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# Radiation Detectors for Nuclear Well-logging Application: A Review

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## Abstract

*The oil and gas industry uses nuclear logging method to survey for the presence of hydrocarbons in a given region of interest. Nuclear logging tools are used to achieve this aim. These tools consist of radiation sources and radiation detectors. $^3$He thermal neutron detector and NaI:Tl for gamma-ray measurements are the conventional detectors used for this application. However, the shortage of $^3$He gas used in $^3$He tube and the high demand for both detectors in many other societal applications has mandated the search for alternative radiation detectors. This paper reviewed other alternatives that are commercially available. Light output, temperature sensitivity, tolerance to vibration and shock are important parameters to consider when selecting a detector for this application. Among the reviewed alternatives, GS20 crystal for neutron and gamma ray measurements, LaBr:Ce and LuYAP:Ce for gamma ray measurement have been reported to have comparable performance to the conventional detectors.*

Keywords: Nuclear logging, $^3$He tubes, NaI:Tl, Temperature, Vibration, Shock

## INTRODUCTION

Well logging, sometimes referred to borehole logging is a process of evaluating and making a record of the constituent of a geological formation. This evaluation can be done through visual inspection of samples collected during the logging process (geological logs) or via physical measurements acquired with a logging instrument lowered into the borehole during the logging process (geophysical logs). Log data provide information that estimate the density, porosity, fluid type (oil, gas or water), concentration of fluid, pressure, temperature,

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type and permeability of a geological formation (Simpson, 2017). This information is acquired by using either acoustic (sonic) tool, electrical tool, or nuclear tool.

For many decades, nuclear method has been an important borehole logging method that employ four (4) common tools to evaluate a geological formation:

1. Natural $\gamma$-ray tool- This tool consists of one or more $\gamma$-ray detector with no radioactive source. It measures $\gamma$-ray emitted by naturally occurring radioactive sources (NORM) in minerals such as the Uranium and Thorium decay chains and the decay of $^{40}$K. This is mostly used to determine rock type.
2. $\gamma$-$\gamma$ tool- This tool consist of a $\gamma$-ray source (usually $^{137}$Cs) and one or more $\gamma$-ray detector (commonly used is NaI:Tl). It utilises Compton-scattered photons from the $\gamma$-ray source to determine the density of materials surrounding the borehole probe.
3. Neutron porosity tool- This tool consists of a fast neutron source (AmBe, AmPu, or D-T) and one or more neutron detector (conventionally used is $^3$He) to determine rock formation porosity (fluid content).
4. Neutron-gamma density tool- This tool consists of a neutron source and one or more $\gamma$-ray detector. It utilises neutron-gamma production reaction.

Because of the very high temperature (typically, 150°C-175°C) and a pressure exceeding 10 MPa encountered during borehole logging activity, the detectors used in any of the above tools must be rugged enough to withstand these conditions. Apart from the oil and gas industries, radiation detectors play a very vital role in other applications such as homeland security, nuclear physics experiments, astrophysics, medical imaging among others. $^3$He detector is the most widely used and conventional thermal neutron detector for thermal neutron measurement.

$^3$He gas is produced as a by-product of nuclear weapons maintenance with tritium (Kouzes *et al*., 2015). Due to reduction in the amount of nuclear stockpile to be maintained, the amount of produced $^3$He gas has declined over the years, but the demand especially in homeland security and oil and gas industries is continually increasing. In 2010, it was reported that the yearly demand for $^3$He gas is ~ 65000 litre, while the production stands at ~ 15000 litres per year (Kouzes *et al*., 2010). This shortage and its wide applications necessitate the need for alternative thermal neutron detector. $\gamma$-ray spectroscopy provides information about the elemental composition of the rock formation. The conventional $\gamma$-ray detector used in this application is NaI:Tl. The choice of $^3$He and NaI:Tl detectors by the oil and gas industries for neutron and $\gamma$-ray measurements respectively is as a result of their ruggedness.

In recent years, alternative radiation detectors with high energy resolution, high counting efficiency, fast decay time, high light yield, high radiation resistance, high interaction probability with desirable radiation, low interaction probability with undesirable radiation, cost effective are available. In this paper, we review the available alternative neutron and $\gamma$-ray detectors that can be used for borehole logging activity. The next session will provide an overview of interaction of radiation with matter. Session 2 covers the basics of radiation detection, session 3 describes neutron porosity, session 4 reviewed some alternative neutron detectors, session 5 describes gamma ray density tool and session 6 reviewed some gamma ray detectors.

