Inorganic Scintillators for Detector Systems

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Inorganic Scintillators for Detector Systems

Physical Principles and Crystal Engineering

With 125 Figures

Springer

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Preface

The last two decades have seen a spectacular increase of interest for inorganic scintillators. This has been to a large part a consequence of the visibility given to this field by several large crystal-based detectors in particle physics. To answer the very challenging requirements for these experiments (huge data rates, linearity of response over a large dynamic range, harsh radiation environment, impressive crystal quantities to be produced in a short time period and at an affordable cost, etc...) an effort of coordination was needed. Several groups of experts working in different aspects of material science have combined their efforts in international and multidisciplinary collaborations to better understand the fundamental mechanisms underlying the scintillation process and its efficiency. Similarly, the stability of the scintillation properties and the role of color centers has been extensively studied to develop radiation hard scintillators. Dedicated conferences on inorganic scintillators have seen an increasing participation from different communities of users outside the domain of high-energy physics. This includes nuclear physics, astrophysics, security systems, industrial applications, and medical imaging. This last domain in particular is growing very fast since a few years at the point that the volume of scintillating crystals to be produced for positron emission tomography (PET) is going to exceed the one for high-energy physics. As more and more crystal producers are also attending these conferences, a very fruitful synergy was progressively built up among scientific experts, technologists, and end users. This aspect of a multidisciplinary collaboration is essential to help people design and build detectors of ever-increasing performance through the choice, optimization or development of the best scintillator, and a thorough investigation of the technologies to produce the crystals of the highest quality.

The idea for this book was born during one of the conferences of the SCINT cycle (eight conferences since the first one in Chamonix, France, in September 1992). It appears that the progress in understanding scintillation process and in material sciences in general opens new ways to answer the challenging requirements of an increasing number of customers. Whereas until recently the only possibility was to scan scintillator databases to select, among the few which are available, the one having reasonable properties, very often at the price of important compromises, the dream of engineering scintillators closely matching the user's requirements is becoming every day more realistic. This is why we have deliberately taken the end user's viewpoint. This book does not follow an academic scenario, starting from theoretical considerations, describing the different scintillation mechanisms in a didactic way, and concluding with a few examples. Several authors have already published excellent monographs of that sort. We have chosen instead a more pragmatic approach trying to answer practical problems and insisting on limiting factors which are not only of theoretical nature but also related to technological difficulties, production yield, and cost.

This book is therefore a practical guide for people, scientists, and engineers who intend to develop a detector using inorganic scintillators for basic research, medical imaging, or industrial applications. It will also interest students and teachers to get an overall picture of a field in rapid expansion. Its multidisciplinary approach is a good illustration of how modern challenges are met. It does not address organic and liquid scintillators.

The introduction defines the vocabulary and describes the different classes of scintillators. Definitions of *luminescence*, *scintillation*, and *phosphorescence* are given. The main parameters of interest for scintillating materials are described with a short and comprehensive definition for each of them.

The following chapter reviews the user's requirements for the different applications. Starting from the problem to be solved in domains as different as fundamental physics, medical imaging, security systems, oil well logging, and other industrial applications, it explains how these requirements influence the development of new scintillators.

The chapter on scintillation mechanism in inorganic scintillators is treated in a practical way. The point is to show how to answer high light yield, short decay time, good energy resolution, etc... as requested by users. The fundamental mechanisms are of course explained, but a particular emphasis is put on the description of factors limiting these performances in good-quality crystals.

In the next section the influence of crystal defects and their role in the degradation of the scintillator performance is thoroughly studied. In particular, problems of nonlinearity of the scintillator response and radiation damage are discussed.

At this stage it is important to address the problems of crystal engineering. This is the subject of the next chapter where the reader will get familiar with the most frequently used technologies of crystal growth and their limitations. The mechanical processing and different methods to optimize the light collection are also discussed in this part.

Finally, two examples of recently developed scintillators are given as an illustration of the approach proposed in this book. The first one describes the huge effort on Lead Tungstate (PWO) for the largest electromagnetic calorimeter ever built in high-energy physics. The second one concerns the development of the Lutetium Aluminum perovskite (LuAP) for medical imaging devices.

The authors hope through their work to contribute to the development of this very active domain of material sciences, to help the people interested in the use of inorganic scintillators, and to promote education in this field.

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August 2005 *Paul Lecoq*

Contents

1 Scintillation and Inorganic Scintillators

Abstract. This chapter introduces the basic definitions and gives the minimum necessary information about the phenomenon of scintillation and the mechanisms which have to be taken into account for the development of scintillation materials. It starts with an historical brief and describes the sequence of the processes leading to scintillation in a dielectric medium. Definitions are then given of the parameters related to the physical process of light production in the medium and not dependent on the shape, surface state and optical quality of the scintillator block. After a survey of scintillation mechanisms it is shown that several self activated scintillators show better scintillation properties when they are doped by appropriate ions. A description is given of the most important activators with a discussion about the conditions for the activator to be efficient in a host matrix. As an example the electron energy level structure of Ce^{3+} and Pr^{3+} ions is described. It is shown that these two ions are good activators with a bright and fast scintillation in many compounds. Several approaches to classify scintillation materials are discussed. This chapter is concluded with a list of the scintillation materials developed so far and of their most important properties.

1.1 The Phenomenon of Scintillation

What is a scintillator?

For a long time the answer to this apparently simple question did not find a clear and unambiguous formulation.

