

Pressure Effects on the Optical Properties of $\text{LuVO}_4\text{:Eu}^{3+}$ Nanoparticles

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Abstract. The effect of hydrostatic pressure (varying up to 110 kbar) at the room temperature on three lines at 594 nm, 615 nm and 619 nm positions in emission spectra and fluorescence lifetime τ of the Eu^{3+} for 0-2 line ($^5\text{D}_0 \rightarrow ^7\text{F}_2$ transition) in $\text{LuVO}_4\text{:Eu}^{3+}$ nanoparticles was studied. The results showed that the increase of the pressure induced lines red shift towards longer wavelengths for all considered lines with different rate. Also, the fluorescence lifetime τ for $^5\text{D}_0 \rightarrow ^7\text{F}_2$ transition nonlinearly decreased with pressure in the considered pressure range. Line positions and fluorescence lifetime τ , were explained by a model which took into account the effect of high pressure on: refractive index of crystal; compression, polarizability of the crystal and individual ions. Satisfactory agreement between measured and theoretical predicted values with error less than 2% was obtained.

1. Introduction

Nanoparticles have been the focus of scientific interest over the past decades due to their extensive possible applications in a wide range of human activities such as spectroscopy [1], DNA analysis [2], industry [3], medicine [4], diagnosing genetic diseases [5] etc. Also, it can be found in literature that the optical properties of nanostructures are highly structure-dependent [6]. On the other hand, there are not many data available on the fluorescence of nanoparticle properties under high pressure. Therefore, the main reason for conducting experiments in this research was to increase and improve the knowledge on the optical properties of nanoparticles under the specific condition of high pressure. These experiments were conducted in order to disseminate our knowledge about them and at this way to give new ideas for possible applications in wide spectrum of areas in human activities, for example tumor marker.

2. Experimental Details

2.1 Sample preparation

The nanoparticles LuVO_4 doped with 1% Eu^{3+} , were prepared using coprecipitation. Detailed procedure for $\text{LuVO}_4\text{:Eu}^{3+}$ nanoparticle was described in literature [7]. The starting reagents of nominal composition gents were Lu_2O_3 (Aldrich, 99.99%), and $\text{Ln}(\text{NO}_3)_3$ (Aldrich, 99.9%), $\text{Ln} = \text{Eu}^{3+}$. Lu_2O_3 was dissolved in a HNO_3 solution and then stichomythic quantities of $\text{Ln}(\text{NO}_3)_3$ were added. The amount of lanthanide ions was 0.995% mol with respect to Lu^{3+} . The obtained solution was dropped in NH_3 aqueous solution (pH=10). The obtained precipitate was filtered under vacuum and then dried at 60°C for 1 day. The samples were heat treated at 500°C for 30 h, ball milled for 30 min and finally heat treated at 90°C for 2 h. The structural characterization has been performed by X-ray diffraction. The results of the refinement performed by using MAUD program

[8] are shown in the Fig. 1. X-ray-diffraction (XRD) patterns were measured with a Thermo ARL X'TRA powder diffract meter, operating in the Bragg-Brentano geometry and equipped with a Cu-anode X-ray source (K_{α} , $\lambda = 1.5418 \text{ \AA}$), using a Peltier Si(Li) cooled solid state detector. The patterns were collected with a scan rate of $0.04^\circ/\text{s}$ in the 5° - 90° 2θ range. The phase identifications were performed with the PDF-4+ 2013 database provided by the International Centre for Diffraction Data (ICDD). The nanocrystalline sample was ground in a mortar and then put in a low-background sample holder for the data collection. From obtained data the calculated lattice parameters are $a = 7.023(3) \text{ \AA}$, $c = 6.195(2) \text{ \AA}$ and the average crystallite size is $11(1) \text{ nm}$, indicating the strongly nanocrystalline nature of the $\text{LuVO}_4:\text{Eu}^{3+}$.

