Atomic and Nuclear Physics

Nuclear physics
γ-*spectroscopy*

LEYBOLD
Physics
Leaflets

P6.5.5.1

Detecting γ radiation
with a scintillation counter

Objects of the experiments

- Studying the scintillator pulses with an oscilloscope
- Determining the pulse heights as a function of the voltage at the photomultiplier of the scintillation counter
- Analysing the pulse-height distribution that corresponds to the absorption of monoenergetic γ radiation using a multichannel analyser
- Identifying the total-absorption peak and determining the half-width
- Identifying the *Compton* distribution
- Identifying the backscatter peak

Principles

The energy of γ radiation can be determined by means of a scintillation counter. The radiation interacts with the scintillator crystal and thus gives rise to light pulses which are transformed into voltage pulses by a photomultiplier. The number of emitted photons and the pulse height are proportional to the γ energy. Pulse-height analysis is performed by means of a multichannel analyser (MCA) which is connected to a computer (PC).

NaI(Tl) scintillators

NaI(Tl) is a common material for the construction of scintillation counters. Doping with thallium (Tl) provides for luminous centres. Due to the iodine content, the detection probability for γ radiation is very high. The detection mechanism is initiated by an energy transfer to electrons which are then slowed down in the scintillator crystal. Pairs of populated states in the conduction band and unpopulated states in the valence band are released. The number of these electron-hole pairs is proportional to the absorbed energy E_S, since the formation of an electron-hole pair always requires the same energy.

The thallium atoms integrated in the crystal are ionized by interaction with holes produced during the slowing down of the primary electron. After subsequent recombination with an electron, they emit photons with an energy between 2.9 and 3.1 eV. The number N_S of photons is thus proportional to the absorbed energy E_S.

Fig. 1   Diagram of a scintillation counter
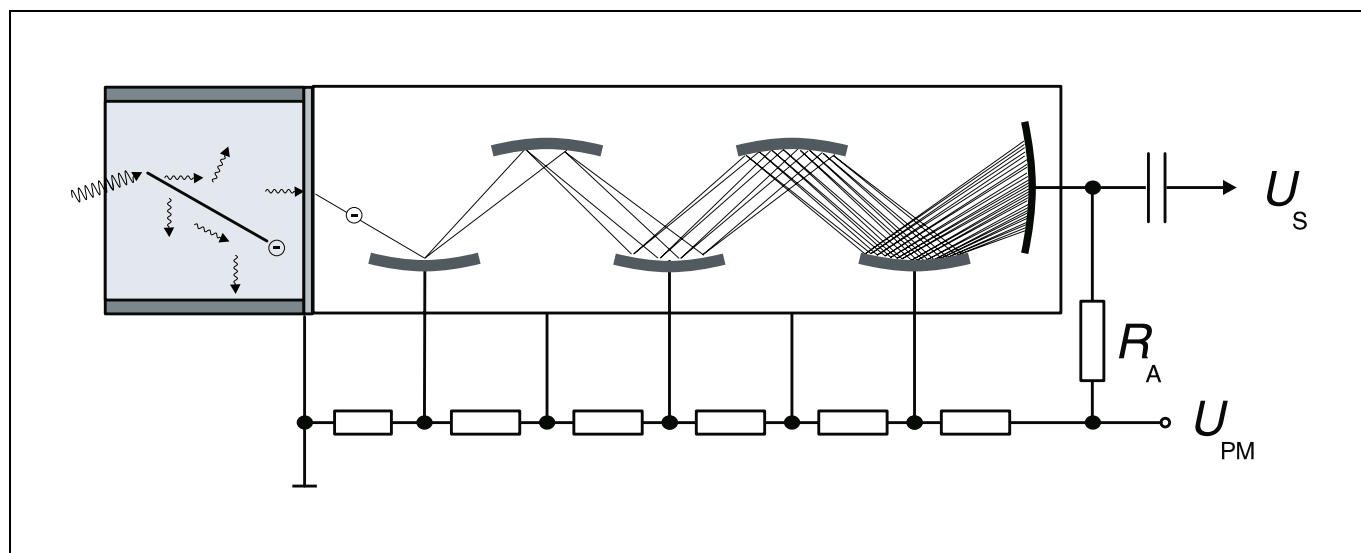
Apparatus

