Access to neutron facilities

Title of proposed experiment

Microscopic investigation of neutron interactions in semiconductor materials in a broad energy range by means of Timepix3 hybrid pixel detectors

Spokesperson

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Preferred facility

n_TOF at CERN

Contact person at ARIEL facility

Enrico Chiavieri

Type of experiment

Time-of-flight measurement with hybrid pixel detectors of Timepix technology;

Requested beam time

40 – 56 h (e.g. in 5-7 days x 8 h shifts)

Preferred measurement period

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Synergy with SANDA

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Each experiment should support early stage researchers and lead to a publication in a peer-reviewed scientific journal and/or a conference presentation. In addition, validated data sets will be transferred to the NEA data bank /EXFOR. The PAC will assess the status of publications and will also monitor the transfer of nuclear data to the NEA data bank.

EURATOM support has to be acknowledged in all publications using: “This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847594 (ARIEL).

Participants list and access period requested. Please put on top the names of the early stage researchers that you would like to be supported. Only users from other European countries than the ARIEL host institute can be supported. Typically, support for travel (400 EUR on average per user) and a per diem (150 EUR) during a maximum of 7 experimental days can be granted for up to four users. For the 'research status' please indicate: UND= Undergraduate, GRA=Graduate (student with a first University degree enrolled in Master or PhD studies), PDOC= Post-doctoral researcher less than 6 years after PhD, TEC= Technician, EXP=Experienced researcher (professional researcher).

Researcher	**Institution**	**Research Status**	**Total number of days**	**Total number of visits**	**First-time user Y or N**
Declan Garvey	IEAP CTU	UND	7	1	Y
Lukas Meduna	IEAP CTU	GRA	7	1	Y (CERN user)
Petr Manek	IEAP CTU	GRA	7	1	Y (CERN user)
Petr Smolyanskiy	IEAP CTU	PDOC	7	1	Y (CERN user)
Benedikt Bergmann	IEAP CTU	PDOC	7	1	Y (CERN user)
Petr Burian	IEAP CTU	EXP	7	1	Y (CERN user)

Date

13.04.2021

Signature of Spokesperson

Benedikt B

Signed applications must be sent to the ARIEL management board at the following address: proposals@ariel-h2020.eu

Disclaimer: by submitting this proposal the group leader accepts that the text of his proposal will be put on the non-public PAC section of the ARIEL website. This password-protected section of the website will be accessible by the PAC members and all group leaders that have submitted a proposal.

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Background

1. Introduction

Due to low interaction cross-sections neutron detection, neutron spectrum measurement and neutron dosimetry are challenging. Hybrid pixel detectors have been proposed and investigated as possible alternatives to current systems allowing for production of small, compact devices with sensitivity to a broad range of neutron energies. Hereby, single or double layer stacks are used in combination with converter materials such as ^{6}Li and ^{10}B (through products of neutron capture reactions) for thermal and polyethylene (through recoil protons) for fast neutron detection [1-3]. The pixelation together with the energy measurement and pattern recognition [4] provide means of reliably separating photon and neutron signals. In mixed fields, where penetrating charged particles are present, e.g. in hadron therapy facilities or at accelerators, two-layer setups interleaved with the set of converters provide additional information via (anti-)coincidence channels [1]: Since neutrons have to be converted they are seen in a single layer only, while penetrating charged particles are seen concurrently in both layers of the detector. Moreover, these stacked approaches allow an assessment of the directionality of the neutron field by comparing the asymmetry of the neutron signal amongst the layers. The two-layer neutron detector, which is proposed to be irradiated at LANSCE, has been developed for the use in one of the most challenging man-made mixed radiation fields, found in the ATLAS experiment at CERN, where a network of them will measure and separate the charged and neutral particle fields and determine the directionality of both components at different locations [5].

