



The basics of TSL and OSL

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Summer school on scintillation, dosimetric and phosphor materials
7-8 September 2018, Prague, Czech Republic

Where is TL/OSL used today?

Diagnostic imaging (computed radiography)



Personal/environmental monitoring



Luminescence dating



in-vivo measurements



LiF TLDs

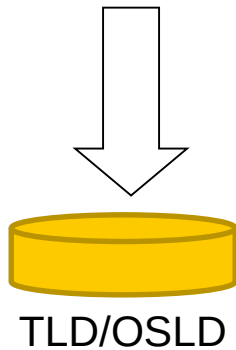


$\text{Al}_2\text{O}_3\text{:C}$ TLDs and OSLDs

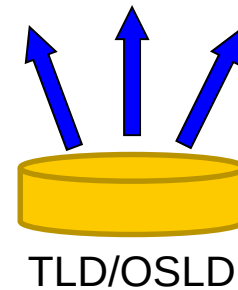


(a) excitation

X-rays, γ -rays, e-beam,
protons, etc.

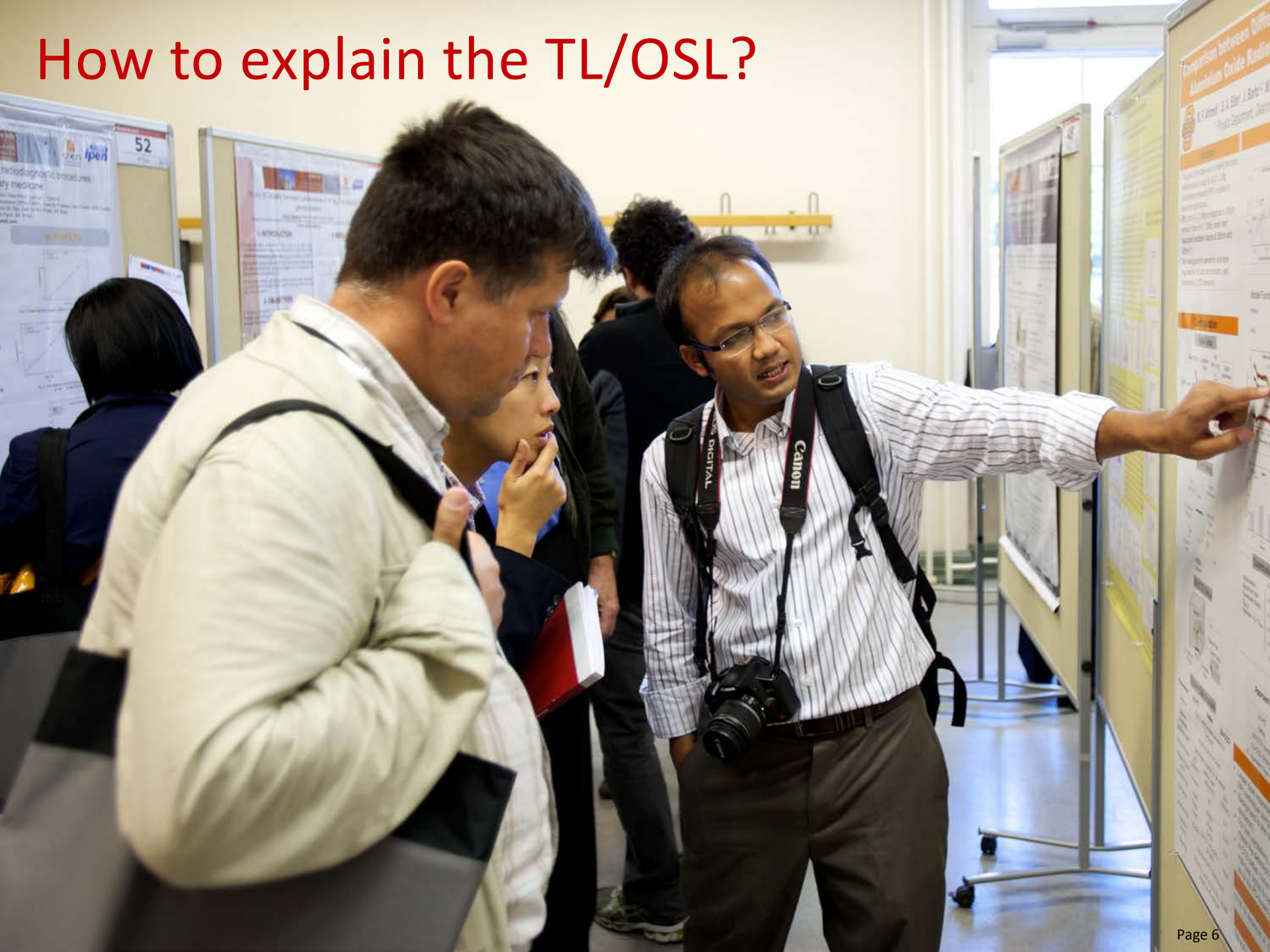
**(b) storage****(c) stimulation**

heating or
illumination

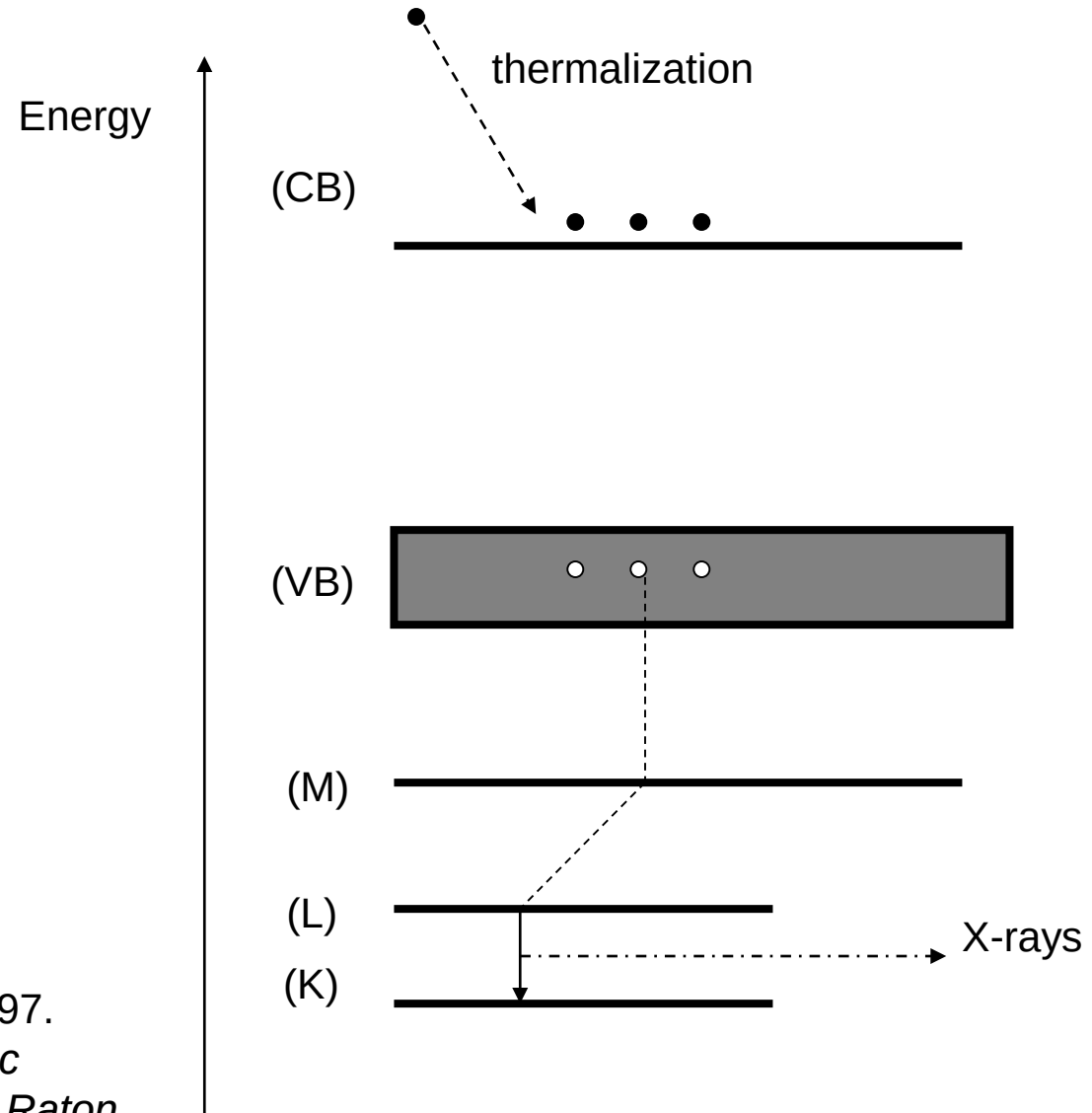


- Fundamentals
- Measurement techniques
- Main characteristics
- Advantages/disadvantages
- Materials R&D and trends

How to explain the TL/OSL?



Energy levels in a crystal

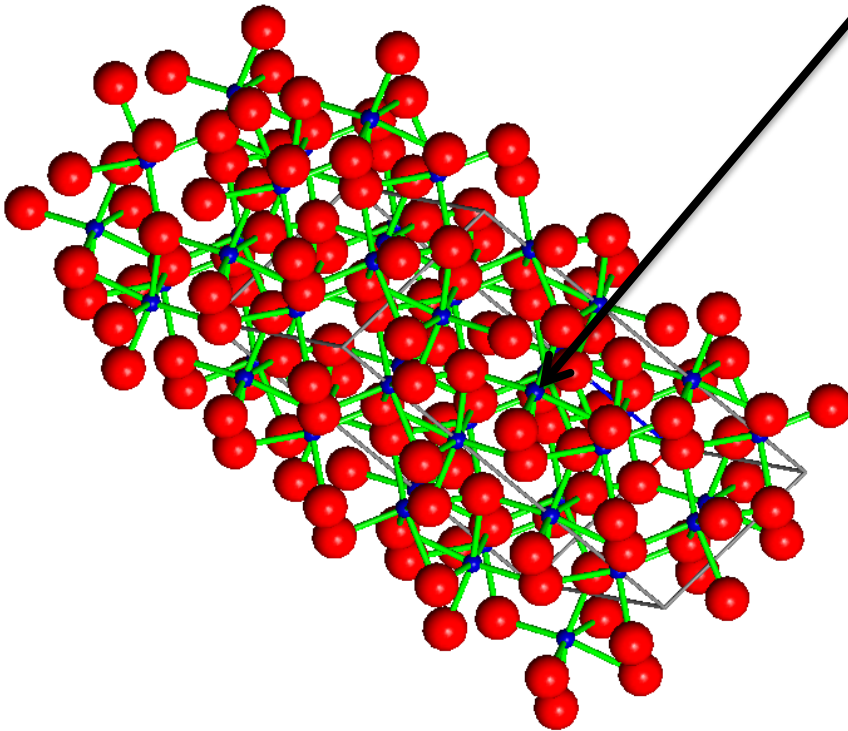


Adapted from Rodnyi, P.A., 1997.
*Physical processes in inorganic
scintillators*. CRC Press, Boca Raton.

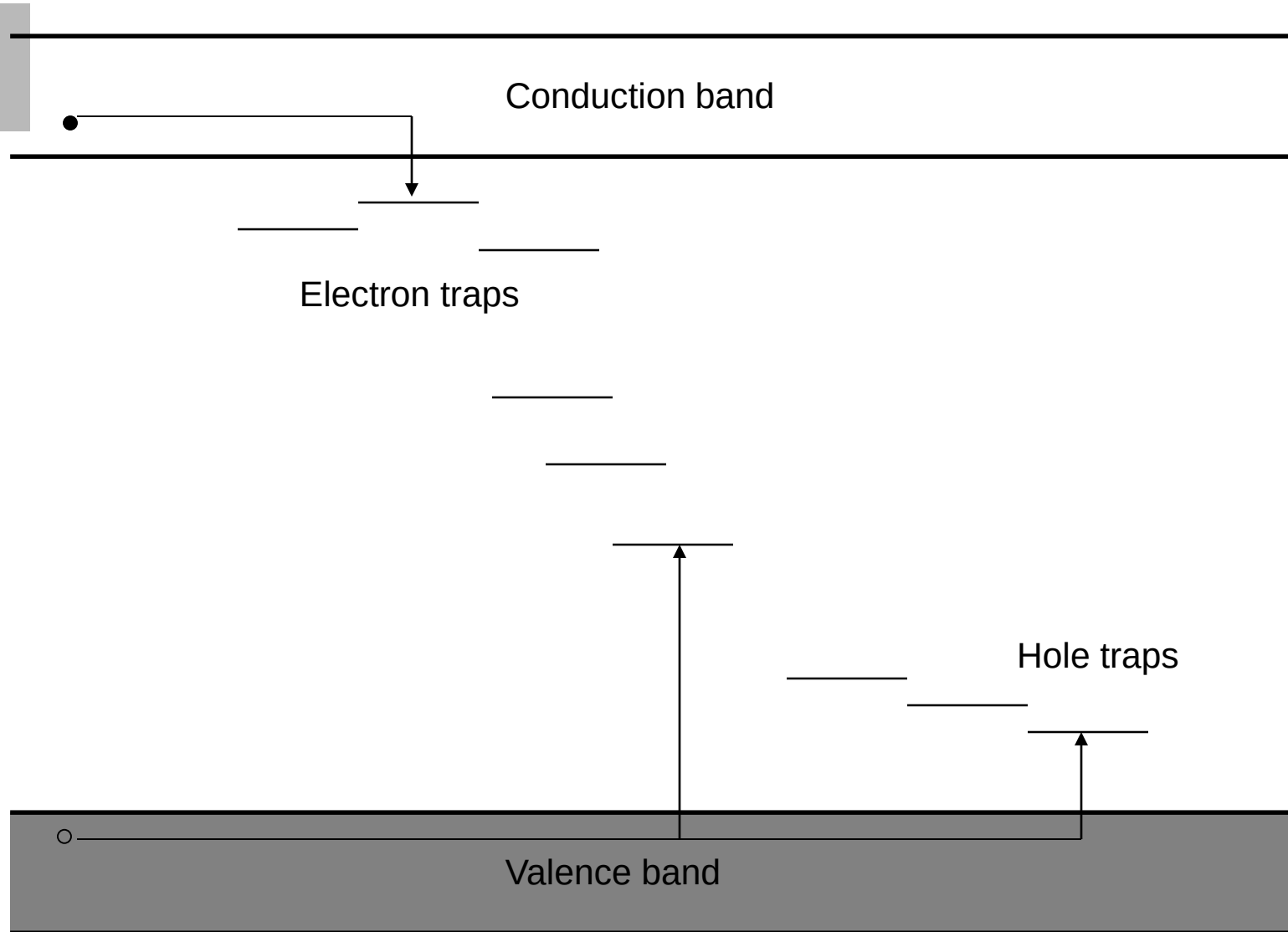
Defects in the crystalline lattice

Impurity (instead of Al^{3+}):

