

# The Nuclear Equation of State and Pulse Shape Discrimination

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Recent developments in nuclear science have shown that the nucleus has an equation of state describing the transition from a liquid drop-like state to a gas-like state. At high excitation energies ( $\sim 4\text{-}5$  MeV/nucleon), the nucleus goes through an evaporation-like process, evident from decreasing nuclear density and the eventual splitting and cooling of the original nucleus to form many smaller intermediate mass fragments (IMF's). This process is called multifragmentation. To study multifragmentation, all of the IMF's produced by a reaction must be isotopically identified in order to reconstruct the original, excited nucleus produced by the collision of a target nucleus with an accelerated nucleus. Methods of identification include time of flight analysis, multiple-detector energy loss plots, and pulse shape discrimination. Pulse shape discrimination (PSD) - the study of the time evolution of a pulse given off by either the charge collection of a silicon detector or the light production of a scintillation detector (such as cesium iodide), which can be used to determine the identity of a particle - will be discussed in detail. PSD practices involving silicon detectors will be focused on, as well as computer simulations that were created to improve the elemental and isotopic resolving capabilities of silicon-detector based experimental setups.

## I. Introduction

The nuclear physics/chemistry community has taken a special interest over the past three decades in the nuclear equation of state. Phase transitions are of interest because they give information on the nuclear states present in stars and in interesting stellar events such as the Big Bang. High-energy accelerator facilities such as Texas A&M's Cyclotron Institute provide the tools necessary to create phase transition conditions in nuclei. Some issues being investigated include whether the phase transition from liquid to gas is instantaneous (first-order) or continuous (second order) [2,3], what excitation energy phase transitions occur at [3,4] and whether larger nuclei have larger or smaller values for the excitation energy than smaller nuclei [4]. Multifragmentation (MF) studies are providing evidence to draw conclusions about these issues, and about the nuclear phase transition in general [1]. MF is a

process in which an adequately excited nucleus fragments into multiple smaller nuclei. MF is studied reconstructively by collecting all of the fragments, identifying them isotopically, and measuring their excitation energy [2]. Pulse shape discrimination as a means of particle identification has been described [5]. This shows promise in the use of single silicon detectors as particle identifiers, which would require less hardware for particle identification than other methods, such as the conventional time of flight technique [7]. Experiments with a neutron transmutation doped (n-TD) silicon detector have shown mixed results, and the resolution has been observed to be heavily dependent on the settings of the pulse processing modules. Experimenting to find optimum settings for each of the modules would be costly in terms of beamtime, and thus a method of testing settings that would not require large amounts of beamtime was developed. LabVIEW software was used

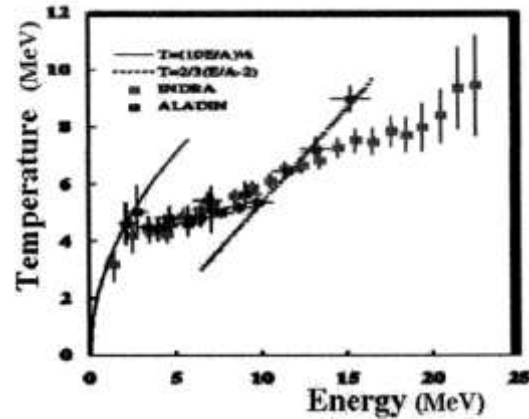
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to model the signal processing functions of various electronic pulse processing modules, including constant fraction discriminators, fast amplifiers, and leading edge discriminators in the interest of simulating an electronics setup for pulse shape discrimination experiments. The objective was to optimize elemental and isotopic resolution of energy vs. risetime plots obtained with actual electronics by testing settings on the simulated modules. The advantage that the simulated modules possess is that they can be run on recorded data repeatedly to test different combinations of settings, rather than requiring continuous beamtime for testing.

Section II discusses the nuclear equation of state and multifragmentation experiments and results. Section III discusses pulse shape discrimination practices. Section IV discusses recent simulation experiments for pulse shape discrimination.

