# ANCILLARY DETECTORS FOR THE EAGLE ARRAY — NEW OPPORTUNITIES TO STUDY NUCLEAR STRUCTURE AT HIL UW*

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The integration of the modernized Recoil Filter Detector with the EAGLE gamma-ray spectrometer at the Heavy Ion Laboratory of the University of Warsaw (HIL UW) offers new opportunities to advance spectroscopic studies of deformed medium-mass nuclei at high spins. This setup is designed to improve sensitivity to gamma rays with high energies, which are typically subject to significant Doppler broadening due to the high recoil velocities of the emitting nuclei. Additionally, the upgraded system will enable the investigation of shape transitions in octupole-deformed thorium nuclei, where gamma-ray spectra are dominated by a significant background from competing processes, such as Coulomb excitation and prompt fission.

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## 1. Introduction

In-beam nuclear spectroscopy employing fusion–evaporation reactions with light and heavy ions has been one of the major tools in nuclear structure research and is one of the richest resources of various data for nuclear structure investigations. At bombarding energies just above the Coulomb barrier,

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fusion–evaporation reactions predominantly occur, with reaction cross sections typically in the range of 0.1 to 1 barn. However, fusion–evaporation reactions leading to very heavy nuclei are of particular interest, where the fusion–evaporation cross section is of the order of microbarns. To enable precise spectroscopic studies, it is crucial to identify and select gamma rays from the desired, often rarely occurring evaporation residues.

The use of germanium multi-detector arrays has made great progress in understanding both individual excitations of nucleons and collective phenomena. However, the still-new information on those excitations is often hard to reach for heavy nuclei ($A \sim 200$) due to a strong background caused by fission. An observation of properties of such nuclei populated in heavy-ion induced fusion–evaporation reactions with only a few microbarns cross sections can be possible when filtering by detecting the recoiled nuclei after particle evaporation. A substantial improvement of $\gamma$-ray spectra can be achieved when $\gamma$ rays are detected in coincidence with those evaporation residues. The coincidence condition and the recoil time-of-flight determination allow to suppress $\gamma$ rays from competing fission, transfer processes, Coulomb excitation, target contaminations, *etc.*

For lighter fast recoiling evaporation residues ($A \sim 40$–70, $\beta \sim 5\%$), the determination of the velocity vector of recoils in event-by-event mode allows for significant Doppler broadening reduction which can lead to considerable improvement in the gamma-energy resolution, especially when high-energy $\gamma$ rays are emitted. With all that in mind, we have constructed the Recoil Filter Detector (RFD), which measures evaporation residues in coincidence with $\gamma$ rays detected in a germanium array, for details, see [1]. The previous RFD campaigns at EUROBALL IV in Strasbourg and at GASP in LNL Legnaro demonstrated that the RFD in conjunction with those Ge arrays was a powerful tool for spectroscopic studies both in light- and heavy-nuclei regions [1–5].

## 2. Installation of a modernized RFD detector at the HIL UW

Coupling of a modernized RFD with the EAGLE [6] array to the Warsaw cyclotron U-200P beamline at the HIL UW will open new possibilities for the laboratory, allowing for efficient in-beam spectroscopic investigations of nuclei in light-, medium-, and heavy-mass regions. Due to the long operation of RFD under vacuum and in a harsh radiation environment, several components of the detector have degraded over time and require replacement. Additionally, the signal readout system needs to be updated to meet modern standards. An upgrade of the RFD detector is currently underway, involving the modernization of its active elements and the implementation of a digital signal readout system.

As illustrated in Fig. 1(a), we have constructed a test chamber in which one of the 18 RFD detection elements is being evaluated using fission fragments of $^{252}$Cf source. The detection of heavy ions hitting a Mylar film is achieved through the formation of a secondary electron (SE) beam focused on a thin scintillator. The SE beam is created by the recoil passing through the Mylar foil. The standard photomultiplier is planned to be replaced by a silicon photomultiplier (SiPM) matrix. An array produced by Onsemi, model ARRAYJ-30020-16P-PCB [7] (Fig. 1(b)) comprising 16 individual $3 \times 3$ mm sensors arranged in a $4 \times 4$ array, is being tested. The use of SiPM technology will enhance the granularity of the detector, enabling the distribution of high rates (mainly due to scattered beam) across multiple SiPMs. This improvement will significantly boost the efficiency of the device.

