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**Nové materiálové koncepty pro scintilátory na  
bázi komplexních oxidů**

**Novel material concepts for complex oxide  
scintillators**

## Summary

Scintillation phenomenon and its mechanism is described in the  $\text{Ce}^{3+}$  doped complex oxide hosts. Novel material concepts are described which considerably enhance scintillation performance. Following single crystal material families are included: (i) aluminum and multicomponent garnets,  $\text{Ln}_3\text{Al}_5\text{O}_{12}$  and  $(\text{Gd,Ln})_3(\text{Ga,Al})_5\text{O}_{12}$ ,  $\text{Ln}=\text{Y,Lu}$ , respectively; (ii)  $(\text{Lu,Gd,La})_2\text{Si}_2\text{O}_7$  pyrosilicates. Apart from the description of luminescence characteristics of the  $\text{Ce}^{3+}$  centers themselves and their interaction with the host, the emphasis is put on the transfer stage of scintillation mechanism and defects/trapping levels in the host forbidden gap which influence the migration of charge carriers. Charge carriers trapping phenomena usually negatively influence the timing characteristics and efficiency of scintillator materials and that is why their study and eventual suppression is of great practical importance. Several examples of successful material optimization in this respect are described.

## Souhrn

Je popsán jev scintilace ve vybraných monokrystalických anorganických pevných látkách a jeho fyzikální mechanismus. Jsou představeny nové materiálové koncepty pro vybrané  $\text{Ce}^{3+}$  dopované komplexní kyslíkaté sloučeniny: (i) hliníkové a multikomponentní granáty,  $\text{Ln}_3\text{Al}_5\text{O}_{12}$  a  $(\text{Gd},\text{Ln})_3(\text{Ga},\text{Al})_5\text{O}_{12}$ ,  $\text{Ln}=\text{Y},\text{Lu}$ , (ii) pyrosilikáty  $(\text{Lu},\text{Gd},\text{La})_2\text{Si}_2\text{O}_7$ . Kromě popisu luminiscenčních charakteristik vlastních emisních center  $\text{Ce}^{3+}$  a jejich interakce s monokrystalickou maticí je důraz položen na popis stadia přenosu elementárních nosičů náboje, elektronů a děr, k emisním centrům, který je silně ovlivňován defekty a souvisejícími záchytnými stavy v zakázaném pásu základního materiálu. Procesy záchytu nocičů náboje obvykle negativně ovlivňují časové charakteristiky a celkovou účinnost scintilačních materiálů a proto má jejich studium a eventuální potlačení velký praktický význam. Je popsáno několik příkladů úspěšné optimalizace materiálů.

## **Klíčová slova**

Scintilátor, luminiscence, záchytné stavy,  $\text{Ce}^{3+}$ , kyslíkaté sloučeniny

## **Keywords**

Scintillator, luminescence, trapping states,  $\text{Ce}^{3+}$ , oxide compounds

## **Content**

|   |    |
|---|----|
| 1. Introduction                                     | 6  |
| 2. Aluminum and multicomponent garnet scintillators | 9  |
| 3. Multicomponent pyrosilicate scintillators        | 14 |
| 4. Discussion and conclusions                       | 17 |
| Literature  | 21 |
| Curriculum vitae Ing. Martin Nikl, CSc.             | 22 |

## 1. Introduction

Scintillator material works as a spectral and energy transformer: it converts a high energy photon from X- or gamma-ray range into a bunch of ultraviolet-visible (UV/VIS) ones, i.e. to the flash of light. Alternatively, the accelerated charged particles (electrons, protons or more heavy ions) or even neutrons can be detected through their energy deposit in the interaction with scintillator host which is again converted into the flash of light. In practice, the scintillator detector consists of two parts, namely (i) scintillating material itself and (ii) photodetector which converts the mentioned UV/VIS photons into an electrical signal  $I(t)$ [1, 2], see **Figure 1**.

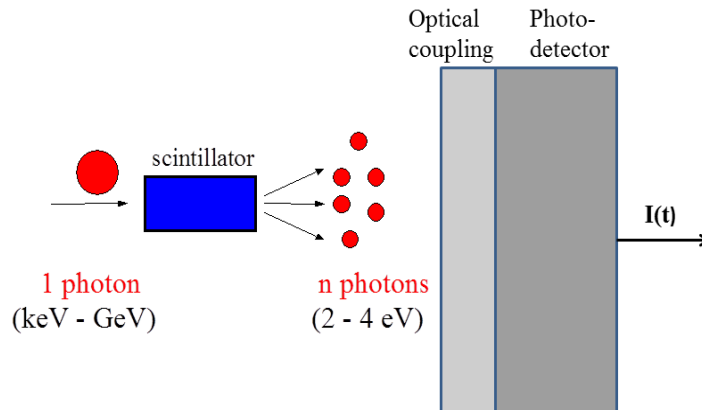


Figure 1. Principle of scintillator material and set-up of scintillation detector.

