Phoswich scintillator assemblies: Application to the Simultaneous detection of Particle and Gamma radiation

Proposal Acronym: ***PASPAG***

Activity number: ***WP9 - JRA1***

Descriptive title of the activity: ***Phoswich scintillator assemblies: Application to the Simultaneous detection of Particle and Gamma radiation***

Webpage: http://www.iem.cfmac.csic.es/departamentos/nuclear/WEB-PASPAG/webstyle1/

OBJECTIVES

The PASPAG JRA aims to improve infrastructure for European Large Scale Facilities such as GSI-FAIR, HIE-ISOLDE, and SPIRAL2 to make the best use of the high investment in delivering radioactive ion beams. Efficient gamma-ray and charged-particle detection are key tools for experimental nuclear physics. Future nuclear physics facilities will make strong demands on the capability and performance of such detector systems. The optimum gamma-ray spectrometer would combine a maximum of solid angle with good rate capability and energy resolution. New scintillator materials and photon detector technologies in combination with high granularity will help to tackle the challenges associated with extreme Doppler shift at relativistic energies.

DESCRIPTION OF WORK

PASPAG exploits novel scintillator materials and explores new techniques and concepts such as phoswich detectors and segmented or hybrid scintillators. We focus on developing the capability to simultaneously detect high-energy gamma rays, neutrons and charged particles. The two main European detectors that are profiting from our R&D are the PARIS and the CALIFA arrays; https://agenda.infn.it/event/10503/contributions/3169/attachments/2350/2582/28m07_Maj.pdf https://www.sciencedirect.com/science/article/abs/pii/S0090375214004694.
We also take this technology out of basic science to be exploited for societal applications within, for example, the areas of nuclear medicine and homeland security. Depending on the applications, features like energy resolution, position sensitivity, high rate capability, and insensitivity to magnetic fields or radiation hardness are of importance.

PROBLEMS ENCOUNTERED DURING THIS PERIOD

The main problems the WG have to face are in the case of TASK1 the delays in the delivery of new scintillator crystals and to obtain beamtime at the different test-facilities synchronized with the availability of the mentioned crystals and electronics.
In the case of TASK2, the problems encountered is related to the negotiations with the suppliers of Phototubes and voltage dividers. The time it takes to obtain new designs and get delivery of new modules is very long; every new try is a delay of 3-4 months.
In TASK3 we are partly aiming for applications, mainly as *proof-of-concepts,* partly this is done in collaboration with companies and details cannot at every stage be of open access.
For the procurement of hard-ware we have partly to rely on the availability of funding from outside of the ENSAR2. Contracting of personnel is also not trivial; the contracting procedures are rather lengthy; the people have to be trained and then shortly the contract is over. However, it is very positive that we have managed to train several persons in this activity, and that they do find work outside academia afterwards.

In continuation we summarize the activity of the WP9 and of its participants during this 2nd period of ENSAR2 between September the 1st of 2017 and February the 28th of 2019.

TASK1 Novel Scintillator Materials: (INFN – CNRS – CSIC – IFJ PAN - USC**)**

The performances of new scintillator materials, and their possible use as detectors, are not well known and thus require specific characterisation. The results of such studies are of particular interest not only for the researchers but especially for the producers of these materials in order to be able to make and sell detectors that can be commonly used in applications and not only for use by specialists of the field.

IPN-Orsay - INFN-Milan: the activity has mainly focused on the characterization of new Lanthanum-based scintillator crystals. The IPN procured from Saint Gobain two CLLB crystals (1'' x 1'' and 2''x2'') and one LaBr3 :Ce,Sr (1.5''x1.5'') using ENSAR2 funds. The crystals were delivered during the year 2017. Since then we have performed a complete characterization of these crystals with gamma rays and with neutrons. In particular, in collaboration IPN-Orsay - INFN-Milan, we have measured the energy resolution, the light yield and the response as a function of the interaction point and we have investigated the neutron-gamma pulse shape discrimination for CLYC, CLLB and CLLBC. Work was also performed on the studies of large-volume LaBr3:Ce. Furthermore, since all the selected scintillators contains radioactive Lanthanum, the intrinsic activity of these scintillator materials were studied. The crystals properties (in terms of radiation detectors) and performances have been measured and the activity produced three publications (two in NIM and one in JINST) and two documents uploaded to open access in arxive, see below. Detailed information on this activity was reported during the ENSAR2-Townmeeting held in Groningen in April 2018 and in the published works. Part of the activity is also described in the PASPAG report of the Milestone MS3.4 see the webpage.

