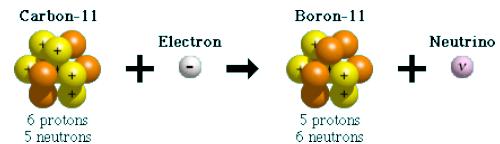
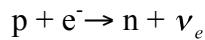
There are two kinds of β decays, β^- and β^+ . Beta particles are negatively or positively charged electrons emitted by the nucleus. The latter is called positron, an anti-particle of the electron. The β^- - and β^+ - particles are emitted in processes:



and



This implies a transformation from an element Z to Z+1 or Z-1 with an unchanged mass number A for β^- and β^+ , respectively. The ν_e and $\bar{\nu}_e$ are neutrino and anti-neutrino, two very weakly interacting and thus hardly detectable particles. A process competing with the β^+ -decay is *electron capture*, which is capture of an orbiting electron by the atomic nucleus:



The electron capture is mostly due to the K-shell electrons, i.e. electrons from the orbit closest the atomic nucleus.

Energy distribution of β -particles from radioactive decay is continuous up to the maximum energy (endpoint energy). This is because the energy is shared between the emitted β -particles and neutrinos. Thus no discrete energies are observed, as is the case with α - and γ -spectra. The β -decay may take place either to the ground state (see *Figure 2*)

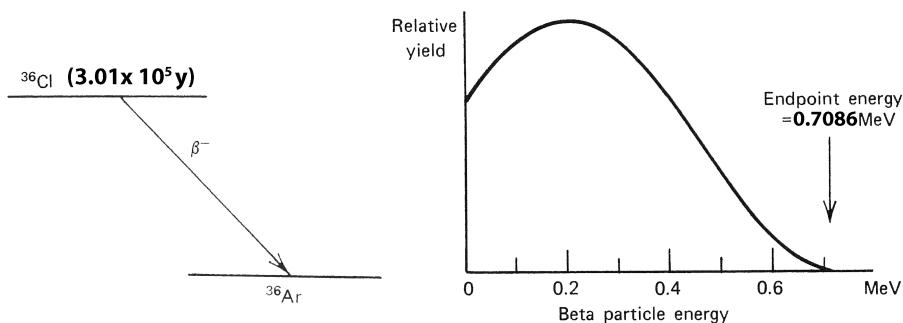


Figure 2: The decay scheme of ^{36}Cl and the resulting beta particle energy distribution

or to the excited state of the atomic nucleus (*Figure 3*). In the latter case the transition to the ground state is followed by emission of γ -rays.

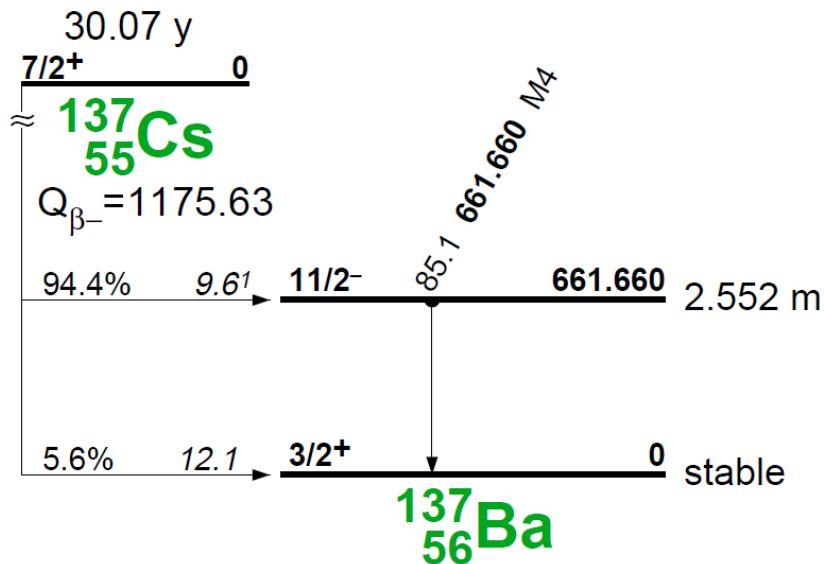


Figure 3: Beta decay of ^{137}Cs followed by gamma decay. Most of the β -decay goes to the first excited state in ^{137}Ba .

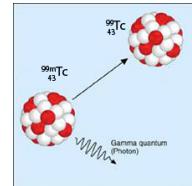
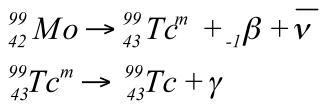
An indication of the β^+ -decay is presence of 0.511 MeV photons in the γ -spectrum. This is due to the $e^+ + e^-$ annihilation process, where the positively charged positrons react with the electrons in the encapsulation material around the radioactive source. The process results in emission of two oppositely directed 0.511 MeV γ -photons, called *annihilation radiation*.

