Detectors for the measurement of ionizing radiation

For the measurement of radiation, the following reactions during the irradiation of matter are predominantly utilized:

- Ionization in gases
  (Ionization chamber, proportional flow counter, release counter)

- Scintillation in solids and liquids
  ($\beta$- and $\gamma$- scintillation counters)

- Ionization in solids
  (semiconductor-detectors)
Detectors for the measurement of ionizing radiation

Ionization of gases (gas-filled detectors)

Ionization chamber:
50 – 300 V, air, no secondary ionization
Detectors for the measurement of ionizing radiation

Geiger-Müller Counter

- GM counter: $\geq 800$ V, Argon, electron cascade is generated ($10^{10}$ electron pairs)
- Quench gas is needed ($\text{Cl}_2$)
  - Only count information can be recorded, no energy
- Dead time: time interval after a pulse during which the counter is insensitive to further ionizing events
- Higher count rates mean more counts will be missed
- Geiger-Müller counters are most suitable for measuring high-energy $\beta$ radiation ($E_{\text{max}} > 1$ MeV)
Detectors for the measurement of ionizing radiation

Proportional Flow Counter

- Proportional counter: 300 – 800 V, argon or xenon, electron cascade is generated ($10^6$ electron pairs)
- Total charge is proportional to the energy deposited

Count rate and energy information on the incident radiation can be obtained

Discerning of alpha from beta radiation

Especially suited for measuring $\alpha$- and $\beta$-emitters
Scintillation

- Scintillation is the property of luminescence when excited by ionizing radiation.

- The energy of the original signal is preserved through the PMT, but precision is lost ⇒ poor energy resolution.

- Inorganic scintillators contain dense high Z materials ⇒ They are very efficient at detecting X- and γ-rays.
Solid Scintillation Detectors

In order to absorb the largest possible amount of the $\gamma$-radiation, thick crystals with large densities are used; e.g. sodium iodide crystals doped with thallium ($\rho = 3.67 \text{ g cm}^{-3}$).

By using organic crystals like anthracene, trans-stilbene or p-terphenyl, $\beta$ radiation can be detected.
Detectors for the measurement of ionizing radiation

Scintillation / $\gamma$-scintillation counter (COBRA 5002)

- Analytical Method: Quantitative
- Detector: Thallium-activated sodium iodide crystal (through-hole design)

Manual Region: 15 – 2000 keV
(e.g. Tc-99m 140 keV)

Efficiency: >72% for I-125
(others have to be distinguished)
Detectors for the measurement of ionizing radiation

Liquid Scintillation Detectors

Primary Scintillators: 320 – 360 nm

Secondary Scintillators: 410 – 470 nm

Aromatic solvent in the scintillation cocktail: Absorbs the kinetic energy from a charged particle and transfers the energy to the primary scintillator molecules.
Liquid Scintillation Detectors

Quenching is the loss of counts due to sample or cocktail characteristics

**Chemical Quenching**
Chemical quenchers absorb radioactive energy before it is converted to light. Chemical quenchers reduce the number of photons generated by each β-particle.

**Color Quenching**
Color quenchers absorb light in the range of the wavelength emitted by the scintillator. The number of photons emitted is not changed, but the number reaching the photomultiplier tube is reduced.
Detectors for the measurement of ionizing radiation

Liquid Scintillation Detectors

- Analytical Method: Quantitative / “Qualitative”
- Scintillation Cocktail: ULTIMA Gold XR
  Compatible with alkaline samples
  High holding capacity (up to 50%)
  High quench resistance
  High counting efficiency (up to 50% for H-3)
- $\beta$-Spectra are recorded
Detectors for the measurement of ionizing radiation

Semiconductor Detector

- Ionizing radiation produces electron-hole pairs as it passes through a semiconductor detector.
- The number of electron-hole pairs is proportional to the energy transmitted by the radiation to the semiconductor.
- Measuring the number of electron-hole pairs (pulse height) allows the energy of the incident radiation to be found.
- Excellent energy resolution.

http://nsspi.tamu.edu/NSEP
Detectors for the measurement of ionizing radiation

Semiconductor Detector

- Measurement of natural probes (Elemental Analysis)
- Measurement of probes after neutron activation
Detectors for the measurement of ionizing radiation

**Semiconductor Detector**

- Measurement of natural probes (Elemental Analysis)
- Measurement of probes after neutron activation

**Aeroradiometrics**

**Whole-body counter @ PSI**
Detectors for the measurement of ionizing radiation

Relationship between activity and counting rate?

