Passive Space Radiation Dosimetry using Optically and Thermally Stimulated Luminescence

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Acknowledgements

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Thanks are due especially to:

Dr. Eduardo Yukihara

Dr. Ramona Gaza

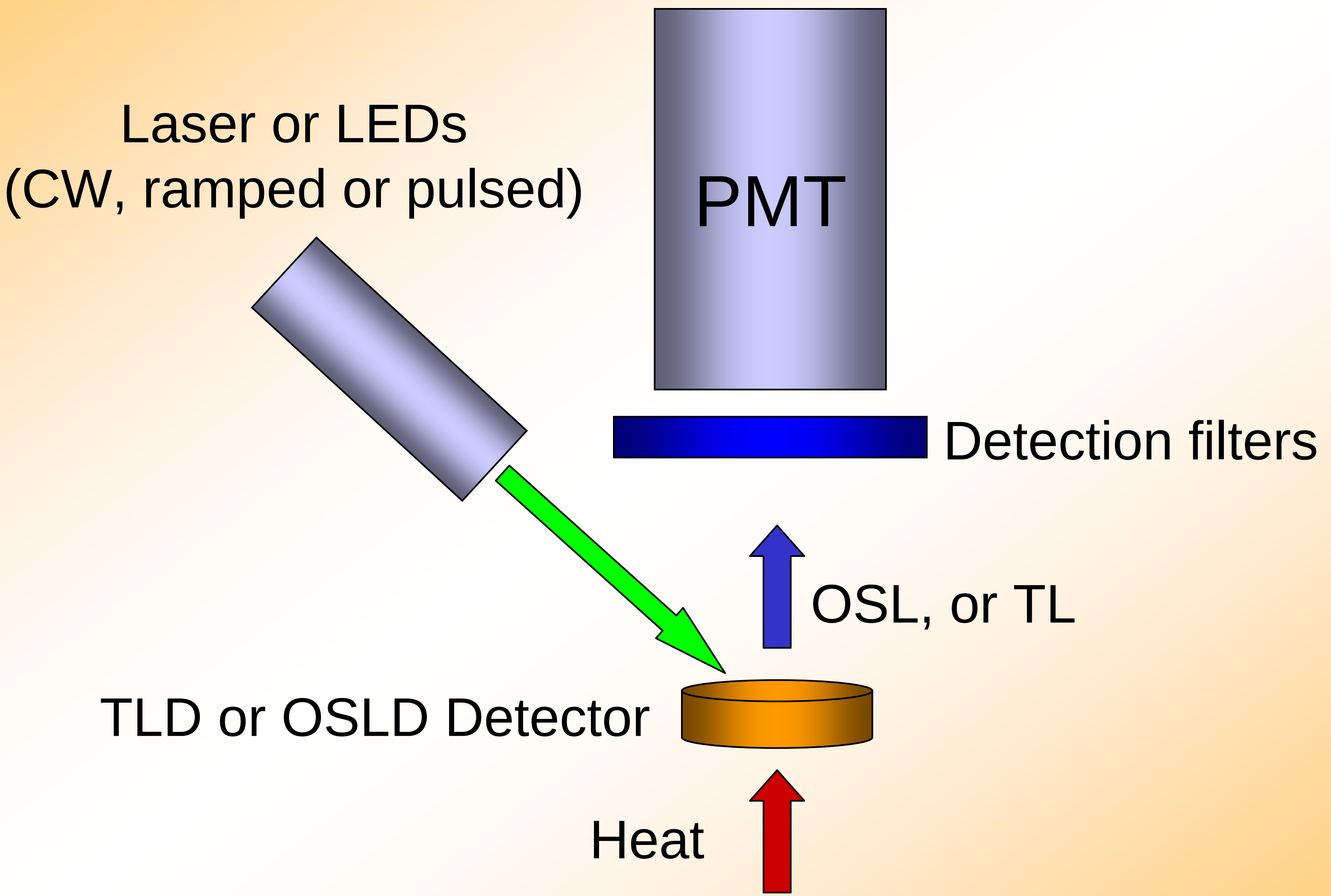
and

Gabriel Sawakuchi

Background:

- Two luminescence dosimetry methods for measurement of absorbed radiation dose
  - Thermoluminescence (TL)
  - Optically Stimulated Luminescence (OSL)
- TL
  - Stored energy from the radiation released from the dosimetry material by **thermal stimulation**. Energy release in form of luminescence
- OSL
  - Stored energy from the radiation released from the dosimetry material by **optical stimulation**. Energy release in form of luminescence
- Methods can reveal the absorbed dose, even years after exposure; contains information about radiation quality

TL and OSL Principles:



TLD and OSLD Materials:

Commercial TLDs

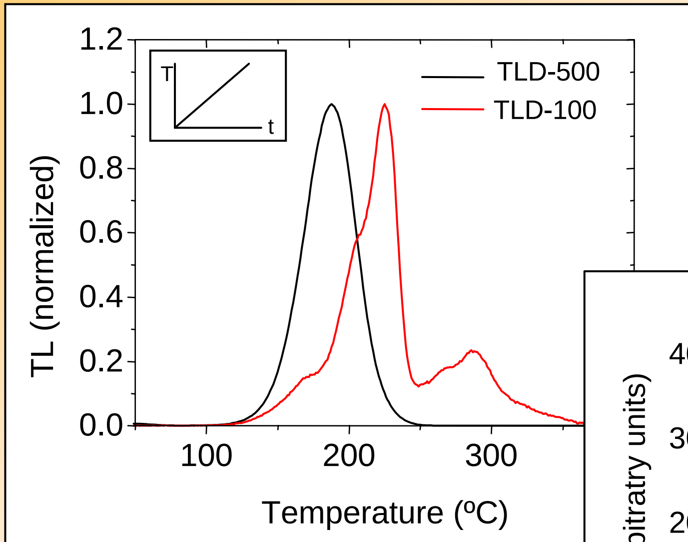
- LiF:Mg,Ti (TLD-100/600/700)
- LiF:Mg,Cu,P (TLD-100H)
- CaF_2:Mn (TLD-400)
- CaF_2:Dy
- CaF_2:Tm, (TLD-300)
- $CaSO_4$:Dy
- $CaSO_4$:Tm
- …….and many others

Commercial OSLDs

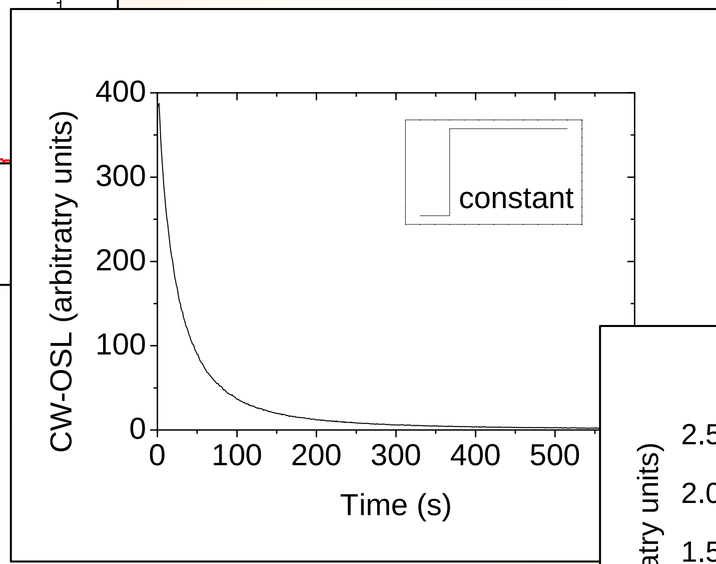
- Al_2O_3:C
- BaFCl:Eu
- ……plus several experimental materials

Typical TL and OSL Signals:

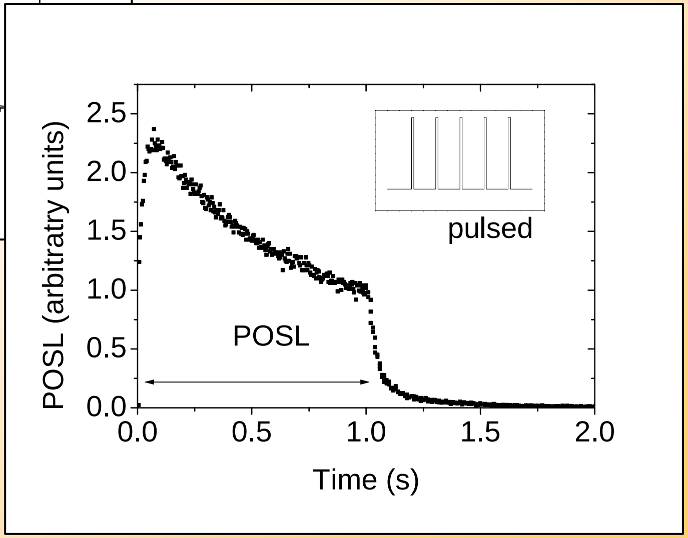
TL



CW-OSL

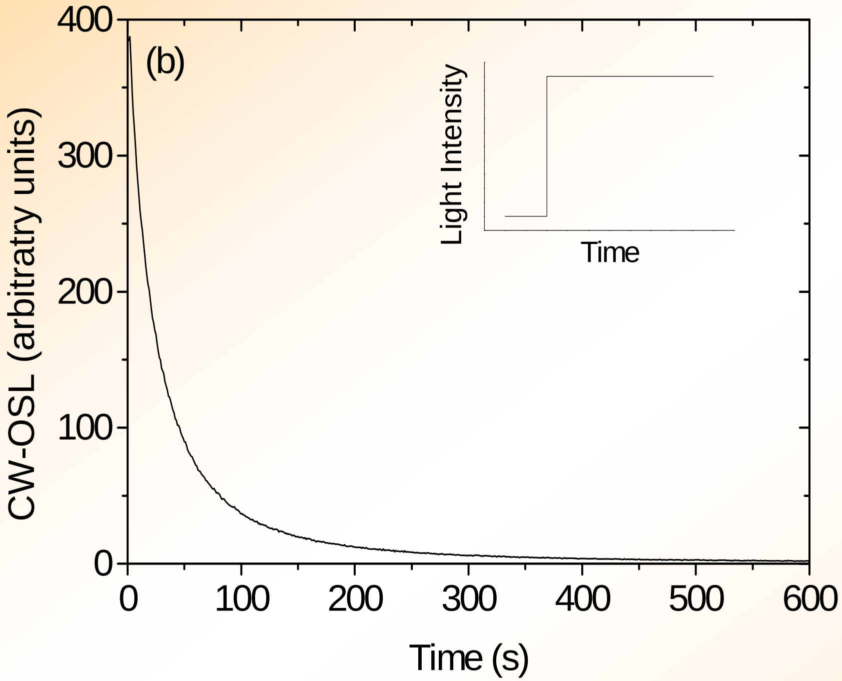


POSL

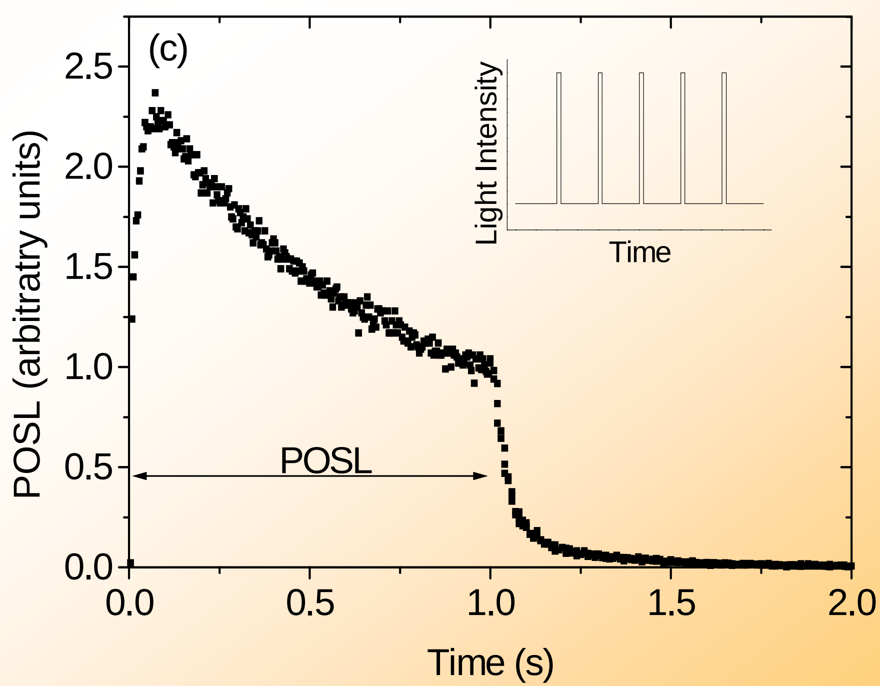


CW-OSL and POSL:

