STUDIES OF THE BETA DECAY OF LIGHT PROJECTILE FRAGMENTS FAR FROM STABILITY

By

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ABSTRACT

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Nuclei far from stability can be produced by the fragmentation of beams at the National Superconducting Cyclotron Laboratory at Michigan State University, and separated by the Reaction Product Mass Separator. Since these fragments maintain a significant fraction of the momentum of the beam broadened by the reaction dynamics, the beta decay of these nuclei can be observed only after they come to rest in a thick layer of material such as an active silicon detector. Here decay products such as the emitted ß particle and any ß-delayed charged particles can be detected and often their energy determined.

New techniques to study beta decay and beta delayed particle emission from projectile fragmentation have been developed. Problems such as the determination of absolute partial and total decay rates, contamination by other isotopes, background and daughter activity, fitting procedures where only a small number of events are available or where data are contaminated with other activity or background and energy calibration are discussed. Techniques for their management are presented.

The Nuclear Shell Model, with an empirical Hamiltonian based upon tabulated nuclear structure information from stable or close to stability nuclei, will benefit particularly from information of the

structure of nuclei far from stability for two reasons. At first, observables such as beta decay rates can be measured and compared to predictions. Any deviations might give insight into the limitations of the present Hamiltonians. Later as more information is gathered, a significant body of excited states will be compiled facilitating a new fit of the matrix elements of the Hamiltonian including far-from-stability configurations. It is however difficult to extract the standard quantities such as beta decay matrix elements from the data in a form comparable to the predicted values. Many levels will be unbound to nuclear decay, often to the emission of two or more particles. The distribution in phase space of all of these particles must somehow be interpreted with a reasonably simple model in order to extract beta decay matrix elements. In this thesis, a simple model is presented in order to interpret such data. This model incorporates the generalized density of states concept into the standard model of beta decay to bound levels.

To My Favorite Scientist
and my Love,
Hiroko Takayasu

ACKNOWLEDGMENTS

I was watching an episode of NOVA a while ago. Two senior scientists were reminiscing an evening which took place in the early days of radar. On that night they were graduate student and advisor, peering into space at a wavelength of a cm or so, seeing for the first time the universe calling out at 4°K. Their two faces became almost those of children as they recreated in their minds the excitement of that night.

The experience of gazing into the controls of some contraption in the middle of the night with my advisor at my side, learning something new about our universe is one which I shall not ever forget. Thank you, Jerry Nolen.

I want also to point out the miracle that my parents Eugene and Ailene Mikolas worked in nurturing ten billion base-pairs of DNA (a few picograms) into what I am today. Wow. They are responsible for putting me in college and making sure I stayed there.

Writing this thesis has been a long process. I hope that it was worth it. I therefore thank its audience Rick Harkewicz in advance, for his (hopefully) reading it.

This whole thing started when my grand-advisor Ruby Sherr was rummaging around in the p shell looking for trouble. He found it. The beta decay branching information for ^9C in Ajzenberg-Selove left a lot to the reader's imagination. He called up Jerry Nolen who told him where to put the ^9C, and there began the practice of implanting delayed

charged particle radioactivity in active Silicon detectors here at NSCL. Thanks Ruby.

I give special thanks to the members of my PhD. committee. They have been both helpful and patient. In particular, Alex Brown's tuition in Nuclear Physics gave to me a sense of purpose for this project. I hope that the techniques discussed in this thesis will ultimately repay him with lots and lots of B(GT)'s! Walter Benenson proved to be a source of guidance and support in both Physics and in the English language itself. I should also thank Jack Hetherington for simply being himself.

I want to emphasize that EVERYONE at NSCL is to be thanked for creating a warm, friendly environment in which to do research. I am always proud of this point when I describe this laboratory to others. If you have a question or need help, one only need wander down the hall and ask. Dick Blue, Ed Kashy, Dave Morrissey and Brad Sherrill have all provided essential help at some point. The NSCL Computer group deserves a standing ovation for maintaining an incredibly reliable network of computers and a damn good data aquisition environment which as far as I can tell surpasses that at any other Nuclear Physics Laboratory.

Michael Maier has been a consistent source of information and perspective. His door has always been open for questions - including those dumb 'emergency' questions. He has been an important resource for me throughout my stay here at NSCL.

Finally, I would like to thank Hiroko Takayasu for all kinds of things. If I did so, it would require another chapter. Instead, I'll just say 'Thanks Hiro!'

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The beta decay properties of nuclei provide a view on the internal structure of the nucleus predominantly by the association of decay rates with the overlaps of calculated wave-functions and known or empirical operators. The study of the decay properties of nuclei far from stability allows us to put theories of nuclear structure and decay to the test. This is because most of the information used in the construction of these theories represents properties of nuclei very close to the line of stability[1]. Often, the beta decay will populate unbound levels. In this case further study of the nuclear structure can be extracted from the nuclear decay properties following beta decay. A recent compilation of beta decay data was produced by BROWN85. While the data spans decades of research, a clear peak in the number of 'new' nuclei measured and B(GT) (see Equation 2.4) occured. The number of newly accessible nuclei has diminished as the current production and detection technologies have matured. This trend is illustrated in Figure 1.1.