## II. The Nuclear Equation of State and Multifragmentation

The nuclear equation of state has been under study for the past three decades, beginning with the suggestion of the phase transition by theoretical investigations of hot nuclear matter and finite nuclei [3]. Multifragmentation experiments have provided data to prove theories, such as whether the phase transition is instantaneous or continuous [3,4], and at what excitation energy MF (and thus the phase transition) occurs at. Using nuclear thermometry methods such as double isotope ratios and measuring average kinetic energies of particles [3,5], it has been shown that a caloric curve (Figure 1) with a plateau exists for nuclei.



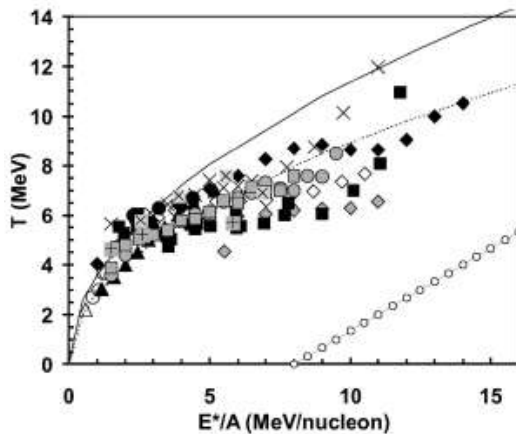
**Figure 1:** Example caloric curve. (Chomaz 2002)

This plateau, much like the plateau observed for critical macroscopic matter, indicates a phase transition.

Experimental results place the start of this plateau at excitation energies between 4 and 9 MeV/nucleon [3,4,5]. Nuclear temperatures remain at ~5 MeV throughout this range, and begin to increase more rapidly at higher excitation energies until the nucleus simply disintegrates [5]. Larger nuclei have lower values for this excitation energy, owing to the increased coulomb repulsion term [2,4]. This is counter to predictions that are based on surface effects.

MF experiments have given double isotope ratios and other temperature data used to generate the caloric curves and other correlating data for studying the equation of state. Experiments such as the EOS Collaboration [2,5] have used accelerators in addition to simulation codes, such as SMM (Statistical Multifragmentation Model) to observe systems including  $^{84}\text{Kr}$ ,  $^{139}\text{La}$  and  $^{197}\text{Au}$  beams on a carbon target. Data on the mass, charge and excitation energy of the remnant of the original nucleus that underwent MF were collected on an event-by-event basis. These experiments show that the heavier elements, lanthanum and gold, show a 2<sup>nd</sup> order,

continuous phase transition characterized by nearly zero latent heat [2], but the krypton phase transition is predicted to be 1<sup>st</sup> order by the simulation codes. Krypton's transition cannot be measured experimentally because the multifragmentation signal gets washed out by finite size effects. There have been numerous other studies on a wide variety of systems [4], and the caloric curves for each of these sets correlate fairly well, as Figure 2 shows.



**Figure 2:** Overlay of many experimentally-obtained caloric curves (Natowitz 2002)

Double isotope ratios are useful as a measure of temperature because there is a fractional distillation effect in the excited nucleus. Due to the fact that the nucleus is composed of two liquids, neutrons and protons, the phase transition should theoretically lead to a distillation phenomenon [1]. Thus, at higher temperatures, the IMFs emitted from the nucleus will have a higher neutron composition ratio than the emitting nucleus. This is because as the emitting nucleus gets smaller, it tends more toward symmetry, and emits the neutrons preferentially to achieve symmetry.

All of this data gathering depends on the ability to acquire as much data on as many of the fragments as possible. All

experiments in multifragmentation use many detectors to cover large areas, and multiple types of detectors to maximize resolution capabilities including isotopic particle identification, kinetic energy, and charge. This is where techniques such as pulse shape discrimination come into play.