Scintillators have played a major role in the development of modern physics. The visual observation of scintillation on a zinc sulfide screen has allowed E. Rutherford to observe α particles, an event which can be considered as the starting point of modern nuclear physics. Till the end of the Second World War, zinc sulfide and calcium tungstate were among the most popular particle detectors found in nuclear physics laboratories. The intensive development of atomic projects in the postwar period stimulated the development of new ionizing-radiation – detecting technique, including scintillation counters. With the development of experimental physics, and in particular with the occurrence of the photoelectric multipliers, it became clear that scintillating materials are ideal devices to detect elementary particles and to measure their parameters [1–3]. In a rather short time (1947–51) it has been discovered that scintillation can be observed in various organic and inorganic crystalline media [4–7], as well as in fluids [8–11], gases [12, 13], and polymeric compounds [14]. At the same time the still most widely used scintillating crystalline material NaI (Tl) [15] has been discovered.

Kallmann [5] has made an attempt to specify the essential parameters of scintillation materials. He made, in particular, the distinction between

(a) the physical light output, which corresponds to the fraction of the absorbed ionizing radiation energy which is transformed into light, and
(b) the technical light output, which is the amount of light actually collected at the extremity of a scintillation element, taking into account all factors of light collection and absorption in the medium.

He defined scintillation as flashes of light in phosphorus. In the Physical Encyclopedia [16], scintillation is defined as "the short light flashes originating in a scintillator under the effect of ionizing radiation." Fünfer and Neuert [17] defined scintillation as "the phenomenon of luminescence in transparent solids, fluids or gases, originating at the propagation of the ionizing radiation through them."

One shall remark that all these definitions of scintillation have some shortcomings. First of all, they are restricted to the phenomenology of light production under excitation by ionizing radiation but they do not consider the mechanism of energy transfer and conversion into light. From this point of view, Cherenkov radiators [18] could be considered as scintillators, which is fundamentally incorrect. A second limitation results from the confusion between scintillation and luminescence, which is at the origin of a semantic imprecision between scintillators and luminophores. Although for the end user "there is no difference between a scintillator and a fluorescent lamp," according to A. Lempicki, there is nevertheless an important difference in the mode of excitation and energy relaxation.

The mechanism of luminescence, which is exploited in fluorescent lamps and in lasers, results from the radiative relaxation of an active ion of the material after the direct excitation between its fundamental state and excited energy levels by an electrostatic discharge or a pulse of light. On the other hand the origin of the scintillation is the energy loss of ionizing radiation through matter.

Electrons and γ quanta lose energy when traversing a medium by the three fundamental mechanisms of electromagnetic interactions:

(a) photoabsorption,
(b) Compton scattering, and
(c) electron–positron pair formation.

The interaction cross section through each of these mechanisms is energy dependent [19], photoabsorption and Compton scattering being dominant at low and medium energy and pair formation at high energy with an onset at 1.02 MeV, the mass energy of an electron–positron pair at rest. Neutral particles and charged hadrons lose energy mainly through direct interactions with nuclei or ionization of atoms for charged particles. Knock-on electrons or γ or β decay from the relaxation of nuclei excited by neutron or neutrino capture will then lose energy through the standard electromagnetic interactions described above. As long as the energy of particles is high enough for multiple scattering and electron–positron pair creation, their energy is progressively distributed to a number of secondary particles of lower energy which form an electromagnetic shower. Below the threshold of electron–positron pair creation, electrons will continue to lose energy through Compton scattering. In the case of an ordered material like a crystal, another mechanism takes place at this stage. The electrons in the keV range from the shower will start to couple with the electrons and atoms of the lattice. They will excite the electrons from the occupied electronic states of the material (valence or deeper bound states) at different levels in the conduction band. At each of these interactions, an electron–hole pair is created. If the energy of the electron is high enough to reach the ionization threshold, we have then free carriers which will move randomly in the crystal until they are trapped by a defect or recombine on a luminescent center. In the case the ionization threshold is not reached the electron and hole will cool their energy by coupling to the lattice vibration modes until they reach the top of the valence band for the hole and the bottom of the conduction band for the electron. They can also be bound and form an exciton whose energy is in general slightly smaller than the bandgap energy. At this stage the probability is maximum for a coupling to luminescent centers through either an energy or a charge transfer mechanism.

For a material to be a scintillator it must contain luminescent centers. They are either extrinsic, generally doping ions, or intrinsic, i.e. molecular systems of the lattice or of defects of the lattice which possess a radiative transition between an excited and a lower energy state. Moreover, the energy levels involved in the radiative transition must be contained in the forbidden energy band, to avoid reabsorption of the emitted light or photo-ionization of the center.

In a way, a *scintillator* can be therefore defined as a wavelength shifter. It converts the energy (or wavelength) of an incident particle or energetic photon (UV, X-ray, or gamma-ray) into a number of photons of much lower energy (or longer wavelength) in the visible or near visible range, which can be easily detected with current photomultipliers, photodiodes, or avalanche photodiodes.

In contrast to Cherenkov radiation, scintillation occurs as the result of a chain of processes which are characterized by different time constants. This is well described by Vasiliev [20] and will be discussed in details in Chap. 4, taking into account the existence of thresholds of "hot" electrons and holes inelastic interactions. Four essential phases are distinguished and listed in Table 1.1.

Table 1.1. The sequence of processes leading to scintillation in a medium

Phase	Characteristic Time, s
1 *Energy conversion:* Initial energy release with formation of "hot" electrons and holes	$\tau_1 = 10^{-18} - 10^{-9}$
2 *Thermalization:* Inelastic processes of interaction of "hot" electrons and holes and their thermalization	$\tau_2 = 10^{-16} - 10^{-12}$
3 *Transfer to luminescent centers:* Formation of excitonic states and groups of excited luminescent centers	$\tau_3 = 10^{-12} - 10^{-8}$
4 *Light emission:* Relaxation of excited luminescent centers and emission of scintillation light	$\tau_4 > 10^{-10}$

The initial energy release in a medium occurs in a wide time range; however, its duration cannot be smaller than $2R/c$, where $R \sim 10^{-10}$ m is the order of atomic radius and c is the light speed. It also cannot exceed the transit time of the particle or γ-quantum in the scintillator and, for crystalline inorganic compounds, is restricted to a few nanoseconds. It must be noticed at this stage that the transfer to the detecting medium of at least a fraction of the energy of a particle does not necessarily require the transit of that particle through the medium. The transverse electrical field associated with a relativistic particle traveling close to the surface of a dielectric inorganic scintillator can in fact penetrate the medium and therefore interact with the electrostatic field of the crystal. This phenomenon could be exploited for the monitoring of intense particles beams near a flat surface or through nanotubes [21].

