Characterization of different flavours of quantum dots for HEP applications

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Acknowledgements

The core expertise on the relevant active material are in the domain of material sciences, while in HEP we are better equipped with the design of the readout of such sensors.

→ A pursuit of development of quantum sensors for applications in a HEP scale experiment is necessarily an interdisciplinary exercise

The materials measured were developed by **T. Choudhury (IEM, Kolkata) and P. Mandal (IISER, Kolkata)**

The measurements shown in the following slides are the result of **direct lab support** of the following members in TIFR:

A. Venugopal, S. Ghosh, S. Prabhu (Dept of Condensed Matter Physics and Material Sciences)

D. Khushalani, K. Nagarajan (**Dept of Chemical Sciences**)

The irradiation was carried out at BARC

Outline

- Introduction
- Facilities for irradiation and measurements
- Characterization of **$CsPbBr_3$** and **$CsPbI_3$** nanocrystals
- Characterization of **CdSe** quantum dots
- Plans ahead

Application of quantum dots for low and high energy physics

In a chromatic calorimeter

leftmost nanodots: absorb wavelengths < 650 nm emit at > 680 nm

next band: absorb wavelengths < 520 nm emit at > 540 nm

…

rightmost nanodots: absorb wavelengths < 410 nm emit at > 420 nm

Thus by simply reading the colour of the light (spectral intensity), we know where the corresponding interaction took place.

Potentially also in a Compton telescope

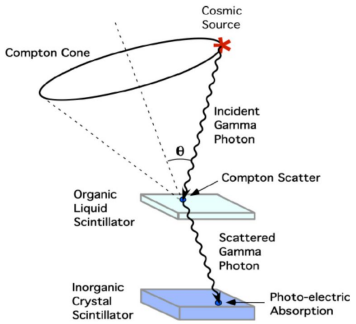
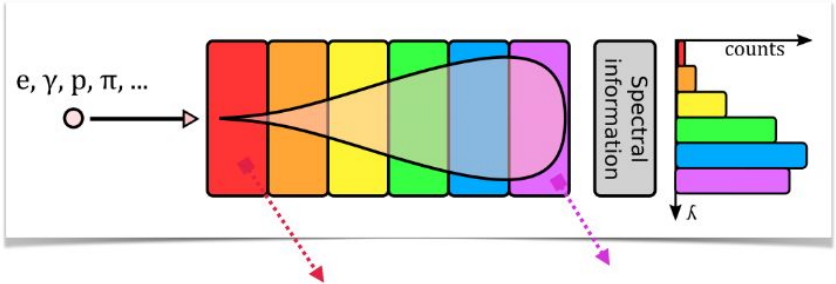
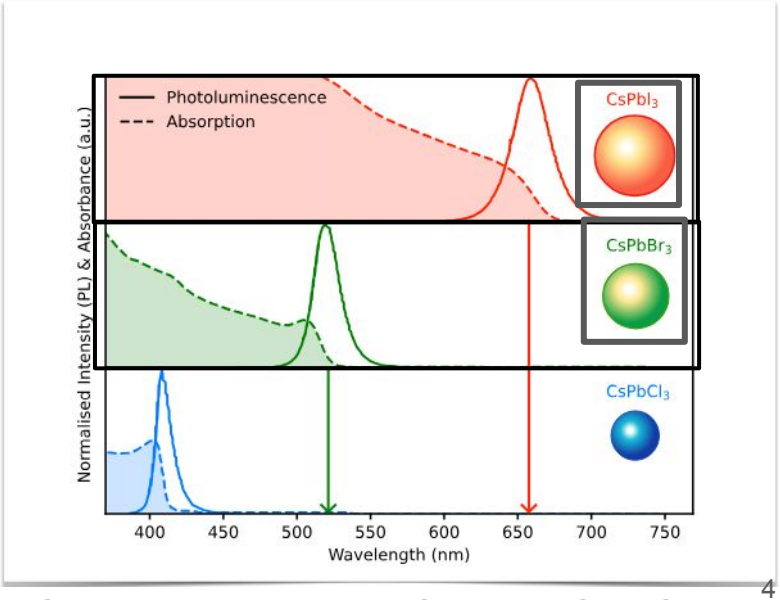