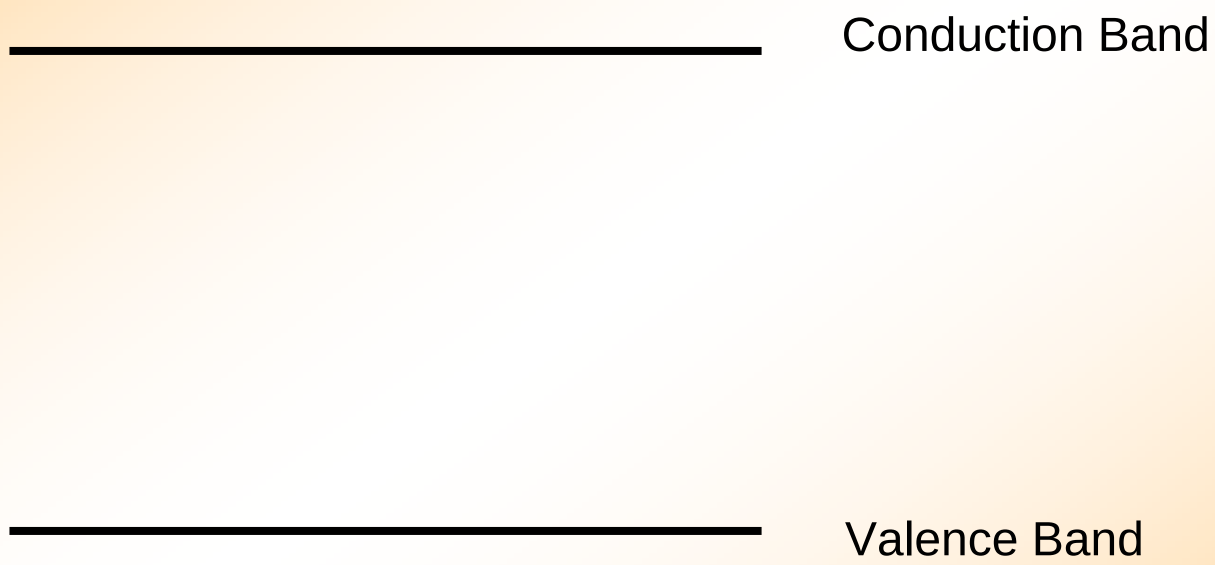
Continuous stimulation (CW-OSL)



Pulsed stimulation (POSL)



A Brief Tutorial:



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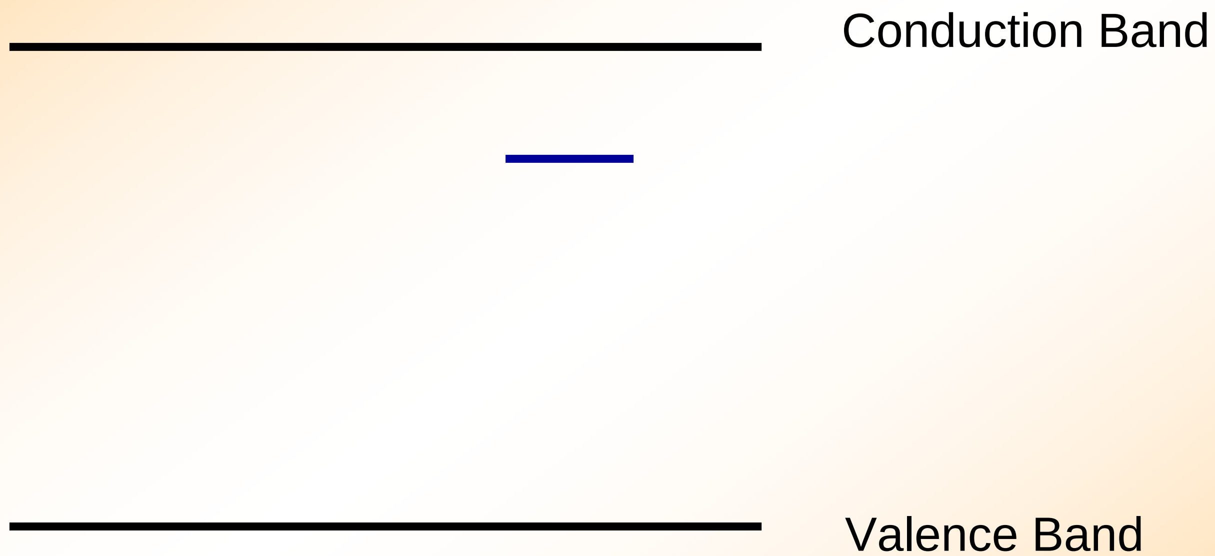

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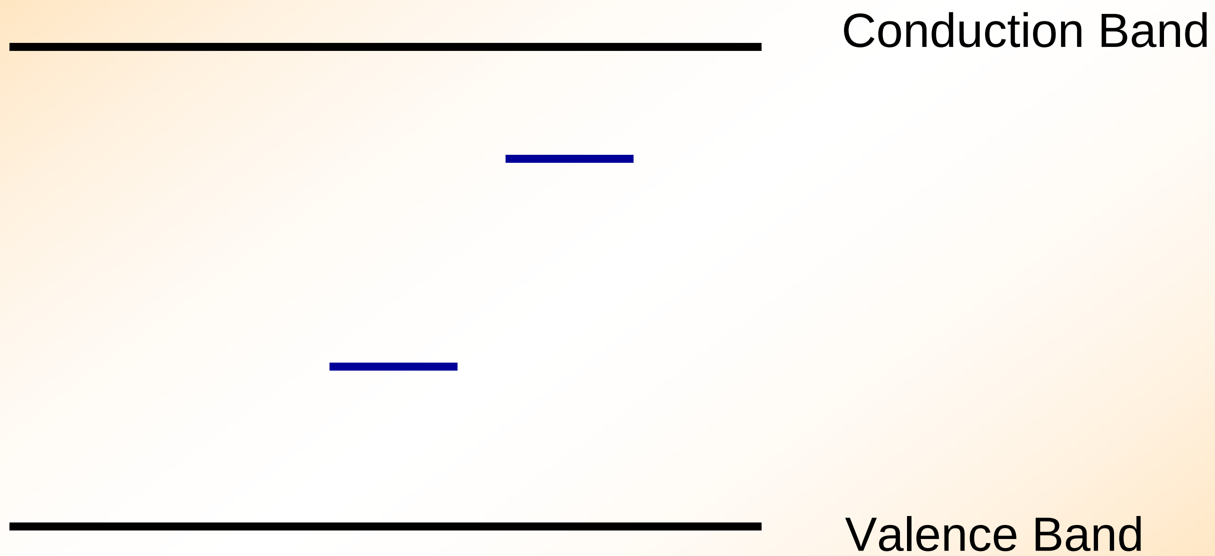

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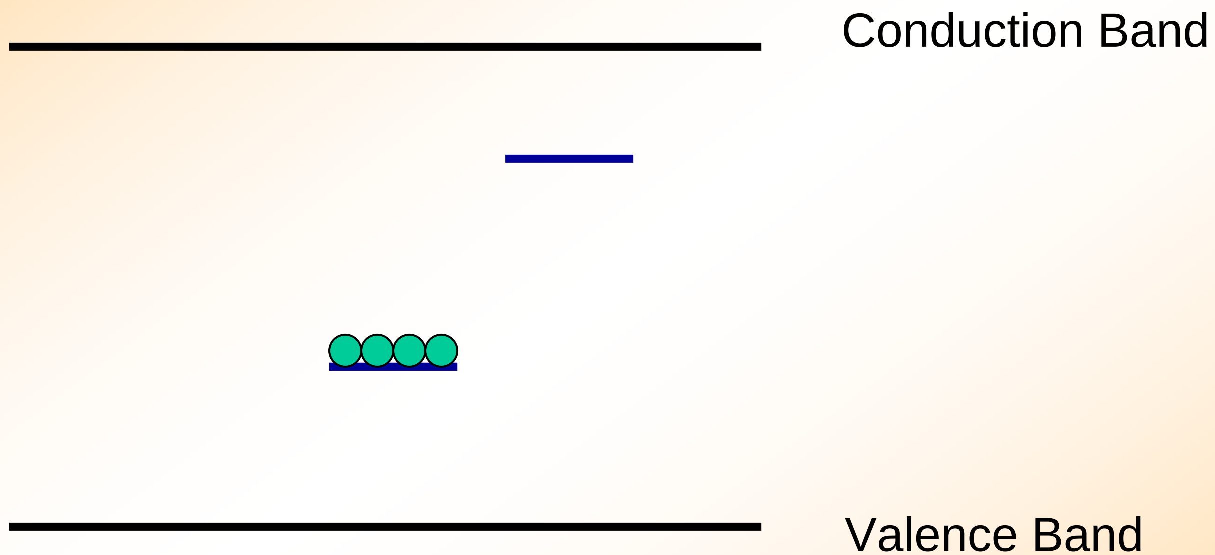
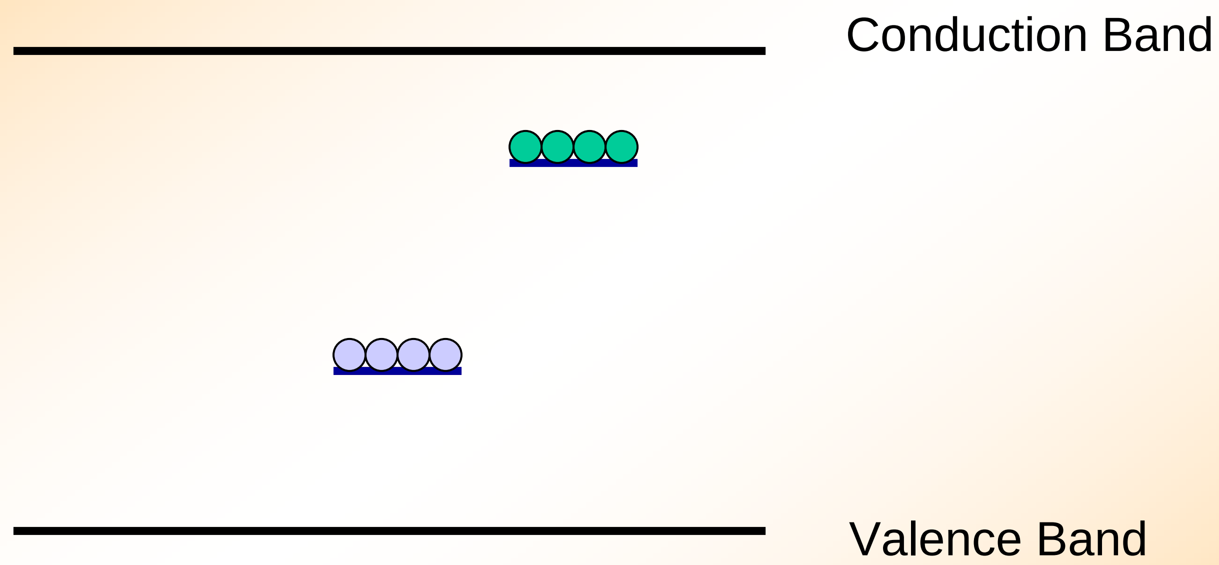