The "hot" electrons and holes inelastic scattering processes and their thermalization are rather fast in heavy crystals generally used as scintillating materials which are characterized by a high density of electronic states.

The formation of excitonic states and the transfer of their excitation to luminescent centers occur with characteristic time constants which are generally in the picosecond range.

At the end of the process the relaxation of the excited luminescent centers and the corresponding light emission is characterized by time constants distributed in a wide time range which are determined by the quantum wavefunction characteristics of the different levels involved in the transitions.

It must be noticed here that the excitation of the scintillation by a charged particle does not necessarily require direct impact of the particle with the electrons and nuclei of the scintillation medium. Energy is transferred from the particle to the scintillation through the electromagnetic field associated to the particle. It is therefore possible to excite the luminescence of a scintillator by a relativistic particle (the transverse extention of the electromagnetic wave is larger in this case) travelling very close to its surface without penetrating it.

Therefore, *scintillation* is a luminescence induced by ionizing radiation in transparent, dielectric media.

This complex sequence of phenomena characterizes the scintillation process, contrary to the photoluminescence which results from the direct excitation of the luminescent centers.

The kinetics is therefore more complex in many cases, contrary to what can be observed in gases, condensed gases, fluids, and their vapors. In such media the atoms of the gas or molecules of organic dyes or anionic complexes of rare-earth ions can be considered to some extent as free with almost no interaction with other particles of the medium. The luminescence decay time is therefore equal to the radiating decay time τ_r of luminescent centers excited states. It means that all the light quanta have been emitted after a few τ_r. On the other hand, crystalline compounds are characterized by a noncontinuous electronic energy distribution with an energy gap $E_g \gg kT$, separating a filled valence electronic band from higher energy and generally not populated levels forming the conduction band. The width of the forbidden band between the valence and the conduction band determines if the material is a semiconductor ($<$ 2–3 eV) or an insulator ($>$3 eV, typically $\geq$4 eV).

For a given material, a plurality of luminescent centers, whose radiating levels are localized in the forbidden zone, can coexist and interfere with each other. Some of these luminescent centers are cations or anionic complexes of the lattice or doping ions such as Ce^{3+} specifically introduced at the crystal growth. Some others are generated by the interaction of the ionizing radiation with the medium. Such induced centers play an important role in the scintillation as they can sensitize or quench luminescence or act as electron or hole donors for existing radiating centers via a secondary excitation process. In practice this secondary excitation is generated not only by direct Coulomb interaction but also by thermoactivation or electron tunneling from matrix host defects which trap electrical carriers produced by the incident particle. The kinetics of primary and secondary excitation processes are different. If we define ω_int as the frequency of interaction between primary and secondary luminescent centers in the medium, we can distinguish different cases, depending on how the mean time between interactions compares with the time of formation of primary excited luminescent centers τ_3 and with their radiating decay time τ_r.

For

$$1/\omega_\mathrm{int} \sim \tau_3 \ll \tau_\mathrm{r} \,, \tag{1.1}$$

the kinetics of the direct scintillation will dominate, characterized by a very fast rise time followed by a single exponential decay, the signature of the radiative relaxation of the luminescent center.

If on the other hand

$$1/\omega_\mathrm{int} \gg \tau_\mathrm{r} \quad \text{and} \quad 1/\omega_\mathrm{int} \gg \tau_3 \,, \tag{1.2}$$

which is frequently the case in real materials, the direct scintillation is accompanied by a phosphorescence which results from the delayed decay of the secondary luminescent centers. The interaction of luminescent centers between themselves or with charge carriers traps leads to a more complex kinetics with generally longer rise time and strong nonexponential decay with long tails in some cases. As a measure of the contribution of phosphorescence in scintillation, the afterglow parameter is used. *Afterglow* is the amplitude of the luminescence signal, excited by ionizing radiation and measured after a fixed time, for example $10 \cdot \tau_{\mathrm{r}}$.

Scintillation is characterized by several parameters. Some of them depend on the shape, surface state, and optical quality of the scintillator block. We list here those which are related to the physical process of light production in the medium.

1.1.1 Scintillation Yield

Following [22,23] we define the quantum yield or the light yield of scintillation Y as the amount of light quanta emitted by a scintillator per unit energy deposited by ionizing radiation in the medium. Thus,

$$Y = \prod_i y_i \; , \tag{1.3}$$

where y_i are the yields of the processes given in Table 1.1.

The yields of the first two processes have been analyzed by the authors [24–29]. The models show approximately the same limiting yields [23] but their experimental measurement is not easy as it is difficult in practice to decouple these processes from luminescence quenching in real crystalline materials. A phenomenological approach leads to the following formulation:

$$y_1 \cdot y_2 = \frac{E_\gamma}{\beta \cdot E_{\mathrm{g}}} \; ,$$

where $\beta \cdot E_{\mathrm{g}}$ is the mean energy necessary for the formation of one thermalized electron–hole pair in a medium with a forbidden zone of width E_{g} and E_γ is the absorbed energy.