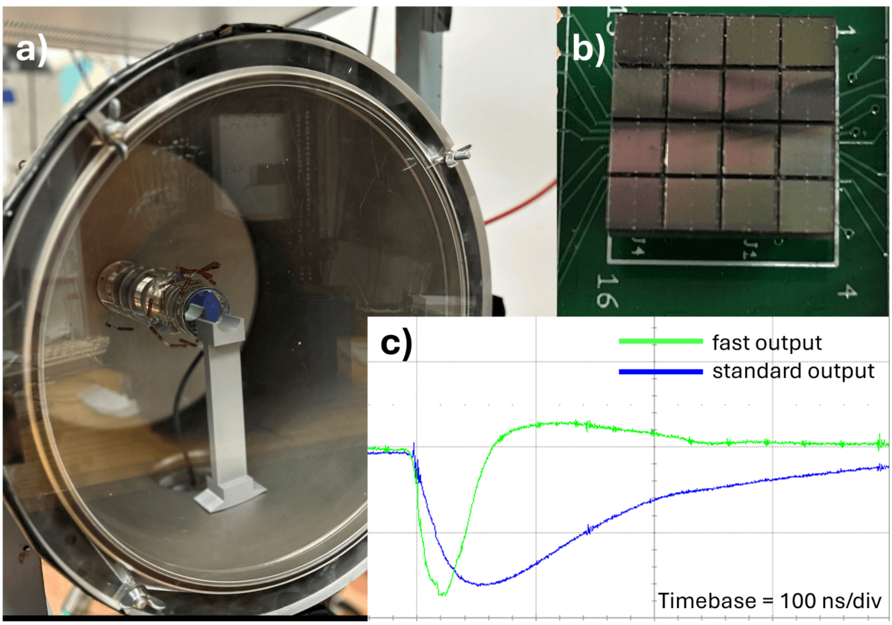


Fig. 1. (Color online) Photo collage showing: (a) vacuum chamber built for testing individual RFD components; (b) the silicon photomultiplier (SiPM) matrix (ARRAYJ-30020-16P-PCB, produced by Onsemi), which was used to replace the standard photomultiplier tube; (c) signals from the fast (green/gray line) and standard (blue/black line) outputs of a single SiPM element.

Furthermore, a new digital electronic readout of the RFD is under development, based on the CAEN [8] solutions dedicated to SiPM readout applications and high-resolution timing applications (such as A5202 and A5204 units). This new digital electronic readout of the RFD will be compatible not only with the data acquisition system of the EAGLE array but also with other state-of-the-art gamma-ray spectrometers such as PARIS [9] and AGATA [10]. The RFD detector can also be combined with the light-charged particle detector DIAMANT [11, 12] and the neutron array NEDA [13–15], enabling more comprehensive investigations of fusion–evaporation reactions. In this project, the inclusion of DIAMANT will facilitate the identification of light-charged particles, such as protons and alpha particles, allowing for precise selection of various fusion–evaporation reaction channels.

## 3. Research program @ HIL UW

The research plan involving the use of RFD in Warsaw is focused on the extension of the knowledge of the excited structures in the nuclei from the $A \sim 40$ mass region especially for $^{42}$Ca, $^{44}$Ti up to, or beyond the rotational band terminating states interpreted so far as particle–hole excitations. In these light nuclei, the so-called superdeformed (SD) bands are composed of short-lived states connected by strong E2 transitions, therefore they are interpreted as collective. We aim to experimentally check if the SD bands continue beyond the Shell Model spin limit (as expected) or terminate. The advantage of the proposed experimental setup will be also the possibility to determine the lifetimes of the high-spin states, for the nuclei of interest. Most of the conclusions regarding the deformation of high-spin structures excited in $A \sim 40$ nuclei were drawn based on theoretical premises. Mainly, the similarities between the experimental and calculated energy sequences of gamma-band transitions were taken into account. Much more rigorous verification of the correctness of the calculations, and specifically the values of the deformations predicted by them, will be possible by measuring the lifetimes of high-spin states in the excited bands — such measurements provide information about the electric quadrupole moment of the nucleus, and thus about the nuclear deformation.