Dielectric or semiconductor wide band-gap materials are employed for such a task. Phenomenological description of the scintillation mechanism and definition of efficiency criteria have been already developed in the 1970's [3] and later further refined [4]. Scintillation mechanism can be divided into three consecutive sub-processes: *conversion, transport and luminescence*, see **Figure 2**.

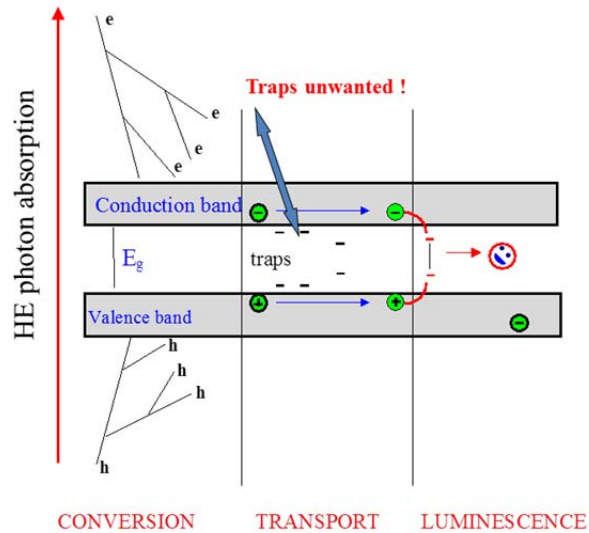
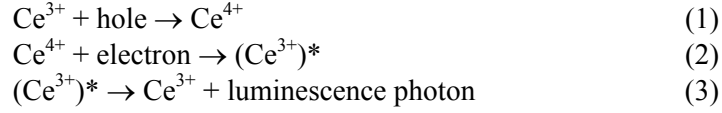


Figure 2. Sketch of scintillator mechanism in a solid state crystalline material.

Depending on the photon/particle energy, its initial multi-step interaction with the scintillator lattice occurs dominantly through (i) the photoelectric effect (below approx. 100 keV), (ii) Compton scattering effect (within 200 – 8000 keV) and (iii) pair production above the latter limit. Created hot electrons and deep holes are gradually thermalized in the conduction and valence band edges, respectively. Thermalization of carriers within the conduction and valence bands is sometimes considered as a separate stage in scintillation process due to its importance in the study of nonproportionality issues in scintillation mechanism [5]. All the conversion process lasts typically few ps, see [5-7] for more detailed description. In the transport process the separated electrons and holes have to reach the emission centers, i.e. migrate through the host material: they can be repeatedly trapped or even nonradiatively recombined at trapping levels in forbidden gap arising due to lattice defects. Considerable delay in the charge carrier delivery to luminescent centers can be introduced due to such trapping processes.

This stage is the least predictable as point defects, flaws, surfaces and interfaces can introduce energy levels into the forbidden gap and strongly modify/degrade scintillation performance. These phenomena are strongly dependent upon manufacturing technology. During the final stage, the trapping and radiative recombination of the electron and hole at the luminescent center give rise to the desired luminescence light.

In case of the  $Ce^{3+}$  emission centers, given their ability to easily oxidize into tetravalent charge state, it is generally accepted that the sequence of charge carrier capture is as follows:



where hole and electron arrive from valence and conduction band, respectively.

All the below described material systems in Section 2 belong to fast scintillators where luminescence output is based on completely allowed 5d-4f radiative transition of  $Ce^{3+}$  ion positioned in UV-visible spectral range with typical photoluminescence lifetimes within 20-60 ns. Scintillation response of these materials is thus dominated by decay time values below 100 ns. Due to carrier trapping in the transfer stage of scintillator mechanism slower components are present as well. Given the fact that concentration of  $Ce^{3+}$  is relatively high, of the order of 0.1at.%, transport of holes towards them is usually fast and efficient. Consequently, the main cause of delayed recombination processes and mentioned slower components in scintillation response is the presence of electron traps.

