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## Thermal quenching of lanthanide luminescence via charge transfer states in inorganic materials

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There are various routes of luminescence quenching such as multi-phonon relaxation from excited states to lower energy states, energy migration to killer sites, and radiation less relaxation to the ground state via the crossing point in a configurational coordinate diagram. In this work, we will consider and review quenching of lanthanide luminescence by means of charge carrier transfer to the valence band or the conduction band of the host compound. We will focus on  $4f^n-4f^n$  emission quenching due to thermally activated electron transfer from the  $\text{Pr}^{3+} \ ^3\text{P}_0$  level and the  $\text{Tb}^{3+} \ ^5\text{D}_4$  level to the conduction band, and due to thermally activated hole transfer from the  $\text{Eu}^{3+} \ ^5\text{D}_0$  level to the valence band. In addition, we will consider the quenching of the  $4f^{n-1}5d-4f^n$  emission of  $\text{Eu}^{2+}$  and  $\text{Ce}^{3+}$  which often (if not always) proceeds by electron transfer to the conduction band. Since all the above quenching routes involve reduction or oxidation of lanthanides, the location of the lanthanide charge transition levels with respect to the host bands is crucial. In other words, we need to know the location of the ground and excited states in the band gap or equivalently the vacuum referred binding energies (VRBE) in the lanthanide states as can be established using the (refined) chemical shift model. A clear correlation between the temperature  $T_{50}$  at which luminescence intensity or luminescence decay time has dropped by 50% and thermal quenching activation energies  $\Delta E$  derived from VRBE schemes will be demonstrated. Since  $T_{50}$  typically changes 400–800 K with a 1 eV change in  $\Delta E$ , and since VRBE energies may contain 0.3–0.5 eV error, it will be clear that the accurate prediction of quenching temperatures from the VRBE data is not yet feasible. Nevertheless, one may derive trends and provide guidelines on how to improve the thermal stability of luminescence.

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### Anniversary statement

Ten years ago, the *J. Mater. Chem. C* was a 'new kid on the block' in our field of luminescence phosphors. It has evolved quite rapidly into a high impact factor journal publishing manuscripts related to luminescence materials and their application in devices. We together with collaborating groups have almost yearly published manuscripts in *JMCC* on topics such as thermal quenching in Ce doped garnets, persistent luminescence, carrier dynamics and trapping in phosphors, computational studies on the spectroscopy of lanthanides, and conduction and valence band engineering of phosphor properties. The high impact factor is reflected in the frequency of citations to our work.

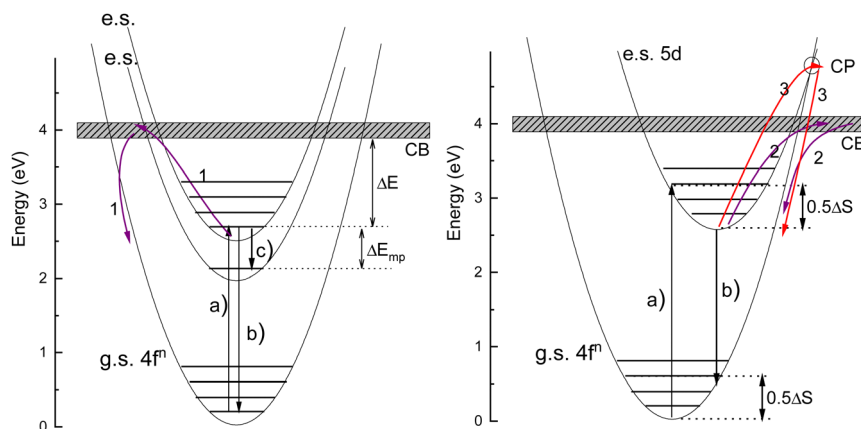
## 1 Introduction and theory

The thermal quenching of luminescence is an important phosphor characteristic for many different applications. For application at room temperature, the onset for thermal quenching should obviously be well above 300 K. Luminescent phosphors in modern day light emitting diode (LED) lighting like  $\text{Ce}^{3+}$  doped garnet  $\text{Y}_3\text{Al}_5\text{O}_{12}$  typically operate at temperatures around 100 C,<sup>1</sup> and phosphors should not start to quench then. High

power white light emitting (WLED) phosphors require thermal stability up to at least 200 C (475 K).<sup>1,2</sup> The thermal quenching of emission intensity or emission decay time is also used in thermometry.<sup>3–5</sup> Thermal barrier coating phosphors (TBCs) are used to sense the temperature in turbine engines up to temperatures as high as 1200 K, see, *e.g.*, ref. 6 and 7. Understanding how the quenching temperature depends on the type of the luminescence activator and the type of host compound is then important for research and development, or even for engineering of new phosphor materials towards a specific application. Luminescence intensity can be decreased by various quenching mechanisms as illustrated in Fig. 1 where a luminescence center with a ground state (g.s.) and several

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**Fig. 1** Illustration of the various quenching mechanisms in lanthanide luminescence. Arrows (1)–(3) in the two configurational coordinate diagrams illustrate the quenching of  $4f^n$  emission via the conduction band (CB), quenching of  $5d$  emission via the CB, and quenching of  $5d$  emission via the crossing point (CP), respectively. Arrow (c) in the left hand panel illustrates the quenching of  $4f$ – $4f$  emissions via multi-phonon relaxation to a  $\Delta E_{mp}$  lower lying excited state. The contributions to the Stokes shift  $\Delta S$  from the excited and ground state relaxation for  $5d$ – $4f$  emissions are indicated in the right hand panel. The Stokes shift is negligible for  $4f$ – $4f$  transitions in the left hand panel.

excited states (e.s.) is shown. Quantum efficiency is 100% when each absorbed photon via transition (a) results in an emitted photon via *e.g.* transition (b). However, the system can also decay to a lower lying level by means of the emission of multiple phonons indicated by transition (c) in the left panel. The rate will depend on the available phonon energies, the temperature, and the energy that needs to be bridged. Energy transfer to a nearby defect is also a well-known route of luminescence quenching. In this work, we will focus on the thermally activated quenching of lanthanide luminescence under conditions where multi-phonon relaxation and energy transfer are improbable. In practice, this means that the activator and defect concentrations should be smaller than typically 1% and that the energy gap  $\Delta E_{mp}$  between the emitting level and the next lower level should be larger than typically 1 eV.

Fig. 2 shows the relevant  $4f^n$  levels of lanthanides  $\text{Pr}^{3+}$  ( $n = 2$ ),  $\text{Eu}^{3+}$  ( $n = 6$ ), and  $\text{Tb}^{3+}$  ( $n = 8$ ). We will consider the thermal quenching of the luminescence from the  $^3\text{P}_0$  level of  $\text{Pr}^{3+}$ , the  $^5\text{D}_0$  level of  $\text{Eu}^{3+}$ , and the  $^5\text{D}_4$  level of  $\text{Tb}^{3+}$ . Here, the energy gaps  $\Delta E_{mp}$  with the next lower  $^1\text{D}_2$ ,  $^7\text{F}_6$ , and  $^7\text{F}_0$   $4f$  levels are 0.5 eV, 1.55 eV, and 1.82 eV, respectively. Whenever the  $^5\text{D}_4$  or  $^3\text{P}_0$  level is close to the CB-bottom, quenching may proceed via the charge transfer state. This means that an electron is thermally excited from the emitting  $4f^n$  excited state to the conduction band (CB) of the host compound as illustrated with arrows (1) in Fig. 1. The energy difference  $\Delta E$  between the location of the emitting state in the band gap and the CB-bottom is then the relevant quenching energy barrier. In the case of  $\text{Pr}^{3+}$ , there is only 0.5 eV energy difference with the next lower  $4f^2$  state and the quenching route via multi-phonon relaxation to  $^1\text{D}_2$  also need to be considered. Charge transfer quenching also applies to  $\text{Eu}^{3+}$ , but instead of electron ionization to the CB quenching proceeds by hole ionization to the valence band (VB), *i.e.*,  $\text{Eu}^{3+} (^5\text{D}_0) \rightarrow \text{Eu}^{2+} (^8\text{S}_{7/2}) + \text{VB}_h$  where a valence band hole ( $\text{VB}_h$ ) is created.



**Fig. 2** Relevant level energies and luminescence transitions of  $\text{Ce}^{3+}$ ,  $\text{Pr}^{3+}$ ,  $\text{Eu}^{3+}$ ,  $\text{Tb}^{3+}$ , and  $\text{Eu}^{2+}$ . The energy of the lowest  $5d$ -level depends on the compound and the range is indicated by the curved dashed arrows.

$\text{Ce}^{3+}$  and  $\text{Eu}^{2+}$  show the dipole allowed  $4f^{n-1}$  and  $5d$ – $4f^n$  emissions. Different from exciting a  $4f^n$  state there will be significant lattice relaxation after exciting to a  $4f^{n-1}5d$ -state. This leads to an offset in the configuration coordinate diagram as illustrated in Fig. 1. Thermal quenching may proceed *via* either electron ionizations to the CB illustrated by arrows (2) or alternatively when the CB is above the crossing point (CP) in the configurational coordinate diagram *via* that CP as illustrated by arrows (3) in Fig. 1.

In this work, we will focus on the quenching route *via* charge transfer to either the CB or the VB, and then the level locations of the emitting levels in the band gap need to be known in order to determine the quenching energy barrier  $\Delta E$ . These level locations will be established with the (refined) chemical shift model developed in 2012 (and 2019).<sup>8–10</sup> It makes use of



the highly systematic changes in the level location with the number  $n$  of electrons in the  $4f^n$ -orbital of the lanthanides which is then combined with the spectroscopic data retrieved from the archival literature. It provides the so-called vacuum referred binding energy (VRBE) diagrams where all divalent and trivalent lanthanide ground and excited state levels are drawn with respect to the VB-top and CB-bottom and also with respect to the vacuum level. This work deals with about 170 different inorganic compounds, and for each compound the available spectroscopic data on the host and on divalent and trivalent lanthanides were gathered and combined to construct their VRBE diagrams. It is not doable to provide the references and analysis for each piece of data used (it would run into many 1000), and the reader has to trust that everything was performed with best scientific effort. Many VRBE schemes have already appeared in the literature where many references to the original data can be found. The reader may also conduct own search in the archival literature to derive, verify or improve the parameters used. The relevant parameters in the VRBE construction will be tabulated for each host and only the reference to information on the thermal quenching data will be provided.

### A. Arrhenius equation, the chemical shift model and the VRBE scheme

The thermal quenching of luminescence intensity  $I(T)$  is traditionally expressed using the single barrier Arrhenius equation

$$I(T) = \frac{I(0)}{1 + \frac{\Gamma_0}{\Gamma_\nu} \exp\left(\frac{-\Delta E}{k_B T}\right)} \quad (1)$$

where  $\Gamma_\nu$  is the radiative decay rate,  $\Gamma_0$  is the attempt rate for thermal quenching which has similar magnitude as the maximum phonon frequency in compounds,  $k_B$  is the Boltzmann constant, and  $\Delta E$  is the energy barrier for thermal quenching.