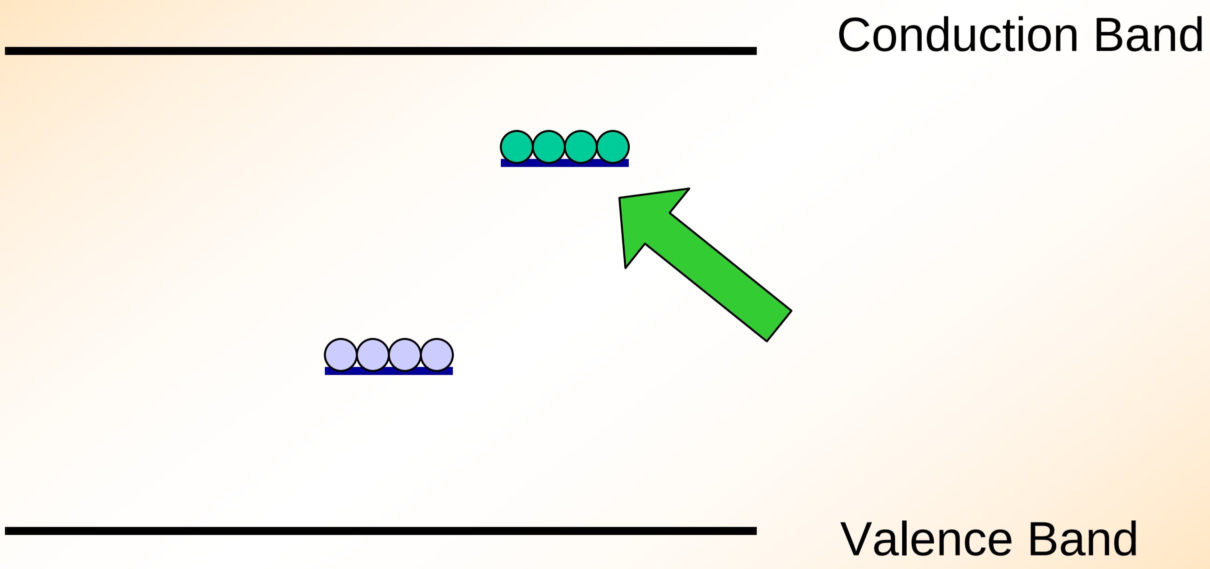
Before irradiation

A Brief Tutorial:



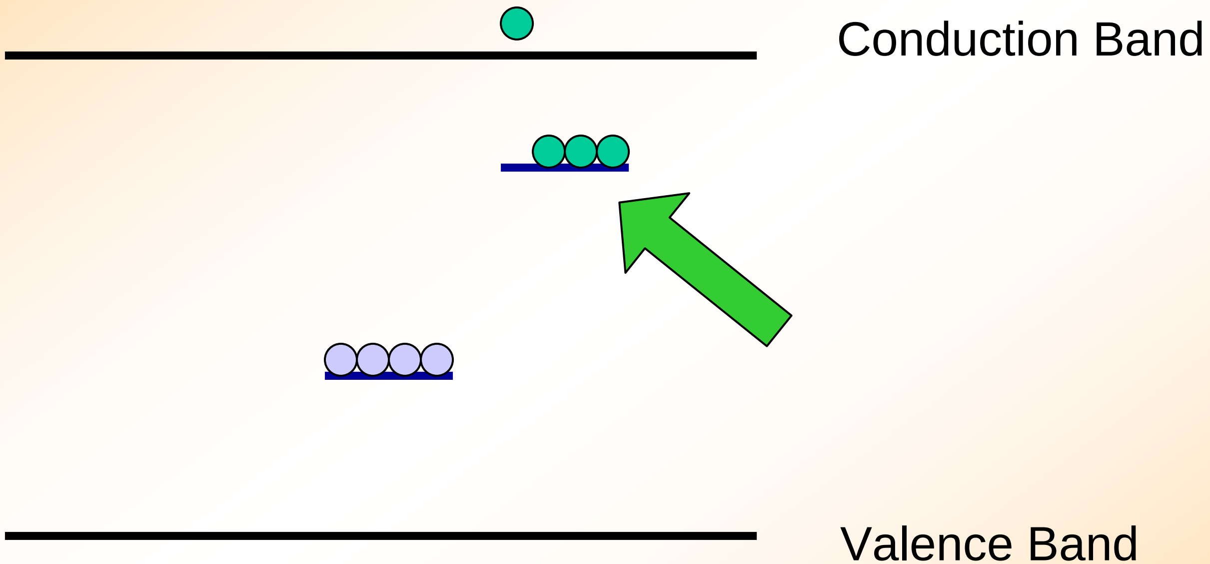
After irradiation

A Brief Tutorial:

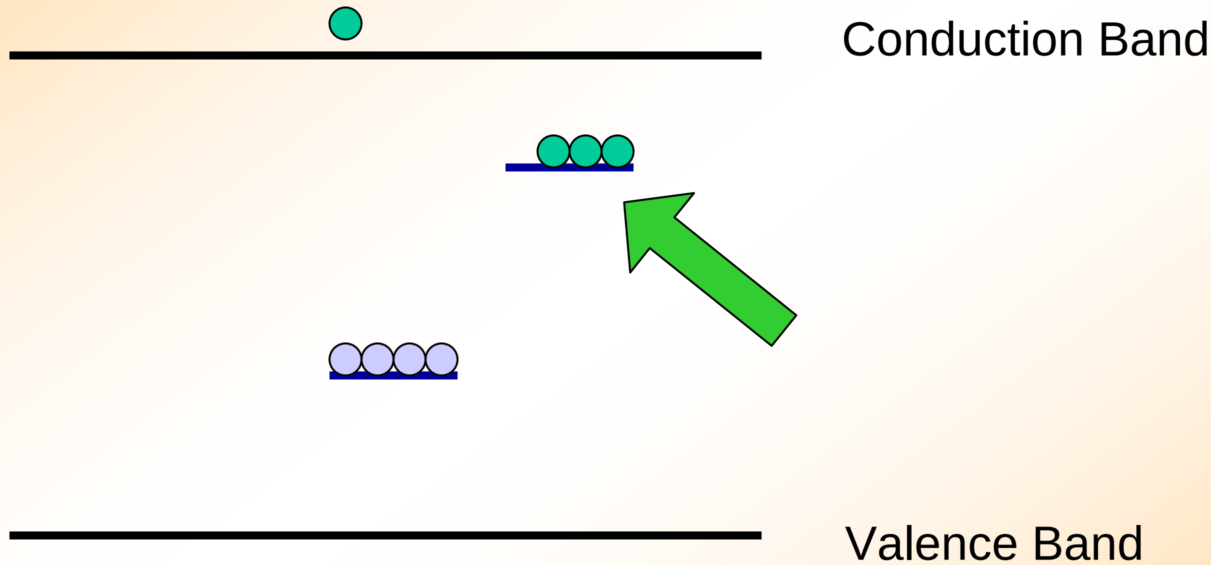


Stimulation

A Brief Tutorial:



A Brief Tutorial:



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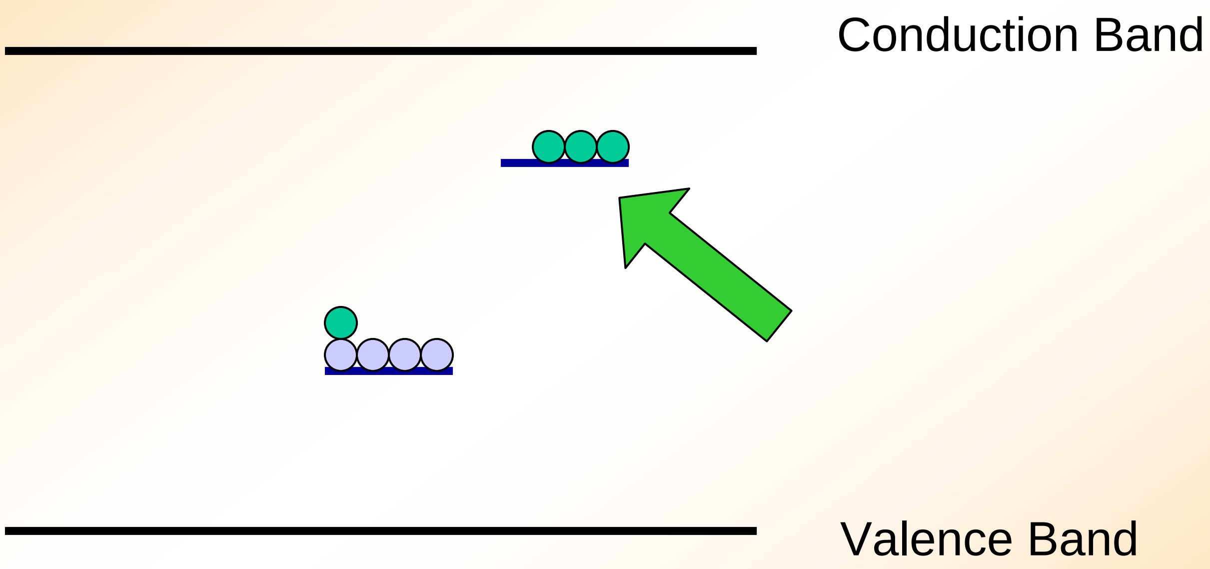

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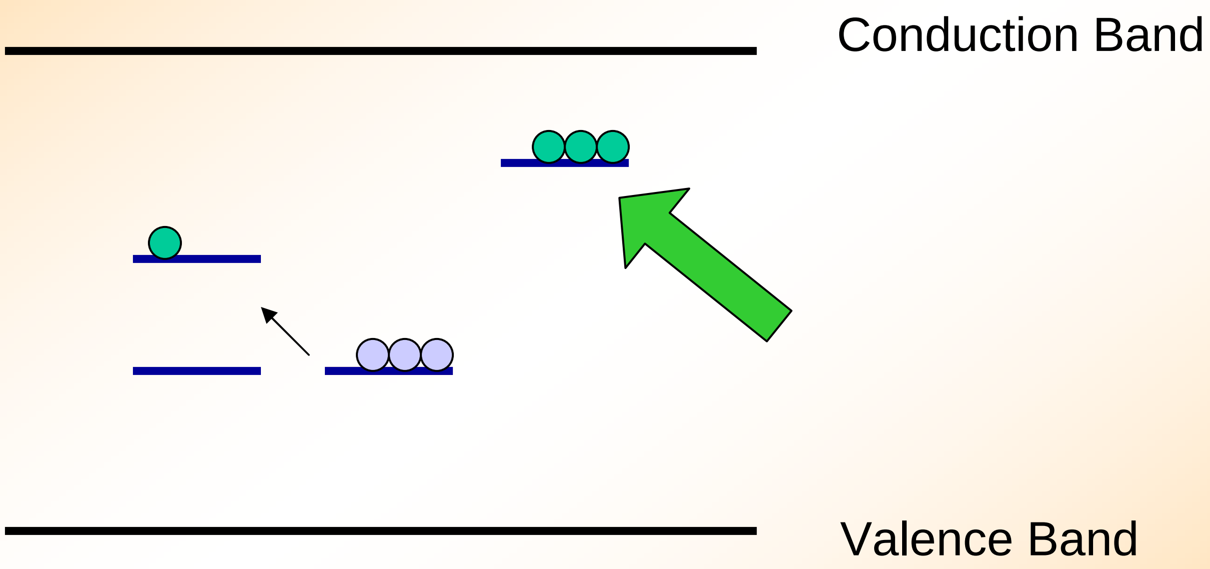