Gamma radiation

Gamma rays are electromagnetic radiation of the same type as for example light, but with much shorter wavelength, which means much higher photon energy. The energies can extend from few up to almost 3000 keV. Gamma emission originates from de-excitation of the nuclei and normally follows immediately the emission of the appropriate radioactive particle, α , β^- or β^+ . However, some nuclei exist in an excited state long enough to be independently identified as a unique energy level. The state of the atoms which can be independently identified in this way is called a “metastable state”.

The metastable state of a ground state nuclide is called an isomer of that nuclide. The de-excitation of an isomer by gamma emission is called an “isomeric transition”. Isomeric transition is often abbreviated IT in nuclear data references.

A specific example of a radioactive decay process involving isomeric transition is:



An alternative to the gamma emission is the *electron conversion process*. Here the nuclear excitation energy E_{ex} is transferred to one of the orbital electrons. Then the electron appears with energy

$$E_e = E_{ex} - E_b$$

where E_b is the electrons binding energy in the atomic shell.

In the process mostly K-shell electrons are involved. However, even conversion to L- and M-shell electrons may occur, but with lower probability. Conversion electrons are the only practical laboratory-scale source of monoenergetic electrons in the high keV up to MeV range.

Dosimetry

Activity of radioactive sources is measured in becquerels (Bq), 1 Bq=1 decay/sec. The absorbed doses are expressed as absorbed radiation energy per mass. The SI unit is gray, 1 Gy=1 J/kg. In order to estimate the biological effect of the radiation, the absorbed dose D has to be multiplied by quality factor Q for different type of radiations. This is so called dose equivalent, $H=DQ$ expressed in sieverts (Sv). The quality factor Q strongly depends on the type of radiation, $Q=1$ for γ -rays, for beta $Q=1-2$ and $Q=20$ for α -radiation. Thus for example for γ -rays 1 Sv=1 Gy. To give some examples, the natural background radiation gives an accumulated dose of roughly 3-4 mSv/year, while the dose from Computed Tomography (CT) or X-ray examinations varies from 0.005 mSv/dental X ray to max of 30 mSv/CT examination.

The activities of the radioactive sources used at the laboratory are of about 400 kBq and during the lab exercises they contribute minimally to the natural dose.

1. Interaction of electron and gamma radiation with matter

For the absorption of the emitted radiation the interaction processes with the matter are of essential importance. This is also valid for the operation of any kind of radiation detector.

1.1 Interaction of electrons

Fast electrons lose their energies in the absorber through the interaction with the orbital electrons, but even electron-nuclear interaction may occur. All this makes that the path of the electrons will follow a very complicated pattern. The interaction processes may be divided in two main categories, namely collisional losses and radiative processes. The former is due to ionisation and excitation. The specific energy loss for these processes follows a very complex expression (Bethe formula). In short, it depends on the energy of the electrons, but also strongly on N_d and Z , atomic density and atomic numbers of the absorber. The atomic density is defined as $N_d = N_A \rho/A$, where N_A is Avogadro's number, ρ is the mass density and A the atomic mass. For low electron energies the energy loss can roughly be approximated as:

$$-\left(\frac{dE}{dx}\right)_c \sim \frac{N_d Z}{m_0 v^2} \left(\ln \frac{m_0 v^2 E}{2I^2} - 1 \right) + \text{constant}$$

where I represents the absorbers average excitation and ionization potential.

Electrons may also lose their energy due to radiative processes as well as by coulomb interactions. The radiative effect takes form of *bremsstrahlung* or electromagnetic radiation. The energy loss through the radiative processes depends very strongly on the energy of the particles, but also on N_d and Z of the absorber and can be roughly expressed as:

$$-\left(\frac{dE}{dx}\right)_r \sim NEZ(Z+1) \left(\ln \frac{2E}{0.511} - \frac{1}{3} \right) + \text{constant}$$

The electron energies of interest here are below 1 MeV and thus this effect only gives a small fraction to the total energy losses, otherwise dominated by the collisional processes. However, it is significant for absorbers with high atomic number. Let us consider a monoenergetic electron beam penetrating an absorber. The electrons will thus undergo a large number of collisions and this scattering process will result in a highly divergent beam. The electron total path length will thus be considerably greater than the distance of

penetration along the beam direction. Therefore in this case the concept of particle range is less definite.

1.2 Gamma radiation

The intensity of a monoenergetic gamma beam varies with the thickness d of the absorber as:

$$I = I_0 e^{-\mu d}$$

where μ is the total linear attenuation coefficient.