**Radiation Detection**

Radiation sources are general categorised into charged and uncharged radiations. Fast electrons (positive and negative beta particles) and heavy charged particles (alpha particle, proton, fission product, ions etc) are considered as charged radiations. The uncharged category is sub-categorised into neutrons (slow and fast neutrons) and electromagnetic radiation (x-rays and $\gamma$-rays). All these radiation sources interact differently with matter, the result of their interaction is however similar. Uncharged radiations are majorly the dominant forms of radiation in this work. Since the interaction of these uncharged radiations result in the production of charged radiations, it is therefore useful to describe the interaction of both types of radiation with matter. This chapter focuses on the physics of radiation interacting with matter.

Neutrons are classified as uncharged particles. They are therefore detected with the help of a converting material. The choice of a converting material depends on many characteristics which includes availability, high reaction cross-section with desirable radiation, low interaction probability with undesirable radiation, high reaction Q-value among others. The most viable and commonly used converting materials are $^3$He, $^{10}$B, and $^6$Li, this is because of their Q-value of 764 keV, 2.78 MeV and 4.78 MeV respectively. Figures 1, 3 and 2 show the dependence of cross-section to their individual reaction processes (Obodovskiy, 2019).

The neutron interact with matter basically happens via two mechanisms:

- Scattering - This occurs when a neutron collides with the nucleus of the target material and changes its path with less energy. This mechanism is further sub-categorized into the following:
  - Elastic scattering (n,n): .
  - Inelastic scattering (n,n ).
- Absorption - In this process, the target nucleus absorbs the incoming neutron and further decay to a stable state or break up to form daughter nuclei. This is also sub-categorized into:
  - Radiative capture (n,$\gamma$).
  - Charge exchange reation (n,p), (n,$a$).
  - Neutron producing reaction (n,xn). – Nuclear fission (n,f).

