Energy loss of Alpha-particles in gases with MCA

(Item No.: P2522415)

Curricular Relevance

Area of Expertise:	Education Level:	Topic:	Subtopic:	Experiment:
ILIAS	Physik	Hochschule	Moderne Physik	Kernphysik - Radioaktivität

Difficulty	Preparation Time	Execution Time	Recommended Group Size
Difficult	1 Hour	2 Hours	2 Students

Additional Requirements:

Experiment Variations:

Keywords:

Range, mean ionization energy of gas atoms, mean energy loss of alpha-particles per collision, differential energy loss, Bethe formula, electron concentration in gases

Overview

Short description

Principle

The energy sensitivity of the detector is calibrated with an uncovered $^{241}\mathrm{Am}$-source in vacuum.

The dependence of the energy loss of α-particles on the concentration of air particles between source and detector is measured.

The dependence of energy loss of the α-particles on the sort of gas particles between source and detector is determined and compared to the electron density in that sort of gas.

Fig. 1: Experimental set-up.

Equipment

Position	Material	Bestellnr.	Menge
1	Multichannel analyser	13727-99	1
2	measure Software multi channel analyser	14452-61	1
3	Alpha and Photodetector	09099-00	1
4	Radioactive source Am-241, 3.7 kBq	09090-03	1
5	Radioactive source Am-241, 370 kBq	09090-11	1
6	Container for nuclear physics exp.	09103-00	1
7	Pre-amplifier f.alpha detector	09100-10	1
8	Vacuum gauge DVR 2, 1 ... 1000 hPa	34171-00	1
9	Diaphragm pump, two stage, 220V	08163-93	1
10	Vacuum tube, NBR, 6/14mm, 1 m	39289-00	3
11	Hose clamp for 10-17 mm diameter	40998-00	9
12	Tubing connector,Y-shape, ID 8-9mm	47518-03	2
13	Pinchcock, width 20 mm	43631-20	1
14	Fine control valve	33499-00	1
15	Compressed gas, helium, 12 l	41772-03	1
16	Compressed gas, nitrogen, 12 l	41772-04	1
17	Compressed gas, CO2, 22 g	41772-06	1
18	Screened cable, BNC, l = 750 mm	07542-11	3

Tasks

Tasks

1. The pulse height spectrum resulting from α-particles coming from an uncovered $^{241}\mathrm{Am}$ emitter is recorded with the MCA. The α-particle energy of the principal peak, $5.486\,\mathrm{MeV}$, is used for calibration.
2. The spectrum of α-particles reaching the detector from a covered $^{241}\mathrm{Am}$ source in $10\,\mathrm{cm}$ distance from the detector is recorded in dependence on air pressure. The rate of energy loss in dependence on particle energy is evaluated and compared to predictions by the Bethe-formula.
3. The spectrum of α-particles reaching the detector from a source at $10\,\mathrm{cm}$ distance in helium, carbon dioxide and nitrogen with $100\,\mathrm{hPa}$ pressure is recorded. The energy loss in dependence on electron density is compared to predictions by the Bethe-formula.

Set-up and procedure

Set-up

Set-up

Fig. 1 shows the experimental set-up. In the beginning no gas bottle is connected to the fine control valve and the pinch cock on the tube leading to the fine control valve is closed.

The black shielding is mounted on the detector and the detector is attached to the flange cover. The uncovered $3.7\,\mathrm{kBq}$ $^{241}\mathrm{Am}$ source is put into the black detector shielding up to the bed stop so the source is as near to the detector as possible.

The sliding rod is retracted and secured with the milled screw.

The flange cover is always mounted to the experimental container without use of the fixing nuts - the ambient pressure will hold the flange of the experimental vessel when the vessel is evacuated and pressurizing the vessel with a gas bottle by mistake is made impossible this way.

The upper two preamplifier switches have to be set to "α" and "Inv.". The "Bias" switch has to be set to "Int." and the polarity switch for the internal bias must be kept to "–" to avoid accidental wrong polarisation of the detector diode.

The short BNC cable is used to connect the experimental vessel to the "Detector" socket of the α-preamplifier. The other BNC cable connects the "Output" socket of the α-preamplifier with the "Input" socket of the MCA. The 5-pole cable connects the "$\pm 12\,\mathrm{V}$" jack of the MCA with the corresponding socket of the α-preamplifier.

Turn MCA and preamplifier on right at the beginning so they have time to thermalise before starting the measurement.

Complete the electrical connections and the preamplifier settings prior to turning on the MCA.

The MCA is connected by USB to a computer with "measure"-software installed on it. It may be necessary to remove a USB driver that was installed by "Windows" automatically and to install the correct USB driver for the MCA manually if the MCA is used with the computer the first time.

