

Related topics

Range, range dispersion, mean free path length, mean ionization energy of gas atoms, mean energy loss of α -particles per collision, differential energy loss, Bethe formula, electron concentration in gases.

Principle and task

A study is made of the connection between the energy E of α -particles and the path x travelled by them in air at standard pressure. The measurements recorded enable the differential energy loss dE/dx to be calculated as a function of x . To improve the measurement accuracy and to exclude the influence of different measurement geometries, the measurements are carried out in a vessel with a fixed distance s between the source and the detector, the pressure p being varied instead of the intervening distance. The path x , at which the same energy loss would occur under standard pressure (1013 hPa)*, is calculated from the formula:

$$x = s \cdot \frac{P}{1013 \text{ hPa}}$$

In the final stage, the influence of the type of gas (He, N₂, CO₂) on the energy loss of α -particles is calculated using the same measuring layout.

Equipment

Americium-241 source, 3.7 kBq	09090.03	1
Americium-241 source, 370 kBq	09090.11	1
Container f. nuclear phys. expts.	09103.00	1
Alpha detector	09100.00	1
Pre-amplifier f. alpha detector	09100.10	1
Impulse height analyser	13725.93	1
Oscilloscope, 20 MHz, 2 channels	11454.93	1

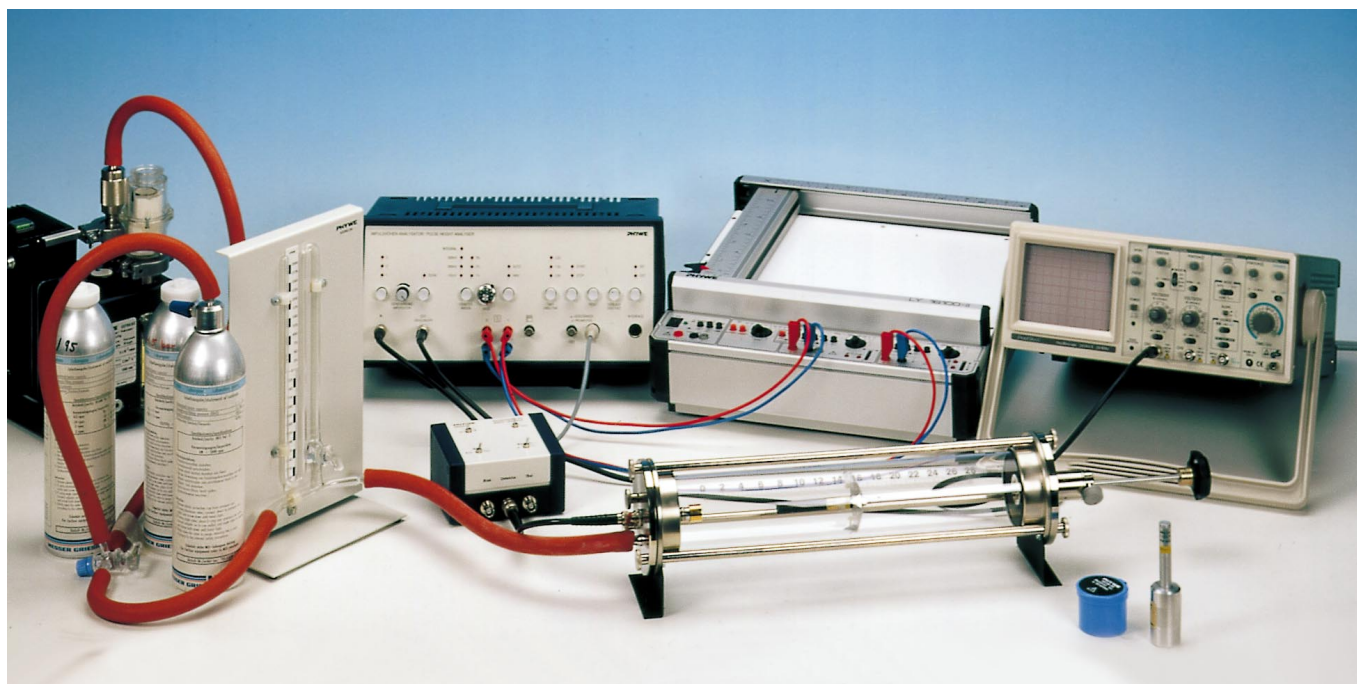
xyt recorder	11416.97	1
U-tube vacuum gauge 0–300 mbar	03092.00	1
Vacuum pump, one stage	02750.93	1
Stopcock, 3-way, t-shaped, glass	36731.00	1
Adapter for vacuum pump	02657.00	1
Rubber tubing, vacuum, i.d. 8 mm	39288.00	2
Fine control valve	33498.00	1
Compressed gas, helium, 12 l	41772.03	1
Compressed gas, nitrogen, 12 l	41772.04	1
Compressed gas, CO ₂ , 21 g	41772.06	1
Screened cable, BNC, l 750 mm	07542.11	3
Connecting cord, 750 mm, red	07362.11	2
Connecting cord, 750 mm, blue	07362.04	2

