

Study of Nuclei Beyond the Proton Drip-Line*

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Abstract:

The study of nuclear structure beyond the proton drip line is most often realized by direct study of the proton emission process or through use of the proton radioactivity as a tag in other types of measurements. The prior study of proton radioactivity has been limited by the inability to produce copious quantities of nuclides beyond the proton drip line and the inability to study the proton radioactivity of a mass-separated nucleus in the first few microseconds of its existence. At the Holifield Facility we have attacked the second of these limitations by means of digital spectroscopy. Through digitization of the preamplifier signals and subsequent software analysis of the resulting waveforms or traces, we have demonstrated that proton decays occurring at times as low as 0.5 microsecond after an implant in a strip detector can be effectively detected and its energy accurately measured. In the same process, the threshold energy at which we can make measurements has been lowered to about 150 keV. These two things should enable the measurement of lower-energy, but faster decays of isotopes in the ¹⁰⁰Sn region and for $Z < 50$ emitters. In addition, for very short-lived species, we plan to make measurements (without residue separation) at points much closer to the target, thus reducing the flight time between the target and detector. As more intense radioactive beams become available, eg. ⁵⁶Ni, we will utilize these to produce more neutron-deficient nuclides with colder reactions than is possible with stable beams.

1 Introduction

Proton radioactivity has been an active research area utilized in mapping the limits of nuclear stability for the last twenty years. The first ground state emitter, reported in 1981[1], was ^{151}Lu which has a half-life of 80(2) ms and an $h_{11/2}$ configuration. Interestingly, a $d_{3/2}$ isomer of this well-studied proton emitter with a half-life of 16(1) μs was first discovered and reported[2] in 1999. Proton radioactivity studies have profited tremendously from the installation of on-line recoil mass separators at heavy ion accelerators and from the development of silicon strip detectors[3]. A strip detector facility was installed at the Holifield Radioactive-Ion Beam Facility HRIBF in recent years to pursue this field of study. Briefly, heavy ions from the HRIBF are directed onto targets at the entrance to the Recoil Mass Spectrometer RMS [4] at energies necessary to produce (HI,pxn) residues to assay for proton radioactivity. The recoiling residues moving in the forward direction are directed through the RMS, pass through a position-sensitive avalanche counter PSAC to determine the mass-to-charge ratio, and are implanted in a double-sided silicon strip detector DSSD behind the focal plane of the RMS. Until recently, the DSSD preamplifier signal was split to feed two amplifiers, one with low gain to treat the implant signal and another with high gain to view any subsequent signals from decay of the implant and its daughters. All implant (DSSD in coincidence with a PSAC signal) and decay events are time-stamped at the time of arrival, thus enabling the correlation of a proton decay signal with a particular implant and determination of the half-life. Please see Ref.[5] for a summary of results obtained with this system. In this paper we discuss some of the ideas we will pursue in future studies of proton emission.

2 The Frontiers of Proton Radioactivity

There are two features that emerge from viewing the list of proton radioactivity discoveries: 1) in general the more recently discovered emitters have been made with increasingly energetic heavy ions, resulting in the evaporation of more neutrons (compare (HI,p2n) for first discoveries with (HI,p4n) and one (HI,p5n) reaction in recent times), and 2) the new half-lives are shorter on the average than the earlier measured ones, though there are some exceptions. The shortest half-life for proton radioactivity measured to date is 3.5 μs for ^{145}Tm [6]. This is at the short half-life limit of what we can measure using our previous strip detector system and

conventional electronics. There are two factors which impose this limit: the time required for the evaporation residue to pass through the RMS and the recovery time of our amplifiers after the large energy deposited by the implanted heavy ion. This paper will discuss recently installed electronics which enable measurement of sub-microsecond half-lives, possible new experimental arrangements to alleviate the time-of-flight problem, and the use of radioactive-ion beams to provide cleaner sources for proton radioactivity studies.