Procedure

Procedure

Task 1:

Close the venting screw of the flange cover and evacuate the experimental vessel. When the final pressure achievable with the pump is reached, close the pinch cock on the tube to the pump and then turn off the vacuum pump. Start the "measure" program, select "Gauge" > "Multi Channel Analyser".

Select "Spectra recording" and use the "Continue" button (Fig. 2).

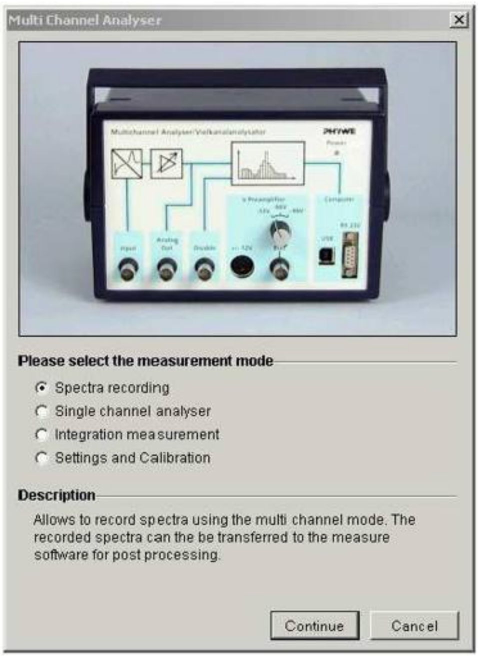


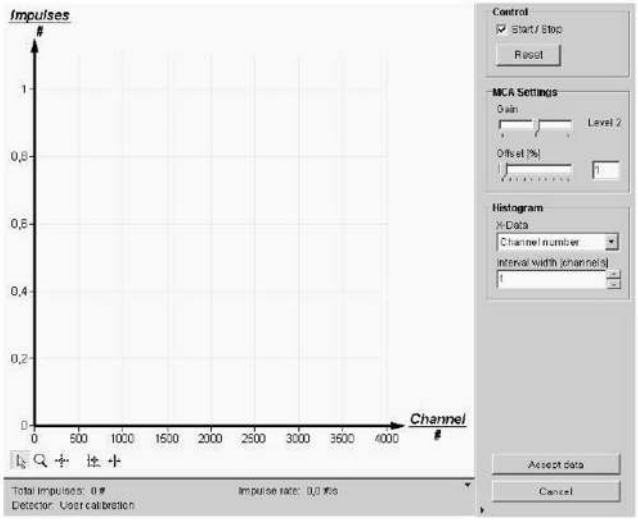
Fig. 2: Start window for the MCA.

Set "Gain" to "Level 2" and "Offset [%]" to 1. The counting rate should be between 50 and 60 per second.

Select "Channel number" as "X-Data" and "1" as "Interval width [channels]" (Fig. 3).

Stop the measurement with the "Accept data" button, when the position of the main $^{241}\mathrm{Am}$-peak is clearly visible for evaluation. 5000 impulses should be sufficient for this purpose.

The recorded data appear now in a window in the "measure" main program. Denote the measurement parameters using the "Display options" dialog and save the measurement data.



Spectra recording window.

Task 2:

Fully vent the experimental vessel, open it and remove the calibration source.

Mount the covered $370\,\mathrm{kBq}$ $^{241}\mathrm{Am}$ source to the end of the sliding rod. Position the source such that the distance between source and detector diode is $10\,\mathrm{cm}$. The position of the detector diode can be seen with the black light shielding removed. Fix the sliding rod with the milled screw so it can not move into the vessel when the pressure is reduced.

Evacuate the vessel, record a spectrum with the settings as before. The counting rate is between 40 and 50 per second again though the distance to the source is much greater because the source's activity is that much higher.

Record for the lowest achievable pressure at least 10000 incidents and for the other pressure values at least 5000 incidents. Save the spectra denoting the pressure.

Increase the pressure in steps of $20\,\mathrm{hPa}$ each time recording a spectrum. Use the fine control valve to control the pressure: open the pinch cock in the tube leading to the fine control valve, adjust the pressure with the fine control valve and close the pinch cock again. The fine control valve is not completely gas tight from handle to outlet - the pinch cock prevents thus the pressure to rise during measurement.

When the counting rate has dropped with rising pressure to half the initial value, there is no more peak visible and the measurement can be terminated.

A background spectrum can be recorded with the vessel fully vented, but above $400\,\mathrm{hPa}$ there should be no recordable incidents except from ambient radon (above channel # 2800). If you measure some background, check presence of light at the detector - darken the room or use cardboard to shield the vessel, presence of nearby mobile phones or nuclear contamination of the vessel.

Task 3:

Connect a compressed gas bottle to the fine control valve and evacuate the vessel again now with the pinch cock open on the tube leading to the fine control valve.