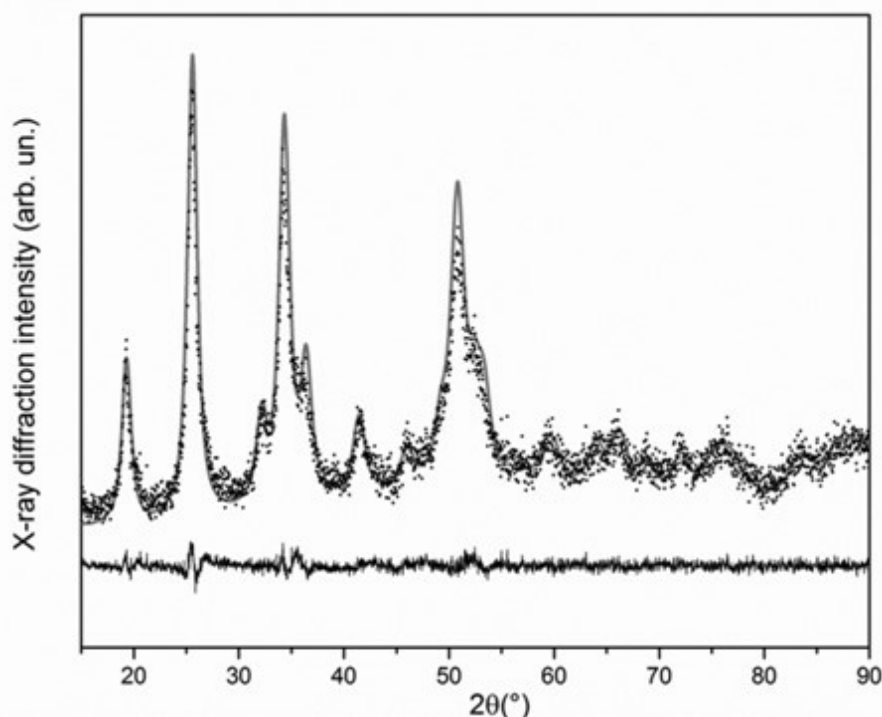


Figure 1. Observed X-ray diffraction for $\text{LuVO}_4:\text{Eu}^{3+}$: pattern (black dots), Rietveld refinement (upper line) and line of the residuals (black lower line) for tetragonal $\text{LuVO}_4:\text{Eu}^{3+}$ nanoparticles.

2.2 Fluorescence measurement

Fluorescence spectra and decay curve for $\text{LuVO}_4:\text{Eu}^{3+}$ nanoparticle was measured with a double grating spectro fluorometer SPEX connected with a PC. For the time resolving measurements, a mechanical chopper (Stanford Research System, SR540) has been used. The samples were excited by the 300mW DPSS laser (473 nm). The fluorescence lifetime was determined with the standard deviations was less than 1% using the technique described in literature [9]. For pressure generation, a diamond anvil cell of the NBS type with 1/3 carat stones has been used. The pressure had been determined by $\text{SrFCl}:\text{Sm}^{2+}$ (0.1%mol Sm^{2+}) the red shift of the 0-0 line, 0.11 nm/kbar [10]. A methanol-ethanol (4:1) mixture was used as a pressure medium to obtained hydrostatic condition in considered pressure range. Pressure was increased at room temperature, and DAC was used to equilibrate the system for at least 24h at each pressure step.

3. Results and Discussions

Experimental obtained line positions from $^5\text{D}_0 \rightarrow ^7\text{F}_2$ transition for Eu^{3+} doped nanoparticle $\text{LuVO}_4:\text{Eu}^{3+}$ are presented in Fig. 2. It can be noticed that there are three high intensity and well defined lines at about 594 nm, 615 nm and 619 nm. Peaks at 615 and 619 nm ($^5\text{D}_0 \rightarrow ^7\text{F}_2$ transition) can be attributed to the electric dipole transition, 594nm ($^5\text{D}_0 \rightarrow ^7\text{F}_1$ transition) are magnetic dipole transitions [7]. The $^5\text{D}_0 \rightarrow ^7\text{F}_1$, $^5\text{D}_0 \rightarrow ^7\text{F}_3$ and $^5\text{D}_0 \rightarrow ^7\text{F}_4$ transition lines are neglected because they are disturbed by sensor ($\text{SrFCl}:\text{Sm}^{2+}$) fluorescence. The spectra with the lines at about the same wavelength was observed in $\text{LuVO}_4:\text{Eu}^{3+}$ microcrystal [11] and nanocrystal [12].