3 Signal Processing for Short-Lived Proton Emitters

In the use of DSSDs to correlate charged-particle decays from rapidly-decaying nuclei implanted in the detector, separation of the small decay signal from the larger implant signal coming from the detector is problematic. The correlated decay signals coming in the first few microseconds after an implant appear as a pile-up pulse. We view such pile-up signals by digitizing the raw preamplifier signals to provide a trace of the pile-up signal with time bins of 25 ns. The input stage of new signal processing CAMAC modules DGF-4C from X-ray Instrumentation Associates has been shown to accomplish this feat[13]. The traces can be analyzed with digital spectroscopy units, also on-board in the DGF-4C modules, to strip determine the time (48 bit) and energy (12 bit) of a small decay signal riding upon a much larger implant signal. The implant times, decay times and energies are buffered into the data stream to our data acquisition system. After some pre-analysis, these data can be analyzed with our standard sorting routines to study fast charged-particle decays. As an alternative, the digital traces of the piled-up implant-decay signals can be output to the host data acquisition computer. An example of this type of data is shown in Fig. 1a, where two traces, one from a front strip and another from a back strip, were generated in a test run utilizing ^{145}Tm implants, and shows the peak shape when the proton is emitted approximately 600 ns after the implant. It is our intent to use this mode of operation for the piled-up signals having starting times below 5 μs . Traces are then analyzed by software to deduce the implant and decay times and the decay energies. These parameters are used to generate separate implant and decay events which are fed to our normal sorting routines to observe correlations. As an example, a contour plot of decay times vs. decay energies for a ^{145}Tm proton emitter, obtained in a 12-hr. test run, is shown in Fig. 1b. It should be noted that the energy shift is minimal all the way down to decay times of 0.5 μs . The previous data[6] ended at

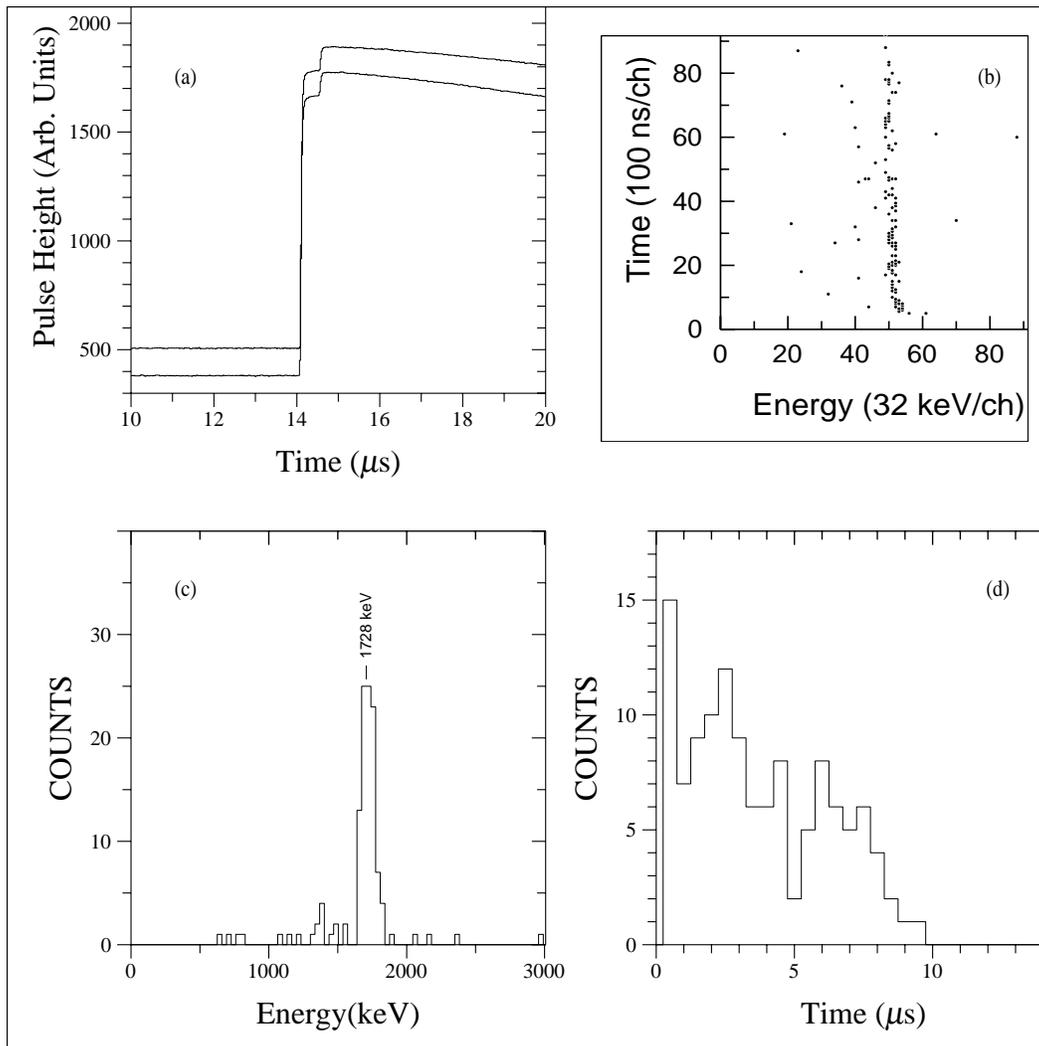


Figure 1: A sample of data taken with a DGF-4C. (a) Two traces, one from a front strip and one from a back strip illustrating the signal of a proton arriving about $1.5 \mu\text{s}$ after the implant. One trace was arbitrarily displaced by 100 counts to facilitate comparison. (b) A contour plot of decay energy vs. time after implant for protons from ^{145}Tm . (c) The proton spectrum from ^{145}Tm . (d) The decay curve for the protons from ^{145}Tm .