Problems

- The spectrum of a covered ²⁴¹Am source is measured at a fixed distance s as a function of the pressure p . The distance s is selected in such a way as to correspond to the maximum range at the highest pressure measurable with the manometer used. The energy corresponding to the central points of the individual spectra are determined (after calibration of the measurement layout with an open ²⁴¹Am-emitter, see 3.) and plotted as a function of the distance x converted to a 1013 hPa basis. Using this function, the differential energy loss ($-dE/dx$) is then calculated as a function of x and again plotted on the graph.
- The spectrum of the source used in 1. is measured initially under the same geometric conditions under vacuum and subsequently with the vessel filled with helium, nitrogen or carbon dioxide, in each case under identical pressures. The different energy loss values are compared with the electron concentration in the particlular gas.

* 1 hPa \triangleq 1 mbar

Fig. 1: Experimental set-up: Energy loss of α -particles in gases.



3. The mean energy with which the α -particles leave the covered americium source is determined by calibration against the open americium emitter ($E = 5.485$ MeV). (This value is required for the evaluation in 1.)

Set-up and procedure

The complete layout is shown in Fig. 1. The distance between the detector located in the vessel and the ^{241}Am source (370 kBq), screwed to the adjustable source holder in the vessel, is 10 cm. The pressure is measured with a U-tube vacuum gauge. A 3-way tap for filling the evacuated vessel with the different gases is located between the vacuum gauge and the pump.

The pulse height analyzer is initially disconnected (no voltage at the α -detector).

Preparation

- Evacuate the vessel until the vacuum gauge indicates approximately 0 hPa.
- Close the flexible hose with a hose clamp and disconnect the pump.
- Connect the pulse height analyser.
- Note the pulse height on the oscilloscope (with a time factor of about 220 $\mu\text{s}/\text{cm}$). Select the amplification value on the pulse height analyzer in such a way to obtain a mean pulse height of about 5 V. Warning: the “magnifier” (Lupe) key may not be pressed.
- Select the 500 mV window and a timing cycle of 1.6 s.

Setting of the xy recorder

- Adjust the zero point setting in such a way that with no input voltage (i.e. with the zero keys on the recorder pressed) the recording stylus is located in the lower left hand corner of the recording surface. Switch the pulse height analyzer to “Manual”.
- Search for the intensity peak of the spectrum, i. e. adjust the pulse height analyzer to the maximum pulse rate (at about 5 V), using the adjustment knob “Basis”, and adjust the y-sensitivity in such a way that proper use can be made of the height of the recording surface.
- Lower the recording stylus briefly, marking the point on the x-axis corresponding to a pulse height of 6 V.

Recording of the spectra

A number of spectra are recorded in succession at different pressure values p , starting with $p \approx 0$ hPa* and increasing the pressure by steps by means of a brief opening of the ventilation screw in the vessel.

The following procedure is adopted for recording the spectra:

- Press the “Zero” key.
- Press the “Start/Stop” key and with the stylus raised depress the fast movement key until the required recording region in the x-direction is reached.