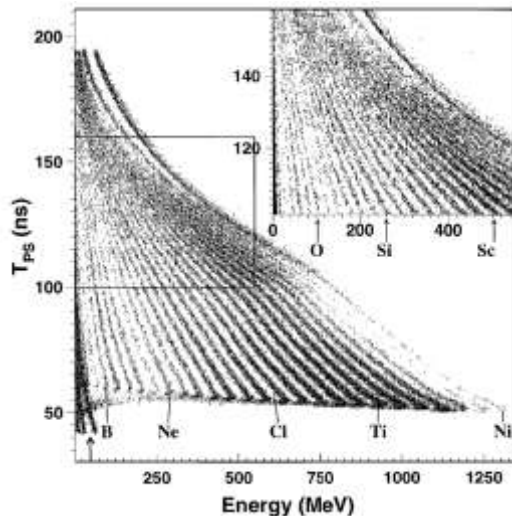
### III. Pulse Shape Discrimination

Pulse shape discrimination was first described with organic scintillation detectors in the 1950s [6]. The technique can be used with scintillation detectors (both organic and inorganic) and with silicon detectors. PSD is based on the principle that the pulse given off by a detector will be characteristic of the particle that hits the detector and incites a measurable response. For scintillation detectors, this measurable response is light intensity output, and for semiconductor detectors, the response is plasma erosion and charge collection. In either case, the maximum height of the pulse and the risetime are the two pieces of information that characterize the impacting particle.

Silicon detectors are ultra-pure elemental silicon with some small amount of either *n* or *p* doping. When large bias voltages are applied to the detector, a neutral area is created in the center of the detector, called the depletion zone. As a charged particle hits the depletion zone, its charge is deposited, as well as its kinetic energy. The energy strips electrons from the detector atoms, creating a plasma. The detector then re-equilibrates, collecting both charges, and it is this re-equilibration that gives rise to the pulse.

Pulse information is processed with electronics modules such as analog to digital converters, constant fraction discriminators, and pulse shapers to obtain the risetime and energy of the

incident particle. Plots of such information look like sweeps of lines, as seen in figure 3.



**Figure 3:** PSD plot. Note the elemental identification. (Lu 2001)

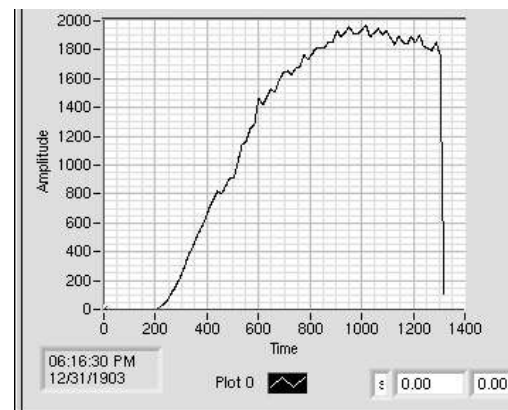
To obtain clean, well resolved results such as those seen in Figure 3, optimum settings for all of the pulse processing modules involved must be used. To test the module settings, beamtime is necessary, so that events can be processed in real time. This is costly in terms of beamtime, and thus in terms of money as well. A method of testing the settings without requiring beam was necessary, and thus a simulation of the electronic modules setup was developed.

#### IV. Simulation of Pulse Shape Discrimination Electronics

LabVIEW software, a graphical development environment, was used to digitally emulate the analog functions of the pulse processing modules. LabVIEW programs are referred to as “virtual instruments” (VIs). A data acquisition VI, moving window deconvolution (MWD) VI, fast amplifier VI, and 2 constant fraction discriminator (CFD)

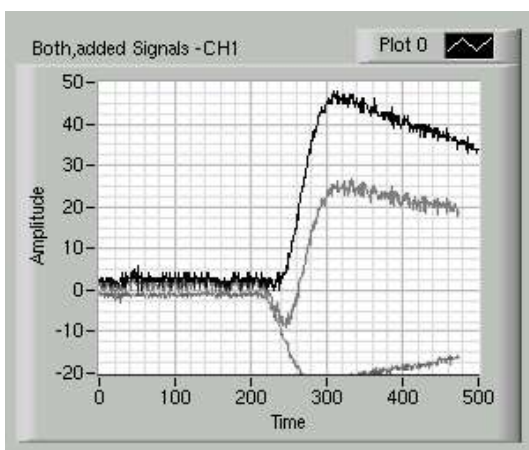
VIs were components of the whole simulation VI.

