On the Edge of History – In the Center of Radiation Protection: Gamma Radiation

Jonny Birkhan, Matthias Bothe, Jörg Feinhals, Rainer Gellermann, Christoph Wilhelm

Around the turn of the century from the 19th to the 20th, several major upheavals occurred in the natural sciences. Röntgen, Becquerel, Rutherford, and the Curies experimentally explored the world of radioactivity, while Planck and Einstein created new theoretical frameworks for the quantum world and relativity. The name of the French physicist and chemist Paul Ulrich Villard (09/28/1860 – 01/13/1934) (Figure 1) rarely appears in history books, even though he discovered something that also has far-reaching effects on modern life: gamma radiation.

Figure 1: *Paul Ulrich Villard (1908), Source: Wikimedia Commons.*

The Discovery of Gamma Radiation

While investigating the properties of radium, Villard found that there was a portion of the radiation emitted by radium that could not be deflected by a magnetic field. Since this portion could also penetrate aluminum and thin lead plates, he presented this radiation as a new type of radiation, alongside the alpha and beta radiation already described by Becquerel, the Curies, and Rutherford. Although Villard correctly interpreted the results of his experiments and thus discovered the new radiation, his discovery was largely ignored by the scientific community at first. It wasn't until 1903 that this new radiation was first named "gamma rays" by Rutherford.

What is Gamma Radiation? How is it Produced?

Gamma radiation (γ-radiation), in the narrow sense, is electromagnetic radiation that is produced during radioactive transformations of atomic nuclei and that passes through layers of material much better than alpha or beta radiation.

In classical physics, gamma radiation is an electromagnetic wave that transports energy through a vacuum or through matter. One common definition distinguishes gamma rays from X-ray in the way that they are emitted by the nucleus, whereas X-rays originate from the electronic shell of an atom.

Within the wave particle dualism, quantum physics describes gamma radiation as corpuscles, so called photons, that propagate at the speed of light and have no rest mass.

Visible light has an energy in the range of electron volts (eV), while gamma quanta are much more energetic. There is no sharp energetic limit between X-ray and gamma rays, but as a rule of thumb, one speaks of X-rays at energies exceeding 100 keV. The gamma quant with the highest energy measured to date originated from the gamma ray burst GRB 190114C in a distant galaxy and was in the range of tera-electron volts (TeV = 10^{12} eV).

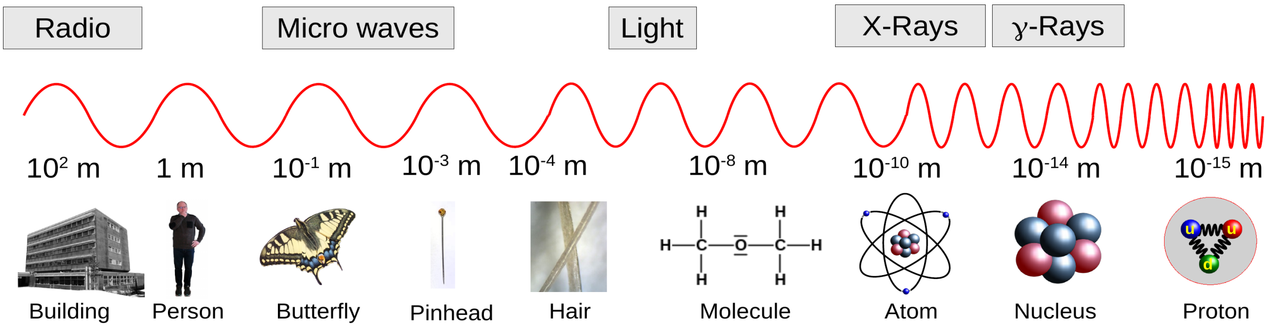

Figure 2: *Wavelengths in the electromagnetic spectrum, compared to objects of our world, from macroscopic to microscopic.*

Since such radiation can also be produced in processes other than radioactive transformations, e.g., in stars, the term "gamma radiation" is now used for any electromagnetic radiation that has sufficiently short wavelengths. For example, gamma radiation also arises when a positron (produced during radioactive decay) meets an electron and they annihilate each other ("annihilation"). The gamma radiation that reaches Earth as part of cosmic radiation originates, among other places, from regions around the supernovae. There, protons are accelerated to very high energies, which then collide with protons of interstellar gas. This leads to a particle reaction between the protons, in which gamma radiation ultimately is produced.