The characteristics of beta decay of nuclei far from stability differ from those closer to stability in many ways. The major difference lies in the greater amount of energy released in each decay. The available phase space for the electron and neutrino behaves roughly

1. The stability line is drawn on the Z,N axis. Z and N represent proton and neutron number respectively. The nuclei which define the stability line are those with the ratio of protons to neutrons which provide the lowest energy configuration for a given number of total nucleons (Z+N).

as the fifth power of decay energy, and thus half lives become dramatically shorter for those nuclei farther from stability.

Many more excited states become energetically accessible with the increase in available energy, and the binding energy of the daughter nucleus simultaneously decreases. This is illustrated in the series of graphs in Figure 1.2. Here the beta decay energy and nucleon separation energy of the daughter are graphed for each element (Z) as a function of 'neutron richness' (N-Z).

With the availability of more isotopes for decay studies, higher production rates and improved and innovative measurement techniques, new decay phenomena and un-expected variances with theoretical models will be discovered as the study of nuclei far from stability continues. One area of particular growth will be the observation and understanding of delayed multi-particle emission. The probability of observing such processes rapidly increases farther from stability. The case of the decay of ^{19}B is illustrated in Figure 1.3, where the beta decay energies and neutron decay thresholds in Mass 19 are shown. Here, up to <u>seven</u> neutrons can be emitted following the beta decay of ^{19}B.

In other fields of nuclear physics, the breakup of light systems is studied as they are emitted from hot nuclear sources. Table 1.1 gives some examples of high energy beta decays which can provide between 1 and 2 MeV of excitation energy <u>per nucleon</u> in the daughter. The associated nuclear temperature T which one might assign to this excitation energy per nucleon from a simple Fermi gas model is given by,

$$T = \sqrt{a\, E_x/A} \quad . \qquad [1.1]$$

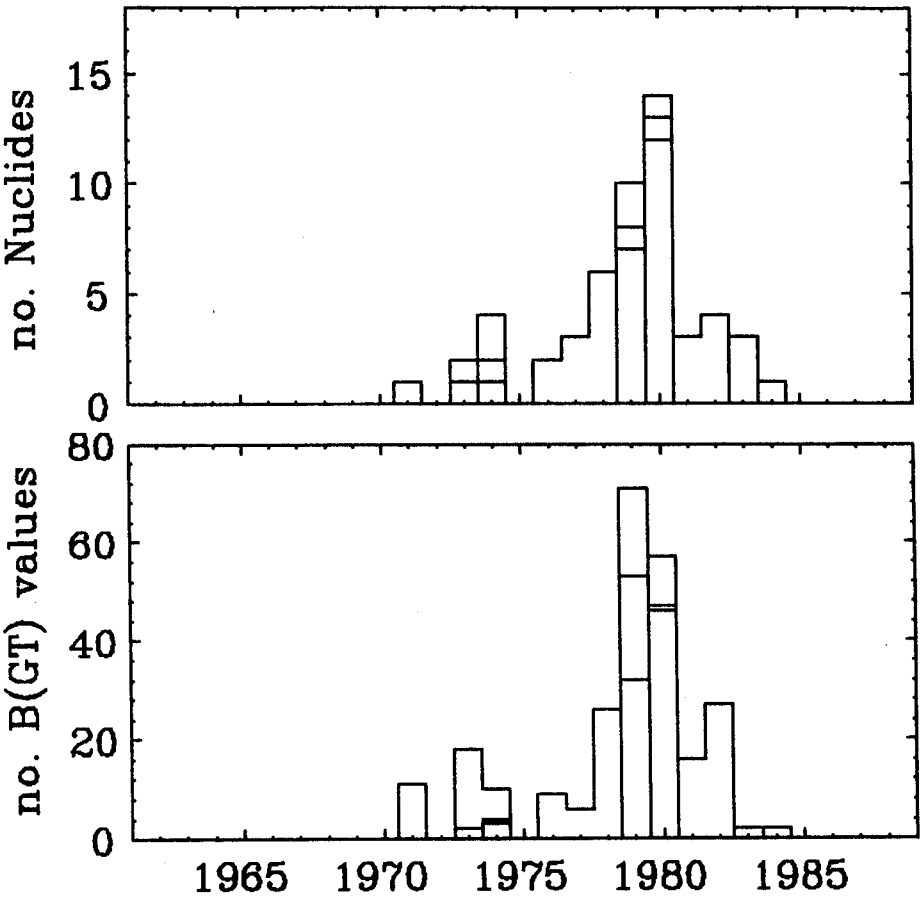


Figure 1.1 Year of publication for the data used in the compilation of BROWN85.