The yield of the formation of radiating centers S is defined by the efficiency of the energy transfer of thermalized pairs to the excited states of luminescent centers.

Finally we define Q as the quantum yield of the intracenter luminescence. Hence,

$$Y = \frac{E_\gamma}{\beta \cdot E_{\mathrm{g}}} S \cdot Q \tag{1.4}$$

and the energy efficiency of scintillation Y_{e} is

$$Y_{\mathrm{e}} = \frac{E_f}{\beta \cdot E_{\mathrm{g}}} S \cdot Q \; , \tag{1.5}$$

where E_{f} is the average energy of scintillation photons. There is therefore a clear advantage of having a host with a small bandgap. In this case however, the risk of photo-ionization of the activator increases if its ground or excited states are too close to the valence or conduction bands respectively. The density of traps in the forbidden band also increases which generally reduces the scintillator yield. P. Dorenbos [146] has calculated a maximum theoretical scintillator yield of 140,000 photons/sec in an ideal Ce^{3+} doped scintillator with a small bandgap, just large enough to host the Ce^{3+} optimal transition.

These expressions become more complex if we take into account additional mechanisms of energy losses, for instance surface losses in a medium [30,31], and the structure of the density of states in the valence and in the conduction bands [20].

1.1.2 Kinetics of Scintillations

The kinetics of scintillation $I(t)$ is defined as the law of the variation in time of the scintillation light intensity and its magnitude $I = \int I(t)\,dt$ is proportional to Y. It is related to the time variation of the population of the excited states of the luminescent centers. For a simple process, with only one radiating center and no interaction between luminescent centers and traps, the decay is exponential and characterized by a time constant τ_{sc}, the time after which the amplitude has decreased by a factor e. For two independent radiating centers the same description with two exponentials is also valid. But in real cases the situation is very often more complex, involving energy transfer between centers and quenching mechanisms, and the resulting light emission is strongly nonexponential. It is nevertheless a common practice to describe this complex emission curve by a series of exponentials with different time constants. This has in most of the cases no physical justification but simplifies the calculations.

1.1.3 Radioluminescence Spectrum

This is the wavelength (or frequency or energy) distribution of the scintillation light when the medium is excited by ionizing radiation. It is generally composed of a series of emission bands which are each characterized by their maximum λ_{sc} or ν_{sc} and half-width $\Delta\lambda_{\mathrm{sc}}(\Delta\nu_{\mathrm{sc}})$ at a given temperature. Radioluminescence is also called cathodoluminescence in reference to the first observations of scintillation at the cathode of an electron gun.

1.1.4 Photoluminescence Spectrum

This is the wavelength (or frequency or energy) distribution of the scintillation light when the medium is excited by photons of energy below the ionization energy of the atoms. This information combined with the structure of the excitation spectrum, generally up to a few tens of eV, is very useful to determine the energy levels involved in the excitation and relaxation mechanisms. On the other hand, one has to be very careful not to draw too rapid conclusions about the properties of the scintillator on the basis of the photoluminescence spectrum only which does not reflect at all the mechanisms of energy transfer and thermalization in the medium. This error is frequently made and leads to several misinterpretations. In the most dramatic case we can find materials with a good photoluminescent yield when excited in the UV range but with no light emitted under gamma-rays excitation. A typical example is given by the tungstate group which exhibits good scintillation properties in some host matrices ($CaWO_4$, $CdWO_4$, $PbWO_4$) and no scintillation at all in some other compounds ($BaWO_4$).

1.2 Survey of Scintillation Mechanisms

As already explained, the mechanisms of excitation of the luminescent centers in a scintillator as well as their properties are strongly influenced by the surrounding medium, particularly if this is a solid, and even more in the case of a crystal with a regular structure. Fundamental aspects of this phenomenon will be discussed in details in Chap. 4. Here we give a survey of scintillation mechanisms. The coupling between the lattice and the luminescent center is essential in the way the energy is transferred between them in both directions. In particular the conditions of localization and delocalization of excitations are strongly affected by the positions of the luminescent centers energy levels relative to the valence and conduction bands formed by the orbitals of the lattice atoms. This is well illustrated for instance by the modifications of the luminescent properties of activating ions such as Ce^{3+} depending on the type of ligand and on the strength and the symmetry of the crystalline field in different host materials.

Electrons and holes produced by ionizing radiation have several ways to be involved in the scintillation process after their thermalization:

1. $e + h \rightarrow h\,\nu$,
2. $e + h \rightarrow ex \rightarrow h\,\nu$,
3. $e + h + A \rightarrow ex + A \rightarrow A^{*} \rightarrow A + h\,\nu$,
4. $e + h + A \rightarrow A^{1+} + e \rightarrow A^{*} \rightarrow A + h\,\nu$,
5. $e + h + A \rightarrow (A^{1-})^{*} + h \rightarrow A + h\,\nu$,
6. $A \rightarrow A^{*} \rightarrow A + h\,\nu$

The simplest emission process (1) is the result of the direct radiative recombination of free thermalized electrons in the conduction band with holes from the valence band or from deeper electronic shells. Usually the ionizing radiation produces deep holes in the lattice which are progressively converted into holes of smaller energy through a succession of Auger conversions. Similarly hot electrons from the first interaction are cooled down to the bottom of the conduction band by inelastic interactions. In most of the cases the recombination takes place when the energy of the electron and hole has sufficiently decreased so that they bind to each other, creating an exciton with an energy slightly smaller than the bandgap.

However, for certain configurations of the valence and core atomic electron bands the Auger conversion cannot take place and the electron recombines directly with a deep hole, giving rise to a fast UV emission [32–34]. Such kind of radiating recombination is called cross-luminescence and it is observed in some wide band gap fluoride and chloride crystals.