Close the pinch cock on the tubing of the pump when final pressure is reached and turn off the pump. Then release some gas from the compressed gas bottle into the vessel with the fine control valve until the pressure is about $100\,\mathrm{hPa}$. Close the pinch cock on the tubing of the fine control valve.

Record a spectrum collecting at least 10000 incidents and save it denoting pressure and sort of gas.

Vent the vessel with air before changing the gas type. Doing so you assure the composition of the rest gas to be the same throughout your measurements. For example if you use the two stage diaphragm pump, the final pressure may be $22\,\mathrm{hPa}$.

Then you know if you have vented the vessel before evacuating it, that the rest gas is always air. If you have filled the vessel up to $100\,\mathrm{hPa}$ with a specific sort of gas, the composition of gases will be $22\,\mathrm{hPa}$ air and $78\,\mathrm{hPa}$ of the specific gas. You can then assume that the constant intermixture of air affects each spectrum in the same manner and does not matter in the evaluation.

Resume with the other available types of gas.

Theory and evaluation

Theory

Theory

For a short sketch of α-decay theory refer to LEP 5.2.20-15. α-particles interact strongly with matter because of their electric charge and are stopped by some cm of air or some tens of $\mu\mathrm{m}$ of condensed matter.

The main deceleration process is scattering at electrons.

Scattering at atomic nuclei can be neglected here.

Because α-particles are much heavier than electrons the α-particles lose only a small fraction of their energy in each impact on an electron. The direction of the α-particle's impulse is only slightly changed and it needs hundreds of interactions with electrons until they are stopped.

A model describing the electronic deceleration process is the Bethe formula (1). It applies for α-particle energies that are high compared to electronic binding energies and assumes the electrons to be free above an electron binding energy threshold equal to the ionisation energy I. The type of interaction is assumed to be Coulomb-like, the electron binding I limiting the interaction for high impact parameters, that is electrons far away from the path of the α-particle. Including electron spin and relativistic calculation yields for the differential energy change dE in a layer dx in a medium with electron density n

$$-\frac{dE}{dx} = \frac{4\pi\, n\, Z^2}{m_e\, c^2\, \beta^2}\left(\frac{e^2}{4\pi\, \varepsilon_0}\right)^2 \ln\left(\frac{2m_e\, c^2\, \beta^2}{I(1-\beta^2)} - \beta^2\right) \qquad (1)$$

where

$e = 1.602 \cdot 10^{19}\, C$ denotes the elementary charge, Ze the charge of the α-particle,

$m_e = 511\,\mathrm{keV/c}^2$ the electron rest mass,

$\varepsilon_0 = 8.854 \cdot 10^{12}\ \mathrm{As/Vm}$ the electric constant,

$c =$ speed of light,

$\beta = \nu / c$ with α-particle speed ν and

$E =$ the relativistic α-particle energy.

The negative of (1), the energy loss, is minimal for the energy E approximately three times the a-particle rest mass ($4u = 4 \cdot 931.5\,\mathrm{MeV/c}^2 \approx 4\,\mathrm{GeV}$). The differential energy loss rises for high energies with the logarithm of the energy but rises at low energies with the square of the inverse energy – before it drops to very low energies where the model does not apply any more.

When trying to plot this equation, remember $E = (\gamma - 1) m_0 c^2$ with

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \text{ thus } \beta^2 = \frac{E^2 + 2m_{He}\, c^2}{(E + m_{He}\, c^2)^2}.$$

Non-relativistic approximation, $\beta \ll 1$, yields

$$-\frac{dE}{dx} = \frac{4\pi\, n\, Z^2}{m_e\, \nu^2}\left(\frac{e^2}{4\pi\, \varepsilon_0}\right)^2 \ln\left(\frac{2m_e\, \nu^2}{I}\right) \qquad (2)$$

(2) is a first-order differential equation with separated variables, but the integral has no elementary solution but may be presented as a series.

With $E = \frac{1}{2} m_{He} \nu 2$, m_{He} the α-particle mass, $Z = 2$, $\mu = m_e / m_{He}$ (2) becomes

$$-\frac{dE}{dx} = \frac{n}{2\pi\mu\, E}\left(\frac{e^2}{\varepsilon_0}\right)^2 \ln\left(\frac{4\mu\, E}{I}\right) \qquad (2)$$

Fig. 4 shows a plot of the logarithm of the stopping power over the logarithm of the a-particle energy for dry air. Presented are the data from the Bethe formula both relativistic and non-relativistic assuming $I = 100\,\mathrm{eV}$ and the semiempiric ASTAR-data on electronic stopping power of air for α-particles from the US-American NIST (National Institute of Standards and Technology). The ASTAR-data account for the necessary modifications of the stopping power data at low energies where the Bethe formula is incorrect. It can be seen that the Bethe formula is applicable for energies above $1\,\mathrm{MeV}$. The non-relativistic calculus begins to loose its accuracy above $100\,\mathrm{MeV}$ which is far above the energies available in this experiment.

