Experiment 29

Neutron Activation Analysis

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Location of the experiment: Room 133 (Control Room of the Tandem Accelerator)

Literature:
• W. Bischof: Zulassungsarbeit, Erlangen 1982 (in German, available by supervisor)
• W. R. Leo: Techniques for Nuclear and Particle Physics Experiments 1.9-1.11, 2.6, 2.7, 4.1-4.4
• G. Musiol, R. Reif, D. Seeliger: Kern- und Elementarteilchenphysik, Kap. 4 und 5
Neutron Activation Analysis

Characteristics:
- A method for nondestructive testing of materials
- High-sensitivity, qualitative and quantitative determination of elements (here: Cu, V)
- Nuclear physics measurement method
  - Radioactivity
  - Radiation protection policy
  - Dosimeter, radiation protection prescriptions

Principle:
1. Activation of the sample → radionuclides
2. Measurement of γ-emission spectrum
3. Analysis
Radioactivity

Definition:
Spontaneous conversion of unstable isotopes of elements into other isotopes with emission of certain particles.
Reaction of the atomic nucleus!

Glossary: $^A_Z X_N$ Z: nuclear charge / number of protons
e.g. $^{65}_{29}\text{Cu}_{36}$ A: mass / nucleon number
N: number of neutrons

Basic types of radioactivity:
• $\alpha$-decay (emission of a helium nucleus 4 He)
• $\beta$-decay ($e^-$ or $e^+$ emission)
• spontaneous fission
...
• $\gamma$-decay
  ➢ Emission of a photon by an excited nucleus
  ➢ A result of a previous $\alpha$- or $\beta$-decay, of a nuclear reaction, or of an inelastic collision with another nucleus or particle
    $\rightarrow$ characteristic spectral lines

Keywords: Karlsruhe nuclide chart
Activation and Activity

- **Activation:**
  Operation of nuclear excitation of a particular isotope by multiple stimulation channels / processes

- **Activation rate (neutron activation):**
  Number $C_\infty$ of activated atoms of a particular isotope for the constant neutron flux per sample and time

- **Activity:**
  Number $C(t)$ of decayed radionuclides per sample and time

- **Formulas:**
  \[ C(t) = \lambda B(t), \quad B(t): \text{Number of existing radionuclides} \]
  \[ \lambda: \text{decay constant} \]

  During activation, the following applies:
  \[ \frac{dB(t)}{dt} = C_\infty - \lambda B(t) \]
  with Ansatz:
  \[ B(t) = \frac{C_\infty}{\lambda} \times (1 - e^{-\lambda t}) \]
  it follows:
  \[ C(t) = C_\infty \times (1 - e^{-\lambda t}) \]

  After the activation is stopped $t > t_B$: $C_\infty = 0$
  \[ B(t) = B(t_B) \times e^{-\lambda(t-t_B)} \]
Step 1 – Activation: Technical Realization

Bombardment of the sample with
- $\gamma$ – radiation
- $e^-$ beam
- Charged particles (protons, deuterons)
- Neutrons

leads to the desired nuclear reactions

Preferably, thermal neutrons, $E_{\text{kin}} = (10-100)$ MeV
- Nuclear reaction of the same type: $(n, \gamma)$-compound
- Large cross section $\rightarrow$ good sensitivity
- Deep penetration $\rightarrow$ analysis of thick samples
- No Coulomb repulsion

Sources in the experiment:
$^{252}$Cf and $^{247}$Am-$^9$Be fission sources with moderator
Scheme of the \((n, \gamma)\)-reaction triggered by a thermal neutron with subsequent \(\beta^-\) decay of the resulting radionuclide.
Step 1 – Activation: Test Samples

<table>
<thead>
<tr>
<th>Element</th>
<th>Use</th>
<th>Isotope</th>
<th>$\sigma_{\text{act}}/b$</th>
<th>Radionuclide</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A/%</td>
<td>T$_{1/2}$</td>
<td>E$_{\gamma}$/MeV</td>
</tr>
<tr>
<td>Vanadium</td>
<td>Tools</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{50}\text{V}$</td>
<td>0.24</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{51}\text{V}$</td>
<td>99.76</td>
<td>4.5</td>
</tr>
<tr>
<td>Copper</td>
<td>Coins</td>
<td>$^{63}\text{Cu}$</td>
<td>69.1</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>Brass</td>
<td>$^{65}\text{Cu}$</td>
<td>30.9</td>
<td>1.8</td>
</tr>
</tbody>
</table>