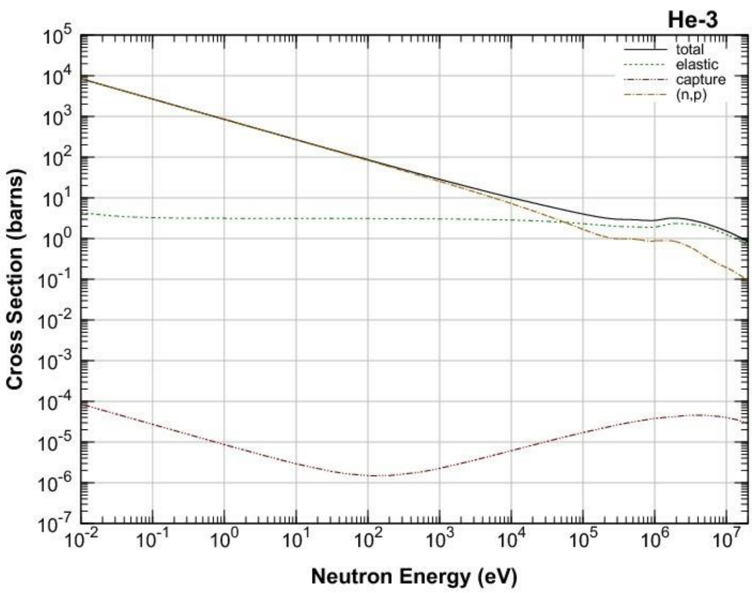


**Figure 1.** Reaction cross-section of $^3$He

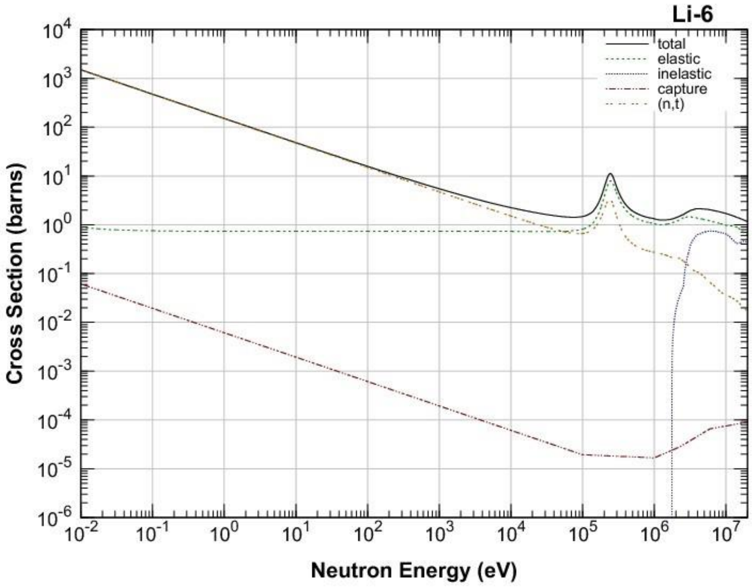


**Figure 2.** Reaction cross-section of $^{6}Li$

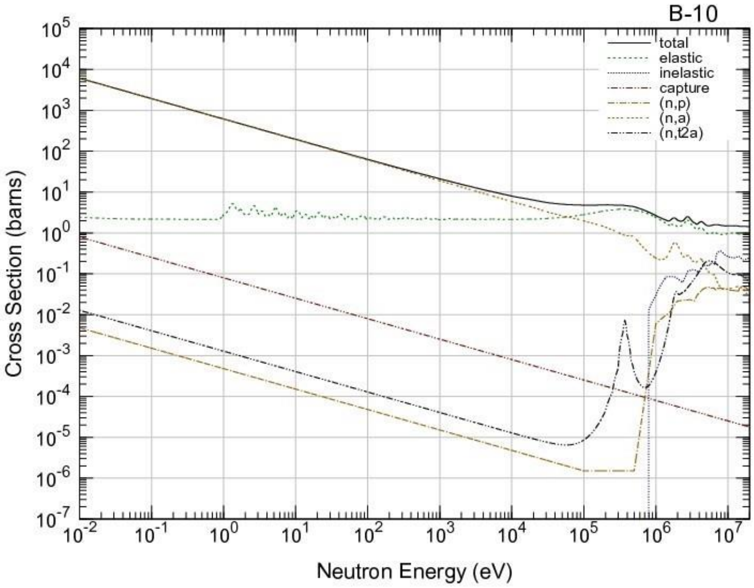


**Figure 3.** Reaction cross-section of $^{10}B$.

Gamma rays on the other hand interact with matter via photoelectric effect, Compton scattering or pair production. The probability of undergoing any of this mechanism depends on the gamma-ray energy and the density of the interacting medium. Photoelectric effect is more dominant at low gamma-ray energy while pair production is more probable at higher gamma-ray energy. Various gamma-ray detectors are commercially available, but not everyone of it is suitable for borehole logging applications. In section 5., we will review the commonly used gamma-ray detectors used in the logging industry and compare them with others that do not meet to the logging requirements.

**Neutron Porosity Tool**

Neutron porosity tool (log) measures the hydrogen content of a rock formation. Some of these logs utilises thermal and epithermal neutrons to provide information about the rock formation under investigation. This type of log bombards the rock formation with fast neutrons from a radioactive source (usually AmBe, AmPu, or DT). These fast neutrons are thermalised (slowed down) mostly by hydrogen atoms in the rock formation. The deflected thermal or epithermal neutrons are counted by two thermal or epithermal neutron detector placed at different position in tens of cm away from the radiaoactive source. The ratio of the counts recorded by the near and far detector infer the hydrogen content of the rock formation. The number of deflected neutrons reaching the detectors is inversely proportional to the hydrogen index in the formation. Therefore, the more porous the rock is, the larger near to far ratio. The conventional thermal neutron detector used in this tool is $_3$He detector.

**$^3$He Based Neutron Detectors**

For many decades, $^3$He proportional counters have been the conventional thermal neutron detector used for nuclear logging application. 3He proportional counters detect thermal neutrons via $^3$He(n, p)$^3$H reaction which has a high thermal neutron absorption cross section (5327 barn). This reaction resulted in a reaction Q value of 0.764 MeV shared between triton and proton in a manner that the laws of energy and momentum are conserved. The very high counting efficiency, non-toxicity, as well as radiation hardness makes it the most preferable choice in the logging industry. However, the high demands and shortage of the fill gas ($^3$He gas) used in this detector as explained in the introductory section necessitate the need to find an alternative detection technology that will compliment or replace its use in some applications.