about $10 \mu\text{s}$ and significant shifting and spreading in the proton energy occurred up to decay times of $\sim 30 \mu\text{s}$. The proton spectrum and decay curve of protons from ^{145}Tm are shown in Figs. 1c and 1d. The minimum decay times observable with this technique is believed to be of the order of 300 ns with our current preamplifiers, and the threshold energy is of the order of 150 keV. We believe this will enable the study of lighter nuclides which decay with lower proton energies and very short half-lives. The lower energy threshold will also be vital in the search for fine-structure peaks in the deformed region.

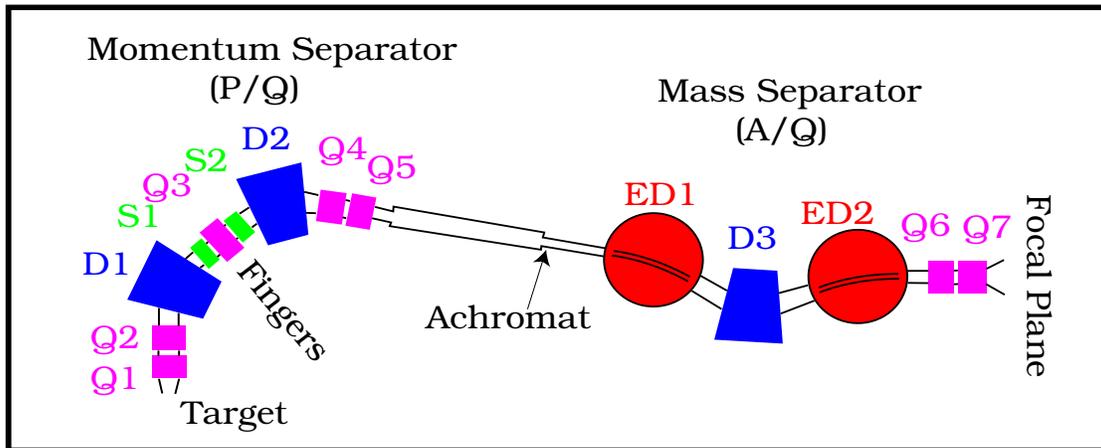


Figure 2: A schematic diagram of the Recoil Mass Spectrometer at HRIBF. In addition to doing experiments at the focal plane with full mass resolution, alternative counting stations can be introduced at the achromat and perhaps closer to the target in order to study decays of isotopes with half-lives in the μs range.

4 Flight Time Limitations

A schematic diagram of the Recoil Mass Spectrometer at HRIBF is shown in Fig. 2. It is comprised of a momentum analyzer followed by a mass separator. The instrument produces needed mass dispersion with a minimum of transmission of scattered beam [4]. The main disadvantage of this instrument for the study of short-lived species at the focal plane is its long length, ~ 25 m from the target to the focal plane. The time-of-flight for proton emitters through the RMS is dependent upon the reaction, but is typically 2-3 μs . This puts a rather severe limit on the minimum half-life which can be studied at the focal plane. On the other hand it is possible that for the very short-lived species, mass separation will not be required to study the correlated activity, since there is usually only one possible proton emitter with short half-life that would be produced with a particular beam and energy. Thus, we have prepared a chamber to make measurements at the achromatic focus of the RMS, which will shorten the time-of-flight by a factor of two. Preliminary plans are underway to investigate the possibility of obtaining appropriate focusing conditions at points even closer to the target. As an alternative to the RMS, there is the possibility of utilizing the split-pole spectrometer online at HRIBF in a gas-filled mode in order to reduce the total flight path to less than 3 meters.

The production of nuclei farther from stability by fusion evaporation reactions becomes problematic due to the large decrease in the cross section for each addi-

tional neutron evaporated, largely due to the fact that proton evaporation becomes more competitive as one approaches the proton drip line. Perhaps the use of rare isotope beams will provide a means for production of isotopes beyond the drip line while utilizing lower beam energies that would increase the probability of evaporating just a few particles leaving the final residue in the isotope of interest. In addition to having a larger cross section for the isotope of interest, the number of other reaction products will be greatly diminished, thus reducing the background and making the measurements much cleaner. An example would be a search for ^{149}Lu proton radioactivity by means of the $^{92}\text{Mo}(^{56}\text{Ni},p2n)$ reaction. This is a case where the split-pole spectrometer could give a clean separation of the evaporation residues from the beam because of the lower-energy projectiles required for the p2n reaction. While the evaporation residues would not be separated, the p2n channel should be one of the dominant ones, thus enabling rather clean measurements of proton radioactivity from ^{149}Lu .

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