Natural Gamma Radiation

Gamma radiation is part of our living environment and causes a significant portion of the natural radiation exposure of humans. An important natural source of radiation are the radionuclides of the natural decay series of Thorium-232, Uranium-238 and Uranium-235, as well as Potassium-40. These radionuclides are contained in the soil with different activity concentrations, see Table 1. The direct, external exposure caused by this terrestrial radiation amounts to approx. 0.5 mSv per year [2].

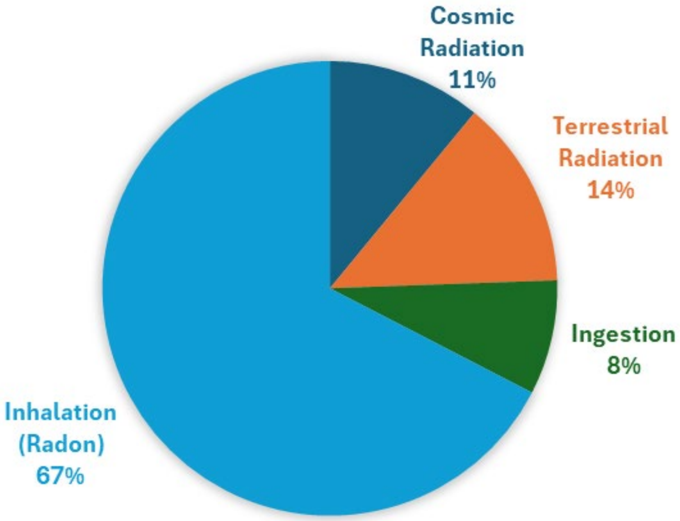

Figure 3: *Distribution of the worldwide natural radiation exposure of 2.4 mSv/year. Data taken from [2]*

The gamma component of cosmic radiation is also part of our living environment. It causes (together with other parts of cosmic radiation) an annual dose of approx. 0.3 mSv and, at least when staying on the Earth's surface, is also neither avoidable nor practically limitable. It is also excluded from radiation protection regulations.

Humans also ingest radionuclides through food, such as Tritium (H-3), Carbon-14, and Potassium-40, the latter being a gamma emitter. About half of the annual dose of 0.3 mSv of internal human exposure is caused by Potassium-40. Since potassium is an essential element of metabolism and the gamma emitter Potassium-40 is an integral part of natural potassium, this radiation is also excluded from radiation protection regulations. Potassium-40 has a half-life of $1{,}25 \cdot 10^9$ years and decays essentially via beta-minus decay (90%) to Calcium-40 as well as electron capture (10%) to Argon-40. The latter transitions to the ground state by emitting a gamma quantum with an energy of 1461 keV. The skin dose rate resulting from the beta rays of a point-shaped Potassium-40 source close to this source is about 57 times greater than the gamma dose rate of the same source at the same distance.

Table 1: *Median range of variation of the activity concentration of various natural radionuclides in the soil world wide [3].*

Radionuclide	**Activity concentration in Bq/kg**
Potassium-40	140-850
Uranium-238	16-110
Thorium-232	11-64

How does gamma radiation interact with matter?

The effect of gamma radiation on matter is of central importance to radiation protection, as it not only poses a health risk, but can also be detected by its interactions with even simple measuring devices.

The most important ways that gamma radiation interacts with matter are the photoelectric effect (Figure 4 a), the Compton effect (Figure 4 b), and pair production (Figure 4 c). In the photoelectric effect, a gamma quantum is absorbed by the material. As a result, an electron is released from the electron shell of the affected atom.

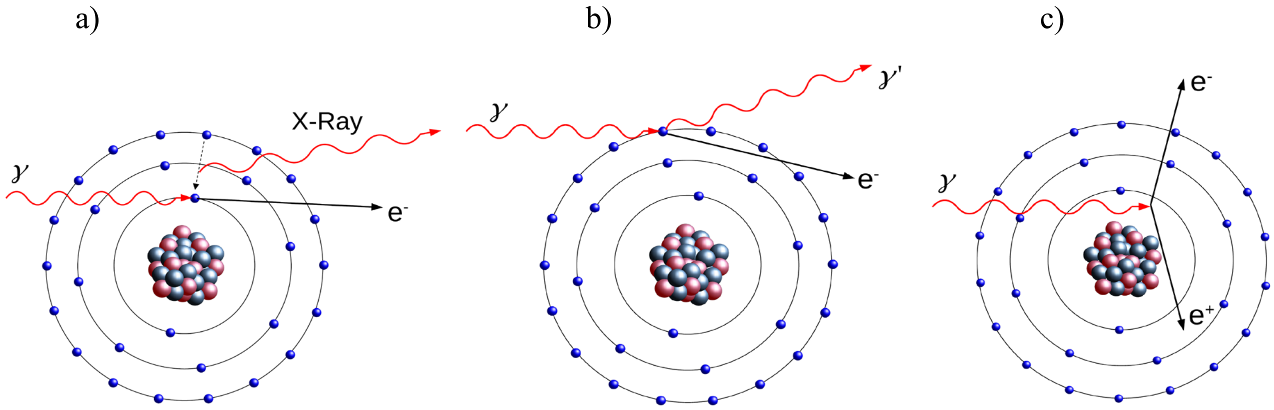

Figure 4: *Schematic diagrams of the photoelectric effect a), Compton effect b), and pair production c).*

In the Compton effect, a gamma quantum strikes an electron in the atomic shell and is scattered by it. In the process, the gamma quantum loses energy and usually changes direction. The energy transfer to the electron is generally so high that it leaves the electron shell. Near an atomic nucleus, a gamma quantum with an energy of at least 1022 keV can be converted into an electron-positron pair. The resulting positron then interacts shortly thereafter with an electron, whereby both particles annihilate emitting two gamma quanta with an energy of 511 keV each. Thus, in all three processes, atoms are ionized. The probability that gamma radiation causes ionization via one of the three processes mentioned above is significantly smaller compared to the interaction of alpha and beta radiation with matter. Its penetration depth into matter is therefore significantly greater than that of alpha and beta radiation. This is why it is also called penetrating radiation.

Applications and Utilizations of Gamma Radiation

Gamma radiation is applied in industry, for example, for the inspection of weldings, see Figure 5, for level measurement in closed facilities, or for the sterilization of objects and products, mostly for medicine or pharmacy. In medicine, gamma radiation is applied for diagnostics and, in some cases, still for tumor therapy.

A much broader field is the utilization of emitted gamma radiation for measuring purposes. From the perspective of science, it is an indispensable probe for investigating complex processes on a microscopic scale, especially in nuclear and particle physics as well as in astrophysics, but also in the physics of the atmosphere. However, it is also important when viewed macroscopically. For example, it allows the detection of the distribution of radionuclides in the environment to be investigated in radioecology or peace research.

Figure 5: *Non-destructive material testing - Inspection of weldings with a gamma ray source, Source:* *www.shutterstock.com*.

For the identification and determination of the activity of radionuclides, for example in the environment or in foodstuffs, the gamma radiation can be measured with relatively low sample preparation effort. The identification and activity determination of the radionuclides is done with gamma ray spectrometry using the energy and intensity of the gamma rays. In this process, high-purity germanium detectors are typically used. Figure 6 shows a gamma ray spectrum, in which the lines of Argon-41 and the annihilation radiation of the positron emitters Carbon-11, Nitrogen-13 and Oxygen-15 in the exhaust air of an accelerator facility are visible. Gamma ray spectrometry is also important for the monitoring of release and disposals of radioactive contaminated substances.

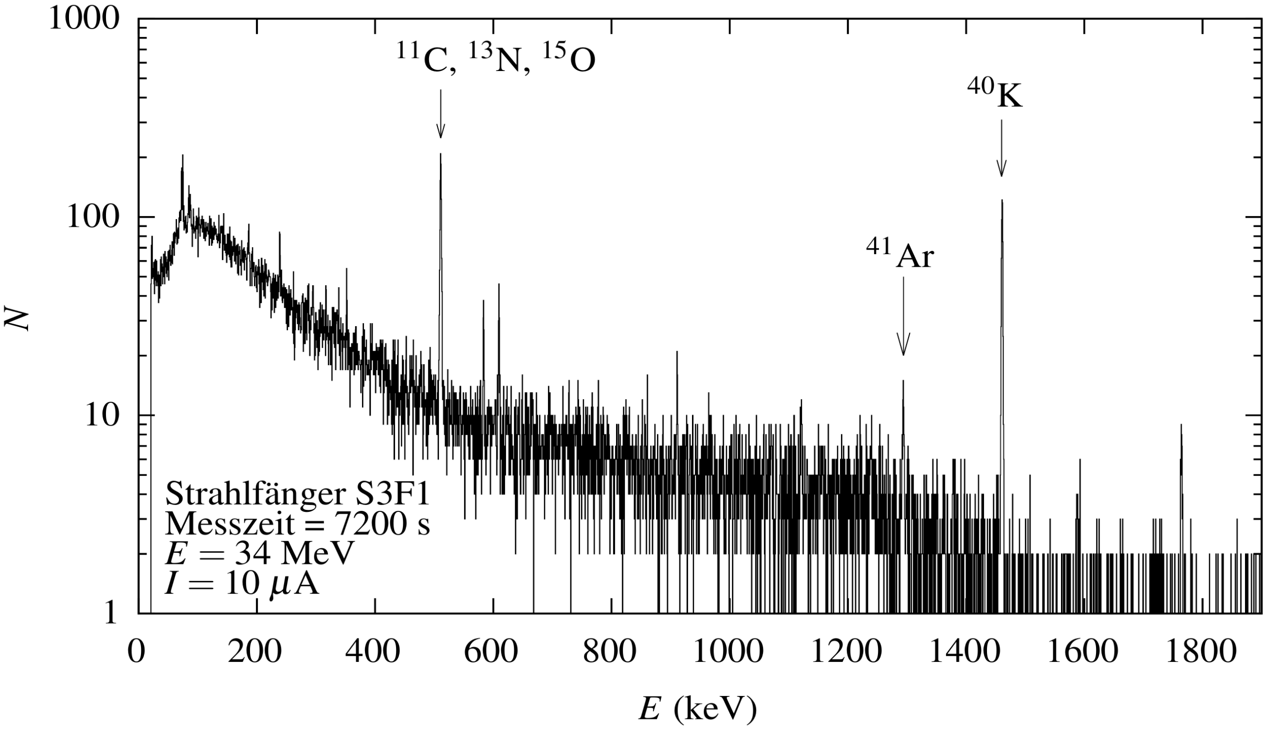

Figure 6: *Gamma ray spectrum for the identification and activity determination of the radionuclides Carbon-11, Nitrogen-13, Oxygen-15 at 511 keV (annihilation radiation) and Argon-41 at 1294 keV in an air sample from the S-DALINAC accelerator facility (TU Darmstadt).*

Risks and Protection from Gamma Radiation

The benefits of the controlled application of gamma radiation are undoubtedly a real opportunity for society. However, it also carries risks. Due to its ionizing effect at a cellular level, depending on the intensity of the radiation, it can also have a harmful effect on the human body. Because of its relatively low interaction probability, it is primarily unintentional exposures with high radiation intensity that can pose a risk. Such situations can occur in radiation accidents. Therefore, protection against exposure, in particular to gamma radiation because of its high range, is a central component of radiation protection.

An important aspect is the design of shielding against gamma radiation. Materials with high density or with large thicknesses manage to effectively reduce the radiation intensity. Lead or concrete are common shielding materials for gamma radiation. With concrete shielding, the wall thickness must be larger because its density is lower than that of lead.

Since gamma radiation, like other types of ionizing radiation, is not perceptible to human senses, measuring devices, which can specifically detect gamma radiation, are of great importance. This becomes in particular clear in critical situations such as the radiation accidents of Chernobyl and Fukushima, where precise measurements are also crucial to assess the radiation exposure. In order to obtain precise and reliable measurement results, the choice of a suitable measuring instrument is important. This device should not only be able to detect the specific type of radiation but also be sufficiently sensitive in the energy range of the radiation quanta.

Figure 7: *Handheld dose rate meter in practical radiation protection.*

The technical effort to detect gamma radiation is relatively small. Even a simple Geiger-Müller counter tube is able to measure gamma quanta with high reliability. Therefore, a Geiger-Müller counter tube is still the most commonly used probe in the common handheld dose rate meters in radiation protection, see Figure 7. Even if the spectrometric measurement of the energy and frequencies of gamma quanta with a high-purity germanium detector is technically much more complex and, above all, more cost-intensive, this fact is compensated by the fact that many gamma-emitting radionuclides can be measured and identified in a sample at once.

Radiation of the Year 2025

Gamma radiation, the "Radiation of the Year 2025," was discovered 125 years ago by Paul Ulrich Villard. It is part of our living environment and a fascinating physical phenomenon. It is an indispensable tool for many technical and medical applications. However, its application entails risks. In order to limit these risks as far as reasonably achievable, radiation protection implements effective protective and control measures for both occupationally exposed persons in companies and for the population.

[1] Wikipedia Commons, Paul_Villard.jpg, visited 21.11.2024
https://commons.wikimedia.org/wiki/File:Paul_Villard.jpg?uselang=en#Licensing

[2] Sources and effects of ionizing radiation, UNSCEAR 2008 Report,
ISBN: 978-92-1-142274-0

[3] Sources and Effects of Ionizing Radiation, UNSCEAR 2000 Report, Volume I: Sources