PLANNED CONTINUATION

In the last period the activity we will concentrate on the imaging properties of large volume (3"x3") scintillation detectors and on the readout of these scintillators using SIPM. In fact, in 2019, the almost 1 year fellowship provided by ENSAR2 will be assigned to perform this experimental work.

SCIENTIFIC OUTCOME OF TASK1

ARXIV http://arxiv.org/abs/1802.00437
ARXIV http://arXiv.org/abs/1807.10759

"**Response function and linearity for high energy gamma-rays in large volume LaBr3:Ce detectors**" – Nucl. Instr. and Meth. A879 (2018) 92-100
"**Fast neutron detection efficiency of 6Li and 7Li enriched CLYC scintillators using Am-Be source**" – Journal of Instrumentation, volume 13, 2018, P11010
"**Detection and Internal activity of newly developed La-containing scintillator crystals** " –
G. Hull, F. Camera, G. Colombi, M. Josselin, B. Million, N. Blasi:
Nucl. Instr. and Meth. A 925 (2019) 70-75
"**Towards an advanced characterization of the n/γ detection properties of the new CLLB elpasolite crystal"** G. Hull, F. Camera, P. Brillouet, G. Colombi, M. Josselin**:** Oral Communication to the IEEE NSS-MIC October 21st-28th 2017 – Atlanta (USA)
"**Advanced instrumentation for neutron-gamma discrimination"**
G. Hull: invited talk, ALTO2.0 – Workshop February 5th-7th, 2018. IPN Orsay (France)
"**Detection properties and internal activity of newly developed La-containing scintillator crystals"**
G. Hull, F. Camera, G. Colombi, M. Josselin: invited talk LIA France-Ukraine Workshop 2018 September 27th, 2018. LAL Orsay (France)

Phoswich scintillator assemblies: Application to the Simultaneous detection of Particle and Gamma radiation

TASK2 Phoswich detectors: (IFJ PAN – USC – CSIC – CTH – U York – TUM **–** U Warsaw **)**

Phoswich detectors are where two different scintillators are optically coupled. Typically, the scintillators are chosen so that the light output of the two materials has very different timing properties so that the energy deposited in the two parts of the phoswich can be extracted. As the peak wavelength of emission from novel scintillators can vary strongly, we explore the optimum coupling to high-performing photo-sensors including metal package PMTs and solid-state replacements such as silicon drift detectors (SDD) and silicon photomultipliers (SiPM).

CSIC – CTH: The group of CSIC together with the associate partner CTH have continued the testing and optimization of the readout of the Phoswich array CEPA4 consisting of a package of 4x (LaBr3:Ce + LaCl3:Ce) crystals. This is a prototype unit for the future CALIFA calorimeter for the R3B experiment at FAIR and should be able to determine the energy of high-energy gamma rays (1-30 MeV) as well as high-energy protons (100 -700 MeV) at a very high rate. We have been encountered with the situation that the sensor saturates and thus we cannot; 1) measure simultaneously gamma rays and protons with good resolution and 2) we cannot get the full range for protons.
We have in this 2nd period obtained, in collaboration with Hamamatsu, several newly designed photo tubes with less dynodes together with new optimized voltage dividers where we can take the signal out also from the last dynode with less amplification and can have two parallel readouts to increase the dynamic range. The first test with one set of these sensors was performed at IFJ PAN in Nov. 2017, and was partly successful. Milestone M3.3 Deliverable D9.4
In Dec. 2018 we got delivered from Saint Gobain the 1st sector of the CEPA (front end cap of CALIFA); in total 12 crystals divided on 3 capsules of 4 crystals. Each crystal is a phoswich of 7cm LaBr coupled with 8 cm of LaCl. We also got delivered from Hamamatsu 2 new PMTs with only 6 Dynodes with modified voltage-dividers. These have to be tested before the full CEPA detector, for the R3B experiment at GSI-FAIR, can be ordered.