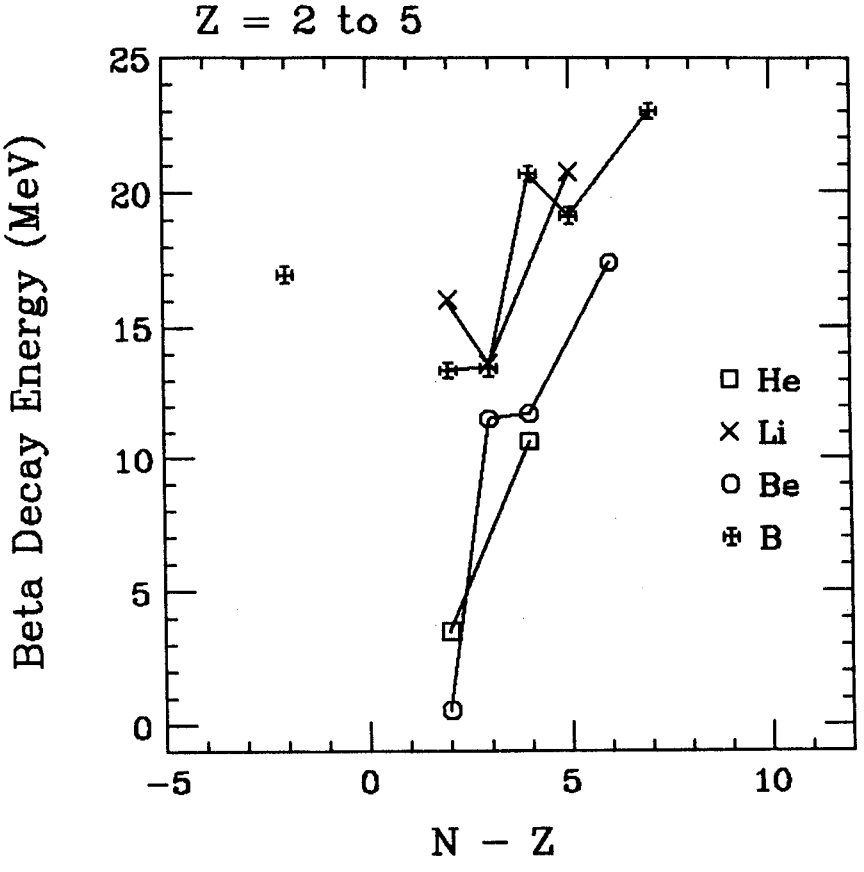


Figure 1.2 Trends in beta decay energies and nucleon decay thresholds of daughters. In both cases data are plotted for N-Z of the parent. Graphs are arranged with beta decay energies and nucleon separation energies on alternate pages so that one can look through two consecutive pages into a source of light and visualize the relationship to distance from stability.

