

English edition

Scintillators around us



Czech Academy
of Sciences



Science 84

around us
Challenges
and questions

Institute of Physics of the Czech Academy of Sciences is a public research institute, oriented on the fundamental and applied research in physics. The founder of the institute is the Czech Academy of Sciences.

The present research programme of the Institute encompasses physics of elementary particles, condensed systems, solid state, plasma physics, and classical and quantum optics.

The research in elementary particle physics is carried out mostly within broad international collaborations. We participate in experiments at the large accelerators at CERN near Geneva in Switzerland and at Fermilab in the USA, where the deepest structure of matter and forces governing the microcosm are studied. Closely connected are our activities in the development of particle detectors.

The particle physics research involves also astroparticle physics – the field in between particle physics and astrophysics. Cosmic rays of the highest energies are studied within an international collaboration at the Pierre Auger Observatory in Argentina, the world's largest experimental facility of its kind. Besides, there is engagement in theoretical and mathematical physics and application of particle beams in medicine.

The physics of condensed systems is focused on dynamical and cooperative phenomena in disordered and inhomogeneous materials, and in systems with reduced spatial dimensions. The main objects of interest are condensed materials exhibiting prominent physical properties, or subject to extreme conditions. We deal with preparation and research of functional materials, such as composites, superconductors, liquid crystals, and shape memory alloys, in the form of single crystals, polycrystals, nanostructured materials, thin films and coatings, combining theoretical, experimental and novel technological approaches.

The research in the domain of solid state physics is oriented towards new forms of solids, new physical phenomena and principles of microelectronic components. The properties of new materials are determined by their surface, defects, nanometric, layered or aperiodic structure. Characteristic is the interconnection of advanced technologies of preparation, unique methods of their characterisation in a broad range of external conditions, down to nanometric and atomic level, as well as processing of results with the aid of microphysical and *ab-initio* theoretical calculations. Great attention is paid to magnetic and optically active materials, nanocrystalline forms of silicon, III-V semiconductors, diamond and graphite, as well as to nanostructures for applications in medicine and microelectronics.

The preparation of new optical materials for optoelectronics is based on use of new plasma and hybrid techniques. The research in the field of quantum optics is focused on development of various types of sources of quantum-correlated photon pairs and on devices for transmission of underlying information.

“Scintillator” – quite a peculiar word, right? Only a few people would say that it stands for something that we can find quite common today. You know that a number of hospitals are equipped, for example, with a computed tomography, popularly called “CT”. This device allows doctors to look inside the patient’s body using X-rays. Whoever has ever travelled by air, he/she certainly remembers baggage checking with another device that uses X-rays to display the baggage content. It is clear that the X-rays passing through the patient’s body or luggage need to be somehow captured and processed, i.e. to be detected. This is what the scintillator is used for. It is a material that converts X-ray energy into ultraviolet or visible light, which is further detected by a suitable light-sensitive sensor, such as a photodiode or a photomultiplier. The photomultiplier is actually a light-sensitive vacuum tube. An electrical signal from these sensors, which depends on the intensity of the X-rays penetrating the displayed object, is further processed by electronics and a program in a computer to create the resulting image of the interior of the object. It can therefore be said, that scintillators convert an invisible radiation into a visible one.

The first scintillators were used at the end of the nineteenth century when X-rays and later natural radioactivity were discovered.

Therefore, scintillators are not only used for detection of X-rays but also for other types of ionizing (often inaccurately called “radioactive”, see below) radiation. Scintillators are widely used, for example, in the detection of particles in nuclear research, cosmic radiation measurements, radiation monitoring in the environment, radiotherapy beam control, and others. Scintillators are a very diverse group of materials. For example, organic crystals and liquids or inorganic powders or ceramic materials can be mentioned. In this publication, however, we will focus on inorganic crystals, which are widely used in most of the applications mentioned above. To explain the operation of scintillators, some important concepts and physical phenomena such as electromagnetic radiation, ionizing radiation and luminescence need to be clarified.

The radiation around us

Without admitting and realizing it, in everyday life we are constantly surrounded by the radiation of all kinds. The most common is electromagnetic radiation, that we daily encounter in the form of visible daylight. White daylight can be dispersed into the constituent colours by a suitable optical element (such as a prism). If the optical element is a water droplet or water drops in the rain showers, a well-known rainbow is created. Each colour corresponds to a certain wavelength light that is associated with the corresponding photon energy. Photons are particles of light. Electromagnetic radiation can be characterized by their energy in electronvolts (abbreviation eV; 1 eV is equivalent to the energy that an electron with its electric charge gains when accelerated in the electric field with a potential difference of 1 V) which is related to the wavelength λ (distance between two oscillation maxima).

If we arrange all known types of electromagnetic radiation according to their energy or wavelengths (Figure 1), we can see that our eye and brain, although highly sophisticated organs, can capture and evaluate only rather limited part of the electromagnetic spectrum in the range of wavelengths of about 380–740 nm,

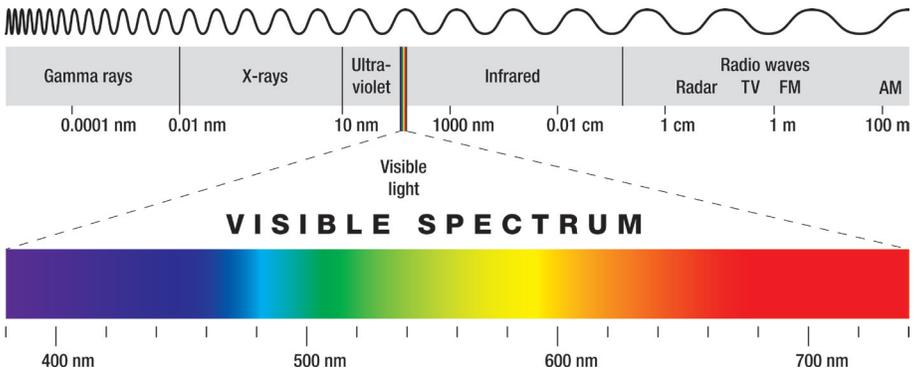


Fig. 1. Electromagnetic spectrum (after <https://luxes.es/basics-of-lighting/?lang=en>)

which we call the visible light. With increasing photon energy we can further distinguish the ultraviolet (UV) radiation, X-rays, and finally gamma rays. A common important feature of the two latter types of high-energy photon radiation is their high penetration through matter. It is necessary to say that the converted type of radiation may not only be photons, but also electrons (beta radiation), positrons (β^+ radiation), helium nuclei (alpha radiation), protons, neutrons, heavier elements, or charged ions, which can be found, for example, in cosmic rays or particle accelerators. A common characteristic of these types of radiation is the ability to ionize the environment, i.e. to remove electrons from the electron shells of the atoms in the environment and to create ions. Therefore, these kinds of radiation are generally called ionizing radiation. We would like to point out that the term radioactive radiation does not make sense, even though it also appears in scientific literature. A substance that emits ionizing radiation can be called radioactive.

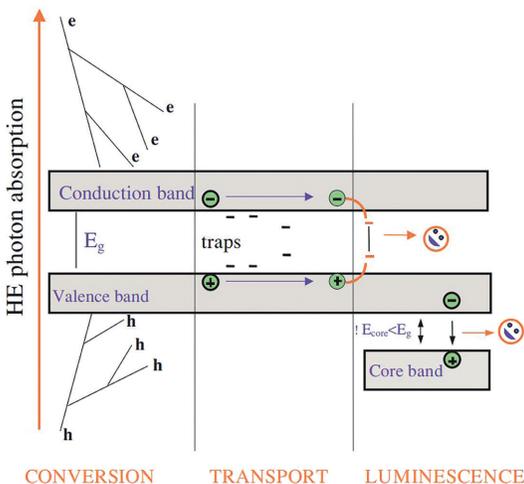


Fig. 2. Stages of the scintillation process (from Martin Nikl 2006 *Meas. Sci. Technol.* 17 R37: Scintillation detectors for x-rays)

Luminescence

Scintillators or scintillation materials are part of luminescent materials. After the invisible ionizing radiation is captured by a scintillator, luminescence occurs. The word luminescence was first used in 1888 by a science historian E. Wiedemann as a term for all the phenomena in which the emitted light is not related to the increase of temperature. Therefore, sometimes luminescence is referred to as the cold light. Thus, glowing ceramic cooking plate or ordinary bulb do not exhibit luminescence.

On the other hand, for example a fluorescent lamp, a light diode, etc. show the luminescence. If the luminescence is excited by X-ray or gamma radiation we talk about radioluminescence, which is from the physical point of view practically identical with the phenomenon of scintillation (emission of scintillation photon). For more information about luminescence, we refer the reader to a nice book by G. Blasse and B. C. Grabmaier *Luminescent Materials*, Springer Verlag 1994.

Processes in scintillators

Now when we know how the scintillator is used, we can further explain how it works. But at first we have to briefly say something about the electron structure of solids, because it is responsible for the entire scintillation process.

It is known that the electron in the atom can occupy only certain orbits, which correspond to permitted energy values. In a very large set of interconnected atoms, such as a crystal, the energy levels are combined into energy bands in which the electrons may be located. Sometimes they are also called bands of allowed energies. The bands which cannot be occupied are called forbidden bands. For a better explanation of theory of solids, we refer the reader to any available university textbook of solid state physics. For our purposes the most important bands will be the highest occupied band, also called the valence band, and the lowest unoccupied band, called the conduction band. There is a gap of forbidden energies between these two bands (Figure 2).

Upon absorption of a high-energy photon or an accelerated particle, the atoms of the material will get ionized which means that the negatively charged electrons are pulled from the atoms while positively charged entities, so-called holes, are created. This complex process is called conversion. Conversion is extremely fast as it usually takes only a few picoseconds (10^{-12} s). The charge carriers (the electrons and holes) reduce their energies to the energy of thermal oscillations of crystal lattice. We say that they become thermalized. Subsequently, another phase of the scintillation process, called transport, takes place. The electrons can remain in the conduction band and the holes in the valence band and can travel through the material. An electron can jump off the conduction band into the valence band to the place where a hole is located. This is called electron-hole recombination. Furthermore, electrons (holes) can be captured (and possibly released later) at the defects in the crystal, which can act as the electron (hole) traps and whose energy levels lie inside the forbidden gap. If the charge carriers reach a luminescence center, they can recombine there and the above-mentioned luminescence occurs, which is the

last step of the scintillation process. It is clear that the second phase of scintillation, transport, can have a detrimental effect on timing characteristics of the whole scintillation process. Therefore, it is necessary to prepare materials of high quality, with low concentration of traps that would complicate the scintillation process.

Role of the matrix and activator

In the previous paragraph we mentioned the luminescence center. Such a center can be, for example, an impurity in a scintillation material which is responsible for its luminescence. Sometimes it is called an activator. Many of the crystals exhibit their own luminescence without any activator. However, the properties of such a luminescence often do not meet the requirements of a specific application of the scintillator (there is no universal scintillator that would fit all applications). Therefore, the activator is often added to the crystal. Its concentration is usually very low, even a fraction of a percent, however, it is enough to change the luminescence properties of the whole crystal significantly. We are talking about the activated scintillators. For activated scintillators, it is also important to pay attention to the relationship between the crystalline matrix and the luminescence center. The role of the matrix is to absorb the high energy photon/particle and to transfer the captured energy to the luminescence center. The matrix often has a very strong influence on the luminescence center, so that different crystals activated by the same luminescence center may have relatively different luminescent properties. On the other hand, the luminescence center itself can influence the matrix on a local level. Since it is a doped substance, a certain type of disorder in a crystal, in some cases it may induce certain defects possibly related to, for example, the charge traps (see above).

It is clear that the energy corresponding to the width of the forbidden gap of the crystalline matrix must be higher than the energy of the photons emitted by the luminescence center. Simply speaking, the crystal must be transparent to the light emitted by the luminescence center.

Classification of materials

As already noted in the introduction, scintillators mostly have the form of a bulk single crystal. In some high-resolution imaging techniques where no deeply penetrating radiation is used, materials in the form of thin single-crystalline layers, often only tens of micrometers thick, have been employed. Similarly, powder layers that are more affordable due to less demanding preparation technology can be used, for example, when the material cannot be prepared as a single crystal. Glass-based materials were also studied. Their advantage is a relatively simple preparation technology and the ability to produce almost any shape as needed. A disadvantage may be that, unlike for single crystals, the structure of the glass is ordered only locally and not in the whole volume of the scintillation element. This may negatively affect the scintillation parameters. Recently, development of technologies for preparation of optical ceramics has begun. The properties of ceramics may sometimes be superior to those of their single crystal counterparts or single crystals of comparable composition. Inorganic scintillation materials may

be represented by various compounds based on complex oxides (silicates, aluminum garnets and perovskites), halides (fluorides, bromides, iodides) or sulfides, oxysulfides and sometimes nitrides (see below). For more information, refer to a very successful review article by M. Nikl, A. Yoshikawa. Recent R & D Trends in Inorganic Single-Crystal Scintillator Materials for Radiation Detection. *Adv. Optical Mater.* 2015, 3, p. 431.

Parameters of scintillating materials

Density and effective atomic number

Due to the high penetration ability of X-rays and especially gamma radiation, density is one of the important characteristics of scintillation materials (ρ in g.cm^{-3}). In general, as the density of the material increases, the probability that the high-energy photon will be absorbed in the material and scintillation will take place also increases. The effective atomic number Z_{eff} of the compound is closely related to density, and it is a kind of average atomic number of individual elements in the compound. The material with probably the highest density among the known scintillation materials is LuTaO_4 (9.75 g.cm^{-3}), whose density is much higher than that of e.g. iron (7.86 g.cm^{-3}). However, in the end, no application was found for this material.

For beta or alpha rays, whose penetration ability is significantly smaller, the high density is, of course, not required. As for the neutrons, the requirements for the material composition are even more specific. It is necessary that neutron scintillators are not sensitive to the high-energy photon radiation that often accompanies neutrons (for example in cosmic radiation or in a nuclear reactor). Therefore, the density of the neutron scintillators is often very low. For example, the LiAlO_2 scintillator recently studied has density of only 2.6 g.cm^{-3} .

Emission position

From the point of view of using a certain type of scintillation photon detector, it is necessary to consider the energy of the scintillation photons produced by the scintillator (which practically means the color of the photons, e.g. blue photons are those with wavelength around 450 nm) which needs to match the detector sensitivity. For UV and blue spectral regions, the photomultipliers will be better suited while for lower energy photons the semiconductor photodiodes are more sensitive.

Overall scintillation efficiency and relative efficiency

Total efficiency of X-ray or gamma-ray conversion to light for certain scintillation material is given by its own (internal) and external characteristics. The number of UV / visible photons that are produced in scintillation process upon excitation by a high-energy photon is inversely proportional to the width of the forbidden gap of the material (for more information, see e.g., D. J. Robbins, On predicting the maximum efficiency of phosphor systems excited by ionizing radiation. *J. Electrochem. Soc.* 1980, 127, pp. 2694–2702; A. Lempicki, A. J. Wojtowicz, E. Berman. Fundamental limits of scintillator performance. *Nucl. Tools. Methods Phys. Res.* 1993, A 333, pp. 304–311). One of the most effective materials is surprisingly the historical ZnS:Ag^+ .

Radiation damage

If any material is exposed to intense ionizing radiation, it can change its properties. The changes are sometimes even irreversible. This phenomenon is called radiation damage and is reflected, for example, in deterioration of the material transparency. That is especially important in the applications where intense radiation beams are used, for example in the particle accelerators.

Time characteristics of scintillation response

The speed of scintillation response is characterized by the decay time τ within which the scintillation material reacts to the interaction with the ionizing radiation. Considering that the emission does not occur at one single moment but it is spread over time, this decay time represents an interval between the interaction and the moment when the emission intensity decreases to $1/e$ (e is the Euler number, the basis of the natural logarithm) of its initial value, which corresponds to approximately one-third of the initial intensity. The fastest known materials have the decay time of less than 1 nanosecond (10^{-9} seconds); However, tens of nanoseconds are more typical. For comparison: blink of an eye takes a tenth of a second, the electronic flash on the camera may take a microsecond.