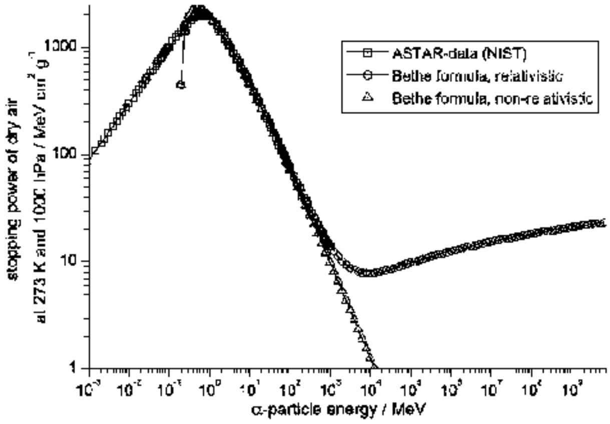


Fig. 4: Stopping power in dependence on α-particle energy, bilogarithmic plot.

The energy loss is not dependent on the density and path length but on the total amount of matter penetrated by the particles. A long path in low density material is assumed to have the same effect as a short path in high density material.

So the stopping power is often specified as energy loss per surface mass density $\mathrm{MeV} \cdot \mathrm{cm}^2/\mathrm{g}$. The electron density n that is responsible for the stopping power can be determined for a given substance of atomic mass A, k electrons per particle and density ρ as

$$n = \frac{k \cdot \rho}{A \cdot u}$$

with atomic mass unit $u = 1.6605 \cdot 10^{-31}\,\mathrm{kg}$. So for dry air assumed to consist of 79% nitrogen ($\mathrm{N2}$) and 21% oxygen ($\mathrm{O2}$) with molar volume $V_m = 22.7\,\mathrm{l/mol}$ (at $0^\circ\mathrm{C} = 273\mathrm{K}$ and $1000\,\mathrm{hPa}$) and Avogadro-number $N_A = 6.022 \cdot 10^{23}\,\mathrm{mol}^{-1}$ it is

$k = 0.79 \cdot 2 \cdot 7 + 0.21 \cdot 2 \cdot 8 = 14.4$,

$A = 0.79 \cdot 2 \cdot 14 + 0.21 \cdot 2 \cdot 16 = 28.8$,

and the density ρ depending on pressure p and temperature T is

$$\rho(p,T) = \frac{p \cdot k \cdot N_A \cdot 273\mathrm{K}}{Tb \cdot V_m \cdot 1000\mathrm{hPa}} = \frac{1.269\,\mathrm{kg/m^3} \cdot \left(\frac{p}{1000\mathrm{hPa}}\right)}{\frac{T}{273\mathrm{K}}}$$

and

$$n(p,T) = \frac{p \cdot k \cdot N_A \cdot 273\mathrm{K}}{T \cdot V_m \cdot 1000\mathrm{hPa}} = \frac{3.825 \cdot 10^{26}\,\mathrm{m}^{-3} \cdot \left(\frac{p}{1000\mathrm{hPa}}\right)}{\frac{T}{273\mathrm{K}}}$$

It is of significance that the stopping power is proportional to the energy per unit length deposited by a beam of $alpha$-particles. This energy is proportional to the number of ion pairs produced which is a measure for the dose of ionizing radiation absorbed. When a beam of monoenergetic α-particles is stopped within matter, the graph plotting the dose deposited along it's path is called Bragg curve and it is governed by the Bethe formula. Since the stopping power is low at high energies, the beam deposits a low dose when entering a body but a high dose at the end of it's trajectory. This can be employed in radiation therapy for example against brain tumours. In medicine use is made of protons from an accelerator with storage ring which show a similar Bragg curve but have a higher penetration depth. The Bragg curve is an integral of the Bethe function plotted over path length.

In this experiment not the x-dependence, but the pressure dependence of the energy loss is measured for a fixed distance $x = 10\,\mathrm{cm}$.