Image from this link

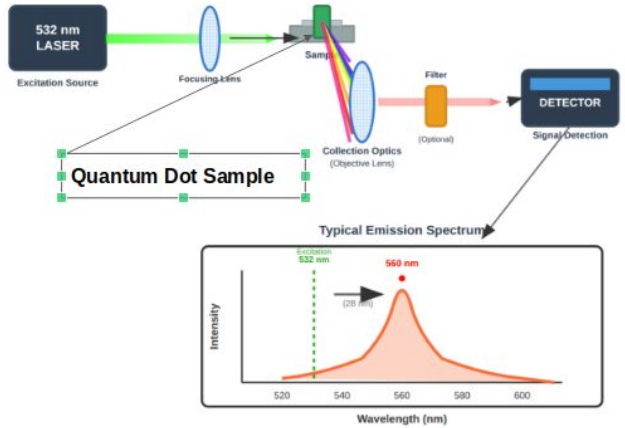




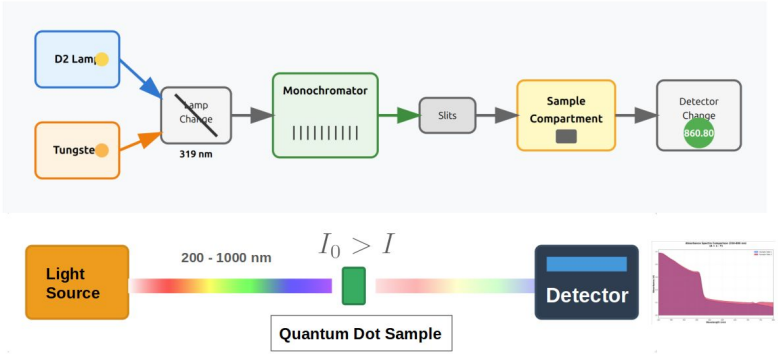
Courtesy: D. Arora (CERN), CALOR'24

Measurements for characterization

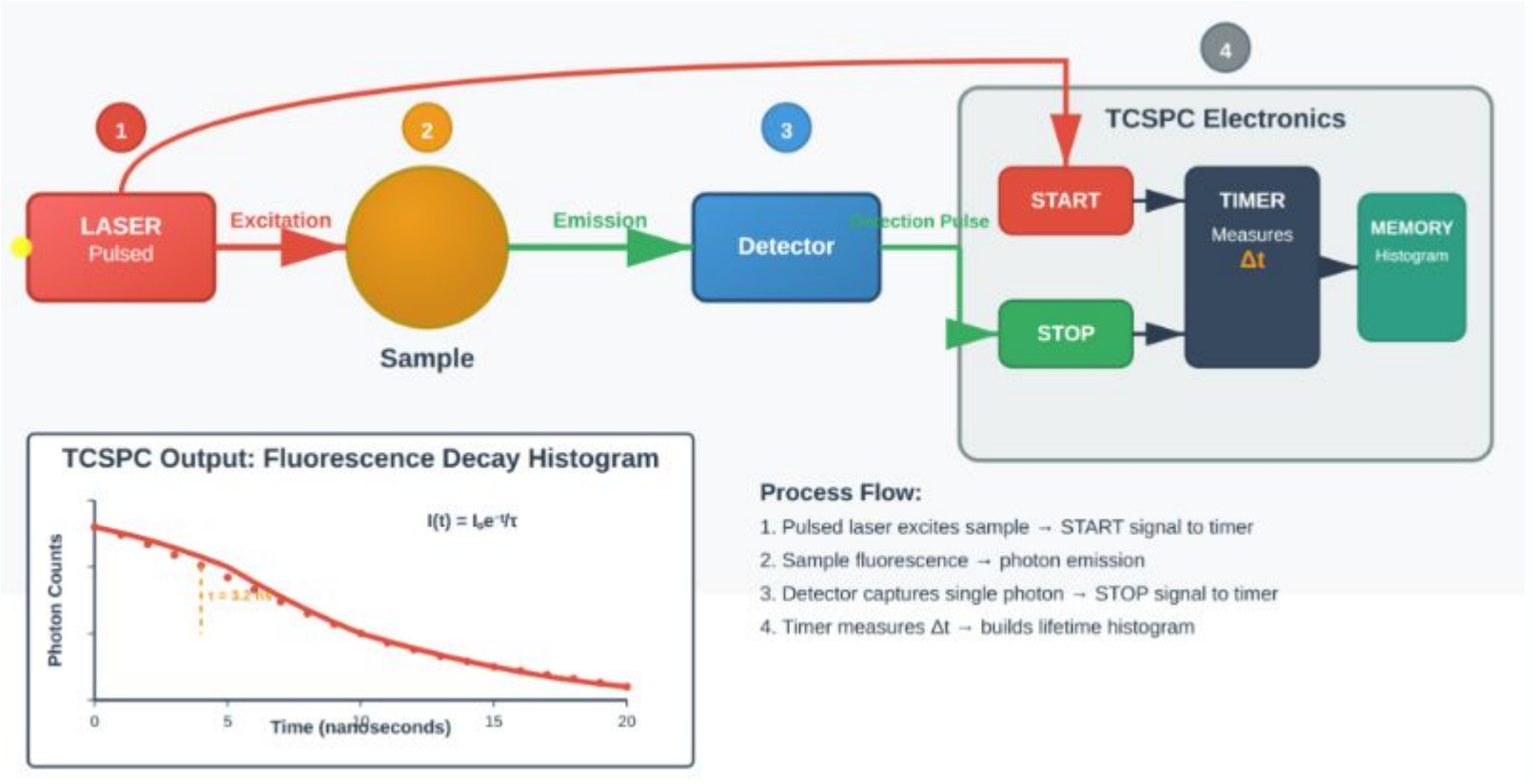
— Emission spectra



— Absorbance in transmission mode



Measurements for characterization



Time correlated single photon counting

Irradiation facilities (with varied levels of access)

The irradiation facilities that are available include those present in the TIFR, Mumbai campus as well as those from sister institutes of our parent organization.

EM irradiation :

– Co-60 source with a "strength" of ~ 4-5 kGray/hour

All irradiated results shown today are with this source

– 5-10 MeV electron beam can deliver a comparable doses as the Co-60 source

Neutron irradiation :

A neutron irradiation facility from the Apsara-U reactor at BARC. This is a swimming pool type reactor with a total power of 2 MW.

→ Dose depends on distance from the core.

Irradiation with 1 MeV neutron equivalents to ~10^{16} n/cm^2 per day is possible.

TIFR pelletron facility :

20 MeV proton beam with a flux of 10^10 particles /s/cm2

Studies with CsPbBr3 and CdSe

Synthesis and Fabrication:

- ❖ CsPbBr3
- Direct polymerization technique
- Polymerization induced by UV light irradiation.

- ❖ CdSe
- Dispersion of ligand-modified CdSe QDs into methyl methacrylate (MMA) monomer (plus initiator).
- Polymerization in a tablet-shaped mold.
- QDs become locked into the PMMA matrix, including both faces.

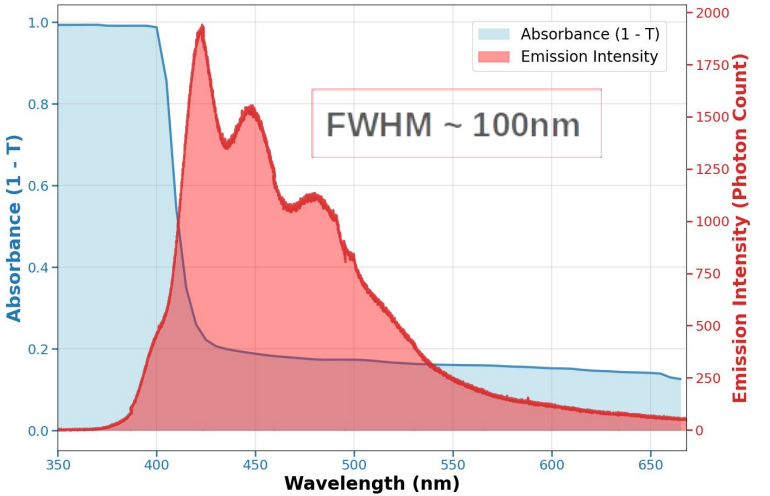
Summary:

- Fast and low-waste approach offering significant advantages over conventional methods for CsPbBr3.
- Large scale and cost-effective.
- Very uniform QD distribution.
- Compatible surface chemistry- good stability and low leaching (compatible ligands).
- Good control over tablet geometry and QD loading profile for CdSe QD sample.

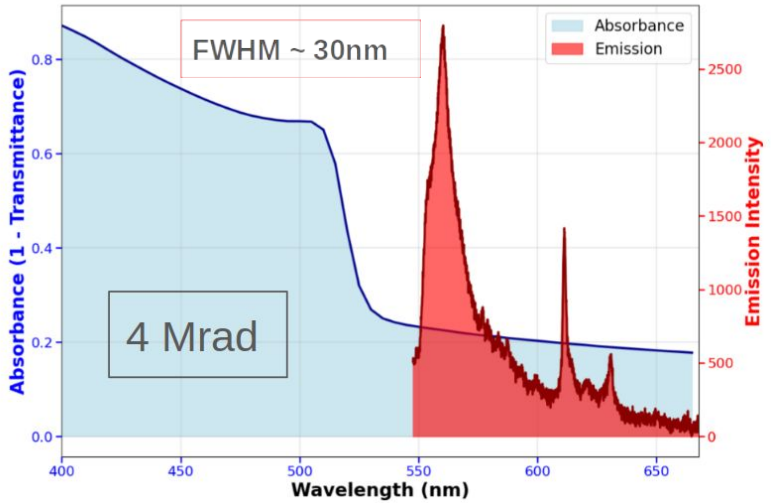
Emission and Absorption spectra

$CsPbBr_3$ nano crystals

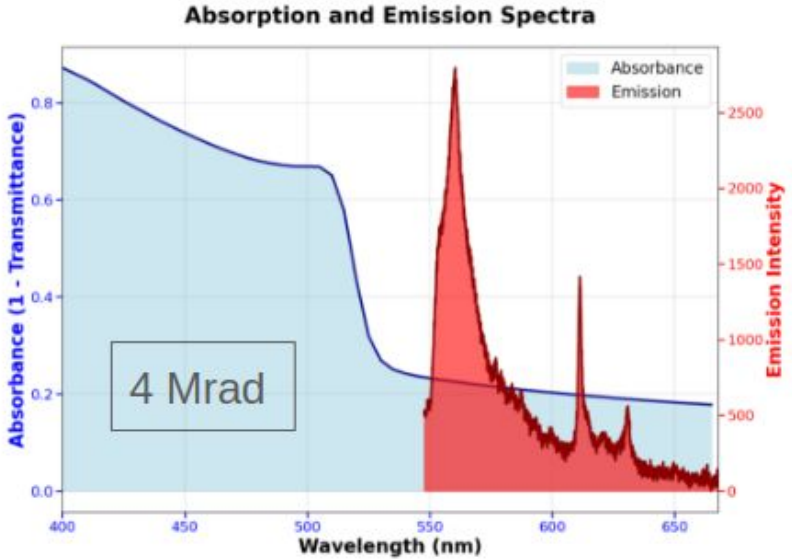
Plastic scintillator (Bicron)



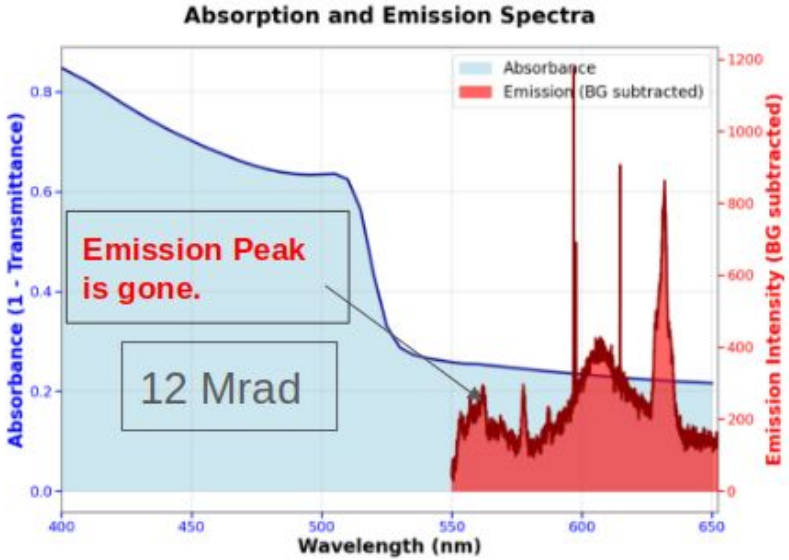
CsPbBr3



$CsPbBr_3$ nano crystals post irradiation



(a) 4 Mrad Irradiation



(b) 12 Mrad Irradiation

Figure 3: $CsPbBr_3$ in PMMA under different irradiation doses

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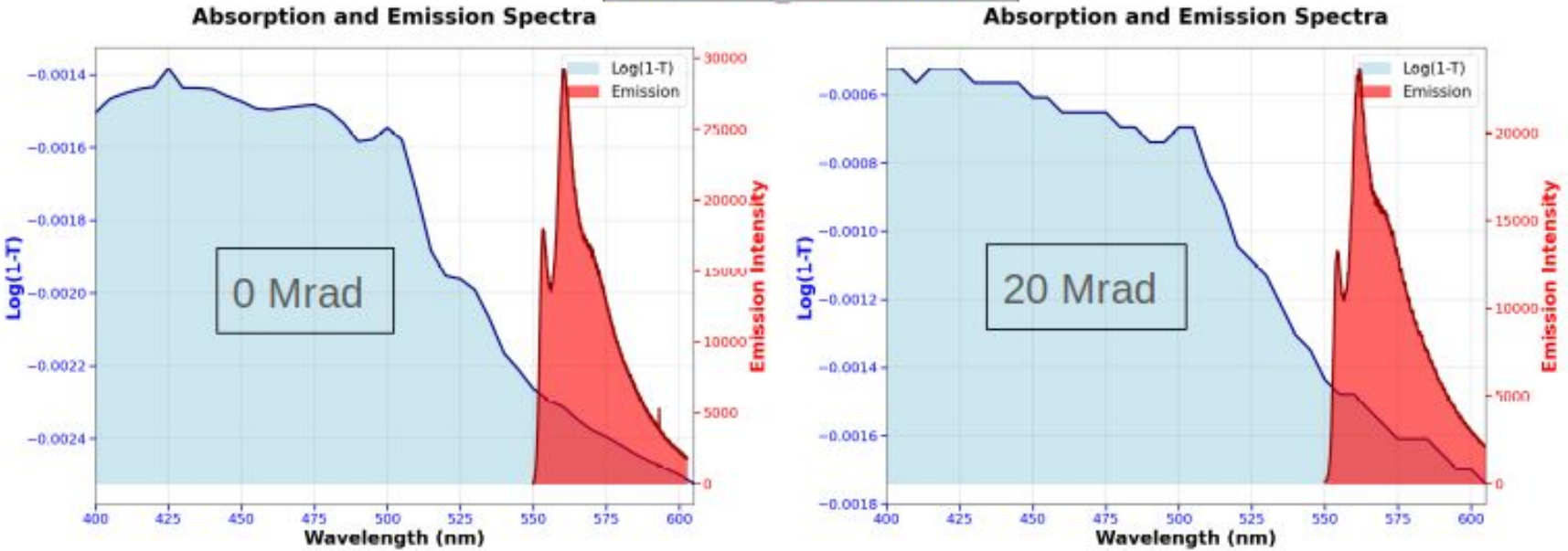
Same conclusion from 2 samples from the same batch

CdSe quantum dots

Emission Peak remains.

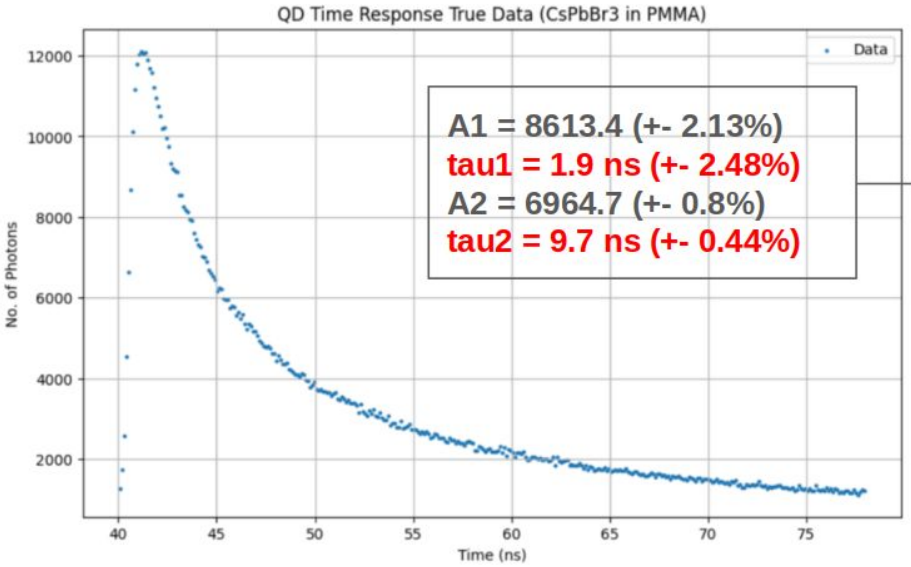


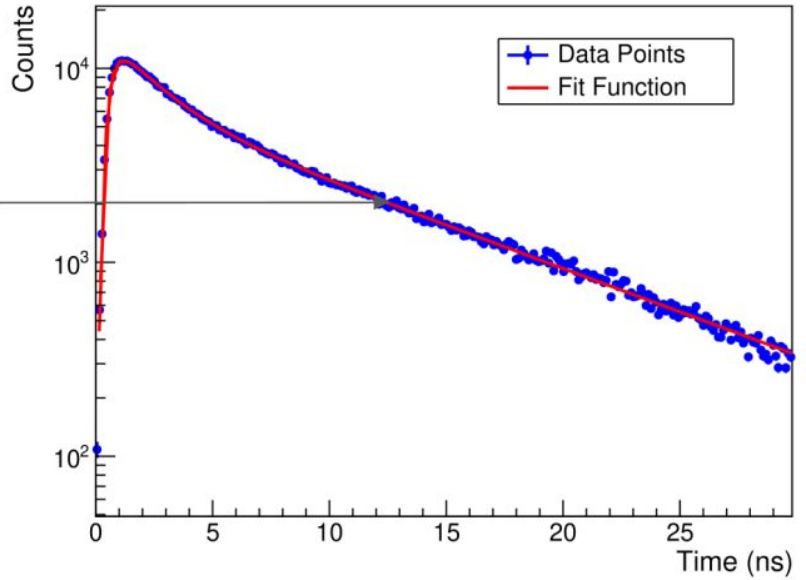
CdSe Samples with different levels of irradiation. Note the absorption spectra is log scale for the poor transmittance of the substrate.

Time resolved photo luminiscence

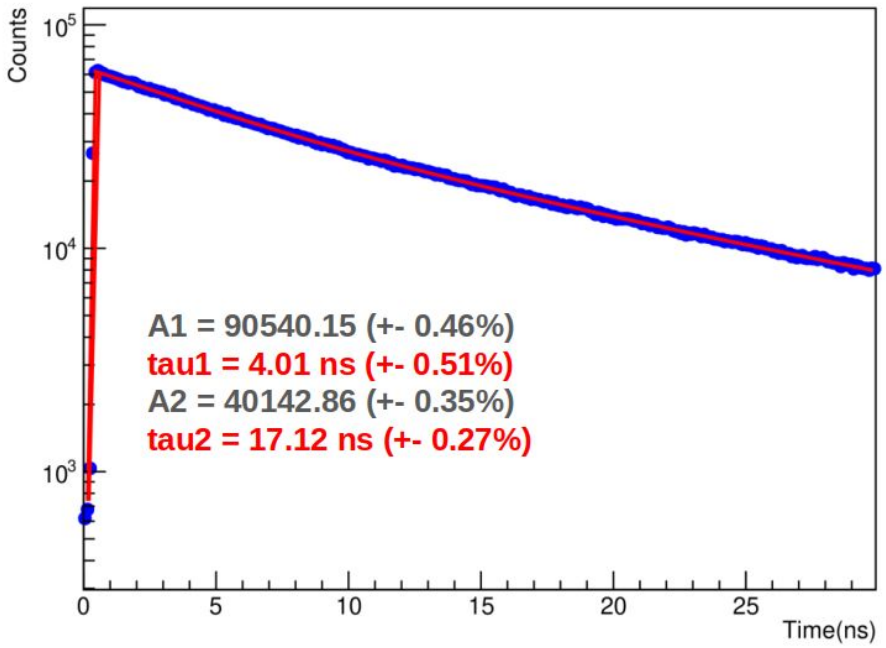
$CsPbBr_3$ nano crystals

Fit function = $f(t) = \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^{\infty} \exp\left(-\frac{(t-t')^2}{2\sigma^2}\right) \left[A_{\mathrm{decay1}} e^{-t'/\tau_{\mathrm{decay1}}} + A_{\mathrm{decay2}} e^{-t'/\tau_{\mathrm{decay2}}} - A_{\mathrm{rise}} e^{-t'/\tau_{\mathrm{rise}}}\right] dt' + bkg$

