Characterization of new detectors containing scintillating nano-crystals for extensive uses in physics research

Emanuele Mazzola – *Ph.D. project proposal in subnuclear physics (research topic B)*

Introduction

Scintillators, materials that emit light after an energy release (due to the interaction with ionizing radiation), find relevant deployments in a variety of technological and scientific fields, as rare event searches, astronomical discovery and medical diagnostics [1]. Scintillation is, as a matter of fact, one of the most common methods for radiation detection and spectroscopy. One of the parameters that characterizes scintillators is their light yield, which is the fraction of energy converted into light. An ideal scintillator should have the following properties [2]:

- Linear conversion of the kinetic energy of charged particles into detectable light with a high scintillation efficiency;
- Transparency to the wavelength of its emission, for good light collection;
- Very short decay times of the induced luminescence, to generate fast signal pulses;
- Refractive index of glass (~ 1.5), to allow efficient coupling of scintillating light to to, for instance, a photomultiplier (PMT).

To meet simultaneously all these criteria is always challenging, and the choice of a scintillator is often a compromise between these factors. The need for ever more reliable detectors generates a growing demand for innovative scintillators, which combine efficient and fast scintillation with a high probability of interaction with ionizing radiation. In large-volume detectors, it is also essential to have a low rate of light reabsorption, to reduce the loss of outgoing photons.

In the last decades, plastic scintillators consisting of polymeric matrices embedding scintillating organic materials have emerged as affordable alternatives to conventional inorganic scintillating crystals [3]. High-energy photons interact with the scintillator, resulting in a luminescence that propagates by total internal reflection to the waveguide edges, where it is detected by highly efficient photomultipliers or photodiodes. A similar fate occurs for the luminescence emerging from direct excitation along the track of fast protons, α and β-rays and other charged particles. Owing to their fabrication versatility and lightweight, plastic scintillators find application in many sectors, such as advanced radiometry applications relying on the time of flight (TOF) technique [3]. These include medical imaging in positron emission tomography (TOF–PET), where fast timing is critical for the image quality and the image reconstruction process.

A huge step forward in the challenge of radiation detection through scintillators is represented by nano-crystal semiconductors synthesized in solid or liquid solutions. Nanometer-sized semiconductors, allows to increase the energy band gap, ensuring a high photon output essential to improve the statistic component of the energy resolution. In addition, the production of nanocrystals has been consolidated over the years [4], allowing to tune the energy separation between the absorption and emission spectra by separating light absorption and emission functions between two distinct parts of the nanostructure. This feature is fundamental to avoid auto-absorption in samples with centimetre dimensions. Given the excellent properties of these materials and their simple and low cost production, they are spreading very quickly both in research and commercial areas.

Proposal

My proposal focuses on the characterization of *Quantum Dots* (QDs), nano-crystals of a semiconducting material with diameters in the range of 2-10 nanometers. Thanks to these dimensions, smaller than the Bohr radius, the quantization of the energy levels occurs and the characteristic emission wavelength progressively increases with the size of the quantum dot. The chemical synthesis of the quantum dots allows for precise control of the size, and so of the emission wavelength. Thanks to their customizability, QDs can be produced to match the needs of specific uses. For example, in case of 0νDBD, $CuInSe_2$, CdSe/ZnS and CdSe/CdS are QDs of particular interest, due to their isotopic composition: ^{116}Cd, ^{82}Se and ^{100}Mo are good candidates for the double beta decay.