While typically neutron converters are employed to increase the sensitivity of neutrons in a given energy range, even the thin semiconductor sensors itself are sensitive to neutrons through a variety of interactions with sensor nuclei such as (in)elastic scattering or nuclear reactions [6][7]. The signals created by recoil nuclei have not yet been broadly exploited for neutron detection due to their relatively low energies, even though they could increase the covered neutron energy range towards the epithermal region. Silicon sensors and sensors of higher nuclear charge or elemental composition each provide distinct energy responses and absorption efficiencies, differing for neutron and photon fields. Thus, their combination could allow the scattering signal to be separated from the signals induced by x- or γ-rays. Neutrons scattering off silicon nuclei, however, do also create defects in the crystal lattice, whose number, even though most of the initial vacancies recombine, is expected to scale with detector degradation (so-called NIEL scaling hypothesis). With finely segmented pixel detectors allowing a simultaneous measurement of time and energy in each pixel, we propose to measure ionizing energy losses after fast neutron interactions in different semiconductor materials and study their characteristic event topologies. This will provide unique data to understand not only permanent damage but also single event effects due to local high charge creation in sensitive parts of electronic cells. Example events measured with Timepix3 at the Los Alamos Neutron Science Center (LANSCE) are depicted in **Figure 1**.

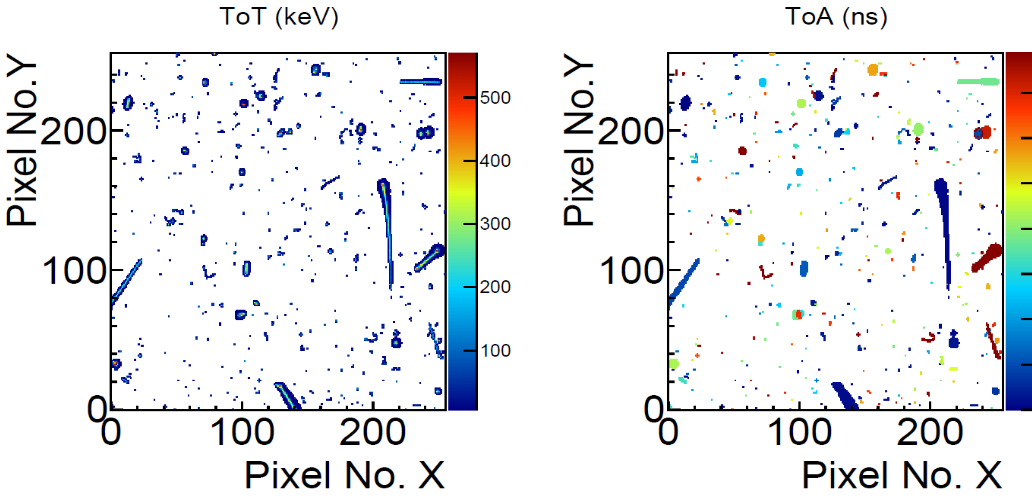

Figure 1: *Tracks as a result of neutron interactions recorded in a 300 µm thick silicon sensor within 1 ms at a distance of ~20 m from the neutron target at WNR FP30R. The left frame shows the per-pixel energy deposition the right frame gives the time stamps of each interaction. The latter is used for the neutron time-of-flight assignment.*

The proposed experiments are a continuation of measurements started at the 20 m long flight paths FP30L and FP30R of the Weapon Nuclear Resarch (WNR) facility of LANSCE, where Timepix and Timepix3 detection setups were exposed to a white spectrum neutron beam with energies up to 600 MeV. Applying the Time-of-Flight technique, we were able to fully characterize the ATLAS-TPX response to fast neutron impact. ATLAS-TPX is a two-layer neutron detector, used for the measurement of the radiation field composition in ATLAS during Run-2 [1][2]. Neutron interactions in silicon itself were studied using Timepix3 [6]. The simultaneous measurement of energy and time (with precision of ~2 ns) allowed to relate the ionizing energy deposition spectra to incident neutron energy. In these spectra, edges from neutron elastic backscattering were identified to determine the partition function of the competition of the energy dissipated by ionization and displacement [6]. It is compared to model predictions and a previous measurement performed by Sattler [7] in **Figure 2**.