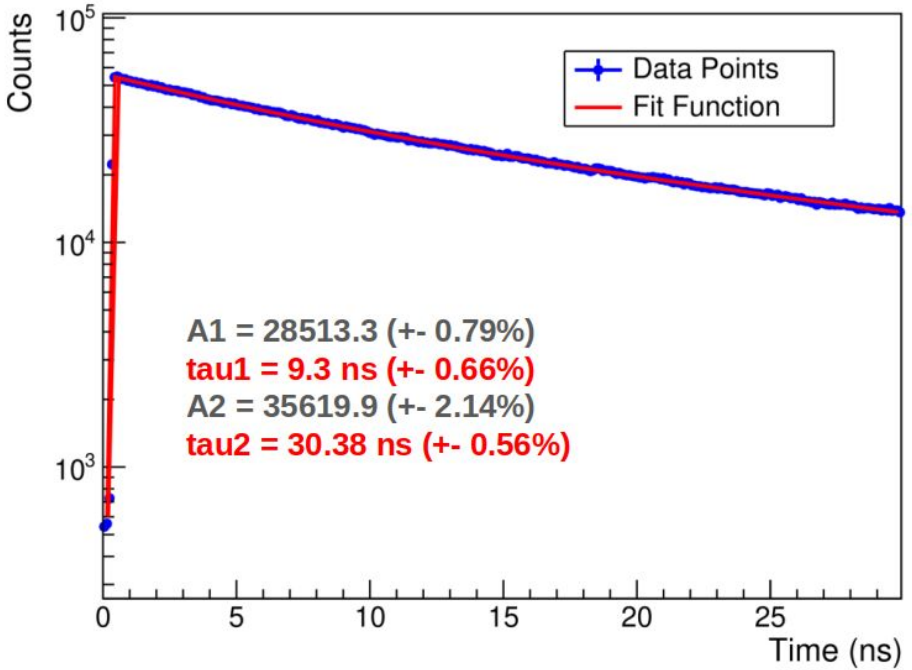




CdSe quantum dots



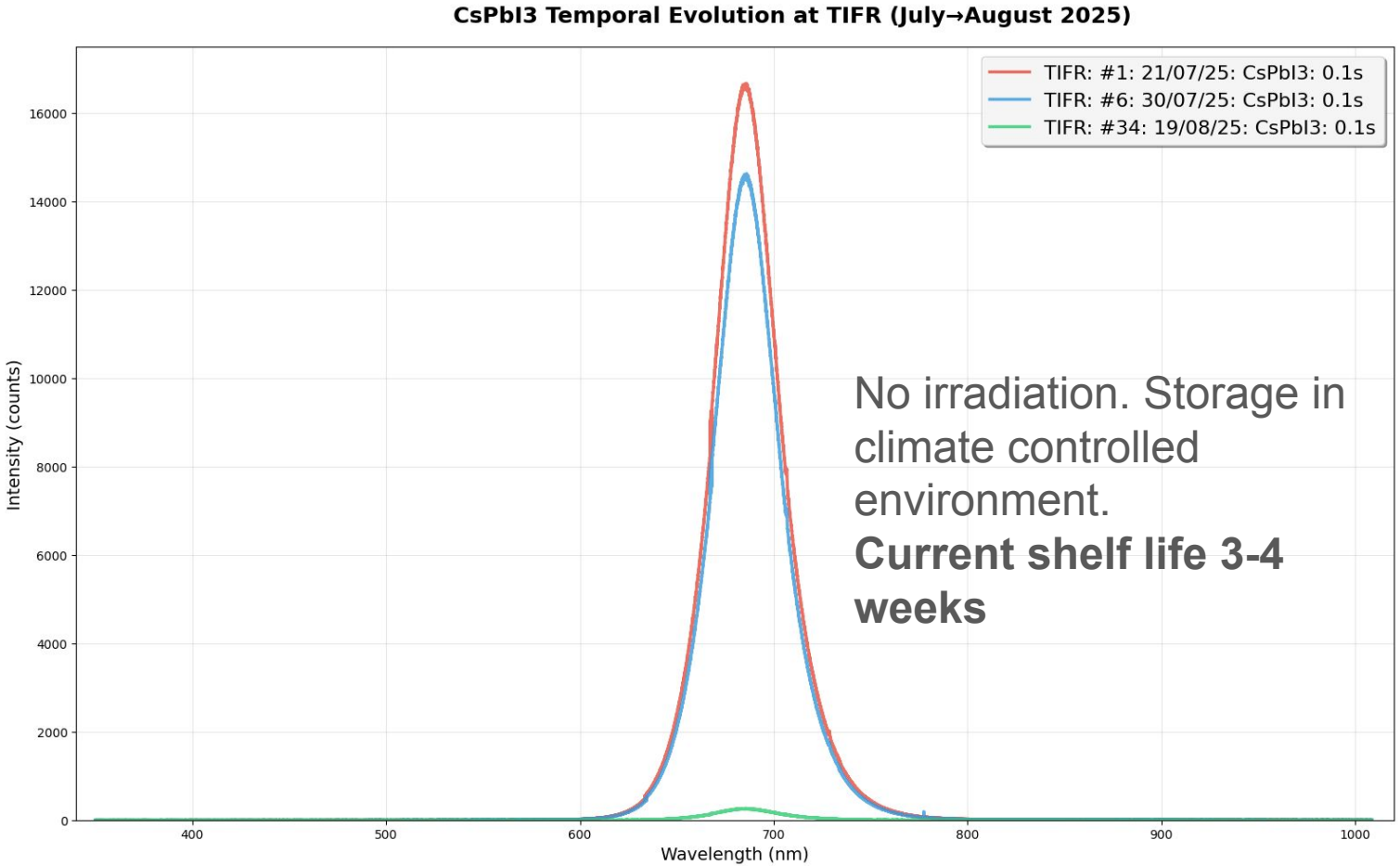
0 Mrad CdSe



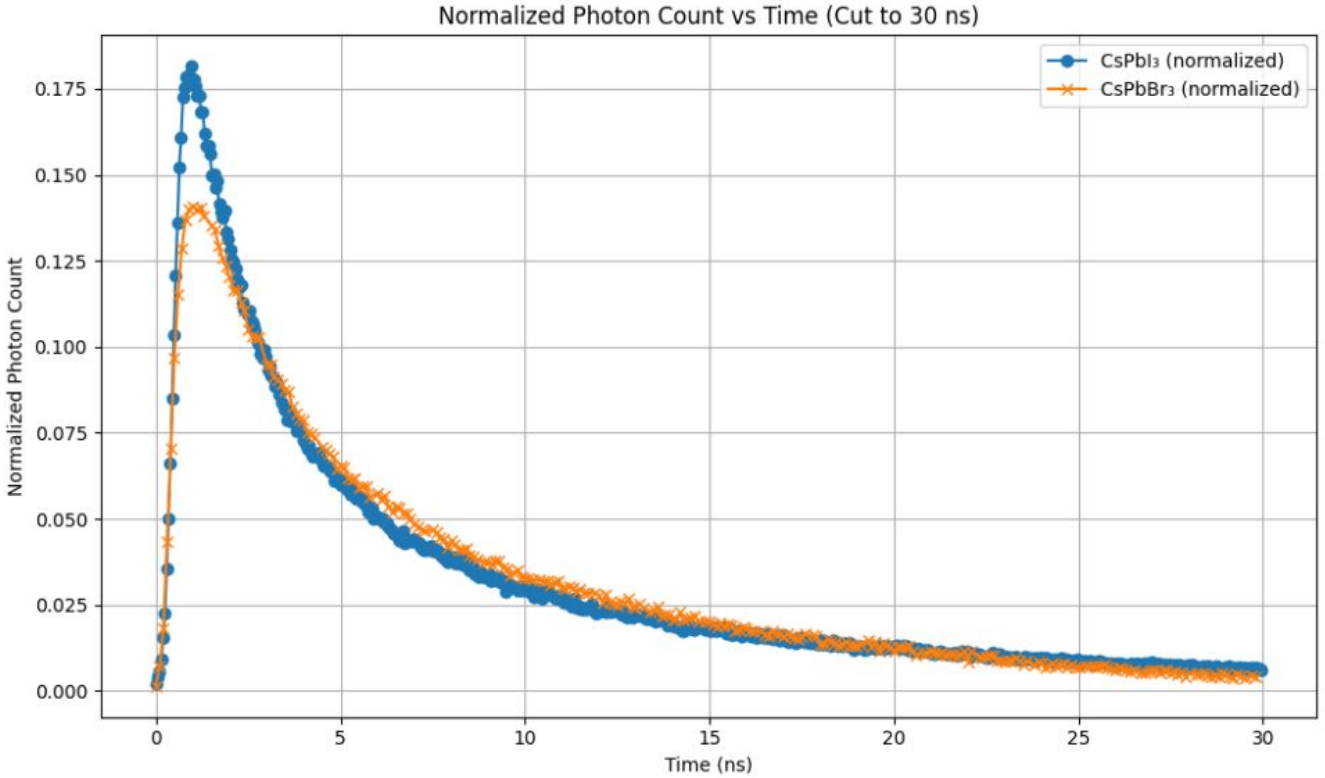
20 Mrad CdSe

Degradation in timing properties after irradiation

$CsPbI_3$ nano-crystals



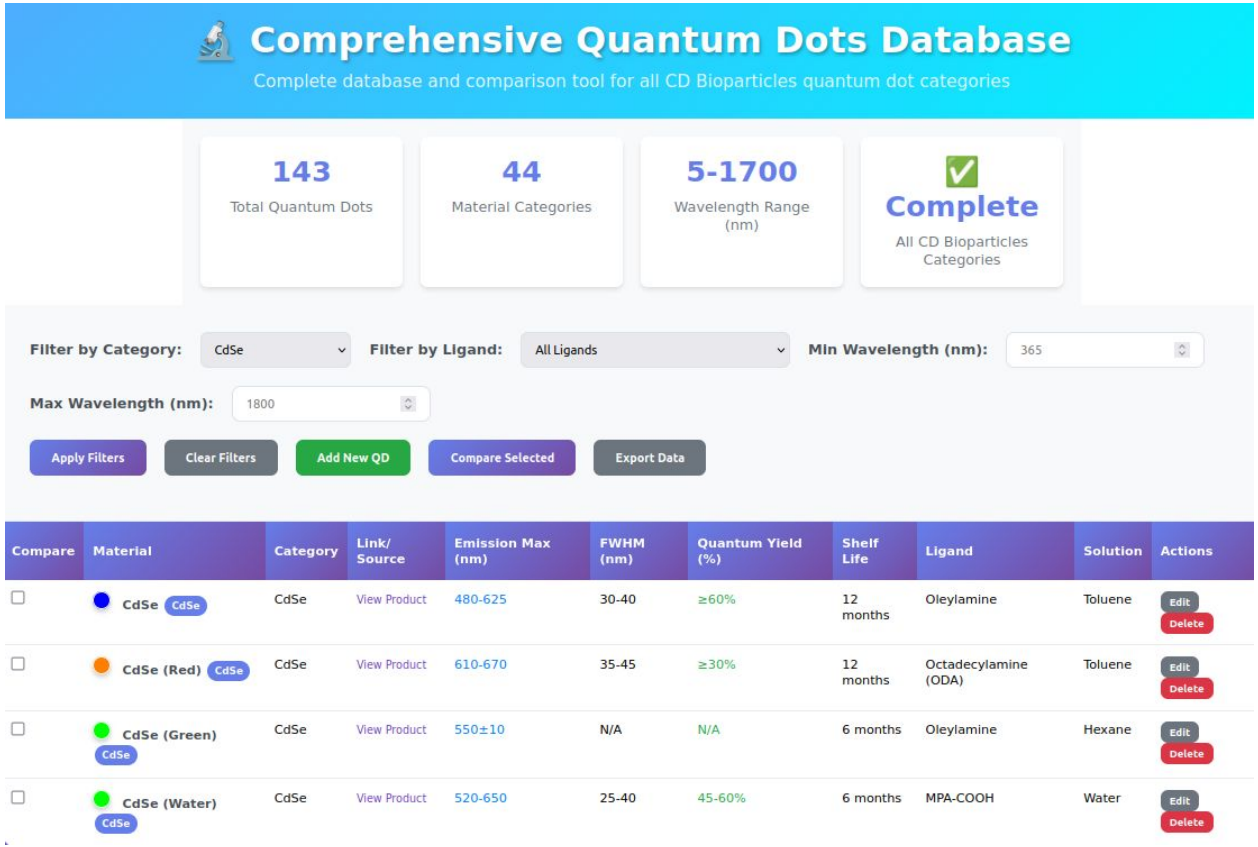
$CsPbI_3$ nano-crystals



$CsPbI_3$ has a faster time response than $CsPbBr_3$

Commercially available quantum dots

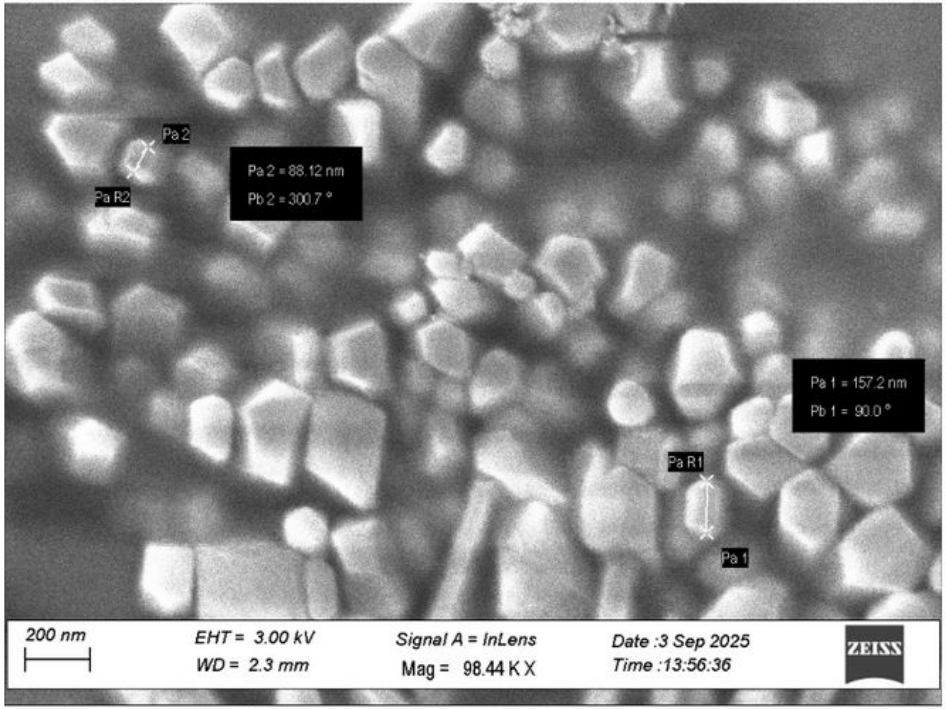
The Merck catalog in one place



https://santanu.web.cern.ch/QD_database/

Special thanks to S. Mahata!