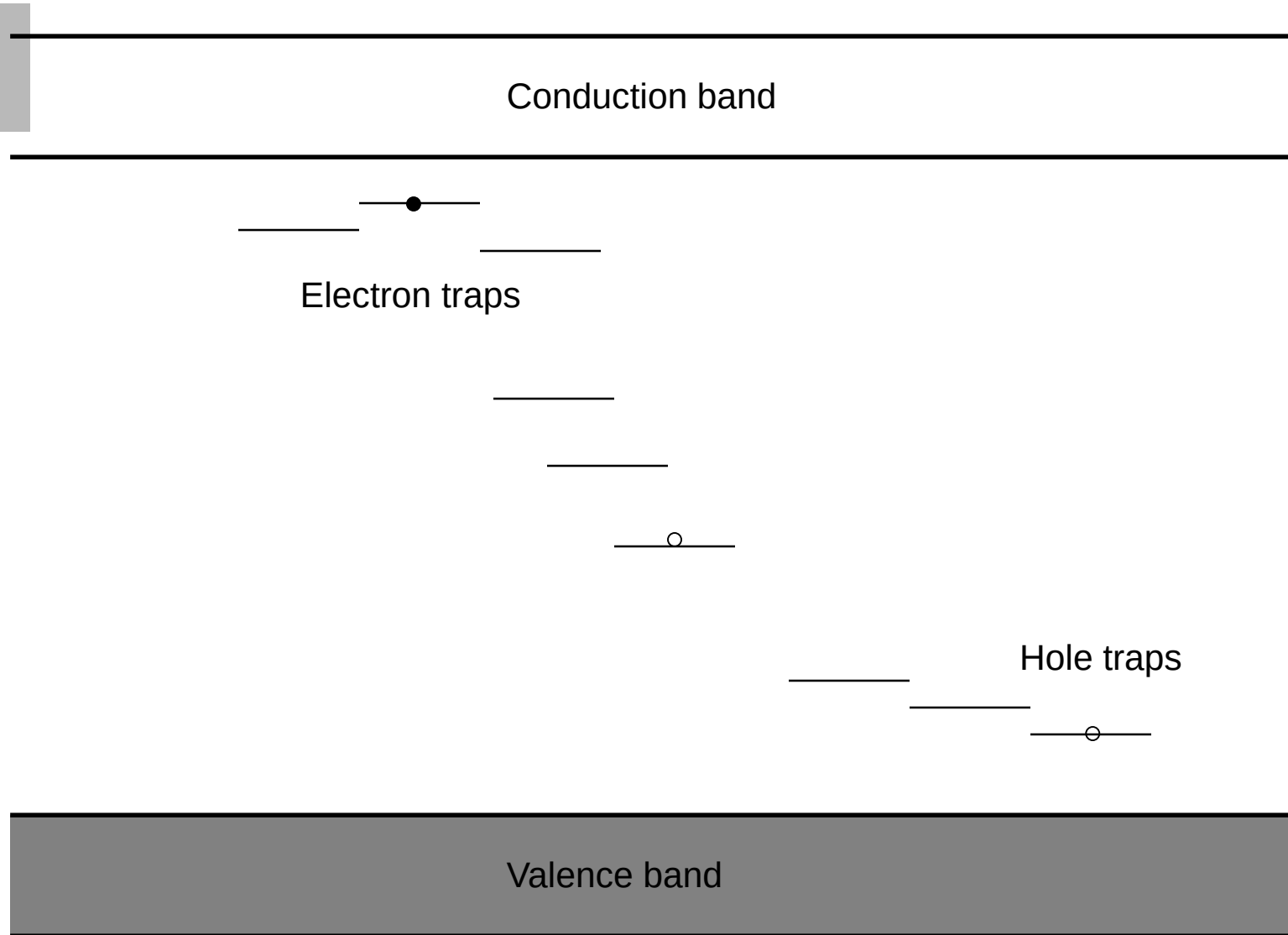
- Fe^{3+}
- Ce^{3+}
- Mg^{2+}



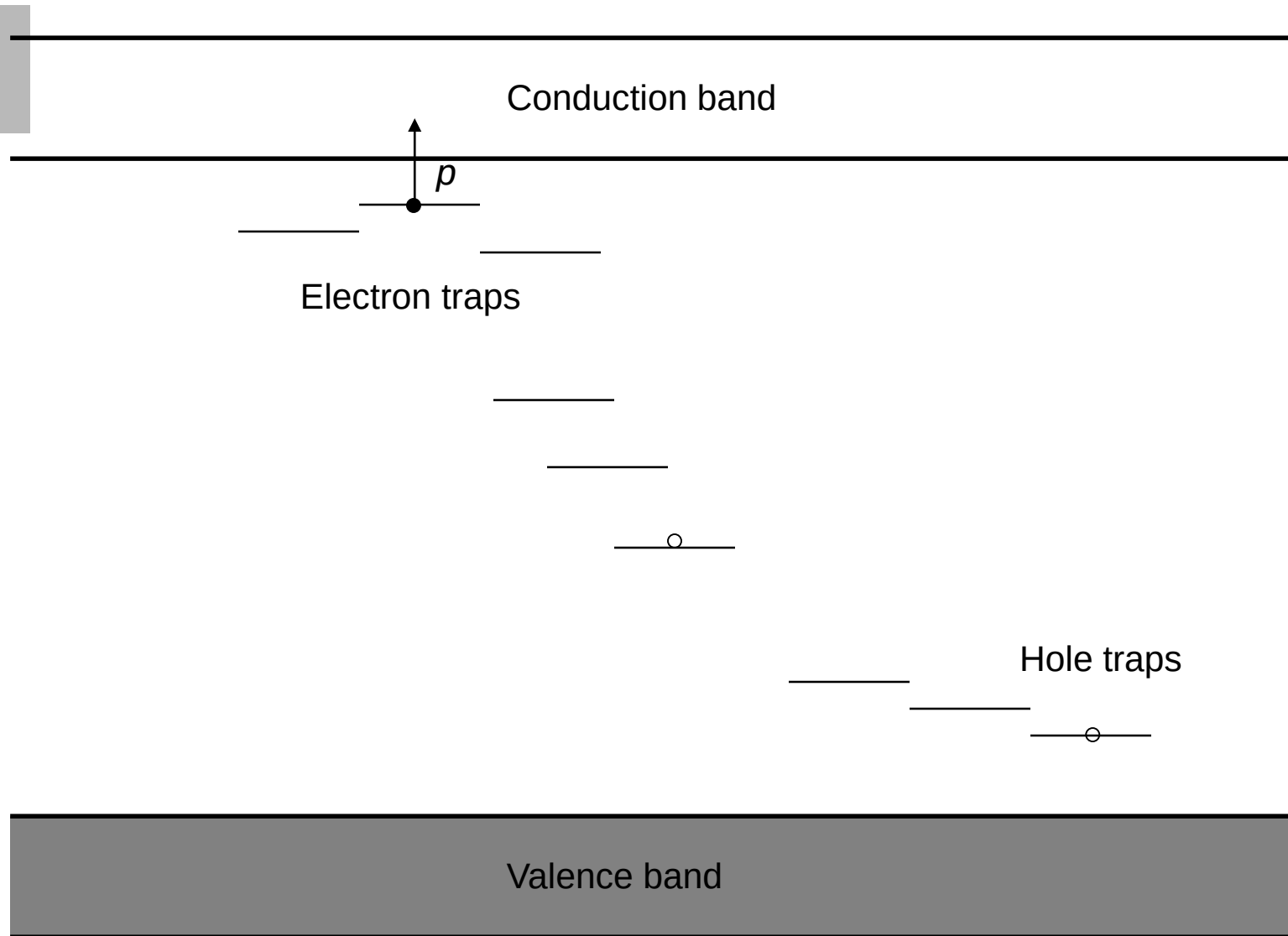
Defects in the crystalline lattice



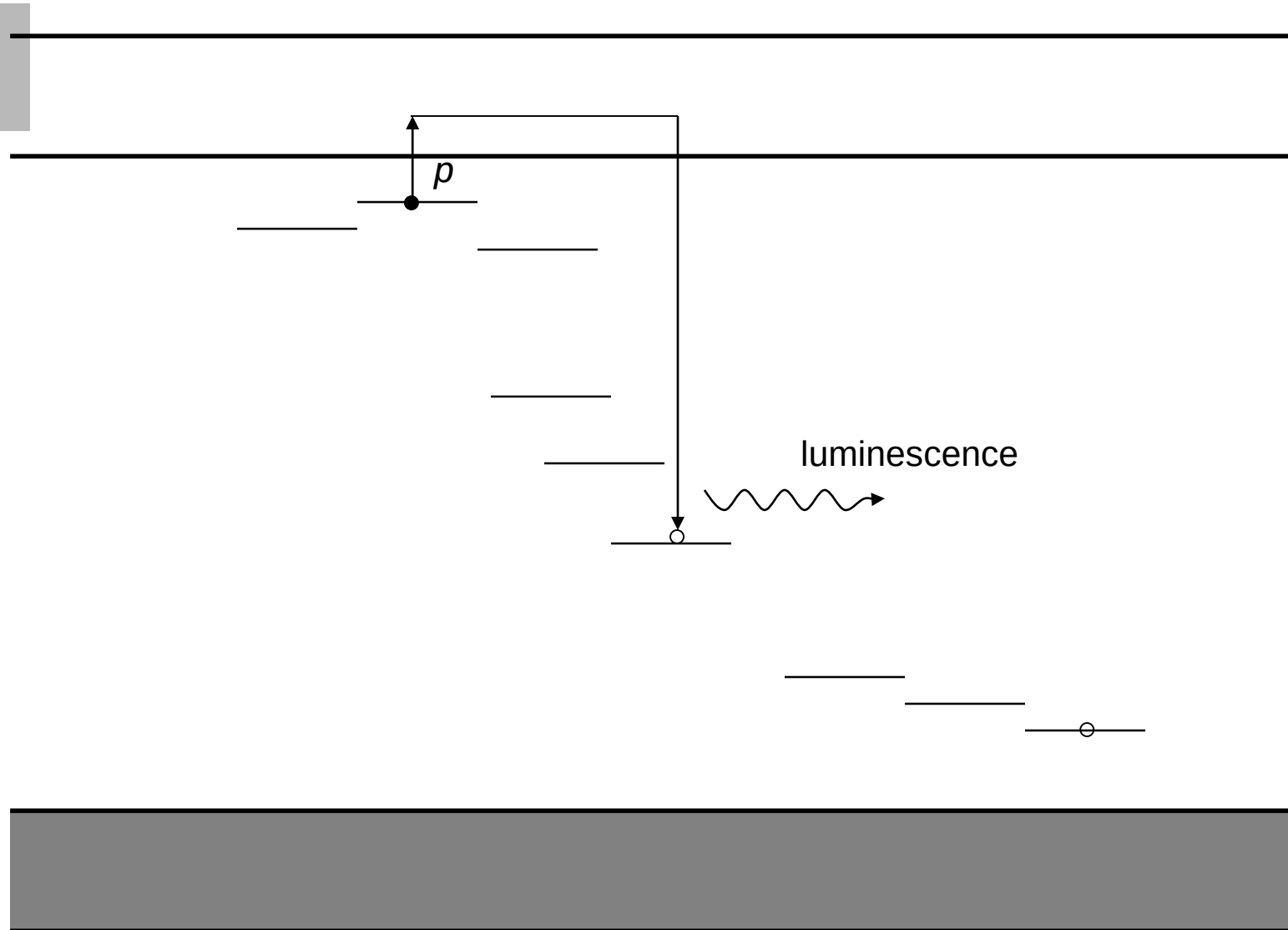
Defects in the crystalline lattice



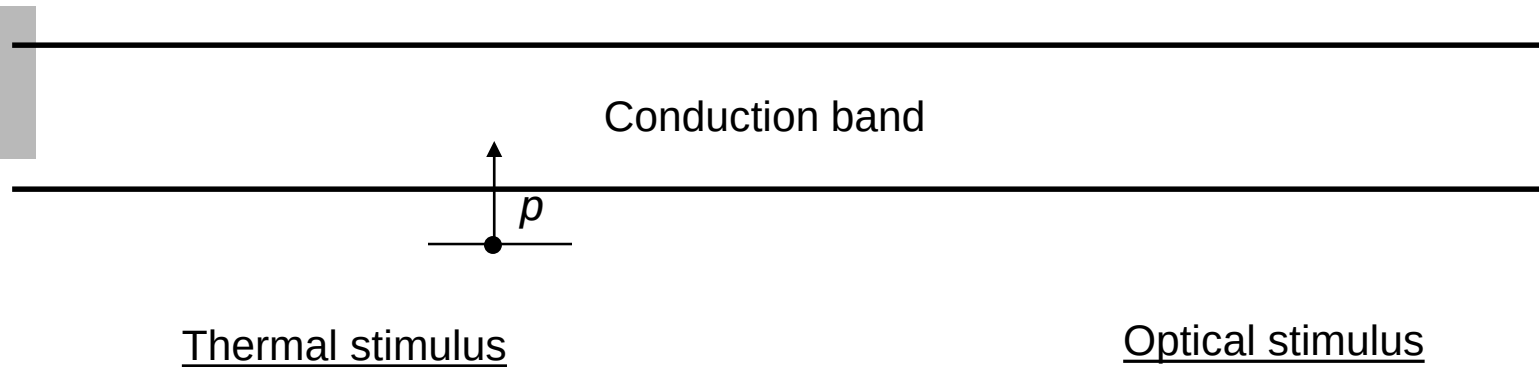
Thermal/optical stimulation



Recombination



Thermal/optical stimulation



$$p = se^{-\frac{E}{kT}}$$

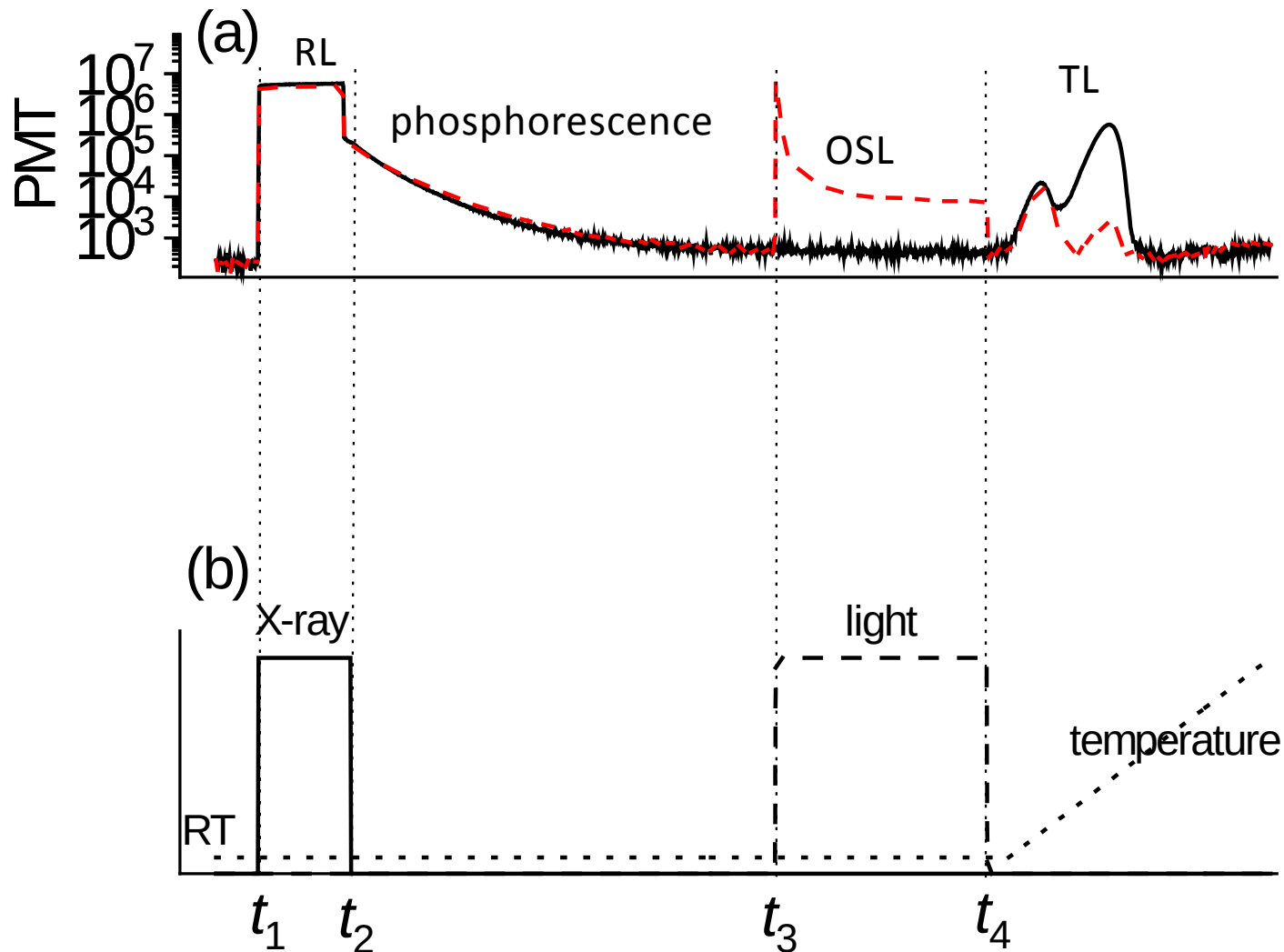
- E = Activation energy
- s = Frequency factor
- k = Boltzmann constant
- T = Temperature

$$p = \sigma(\lambda)\phi(\lambda)$$

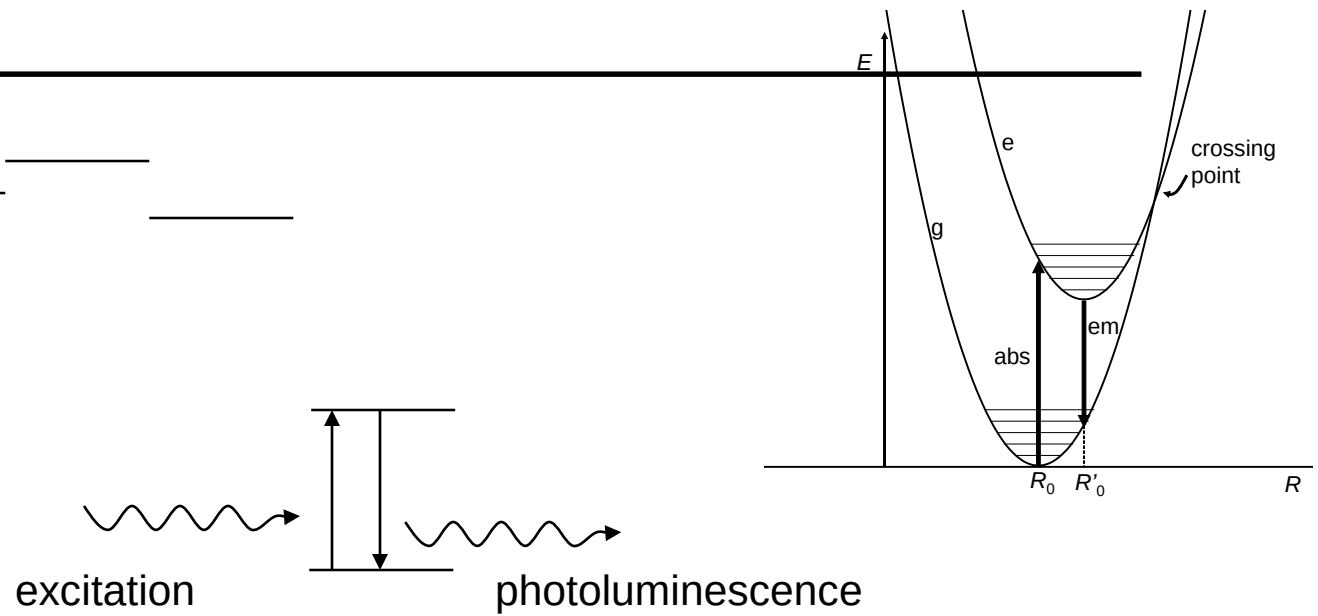
- σ = photoionization cross-section (cm²)
- ϕ = photon flux (fótons cm⁻² s⁻¹)
- λ = wavelength

$$E(\text{eV}) \cong \frac{1240}{\lambda(\text{nm})}$$

Other processes



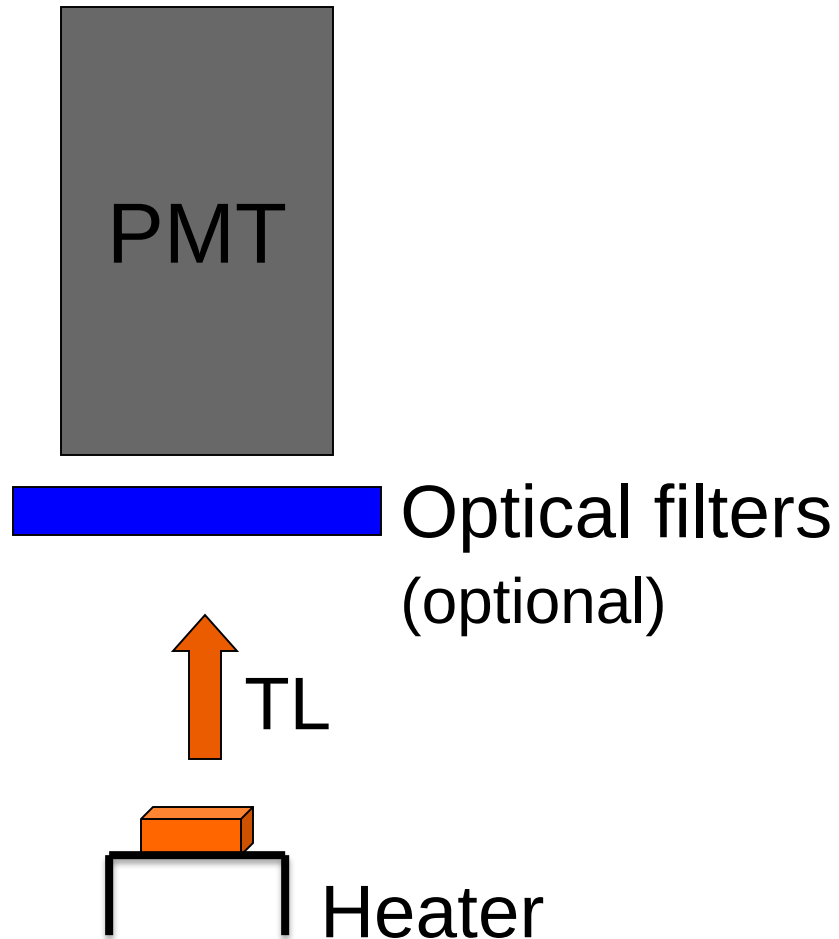
Radiophotoluminescence



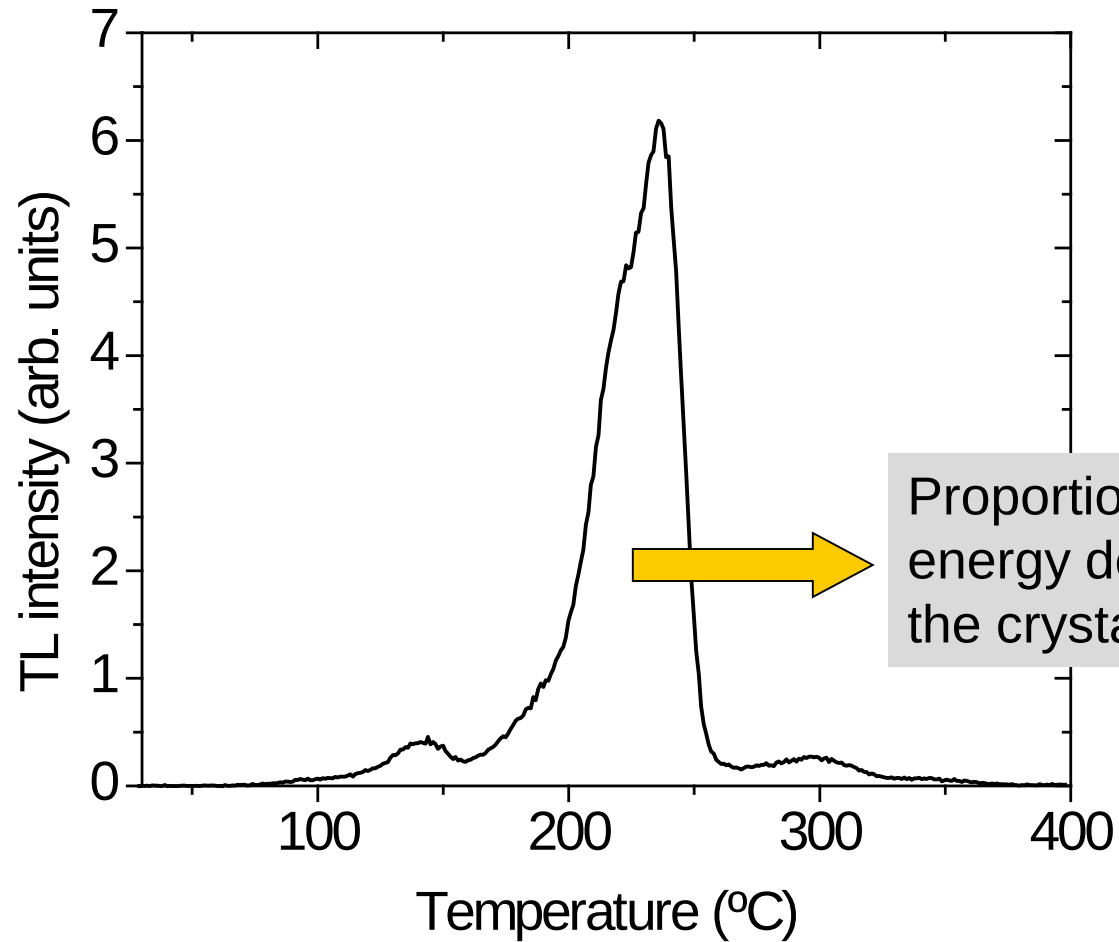
How to measure TL/OSL?



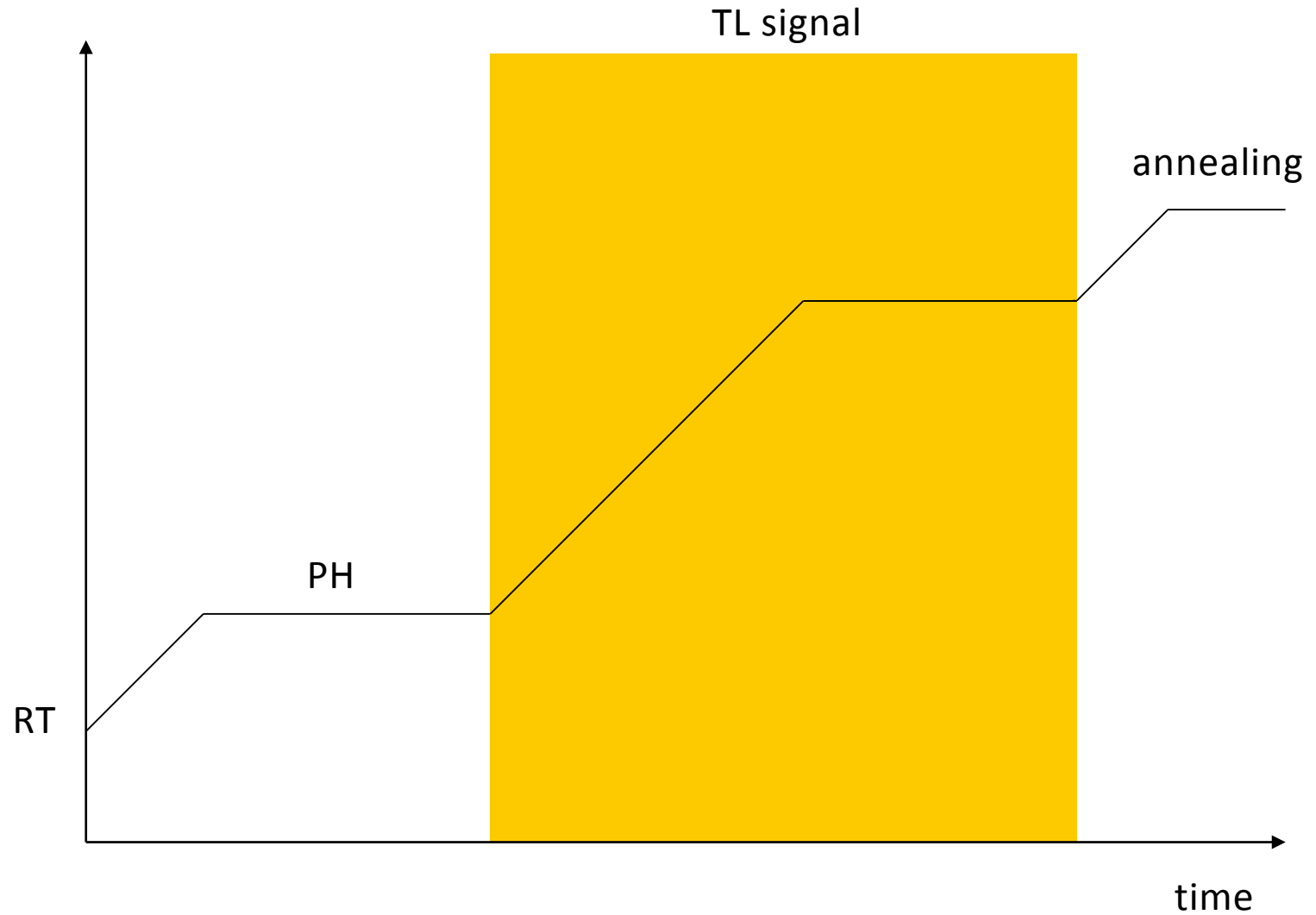
TL readout



TL readout

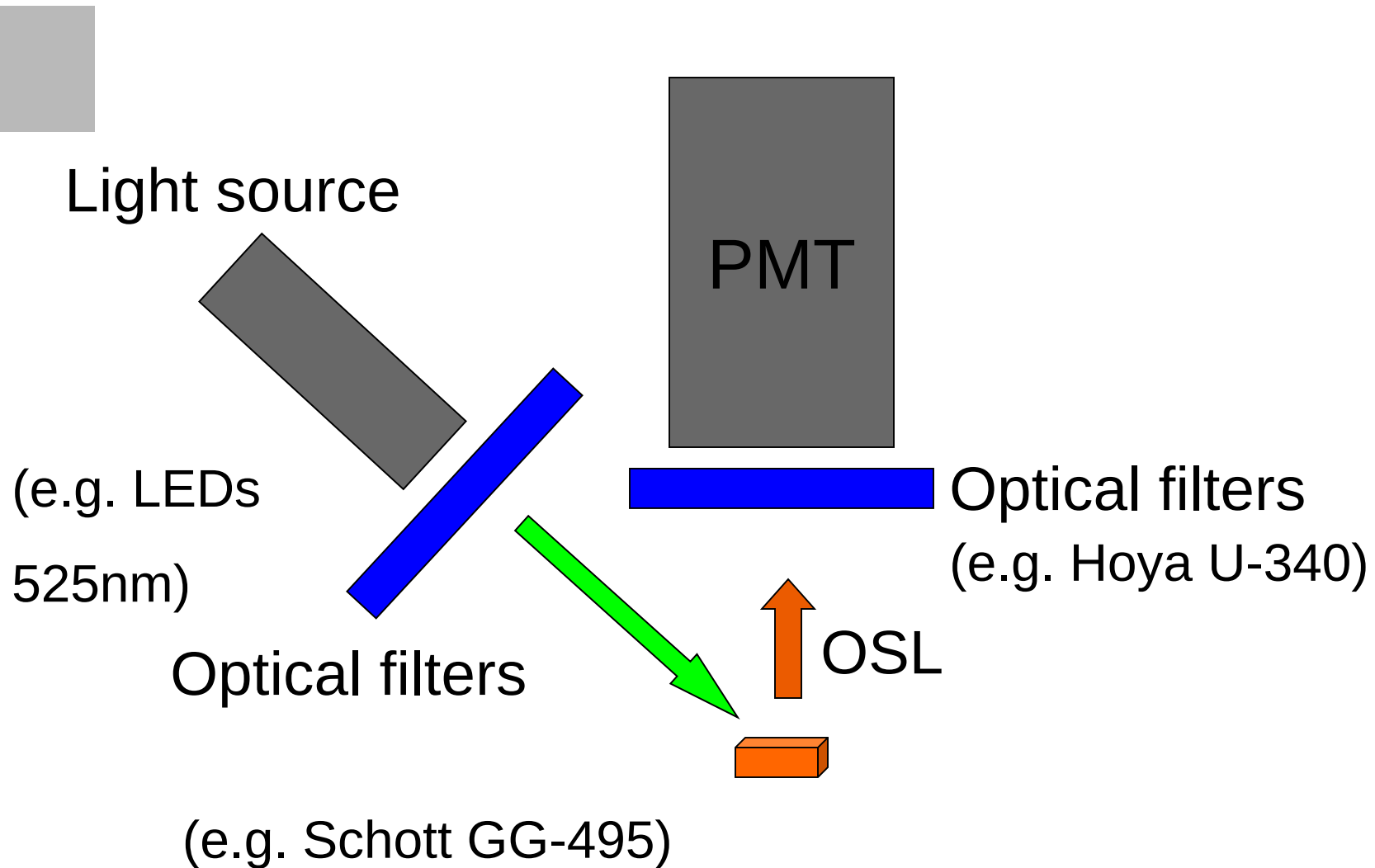


Time-temperature profiles (TTP)