For my bachelor thesis project, I have already worked with scintillating nano-crystals [5], characterizing them and evaluating their LY. Thus, I propose, also for the complete characterization of QDs, to proceed through different steps. First of all, to collect the light emitted by QDs, a photo-detector is needed. For the photons collection from the first QDs prototypes, I will employ a *Silicon photomultiplier* (SiPM). This will allow me to identify the most performing samples, to be coupled with *Silicon Drift Detectors* (SDDs). SiPM are in fact limited in the Poissonian component of the energy resolution by the limited quantum efficiency (inferior to the one offered by the SDDs, that is ~80%) and by the intrinsic spread in the multiplication gain. SDDs, with which I have already practised during my master thesis work [6], are usually used for low energy X-ray spectroscopy thanks to the presence of very low capacitance and a small anode for collecting electrons, that allow reaching a formidable resolution and very high count rate (10^5 cps, resolution of 120 eV for the ^{55}Fe peak) [7]. I will directly calibrate the SDD detectors in terms of detected photoelectrons, as to be sure that the light yield can be properly determined from the radiation measurements. Particularly, it is possible to evaluate self-absorption through dedicated measurements with radioactive X-rays sources (e.g. ^{55}Fe) that will allow to study the detector response as a function of the source position. After the calibration of the SDD, the second step will consist of the investigation of the overall *light yield* (LY) and the *quenching factor* (QF) of the system (QDs coupled with SDDs) through measurements with gamma and alpha sources.

In parallel, I will develop a Monte-Carlo based simulation, by means of the *Geant4* toolkit. To properly describe the optical processes, it is crucial to know exactly several experimental parameters, such as the transmittance, the absorbance and the reflectivity of the samples and surrounding materials [8]. After implementing all this information in the simulation, I will perform several dedicated measurements for the validation of the simulations which will allow us to optimize our setup.

Another topic I will have to deal with during the various measurement campaigns, is the different pulse shape produced by different events in standard scintillators. This would be useful also for QDs, since it would allow to recognize the incident particles. In my Ph.D. project I will also implement *Artificial Intelligent* (A.I.) and *Machine Learning* (ML) algorithms to study in detail the shape of the pulses.

Plan of activities

My Ph.D. will be divided into the following structure:

- During the **first year**, I will couple the QD prototypes with SiPM and perform a preliminary analysis with alpha, beta and gamma sources. I will implant the alpha source directly on the QD sample, to reduce the auto-absorption of photons. I will carry out X-ray excited radioluminescence. All this with the purpose of identifing the most performing scintillator in terms of LY and QF. Also, I will implement A.I. algorithms for pulse shape discrimination, through the common Python libraries (Tensorflow, PyTorch).
- During the **second year**, I will characterize the SDDs performing X-rays measurements, using different sources (for example ^{55}Fe) placed in a vacuum chamber, in order to reduce energy loss between the source and the target. At the same time, I will develop the Geant4 simulation, in order to extrapolate information useful for the setup optimization.
- During the **third year**, I will couple the selected QDs with the SDDs and characterize the system with alpha and gamma radiation. I will finalize all the programs and the analysis to obtain a reliable measure of the LY and QF of the final setup, with the final purpose of achieving a complete characterization of the provided QDs.

References

[1] Gandini, M., Villa, I., Beretta, M. et al. *Efficient, fast and reabsorption-free perovskite nanocrystal-based sensitized plastic scintillators*. Nat. Nanotechnol. 15, 462–468 (2020).

[2] Knoll, Glenn F, *Radiation Detection and Measurement*, 3rd ed., University of Michigan Ann Arbor (1999)

[3] Hajagos, T. J., Liu, C., Cherepy, N. J. & Pei, Q. *High-Z sensitized plastic scintillators: a review*. Adv. Mater. 30, 1706956 (2018).

[4] F. Meinardi et al., *Large-area luminescent solar concentrators based on 'Stokes-shift-engineered' nanocrystals in a mass-polymerized PMMA matrix*, Nature Phot. 8 (2014) 392

[5] E. Mazzola, *Caratterizzazione di nuovi materiali scintillanti contenenti nanocristalli,* Bachelor degree thesis, Università degli Studi di Milano-Bicocca (2018)

[6] E. Mazzola, *Study of the impact of backscattering systematics on electron spectra for the KATRIN experiment,* Master degree thesis, Università degli Studi di Milano-Bicocca (2023)

[7] P. Lechner et al., Silicon drift detectors for high resolution room temperature X-ray spectroscopy, Nucl. Instr. and Meth. (1996); A 377, pp. 346-351

[8] M. Gregori, Monte Carlo simulations of optical processes for rare event searches, Master degree thesis, Università degli Studi di Milano-Bicocca