For gamma rays three interaction mechanisms play an important role in the absorption process and thus in the radiation measurements, namely *photoelectric absorption*, *Compton scattering* and *pair production*. Thus the coefficient μ will be a sum of components for all interactions. *Figure 4* shows the μ coefficient versus gamma energy for NaI scintillator (detector material used at the laboratory), lead – Pb – material used frequently for shielding and plastic scintillator (detector material used at the laboratory)

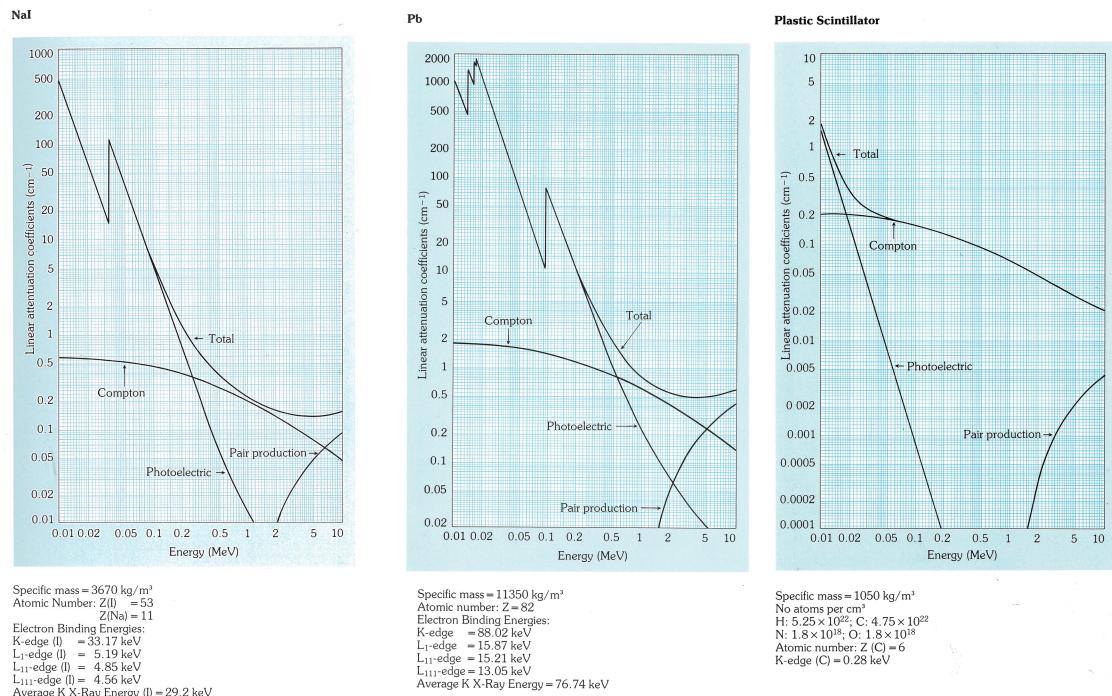


Figure 4: Linear attenuation coefficient μ versus gamma energy for NaI scintillator, Pb and plastic scintillator

Photoelectric absorption

In this process the energy of the gamma photon is transferred to an orbital electron of the absorber. The energy of the photoelectron appears as:

$$E_e = h\nu - E_b$$

where E_b is electrons binding energy.

This interaction creates a vacancy in the atomic shell and when this vacancy is filled, X-rays are generated. The probability for the photoelectric process can be roughly expressed as:

$$\mu_{ph} \sim \frac{Z^n}{E_\gamma^{3.5}}$$

where n varies between 4 and 5.

As can be seen from the expression above the process is enhanced for absorbers with high atomic number.

Compton scattering

In the Compton scattering the incoming gamma-ray photon is scattered against an electron through an angle θ with respect to the original direction (*Figure 5*). A portion of the photon energy is transferred to the electron and since all angles of scattering are possible, the transferred energy can vary from zero to a large fraction of the initial photon energy. The energy of the scattered photon and the recoil electron are given by:

$$h\nu' = \frac{h\nu}{1 + \frac{h\nu(1 - \cos\theta)}{0.511}} \quad \text{in MeV}$$

and $E_e = h\nu - h\nu'$.

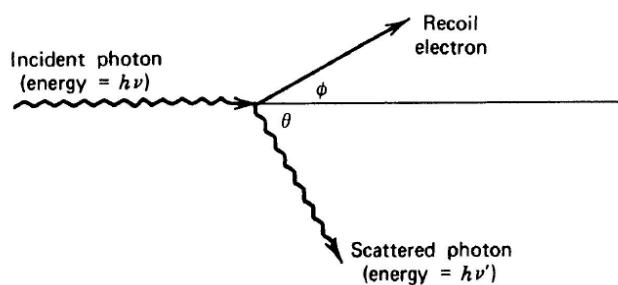


Figure 5: Compton scattering.

The probability of the Compton scattering increases linearly with the atomic number Z, i.e.

$$\mu_{Compton} \sim Z$$

but also shows an energy dependence, in form of a gradual decrease with increasing energy.