## 2. Aluminum and multicomponent garnet scintillators

Single crystals of  $Y_3Al_5O_{12}$  (YAG) were grown already in 1960's [8] and 5d-4f photoluminescence decay kinetics of the  $Ce^{3+}$  and  $Pr^{3+}$  centers in single crystal YAG host was reported soon after [9] revealing the absence of nonradiative thermal quenching up to about 550 K and 250 K, respectively. The potential of  $Ce^{3+}$ -doped YAG single crystal for fast scintillators was revealed several years later [10]. The first comprehensive description of YAG:Ce scintillator characteristics was



reported by Moszynski et al [11], who included this material among the high figure-of-merit oxide scintillators. Isostructural  $\text{Lu}_3\text{Al}_5\text{O}_{12}$  (LuAG) has a higher density and effective atomic number  $Z_{\text{eff}}$  ( $6.67 \text{ g/cm}^3$ ,  $Z_{\text{eff}}=63$ ) than YAG ( $4.56 \text{ g/cm}^3$ ,  $Z_{\text{eff}}=32.6$ ), which is critically important in the case of hard X- and  $\gamma$ -ray detection. To obtain fast scintillator the Ce and Pr-doped LuAG grown from the melt became of systematic interest in year 2000 [12] and 2005 [13], respectively. Contrary to YAG host, 5d-4f emission of  $\text{Pr}^{3+}$  is not thermally quenched around room temperature in LuAG one and radioluminescence spectra indicated the absence of quenching up to at least 450 K. This characteristics together with short decay time of  $\text{Pr}^{3+}$  center (20 ns) made the LuAG:Pr R&D immediately hot topic. Very soon in the research of these modern, highly efficient scintillators the problem of trapping electrons at shallow traps in the transfer stage was recognized [14]. The nature of these traps was proposed as due to the antisite  $\text{Lu}_{\text{Al}}$  defects in the garnet structure, **Figure 3**. Such defects are due to the natural lattice disorder the concentration of which is strongly increasing with preparation temperature [15]. Their concentration can be as high as several tenths of percent and is influenced also by the host stoichiometry [16].

The effect of the antisite  $\text{Lu}_{\text{Al}}$  and  $\text{Y}_{\text{Al}}$  defects in LuAG:Ce and YAG:Ce scintillation mechanism, respectively, is in fact twofold [17]: (i) slower emission centers in UV region peaking at RT within 300-350 nm, which create an unwanted competitive de-excitation pathway in addition to  $\text{Ce}^{3+}$  ( $\text{Pr}^{3+}$ ); (ii) shallow electron traps, which effectively delay the radiative recombination at the fast emission center and strongly degrade scintillator timing characteristics and LY value. Furthermore, it was found that agglomeration of these traps and  $\text{Ce}^{3+}$  ( $\text{Pr}^{3+}$ ) centers occurs which gives rise to tunneling-driven radiative recombination of an electron from the trap and hole localized at  $\text{Ce}^{3+}$  center. Such a process gives rise to the inverse power time dependence of the slow component in the scintillation decay of  $\text{Ce}^{3+}$  and  $\text{Pr}^{3+}$  doped LuAG at room temperature, see **Figure 4**. Deeper electron traps around the antisite defect and presumably higher concentration of these defects in LuAG with respect to YAG [17] result in a more severe delay in energy delivery to the  $\text{Ce}^{3+}$  centers in LuAG host and can thus explain the more severe LY degradation in the Lu-based garnet structure.

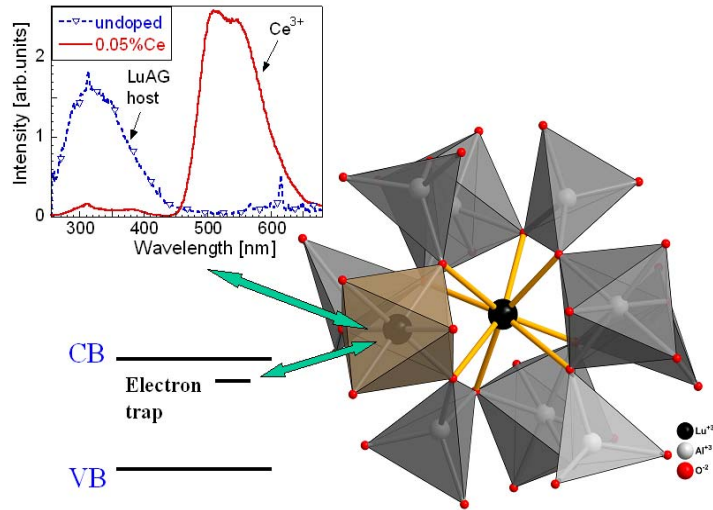


Figure 3. The  $Lu_{Al}$  ( $Y_{Al}$ ) antisite defect in the LuAG (YAG) structure. Resulting electron trap in the material forbidden gap is sketched on the left. Emission band within 300-350 nm due to antisite defect and its competition with that of the  $Ce^{3+}$  center can be derived from radioluminescence spectra at RT - upper left. Emission lines around 312 nm and 615 nm in the undoped sample are due to  $Gd^{3+}$  and  $Eu^{3+}$  accidental impurities, respectively. See also [17].