In this work we focus on strongest, the best defined and well separated line in emission spectra at 619 nm. This line is far from the nearest line, and therefore it is well separated from them. For this line were obtained lines red shift towards longer wavelengths namely, red shift rate (RSR) about $0.0431 \text{ nm} \times \text{kbar}^{-1}$. Obtained RSR for other two lines at about 594 nm and 615 nm are $0.045 \text{ nm} \times \text{kbar}^{-1}$ and $0.041 \text{ nm} \times \text{kbar}^{-1}$, respectively. Obtained different red shift of the considered lines are not unexpected. Similar effect of high pressure on line position in fluorescence spectra, red shift, for the $^5D_0 \rightarrow ^7F_{(0,1,2)}$ transitions of the Eu^{3+} ions was observed in other nanomaterials for examples as in $\text{GdVO}_4:\text{Eu}^{3+}$ [13], $\text{Y}_2\text{O}_3:\text{Eu}^{3+}$ [14] and $\text{YVO}_4:\text{Eu}$ [15]. Also, high pressure have the same effect on mentioned lines position (RSR) in other materials doped with rare elements (RE) as Tb^{3+} [16], Sm^{3+} [17], Pr^{3+} [18]. On the other hand comparing RSR for $\text{GdVO}_4:\text{Eu}^{3+}$ nanoparticles and RSR obtained for nanoparticles considered in this work $\text{LuVO}_4:\text{Eu}^{3+}$ it can be seen that last one are practically half the value than for GdVO_4 : $0.095 \text{ nm/kbar}^{-1}$, $0.092 \text{ nm/kbar}^{-1}$ and $0.093 \text{ nm/kbar}^{-1}$ for line at 594 nm, 615 nm and 619 nm, respectively. Also, not only in nanoparticles doped with Eu^{3+} show the same high pressure effect on RSR for was observed in crystal [19], small crystal particle [20] and fine-particle-size powders few μm fine-particle-size powders [21].

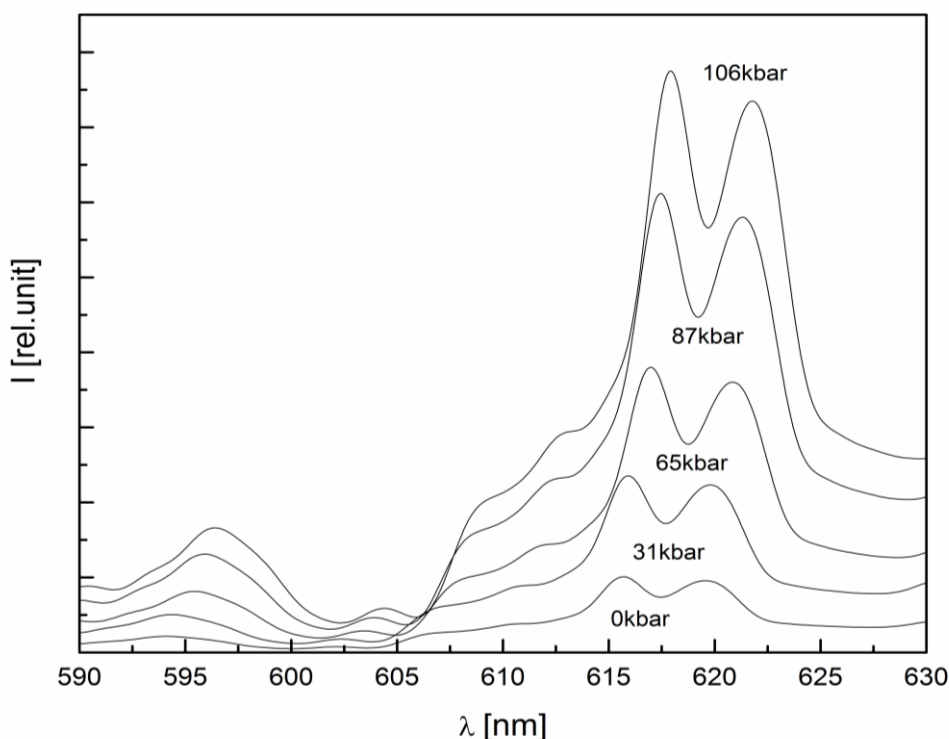


Figure 2. Normalized emission spectra for $\text{LuVO}_4:\text{Eu}^{3+}$ nanoparticle at 300K and different pressure.

Possible explanations of mentioned effect of high pressure on spectra line positions may be connect with pressure effect on optical properties of rare earth (RE) ions. Namely, in literature related to high pressure experiments one can find that high pressure changes the optical properties of lanthanide ions in two significant ways [22]: (a) Decreases of the rare earth free-ion atomic parameters shift emission bands to longer wavelength. This is correlated with an expansion of the 4f-electron wave functions with increasing covalence and (b) enhancement of the crystal-field interactions of the lanthanide 4f electrons is ascribed to a change in the sum of various interactions such as covalence, overlap, and Coulomb interactions between the 4f electrons and their ligands. Mentioned above factors can be tuned by changing the distances and bond angles between the RE ion and ligands under pressure [18].

Since the 4f state is well shielded from the lattice it is expected too be insensitive or very small sensitive to the pressure. This is in agreement with high pressure experimental data on small crystal particle for the Eu^{3+} ions emission line ($^5D_0 \rightarrow ^7F_2$ transitions) in small crystal particle which do not show any significant line position change up to 80Kbar. Also, this is in agreement with obtained (RSR) from the $^5D_0 \rightarrow ^7F_2$ transition for Eu^{3+} in EuPO_4 single-crystal [23].

Pressure dependence for a line position at about 619 nm in LuVO₄:Eu³⁺ nanoparticles we have described using the Equation(22) from literature data [24] which obtained good agreement between experimental and theoretical predicted values for RE doped nanoparticle [6, 13, 25]. The procedure was described in details in literature data [6, 13]. So pressure dependence of the line position is described with:

$$W = \{619.146 + 615.146 \times [k^{-0.512} \times \exp(-3.86 \times (1-k)^2 + 5.147 \times (1-k)^3 - 1)]^{-1} \times 10^8. \quad (1)$$

In equation (1) k is compression rate for nanomaterials and was obtained by rearranging Murnaghan equation of the state and defined as $k = (1 + B_0 \times B_0^{-1} \times P)^{-1/(3 \times B_0)}$ [24]. B_0 and B_0' are the isothermal bulk modules and its derive with respect to the pressure where taken from literature [6]. Discrepancy between calculated W using equation (1) and experimentally obtained W were less than 2%.

Experimental obtained fluorescence lifetime τ for line at 619nm (⁵D₀→⁷F₂ transition) in LuVO₄:Eu³⁺ nanoparticle are presented in Fig. 3. As one can see with increasing a pressure τ slowly non-linearly decrease. From high pressure experiments literature data one can see that τ change with pressure at the same mangier as we obtained in this experiments like in a Y₂O₃:Eu³⁺ nanoparticle [25], Gd₃Ga₅O₁₂:Eu³⁺ nanomaterial [6], GdVO₄:Eu³⁺ nanoparticle [13] and Y_{0.9}Eu_{0.1}O₃ crystal [26]. Also, one can found in literature data that in other materials doped with other RE ions fluorescence lifetime decrease with pressure [10, 22]. There is no unanimous opinion about the reasons of mentioned effect of high pressure on fluorescence lifetime. Some authors concluded that decreasing τ for the Eu³⁺ fluorescence lifetimes in nanoparticle may be the due change of nanoparticle size upon pressure [27]. Other one concluded that the decrease in the lifetime with increasing pressure is caused by an increase in the electronic transition probabilities, which is a result of the enhanced crystal-field strength around the Tb³⁺ ions [22].

We assumed that effect of high pressure on τ is not so simple as it was mentioned above. Therefore we have explanation the effect of the high pressure on fluorescence lifetime τ on strongest line in fluorescence spectra at 619 nm (⁵D₀→⁷F₂ transition) in LuVO₄:Eu³⁺ nanoparticles used the model which was successfully applied on materials doped with the Eu³⁺ ion [6,13] and other RE ion [17] and other ions [28]. We want to point out main reason for using mentioned model is the excellent agreement between experimental and theoretically predicted obtained fluorescence lifetime τ with discrepancy less than 2% in all considered pressure range.

The starring points in this model are following assumptions: 1. Fluorescence lifetime τ is not simple function of the emitted light λ , nanoparticle size or electronic transition probabilities, 2. Material's refractive index is function of the pressure induced change in interionic distance and at this way on material volume, 3. Change in individual molecular constituent polarizability α and 4. Fluorescence lifetime τ can be express with equation in mentioned above references.

Literature data lead on conclusion that for nanoparticles refractive index n must be considered as an effective index of refractions n_{eff} [29] which was defined as $n_{eff} = xn_{np} + (1-x)n_{med}$. In given relation for n_{eff} parameter x is filling factor shoving what fraction of space is occupied by nanoparticle with refractive index, n_{np} and n_{med} is the refractive index of the surrounding medium. Therefore, taking account mentioned above the dependence between pressure P and τ fluorescence lifetime for 0-2 line (⁵D₀→⁷F₂ transition) in LuVO₄:Eu³⁺ nanoparticle was described with the same equation which we have previously successful used. Now fluorescence lifetime for 0-2 line (⁵D₀→⁷F₂ transition) in LuVO₄:Eu³⁺ nanoparticle can be express with:

$$\tau = \tau_0 \times K \times W^{-3} \times k^2 \times n_{eff}^{-1} (n_{eff}^2 + 2)^{-2}, \quad (2)$$

where W [cm⁻¹], τ_0 [s], K [dimensionless], k [dimensionless] and n_{eff} are: energy of observed line, fluorescence lifetime at ambient pressure, zero fitting constant; compression rate and material (nanoparticle) refractive index, respectively. For more detailed see references [6, 17]. Pressure dependence of the energy transition W for ⁵D₀→⁷F₂ we obtained using equation (1) given in

pervious section. K is zero fitting constant, n_{med} is refractive index for hydrostatic medium (methanol: ethanol mixture). In our case, medium is hydrostatic mixture of menthol: ethanol (4:1) in working chamber in DAC in which nanoparticle $\text{LuVO}_4:\text{Eu}^{3+}$ are dispersed. Therefore, one can write $n_{med} = n_{\text{methanol}+\text{ethanol}}$. Pressure dependence of the medium refractive index n_{med} was obtained using high pressure experiments data on methanol mixture: ethanol (4:1) alcohol pressure dependence of a refractive index n_{med} can be expressed as with $n_{med} = 1.352 + 0.056 \times P^{0.356}$ [30]. Also, some authors concluded that change of the nanoparticles refractive index arise due the modification of the polarizabilities of the surrounding medium [31]. In consideration the variation on the refractive index n_{np} for nanoparticle with pressure we have takes in account molecular volume and electronic polarizability for individual ions for nanoparticles as in literature data [6]. The refractive pressure dependence, in our case $\text{LuVO}_4:\text{Eu}^{3+}$ nanoparticle, n_{np} can be express with relation from our previous papers with successful ware applied on several nanomaterials exposed to the high pressure [6, 13, 14, 25, 35]. In agreement mentioned above nanoparticles $\text{LuVO}_4:\text{Eu}^{3+}$ refractive index n_{np} , can be expressed with:

$$n_{np} = \left(V_{\text{LuVO}_4:\text{Eu}^{3+}} + 2 \times L \times \alpha_{\text{LuVO}_4:\text{Eu}^{3+}} \right)^{0.5} \times \left(V_{\text{LuVO}_4:\text{Eu}^{3+}} - L \times \alpha_{\text{LuVO}_4:\text{Eu}^{3+}} \right)^{-0.5} \quad (3)$$

