Optical Observation of Single Neutron Detection

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Abstract. The feasibility of using highly pixelated light sensors as neutron detectors is the subject of a collaboration between ILL and ESS Bilbao. The fast paced development of camera sensors can meet the future challenges of neutron detection if an optical coupling able to increase the signal to noise ratio and enlarge the detection area is identified. Fiber optics tapers seem the best candidates, but issues about their radiation resistance and price make photographic objectives a more sensible choice. The performances of photographic optics have been tested as well as the light output of several thermal neutron scintillators. Thanks to the use of a highly transmissive optics, single neutrons could be observed in $^6$LiF/ZnS(Ag) for the first time.

1. Introduction
The planned ESS instrument suite challenges the state of the art of the position sensitive neutron detection by requesting detectors able to sustain count rates which may reach the MHz range [1] (a $^3$He proportional counter can sustain up to 150 kHz [2]) at a finer spatial resolution (from the micrometric range to some mm) over relatively large areas (up to tens of m$^2$).

Current scientific CMOS camera sensors, considerably more robust and cheaper than ECCD, have reached sensitivities of the order of a few photons. As a consequence, the observation of single neutron detection in scintillators coupled to these sensors with lenses may be possible. This technique would allow a single sensor to cover an area large enough to make this detection profitable for relatively large areas and the high pixelation would assure a competitive spatial resolution. Optical observation of the light emitted by ZnS based scintillators interacting with charge particles played an important role in the physical research at the beginning of the 20th century (see, for example, the so-called “Rutherford gold foil experiment” [3]). Those observation were done using microscopes with a magnification at least of the order of x20 [4] and Regener first stressed the importance of maximizing the light collection [5]. Nowadays, Miller et. al reviewed several scintillators and proposed a system able to take pictures of any scintillator by transporting its light to an intensifying plate through a fiber optic taper [6]. Being ZnS massively employed in thermal neutron detection, this kind of scintillators seems the best candidate to prove the concept and investigate how to fine tune the technique. Apart $^6$LiF/ZnS based scintillators which are cheap, bright, with low $\gamma$-sensitivity [7], but limited in efficiency [8], mainly $^6$Li glasses are used when detection efficiency is the main requirement and other scintillators can be considered once a highly transmissive optical system has been designed. Because coupling high speed photography and sensitivity is still a problematic issue, the design of the most suitable electronics able to
detect spots of light in a highly pixelated silicon sensor has to be investigated. ILL is tackling the problem and a developments of a board able to count single neutrons is presented in [9].

2. Tests of transmission in photographic objectives
The potentiality of photographic objectives have been tested using four samples: two reference lenses whose transmission value $T$ has been already measured and two lenses of higher acceptance. The brightest lens is a 50 mm f/0.75 branded by Canon under the name of Canon XI. The other lenses are a C-mount Tamron 8mm f/1.4, which can focus from 8 cm to infinity, a Nikon-mount AF Nikkor 50mm f/1.8D t/2.0 [10], which can focus from 45 cm to infinity and a Nikon-mount AF-S DX Micro Nikkor 40mm f/2.8G t/3.3 [10], which can focus from 16 cm to infinity. Pictures of a homogeneous white surface under controlled illuminations are used to measure the brightness of the objectives. By different amount of time exposures, the effective transmission of an objective can be deduced by the slope of the relation between exposure time and luminosity of the pictures. Pictures are taken in focus on the subject and focusing at infinity, if possible. In figure 1 the luminosity captured at the different exposure times, normalized over the field of view, is shown as the averaged gray level of the picture. The Canon XI lens has been identified as the brightest lens of the group with a transmission not better than t/1.4.