R&D of these garnet scintillators has been recently reviewed [18]: as an outcome of a decade lasting intense research, new ultra-efficient single crystal family of so called multicomponent garnets  $(Gd,Ln)_3(Ga,Al)_5O_{12}$ ,  $Ln = Y, Lu$ , doped with cerium has been discovered [19]. The balanced admixture of Gd and Ga cations into aluminum garnet efficiently decreased mentioned trapping effects and prevented ionization-induced quenching of the  $Ce^{3+}$  excited state around room temperature. As a result the light yield of these materials was increased more than two times with respect to the LuAG:Ce, see **Figure 5**. Being currently the most efficient bulk single crystal oxide scintillators, in the latest optimized material compositions their LY is approaching 60 000 photons/MeV [20] which is a theoretical limit of these garnet scintillators [21].

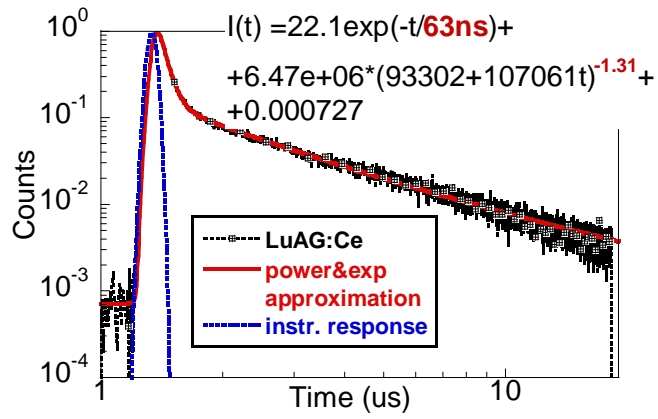


Figure 4. Spectrally unresolved scintillation decay of LuAG:Ce single crystal grown by Czochralski method. Red line is convolution of instrumental response and function  $I(t)$  displayed in the figure.

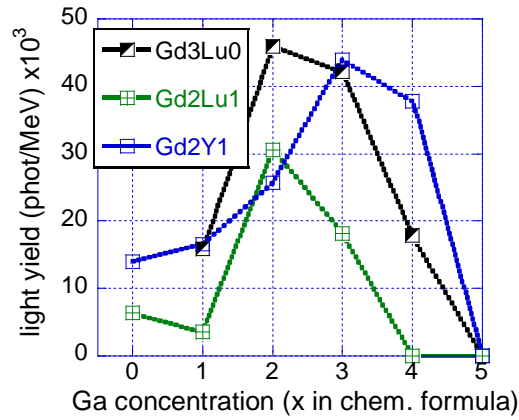


Figure 5. Light yield dependence on chemical composition of multicomponent garnet  $(\text{Lu,Gd})_3(\text{Ga,Al})_5\text{O}_{12}:\text{Ce}$  samples prepared by micropulling down method. See also [19].

The decreased edge of the conduction band in these compounds due to mainly gallium admixture [22, 23], however, considerably lowered the

onset of thermal quenching in these materials which limits their usage to room temperature applications. This problem has been studied in detail and ionization of the  $Ce^{3+}$  excited state was determined as its main cause [24-26].

Interestingly, another strategy preserving high temperature stability of cerium emission centers has been recently formulated to approach the problem of electron trapping in transfer stage of scintillation mechanism in garnet scintillators with an evident positive impact on LY, speed of scintillation response and afterglow as well. The above described modification of chemical composition of garnet scintillators results in the immersion of shallow electron traps in the bottom edge of the conduction band which diminishes charge trapping. An alternative strategy consists in creation of an additional fast radiative recombination pathway which would efficiently compete in electron trapping from the conduction band with the mentioned shallow electron traps in YAG and LuAG hosts. Such a pathway is realized by the stabilization of tetravalent  $Ce^{4+}$  center in garnet lattice by the divalent rare earth ion codoping [28-31] and/or by air annealing [32]. Positive role of  $Ce^{4+}$  in scintillation mechanism in orthosilicates have also been recently reported in literature [33] and the same mechanism is apparently also functioning in garnets, **Figure 6**.

In step 1, in the first picoseconds of scintillation mechanism, the  $Ce^{4+}$  center can efficiently compete with any electron traps for an immediate capture of electrons from the conduction band. The stable  $Ce^{3+}$  center is much less effective in such competition as first it needs to capture the hole from the valence band in the step no. 1.

In step 2 the  $Ce^{4+}$ , transformed into an excited  $Ce^{3+}$  center, emits scintillation photon and contributes to the fastest part of scintillation response. In the same step the  $Ce^{3+}$  center, converted into temporary  $Ce^{4+}$ , captures an electron from the conduction band and becomes excited.