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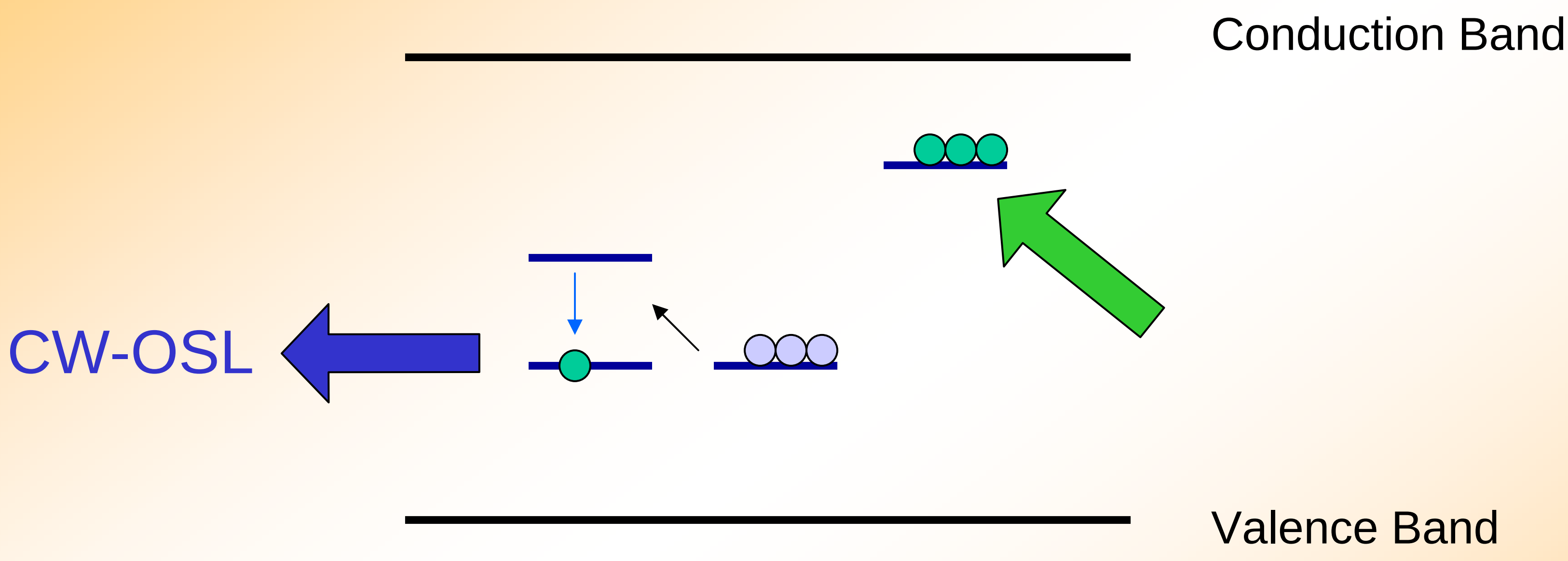

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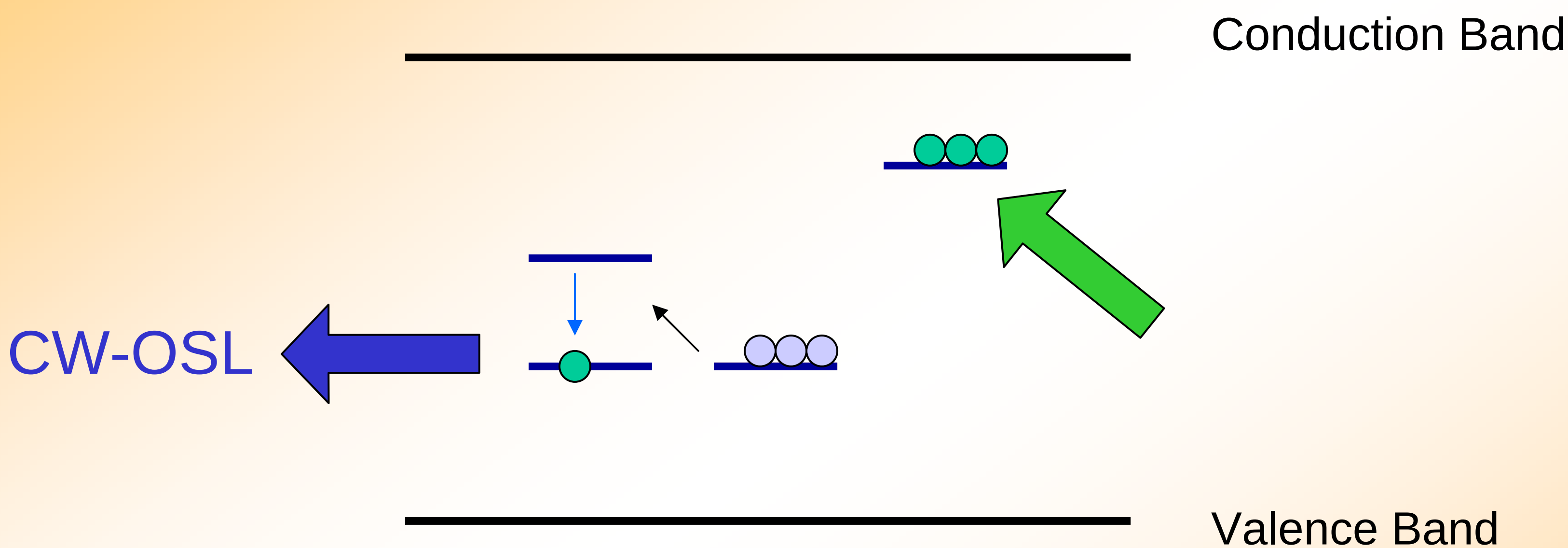
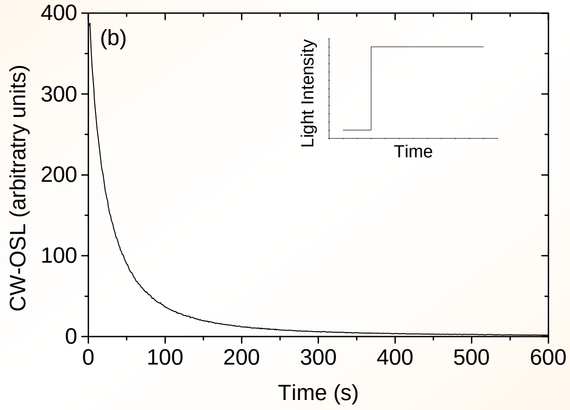
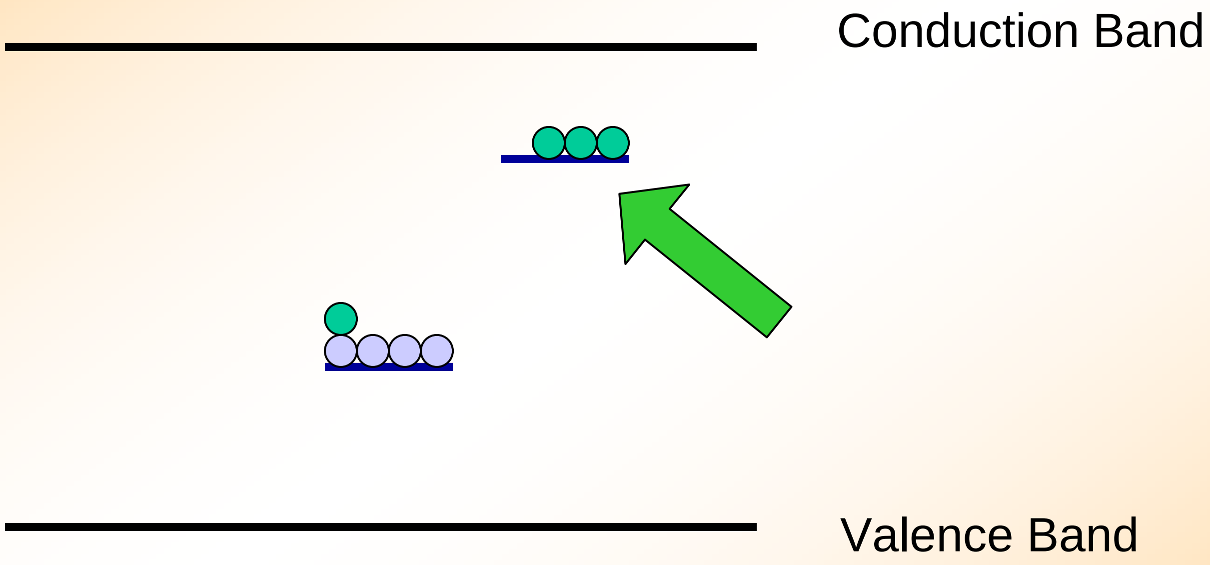


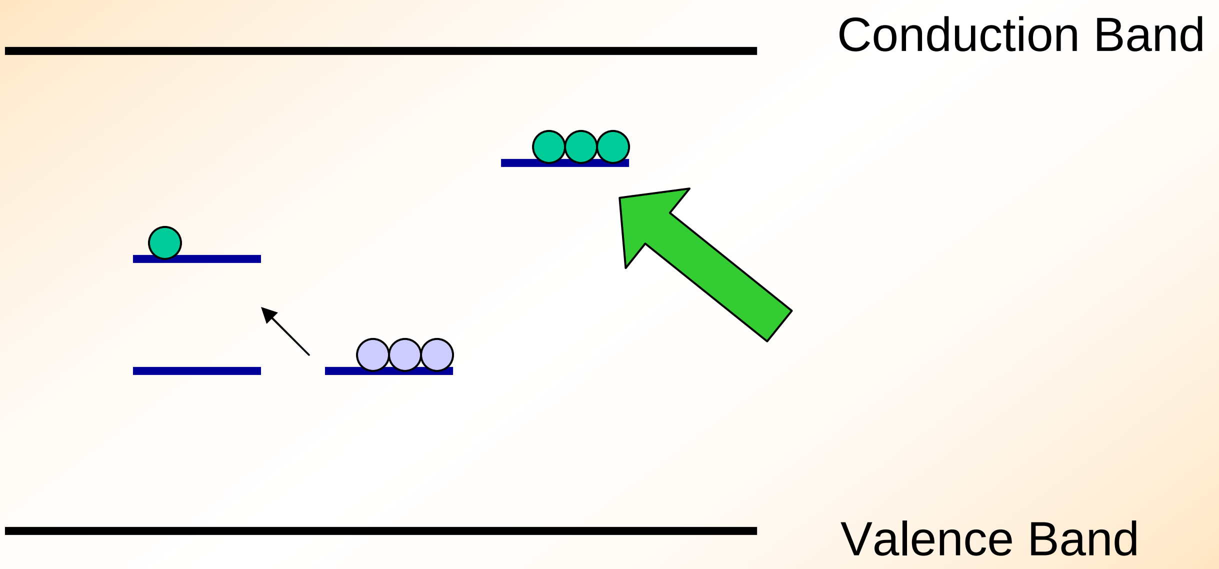


Continuous stimulation and depletion

A Brief Tutorial:



A Brief Tutorial:



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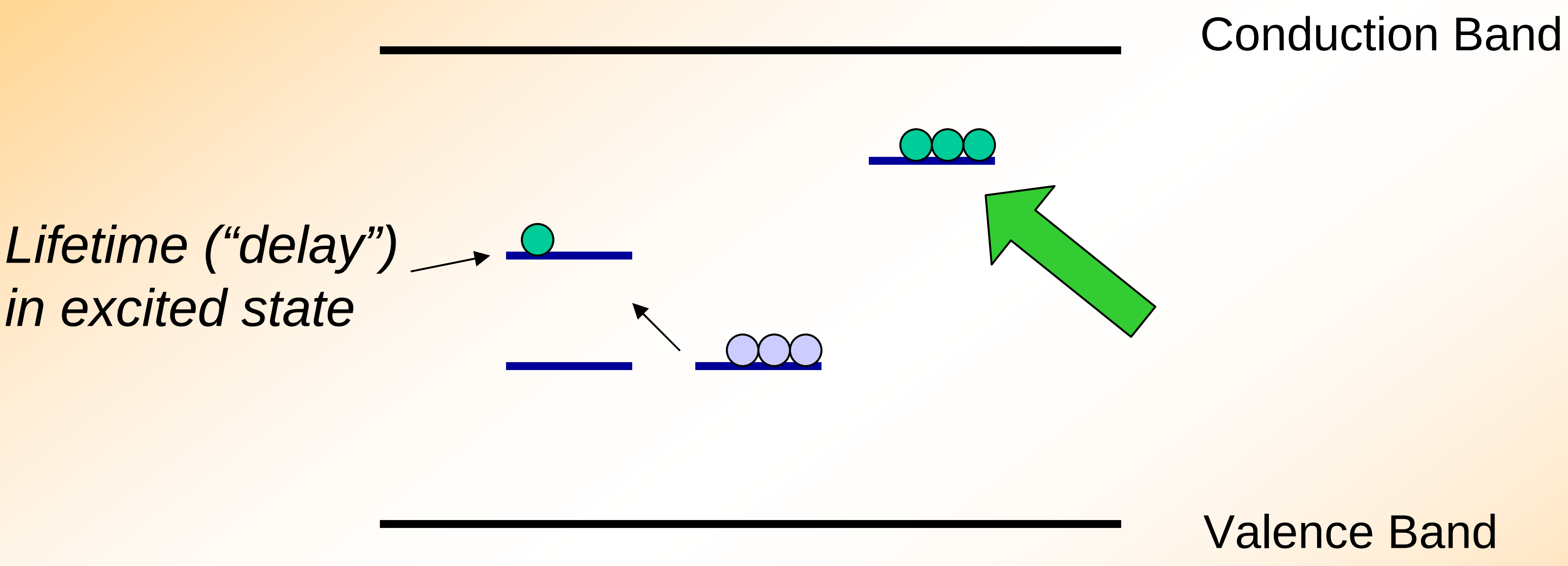

