Novel scintillators and silicon photomultipliers for nuclear physics and applications

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Abstract. Until comparatively recently, scintillator detectors were seen as an old-fashioned tool of nuclear physics with more attention being given to areas such as gamma-ray tracking using high-purity germanium detectors. Next-generation scintillator detectors, such as lanthanum bromide, which were developed for the demands of space science and gamma-ray telescopes, are found to have strong applicability to low energy nuclear physics. Their excellent timing resolution makes them very suitable for fast timing measurements and their much improved energy resolution compared to conventional scintillators promises to open up new avenues in nuclear physics research which were presently hard to access. Such "medium-resolution" spectroscopy has broad interest across several areas of contemporary interest such as the study of nuclear giant resonances. In addition to the connections to space science, it is striking that the demands of contemporary medical imaging have strong overlap with those of experimental nuclear physics. An example is the interest in PET-MRI combined imaging which requires putting scintillator detectors in a high magnetic field environment. This has led to strong advances in the area of silicon photomultipliers, a solid-state replacement for photomultiplier tubes, which are insensitive to magnetic fields. Broad application to nuclear physics of this technology may be foreseen.

1. Introduction
Gamma-ray spectroscopy is a key tool in experimental nuclear physics. It has many applications within the field, in particular, it is used to observe transitions between bound nuclear excited states. The observation and characterisation of such transitions in terms of their strength is an important test of contemporary models of nuclear structure. Such transitions between bound states are typically in the energy range 100 keV to a few MeV depending on the mass of the nucleus of interest, while giant resonances are also often probed through their gamma-ray emission and, here, the energy range of interest extends up to 10s of MeV. In all applications, a key driver is energy resolution. Over the last thirty years or so, the high-purity germanium detector has achieved particular prominence given its excellent energy resolution of 2-3 keV at 1.33 MeV. Given that in many areas of interest, there is a high multiplicity of emitted gamma rays leading to a highly complex spectrum, detectors are often deployed in large, multi-element arrays. Traditionally, Compton suppression was employed to improve the peak-to-total but in the last decade, gamma-ray tracking arrays of pure germanium have been developped which can reconstruct the position of individual gamma-ray interactions to high precision using pulse shape analysis. With the advent of germanium detectors, the well-established technology of scintillator detectors has taken a back seat as far as gamma-ray spectroscopy has been concerned. It has
been largely relegated to the study of giant resonances, where good efficiency for high-energy gamma rays is important but in general, good energy resolution is not warranted. The other main area where scintillator detectors are used extensively is in fast-timing measurements, which allow the lifetimes of excited states of the order of 100 ps to be measured. Historically, these were carried out with barium fluoride detectors, using the fast component of the BaF₂ signal to extract the timing information.

2. Next-generation scintillators in nuclear physics

Next-generation inorganic scintillator materials such as lanthanum bromide, cerium bromide and related materials have reawakened the relevance of scintillator detectors in low energy nuclear physics. Such detectors may achieve energy resolutions of around 3% at 662 keV which is a factor of two better than standard scintillator materials such as NaI(Tl) and CsI(Tl). They also have excellent timing resolution and relatively high intrinsic efficiency. The excellent timing resolution of next-generation scintillators like LaBr₃:Ce has allowed them to be rapidly applied to fast-timing measurements, displacing the earlier technology of BaF₂ detectors. The key advantage here is their energy resolution, which makes it easier to select γ-ray transitions of interest and study complex decay schemes [1, 2]. Fast-timing detectors are generally small, cylindrical and relatively cheap which has led to a quick uptake of the next-generation technology.

The improved energy resolution of next-generation scintillators could also be applied to what one might term “medium-resolution” spectroscopy. This is applicable to discerning structure within giant resonances e.g. the so-called pygmy dipole resonance [3]. It would also be of high relevance to investigation of exotic nuclear phenomena such as Jacobi shape transitions [4], and the study of light nuclei where transition energies are often large (few MeV) and the level density is relatively low.

The main barrier to a wide application of next-generation scintillators for medium-resolution spectroscopy is the high intrinsic cost of the material. The focus has been on LaBr₃ but some groups have obtained individual CeBr₃ detectors which are somewhat cheaper but have slightly poorer energy resolution. Other detector materials such as SrI₂ and CLYC have been investigated by nuclear physicists but their high cost and other factors have precluded their extensive use thus far. The high cost of the materials is compounded by the desire to produce close-packed arrays of detectors which needs detectors with a square geometry. Different approaches have been taken to this problem. For example, the PARIS calorimeter [5], foreseen to ultimately comprise an array of 200 detectors, will comprise two shells of detectors: an inner shell of LaBr₃(Ce) and an outer shell of NaI(Tl). The inner shell will have high resolution up to 10 MeV while the outer shell is designed to efficiently stop gamma rays up to 50 MeV. The present design of PARIS comprises individual phoswich elements [6], each of a 2” cubic LaBr₃(Ce) crystal coupled to a 2” x 2” x 6” NaI(Tl) crystal, with the scintillation light collected with a common photomultiplier tube. Pulse shape analysis may be used to disentangle the signals from the two crystal elements based on their significantly different rise and decay times (see Fig. 1). This is challenging in terms of digital electronics. The high intrinsic activity of LaBr₃(Ce) may prove challenging when a large calorimeter is assembled, although in general most measurements would be made in coincidence with detection of another radiation type such as charged particles or in coincidence with a pulsed beam, which could remove random coincidences with intrinsic background.