- Lower the recording stylus and record the spectra.
- Release the “Start/Stop” key and raise the stylus. Enter the corresponding pressure p on the graph sheet.

At a pressure between 200 and 250 hPa the residual energy of the α -particles will be so small that resolution of the spectrum from the noise is no longer possible. This brings the series of measurements to an end.

The vessel is then evacuated (with the pulse height analyzer switched off) and the ^{241}Am spectrum again recorded under vacuum conditions on a new sheet of recording paper. The spectrum is measured in succession after filling the vessel with He, N_2 and CO_2 at equal pressures (without changing the settings of the pulse height analyzer and recorder).

The following procedure should be adapted for filling the vessel with the gases:

- Connect the gas cylinder (pressure vessel) to the free connection of the 3-way tap with a piece of flexible vacuum tube.
- Switch on the vacuum pump.
- Turn the 3-way tap in such a way that the vessel and pipeline are evacuated into the gas cylinder.
- As soon as the vacuum gauge shows about 0 hPa, turn the 3-way tap in such a way that the vessel and gas cylinder are connected, but disconnected from the pump. Switch off the pump.

Warning

No overpressures are permissible in the vessel in view of the explosion hazard. The three knurled nuts on the preparation side of the vessel should therefore be unscrewed on safety grounds (the cover will remain tightly sealed so long as a vacuum is present in the vessel).

- Open carefully the fine regulator valve on the gas cylinder or pressure element and allow the gas to flow into the vessel, maintaining constant observation of the manometer.
- Close the fine regulator valve as soon as the required pressure has been reached (recommended value : 130 hPa). Record the spectrum, as described above.

The final step is to determine the absolute value of the mean energy at which the α -particles leave the emitter used in the preceding measurements, the measurement layout being calibrated with the open ^{241}Am -emitter for this purpose. It is recommended that the spectrum of the covered americium source should be recorded once again, selecting the amplification of the pulse height analyzer and the sensitivity on the x-input of the recorder in such a way that the calibration spectrum fits the recording paper properly without having to change the settings. The pulse height analyzer is then temporarily switched off and the vessel opened and ventilated so as to permit replacement of the source. After further evacuation, the open americium source is moved to a distance of 1 mm from the detector and the calibration spectrum recorded.

* This measurement is also used for calibration purposes; the energy of the α particles is determined in 3.

Fig. 2: Pulse rate measurement for different pressure values.
(See Table 1)

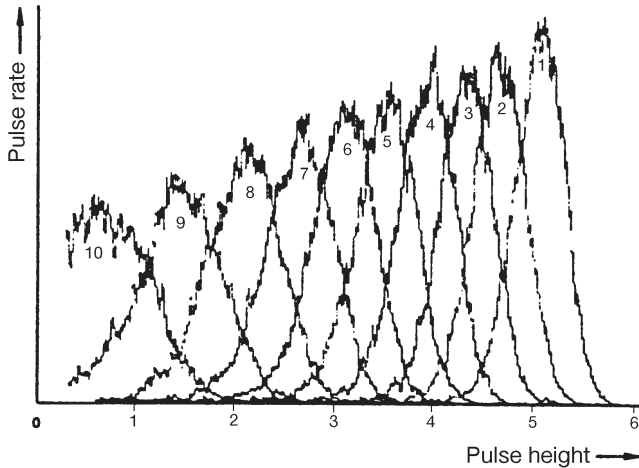


Table 1

Serial-No.	p hPa	x * mm	E MeV	$\frac{dE}{dx}$ MeV/mm
1	0	0	4.00	0.13
2	25	2.5	3.67	0.10
3	50	4.9	3.42	0.13
4	75	4.9	3.09	0.12
5	100	9.9	2.80	0.15
6	125	12.3	2.45	0.14
7	150	14.8	2.10	0.18
8	175	17.3	1.66	0.21
9	200	19.7	1.16	0.25
10	225	22.2	0.35	

* Calculated for $p = 1013$ hPa (distance from preparation to detector $s = 10$ cm).