Thermalized carriers can also be bound in some places of the lattice, for instance, in the vicinity of a specific atom or a structural defect (2). They are called autolocalized excitons (ex) and their radius, small or large, depends on the electrostatic field in this configuration. In many inorganic compounds these excitons have a radiative decay channel [35]. The luminescence of free excitons or bound excitons is generally absent in complex compounds and has been observed so far only in simple oxides [36, 139].

Under certain conditions in the presence of impurity centers or activating ions A the exciton luminescence is efficiently quenched, causing thus a sensitization of the luminescence of the activating ions $A(3)$. In this case the excitation of radiative centers results from an energy transfer from excited matrix states.

The process competing to the formation of excitons is the direct capture of free thermalized carriers, electrons (4) or holes (5) by activating ions A with the subsequent formation of their excited state A^*. The cross section for electron or hole capture depends on the nature of the activating ion and on the structure of the local electrostatic field in its vicinity. In contrast to the previous case the excitation of radiating centers is now the result of a charge transfer mechanism from excited matrix states.

Finally the direct excitation of activating centers by ionizing radiation (6) provides an important contribution to the scintillation in the case of heavy doped or self-activated scintillators. A typical example is cerium fluoride (CeF_3).

Besides these mechanisms, an intrazone luminescence caused by radiating transitions of hot electrons and holes from the conduction and valence bands has also been reported [37]. This luminescence is distributed in a wide spectral region and characterized by a low yield, independent of the temperature, of typically 10^{-3}–5×10^{-6} eV/eV in $NaNO_3$ and $BaMgAl_{10}O_{17}$ crystals. The decay time τ_{sc} is very fast, of the order of a few nanoseconds only.

The efficiency of activated scintillators is strongly dependent on the ratio of the bandgap in the crystal to the energy of the activator radiating state as well as on the relative position of its ground and excited states to the top of valence band and to the bottom of the conduction band, respectively. The first requirement for an activator with an excited state energy E_r to be efficient in a host matrix with a bandgap E_g is

$$E_{\mathrm{g}} \geq E_{\mathrm{r}} \; . \tag{1.6}$$

This condition prevents the reabsorption of the luminescence in the medium, at least if the crystal is free from impurities or structural defects having energy levels in the bandgap.

Another condition to avoid the delocalization of electrons in the conduction band from the activator excited state is related to the energy gap ΔE between the radiating level of the doping ion and the bottom of the conduction band.

Thus,

$$\Delta E \leq 0, \quad \text{the scintillation yield } Y = 0 \; , \tag{1.7}$$

$$\Delta E > 0, \quad \text{the scintillation yield } Y \geq 0 \; . \tag{1.8}$$

Moreover, if

$$\Delta E \gg kT \quad \text{or} \quad \tau_{\mathrm{r}} \ll \tau_{\mathrm{d}} \; , \tag{1.9}$$

where the delocalization time $\tau_{\mathrm{d}} \approx (1/S)\exp(-\Delta E/kT)$, with S is the frequency factor, k is the Boltzman constant, and T is the temperature, the scintillation yield is not strongly dependent on the temperature. In the reverse case, one can anticipate a reduction of the scintillation yield when the temperature increases (temperature quenching).

The energy gap between the ground state of the activating ion and the top of the valence band plays also an essential role in the hole capture by the activator through the mechanism (4). In the case of a ground state localization in the valence band, the hole remains delocalized and its trapping never occurs. If on the other hand the activator ground state lies too high above the valence band, the probability of hole capture by the radiating center is low, resulting in a poor efficiency of the scintillator.

The characteristic decay time for the direct electron–hole recombination (1) does not exceed a few nanoseconds if the final state involves a core atomic band. If on the other hand there is a participation of the valence band in the direct or excitonic recombination (1,2), the scintillation, as a rule, is characterized by slowly decaying kinetics due to radiating recombination process with characteristic time constants in the µs–ms region. The fact that some self-activated scintillators, like $PbWO_4$ [38], exhibit a fast room temperature scintillation in the nanosecond range is only the consequence of a luminescence-quenching mechanism competing with the radiative relaxation of the excitation. In this case the decay is nonexponential, which is a common signature of temperature-quenched scintillators.

In the case of radiating transitions in the simple model of the dipole electrical transition the lifetime of the activator luminescence (radiant time) is defined by the well-known formula:

$$\tau_{\mathrm{r}} \sim 1/(\nu^3 \langle \Psi_A \, |d| \, \Psi_A^* \rangle^2) \tag{1.10}$$

where $\langle \Psi_A |d| \Psi_A^* \rangle$ is the operator of the dipole electrical transition between the excited and ground states of the activating ion and ν is the frequency of the transition. The general expression is given in [39]:

$$\tau_{\mathrm{r}} = \frac{1.5 \times 10^5 \lambda^2}{f \frac{1}{9} (n^2 + 2)^2 \, n} , \tag{1.11}$$

where$f$ is oscillator strength, λ is averaged wavelength of transition equal to $1/\nu$, and n is index of refraction of the medium.

When the requirements (1.8) and (1.9) are satisfied and in the absence of quenching mechanisms the radiating time is close to the radiant time. Figure 1.1 shows the room temperature radiant (τ_{r}) and scintillation (τ_{sc}) time of the interconfiguration $5d \rightarrow 4f$ transition of the Ce^{3+} ion in different crystals as a function of the frequency ν of the peak of the luminescence. GSO and YSO have two different coordinations of Ce^{3+} with different maxima and kinetics of the luminescence. The luminescence decay time correlates well with a square-law dependence of the radiating time with the frequency of the peak of the luminescence band.

