Towards new proton radioactivities with radioactive beams and digital signal processing

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Abstract

Particle radioactivity studies using the XIA DGF-4C digital signal processing units at the Recoil Mass Separator of Oak Ridge National Laboratory are presented. Proton emission signals were observed starting from 500 ns after recoil implantation. An energy threshold below 100 keV for particle detection was achieved. For the ^{145}Tm and ^{146}Tm decay, evidence for the fine structure in proton emission was obtained. An experiment to search for a new proton emitter ^{149}Lu is described as an example where the combination of a ^{56}Ni radioactive beam and digital signal processing is a major advantage.

Key words: RADIOACTIVITY ^{113}Cs [from ^{58}Ni(^{58}Ni,p2n)], and ^{146}Tm [from ^{58}Ni(^{92}Mo, p3n)]; measured E_p, recoil mass separation, Si detectors
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1 Introduction

One of the main motivations for development of radioactive beam facilities is related to the extension of nuclear structure studies towards and even beyond particle drip lines. Study of proton radioactivity, a phenomenon related to the structure of unbound narrow resonance states, fits this motivation particularly well. It is clear, in order to investigate even more proton–rich nuclei, that intense postaccelerated radioactive ions and fast postfragmentation beams (RIBs) are needed. New efficient separators should increase the selectivity offered by production methods involving RIBs. Large detector arrays will allow us to count rare signals of very exotic nuclei. All three of these elements of RIB experiments were very well documented during the RNB2000 meeting (see these proceedings). However, since we aim to investigate extremely exotic nuclei, far from the beta stability line and thus very short-lived, a new method of processing our rare signals is needed. This fourth element, important for several areas of RIB experimental physics, is the topic of this report, which is based on experience gained at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge during the last year.

2 Proton Radioactivity Studies at HRIBF

Five new proton emitting resonances (^{140}Ho and ^{141m}Ho [1], ^{145}Tm [2], ^{150m}Lu [3] and ^{151m}Lu [4]) were discovered during the last three years at HRIBF using the Recoil Mass Separator and its particle detector system [5]. Fine structure observed in proton emission from the odd-odd nucleus ^{146gs,m}Tm [6] represents the first evidence for this phenomenon for a spherical system (compare this to the deformed emitter ^{131}Eu [7]). Five detected proton transitions were assigned to originate from two parent states based on similar decay patterns. The difference of about 250 keV for respective proton transitions reflects the energies of $s_{1/2}$ and $h_{11/2}$ neutron states in the even-Z odd-N daughter nucleus ^{145}Er. For the first time, information on neutron levels is deduced from proton radioactivity studies. This type of investigation should be extended to other odd-odd proton emitters, since it might be the only way to learn about neutron states in such extremely exotic nuclei. These experiments are particularly attractive when suitable neutron-deficient radioactive beams become available. At the HRIBF, a continuation of this study is foreseen when the stable ^{58}Ni beam is replaced by a radioactive ^{56}Ni beam allowing us to profit from the stronger *pn* reaction channel. There is also a need for an experiment with postfragmentation beams. For example, the ^{146}Tm fragments could be used to study proton partial halflives. This could be done by means of a heavy-ion fragmentation experiment (e.g. with primary RIA beams, [8]), in which ^{146}Tm ions are identified and counted in–flight. Direct comparison of the number of implanted ions with the number of emitted protons yields the absolute branching ratio.

Four out of the five new proton radioactivities detected at the HRIBF have the halflives in a μs range, including the shortest–lived proton emitter observed to date, the 3.5 μs activity of ^{145}Tm [2]. The detection system based on a Double-sided Silicon Strip Detector (DSSD) [9,10] was pushed to its limits to achieve such performance. The decays were observed, with at least partial efficiency, from about 5 to 7 μs after recoil implantation. With a time–of–flight through the separator of 2.5 μs this corresponded to the detection of proton decays about 10 μs after the production at the target. In order to search for particle radioactivities with halflives in the submicrosecond range (e.g. ^{103}Sb, ^{149}Lu and others), a new system of digital DSSD signal processing has been implemented at the HRIBF within last year. The main contributors to this development are Robert Grzywacz and Marek Karny of UTK/UW, Jim McConnell of ORNL and Michael Momayezi of XIA.

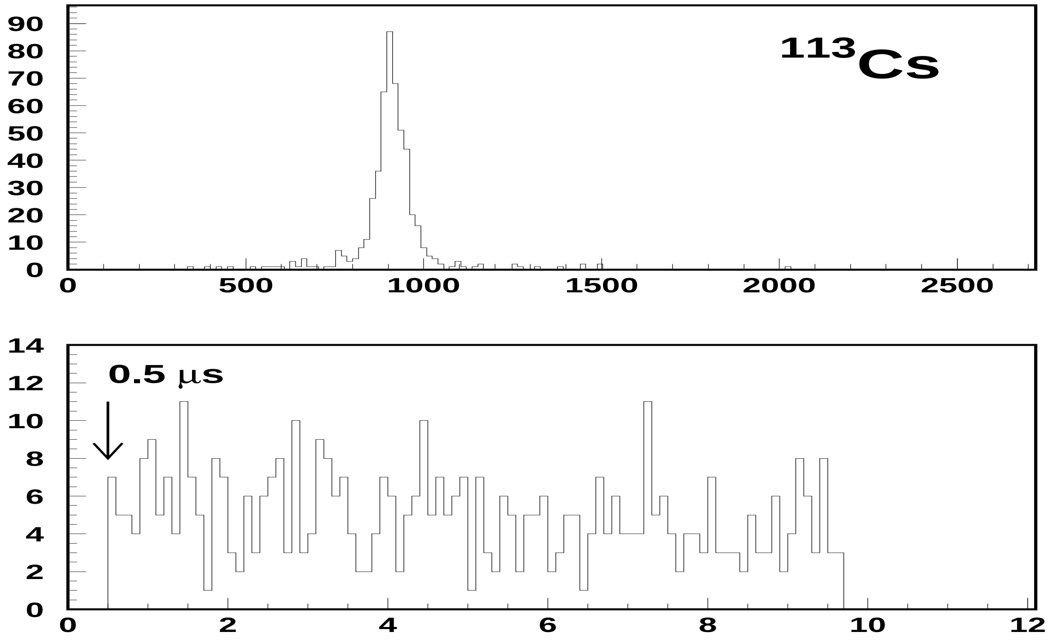
3 Digital Signal Processing for Particle Decay Studies

The HRIBF digital processing system for DSSD signals is based on the 4-channel Digital Gamma Finder (DGF-4C) single–slot CAMAC units [11,12]. It is operational at the RMS final focus as well as at the RMS acromat [5], where the time–of–flight of the selected ions is reduced to about 1.2 μs at the cost of mass selectivity. Thirty six strips on each side of the DSSD are presently connected to the DGF channels. One DGF module is used to analyze the signals from the position sensitive gas detector PSAC [5]. Two main operational modes are used for the particle decay studies at the HRIBF. The first mode reproduces and improves the capabilities of the previous analogue system. The signals from the DSSD preamplifiers [9,10], with e.g. 1 MeV decay signal on top of a 12 MeV implantation signal, are analyzed inside the DGF unit. The amplitude and time of both ion implantation and particle decay signals are sent to the VME processor. Pile-up events, e.g a decay on top of implantation signal with time difference between the two of less than 5 μs, are rejected. The energy thresholds for decay signals achieved on-line in this mode using a standard 75 μm thick (40 strips on each side, 1 mm wide) Micron DSSD of BB-1 design [13] were as low as 150 keV. A lower energy threshold (below 100 keV) was obtained off-line using a ^{90}Sr source and a 754 μm thick (48 strips on each side, 1 mm wide) EURISYS DSSD [14]. These results are relevant for future studies on short-lived superallowed beta emitters. Besides the decay properties of such emitter, one can study the levels in the parent nucleus via Recoil Beta Decay Tagging. Also, decays involving multiparticle emission after beta decay, e.g. β2p mode [15], can be studied more precisely counting all particles including low–energy beta signals.

The second main mode of DGF operation, the so called "proton catcher" mode, is designed for the studies of very short lived particle emitters. The DGF recognizes a pile-up event (e.g. a decay on top of the implantation signal), and rather than rejecting it records the signal waveform. Events not piled up, however, are now rejected. The 25 μs traces consist of 1000 points, 25 ns apart. The 200 pretrigger points (5 μs) help to measure the baseline, and 400 points at the end (10 μs) help to determine the electronic signal decay. The 400 samples in the center, spanning 10 μs, contain the implantation and decay pulse. In real experimental conditions, decay signals were observed starting about 0.5 μs after the implantation signal (see Fig. 1). The total event rate is low since the "proton catcher" mode selects up-front only the pile-up events and rejects all others. It is clear that having electronic noise free system is crucial for this type of operation.

For the 3.5 μs activity of ^{145}Tm [2], the application of the "proton catcher" mode resulted in an order of magnitude higher rate of detected protons (ca. 10 per hour). This was due to the coverage of the time interval when most of this activity was decaying after implantation into the DSSD. Increased counting statistics for the ^{145}Tm decay yielded an evidence for the fine structure in this proton emission [16].

Figure 1. The 0.96 MeV protons emitted by the 18 μs ^{113}Cs activity were observed in a "proton catcher" mode at the RMS acromat. Proton events were observed starting from 0.5 μs after an implantation of recoiling ion.



One can consider an experiment to search for the short-lived proton emitter ^{149}Lu as an example of a study profitting from radioactive projectiles and digital signal processing. Use of a radioactive ^{56}Ni instead of a stable ^{58}Ni beam makes the production reaction with a ^{92}Mo target colder. Since the initial beam is more neutron deficient, the *p2n* channel leads to the ^{149}Lu. A colder reaction and larger cross section (although lower beam intensity) should allow us to use the less selective but more efficient Enge spectrometer. Short time-of-flight of 250 ns of the products (see Fig. 5 in [17]), and digital signal processing starting 0.5 μs after implantation into the DSSD should be sufficient to detect the proton emission from ^{149}Lu.

Another obvious application for particle decay studies with digital signal processing is the search for new elements. The development of neutron-rich radioactive beams is very strongly influenced by the importance of these investigations. However, as a step towards Z> 118, one can attempt to study element 120 produced with a stable ^{88}Sr beam on a ^{208}Pb target. Starting with 2 μs ^{295}120 activity, the six subsequent alpha decays are predicted to be in the μs range [18]. To truly profit from the long multi-alpha correlation chain defining the superheavy element, one needs to record the entire sequence of decays with overlapping signals during the first microseconds after implanation. Intelligent front-end electronics is a must, also to reject non-decaying recoils and limit the raw data rates !

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