1 set of radioactive preparations	559 83
1 scintillation counter	559 901
1 high voltage power supply 1.5 kV	521 68
1 MCA-CASSY	529 780
1 MS-DOS-Connector L	524 001
or from	524 007
1 stand rod, 47 cm	300 42
1 Leybold multiclamp	301 01
1 universal clamp S	666 555

additionally required:

1 PC with MS-DOS > 3.0

additionally recommended:

1 two-channel oscilloscope 303	575 211
1 BNC cable, 1 m long	501 02

The NaI crystal is transparent for the emission photons. In addition, the absorption of these photons by other thallium atoms is very unlikely as the concentration of thallium atoms is low. Moreover, the crystal is sealed against light in a housing made from strongly reflecting material. So a large part of the emitted photons reaches the attached photocathode of the photomultiplier.

The emitted photons knock out electrons in the photocathode. Subsequently, the electron current is amplified in an avalanche-like manner through production of secondary electrons in a number of series-connected dynodes (see Fig. 1). The amplification factor for one dynode depends, among other things, on the potential difference between the dynodes and

on the dynode material. The dynode potentials are tapped at a voltage divider that is fed with the heat and long-term stable high voltage U_{PM}.

An amount of charge Q_S proportional to N_S reaches the anode. The corresponding anode current through a load resistor R_A generates a voltage signal U_S. U_S is proportional to Q_S if the decay time constant of the primary pulse is considerably larger than the time constant of the light emission by the excited thallium atoms ($\tau = 0.23\ \mu s$). Altogether, the pulse amplitude U_S is thus proportional to the absorbed radiation energy E_S.

Multichannel pulse-height analysis

The scintillator signals are then processed in a multichannel analyser, the central component of which is an analog-digital converter. The analog-digital converter measures the pulse height U_S and converts the measuring value into a proportional digital value k_S. More precisely, k_S corresponds to a pulse-height interval, the width of which depends on the resolution of the analog-digital converter. The computer allocates a storage location for every digital value and counts the events at every storage location. The result is a histogram representing the pulse-height distribution. The histogram can be displayed graphically on the computer screen or in the form of a table. An energy calibration is required for a quantitative evaluation because the coefficients of the proportionalities $E_S \sim N_S \sim Q_S \sim U_S \sim k_S$ are at first unknown.

Interaction of γ radiation with matter

In the γ-energy range from 50 to 2000 keV two interaction processes of the γ radiation with the scintillator crystal play a predominant role.

1. Photoeffect: The γ quantum transfers its total energy E_γ to an atom of the crystal knocking out a bound electron. Apart from the amount that corresponds to the binding energy, the γ energy turns into kinetic energy of the electron. This kinetic energy is transferred to the scintillator crystal by inelastic scattering. The ionized atom emits roentgen quanta or *Auger* electrons, the energy of which is, as a rule, also completely absorbed within the detector. This means that the total of the absorbed energy E_S is equal to the energy E_γ. In this case, the γ radiation is registered in the total-absorption peak (see Fig. 2).