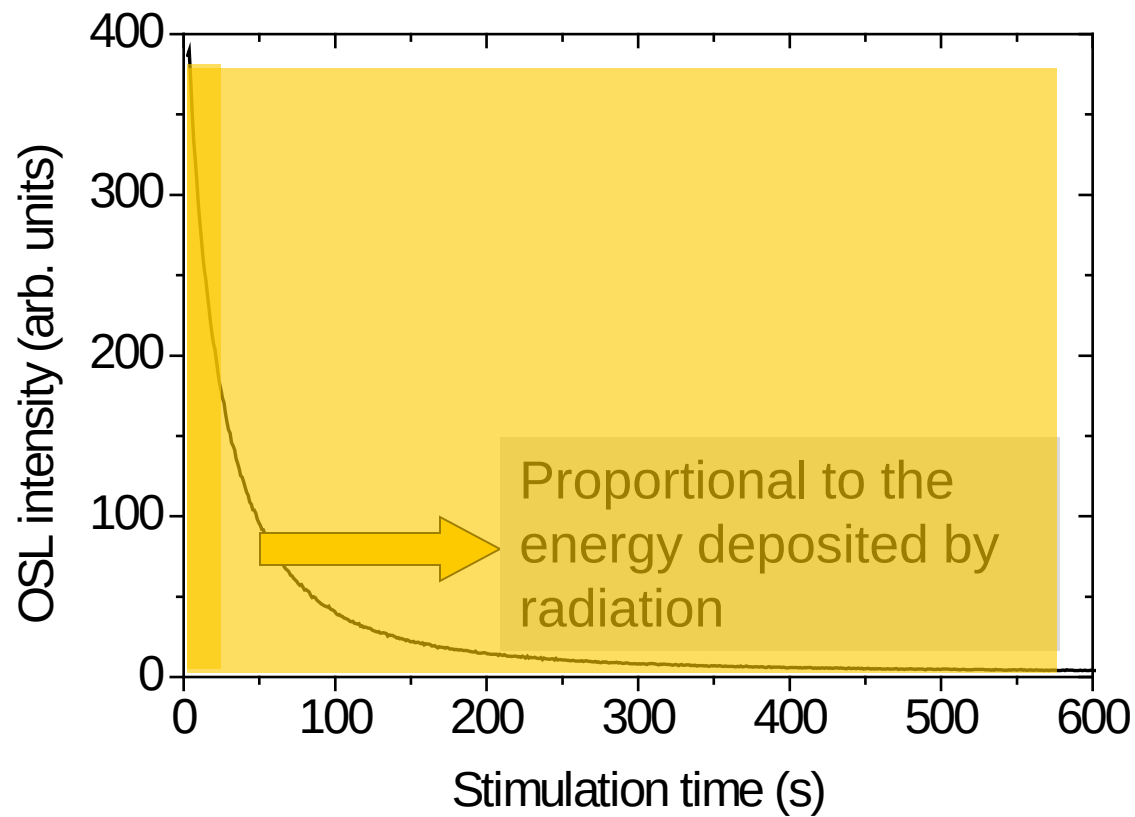


Examples of TL systems

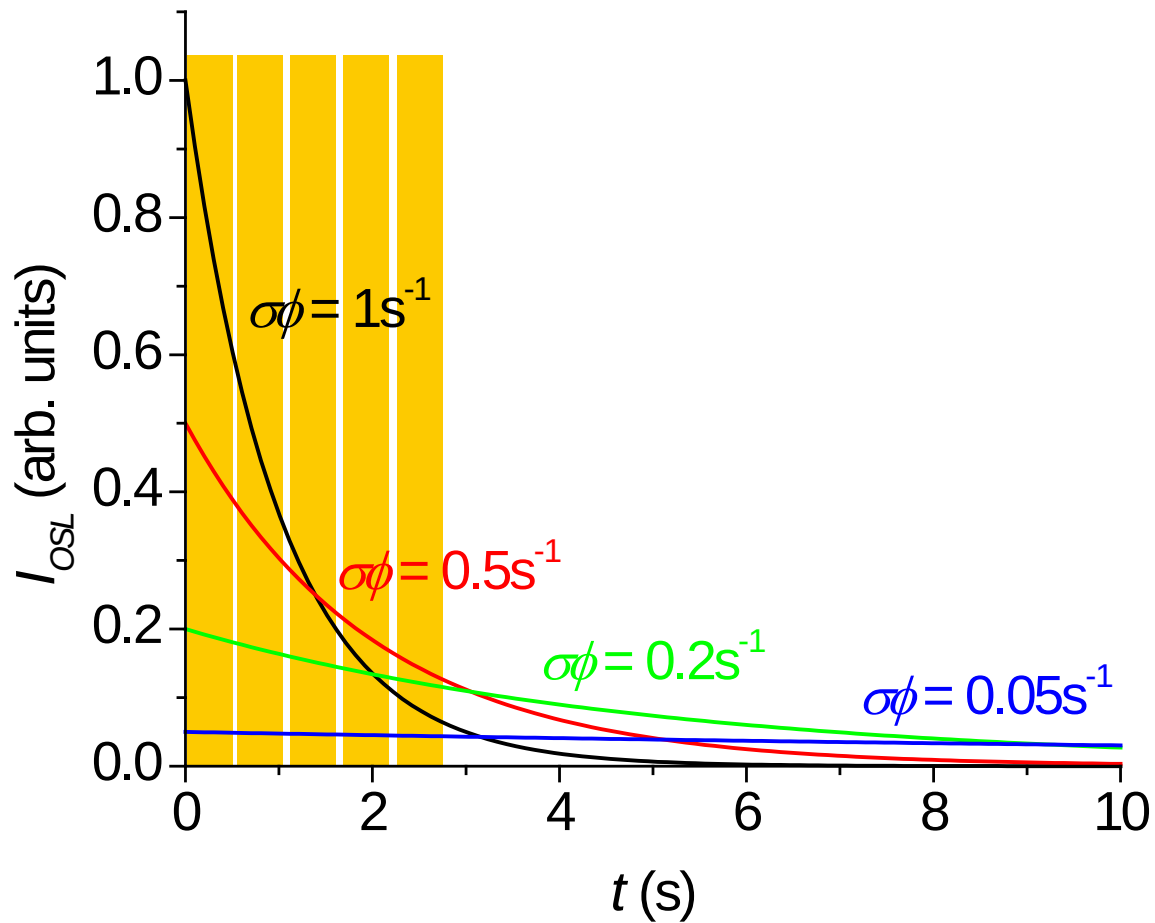




OSL readout



OSL dependence with stimulation intensity



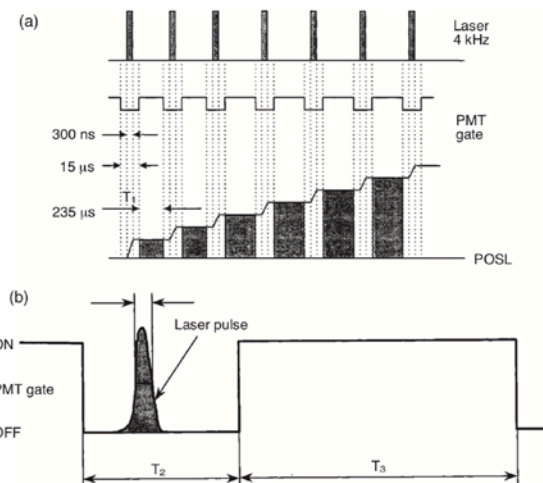
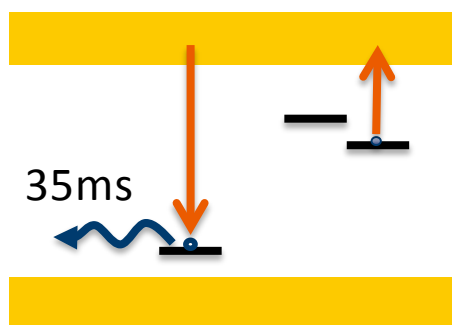
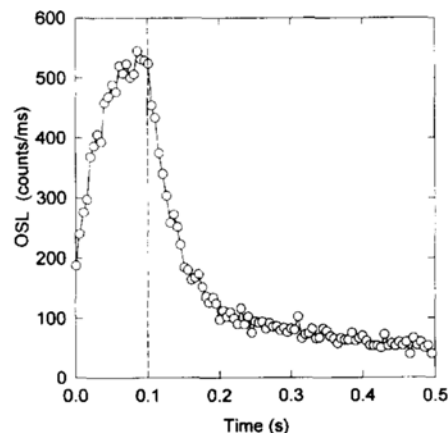
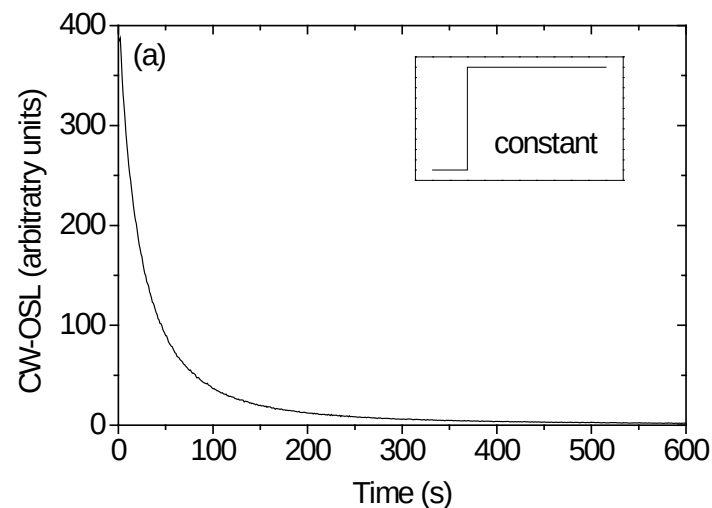
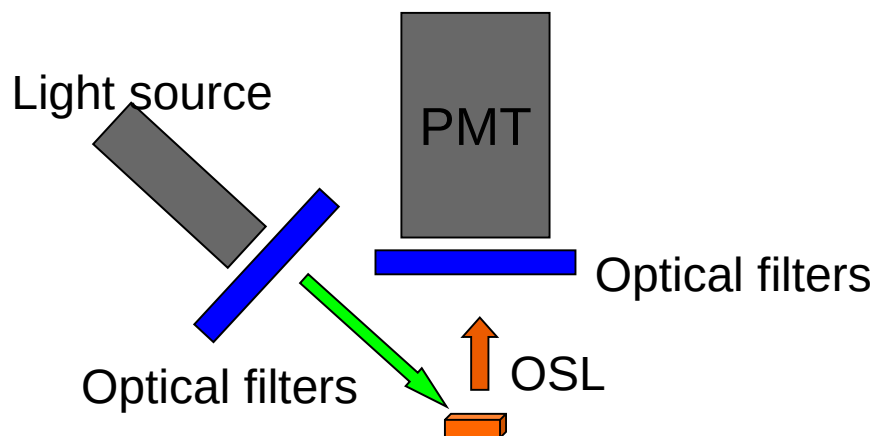
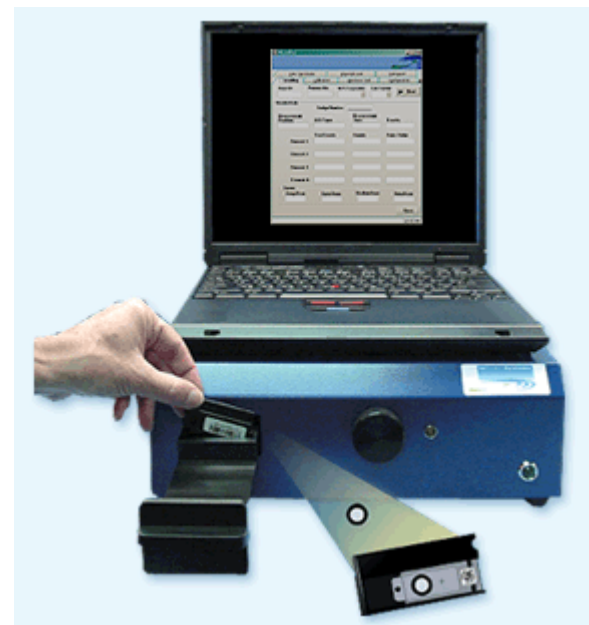


Fig. 2. Time-resolved OSL from α - $\text{Al}_2\text{O}_3\text{:C}$ following irradiation at room temperature with a dose of 0.04 Gy $^{90}\text{Sr}/^{90}\text{Y}$. A single laser pulse (150 mW, 100 ms wide) was used to excite the OSL. The measurement temperature was 25°C.

Figure 1. (a) Schematic of the timing diagram to synchronise the POSL measurement with the laser pulses. (b) Detail indicating the actual laser pulse and the PMT gate, with the pulse width T_1 , the 'dead time' T_2 , and the 'acquisition time' T_3 .

Akselrod & McKeever. **A radiation dosimetry method using pulsed optically stimulated luminescence.** Radiat. Prot. Dosim. 81, 167-176 (1999).

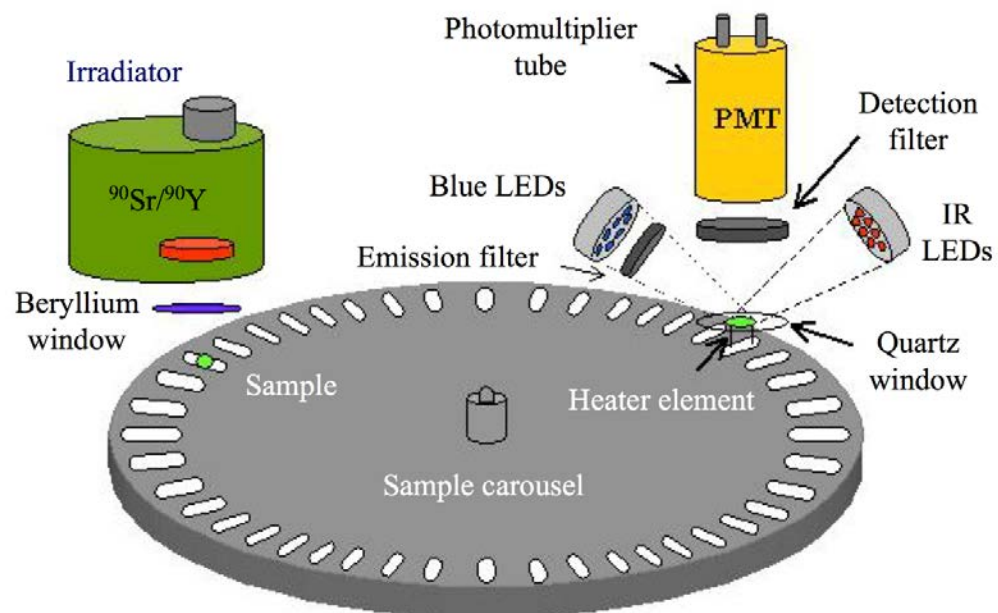
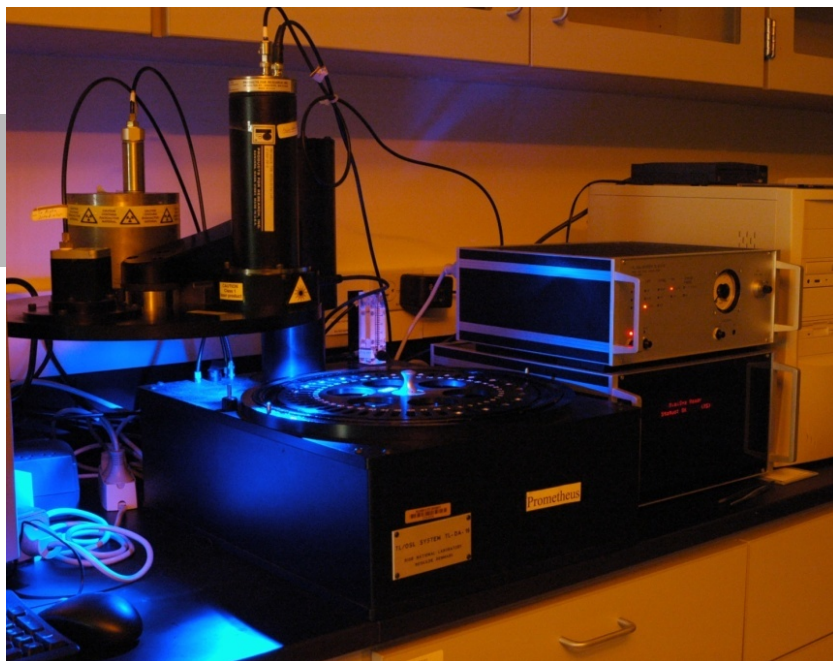
Example of $\text{Al}_2\text{O}_3:\text{C}$ OSL system



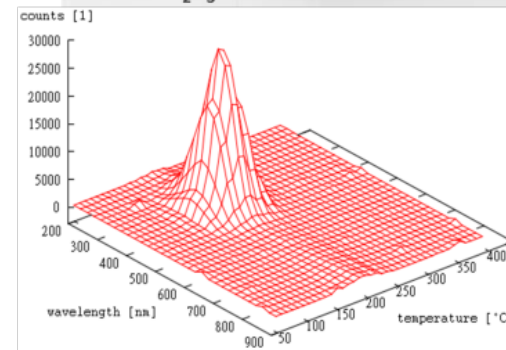
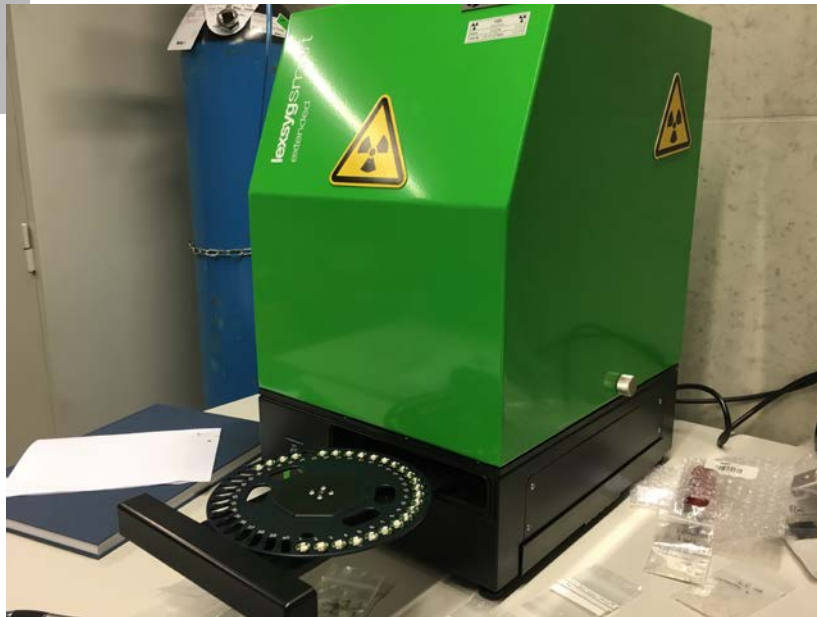
Example of BeO OSL system



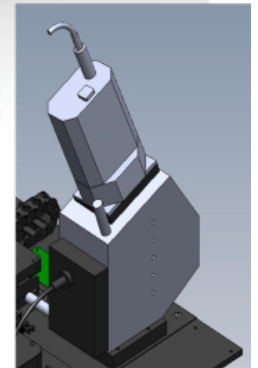
Automated TL/OSL readers



Automated TL/OSL readers



sample courtesy R. de Witt



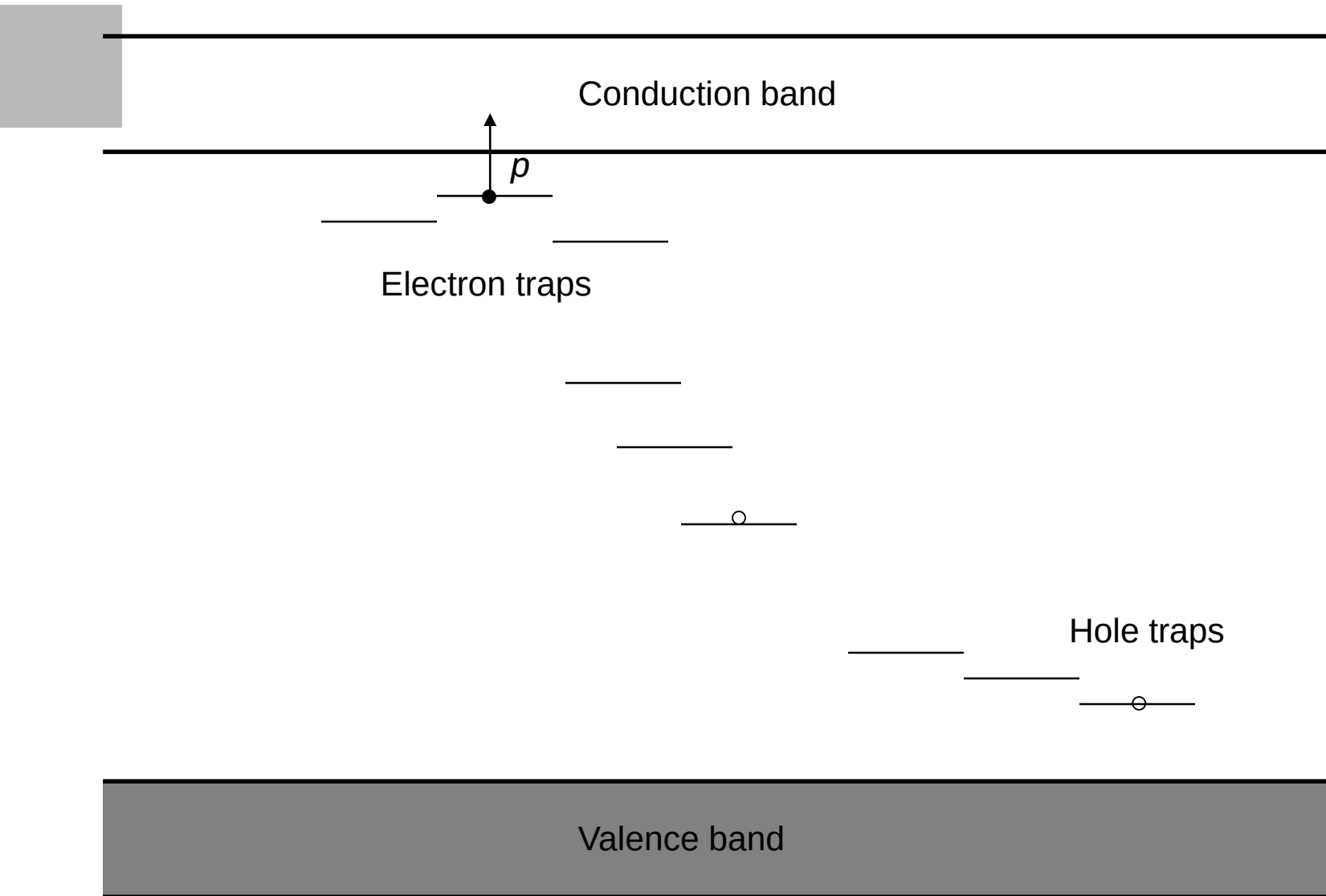
What are the main characteristics?