IFJ PAN Krakow: A postdoc, Dr Paweł Kulessa, was hired for a year until June 2018. The IFJ PAN have been studying the response of the CeBr3:NaI (new type of phoswich detectors) for gamma rays up to 17.6 MeV. The work was performed at the ATOMKI Van de Graff facility in Hungary. Analogue electronic based on VME ADC and TDC and PARISPro-modules read by Kmax data acquisition software was used. Efficiency, energy resolution and detectors responses were obtained. For high energies of gamma-rays add-back procedures of PARIS cluster (pack of 9 phoswiches) were validated, showing good performance. In November 2017 at CCB in Krakow in-beam test for CALIFA detectors was performed. First time the real geometry CEPA LaBr3/LaCl phoswich response to protons and its linearity was measured. 8 young researchers were supported by the TNA NLC-CCB. Data are being analyzed. We have further, added segmented plastic detectors to the existing KRATTA Si:CsI detectors to improve the timing and angular resolutions. In beam tests at CCB Krakow in 2018/2019 shows good efficiency (~90%) as well as good timing properties. Tests of the Caen V1730B digitizer with DPP firmware shows good performance (both in time and energy resolutions) when used with the phoswiches (LaBr3:NaI and CeBr3:NaI) of the PARIS project. Starting from 2019 PARIS detector readout will use this digitizer model.

USC: The Goal of the work of USC has been to study gamma and particle response of Phoswich detectors based on non-hygroscopic scintillator crystals. A set of crystals of CsI(Tl) and GAGG:Ce (1x1x1 cm^3 and 1x1x5 cm^3) were purchased and tested in phoswich configurations. The study of these promising new Phoswich combinations has been initiated. These materials have so far been characterized with gamma rays. The features of the materials are being characterized especially for the possibility to disentangle and separate the individual and combined response to impacting radiation. There were several studies and comparisons done aiming to go from crystals to actual performing detectors. Further, work have been dedicated to obtain the best algorithm for the signal separation. The response to charged particles are to be tested as well as the time response of the crystals, in the continuation of this work. See deliverable D9.3.

TASK3 Hybrid arrays and their applications: (U York – USC – IFJ PAN – CSIC)

A third task of this project investigate hybrid detector arrays. By hybrid arrays, we mean highly-segmented assemblies of different scintillator materials, and also the combined use of photosensors on the same detector package; for example, position sensitivity achieved with SiPMs on one side and a PMT on the other to obtain the best energy or timing resolution. This task also address societal applications outside fundamental research, spanning over a broad range from medical imaging to homeland security.

U York and IFJ PAN have jointly been investigated SiPM readout for the PARIS phoswich array. The SiPM technology is becoming a standard for scintillators and light applications, replacing PMT's which are getting more difficult to buy. Although trey are still some applications where PMT's demonstrate better results in terms of spectrometry and timing resolutions, the SiPM performance in terms of dark count rate, dynamic range, chip-to- chip uniformity (breakdown voltage) is becoming very good. Considering also the immunity to the magnetic field it makes it a good candidate for the replacement of current PMT's for the PARIS detector as was reported in Milestone M3.2.