An example application of PARIS may be to the study of alpha clustering in nuclei, for example, by studying the very weak decay branches between highly-excited cluster states [7]. Fig 2 compares real data obtained on the $^{12}\text{C}(^{12}\text{C},\gamma)$ reaction using a BGO scintillator array and the DRAGON spectrometer at TRIUMF [8] with the results of a GEANT3 simulation of the same process using the PARIS calorimeter. The significant advantages of the LaBr₃(Ce) component in resolving individual excited states in this reaction are very evident.

It is interesting to note, significant advances in imaging with large LaBr₃ crystals. It is not
obvious with large crystals that the position where scintillation light is recorded retains any memory of where it is produced in the crystal. However, Giaz et al. [9] have recently shown that 1-cm position resolution can be achieved in a 3” cubic LaBr₃ crystal using a segmented photomultiplier tube and a collimated source. This discovery is of some significance for nuclear physics as Doppler correction of gamma rays must be applied and so knowing the angle of interaction well helps with this. Moreover, Doppler broadening is reduced if the effective opening angle of the detector is constrained.

3. Silicon photomultipliers

Silicon photomultipliers (SiPMs), which are dense arrays of avalanche photodiodes (APDs), are a disruptive technology that may, in the coming years, displace conventional photomultipliers for many applications. Their performance is well-matched to the requirements of scintillator detectors in nuclear physics since they can preserve good energy resolution and timing resolution. In particular, they are insensitive to magnetic fields, unlike conventional photomultipliers. A major driver in the development of SiPMs has been the PET imaging sector. Indeed, there is currently a push to integrate PET with MRI (magnet resonance imaging) [11, 12] which emphasises the need for photosensors which are insensitive to magnetic fields. The medical advantages in this area are clear since functional and anatomical information can be obtained simultaneously in a single image, providing improved diagnostics leading to a more effective treatment. The main difficulty in achieving this is that PMTs are affected by magnetic fields and it is impractical to shield them within the high field of an MRI magnet. Practically speaking, there are various ways to achieve combined PET-MRI: for example, splitting the magnetic field volume so that the PMTs sit in zero field, or using fibre-optic cables (a nonmagnetic component) to transfer light from the scintillation crystals to PMTs which are placed outside of the magnetic field [13]. The other approach to PET-MRI is to use APDs or SiPMs which can be placed directly in the magnetic field [14, 15, 12]. Several different prototype systems have been successfully demonstrated. For example, Woody et al. explored their RatCAP detector containing 12 LSO (lutetium oxyorthosilicate) arrays coupled to APDs and found that it was not affected by magnetic fields and strong RF pulses, allowing them to succeed in obtaining a high quality medical image [15].

There are also a number of areas of nuclear physics where gamma-ray detectors could be operated in regions of high magnetic field, for example in the vicinity of large spectrometers.
Figure 2. (top) Gamma-ray energy spectrum for the $^{12}\text{C}(^{12}\text{C},\gamma)$ reaction at $E_{c.m.}=6.0$ MeV measured with a BGO detector array (bottom) Simulation of the same experiment using the PARIS calorimeter which incorporates an inner shell of LaBr$_3$ detectors.

An example where detectors would be placed directly within a high field is the HELical Orbit Spectrometer (HELIOS) built at Argonne National Laboratory [16] which is used to study single-particle transfer reactions in inverse kinematics. The basic component of this device is a large-bore solenoidal magnet, in fact, a former hospital MRI magnet. The addition of scintillator-based gamma-ray detectors inside the field volume would present advantages in understanding nuclear structure through decay cascades, and if timing resolution were sufficiently high then
lifetimes of states could be obtained in some cases and decay cascades ordered. Operating γ-ray detectors inside such a solenoidal spectrometer would have all the same demands and constraints as for PET-MRI, and SiPM-based readout is again an attractive solution. Such a system could be envisaged for a solenoidal spectrometer presently under construction for the HIE-ISOLDE facility at CERN [17]. The SiPM technology is already moving very rapidly. Fig. 3 shows an 8 x 8 array of 6-mm square C-series SiPMs available from SensL. This sensor is well-matched to a 2” cubic scintillator crystal and the multi-channel output would make it suitable for exploring the imaging applications discussed above [9].

![Figure 3. An 8X8 array of 6-mm SiPMs from SensL. The array is mounted on a inspection board with the individual energy and fast-timing outputs coupled together.](image)

4. Conclusions

Next-generation scintillator detectors offer considerable potential for employment in low energy nuclear physics on the basis of their excellent energy and timing resolution. Such detectors have rapidly been adopted in the area of fast timing, superseding the earlier approach using BaF₂ detectors. There is strong interest in using larger detectors of next-generation scintillators for medium-resolution spectroscopy, opening up new avenues of research in the areas of giant resonances and exotic nuclear shapes. Take-up of technology here has been slower due to the high intrinsic cost of the material. Nevertheless, initiatives such as the PARIS calorimeter are already beginning to explore the potential in this area. Silicon photomultipliers are another new technology which is advancing very quickly in performance, driven by demands of medical imaging and other areas. This also has strong application to nuclear physics, both to replace PMTs in conventional applications but also to open up scope to readily put high-performing gamma-ray detectors directly in high magnetic field environments. The drive by nuclear physicists to obtain best possible energy resolution and performance from scintillators and
photosensors places them in an enviable position for exploiting this technology for societal applications in homeland security and other areas.

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