On the other hand, the values for the scintillation decay time τ_{sc} are in some cases very different from the intracenter-excited luminescence radiating

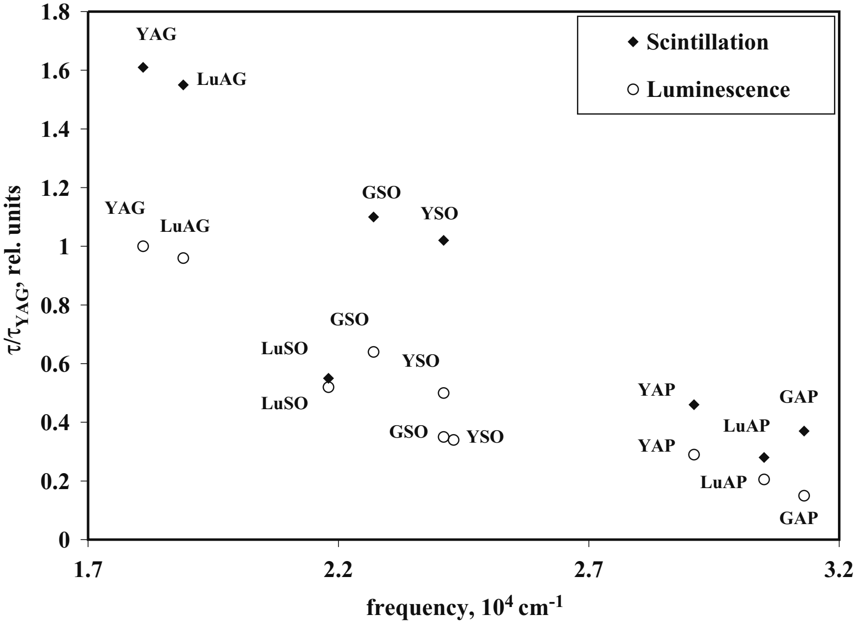

Fig. 1.1. Luminescent decay time τ_{r} of the interconfiguration $5d \rightarrow 4f$ transition of the Ce^{3+} ion and scintillation decay time τ_{sc} versus frequency ν of the luminescence band maximum at room temperature. Data are taken from [42–48]

time. This is caused by the time needed to transfer the energy to the radiating centers through the different mechanisms described in this paragraph. If this transfer occurs preferentially through the energy transfer mechanism, the decay time of scintillation is closer to the radiating time of the activator. This is explained within the Förster–Dexter model [40, 41] describing the sensitization of activating ions by randomly distributed donors in the crystal. According to the model the luminescence kinetics in a dipole approximation is described by the expression

$$I(t) = I_0 \exp[-(t/\tau_{\mathrm{r}}) + 4\sqrt{t}\pi^{3/2} N_{\mathrm{a}} (C_{\mathrm{DA}})^{1/2}/3 + \bar{w}t] \ , \tag{1.12}$$

whereN_{a} is the concentration of activators,C_{DA} is a parameter of donor–acceptor dipole–dipole interaction, and $\bar{\varpi}$ the rate of migration-restricted energy transfer. For a large migration rate $\bar{\varpi}$ and interaction probability C_{DA}, the rise time of the scintillation is fast and the scintillation kinetics approaches the intracenter-excited luminescence kinetics.

For the direct recombination of thermalized electrical carriers as well as for the excitonic emission according to the processes (1) and (2), the peak emission of the scintillation correlates with the band-gap value. The set of possible radiating states is in this case limited to excited levels of metallic ions of the host matrix, polaronic or excitonic states, or shallow traps. All these states are located near the bottom of the conduction band. As the relaxation involves energy levels situated at the top of the valence band, the energy of the transition is generally close to the bandgap energy. However, the interaction of the electrostatic field of the lattice with the radiating center, which is in practice different for the excited and the ground state, introduces a modification of the orbital configurations through vibronic interactions [49]. This effect results in a shift of the luminescence band maximum to longer wavelength (the Stockes shift). Figure 1.2 shows the wavelength of the scintillation band maximum of various undoped scintillation crystals versus their respective bandgap energy.

In doped crystals the luminescence properties of the doping ions can be predicted by the effect of the crystalline field for ions of the iron group [50,51] and for the rare-earth ions in the frame of the model described in [52]. It has been shown that for a given crystalline matrix the energy difference between the first excited state $4f^{n-1}5d$ and the ground state configuration $4f^n$ is given by

$$\Delta_{fd} = \Delta_{fd}^0 - \sigma_2 S_{\mathrm{host}} \tag{1.13}$$

where Δ_{fd}^0 is the energy difference between the first excited state $4f^{n-1}5d$ and the ground state configuration $4f^n$ of a free ion, and S_{host} is the parameter defined by the specificity of the matrix host,

$$\sigma_2 = [\langle 4f^{n-1}5d \left| r^2 \right| 4f^{n-1}5d\rangle - \langle 4f^n \left| r^2 \right| 4f^n\rangle] \sum_i \alpha_i Z_i e^2 / R_i^6 \ , \tag{1.14}$$

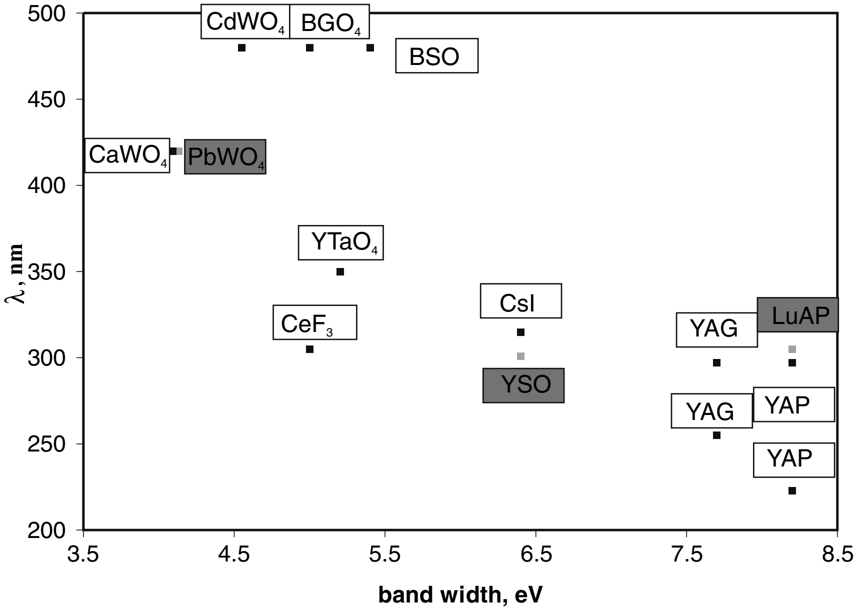

Fig. 1.2. Luminescence band maxima of various undoped scintillation crystals versus band gap. The data from [55–57] have been used

where Z_i is the quantity of ligands with polarizability α_i and distance R_i from the doping ion. Using this expression, the authors of reference [53] have shown that the energy of the first excited state $4f^{n-1}5d$ of any trivalent rare-earth ion of the Lanthanide family scales with the one of the Ce^{3+} ion and is equal to

$$\Delta_{fd}(Ln^{3+}) = C\Delta_{fd}(Ce^{3+}) + B \ , \tag{1.15}$$

where B and C are independent of the crystal parameters constants. The decrease of this energy for a given crystalline compound is about the same for all rare-earth ions because σ_2 is about the same for all lanthanides and S_{host} depends only on lattice parameters of the compound.

The surveyed model has found convincing confirmation in the analysis of spectroscopic parameters of trivalent rare-earth ions in more than 300 various compounds [54,58,59]. The basic conclusion concerning interconfiguration optical transitions in trivalent rare-earth ions is that the effects of the crystalline matrix and of the activator ion on the parameters of the optical transition are independent. Thus, knowing the energy of one allowed interconfiguration transition of any of the rare-earth ions, for example Ce^{3+} in a given matrix, it is possible to calculate similar transitions for another Lanthanide ions in the same crystalline compound.

1.3 Scintillation-Radiating Centers

We will consider here the different impurity ions which can activate a scintillator. Several self-activated scintillators show better scintillation properties when they are doped by appropriate ions. As explained in the previous paragraph, there are some conditions to be met for the activator to be efficient in a host matrix. These conditions are related to the position of the activator energy levels involved in the luminescence relative to the conduction and valence bands of the matrix. More generally the two basic practical requirements are the stability of the charge states of the luminescent center in the host and the high-quantum yield of the intracenter luminescence. They limit the number of centers to be considered and exclude, for instance, point structure defects associated to the substitution of a host matrix ion by an activator ion with a different valence state (nonisovalent doping), however, do not guarantee an efficient scintillation yield through the activation of the specific centers of a crystal.

1.3.1 Ions of the Iron Group

Radiating transitions in these ions arise between the Stark components of the $3d^n$ electronic configurations. As the $3d^n$ shell is the outer shell for the light ions of this group, the effect of the crystalline field is stronger than the spin–orbit interaction. The peak position of the luminescence band is therefore rather sensitive to the strength of the crystalline field created by the coordination of the ligands. The energies of the Stark components of the terms of the $3d^n$ configurations depend on the strength of the crystalline field. They are described by the Tanabe–Sugano diagrams [50] and discussed explicitly in the literature [60].

The lightest ion of the iron group is the titanium. Its trivalent ion Ti^{3+}has the $3d^1$ electronic configuration and is localized in an octahedral oxygen coordination. Its wide luminescence band with a maximum of 790 nm is observed in the garnet $Y_3Al_5O_{12}$. In the yttrium perovskite crystal $YAlO_3$ the Ti^{3+} ion has a luminescence band with a maximum at 610 nm and a mono-exponential kinetics with $\tau_r = 3\,\mu s$. Figure 1.3 compares the radioluminescence spectra of BGO and $YAlO_3$:Ti^{3+} (0.2 at. %). The room temperature light yield of Ti^{3+} doped crystal is 30% higher than that of BGO. Al_2O_3:Ti^{3+} crystal codoped with Ca has also an intense luminescence in the near IR with a maximum at 780 nm and a decay time $\tau_r = 4.3\,\mu s$. It has a high scintillation yield [61] and is optimally combined with semiconductor photo-detectors with high sensitivity in the IR region [62].

Ion of vanadium V^+ ($3d^4$) shows an IR luminescence in narrow band gap compounds [63]. The oxide compounds doped with vanadium ions of other valence states V^{2+} ($3d^3$), V^{3+}($3d^2$), V^{4+}($3d^1$) do not show an intense radioluminescence in the visible region at room temperature. Alcali-vanadates,