Pair production

This process is energetically possible first when the gamma-ray energy exceeds 1.02 MeV, which is the energy threshold for creation of an electron-positron pair ($e^+ - e^-$). The positron annihilates with another electron by emission of two photons with energy 0.511 MeV. The pair production is of importance first at photon energies of several MeV, which is much above the energy region of present interest.

2. Radiation detectors

The detection processes utilize the interaction effects described above. These effects result in generation of energetic electrons.

2.1 Gaseous detectors

The simplest construction is a gas-filled chamber with a wire in the central position. An electrical field is applied across the chamber. The electrons originating from the interaction processes along its track ionize the gas molecules. The total charge collected at the wire will give rise to an electric pulse. At increased electrical field a secondary ionisation occurs and the counter will work as electron multiplier, giving much larger pulses. By further increase of the electrical field the Geiger-Müller region is reached, where the pulse height is independent on the radiation energy deposited in the counter. In short, the G-M counter gives no information on the incoming radiation, except for the fact of existence of radiation. Therefore these counters are used mostly as radiation survey monitors. However, the choice of the entrance window material and the thickness of the may be decisive for the kind of radiation detected by the counter.

2.2 Scintillation counters

Scintillators are among the most widely used radiation detectors. The basic phenomenon is that in the crystal the radiation absorption is followed by light emission. The light is detected by a photo-counter attached to the scintillator, which transfers the scintillation light into electrical pulses. As was mentioned previously, interaction of gamma rays or charged particles with the detector material generates electrons. In a scintillator these electrons excite the crystal structure and the de-excitation is followed by light emission. There are a large number of scintillator materials, both organic and inorganic, with a variety of properties, different light output, wavelength region of the emitted light and speed of the response, etc. In the present set-up for gamma detection NaI(Tl) and plastic for electrons are used. The crystals are attached to a photomultiplier (PM-tube), see Figure 6.

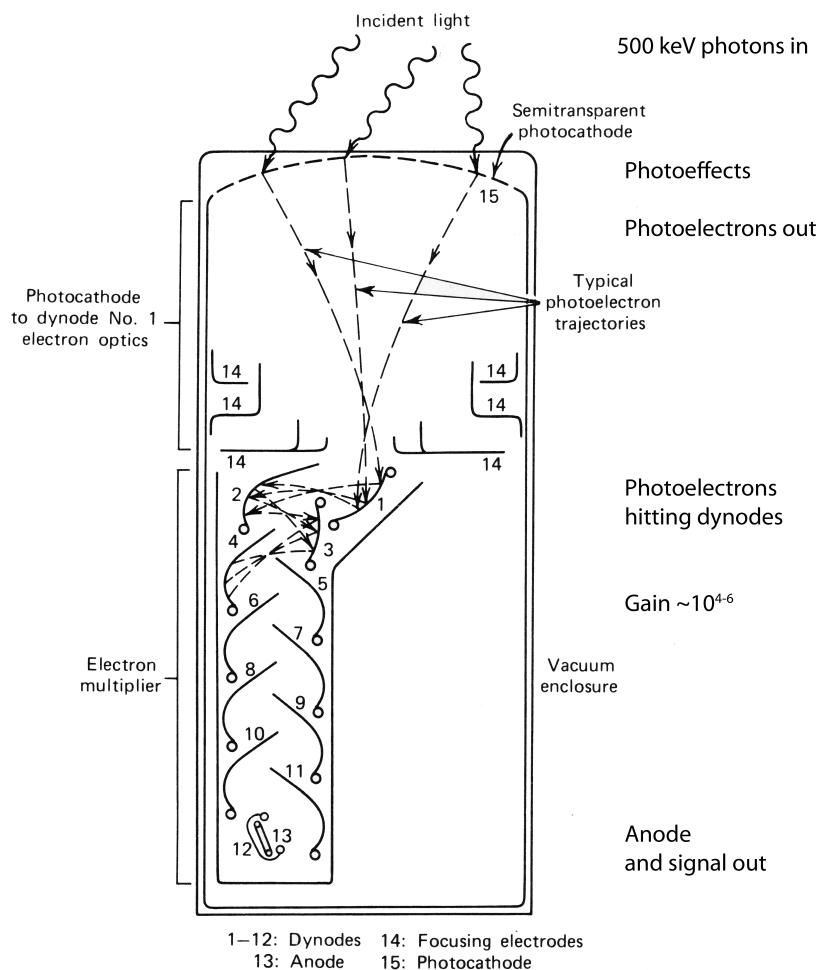


Figure 6: Schematic of a photomultiplier operation. Due to the scintillation light electrons are released from the cathode, attracted to the first dynode and multiplied. Each successive dynode is at higher electrical potential (a typical number of dynodes is 10-14) and the number of electrons is increased at each stage. Finally, the generated electrons are extracted through the anode.

