Detecting $\gamma$ 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 $\gamma$ 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 $\gamma$ 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 $\gamma$ energy. Pulse-height analysis is performed by means of a multichannel analyser (MCA) which is connected to a computer (PC).

$\text{NaI(Tl)}$ scintillators

$\text{NaI(Tl)}$ 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 $\gamma$ 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 $E_S$.

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**Fig. 1** Diagram of a scintillation counter
The NaI crystal is transparent to 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 $U_{PH}$.

An amount of charge $Q_S$ proportional to $N_S$ reaches the anode. The corresponding anode current through a load resistor $R_L$ generates a voltage signal $U_Q$. $U_Q$ 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 $U_Q$ 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 $U_Q$ 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 $E_S \sim N_S \sim Q_S \sim k_S$ are at first unknown.

**Interaction of $\gamma$ radiation with matter**

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

1. Photoeffect: The $\gamma$ quantum transfers its total energy $E_{\gamma}$ to an atom of the crystal knocking out a bound electron. Apart from the amount that corresponds to the binding energy, the $\gamma$ 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 $E_{\gamma}$ In this case, the $\gamma$ radiation is registered in the total-absorption peak (see Fig. 2).

![Histogram of a simplified pulse-height distribution corresponding to the absorption of monoenergetic $\gamma$ radiation](image)

- **Compton-distribution**
- **Total-absorption peak**

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**Safety notes**

Country-specific regulations must be observed, such as the Radiation Protection Regulation (StrSchV) in Germany, when radioactive preparations are handled. The radioactive substances used in this experiment are approved for teaching purposes at schools in accordance with the StrSchV. Since they produce ionizing radiation, the following safety rules must nevertheless be complied with:

- Prevent access to the preparation by unauthorized persons.
- Before using the preparation make certain that it is intact.
- With the object of shielding, keep the preparation in its safety vessel.
- To ensure minimum exposure time and minimum activity, take the preparation out of the guard vessel only as long as is necessary in order to perform the experiment.
- To ensure maximum distance, take hold of the preparation only at the upper end of the metal holder.
2. **Compton effect**: In an elastic collision with an electron, a part of the $\gamma$ energy turns into kinetic energy of the electron. The rest of the $\gamma$ energy remains with the scattered $\gamma$ 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 $\gamma$ quantum) and a maximum value $E_C$ (backward scattering of the $\gamma$ quantum), which is smaller than $E_\gamma$. The primary $\gamma$ quantum is registered in the Compton distribution (see Fig. 2). A large part of the scattered $\gamma$ 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 $E_\gamma$. The primary $\gamma$ quantum is registered in the total-absorption peak.

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**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.

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**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.
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>.

![Diagram of parameters of the total absorption peak](image)

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

<table>
<thead>
<tr>
<th>$U_{PM} / V$</th>
<th>$U_S / V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>510</td>
<td>-0.04</td>
</tr>
<tr>
<td>540</td>
<td>-0.06</td>
</tr>
<tr>
<td>570</td>
<td>-0.1</td>
</tr>
<tr>
<td>600</td>
<td>-0.14</td>
</tr>
<tr>
<td>630</td>
<td>-0.20</td>
</tr>
<tr>
<td>660</td>
<td>-0.29</td>
</tr>
<tr>
<td>690</td>
<td>-0.40</td>
</tr>
<tr>
<td>720</td>
<td>-0.56</td>
</tr>
<tr>
<td>750</td>
<td>-0.78</td>
</tr>
</tbody>
</table>

![Graph showing pulse height $U_S$ as a function of voltage $U_{PM}$](image)

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

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**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 \( \gamma \) radiation of Cs–137 (see Fig. 9). The dependence on the voltage $U_{PM}$ can be seen from Table 1 and Fig. 6.

![Oscilloscope presentation of pulse-height distribution](image)

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

<table>
<thead>
<tr>
<th>$U_{PM} / V$</th>
<th>$k_{max}$</th>
<th>$N_{max}$</th>
<th>$\Delta k_{1/2}$</th>
<th>$N_{int}$</th>
<th>$\Delta k_{1/2} / k_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>510</td>
<td>11.5</td>
<td>29000</td>
<td>3.8</td>
<td>118700</td>
<td>21.1 %</td>
</tr>
<tr>
<td>540</td>
<td>18</td>
<td>29000</td>
<td>3.8</td>
<td>118700</td>
<td>21.1 %</td>
</tr>
<tr>
<td>570</td>
<td>29</td>
<td>21100</td>
<td>4.1</td>
<td>103700</td>
<td>14.1 %</td>
</tr>
<tr>
<td>600</td>
<td>45.5</td>
<td>17300</td>
<td>5.5</td>
<td>100500</td>
<td>12.1 %</td>
</tr>
<tr>
<td>630</td>
<td>66</td>
<td>14000</td>
<td>6.4</td>
<td>97700</td>
<td>9.7 %</td>
</tr>
<tr>
<td>660</td>
<td>95</td>
<td>11500</td>
<td>7.7</td>
<td>95500</td>
<td>8.1 %</td>
</tr>
<tr>
<td>690</td>
<td>131.5</td>
<td>9100</td>
<td>9.5</td>
<td>93200</td>
<td>7.2 %</td>
</tr>
<tr>
<td>720</td>
<td>178</td>
<td>6600</td>
<td>13.3</td>
<td>93300</td>
<td>7.5 %</td>
</tr>
<tr>
<td>750</td>
<td>232</td>
<td>4400</td>
<td>19.7</td>
<td>92300</td>
<td>8.5 %</td>
</tr>
</tbody>
</table>
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 $\gamma$ radiation. Fig. 8 shows the dependence of the relative width $\frac{\Delta k_{1/2}}{k_{max}}$ on the voltage $U_{PM}$.

**Fig. 7** The integrated number of counts $N_{max}$ (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 $\frac{\Delta k_{1/2}}{k_{max}}$ of the total-absorption peak as a function of the voltage $U_{PM}$

![Graph of the pulse height spectrum of $\gamma$ radiation of Cs–137](image)

**c2) Compton distribution**

The energy of a $\gamma$ quantum Compton scattered under the angle $\phi$ is

$$E'_{\gamma} = \frac{E_{\gamma}}{1 + \frac{E_{\gamma}}{m_0 \cdot c^2} \cdot (1 - \cos \phi)}$$

$E'_{\gamma}$: energy of the incoming $\gamma$ quantum,

$E_{\gamma}$: energy of the scattered $\gamma$ quantum,

$m_0 \cdot c^2 = 511$ keV: rest energy of the electron

For the Compton edge of the Cs–137 radiation one obtains $E_C = E_{\gamma} - E'_{\gamma}(\phi = 180^\circ) = 477$ 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 $E_{\gamma}$ are also registered.

**c3) Backscatter peak**

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

**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 ($E_{\gamma} = 662$ keV, $k_{max} = 219$) and the 60-keV radiation of the Am–241 isotope ($E_{\gamma} = 60$ keV, $k_{max} = 21.7$) which is admixed with the preparation.

This results in $E_{\gamma} = 3.05$ keV $\cdot k - 6.7$ keV