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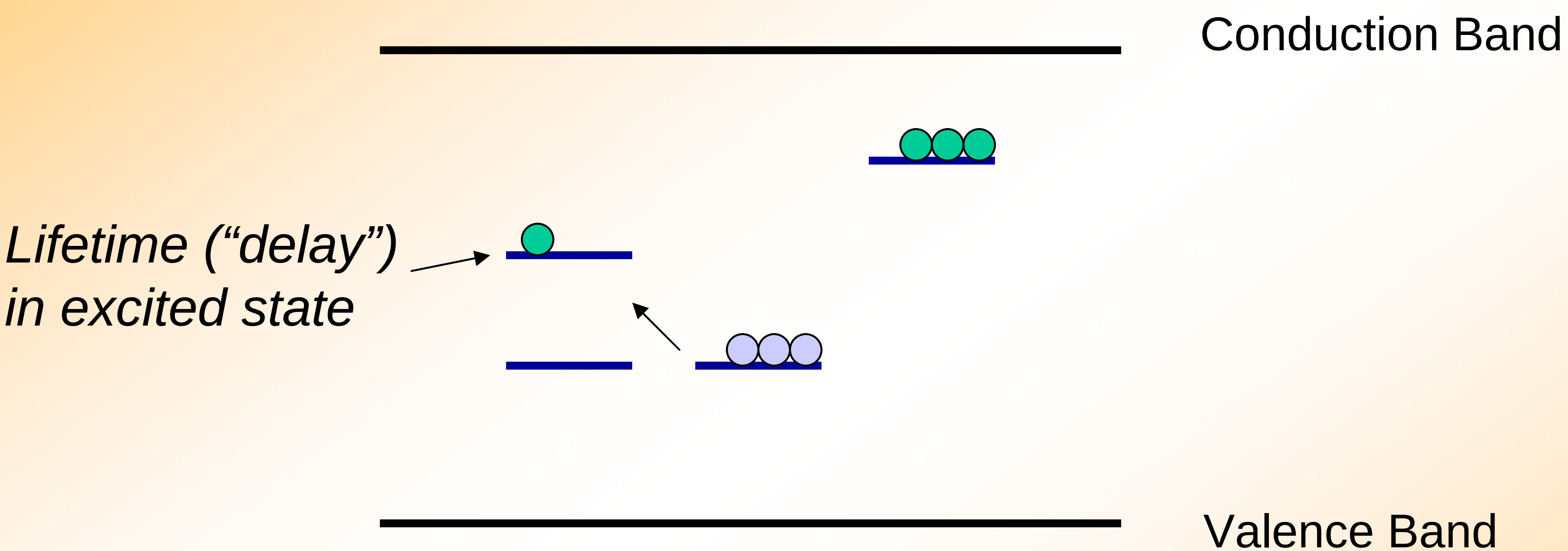
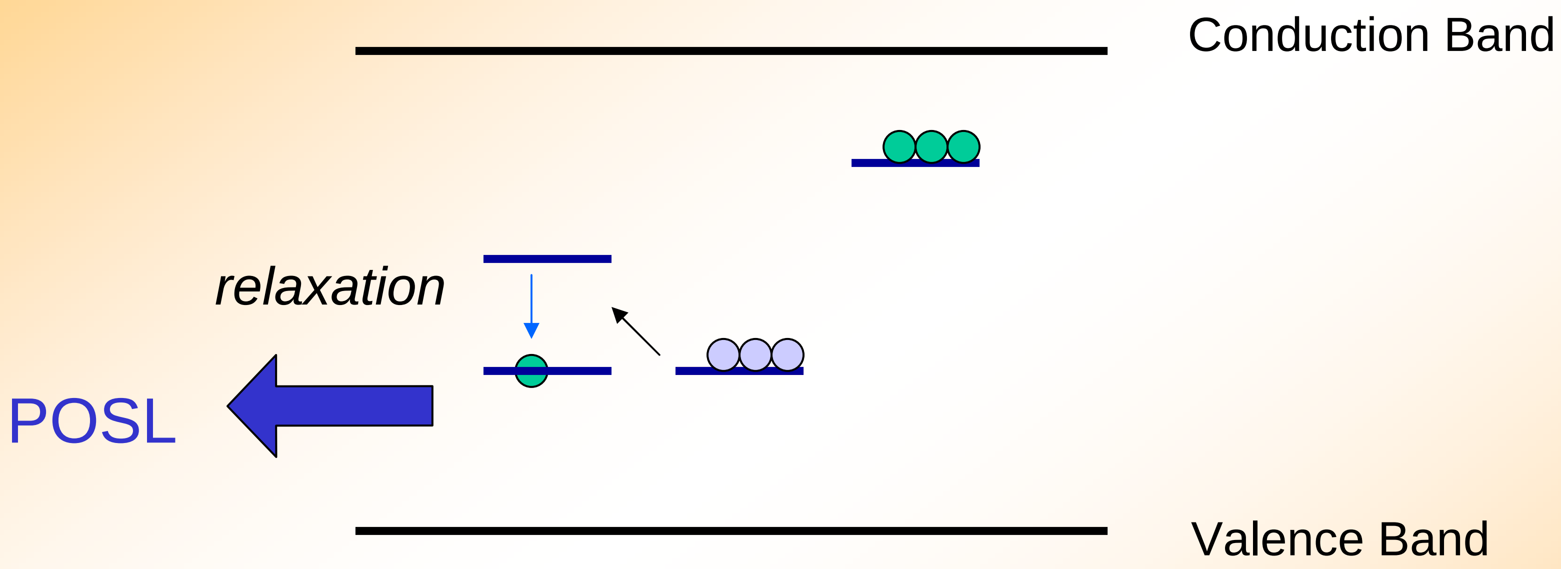
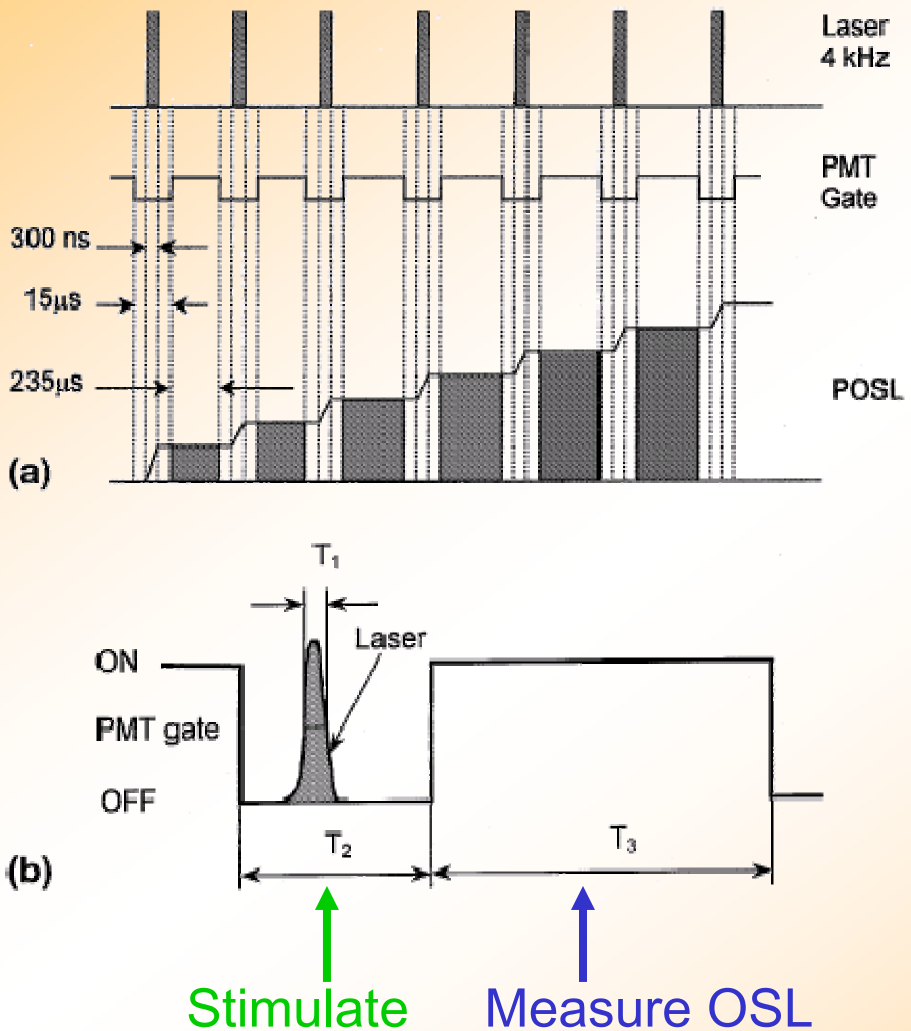


A Brief Tutorial:



Detect OSL after stimulation pulse removed

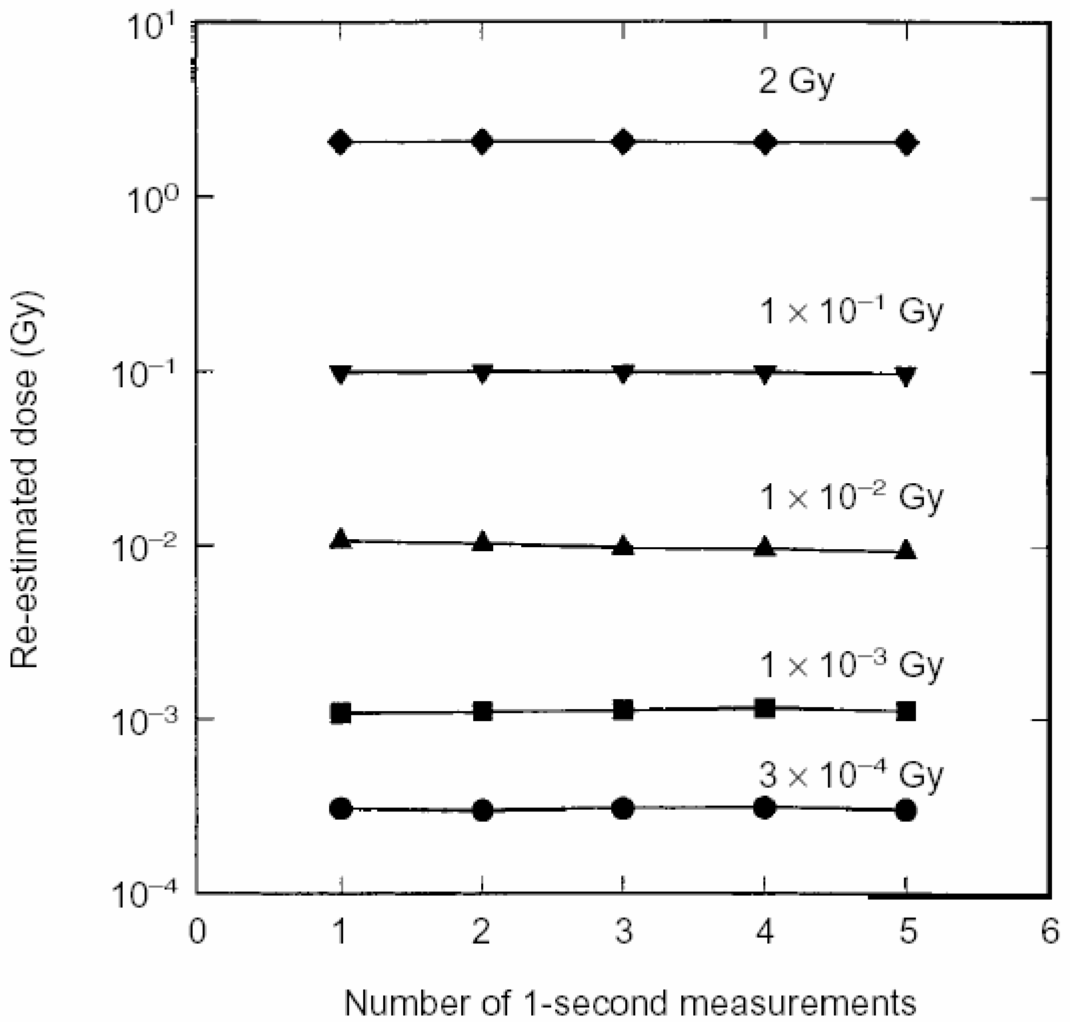
The Pulsed OSL (POSL) Technique:



Pulsed OSL (POSL) Measures OSL emission between stimulation pulses, not during the pulse. Better separation between the signal and the stimulation light.