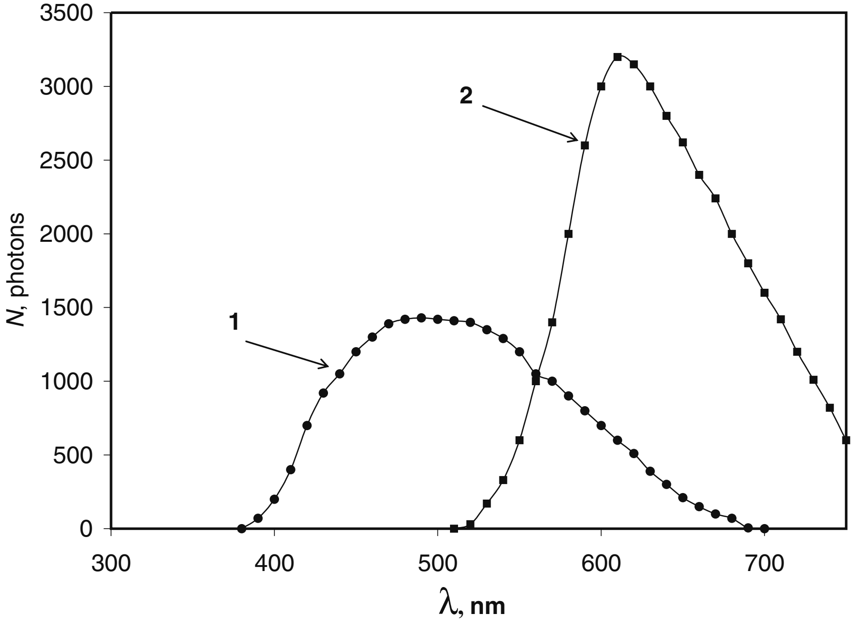

Fig. 1.3. Radioluminescence spectra of BGO (1) and $YAlO_3$:Ti (2) crystals at $T = 300\,K$

where the vanadium ion is in its maximum oxidation state V^{5+}, have an intense cathodoluminescence and are used as luminophore. Double vanadates also exhibit an intense photoluminescence. The luminescence kinetics of double vanadates has a decay time of the order of tens of microseconds at room temperature.

Another well-known activating ion, Cr^{3+} $(3d^3)$, can exhibit a narrow luminescence band at 694 nm due to the $^2E \rightarrow {}^4A_2$ transition, or a wide band in the near-IR region related to the $^4T_2 \rightarrow {}^4A_2$ transition [64], depending on the crystalline field strength in the position of its localization. While crystalline field is weak, the ^{2}E term is lower than the $^4T_2$ term and causes luminescence properties of the material like in ruby. In strong crystalline field in oxygen octahedron, like in emerald, $^4T_2$ level becomes lower showing wide luminescence band. As the $^2E \rightarrow {}^4A_2$ transition is a spin-forbidden transition, the decay kinetics constant is large, of the order of milliseconds. On the other hand, the wide band decays with a characteristic time constant in the microsecond range. $Cr^{4+}(3d^2)$ ion also emits IR luminescence with a decay time constant in the microsecond range in some oxygen compounds [65].

Divalent manganese $Mn^{2+}(3d^5)$ has a strong green luminescence in many compounds with long decay times (milliseconds) because of a spin-forbidden transfer $^4T_1 \rightarrow {}^6A_1$. For instance, Zn_2SiO_4:Mn is one of the best known phosphors [66], which was applied in the first color TVs and is also used in modern plasma panels. In this compound the Mn^{2+} ion has an intense green luminescence with a maximum near 520 nm and τ_r of about 25 ms.

The trivalent ion of iron $Fe^{3+}(3d^5)$ localized in tetrahedral oxygen coordination is also responsible for a slowly decaying IR luminescence [67]. Its $^4T_1 \rightarrow {}^6A_1$ luminescence can be either directly excited through intracenter transitions or due via a charge transfer process: $O^{2-} \rightarrow Fe^{3+}$ [68]. Iron-doped YAG, $Y_3Al_5O_{12}$:Fe, has radioluminescence spectrum with a peak at 810 nm and a scintillation yield of about 1,000 ph MeV^{-1} at room temperature. The Ni^{2+}-doped crystals also show an intense IR radioluminescence when excited by an electron beam at room temperature [69].

A general drawback of the $3d^n$ ions as activating ions in inorganic scintillator is related to their heterovalence which means that they can change their valence state under ionizing radiation. The localization of their luminescence in the near IR region and the relatively slow decay time of the luminescence are also limiting factors for several applications. It seems that from this group only the Ti^{3+} ion can be considered as a prospective activator if it is in a rather strong crystalline field environment. Apparently, rare-earth aluminium perovskite and some hafnium and zirconium compounds are good host candidates from this point of view.

1.3.2 Ions With s^2 Outer Shell (Mercury-Like Ions)

Ions with s^2 outer shell form a large class of luminescent centers. They are easily introduced into various crystalline compounds which find wide application as phosphors for fluorescent lamps and various fluorescent transducers [70,71]. Ga^+, Ge^{2+}, Se^{4+} with $4s^2$ outer shell; In^+, Sn^{2+}, Sb^{3+}, Te^{4+} with $5s^2$ shell; Hg, Tl^+, Pb^{2+}, Bi^{3+} with $6s^2$ are all in this class. These ions have an intense interconfiguration transition $s^2 \rightarrow sp$ in the vacuum ultraviolet (VUV) range. However the associated luminescence is not observed due to quenching by underlying excited terms $^1P_1$, $^3P_2$, $^3P_1$, $^3P_0$ of s^2-configuration. The intraconfiguration luminescence $^3P_0 \rightarrow {}^1S_0$ is characterized by a large Stokes shift in many compounds and, hence, has strong temperature quenching [72]. The radiant decay time is of the order of hundreds of microseconds at low temperatures but is reduced by three orders of magnitudes (hundreds of nanoseconds) at room temperature by temperature quenching. Moreover the spin–orbit interaction mixes singlet and triplet excited states, reducing further more τ_r in heavy $6s^2$ ions as it is observed for Tl^+, Pb^{2+}, Bi^{3+} ions in an alcali halide and oxide compounds. Ions of s^2 type have played a prominent role in inorganic scintillators development. The discovery of the most widely applied scintillation crystal NaI (Tl) [15] became possible because of the numerous studies of the luminescent properties of the Tl^+ ion in alcali halides. Moreover the first heavy scintillator, BGO, is also the result of systematic investigations of the Bi^{3+} ion in various oxide compounds.