Important characteristics

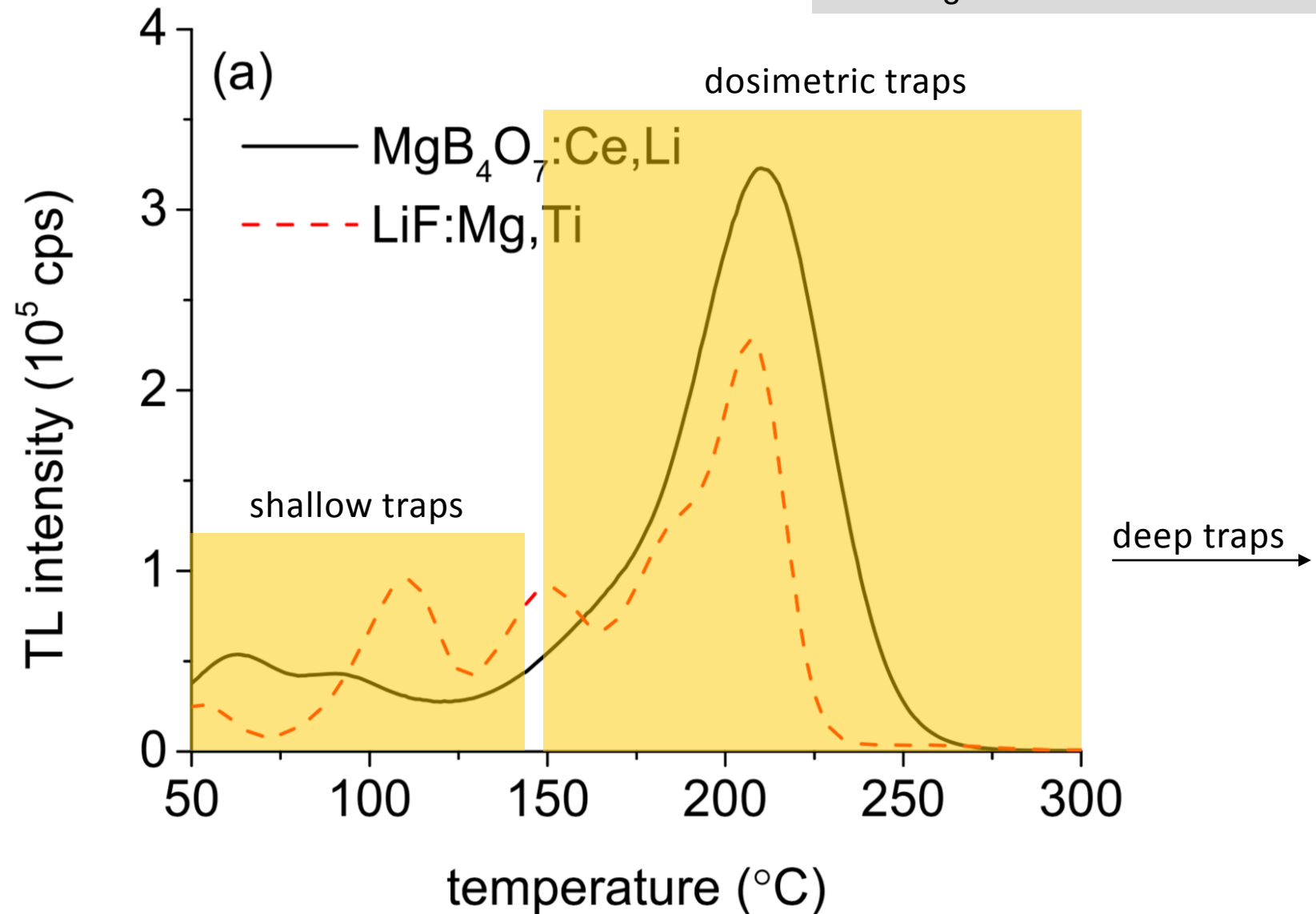
- TL curve (thermal stability)
- OSL stimulation spectrum (optical stability)
- Emission spectrum (recombination/luminescence centers)
- Luminescence lifetime (CW-OSL vs. POSL)
- Mathematical models

Detrapping process

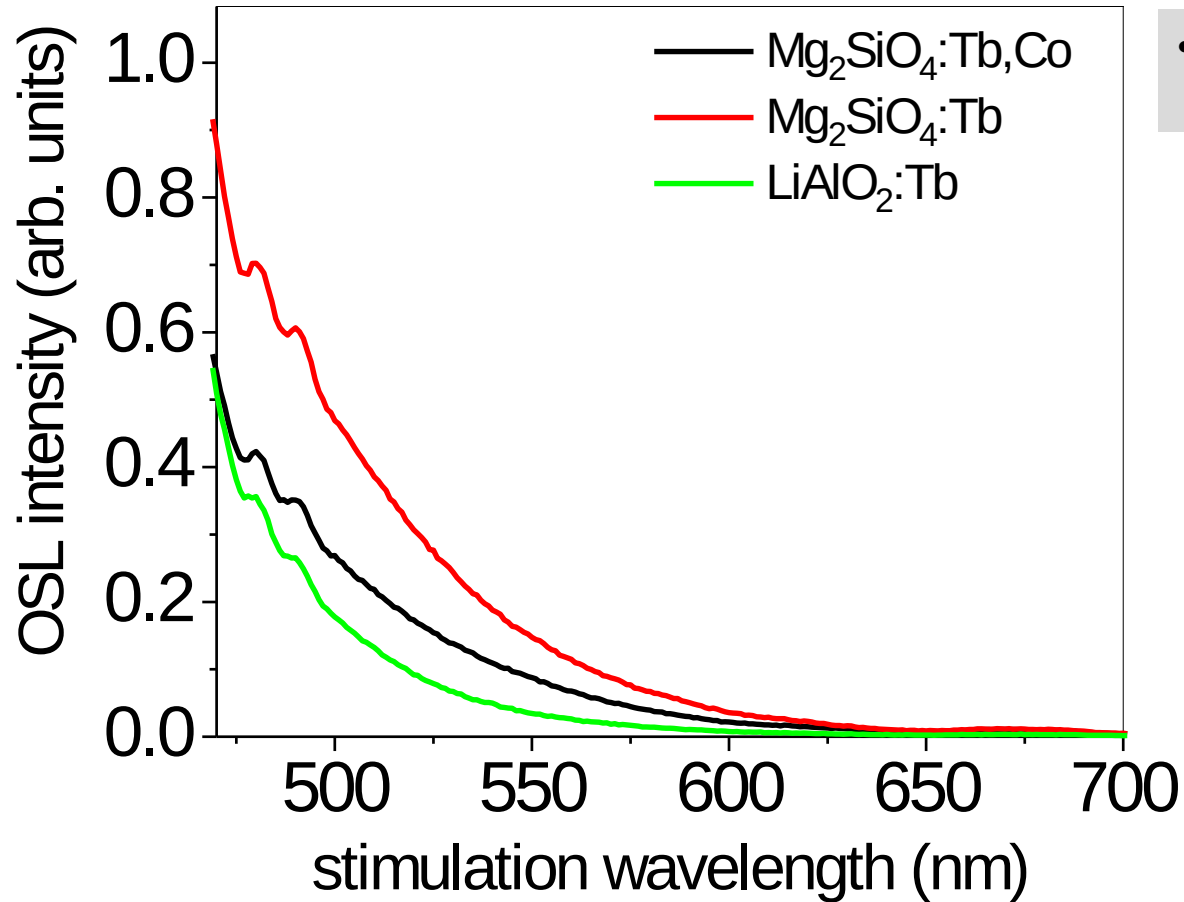


TL curves

- thermal stability of trapped charges

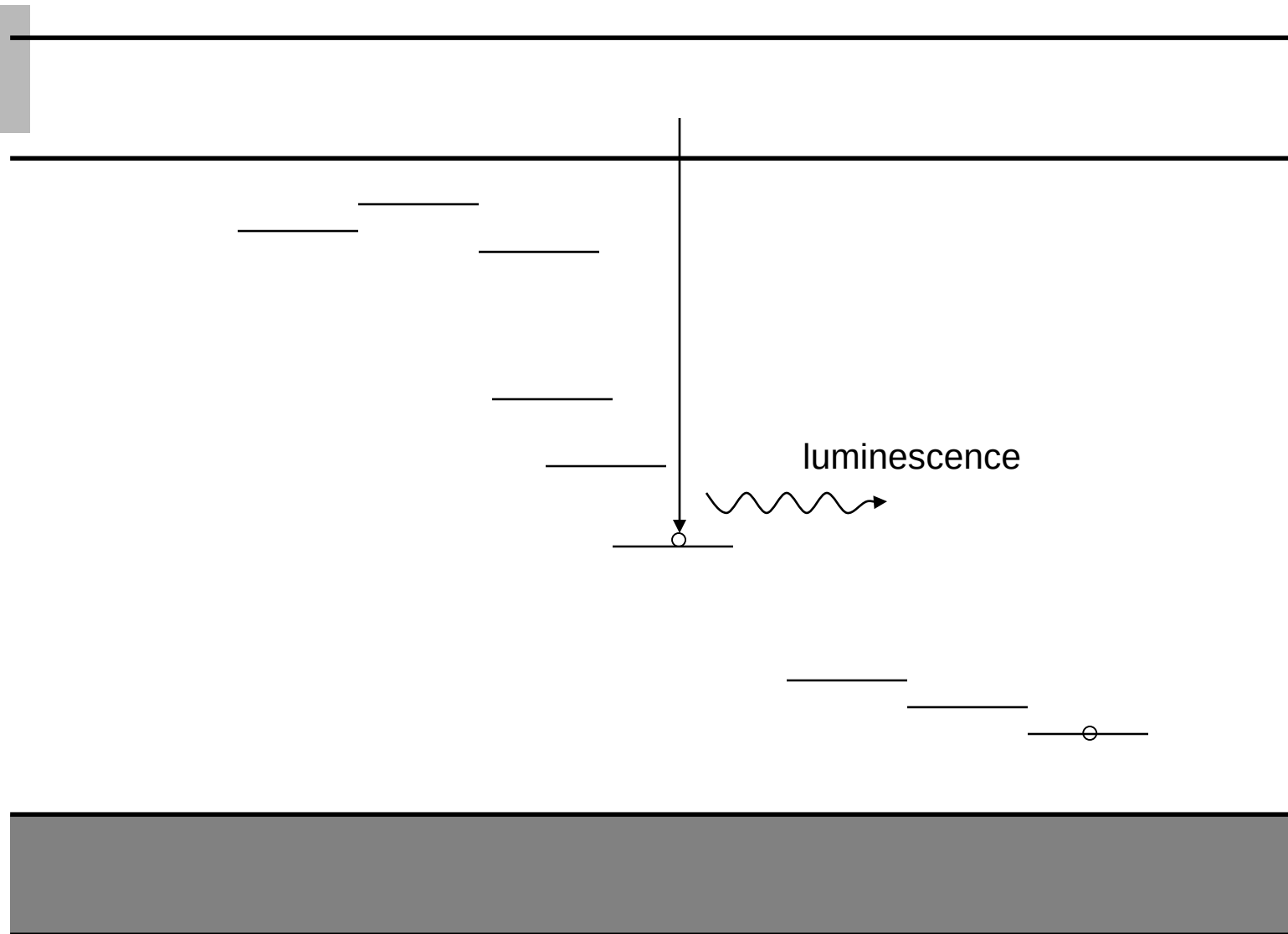


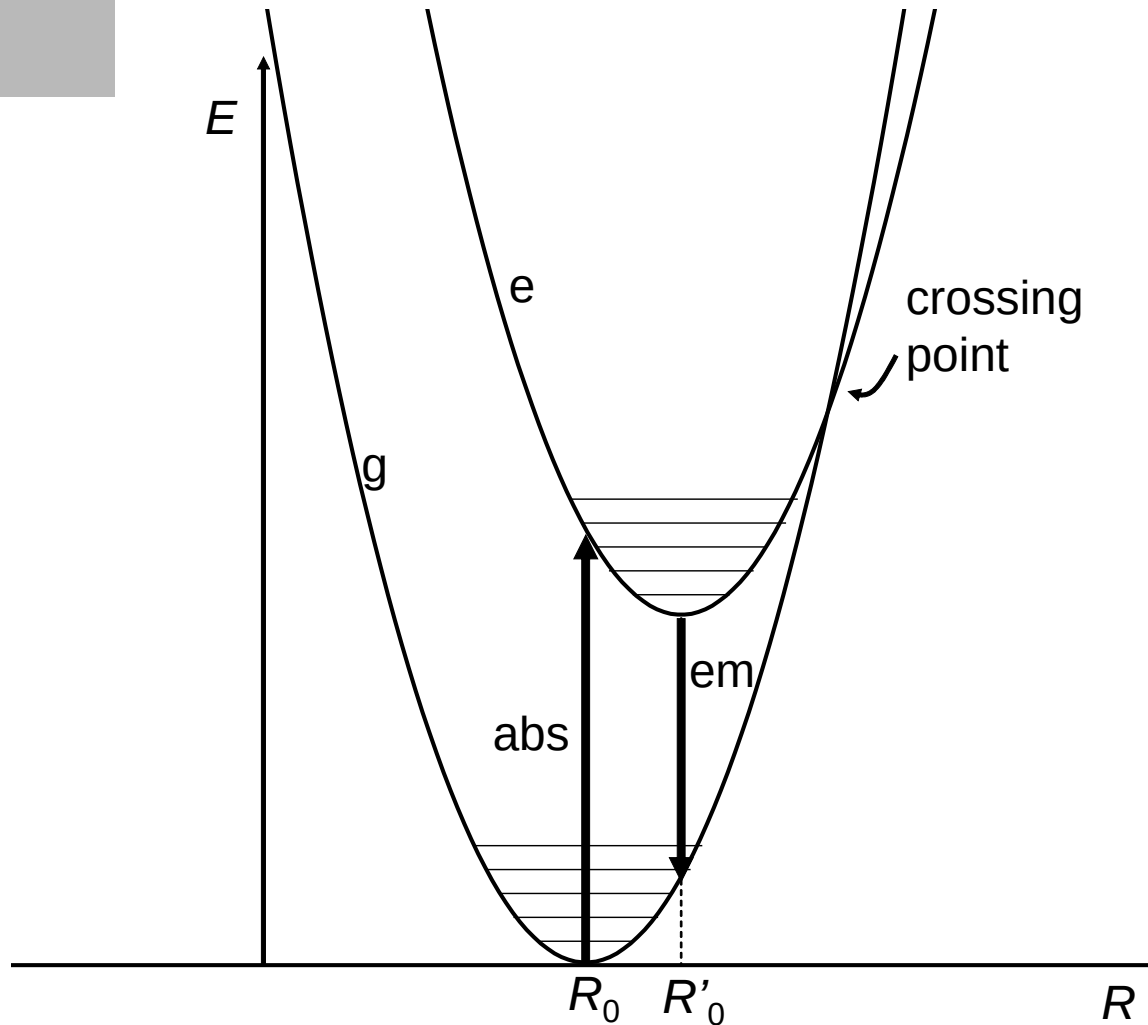
OSL stimulation spectrum



- optical stability of the trapped charges

Recombination process

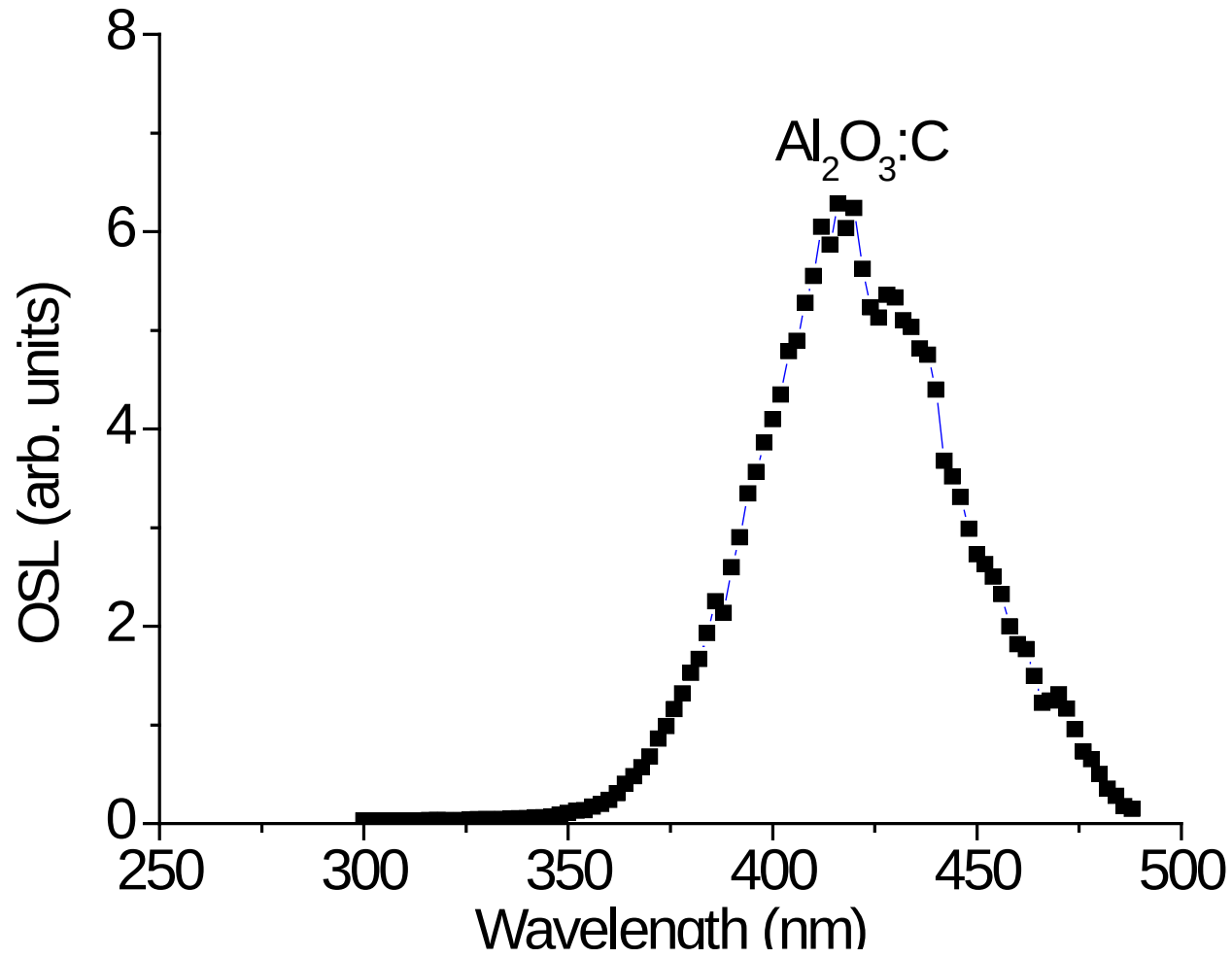




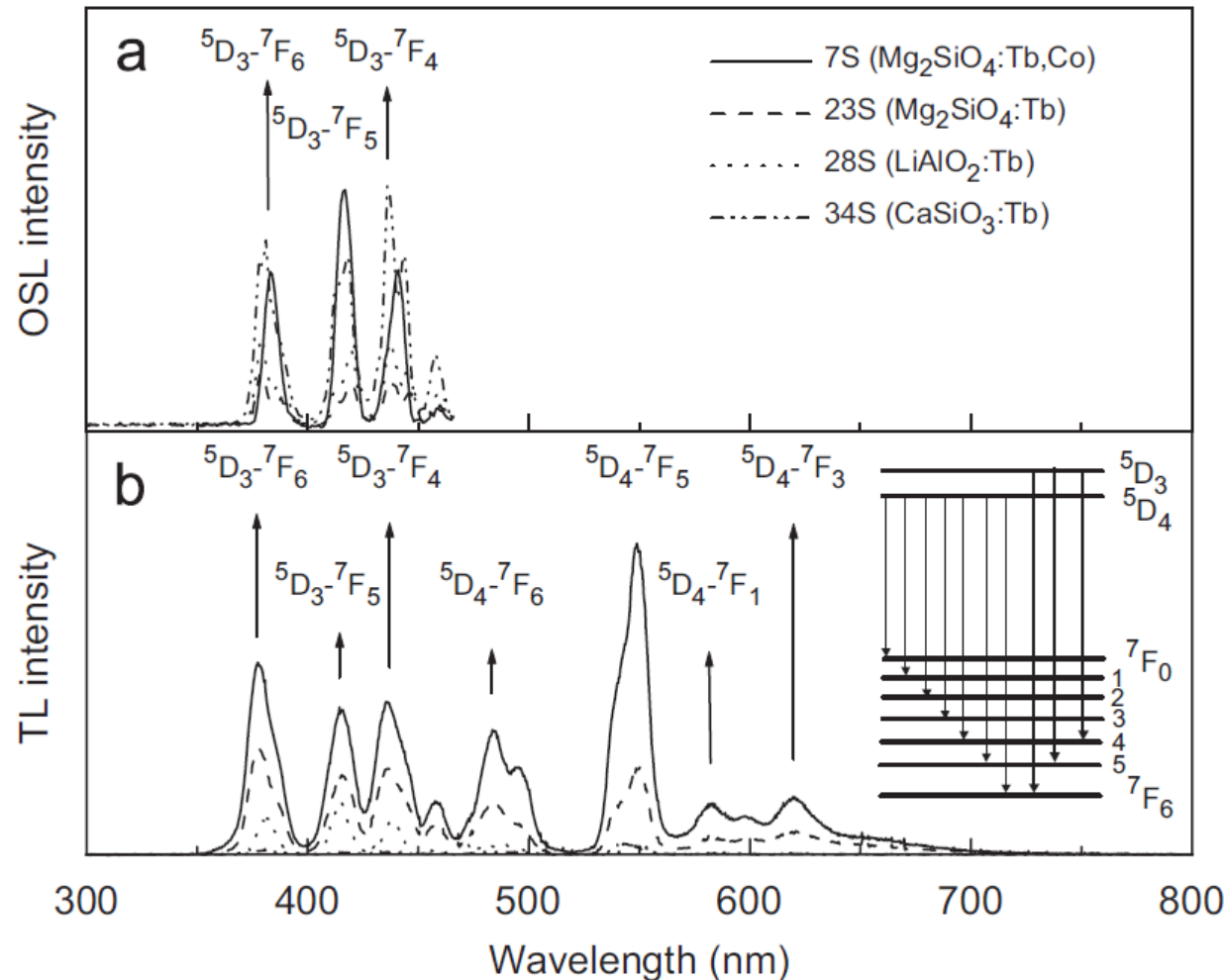
Note that relationship between energy levels determines:

- Width of the emission band
- Stokes-shift
- Relationship between radiative and non-radiative processes

