Imaging of CsI(Tl) crystal event and double-slit Young's interference by a single photon sensitive camera

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Abstract We will discuss an imaging measurement with a single photon sensitive and low-noise camera aiming at a new paradigm in the optical readout of scintillation detectors. The features of the single photon sensitive camera will be characterized and demonstrated with a measurement of double-slit Young's interference in single photon mode. An imaging test on CsI(Tl) crystal and alpha source will be performed further for preliminary measurements on the noise level and sensitivity of the system with a 1/2″, f/1.4 lens, which reaches a sensitivity on light intensity around 1/10 of the 3-inch PMT and shows a potential to realize imaging of single alpha event. An application proposal for scintillation detectors will be further discussed, where it is usually assumed that imaging is not possible in such a photon-starved and large-emittance regime.

1 Introduction

Photon detection is one of the fundamental technologies widely used in particle physics, astronomy, and industry, such as Super-K [1], KamLAND [2], JUNO [3, 4], Hubble [5], clinically and preclinically [6], X-ray imaging [7], and long-range imaging [8]. The reconstruction of vertex and tracks is critical in most particle physics experiments, where it is always trying to use most of the information from photons. Ignoring polarization, each photon can be described by six coordinates when it is detected: its impact position on the photodetector surface (x,y), the time of arrival \( t \), two directions of propagation, \( \theta \) and \( \phi \), and the wavelength \( \lambda \) [9]. Photodetectors, typically PMT or SiPM in particle physics experiments, are commonly used for light strength and timing measurements and some crude event localization. Generally, full coverage of photodetector assemblies to the whole target guarantees an overall light collection efficiency for better precision measurement as proposed in [3].

The search for a novel technology able to detect and reconstruct events in scintillation detectors has become more and more important for dark matter and neutrino studies. An idea of detecting the light, optical, and directional readout approach, proposed many years ago [10] has received renewed attention in recent years, where the challenges are the need for high spatial resolution over large volumes, limited signal strength and non-negligible noise level [11]. The charge-coupled devices (CCD) have been widely used in the past as high-granularity light sensors and an upgrade of classical emulsion radiograph, such as GEM-based TPC with a 2-D CCD readout for directional dark matter experiments [12–16], thermal neutron imaging [17], single photon counting X-ray CCD camera spectrometer [7], photonic graph states [18], transparency measurement [19], a kilogram-scale Skipper CCD to detect coherent elastic neutrino-nucleus scattering [20–22], and classical emulsion radiograph replaced by digital detector imaging, especially in medicine applications [23]. At the same time, some other similar devices are also developed and used for single-photon light detection and ranging (lidar) [8, 24], and single image 3-D photography [25].

But a critical limitation of CCD is its high level of readout noise up to one to tens electrons per pixel (RMS) compared to the signal strength in photon counting level of particle physics experiments. A bubble chamber is an example: its imaging can be realized via appropriate wide-angle lenses with finite aperture, but external illumination is essential to provide sufficient track brightness over the noise to produce a conventional image (efficient signal-to-noise ratio). Furthermore, it is commonly concluded that the scintillation detectors are fundamentally unsuitable for imaging applications owing to the photon-starved regime and uniform angular distribution of the light produced in the scintillation process, where the limited photons emitted over a large angular range cannot be imaged through a modest aperture optical system under the limitation of the sensor noise. Homogeneous scintillation detectors give up imaging entirely, as the price to pay to collect a large fraction of the emitted photons by maximizing the coverage with low noise photon sensors, and some equal options are discussed such as “distributed imaging” with PMTs in [9].

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More recently, cameras based on active pixel sensor (APS) technology developed on complementary metal-oxide semiconductors (CMOS) have been developed that can reach tens of millions of pixels with sub-electron readout noise and single photon sensitivity (usually referred to as scientific CMOS (sCMOS)), where imaging, single photon imaging in particular, is providing another new possibility. It could overcome the main limitation of the CCDs on noise used for scintillation detectors to offer several advantages: highly performing optical sensors can be easily procured and developed for commercial applications; the use of suitable lenses allows the possibility of imaging large areas with few sensors and better spatial resolution. A combined system of the low-noise and high-granularity cameras and fast light sensors will provide more powerful technologies and possibilities for better reconstruction of vertex and tracks and benefit for a better particle identification [26].