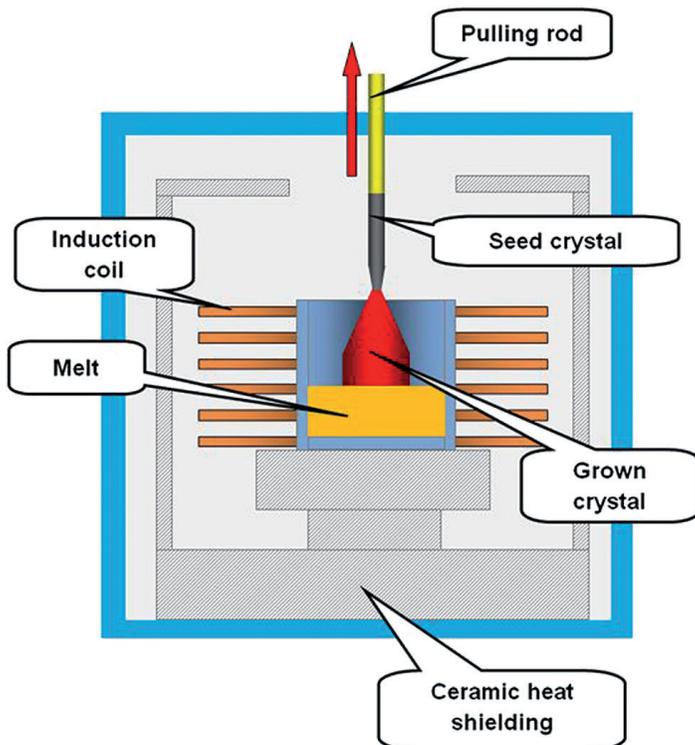


Fig. 3. Schematic of the crystal growth by Czochralski method

Light yield, proportionality and energy resolution

Light output is a quantity that gives the amount of light released from the scintillation material upon 1 megaelectronvolt (MeV, see above) photon excitation. This quantity is closely related to proportionality, or non-proportionality of the response of scintillation materials. It tells how much the value of the light output will change with the change of energy of the incident radiation. If a scintillator has light output of, for example, 10,000 photons per 1 MeV, then one would expect that when absorbing the radiation with double the energy, i.e. 2 MeV, it would emit 20,000 photons, which is twice as much, and so on. This is often not true due to various processes in the material. This proportionality (non-proportionality) is very important for achieving a better energy resolution of scintillation detectors. Energy resolution indicates the relative energy difference (in percent) of two particles that can still be distinguished. If we have scintillation detectors with good energy resolution, we can then experimentally determine not only that the detector has detected ionizing radiation, but also what the energy of the incident particle or photon was. Information about the energy then enables us to identify an unknown isotope (source of radiation), which is the principle of gamma radiation spectrometry. It can be used, for example, to determine the presence of various elements in the given sample material even in the trace concentrations or to reveal the content of radioactive elements in the environment or in space. Every radioactive isotope has its own characteristic radiation that acts as a kind of fingerprint, according to which the isotope can be unambiguously identified.

Time resolution

Time resolution determines the minimum time interval between two particle interactions with the scintillation detector, which can be distinguished from each other. Time resolution is especially important for applications using so-called time-of-flight detection technique, such as in positron emission tomography (PET), see below.

Temperature stability of the emission

The luminescence properties of each scintillation material change with the temperature of the surroundings. Usually the luminescence is the most effective at low temperatures at which no quenching phenomena that would reduce the efficiency (so-called thermal quenching processes) take place. For a large number of applications no differences in the efficiency at room temperature and low temperatures would be desirable, but there are also many applications requiring emission stability often up to 300 °C (e.g. geological survey, logging probes, light converters ...).

Chemical and physical stability

Some high-performance halide-based scintillation materials with considerably high density and light yield can have a significant deficiency – they are highly hygroscopic. It means they react very quickly with the moisture in the air. Therefore, these materials need to be protected from the atmosphere, for example by a special encapsulation. However, such protection obviously complicates handling and increases the cost of the detector. Other materials are even chemically unstable and can undergo oxidization to different substances.

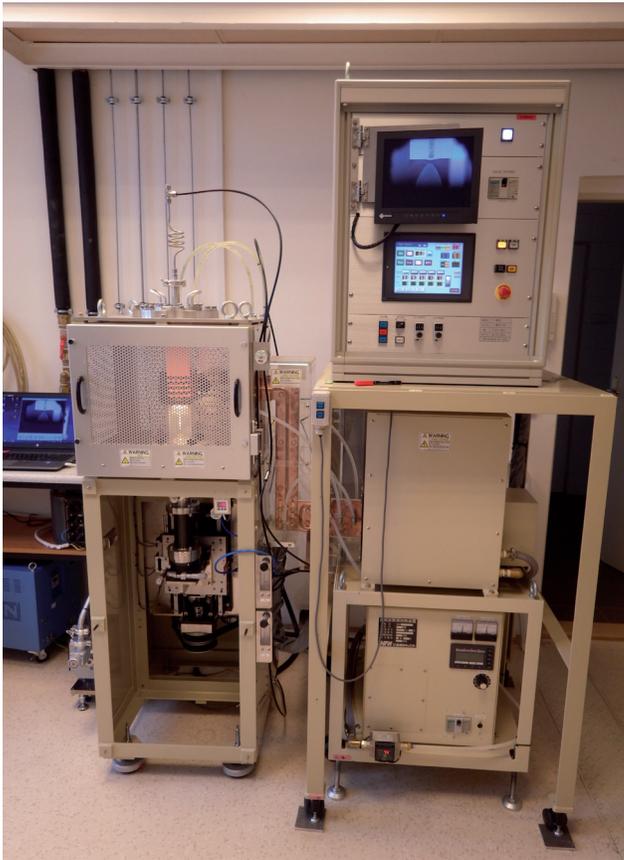
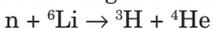


Fig. 4. Apparatus for crystal growth by the micro-pulling-down method installed in the Institute of Physics, Czech Academy of Sciences

Composition

Obviously, most of the above characteristics depend on composition of the material. For example, to achieve high density and effective atomic number, it is preferable to use heavy elements, such as lutetium, hafnium, lead, etc. However, the composition also influences toxicity, mechanical and chemical stability of the material and its price. It is also necessary to point out that some elements have radioactive isotopes, which can invoke false scintillation pulses (typically ^{176}Lu can invoke up to 300 pulses per second in 1 cm^3 of crystal). Regarding the composition, neutron scintillators represent a rather specific group. Their matrices must be capable of effective neutron capture, so they must contain an element whose nuclei can capture neutrons with high efficiency and the resulting suitable nuclear reaction should lead to efficient excitation of the matrix. These elements may be, for example, lithium ^6Li or boron ^{10}B isotopes. When a neutron is captured by the ^6Li nucleus, the following reaction takes place:



Charged nuclei of hydrogen ^3H and helium ^4He (alpha particles) escaping from the point of interaction of the lithium nucleus with neutron then create the excited states in the matrix. For more details the reader should check the review article by M. Nikl. Scintillation detectors for x-rays. *Meas. Sci. Technol.* 2006, 17, R37.

Methods of preparation

As has been already said, scintillators may be in the form of powder, glass or ceramics, but in most of the applications they are used in the form of single crystals. For the industrial production of single crystals, the Czochralski method is used. It consists in a gradual pulling of the crystal from the free melt level (Figure 3). The starting material is melted in a crucible. Then a seed crystal attached to the pulling rod touches the melt level. The melt gradually crystallizes on the seed crystal and by pulling and rotating the rod with the seed crystal upwards the single crystal is grown. This method can be used to prepare crystals weighing from tens to hundreds of kilograms. Another widespread method is the Bridgmann method which consists in moving an ampoule with the starting material through a furnace with the selected temperature field. There are also other industrial methods of crystal growth. For research purposes, they may be unsuitable due to the high material and energy consumption and low growth rate. One of the methods suitable for research is for example the micro-pulling-down method. The micro-pulling-down crystal growth equipment was installed for the first time in the Institute of Physics, Czech Academy of Sciences in 2015 (Figure 4) as the only apparatus of its kind in the Czech Republic. It is worth mentioning that this apparatus is the most

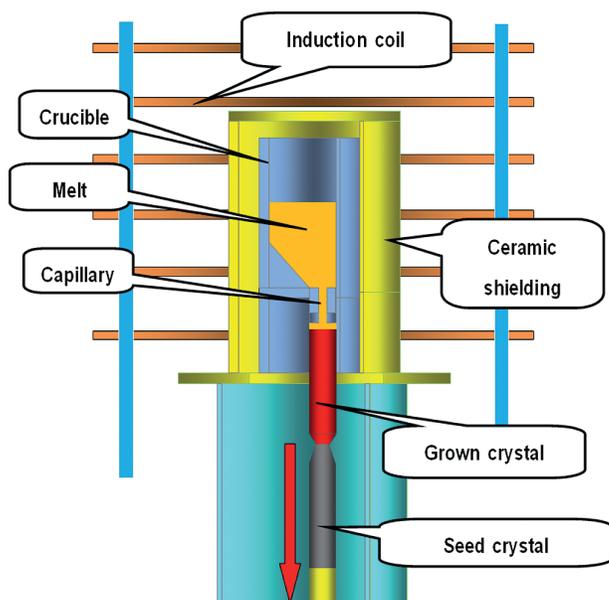


Fig. 5. Schematics of the crystal growth by the micro-pulling-down method

advanced one outside Japan, where it was manufactured. The method consists in pulling the crystal from the bottom of the crucible with the melt (Figure 5). The method was developed to the present state at the beginning of the 1990s in the Tohoku University in Sendai, Japan for the preparation of thin crystalline fibers. The melt flows from the bottom of the crucible through a micro-capillary (that is the reason for the first word “micro”). A seed crystal touches the melt which partially solidifies. Pulling down the seed crystal, a new crystal fiber is grown. The method was modified so that crystals up to a diameter of 5 mm and a few centimeters in length can be produced. The advantage of this method is the low consumption of raw materials and very fast growth. The growth rates are about 0.1 mm/min, so that a crystal ready for optical and scintillation characterization can be prepared in a single day. The method is therefore suitable for material composition screening and significantly accelerates the research of scintillators as well as other crystalline materials. However, due to the high growth rate, the crystal quality is slightly lower compared to the crystals grown for example by the Czochralski method.

Examples of scintillation materials

In the following section we will have a look at some of the most advanced scintillation materials and we will discuss their properties and potential use in science, nuclear medicine or industry.

NaI:Tl⁺, CsI:Tl⁺

One of the longest-in-use scintillation material is NaI:Tl⁺. The chemical element behind the colon in the formula denotes the activator, in this case the thallium. One of the greatest advantages of NaI:Tl⁺ is the technological availability for the production of arbitrary shapes and volumes of such a crystal allowing its usage in a number of common applications that do not put high demands on material performance. Furthermore, NaI:Tl⁺ has a relatively good scintillation efficiency, the light yield exceeding 40,000 phot/MeV, and a satisfactorily short decay time of 230 ns. Caesium iodide, CsI:Tl⁺, a heavier analogue of NaI:Tl⁺, has similar properties. The main disadvantages of these crystals are their fragility and hygroscopicity. Therefore, crystals must be hermetically sealed, mostly in an aluminum case.

LaBr₃:Ce³⁺, Sr²⁺

This heavy halide class scintillator is known and studied primarily for its excellent energy resolution, which, due to its good proportionality, attacks the 2% limit (at the energy of 662 keV, gamma radiation of the ¹³⁷Cs isotope). Therefore, potential use involves scintillation detectors with spectroscopic properties and nuclear medicine, also due to its high light output of up to 80,000 phot/MeV. One disadvantage for its use in the low-background detectors is that the chemical element lanthanum naturally contains one radioactive isotope (¹³⁸La), which represents 0.09% of natural La and has a long half-life of 10¹¹ years. (M. S. Alekhin, J. T. M. de Haas, I. V. Khodyuk, K. W. Kramer, P. R. Menge, V. Ouspenski, P. Dorenbos. Improvement of LaBr₃:5%Ce scintillation properties by Li⁺, Na⁺, Mg²⁺, Ca²⁺, Sr²⁺, and Ba²⁺ codoping. *Appl. Phys. Lett.* 2013, 102, 161915).

SrI₂:Eu²⁺

The first use of SrI₂:Eu²⁺ as a radiation detector is already mentioned in 1968 when SrI₂:Eu²⁺ crystal was patented by R. Hofstadter. However, due to its high production cost and strong hygroscopicity it was not studied until recently. The best SrI₂:Eu²⁺ crystals reach a light yield of 120,000 phot/MeV with a very favourable energy resolution of less than 3% at 662 keV; SrI₂:Eu²⁺ is therefore supposed to replace existing crystals in medical applications.

Bi₄Ge₃O₁₂ (BGO)

Together with NaI:Tl⁺ and CsI:Tl⁺, BGO is among the oldest used scintillation materials. This is an intrinsic scintillator (does not contain additional activator) and it was introduced in 1973 (M. J. Weber, R. R. Monchamp. Luminescence of Bi₄Ge₃O₁₂: spectral and decay properties. *J. Appl. Phys.*, 1973, 44, p. 5495–5499). Thanks to the combination of high density ($\rho = 7.13 \text{ g.cm}^{-3}$), high effective atomic number ($Z_{\text{eff}} = 74$) and the possibility of cheap and fast preparation of large-volume crystals of different shapes and sizes, its application has spread rapidly to many branches of science and industry. The emission maximum is located at 480 nm with a characteristic decay time of 300 ns. In addition, BGO can boast a very high mechanical and radiation hardness. Its biggest drawback is its relatively low light output of around 8,000 phot/MeV, but it is still used nowadays in many applications (medical imaging, γ -ray spectroscopy, space applications).

PbWO₄ (PWO)

Similarly to BGO, PWO (lead tungstate) is a scintillation material without an activator, probably with the highest density among the materials currently used ($\rho = 8.23 \text{ g.cm}^{-3}$ and $Z_{\text{eff}} = 73$). Therefore, it is also used, thanks to the very fast response on the order of nanoseconds, mainly in the high energy physics (Figure 6) and in detectors of the most energetic photons whose energy can reach up to tens of TeV (10,000,000,000,000 eV). A certain disadvantage is the very low light yield, which reaches only 300 phot/MeV. It has been extensively studied all over the world, including the Institute of Physics, Czech Academy of Sciences (Figure 7). The aim was to achieve a higher light output, accelerate the scintillation response, but most importantly, to increase the radiation hardness. One of the possible options is to introduce Mo³⁺ and La³⁺ or Nb⁵⁺ ions into the PWO structure (for more information, see for example M. Nikl Wide band gap scintillation materials. Progress in the technology and material understanding. *Phys. Status Solidi A*, 2000, 178, p. 595–620).