In step 3 the return into initial state (beginning of the cycle) is accomplished by the hole capture from the valence band ( $Ce^{4+}$  in the right part) and by emission of scintillation photon ( $Ce^{3+}$  in the left part). It is worth mentioning that the last step in the  $Ce^{4+}$  scintillation mechanism (right part), the hole capture from the valence band, must always be nonradiative, i.e. not contributing to an afterglow.

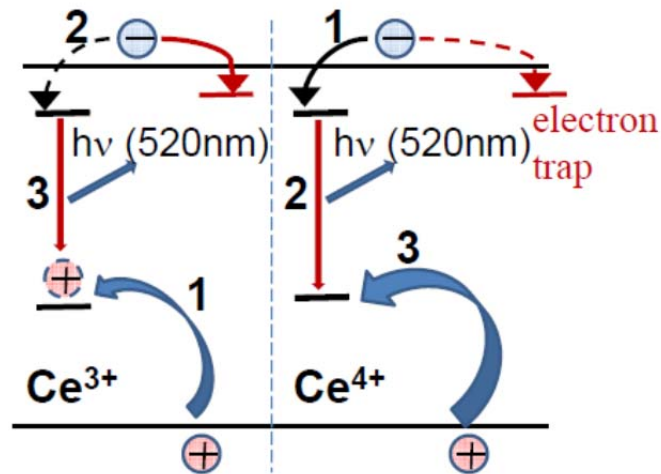


Figure 6. Sketch of the scintillation mechanism at the stable  $Ce^{3+}$  (left) and  $Ce^{4+}$  (right) emission centers in aluminum garnet host, see also [28].

### 3. Pyrosilicate scintillators

More than a decade ago lutetium pyrosilicate  $Lu_2Si_2O_7$  (LPS) was also found as potentially interesting scintillator host [34]. Comparative EPR study of the  $Ce^{3+}$ -doped LSO and LPS showed that the Ce ion in LPS structure substitutes for Lu in its single crystallographic site while in the structure of LSO it is found in both Lu crystallographic sites [35]. The light yield of LPS:Ce single crystals, which were grown from the melt, can reach the value comparable to that of LSO:Ce, the dominant scintillation decay time is around 37 ns with no observable afterglow [34,36]. Furthermore, similarly to LSO:Ce post-growth annealing in air at elevated temperatures was found efficient in increasing the scintillation efficiency [37]. The lack of afterglow in LPS:Ce in contrast to its observation in LSO:Ce was correlated with the significantly higher temperature maxima of TSL glow peaks above room temperature [38].

More recently,  $Gd_2Si_2O_7:Ce$  (GPS:Ce) pyrosilicate has been introduced showing much higher light output and faster scintillation response compared to GSO:Ce [39]. GPS:Ce shows an incongruent growth from the melt [40], but heavy Ce-doping (at least 10 mol %) in GPS host does enable its congruent growth [41]. However, at such a

high Ce-concentration, the light output is significantly reduced because of the self-absorption and concentration quenching. An optimal cerium concentration in oxide hosts is usually within 0.1 - 1 at. %. The congruent crystal growth of GPS:Ce is achieved by expansion of average ionic radius in the Gd site resulting from Ce-doping. At the same coordination number the  $\text{La}^{3+}$  ion has very similar ionic radius as  $\text{Ce}^{3+}$  so that the substitution of La for Ce can also be applied to stabilize the pyrosilicate phase avoiding unwanted concentration quenching of  $\text{Ce}^{3+}$  emission. The optical and scintillation properties of  $(\text{Ce}_{0.01}, \text{Gd}_{0.90}, \text{La}_{0.09})_2\text{Si}_2\text{O}_7$  were reported for the first time by Suzuki et al [42] where these single crystals were grown by the floating zone method under argon atmosphere. Using Si-avalanche photodiode detector, excellent values of light output of  $41.000 \pm 1000$  photons/MeV and FWHM energy resolution at 662 keV of  $4.4 \pm 0.1\%$  were achieved [43]. The impact of La and Sc admixture in GPS:Ce prepared by the top seeded solution growth with  $\text{SiO}_2$  self-flux was also studied regarding their structure, optical and scintillation properties [44].