A similar equation applies for the lifetime  $\tau(T)$  of the excited state

$$\tau(T) = \frac{\tau_\nu}{1 + \frac{\Gamma_0}{\Gamma_\nu} \exp\left(\frac{-\Delta E}{k_B T}\right)} = \frac{I(T)}{I(0)} \tau_\nu \quad (2)$$

where  $\tau_\nu$  is equivalent to  $1/\Gamma_\nu$ .

Depending on whether defects or dislocations happen to be nearby the activator or not,  $\Delta E$  may change from activator to activator and therefore become spatial dependent. In cases where quenching proceeds by electron transfer to the CB or hole transfer to the VB,  $\Delta E$  will also show a temperature dependence because the bandgap of the host compound will be temperature dependent. Due to lattice expansion when the temperature increases the (mobility) bandgap reduces typically by 0.05 eV per 100 K temperature increase. Therefore, the often made assumption of a temperature independent and a single value  $\Delta E$  fails largely in practice. Furthermore, the radiative decay time usually shows a temperature dependence, *i.e.*, it tends to increase with the temperature increase, see *e.g.* the quenching curves in ref. 11. Considering all the above, a single barrier Arrhenius fit to an experimental quenching curve will

not provide good parameters for the activation energy and frequency factor. Instead of fitting, we will use a fixed value for  $\Gamma_0$  and estimate the average quenching energy barrier  $\Delta E$  from the temperature where the luminescence intensity or decay has decreased by 10% ( $T_{10}$ ) or 50% ( $T_{50}$ ).

Using eqn (1) and (2), one obtains

$$T_{50} = \frac{11\,600}{\ln(\tau_\nu \Gamma_0)} \Delta E \quad (3)$$

and

$$T_{10} = \frac{11\,600}{\ln 9 + \ln(\tau_\nu \Gamma_0)} \Delta E \quad (4)$$

where  $\Gamma_0$  depends on the type of compound and ranges from  $4 \times 10^{12}$  Hz for iodide compounds with weakly bonded heavy ions up to  $4 \times 10^{13}$  Hz for strongly bonded borate and phosphate compounds.<sup>12</sup> This corresponds with phonon energies ranging from  $130 \text{ cm}^{-1}$  to  $1300 \text{ cm}^{-1}$ . In this work, we adopt the same typical value of  $\Gamma_0 = 2 \times 10^{13}$  Hz for each compound. For each lanthanide (A), we adopted a typical decay time  $\tau_\nu$ , as listed in Table 1. The nature of the transitions and their typical emission wavelengths  $\lambda$  are also compiled in Table 1. Those for  $\text{Tb}^{3+}$ ,  $\text{Pr}^{3+}$ , and  $\text{Eu}^{3+}$  are almost independent of the type of compound but those for the 5d–4f emissions of  $\text{Eu}^{2+}$  and  $\text{Ce}^{3+}$  depend strongly as illustrated in Fig. 2. Since the product  $\tau_\nu \Gamma_0$  appears as an argument in the natural logarithm of eqn (3), a factor 4 error in  $\tau_\nu \Gamma_0$  will lead to only 5% error in  $T_{50}$ . The dependences of  $T_{50}$  and  $T_{10}$  on  $\Delta E$  in columns 5 and 6 are obtained using eqn (3) and (4). The ratio, or the slope in  $\text{K eV}^{-1}$ , increases with a shorter decay time of the luminescence.

### B. Chemical shift model with the characteristic VRBE diagram

Fig. 3 shows the vacuum referred binding energy diagram for the lanthanides in  $\text{YPO}_4$  as constructed using the (Refined) Chemical Shift model. The model was first introduced in 2012<sup>8</sup> and refined later in 2019.<sup>9,10</sup> The diagram shows the location of the divalent and trivalent ground states within the band gap and relative to the vacuum level. The vacuum referred binding energies are equivalent to the  $\text{Ln}^{3+/2+}$  and  $\text{Ln}^{4+/3+}$  charge transition levels. The most crucial parameter needed to construct a VRBE scheme is the  $U$ -value defined as the energy difference between the  $\text{Eu}^{3+/2+}$  and  $\text{Eu}^{4+/3+}$  CTLs which was determined as 7.09 eV for  $\text{YPO}_4$ . The chemical shift model relates the  $U$ -value

**Table 1** The dependences of  $T_{50}$  and  $T_{10}$  on the activation energy  $\Delta E$  calculated for  $\Gamma_0 = 2 \times 10^{13}$  Hz and using the typical value for  $\tau_\nu$  in column 4

A	Transition	$\lambda$ (nm)	$\tau_\nu$	$T_{50}/\Delta E$ (K eV <sup>-1</sup> )	$T_{10}/\Delta E$ (K eV <sup>-1</sup> )
Eu <sup>3+</sup>	<sup>5</sup> D <sub>0</sub> → <sup>7</sup> F <sub>1,2</sub>	≈ 610	2 ms	475	435
Tb <sup>3+</sup>	<sup>5</sup> D <sub>4</sub> → <sup>7</sup> F <sub>5</sub>	≈ 545	2 ms	475	435
Pr <sup>3+</sup>	<sup>3</sup> P <sub>0</sub> → <sup>3</sup> H <sub>4,5,6</sub>	490, 550, 620	50 μs	560	510
Eu <sup>2+</sup>	5d → 4f [ <sup>8</sup> S <sub>7/2</sub> ]	380–600	1000 ns	690	610
Ce <sup>3+</sup>	5d → 4f [ <sup>2</sup> F <sub>5/2,7/2</sub> ]	300–550	40 ns	850	735





was found which agrees well with the prediction from eqn (4) as listed in Table 1.

In this work, we added new information. We selected compounds with a relatively low  $\text{Eu}^{3+}$  concentration (about 1%). Often, the data for decay time quenching were preferred over those of intensity quenching because the latter tend to be less accurate. The results are shown in Fig. 4 and the data and references are found in Table 2. We also added information on  $E^{\text{ex}}$  and the  $U$ -values from which the data on  $E_{\text{V}}$  and  $E_{\text{C}}$  are obtained using the refined chemical shift model. The typical error bars are  $\pm 0.12$  eV in the CT-energy and  $\pm 50$  K in the  $T_{10}$  value.  $\Delta E$  on the horizontal axis was obtained by

$$\Delta E = E^{\text{CT}} - E(^5\text{D}_0) - 5 \times 10^{-5} T_{10} E^{\text{ex}} \quad (5)$$

where  $5 \times 10^{-5} T_{10} E^{\text{ex}}$  is the estimated lowering of the bandgap at a temperature  $T_{10}$  where we assumed that the amount of lowering scales with  $E^{\text{ex}}$ . This is motivated as follows. The VRBE of cation electrons lowers (becomes more negative) when neighboring anions move further away; this is simply a matter of less Coulombic repulsion from the negatively charged anions. The VRBE of anion electrons raises (becomes less negative) when neighboring cations move further away; this is a matter of decreased Coulombic attraction from the positively charged cations. As a result, the cation related CB-bottom moves down and the anion related VB-top moves up causing the bandgap to decrease. For  $\text{Eu}^{2+}$ , being a cation, we will assume that its VRBE lowers with the same pace as the CB-bottom. Since the VB-top moves upwards,  $\Delta E$  will decrease with the same amount as the bandgap lowering.

There are few outliers notably  $\text{ScBO}_3$ ,  $\text{ScPO}_4$  and  $\text{YVO}_4$  as shown in Fig. 4. Disregarding these, a linear least square fit through the data yields the dashed line with a slope of  $421 \text{ K eV}^{-1}$  which agrees very good with a predicted value of  $435 \text{ K eV}^{-1}$  as shown in Table 1. The compound to compound variation in decay time, in maximum phonon frequencies, and

Table 2 Data on  $T_{10}$  values for the  $\text{Eu}^{3+} ^5\text{D}_0$  emission and the quenching energy barriers  $\Delta E$  derived from  $E^{\text{CT}}$  and  $E^{\text{ex}}$  energies. The parameters used for the VRBE-diagram construction are provided. All energies are in eV

A	$U$	$E^{\text{CT}}$	$E_{\text{V}}$	$E^{\text{ex}}$	$E_{\text{C}}$	$\Delta E$	$T_{10}$	Ref.
LaOCl	6.65	4.20	-8.10	6.45	-1.32	1.85	550	19
YOCl	6.65	4.54	-8.44	7.10	-0.94	2.14	630	20
YOBr	6.57	4.32	-8.18	6.50	-1.34	1.93	650	20
LaPO <sub>4</sub>	7.18	4.84	-9.00	8.10	-0.38	2.37	720	7
LuPO <sub>4</sub>	7.08	5.74	-9.85	8.70	-0.55	3.09	1085	7,21
ScPO <sub>4</sub>	7.02	5.95	-10.0	7.40	-2.19	3.42	950	7,22
LaBO <sub>3</sub>	6.93	4.51	-8.54	7.05	-1.10	2.10	650	23,24
ScBO <sub>3</sub>	6.86	5.44	-9.44	7.10	-1.94	3.01	700	24
Ca <sub>2</sub> Gd <sub>6</sub> (SiO <sub>4</sub> ) <sub>6</sub> O <sub>2</sub>	6.80	4.59	-8.56	7.00	-1.17	2.20	600	7
X <sub>2</sub> -Y <sub>2</sub> SiO <sub>5</sub> :(Ce1)	6.86	4.80	-8.80	6.82	-1.61	2.32	890	7,25
LaAlO <sub>3</sub>	6.76	3.91	-7.86	6.10	-1.47	1.58	500	26
GdAlO <sub>3</sub>	6.75	4.75	-8.70	7.36	-0.90	2.31	700	4
Y <sub>3</sub> Al <sub>5</sub> O <sub>12</sub>	6.77	5.23	-9.19	7.10	-1.69	2.69	1020	7
Li <sub>2</sub> Mg <sub>2</sub> (WO <sub>4</sub> ) <sub>3</sub>	7.15	4.07	-8.21	4.70	-3.34	1.78	465	27
YVO <sub>4</sub>	6.80	4.10	-8.07	4.00	-3.94	1.76	800	7
MgLa <sub>2</sub> TiO <sub>6</sub>	6.68	3.88	-7.79	4.50	-3.13	1.60	410	28
Gd <sub>2</sub> Ti <sub>2</sub> O <sub>7</sub>	6.79	3.94	-7.91	4.15	-3.62	1.68	400	29
Y <sub>2</sub> Ti <sub>2</sub> O <sub>7</sub>	6.79	3.85	-7.82	4.25	-3.42	1.56	500	2
Zr <sub>0.83</sub> Y <sub>0.17</sub> O <sub>1.91</sub>	6.70	4.34	-8.26	5.40	-2.63	1.96	740	7,30
La <sub>2</sub> Zr <sub>2</sub> O <sub>7</sub>	6.66	4.43	-8.33	6.00	-2.05	2.06	620	5,31
La <sub>2</sub> Hf <sub>2</sub> O <sub>7</sub>	6.65	4.40	-8.30	6.00	-2.01	2.03	625	5,31
La <sub>2</sub> Be <sub>2</sub> O <sub>5</sub>	6.70	4.11	-8.03	6.28	-1.44	1.78	480	32
Gd <sub>2</sub> Zr <sub>2</sub> O <sub>7</sub>	6.65	4.81	-8.71	6.00	-2.42	2.41	725	6
C-Gd <sub>2</sub> O <sub>3</sub> :(S <sub>6</sub> )	6.60	4.86	-8.74	5.50	-2.99	2.47	775	33
C-Y <sub>2</sub> O <sub>3</sub> :(S <sub>6</sub> )	6.60	5.05	-8.93	6.10	-2.53	2.60	890	33,34
C-Sc <sub>2</sub> O <sub>3</sub> :(C <sub>2</sub> )	6.60	5.02	-8.90	6.30	-2.28	2.54	950	33
La <sub>2</sub> O <sub>2</sub> S	6.37	3.64	-7.41	4.75	-2.48	1.37	400	19,35
Y <sub>2</sub> O <sub>2</sub> S	6.37	3.76	-7.53	4.85	-2.49	1.47	460	19
KLuS <sub>2</sub>	6.20	3.02	-6.71	4.35	-2.21	0.81	150	36
YSiO <sub>2</sub> N	6.70	3.89	-7.81	6.10	-1.41	1.58	425	37
AlN-wurtzite	6.40	3.49	-7.27	6.20	-0.76	1.22	300	38
GaN-wurtzite	6.40	3.25	-7.03	3.48	-3.45	1.04	200	38-40

in relaxation effects, and the experimental errors in  $E^{\text{CT}}$  and  $T_{10}$  then provide the scatter of data.