Akselrod and McKeever, Radiat. Prot. Dosim. 81, 167-176 (1999)

An OSL advantage:



Possibility of Re-estimation of doses

Can re-read the OSL signal, if the signal is strong enough. (No need to deplete the signal in order to measure it.)

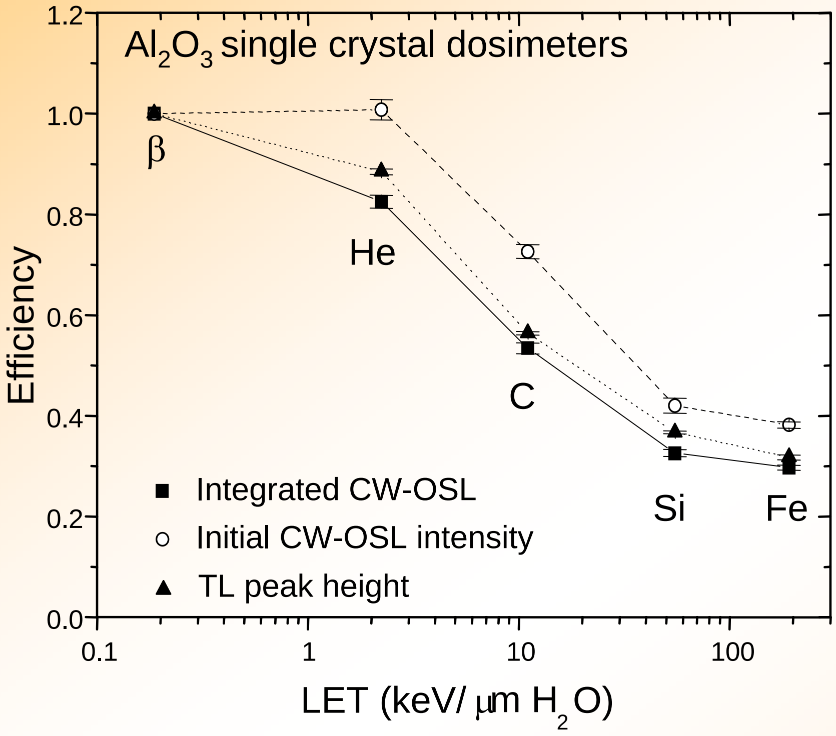
Akselrod and McKeever, Radiat. Prot. Dosim. 81, 167-176 (1999)

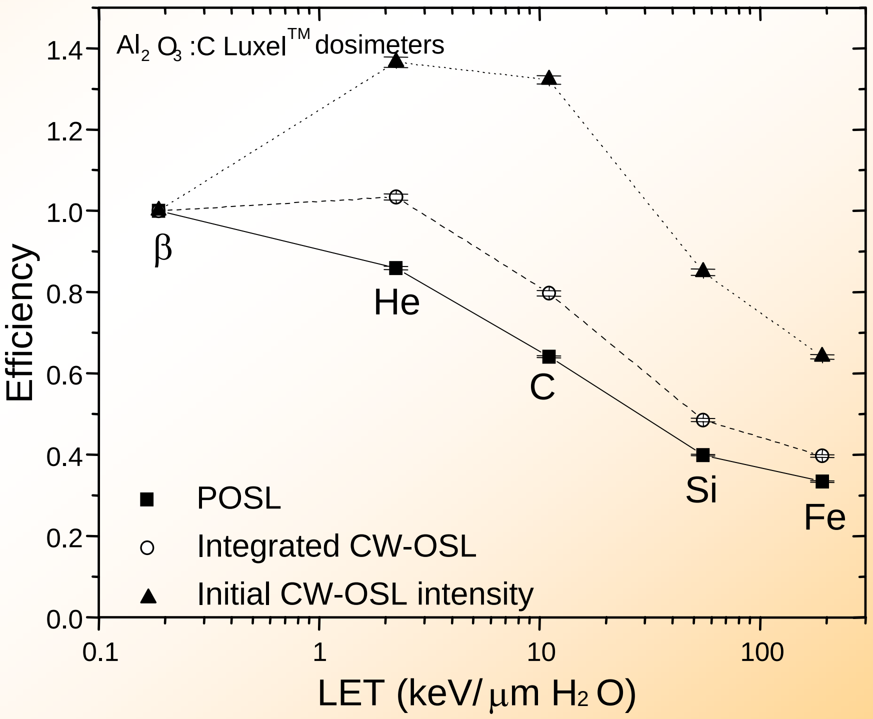
Some OSL and TL comparisons:

- Both have adequate sensitivity for space dosimetry
- Both have stable signal (no fading)
- All-optical method for OSL; lends itself to multiple configurations and devices
- Re-read of OSL signal (period dose plus total dose)
- Re-setting of OSL signal by bleaching; TL signal by heating
- Faster readout for OSL
- Lower (electrical) power requirements for OSL
- Various on-board readout configurations
- Thin OSL powder dosimeters (e.g. Luxel™) for reliability and ease of use
- Potential for integration with microelectronics
- Can combine OSLD/TLD/PNTD badges
- Can combine OSLD/TLD readers
- Both TL and OSL contain information about LET spectrum

OSL/TL and the LET Spectrum:

OSL and TL have different efficiencies for different HCPs (LETs)



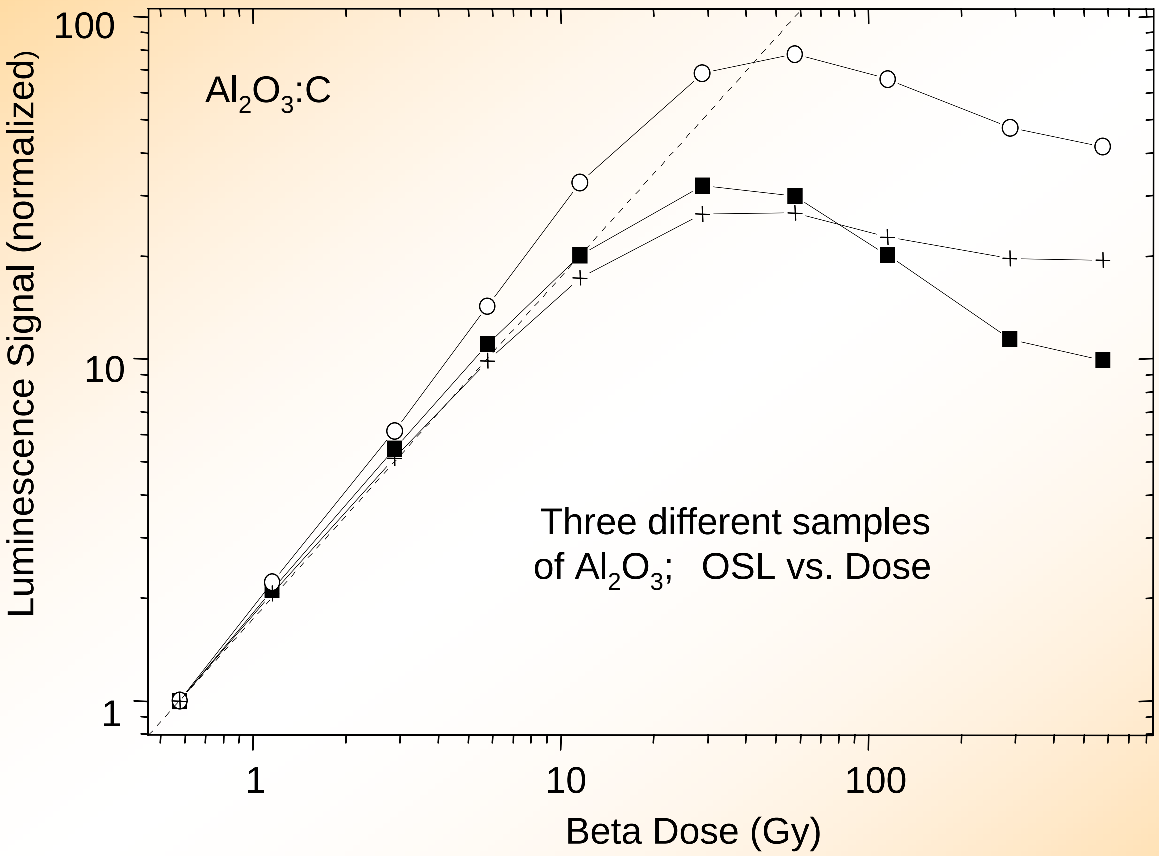


(1) Sensitivity to HCP of LET > 10 keV/μm (up to Fe^{56})

(2) Sensitivity depends on:

method of readout; material; material type (chip, powder); annealing; emission wavelength

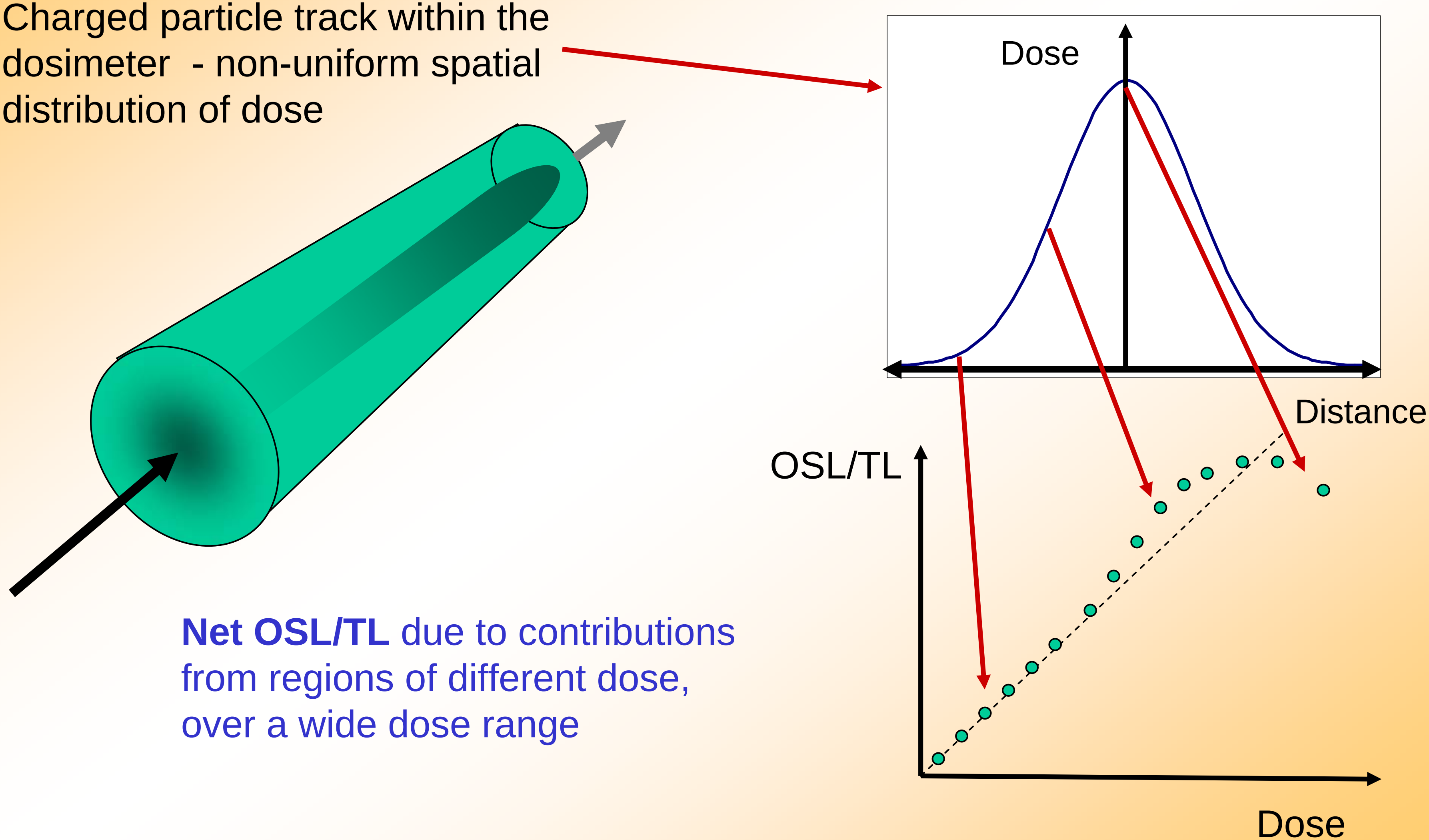
OSL/TL and the LET Spectrum:



Sensitivity decrease with LET due to loss of sensitivity at high doses
Supralinearity causes increase in efficiency with LET

OSL/TL and the LET Spectrum:

Charged particle track within the dosimeter - non-uniform spatial distribution of dose



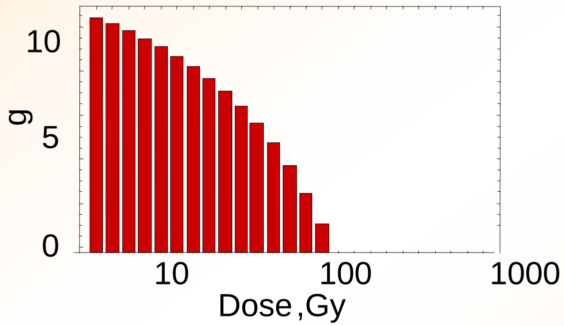
Net OSL/TL due to contributions from regions of different dose, over a wide dose range

Dose Distributions:

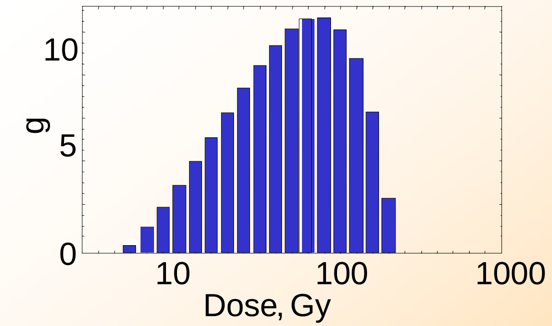
Possibility of extracting dose due to low LET from dose due to high LET

Dose distributions extracted from deconvolutions of OSL decay curves

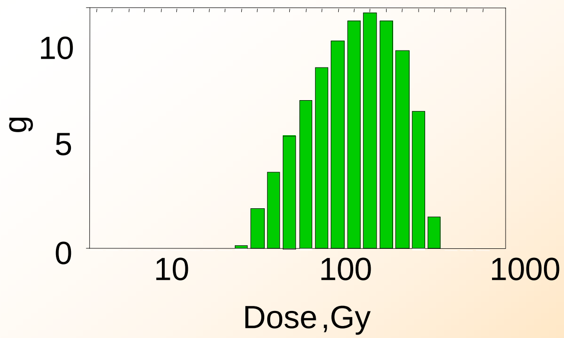
100 mGy beta



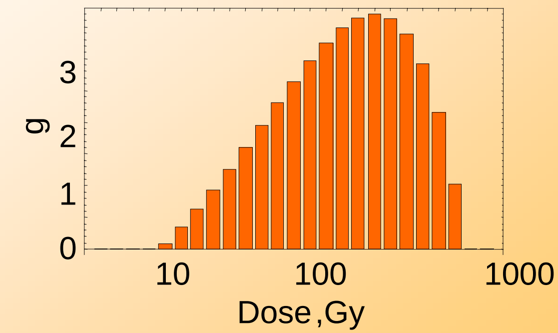
100 mGy He



100 mGy C



100 mGy Fe



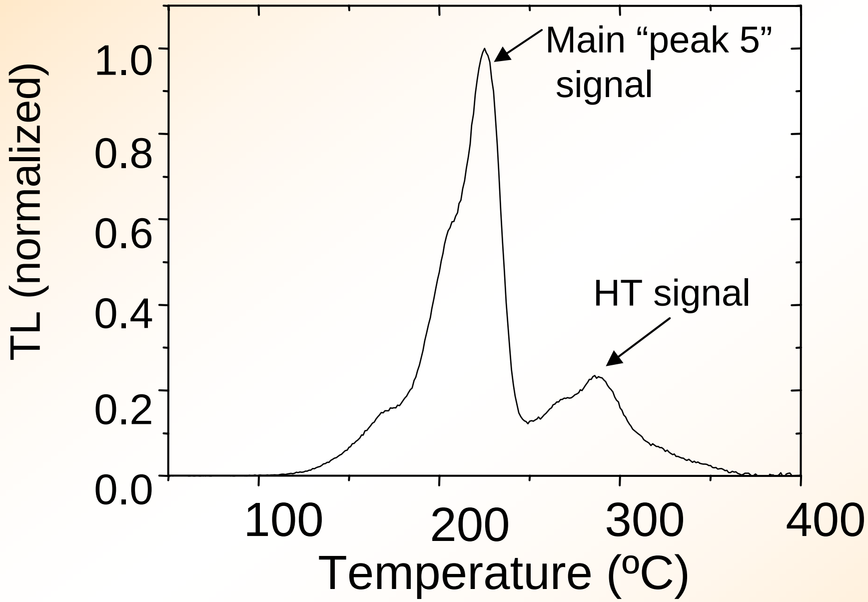
Courtesy: Dr. Eduardo Yukihara

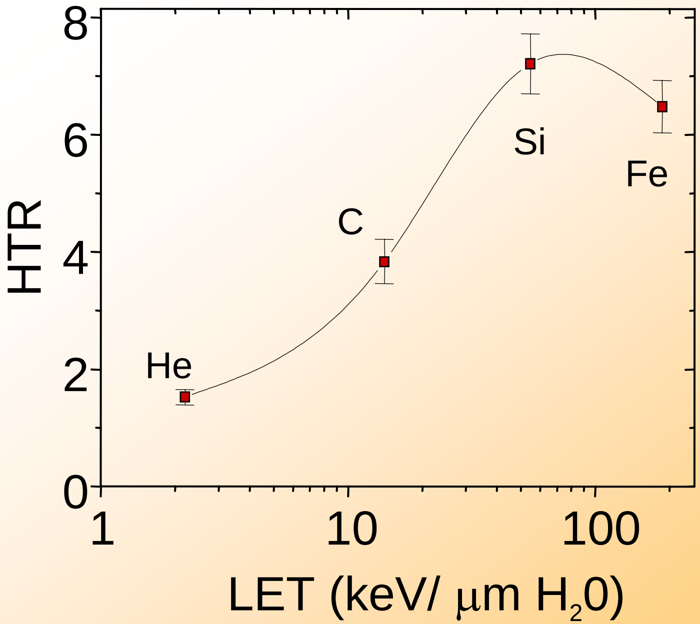
An “LET Meter”:

Use two or more parts of the TL or OSL signal that have different efficiencies with respect to LET.

Examples:

TLD-100 “HTR” method



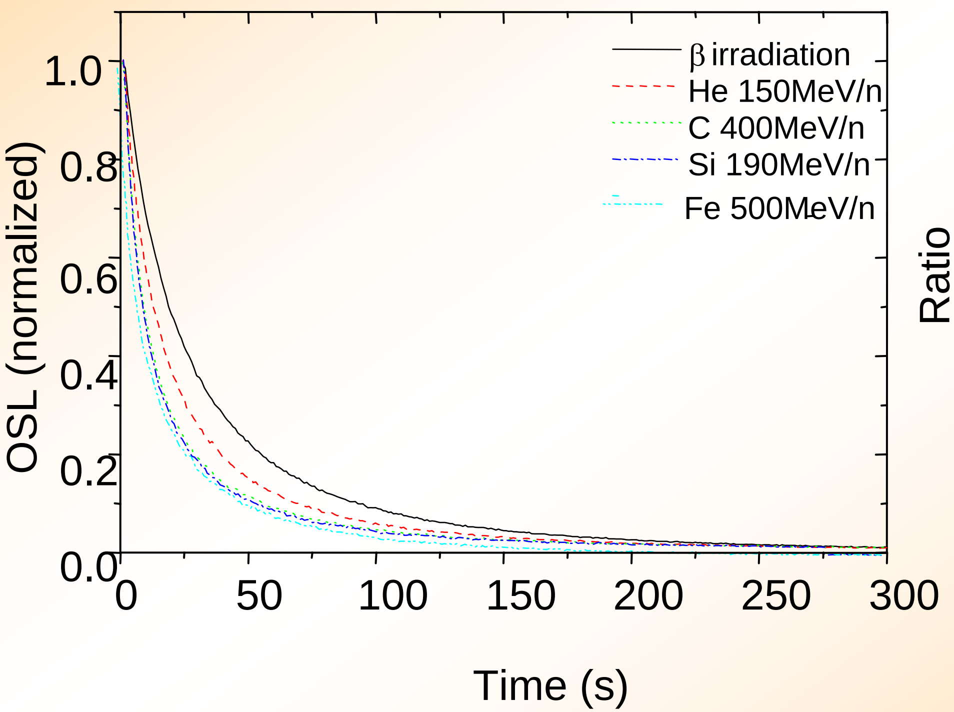


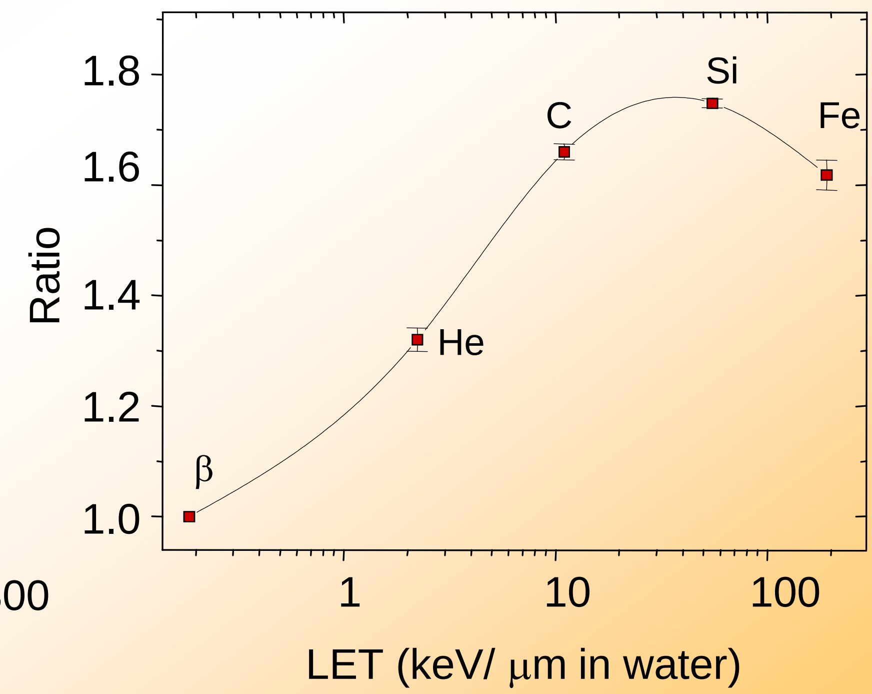
An “LET Meter”:

Use two or more parts of the TL or OSL signal that have different efficiencies with respect to LET.

Examples:

OSL Peak intensity/Area Ratio



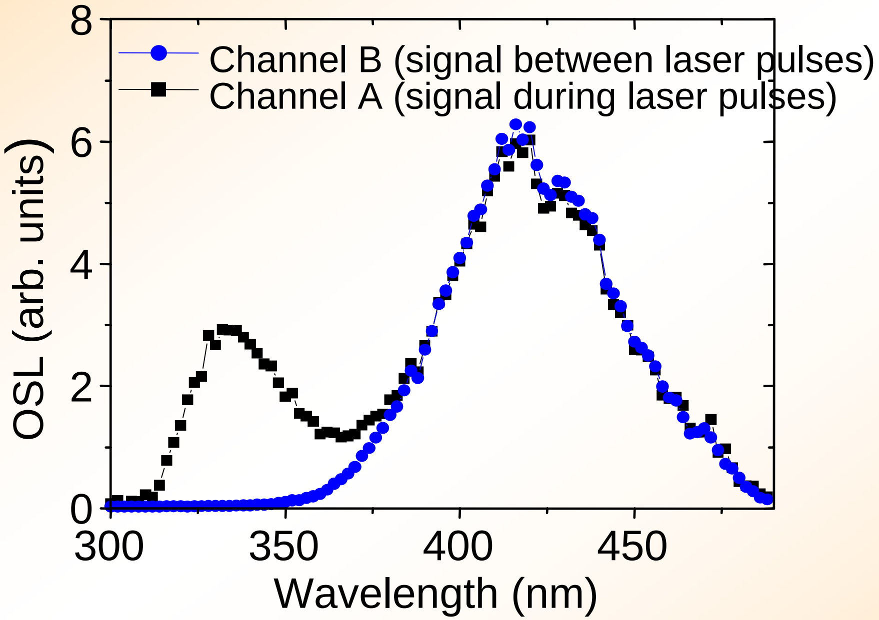


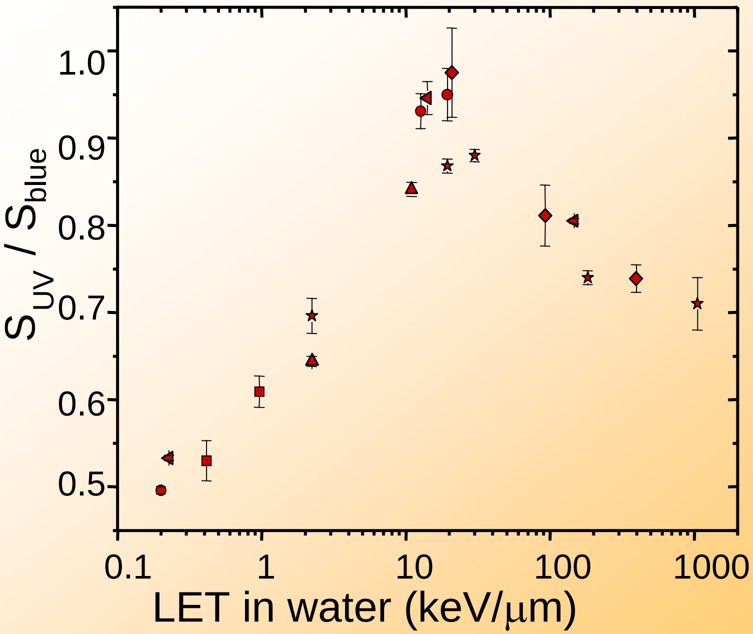
An “LET Meter”:

Use two or more parts of the TL or OSL signal that have different efficiencies with respect to LET.

Examples:

OSL emission Wavelengths; Time-resolved Using POSL





An “LET Meter”:

Can we use these measurements to determine a “mean” or “effective” LET for space radiation (unknown mixed radiation field)?

- Absorbed dose

$$D = \sum_i D_i = \sum_i \frac{D_{\gamma,i}}{\eta_i}$$

- ‘Effective’ efficiency

$$D = \frac{D_\gamma}{\eta_{effective}}$$

Uncorrected OSL/TL dose (→ D_γ)

Corrected OSL/TL dose (→ D)

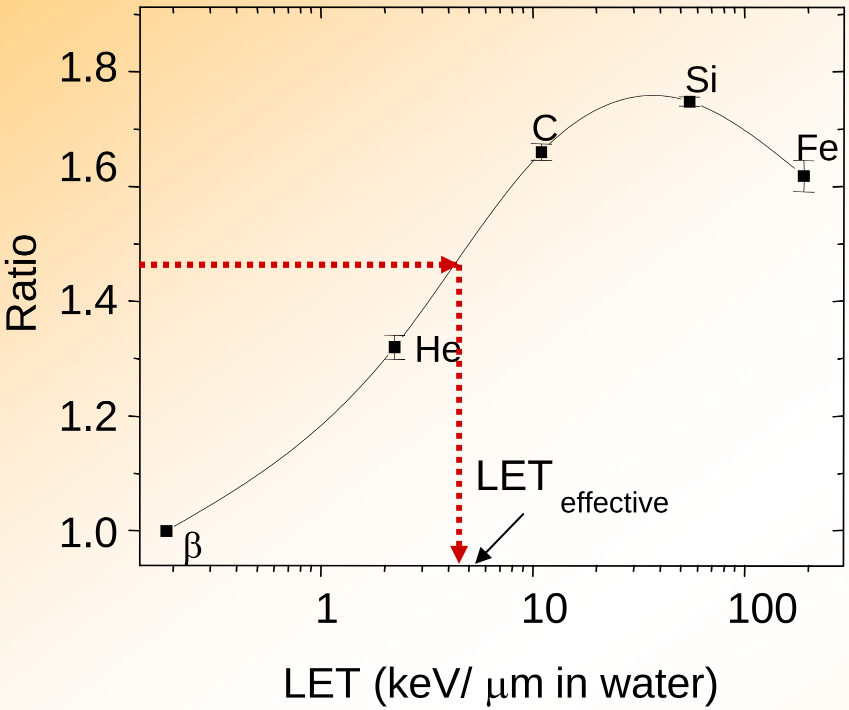
? (→ $\eta_{effective}$)

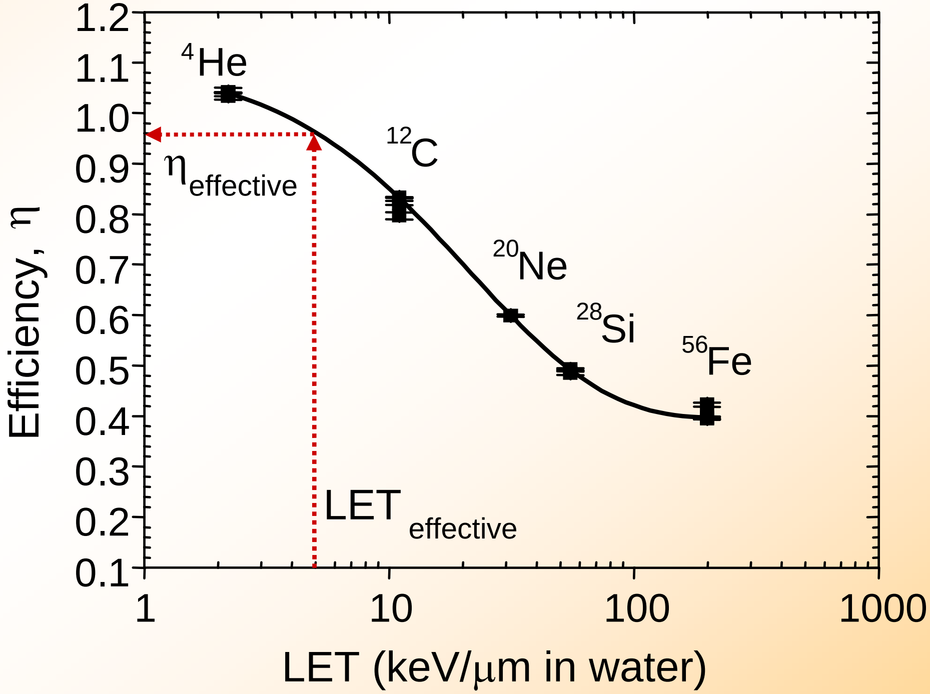
then

- Dose equivalent

$$H = Q_{effective} D$$

An “LET Meter”:





Measure Ratio and estimate effective LET

Use effective LET to estimate effective efficiency

Then, Corrected Dose = Measured Dose/effective efficiency

How well does it work? Absorbed Dose:

‘Unknown-ion’ exposure	Uncorrected dose (mGy)	Corrected dose (mGy)	Actual dose (mGy)
Unknown #1 single low-LET particle	31.0 ± 0.2	28.5 ± 0.3	27.8
Unknown #2 single low-LET particle	26.2 ± 0.0	25.3 ± 0.4	25.0
Unknown #3 mixed field-strong low-LET component	13.4 ± 0.0	12.5 ± 0.2	12.6
Unknown #4 mixed field-strong high-LET component	8.4 ± 0.1	11.2 ± 1.0	10.2
Unknown #5 single high-LET particle	20.8 ± 0.2	25.4 ± 1.3	25.0

How well does it work? Dose Equivalent:

'Unknown-ion' exposure	Dose equivalent *H* (Sv)	Corrected dose equivalent (Sv)
Unknown #1 single low-LET particle	27.8	28.5 ± 0.3
Unknown #2 single low-LET particle	25.0	25.3 ± 0.4
Unknown #3 mixed field-strong low-LET component	20.4	12.5 ± 0.2
Unknown #4 mixed field-strong high-LET component	64.9	35.7 ± 1.0
Unknown #5 single high-LET particle	33.0	25.4 ± 1.3

How well does it work?

Measured doses (before efficiency correction) using

- TL or OSL
- TLD-100 or TLD-500 or Luxel, etc.

will all be different.

This is caused by the different efficiency curves for each.

Must correct using particular efficiency curve measured in specific lab.

Correcting for the efficiency curves works for:

- Single particle irradiation
- Mixed field dominated by Low LET

However, does not work for high LET radiation dominated mixed fields. OSL/TL cannot measure dose from high LET component of space radiation because of low sensitivity.

Space Dosimetry

To measure dose from full spectrum, use TLD and/or OSLD in conjunction with PNTDs.

NCRP 142, 2002 Recommendation 11:

$$D = D_{OSLD/TLD} + \int D_{PNTD}(L)\, dL$$

Join together OSLD/TLD data and PNTD data (method of Benton & Benton)

$$D^{OSL/TL}_{<5\,keV/\mu m} = D^{OSL/TL}_{Uncorrected} - \sum_{i=5\,keV/\mu m}^{1500\,keV/\mu m} \eta_i^{OSL/TL} D_i^{CR-39}$$

$$D_{Total} \cong \frac{D^{OSL/TL}_{<5\,keV/\mu m}}{\eta^{OSL/TL}_{effective}} + \sum_{i=5\,keV/\mu m}^{1500\,keV/\mu m} D_i^{CR-39}$$

Dose & Dose Equivalent

For Dose (Gy)

Can use EITHER:

$$D_{corrected} = D_{uncorrected} / \eta_{effective}$$

OR:

$$D^{OSL/TL}_{<5\,keV/\mu m} = D^{OSL/TL}_{Uncorrected} - \sum_{i=5\,keV/\mu m}^{1500\,keV/\mu m} \eta_i^{OSL/TL} D_i^{CR-39}$$

$$D_{Total} \cong \frac{D^{OSL/TL}_{<5\,keV/\mu m}}{\eta^{OSL/TL}_{effective}} + \sum_{i=5\,keV/\mu m}^{1500\,keV/\mu m} D_i^{CR-39}$$

For Dose Equivalent (Sv)

Must use:

$$H_{Total} \cong \frac{H^{OSL/TL}_{<5\,keV/\mu m}}{\eta^{OSL/TL}_{effective}} + \sum_{i=5\,keV/\mu m}^{1500\,keV/\mu m} Q_i D_i^{CR-39}$$

Cannot use:

$$H = Q_{effective} D_{corrected}$$

Space Dosimetry

On-Board OSLD reader:

- OSL personal dosimeter readout capability for long-duration missions (ISS, CEV, Moon, Mars)
- Design and build a functioning prototype OSL reader for on-board use (light source, light transducer, associated electronics, software)
- Design an astronaut personal dosimeter badge including capability for PNTD and TLD
- Design interface to the reader

Space Dosimetry

Requirements

- Sensitivity < 0.01 mGy
- Days to years of accumulated dose (up to 3 year missions)
- Fast and easy readout
- Dosimeter – easy to wear, use, handle, read
- Light-weight, low power, etc.

Summary:

1. **Uncorrected doses** determined by OSL or TL will be different, depending upon the readout method, material, annealing conditions, etc., etc.

2. **Corrected doses**, using the concept of “effective” efficiency and “effective LET”, will be the same, independent of readout method, material, etc., etc.

3. Therefore, OSL/TL provide simple and reliable methods for determining **Dose (Gy)** - expressed as gamma dose equivalent in a reference material (water)

4. However, since TL/OSL sensitive to low LET only, cannot use corrected OSL or TL doses to calculate Dose Equivalent (Sv)

5. Must use TLDs/OSLDs in combination with PNTDs to evaluate Dose Equivalent.

6. Possibility of versatile on-board readers for long-duration flights