The procedure was as follows: pulses from an n-TD silicon detector were recorded from an Ethernet-connected Tektronix TDS-3052B oscilloscope and saved to disk using a TCP/IP-based data acquisition VI. The signal was then passed to the MWD VI for energy determination and the fast amp for pulse shaping. The MWD VI, which serves as an analog-to-digital converter, is based on the method described by Georgiev, Gast and Lieder [9,10]. The fast amplifier, which shapes signals by means of an RC circuit, was modeled using exponential decay equations [11], with user-definable time constants. The tail of this signal is truncated to save on processing time with the interpolator in the next step. An interpolator program is run a user-definable number of times to fill in some of the gaps in the waveform characteristic of analog to digital conversion. The interpolator program averages two points, then inserts the average point between the two points. This was done to aid in the accuracy of the level trigger of the constant fraction discriminators. The end result is a shaped pulse with average points inserted. Figure 4 is a screenshot of the processed fast amplifier signal.



**Figure 4:** the processed fast amplifier signal.

The fast amp signal is then passed to the two CFD VIs, where it is multiplied by an attenuation factor (the constant fraction), inverted, and truncated by a number of points to simulate a delay in the original signal. This modified signal is then added to the original signal, and a level trigger detects the zero-crossing time of this summed signal. Figure 5 is a screenshot of the original, modified, and added signals.

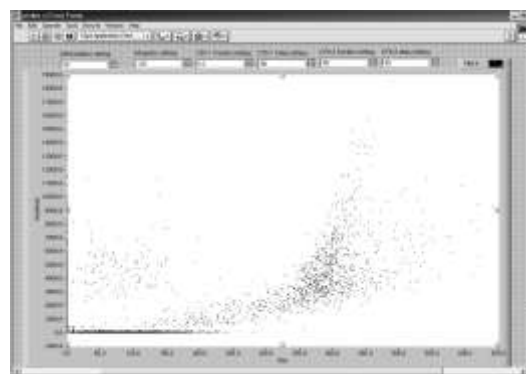


**Figure 5:** The CFD signals. The top signal is the delayed original signal, the bottom is the attenuated, inverted signal, and the middle is the sum.

The constant fraction and the simulated delay are user-definable. The zero-crossing time of the lower-fraction CFD is subtracted from that of the higher-fraction CFD to obtain the risetime. The energy and the risetime are then written to a spreadsheet file, whose filename reflects the settings for the fast amp VI and the two CFDs.

The process of testing settings was automated using a nested while loop structure. An initial set of parameters is defined, and the loops test all possible combinations of the parameters. Processing time is reduced by stopping combinations that will give false results using logic arguments. Examples would be if any of the settings are 0 – the fast

amp differentiator term goes to infinity, the integrator term to negative infinity, and the CFD attenuated signal becomes 0. Approximations of zero, such as 0.00001, were used to simulate zero settings. Completed sets can be viewed using a VI written for displaying the data sets. The original un-processed data set is specified as the data-set identifier, and then any processed energy vs. risetime plots can be viewed, according to the combination of each variable. Figure 6 is a screenshot of a viewer window.



**Figure 6:** The viewer program. The sweep pattern is similar to that observed with actual electronics.

The method has been successful. Basic energy vs. risetime plots have been calculated, as seen in Figure 6. The results show that differentiator time constant settings around 50 and high integrator time constant settings (125-150) improve resolution. Additionally, increasing the difference between the constant fraction of the two CFDs, as well as increasing the difference in the delay between the two CFDs gives optimal resolution.

A series of 10,000 waveforms from the oscilloscope takes about one hour to process. This is significantly slower than the electronic methods used, which process 10,000 data points in roughly five minutes. It does not, however, require any beamtime other than the initial data set recording, which

needs only about one hour of beam to capture its set of events.

This experiment has proven the viability of using software simulations to find optimal settings for electronic devices. The software simulations do not process data quickly enough to replace electronic methods, but they do serve well as tuning aids.

### V. Conclusion

The nuclear equation of state and experimental methods used to help explore it have been discussed. There are numerous pieces of evidence supporting a phase transition, including the evaporation of small nuclei which can be taken as the emission of a gas from the liquid drop nucleus, a plateau in the caloric curve and distillation of neutron-rich nuclei. It is seen that larger nuclei are more likely to follow 2<sup>nd</sup> order phase transitions and exhibit multifragmentation at lower excitation energies than smaller nuclei. Pulse shape discrimination is a method that will continue to be useful in the exploration of this transition. In conclusion, the existence of the nuclear phase transition has been well established, but specific details on it still require research. Pulse shape discrimination will allow the particle identification required by the research to be done more cost effectively than other methods.

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