where $V_{\text{LuVO}_4:\text{Eu}^{3+}}$, $\alpha_{\text{LuVO}_4:\text{Eu}^{3+}}$ and L are molecular volume, polarizability of the $\text{LuVO}_4:\text{Eu}^{3+}$ and Lorenz factor in units of $4 \times \pi / 3$, respectively. There is no single opinion on the affect of high pressure on refractive index. Some authors take into account only molecular volume pressure dependence [32]. On the other hand some authors concluded that a change in polarizability is results only of the screening effects [33]. But regardless of the reason for polarizability change, and from Equation (3) it is clear that electronic polarizability of individual ions can not be neglected and must be taken into account when analysing the high pressure effect on molecular volume [34]. Therefore, in order to obtain nanoparticle refractive index pressure dependence it must be considered as functions of the: a) nanoparticle molecular volume pressure dependence and b) nanoparticle polarizability pressure dependence. Molecular volume (\AA^3) pressure dependence was expressed by commonly used equation $V = V_0 \exp[-P \times (B_0)^{-1}]$ [35]. Taking account that for describing nanoparticle volume pressure dependence, it is necessary to use the Murnaghan equation [36]. In our case Murnaghan equation of state for molecular volume pressure dependence is

$$\left(V_{\text{LuVO}_4:\text{Eu}^{3+}} \right)_P = V_0^{\text{LuVO}_4:\text{Eu}^{3+}} \times \exp(-P_i \times B_0^{-1}),$$

where $V_0^{\text{LuVO}_4:\text{Eu}^{3+}}$ is molecular volume at zero pressure. Using literature data for zero pressure molecular volume $\left(V_{\text{LuVO}_4:\text{Eu}^{3+}} \right)_0 = 76.90 \text{ \AA}^3$ and $B_0 = 1696(\text{kbar})$ and $B'_0 = 5.50$ [38] and after certain rearrangement mathematic pressure dependence $V_{\text{LuVO}_4:\text{Eu}^{3+}}$ can be express with:

$$\left(V_{\text{LuVO}_4:\text{Eu}^{3+}} \right)_P = 76.90 \times \exp(-P_i \times B_0^{-1}) \quad (4)$$

Since the rule of additives can be regarded as a good approximation, the total molecular polarizability α^M can be expressed as $\alpha^M = \sum_{I=1}^N n \alpha^{\text{Ion}}$ [37,39], where I varies over the total number (N) of ion types (I), n is the number of ions type I . On the other hand one can see in literature data that find relationship between polarizability and ionic radius exist [39, 41].

Therefore, pressure dependence of individual ion electronic polarizability α_{ion} can be expressed as $(\alpha_{\text{ion}})_P = (\alpha_{\text{ion}})_0 (r_{\text{ion}})_P (r_{\text{ion}})_0^{-1}$ [39], where $(\alpha_{\text{ion}})_P$ and $(r_{\text{ion}})_P$ are individual ion electronic polarizability and ionic radii at pressure P and ambient pressure $(\alpha_{\text{ion}})_0$ and $(r_{\text{ion}})_0^{-1}$.

Pressure dependence of the individual ion radius can be expressed using rearranged Murnaghan equation $(r_{ion})_P = (r_{ion})_0 \times [1 + B_0' \times B_0^{-1} \times P]^{-(3B_0)^{-1}}$, where B_0 and B_0' are previously defined in text above. Taking into account the mentioned above pressure dependence of individual ion electronic polarizability can be expressed with:

$$(\alpha_{ion})_P = (\alpha_{ion})_0 \times [1 + B_0' \times B_0^{-1} \times P]^{-(3B_0)^{-1}} \quad (5)$$

Finally, in agreement with mentioned above discussion, literature data [42] and our previous experiment for high pressure effect for nanoparticle [6] and Table 1 molecular polarizability for $\text{LuVO}_4:\text{Eu}^{3+}$ nanoparticle can be express with:

$$\alpha_{\text{LuVO}_4:\text{Eu}^{3+}} = 1 \times \alpha_{\text{Lu}} + 1 \times \alpha_{\text{V}} + 4 \times \alpha_{\text{O}} + \alpha_{\text{Eu}} \quad (6)$$

In the Table 1 are given all quantities need for calculation of the changing for individual ion electronic polarizability due the applied pressure [43-45].

Table 1. Ion polarizability α_0 at normal (zero pressure), B_0 isothermal bulk module and B_0' its first derivative with respect to pressure.