**Review of Some Alternative Thermal Neutron Detector Technologies**

After $^3$He gas, $^{10}$B and $^6$Li are more commonly used as neutron conversion materials. This section will review some alternative neutron detection technology based on these two converting materials:

**$^6$Li Based Neutron Detectors**

Neutrons are detected using $^6$Li as a converting material via $^6$Li(n, $^4$He)$^3$H reaction which a reaction Q value of 4.78 MeV. This high Q value compensate for the material thermal neutron absorption cross section, making it easy to differentiate the full energy peak from background. $^6$Li as a converting material can be used for both thermal and fast neutron detection, unlike $^3$He proportional counters that are only sensitive to thermal neutrons.

Neutron detection using $^6$Li as a converting material is based on the following reaction:

**(a) $^6$Li-loaded glass scintillation detectors**

After $^3$He detector, the most famous thermal neutron detector used by the oil and gas for neutron porosity measurements is the $^6$Li-loaded glass scintillator. GS20 is a class of this detector that have been used in borehole logging applications (Spowart, 1977; Schneider & Hubner, 1991). The lack of long-range order in the atomic structure of GS20 serves as a constrain to increase its light yield. One way to overcome this constrain is by the use dopants like $Ce^{3+}$ ion. The heterovalent properties of cerium makes this technologically challenging. A study (Nikitin *et al*., 2013) showed how this limitation can be overcomed. Nanocrystals were incorporated into the glass matrix to synthensized glass ceramic scintillator by partial crystallization of Ce-doped lithium-silica glass scintillator (KGS3-3). Both GS20 and KGS3-3 were reported to have decay time constant of 70 ns with the measured light output from KGS3-3 crystal more than twice that of the pure GS20. A very recent work (Kawaguchi *et al*., 2020) compared the temperature dependence of GS20 and some lithium-calcium-aluminium-floride based scintillators. The measurements were made between 25°C and 150°C. Even at the highest temperature, the light output was 42% as compared to the lowest temperature measurement. Another recent study (Ruan *et al*., 2020) investigated the luminescent properties of GS20 at low temperature (between 37°C and -213°C). The use of GS20 for other applications can be found in (Rich *et al*., 2015; Mayer *et al*., 2015).

**(b) $^{6}$Li foil scintillator sandwich**
This technology stack multiple layers reactive film with light guide in a sandwich arrangement. An intrinsic efficiency between 20% and 35% has been reported using this technology by (Ianakiev *et al*., 2011). The same work reported that this technology shows high thermal neutron counting efficiency in comparison to $^{3}$He detector.

Pappalardo *et al*. (2016) reported and alternative thermal neutron detector based on silicon detectors coupled with thin layers of $^{6}$LiF that is deposited on a substrates of carbon fiber. A detection efficiency of ≈ 5.2% was obtained from this technology. In another work reported by (Finocchiaro *et al*., 2018), a detection efficiency of 8% was achieved. This comparable neutron detection efficiency as compared to $^{3}$He tubes, the low cost, and the gamma ray rejection capability means that the technology can be used in various applications where thermal neutron detectors are required, thereby reducing the very high high demand.

**(c) $Cs_2LiYCl_6$:Ce (CLYC) Crystal**
$Cs_2LiYCl_6$:Ce (CLYC) crystal is a type of detection technology that allows for both neutron and gamma ray measurements (Bourne *et al*., 2014; Mentana *et al*., 2016). Due to its dual particle detection capability, pulse shape discrimination techniques will be required to discern between both particle's signals. This technique relies on the fact that the light produces by neutrons and gamma ray have different time profiles. This difference makes it easier for electron pulse shape discrimination. A work by (Shirwadkar *et al*., 2011) shows that CLYC can provide up to 3.9% energy resolution at 662 keV $^{137}$Cs gamma ray energy.

This detector has been used in borehole logging application (Zhang *et al*., 2018) to derive a new density measurement method using fast neutrons and $\gamma$-ray counts only. This detector can provide porosity information with its thermal neutron detection capability. This method not only replaced the conventional detector for neutron and gamma measurements, but also avoids the use of multiple detectors in a logging tool.

**(d) $Cs_2LiLaBr_6$ (CLLB) Crystal**
$Cs_2LiLaBr_6$ (CLLB), just like $Cs_2LiYCl_6$:Ce (CLYC) crystal is another class of elpasolite family that also permit dual neutron and gamma ray measurements. An improved energy resolution has been reported for CLLB over CLYC crystal (Woolf *et al*., 2016; Mesick *et al*., 2017). Its density of 4.2 g/cm$^3$ gave it high gamma ray energy resolution 2.9% at 662 keV better than some gamma ray detectors (Shirwadkar *et al*., 2011). It can be grown in different shapes, making it suitable for many applications. Increase in temperature affect the light output and increase the gain in the photo sensor used. This crystal and its family must be able to provide a decent pulse shape discrimination between neutron and gamma ray signals when used as a dual detector in the logging application. A study by (Yang *et al*., 2013) shows that this crystal can provide a good separation between neutron and gamma ray peaks between -13$^{o}$C and 140$^{o}$C.

**(e) LiCAF Scintillator**
Another lithium-based detector is the Lithium calcium aluminium flouride (LiCAF) scintillator. It is commonly available either in Ce (Ce:LiCAF) or Eu (Eu:LiCAF) dopants. One key difference between them is the decay time, 40 ns and 100 ns for Ce:LiCAF and Eu:LiCAF respectively. Ce:LiCAF is less dense as compared to Eu:LiCAF crystal, making it less sensitive

to gamma ray (Fujiwara *et al*., 2012), (Ford *et al*., 2018). Both scintillators are transparent and non-hygroscopic, this property gave them an advantage over many gamma ray detectors.

**$^{10}B$ Based Neutron Detectors**

Boron is another neutron converting material widely studied. It utilizes $^{10}B(n, {}^4He)^7Li$ reaction to convert the neutron into measurable charge particles. The reaction can either proceed directly into the ground state of $^7Li$ or into an excited state of $^7Li$. The $^{10}B(n, {}^4He)^7Li$ (ground state) reaction produce a Q value of 2790 keV while the $^{10}B(n, {}^4He)^7Li^*$ (excited state) produces a Q value of 2300 keV.

**(a) Boron Trifluoride ($BF_3$) Proportional Counters**

Geometrically, this technology can serve as a direct replacement to $^3He$ tube (Kouzes *et al*., 2010). The $B_3F$ gas is the fill gas and serves as the target for the neutrons. The useable pressure range of only about 200 kPa as compared to more than 1500 kPa in $^3He$ gas detector (Wilpert, 2012). This limitation in pressure coupled with the toxicity and hazardous nature of the $B_3F$ gas makes it less attractive as an alternative detector in the oil and gas industry because of the high temperature and pressure encountered during logging activities. Due to a lower conversion cross section as compared to $^3He$ gas detector and a reduced useable maximum pressure, these detectors are best suited to applications that detect cold neutrons. They are often used in homeland security applications. Two $BF_3$ tubes filled to ≈ 1 atm were reported to perform better when compared to $^3He$ tube filled to 3 atm (Kouzes *et al*., 2010).

**(b) $^{10}B$ lined proportional counters**

With this technology, the high-pressure limitation has been overcome. It is also a direct replacement to $^3He$ tubes. The inner wall of the tube is lined with $^{10}B$ to capture the incoming neutron, this will allow for the use of a non-toxic fill gas like argon (Lacy *et al*., 2011; Xie *et al*., 2018). Careful determination of the coating thickness and the total available active area of the detector is one limiting factor.

A more recent novel approach was the use $^{10}B$ nanoparticle aerosol in a non-toxic or hazardous gas (Amaro *et al*., 2017) like the $BF_3$ gas. In this approach, $B_4C$ particles with radius smaller than the range of *a* particle and $^7Li$ nucleus are dispersed in Ar-$CH_4$ (90-10) gas mixture. The neutron conversion takes place within the particle, the decay products escape the particle and deposit all or part of their energies within the gas mixture. This technology can perfectly replace $^3He$ gas detector in neutron porosity tool.

**(c) $^{10}B$ lined high surface area detectors**

A very recent technology that overcome the surface area limitation is the coated straw tubes manufactured by Proportional Technology (Lacy *et al*., 2011). This technology uses cheap materials such as aluminium to make straws that are coated with $^{10}B$. The straws were initially manufactured in cylindrical shapes. More recent designs are in star like shape to increase the total active area of the detector. These straws are stack together in a 1" cylindrical tube that is filled with Ar/Co (90:10) as the ionisation gas. It has been reported that this technology provides comparable gamma ray rejection to $^3He$ tube with faster electronic signals (Lacy *et al*., 2011). This tube is as safe as $^3He$ tube, unlike the $BF_3$ gas that is toxic.

From geometric and safety perspective, $^{10}B$ coated straws tubes are direct replacement to $^3He$ tube in any application where thermal neutron count is the required. In terms of cost and availability of materials for manufacturing, $^3He$ tube is at disadvantage as compared to $^{10}B$ coated straws tubes. This technology can therefore replace $^3He$ tubes used in neutron porosity tool to access the fluid content of a logging environment. This detector was also tested using the China Spallation Neutron Source at IHEP, it shows very clear background discrimination (Xie *et al*., 2018).

**(d) $^{10}B$ doped scintillators**
Plastic scintillators are coated with $^{10}B$ in this technology. Due to fast decay time of plastic scintillators, this method is used to achieve high counting rates. Plastic scintillators are also cheap materials and can be manufactured in large sizes. It is more suitable for applications that requires fast neutrons detection. The presence of the $^{10}B$ coating makes it sensitive to thermal and epithermal neutrons.

NaI crystal has also been doped with $^{10}B$ to measure neutrons (Metwally, 2014). It can also serve as both neutron and gamma-ray detector. In another work by (Metwally & Emam, 2018), this technology was used to demonstrate its dual capability.

**Gamma-ray Density Tool**
The oil and gas industries use density logging tool to infer the bulk density of the formation. This tool consist of one or more NaI:Tl $\gamma$-ray detectors and a $\gamma$-ray source (commonly $^{137}Cs$). The $\gamma$-rays undergo Compton scattering upon entering the formation thereby interacting with the electrons in the atoms present in the formation. Compton scattering with the atoms in the formation result in reduction of energy of the $\gamma$-rays thereby scattering in all directions. Both the $\gamma$-ray detector(s) and source are collimated and shielded from each other so that the $\gamma$-rays reaching the detector(s) are those that have interacted with the atoms in the formation. The $\gamma$-ray flux reaching the detector(s) are attenuated by the atoms in the formation, and the amount of attenuation translate to the density of electrons in the formation. Bulk density is directly related to electron density. Formation with high bulk density will have high electron density, and hence will attenuate the $\gamma$-rays significantly as compared to formations with low bulk density. The amount of attenuation is inversely proportional to the number of $\gamma$-rays reaching the detector(s). The industrial and laboratory settings of how NaI:Tl are used to measure density can be found elsewhere (John, 1997; J *et al*., 2019) and (Margret *et al*., 2015; Ashrafi *et al*., 2014) respectively.

As stated in section 1., the simplest nuclear method employed in well logging uses one or more $\gamma$-ray detector consisting of a scintillator crystal coupled to a photomultiplier tube (PMT) to measure the natural radioactivity emitted by the atom in the formation. In other method, the tool carries a $\gamma$-ray source (usually $^{137}Cs$) to irradiate the rock formation and $\gamma$-ray detectors to measure the gamma rays scattered back to the tool. The last method uses neutron source to induce $\gamma$-ray producing reactions which are characteristic of the elements in the rock formation. Most of the parameters measured in the laboratory during $\gamma$-ray spectroscopy are also useful to one application or the other in borehole logging. Due to the harsh conditions encountered during borehole logging, there are some key requirements a detector need to meet to be suitable for borehole logging application.

While the very high temperature encountered during logging affects the scintillation properties of the scintillator used, vibration and shock adds to the physical property's requirements. Limited space in the logging tool and the borehole adds another physical property a detector needs to meet. Light output, decay time and the emission spectrum are very important scintillation properties a scintillator must meet, while ruggedness, atomic number, density, hygroscopicity of the material are the most important physical properties (Melcher, 1989). In this section we will review some $\gamma$-ray detectors as used in borehole logging application.

**NaI:Tl Crystal**

Many scintillation materials could be considered for use for borehole logging application. The standard material currently in use is NaI:Tl which has been well established as a fairly bright scintillator for several decades, and as such has become very economical. Many $\gamma$-ray detectors are commercially available as alternative to NaI:Tl scintillator. However, not all these alternatives have been successfully used in borehole logging application.
Inorganic crystal scintillation properties are mostly dependent on temperature.

As the temperature rises above room temperature, the effect to the scintillation properties becomes obvious. These effects as a result of temperature rise is however, dependent on crystal type. Some crystals are less affected than others. In borehole logging application, because the detectors may be subjected to many hours of operation under severe temperature condition, any crystal whose scintillation is easily affected by temperature is therefore not suitable for logging application. As NaI:Tl crystal is the conventional crystal for density measurements, we will used its scintillation and physical properties to evaluate the suitability of any alternative detector for use in density or related measurements.

**Review of Alternative Gamma ray Detectors**

**$LaBr_3$:Ce**

As summarised in 1, a lot of crystals have comparable scintillation and physical properties to NaI:Tl crystal. $LaBr_3$:Ce is one of those crystals with a density of 5 g/$cm_3$, a decay time of 20 ns, maximum peak emmision around 380 nm and a light output of ~ 65000 photons per MeV (Van Loef *et al*., 2001; Shah *et al*., 2002). In terms of energy resolution, a comparison made between 230 g $LaBr_3$:Ce and 234 g NaI:Tl crystals shows a far superior performance in favor of $LaBr_3$:Ce crystal. The energy resolutions at 662 keV were reported to be ~ 3% and ~ 7% for $LaBr_3$:Ce and NaI:Tl crystals respectively (Milbrath *et al*., 2005). This superiority is however, only above 100 keV. Below this energy range, due to low energy response and internal radioactivity caused $^{138}$La and $^{227}$Ac, the energy resolution goes below that of NaI:Tl crystal.

The temperature sensivity of $LaBr_3$:Ce as compared to NaI:Tl was recently reported by (Hou *et al*., 2019). The comparison was made between 25°C and 175°C. In every step between this temperature range, the energy resolution, light output, and count rate of $LaBr_3$:Ce is better than that of NaI:Tl crystal. The fluctuation in light output as a function of temperature is worse for the NaI:Tl scintillator. According to the same report, the energy resolution of NaI:Tl crystal at a room temperature of 25°C is worse than the energy resolution of $LaBr_3$:Ce at the highest temperature of 175°C. The count rate was stated to be about 6 times higher for $LaBr_3$:Ce as compared to NaI:Tl at high temperature for similar crystal sizes.

**LuYAP:Ce**

Cerium activated Yttrium Aluminium Perovskite (YAP:Ce) is a well-studied scintillator (Moszynski *et al*., 1998; Randazzo *et al*., 2008; Klamra *et al*., 2002; H. Zhang *et al*., 2015). This crystal is also characterised with high light output of about 40% relative to the conventional detector (NaI:Tl), moderate efficiency and a decay constant of 25 ns (Moszynski *et al*., 1998). Due to its low effective atomic´ number of 32, LuAP:Ce, which is a more dense crystal with effective atomic number of 65 was proposed (Moses *et al*., 1995; Balcerzyk *et al*., 2004). (Neal *et al*., 2011) compared the temperature dependence of BaF, BGO, $CdWO_4$, CsI (Na), CsI (T1), GSO, GYSO, LSO, LYSO, LuAG, LuAP, NaI:Tl, YAG, YAP, and ZnWO, it was found that the performance of most of the detectors degraded above 150°C, with LuAP and LuAG showing an excellent performance even above 300°C. Technological limitation growing large LuAP:Ce lead to the development of a mixed yttrium-lutetium aluminium perovskite (LuYAP:Ce). The detector's light yield increases with temperature, this, coupled to its high stopping power makes it attractive in apllication like borehole logging. A deteiled comparison between LuYAP:Ce, NAI:Tl, BGO and GSO of the same dimension was made by (Baberdin *et al*., 2008).