The electron density per area N is for a gas layer thickness of $10\,\mathrm{cm}$ passed by the α-particles at $293\,\mathrm{K}$ then

$$n = k \cdot \frac{N_A}{V_m} \cdot \frac{p}{1000\,\mathrm{hPa}} \cdot \frac{273\mathrm{K}}{293\,\mathrm{K}} = k \cdot p \cdot\, 2.47 \cdot 10^{19}\,\mathrm{l}^{-1}\,\mathrm{hPa}^{-1}. \qquad (3)$$

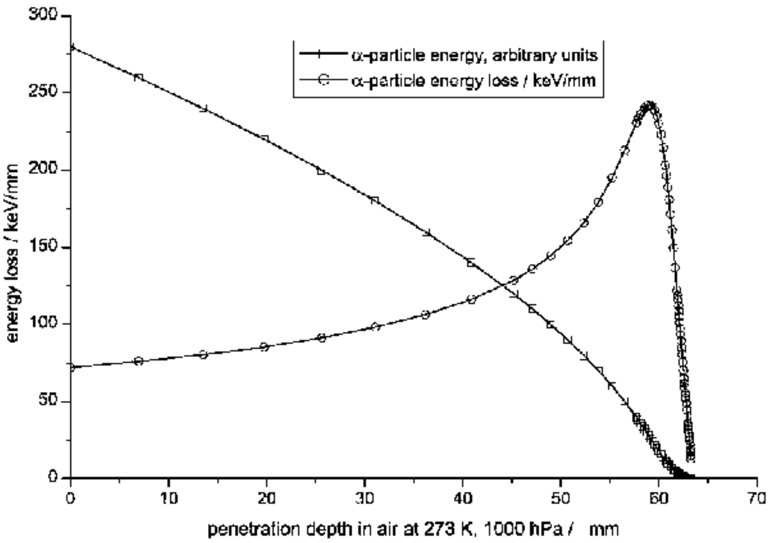


Fig. 5: Bragg curve plotted with help of spread sheet calculation from the STAR-data for an α-particle starting with 7 MeV in air.

(2) becomes with

$\mu = m_e/m_{He} = 511\,\mathrm{keV}/3.727\,\mathrm{GeV} = 1.371\cdot 10^{-4}$ and $Z=2$

$$-\frac{dE}{dx} = \frac{2\pi\, n\, Z^2}{\mu\, E}\left(\frac{e^2}{4\pi\,\varepsilon_0}\right)^2 \ln\left(\mu\frac{4E}{I}\right)$$

$$-\frac{dE}{dx} = \frac{2\pi\, Z^2}{\mu\, E}\cdot\frac{N(p)}{p}\cdot\left(\frac{e^2}{4\pi\,\varepsilon_0}\right)^2 \ln\left(\mu\frac{4E}{I}\right)$$

$$-\frac{dE}{dx} = k\cdot\frac{1}{E}\cdot 2.41\cdot 10^{-29}\,\mathrm{J}^2/\mathrm{hPa}\cdot\ln\left(\frac{5.848\cdot 10^{-4}\cdot E}{I}\right)$$

or

$$-\frac{dE}{dx} = k\cdot\frac{1}{E}\cdot 940\,\mathrm{keV}^2/\mathrm{hPa}\cdot\ln\left(\frac{5.848\cdot 10^{-4}\cdot E}{I}\right) \qquad (4)$$

$^{241}\mathrm{Am}$ decays to 100% to stable $^{237}\mathrm{Np}$ and in 85% of the decays an α-particle of $5486\,\mathrm{keV}$ is emitted which contributes to the main peak.

Fig. 6 shows a decay scheme. The $5.486\,\mathrm{MeV}$ line is used here for calibrating the set-up.

The main peak α-particles are of interest here.

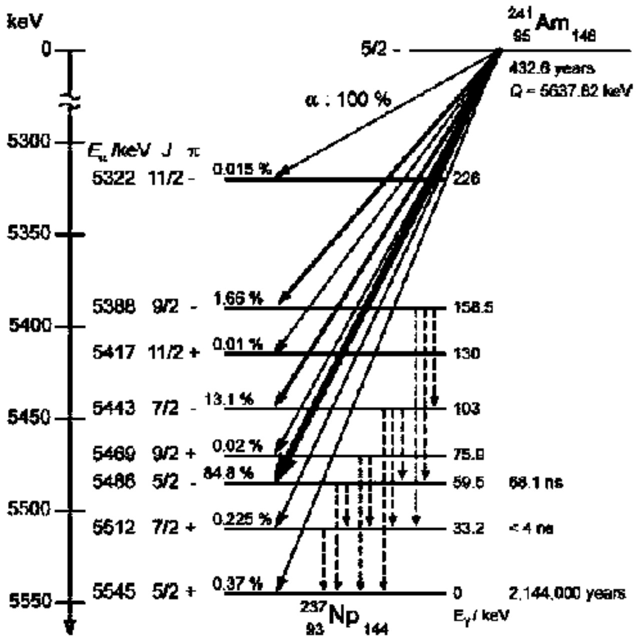


Fig. 6: 241Amdecay scheme.

Evaluation

Evaluation

Task 1:

For details of the α-particle energy detection refer to LEP 5.2.23-15.