Ion	α_0 (\AA^3)	B_0 (kbar)	B_0'
Lu^{3+}	3.65^{43}	1695^{46}	5.50^{46}
V^{5+}	2.94^{43}	226^{47}	4.15^{47}
O^{2-}	2.00^{43}	375^{48}	3.31^{48}
Eu^{3+}	4.53^{43}	1350^{49}	2.8^{49}

Finally, one can obtain relations for all the relevant parameters needed for the calculation of the fluorescence lifetime τ for 0–2 line ($^5\text{D}_0 \rightarrow ^7\text{F}_2$ transition) in $\text{LuVO}_4:\text{Eu}^{3+}$ at any pressure using Equation (2). Calculated and experimentally obtained fluorescence lifetime τ for 0–2 line ($^5\text{D}_0 \rightarrow ^7\text{F}_2$ transition) in $\text{LuVO}_4:\text{Eu}^{3+}$ are presented on Fig. 3.

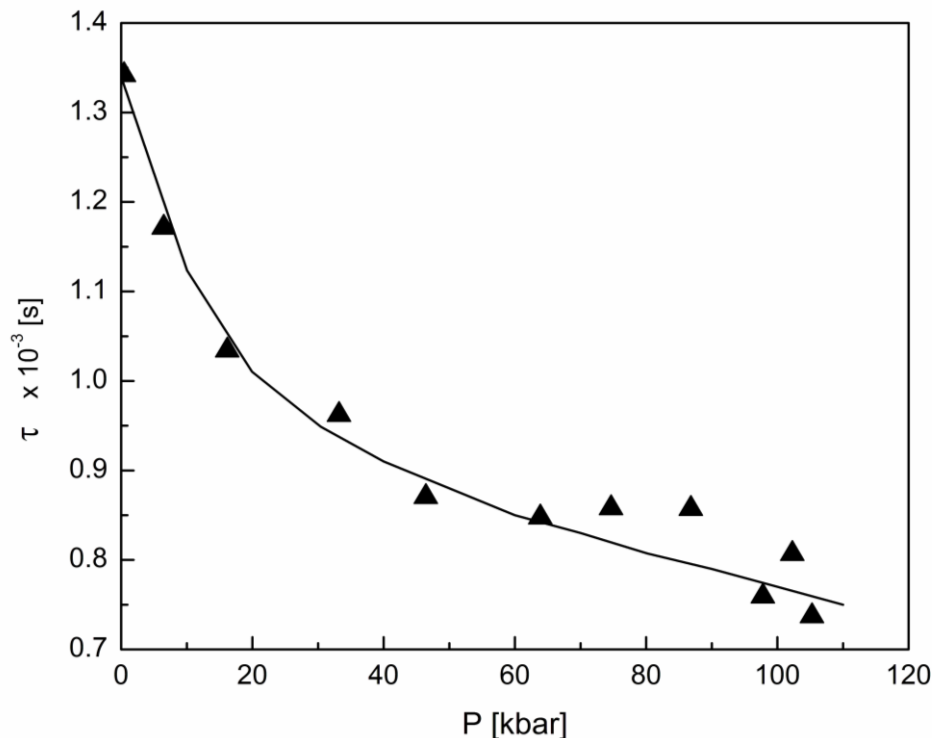


Figure 3. Pressure dependence of the 0–2 line fluorescence lifetime τ for the $^5\text{D}_0 \rightarrow ^7\text{F}_2$ transition for $\text{LuVO}_4:\text{Eu}^{3+}$ nanoparticle at room temperature. (▲) Experimental data, (—) equation (2).