Note that the fitted line does not cross the horizontal at zero energy but near 0.5 eV. We assumed that quenching occurs by the full ionization of the hole. However, this is not necessarily needed. The CT-state is a hole at the valence band that is still Coulomb bonded with the transferred electron, *i.e.*,  $\text{Eu}^{2+}$ , and radiation less recombination may start from this bonded state which will lower  $\Delta E$ . Furthermore, 0.5 eV is of the same magnitude as the energy involved in lattice relaxation and Stokes shift.<sup>15,41</sup> We therefore interpret the intercept near 0.5 eV as an effect of electron-hole bonding and lattice relaxation.

## B. Thermal quenching of the $\text{Tb}^{3+} ^5\text{D}_4$ emission

The energy gap between the emitting  $^5\text{D}_4$  level of  $\text{Tb}^{3+}$  and the next lower  $^7\text{F}_0$   $4\text{f}^8$ -level is about 1.8 eV. This is even larger than that in the case of  $\text{Eu}^{3+}$  considered above, and multi-phonon relaxation is like for  $\text{Eu}^{3+}$  not a feasible quenching mechanism. Instead, in cases where the CB-bottom is not too far above the  $^5\text{D}_4$  level, thermal quenching can proceed by electron ionization to the CB. For  $\text{YPO}_4$  in Fig. 3 with the CB-bottom at  $-0.63$  eV, the distance is 4.5 eV which is clearly too large. However, in transition metal based compounds like tantalates, tungstates, vanadates, niobates, molybdates and titanates, the CB-bottom appears at  $-3$  eV to  $-4$  eV.<sup>42</sup> The excitation spectra

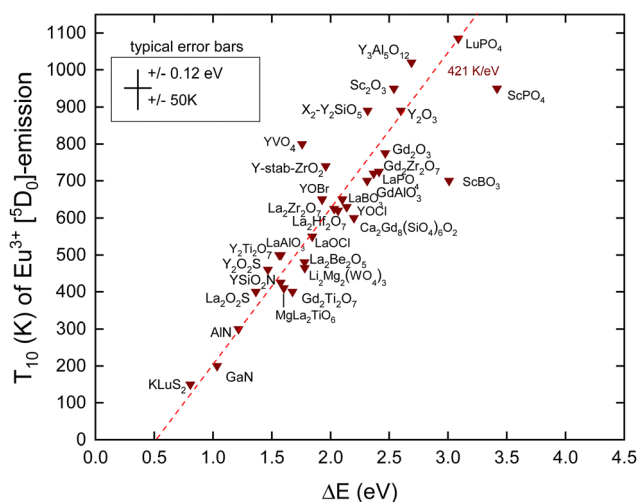


Fig. 4 10% Quenching temperature  $T_{10}$  for the  $\text{Eu}^{3+}$  emission from the  $^5\text{D}_0$  level against the energy difference between the  $^5\text{D}_0$  hole state and the VB-top. The fitted dashed line has a slope of  $421 \text{ K eV}^{-1}$ .



of the  $Tb^{3+}$  emission in these compounds often reveal a so-called intervalence charge transfer (IVCT) band attributed to the excitation of an electron from the  $Tb^{3+} 7F_6$  ground state<sup>43,44</sup> to the CB. Whereas the CT-band energy of  $Eu^{3+}$  provides the location of the  $Eu^{2+}$  ground state above the VB, the IVCT band provides the  $Tb^{3+}$  ground state below the CB. Therefore, the IVCT band energy determines the quenching energy barrier  $\Delta E$  and therewith the quenching temperature  $T_{50}$ . This was already demonstrated for  $Tb^{3+}$  in transition metal element based compounds in ref. 42. In ref. 14, compounds such as  $SnO_2$ ,  $Ga_2O_3$ ,  $Lu_2O_3$ , and  $GaN$  with low lying conduction bands were added to the collection.

IVCT bands are  $\approx 0.8$  eV broad and in many compounds they tend to overlap partly with the host excitation band. This introduces often larger errors in the derived value for the IVCT energy  $E^{IVCT}(Tb^{3+})$ . To improve accuracy, one may construct a VRBE diagram as shown in Fig. 3 that combines the spectroscopic data on many different lanthanides thus leading to more accurate  $\Delta E$  values. This method was followed in ref. 14 and 42 where VRBE diagrams were constructed using the 2012 chemical shift model.<sup>8</sup> We will adopt here the same method but now using the refined chemical shift model which provides few 0.1 eV different  $Tb^{4+/3+}$  CTL energies. The results are compiled in Table 3 and are shown in Fig. 5. Other than for  $Eu^{3+}$ , there is no need to correct for bandgap lowering with the increase of temperature because we assume that the  $Tb^{3+}$  levels move down with the same pace as the downward movement of the CB-bottom.

When assuming that the energy  $E^{IVCT}$  at the maximum of the IVCT band locates the  $Tb^{3+}$  ground state below the CB-bottom, one obtains for  $\Delta E$

$$\Delta E = E^{IVCT}(Tb^{3+}) - E(^5D_4) \quad (6)$$

where  $E(^5D_4) = 2.55$  eV is the energy of the  $^5D_4$  level above the ground state and the values on  $E^{IVCT}(Tb^{3+})$  can be found in ref. 62.

**Table 3**  $T_{50}$  data for emission from the  $^5D_4$  level of  $Tb^{3+}$  in compounds against the energy difference  $\Delta E$  between the  $^5D_4$  level and the CB-bottom. The parameters used for the VRBE-diagram construction are provided. All energies are in eV

A	U	$E^{CT}$	$E_V$	$E^{ex}$	$E_C$	$\Delta E$	$T_{50}$	Ref.
$SnO_2$	7.00	3.85	-7.92	3.59	-4.23	0.79	190	45
$CaSnO_3$	6.80	4.37	-8.34	4.93	-3.21	1.55	420	46
$\beta\text{-Ga}_2O_3$	6.90	4.28	-8.40	5.05	-3.15	1.80	385	47
$CaMoO_4$	7.00	4.40	-8.47	4.60	-3.70	1.32	450	48
$KLa(MoO_4)_2$	7.05	4.20	-8.29	4.60	-3.52	1.56	455	49
$KY(WO_4)_2$	7.15	4.60	-8.74	4.55	-4.03	1.18	410	50
$KLu(WO_4)_2$	7.15	4.55	-8.69	4.50	-4.03	1.18	325	51
$LaVO_4$	6.80	3.95	-7.92	4.25	-3.53	1.24	230	52
$GdVO_4$	6.84	4.05	-8.04	4.00	-3.91	0.90	140	53
$LuVO_4$	6.80	4.06	-8.03	3.85	-4.06	0.70	80	53
$LiNbO_3$	6.87	4.47	-8.47	4.62	-3.68	1.17	200	54,55
$CaNb_2O_6$	6.85	4.10	-8.10	4.75	-3.16	1.66	490	56
$YNbO_4$	6.84	4.60	-8.59	4.96	-3.43	1.38	455	56
$LiTaO_3$	6.65	4.54	-8.44	5.50	-2.70	1.87	585	55
$M'YTbO_4$	6.78	5.10	-9.06	5.95	-2.83	1.91	750	57
$C-Lu_2O_3:(C_2)$	6.60	4.81	-8.69	5.90	-2.51	2.00	525	58
$Ga_{0.7}Al_{0.3}N$	6.40	3.22	-7.01	4.05	-2.83	1.44	250	59
$GaN\text{-wurtzite}$	6.40	3.25	-7.03	3.48	-3.45	0.81	30	59-61



**Fig. 5**  $T_{50}$  data for emission from the  $^5D_4$  level of  $Tb^{3+}$  in compounds against the energy difference  $\Delta E$  between the  $^5D_4$  level and the CB-bottom.

When the quenching energy barrier is derived from the VRBE diagram construction one obtains for  $\Delta E$

$$\Delta E = [E^{ex} + 0.008(E^{ex})^2] - [E^{CT} - U + \Delta E(Eu, Tb) + E(^5D_4)] \quad (7)$$

where the first term between square brackets is the energy of the CB-bottom with respect to the VB-top and the second term of the  $^5D_4$  state with respect to the VB-top where  $\Delta E(Eu, Tb) \approx 3.5$  eV is the slightly compound dependent energy difference between the  $Eu^{3+}$  and  $Tb^{3+}$  ground state energies. The energy  $E^{CT}$  is not necessarily experimentally determined from the energy of the  $Eu^{3+}$  CT-band. It is often deduced from the constructed VRBE schemes that can be based, e.g., on CT-bands other than that of  $Eu^{3+}$ , experimental IVCT energies, or photoelectron spectroscopy data.

The dashed line in Fig. 5 is from a linear least squares fit through the data and has a slope of  $407 \text{ K eV}^{-1}$ . This is somewhat smaller than the value of  $475 \text{ K eV}^{-1}$  predicted in Table 1. Nevertheless, a clear correspondence between the quenching temperature and the energy at the CB-bottom is evident. The situation and figure much resemble that of hole ionization in the case of  $Eu^{3+}$  as shown in Fig. 4. The similar lifetimes of 1–2 ms for  $Eu^{3+}$  and  $Tb^{3+}$  emissions result in similar slopes in the linear fits. Also, the intersection with the horizontal axis for both dopants occurs near 0.5 eV.