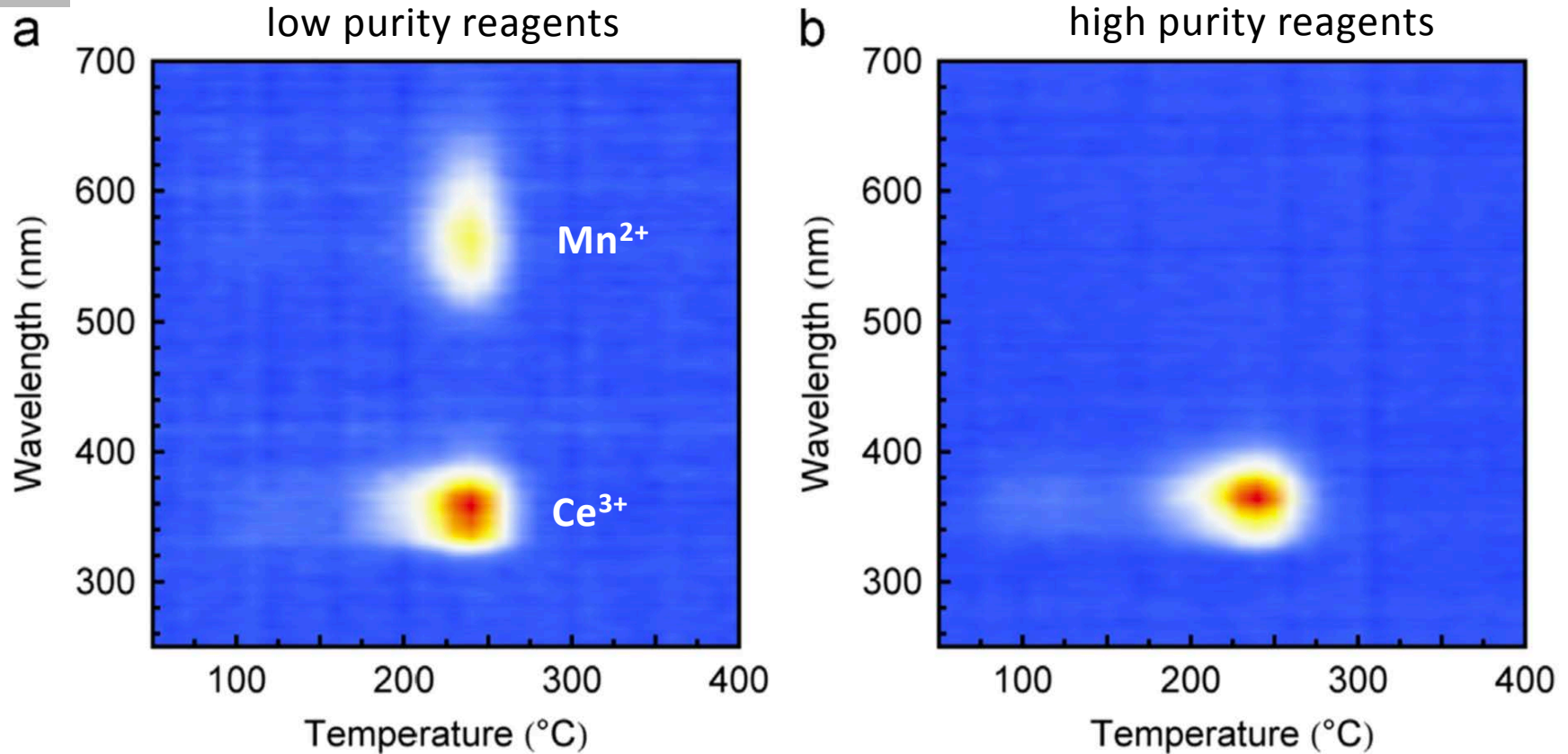
OSL emission spectrum



TL and OSL emission spectrum

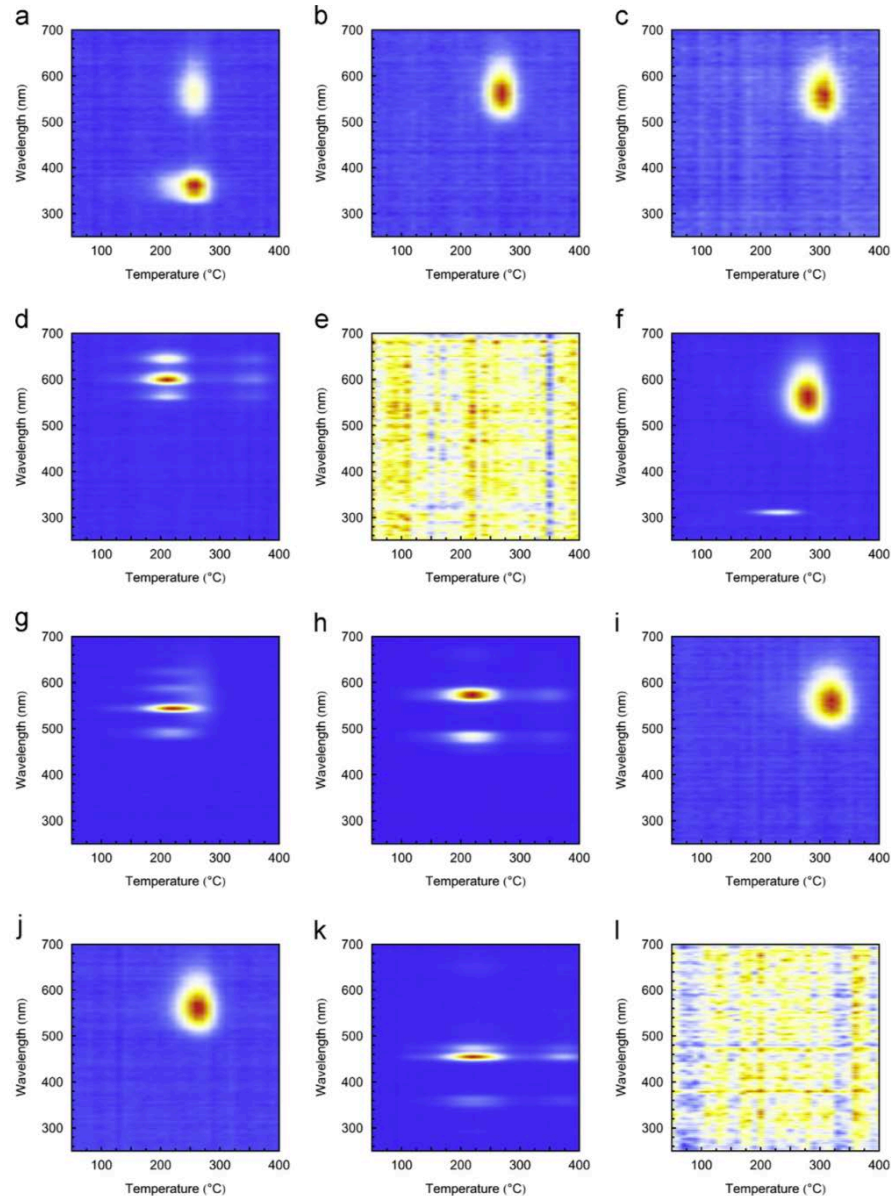


Mittani, J.C., Prokić, M., Yukihiro, E.G., 2008. Optically stimulated luminescence and thermoluminescence of terbium-activated silicates and aluminates. Radiat. Meas. 43, 323-326.



Yukihara, E.G., Milliken, E.D., Doull, B.A., 2014. Thermally stimulated and recombination processes in MgB_4O_7 investigated by systematic lanthanide doping. *J. Lumin.* 154, 251-259.

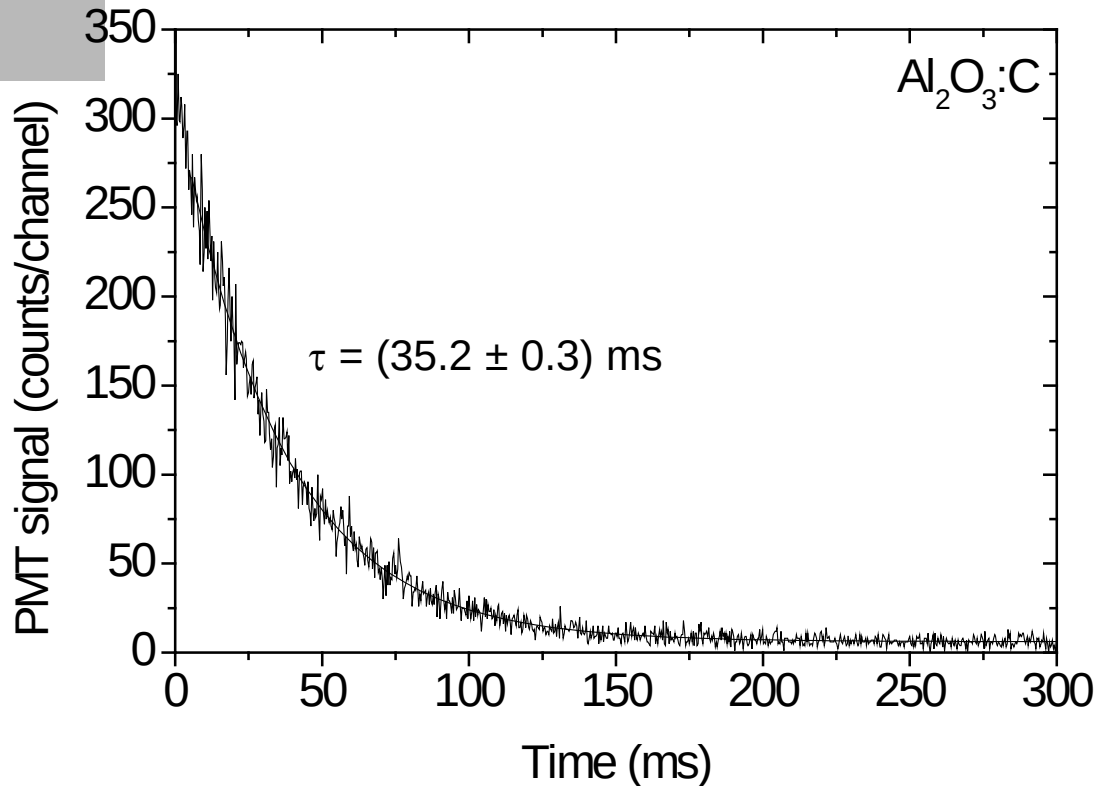
Systematic characterization of TL emission



- Detection window
- Underlying recombination processes

Yukihara, E.G., Milliken, E.D., Doull, B.A., 2014. Thermally stimulated and recombination processes in MgB_4O_7 investigated by systematic lanthanide doping. *J. Lumin.* 154, 251-259.

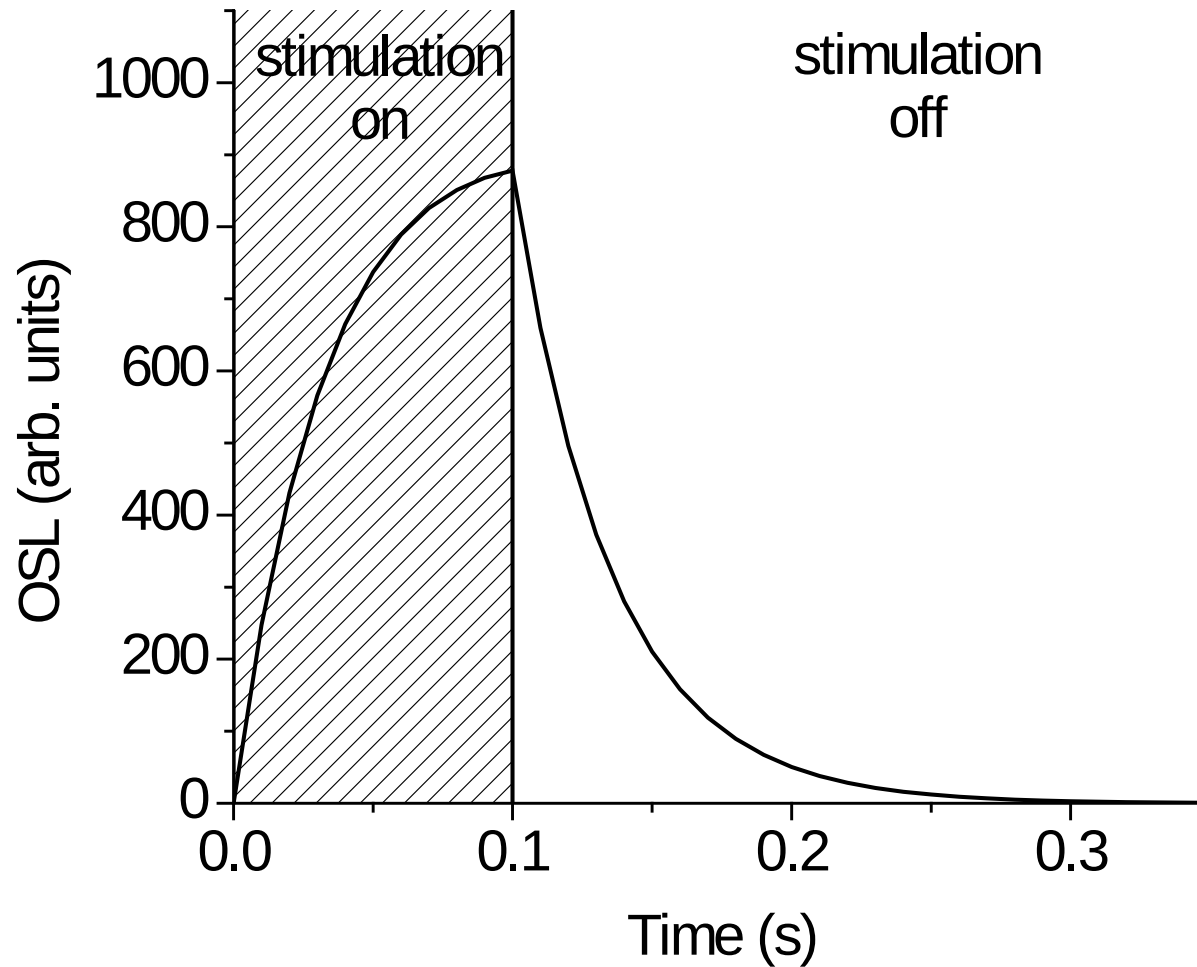
Luminescence lifetime



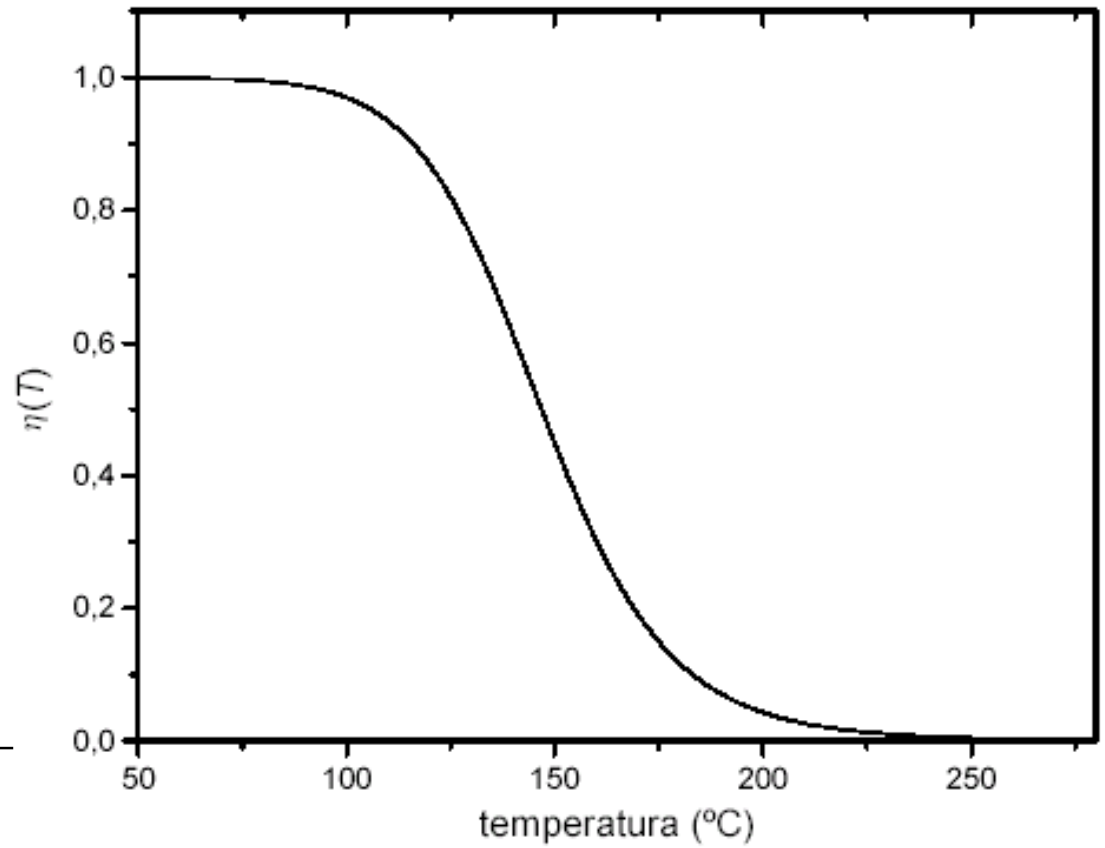
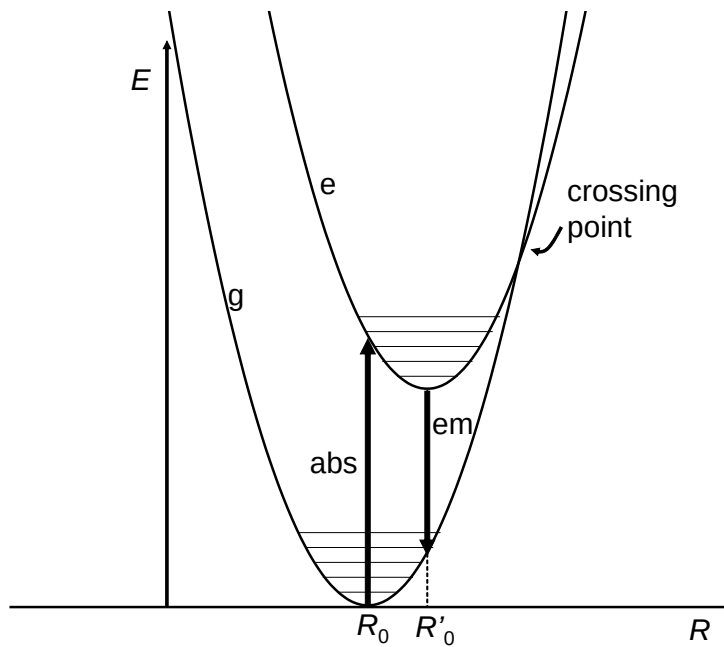
$$N_e(t) = N_e(0)e^{-\frac{t}{\tau_R}}$$

Yukihara, E.G., McKeever, S.W.S., 2006. Spectroscopy and optically stimulated luminescence of $\text{Al}_2\text{O}_3:\text{C}$ using time-resolved measurements. J. Appl. Phys. 100 (8), 083512.