According to this report:

- The light yield was found to be 18%, 10%, and 13% for GSO, BGO and LuYAP respectively relative to NaI:Tl crystal.
- LuYAP is reported to have an background intrisic radioactivity due to the presence of about 2.7% $^{176}$Lu. This however, does not affect the signal-to-noise ratio in real time measurements.
- LuYAP crystal shows excellent temperature stability in contrast to GSO and more especially BGO.
- 14%, 25%, 24% and 28% FWHM was found NaI:Tl, GSO, BGO and LuYAP respectively at a temperature of 25°C. As compared to the other crystals, LuYAP energy resolution degrade slightly with temperature with its photo statistic improving with temperature.
- The measured spectra show a stable operation up to 175°C with LuYAP. This implies that there won't be a need for thermo stabilisation as in the case of GSO.
- Integral neutron-gamma well logging measurements shows higher count rates with LuYAP as compared to the conventional NaI:Tl crystal. At an energy of 2 MeV, LuYAP sensitivity exceed that of NaI:Tl with a factor 8 and about 30% for GSO.
- Resistance to neutron activation was better for LuYAP as compared to GSO and NaI:Tl crystals.
- A shock acceleration of 500 g (300 impacts in 5 minutes) and vibration up to 14 g (20, 60, 70 and 300 Hz, at 5 minutes during each frequency). No damage was observed.

Since LuYAP is not hygroscopic, wraping is not necessary, thereby maintaining its dimension and subsequently occupy less space when used in a logging tool.

**Table 1.** Scintillation and physical properties of some selected gamma-ray detectors.

| Crystal | Light output | Scintillation properties | | Physical properties | | |
|---|---|---|---|---|---|---|
| | | Decay constant (ns) | Emission spectrum (nm) | Effective Z | Density (g/cm$^3$) | Hygroscopic |
| NaI:Tl | 40000[b] | 230[a] | 413[a] | 51[b] | 3.67[a] | YES |
| NaI:Na | | | | | | YES |
| CsI:Tl | | 1000[i] | 550[i] | 54[e] | 4.51[e] | YES |
| CsI:Na | | 650[a,h,i] | 420[a,i] | | 4.51[a] | YES |
| BGO | 8000[b] | 300[a] | 480[a] | 75[b] | 7.13[a,b] | NO |
| GAGG:Ce | 46000[b] | 90[b] | 520[b] | 54[b] | 6.6[b] | |
| LYSO:Ce | 32000[b] | 41[b] | 420[b] | 66[b] | 7.1[b] | |
| $LaBr_3$:Ce | 65000[c,d] | 20[c,d] | 380[c] | 47[b] | 5.0[c,d] | YES |
| $CeBr_3$ | 68000[g] | <20[f,g] | 370[g] | 45.9[e] | 5.18[e] | YES |
| LuYAP | 5456[j] | 25[j] | | 32[j] | 7.4[j] | NO |

*Source*: [a](Stromswold, 1981), [b](Seitz *et al*., 2016), [c](Van Loef *et al*., 2001), [d](Shah *et al*., 2002), [e](Sibczynski *et al*., 2017), [f](Kaburagi *et al*., 2021), [g](Shah *et al*., 2004), [h](Menefee *et al*., 1967), [i](Bala *et al*., 2021)

## CONCLUSIONS

The work presented here has stated some key requirements a detector have to meet to be suitable for use in nuclear logging applications. No doubt $^3$He thermal neutron detector is the best for this application with regard to thermal neutron measurements. However, other thermal neutron alternatives capable of providing comparable counting efficiency such as the GS20 has been reviewed. This crystal is also capable of measuring gamma rays, thereby having dual capabilities unlike the $^{3}He$ tube capable of detecting thermal neutrons only. Other $^{6}Li$ and $^{10}B$ based neutron detectors have been reviewed, however, not all of them meet to the logging requirements such as very high temperature and shocks.

Many gamma-ray detectors provide comparable light output as compared to the conventional NaI:Tl scintillator used in gamma ray density measurements. The light out of many of these detectors decreases with increasing temperature. LaBr:Ce, LuYAP:Ce, LuAP, and LuAG has been tested at very high temperature and showed a comparable or better light output as compared to the conventional gamma-ray detector (NaI:Tl). The energy resolution of these detectors has also been reported to be better than that of NaI:Tl at certain energy range. They are however, slightly more expensive as compared to the NaI:Tl. Some gamma ray detectors scintillation and physical properties such as light output, decay constant, emission spectrum, effective Z density and their hygroscopic nature has been summarised in Table 1.

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