T$_{1/2}$ $\leftrightarrow$ activation time (15 min), measurement time (10 min)

Higher detection sensitivity for Vanadium:

- Mass fractions A
- Activation cross-section $\sigma_{\text{act}}$
- Decay schemes
Step 1 – Activation: Vanadium V

\[
\begin{align*}
^{50}\text{V} + n & \rightarrow 11.052 \text{ MeV} \\
^{51}\text{V} + n & \rightarrow 11.290 \text{ MeV} \\
^{52}\text{V} & \rightarrow 3.979 \text{ MeV} \\
^{52}\text{Cr} & \rightarrow 0 \text{ MeV}
\end{align*}
\]
Step 1 – Activation: Copper Cu

$^{63}\text{Cu} \ + n \rightarrow 9.593 \text{ MeV}$

$^{64}\text{Ni} \rightarrow 0 \text{ MeV}$

$^{64}\text{Cu} \rightarrow 1.348 \text{ MeV}$

$^{64}\text{Cu} \rightarrow 1.677 \text{ MeV}$

$^{64}\text{Zn} \leftarrow \beta^+ \rightarrow 0.511 \text{ MeV}$

$^{64}\text{Zn} \leftarrow \beta^- \rightarrow 1.041 \text{ MeV}$

$^{65}\text{Cu} \ + n \rightarrow 9.698 \text{ MeV}$

$^{66}\text{Cu} \rightarrow 2.633 \text{ MeV}$

$^{66}\text{Zn} \rightarrow 1.039 \text{ MeV}$

$P = 9.25\%$
Step 2 – measurement of $\gamma$-spectrum: test setup

P: Probe
Ge(Li): Germanium (lithium doped) semiconductor detector cooled with liquid $\text{N}_2$
PA: preamplifier
MA: main amplifier
LGS: Linear gate stretcher
MCA: Multi-channel analyzer
⇒ Pulse height analysis: energy spectrum
⇒ multi-channel scanning: half-life
Step 2 – measurement of $\gamma$-spectrum: Interaction of $\gamma$-radiation with matter

3 processes:
- Photoeffect
- Compton effect
- Pair production

Process of electron-positron pair production as a result of the absorption of a $\gamma$-quantum in the Coulomb field of the nucleus (or an electron).

Requirement: $E \geq 2 \cdot m_e c^2 \geq 1022$ keV

$\Rightarrow$

1. Deep penetration of $\gamma$-rays in matter
2. Validity of the Beer-Lambert law

$$I(x) = I_0 e^{-\mu x}$$

with $I$: intensity
$\mu$: linear absorption coefficient

Here: $\mu = n \sigma = n (\sigma_{\text{ph}} + \sigma_{C} + \sigma_{P})$

with $\sigma$: absorption cross section
$n$: atomic density
Step 2 – measurement of $\gamma$-spectrum: Interaction of $\gamma$-radiation with matter

- **Photoeffect**
- **Compton effect**
- **Pair production**
Step 2 – measurement of γ-spectrum: absorption cross section
Step 3 – Analysis

a) Calibration of the MCA (pulse height analysis mode) with a gamma calibration source (known emission lines)

b) Background investigations of Ge detector

c) Spectroscopy – following the scheme:
   – Activation ($t_B$)
   – Transportation to the test setup ($t_T$)
   – Measurement of the activity over the period $t_M$. The spectra are measured for:
     • A standard sample Cu/V (known mass)
     • Samples with unknown content of Cu/V, determination of the Cu/V content by comparing the heights of the characteristic spectral lines

d) Determine the half-life of $^{52}V$:
   Activation and transport as above, but then data acquisition in multi-channel scanning mode (count rate as a function of time)