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# Pulse shape discrimination between (fast or thermal) neutrons and gamma rays with plastic scintillators: State of the art

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ABSTRACT

We would like to present here with the eyes of the chemist the most recent developments of plastic scintillators (PS) for neutron detection. This review covers the period from 2000 to August 2014, and is fragmented in two main chapters. The first chapter deals with the chemical modifications for thermal neutron capture, whereas the second chapter presents the various strategies used to enhance the response to fast neutrons *via* pulse shape discrimination. For each chapter the theory is also explained.



**Contents**



*Abbreviations:* AIBN, aso-bisisobutyronitrile; CBRN-E, Chemical, Biological, Radiological, Nuclear, Explosives; Eu(phen)(DBM)$_3$, Europium(III)(phenanthroline)(dibenzoylmethane)$_3$; FOM, Figure Of Merit; HMPA, hexamethylphosphoramide; LGB, Lithium Gadolinium Borate; LiMA, Lithium Methacrylate; Li-Sal, Lithium Salicylate; MMA, Methyl Methacrylate; *p*-T, *p*-terphenyl; PBD, 2-(4-Biphenylyl)-5-phenyl-1,3,4-oxadiazole; PEG, poly(ethylene glycol); PEN, polyethylene naphthalate; POPOP, 1,4-Bis(5-phenyl-2-oxazolyl)benzene; PPO, 2,5-Diphenyloxazole; PS, Plastic scintillator; PSD, Pulse shape discrimination; PSt, polystyrene; PVK, Polyvinylcarbazole; PVT, Polyvinyltoluene; SSD, Spectral shape discrimination; St, styrene; TTA, Triplet-triplet annihilation

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## 1. Introduction

Protections of civilians and facilities against CBRN-E (Chemical, Biological, Radiological, Nuclear, and Explosives) threats represent a true challenge due to the constant increase of world's population movements. According to Dr. El Baradei (1997–2009 IAEA Director General), terrorists who are unconcerned about exposing themselves to radiation could easily conceal a source in a truck or a suitcase. "*The danger of handling powerful radioactive sources can no longer be seen as an effective deterrent, which dramatically changes previous assumptions.* […] *Security of nuclear and other radioactive material has taken on dramatically heightened* [*in IAEA's work*] *significance in recent years.*"

As an example, a (neutron/gamma) PuBe source was stolen in August 2013 from a storage location near Tabriz, in the Islamic Republic of Iran. The source was registered with the activity of 130 GBq (3.5 Ci). Results of first inspection and other evidences showed that the source was taken out of its shielding. The investigations have not reached to any finding at the date of this review. The event is provisionally rated at level-2 on International Nuclear Events Scale (INES) [1].

To this threat must be added the shortage of the most suitable neutron detector, based on $^{3}$He. $^{3}$He is an extremely rare isotope of helium gas with a natural abundance of 1.37 ppm. Fusion research, cryogenic and medical imaging are demanding $^{3}$He as well as neutron detectors, where high purity $^{3}$He is required. Since a decade, the $^{3}$He production does not support anymore the demand, and the unavailability's strategic problem is almost reached, so alternatives need to be found rapidly.

In this context, numerous solutions could be used to detect Special Nuclear Materials. Among them, we will focus in this review on plastic scintillators (hereafter abbreviated as PS). These materials can be defined as one or several fluorescent probes embedded in a polymer matrix, and the resulting system is able to produce light while interacting with a ionizing radiation. For instance, a typical scintillation cocktail can be prepared with *p*-terphenyl and POPOP dissolved in polystyrene. This formulation was widely used for half of a century, as a result from the first described recipe of a PS in the late 50s [2].

To detect Special Nuclear Materials, plastic scintillators present several advantages. They are cheap (especially interesting for large size detection systems), efficient enough for total gamma ray counting, can be handled without any specification, reliable, stable in time and can be prepared in large volumes. More particularly, the choice of the detector will become extremely important in the future due to the combination of the cheapness of PS ($2000 for a 3.8 cm × 36 cm × 173 cm large PVT detector, compared to $6000 for a 5 cm × 10 cm × 41 cm NaI(Tl) inorganic scintillator [3]) and the necessity for some countries to cover at the best their borders with radiation portal monitors. But some drawbacks have incited several groups to renew with chemical developments of plastic scintillators: they display a poor resolution, afford relative low scintillation yields compared with inorganic scintillators, cannot give access to the full energy of an incident gamma, and were presumed for a long time to be unable to perform fast neutron/gamma discrimination. This last point was very problematic for neutron detection as neutron radiation always goes along a strong gamma background, and their responses were not differentiable with classic PS. We will see in this Review that chemical modifications of these materials can lead to differentiations in the particles' responses.

To this aim, the goal of this review is to define new developments of plastic scintillators, from the chemists point of view, in the frame of neutron detection. Despite the fact that many tools for detection devices have been improved (electronics, signal processing, etc.), most of the commercial PS are those which were developed in the 50s and 60s. This review is limited to the literature from 2000 to August 2014, unless particularly relevant data were published before this date. It is also restricted to scintillators for thermal or fast neutrons detections, and their discrimination with gamma background. The reader can refer to other reviews in this field for more global descriptions of plastic scintillators [4]. This review will discuss mainly about chemical developments, and is thus less oriented to the nuclear physics point of view, even if the results of neutron detection and regular photophysical characteristics (scintillation yield, decay time, and scintillation wavelength) are given, as well as pictures of plastic scintillators when available. No data will be given regarding improvements on organic single crystals, liquid scintillators and inorganic scintillators.

## 2. Thermal neutrons detection

### 2.1. Theory

Absorption of thermal neutrons (generated after multiple collisions with protons) is unlikely to occur in a standard plastic scintillator, as they are usually composed of C, H, N, S or O, which have a low thermal neutron cross-section. In order to observe the absorption of thermal neutrons, nuclei with a higher thermal cross-section need to be incorporated within the plastic scintillators. The isotopes of interest are enlisted in Table 1.

**Table 1**
Radionuclides sensitive to thermal neutrons, their reaction of interest, including the thermal cross-section and the isotope abundance.

| Isotope | Reaction of interest | **Thermal** cross-section **(barns)** | Isotope abundance (%) |
|---|---|---|---|
| $^{6}$**Li** | $^{6}Li+n\rightarrow{}^{3}H+\alpha+4.78$ MeV | 940 | 7.5 |
| $^{10}$**B** | $^{10}B+n\rightarrow{}^{7}Li^{*}+\alpha+2.8$ MeV$\rightarrow{}^{7}Li+\alpha+\gamma$ (0.48 MeV) | 2000 | 19.9 |
| $^{113}$**Cd** | $^{113}Cd+n\rightarrow 114Cd+\gamma's$ (9 MeV) | 30,000 | 12.2 |
| $^{155}$**Gd** | $^{x}Gd+n\rightarrow{}^{x+1}Gd^{*}\rightarrow{}^{x+1}Gd+e^{-}+\gamma's$ (8 MeV) | 60,700 | 14.7 |
| $^{157}$**Gd** | | 254,000 | 15.7 |