In the very recent study [45] the absorption spectra, photoluminescence spectra as well as decays, and selected scintillation characteristics were studied for Ce-doped LPS, GPSLa30% and GPSLa48% single crystals grown by the Czochralski technique. The  $4f - 5d_x$ ,  $x = 1 - 5$ ,  $\text{Ce}^{3+}$  absorption bands in GPSLa30% were determined at 338, 320, 294, 242 and 219nm, respectively. The  $5d - 4f$  emission of  $\text{Ce}^{3+}$  is peaking at 377 nm and 372 nm in LPS and GPSLa hosts, respectively. The very onset of nanosecond decay times shortening appears around 380 K (LPS:Ce) and 440 K (both GPSLa30%:Ce and GPSLa48%:Ce) and is due to thermally-induced excited state ionization. The  $\text{Ce}^{3+}$  ionization onset favourably occurring well above RT provides an opportunity to exploit LPS:Ce and particularly GPSLa:Ce in high temperature applications.

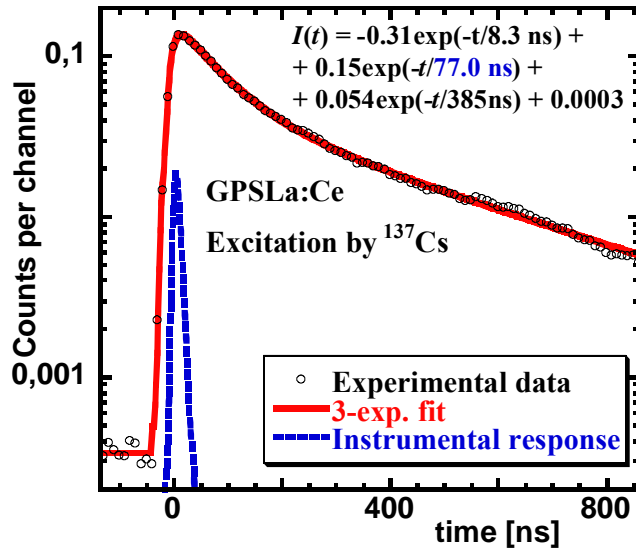


Figure 7. Scintillation decay of Ce-doped GPSLa30% single crystal grown by Czochralski technique. Solid line is convolution of instrumental response and function  $I(t)$  given in the figure.

Scintillation decay is shown in **Figure 17**. The leading decay component with 77 ns decay time is distinctly slower compared to photoluminescence decay with the decay time value of approx. 30 ns. Another slower component with decay time of 385 ns and a rising one with decay time of 8.3 ns point to complex energy transfer from the host lattice, **Figure 18**. Evaluated scintillation efficiency (integral of radioluminescence spectrum) reach about 250 %, 1210 % and 1530 % of that of BGO single crystal standard for LPS:Ce, GPSLa48%:Ce and GPSLa30%:Ce, respectively. In the latter compound the efficiency is almost doubled with respect to that of commercial high performance LYSO:Ce,Ca [46]. Afterglow of La admixed gadolinium pyrosilicates is fairly low and tends to get less intense with increasing La concentration becoming comparable to that of BGO. Taking further into account about two orders of magnitude lower intrinsic radioactivity (due to  $^{138}\text{La}$  isotope, 0.09% natural abundance,  $T_{1/2} \sim 10^{11}\text{y}$ ) compared to Lu-based scintillators, the La-admixed GPS:Ce single crystals show a

combination of characteristics highly favourable for medical imaging, oil industry and geophysical applications.

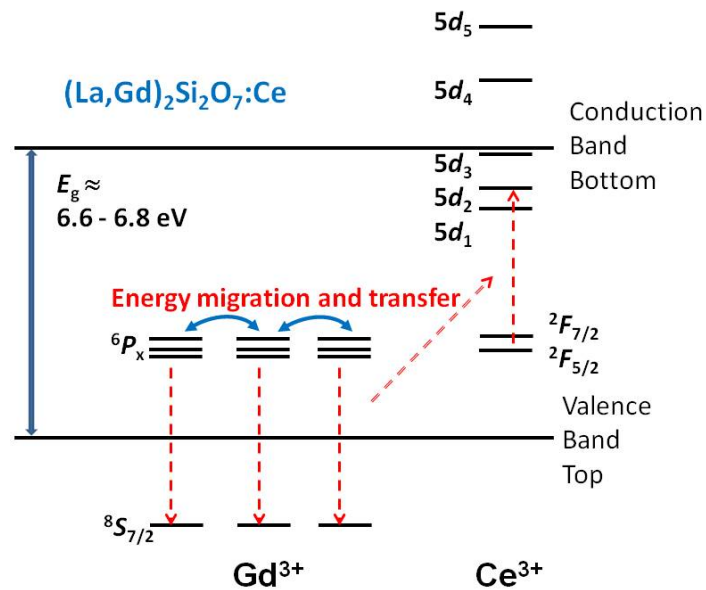


Figure 8 The sketch of energy transfer and  $\text{Ce}^{3+}$  energy level positioning of  $\text{Ce}^{3+}$  in GPSLa host.