Use the "Survey" function (-button) to determine the position of the main peak. In the measurement example the peak was found at ch. # 2454. For calculating the energy sensitivity s, that is particle energy per channel, the offset has to be accounted for. With an offset of 1% of 4000 cannels, that is 40 channels, it is $s = (2454 + 40)$ channels $/5486\,\mathrm{keV} = 0.4546$ channels $/\mathrm{keV}$ or one channel corresponds to $2.2\,\mathrm{keV}$. So in the following $\Delta E = \Delta ch./s$.

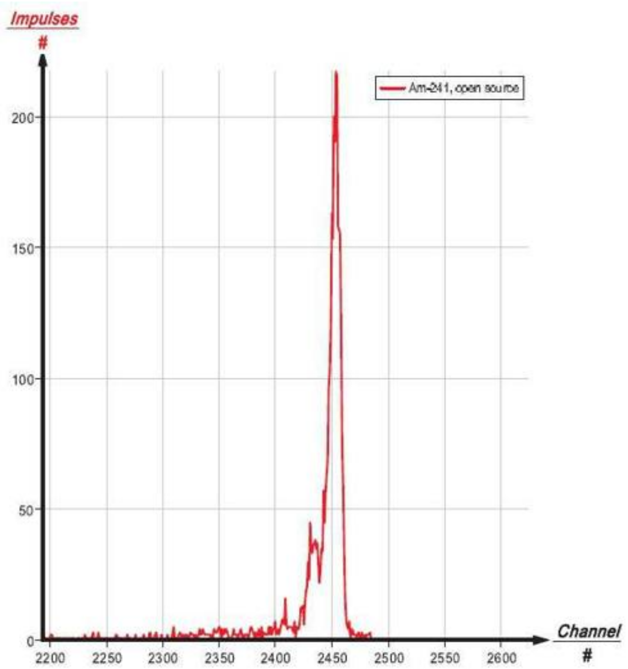


Fig. 7: Number of incidents per channel for the calibration source.

Task 2:

Use the "smooth" function on the recorded curves ("" button or "Analysis" > "Smooth..."). Select "strong" smoothing. It may be useful to select "Measurement" > "Display options..." > "Interpolation: straight lines" for displaying the curves. Fig. 8 shows an example with and without smoothing.

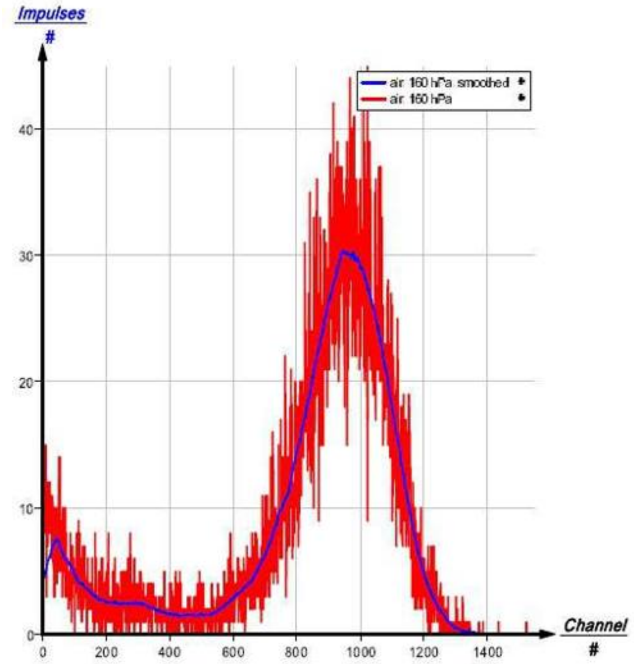


Fig. 8: Example of α -energy spectrum.

Use the "survey" tool ("" button) to determine the channel number of the peak position.

If you merge all the curves into one diagram with "Measurement" > "Adopt channel..." and scale them with the "" button using "fit individually" you may obtain a diagram as Fig. 9.

