Neutron detection array based on stilbene scintillators.
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I. Motivation

Neutron detectors are used extensively at almost every nuclear research facility world over. Their range of application covers nearly all the topics in basic and applied nuclear research: in nuclear structure, for decay studies and as ancillary detectors for powerful in-beam spectroscopy arrays; in nuclear reactions, for the identification of the reaction channels and reconstruction of the complete kinematics; in nuclear astrophysics, for determining the neutron emission probabilities; in nuclear technology, for nuclear data measurements and in-core/off-core monitors; in nuclear medicine, as radiation monitors and dosimeters and in material science, for neutron imaging techniques.

Paradoxically, the improvements during the last decades in neutron detection techniques have been modest in comparison to other fields of nuclear instrumentation. Materials, techniques and electronics developed a few teens years ago are still the state of art in neutron detection.

Experiments planned at number of facilities like GANIL/SPIRAL, GSI/FRS, INFN LNL - Legnaro, Jyväskylä, REX-ISOLDE, JINR/ACCULINNA require more efficient and sensitive neutron detectors. In decay spectroscopy, innovative neutron detector arrays are necessary for the challenging low yield $\beta n$ and $\beta 2n$ experiments and crucial in in-beam experiments for the identification of nuclei in fusion-evaporation reactions with radioactive beams. For the very exotic and low production isotopic species, high efficiency neutron calorimeters based on gas position sensitive detectors could lead to really low energy resolution spectroscopy. In studies of an extremely neutron rich nuclei via nuclear reactions a neutron detection is needed for reconstruction of a complete kinematics of the reaction and the decay channels. In the latter studies a detector array for neutrons emitted in heavy ion induced reactions at low to intermediate energies DEMON modules based on liquid scintillator NE213 [1] has been frequently used.

With the recent progress in computing technology, material science, digital electronics and data analysis, several fields in which the performance of existing and future neutron detection systems can be improved have been identified. In general these improvements are related to:

- Detector construction and assembly.
- Data acquisition and electronics.
- Monte Carlo simulation codes as the standard and necessary tools for detector design and data analysis.

Therefore, due to interesting problematic and importance of the neutron detection systems in experimental studies at world leading facilities, practical exercises devoted to neutron detectors and detection systems are proposed at ACCULINNA set-up.

II. ACCULINNA separator

ACCULINNA fragment separator has been working with full load since 1996 [2]. Initially, the fragment separator ACCULINNA was designed an injector for the K4/K10 acceleration/storage complex [3]. It was built out of magnets that were at hand from the spare set of the U-400M cyclotron beam lines and was commissioned in 1996. The first experiments at ACCULINNA were performed in the autumn 1996 in the hall of the U-400M cyclotron. Later on, in 2000 the separator beam line was extended into the neighboring low-background hall and equipped with a modern reaction chamber and unique cryogenic tritium target [4] (see fig. 1). Since that time a series of precision experiments aimed at the study of the lightest neutron-rich isotopes $^4,5,7\text{H}$ and $^6,7,8,9,10\text{He}$ has been performed. The obtained scientific results are recognized by the nuclear physics community which is reflected by the list refereed publications and conference proceedings (see http://aculina.jinr.ru/publications). The ACCULINNA group actively works in all modes of operations typical for modern international centers:

- Numerous experiments are performed “in-house”; average workload is 3 – 4 months of the beam-time per year.
- The facility hosts external guest experiments.
- The group members actively participate in external experiments.
- The ACCULINNA group participates in the development of instrumentation for other world leading facilities.
**Fig. 1.** Scheme of "ACCULINNA" fragment separator with the main characteristics and an example of RIB monitoring with the use of time-of-flight method by two plastics 0.5 mm thick.

**Major accomplishments**

Within the recent years the ACCULINNA group has not only used recognized approaches to RIB research. It has proposed, developed, and practically applied a novel approach to the investigation of resonant states of nuclei in proximity and beyond the neutron drip-line. The ACCULINNA group did not restrict the study of resonant states to the derivation of the invariant/missing mass spectra. It succeeded to show that, in the experiments performed with certain kinematical settings, correlations inherent to the reaction products become an extremely rich source of the information. Unique technical feature of the ACCULINNA separator is the availability of tritium beams and cryogenic tritium targets. At the moment it is the only place in the world where the availability of the tritium target and the beam is combined with the RIB research.

Within the operation time of ACCULINNA, the following main results were obtained at this facility:

- The dineutron and t+t configurations in the structure of the $^6$He neutron halo nucleus were experimentally established as a result of measurements done in wide angular ranges for the elastic $^6$He + $^4$He scattering and for the two neutron transfer reaction $^3$He + p → $^4$He + t.

- For the first time the spectra of the $^3$H($^2$H,p)$^4$H and $^3$H($^3$H,d)$^4$H reaction products arising from the population of the $^4$H ground state resonance were disentangled from events coming from different reaction mechanisms and the parameters of the $^4$H ground state were reliably derived.

- A lower limit for the $^7$H decay energy was established.

- The $^5$H spectrum has been reliably established. This result was achieved in a series of works, in active polemics with the results coming from other groups.

- Experimental methods (so named zero-angle geometry) for the analysis of the three-body decays of spin-aligned states were developed and applied.