In the PM-tube the scintillation light at the photocathode stimulates electron emission. The PM-tube also consist of a chain of electrodes, so called dynodes, each at successively higher electrical potential. The electrons from the photocathode are accelerated to the first dynode and due to the kinetic energy in the electrical field generate there secondary electrons. The multiplying effect takes place at each dynode and typical gain factor can be of order of 10^6 . The total generated charge is extracted via the anode in form of an electrical pulse. The whole conversion process from the absorption of the radiation in the scintillator to the pulse generated by the PM-tube is linear, in the sense that the energy of the absorbed radiation is proportional to the amplitude of the output pulse. This is an important principle, since the energy spectrum, i.e. energy distribution of the radiation, can be obtained by sorting the pulses according to their amplitudes (pulse height analysis).

2.3 Nuclear electronics and counting systems

A detector can be imagined as a capacitor into which a charge is deposited. This charge is collected by means of the applied high voltage, *Figure 7*. In the detectors at the present set-up, a preamplifier is connected directly to the anode of the PM-tube. The purpose of

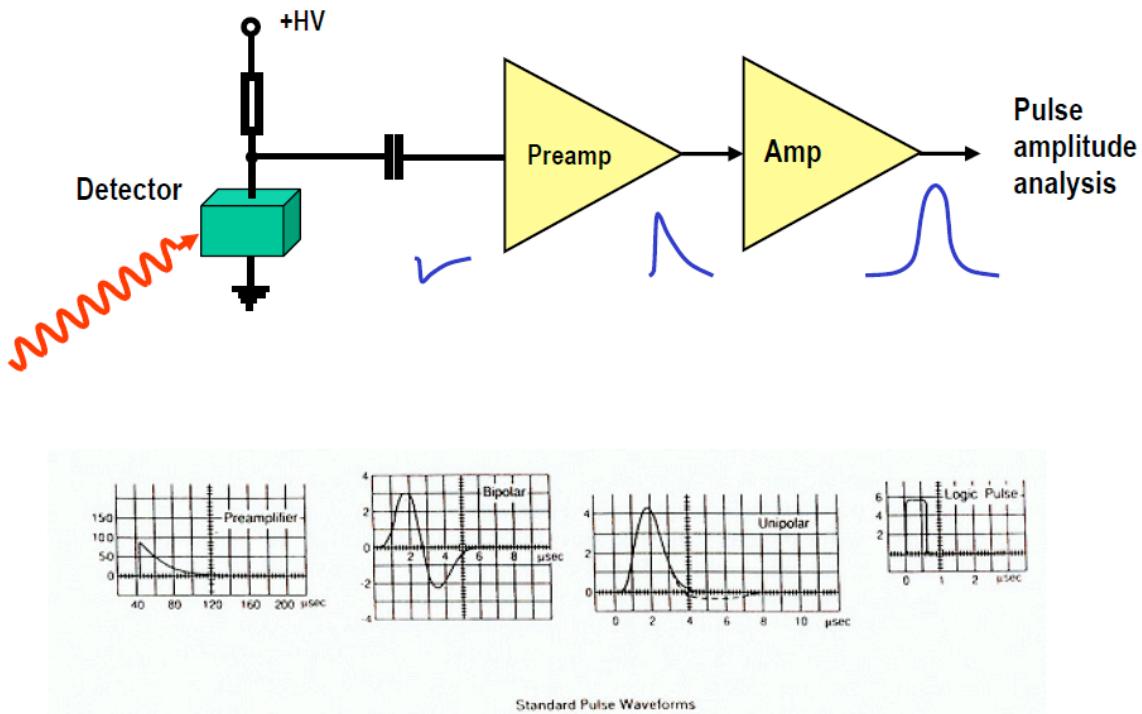


Figure 7: Typical preamplifier and amplifier pulses.

this preamplifier is to transfer the generated charge into an electrical pulse and to shape the pulse properly. Typical amplitudes for the pulses from the preamplifier can be in the order of a few hundred mV. The amplifier serves to further amplify the pulses. It results in two forms of pulses, bipolar or unipolar, both with amplitudes of a few volts. Unipolar pulses may indicate undershoot, below zero level, typically occurring at medium or high counting rate. It can be compensated by means of a pole/zero cancellation circuit in the amplifier. The bipolar pulse has an advantage over the unipolar in that the zero crossing point is nearly independent of the time (relative to the start of the pulse) for a wide amplitude range. This is very useful in timing applications. However, the unipolar pulse has lower noise.