Theory and evaluation

α -particles undergo various interactions during their passage through material. One possibility is that of scattering on contact with atomic nuclei. These elastic Rutherford scattering processes in which the α -particles suffer virtually no energy losses are extremely rare in relation to their inelastic interactions with atoms. These inelastic collisions cause ionization of the atoms, i.e. the α -particles loses a small proportion of their energy to an electron in the atomic shell. The mean energy loss per collision in air is 33.7 eV. The frequency of such collisions and in consequence the energy loss per unit of length is a function of the electron density in the absorber material and of the energy of the α -particles. The slower the speed of movement of the α -particles along their path, the more likely are interactions to occur with shell electrons, giving rise to an increase in the differential energy loss and a decrease in particle energy.

The probability of an electron colliding with an α -particle is proportional to the electron density in the absorbent gas. At identical pressure and temperature values this electron density in different gases follows the same behaviour pattern as the electron number N in the gas molecules.

N is equal to the atomic number of the atom in question and, in the case of molecules, to the sum of the atomic numbers of the atoms contained in the molecule.

Fig. 2 shows an example of a measurement carried out on a group of spectra recorded at different pressure values p . The individual spectra have been numbered and the corresponding data will be found in the table under these serial numbers.

The measuring device has to be calibrated for determination of the energy values. The table shown above is based on the mean energy at which α -particles leave the source, a value of 4.00 MeV. The remaining energies are determined from the central points of the energy distributions (the central point between the values along the abscissa of two points on the curves having the same ordinate value $N_0/2$, N_0 being the ordinate value at the peak of the curve).

In Fig. 3 the mean energy and the differential energy loss $-dE/dx$ of the α -particles has been plotted as a function of x . The increase in the differential energy loss as the particle approaches the end of its path is clearly apparent.

It is to be noted that the differential energy loss of the α -particle again decreases toward the end of its path as described by the Bethe formula:

$$\frac{dE}{dx} = - \frac{n Z z^2 e^4}{4\pi \epsilon_0^2 m_0 v_a^2} \cdot \ln \frac{2 m_0 v_a^2}{E}$$

in which

- n = atomic concentration in the retarding material,
- z = atomic number of the atoms in the retarding material,

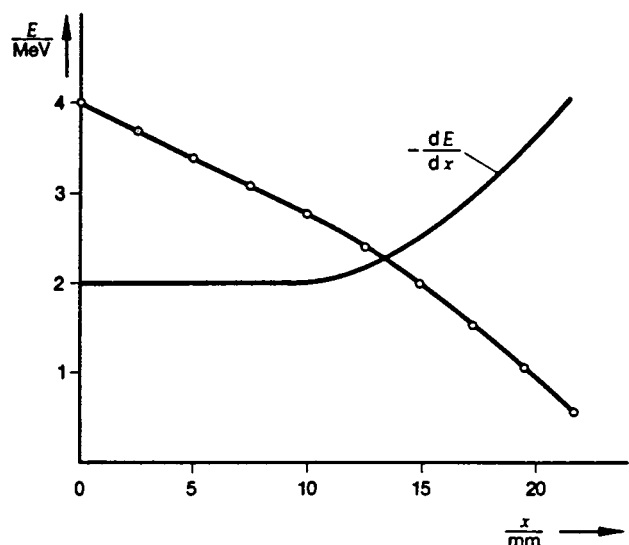
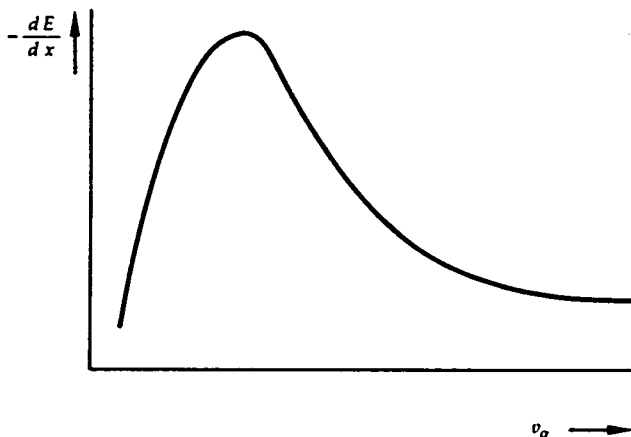


Fig. 3: Mean energy and differential energy loss $-dE/dx$ of α -particles as a function of x .

Fig. 4: Theoretical curve for the energy loss of α -particles as a function of their velocity.



- z = atomic number of the charged particles ($z = 2$ for α -particles),
- e = elementary charge,
- ε_0 = electric mass,
- v_α = velocity of the α -particles,
- \bar{E} = mean ionization potential

This connection between the differential energy loss and the α -particles velocity is shown in diagrammatic form in Fig. 4. The present experiment provides confirmation of this state of affairs only for the velocity range above the peak of the function shown in Fig. 4. The extremely low velocity range, in which the differential energy loss value again decreases, cannot be recorded with the semi-conductor detector as result of the noise produced by the measuring device.

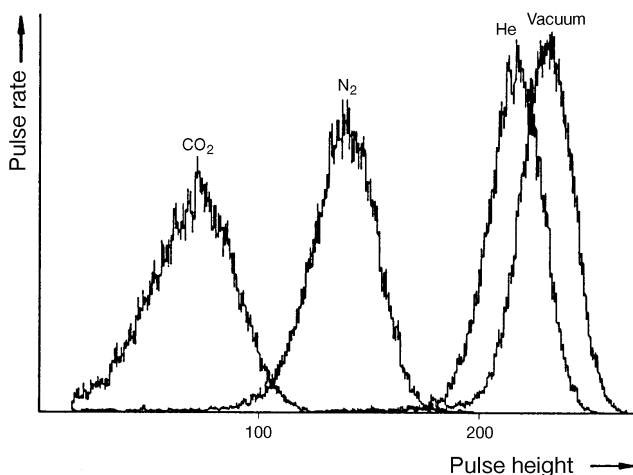


Fig. 5: Influence of the type of gas on the energy loss of α -particles.

A measurement example illustrating the influence of the type of gas on the energy loss of α -particles is shown in Fig. 5. The spectrum of the ^{241}Am source (370 kBq) is shown in this figure, for the three gases in each case with the same distance between source and detector (10 cm) and the same pressure (130 hPa), together with a spectrum measured under vacuum.

Whereas only a very minor displacement of the spectrum is observable in the case of helium, a substantial energy loss occurs in nitrogen and an even greater loss in carbon dioxide.

The data required for checking the connection between the energy loss ΔE and the number of electrons per molecule N are summarized in the table below:

Gas	$\frac{\rho}{\text{hPa}}$	ΔE^*	N	$\frac{\Delta E}{N}$
He	130	14	2	7.0
N ₂	130	93	14	6.6
CO ₂	130	163	22	7.4

It is evident that $\Delta E/N$ is constant within the limits of measurement accuracy.

Note

The expression

$$\frac{\Delta E}{N} = \text{const}$$

is not strictly valid for the absolute energy loss ΔE along a fixed path. The expression relates rather to the differential energy loss $dE(E_\alpha)/dx$ at any fixed energy E_α .

The ratio $\Delta E/N$ is only assumed to be constant if the measurement path for all three gases is not substantially greater than half the α -particle range, since in this case the differential energy loss will be approximately constant over the complete path (see Fig. 4). If this condition is not met (in contrast to the situation in the present experiment), $\Delta E/N$ will increase with N , since with an increase in N the α -particles will be increasingly retarded to energies at which the differential energy loss rises sharply.

A more correct but very much more laborious procedure would therefore be to fill the vessels with the different gases of different pressures p in such a way as to obtain the same energy loss in each case (i.e. the plot of the different spectra would virtually coincide). To obtain a constant energy loss, the electron concentration n in the gas must in each case be constant. Since:

$$n \sim N \cdot p,$$

it is to be expected that $N \cdot p$ will be constant and that this result will not be prejudiced by the energy-dependence of the differential energy loss.

* Arbitrary units, identical for all measurements.