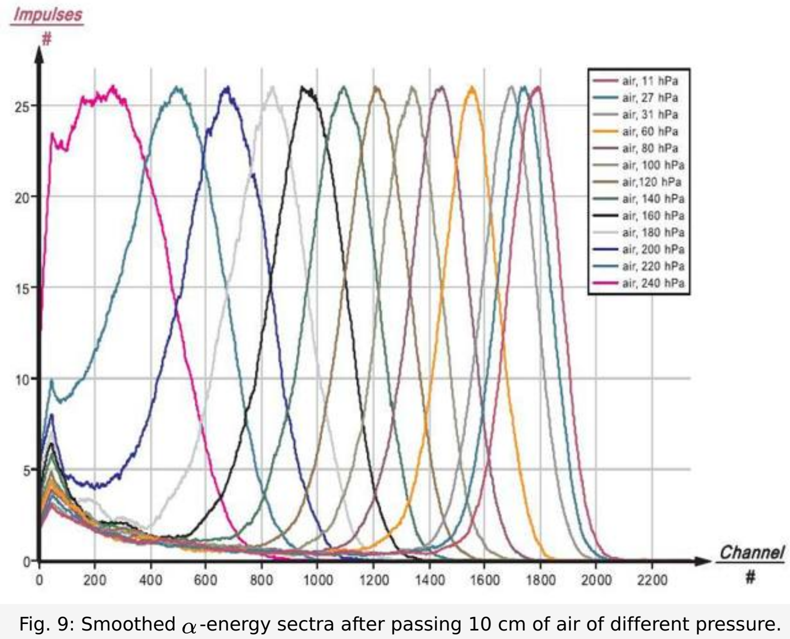


Fig. 9: Smoothed α-energy sectra after passing 10 cm of air of different pressure.

Fig. 10 is a plot of the last two columns of Table 1 over the average energy. The data show a good agreement.

There is a statistical error due to the uncertainty of the peak position of a peak with noise and a systematic error due to the fact, that the a-particles from the covered source are not strictly monoenergetic but show an energy distribution. Since the deceleration behaviour is not linear, the peak gets deformed and displaced which falsifies the values mainly for almost stopped particles or relatively high pressure.

pressure p / hPa	peak position / ch.#	E / keV	average energy / keV	Δp / hPa	$-\Delta E$ / keV	$-\Delta E/\Delta p$ / keV/hPa	theoretical value from (4) / keV/hPa
11	1781	4025					
			3931	20	189	9.5	10.8
31	1688	3836					
			3679	29	315	10.8	11.3
60	1546	3522					
			3401	20	242	12.1	11.9
80	1438	3280					
			3163	20	233	11.7	12.5
100	1336	3047					
			2916	20	262	13.1	13.2
120	1212	2785					
			2615	20	271	13.5	14.0
140	1087	2514					
			2373	20	282	14.1	15.0
160	964	2233					
			2086	20	293	14.6	16.2
180	815	1940					
			1767	20	345	17.3	17.9
200	663	1595					
			1395	20	400	20.2	20.3
220	462	1194					
			926	20	537	26.8	24.7
240	250	658					

Table 1: Example of measurement results for retarding of α-particles in dependency on air pressure

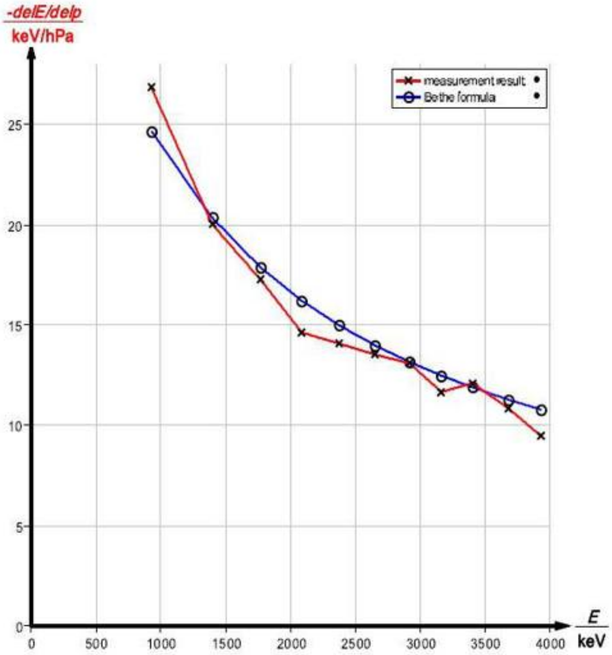


Fig. 10.

Fig. 11 plots a Bragg curve using first and third column of Table 1. The differential energy loss is derived using "Analysis" > "Channel modification..." > "differentiate".

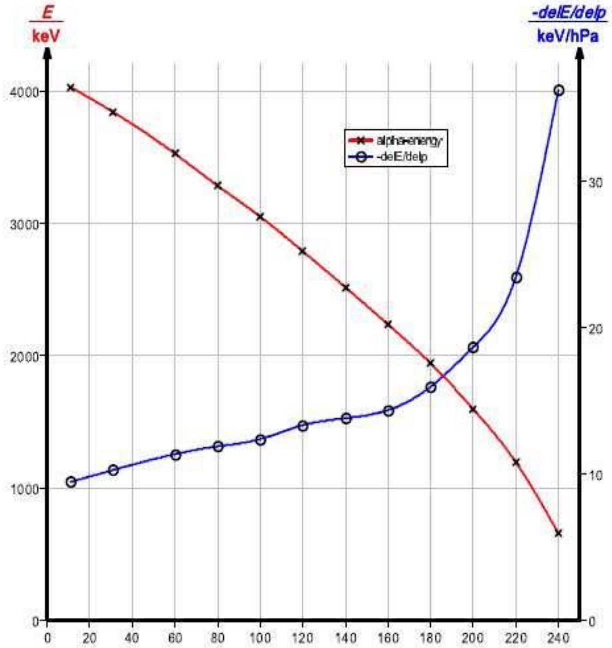


Fig. 11: Bragg plot, α-energy and differential energy loss over pressure in hPa.