Note that the  $^5D_3$  level of  $Tb^{3+}$  is located 0.7 eV above the  $^5D_4$  level and therefore located 0.7 eV closer to the CB-bottom. Since the  $^5D_3$  and  $^5D_4$  lifetimes differ not too much (factor of 2), one may expect about 350 K lower thermal stability of the  $^5D_3$  emission. Indeed, the difference amounts 375 K for  $CaMoO_4$ <sup>63</sup> and 370 K for  $CaNb_2O_6$ .<sup>56</sup> Furthermore, whenever  $T_{50}(^5D_4) < 300$  K, the emission from  $^4D_3$  is absent even down to 4 K. This can be verified with the data compiled in ref. 42.

### C. Thermal quenching of the $Pr^{3+} 3P_0$ emission

The  $Pr^{4+/3+}$  CTL is near the same energy as that for  $Tb^{4+/3+}$ . Also, the emitting  $3P_0$  level of  $Pr^{3+}$  is near the same VRBE as that for



the  $^5D_4$  level of  $Tb^{3+}$  as can be seen in the scheme for  $YPO_4$  in Fig. 3. This means that like for  $Tb^{3+}$  thermal quenching may proceed by electron ionization to the CB in compounds with the low lying CB-bottom. Other than  $Tb^{3+}$  and  $Eu^{3+}$ , the next lower excited state ( $^1D_2$ ) is only at  $\Delta E_{mp} = 0.5$  eV lower energy. At a sufficiently high temperature, the multi-phonon relaxation to  $^1D_2$  then becomes also a possible quenching route. The radiative lifetime of the  $^3P_0$  state is usually between 10 and 50  $\mu s$  and is therefore shorter than those of  $Eu^{3+}$  and  $Tb^{3+}$ . This translates to a steeper  $T_{50}/\Delta E = 560$  K  $eV^{-1}$  slope as shown in Table 1. In ref. 42, a relationship between  $T_{50}$  of the  $^3P_0$  emission and the energy of the IVCT band, or equivalently the energy distance from the CB-bottom, was already demonstrated. Since then, more data have become available. Here, we have re-analyzed everything with the refined chemical shift model. The results are shown in Fig. 6 and compiled in Table 4.

For the quenching energy barrier, we used the same method as for  $Tb^{3+}$ . When assuming that the energy  $E^{IVCT}(Pr^{3+})$  at the maximum of the IVCT band locates the  $Pr^{3+}$  ground state below the CB-bottom one obtains for  $\Delta E$

$$\Delta E = E^{IVCT}(Pr^{3+}) - E(^3P_0) \quad (8)$$

where  $E(^3P_0) = 2.55$  eV is the energy of the  $^3P_0$  level above the ground state and the values on  $E^{IVCT}(Pr^{3+})$  can be found in ref. 62.

When the quenching energy barrier is derived from the VRBE construction one obtains for  $\Delta E$

$$\Delta E = [E^{ex} + 0.008(E^{ex})^2] - [E^{CT} - U + \Delta E(Eu, Pr) + E(^3P_0)] \quad (9)$$

where  $\Delta E(Eu, Pr) \approx 3.49$  eV is the energy difference between the  $Eu^{3+}$  and  $Pr^{3+}$  ground state energies.

The dashed line drawn through the data has a slope of 560 K  $eV^{-1}$  as predicted from Table 1. It crosses the horizontal axis near 0.3 eV which compares with that for  $Tb^{3+}$  and  $Eu^{3+}$



Fig. 6  $T_{50}$  data for the emission from the  $^3P_0$  level of  $Pr^{3+}$  in compounds against the energy difference  $\Delta E$  between the  $^3P_0$  level and the conduction band bottom.

Table 4  $T_{50}$  data for emission from the  $^3P_0$  level of  $Pr^{3+}$  in compounds against the energy difference between the  $^3P_0$  level and the CB-bottom. The parameters used for the VRBE-diagram construction are provided. All energies are in eV

A	$U$	$E^{CT}$	$E_V$	$E^{ex}$	$E_C$	$\Delta E$	$T_{50}$	Ref.
BiOCl	6.70	3.55	-7.47	4.00	-3.34	1.12	525	64
SrSnO <sub>3</sub>	6.96	4.00	-8.05	4.70	-3.17	1.69	390	65
CaSnO <sub>3</sub>	6.80	4.37	-8.34	4.93	-3.21	1.40	490	65
Ca <sub>2</sub> SnO <sub>4</sub>	6.85	4.43	-8.42	5.05	-3.17	1.52	550	65
SrMoO <sub>4</sub>	7.05	4.25	-8.34	4.75	-3.41	1.59	≈ 370	66
CaMoO <sub>4</sub>	7.00	4.40	-8.47	4.60	-3.70	1.23	440	67
LaVO <sub>4</sub>	6.80	3.95	-7.92	4.25	-3.53	1.09	450	44
GdVO <sub>4</sub>	6.84	4.05	-8.04	4.00	-3.91	0.76	220	53
LuVO <sub>4</sub>	6.80	4.06	-8.03	3.85	-4.06	0.55	120	53
CaNb <sub>2</sub> O <sub>6</sub>	6.85	4.10	-8.10	4.75	-3.16	1.53	380	56
YNbO <sub>4</sub>	6.84	4.60	-8.59	4.96	-3.43	1.24	370	56
LuNbO <sub>4</sub>	6.85	4.58	-8.58	5.00	-3.38	1.32	400	68
SrTiO <sub>3</sub>	6.75	3.44	-7.39	3.46	-3.83	0.71	≈ 300	69,70
CaTiO <sub>3</sub>	6.75	3.84	-7.79	3.85	-3.82	0.72	≈ 100	69,70
Na <sub>2</sub> La <sub>2</sub> Ti <sub>3</sub> O <sub>10</sub>	6.75	3.70	-7.65	4.00	-3.52	1.02	375	71
MgLa <sub>2</sub> TiO <sub>6</sub>	6.68	3.88	-7.79	4.50	-3.13	1.30	350	72
CaZnOS	6.35	3.73	-7.49	4.51	-2.82	1.11	380	73
Gd <sub>2</sub> O <sub>2</sub> S	6.37	3.72	-7.49	4.83	-2.47	1.49	460	74
GaN-wurtzite	6.40	3.25	-7.03	3.48	-3.45	0.55	250	75,76

where the crossing was near 0.5 eV. The data seem initially to follow this slope, but when  $T_{50}$  approaches 400 K many data points start to level off. The mentioned multi-phonon relaxation to the  $^1D_0$  level may be responsible for this. A detailed analysis for each compound would be required to resolve this further. It is interesting to compare the results for the sequence of compounds  $LaVO_4$ ,  $GdVO_4$ , and  $LuVO_4$  where the bottom of the CB-band is formed by the lowest 3d-orbitals of  $V^{4+}$ .<sup>42</sup> In this sequence, this CB-bottom lowers by about 0.5 eV, see column 6 in Tables 3 and 4. For both the  $Tb^{3+}$   $^5D_4$  emission and the  $Pr^{3+}$   $^3P_0$  emission, this leads to increasingly lower  $T_{50}$  as seen in Fig. 5 and 6.

The  $^1G_4$  level of  $Pr^{3+}$  is  $\Delta E_{mp} = 0.86$  eV below the  $^1D_2$  level which makes multi-phonon relaxation from  $^1D_2$  less probable than that from the  $^3P_0$  level. The quenching of the  $^1D_2$  emission may again proceed *via* the CB. Although the lifetime of the  $^1D_2$  level is about 10 times longer than that of  $^3P_0$  its 0.5 eV further distance below the CB is more important leading to the significantly higher thermal stability of the  $^1D_2$  emission. The difference in  $T_{50}$  for  $CaNb_2O_6$ ,<sup>56</sup>  $LuNbO_4$ ,<sup>68</sup> and  $MgLa_2TiO_6$ <sup>72</sup> appears about 200 K in line with the expectation.

#### D. Thermal quenching of the $Eu^{2+}$ $4f^6$ $5d-4f^7$ emission

Techniques such as photoconductivity, excited state absorption, delayed fluorescence, and thermoluminescence charging studies have evidenced that the quenching of the  $Eu^{2+}$  emission proceeds often, if not always, by means of the thermal ionization of the 5d electron to the CB. The consistency between quenching *via* the CB and  $Eu^{2+}$  level locations with respect to the CB-bottom was demonstrated in ref. 77. The same was concluded from first principles studies on fifteen representative  $Eu^{2+}$ -doped phosphors by Jia *et al.*<sup>78</sup>

The nature of the  $5d-4f$  emission is much different from that of the  $4f^n-4f^n$  emission. The transition is dipole allowed



**Table 5**  $T_{50}$  data for the  $\text{Eu}^{2+}$  5d–4f emission in compounds (A) against the energy difference between the lowest energy of the relaxed 4f<sup>6</sup> 5d level and the CB-bottom. The parameters used for the VRBE-diagram construction are provided. All energies are in eV