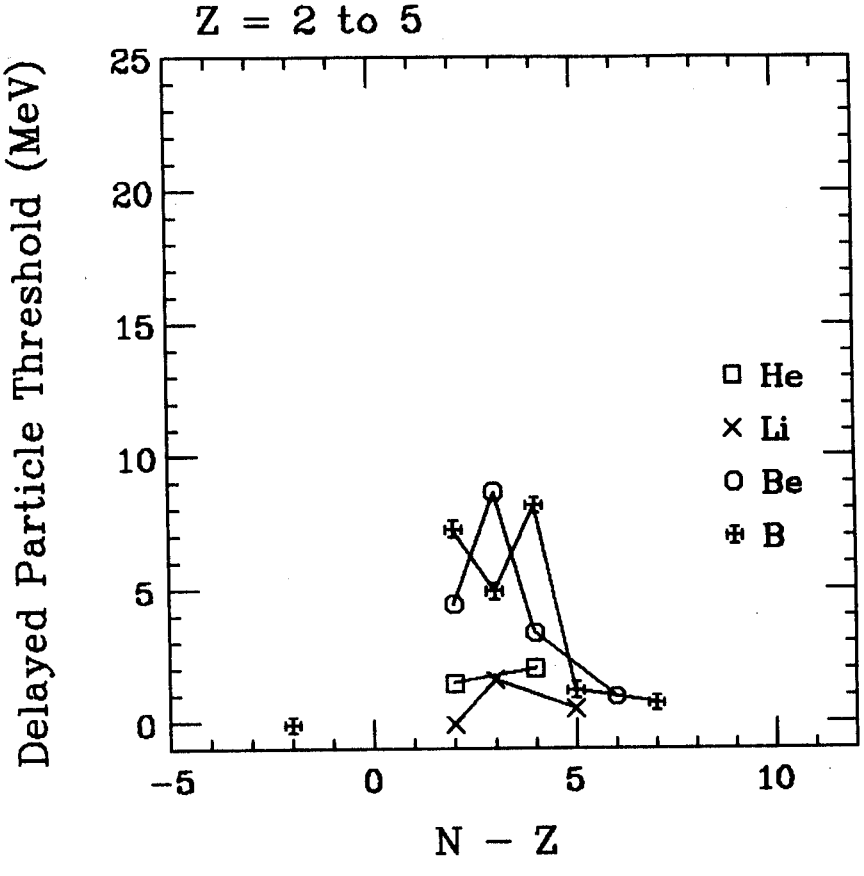
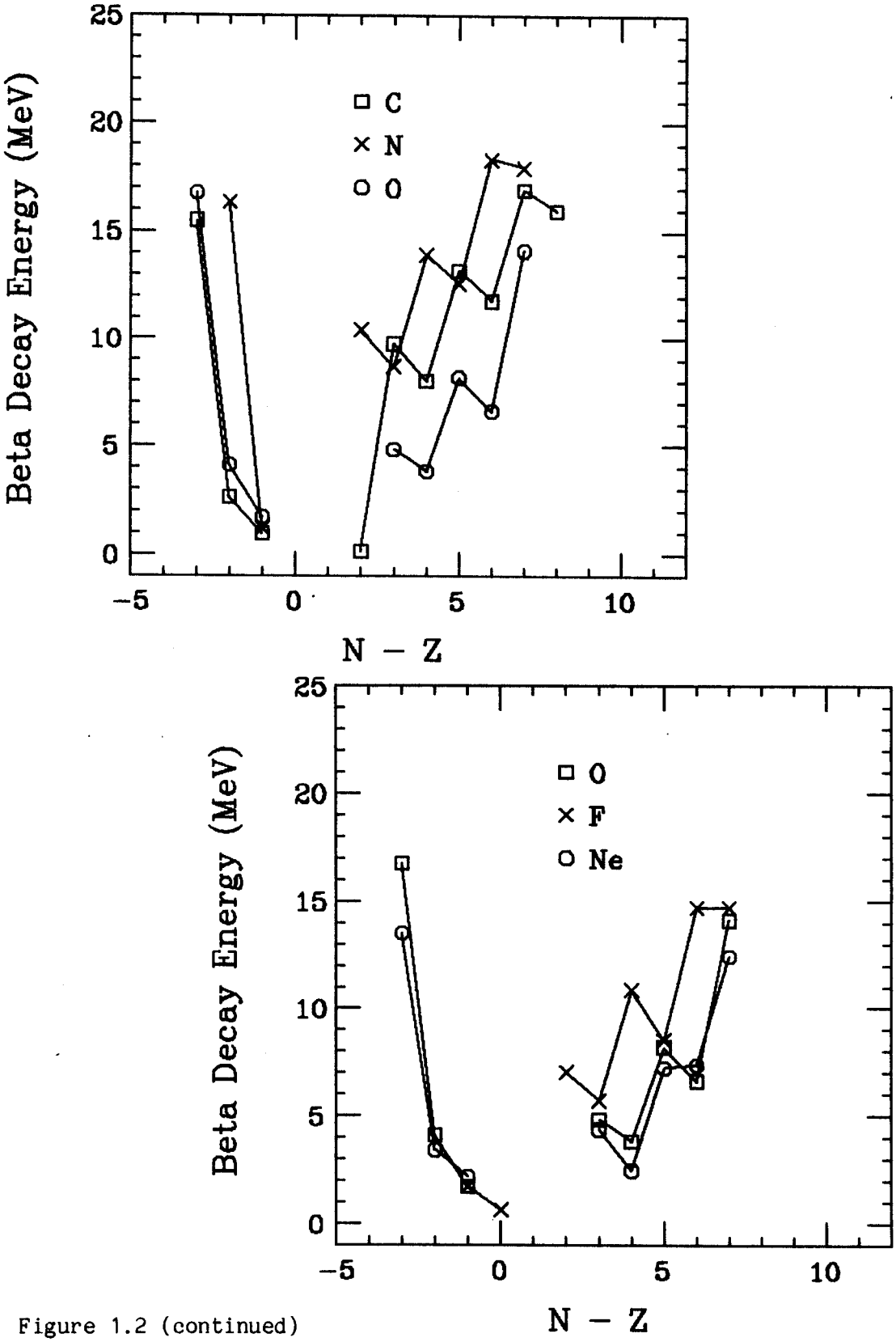


Figure 1.2 (continued)



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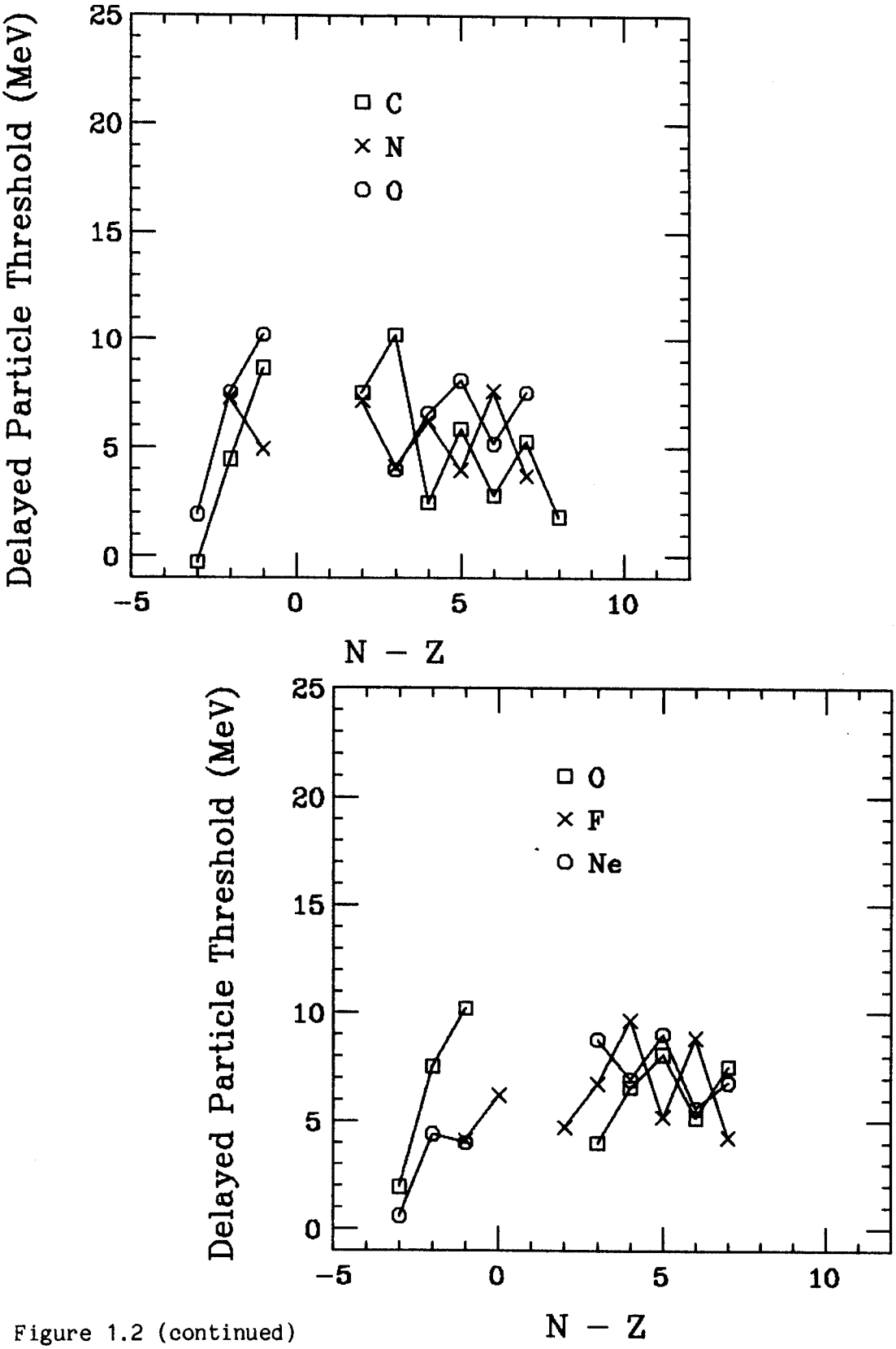