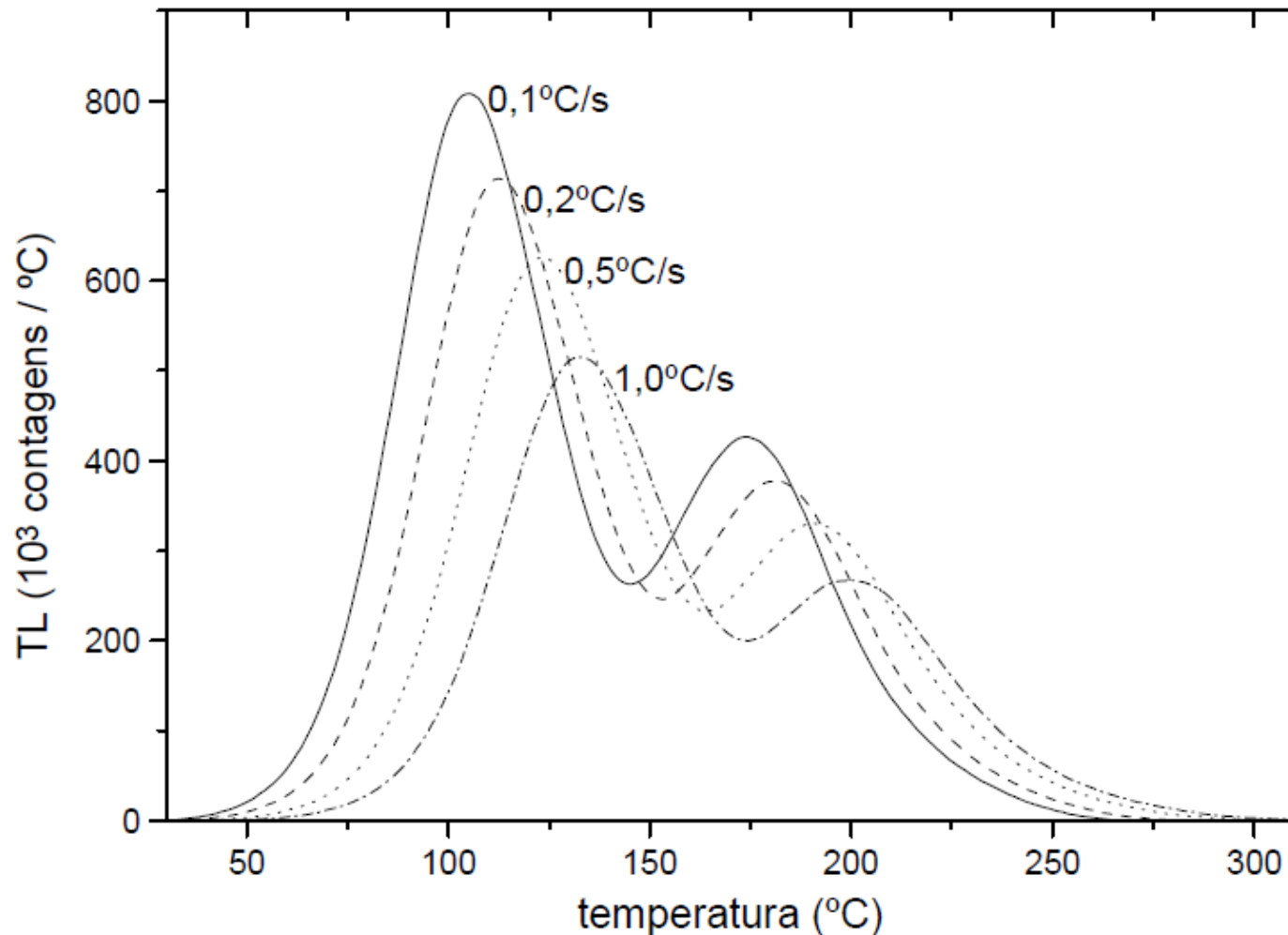
Luminescence lifetime and POSL



Thermal quenching

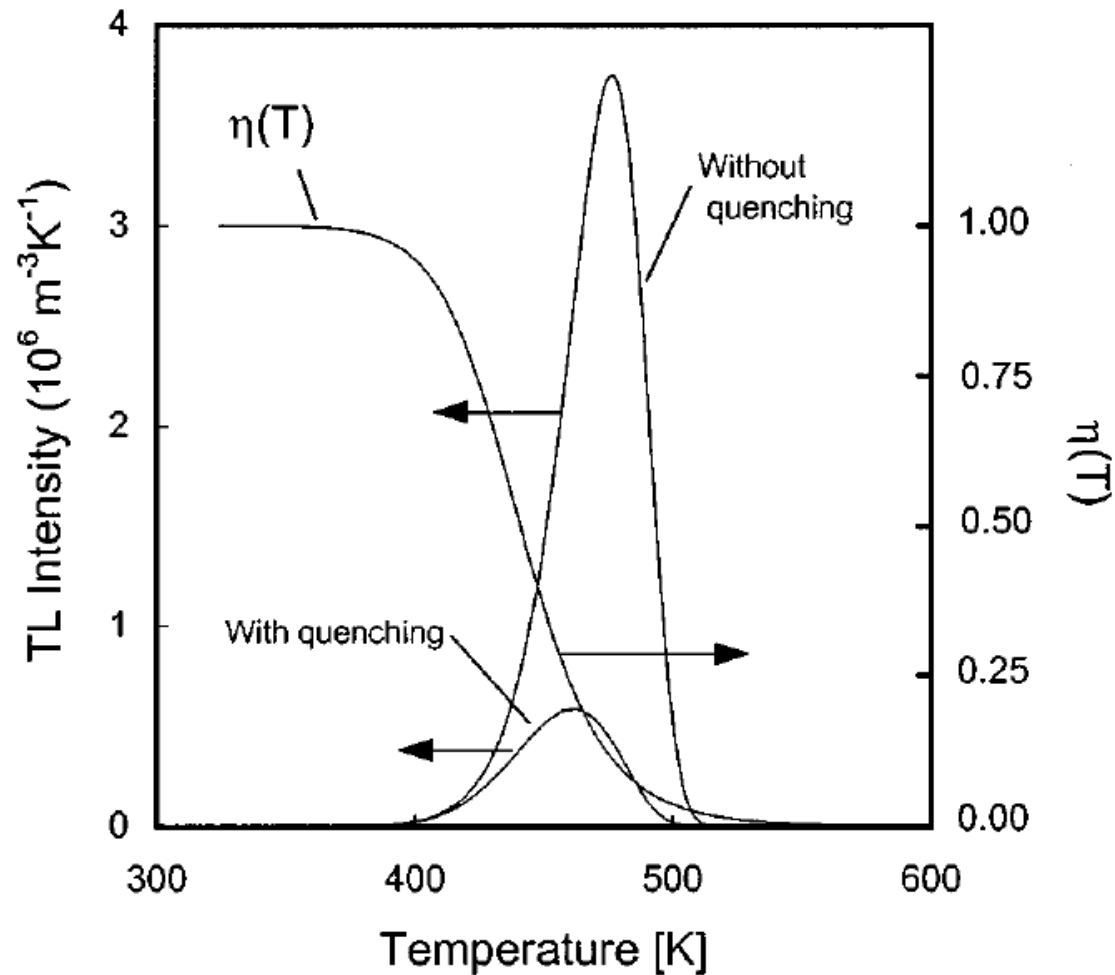


Thermal quenching



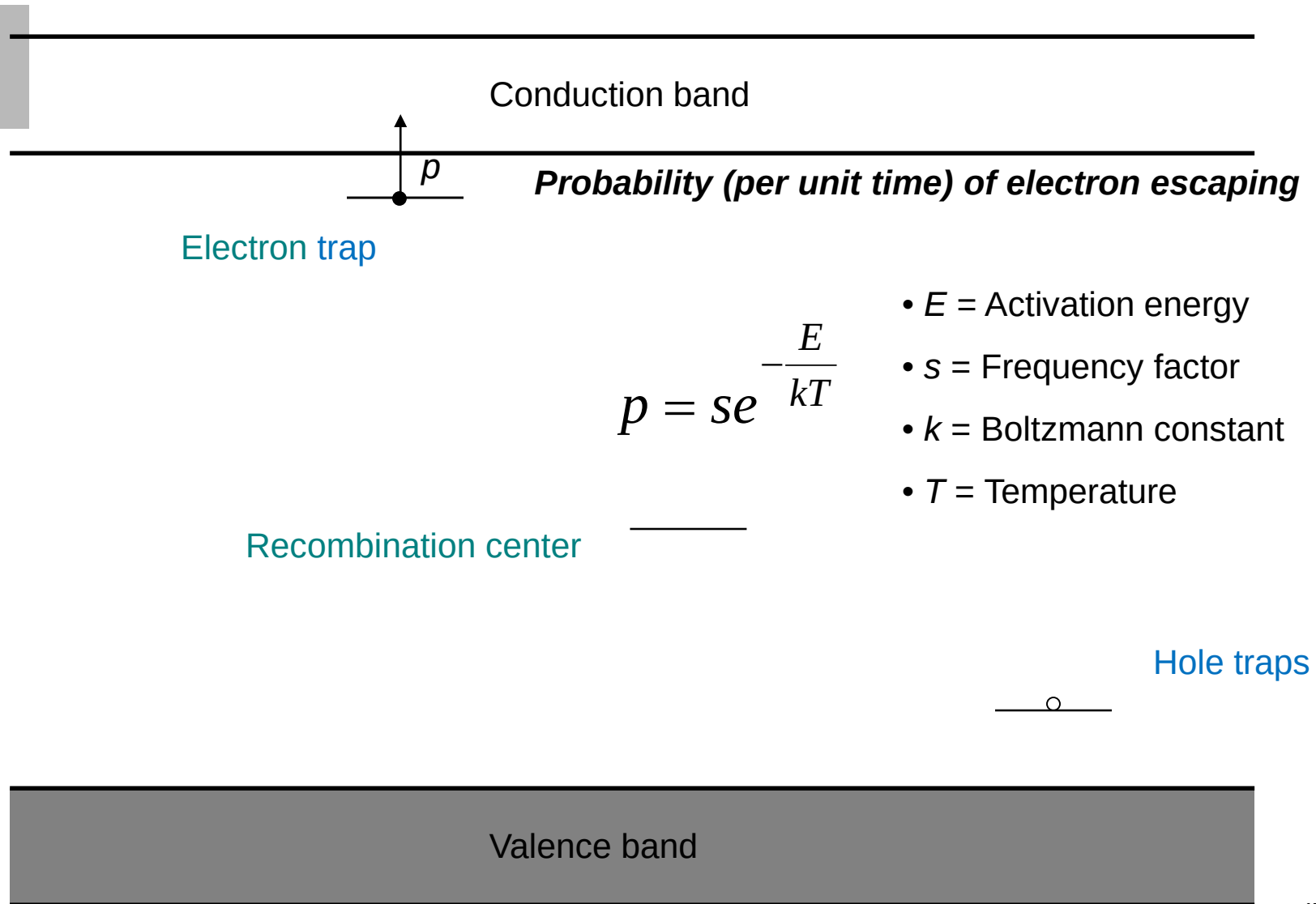
Yukihara, E.G., 2001. *Desvendando a cor e a termoluminescência do topázio*. Ph. D. Thesis, Universidade de São Paulo.

Thermal quenching



Akselrod, M.S., Agersnap Larsen, N., Whitley, V.H. and McKeever, S.W.S., 1998. *Thermal quenching of F-center luminescence in $\text{Al}_2\text{O}_3:\text{C}$* . J. Appl. Phys. 84, 3364-3373.

TL models



First-order TL model (RW)

$$T(t) = T_0 + \beta t$$

T_0 = temperature at $t = 0$

β = heating rate

$$\beta = \frac{dT}{dt}$$

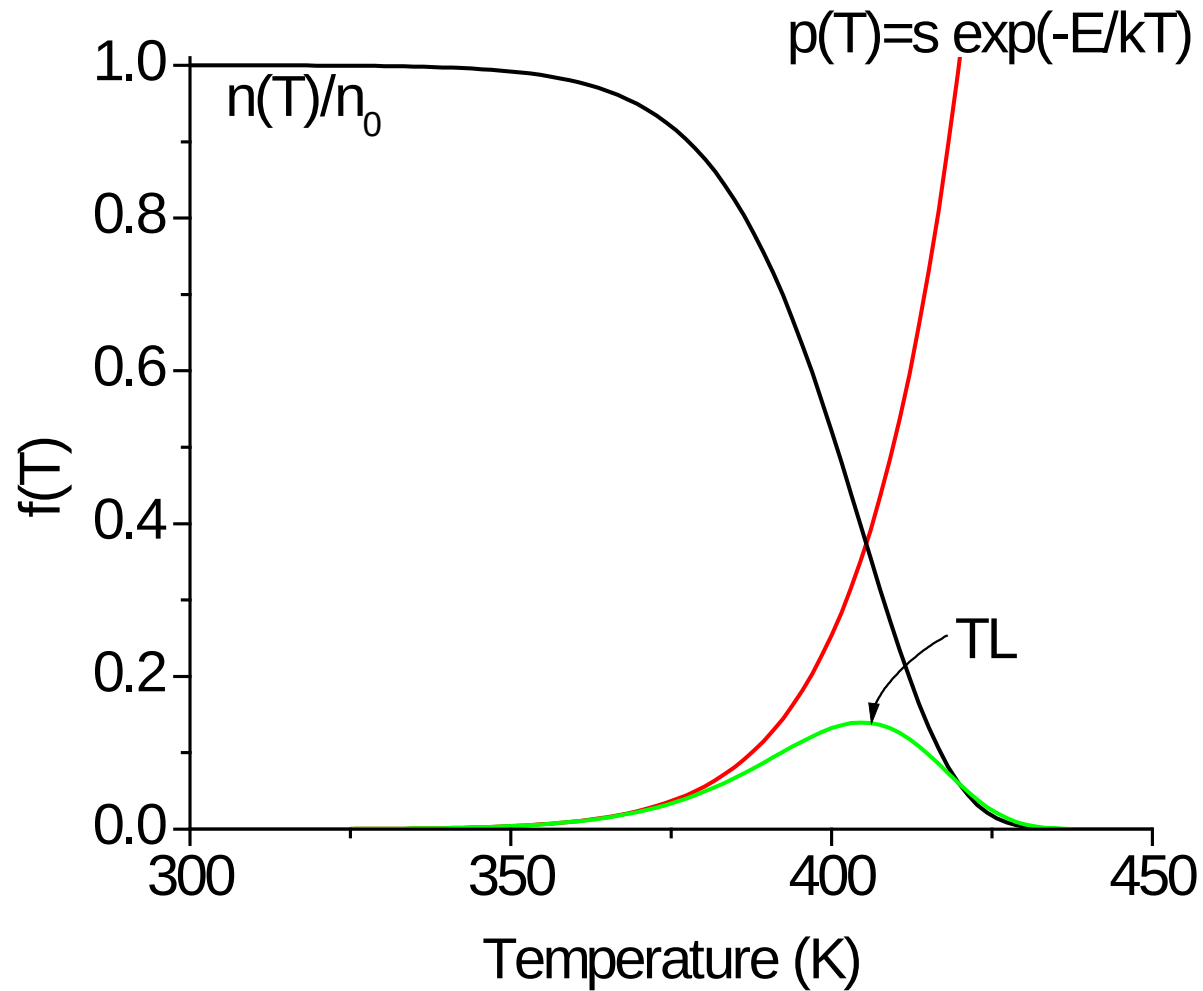
$$I_{TL} \propto \left| \frac{dm}{dt} \right| = \left| \frac{dn}{dt} \right| = np$$

$$\frac{dn}{dt} = \frac{dn}{dT} \frac{dT}{dt} = \frac{dn}{dT} \beta = -np$$

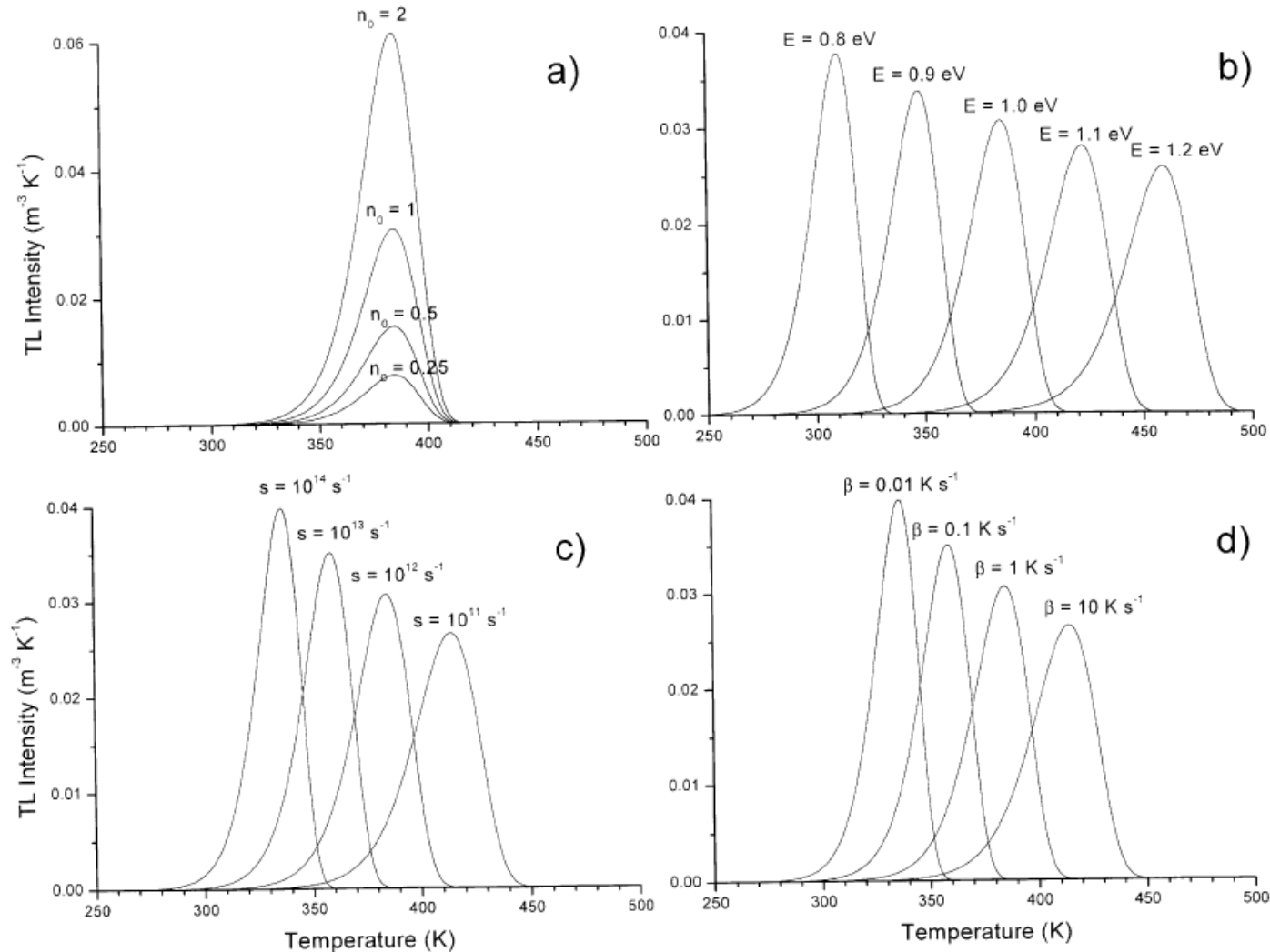
$$n = n_0 \exp \left[-\frac{s}{\beta} \int_{T_0}^T e^{-E/k\theta} d\theta \right]$$

$$I_{TL}^{RW}(T) \propto n_0 \frac{s}{\beta} \exp \left(-\frac{E}{kT} \right) \exp \left[-\frac{s}{\beta} \int_{T_0}^T \exp \left(-\frac{E}{k\theta} \right) d\theta \right]$$

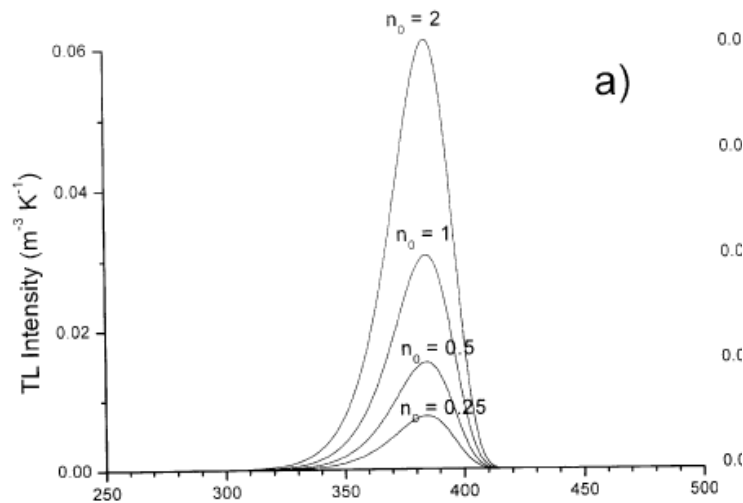
First-order TL model (RW)



First-order TL model (RW)



First-order TL model (RW)



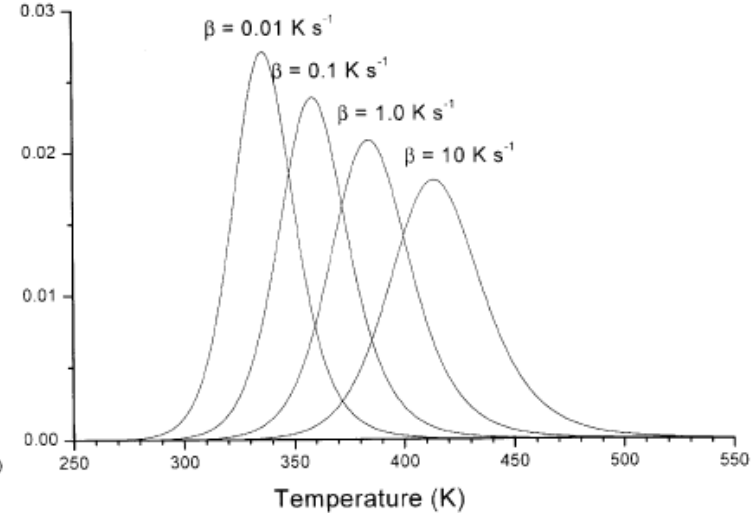
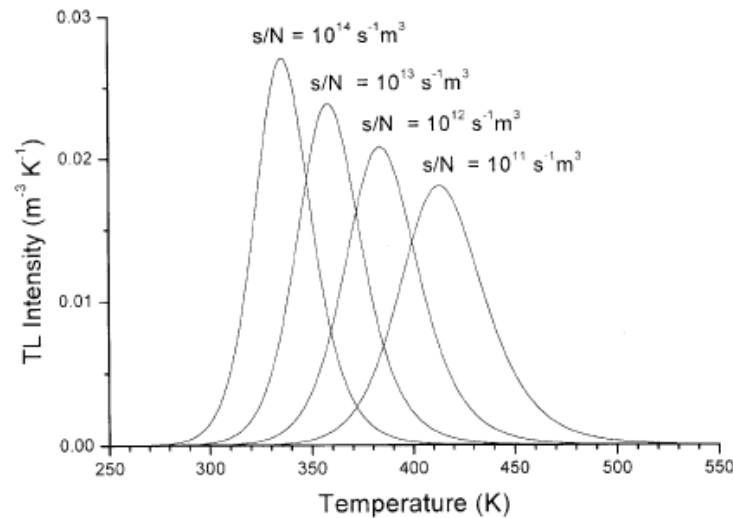
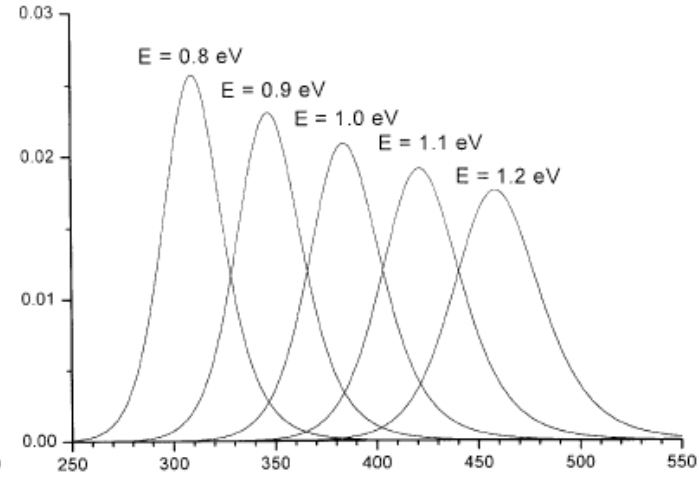
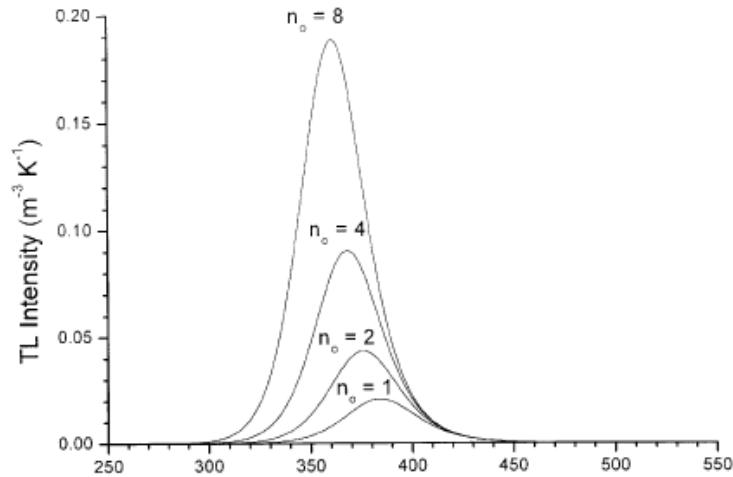
- Recombination is instantaneous
- TL peak is asymmetric
- TL peak position is not dependence on trap occupancy

Second-order TL model (GG)

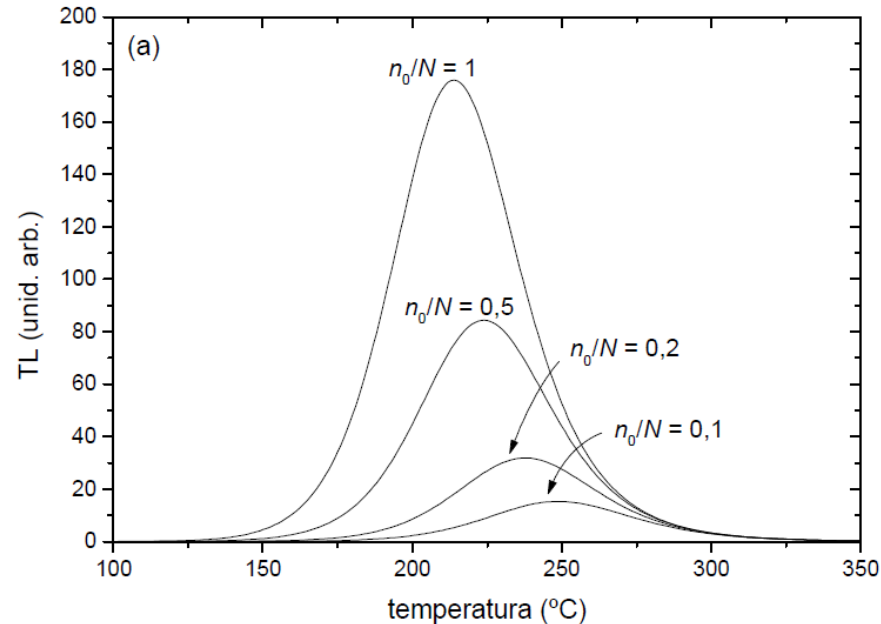
$$I_{TL}^{GG}(t) \propto \left| \frac{dm}{dt} \right| = \left| \frac{dn}{dt} \right| = \frac{n^2 p}{N}$$

$$I_{TL}^{GG}(t) = \frac{n_0^2 s}{N\beta} \exp\left(-\frac{E}{kT}\right) \exp\left[1 + \frac{n_0 s}{N\beta} \int_{T_0}^T \exp\left(-\frac{E}{kT'}\right) dT'\right]^{-2}$$

Second-order TL model (GG)



Second-order TL model (GG)



- Recombination is delayed
- TL peak is more symmetrical than 1st order
- TL peak position depends on trap occupancy

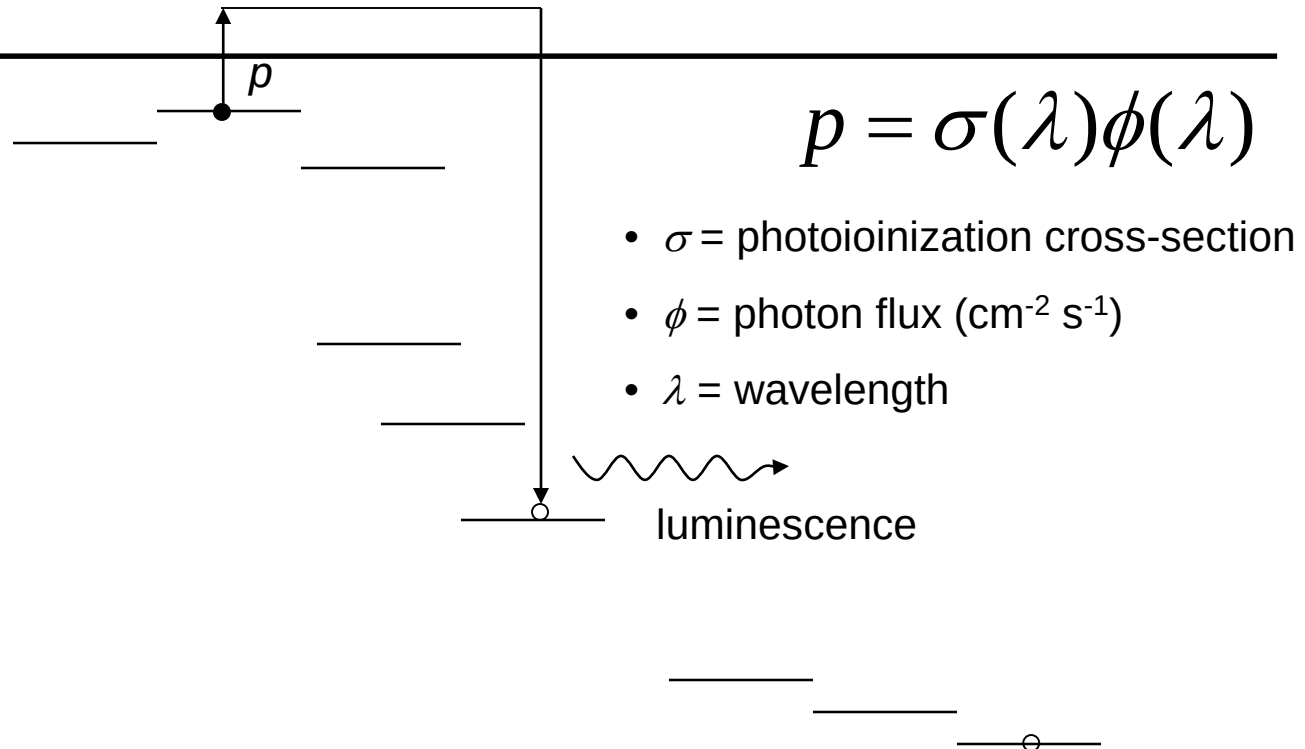
1st order $I_{TL}^{RW}(t) \propto np$

2nd order $I_{TL}^{GG}(t) \propto \frac{n^2 p}{N}$

GOK $I_{TL}^{GOK}(t) \propto \frac{n^b}{N^{b-1}} p$

$$I_{TL}^{GOK}(t) \propto \frac{n_0^b}{N^{b-1}} s e^{-E/kT} \left[1 + (b-1) \left(\frac{n_0}{N} \right)^{b-1} \frac{1}{\beta} \int_{T_0}^T \exp\left(-\frac{E}{k\theta}\right) d\theta \right]^{-\frac{b}{b-1}}$$