#### 4. Discussion and conclusions

Selected results achieved at the garnet and pyrosilicate single crystal scintillators have been presented in the context of R&D activities all over the world in the field of single crystal scintillators based on the complex oxide compounds. They provide an overlook as for the emission properties of the doped fast  $\text{Ce}^{3+}$  luminescence center which enables to obtain the dominant part of scintillation response in the time scale of tens-hundreds of nanoseconds. The problem of trapping charge carriers in the transfer stage of scintillator mechanism is also clearly demonstrated which introduces in these materials delayed radiative recombination processes responsible for slower components in scintillation decay in time scale of units-tens of microseconds. Considerable effort has been paid to the study of the defects and traps



responsible for these unwanted phenomena with quite some success in understanding their nature and relation to the manufacturing technology.

Two modern strategies of the development of novel and/or optimization of existing single crystal scintillators were demonstrated: So called band gap engineering approach consists in the essential change of the electronic band structure of the original material, mostly by alloying it with another component providing a solid solution single crystal material. This strategy appeared extremely productive in the group of garnet scintillators, where balanced admixture of Gd and Ga into the structure of classical  $Y_3Al_5O_{12}$  or  $Lu_3Al_5O_{12}$  aluminium garnets gave rise to new ultraefficient multicomponent garnet scintillators with light yield approaching 60 000 phot/MeV though at the expense of their temperature stability due to  $Ce^{3+}$  excited state ionization early above room temperature. Provided example of La-admixed pyrosilicate is also a successful outcome of such a strategy which enables congruent growth of big size single crystals and improves considerably some scintillation characteristics compared to the limit ( $La_2Si_2O_7$  and  $Gd_2Si_2O_7$ ) compositions. Apart from specific changes in the band structure it seems from already several recent examples of cation-mixed compound scintillators [47] that atomistically inhomogeneous arrangement of cations may give rise to local variation of electronic structure of band edges which effectively limits the out-diffusion of charge carrier from ionization track and consequently increase the probability of their radiative recombination, i.e. increase the light yield of such a scintillator. The increase of scintillation efficiency and/or light yield was reported both in the undoped CsI-CsBr and  $ZnWO_4$ - $MgWO_4$  solid solutions or in the Ce-doped solid solutions of  $LaBr_3$ - $LaCl_3$ ,  $Lu_2SiO_5$ - $Y_2SiO_5$ ,  $Lu_2SiO_5$ - $Gd_2SiO_5$  and  $LuAlO_3$ - $YAlO_3$ . In the most recent case of La-admixed GPS host, such inhomogenities will arise due to atomistic disorder of La and Gd cations at the  $RE^{3+}$  site of pyrosilicate structure. Due to the fact that  $La^{3+}$  energy levels are expected to provide dominant contribution to the very bottom of conduction band, such an effect is indeed expected.

The second, so called defect engineering strategy has been exploited in a number of cases throughout all the history of scintillators focusing on optimization of particular parameter(s) important in applications by the suppression or creation of specific defect(s). Doping and codoping by a specific ion often accompanied by post-preparation annealing in a

defined (and often proprietary) atmosphere are used for such a purpose. Within last two decades, e.g. (Ce,F) codoping in  $\text{Gd}_2\text{O}_2\text{S}:\text{Pr}^{3+}$  powder phosphor,  $\text{La}^{3+}(\text{Y}^{3+})$  doping of  $\text{PbWO}_4$  single crystal and here described  $\text{Zr}^{4+}$  codoping of  $\text{YAP}:\text{Ce}$  and especially  $\text{Me}^{2+}$  codoping ( $\text{Me} = \text{Ca}, \text{Mg}$ ) in Ce-doped orthosilicate and garnet single crystals are successful examples of such material optimization. It is worth noting, however, that these concepts are critically compound-specific and cannot be simply transferred from one material system to another one. In the reported results, probably most interesting and unexpected was revealing the role of stable  $\text{Ce}^{4+}$  center in scintillation mechanism of Ce-doped garnet and silicate single crystal scintillators.

Furthermore, agglomeration of electron traps with  $\text{Ce}^{3+}$  emission centers was evidenced in garnet family and becomes almost a general aspect to be always considered [48]: space correlation of trap and recombination center enables tunneling transitions in the radiative electron-hole recombination. It has a significant influence on the timing characteristics of scintillation response and is therefore of great practical importance. Theoretical calculations of electronic band structure or defect creation energy can often provide a guide and indicate possibly promising concepts in such material studies.