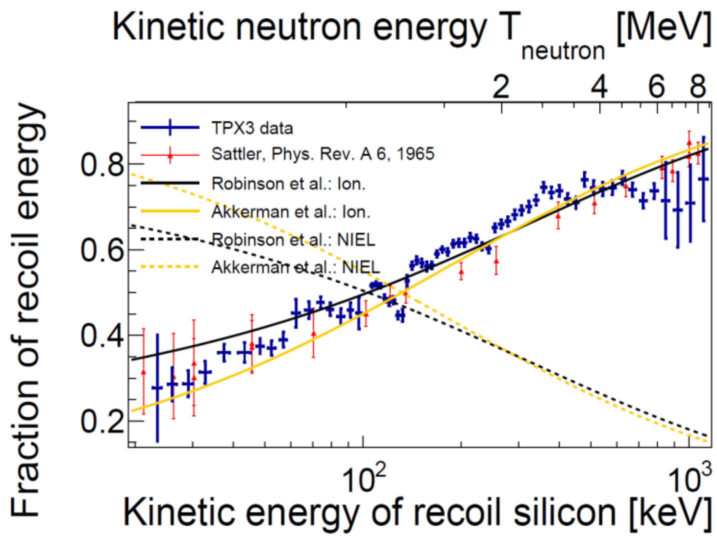

Figure 2: *Partition function of ionizing and non-ionizing energy losses in silicon in a*

300 µm thick silicon sensor measured with Timepix3 at ICE House I (FP30R). The measurement results are compared with a previous measurement by Sattler [7] and models by Robinson [14] and Akkerman [15]. More details about the figures and corresponding analysis can be found in [6].

Due to the "short" flight path at WNR and the micro-pulse separation of 1.8 µs, the neutron energy range for nTOF assignment is limited and neutron energy assignment uncertainties are large, especially at higher neutron energies. Even though the Timepix3 measurement uncertainties are lower than those of previous measurement (see **Figure 2**), it was still not decisive for model selection. The longer flight path at n_TOF together with improved detector readout electronics and calibration methodology will allow to **measure the fraction of ionizing energy losses and non-ionizing energy losses in different sensor materials with so far unprecedented accuracy**. In parallel, we will **calibrate the detector response of ATLAS-TPX3**, the successor of ATLAS-TPX in the energy range from thermal to fast neutrons up to 250 MeV. Hereby, we will pay particular attention to the response of the ^{6}LiF converter to epithermal neutrons, since the signal from epithermal neutrons is currently the key source of uncertainty in the determination of thermal neutron fluxes with ATLAS-TPX.

For completeness, we describe the detector technology and detection systems used in the experiments in the following.

2. Materials and Methods

2.1 Timepix3

Timepix3 [8] is the latest generation of the Medipix/Timepix series of pixel detectors. It consists of the readout ASIC and a matching sensor. The ASIC is based on 130 nm CMOS technology and implements 65,536 spectroscopic channels forming a 256×256 pixel matrix with a pixel pitch of 55 µm (total sensor area: ~1.98 cm^2). Timepix3 permits the measurement of the energy (ToT) and the time of arrival (ToA) with a resolution of 1.6 ns simultaneously in each pixel. A key strength of Timepix3 is that ionizing particle interactions in the sensor are seen as imprints in the pixel matrix (clusters and tracks) with a rich set of features which can be exploited for the identification of impinging particles as well as particle trajectory or reaction kinematics reconstruction [9][10]. Sensor layers have been made of different semiconductor materials such as silicon, Cd(Zn)Te, or high resistivity GaAs:Cr. Moreover, recent efforts of our team and the University of Manchester have resulted in the production of prototype Timepix3 assemblies with 3D pillar silicon sensors [11][12]. These sensors are characterized by electrodes protruding into bulk material creating a pillar structure reducing charge carrier drift distances to less than 55 µm. Besides their better timing properties, such sensors are inherently less affected by radiation damage so that they have and will be increasingly employed in particle physics experiments in places with the highest radiation levels. GaAs:Cr (with drift times below 2 ns [13]) and 3D pillar sensor are up to date the fastest sensors available with Timepix3.

2.2 ATLAS-TPX3

ATLAS-TPX3 is the successor of ATLAS-TPX [1] designed for the measurement of the composition of the complex radiation fields in the ATLAS experiment at the CERN

Large Hadron Collider (LHC) [5]. Two layers of Timepix3 (500 µm thick silicon) are arranged in a face-to-face geometry and interleaved with a set of thermal (^{6}LiF) and fast (PE) neutron converters. In combination with pattern recognition these converters provide the capability of reliably separating neutron and photon events [1]. Penetrating charged particles are discriminated against neutrons by their coincidence behavior. 14 ATLAS-TPX3 devices will be installed in ATLAS to provide a measurement of the composition of the mixed radiation fields at different locations in the cavern.

Goals of the proposal

The proposal aims at the following:

- Improve the understanding of neutron interactions in semiconductor materials by determining the energy deposition spectra and charge distribution in dependence of neutron energy and interaction type. This will provide means of modeling sensor degradation and single event effects. Hereby, we plan to measure the competition of ionizing (IEL) vs non ionizing energy losses (NIEL) in different semiconductors with so far unprecedented accuracy;

- Fully characterize the fast neutron response of a two-layer neutron detector based on cutting-edge hybrid pixel detector technology for neutron detection in the ATLAS experiment (or life science applications such as hadron therapy).

Science areas: Neutron detector development; Radiation effects in semiconductor devices.

Description of work

Study of neutron interactions in semiconductor materials:

We propose to continue the study of intermediate and fast neutron interactions in different sensor materials hybridized with the Timepix3 chip. In addition to silicon sensors, we will include sensor materials such as GaAs:Cr and Cd(Zn)Te and perform measurements with 3D Si pillar sensors to increase the timing resolution and thus the TOF assignment. From the measured spectra, we will determine the partition functions of IEL vs NIEL.

Besides increasing the knowledge of neutron interactions, the measured energy spectra create a response matrix, which will be applied to spectra measured in neutron environments of unknown spectral characteristics in unfolding methods. In this way Timepix3 would represent a small, compact recoil spectrometer covering neutron energies down to ~200 keV. Combining different sensor materials facilitates the discrimination against the photon component of the radiation field.

Calibration of the response of ATLAS-TPX3 to neutrons:

The responses of the ATLAS-TPX3 to neutrons will be determined in dependence of neutron energy and impact angle. The measurement results will be used for fast neutron efficiency calibration, validation of the detector response simulations, and as an input for machine learning models.

Time schedule and beam time estimate

We calculate 0.5-1 day for setup and testing the triggering. For calculation of the necessary measurement times, we assume that proton pulses hit the target every 1.2 sec and create a total neutron fluence of 5.5 x 10^7 per pulse with the spectrum given in [16] (Figure 2 and Table 2). Experiment 1 and Experiment 2 are done in parallel.

Justification of the requested beam time

Experiment 1: Study of neutron interactions in silicon.

Time estimation per sensor: Interaction probability in 500 µm thick sensor layers is assumed to be 10^{-4} (uniformly) in the energy region of interest (200 keV – 15 MeV). The minimum desired statistics per energy bins with widths of 50-400 keV (energy dependent) is 5 x 10^5. From Figure 2 and Table 2 in [16], we extract a fluence of approximately 2.7 x 10^6 neutrons/pulse in the energy range from 0.1-1 MeV. Assuming uniform distribution, the number of neutrons in a bin of 50 keV in the given energy range is:

$N_{n,bin} = 0.05/0.9 \times 2.7 \times 10^6 = 150{,}000$.

This corresponds to a detected number of neutrons in the energy bin of:

$N_{det} = \varepsilon_{det} \times N_{n,bin} = 10^{-4} \times 150{,}000 = 15.$

The minimal measurement time for the desired statistics is thus:

$\mathbf{t_{min}} = N_{desired}/N_{det} \times 1.2\ s = \mathbf{9.25\ hours}$.