Fig. 2   Histogram of a simplified pulse-height distribution corresponding to the absorption of monoenergetic γ radiation
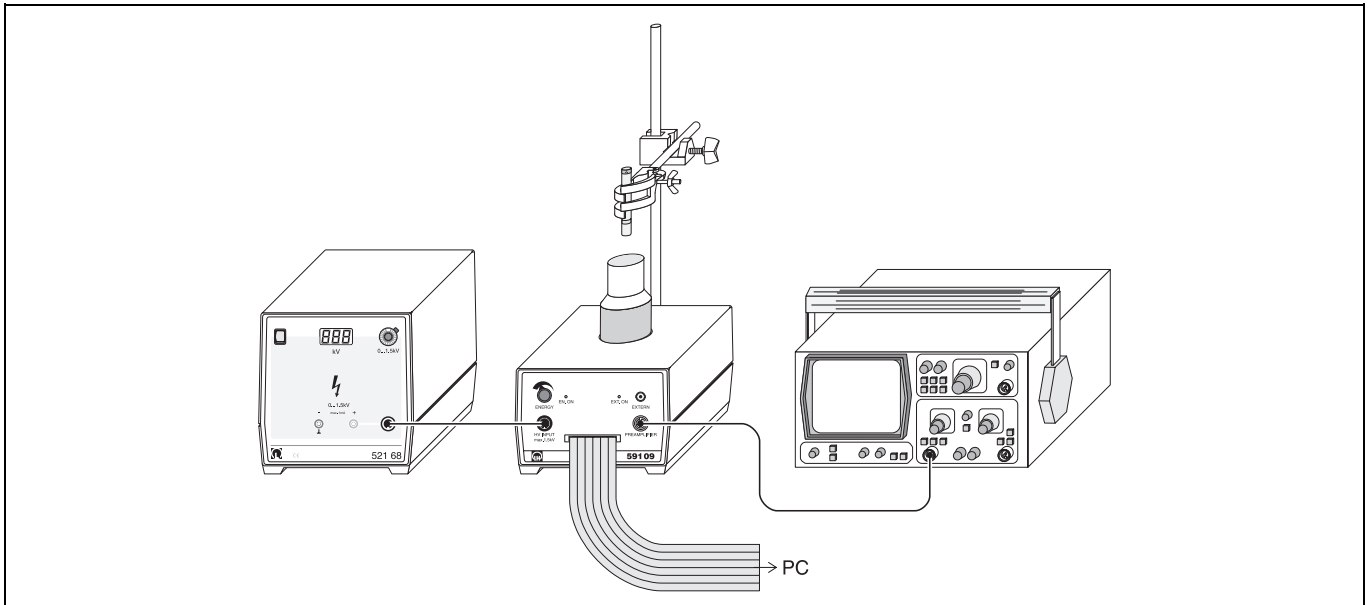**a** *Compton*-distribution
b total-absorption peak
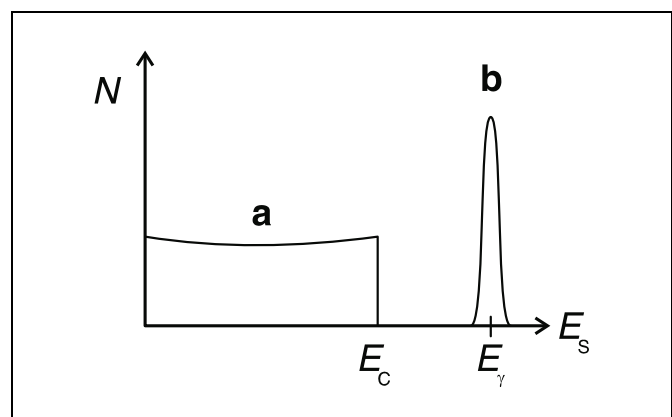
2. *Compton* effect: In an elastic collision with an electron, a part of the γ energy turns into kinetic energy of the electron. The rest of the γ energy remains with the scattered γ quantum which, with a certain probability, leaves the crystal without further interaction. The energy E_S absorbed in the detector then lies between 0 keV (forward scattering of the γ quantum) and a maximum value E_C (backward scattering of the γ quantum), which is smaller than E_γ. The primary γ quantum is registered in the *Compton* distribution (see Fig. 2). A large part of the scattered γ quanta is absorbed by the scintillator crystal in a second process through the photo effect. In this case, the energy E_S absorbed by the detector is equal to E_γ. The primary γ quantum is registered in the total-absorption peak.

Setup

The experimental setup is illustrated in Fig. 3.

Mechanical setup:

–   Clamp the stand rod with the Leybold multiclamp and the universal clamp on the back of the MCA-CASSY.
–   Plug the connections of the photomultiplier into the detector base socket of the MCA-CASSY.

Connection of the MCA-CASSY:

–   Connect the MCA-CASSY with a high-voltage cable to the high voltage power supply and to the MS-DOS-Connector L with a flat line.
–   Switch the MCA-CASSY on to activate the amplifier stage.