Fig. 3 present the pressure dependence of the experimental obtained fluorescence lifetime τ ($^5D_0 \rightarrow ^7F_2$ transition) for Eu^{3+} in LuVO_4 nanoparticle and calculated fluorescence lifetime τ . In Fig. 3, triangles (\blacktriangle) are used to show the experimentally obtained fluorescence lifetime and full line (—) presents values for τ in $\text{LuVO}_4:\text{Eu}^{3+}$ calculated in the considered pressure range with Equation (2). This filling factor indicating that the $\text{LuVO}_4:\text{Eu}^{3+}$ nanoparticle occupies 10% of the working chamber in DAC. Fluorescence lifetime τ nonlinearly decrease with pressure from ambient pressure in considered pressure range. As it is mentioned above a similar decrease of the fluorescence lifetime under the pressure was observe in EuPO_4 small crystal particle [19]. Also, experimentally was observed the same type of change for the fluorescence lifetime for τ for $^5D_0 \rightarrow ^7F_2$ transitions for Eu^{3+} in $\text{Y}_{0.1}\text{Eu}_{0.1}\text{O}_3$ crystal [26] and in $\text{Y}_2\text{O}_3:\text{Eu}^{3+}$ nanoparticle [25]. A decrease of τ with pressure was observed for the 4f–4f transition of Eu^{3+} in lithium borate glass [46]. The same type of decreasing τ with pressure was observed in several materials doped with other RE [47–49].

Mentioned above and high pressure literature data lead on conclusion that there are main reasons for this type of observed change fluorescence lifetime τ due the pressure. First, arise due great sensitive of the Eu^{3+} fluorescence lifetime τ for $^5D_0 \rightarrow ^7F_2$ transitions. Exactly, high pressure experiment have shown that the $^5D_0 \rightarrow ^7F_2$ electric dipole transition is hypersensitive to the local environment of the Eu^{3+} [11]. Some high pressure experiments have shown that that local environment dramatically changing (rising of the site symmetry) and the weakening of the covalence of Eu–O bond [50]. Some authors assumed that this changing of asymmetry can be connect with changing of the of the negative charge Q of the Eu^{3+} surrounding ligands due the pressure as it was shown in $\text{Eu}^{3+}:\text{Te}_2\text{-K}_2\text{-Nb}_2\text{O}_5$ glass [20] and lithium borate glass [22]. The shape of the line which present change of the fluorescence lifetime τ for $^5D_0 \rightarrow ^7F_2$ transitions due pressure obtained in this paper is similar to one obtained for $\text{Eu}^{3+}:\text{Te}_2\text{-K}_2\text{-Nb}_2\text{O}_5$ glass [20] and lithium borate glass [22]. Mentioned explanation is quite reasonable therefore we concluded that negative charge Q of the Eu^{3+} surrounding ligands in $\text{LuVO}_4:\text{Eu}^{3+}$ nanoparticle can change with pressure at the same manner. Second, arise due the fact that fluorescence lifetime for the $^5D_0 \rightarrow ^7F_2$ transition for Eu^{3+} ion is a function of the nanoparticles size [51]. This is for understanding knowing that the main effect of high pressure is the change in the nanoparticle diameter. This is in harmony with high-pressure effects on the fluorescence lifetime τ for 4f–4f transitions for rare earth ions when the samples are 10–100 μm in size. In our case sample diameter was 10 μm . What is dominant one it is not important because we have opinion that no one of them cannot be neglected.

Based on results it can be concluded that presented explanation of obtained change of τ for $^5D_0 \rightarrow ^7F_2$ transitions in nanoparticle with pressure can be connect with possible change of: 1. Nanoparticle diameter and 2. The formal negative charge Q of the Eu^{3+} surrounding ligands.

4. Conclusions

The fluorescence spectra of $\text{LuVO}_4:\text{Eu}^{3+}$ nanoparticles have shown three well defined lines at about 594 nm, 615 nm and 619 nm up to a 110 kbar. For all three lines high pressure induced red-shift rate at about a 0.045 nm kbar⁻¹, 0.041 nm kbar⁻¹ and 0.043 nm kbar⁻¹, respectively. Fluorescence lifetime τ nonlinearly decrease with pressure in considered pressure range, from ambient pressure up to about 110 kbar. The pressure effect of the fluorescence lifetime τ for the 0–2 line at 619 nm ($^5D_0 \rightarrow ^7F_2$ transition) was explained by using a model which considers the pressure effect on the line position, the individual ion volume and the polarizability, the molecular volume, refractive index, inter-ionic distance and the hydrostatic medium refractive index. The fluorescence lifetime as calculated by the presented model is in close correspondence with the experimental values.

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