A	$U$	$E^{\text{CT}}$	$E_{\text{V}}$	$E^{\text{ex}}$	$E_{\text{C}}$	$E_{\text{fd}}$	$\Delta S$	$\Delta E$	$T_{50}$	Ref.
RbCl <sup>a</sup>	6.70	4.20	−8.12	7.54	−0.13	3.19	0.21	1.01	670	83
KCl <sup>a</sup>	6.70	4.23	−8.15	7.79	0.12	3.10	0.17	1.16	770	83
NaCl <sup>a</sup>	6.70	4.48	−8.40	7.96	0.06	3.02	0.12	1.15	850	83
RbBr <sup>a</sup>	6.60	3.10	−6.98	6.64	0.02	3.16	0.17	1.02	690	83
KBr <sup>a</sup>	6.60	3.53	−7.41	6.80	−0.24	3.14	0.22	1.14	717	83
NaBr <sup>a</sup>	6.60	3.40	−7.28	6.75	−0.16	3.02	0.13	0.96	740	83
CsI <sup>a</sup>	6.25	2.60	−6.31	5.80	−0.24	2.97	0.19	0.50	220	84
KI <sup>a</sup>	6.25	3.00	−6.71	5.88	−0.56	3.07	0.20	0.99	450	85
Ba <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> Cl	6.89	4.40	−8.41	7.30	−0.69	3.05	0.20	0.37	510	86,87
Sr <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> Cl	6.90	4.66	−8.68	7.50	−0.73	2.92	0.15	0.45	460	88
Ca <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> Cl	6.88	5.04	−9.05	7.70	−0.88	2.97	0.24	0.28	480	87,89
Ca <sub>2</sub> BO <sub>3</sub> Cl	6.77	4.49	−8.45	7.15	−0.89	2.68	0.43	0.60	450	90
Ca <sub>8</sub> Mg(SiO <sub>4</sub> ) <sub>4</sub> Cl <sub>2</sub>	6.60	4.47	−8.35	6.95	−1.01	2.61	0.16	0.34	425	91
α-Sr <sub>2</sub> P <sub>2</sub> O <sub>7</sub>	7.13	4.68	−8.81	7.85	−0.47	3.12	0.16	0.62	470	92
LiSrPO <sub>4</sub>	7.05	4.77	−8.86	7.75	−0.63	2.95	0.20	0.61	450	93
Ca <sub>10</sub> K(PO <sub>4</sub> ) <sub>7</sub>	7.05	5.06	−9.15	8.00	−0.64	2.95	0.27	0.64	450	94
NaCaPO <sub>4</sub>	7.07	4.77	−8.87	7.75	−0.64	2.77	0.31	0.85	600	95,96
YPO <sub>4</sub>	7.09	5.65	−9.77	8.55	−0.63	2.94	0.04	0.57	230	97
LuPO <sub>4</sub>	7.08	5.74	−9.85	8.70	−0.55	2.94	0.05	0.65	230	97
BaB <sub>8</sub> O <sub>13</sub>	7.30	5.15	−9.38	8.15	−0.69	3.35	0.24	0.30	500	98,99
SrB <sub>6</sub> O <sub>10</sub>	7.31	5.49	−9.71	8.30	−0.86	3.35	0.15	0.08	300	100
Ba <sub>2</sub> Ca(BO <sub>3</sub> ) <sub>2</sub>	6.93	4.61	−8.64	6.90	−1.36	2.79	0.38	0.07	190	101
NaBa <sub>4</sub> (BO <sub>3</sub> ) <sub>3</sub>	6.84	4.58	−8.57	7.00	−1.18	2.64	0.35	0.35	280	102
NaSr <sub>4</sub> (BO <sub>3</sub> ) <sub>3</sub>	6.85	4.65	−8.64	7.20	−1.03	2.67	0.69	0.64	370	102
BaBPO <sub>5</sub>	7.24	4.81	−9.00	8.53	0.12	3.42	0.16	0.97	565	103
SrBPO <sub>5</sub>	7.22	4.96	−9.14	8.53	−0.03	3.49	0.29	0.80	450	103
α-CaAl <sub>2</sub> B <sub>2</sub> O <sub>7</sub>	7.03	4.96	−9.04	7.30	−1.32	3.06	0.18	−0.21	60	104
CaBPO <sub>5</sub>	7.22	5.06	−9.24	8.55	−0.11	3.31	0.23	0.88	265	103
α-SrSiO <sub>3</sub>	6.63	5.04	−8.93	7.70	−0.76	3.02	0.21	0.21	130	105
CaMgSi <sub>2</sub> O <sub>6</sub>	7.03	5.10	−9.18	7.95	−0.73	2.97	0.20	0.49	390	106
Ba <sub>2</sub> MgSi <sub>2</sub> O <sub>7</sub>	6.95	4.34	−8.38	7.00	−0.99	2.84	0.37	0.40	460	107,108
Sr <sub>2</sub> MgSi <sub>2</sub> O <sub>7</sub>	7.03	4.75	−8.83	7.29	−1.12	2.82	0.19	0.24	250	109,110
BaCa <sub>2</sub> Mg(SiO <sub>4</sub> ) <sub>2</sub>	6.90	4.20	−8.22	7.85	0.12	3.31	0.42	1.05	530	111,112
Ba <sub>2</sub> SiO <sub>4</sub>	6.87	4.35	−8.36	7.05	−0.91	2.70	0.24	0.52	420	113–115
Sr <sub>3</sub> Mg(SiO <sub>4</sub> ) <sub>2</sub>	6.91	4.54	−8.57	7.45	−0.67	3.02	0.32	0.49	515	116
Sr <sub>2</sub> SiO <sub>4</sub>	6.81	4.64	−8.61	7.20	−1.00	3.19	0.55	0.07	425	117
Li <sub>2</sub> SrSiO <sub>4</sub>	6.91	4.81	−8.83	7.12	−1.30	2.43	0.26	0.42	525	118
CaAl <sub>2</sub> (SiO <sub>4</sub> ) <sub>2</sub>	6.95	4.44	−8.48	7.50	−0.53	3.08	0.19	0.53	480	119
Ca <sub>3</sub> Mg(SiO <sub>4</sub> ) <sub>2</sub>	6.86	4.96	−8.96	7.60	−0.90	3.02	0.41	0.28	435	116,120
β-Ca <sub>2</sub> SiO <sub>4</sub>	6.80	4.77	−8.74	7.25	−1.07	2.86	0.41	0.24	390	107
Li <sub>2</sub> CaSiO <sub>4</sub>	6.92	4.77	−8.80	7.55	−0.79	2.73	0.14	0.58	450	121
Sr <sub>3</sub> SiO <sub>5</sub>	6.74	4.07	−8.01	6.50	−1.17	2.43	0.29	0.48	485	122
BaAl <sub>2</sub> O <sub>4</sub>	6.82	4.63	−8.61	7.20	−1.00	2.92	0.44	0.29	270	123,124
Sr <sub>2</sub> Al(AlSiO <sub>7</sub> )	6.82	4.79	−8.77	7.50	−0.82	2.88	0.23	0.39	300	125
SrAl <sub>12</sub> O <sub>19</sub>	7.06	4.75	−8.85	8.00	−0.33	3.54	0.43	0.43	375	126
SrAl <sub>4</sub> O <sub>7</sub>	6.89	5.02	−9.03	8.00	−0.52	3.10	0.47	0.63	260	126
SrAl <sub>2</sub> O <sub>4</sub> :(site 2)	6.80	4.55	−8.52	6.85	−1.30	3.06	0.28	−0.25	210	127,128
SrAl <sub>2</sub> O <sub>4</sub> :(site 3)	6.80	4.19	−8.16	6.85	−0.94	2.76	0.37	0.46	420	127,128
Sr <sub>4</sub> Al <sub>14</sub> O <sub>25</sub> :[HE-site]	7.10	4.77	−8.89	7.70	−0.72	3.49	0.44	0.13	400	129
Sr <sub>4</sub> Al <sub>14</sub> O <sub>25</sub> :[LE-site]	6.85	4.77	−8.77	7.70	−0.59	2.82	0.30	0.73	380	129
Ca <sub>2</sub> Al(AlSiO <sub>7</sub> )	6.83	4.98	−8.97	7.60	−0.90	2.58	0.24	0.62	340	130,131
CaAl <sub>2</sub> O <sub>4</sub>	6.80	4.73	−8.70	7.40	−0.86	3.14	0.32	0.13	320	132,133
CaO	6.31	4.88	−8.62	6.94	−1.30	1.89	0.21	0.66	250	134
Ca <sub>2</sub> SiS <sub>4</sub>	6.40	2.06	−5.84	5.00	−0.64	2.38	0.18	0.85	445	135
SrGa <sub>2</sub> S <sub>4</sub>	6.30	1.87	−5.61	4.77	−0.65	2.55	0.23	0.65	470	136,137
CaGa <sub>2</sub> S <sub>4</sub>	6.25	1.90	−5.61	4.52	−0.93	2.36	0.14	0.49	450	138
CaS	6.17	2.35	−6.03	4.70	−1.15	2.07	0.16	0.54	475	139
SrSi <sub>2</sub> O <sub>2</sub> N <sub>2</sub>	6.70	3.44	−7.36	6.35	−0.69	2.51	0.21	0.83	600	81
SrSi <sub>2</sub> AlO <sub>2</sub> N <sub>3</sub>	6.60	2.97	−6.85	5.60	−0.99	2.73	0.23	0.27	450	140
CaSi <sub>2</sub> O <sub>2</sub> N <sub>2</sub>	6.70	3.10	−7.02	6.30	−0.41	2.56	0.33	1.13	455	81
Sr <sub>2</sub> Si <sub>5</sub> N <sub>8</sub>	6.33	2.56	−6.31	5.00	−1.11	2.19	0.18	0.53	550	141
Ca <sub>2</sub> Si <sub>5</sub> N <sub>8</sub>	6.35	2.93	−6.69	5.15	−1.33	2.27	0.21	0.26	370	142
CaAlSiN <sub>3</sub>	6.22	2.64	−6.34	5.05	−1.09	2.14	0.23	0.59	640	143,144
SrMg <sub>2</sub> Al <sub>2</sub> N <sub>4</sub>	6.15	2.21	−5.88	4.10	−1.64	2.13	0.12	−0.05	290	145

<sup>a</sup> For the alkaline halides, the spectroscopic data on  $E^{\text{CT}}$  are not available. The values listed are the energy differences between the  $\text{Eu}^{3+/2+}$  CTLs and  $E_{\text{V}}$  that was obtained directly from the published photoelectron spectroscopy data.





**Table 6**  $T_{50}$  data for the  $Ce^{3+} 5d-4f$  emission in compounds (A) against the energy difference between the lowest energy of the relaxed 5d level and the CB-bottom. The parameters used for the VRBE-diagram construction are provided. All energies are in eV