In this paper, we will show a preliminary measurement on a single photon sensitive and low-noise camera with a CsI(Tl) crystal. Sect. 2 will introduce the setup of the camera testing system. Section 3 will discuss the characterization of the camera following a measurement with single photon imaging of double-slit Young’s interference. Section 4 will present a preliminary test on a CsI(Tl) crystal and alpha source with the camera system. Section 5 will provide a proposal on a spatial coincidence measurement by cameras associated with real-time photon sensors, and a summary is given in Sect. 6.

2 Imaging setup

The single photon sensitive and low-noise camera of ORCA-Quest qCMOS C15550-20UP are a new product of Hamamatsu Photonics [27] with a rolling shutter, 4096 (H) × 2304 (V) pixels (4.6×4.6 μm²/pixel), a low dark current of 0.006 electrons/pixel/s and an ultra-low readout noise of 0.27 electrons rms under ultra quiet scan, which can be reached at −35 °C with water cooling while at −20 °C (the temperature used in our measurements with air cooling) the expected value is 0.016 electrons/pixel/s. The camera can be coupled with lenses through C-type interface. For our study, a combined system except the camera is designed with 3-inch PMTs [28] which are working at a gain of 3 × 10⁶ with a × 10 fast amplifier to cover single photon level and acquired by a CAEN digitizer DT5751 [29] for signal intensity monitoring in particular. The system will be re-configured manually in the following measurements including pulsed LED, crystal, and double-slit Young’s interference.

Figure 1 shows the setup for pulsed LED measurement. The PMT (and the camera) is located at a distance (~15 cm) to the light source to monitor the light intensity of the LED pulses. The LED is encased in a nylon diffuser ball to illuminate uniformly the PMT and the camera. The LED is powered by a driver pulse with 30 ns width under different frequencies, and its wavelength is around 420 nm. The light intensity viewed by the PMT (and the camera) can be adjusted from a single photon to multi-photons by tuning the driver amplitude. The camera can be configured manually to different exposure times. The data of the camera is saved in tagged image file format (tif) with 16 bits per pixel, and each image is normally 18 MB in size.

Thanks to the excellent ability of the system on light intensity control and imaging, it is exciting to realize a double-slit Young’s interference measurement by a single photon with the re-configured system as shown in Fig. 2a. The width of slit d₁ and each slit of d₂ is 0.1 mm and 0.029–0.040 mm, respectively, and the distance between the slits of d₂ is 0.2 mm. The distance between slit d₁ and d₂ is 15 cm, and between the slit d₂ and the output end of the interferometer tube are 60 cm, respectively. Another bare LED with a wavelength of around 500 nm will be used to provide stronger light intensity in pulsed mode for the interference. The light intensity at the output end of the interferometer tube will be measured by the PMT and in turn with the camera. The light intensity received on average by the PMT is set to around 0.1 photons of each pulse following a Poisson distribution. The camera will be run without a lens to view the interference fringes directly.

For a crystal measurement, the system is re-configured as shown in Fig. 2b aiming for the imaging test on the event vertex or track in the scintillation detector. Here, a CsI(Tl) crystal (light yield ~45,000 photons/MeV [30, 31]) and ²⁴¹Am alpha source (alpha energy 5.5 MeV [32]) are used to replace the LED and located at around 10 cm in front of the PMTs and camera. The PMTs are used to monitor the signal intensity, the coincidence of which will be used to trigger the PMT waveform data taking.
Fig. 2 Re-configured systems for single photon double-slit Young’s interference (a) and crystal (b) measurements

(a) Setup of Young’s interference.  (b) Setup of crystal test.