Pulse height analysis may be performed either by using a Single Channel Analyzer (SCA) and a Counter or a Multi Channel Analyzer (MCA). The SCA has a lower and upper level discriminator and produces at the output a logic pulse whenever an input pulse falls between the discriminator levels. For a full voltage (i.e. full energy) spectrum the SCA range, window, can be set to a narrow range and then successively stepped through a range of voltages. This is a very time consuming method and with a bad accuracy. A Multi Channel Analyzer (MCA) can be considered as a series of SCAs with incrementing narrow windows. It basically consists of an Analog to Digital Converter (ADC), control logic, memory and display. The pulses are collected in all voltage ranges at once and the information is displayed in real time. An Analog to Digital Converter (ADC) generates a number proportional to the amplitude of the input pulse. In nuclear applications, ADCs are used to digitise the output signal from amplifiers. Since the amplitude of the pulses from the amplifiers is directly proportional to the energies of the incident radiation, the ADC can be used with a MCA to generate energy distribution (spectrum) of a radioactive sample. In the present set-up the MCA is in the form of a PC-based card. In *Figure 8* and *Figure 9* are presented two types of ADCs, Wilkinson and successive approximation. The later is used at the laboratory.

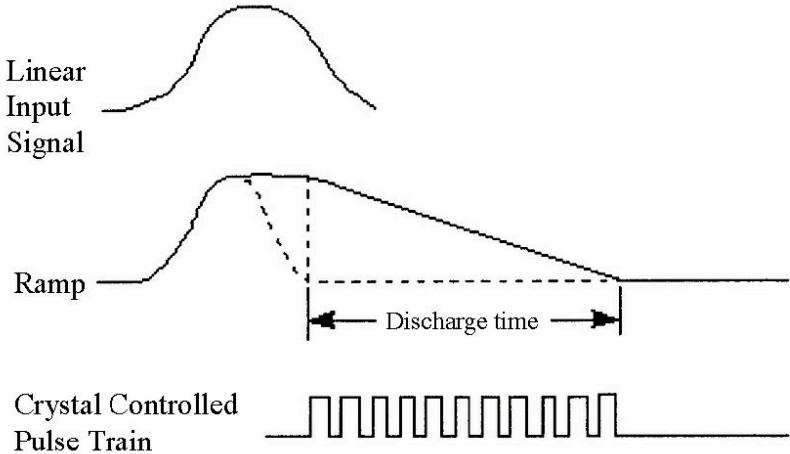


Figure 8: Wilkinson ADC. The pulse is digitised by charging a capacitor to the amplitude of an input pulse. The capacitor is then discharged at a constant rate until the voltage ramp returns to a baseline reference. The capacitor discharge time, determined by a crystal controlled clock and register, is directly proportional to the amplitude of the input signal. Thus the number of generated pulses represents the analogue signals pulse height.

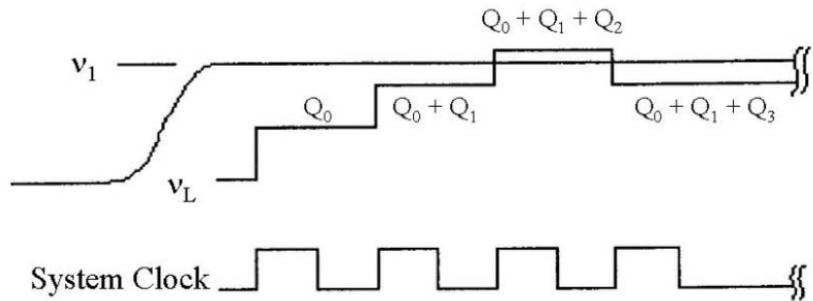


Figure 9: Successive approximation ADC. Successive approximation ADC. The incoming pulse is compared to a series of binary weighted reference voltages. During the conversion process each bit is synchronously activated by the system clock, and tests each bits contribution. Only bit contributions that do not exceed the analog input are left on and this repeats until all bits have been tested. When completed, a digital word or address will represent the amplitude of the analog input signal.

3. Radioactive decay

The radioactive decay is a statistical process where the number of decays dN^* during time dt is always proportional to the number of radioactive atoms N^* present at the time, i.e.

$$dN^* = -\lambda N^* dt$$

where λ is the proportionality constant (decay constant).

If the expression above is integrated, one gets after introducing the decay intensities $I(0)$ and $I(t)$ ($I=dN^*/dt$):

$$I(t)=I(0) \exp(-\lambda t)$$

This is the exponential decay law, where frequently the decay constant λ is replaced by the lifetime τ or the half-life $t_{1/2}$, defined as the time interval during which the decay intensity $I(t)$ has dropped to $1/e$ and $\frac{1}{2}$, respectively, of $I(0)$. The decay constant can be simply derived as:

$$\lambda = 1/\tau = \ln 2 / t_{1/2} = 0.693 / t_{1/2}$$

Half-lives of nuclei vary from less than a fraction of a second to $>10^{10}$ years, i.e. they may be as long as the age of the universe. The heaviest isotopes found in nature are ^{235}U and ^{238}U , with lifetimes of 7×10^8 y and 4.5×10^9 y, respectively. The latter lifetime is comparable with the age of the solar system and both isotopes have therefore survived since the formation of the earth, although the shorter lifetime of ^{235}U has caused a strongly reduced abundance (0.7 %) of this isotope. An example of another longlived isotope widely found in the nature is ^{40}K , with half-live 1.28×10^9 y. It is found together with natural K with an abundance of 0.0117 %.