YAG:Ce³⁺, LuAG:Ce³⁺

One of the best-known and most used scintillation material is yttrium aluminum garnet activated by cerium ions – Y₃Al₅O₁₂:Ce³⁺, often called YAG:Ce³⁺ in the literature (Figures 8, 9). Along with the LuAG – lutetium aluminum garnet (Figure 10) – they have the structure derived from that of garnet, one of the well-known Czech gemstones. With density of 6.67 g.cm⁻³ (versus 4.56 g.cm⁻³ for YAG) and effective atomic number of 63 (versus 32 in YAG), LuAG:Ce³⁺ (Lu₃Al₅O₁₂) is one of the heaviest scintillators. The advantage of these garnets is, among other things, the high thermal stability of luminescence. However, upon studying LuAG:Ce³⁺ in detail, it was

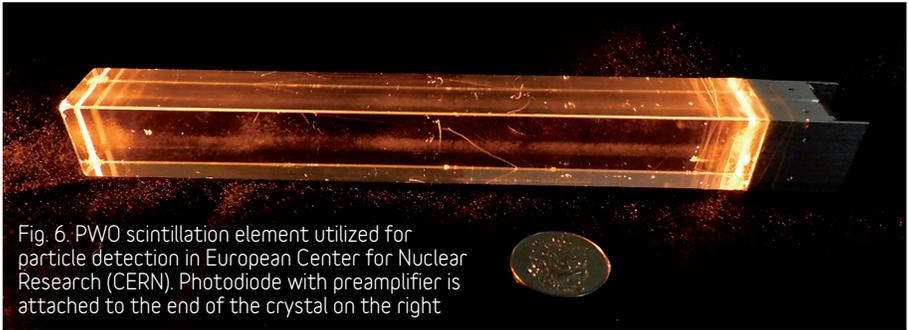


Fig. 6. PWO scintillation element utilized for particle detection in European Center for Nuclear Research (CERN). Photodiode with preamplifier is attached to the end of the crystal on the right



Fig. 7. Scintillation crystal of PWO grown by the Czochralski method in the Institute of Physics, Czech Academy of Sciences

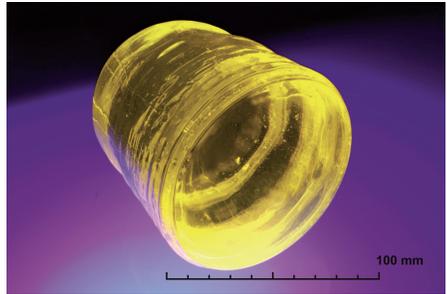


Fig. 8. Scintillation crystal of YAG:Ce grown by the Czochralski method (Published with permission of Crytur Ltd.)

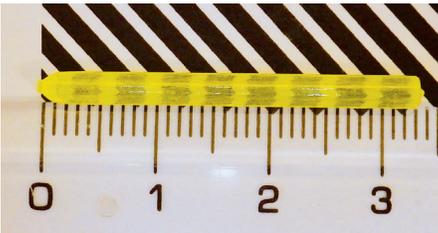


Fig. 9. Scintillation crystal of YAG:Ce grown by the micro-pulling-down method in the Institute of Physics, Czech Academy of Sciences

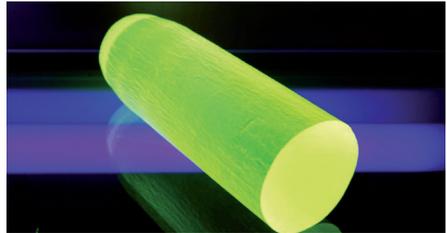


Fig. 10. Scintillation crystal of LuAG:Ce grown by the Czochralski method (Published with permission of Crytur Ltd.)

found that the light yield of the finest crystals reached only 26,000 phot/MeV, which is not even half of the theoretical limit. In addition, there is a slow component in the scintillation decay, significantly degrading overall efficiency and real use. Based on the structural works it has been known that there are places in the LuAG structure where aluminum and lutetium exchange their regular lattice positions. This structural defect then creates shallow electron traps in the forbidden gap and can capture electrons produced in scintillation and delay their radiative recombination, which results in slow components in the decay (see above). For more information, see for

example M. Nikl, A. Yoshikawa, K. Kamada, K. Nejezchleb, C. R. Stanek, J. A. Mares, K. Blazek. Development of LuAG-based scintillator crystals – A review. *Prog. Cryst. Growth Charact. Mater.* 2013, 59, p. 47.

GGAG:Ce³⁺

The most advanced scintillation material from the group of oxides is undoubtedly $\text{Gd}_3\text{Ga}_3\text{Al}_2\text{O}_{12}:\text{Ce}^{3+}$, (abbreviated as GGAG: Ce, Fig. 11). It is derived from the LuAG garnet structure by replacing the Lu atoms with Gd and part of the Al atoms with Ga. This material is a demonstration of perfect optimization strategy and indispensable collaboration of physicists with crystal growth technologists. The challenge behind GGAG development was to improve the properties of LuAG crystals due to their shortcomings described above. An optimization strategy applied to this and other scintillation materials is called “bandgap engineering” and represents the modification and optimization of the forbidden gap. At the birth of this strategy was, among others, doc. Ing. Martin Nikl, CSc., from the Institute of Physics, Czech Academy of Sciences. The addition of the Ga atoms to the LuAG structure shifts the edge of the conduction band to lower energies. In this way energy levels of the above-mentioned shallow traps become buried in the conduction band and the traps, therefore, will lose their ability to retain electrons. As a result, the slow components of the scintillation decay are suppressed and the light yield increases. On the other hand, the lower edge of the conduction band is disadvantageous in terms of temperature stability of the emission, which is compensated by addition of Gd. For the best GGAG:Ce³⁺ crystals, light yield up to 60,000 phot/MeV is achieved, which attacks the theoretical limit. With scintillation decay time of 90–170 ns, relatively high density (6.2 g.cm⁻³), good energy resolution (4.2% at 511 keV) and especially high mechanical and chemical stability, GGAG:Ce³⁺ ranks among the best modern scintillators with high application potential (see for example K. Kamada, S. Kurosawa, P. Prusa, M. Nikl, V. V. Kochurikhin, T. Endo, K. Tsutumi, H. Sato, Y. Yokota, K. Sugiyama, A. Yoshikawa. Cz grown 2-in. size Ce:Gd₃(Al,Ga)₅O₁₂ single crystal; relationship between Al, Ga site occupancy and scintillation properties. *Opt. Mater.* 2014, 36, p. 1942).

(Gd;La)Si₂O₇:Ce³⁺

This heavy scintillator from the pyrosilicate class has been intensively studied since 2012 and it is another demonstration of the need for collaboration between physicists and crystal growth technologists (Figure 12). The pure undoped $\text{Gd}_2\text{Si}_2\text{O}_7$ crystal cannot be technically grown as a bulk material due to incongruent melting. It means that, during the crystal growth, the solid phase composition is not the same as that of the melt. The addition of several tens of percent of lanthanum stabilizes the pyrosilicate phase, which changes the situation significantly. The light yield exceeds 40,000 phot/MeV and the Ce³⁺ emission in this matrix is thermally stable up to approximately 230 °C, which is sufficient to allow the material usage in the so-called carotage probes and other geophysical applications (for more information see for example V. Jary, M. Nikl, S. Kurosawa, Y. Shoji, E. Miho-kova, A. Beitlerova, G. P. Pazzi, A. Yoshikawa. Luminescence characteristics of the Ce³⁺-doped pyrosilicates: The case of La-Admixed $\text{Gd}_2\text{Si}_2\text{O}_7$ single crystals. *Journal of Physical Chemistry C.* 2014, 118, p. 26521–26529).