Initial studies with Merck's $CsPbBr_3$ NC product



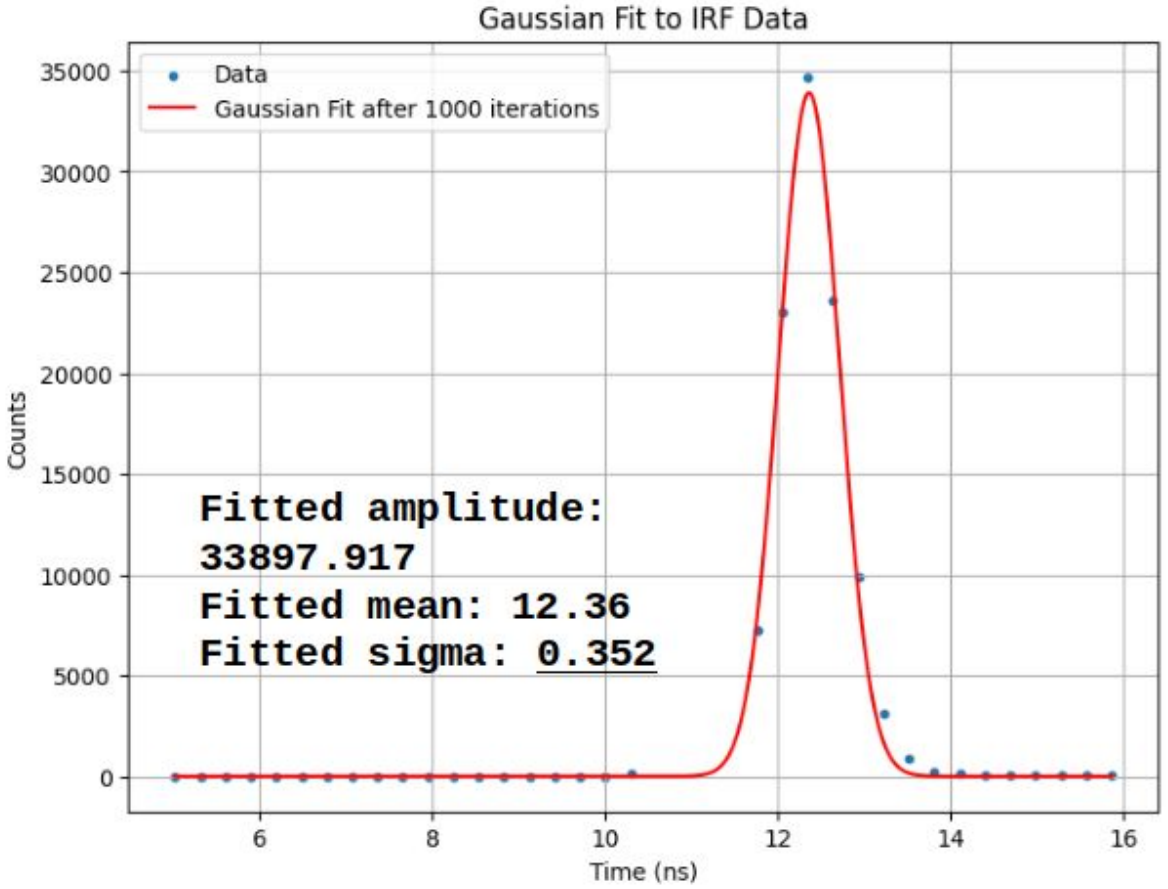
From an SEM scan we find varied shapes and sizes of nano-crystals

Summary and plans

- **Over the past ~year we have set up a measurement pipeline to characterise different species of QDs including after irradiation (so far only EM).**
- Initial conclusions are :
  - $CsPbBr_3$ retains its performance up to at least 4 MRad of irradiation while the same for CdSe is above 20 MRad.
  - In terms of timing performance $CsPbI_3$ is the fastest while CdSe is significantly slower.
  - For $CsPbI_3$, which currently suffers stability issues work is underway in P. Mandal's group to improve its longevity.
- Going forward we will repeat the studies particularly with p/n irradiation and include additional materials at other wavelengths.
- In parallel we are working on integrating a pixellated crystal + QD test stand readout with MPPCs focussed on 511 KeV Gamma ray reconstruction.

BACKUP

Instrument Response Function for TCSPC



IRF for Time Response Measurement

Laser:
532 nm pulse laser with pulse width of 5ps