A	$U$	$E^{CT}$	$E_V$	$E^{ex}$	$E_C$	$E_{fd}$	$\Delta S$	$\Delta E$	$T_{50}$	Ref.
BaF <sub>2</sub>	7.38	7.67	-11.9	10.10	-1.02	4.25	0.19	1.01	400	146-148
SrF <sub>2</sub>	7.32	7.90	-12.1	10.60	-0.64	4.17	0.15	1.36	490	146
CaF <sub>2</sub>	7.31	8.21	-12.4	11.10	-0.35	4.04	0.09	1.73	620	11
LaF <sub>3</sub>	7.51	7.43	-11.8	10.45	-0.44	4.98	0.64	1.29	450	11
LiYF <sub>4</sub>	7.52	8.09	-12.4	11.00	-0.46	4.32	0.19	1.72	1025	11
LaBr <sub>3</sub>	6.60	2.00	-5.87	5.40	-0.24	4.07	0.54	0.94	750	149
YI <sub>3</sub>	6.29	1.48	-5.21	4.45	-0.60	3.07	0.60	1.14	650	150
Sr <sub>3</sub> (Al <sub>2</sub> O <sub>5</sub> )Cl <sub>2</sub>	6.77	4.51	-8.47	6.70	-1.41	3.70	0.75	0.51	525	151
LaOBr	6.58	4.11	-7.98	6.25	-1.41	3.47	0.43	0.28	300	152,153
GdOBr	6.56	4.24	-8.10	6.40	-1.37	3.34	0.26	0.34	450	153
LaP <sub>3</sub> O <sub>9</sub>	7.26	5.84	-10.0	8.45	-1.02	4.28	0.21	0.80	690	154
LiYP <sub>4</sub> O <sub>12</sub>	7.26	6.17	-10.4	8.63	-1.15	4.19	0.21	0.77	700	155
YPO <sub>4</sub>	7.09	5.65	-9.77	8.55	-0.63	3.85	0.13	1.32	725	156
Ca <sub>9</sub> Y(PO <sub>4</sub> ) <sub>7</sub>	7.08	4.86	-8.97	7.40	-1.13	4.31	0.68	0.62	600	157
Ba <sub>2</sub> Ca(BO <sub>3</sub> ) <sub>2</sub>	6.90	4.61	-8.63	6.90	-1.35	3.14	0.49	1.20	550	158
LiSr <sub>4</sub> (BO <sub>3</sub> ) <sub>3</sub>	6.89	4.66	-8.67	7.04	-1.24	3.73	0.75	0.82	525	159
Li <sub>6</sub> Gd(BO <sub>3</sub> ) <sub>3</sub>	6.98	4.88	-8.94	7.10	-1.44	3.59	0.36	0.71	310	160,161
Li <sub>6</sub> Y(BO <sub>3</sub> ) <sub>3</sub>	6.98	4.98	-9.04	7.20	-1.42	3.58	0.39	0.75	440	162
La <sub>2</sub> Si <sub>2</sub> O <sub>7</sub>	6.95	5.54	-9.58	7.45	-1.69	3.79	0.29	0.18	625	163
Gd <sub>2</sub> Si <sub>2</sub> O <sub>7</sub>	6.64	4.92	-8.81	7.20	-1.20	3.53	0.38	0.50	520	164,165
Lu <sub>2</sub> Si <sub>2</sub> O <sub>7</sub>	7.01	5.50	-9.57	7.30	-1.85	3.54	0.29	0.36	500	166-168
CaAl <sub>2</sub> (SiO <sub>4</sub> ) <sub>2</sub>	6.95	4.44	-8.48	7.50	-0.53	4.22	0.43	0.98	635	169
LiYSiO <sub>4</sub>	6.89	5.51	-9.52	7.55	-1.52	3.55	0.44	0.57	600	170
Ca <sub>3</sub> Sc <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>	6.85	5.15	-9.14	7.20	-1.53	2.77	0.34	1.24	1150	171,172
LaBO(SiO <sub>4</sub> )	7.03	4.84	-8.92	7.80	-0.64	4.34	0.46	0.90	600	173
La <sub>5</sub> (SiO <sub>4</sub> ) <sub>2</sub> BO <sub>4</sub> O	6.84	4.38	-8.37	6.70	-1.31	3.57	0.59	0.76	395	174
X1-Gd <sub>2</sub> SiO <sub>5</sub> :(Ce1)	6.85	4.90	-8.90	6.80	-1.73	3.61	0.70	0.37	350	175,176
X1-Gd <sub>2</sub> SiO <sub>5</sub> :(Ce2)	6.85	4.90	-8.90	6.80	-1.73	3.32	0.69	0.67	250	175,176
X2-Y <sub>2</sub> SiO <sub>5</sub> :(Ce1)	6.86	4.80	-8.80	6.82	-1.61	3.45	0.31	0.47	440	177,178
X2-Y <sub>2</sub> SiO <sub>5</sub> :(Ce2)	6.80	4.81	-8.78	6.82	-1.59	3.25	0.67	0.78	410	178
X2-Lu <sub>2</sub> SiO <sub>5</sub> :(Ce1)	6.83	5.15	-9.14	6.85	-1.91	3.46	0.31	0.11	350	178,179
X2-Lu <sub>2</sub> SiO <sub>5</sub> :(Ce2)	6.83	5.15	-9.14	6.85	-1.91	3.36	0.68	0.40	290	178,179
Sr <sub>3</sub> Y <sub>2</sub> Ge <sub>3</sub> O <sub>12</sub>	6.85	4.43	-8.43	5.96	-2.18	2.86	0.38	0.51	300	172,180
Ca <sub>3</sub> Y <sub>2</sub> Ge <sub>3</sub> O <sub>12</sub>	6.85	4.77	-8.77	6.20	-2.26	2.92	0.36	0.37	265	180
Mg <sub>3</sub> Y <sub>2</sub> Ge <sub>3</sub> O <sub>12</sub>	6.90	4.70	-8.72	6.00	-2.43	2.59	0.40	0.61	300	181
Sr <sub>2</sub> Al(AlSiO <sub>7</sub> )	6.82	4.79	-8.77	7.50	-0.82	3.69	0.25	0.94	500	182
Ca <sub>2</sub> Al(AlSiO <sub>7</sub> )	6.83	4.98	-8.97	7.60	-0.90	3.48	0.30	1.09	570	182
Gd <sub>3</sub> Al <sub>5</sub> O <sub>12</sub>	6.84	5.39	-9.38	6.55	-2.49	2.64	0.42	0.43	400	183,184
GdAlO <sub>3</sub>	6.75	4.75	-8.70	7.36	-0.90	4.09	0.37	0.41	345	185
Y <sub>4</sub> Al <sub>2</sub> O <sub>9</sub>	6.75	5.19	-9.13	6.45	-2.35	3.18	0.35	-0.14	60	186
Y <sub>3</sub> Al <sub>5</sub> O <sub>12</sub>	6.77	5.23	-9.19	7.10	-1.69	2.71	0.33	1.01	645	11,187,188
Y <sub>3</sub> Sc <sub>2</sub> Al <sub>3</sub> O <sub>12</sub>	6.56	5.28	-9.14	6.90	-1.86	2.86	0.48	0.44	530	189
YAlO <sub>3</sub>	6.81	5.06	-9.04	8.00	-0.52	4.09	0.54	0.96	660	11,190
LuAlO <sub>3</sub>	6.83	5.30	-9.29	8.35	-0.38	4.03	0.51	1.18	850	190
Ca <sub>2</sub> Ga(GaSiO <sub>7</sub> )	6.95	4.48	-8.52	5.85	-2.40	3.54	0.49	-0.18	450	191
Gd <sub>3</sub> Ga <sub>1</sub> Al <sub>4</sub> O <sub>12</sub>	6.84	5.37	-9.36	6.50	-2.52	2.75	0.45	0.30	405	192,193
Gd <sub>3</sub> Ga <sub>2</sub> Al <sub>3</sub> O <sub>12</sub>	6.86	5.28	-9.28	6.36	-2.59	2.81	0.47	0.21	405	192,193
Gd <sub>3</sub> Ga <sub>3</sub> Al <sub>2</sub> O <sub>12</sub>	6.86	5.21	-9.21	6.29	-2.60	2.81	0.48	0.20	310	183,194,195
Gd <sub>3</sub> Ga <sub>4</sub> Al <sub>1</sub> O <sub>12</sub>	6.88	5.00	-9.01	6.07	-2.65	2.88	0.49	0.12	150	193
Y <sub>3</sub> Al <sub>4</sub> GaO <sub>12</sub>	6.77	5.21	-9.17	7.10	-1.66	2.78	0.36	0.98	605	192,196
Y <sub>3</sub> Al <sub>3</sub> Ga <sub>2</sub> O <sub>12</sub>	6.77	5.23	-9.19	6.93	-1.87	2.83	0.32	0.70	525	192,196
Y <sub>3</sub> Al <sub>2</sub> Ga <sub>3</sub> O <sub>12</sub>	6.77	5.19	-9.14	6.52	-2.28	2.85	0.39	0.30	380	192,196
Y <sub>3</sub> AlGa <sub>4</sub> O <sub>12</sub>	6.80	5.12	-9.09	6.44	-2.32	2.93	0.45	0.26	275	192,196
Y <sub>3</sub> Ga <sub>5</sub> O <sub>12</sub>	6.85	5.05	-9.05	6.10	-2.65	2.90	0.35	-0.01	100	197,198
SrHfO <sub>3</sub>	6.62	4.40	-8.28	6.35	-1.61	4.07	0.84	-0.25	285	199
CaHfO <sub>3</sub>	6.64	4.51	-8.40	6.95	-1.07	3.71	0.77	0.65	360	200
LaLuO <sub>3</sub>	6.58	4.25	-8.11	6.35	-1.44	3.71	0.99	0.29	339	200
LaScO <sub>3</sub>	6.66	4.20	-8.10	6.20	-1.60	3.85	0.80	0.03	255	200
La <sub>2</sub> Be <sub>2</sub> O <sub>5</sub>	6.70	4.11	-8.03	6.28	-1.44	3.64	0.85	0.49	360	32
GdScO <sub>3</sub>	6.70	4.73	-8.65	6.10	-2.25	3.59	0.74	-0.34	232	200
CaSc <sub>2</sub> O <sub>4</sub>	6.65	4.35	-8.25	6.35	-1.58	2.76	0.32	0.88	530	201,202
Y <sub>2</sub> O <sub>2</sub> S	6.37	3.76	-7.53	4.85	-2.49	2.68	0.65	-0.21	63	203
CaGa <sub>2</sub> S <sub>4</sub>	6.25	1.90	-5.61	4.52	-0.93	2.92	0.26	0.74	575	204
LaSiO <sub>2</sub> N	6.65	3.43	-7.33	5.65	-1.42	3.50	0.32	0.29	275	205
SrAlSi <sub>4</sub> N <sub>7</sub>	6.40	2.88	-6.66	5.05	-1.41	2.80	0.42	0.69	525	206
La <sub>3</sub> Si <sub>6</sub> N <sub>11</sub>	6.50	3.04	-6.87	4.60	-2.10	2.72	0.36	0.19	525	207
LaSi <sub>3</sub> N <sub>5</sub>	6.48	2.58	-6.40	4.85	-1.36	3.56	0.55	0.15	550	208



typical for almost all compounds, and such an energy difference will imply a higher quenching temperature  $T_{50}$  for Ce. The lifetime of the  $\text{Ce}^{3+}$  5d–4f emission varies between 15 ns and 65 ns<sup>79</sup> which is about 25 times shorter than that of  $\text{Eu}^{2+}$ . This leads to the  $T_{50}/\Delta E = 850 \text{ K eV}^{-1}$  rate in Table 1.

For the study of the quenching of the  $\text{Ce}^{3+}$  5d–4f emission, the same method as for the quenching of the  $\text{Eu}^{2+}$  emission was adopted, and the used expression for  $\Delta E$  is

$$\Delta E = [E^{\text{ex}} + 0.008(E^{\text{ex}})^2] - [E^{\text{CT}} - U + \Delta E(\text{Eu, Ce}) + E_{\text{fd}}^{\text{Ce}} - 0.5\Delta S] \quad (11)$$

where  $E_{\text{fd}}$  are compiled in Table 6, and where  $\Delta E(\text{Eu, Pr}) \approx 5.52 \text{ eV}$  is the energy difference between the  $\text{Eu}^{3+}$  and  $\text{Ce}^{3+}$  ground state energies.

For  $\text{Eu}^{2+}$ , the used value for the parameter  $U$  was not of relevance for obtaining the quenching energy barrier. However, for  $\text{Ce}^{3+}$ , it will be and this adds additional uncertainty to  $\Delta E$  as derived from the VRBE scheme. The  $T_{50}$  values with references and the parameters used in the VRBE construction are compiled in Table 6.

The  $T_{50}$  and derived quenching energy barriers  $\Delta E$  are shown in Fig. 8. The data appear to scatter like those for  $\text{Eu}^{2+}$  obscuring a clear relationship between the quenching temperature  $T_{50}$  and the quenching energy barrier  $\Delta E$ . The dashed line with a slope of  $850 \text{ K eV}^{-1}$  is the predicted relationship shown in Table 1, whereas a linear fit provides only a slope of  $325 \text{ K eV}^{-1}$ . One might argue that for thermal quenching the electron need not to reach the CB-bottom but it may quench *via* CB-derived states that are still bonded to  $\text{Ce}^{4+}$ . The VRBE is then expected between  $E_X$  and  $E_C$  leading to a lowering of  $\Delta E$ . It will shift and move around the data points several 0.1 eV but the general picture remains the same.