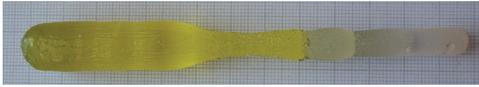


Fig. 11. Scintillation crystal of GAGG:Ce grown by the Czochralski method in the Institute of Physics, Czech Academy of Sciences. The millimeter paper gives the scale. The white part on the right is a seed crystal that does not contain the Ce^{3+} activator

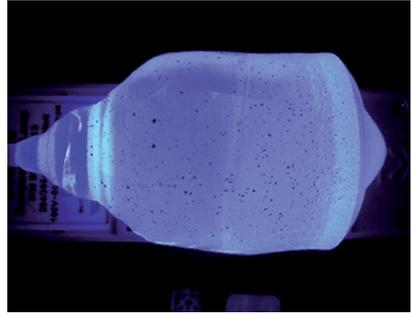


Fig. 12. Blue luminescence of the $(\text{Gd};\text{La})\text{Si}_2\text{O}_7:\text{Ce}^{3+}$ crystal excited by the UV lamp (Published with permission of Prof. Kurosawa from Tohoku University in Japan) >

$(\text{Lu};\text{Y})_2\text{SiO}_5$ (LYSO): Ce^{3+}

Mixed lutetium yttrium oxy-orthosilicate activated by cerium ions (LYSO:Ce) belongs to the latest generation of modern scintillation materials, mainly due to its high light output of about 32,000 phot/MeV, fast scintillation response of 40 ns without slow components, high density and very good energy resolution. In addition, the preparation of large scale crystals is highly technologically viable today at relatively low cost. Although the pure lutetium oxy-orthosilicate Lu_2SiO_5 (LSO) would have higher density (7.4 g/cm^3), several tens percent of yttrium are added to LSO, mainly to decrease the amount of the radioactive isotope ^{176}Lu (β -emitter, a half-life of 4.10^{10} years) present in LSO, which can invoke a fake signal to a detector. At present, $\text{LYSO}:\text{Ce}^{3+}$ is mainly used in medical applications (V. Jary, M. Nikl, E. Mihokova, J. A. Mares, P. Prusa, P. Horodysky, W. Chewpraditkul, A. Beitlerova. Influence of yttrium content on the Ce1 and Ce2 luminescence characteristics in $(\text{Lu}_{1-x}\text{Y}_x)_2\text{SiO}_5:\text{Ce}$ single crystals. *IEEE Trans. Nucl. Sci.* 2012, 59, p. 2079).

SrHfO_3 -based scintillators

Ce^{3+} -doped SrHfO_3 was patented as a scintillator already in 1992. Due to the very high melting point of this compound ($> 2400 \text{ }^\circ\text{C}$), a single crystal has not yet been grown, but the properties of microcrystalline powder and SrHfO_3 optical ceramics have recently been studied in detail. Its advantages include high density (7.56 g.cm^{-3}), high effective atomic number (60.2), absence of natural radioactivity and fast scintillation response around 20 ns thanks to the Ce^{3+} activator.

Due to high price of rare earth metals (for example La, Ce, Pr, Eu, Lu ...), rare-earth-free scintillation materials have been extensively searched for in recent years. In a detailed study of $\text{SrHfO}_3:\text{Ce}^{3+}$ in the Institute of Physics in Prague, it was possible to prepare and characterize a non-activated non-stoichiometric SrHfO_3 of the $\text{Sr}_{0.98}\text{Hf}_{1.02}\text{O}_{3.02}$ compositions, which provides high intensity emission in near UV spectral range while preserving all the advantages of $\text{SrHfO}_3:\text{Ce}^{3+}$. Thanks to the above-mentioned properties, it can be used as an effective fast-converting X-ray and gamma-ray radiation material for 2D imaging techniques (see for example P. Boháček, B. Trunda, A. Beitlerová, J. Drahokoupil, V. Jary, V. Studnička, M. Nikl. Rare-earth-free luminescent non-stoichiometric phases formed in SrO-HfO_2 ternary compositions. *J. Alloy. Compd.* 2013, 580, p. 468–474).

YAlO₃:Ce, LuAlO₃:Ce

Perovskite scintillators are now studied mainly because of their good proportionality and consequently a good energy resolution of about 4% (at 662 keV), the best among oxide scintillators. In addition, the LuAlO₃ (LuAP) lutetium aluminum perovskite has a considerably high density (8.34 g.cm⁻³) and the decay time of cerium luminescence of about 18 ns in these materials is three times shorter than that in garnet analogues (YAG, LuAG). Growth of YAP (yttrium aluminum perovskite) crystals, and in particular LuAP, is, however, highly demanding, as the perovskite phase is unstable and the garnet phase often forms during the growth process. However, increased stability was found to occur in the mixed Y–Lu system (K. V. Ivanovskikh, J. M. Ogiegło, A. Zych, C. R. Ronda, A. Meijerink. Luminescence Temperature Quenching for Ce³⁺ and Pr³⁺ d-f Emission in YAG and LuAG. *ECS J. Solid State Sci. Technol.* 2013, 2, R3148). The best YAP:Ce³⁺ crystals has a light yield over 25,000 phot/MeV.

KLuS₂:Eu²⁺

This intriguing scintillation material from the sulfides material family was first described and patented in 2013 in the Institute of Physics in Prague. From the structural point of view, it is interesting that the divalent Eu²⁺ occupies both the trivalent and monovalent positions of Lu³⁺ and K⁺, respectively, in the structure of KLuS₂, which naturally compensates the electrical charge imbalance. Attention is also paid to the high efficiency of the excitation energy transfer from the KLuS₂ host to the Eu²⁺ emission center as it achieves the light yield of more than 35,000 phot/MeV at low concentrations of Eu²⁺ (0.05%). Due to relatively high density and effective atomic number, this material can be used for high-energy photon detection (V. Jarý, L. Havlák, J. Bárta, E. Mihóková, M. Nikl. Optical properties of Eu²⁺-doped KLuS₂ phosphor. *Chem. Phys. Letters* 2013, 574, p. 61–65).

Scintillators based on nitride semiconductors

Approximately 20 years ago, the production of nitride semiconductor luminescent diodes using InGaN and GaN quantum structures began. The Nobel Prize was awarded to Japanese scientists Isamu Akasaki, Hiroshi Amano and Shuji Nakamura in 2014 for developing the technology for the preparation of nitride luminescent diodes emitting in blue spectral region. Ten years later, scientists realized that a similar, slightly modified structure could also be used for scintillators. Due to the strong bond among the atoms, these materials are of a high radiation hardness. The large exciton's binding energy allows high luminescence intensity at room temperature and the character of the luminescence process to have a fast luminescence response of around 1 ns, which is mostly unattainable in scintillation materials. Such high-speed scintillators are currently required for electron microscope detection units used in inspection device in semiconductor industry where ultra-fast scanning electron microscopes are needed to control the quality of integrated circuits. However, due to the high intensity of luminescence, nitride heterostructures (structures in which GaN and InGaN alternate) are also prospective for other types of scintillators, detecting X-ray or other particle radiation. Since luminescence is generated in a relatively thin area (several hundred nm), nitride

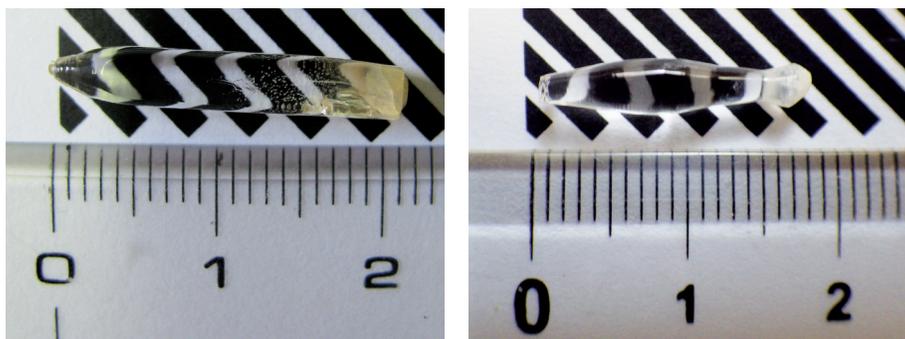


Fig. 13. Crystals LiAlO_2 (left) and Li_4SiO_4 (right) grown by the micro-pulling-down technique

heterostructures are also suitable for usage as high resolution 2D scintillators. The development of these nitride heterostructures with different thicknesses of the active region for various scintillation applications is carried out in the Institute of Physics, see for example A. Hospodková, M. Nikl, O. Pacherová, J. Oswald, P. Brůža, D. Pánek, B. Foltynski, E. Hulicius, A. Beitlerová, M. Heuken. InGaN/GaN multiple quantum well for fast scintillation application: radioluminescence and photoluminescence study. *Nanotechnology* 2014, 25, 455501).

Neutron scintillators

Absorption of neutron radiation is highly dependent on material composition and it is used in special imaging methods, detection of explosives, drugs, or fissionable materials used for the nuclear weapons production. Neutron radiation is also used to study the structure of new materials and in nuclear reactors or nuclear fusion experiments, a potential new source of energy for mankind. It can also be used to treat some types of cancer. Neutron scintillators include, for example, lithium glass doped by cerium, which is characterized by a fast response of 70 ns but a relatively low light yield of 7,000 photons per neutron. Another material under consideration is the $\text{Cs}_2\text{LiLaBr}_6:\text{Ce}$ crystal, which also has a fast response and a very high light output of 180,000 photons per neutron. However, this material is highly hygroscopic. In the Institute of Physics of the Czech Academy of Sciences in collaboration with Tohoku University, Japan, materials such as titanium-activated $\text{LiAlO}_2:\text{Ti}$ (with response of 2.5 microsecond and light yield of 10,000 photon per neutron) and $\text{Li}_4\text{SiO}_4:\text{Ti}$ (50 microsecond response and 12,000 photon per neutron light yield) – see Figure 13, have been investigated (J. Pejchal, Y. Fujimoto, V. Chani, F. Moretti, T. Yanagida, M. Nikl, Y. Yokota, A. Beitlerova, A. Vedda, A. Yoshikawa. Crystal growth and luminescence properties of Ti-doped LiAlO_2 for neutron scintillator. *Journal of Crystal Growth* 2011, 318/1/, p. 828–832; J. Pejchal, V. Babin, A. Beitlerova, S. Kurosawa, Y. Yokota, A. Yoshikawa, M. Nikl. Improvement of the growth of Li_4SiO_4 single crystals for neutron detection and their scintillation and luminescence properties. *Journal of Crystal Growth* 2017, 457/1/, p. 143–150).

Application of scintillation materials

LHC particle accelerator, CMS detector

Part of the European Center for Nuclear Research (CERN) complex is the world's largest LHC particle accelerator (Large Hadron Collider; hadrons are heavy particles such as protons, neutrons). This device can accelerate charged particles (typically positively electrically charged protons) to extremely high energies and speeds. At these speeds particles are purposely mutually collided thanks to which a huge amount of energy is released, today up to dozens of TeVs. These extreme collisions create very exotic particles that do not exist in earthly conditions and can help to understand the basics of physics and the world around us. One of the detection systems called ECAL (Electromagnetic CALorimeter) uses scintillation materials (for more information, we refer those who would be interested to, for example, <http://cms.web.cern.ch/news/howcmsdetectsparticles>; <http://home.cern/topics/largehadroncollider>). The scintillation material that would manage to operate in these extreme conditions is subject to very strict requirements. The material must resist an extremely strong magnetic field, it must be able to operate at extremely high energies of the incident particles and must be fast enough because the time between two collisions is only 25 ns! After careful consideration, PWO was selected as the most suitable material. Upon the impact of electrons and photons from collisions on the PWO crystal, scintillation flashes proportional to the energy of impinging particles are created and further processed by powerful computers. The ECAL detector uses 75848 PWO monocrystals with the dimensions of about $3 \times 3 \times 22$ cm, weighing more than 1.5 kg each. Taking into account high density of each crystal, the whole detector contains more than 100 tonnes of scintillation material. Nowadays it is considered that large volume PWO scintillators would be replaced by LuAG and LuAG:Ce³⁺ scintillation fibers that would better characterize different types and energies of particles based on different material time response. In order to optimize and use crystals in similar detectors, a special international group was established, which is also represented by the Czech Republic (Institute of Physics of the Czech Academy of Sciences). Its task is the development of new detection concepts based on scintillation crystals. The group is called Crystal Clear Collaboration (CCC), it was founded in 1990 and it has been coordinated from CERN. The CCC group is mainly involved in the research of scintillating materials suitable for detection in high energy physics, nuclear physics, astrophysics, dark matter research, medical imaging and industrial applications. In addition, new ways of preparing these materials and their forms are sought (for more information see <http://crystalclear.web.cern.ch/crystalclear/>).

CT - Computed tomography

Currently, CT (computed tomography) is one of the most used medical devices. Whether it is a post-accident examination, a cancer scan, or a check for the correct build-up of more complicated fractures, and many others, CT examinations allow doctors to look inside the patient and decide about treatment. The principle of CT operation is similar to that of conventional X-ray. However, unlike X-ray, one

CT scan gets the image in different cross-sectional (tomographic) images (virtual “slices”). X-ray radiation is attenuated in the body of the patient, depending on the composition of the individual tissues, and based on differences in measured attenuation, it is possible to reconstruct the body image of the patient in the transverse section. The drawback is that even the latest CT devices cannot display soft tissue with high contrast (such as magnetic resonance imaging can). The latest generation of CTs works with a fan beam of X-rays, so it is possible to cover the entire cross section of the investigated volume. Directly opposite to the X-ray source, detectors in an arc arrangement are placed on a common axis. During the examination, the whole system rotates around the patient. With the most advanced devices, patient is shifting as well which gives rise to creating a 3D spiral image. This reduces the examination time to several minutes, ideally down to tens of seconds. In the detectors, BGO or CdWO_4 crystals are still commonly used, as well as ceramic scintillators based on $(\text{Gd,Y})_2\text{O}_3:\text{Eu}$ or $\text{Gd}_2\text{O}_2\text{S}:\text{Pr}$. Recently, materials based on cerium-doped multi-component garnets are under development. Currently, CT is the only diagnostic device that allows us to perform very fast and complex high resolution examinations. Thanks to the imaging speed, CT is used, among other things, for the preoperative examination of polytraumatized patients, where it helps to save lives (for more information, please refer to, for example, <https://www.fda.gov/RadiationEmittingProducts/RadiationEmittingProductsandProcedures/Medical-Imaging/MedicalX-Rays/ucm115318.htm>).

Positron emission tomography

Positron emission tomography (PET) is a diagnostic method providing a 3D view of the distribution of intravenously applied radiopharmaceuticals emitting positrons in the patient's body. Positrons (anti-electrons or electrons with positive charge), which are antimatter particles, instantly interact with electrons in the immediate neighbourhood. As a result of this interaction, called annihilation, two gamma photons with exactly defined energy (511 keV per one) are created. These two photons fly from the location of interaction along a straight line in opposite directions (this follows from the law of momentum conservation). The gamma photons are registered with a ring of scintillation detectors circularly distributed around the patient's body. The electronics only registers the signals coming simultaneously from opposite scintillation detectors, and other signals are excluded. This trick is used to limit the influence of radiation coming from the environment (so-called natural background). For example, it is difficult to imagine that two high-energy photons from cosmic radiation hit exactly the opposite scintillation detectors at the same time. Unlike in CT technology, the natural background signal does not have to be surpassed. Since we can accurately detect the interaction of the photon in scintillation detector, we know its energy, and we know that two photons are emitted from each other on a straight line, we can use the computer technology to accurately determine where the photons were created. After registration and computer data processing, one can view the distribution of the radiopharmaceutical in the body in three dimensions and make tomographic cross-section in any plane. The most commonly used radiopharmaceutical is fluorodeoxyglucose (FDG), labelled with fluorine- ^{18}F radioisotope, which has a radioactive half-life of 109 minutes. Simply speaking, it is a radioactive

sugar (glucose). After intravenous application, FDG enters the cells with the same mechanisms as glucose, but does not undergo subsequent metabolic processes and it is therefore captured in cells. The level of capture corresponds to the consumption of glucose (metabolic activity) in the tissues. Therefore, PET examination with ^{18}F FDG is predominantly used in oncology diagnostics because most malignant tumours and their metastases show increased glucose metabolism. The tumour location is then given with the units of mm accuracy for the most advanced devices. The properties of scintillation materials which could be used in PET scanners are similar to those of a CT device, i.e. they must have a high density, an effective atomic number, they must work fast and there must be no slow components in their response. For these reasons, BGO is still in use but more modern devices employ $\text{LYSO}:\text{Ce}^{3+}$ crystals based detectors. In addition, the latest generation of PET scanners can determine the exact time in which the annihilation photon is detected. As the annihilation photon which was created closer to the detector reaches the detector earlier, the difference in detection times of these annihilation photons can help to improve the accuracy of determining the annihilation event, therefore improving the tumour location as well. This method is called time of flight PET (abbreviated as TOF-PET). For TOF-PET purposes, the detectors must meet even more demanding requirements in terms of the speed of response. The $\text{LYSO}:\text{Ce}^{3+}$, Ca^{2+} scintillator is currently being used clinically, but also, for example, $\text{GAGG}:\text{Ce}$ with a small amount of Mg is tested. There are more than a dozen workplaces equipped with PET imaging technology in the Czech Republic.

Geophysical probing

An interesting application of scintillation materials is the search for new oil, natural gas or ores deposits. A so-called carotage probe containing a radionuclide source and a well-shielded scintillation detector (so that the detector does not register the radiation from the source) is inserted into the geological well. The radionuclide source emits ionizing radiation into the environment in which this radiation excites the gamma radiation characteristic for the chemical elements found in the rock. From the knowledge of radiation energy, we can obtain information about rock formation around the geological well, and thus information on the possible presence of oil, natural gas or ores. Scintillators suitable for this application must be sufficiently mechanically resistant and thermally stable up to high temperatures. One of the materials used is $\text{GSO}:\text{Ce}^{3+}$ ($\text{Gd}_2\text{SiO}_5:\text{Ce}^{3+}$).

Electron microscopy

Electron microscopes are devices that use electrons accelerated by an electric field instead of a light beam, and electromagnetic lenses are used instead of glass lenses. Electron beam with a substantially shorter wavelength ($\sim 0.01\text{--}0.001\text{ nm}$) compared to that of visible light ($450\text{--}780\text{ nm}$) allows much higher resolution, and the most modern current devices can display objects with dimensions on the order of 0.1 nm , therefore the dimensions of an atom. The principle of operation of an electron microscope is schematically illustrated in Figure 14. The accelerated electron beam passes through a central hole in the $\text{YAG}:\text{Ce}$ scintillator disc, reflects from the surface of the sample being examined, and is stopped on the surface of the

scintillator. These reflected electrons carry information about the sample surface. The scintillation flashes are guided through the side of the disk to the detector, and after being converted to an electrical signal, this signal is used to form the image of the sample surface. An important worldwide manufacturer of detectors for electron microscopy is the Czech company Crytur (for more information, please refer to, for example, <https://www.nanoscience.com/technology/sem-technology/>).

Airborne monitoring of radioactive contamination by unmanned helicopter

A special detection probe based on scintillators, which can be attached to an unmanned helicopter, has been developed in Japan. It can thus monitor the presence of radioactive isotopes, mainly ^{137}Cs , from high in the air, especially in the area of the Fukushima nuclear power plant. The probe must therefore be very light and use little energy. GGAG:Ce $^{3+}$ crystals were selected as suitable scintillation material for gamma radiation detection. The helicopter path was programmed in advance to cover the area of $65 \times 180 \text{ m}^2$ at a height of 10 m for a period of approximately 30 minutes at a speed of 1 m/s and a measuring interval of 10 m. The first attempts prove that in the future this system can serve to quickly and accurately measure the decontamination process, to search for hot zones (local areas with heavily increased radioactivity), and to monitor the spread of ^{137}Cs within the environment around Fukushima; for more information, see *Journal of Nuclear Science and Technology* 2016, 53(12).

Earthquake prediction

After a major earthquake in Tashkent in 1966, and in connection with the observation of the presence of radon in China, a new system has been in place in Japan to build a new earthquake forecasting system based on the monitoring of radon in groundwater. Its concentrations in groundwater are likely to reflect structural changes in bedrock, and it has been found to increase significantly, up to ten times, before large earthquakes. Radon detection in these underground conditions is possible with scintillation detectors that are sufficiently mechanically resistant and can work for years.

Acknowledgement

The authors would like to express their acknowledgement to Dr. Eva Mihóková for careful language corrections and to EC H2020, ASCIMAT project, no. 690599, for financial support.

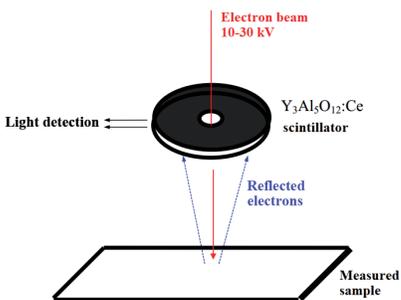


Fig. 14. Use of scintillation crystals in electron microscopy (from Martin Nikl 2006 *Meas. Sci. Technol.* 17 R37: Scintillation detectors for x-rays)

In the field of High Power Photonics, we study lasers and laser produced plasmas. The HiLASE laser centre (www.hilase.cz) is the spin-off of the terawatt iodine laser system PALS. HiLASE project focuses on the research and experimental development of novel high energy, pulsed diode-pumped solid state laser systems with high repetition rates and average output power on kW level. Our laser systems will be significantly more powerful, compact, efficient and will offer an easier maintenance. Therefore they have a great potential not only in basic science but also in applied research and high-tech industry.

The largest currently built infrastructure of the Institute of Physics of the AS CR belongs to the field of laser physics and it is called the Extreme Light Infrastructure (ELI). This project is part of a European plan to build a new generation of large research facilities selected by the European Strategy Forum for Research Infrastructures (ESFRI). The main goal of ELI is to create one of the latest laser equipment in the world. There will be accomplished and implemented research projects covering the interaction of light with matter at intensity being many times higher than currently achievable values. ELI will provide ultra-short laser pulses of a few femtoseconds (10^{-15} fs) duration and give performance up to 10 PW. ELI will bring new techniques for medical image-display and diagnostics, radiotherapy, tools for new materials developing and testing, latest in X-ray optics, etc. ELI will also be an attractive platform for educating a new generation of scientists. More information about the ELI Beamlines project is available at www.eli-beams.eu.

In the optical materials department, from which the authors of the brochures come, technologies for the preparation of bulk and thin-layer material systems potentially used in optical applications (luminescent and scintillation materials, diamond layers, photovoltaics, nanotechnologies), are developed. To measure the characteristics of these and other externally obtained materials, a wide variety of experimental techniques is used in the department, namely optical, magnetic and photoelectron spectroscopies. In addition to technological and experimental activities, the theoretical activities are included in the scope of the department, especially in the field of nucleation processes, phase transitions and kinetic models of luminescence.

During 2014–2017, research in the department was supported by 24 Czech and 20 international projects. Domestic projects were awarded mostly within the framework of a competition announced by the Grant Agency of the Czech Republic. Bilateral cooperation with foreign countries (in particular laboratories in Japan and China) is supported by bilateral projects of the Ministry of Education, Youth and Sports or the Academy of Sciences of the Czech Republic.

Cooperation with industrial partners in the CR (Crytur s. r. o, Nuvia) or abroad (Tokuyama, GE) is supported by research projects and agreements. The department is a partner in European projects EU FP7 “Luminet”, FP7-PEOPLE-2012-ITN, No. 316906 (2012–2016); Horizon2020 INTELUM, H2020-MSCA-RISE-2014, No. 368921 (2015–2018); COST TD1401 (2015–2018) and coordinates project H2020-TWINN-2015 ASCIMAT, No. 690599 (2016–2018).

In recent years, number of industrial, medical, safety and scientific applications, in which invisible ionizing radiation (e.g. gamma-rays, X-rays) has to be detected, have been developing rapidly. This booklet deals with the description of scintillation materials that are suitable for this purpose. Scintillation materials convert the energy of high-energy ionizing radiation into ultraviolet (UV) or visible photons, which can then be converted into an electrical signal by conventional photodetectors and further processed. Among the best known scintillation applications are computed tomography (CT), positron emission tomography (PET), LHC particle accelerator detectors in European Center for Nuclear Research (CERN), or modern monitoring unmanned drones used around Fukushima nuclear power plant in Japan.

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Published by the Center of Administration and Operation CAS, v. v. i. Layout: Jakub Krč; Type: Serifa. Editor in charge: Petra Královcová. First edition, 2018. Edition number 12413. Print: **SERIFA**®, s. r. o., Jinonická 80, 158 00 Praha 5.

ISSN 2464-6245

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