Task 3:

In the measurement example the total pressure was $105\,\mathrm{hPa}$, of which $11\,\mathrm{hPa}$ were air, so $94\,\mathrm{hPa}$ of the specific gas was relevant for the peak energy loss. The spectra were smoothed as above and the peak positions were evaluated using the "survey" function of "measure". The peak displacement with respect to the reference peak of air at lowest attainable pressure was calculated. Table 2 shows the experimental data. The reference peak corresponds to an energy of $E = 4025\,\mathrm{keV}$. Assuming the energy loss linear, that is $-dE/dp = -\Delta E/\Delta p$, (4) yields with $\Delta p = 94\,\mathrm{hPa}$:

$$-\frac{\Delta E}{k} = \frac{94\,\mathrm{hPa}}{4025\,\mathrm{keV}} \cdot 940\frac{\mathrm{keV}}{\mathrm{hPa}} \cdot \ln(23.54) = 69\,\mathrm{keV}$$

The deviation of about 15% may be assigned to the in fact higher energy loss due to lower α-particle energy and in case of He the uncertainty of the peak position. Fig. 12 plots the results.

sort of gas	k	-ΔE/$ch.\#$	-ΔE/keV	-$\Delta E/k$/keV
He	2	77	169	85
N_2	14	478	1057	75
O_2	22	781	1717	78
			average	79

Table 2: Example of measurement results for retarding of α-particles in dependency on sort of gas, k the number of electrons per gas particle

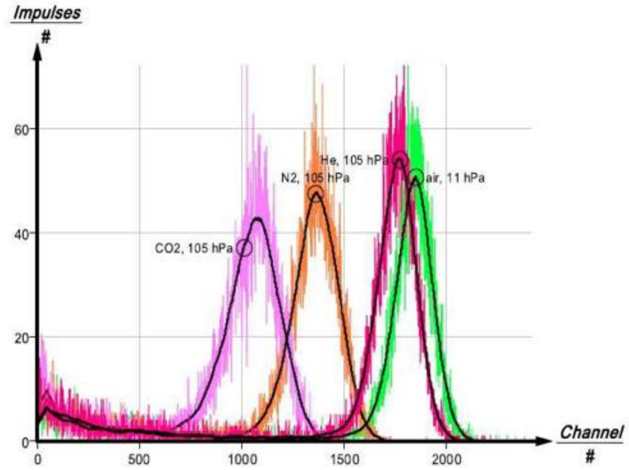


Fig. 12: Different spectra for different retarding gases at same pressure.

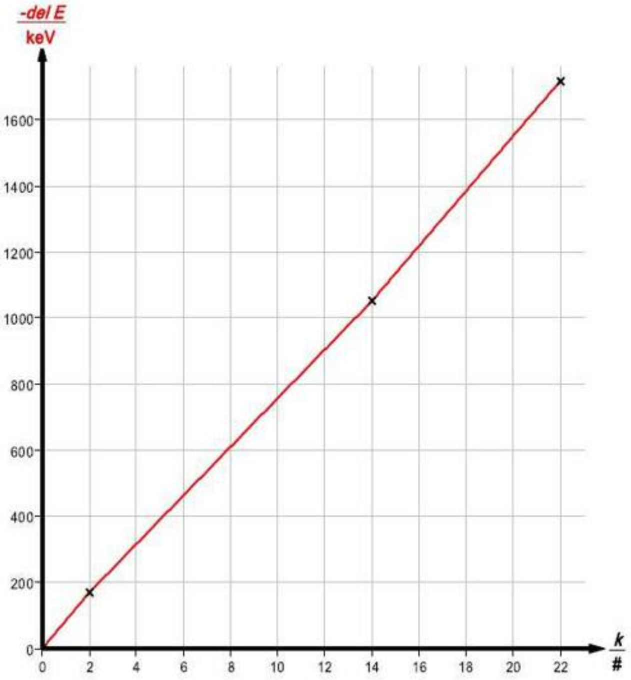


Fig. 13: Energy loss over number of electrons per gas particle. In ideal gases the particle density is independent on the sort of gas at the same pressure and temperature. So k is proportional to electron density.