# DIGITAL SIGNAL PROCESSING IN DECAY STUDIES

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The development of a data acqusition system based on digital processing of detector signals is described. This system, initiated within the UNIRIB collaboration, was developed originally for proton radioactivity studies at the Holifield Radioactive Ion Beam Facility. It was applied successfully for $\gamma$- and $\beta$-spectroscopy, as well as in decay studies of the relativistic heavy-ion fragmentation products. A short summary of the results achieved with this system and the possible future applications are given.

## 1. Introduction

Hybrid systems using shaping amplifiers and peak sensing Analog-to-Digital Converters (ADC) have been successfully used in nuclear spectroscopy for many years. It is still the most common method of data acqusition. With recent advances in technology this type of electronics can be compacted and serve large detector systems. However, already in early nineties, there were attempts[1,2] to digitize the detector signals much earlier, at the detector preamplifier level.

Some advantages of applying fully digital systems in nuclear spectroscopy are presented in the recent reviews[3,4,5,6]. The first profit is obvious - once digitized, the signal will not be disturbed by electronic noise. The digitized signal can be numerically filtered in real time, thus providing equivalent functionality to the analog system. Digital pulse processing provides several options not available within traditional methods. The digitized preamplifier waveform can be recorded, awaiting for a more sophisticated off-line signal shape analysis. It translates to the analog language of having a chance to change and test different settings of the amplifier/shaper module, in order to find the best processing of an incoming signal. Besides obtaining global parameters like the arrival time and amplitude of single signals, one can also process overlapping pulses. One can choose pile-up rejection within a preset range and measure individual signal properties beyond this limit. More sophisticated analysis uses the shape of the signal's rising edge to trace charge collection effects in the detector. The most ambitious projects are aiming now in tracking the absorption of $\gamma$-rays in a detector volume, compare[7,8,9].

## 2. Analog and digital detection systems

Proton radioactivity studies started at the HRIBF[10,11,12,13] with a hybrid system of analog shapers and peak sensing ADCs[14,15]. Fusion-evaporation reaction products recoiling from the target were separated by the Recoil Mass Separator[16] according to their mass-over-charge ratio, with a $\pm$ 10% kinetic energy acceptance. The selected recoils triggered a position sensitive gas avalanche counter (PSAC) and were slowed down by a degrader foil before implantation into a double-sided silicon strip detector (DSSD). Ion implantation signals as well as the proton and alpha decays were preamplified and shaped with the analog electronics[14,15]. The signals were finally recorded by a system of CAMAC 8-channel peak sensing ADCs (Silena 4108). With a DSSD having 40 front strips and 40 back strips, i.e., 80 DSSD detector channels, there were 160 shaping amplifiers and 160 ADC channels used for the recoil implantation and decay signals. The presence or absence of a PSAC signal selected the implantation signal (after a low gain amplifier) from the decay signal (after a high gain amplifier). The charged particle signals were recorded together with a continuosly running recoil- or decay-gated clock. The high gain amplifiers were overloaded by the implantation signal blocking the detection of the decay signal occuring within first $\approx$ 10 $\mu$s after the ion arrival. It was preventing the detection or at least strongly reducing the rate of recorded signals from short-lived $\mu$s activities.

Experiments on proton radioactivity usually were seen as an identification of single-particle proton orbitals beyond the limit of proton drip-line and as a measurement of the nuclear mass differences for exotic nuclei[17,18]. In the late nineties, there was a progress made in the theoretical analysis of the emission process[19]. Also, experimental studies reached several new deformed proton emitters[20,11]. Understanding of the wave function of these unbound narrow resonance states became a main goal of proton radioactivity studies[21,22]. Mapping the wave function of the emitter requires precise data on the partial decay width, free from the inaccuracies resulting from unknown partial beta half-life. This pointed to the proton emitters with $\mu$s half-lives, where the competing $\beta$ decay width can be neglected.

However, to achieve efficient counting of proton signals in the $\mu$s-range, the data acquisition system[14,15] developed at the late eighties had to be modified. At the HRIBF, it was proposed in 1998 to change the system to fully digital processing of the detectors signals, in particular for the DSSD. This decision was supported by the university collaboration UNIRIB as well as by the ORNL Physics Division. The four-channel Digital Gamma Finder (DGF-4C) modules[7], designed by the X-ray Instrumentation Associates (California), were selected for the new data acquisition system[5,6]. These are single-slot CAMAC modules digitizing the incoming signal within 25-nanosecond steps (40 MHz clock). There are 4096 channels (12-bit) available for the amplitude analysis. The incoming signal is adjusted by the analog part before the digitization, to fit a range of a flash ADC. There is no need for separating the data acquisition for the low and high gain signals, i.e., the number of channels for the DSSD electronics was reduced to 80. The time and amplitude of a signal can be analyzed on-board, using an adjustable trapezoidal filter algorithm. This filtering scheme has a built-in option of detecting and analyzing (or rejecting) the overlapping signals in real time.