On the other hand, nuclei from the Ac–Th region are the best-known examples of the reflection asymmetric nuclear shapes. The presence of collective bands of alternating parity states is a typical feature of these nuclei. However, such collective structures, known in the actinides, are extended to a relatively low angular momentum of $I \sim 20\,\hbar$. Therefore, it is still not clear if at the high-spin regime, the octupole–quadrupole shape transition takes place, as predicted by the theory. The incomplete knowledge of the high-spin structure of the octupole-deformed actinides is due to a very limited number of possible beam–target combinations leading to the nuclei of interest, very low cross section, and dominant fission background.

Additionally, the installation of RFD at HIL UW will allow us to investigate the structure of even heavier nuclei, for example, $^{252}$Fm. Such residues produced in a $^{238}$U($^{18}$O, $4n$)$^{252}$Fm reaction, using an intense beam and a thin metallic $^{238}$U target, with a cross section of a fraction of microbarn [16] can be effectively selected from the fission background and their prompt gamma radiation examined.

The advantages of RFD coupled to the EAGLE system (as presented in Fig. 2) can be summarized as follows:

— good selection of evaporation residues,

— high efficiency of $\gamma$-recoil coincidences: 20–50%,

— background reduction and filtering out of unwanted processes, *i.e.* fission, transfer processes, Coulomb excitation, target contaminations,

— precise Doppler broadening correction,

— determination of a lifetime of highly excited states in the fs range,

— possibility of coupling to other ancillary particle detectors.

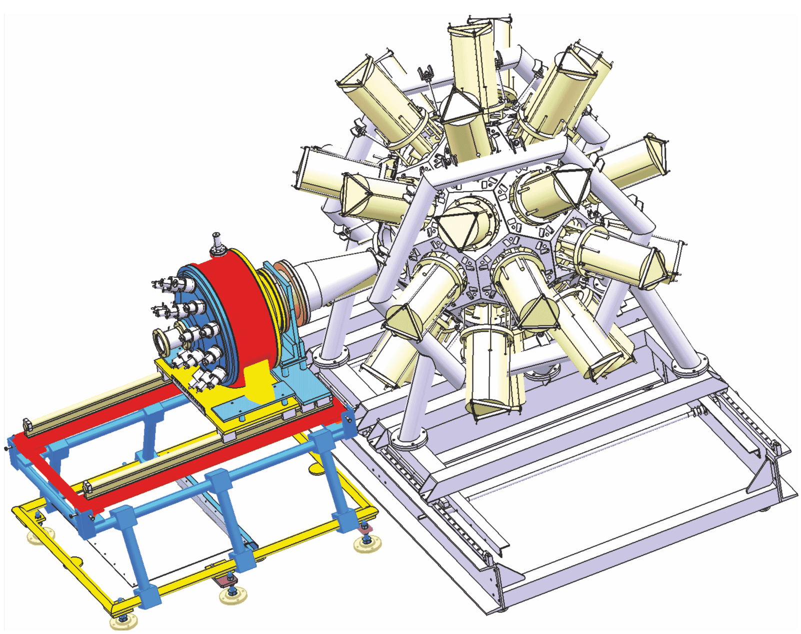

Fig. 2. Visualization of the RFD detector coupled to the EAGLE array at the Heavy Ion Laboratory, University of Warsaw (HIL UW).

In summary, the application of the modernized version of the RFD detector with the EAGLE gamma-ray spectrometer will make feasible gamma-ray spectroscopic studies of fast recoiling nuclei in light- and medium-mass regions as well as very heavy nuclei produced in fusion–evaporation reactions with very low cross section. The combined use of the RFD and the particle detector DIAMANT will improve the EAGLE setup's sensitivity, especially in experiments aimed at high-spin studies in exotic nuclei.

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