![Figure 1. Above: tested optics, from right: Canon XI, Tamron, Nikkor f/1.8, Nikkor f/2.8. Right: Luminosity captured by the tested optics at different exposure times.](image)

3. Tests on scintillators
Several thermal neutron scintillators have been tested at the same conditions at the beam line CT1 of the Institut Laue-Langevin: the Scintacor $^{6}$LiF/ZnS(Ag) (yielding blue light, in the following quoted also as blue scintillator) and $^{6}$LiF/ZnS(Cu,Al,Au) (yielding green light, in the following quoted also as green scintillator) screens in two formulations (2:1 and 4:1, ZnS:$^{6}$LiF) and thicknesses (250 $\mu$m and 450 $\mu$m), two Eljen $^{6}$LiF/ZnS(Ag) scintillators (thicknesses 320 $\mu$m and 500 $\mu$m) and two $^{6}$Li glasses doped with increasing amount of $^{6}$Li (GS20 and KG2) in the thickness of 2 mm. The scintillators were placed in beam facing a mirror inside a dark box and their light output recorded by a Hamamatsu ORCA-Flash4.0 camera mounting a f/0.95 MVL50HS objective for tests with full neutron beam and the Canon XI for imaging single neutrons. The use of the mirror allows to avoid to expose the camera at the direct neutron beam. The interior of the dark box during the experiments can be seen in figure 2. The unattenuated beam was scarcely visible by Li glass scintillators so no further analysis has been undertaken. The absorption in the other scintillators is evaluated by measuring the beam flux with a $^{3}$He proportional counter without scintillator and after it. The absorption in $^{6}$LiF/ZnS(Ag) 2:1
450 μm is the largest, but the its total light output is inferior to a green scintillator of the same thickness and even to the $^6$LiF/ZnS(Ag) 4:1 450 μm. Indeed, the luminosity relative to the absorption confirms the thinner scintillators, green scintillators and formulations containing more ZnS with respect to $^6$LiF brighter than their counterpart.

In order to observe single neutrons, the flux of the beam line CT1 has been reduced by inserting plastic scatterers. Pictures were taken with exposures ranging from 10 ms to 100 ms in steps of 10 ms and from 200 ms to 500 ms in steps of 100 ms. The identification of single neutrons rely on the localization of the spots of light at the beam position which is a small portion of the total area of the pictures as can be visible in figure 3 and in the comparison with the events identified in the picture taken during the campaign [11] where an area free of neutrons was defined by inserting a cadmium slab. Such events appear as a cluster of pixels having gray level of the order of the highest value of the dark noise or slightly above as can be seen in figures 6 and 8. This events are identified by filtering the pictures using the standard Non-Local Mean Denoising tool of ImageJ [12] as it is shown in figure 6 and 8. The possibility that the dark noise may form such spots of intensities is excluded by putting a threshold in the spot size at 25 pixels and checking the number of events identified outside the localized beam.
position. Neutrons detected in blue scintillators appear similar in shape and size but their signal to noise ratio is smaller. Also the number of visible neutrons is reduced of at least one order of magnitude with respect to green scintillators. The direct detection of $\gamma$-rays (cross checked by exposing a camera sensor to a $\gamma$ source) or charge particles in the silicon pixels is easily discriminated from a neutron as it has usually a well defined peak of intensity well above the dark noise of the camera, at least twice as much up to saturation. The characteristic intensities of those events are evaluated by the events showing a clear track like the one in figure 4. The number of neutron events is counted by the standard ImageJ routine Analyze Particles which search pictures for spots in a chosen range of intensities yielding for each identified object the total intensity, position and shape information. Direct detection in the sensor can be filtered on the base of this data. An analysis algorithm is under development and additional experiment campaigns are scheduled in order to test improvements in the setup in terms of optical coupling, focus and stability of the electronics.

![Figure 7. Neutron detection in a blue scintillator as seen in the raw picture, 200 ms exposure.](image)

![Figure 8. Denoised figure 7 using ImageJ Non-Local Mean Denoising routine.](image)

4. Conclusions
Visualization of detections of single neutrons in ZnS based scintillators is possible by using a sensitive camera and an optic with a transmission achievable also in commercial objectives. The possibility to visualize neutron detections in ZnS(Ag), the scintillator employed in many neutron scattering instruments, makes this technique suitable for fast detections of neutrons by the use of a suitable electronics or a fast enough camera. Additional experiments will be done to assess the technique by further improving the optical coupling and establish the correct measurement procedure. The determination of the best picture analysis algorithm is ongoing.

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