USC and CSIC together with the associates CTH and TUM have been working on the design and R&D of the CALIFA calorimeter intended for the high-efficiency detection of gammas and light charged particles produced in secondary reactions at relativistic velocity i.e. R3B@FAIR. Strongly Doppler shifted gamma energies as well as total energies up to 30 MeV together with high-energy protons up to 700 MeV are to be detected. As the energy of the involved irradiation is strongly angular-dependent this hybrid design is divided into 3 regions;
The Barrel 40 – 140 degrees, where the gamma rays, due to emission in flight, are detected with strong Doppler Broadening and protons of <200 MeV; finger like 15cm long CsI(Tl) crystals coupled to LAPD are used.
The iPhos 20 – 40 degrees, region with strong Doppler shift and protons > 250 MeV will no longer be stopped, also here long 17cm CsI(Tl) crystals coupled to LAPD are used, but a special reconstruction pulse shape analysis was developed to obtain the full proton energy deposit.
The CEPA 7 – 20 degrees, region with the highest rate and Largest Doppler shift, and not space enough for longer crystals. Here a faster scintillator is needed and Phoswich technique in combination it pulse shape analysis has to be done.
The different concepts have been tested in-beam in Lisbon, at CCB Krakow and at KVI Groningen.

CSIC have had one student employed on the project to perform R&D towards societal application for Homeland Security. Also, for this purpose we were granted a technician funded from the Community of Madrid via de program Young *Employment Initiative* co-financed by the European Social Funds.
In the case of Homeland Security and crime scene management there are several measurement and sampling scenarios that are too risky for humans to carry out, especially it is identified the need for remote-controlled radiation measurements and sampling using unmanned vehicles (robots or drones). Such devices need to incorporate Time- & Geo- stamping. As previously mentioned for societal applications, features like energy resolution, position sensitivity, high rate capability, and insensitivity to magnetic fields are important. A potential set-up with all necessary elements has been assembled and taken into operation as a *proof-of-concept*. It is still necessary to improve certain aspects like the wireless communication with the base station and the conversion of signals from the detector to spectra for its final analysis. This part of the work was presented to the EMIS2018 conference https://indico.cern.ch/event/616127/ at CERN, and is being published in the proceedings of the conference in Nuclear Instruments and Methods. See Deliverable D9.5.

SUBTASK 3.3 Secondary Electron Emission: (GSI – U Cologne – U Rzeszow)

This part of the collaboration is investigating basic properties of secondary electron emission (SEE) from selected nanomaterials. It is still unknown what properties of material influence the enhancement of SEE under influence of ionising radiation. There has been a vast amount of new materials developed around the globe. Most of them have never been tested for SEE properties and as potential candidates for development of new class of radiation detectors. There is a constant demand in the scientific community and industry for highly efficient and high-speed detectors systems. We are here investigating a new class of detectors based on nanomaterials.

Jointly the group has been studying high band material, grown on a silicon nitride substrate; ZnO nano-rods with GaN coating. Three different studies were performed. In August 2017 measurement with 73Ge ions at the Institute of Nuclear Physics Cologne were performed.
We continued with experiments at the Cologne Tandem Accelerator facility. This time the study was performed with ^{73}Ge and ^{16}O as beams with energies of 1.4 AMeV and 2.5 AMeV respectively. A higher SSE yield was observed from the investigated nano-materials compare to gold evaporated on the same substrate. A publication of these results is in preparation. The Collaboration meeting was held at GSI in October 2018 to discuss the results from the Cologne experiments and plan the future work in light of the difficulties in obtaining the desired nano-materials. This year we have launched two experiments already; in February an experiment at the CCB Krakow using a proton micro-beam of 2 MeV. The experimented aimed at understanding the source of the observed enhanced SEE yield in the measurement of September 2018. The measurement failed, why we continued this time at GSI with a heavy ion micro-beam. This time the experiment was successful. The enhancement of the SEE yield was quantified and its was correlated to the nano-rods grown on the silicon nitride substrate. The results are under analysis. The preliminary data shows that these results will be of general interest for the field and will be published accordingly.

The problems encounter in the production of thin ZnO nano-materials will hinder the development a large area secondary electron detector, as planed in this task of the project. Therefore, the collaboration will concentrate of investigation the properties of the available small samples. In order to determine the optimum geometry of the investigated nano-materials, we plan two more experiment.

Mario Cappelazzo (U. Cologne), reported on some of the results at a workshop on nano-materials in Rzesow, Poland In October 2017. ***Production of ZnO nano-rods with GaN coating. Multiple technological problems in the production delayed the planed investigations with heavy ions.***