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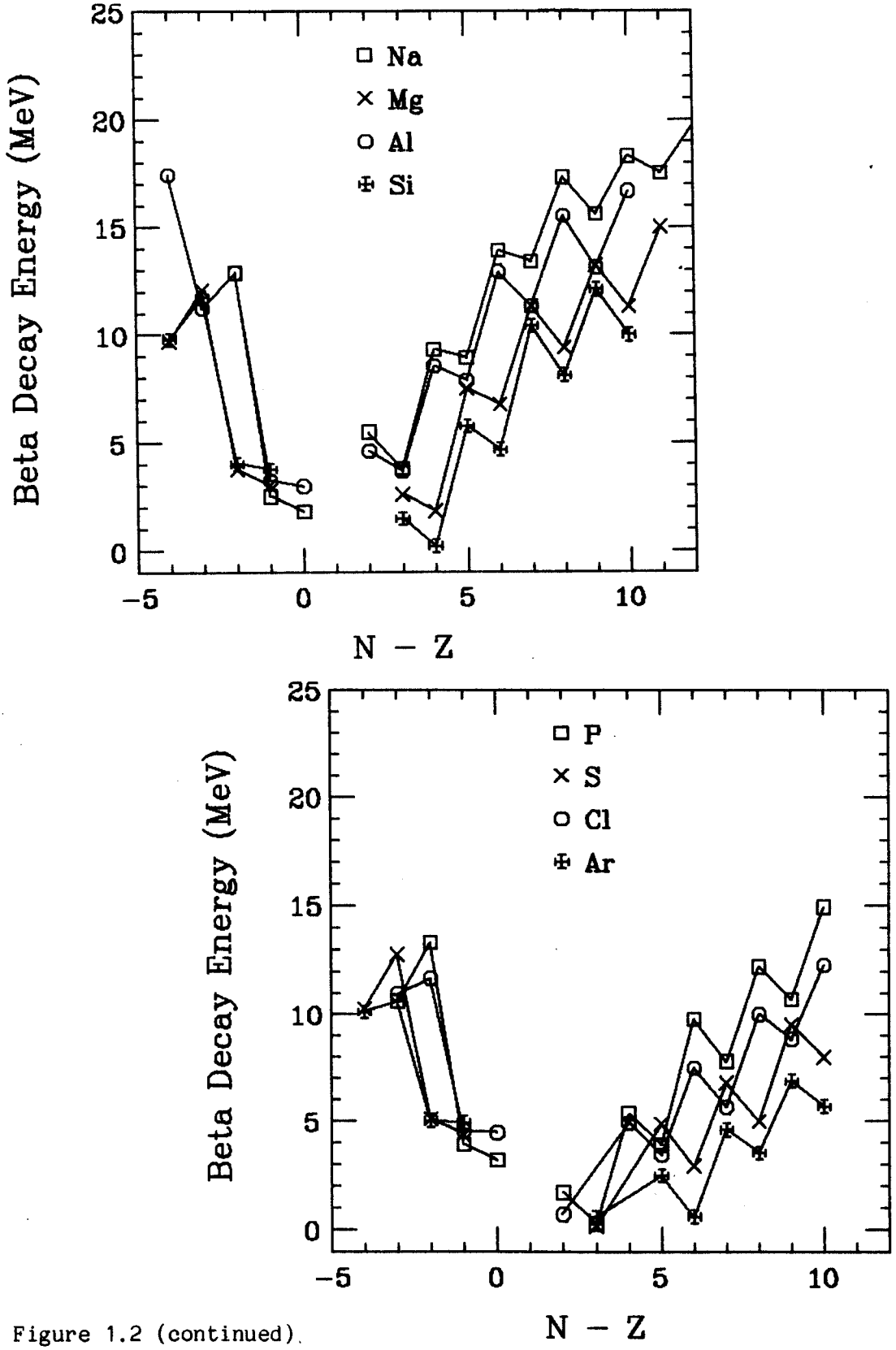

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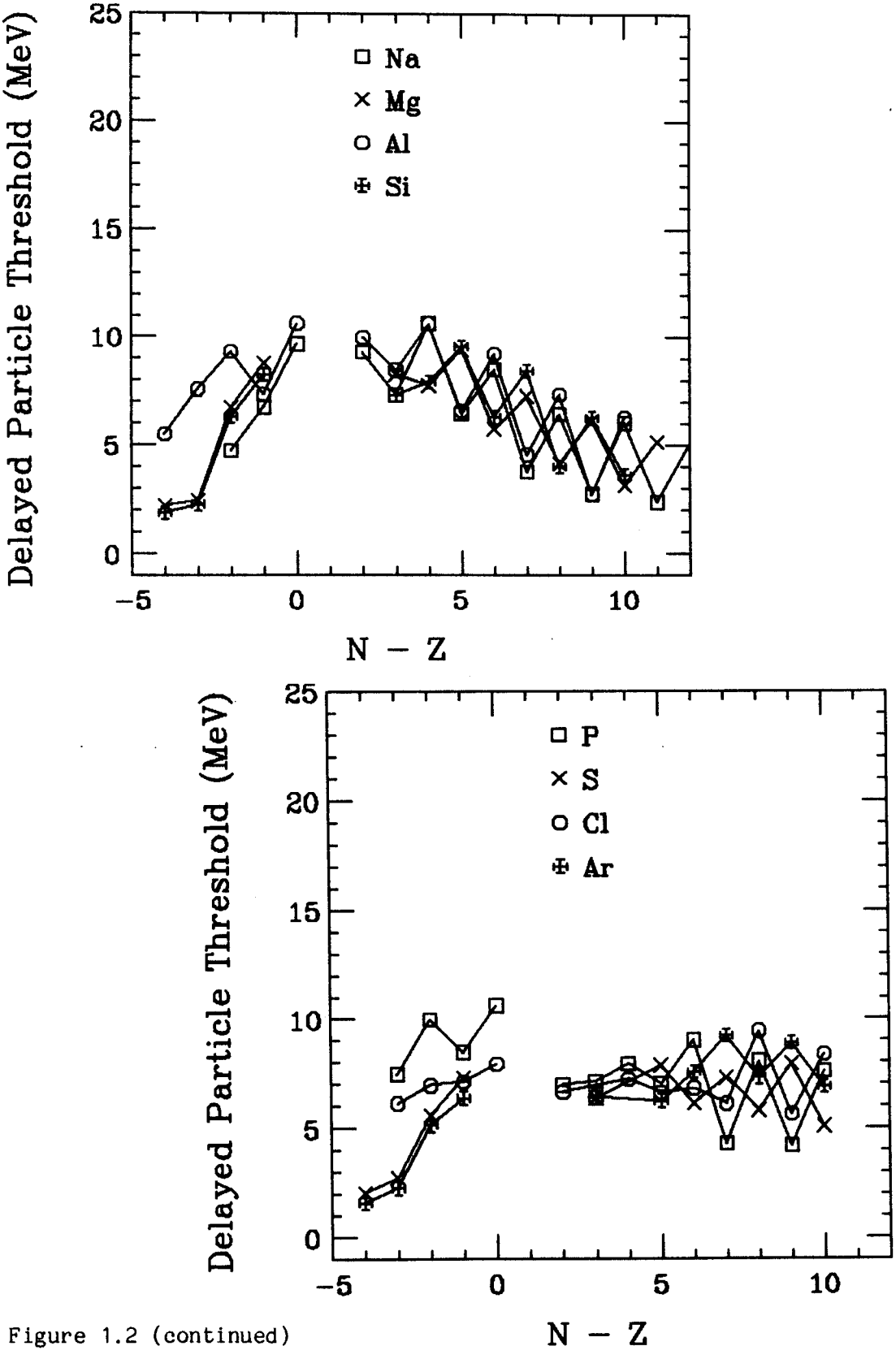