3 Single photon sensitive camera

3.1 Single photon response and noise

The noise of the camera is measured in dark firstly, where the camera is configured in ultra-low-noise mode (low-frequency mode) as mentioned. Figure 3a shows an example of the 2-D images taken by the camera with 1 s exposure time, 9,437,184 pixels in total. Figure 3b shows the 1-D noise plot of pixels in units of photoelectrons (p.e.) to compare different cameras, where the baseline is artificially shifted to 50 photoelectrons only for the comparison here by (ADC/7.8+OFFSET), and the 7.8 ADC ch./photoelectron is the conversion factor from ADC ch. to photoelectron (the gain factor of the camera, the mean baseline in ADC at 200 ADC ch.). The standard deviation (rms) of the distribution of all the pixels will be used to evaluate the noise level of the camera. The noise of the Hamamatsu camera is much smaller than the other two typical cameras (ANDOR Zyla-4.2P sCMOS, PCO edge 4.2) with the same exposure time.

The calculated noise level versus exposure times from 172 µs to 60 s is shown in Fig. 3c, where a linear fitting is applied. It is confirmed that the readout noise of pixels is around 0.28 electrons (around 2.2 ADC ch.), and the dark current noise, proportional to the exposure time, is around 0.08 electrons/pixel/s (around 0.62 ADC ch.), which mean an excellent performance. Considering the total 4096×2304 pixels with 1 s exposure time (the noise level around 0.36 photoelectrons/pixel), the number of pixels over 0.5 photoelectrons is around 478,203 (count the pixels which satisfy (ADC-200)/7.8>0.5 photoelectrons), which can be treated as a dark count rate of 478 kHz as one channel of the camera, and is much higher than for a traditional PMT (only hundreds to thousands of counts per second). At the same time, there are also some pixels showing higher noise over 3.5 photoelectrons, which reaches 713 Hz.

A LED with a diffuser ball diameter of 4 cm is used to illuminate uniformly the 3′ PMT and the camera coupled with a lens (2/3′′, C, 25~∞ mm, f/1.4, 2 MP) as shown in Fig. 1. The LED is driven by a positive rectangular pulse of 30 ns duration. The LED intensity per pulse, at single photon level, is adjusted to around 0.34 p.e. on average viewed by the 3′ PMT according to Poisson distribution as shown in Fig. 4a, or around 1.5 photons considering the PMT QE (∼23%). Considering the quantum efficiency (QE) (∼23% and ∼85% for the camera) at 420 nm, the effective aperture (3′′ and 2/3′′, f/1.4), and the distance to LED (∼18 cm and ∼15 cm) of the PMT and camera, respectively, the expected light intensity per LED pulse viewed by the camera is around 1/9 (or 0.15 p.e./pulse) of the expected photons viewed by the PMT. Figure 4b shows an image of the LED with 500 kHz driver frequency taken by the camera with 5 s exposure time. The center of the LED is located at pixel (1080, 1354) with a radius of around 675 pixels (the whole region contains about 1.4 million pixels). The measured dimension (3.7 ± 0.3 cm) is consistent with the diffuser ball considering the focal length and object spacing, where the magnification is around 1/6.

The 1-D intensity of all the pixels of the LED region is shown in Fig. 4c, where the background is gotten from an equal area as the LED but with a shifted center at pixel (3080,1354). The measured strength of each pixel covers from a single p.e. (around 208 ADC ch. with baseline at 200 ADC ch.) to several p.e., where individual p.e. can be identified clearly. The LED is further imaged with different exposure times, and the measured light intensity after camera noise correction (based on the background region) is shown in Fig. 4d. The light intensity received on average by the camera is around 52032 p.e. by a linear fitting, which derives around 0.10 p.e./LED pulse or 0.04 p.e./pixel with 1 s exposure time on average following a Poisson distribution. It is a little bit smaller than the expected value, but consistent considering the uncertainties on the acceptance solid angle, QE, and the transparency of the lens, which still needs careful validation for a precise quantitative relationship. But the measured intensity by the camera is exactly proportional to the exposure time down to very short times. The minimum exposure time to identify the LED here is around 0.05 s (integrated LED intensity to ∼2600 p.e. or 25 k pulses) when it is dominated by the camera noise of the LED region. Therefore, it is possible to identify a light source in a single pulse from few to tens p.e. by a smaller target region (for example a radius in 1 mm or 1/400 of the current LED area), where the camera noise can be controlled to a limited level. It will be further discussed in the following sections.

1 Here, we will equally use the electron and photoelectron to evaluate the noise level or light intensity.
3.2 Double-slit Young’s interference

As known, the wave-particle duality is one of the fundamental features of quantum mechanics, which has been measured by a lot of experiments with photons, electrons, and atoms, even at single particle level [33–44]. The double-slit Young’s interference measurement is one of the famous experiments in the physics history and an excellent interpretation of quantum mechanics [45–48]. But most of the previous measurements on double-slit Young’s interference with single photon are configured with a special light source, limited on the spatial resolution, single photon sensitivity, and dynamic range of the photon sensors [44–46, 49–51]. The newly developed single photon sensitive camera, monitored by PMT in particular, provides an excellent opportunity to realize the double-slit interference fringes at single photon level to verify the basic quantum theory directly.

With a traditional Young’s double-slit interferometer as shown in Fig. 2a, we will try to measure the interference fringes at single photon level and normal LED source. The light source used here is another bare LED (3 mm, $\lambda \sim 500$ nm) without a diffuser ball and working in pulse mode by a pulse driver of 100 ns width. The light intensity at the output end of the interferometer with all the d1 and d2 slits inserted is adjusted to a single photon level, which is around 0.02 p.e./pulse on average viewed by the PMT and much smaller than that shown in Fig. 4a. It means around 0.1 photons/pulse on average considering the QE of the PMT, where the probability of a single photon per pulse is around 0.1, and that of more than 2 photons per pulse is around 0.005, respectively. The relative stability of the light source monitored by PMT is around 5%. The intensities viewed by PMT with or without the slits are further measured at the output end of the interferometer: around 7.7 p.e./pulse without either slits d1 or d2, around 3.6 p.e./pulse only with slit d1 under the same LED configuration.

After the replacement of the PMT by the camera, a survey on exposure time is further performed from 172 $\mu$s to 60 s as shown in Fig. 5. The LED flashing frequency here is set to 2 MHz, where there is still enough time between pulses to ensure only one photon in maximum 100 ns duration traveling to the camera after the double-slit d2 inside the tube of the interferometer (length 60 cm). The interference fringes are getting more clear when the exposure time increases from 0.1 s in Fig. 5a to 60 s in Fig. 5d. The middle row of Fig. 5 is showing the light intensity, projected on the horizontal axis, of each of the interference fringes, where the intensity
Fig. 4 Image testing with pulsed LED.  
(a) the intensity of LED pulse in photoelectrons monitored by PMT;  
(b) 2-D image of the LED with 5 s exposure time, where the shape of diffuser ball can be identified obviously; 
(c) the 1-D intensity in ADC ch. of all the pixels of the diffuser ball target region (blue) in (b), where the background (red) is from a shifted area;  
(d) the measured light intensity by the camera versus different exposure times.

Fig. 5 Single photon interference fringes measured by the camera with different exposure times:  
(a) 0.1 s, (b) 1 s, (c) 5 s, (d) 60 s

of the interference fringes is gradually strengthening when the exposure time is increasing. According to the 1-D intensity plot of all the pixels of the camera (camera noise subtracted) as shown on the bottom row of Fig. 5, it is clear that most of the pixels do not receive any photon (baseline at around 200 ADC ch.), few of the pixels receive only one photon (around 208 ADC ch.), and the maximum is around 2 photons (around 216 ADC ch.) with 0.1 s exposure time. Please note that the photons received by the camera cannot arrive at the camera at the same time (in a single pulse duration) due to the controlled light intensity per pulse, and a single pixel cannot receive more than one photon too. Both the number of pixels with more than 1 photons and the maximum intensity of a single pixel are increasing when the exposure time increases as expected.

The projected intensity of the interference fringes with 60 s exposure time is fitted following the intensity model from [47] as shown in Fig. 6a, where a constant plateau and an extra Gaussian part are considered relative to the maximum line in addition to
the double-slit interference intensity model. The intensity of the constant plateau is related to the exposure time and should be due to the camera noise and the non-ideal interference system. The contribution of the Gaussian part should be related to the non-ideal interference system (such as the width difference of the slits of \(d_2\)) and also observed in other double-slit experiments [45, 46]. The measured wavelength of the LED is \(477 \pm 2\) nm from the derived distance \(0.213\) mm between the slits of \(d_2\) and the distance between the interference fringes of 292 pixels. Figure 6b shows the image of the bare LED by removing all the slits of \(d_1\) and \(d_2\) with a little lower light intensity and 1 s exposure time, where we can identify a clear asymmetry along the horizontal or vertical direction on the 2-D image and in the 1-D intensity, by projecting along the horizontal direction. Figure 6c shows the image only with slit \(d_1\) with 5 s exposure time, where the asymmetry, even if different from that shown with the bare LED, can be still identified on the 2-D image and in the 1-D intensity along the horizontal direction. The asymmetry distribution could contribute to the constant and Gaussian part of the interference fringes after the double-slit \(d_2\).

As shown in Fig. 7, the average light intensity measured by the camera is around 0.04 p.e. per pulse only considering the fringes (0.12 p.e. per pulse considering all the parts including the Gaussian and plateau except the camera noise)\(^2\), or 80,000 p.e./s only considering the fringes (around 240,000 p.e./s considering all the others except camera noise), respectively. It is consistent with the prediction by the PMT, and their difference is mainly due to the QE and acceptance area, which still needs detailed validation.

\(^2\) Which is calculated by \(\frac{\sum(\text{ADC}_{\text{fringes}} - \text{ADC}_{\text{baseline}})}{7.8}}/(\text{frequency} \times \text{ExposureTime})\) or \(\frac{\sum(\text{ADC}_{\text{fringes}} + \text{ADC}_{\text{Gaussian}} + \text{ADC}_{\text{plateau}} - \text{ADC}_{\text{baseline}})}{7.8}}/(\text{frequency} \times \text{ExposureTime})\).
Fig. 7 Average light intensity measured by the camera during the interference measurements with single photon considering or not the Gaussian and the plateau part, which is normalized to each LED pulse.

Fig. 8 Monitoring results by PMT of the crystal and alpha source. 10 cm or 15 cm is the distance from the crystal to the camera. The number in the round brackets after background or alpha source in the legend is the number of events in the distribution.

Fig. 9 Crystal and alpha source with 60 s exposure time.
4 Imaging of crystal

A 7.5×7.5×15 cm$^3$ CsI(Tl) crystal is put in front of the camera with a distance around 10 cm (around 15 cm to the PMT) as shown in Fig. 2b, where the camera is coupled to another lens with much short focus length (1/2", C, 6-∞ mm, f/1.4). The 3-inch PMTs are used to monitor the signal intensity of the crystal, and the coincidence of the two PMTs is used as the trigger of the DT5751, where the threshold of each PMT is set to around 1 p.e.

An $^{241}$Am alpha source (10 kBq, side/surface source, used for smoke alarm with a diameter of around 4 mm) is put on the top surface along the horizontal direction of the crystal directly, and its rate is around 150 count per second measured by a Geiger counter near to the source surface. Here, it is considered the alpha particle only (energy around 5.5 MeV), which is still the main contributor to the energy deposition with respect to the X-ray (59 keV) even considering the quenching factor [52–54].

The rate monitored by the data acquisition system is around 10 ± 1 counts per second with only the crystal and around 130 ± 10 counts per second with the source after the dead time correction according to the selected muon rate. Figure 8a shows the averaged waveform from one of the monitoring PMTs, which demonstrates the slow fluorescent decay time in µs of the CsI(Tl) crystal and the response feature of the crystal to different particles [55, 56]. The PID of CsI(Tl) [57, 58] is calculated for all the events with a fast signal window of 500 ns as shown in Fig. 8b, where the alpha events (selected by PID > 0.45) can be identified clearly from the background, and the identified rate of muon and alpha is around 3.0 ± 0.1 Hz (by PID and total charge) and 90 ± 10 Hz at 10 cm distance (the distance from the crystal to the camera), respectively. The PMT-measured charge of selected alpha events is further
Fig. 12 Schema of the camera spatial coincidence system with crystal

plotted as shown in Fig. 8c, which considered the integration window of 6 µs. The typical intensity of a single alpha event viewed by the PMT is around $80 \pm 2$ p.e. at 10 cm distance to the PMT. It is expected to be around $8 \pm 1$ p.e. per alpha event viewed by the camera, which is around 1/10 of that viewed by the PMT considering the solid angle of the lens, the QE, and lens transparency.

An image taken with 60 s exposure time is shown in Fig. 9b, where the location of the alpha source can be identified clearly as shown in the dashed red line circle. According to the zoom-in of the projected plot along the horizontal as shown in Fig. 9d, the source dimension along the horizontal direction is around 45 pixels, which means 3.4 mm considering the imaging magnification and consistent with the source dimension. According to the zoom-in of the projected curve along the vertical as shown in Fig. 9a, the energy deposition width in the vertical direction is around 15 pixels, which means around 1.1 mm considering the imaging magnification.

A radius of 22 pixels of the alpha source region (center at around pixel (2047,1497)) is used finally to calculate the signal intensity in the following discussion. At the same time, the shape of the crystal can be identified dimly against the discrete noise because of the reflection of the crystal surface. The measured intensity of each pixel in the region of the alpha source is plotted in Fig. 9c, including a curve of the source region, and a curve of background from a shifted equal area far from the source. It is seen that the typical intensity of each pixel of the source region is around 260 ADC ch. (baseline 200) or 8 p.e., and the integrated intensity of the source region on this image is around 50,000 p.e., which will be used as the measured signal strength.

The alpha source region is further measured with different exposure times to derive the signal strength as shown in Fig. 10, where the destination region is zoomed in for detailed checking. The significance of the source signal is decreasing when the exposure time is decreased from 5 s to smaller values; therefore, for times smaller than about 0.02 s, it is not possible to discriminate the signal from the noise. Figure 11 shows the measured signal intensity (with background subtraction) versus the exposure time, which gives a slope factor around 860 p.e./s or 6700 ADC ch./s, which means around 9.5 p.e./alpha event. The calculated signal intensity reaches a plateau at 100 ADC ch. or 12 p.e., dominated by the fluctuation of camera noise in the target region, when the exposure time is smaller than 0.02 s. It will only provide a signal-to-noise ratio of around 0.8 with a single alpha event. It would be needed to further improve the signal-to-noise ratio by increasing the signal strength (including the enlargement of the effective aperture) or reducing the noise level (and a smaller target area).

5 Discussion

According to the previous measurements with the single photon sensitive camera, it is approaching to have event-by-event imaging for the scintillation detector under the photon-starved regime and uniform angular distribution of the light produced in the scintillation process. Following the testing results of the CsI(Tl) crystal and alpha source, it is valuable to increase the effective aperture from the used lens with f/1.4 to a larger one or to measure tracks with a smaller and predictable target area to reach a better signal-to-noise ratio.

\[
\sum (ADC_{source} - ADC_{baseline})/7.8.
\]
ratio. Considering the noise of the camera, further reducing it is still favored, even if it is already smaller than 0.3 p.e. per pixel, i.e., an unprecedented value.

At the same time, drawing lessons from the coincidence of PMTs in time, a spatial coincidence system with more than one single photon sensitive camera is also valuable and workable to suppress the noise, as proposed in Fig. 12. With this system, the PMTs mainly focus on a real-time event measurement of timing, energy, and crude spatial vertex. The cameras will help with precisely spatial vertex imaging, and the spatial coincidence among cameras could suppress the random noise effectively.

6 Summary

The single photon sensitive and low-noise camera provide another novel possibility for imaging for the photon-starved regime and uniform angular distribution of scintillation detectors. This study confirms the performance of the newly developed camera for photon counting with sub-photon-electron noise per pixel per second. With a combined system constituted by 3-inch PMTs and the camera, the double-slit Young’s interference with a single photon can be achieved, and a single $^{241}$Am alpha event with CsI(Tl) crystal is closely to be distinguished, where the camera with a $1/2''$, f/1.4 lens can collect around 1/10 of that viewed by the 3-inch PMT. A spatial coincidence system is further proposed as an attractive option to suppress the random noise of the camera and improve the signal-to-noise ratio, where the lenses with a larger effective aperture are also favored for further applications.

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Data availability statement

The datasets supporting the conclusions of this article are included within the article and its additional files.

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