Since the measurement should be done for 3-4 different sensor materials we ask for **4 x 10 h** beam time. Change of the detectors can be done remotely using linear stages or manually. Hereby manual exchange is preferred in order to reduce the amount of radiation exposure of detectors.

Experiment 2: Calibration of the ATLAS-TPX3 response to neutrons.

The detection efficiency for thermal neutrons is ~0.5%, for fast neutrons it is ~0.05-0.2%. For impact at angle α the efficiency is reduced approximately by a factor $cos(\alpha)$. Since the device is symmetric, it is sufficient to study the fast neutron signal angle dependence only in the range from 0 - 90 degrees. At 90 degrees, the neutron signal will be strongly reduced, but still visible.

a) Thermal neutrons: $N_{n,bin} = 3.3 \times 10^5$ (per pulse) → $N_{det} = 3{,}300$; In order to detect 10^6 thermal neutrons, we require $\mathbf{t_{min} = 364\ s}$. The thermal neutron detection efficiency is angular independent.
b) Epithermal neutrons: The efficiency for epithermal neutron detection has not yet been measured. We extrapolate the efficiency at 25 meV to 100 keV using the expected 1/v behavior of the ^{6}Li neutron capture cross section. → $\varepsilon_{epi} = 0.025\%$. Assuming a bin width of 10 keV, we get $N_{n,bin} = 10/90 \times 9.4 \times 10^5 = 10.4 \times 10^4$ and $N_{det} = 26$ (per pulse). → 10^5 epithermal neutrons are detected within $\mathbf{t_{min} = 1.3\ h}$.
c) Fast neutrons: $N_{n,bin} \sim 1/9 \times 3.1 \times 10^6$ (per pulse) bin width 1 MeV.
   → $N_{det} = 0.001 \times 2 \times 10^6 \times cos(\alpha) = 222 \times cos(\alpha);$ (per pulse)
   In order to detect 10^6 neutrons per bin, we find:
   $\alpha = 0\ deg$: $t_{min} = 1.5$ h
   For $\alpha = 60\ deg$: $\mathbf{t_{min} = 3\ h}$

The ATLAS-TPX3 calibration measurements can be done with sufficient statistics within 5 (different angles) x 3 h = **15 h.**

Beam time schedule:

The expected time schedule for the different measurements is shown in a timeline in **Figure 3**. 1.5 days are added as buffer to be able to redo a measurement in case of previous failure or additional required interventions, e.g. due to failure of the rotation stage. While Timepix3 can handle radiation well, the electronics in the commercially available rotation stage might be affected by soft errors even though not being directly in the beam.

Day	1					2					3					4					5					6					7				
Shift (2 h) No.	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4
Setup change																																			
Experiment 1				500 µm thick silicon						500 µm thick GaAs:Cr						3D sensor silicon						CdTe or si (1 mm)						Reserve							
Experiment 2				0 deg		30 deg				60 deg			90 deg			90 deg			180 deg			Reserve													

Figure 3: *Time schedule.*

Justification for expenses

In principle, all travel expenses could be covered by IEAP CTU resources.

However, we would be appreciate funding for:

- up to 3 x 5-7 days for UND/GRAD/PDOC
- Travel costs ~ 200 EUR (journey by car, 1000 km one way)

Education and training benefits

Education:

- First test beam experience for the undergrad student (Declan Garvey);
- The computer sciences graduate students (Petr Manek, Lukas Meduna) will have the opportunity to participate at a test beam campaign, use their developed software and adapt it to the needs of physicists. They will understand the signatures of neutron interactions in silicon and define the track features allowing a separation of different event categories;
- Measured data shall be used as training data for Machine Learning models, which are topic of the PhD theses of Lukas Meduna and Petr Manek.

Deliverables and Publication plan

All results shall be published in impacted journals. Data can be made publicly available.

References

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