First-order OSL model



$n(t)$ = concentration of trapped electrons

n_0 = initial concentration of trapped electrons

$$\frac{dn}{dt} = -np$$

$$p = \sigma(\lambda)\phi(\lambda)$$

$$\frac{1}{n} dn = -p dt$$

$$\ln n - \ln n_0 = -pt$$

$$\ln\left(\frac{n}{n_0}\right) = -pt$$

$$n = n_0 e^{-pt} = n_0 e^{-\sigma\phi t}$$

First-order OSL model

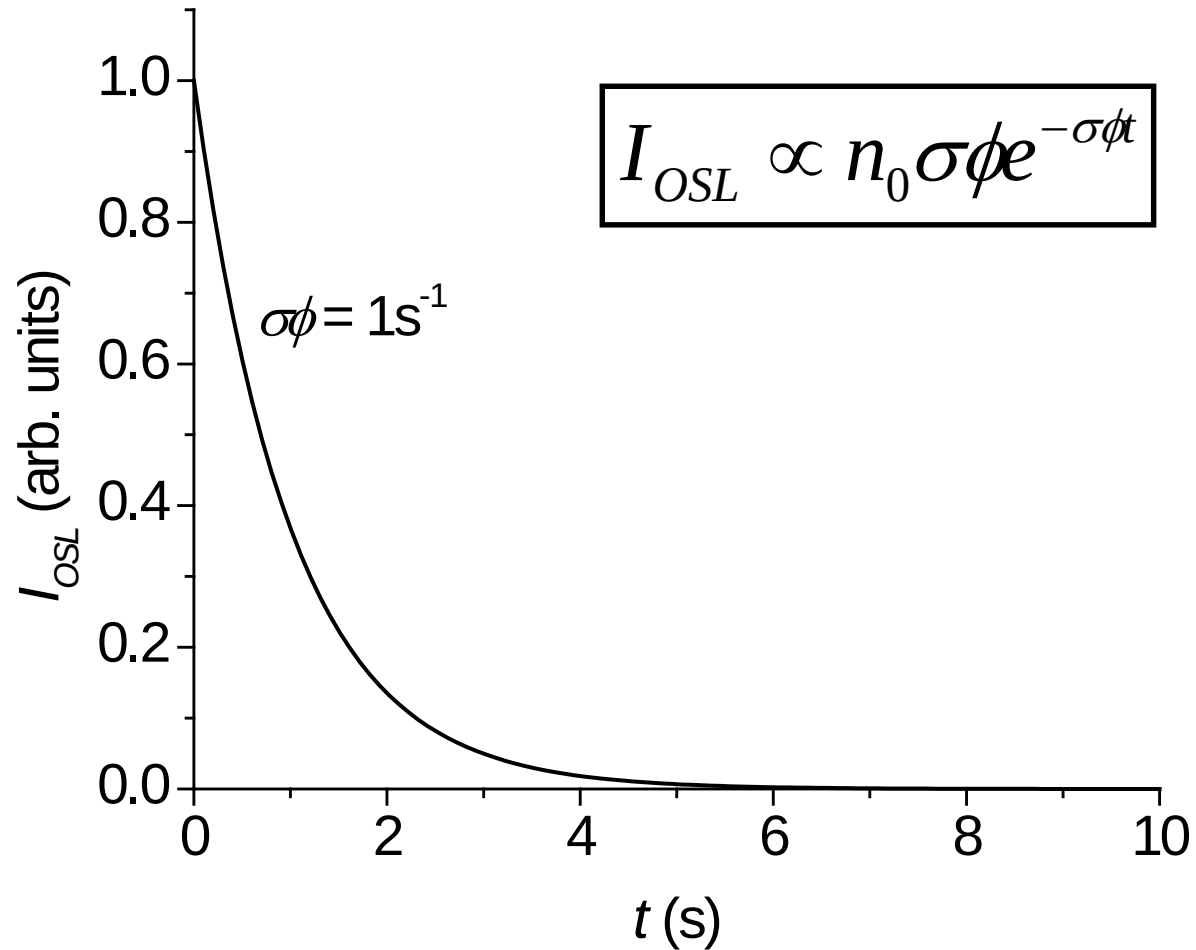
$$\frac{dn}{dt} = -np$$

$$n = n_0 e^{-\sigma\phi t}$$

$$I_{OSL} \propto \left| \frac{dn}{dt} \right| = np = (n_0 e^{-\sigma\phi t}) (\sigma\phi)$$

$$I_{OSL} \propto n_0 \sigma \phi e^{-\sigma\phi t}$$

First-order OSL model



First-order OSL model

type of defect and wavelength

$$I_{OSL} \propto n_0 \sigma \phi e^{-\sigma \phi t}$$

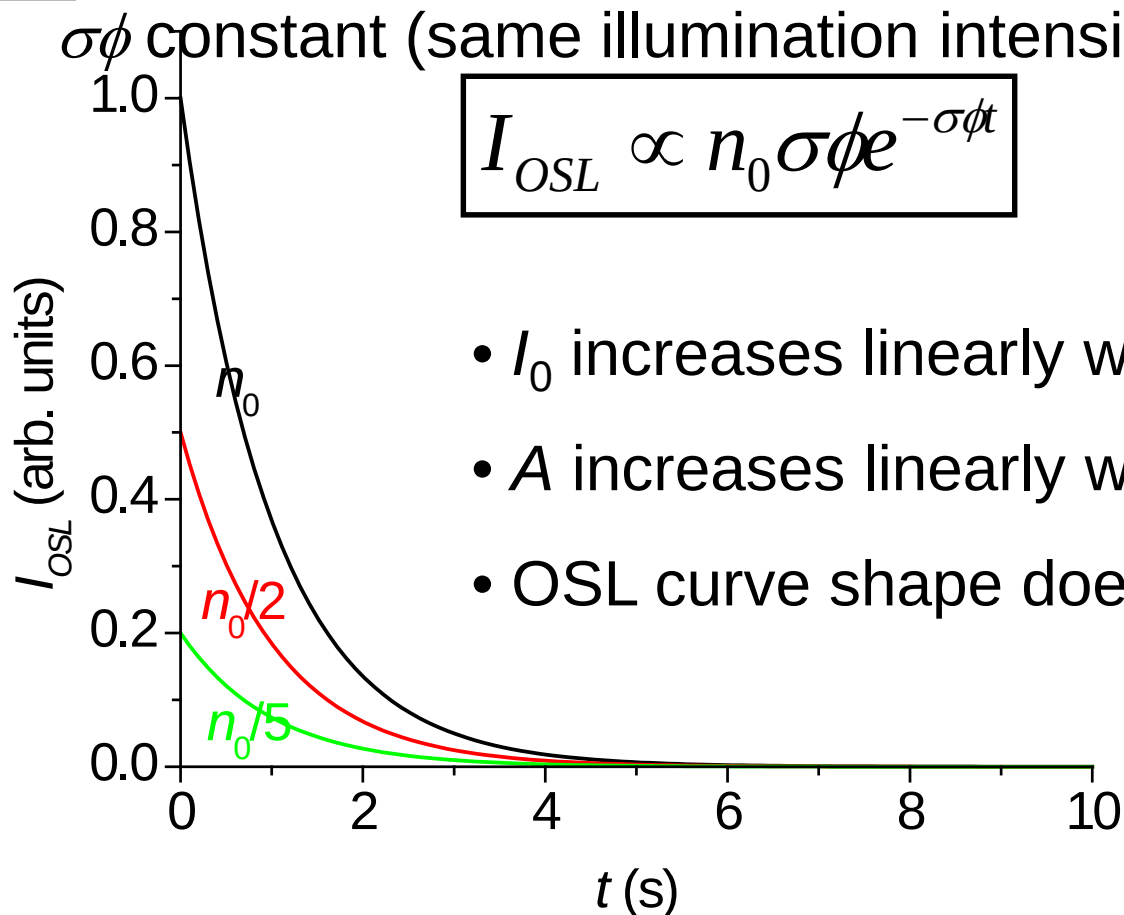
dose

Illumination intensity

Dose dependence

$\sigma\phi$ constant (same illumination intensity)

$$I_{OSL} \propto n_0 \sigma \phi e^{-\sigma \phi t}$$



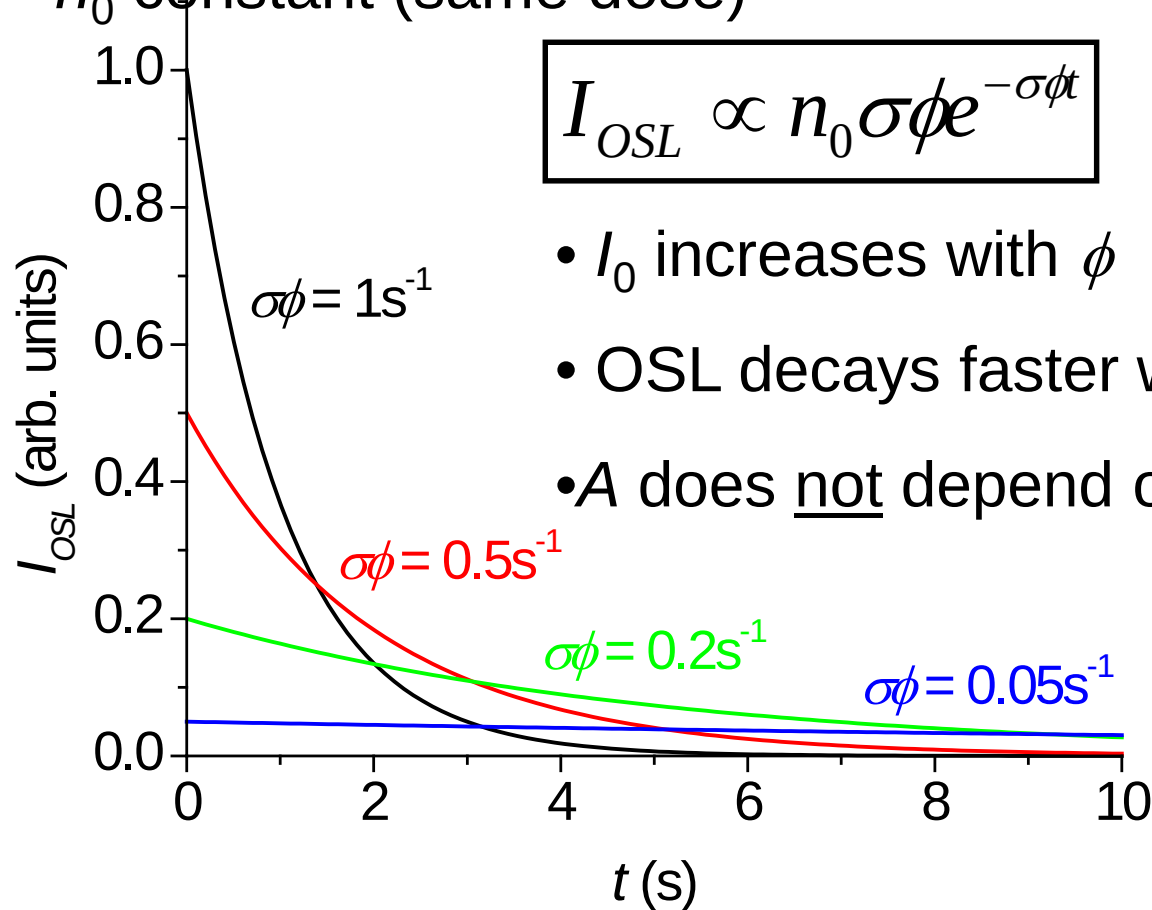
- I_0 increases linearly with dose
- A increases linearly with dose
- OSL curve shape does not depend on dose

Dependence with stimulation

n_0 constant (same dose)

$$I_{OSL} \propto n_0 \sigma \phi e^{-\sigma \phi t}$$

- I_0 increases with ϕ
- OSL decays faster with increase in ϕ
- A does not depend on ϕ



Dependence with stimulation

n_0 constant (same dose)

$$A = \int_0^{\infty} I_{OSL} dt \propto \int_0^{\infty} n_0 \sigma \phi e^{-\sigma \phi t} dt = n_0 \sigma \phi \int_0^{\infty} e^{-\sigma \phi t} dt$$

$$A \propto n_0 \sigma \phi \left[-\frac{e^{-\sigma \phi t}}{\sigma \phi} \right]_0^{\infty} = n_0 (-0 + 1)$$

$$\boxed{A \propto n_0}$$

Other OSL models

1st order

$$I_{OSL}^{RW}(t) \propto np$$

2nd order

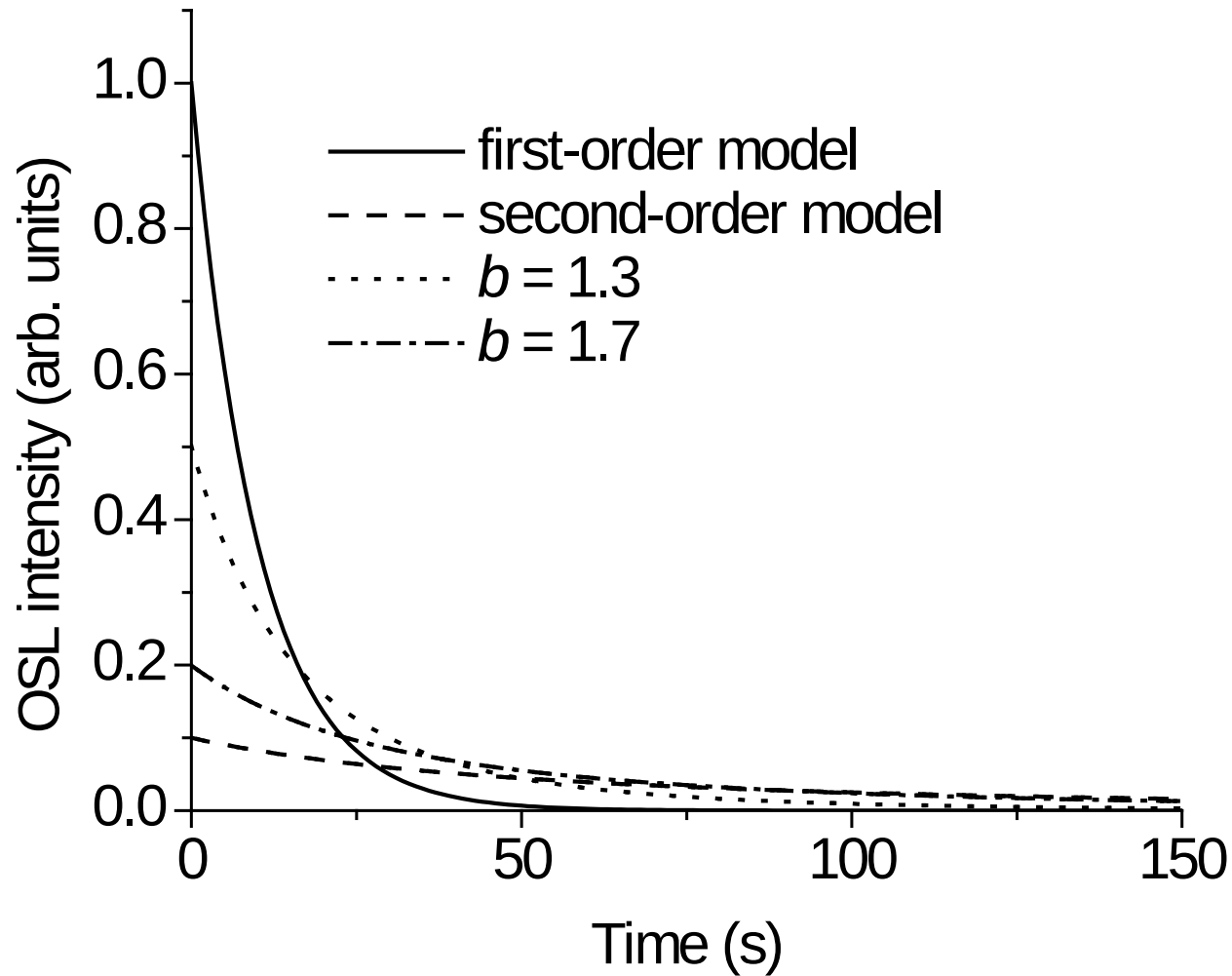
$$I_{OSL}^{GG}(t) \propto \frac{n^2 p}{N}$$

GOK

$$I_{OSL}^{GOK}(t) \propto \frac{n^b}{N^{b-1}} p$$

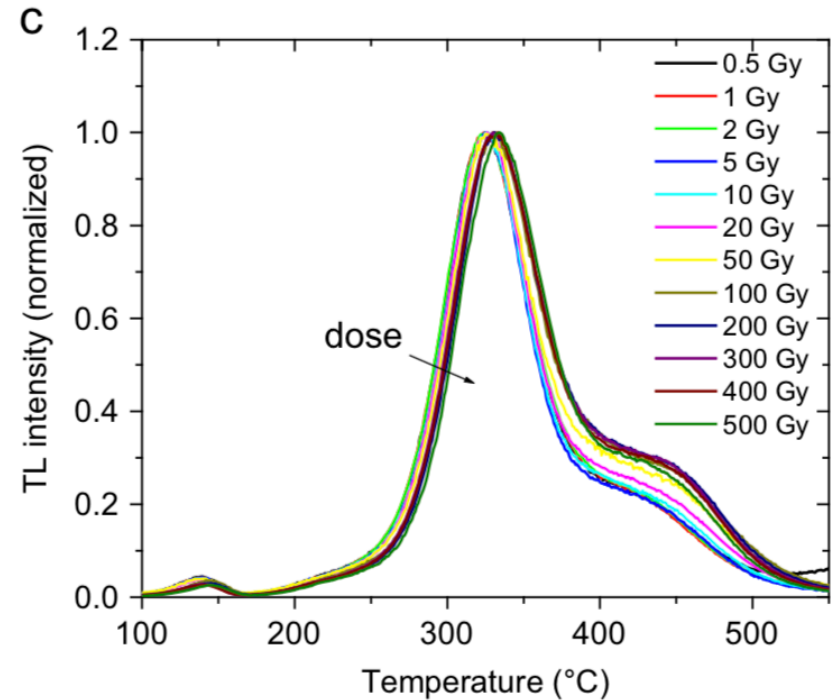
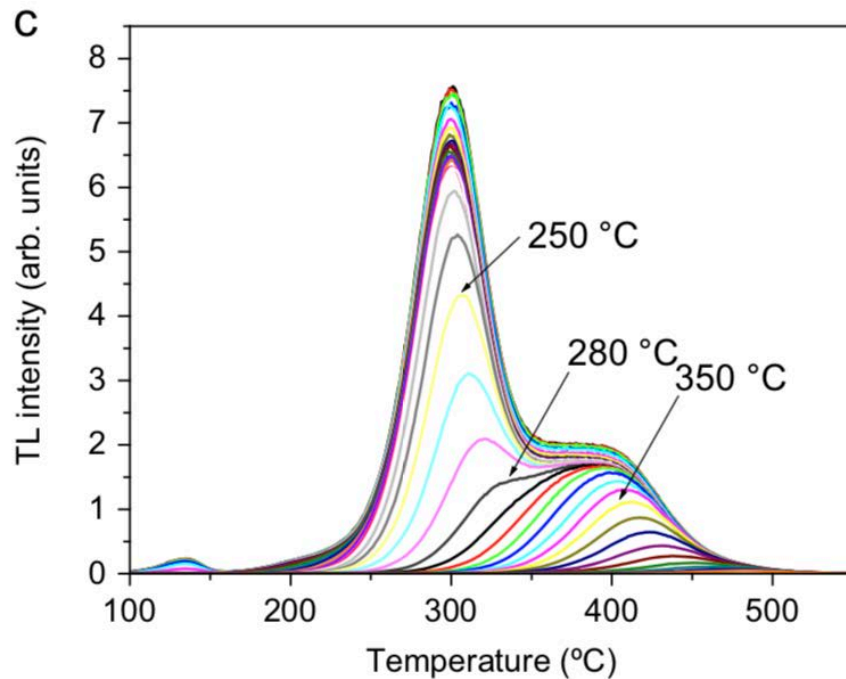
$$I_{OSL}^{GOK}(t) \propto \frac{n_0^b p}{N^{b-1}} \left[1 + (b-1) \left(\frac{n_0}{N} \right)^{b-1} pt \right]^{-\frac{b}{b-1}}$$

Other OSL models



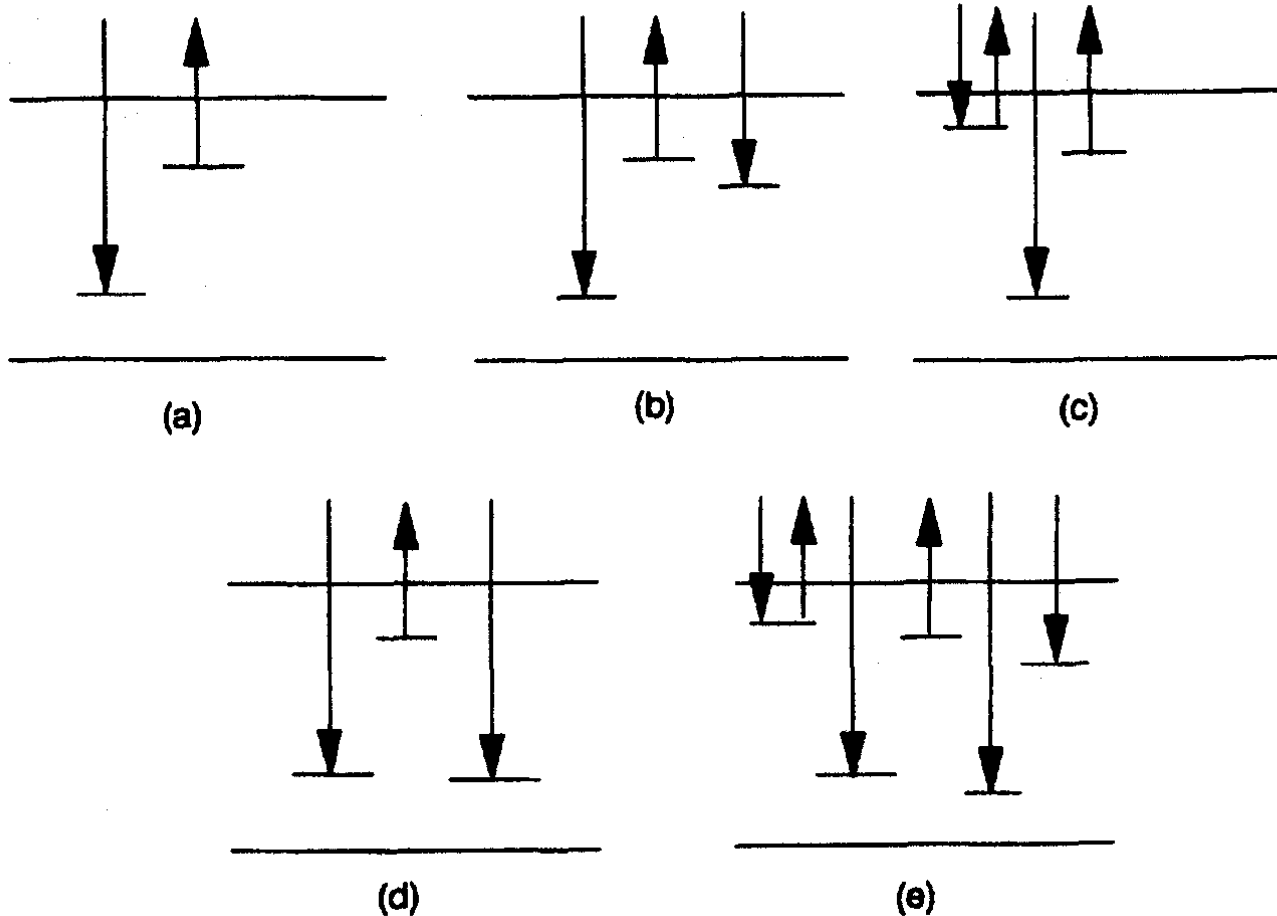
Word of caution about $b \neq 1$!