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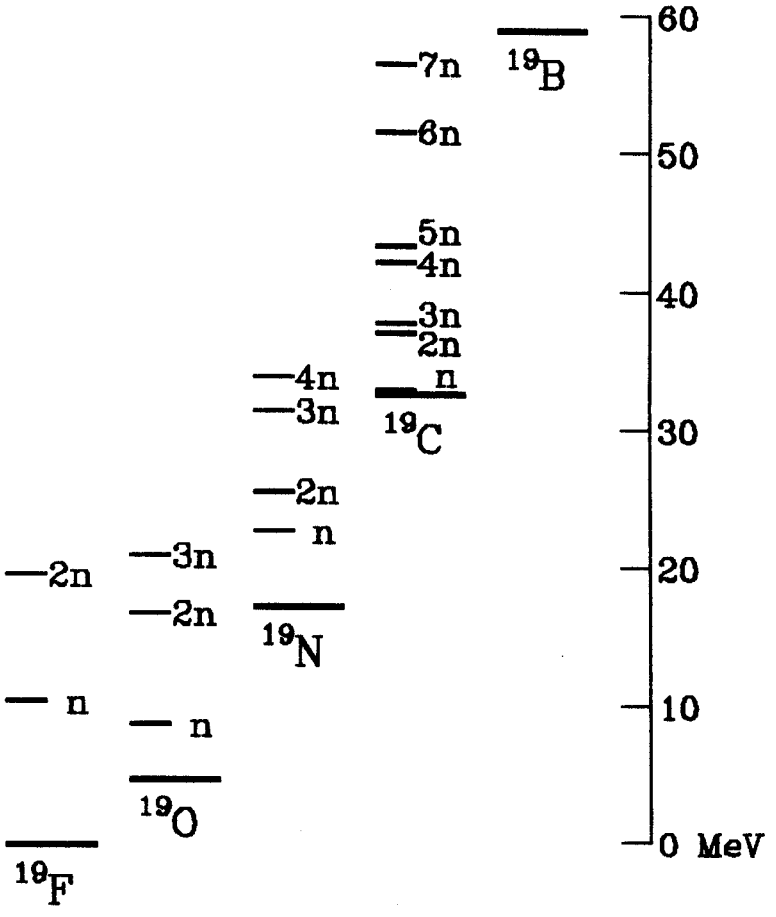

Figure 1.3 Beta decay energies and neutron decay thresholds in Mass 19.

Table 1.1 Some maximum excitation energies and inferred temperatures following beta decay.

Parent Isotope	Daughter Isotope	Maximum E_x (MeV)	Maximum Inferred Temperature (MeV)
^{8}He	^{8}Li	10.65	3.3
^{8}Li	^{8}Be	16.00	4.0
^{8}B	^{8}Be	16.96	4.1
^{9}Li	^{9}Be	13.61	3.5
^{9}C	^{9}B	15.48	3.7
^{11}Li	^{11}Be	20.73	3.9
^{11}Be	^{11}B	11.51	2.9
^{12}Be	^{12}B	11.71	2.8
^{12}B	^{12}C	13.37	3.0
^{12}N	^{12}C	16.32	3.3
^{13}O	^{13}N	16.74	3.2
^{14}Be	^{14}B	17.36	3.1
^{14}B	^{14}C	20.64	3.4
^{15}B	^{15}C	19.10	3.2
^{17}B	^{17}C	22.98	3.3
^{19}B	^{19}C	26.	3.3
^{22}Al	^{22}Mg	17.41	2.5

The level density parameter a is set to 8 MeV in this case (from NAYAK88).