Connection of the oscilloscope (if available):

–   Connect the BNC socket "EXTERN" of the MCA-CASSY to channel I of the oscilloscope.
–   Use the light shield of the oscilloscope or darken the room.

Carrying out the experiment

a) Studying the scintillator pulses with an oscilloscope (if available):

–   Clamp the set of radioactive preparations in the universal clamp with the outlet directed downward and align it so that the preparation is centred above the aperture of the scintillation counter at a distance of about 1 cm.
–   Slowly increase the voltage U_{PM} of the high voltage power supply from 0 V to 500–700 V and study the voltage pulses with the following oscilloscope settings:

    time base: ca. 0.2 μs/DIV.
    Y scan: 0.2–0.5 VOLT/DIV.
    coupling: DC
    zero line: upper edge of the screen
    trigger: – (negative flank)

–   Vary the voltage U_{PM}, determine the height U_S of the bright signal on the oscilloscope screen and record it.

b) Studying the scintillator pulses with a multichannel analyser:

–   Get the program "MCA" started.
–   Choose "Define settings" in the main menu:

    resolution = 8 bit (256 channels)
    line diagram (confirm with <CR>)
    measuring time = 60 s

–   Choose "Record measurement" in the main menu:

    choose spectrum = spectrum 1

–   Get the measurement started in the measurement screen with "F1".
–   Slowly increase the voltage U_{PM} of the high voltage power supply from 0 V until pulses are counted around the middle of the screen.

–   Erase the old measuring values with <Ctrl + C> and start a new measurement with <F1>.
–   After finishing the measurement, change to "Evaluate in graph" in the main menu, switch the graphic cursor on with <F9>, determine and record the following form parameters of the total-absorption peak which are explained in Fig. 4:

   peak position k_{max}
   peak height N_{max},
   half-width $\Delta k_{1/2}$ (accuracy ±0.1)
   integrated counting rate (area) N_{int}.

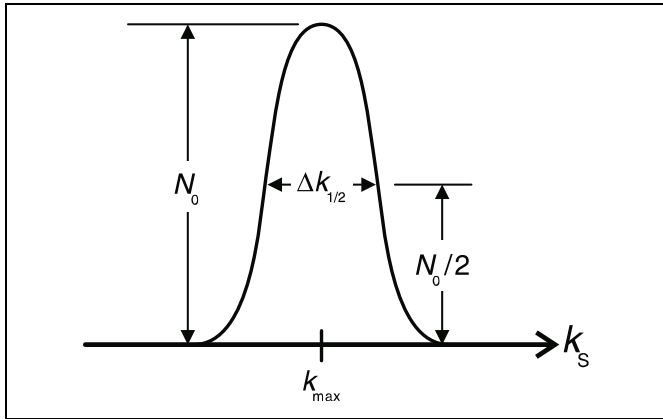–   Repeat the measurement at other voltages U_{PM} (see Table 2).

Fig. 4   Form parameters of the total absorption peak

c) Recording a histogram:

–   Select "Define settings" in the main menu: measuring time = 300 s
–   Select the voltage U_{PM} so that the position of the total-absorption peak is at about $k_S = 220$.
–   Erase the old measuring values with <Ctrl + C>, and start a new measurement with <F1>.

Measuring example and evaluation

a) Studying the scintillator pulses with an oscilloscope:

Fig. 5 shows the pulse-height distribution on an oscilloscope screen. The signals with high counting rates correspond to the total-absorption peak of the monoenergetic γ radiation of Cs–137 (see Fig. 9). The dependence on the voltage U_{PM} can be seen from Table 1 and Fig. 6.