Radioactive decay is a random process and consequently, any measurement based on observing the radiation emitted in nuclear decay is a subject to statistical fluctuations. It can be shown that it follows the Poisson distribution. A feature of this distribution is that is that if the average value is \bar{x} then the standard deviation is $\sqrt{\bar{x}}$. This means that the relative error strongly depends on the number of counts obtained in the measurement. For example, if the number of counts is 100, the relative error is $\sqrt{100}/100$, which is 10 %, while for 10 000 counts the error is $\sqrt{10000}/10000$, which is 1 %.

4. Laboratory

4.1 PC-based Multi Channel Analyser Tukan

The Tukan MCA PC-card also includes a very complex software for data handling. Details for the software may be found under “*help*” and therefore only basic command will be described here. The most important “*start*”, “*stop*” and “*delete*” commands can be found in the upper right corner. The data recording can be also controlled by setting a measuring time under “*parameters*”, “*stop criteria*”. The spectrum can be expanded between the

markers by commands in the upper row. The radiation intensity is represented by the net area under the peaks. The peak parameters, like the centroid, net area, FWHM (full width at half maximum) can be obtained automatically by setting the markers to limit the individual peak region.

Figure 10 shows the energy spectrum of three gamma sources used at this lab: ^{241}Am at 59.5 keV, ^{137}Cs at 661.7 keV and ^{60}Co having 2 gamma energies of 1173.2 keV and 1332.5 keV. Upper plot shows spectrum in linear Y-axis, lower plot shows the spectrum in more practical logarithmic Y-axis.