A great deal of research is presently underway at NSCL and other laboratories to infer the conditions which occur in a heavy ion reaction from the break-up of light nuclei emitted from the reaction environment. The observation of the breakup of these nuclear systems in the 'clean environment' of beta decay (no nuclear spectators or contamination from other processes when beam strikes target) may improve our understanding of such processes, and may indeed yield important spectroscopic information not easily obtainable in any other way.

Some beta delayed particle decay channels will be quite complex, or compete with two or more other particle decay channels. In Figure 1.4 the beta delayed particle decay channels for ^{22}Al are shown. In Appendix B maximum beta decay energies and particle decay thresholds for all energetically accessable channels are tabulated for nuclei with protons and neutrons in the 0p and 0s1d shells.

While it will become more difficult to extract detailed structure information from delayed particle distributions as the decay process becomes more complex (more particle decay channels and greater multiplicities), the large number of isotopes which will be available for study in the future will make these types of investigations very attractive and productive. Projectile fragmentation will be a predominant source of unstable nuclei for nuclear structure studies. However the study of the decay properties of projectile fragments beyond half-life is still in it's infancy. This reaction provides it's

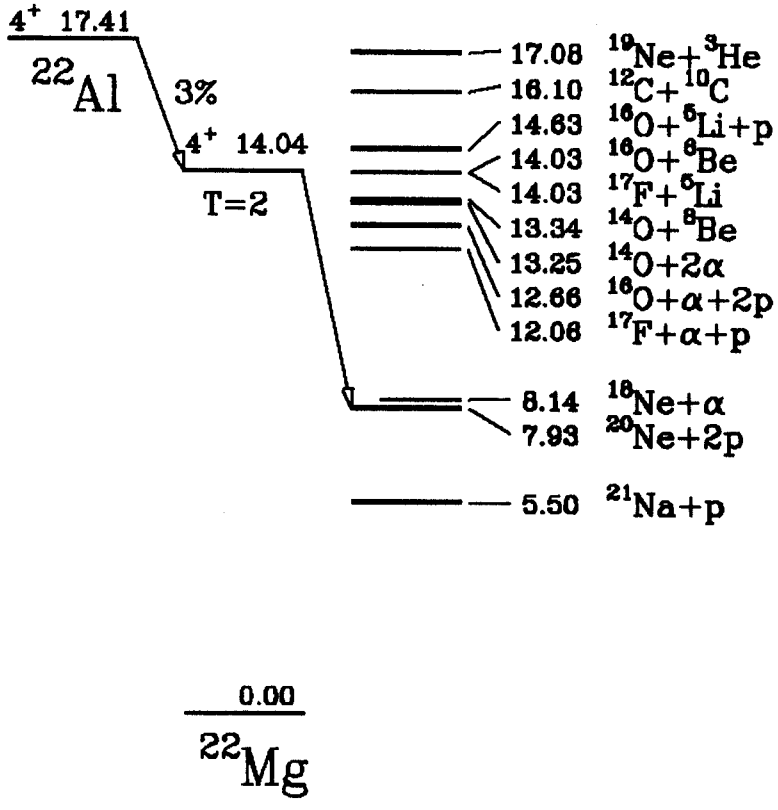

Figure 1.4 Beta delayed particle decay thresholds for ^{22}Al.

own advantages and disadvantages to the experimenter with a particular observable in mind. New techniques are presently being developed, and more will no doubt be necessary in the future to push the quantity and quality of nuclear structure information obtainable from nuclei far from stability to their limit.

This thesis is the result of a fusion between two goals. The first goal is to provide a discussion of a set of studies of the decay properties of a particular nucleus ^{9}C, which involved the development of a formalism with which to study the beta delayed multi particle final states and extract information which can be compared to shell model calculations. The second is an attempt to create a 'how to manual' for investigators interested in the study of the beta decay properties of nuclei produced by projectile fragmentation. This work is then naturally divided in two halves. The first half dealing with specific experiments, results, and comparisons to theoretical calculations. These are given in Sections II through IV. The second half is represented by the remaining sections, which contain detailed discussions of the various elements of an experiment and subsequent analysis which have been worked out over the years I have been at NSCL.

In section II, the standard formalism for connecting 'observables' such as beta decay half-life and branching ratio with 'calculables' such as nuclear wave functions, beta decay operators, and phase space factors for the beta-neutrino pair are presented. In section III, this connection is rederived for the situation where the final state is unbound. While various approximations are made, a system is developed to make preliminary interpretation of beta-delayed breakup spectra, even