- Rarely seen in nature (why?)
- Implies TL peak shift to lower temperatures with dose
- b may vary even during TL readout (fitting with fixed b is meaningless)
- Superposition principle is not valid (fitting of multiple peaks is meaningless)

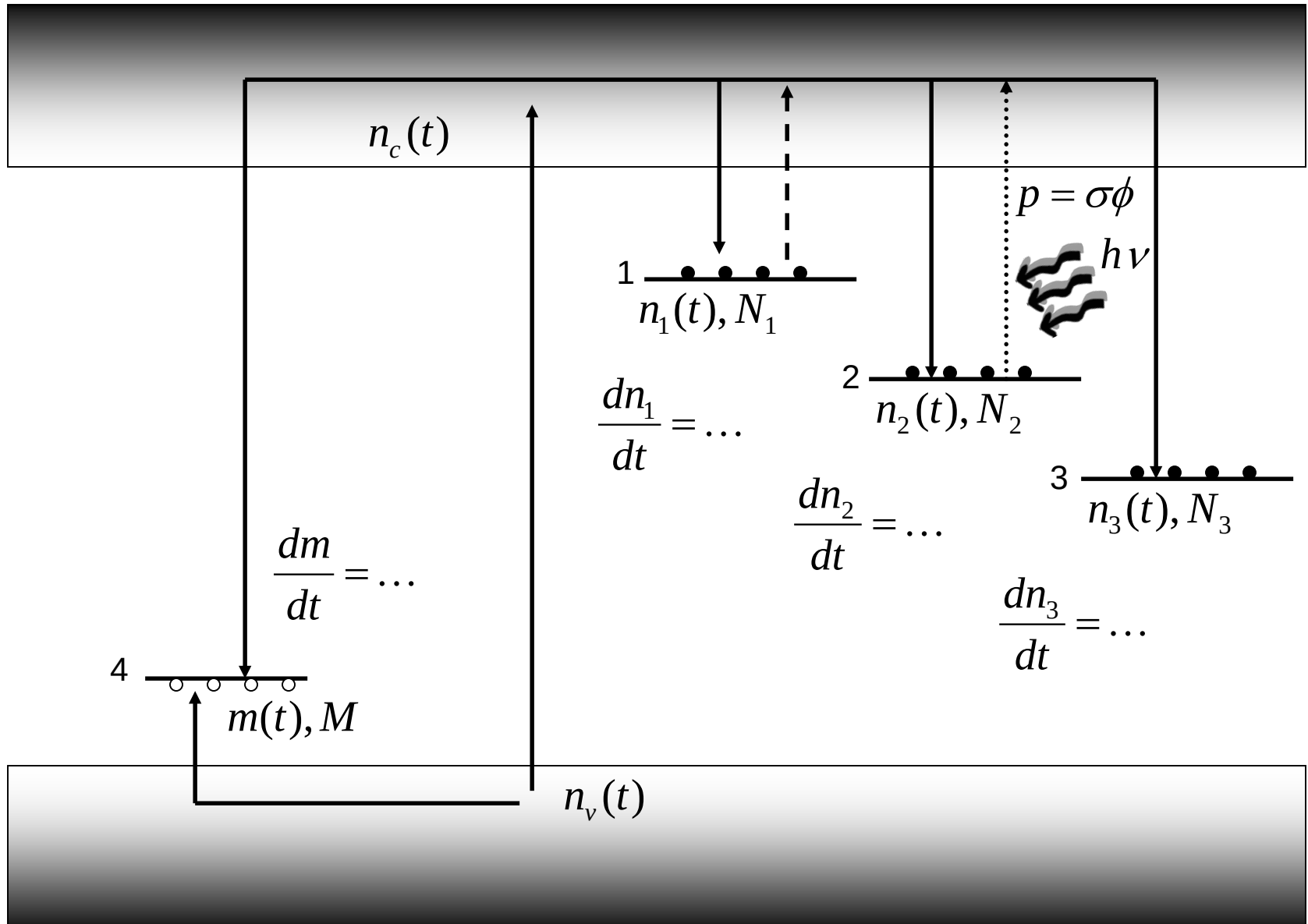


Doull, B.A., Oliveira, L.C., Wang, D.Y., Milliken, E.D., Yukihiro, E.G., 2014. Thermoluminescent properties of lithium borate, magnesium borate and calcium sulfate developed for temperature sensing. J. Lumin. 146, 408-417.

Other models



S. W. S. McKeever, L. Bøtter-Jensen, N. Agersnap Larsen, G. A. T. Duller. Temperature Dependence of OSL Decay Curves: Experimental and Theoretical Aspects. *Radiat. Meas.* 27, 161-170 (1997).



$$\frac{dn_1(t)}{dt} = -n_1(t)s_1e^{-\frac{E_1}{kT}} + [N_1 - n_1(t)]A_1n_c(t)$$

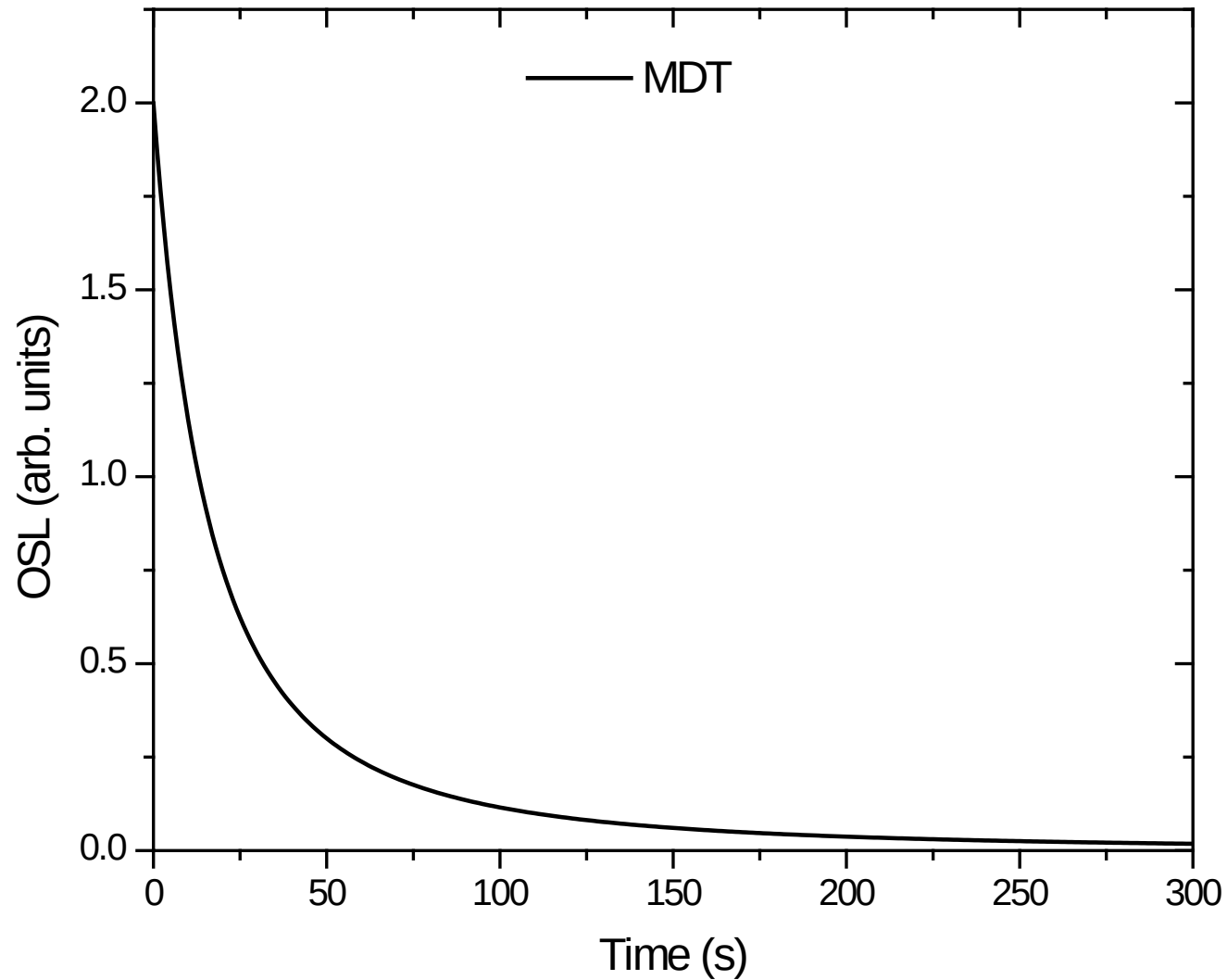
$$\frac{dn_2(t)}{dt} = -n_2(t)\sigma_2\phi + [N_2 - n_2(t)]A_2n_c(t)$$

$$\frac{dn_3(t)}{dt} = [N_3 - n_3(t)]A_3n_c(t)$$

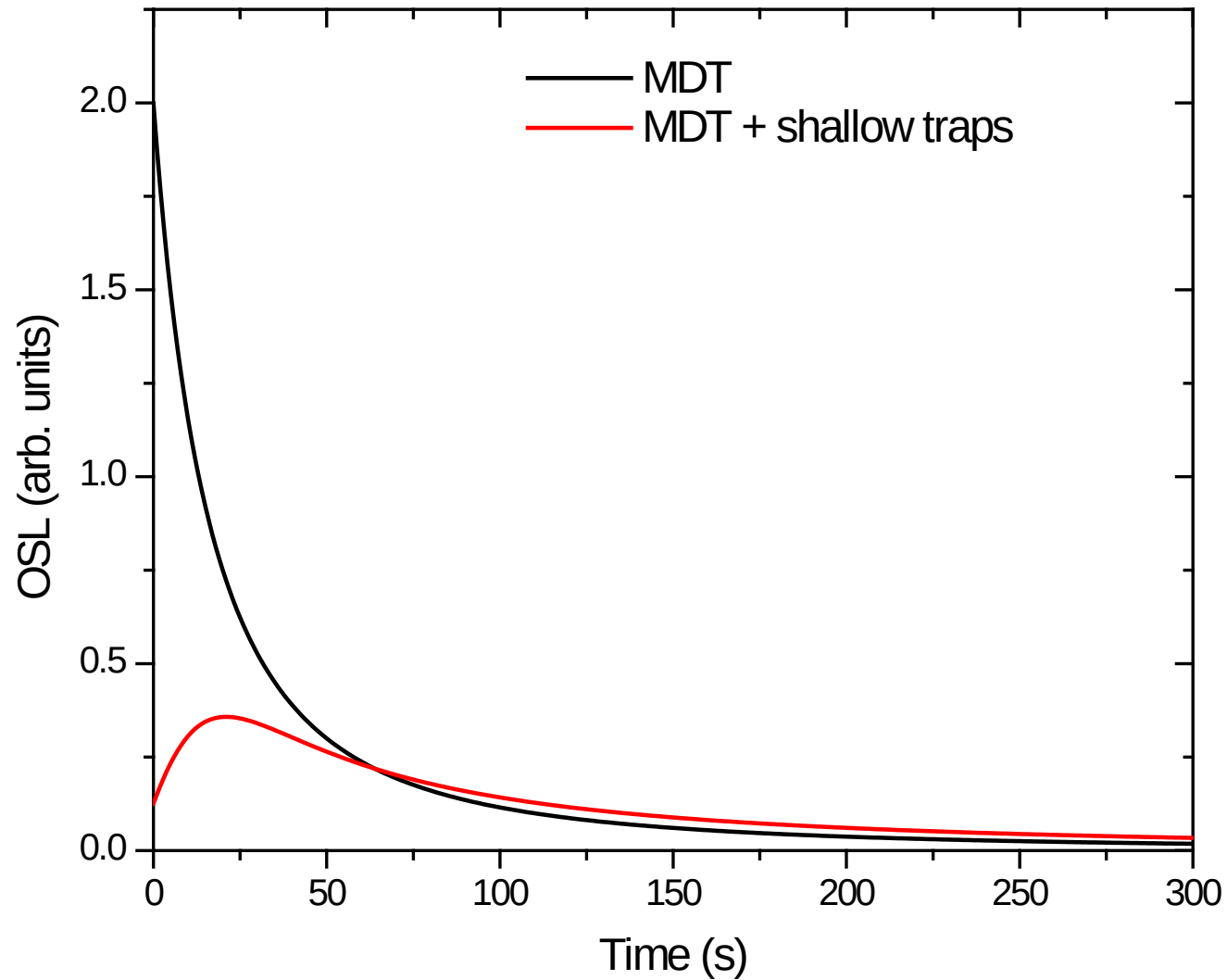
$$\frac{dm(t)}{dt} = -m(t)A_mn_c(t) + f$$

$$n_c(t) = \frac{f + n_1(t)s_1e^{-\frac{E_1}{kT}} + n_2(t)\sigma_2\phi}{[N_1 - n_1(t)]A_1 + [N_2 - n_2(t)]A_2 + [N_3 - n_3(t)]A_3 + m(t)A_m}$$

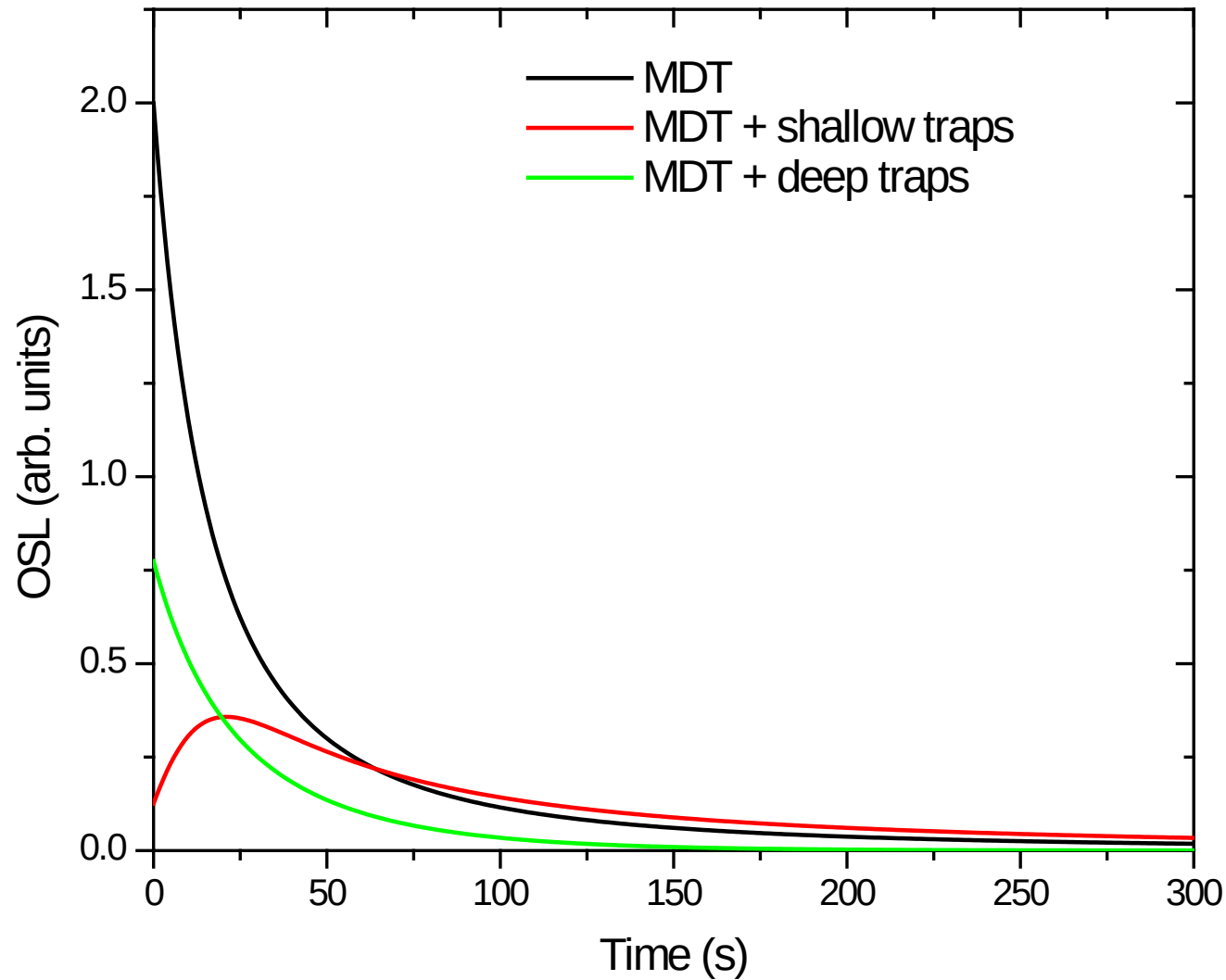
Effect of shallow traps and deep traps on OSL



Effect of shallow traps and deep traps on OSL



Effect of shallow traps and deep traps on OSL



Advantages/disadvantages

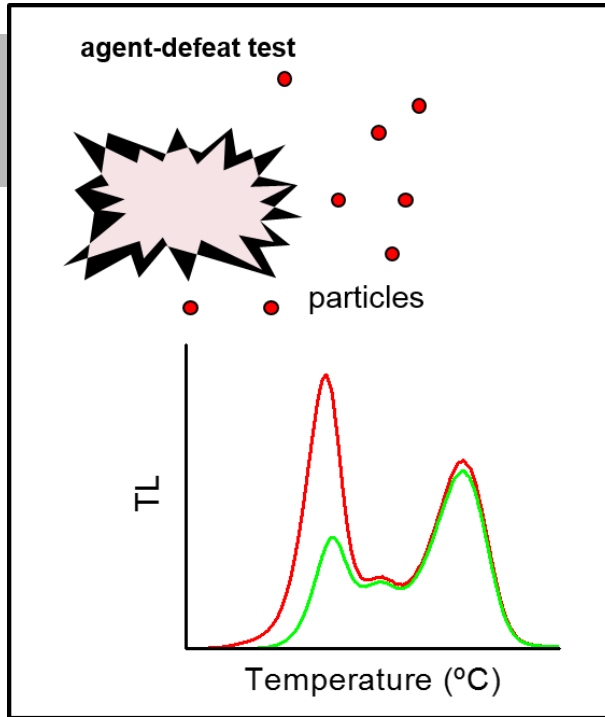
TL

- Relatively slow (~seconds)
- Wide availability of materials
- Possibly light insensitive
- Intrinsic neutron sensitivity (Li, B)
- Easy to select stable signal

OSL

- Fast readout (~1 s)
- Only $\text{Al}_2\text{O}_3:\text{C}$ and BeO
- Sensitive to light
- Neutron insensitive / need converters
- Shallow traps leads to fading

TL temperature sensing

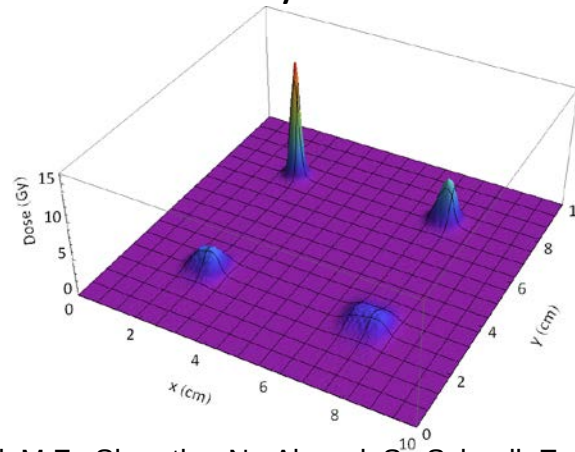


J. J. Talghader, M. L. Mah, E. G. Yukihiro, A. C. Coleman, *Microsystems & Nanoengineering* 2 (2016) 16037.

new TL/OSL materials

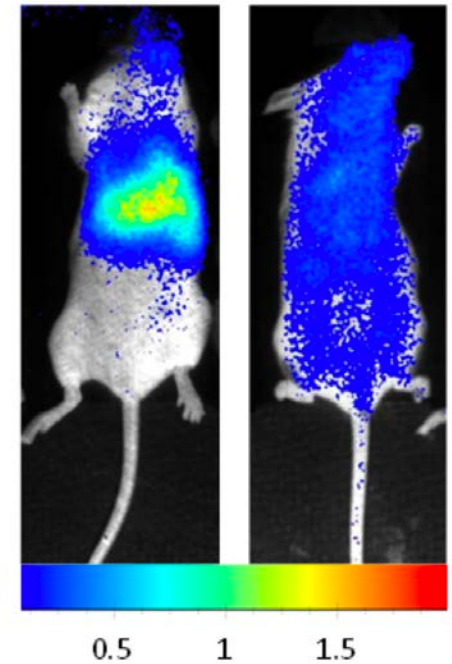


2D dosimetry



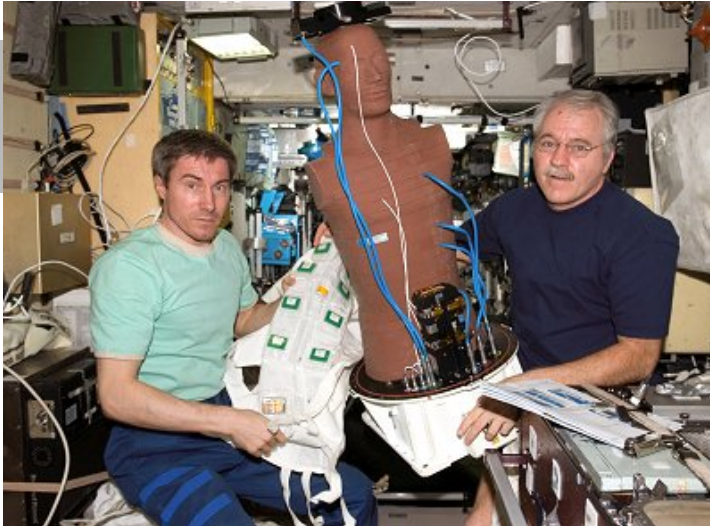
Ahmed, M.F., Shrestha, N., Ahmad, S., Schnell, E., Akselrod, M.S., Yukihiro, E.G., 2017. Demonstration of 2D dosimetry using Al₂O₃ optically stimulated luminescence films for therapeutic megavoltage x-ray and ion beams. *Radiat. Meas.* 106, 315-320.

persistent phosphors



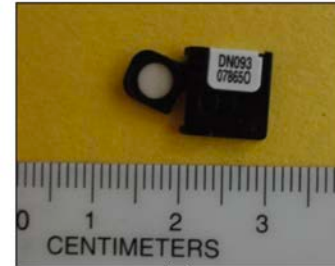
M. Pellerin, E. Glais, T. Lecuyer, J. Xu, J. Seguin, S. Tanabe, C. Chanéac, B. Viana, C. Richard, J. Lumin. 202 (2018) 83-88.

space dosimetry



Berger et al., 2016. DOSIS & DOSIS 3D: long-term dose monitoring onboard the Columbus Laboratory of the International Space Station (ISS). J. Space Weather Space Clim. 6, A39.

medical applications



(a)



(b)



Scarboro, S.B., Cody, D., Alvarez, P., Followill, D., Court, L., Stingo, F.C., Zhang, D., McNitt-Gray, M., Kry, S.F., 2015. Characterization of the nanoDot OSLD dosimeter in CT. Med Phys 42, 1797-1807.

Stepusin, E.J., Long, D.J., Ficarrota, K.R., Hintenlang, D.E., Bolch, W.E., 2017. Physical validation of a Monte Carlo-based, phantom-derived approach to computed tomography organ dosimetry under tube current modulation. Med Phys 44, 5423-5432.

We discussed...

- ... fundamentals of the TL/OSL process
- ... main TL/OSL characteristics
- ... advantages and disadvantages
- ... trends



Thank you for attention

Many thanks to...

- Martin Nikl
- LUMDETR scientific committee

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