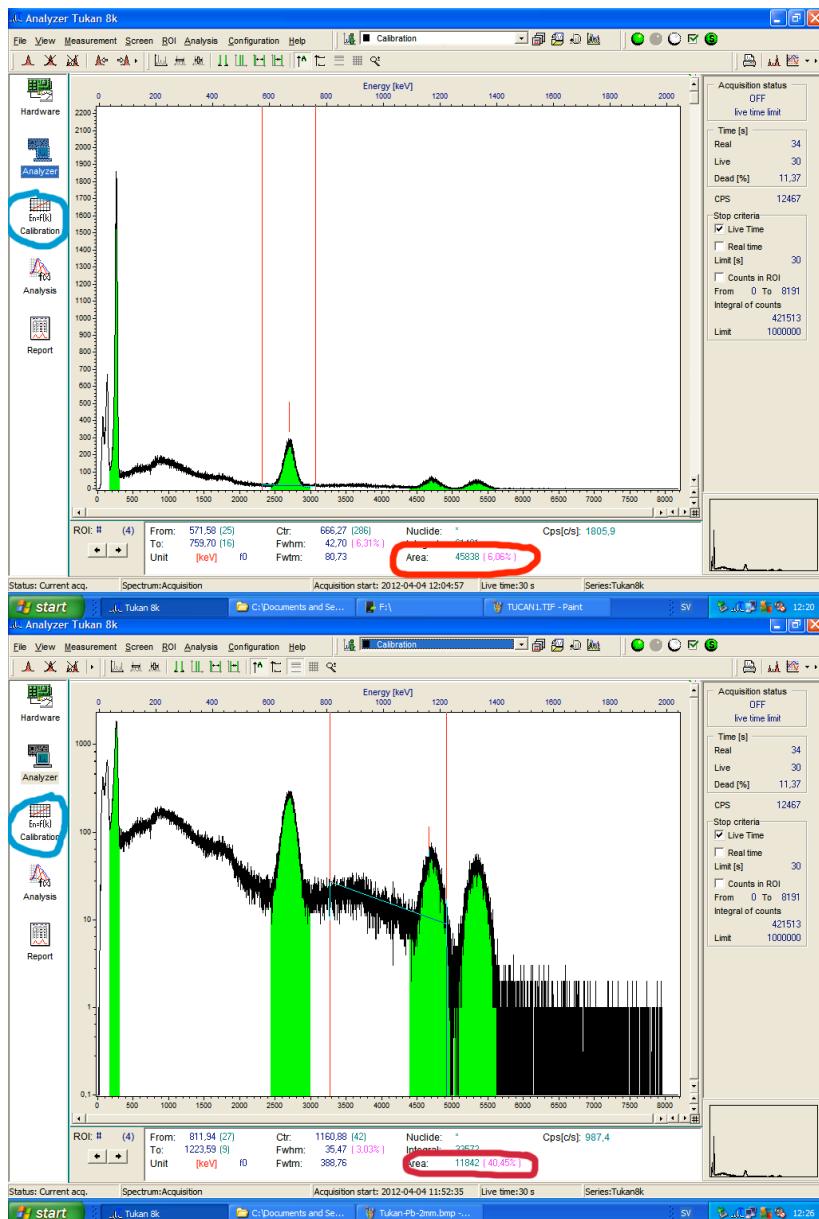


Figure 10: An energy spectrum of 3 gamma sources used at AM36 lab and registered by TUKAN multichannel analyser. Pay attention to "Region of Interest" (RoI) painted in green corresponding to 4 gamma energies: 59.5 keV, 661.7 keV, 1173.2 keV and 1332.5 keV. Upper x-axis on the plots corresponds to energy, lower x-axis to the channel number.

Lower plot is in logarithmic Y-axis, upper plot in linear Y-axis. Logarithmic Y-axis is more practical for analysis of spectra.

Pay attention to data given under the channel number axis showing in particular area of the indicated – with red markers – peak (red line around this parameter). Error of the area estimation is given in parenthesis in %.

4.2 Calibration and Gamma absorption

The gamma intensity after passage of an absorber with thickness x is:

$$I(x) = I(0) \exp(-\mu x)$$

where μ is the absorption coefficient.

Mostly a mass absorption coefficient is used, $\mu_m = \mu/\rho$ (ρ – absorbers density) and thus:

$$I(x) = I(0) \exp(-\mu_m \rho x)$$

The absorption coefficient is strongly energy dependent. In this exercise the gamma absorption will be studied for two materials, namely tin, $\rho = 7.28 \text{ g/cm}^3$, and lead, $\rho = 11.35 \text{ g/cm}^3$. In the measurements three radioactive sources will be used, which gives four gamma lines with the following energies:

^{241}Am	59.5 keV
^{137}Cs	661.7 keV
^{60}Co	1173.2 keV
	1332.5 keV

First, those four gamma energies will be used to calibrate the TUKAN multichannel analyser, i.e. to assign energy values to each counting channel. The collected spectrum will be used to assign energy to channels corresponding to the lines of the gamma sources. After measuring the spectrum for about 30 seconds energies will be assigned to the peak positions in the “Calibration” mode (blue lined around on the left hand side vertical bar of options) of the TUKAN operation.

For each gamma energy the dependence of the intensity versus thickness will be obtained. Using a fit with one component exponential function the mass absorption coefficient can be derived. A typical ^{137}Cs gamma spectrum is displayed in *Figure 11*.

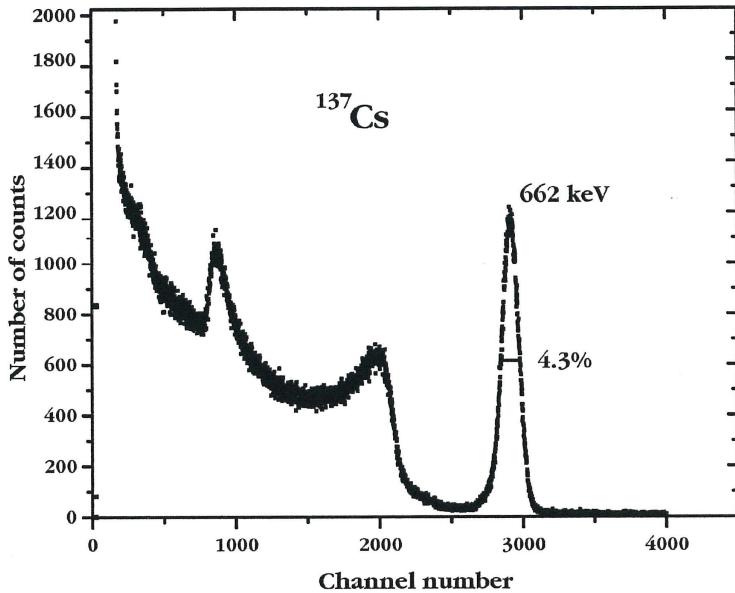


Figure 11: Pulse height spectrum of the 661.6 keV γ -line from ^{137}Cs . The main components of this typical spectrum are the photopeak and Compton distribution. The peak observed at lower energies is due to backscattering.

The best way to record the measurement is to prepare a table of measurement, which may look like the **Table 1**

Another way of saving the measurements data is to print “a report” from each measurement using the “Report” option of TUKAN at the left hand side vertical bar paying attention to use a file name to record material type and thickness. However, the TUKAN report does not contain an error data of peak areas, so it must be noted elsewhere.