Fig. 5   Oscilloscope presentation of th pulse-height distribution of the monoenergetic γ radiation of Cs-137
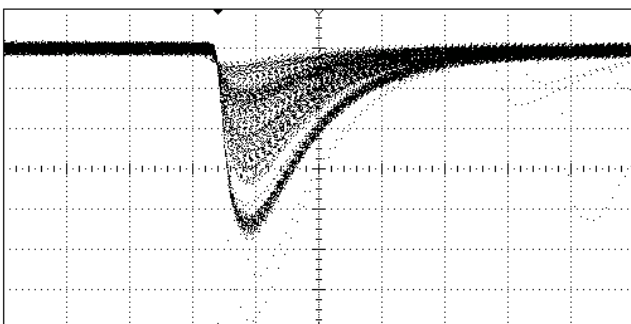

Table 1: The pulse height U_S of the total-absorption peak as a function of the voltage U_{PM} at the photomultiplier

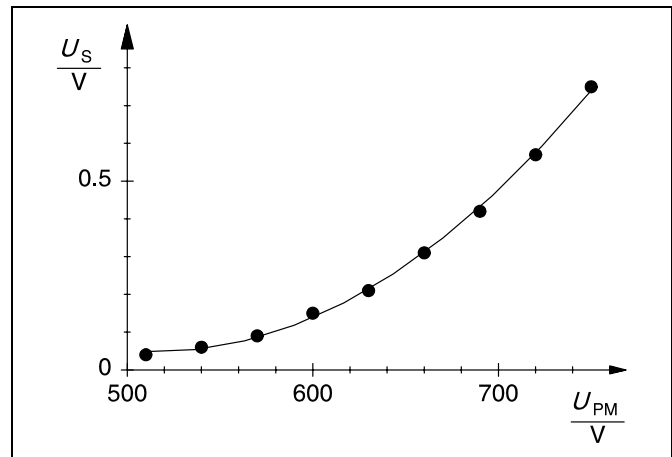| $\dfrac{U_{PM}}{V}$	$\dfrac{U_S}{V}$
510	−0.04
540	−0.06
570	−0.1
600	−0.14
630	−0.20
660	−0.29
690	−0.40
720	−0.56
750	−0.78

Fig. 6   The pulse height U_S of the total-absorption peak signals U_{PM}

b) Studying the scintillator pulses with a multichannel analyser:

Table 2: Parameters characterising the total-absorption peak as functions of the voltage

$\dfrac{U_{PM}}{V}$	k_{max}	N_{max}	$\Delta k_{1/2}$	N_{int}	$\dfrac{\Delta k_{1/2}}{k_{max}}$
510	11.5				
540	18	29000	3.8	118700	21.1 %
570	29	21100	4.1	103700	14.1 %
600	45.5	17300	5.5	100500	12.1 %
630	66	14000	6.4	97700	9.7 %
660	95	11500	7.7	95500	8.1 %
690	131.5	9100	9.5	93200	7.2 %
720	178	6600	13.3	93300	7.5 %
750	232	4400	19.7	92300	8.5 %

In Table 2, the form parameters of the total-absorption peak are listed as functions of the voltage U_{PM}. Fig. 7 shows that if the voltage increases with the other measuring conditions being the same, then the peak height drops and the width broadens, whereas the area under the peak remains approximately constant. Thus the peak area is the only useful measure for the intensity of the registered γ radiation. Fig. 8 shows the dependence of the relative width $\dfrac{\Delta k_{1/2}}{k_{max}}$ on the voltage U_{PM}.
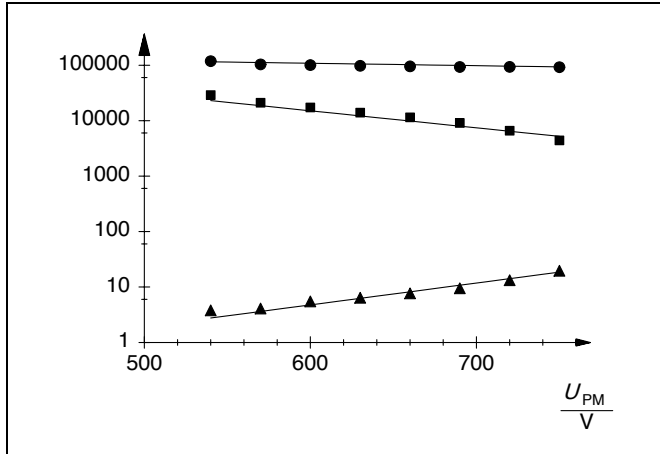

Fig. 7   The integrated number of counts N_{int} (circles), the height N_{max} (boxes) and the width $\Delta k_{1/2}$ as functions of the voltage U_{PM}
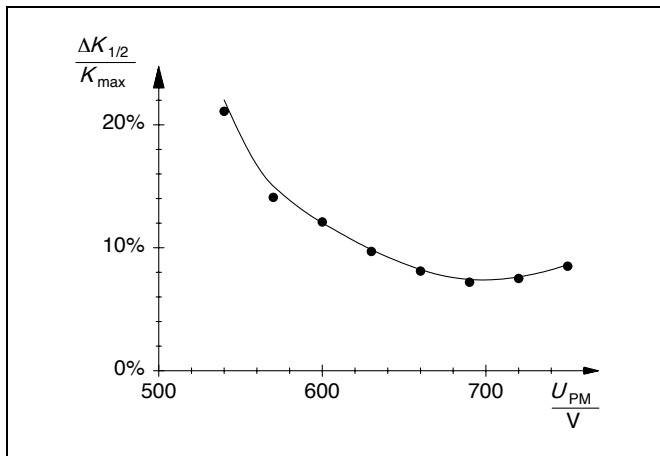

Fig. 8   The relative width $\dfrac{\Delta k_{1/2}}{k_{max}}$ of the total-absorption peak as a function of the voltage U_{PM}

c) Recording a histogram:

c1) Energy calibration

For the energy calibration of the histogram shown in Fig. 9, a two-point calibration has to be made because the zero of the analog-digital converter cannot be precisely adjusted. The adjustment is made with the 662-keV radiation of the Cs–137 isotope (E_γ = 662 keV, k_{max} = 219) and the 60-keV radiation of the Am–241 isotope (E_γ = 60 keV, k_{max} = 21.7) which is admixed with the preparation.

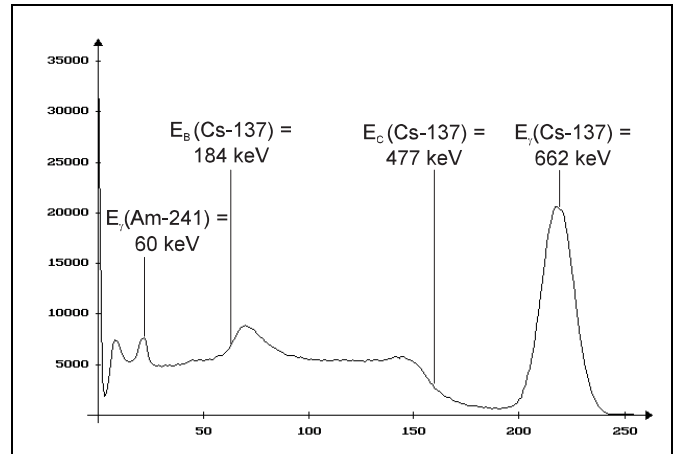This results in E_γ = 3.05 keV $\cdot$ k – 6.7 keV

Fig. 9   Graph of the pulse height spectrum of γ radiation of Cs–137

c2) Compton distribution

The energy of a γ quantum *Compton* scattered under the angle ϑ is

$$E_{\gamma'} = \frac{E_\gamma}{1 + \dfrac{E_\gamma}{m_0 \cdot c^2} \cdot (1 - \cos\vartheta)} \qquad (I)$$

E_γ: energy of the incoming γ quantum,
$E_{\gamma'}$: energy of the scattered γ quantum,
$m_0 \cdot c^2$ = 511 keV: rest energy of the electron

For the *Compton* edge of the Cs–137 radiation one obtains E_C = $E_\gamma - E_{\gamma'}(\vartheta = 180°)$ = 477 keV. This value corresponds to k = 159 in the histogram. The edge is smeared out in the histogram because the scintillation counter has a finite resolution and because events in the range between E_C and E_γ are also registered.

c3) Backscatter peak

There are also events in the histogram that go back to *Compton* scattering of γ quanta in the preparation. The scattered γ quantum is then absorbed in the scintillation counter. In the Compton scattering of the Cs–137 radiation at least the energy $E_B = E_{\gamma'}(\vartheta = 180°)$ = 184 keV is transferred. This energy corresponds to k = 63.