The net counting rate \( (R_N) \) is proportional to the activity \( (A) \) of the sample and the average number of the emitted quanta per decay \( (\nu) \)

\[ R_N = f \cdot A \cdot \nu \]

\( f = f_G \cdot f_A \cdot f_S \cdot f_R \cdot f_i \)

- \( f_G \): Geometric factor
- \( f_A \): Absorption factor
- \( f_S \): Self absorption factor
- \( f_R \): Backscattering factor
- \( f_i \): Response probability
Analysis of intercepted illicit nuclear or radioactive material and any associated material to provide evidence for nuclear attribution.


Scientific analysis of nuclear or other radioactive material, or of other evidence that is contaminated with radioactive material in the context of legal proceedings, including administrative, civil, criminal or international Law.

Nuclear Forensics in Support of Investigations, IAEA Nuclear Security Series No.2

Analysis of nuclear material of unknown origin.

How to provide evidence for nuclear attribution?

What can be analyzed?

- Isotopic Signatures of Plutonium and Uranium
- Age Dating
- Chemical Impurities
- Morphology of Nuclear Material Powders
Isotopic Signatures

Uranium and plutonium are the materials of primary concern

\[
\begin{align*}
238\text{U} & \xrightarrow{(n, \gamma)} 239\text{U} & \beta^- & \rightarrow 239\text{Np} & \beta^- & \rightarrow 239\text{Pu} & \xrightarrow{(n, \gamma)} 240\text{Pu} & \xrightarrow{(n, \gamma)} 241\text{Pu} & \beta^- & \rightarrow 242\text{Pu} \\
237\text{U} & \xrightarrow{\beta^-} 237\text{Np} & \xrightarrow{(n, \gamma)} 238\text{Np} & \xrightarrow{(n, \gamma)} 238\text{Pu} & 241\text{Am} & \\
235\text{U} & \xrightarrow{(n, \gamma)} 236\text{U}
\end{align*}
\]

- The probability of the different neutron reactions (capture and fission) is a function of the neutron energy
- Different types of reactor show different neutron energy distributions
- The isotopic profile of plutonium can serve as signature of the type of reactor it was produced from
Isotopic Signatures

Uranium and plutonium are the materials of primary concern

- Determination of the reactor class ($^{242}\text{Pu}$ compared to $^{240}\text{Pu}$)
- Date of discharge ($^{241}\text{Pu}$ relationship to $^{240}\text{Pu}$ and $^{242}\text{Pu}$)
- Time since the last chemical processing ($^{241}\text{Am}$ compared to $^{241}\text{Pu}$)
Production date or age

Time elapsed since the last chemical processing of the material

Can be distinguished by daughter/ parent ratio measurements (s. radio chemical equilibrium)

<table>
<thead>
<tr>
<th>sample type</th>
<th>chronometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>highly enriched uranium</td>
<td>$^{214}\text{Bi}/^{234}\text{U}$</td>
</tr>
<tr>
<td></td>
<td>$^{230}\text{Th}/^{234}\text{U}$</td>
</tr>
<tr>
<td></td>
<td>$^{231}\text{Pa}/^{235}\text{U}$</td>
</tr>
<tr>
<td>uranium oxides</td>
<td>$^{230}\text{Th}/^{234}\text{U}$</td>
</tr>
<tr>
<td>uranium ore concentrates</td>
<td>$^{228}\text{Th}/^{232}\text{Th}$</td>
</tr>
</tbody>
</table>
Heaviest stable element is Bismuth
Holes in the periodic Table: Technetium, Promethium
Synthesis of Elements

Artificial elements

\[ ^{96}_{42} \text{Mo} + ^{2}_{1} \text{H} \rightarrow ^{97}_{43} \text{Tc} + ^{0}_{1} \text{n} \quad \text{Molybdenum} \rightarrow \text{Technetium} \]

\[ ^{209}_{83} \text{Bi} + ^{4}_{2} \text{He} \rightarrow ^{211}_{85} \text{At} + ^{2}_{0} \text{n} \quad \text{Bismuth} \rightarrow \text{Astatinium} \]

\[ ^{230}_{90} \text{Th} + ^{1}_{1} \text{H} \rightarrow ^{223}_{87} \text{Fr} + ^{4}_{2} \text{He} \quad \text{Thorium} \rightarrow \text{Francium} \]

<table>
<thead>
<tr>
<th>Atomic number Z</th>
<th>Name of the element (Symbol)</th>
<th>Longest-lived nuclide (Half-life)</th>
<th>Discovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>84</td>
<td>Polonium (Po)</td>
<td>$^{209}$Po (102 y)</td>
<td>1898 P. and M. Curie</td>
</tr>
<tr>
<td>85</td>
<td>Astatine (At)</td>
<td>$^{210}$At (8.1 h)</td>
<td>1940 Corson, McKenzie and Segrè</td>
</tr>
<tr>
<td>86</td>
<td>Radon (Rn)</td>
<td>$^{222}$Rn (3.82 d)</td>
<td>1900 Rutherford and Soddy</td>
</tr>
<tr>
<td>87</td>
<td>Francium (Fr)</td>
<td>$^{223}$Fr (22 m)</td>
<td>1939 Peres</td>
</tr>
<tr>
<td>88</td>
<td>Radium (Ra)</td>
<td>$^{226}$Ra (1600 y)</td>
<td>1898 P. and M. Curie</td>
</tr>
<tr>
<td>89</td>
<td>Actinium (Ac)</td>
<td>$^{227}$Ac (21.6 y)</td>
<td>1899 Debieme</td>
</tr>
<tr>
<td>90</td>
<td>Thorium (Th)</td>
<td>$^{232}$Th (1.41 \times 10^{15} y)</td>
<td>1828 Berzelius</td>
</tr>
<tr>
<td>91</td>
<td>Protactinium (Pa)</td>
<td>$^{233}$Pa (3.28 \times 10^4 y)</td>
<td>1917 Hahn and Meitner</td>
</tr>
<tr>
<td>92</td>
<td>Uranium (U)</td>
<td>$^{238}$U (4.47 \times 10^9 y)</td>
<td>1789 Klaproth</td>
</tr>
</tbody>
</table>
Synthesis of Trans-Uranium Elements

- $^{238}\text{U}$ → $^{239}\text{U}$ → $^{239}\text{Np}$ → McMillan 1940 (fission product)
- $^{238}\text{U}$ → $^{237}\text{U}$ → $^{237}\text{Np}$
- $^{235}\text{U}$ → $^{237}\text{U}$ → $^{237}\text{Np}$
- $^{238}\text{U}$ → $^{238}\text{Np}$ → $^{238}\text{Pu}$ → Seaborg 1940
- $^{239}\text{Pu}$ → $^{241}\text{Pu}$ → $^{241}\text{Am}$ → Seaborg 1944
- $^{241}\text{Am}$ → $^{242}\text{Am}$ → $^{242}\text{Cm}$ → Seaborg 1944
- $^{242}\text{Cm}$ → $^{245}\text{Cf}$ → Thompson 1950
Synthesis of Trans-Uranium Elements

$^{26}\text{Mg}$ $^{248}\text{Cm}$ $^{274}\text{Hs}$ $^{270}\text{Hs}$

$1 \cdot 10^{17}$ $1 \cdot 10^{16}$ $5 \cdot 10^6$ $1$

projectiles on target compound nuclei atom
## Synthesis of Trans-Uranium Elements

The artificial radioelements

<table>
<thead>
<tr>
<th>Atomic number $Z$</th>
<th>Name of the element (Symbol)</th>
<th>Longest-lived nuclide (Half-life)</th>
<th>Discovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>43</td>
<td>Technetium (Tc)</td>
<td>$^{98}_{43}$Tc $(4.2 \cdot 10^6 \text{ y})$</td>
<td>1937 Perrier and Segrè</td>
</tr>
<tr>
<td>61</td>
<td>Promethium (Pm)</td>
<td>$^{148}_{61}$Pm $(17.7 \text{ y})$</td>
<td>1947 Marinsky, Glendenin and Coryell</td>
</tr>
<tr>
<td>93</td>
<td>Neptunium (Np)</td>
<td>$^{237}_{93}$Np $(2.14 \cdot 10^8 \text{ y})$</td>
<td>1940 McMillan and Abelson</td>
</tr>
<tr>
<td>94</td>
<td>Plutonium (Pu)</td>
<td>$^{244}_{94}$Pu $(8.26 \cdot 10^7 \text{ y})$</td>
<td>1940 Seaborg et al.</td>
</tr>
<tr>
<td>95</td>
<td>Americium (Am)</td>
<td>$^{243}_{95}$Am $(7380 \text{ y})$</td>
<td>1944 Seaborg et al.</td>
</tr>
<tr>
<td>96</td>
<td>Curium (Cm)</td>
<td>$^{247}_{96}$Cm $(1.6 \cdot 10^7 \text{ y})$</td>
<td>1944 Seaborg et al.</td>
</tr>
<tr>
<td>97</td>
<td>Berkelium (Bk)</td>
<td>$^{247}_{97}$Bk $(1380 \text{ y})$</td>
<td>1949 Thompson, Ghiors et al.</td>
</tr>
<tr>
<td>98</td>
<td>Californium (Cf)</td>
<td>$^{251}_{98}$Cf $(898 \text{ y})$</td>
<td>1950 Thompson, Ghiors et al.</td>
</tr>
<tr>
<td>99</td>
<td>Einsteinium (Es)</td>
<td>$^{252}_{99}$Es $(350 \text{ d})$</td>
<td>1952 Thompson, Ghiors et al.</td>
</tr>
<tr>
<td>100</td>
<td>Fermium (Fm)</td>
<td>$^{252}_{100}$Fm $(100.5 \text{ d})$</td>
<td>1953 Thompson, Ghiors et al.</td>
</tr>
<tr>
<td>101</td>
<td>Mendelevium (Md)</td>
<td>$^{258}_{101}$Md $(55 \text{ d})$</td>
<td>1965 Ghiors et al.</td>
</tr>
<tr>
<td>102</td>
<td>Nobelium (No)</td>
<td>$^{256}_{102}$No $(58 \text{ m})$</td>
<td>1958 Ghiors et al.</td>
</tr>
<tr>
<td>103</td>
<td>Lawrencium (Lr)</td>
<td>$^{262}_{103}$Lr $(3.6 \text{ h})$</td>
<td>1961 Ghiors et al.</td>
</tr>
<tr>
<td>104</td>
<td>Rutherfordium (Rf)</td>
<td>$^{261}_{104}$Rf $(65 \text{ s})$</td>
<td>1969 Ghiors et al.</td>
</tr>
<tr>
<td>105</td>
<td>Hahnium (Hs)</td>
<td>$^{262}_{105}$Hs $(34 \text{ s})$</td>
<td>1970 Ghiors et al.</td>
</tr>
<tr>
<td>106</td>
<td>Seaborgium (Sg)</td>
<td>$^{266}_{106}$Sg $(30 \text{ s})$</td>
<td>1974 Ghiors et al., Flerov et. al.</td>
</tr>
<tr>
<td>107</td>
<td>Nielsbohrium (Ns)</td>
<td></td>
<td>1981 Münzenberg, Armbruster et al.</td>
</tr>
<tr>
<td>108</td>
<td>Hassium (Hs)</td>
<td></td>
<td>1984 Münzenberg, Armbruster et al.</td>
</tr>
<tr>
<td>109</td>
<td>Meitnerium (Mt)</td>
<td></td>
<td>1982 Münzenberg, Armbruster et al.</td>
</tr>
</tbody>
</table>
Synthesis of Elements

Synthesis of Trans-Uranium Elements

Current Periodic Table of the Elements with IUPAC approved numbering of groups and element symbols. The names for elements 114 (Flerovium, Fl) and 116 (Livermorium, Lv) suggested by the team of discoverers have recently been officially accepted by IUPAC.

atomic no.  element name  symbol

101  mendelevium  Md
102  nobelium  No
103  lawrencium  Lr
104  rutherfordium  Rf
105  dubnium  Db
106  seaborngium  Sg
107  bohrium  Bh
108  hassium  Hs
109  meitnerium  Mt
110  darmstadtium  Ds
111  roentgenium  Rg
112  copernicium  Cn
113  ununtrium  Uut
114  flerovium  Fl
115  ununpentium  Uup
116  livermorium  Lv
117  ununseptium  Uus
118  ununoctium  Uuo

Andreas Türler; Valeria Pershina; Chem. Rev. 2013, 113, 1237-1312.