Fig. 8  $T_{50}$  quenching data of the  $\text{Ce}^{3+}$  5d–4f emission against the energy difference  $\Delta E$  between the relaxed 5d-state and the CB-bottom. The typical error bars are shown. Data points for the sequence of compounds  $\text{Y}_3\text{Al}_{5-x}\text{Ga}_x\text{O}_{12}$  and  $\text{REAlO}_3$  (RE = La, Gd, Y, Lu) are connected by straight line segments.

When we deal with a sequence of similar type of compounds systematic errors will drop out yielding better correspondence with the  $850 \text{ K eV}^{-1}$  prediction. One such sequence is  $\text{BaF}_2$ ,  $\text{SrF}_2$ , and  $\text{CaF}_2$ , where for both  $\text{Eu}^{2+}$  and  $\text{Ce}^{3+}$  the quenching temperature increases in accordance with the VRBE prediction. Furthermore,  $\text{Ce}^{3+}$  quenches at about 210 K higher temperature as  $\text{Eu}^{2+}$  also in accordance with the VRBE schemes. However, the data are located at about 0.5 eV too high  $\Delta E$  values with respect to the data on other compounds. The reason is not known but it may indicate systematic errors in the VRBE-diagram construction. Another well-studied sequence is the  $\text{Ce}^{3+}$  doped  $\text{Y}_3\text{Al}_{5-x}\text{Ga}_x\text{O}_{12}$  and  $\text{Gd}_3\text{Al}_{5-x}\text{Ga}_x\text{O}_{12}$  garnet compounds. For the sequence  $x = 0, 1, 2, 3, 4$ , and 5, the data points for  $\text{Y}_3\text{Al}_{5-x}\text{Ga}_x\text{O}_{12}$  in Fig. 8 have been connected with straight line segments. These data appear to follow the steeper slope of  $850 \text{ K eV}^{-1}$  much better. The same applies for the sequence  $\text{REAlO}_3$  (RE = La, Gd, Y, and Lu).  $\text{Ce}^{3+}$  does not emit in  $\text{LaAlO}_3$  and we assumed a  $\Delta S = 0.4 \text{ eV}$  to place the data point in Fig. 8. For  $\text{LuAlO}_3$ , we assumed  $T_{50} \approx 850 \text{ K}$  based on the work of ref. 190. Note that in the review work by Ueda and Tanabe<sup>209</sup> on  $\text{Ce}^{3+}$  doped garnet compounds the quenching data followed a slope of  $620 \text{ K eV}^{-1}$ .

Like for  $\text{Eu}^{2+}$ , there is an entire class of materials with a low lying CB-bottom and then the emitting 5d-level of  $\text{Ce}^{3+}$  is above the CB-bottom. Emission is then not observed even down to 0 K. This applies to all compounds in Tables 3 and 4.

### III. Discussion

The common aspect of the luminescence quenching of all five lanthanides considered in this work is that it proceeds *via* charge carrier transfer to the CB or the VB, and the energy difference  $\Delta E$  between the emitting level and the host band is the most relevant parameter. In this work, this value is derived from the constructed VRBE schemes. Table 1 shows the predicted relationship between  $T_{50}$  and  $\Delta E$  where a typical value for the vibrational frequency and the luminescence lifetime was assumed. A compound to compound variation in these values is unavoidable, and this will lead to the data scatter around the predicted relationships. The data for  $\text{Eu}^{3+}$  in Fig. 4 follow the predicted slope of  $435 \text{ K eV}^{-1}$  surprisingly closely. The error in  $\Delta E$  is relatively small because only the error in  $E^{\text{CT}}$  provides a dominant contribution, see eqn (5). For  $\text{Tb}^{3+}$  and  $\text{Pr}^{3+}$  in Fig. 5 and Fig. 6,  $\Delta E$  is either based on the energy at the maximum of the IVCT band, see eqn (6) and (8), which usually overlaps partly with the host excitation band preventing accurate determination. The IVCT data together with the data from other lanthanides can also be used to construct VRBE schemes. Eqn (7) and (9) can then be used to determine  $\Delta E$ . For both methods, the error in  $\Delta E$  and the scatter in data appears larger than that for  $\text{Eu}^{3+}$ ; yet, the data show consistency with the predicted slopes of  $475 \text{ K eV}^{-1}$  and  $560 \text{ K eV}^{-1}$ . For  $\text{Pr}^{3+}$ , it was suggested that above 400 K multi-phonon relaxation to the lower lying  $^1\text{D}_2$  level becomes the dominant quenching route which then causes the data to deviate from the predicted trend.



Errors and resulting scatter of data become larger for the 5d–4f emitters  $\text{Eu}^{2+}$  and  $\text{Ce}^{3+}$  in Fig. 7 and 8. For  $\text{Eu}^{2+}$  errors in  $E^{\text{CT}}$ ,  $E^{\text{ex}}$ , and exciton binding energy, all add to the error in  $E_{\text{C}}$  and therewith  $\Delta E$ , see eqn (10) and (11). A standard random error of  $\pm 0.2\text{--}0.3$  eV is estimated. In addition, there may be a systematic error related to the entire method of the VRBE construction. Particularly, the assumption that the energy at the maximum of the  $\text{Eu}^{3+}$  charge transfer band is always equal to the energy difference between the VB-top and the  $\text{Eu}^{3+/2+}$  CTL might not apply for all compounds alike.<sup>41</sup> In a sense, the scatter of data provides insight into how accurate one can/should interpret the constructed VRBE schemes using the (refined) chemical shift model. Clearly, VRBE schemes are at this stage not accurate enough to predict the  $T_{50}$  values beforehand with a  $\pm 200$  K accuracy.

To derive  $\Delta E$  for  $\text{Ce}^{3+}$  requires in addition to  $E^{\text{CT}}$ ,  $E^{\text{ex}}$ , and exciton binding energy also the parameter  $U$  which is a further source of error. The five outlying data points for the fluorides  $\text{LaF}_3$ ,  $\text{LiYF}_4$ , and  $\text{Ba-Sr-CaF}_2$  in Fig. 8 may indicate either a systematic too large value for  $U$  or that  $E^{\text{CT}}$  systematically under-estimates the  $\text{Eu}^{3+/2+}$  CTL to the VB energy difference for fluoride compounds. Systematic errors are minimal when considering a series of similar compounds like the  $\text{Y}_3\text{Al}_{5-x}\text{Ga}_x\text{O}_{12}$  ( $x = 0, 1, 2, 3, 4, \text{ and } 5$ ) or the  $\text{LnAlO}_3$  ( $\text{Ln} = \text{La, Gd, Y, and Lu}$ ) family. In these cases, data follow better the predicted  $850 \text{ K eV}^{-1}$  relationship as shown in Fig. 8.

The Stokes shift  $\Delta S$  between the  $4f^7\text{--}4f^6$  transitions in  $\text{Eu}^{3+}$ ,  $\text{Tb}^{3+}$ , and  $\text{Pr}^{3+}$  is negligible. This is not the case for the 5d–4f transitions in  $\text{Eu}^{2+}$  and  $\text{Ce}^{3+}$  where it may amount 0.2 to above 1 eV.<sup>80,210</sup> One may then question how the Stokes shift will affect the value for  $\Delta E$ . In deriving  $\Delta E$ , we added the energy  $E_{\text{fd}}$  of the first 4f–5d excitation band to the  $\text{Eu}^{3+/2+}$  and  $\text{Ce}^{4+/3+}$  CTLs and subtracted  $0.5 \times \Delta S$ . Following the same argumentation as for the charge transfer quenching in  $\text{Eu}^{3+}$ ,  $\text{Tb}^{3+}$ , and  $\text{Pr}^{3+}$ , the 5d electron not necessarily needs to fully delocalize to the conduction band. Quenching may proceed *via* the lanthanide trapped exciton state where the electron VRBE will be somewhere between  $E_{\text{C}}$  and  $E_{\text{x}}$ . This phenomenon was used to interpret the 0.3–0.5 eV intercept of the drawn dashed lines with the horizontal for  $\text{Eu}^{3+}$ ,  $\text{Tb}^{3+}$ , and  $\text{Pr}^{3+}$  in Fig. 4–6. In Fig. 7 and 8 we observe the intercept near  $\Delta E \approx 0$  or even at negative values. The latter would mean that the emitting 5d-level is found inside the CB while still generating the 5d–4f emission which seems strange at least. This may indicate the limitations in the method of the VRBE construction using the chemical shift model. There may be, as noted earlier, a systematic error in the assumption that the maximum of the  $\text{Eu}^{3+}$  CT-band always defines the top of the valence band. For sure, the method of the VRBE construction does not deal with the effect of lattice relaxation. Both the Stokes shift in 4f–5d transitions and the lattice relaxation following charge transfer in the quenching phase will change level locations that can be very compound dependent. This is one of the most difficult aspects of luminescence that cannot be solved at this moment.

The difficulty in dealing with lattice relaxation and local effects can be demonstrated with the quenching of  $\text{Ce}^{3+}$

emission in oxysilicates  $\text{Gd}_2\text{SiO}_5$ ,  $\text{Y}_2\text{SiO}_5$ , and  $\text{Lu}_2\text{SiO}_5$ . There are two different lanthanide sites in these compounds where  $\text{Ce}^{3+}$  is emitting at different energies. The chemical shift model assumes that the  $U$ -value is the same for both sites resulting in the site independent energy of the  $\text{Ce}^{4+/3+}$  CTL. The site with the highest ( $E_{\text{fd}} - 0.5\Delta S$ ) will have the smallest  $\Delta E$  with the CB-bottom and lowest  $T_{50}$ . Yet, the opposite is observed, see Table 6. For example, the low energy emission of  $\text{Ce}^{3+}$  in  $\text{Gd}_2\text{SiO}_5$  quenches at 100 K lower temperature than the high energy emission.<sup>175,176</sup> The value for  $U$  at a cation site depends on the bond lengths to the surrounding anions and on how strong anion ligands are bonded.<sup>211,212</sup> These are not the same for different sites in the same compound. It may well lead to few 0.1 eV difference in the  $U$ -value translating to few 0.1 eV difference in the  $\text{Ce}^{4+/3+}$  CTL energy which then directly contributes to  $\Delta E$  and  $T_{50}$ . We mentioned already that quenching may proceed *via* the lanthanide trapped exciton state. The VRBE in such a localized electron state is likely to be site dependent also. The message is therefore that the site dependent  $U$ -value (or  $\text{Ce}^{4+/3+}$  CTL) and site dependent VRBE in the trapped exciton state are not incorporated in the general equations (10) and (11).

It is concluded that the random and systematic errors in  $\Delta E$  for 5d levels as derived from VRBE schemes are generally too large to provide good predictive potential on the thermal quenching temperatures of  $\text{Eu}^{2+}$  or  $\text{Ce}^{3+}$  emission. However, in a series of related compounds, the VRBE schemes do provide the trend in the quenching temperature which can then be exploited to engineer compounds towards a better performance. Such engineering efforts are frequently performed for the garnet system of compounds. Starting with  $\text{Y}_3\text{Al}_5\text{O}_{12}$  one may form a solid solution by replacing a fraction of Y for Lu or Gd, and a fraction of Al for Ga. The chemical shift model has demonstrated that the lanthanide CTLs remain fairly constant in this family of compounds. By means of solid solutions one may then change the VRBE at the CB-bottom or VB-top that translates to changing  $\Delta E$  and  $T_{50}$  for the charge transfer quenching.