DGF-4C can act as an *intelligent* digitizer. It can record the waveform of the incoming signal up to 100 $\mu$s range. Moreover, it can *select* on-board the signals of interest, like. e.g., the pile-up's occuring within 10 $\mu$s interval. Only the signals fullfilling the latter condition are accepted for further readout, which dramatically reduces the data stream and respective dead-time of the system. Such an operating mode, nicknamed "proton-catcher"[23] proved to be extremely useful for the studies of $\mu$s proton emitters like a 3-$\mu$s activity of $^{145}$Tm[24].

The DGF-4C has adjustable fit parameters for the algorithm identifying and analysing on-board the valid signals. It helps to achieve and keep good energy resolution by reducing the effects of noisy experimental conditions (e.g., by requiring a minimum signal length for a fast trigger). The observation of a fine structure in the proton emission from 4-millisecond activity of $^{141gs}$Ho profitted from this feature. In a one-week long irradiation with energetic recoils resulting in a high ion dose in the DSSD, a good energy resolution was kept by the DGF-based acqusition. It enabled the measurement of a very weak (0.7%) fine structure branching[25]. The digital rejection of high frequency noise was also crucial for achieving 1 keV energy resolution and a low energy threshold for conversion electron counting in on-line conditions at the mass separator[26].

DGF-4C modules store the valid signals in internal memory. The simultaneous readout of time-synchronized modules occurs, when the memory of one of the modules in the system is filled. This feature allows us to record several subsequent signals, without blocking the detection for the readout time after the first valid trigger. It turned out to be very important for the discovery of a new type of radioactivity. Two-proton radioactivity of $^{45}$Fe, with a few millisecond half-life, was identified among the fragmentation products of 650 MeV/u $^{58}$Ni beam at the Fragment Separator (FRS) at GSI Darmstadt with the DGF-based data acquisition[6,27,28].

Each event recorded by the DGF-4C gets an absolute time stamp, with the 25-nanosecond clock precision. It allowed us to select and correlate the signals of isomeric recoils with the following $\gamma$-radiation, e.g., for an exotic nucleus $^{96}$Ag produced and studied at the HRIBF[29]. Moreover, within the same data set, one can inspect isomeric decays with very different lifetimes. In the HRIBF experiment on mass A=140 nuclei, the decay of drip-line radioactivity of 7$\mu$s $^{140m}$Dy[30] and of 300-ns $^{140m}$Eu[31,32] were discovered and studied simultaneously. The relative position of the two isomers present in $^{140}$Eu could be experimentally proven for the first time. The decay of 300-ns $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration is feeding the 125-millisecond $\pi h_{11/2} \otimes \nu s_{1/2}$ excited state at lower energy[31].

The processing of overlapping signals was used also in studies of short-lived isomers produced at GSI in relativistic heavy-ion fragmentation at the FRS[5]. The detection scheme requires slowing down and stopping of the energetic isomeric fragments in the catcher material surrounded by the $\gamma$-detectors[33]. These studies often offer the only way to access excited states in very exotic nuclei, in particular in very neutron rich isotopes[34,35,36]. The process of slowing down and stopping of very heavy fragments is accompanied by a few hundred nanosecond long burst of radiation (delta-electrons, bremsstrahlung) blocking the detection of subsequent isomeric $\gamma$-rays. Analog acqusition systems for $\gamma$-detectors record the first burst event, which stops the acqusition until the end of the readout. It results in a strong reduction of the detection rate for isomeric decays, up to 90% for Pb-like fragments. The application of a DGF-based system helps to solve this problem, in two ways. The DGF can analyze properly the overlapping signals and extract the time and amplitude, up to an interval of a few microseconds. This information is stored in the DGF memory, so the observation of photons is still possible after the first burst signal. Also, the pulse shape recording mode of acqusition can be selected, with an external trigger reducing the total data rate. These recorded waveforms contain the burst radiation and overlapping isomeric $\gamma$-rays. They can be analyzed off-line, and information on the decay properties of produced metastable states is restored.

## 3. Future applications

The development of a novel data acquisition system based on digital signal processing was made following the funding decision made at the UNIRIB meeting in November 1998. It helped to achieve a number of unique experimental results. Further decay spectroscopy studies, planned at the HRIBF and expected to profit from the DSP system, are aiming at the structure of exotic particle emitters. Among them are nuclei near the doubly-magic $^{100}$Sn, important for testing the predicted rp-process path and its termination region[37,38].

New applications of the HRIBF DSP system are under development, in a close collaboration with XIA. They include the separation of isobars in the radioactive "cocktail" beam by using a "Bragg-curve" detector[39,40,41]. This separation can be achieved through the analysis of the properties of the charge collection[6].

There are projects to apply digital signal processing in the studies of cold neutron decay[42]. The electron and proton emitted in the neutron decay process will be detected in a pair of segmented silicon detectors placed opposite to each other in an electromagnetic field. The reconstruction of the origin of the electron signal should help to obtain the electron energy spectrum corrected for effects related to the electron backscattering at the detector surface.

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