It was also the aim of this lecture to demonstrate the complexity of R&D of scintillator materials. In fact, it is typical material science field where close collaboration among experts in technology, chemistry, physics and further considering the end-user requirements is truly a must. In several examples above the correlated use of several experimental techniques from optical and magnetic spectroscopies correlated further with theoretical calculations enabled deep understanding of atomistic aspects of scintillation mechanism, the nature of point defects and related traps and their role in the processes of energy transfer and capture in the host lattice. Such fundamental knowledge is then of great importance in further development and optimization of a particular material system.

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**Ing. Martin Nikl, CSc.** - curriculum vitae ([www.fzu.cz/~nikl](http://www.fzu.cz/~nikl))



- 1976 - 1981 study of solid state physics at the Technical University in Prague, Faculty of Nuclear Physics and Physical Engineering, graduated summa cum laude in 1981 (title Ing.)
- 1982 - 1986 CSc.(equiv. PhD.) studies in Institute of Physics
- from 1986 – appointed in the Institute of Physics, CSAV as junior scientist
- from 1995 promoted to the senior scientist level
- from 1997 promoted to the leading senior scientist level, head of Luminescence Laboratory
- from 2008 the Chair of the Dept. of Optical Materials

- from 2012, the member and vice-chair of the Institute Board, Deputy Director for targeted research

*Field of interest*

Luminescence and scintillation materials, energy transfer and storage phenomena in scintillation mechanism, physics of defects, luminescence of excitons, nanoaggregates, quantum dots.

*Awards and evaluations:*

- The Prize of Czechoslovak Spectroscopic Society for young scientists in 1991
- The Prize of the AS CR for outstanding scientific results, 2003: „PbWO<sub>4</sub> scintillator for high energy physics. Physical description and material optimisation“.
- Praemium Academiae 2013, awarded by the President of Academy of Science of CR.

Selected invited stays abroad:

- Fellowship from ICTP Programme for Training and Research in Italian Laboratories, ICTP, Trieste, Italy, February 93 - August 94, IROE del CNR, Florence, Italy.
- Visiting professor position at the Institute of Material Research, Tohoku University, Sendai, Japan, April-September 2001; June-July 2013.
- Visiting professor (part time position) at Dept. of Materials Science, University of Milan-Bicocca, Milan, Italy, March 2006-February 2008
- Visiting professor position (CAS award) at the Shanghai Institute of Ceramics, CAS, May 11-July 11, 2014.

Awarded grants and projects, collaboration agreements, patent applications:

- Coordinator of nine domestic grant projects awarded by the Grant Agency of the Academy of Sciences and the Czech Science Foundation in the period 1995-2013. All the finished projects evaluated as excellent.
- Co-director and director of four NATO Linkage grants awarded in 94-95, 97-98, 01-02, 11-13 periods, collaboration among teams in Italy, Czech Republic, Poland, Ukraine and Estonia.
- Co-director in NATO Science for Peace grant no. 973510-Scintillators (2000-2003), five participating teams in Italy, Czech Republic and Estonia
- Holder of ten projects from Ministry of Education, Youth and Sports, CR, program KONTAKT: bilateral international collaborations with Japan and China in 1998-2016.
- Coordinator of EU INTAS project (2005-7), no. 04-78-7803, seven participating teams in Ukraine, Russia, Estonia, Italy and Czech Republic.
- Partner of EU FP7 project “Luminet”, FP7-PEOPLE-2012-ITN, no. 316906 (2012-2016) and Horizon2020 project INTELUM no.368921 (2015-2018).
- Seven national patents awarded in the field of scintillation materials

*Pedagogical activities*

Member of PhD study councils F-6 and F-14 at FMP CU and “Nuclear engineering” at FNSPE CTU. Lecturer for Master and PhD students at FNSPE CTU. Supervised 10 Diploma students and 7 PhD students from Czech universities so far.

*Other activities:*

Chairman of international LUMDETR2003 conference, September 2003, Prague, Czech Republic, chairman of ISLNOM-4 international conference, June 2006, Prague, vice chairman of ICDIM2012, June 2012, Santa Fe, USA.

Member of the Advisory committees of LUMDETR, ISLNOM, Eurodim and ICDIM international conferences.

Member of the Editorial Board of the Optical Materials and Radiation Measurement (Elsevier) and of Measurement Science and Technology (IoP UK) journals. Referee for journals of Wiley-VCh, Elsevier, IoP UK, APS and ACS.

Member of AS CR assembly from 2010.

*Author and co-author* of 590 papers in the refereed impacted international journals, 47 papers in non-impacted journals, six chapters in books and 49 papers in conference proceedings. Author and co-author of 37 invited keynote and plenary lectures at International Conferences. The publications received more than 6600 citations (Scopus, auto-citations excluded), Hirsch factor, H=49.