The above can also be demonstrated with the behavior of  $\text{Tb}^{3+}$  emission in the  $\text{Al}_{1-x}\text{Ga}_x\text{N}$  solid solution.<sup>60,61,213</sup> From studies with  $\text{Eu}^{3+}$ , we know the energy  $E^{\text{CT}}$  and  $E^{\text{ex}}$  as a function of Ga concentration.<sup>214</sup> Occasionally, we also know the quenching temperature  $T_{10}$  providing data points in Fig. 4. The  $U$ -value can be estimated from that of other nitrides. Fig. 9 shows a stacked VRBE scheme of the  $\text{Al}_{1-x}\text{Ga}_x\text{N}$  system with the  $\text{Eu}^{3+/2+}$  and  $\text{Tb}^{4+/3+}$  CTL. With the increase of the Al concentration, the VB lowers by several 0.1 eV and this leads to more stable  $\text{Eu}^{3+}$  emission as seen for the GaN ( $T_{10} = 200$  K) and AlN ( $T_{10} = 300$  K) data points in Fig. 4. The  $\text{Tb}^{3+} {}^5\text{D}_4$  emission has a  $T_{50}$  of 30 K for pure GaN, but with the increase of the Al content the CB moves up and the  ${}^5\text{D}_4$  emission stabilizes with a  $T_{50}$  of 250 K for  $x = 0.3$ . Around  $x = 0.5$   ${}^5\text{D}_3$  is far enough below the CB-bottom to enable emission from the  ${}^5\text{D}_3$  level of  $\text{Tb}^{3+}$  at 80 K although still quenched at room temperature.<sup>59</sup>

Horai *et al.*<sup>190</sup> showed that upon replacing 20% of the  $\text{Y}^{3+}$  in  $\text{YAlO}_3$  for  $\text{Lu}^{3+}$ , the  $T_{50}$  for  $\text{Ce}^{3+}$  increases from 683 K to 767 K.





Fig. 9 Stacked VRBE scheme of the  $\text{Al}_{1-x}\text{Ga}_x\text{N}$  system with the  $\text{Tb}^{3+}$  ground and excited state levels. The  $\text{Eu}^{3+}$  ground and excited  ${}^5\text{D}_0$  levels are drawn as hole states.

With a slope relationship of  $850 \text{ K eV}^{-1}$ ,  $0.1 \text{ eV}$  increase of the CB-bottom can already accomplish this increase.  $\text{Lu}^{3+}$  has a smaller ionic radius than  $\text{Y}^{3+}$ ; the lattice parameters decrease and the bandgap and CB-bottom increase upon introducing Lu. Incorporating larger lanthanides such as  $\text{Gd}^{3+}$  and  $\text{La}^{3+}$  would likewise reduce the quenching temperature. Indeed, the  $T_{50}$  of  $\text{GdAlO}_3$  is only  $345 \text{ K}$  and for  $\text{LaAlO}_3$  there is no  $\text{Ce}^{3+}$  emission because the  $5\text{d}$ -level is located above the CB-bottom. This is all illustrated by the corresponding data points in Fig. 8.

The sensitivity of  $T_{50}$  on slight changes in the  $\Delta E$  is also well demonstrated with  $\text{Ce}^{3+}$  doped  $\text{Y}_3\text{Ga}_5\text{O}_{12}$ . Depending on the synthesis temperature, part of the octahedral  $\text{Ga}^{3+}$  sites can be occupied by the larger  $\text{Y}^{3+}$  cations. This is known as the anti-site occupancy which leads to slight lattice expansion and band gap narrowing. In Czochralski grown crystals the  $\text{Ce}^{3+}$  emission is absent at  $10 \text{ K}$ <sup>197</sup> but for powders grown with a relatively low temperature solid state synthesis there will be less anti-site occupancy, smaller lattice parameter, and wider bandgap. As a result the  $\text{Ce}^{3+}$  emission is observed at RT.<sup>198</sup>

Fig. 3 shows that the VRBE in the lowest  $5\text{d}$ -state of  $\text{Pr}^{3+}$  is about  $0.5 \text{ eV}$  below that for  $\text{Ce}^{3+}$  and similar will hold for other compounds. This implies that when quenching proceeds *via* the CB, the  $T_{50}$  for the  $4\text{f}^1 5\text{d} - 4\text{f}^2$  emission of  $\text{Pr}^{3+}$  should be about  $400 \text{ K}$  higher than that for  $\text{Ce}^{3+}$ . For  $\text{BaF}_2$  indeed, the  $5\text{d} - 4\text{f}$  emission from  $\text{Pr}^{3+}$  is at least  $200 \text{ K}$  more stable than from  $\text{Ce}^{3+}$ .<sup>146</sup> However, the  $T_{50}$  values of  $\text{Ce}^{3+}$  and  $\text{Pr}^{3+}$  in  $\text{Y}_3\text{Al}_{5-x}\text{Ga}_x\text{O}_{12}$  are  $640 \text{ K}$  and  $321 \text{ K}$  for  $x = 0$ ,  $583 \text{ K}$  and  $377 \text{ K}$  for  $x = 1$ ,  $491 \text{ K}$  and  $407 \text{ K}$  for  $x = 2$ ,  $344 \text{ K}$  and  $316 \text{ K}$  for  $x = 3$ , and  $301 \text{ K}$  and  $173 \text{ K}$  for  $x = 4$ .<sup>196,215</sup> For  $x = 0, 1, 2, 3$ , and  $4$ ,  $T_{50}(\text{Ce})$  decreases because the  $5\text{d}$  VRBE moves up and the CB-bottom moves down. However,  $T_{50}(\text{Pr})$  increases for  $x = 0, 1$ , and  $2$  and this was attributed to quenching *via* the crossing point (CP) of the  $4\text{f}^2 [{}^3\text{P}_2]$  and  $4\text{f}5\text{d}$  parabolas where the former remains stationary and the latter moves up with increasing  $x$ .<sup>215</sup> For  $x = 3$  and  $4$ , the CB moves down below the CP and both Ce and

Pr quench *via* the CB. The question remains though why  $T_{50}(\text{Pr}) < T_{50}(\text{Ce})$  for  $x = 3$  and  $x = 4$ .  $T_{50}(\text{Pr}) < T_{50}(\text{Ce})$  was also observed in  $\text{Y}_2\text{SiO}_5$  and  $\text{Lu}_2\text{SiO}_5$  by van der Kolk *et al.*<sup>216</sup> where photocurrent studies did evidence quenching *via* the CB. It was suggested that the  ${}^1\text{S}_0 4\text{f}^2$  level of  $\text{Pr}^{3+}$  located above the lowest energy  $4\text{f}^1 5\text{d}$ -level assists in the quenching *via* the CB thus lowering  $T_{50}$ .<sup>216</sup> The final answer remains open and deserves a more dedicated study.

## IV. Summary and conclusions

This work confirmed that the thermal quenching of  $\text{Eu}^{3+}$ ,  $\text{Tb}^{3+}$ ,  $\text{Pr}^{3+}$ ,  $\text{Eu}^{2+}$ , and  $\text{Ce}^{3+}$  emissions proceeds *via* charge transfer to the host band states. By using a frequency factor of  $2 \times 10^{13} \text{ Hz}$  and the typical value for the radiative lifetime of the emitting energy level, the rate of change in  $T_{50}$  with a quenching energy barrier  $\Delta E$  was predicted as shown in Table 1. Using the refined chemical shift model for the VRBE diagram construction, the  $\Delta E$  values of thermal quenching were derived. For the characteristic  $4\text{f}^n - 4\text{f}^n$  emissions of  $\text{Eu}^{3+}$ ,  $\text{Tb}^{3+}$ , and  $\text{Pr}^{3+}$ , the predicted slopes  $T_{50}/\Delta E$  ( $\text{K eV}^{-1}$ ) were indeed observed. The  $0.3 - 0.5 \text{ eV}$  intercept with the horizontal in Fig. 4–6 was attributed partly to the relaxation energy accompanying the charge transfer and to the possibility/probability of quenching *via* the impurity trapped exciton state. The effect of relaxation is very compound dependent and is not accounted for in the VRBE diagram construction. When the quenching temperature is above  $400 \text{ K}$  for  $\text{Pr}^{3+}$ , it was suggested that multi-phonon relaxation from  ${}^3\text{P}_0$  to  ${}^1\text{D}_0$  becomes a dominating route for quenching.

The  $\Delta E$  values for the  $5\text{d} - 4\text{f}$  emissions of  $\text{Eu}^{2+}$  and  $\text{Ce}^{3+}$  derived from VRBE diagrams carry substantial larger errors than those for  $\text{Eu}^{3+}$ ,  $\text{Tb}^{3+}$ , and  $\text{Pr}^{3+}$ . This is due to the contribution from the error in  $E^{\text{ex}}$ , the Stokes  $\Delta S$  and for  $\text{Ce}^{3+}$  also the  $U$ -value. These error sources are held responsible for the wide scatter of the the data points in Fig. 7 and 8. Nevertheless, clear trends are observed particularly when dealing with a sequence of a similar type of compounds like the garnet or rare earth perovskite family of compounds.

This work deals with about 170 different compounds, and for each of them all parameters needed to construct VRBE schemes like that for  $\text{YPO}_4$  in Fig. 3 have been provided in various tables. This work has demonstrated that changes as small as  $0.1 \text{ eV}$  in level locations may already lead to a  $50 - 100 \text{ K}$  shift in  $T_{50}$ . Such changes can be accomplished by intentional or unintentional defects, the activator concentration, the occupation of anti-sites in garnets, and the application of pressure, synthesis conditions, *etc.* As a result, the often made assumption that  $\Delta E$  in the Arrhenius equations is a constant will not hold for charge transfer quenching and then there is not much scientific sense in fitting a quenching curve with this Arrhenius equation. This work has also demonstrated the limitations of VRBE diagrams as shown in Fig. 3. (1) They do not deal with lattice relaxation effects leading to the very compound dependent Stokes shifts. (2) The assumption that the maximum of the



Eu<sup>3+</sup> charge transfer band always defines the energy difference between the Eu<sup>3+/2+</sup> CTL and the VB-top may not hold for all types of compounds. One may not exclude a few 0.1 eV differences between fluorides, oxides, and sulfides leading to systematic errors in level locations and  $\Delta E$ . (3) For compounds with different sites for the activator, the same  $U$ -value is always used. A few 0.1 eV differences between different sites cannot be excluded, and there are indications of such differences. (4) The used  $U$ -values are not rigorously based on experimental or theoretical evidence and may still carry substantial errors. Despite all the above limitations, consistency between the quenching data and VRBE diagrams has been demonstrated. With a more dedicated study one might then use the quenching data as a means to further improve the method of the VRBE-diagram construction and therewith its accuracy and predictive potential.

## Conflicts of interest

There are no conflicts to declare.

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