- The $^8$He, $^9$He, and $^{10}$He spectra were revised. The low-lying spectra of these nuclei have been considered as reliably established for more than a decade.

All references are given in [5,6].
III. Neutrons at ACCULINNA

In accordance with the topical plan of FLNR, all experimental studies on the fragment separator ACCULINNA are focused on synthesis and investigation of the properties of light nuclei near and beyond the stability limits. Research of the structure of $^8$He, $^6$Be, $^{17}$Ne nuclei are ones of the front lines studies with light radioactive ion beams physics. The scientific interest to study of properties of such nuclei is reflected in a number of scientific articles and many presentations of the new results coming from world leading laboratories. The availability of a tritium target at the ACCULINNA separator and intensive secondary beams of $^{6}_2$He offers a unique possibility to study extremely neutron-reach light nuclei. As an example is $^{10}_2$He, low laying resonance states of this very neutron–reach nuclear system were recently studied. The properties of such system are very important form the point of systematic for the magic number of neutrons $N = 8$.

One of the experimental problems in measurements performed for neutron-rich systems is to reconstruct complete kinematics of the reaction. The identification of the reaction channels and reconstruction of the reaction kinematics, as well as decay modes require detecting neutrons in a wide energy range $E_n=0.5\div10$ MeV. Therefore, a neutron detection system especially with possibility of $n$-$\gamma$ discrimination by pulse shape analysis plays a crucial role in the experiment. Neutron detectors are used extensively at almost every nuclear research facility across Europe. One of the largest is well known European neutron detection system DEMON based on liquid scintillator NE213. Such a detection system travels around the European leading facilities to be used in experiments with radioactive and stable beams. Three times it has been used at ACCULINNA in experiments devoted to studies of the structure of extremely neutron rich hydrogen and helium isotopes. An example of the experimental layouts aimed to studies of the structure of $^3$H with DEMON modules is presented in fig. 2. The motivation to build stilbene based neutron array at FLNR JINR is following: 1) been more compact these detectors will cover a large area of solid angle in both forward and backward directions; 2) its have a better energy resolution then liquid scintillator NE213 and a lower threshold of n-$\gamma$ discrimination. A wall of 32 modules of stilbene scintillators ($\odot 80$mm, 50 mm thick) is planned to build in 2010 with possibility of further extension to 64 modules for the years 2011-2016. The stilbene based neutron array will offer the possibility to use it in any experiments planned not only at the ACCULINNA separator but at any other experimental facilities of ACCULINNA collaborators. It will give the possibility to continue unique studies the structure of extremely neutron rich systems of $^{8,10}_2$He, $^{11,13}_3$Li, $^{15}_4$Be, $^{18}_6$C etc combined with tritium target.

![Experimental Layout 2001](image1.png)

![Experimental Layout 2003](image2.png)

Fig. 2. Two different geometry of the experiment devoted to study of the structure of $^3$H proton with triton beam. Top – forward angles of proton detection, bottom – backward angles of proton detection. Demon modules were used for neutron detection in the angular ranges of $\theta_{lab}=18^\circ\div56^\circ$ and $\theta_{lab}=5^\circ\div40^\circ$ respectively.
IV. Neutron detector: construction and operating

The schematic view of DEMON and stilbene crystal based modules and the comparison of the resolution of $\gamma$ and n energy detection spectra is presented in fig. 3. The advantage of stilbene crystal based module are: a) good amplitude resolution (better than liquid); b) more compact (having 2 times smaller volume of crystal than that of liquid can obtain the same neutron efficiency; it also means that the same accuracy of time-of-flight method could be achieved at about two times shorter base) and c) long live construction (liquid grows old and needs precautions). Actually we have 26 stilbene crystals ($\varnothing$ 80mm, 50 mm thick) fully equipped with photomultipliers, voltage dividers high voltage suppliers and signal processing electronics modules (QDC, TDC, constant fraction discriminators, both CAMAC and VME readout systems). The calculated neutron detection efficiency in stilbene crystals as a function of neutron energy is plotted in fig. 4. The efficiency is a little bit lower (~15%) then for DEMON modules.

![Fig. 3. The schematic view of DEMON and ACCULINNA modules based on NE213 and stilbene crystal respectively with the comparison of n-$\gamma$ discrimination obtained at the same conditions and energy resolution.](image)

![Fig.4. Calculation of stilbene crystal efficiency to detect neutrons with energy in the range of 1-10 MeV.](image)
V. Students tasks

The main tasks for students within the training practice period are focused on the neutron detector construction, testing, learning about the problematic of digital signal processing and analysis.

Within the part devoted to the characterisation of the scintillator material properties student will be introduced to scintillation modes, light yield, proportionality, linearity and temperature dependence, particle identification, radiation hardness. Students will also learn about the detector readout, noise reduction, linearity, position sensitivity, light collection and optical coupling, detection efficiency, time and energy resolution. Practical exercises with detectors and electronic tests with calibrated sources and beams are planned. In the part devoted to digital signal processing and analysis student will learn about the specifications of the data acquisition electronic modules. This part is devoted to the problematic of dynamic ranges, time resolution, pulse height resolution, linearity, sampling rate and bandwidth of DAQ system. Practical exercises dedicated to amplitude and time calibration, n-γ selection are planed.

References: