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Nuclear Spectroscopic Studies of Some Short-Lived and Neutron Deficient Ga and Zn Isotopes

GREGG CARL GIESLER

ABSTRACT

NUCLEAR SPECTROSCOPIC STUDIES OF SOME SHORT-LIVED AND NEUTRON DEFICIENT Ga AND Zn ISOTOPES

By

Gregg Carl Giesler

The decay schemes of 63 Zn, 62 Zn and 63 Ga were investigated by high-resolution Y-ray spectroscopy in an effort to further elucidate their nuclear properties. Also, a search for β -delayed α emission from the light Ga isotopes was conducted.

Such γ -ray spectroscopic techniques as Ge(Li) singles, Ge(Li)-Ge(Li) megachannel coincidence, Ge(Li)-NaI(Tl) coincidence, and Ge(Li)time coincidence techniques have been utilized to study these isotopes. A He-jet thermalizer was utilized in the search for β -delayed α emission. Several programs written for data analysis are presented.

Forty-five γ rays have been assigned to the decay of 38.4minute ⁶³Zn and have been incorporated into a decay scheme containing 24 levels with energies of 0, 669.71, 962.14, 1327.0, 1412.07, 1546.8, 1860.9, 1865.7, 2012.0, 2062.3, 2081.4, 2093.5, 2336.8, 2497.5, 2512.5, 2536.2, 2697.0, 2717.2, 2780.1, 2857.8, 2889.5, 3044.0, and 3100.3 keV. A search for γ rays with energies above 700 keV from the decay of 9.3hour ⁶²Zn was conducted and six were found at energies of 881.4, 915.6, 1142.5, 1280.8, 1389.1, and 1429.9 keV. They were placed in a decay scheme containing seventeen γ -rays and ten levels with energies of 0, 40.94, 243.44, 287.98, 548.41, 637.53, 915.6, 1142.5, 1280.8, and 1429.9 keV. The decay of 32.4-second ⁶³Ga has sixteen γ rays which were placed in a decay scheme containing nine levels with energies of 0, 193.0, 248.0, 627.1, 637.0, 650.1, 1065.2, 1395.4, and 1691.7 keV.

Spin and parity assignments for the nuclear states investigated are based on log ft values, relative γ -ray intensities to states of known spin and parity and charged particle scattering results.

A survey of and comparison with previously reported Ge(Li) detector results and with charged particle scattering results is presented for these isotopes. The structures of the low-lying states in these nuclei are discussed and compared with theoretical calculations and systematics of the region.

A search for β -delayed α emission from the short-lived (<5 sec) Ga isotopes through 60 Ga was conducted. The γ -ray and α particle spectra from the nuclei produced are presented. An upper limit of ten parts per million was placed on β -delayed α branching from the decay of these nuclei.

NUCLEAR SPECTROSCOPIC STUDIES OF SOME SHORT-LIVED

AND NEUTRON DEFICIENT Ga AND Zn ISOTOPES

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Chapter I

INTRODUCTION

Any study of the nucleus involves the use of many models, since no one model fits more than a small number of nuclei. Although these models vary widely in their description of the nucleus, they are all semi-empirical, that is, require a number of experimentally determined parameters in order to make any predictions. Therefore, any improvement in quality or quantity of the experimental results will not only aid in improving the results obtained from the model, but also aid in the further development of the model and the description of nuclei as a whole.

One of the most useful methods of obtaining information about nuclear properties is γ -ray spectroscopy. With the development of Ge(Li) detectors with their present efficiency and resolution, even the very weak γ rays in a complex spectrum can be seen and easily resolved from their neighbors. As a result, decay schemes previously considered relatively simple have become much more complex. γ -ray spectroscopy, therefore, has become an important part of the study of nuclear properties.

The nuclear shell model is one of the more popular models used to describe the nucleus. The nucleus, according to this model, is like an atom with the protons and neutrons individually going around in their own orbits. In addition, closed shells occur at neutron or proton "magic" numbers of 2, 8, 20, 28, 50, 82, and 126. It is found that this model only works well near these closed shells. Accordingly,

most of the study of this model has occurred in the following regions: nuclei with fewer than 23 protons, those with 28 protons, 50 neutrons or protons, 82 neutrons, and nuclei in the region of the ²⁰⁸Pb doubly closed shell.

A primary interest is in the region with fewer than 23 protons, since in this region the β stability line lies on or near N=Z. Here also there is an abundance of doubly closed shells, and each closed shell consists of at most three low spin orbits which makes the calculations relatively easy. The stable isotopes of calcium which go from the doubly magic ⁴⁰Ca to the also doubly magic ⁴⁸Ca are found at the upper end of this region.

One more doubly magic nucleus occurs near this region, ⁵⁶Ni. It is different from the others because it is unstable to β decay and rather far from the line of β stability. The two closed shells are the $l_{7/2}$ for both protons and neutrons. In the region immediately beyond this nucleus are the $2p_{1/2}$, $2p_{3/2}$, $l_{f_5/2}$ and $l_{g_9/2}$ orbits, which, even when considering only the lowest levels populated, require a complex set of calculations. Coupled with the complexity of the calculations is the small amount of information available about the isotopes just above this doubly closed shell. The present investigation is intended to help provide information about some of the nuclei outside this doubly closed shell.

In Figure 1, the portion of the Chart of the Nuclides covering this region is shown. When Nurmia and Fink (Nu65) reported the discovery

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Mn 50 '	Mn 51 *	"Mn 52"	Mn 53	Mn 54 **	Mn 55 *	Mn 56 "	Mn 57	Mn 58			
2m 0285. 8* 8*44	45.9m	214m 263d	2 x 10"y	3130	100	2 582h	17mn #12611	1 im 8-			
145 E763	es:	143 936 M	• • • • • • • • •	a, e	54 93025	9 046 (1490) 2 113 6 37 - 2		67			

Fig. 1. Portion of the Chart of the Nuclides, including the copper-zinc-gallium region of interest in this thesis. Taken from the Chart of the Nuclides compiled by the Knolls Atomic Power Laboratory, Tenth Edition.

of 63 Ga, they mentioned the possibility of β -delayed α emission in this region. According to the calculations of Taagepera and Nurmia (Ta61), 63 Ga as well as the lighter Ga isotopes should all be β -delayed α emitters. Nurmia and Fink did not, however, report a decay scheme for the 63 Ga. This region of the neutron deficient Zn and Ga isotopes holds strong promise of providing valuable information that can be used for the application of the shell model to this region.

In Chapter II many of the techniques used in the course of this study of both the γ -ray decay and a search for β -delayed α emission in this region are discussed. Included in this chapter is the chemical separation used in the study of the decay of the Zn isotopes.

After the data are obtained, they must be analyzed to obtain the energies and relative intensities. The methods used for this analysis are described in Chapter III. Various computer programs written for or adapted for the XDS Sigma 7 computer at the Michigan State University Cyclotron Laboratory were used to sort the megachannel coincidence data, analyze the many singles spectra, and finally calculate the parameters needed for the final decay schemes.

The Ge(Li)-Ge(Li) megachannel coincidence system discussed in Chapter II has several interesting characteristics that have been studied further. These include the effects of the Compton scattering between detectors and the possibility of using the data obtained from a $\gamma-\gamma$ coincidence experiment as γ -sum coincidence data. A study of these characteristics and the results are discussed in Chapter IV.

The results of this study of the neutron deficient Ga and Zn isotopes are described in the following chapters. Several interesting

results that were obtained in the study of 63 Zn comprise Chapter V. Chapter VI describes results obtained from a study of 62 Zn in a search for γ transitions above 700 keV. The decay of 33 second 63 Ga is described in Chapter VII. Chapter VIII presents the results obtained in the search for β delayed α emission in the light Ga isotopes.

Finally, in Chapter IX, these results and their application to this region of light Zn and Ga isotopes are discussed.

CHAPTER II

EXPERIMENTAL APPARATUS AND TECHNIQUES

Each of the isotopes of Zn and Ga studied in this investigation decayed by position emission and electron capture to states in its daughter. The excited states in the daughter in general then decayed by γ emission to the ground state. To study the γ emission and thereby learn about the excited states, many different techniques, both standard ones and newly-developed ones, were utilized. Some of the excited states also have the possibility of decaying by α emission. In order to examine this possibility, some new techniques were utilized to collect the radioactive parent so that this β -delayed α emission could be more precisely studied. This chapter describes the techniques and apparatus used for the data acquisition. Section 2.1. describes the γ -ray spectrometer systems used and the techniques involved in their utilization. In Section 2.2. the α spectrometer and the He jet thermalizer used to prepare the α sources and short-lived γ sources are described. Some of the experiments performed studying the decays of 62 Zn and 63 Zn required the chemical separation of the Zn from the Cu targets. This separation is described in Section 2.3.

2.1. y-Ray Spectrometers

With the development of Ge(Li) detectors great interest developed in the examination of new decay schemes as well as many old ones. These decay schemes became more and more refined as Ge(Li) detectors with greater efficiencies and better resolution were developed. In the period of the four years involved in this study, the Ge(Li) γ -ray spectrometers used have gone from one with a resolution of \approx 5.6 keV FWHM for the 1332-keV γ of ⁶⁰Co and an efficiency of <<1% as compared to a 7.6×7.6 cm NaI(T1) detector with the source 25 cm from the detector to a Ge(Li) detector with a resolution of 2.1 keV FWHM and an efficiency of 10.4%.

The γ -ray spectrometers were not the only instruments to improve greatly over these few years. Many improvements have been added to the amplifiers used with these systems, including such developments as adjustable base-line restoration and pole-zero cancellation. Last but not least, the multichannel analyzers (MCA) have also shown vast improvements in going from a hardwired MCA with 1024 channels and a digitizing rate of 4 MHz to computer interfaced analog-to-digital converters (ADC) with 8192 channels and a digitizing rate of 50 MHz. The preamplifiers improved from room temperature FET's mounted in external units to ones with cooled FET's mounted along with the detector (with a corresponding decrease in noise).

2.1.1. Ge(Li) Singles Spectrometers

A typical γ -ray singles spectrometer system used in this study consisted of a Ge(Li) detector and its bias supply, a charge sensitive FET preamp, a spectroscopy amplifier, an ADC, and some type of memory

storage unit plus its associated readout. Almost all of the electronics equipment are in modular form and are mutually compatible so that equipment from various manufacturers may be used together for a particular experiment.

A variety of different Ge(Li) detectors were used for the experiments in this study. In Table 1 some of the detectors used are listed along with their characteristics. Since each detector is different, the choice of which detector to use for a particular experiment depended on several considerations. Some of them are the relative experimental importance of resolution to efficiency, the count rate involved, and, of course, whether the desired detector is in use for another experiment running concurrently. Another important consideration is whether we possessed the desired detector at the time of the experiment, since the detectors represent the improvements in the stateof-the-art over a period of several years.

The spectroscopy amplifiers which were used contain several features to improve the resolution, especially at higher count rates. Both unipolar and bipolar output pulses shaped with various time constants ranging from 0.25 µsec to 4 µsec can be obtained with various maximum amplitudes of either polarity for use as an input to an ADC or for timing purposes. These amplifiers have highly linear amplification responses and include such features as adjustable pole-zero cancellation, base-line restoration, and DC offset.

The use of pole-zero cancellation permits precise elimination of undershoot on the amplifier pulse after first differentation. This becomes important at higher count rates because succeeding pulses

Manufacturer	Shape	Efficiency ^a	Resolution ^b	Peak to Compton Ratio	Preamp FET
MSU Cyclotron Lab.	Trapezoidal	0.42%	5.6 keV	4.5 to 1	room temperature
Nuc lear Díodes	Trapezoidal	2.0%	3.4 keV	8 to 1	room temperature
Nuclear Diodes	Trapezoidal	2.5%	2.2 keV	16.5 to 1	cooled
ORTEC	True Coaxial	3.6%	2.0 keV	22 to 1	room temperature
ORTEC	True Coaxial	4.6%	1.9 keV	24 to 1	room temperature
Nuclear Diodes	True Coaxial	10.4%	2.1 keV	38 to 1	cooled

Table 1. Ge(Li) Detector Characteristics

^aWith respect to the 1332 keV peak of 60 Co at 25 cm from a 7.6×7.6-cm NaI(T1) detector.

 $^{b}FWHM$ for the 1332 keV peak of $^{\rm ô\, 2}Co.$

may fall into the undershoot and will have an apparent area smaller than the actual area, thus causing a loss in resolution. Base-line restoration also improves resolution at higher count rates by restoring the undershoot of the amplifier signals to a DC base-line after all other shaping has been performed. This improves the resolution by reducing the pileup distortion that is produced when one pulse occurs in the undershoot of another. The DC level adjustment matches the DC level of the amplifier unipolar output to the DC level of the direct input to the ADC. This input bypasses the ADC internal base-line restorer, amplifier, and pulse amplitude discriminator stages, thus lessening the distortion of the input pulse. Also eliminated is the fixed delay (1.25 μ sec) added to each pulse to allow time for the discriminators to operate. Eliminating this delay allows a higher count rate for the same ADC dead time.

In this laboratory a variety of analyzers has been used for data acquisition and represents the change in the state-of-the-art over several years. Some of their characteristics are listed in Table 2. With the interfacing of ADC's to a computer, many different modes of data acquisition not available in hardwired analyzers became available. Some of these new modes were used in this study and are discussed in later sections.

2.1.2. Coincidence Spectrometers

Singles experiments are useful in determining the energies and intensities of γ rays from the decay of a nucleus but tell nothing of their placements in the decay scheme. To aid in the placement of these γ transitions, various coincidence experiments were performed.

ADC	Max of	Maximum Number of Channels		izing Rate	Memory
Nuclear Data 160		1024	4	MHz	Hard wired
Nuclear Data 2200		4096	16	MHz	Hard wired
Northern Scientific	e 625 dual	4096	40	MIZ	Interfaced to DEC PDP-9
Northern Scientific 629	quadruple	8192	50	MHz	Interfaced to XDS Sigma-7

Table 2. Characteristics of Some ADC's

These include anti-(revealing direct ground state transitions), prompt-(revealing cascade transitions), delayed- (revealing transitions in cascade with states having a measureable lifetime), and 511-511- γ (revealing double escape peaks and β^+ -fed levels) coincidence experiments. Descriptions of these techniques are given in the following sections.

2.1.2.A. Ge(Li)-NaI(T1) Split Annulus Spectrometer

One of the most useful spectrometers at MSU is the 20.3×20.3 cm NaI(T1) split annulus. Several of its uses in conjunction with a Ge(Li) detector are described by Auble et al. (Au67). In the present study it was used as an anticoincidence spectrometer and a 511-511- γ coincidence spectrometer. Figure 2 gives a block diagram of the electronics used for these experiments.

For the anticoincidence experiment, a 7.6×7.6 cm NaI(T1) detector was placed inside one end of the annulus tunnel to increase the solid angle subtended by the annulus. A Ge(Li) detector was placed inside the other end of the annulus with the sample between these two detectors, approximately in the center of the annulus. The timing signals from the three NaI(T1) detectors were combined in an AND/OR gate to produce a timing signal whenever a signal was produced by any of the three NaI(T1) detectors. An ORTEC universal coincidence unit with the coincidence requirement set to 1 was used for the AND/OR gate. The resolving time control on this unit therefore had no effect. The timing signal from this unit was then required to be in coincidence, within a 110-nsec resolving time, with the timing signal from the Ge(Li)



on the 511-keV region and the linear gate is in normal mode. For an anticoincidence Experimental setup for recording anti- and 511-511- γ coincidence spectra. For a 511-511- γ coincidence spectrum the TSCA's are adjusted such that the window falls spectrum the TSCA's are wide open and the linear gate is in the "anti" mode. . 7

detector. The output from the fast coincidence was used to trigger a linear gate operated in anticoincidence mode.

The 511-511-γ coincidence experiments required the two halves of the annulus to be operated independently with the 7.6×7.6 cm NaI(T1) detector but with its associated electronics removed from the setup. The TSCA for each annulus half was set to gate on the 511-keV region. A triple coincidence among the annulus halves and the Ge(Li) timing signals was then required. As a result the AND/OR gate was bypassed. These along with operating the linear gate in "normal" mode are the only differences between the two coincidence systems.

2.1.2.B. Ge(Li)-Ge(Li) Megachannel Spectrometer

 $\gamma-\gamma$ coincidence spectroscopy was first developed in the early 1950's. The coincidence experiment was performed by placing a window on the output of one detector and using this signal to gate the output of the other detector. The result was a one-dimensional spectrum showing everything in coincidence with this window. However, because of the poor resolution of NaI(T1) detectors, this window was rather wide and allowed coincidences with a wide region of Compton background and with peaks very close to the central peak. As a result it was possible to enhance peaks not in coincidence with the peak of interest.

With the advent of Ge(Li) detectors and their low efficiencies, a NaI(T1) detector was retained more often than not as the gate detector in a coincidence system. Although the resolution in the resulting onedimensional spectrum improved, the gate width was still much wider than a photopeak. As Ge(Li) detectors grew in efficiency and improved

in resolution, the use of two Ge(Li) detectors for a coincidence experiment became more feasible. Because of the better peak to Compton ratio, narrower photopeaks, etc., good coincidence data can be obtained with fewer counts per channel with Ge(Li) detectors than necessary with NaI(Tl) detectors! However, using one Ge(Li) detector to gate the other detector still produces only a one dimensional spectrum and requires many experiments to gate on all the peaks of interest. This problem of performing many experiments to obtain a complete set of coincidence spectra can be solved by storing the addresses produced by the ADC's in a list rather than using one to gate the other. This list of stored addresses is later digitally sorted to produce the desired coincidence spectra. With this system only one "mega" two-dimensional coincidence experiment is necessary to obtain the data that formerly took many simple two-dimensional coincidence experiments to obtain.

A system of this type with the code name EVENT was developed by D. Bayer (Ba71) at the MSU Cyclotron Laboratory. Figure 3 shows a block diagram of this system. An absorber was placed between the detectors to reduce the Compton scattering from one detector to the other. A further explanation of this problem is given in Section 4.1. The timing system and linear gates were used to allow only coincident signals from the linear amplifiers to be input to the ADC's. This is necessary since the resolving time of the ADC's is much greater than that of the fast coincidence circuit. The ADC's are operated in synchronous mode so that both would be controlled as one unit rather than as two separate ADC's. They are read through the interface to the XDS Sigma-7 by the task EVENT which runs under the JANUS (Ja69) time sharing monitor system. The



Fig. 3. Block diagram of the megachannel two-dimensional $\gamma-\gamma$ coincidence system.

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addresses are stored in two halves of a 32-bit computer word, each address in the least significant 13 bits of the half word. As a result, the 3 most significant bits may be used for routing, ADC designation, or some similar purpose. These computer words, each containing a coincidence event, were stored in a 240-word buffer, which when full was written onto magnetic tape while further events were stored in another similar buffer. The tape movement speed of the tape transport limits the system to \approx 2000 events per second, although a typical coincidence rate is \approx 20 events per second. A 2400-foot, 9-track magnetic tape will hold approximately 1.8 million events written in 60-word records. Recovery of the data written on magnetic tape was performed off-line by the program EVENT RECOVERY, which is described in Section 3.1.

This system allows an *n*-dimension coincidence experiment with a maximum of 8192 channels per dimension to be performed, since task EVENT is limited only by the number of ADC's available. Currently, four NS-629 ADC's are interfaced to the Sigma 7, thereby limiting the number of dimensions to four. These four ADC's need not necessarily be operated together but can also be operated as two independent two-dimensional coincidence experiments or any combination of single and multiparameter experiments at the same time (dependent only on ADC availability).

2.1.2.C. Ge(Li) - Time Spectrometer

For short-lived isotopes the determination of which γ rays decay with the same half-life becomes difficult. The method of taking many successive spectra during the decay of one or a few samples grows rapidly out of hand for short (less than a few minutes) half-lives because of the poor statistics of each spectrum. The result is a mountain of data which

must be added together to obtain statistically meaningful results.

To solve this problem a modification of a two-dimensional coincidence system was used. A block diagram of the system which is operated by the task TOOTSIE under the JANUS monitor system is shown in Figure 4. One side of the coincidence system is a Ge(Li) spectrometer, while the other side is a gated sawtooth ramp that was obtained from one of two different sources. Initially, SAWTOOTH A of a Textronics oscilloscope was used with its amplitude reduced by a potentiometer. However, the linearity of this source was poor, so it was replaced by an operational amplifier used as an integrator. In both cases, the slope of the ramp was set to reach the maximum ADC input voltage after several half-lives. The slowly rising DC level was converted to a pulse acceptable to the ADC by using an ORTEC linear gate stretcher operated in DC input mode. The output was gated by a TSCA such that both the time pulse and the linear signal were in coincidence. The time scales available from the operational amplifier range from $<<10^{-1}$ sec to $>>10^{4}$ sec.

The task TOOTSIE, written by D. Bayer of the MSU Cyclotron Laboratory and described elsewhere (Ba71), has two operational modes: Setup and Run. In Setup mode the task functions as a two-dimensional analyzer of maximum size 128×128 channels using the seven most significant bits of the ADC's. Bands can be drawn on this two-dimensional array, each band corresponding to a spectrum in Run mode. The maximum number of bands depends on the size of the spectra. For example, if a spectrum size of 4096 channels is chosen, five bands are the maximum number allowed. Once the bands are drawn the task can be changed to Run mode, in which each band becomes a spectrum of the designated size and the data are then taken as n one-dimensional spectra.


Fig. 4. Block diagram of the $\gamma\text{-time}$ coincidence system.

Figure 5 shows the display produced by TOOTSIE operated in Setup mode. The display is a horizontal slice parallel to the energytime plane, displaying all the locations having counts between the limits specified in the upper left corner. The vertical axis is the time axis and the horizontal axis is the energy axis. The numbers next to the arrows along the axis give the location of the arrows. These arrows are used to locate channel numbers and to define limits for expanding the display.

This display was produced by counting a 60 Co source. The solid area on the left portion of the area is the Compton tail with the two lines on the right being the two photopeaks. Discriminator cutoff in the linear gates and ADC's produces the dark areas along the left and lower sides of the display. The horizontal lines represent the lower and upper limits of five bands. The same line may be used as an upper limit of one band and the lower limit of the next band, since each band is defined as the region from the lower limit inclusive up to but not including the upper limit. These bands do not need to be of equal size and the limits can also be curves of any order polynomial up to 10. By using many bands of small size the half-life of the sample can be accurately measured, or by using a few bands of large size the determination of the parent isotope of each γ ray can be made. Operational control of the task and its display is performed by use of both sense switches and teletype input.

In Figure 6 the display of TOOTSIE in *Run* mode is shown. The upper spectrum is the first band and the lower spectrum is the fifth band of the decay of 63 Ga. Each spectrum represents a band of about 20 seconds time and has been expanded to show the region from \approx 550 keV to



Fig. 5. Display produced by TOOTSIE in Setup mode.



Fig. 6. Display produced by TOOTSIE in Run mode.

 \approx 1000 keV. The numbers next to the arrows at each end of a spectrum are the limits of the expanded region. The number of counts in the highest channel of each spectrum is shown in the upper left corner of the spectrum. Below it is the number of the band, the bands being numbered from 0 to n-1, even though the limits in the *Setup* mode are numbered 1 to 2n. The numbers in the upper left corner are the same as those in *Setup* mode.

2.1.3. Ge(Li) Detector Efficiency Curves

The photopeak efficiencies of Ge(Li) detectors are not constant with energy but generally decrease with increasing γ -ray energy. The exact behavior of this decrease is dependent on many factors such as the total active volume of the crystal, the ratio of depth to width of the active region, and the source to detector distance. Therefore, in order to obtain the relative intensities of the γ -rays emitted from a source, a photopeak efficiency curve for the particular detector and geometry used must be available.

Efficiency curves for the detectors used in the present study were determined by using a set of γ -ray sources, each of which emitted two or more γ -rays whose relative intensities are well known. These sources were chosen to provide data points over the widest energy range possible, and yet, having each source overlapping, at least at one point, with another. This allows the efficiency curves to be bootstrapped to higher and lower energies. A list of the γ -ray relative intensity standards used to obtain the efficiency curves is given in Table 3.

Previous to this work on the efficiency curves, the data were fit to a straight line on a log-log scale. However, systematic deviations

Isotope (Ref.)	Photon Energy (keV)	Relative Intensity	Isotope (Ref.)	Photon Energy (keV)	Relative Intensity	Isotope (Ref.)	Photon Energy (keV)	Relative Intensity
^{110^mAg}	446.78	3.5	56 Co	846.78	100.	¹⁸² Ta	65.72	30.0
(c)	620.24	2.7	(b)	1037.83	14.0	(a)	67.75	430.
	657.72	100.		1175.13	2.28		84.67	21.8
	677.56	11.5		1238.28	67.6		100.10	119.
	686.83	7.1		1360.22	4.33		113.66	17.7
	706.66	17.2		1771.49	15.7		116.40	4.30
	744.20	4.7		2015.36	3.08		152.44	71.0
	763.88	23 .9		2034.92	7.89		156.39	27.2
	818.01	7.7		2598.58	16.9		179.39	31.7
	884.66	78.0		3010.20	1.00		198.30	15.3
	937.47	36.3		3202.30	3.04		222.11	79.8
	1384.22	27.6		3253.60	7.41		229.26	38.0
	1475.74	4.6		3273.25	1.75		264.07	37.6
	1504.91	14./		3451.55	0.875		927.70	8.00
	1562.23	1.34		3548.05	0.180		959.11	4.40
14010	100 60	0.22	192 -	126 25	0.15		1112 10	24.3
	109.00	0.22	(a)	130.33	0.15		1113.10	4.10
(a)	241 91	0.455	(a)	201.20	3 30		1157 41	11 0
	241.71	0.555		205.01	29.2		1188 95	171
	328.75	21.6		308.44	30.6		1221.31	289.
	432.54	2.95		316.49	85.8		1230.93	121.
	487.03	46.5		374.40	7.70		1257.34	16.0
	510.95	0.350		416.40	6.90		1273.67	6.90
	751.66	4.50		468.05	50.5		1289.07	14.7
	815.80	24.0		484.55	3.30		1342.60	2.80
	867.87	5.70		489.10	0.510		1373.80	2.40
	919.60	2.50		588.56	4.60		1387.20	0.810
	9 25 . 25	6.70		604.40	8.90		1410.00	0.470
	951.02	0.600		612.44	5.48		1453.00	0.330
	1085.30	1.05		884.50	0.170			
	1596.20	96.5	2.0.1			^{1.3.3} Ba	53.17	1.95
	2010.40	0.430	²⁰ ³ Hg	72	11.9	(a)	79.59	3.04
	2348.20	0.820	(e)	82	3.44		81.01	36.0
	2521.83	3.25		279.2	100.		160.62	0./60
	2547.70	0.090	207		00.0		2/6.29	/.50
24	1000 50	100	~~'B1	569.62	98.0		302./1	19.0
~ 'Na	1308.53	100.	(a)	1003.05	//.0		322.00	0/.0
(a)	2/34.14	100.		1//0.18	0.4		202.10	9.40

Table 3. y-Ray Relative Intensity Standards

(a) Gu69		(b) Ca71		(c) Ha69	.69 (d) Be69a		(e) Le66	
(a)	1332.51	100.	(a)	1836.13	100.			
ьоСо	1173.23	100.	88Y	898.02	92.0			
<u> </u>			0.0				1312.17	40.0
(a)	136.46	8.40	(a)	1120.50	100.	·	1271.90	103.
⁵⁷ Co	122.05	85.3	⁴⁶ Sc	889.30	100.		1251.30	1.70
							1199.92	33.0
	466.0	20.		1407.92	243.		1177.98	206.
	418.5	172.		1299.20	19.0		1115.16	21.6
	413.6	135.		1212.90	17.0		1002.90	16.3
	378.5	240.		1112.05	164.		966.17	344.
	327.7	152.		1085.80	100.		962.46	140.
	281.8	118.		964.00	173.		879.31	400.
	228.4	310.		867.42	51.0		765.20	17.0
	208.3	512.		778.85	152.		392.43	19.0
	204.1	117.		688,80	91.0		337.30	5.40
	153.3	144.		443.89	33.0		309.49	11.0
	128.5	131.		411.05	25.3		298.54	350.
	113.0	184.		344.27	314.		215.62	50.0
(d)	105.3	100.	(a)	244.70	72.0	(a)	197.04	65.0
^{177^m} Lu	71.7	7.2	¹⁵² Eu	121.78	332.	¹⁶⁰ Tb	86.79	209.

Table 3. - Continued

of the data from a straight line suggested a third order fit of the form,

log (efficiency) = $A + B \log E + C (\log E)^2 + D (\log E)^3$,

where A, B, C, and D are empirical constants and E is the energy in keV. (Gi69) A computer program was written for fitting the data to this equation. Actually, the data are divided into two overlapping sections, one with energies above \approx 400 keV and one with energies below \approx 400 keV. A curve for each section is obtained by calculating the curve for one isotope, then for a second isotope, normalizing the two curves for the best overall fit, and finally repeating for as many isotopes as used. The curves for the two sections are then normalized at 400 keV. The final curves are good to about 3% for energies greater than 400 keV, about 5% for 100 keV to 400 keV, and about 20% below 100 keV. The increasing error results from the fewer points available, the rapid drop in efficiency, and the increasing complexity of the function at lower energies.

The efficiency curve for our 10.4% Ge(Li) detector for a source at 10 inches is shown in Figure 7. This curve is for the detector without any absorbers. The shape of the curve can be changed, enhancing a particular energy region, by a judicious choice of absorbers. This is further described in Section 6.1.

2.2. β -Delayed α -Emission Spectrometer

In order to examine the possible β -delayed α emission of the Ga isotopes, a different system of sample preparation and counting was required. Because of the short range of α particles, the sample needed to be counted in a vacuum and preferably from a massless target. Also the short half-lives of the isotopes studied precluded any manual handling



with the sources placed 10 inches in front of the detector.

of the samples. The He-jet thermalizer was utilized to transport the activated nuclei from the vicinity of activation to another location in vacuum. This eliminated the possibility of any prompt α 's from the target being counted as well as produced a "massless" source for α particle counting. Any α particles were then counted using Si(Li) surface barrier detectors.

2.2.1. *a*-Particle Spectrometer

The α -particle used in this study consisted of a Si(Li) surface barrier detector and its bias supply, a charge sensitive FET preamplifier, a spectroscopy amplifier, an ADC, and some type of memory storage unit plus its associated readout. The Si(Li) barrier detectors used for the experiments were obtained from ORTEC. They had an active area of about 25 mm² and a sensitive thickness of about 100 microns. Their resolution for the 5.545-MeV α particles of ²⁴¹Am was about 16 keV. For these experiments the detectors were used with ORTEC model 125 preamplifiers. The rest of the spectrometer system utilized the same equipment as the γ -ray spectrometers described in Section 2.1.1.

2.2.2. He-Jet Thermalizer

In order to determine the existence of β -delayed α emission, a system was needed to transport the activated nuclei quickly into a vacuum chamber in a suitable form to count the α particles. This becomes rather difficult, since the half-lives of the nuclei under investigation were expected to be on the order of 1 second or less. A He-jet thermalizer built by K. Kosanke (Ko70) at the MSU Cyclotron Laboratory was utilized for this purpose. The system thermalizes the

recoils produced by the interactions of the cyclotron beam with the target in $^{2}1-2$ atmospheres pressure of He. These recoils are collected with the He into a polyethylene capillary and transported at sonic velocities to the counting chamber. In the counting chamber, which is at $^{2}10^{-2}$ torr pressure, the He flow exiting the capillary diverges much more rapidly than the heavier recoils, thus allowing them to be collected on a surface placed near the exit of the capillary. This produces a "massless" source for counting with an α detector.

Figure 8 shows a view of the thermalizer box. The cyclotron beam enters from the left and passes through a water cooled collimator. Mounted to the rear of the collimator are several teflon blocks containing an $\approx 1" \phi$ hole. The target foil is placed between the collimator and the first teflon block and if more targets are used, they are placed between the teflon blocks. The recoils are collected by He entering the rear of the teflon blocks and being drawn past the targets into the capillary which is placed in the first teflon block. The beam is stopped in the water-cooled Faraday cup to the right of the collection assembly, while the capillary exits through the rear of the box.

The recoil counting chamber is shown in Figure 9. The capillary enters the chamber through a port in lower right side of the figure. A Si(Li) surface barrier detector is in the cooled mounting and is connected to the coaxial cable connected to one of the feedthroughs in the upper right. A collector is placed between the detector and the port facing it. The port may be fitted with a thin plate so that the sample may be counted simultaneously with a Ge(Li) γ -ray



Fig. 8. Recoil thermalizer showing target holder-collector and Faraday cup.



Fig. 9. Recoil counting chamber showing capillary and detector in cooled mount.

detector. The chamber is evacuated through the pipe located in the lower right corner.

2.3. Cu-Zn Chemical Separation

Some of the experiments using Cu targets required a chemical separation to insure that only the Zn isotopes produced and their daughters were present. Because of the 38.4-min half-life of ^{6.3}Zn, long involved procedures could not be used. The method utilized was found to be somewhat rapid, very simple, and efficient as compared to other methods.

A 1"×1"×0.01" target was dissolved in a solution containing 5 ml 30% H₂O₂, 10 ml 6N HCl, and 1 meq Zn⁺⁺ carrier. The solution was evaporated to dryness and the residue taken up in a minimum volume of 2N HCl. This solution was then eluted through a column of Dowex 1×8 50-100 mesh anion-exchange resin that had been previously washed with 2N HCl. Following this eluent, the column was washed with 2N HCl until no trace of Cu could be observed. The resin was removed from the column, dried, and mounted for counting.

Chapter III

DATA ANALYSIS

Data analysis played a very important part in the development of the final decay schemes. Several programs have been used at MSU for the analysis of γ -ray singles and coincidence spectra. One program was used to sort through the data tapes from a megachannel coincidence experiment to produce several types of coincidence results. Some of the other programs were used to determine the energies and relative areas of the photopeaks observed. These results were then used by another program to determine the relative intensities of the γ -ray transitions. Finally, these results were used in the computation of the necessary values used in a decay scheme. Section 3.1. describes the program EVENT RECOVERY, which is utilized to sort through the multimillion coincidence events to obtain the desired coincidence spectra. The programs utilized for γ -ray energy and area determination are described in Section 3.2. In Section 3.3. the program which performed many of the decay scheme calculations is described.

3.1. EVENT RECOVERY Program

In Section 2.1.2.B. the task EVENT which was used to store the data from megachannel coincidence experiments was described. In the several years EVENT has been in use, several changes have been made in it. Some of the changes involved the three most significant bits of each data half word. Initially these bits were unused, but now they are used to designate the ADC producing the data address or to produce routing information. Also, the coincidence data may be used for γ -sum coincidence experiments as well as γ - γ coincidence experiments. Since task EVENT only stores the data, another program was therefore necessary to sort or recover the data in the desired modes. The program utilized for this sorting is called EVENT RECOVERY.

Since all the coincidence data are stored on magnetic tape without gating limitations, all the gating must be done by the recovery program. In order to perform this most efficiently, the program is a FORTRAN main routine, with most of the sorting being performed by a SYMBOL machine language subroutine. In this way, the data addresses may be stored in internal registers instead of core memory, thereby increasing greatly the rate of sorting the data. Basically, the program takes the two addresses of the coincidence event, places a digital gate on one address, and increments the location specified by the other address only if the first address falls within the digital gate.

However, in order to perform this gating, many items of information must be evaluated. For each gate to be performed, EVENT RECOVERY reads one control card, with a limit of ten control cards per pass of the data tapes. The limit results from the core size of the Sigma 7 and

the amount of swapping of core pages involved. A flow scheme of this program is shown in Figure 10. After reading the control cards for a pass of the data tapes, the program starts reading the tapes. If the end of a tape is encountered while reading, the program then determines if more data tapes are to be read. If no tapes are left to be read, the data are punched out and more control cards are read. If there are tapes left to be read, the program calls for new tape and then continues reading data when the tape is mounted. When an event is read, the sum of the two addresses is computed and stored in a register for later use. With the two addresses and the sum address stored in registers, the program now checks the parameters on each control card: which of the three axes, x, y, or sum, is to be displayed, whether there are any limitations on the sum address, and which axis if any is to be gated. If the gated axis address falls within the background limits, a weighted amount is subtracted from the display spectrum, whereas if the gated axis address fall within the peak limits, the address in the display spectrum is incremented by one count. This process is repeated for this coincidence event until all the control cards have been checked. When all the cards have been checked, the process is repeated for each succeeded coincidence event until the last tape has been read. A complete listing of this program is found in the Appendix A. A four-dimensional version of this program is being developed for experiments using more than two parameters, such as $\gamma-\gamma$ resolving time experiments.

3.2. y-Ray Energy and Intensity Determination

The centroids and areas of the photopeaks in a spectrum were found by subtracting various order interpolated backgrounds from the



Fig. 10. Flow diagram of EVENT RECOVERY program.

data. These computations were performed with the aid of two spectrum analysis routines used at the MSU Cyclotron Laboratory: MOIRAE and SAMPO.

3.2.1. MOIRAE Spectrum Analysis Routine

MOIRAE is a machine language task under the JANUS monitor that utilizes a Fairchild 737A live-display oscilloscope and sense switches to perform the spectrum analysis. MOIRAE was developed by R. Au and G. Berzens at the MSU Cyclotron Laboratory. A modified version of this task called MOD7 was developed by D. Bayer, also at the Cyclotron Laboratory. The primary difference between the two is that MOD7 utilizes a Textronics 611 storage oscilloscope for its display. The following description will be of MOIRAE but for the most part applies also to MOD7. The primary purpose of MOD7 is to alleviate the large amount of computer time used to drive the live display.

All the analysis performed by MOIRAE is controlled by instructions to the computer via interfaced sense switches arranged below the display oscilloscope as shown in Figure 11. Once the data have been read in from the card reader or transferred from a data acquisition task, the switches control the type of display, log or linear, expansion and shifting of the axes, various computational routines, and the outputs of the results. Figure 12 shows a closeup of the switches with labels for the routines they control.

A display of the \approx 1300 keV to \approx 1500 keV region of the 63 Zn spectrum is shown in Figure 13. The information across the top of the display gives the number of counts in and the channel location of the long pointer, the run number, the subroutine presently in use, and the order, up through 9th, of the background fit being used. If a log display had been used instead of this linear display, the number of cycles



Fig. 11. MOIRAE display oscilloscope and sense switches.



Fig. 12. Closeup of MOIRAE sense switches.



Fig. 13. MOIRAE oscilloscope display of a portion of the 63 Zn γ -ray spectrum with a seventh order background fit.



Fig. 14. Display of peaks after calculated seventh order background has been subtracted.

would be displayed to the left of the run number. The background displayed with the data was determined by fitting all the points between each pair of short lines (BACK 2) inclusive to a 7th order polynomial. The sense switches were used to move the tall pointer to the position of the points used for the limits of the background regions, with the short lines indicating the points that have been accepted. Instead of using several regions for the fitting of the background, a set of individual points (BACK 1) may be used.

The two tall lines indicate the points selected as the limits of the 1412-keV peak, with the short mark indicating the centroid of the peak. Either the full raw peak (PEAK 1) or the portion of the peak with counts greater than one-third the maximum (PEAK 2) may be used to calculate the centroid. In both cases the task then finds the centroid, area, sum of the raw data and background, and the square root of that sum. This information may be punched on cards, printed, and/or plotted on a Calcomp plotter. Figure 14 displays the difference between the background and the data displayed in Figure 13 in addition to the data. The points at the top of the display indicate those channels with fewer counts than the fitted background.

In order to convert the centroids and areas produced by MOIRAE into energies and relative intensities, the program MOIRAE E(I) is used. This FORTRAN program written by myself and D. Beery uses the card output from MOIRAE for its data. The centroids of several strong γ -rays in the Spectrum are used to perform a least-squares fit to a quadratic energy calibration curve. This curve is then used to calculate the energies of all the peaks in the spectrum. Using these energies and a detector

efficiency curve calculated by the method described in Section 2.4., the relative area for each peak is calculated. The energies and relative intensities as well as all the input information are then printed. A listing of this program is found in Appendix *B*.

The advantages of MOIRAE include the immediate operator control over such parameters as background order, background points, and intervals and peak end points. This control is especially helpful for regions with complex or unusual background such as Compton edges. The disadvantages also become rather obvious. One is its inability to strip unresolved peak multiplets. Since no standard peak shape is used, another strong disadvantage is that, although the operator has visual control of the analysis, the analysis of one γ -ray spectrum may take 2 to 3 hours.

Some of the disadvantages of MOIRAE are also of the subjective type. Because the determination of the background and the peak limits are under operator control, the choice of what background order and what collection of data points produce a good background fit can be difficult. Also, the choice of how large a region to fit the background over and then what peak limits to use may be very difficult to make, especially if the peak has tailing. For an ideal peak of high intensity situated on a smooth background, a good low order fit is easy. However, for several closely spaced peaks, a peak on a Compton edge, or a peak in a region of poor background, what is the best background? In general, an ideal fit would be a linear background approximation; however, it seems reasonable that any single polynomial curve may be used as long as the background is fit smoothly and approximates the desired background shape

under each of the peaks included in the interval. A change in the background shape changes the peak control only slightly while producing a much larger effect on the area.

3.2.2. SAMPO Spectrum Analysis Routine

SAMPO is a FORTRAN program written and modified by J. Routti and S. Prussin (Ro69) at the University of California, Berkeley, and modified for use on the MSU XDS Sigma 7 by C. Morgan. It can be controlled either via storage scope sense switches and teletype or by FORTRAN control cards. This program utilizes the photopeak method analysis, with each experimental peak being fit to a Gaussian function having exponential The mathematical evaluation involves initial shape calibrations tails. using strong well-resolved peaks well-spaced over the region to be analvzed. The shape parameters are stored and a linear interpolation is used to obtain the parameters for any other peaks under consideration. Once the shape parameters have been calculated for a given spectrum, for subsequent runs they may be reread directly into the program from FORTRAN control cards, thereby saving computational time. After a shape calibration has been established, an energy calibration curve using these and/or other peaks may be calculated at the operator's discretion either by linear interpolation or by a linear or higher order least-squares Similarly, efficiency calibrations may be performed polynomial fit. using a number of well-spaced peaks and their relative efficiencies.

The analysis by SAMPO of the data may be performed in two modes, "automatic" or "manual". In "automatic" mode, SAMPO searches out all the statistically meaningful peaks based on the calculated shape parameters, evaluates suitable fitting intervals, and fits the peaks using the shape, energy, and efficiency calibration data. For peaks that fall below the minimum statistical limit for the automatic search, for multiplets that are not clearly resolved, or for any other peaks or regions of interest the manual mode may be used. In this mode, the fitting intervals and the peak locations are input and the program then fits these peaks similarly to the automatic mode. The program may operate entirely in manual mode if desired.

Figure 15 shows a portion of the program's output for the 1392-keV doublet from ⁶³Zn decay. The plot displays the data, the calculated fit, and the calculated background. Above the plot are the upper and lower limits of the plot, and below the plot is the legend. The channel number, standard deviation of the difference between the data and the calculated fit, and the calculated background are printed to the left of the plot, while the data and calculated fit are found at the right. Below the plot is given the sum of the difference between the data and the calculated background and the sum of the difference between the calculated fit and the calculated background. For each peak fit, the program returns the centroid and its error, the energy and the error due to the calibration curve and the overall error, the fit peak area and its error, the fit peak relative intensity, the error due to the efficiency curve, and the total error.

Since its inclusion into the data analysis program in this laboratory, SAMPO has proven invaluable in the time saved stripping multiplets. An example of its ability to strip multiplets including unresolved ones is shown in Figure 15. The deviation from the average energy over three separate ⁶³Zn runs was less than 0.4 keV for the



1389.5 keV peak and less than 0.25 keV for the 1392.3 keV peak, while the deviation from the average intensity for the 1389.5 keV peak was less than 10% and the stronger 1392.3 keV was less than 6%. In general, the range of values for the energy and especially the intensity of a peak from several runs is less for SAMPO than for MOIRAE.

Another advantage of SAMPO is the relative amount of time necessary to obtain results. Much less time is involved in using SAMPO even if many regions have to be fitted in manual mode than in a MOIRAE analysis. In return for these advantages, SAMPO has some disadvantages that might require fitting many peaks in manual mode. Primary among these is the low order (2nd) background fit and the associated small limits of the fitting region. The result of this is very poor background fits in regions of poor statistics or near Compton edges, requiring these peaks to be refit in manual mode.

SAMPO may be operated with and controlled by a storage oscilloscope and sense switches. This allows the user an opportunity to examine each fit before it is finalized. If the fit is not good, the limits of the region may be changed or perhaps the number of peaks to fit and their centroids may be changed; however, the background remains the second order fit. While this produces better fits to the data, this procedure also consumes more of the user's time, thus returning to the disadvantages of MOIRAE.

3.2.3. Y-Ray Energy and Intensity Calculation

After several sets of data have been analyzed by the methods described above, the results must be evaluated to obtain the final γ -ray energies and intensities. The γ -ray energies were calculated by SAMPO or MOIRAE E(I) by a least-squares quadratic calibration equation

using the centroids of well-known standard γ rays and then computing the energies of "unknown" γ rays from their centroids and the standard curve. These calibration curves were computed from "internal" energy calibration spectra taken by simultaneously counting the unknown and standard calibration sources. The energies of the weaker peaks were then cal-culated by using the strong, calibrated peaks as internal secondary standards for computing the energy calibration curve. The final results in this work were obtained by averaging the results from 3 to 6 runs for each isotope.

Choosing the standard calibration sources is an important factor in the γ -ray energy calibration. Ideally, the standards are chosen to "bracket" the unknown peaks closely and contain only the γ rays used in the calibration, since a spectral distribution may obscure photons of interest. This, however, must be tempered with the need for many good calibration points in order to establish a reliable calibration curve.

The γ -ray relative efficiencies were calculated by using detector efficiency curves for the energy range from ~100 to ~3000 keV. These efficiency curves were produced using the program DETECTOR EFFICIENCY described in Section 2.1.3. and were incorporated into the program MOIRAE E(T) described in Section 3.2.1. In this work, the relative areas from 3 to 6 runs for each isotope were averaged and then the final relative intensities were calculated from these areas using the program MOIRAE E(T).

3.3. Decay Scheme Construction

A nuclear decay scheme represents one result of the investigation of a radioactive nucleus. Placing the γ transition in a

consistent decay scheme may be a difficult process, since as the number of interlevel transitions and the number of states increases the more complex the decay scheme becomes. With the aid of sums of γ -ray energies and the results of anti-, megachannel, prompt, delayed, and 511-511- γ coincidence experiments, the placement of these transitions becomes easier. In addition, the results from charged particle reactions and particle- γ excitation experiments may provide a good level scheme in which to place transitions. However, since each decay is different, some of these methods may not be able to be used. Even with the help of these aids, the process still requires much inspiration and perspiration.

Once a tentative decay scheme has been determined, many parameters are still to be evaluated. Using the total β decay energy and the relative β feedings to each level as determined by the relative intensity feeding to and from each level, the log ft for the β transition to each level can be calculated using the values calculated by several authors (Mo51, Br55, Zw54, Wa59), and collected in reference (Le66). Since this becomes tedious if many levels are present, a program was written by D. Beery (Be69) to perform these calculations. This program, DECAY SCHEME, uses the values from the tables and performs the many repetitive operations required to obtain the log ft for the β transition to each level.

The spin and parities of these levels may be assigned with the aid of several factors. The various selection rules governing β and γ decay often limit the spin to a few values integrally spaced and also somewhat limit the parity assignment. In addition, the results of charged particle reactions and γ -ray angular correlation experiments narrow these assignments often to only one value for spin and parity.

the higher the energy of the excited state, the less available the data and the wider the limits on spin and parity assignments.

With the placing of spin and parity assignments, the long task of producing a nuclear decay scheme is completed. With this completion, however, the difficult and rewarding task of interpreting the results is only beginning.

CHAPTER IV

EXTENSIONS OF Ge(Li)-Ge(Li) MEGACHANNEL COINCIDENCE SYSTEM

The Ge(Li)-Ge(Li) megachannel coincidence system described in Section 2.1.2.B. has been used at this laboratory to study various decay schemes. In the course of these experiments, unexpected peaks were observed. After examining these (misshaped) peaks, it was determined that they occurred from Compton scattered γ rays from one detector being observed in the other detector. The $\gamma-\gamma$ coincidence results also provided a system with which to reexamine the γ -sum coincidence experiments and their results. In Section 4.1. the results of the examination of Compton scattering in a Ge(Li)-Ge(Li) coincidence system are presented. In section 4.2. the results of the γ -sum coincidence system are described and its possibilities are discussed.

<u>4.1. Compton Scattering Problems In</u> Ge(Li)-Ge(Li) Coincidence Gamma-Ray Spectrometers (Gi71)

In $\gamma-\gamma$ coincidence spectrometry Compton scattering is often regarded as a benign nuisance, its worst effects being a wasteful increase in the number of spurious coincident events and an effective obscuring of the weaker peaks. When the gate and full-energy peak widths approach each other in magnitude, however, more insidious effects can set in, such as the generation of "artificial full-energy peaks". Thus, in the days when NaI(T1)-NaI(T1) coincidence spectrometers were standard, a number of such false γ rays found their way into the literature and a number of precautionary papers appeared to discuss ways of recognizing and avoiding such effects (Be55).

With the advent of Ge(L1) detectors with their low efficiencies, a NaI(T1) detector was retained more often than not as the gate detector in a coincidence system, and, because now the gates were much wider than even the widest photopeaks, such problems largely disappeared. But now that larger Ge(L1) detectors are available and Ge(L1)-Ge(L1) coincidence spectrometers are coming into general use, misleading Compton-generated γ rays are again making their appearance. The problem is especially acute for experiments with short-lived radioactivities for which repeated bombardments and/or source preparations are required in order to accumulate enough data to make the results statistically significant. The highest count rates possible are desired to minimize the number of necessary bombardments, and this often leads to the use of close 180° geometry, which is very efficient but somewhat unfavorable with respect to Compton scattering.

The basic problem that can arise from the ability to gate on a region only a few keV wide in a Ge(Li)-Ge(Li) coincidence experiment is quite simple in concept. Each tiny region in a Compton distribution from one detector has a one-to-one correspondence, both with respect to energy and with respect to angle, with a specific region in the Compton distribution resulting from scattering from that detector into a second detector. And, at a fixed angle, if the gate from the first detector be made small enough, the corresponding coincident region from the second detector could also be quite small or narrow, narrow to the point of having the width of full-energy peak. In a simple spectrum these are easy to spot, but in a complex spectrum one may confuse them with full-energy peaks if he is not wary of them. In some instances the spurious peaks may well fall at the very same energies as a real γ ray itself. Herein lies perhaps the greatest danger of all, for one could easily be misled by false coincidence results into placing the y ray into an incorrect position in a decay scheme. Thus, when we found ourselves on the verge of coming up with such "new" full-energy peaks in the 63 Zn experiment, we decided to make a thorough study of the effects of Compton scattering and narrow gates. This section describes the interesting results and the methods that can be used to suppress these unwanted additions to the coincidence spectrum.

4.1.1. Experimental Apparatus

Sources were counted with the megachannel coincidence system described in Section 2.1.2.B. utilizing the 2.5% efficient and 2.0% efficient Ge(Li) detectors.

Figure 16 shows the relative positioning of the detectors. Since both detectors were mounted on right-angle dipstick cryostats, it was possible to adjust their relative angular positions to almost any angle. For some of the experiments a 1.27-cm thick graded Pb collimator was placed between the detectors. A small biconical hole, ≈ 0.64 -cm¢, was drilled in an absorber and the source was placed at the center of this hole so that γ rays from the source itself would not be absorbed. The source was normally placed such that it was 3.8 ± 0.2 cm from each detector and on a line with the axis of each detector. The various angles were measured from detector axis to detector axis, with the collimator, if used, bisecting the angle as closely as possible.

4.1.2. ⁶³Zn Results: A Complex Spectrum

In Figure 17 a portion of the spectra obtained from a twodimensional $\gamma-\gamma$ coincidence experiment on 38-min 63 Zn is shown. The detector angle was 150° and an absorber was placed between the detectors but only up to the source. The integral or "any" coincidence spectra taken with the 2.5% and 2.0% detectors are shown at the top in parts A and D, respectively. In these the various gates have been denoted. The only remarks that need be made here about the decay scheme are that the intense 669.71- and 962.14-keV γ 's are ground state transitions from the first and second excited stated in 63 Cu and that the weak 449.8-keV γ feeds the second excited state. Further results are given in Chapter 5 of this thesis.

As part of the examination of the coincidence data, a very narrow gate as indicated by the bar B was set on the weak 449.8-keV peak, and the result is shown in part B. Since the 962.14-keV peak is





the Compton scattering coincidence experiments.

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CHANNEL NUMBER Coincidence spectra for ⁶³Zn. The integral coincidence spectra are shown in Fig. 17. A and D. Gates were set on the spectrum in D as indicated by the bars, with E and F, same as B and C except that the background indicated by bar H has been subtracted. Spectrum G was produced by gating on the spurious "220-keV" peak.

more intense in this spectrum than the 669.71-keV peak but is much weaker in the singles and any coincidence spectra, the 962.14-keV γ is shown to be in coincidence with the 449.8-keV γ . A new peak also appears at 220 keV. There was never any sign of this peak in the singles spectra, so further gates were used.

Part C shows the results of a gate on the 449.8-keV peak with a width four times that of B. Here the entire spectrum increases in intensity, but the peak at 220 keV has also increased greatly in width and is now much wider than the three known photopeaks.

In parts E and F the results of background subtraction are shown. The background used was the region denoted by the bar H but excluding the regions in gates B and C, respectively. Region H is 50 keV wide and centered on the 449.8-keV peak. In spectra E and Fthe 669.71-keV peak has disappeared, confirming our previous conclusion, but the γ^{\pm} and 962.14-keV peaks are weakly though definitely present. The 220-keV "peak", however, has increased greatly with respect to these and the regions on either side of it have gone to zero. This shows clearly that the Compton distribution in the gates was not only in coincidence with other regions of the spectrum in general, but also with this region in particular.

By gating on the 220-keV "peak", as shown in spectrum G, new peaks appear at 290, 740, 895, and 1180 keV in addition to the one at 450 keV. These energies are 220 keV less than the strong γ^{\pm} , 669.71-, 962.14-, 1115- (⁶⁵Zn contaminant), and 1414.1-keV peaks, corresponding to Compton-scattered γ rays from one detector being captured in the other detector.
4.1.3. Angular Dependence

In order to insure that the effects observed came strictly from Compton scattering between the detectors, further studies were performed with a 137 Cs source.

The effects of variations in the angle between the detectors on Compton scattering can be seen in Figure 18. The full-energy chance-coincidence peak is noticeably narrower than the large Compton edge and backscatter peaks. As the detectors are moved from 90° geometry toward the unfavorable 180° geometry, the increase in the Compton edge and backscatter peaks is very apparent, indicating that the primary direction of the Compton-scattered photons is back toward the source of the incident radiation. Table 4 gives the total, chance, and true coincidence rates.

Calculations of these angular effects are well known. With E_{γ} as the energy of the incoming photon, E_{γ}^{*} that of the scattered photon, E_{0} the electron rest energy, and θ the scattering angle of the photon, one obtains

$$E_{o}\left(\frac{E_{\gamma} - E_{\gamma}'}{E_{\gamma}'}\right) = 1 - \cos \theta$$

which has a maximum at $\theta = 180^\circ$; E'_{γ} is related to E_{γ} and E_{O} by

$$E'_{\gamma} = \frac{E_{o}E_{\gamma}}{2E_{\gamma} + E_{o}}.$$

For ${}^{137}Cs$, $E'_{\gamma} = 184.4$ keV, which is the energy of the backscatter peak observed at all angles; in these close geometries the angular



Fig. 18. ¹³⁷Cs Compton-scattering coincidence spectra showing the effects of the angle between detectors.

¹³⁷Cs Coincidence Counting Rates as a Function of Detector Angle and Absorber Usage.

Angle	Absorber	Total cps	Random cps $(R_1 R_2 \tau)$	Net cps
90°	no	2.74	2.55	0.19
90°	yes	1.51	1.33	0.18
120°	no	9.84	1.85	7.99
150°	no	10.95	2.21	8.74
180°	no	12.08	1.61	10.47
180°	yes	3.21	2.45	0.76

acceptance of the detectors is large enough to wash out most of the predicted angular dependence.

When a graded Pb collimator, as shown in Figure 16, is placed between the detectors, we see the effects illustrated in Figure 19. At 90° the huge Compton edge and backscatter peaks have been almost removed. At 180°, while not removed, they have been decreased to an almost reasonable level. This points up the fact that such collimators are all but essential for serious Ge(Li)-Ge(Li) coincidence experiments, but even they cannot insure completely valid results at close 180° geometry. These results are also included in Table 4.

4.1.4. Gate Widths

Figure 20 shows the effects of varying gate width on the coincident backscatter and Compton edge peaks. The display spectrum (from the 2.5% detector) is shown in part A, while the gates (from the 2.0% detector) are shown in part F. In parts B through E the effects of the various widths of gates on the backscatter peaks are shown. The gates correspond to the regions denoted in part F. For the narrowest gate (in B) the Compton edge peak is about twice the width of the photopeak, and by decreasing the gate width even further, it could undoubtedly be made the same width as the photopeak. As the gate width is increased, the Compton edge peak broadens somewhat but does not increase in height. This is rather graphic evidence for the one-to-one correspondence between portions of the spectra resulting from Compton scattering between detectors.

A similar effect is seen by gating on the Compton edge and looking at the resulting spectra, G through J. Notice the dip that



CS¹³⁷ COINCIDENCE



between the detectors. The spectra on the left were taken without an absorber; those on the right, with a 1.27-cm thick graded Pb absorber placed as shown in Fig. 16. $^{137}{
m Cs}$ Compton scattering coincidence spectra showing the effects of placing an absorber F1g. 19.

CHANNEL NUMBER



Fig. 20. ¹³⁷Cs Compton-scattering coincidence spectra showing the effects of varying gate width. The two integral coincidence spectra are shown at the top in A and F, and the gate widths are indicated in F.

appears in the spectrum below the backscatter peak. This is discussed in the next section, where gates are applied on different regions of the Compton distribution.

In Figure 21 a plot of the full width at half and tenth maximum vs the gate width is shown. Gating on the backscatter peak and on the Compton edge produced identical results, so both are included in the points on the graph.

The flattening out of the FWHM curve could be reproduced fairly well by a very simple calculation. Two Gaussian-shaped peaks were used, a wider one for the gate (G) and a narrower one for the displayed peak (P), this because customarily (but not always) one gates on the spectrum with the poorer resolution. For these Gaussians the experimental FWHM for our two detectors as found from the worst integral coincidence spectrum, the one at 180° with no absorber, were used.

Each channel in G then corresponded to a complete peak P, the amplitude depending on the height of the channel in G. Thus, a particular gate width in G was represented by a sum of peaks P having shifted centroids and differing amplitudes. The results showed that, for this idealized case, the limiting value of the FWHM is twice that of the display peak in its integral coincidence spectrum. This limiting value is reached at a gate width twice that of the FWHM of G, the same as was found experimentally in Figure 21. However, the calculated limiting value is about half that observed experimentally.



4.1.5. Gate Positions

In Figure 22 gates have been set on various regions of interest in the coincidence spectrum resulting from 180° geometry without using an absorber. Parts A and F show the 2.5% and 2.0% detector integral coincidence spectra, respectively. All gates were set as indicated in part F.

Gates B, C, and D study the region with energies less than the backscatter peak. In part B the large Compton edge and the fullenergy photopeak are seen on top of a rather typical Compton background. Part C shows the Compton edge broadening and with lower intensity and another broad, weak peak at about channel 820. By the time gate D is reached, the edge has again narrowed and the new peak has increased in intensity and has moved to a lower energy. The distance of this shift is the same as and in the opposite direction of the movement of the gate from C to D. Other gates show that as the gate is moved toward the backscatter peak, the new peak moves toward the Compton edge. In all cases the sum of the energy of the new peak and that of the gate equals that of the photopeak. That, plus the fact that the new peak appears in the Compton-forbidden region between the edge and the photopeak, indicates that this is the result of multiple Compton scattering. It arises when a photon is emitted from the source, then is Compton scattered in the first detector, rescattered in the second detector, and finally captured completely in the first detector. As a result, the Compton valley for the backscatter occurs at C instead of adjacent to the backscatter peak, at D.

Gate E is the center of the backscatter peak, and it is, as expected, mostly in coincidence with the Compton edge. In part G, in



Fig. 22. ¹³⁷Cs Compton-scattering coincidence spectra showing the effects of gating at different positions. The display integral coincidence spectrum is shown in A, while the gate integral coincidence spectrum is shown in F. The other spectra correspond to their respective gates as indicated in F.

addition to the weak backscatter and Compton edge peaks and the fullenergy peak, a broad peak is present at about channel 600. The centroid of this peak when added to that of gate G again equals the fullenergy peak. This also is a Compton scattered photon in coincidence with a captured Compton scattered photon.

The backscatter peak plus the lower energy region are found in coincidence with gate H. In this gate the drop in the Compton background is even more prominent and is strong evidence for the double Compton scattering.

The gate I on the valley between the Compton edge and the photopeak shows the photopeak, a Compton background, and a weak peak at the backscatter position. Evidently these are mostly chance coincidences. Finally, in part J a coincidence spectrum where the gate was on the photopeak is shown. This appears as a normal ¹³⁷Cs spectrum, resulting entirely from chance coincidences.

4.1.6. Conclusions

Large, high-resolution Ge(Li) detectors present many exciting new possibilities for nuclear research; yet, along with all their advantages, several problems appear. Potentially one of the most troublesome is the Compton scattering between detectors in a coincidence experiment, which has been illustrated and discussed here. In many cases it is possible to use a 90° geometry with a large graded Pb absorber between the detectors to eliminate the problem, but when working with short half-lives, more care must be used. An absorber of the type described in Section 4.1.1. has been found useful, and using a geometry of 150° or so instead of 180° can be helpful. Most of all, however, one must simply be aware of the problems that now exist

with such coincidence experiments. For without consideration of Compton scattering, newly found coincidence peaks may unknowingly be considered to arise from γ transitions in the nucleus under study, when in fact they are only Compton scattered photons.

4.2. Ge(Li)-Ge(Li) Sum Coincidence Spectrometer (Gi71a)

During the 1950's when γ -ray coincidence spectroscopy came into its own with NaI(T1) detectors and the newly developed fast electronics, a number of modifications and improvements on the straightforward γ - γ coincidence experiments were made. Most of these were designed to improve the poor peak-to-Compton ratios and the poor resolution of the NaI(T1) detectors. Among these improvements was the "sum-coincidence" method introduced by Hoogenboom (Ho58) in 1958 In this method the coincident pulses from two NaI(T1) detectors were passed through a summing network, producing a "sum-coincidence" spectrum. A single-channel analyzer was used to set a window on a sum peak in this spectrum, and this window was then used to gate the output of one of the NaI(T1) detectors.

Some major advantages of the sum-coincidence technique were readily apparent:

a) Attention was focused on the cascade de-excitation of nuclear states themselves rather than on individual γ rays. Thus, in principal one could work his way up a level scheme, setting the sum-window gates on the energies corresponding to each state in turn and observing the various (two component) cascades that de-excite this state. b) The method does improve the peak-to-Compton ratio in the gate, thereby helping to eliminate some of the ambiguities caused by the underlying Compton backgrounds from stray, unwanted peaks.

c) The resolution of the NaI(T1) detectors was effectively
 improved, especially at higher energies, for it was shown
 (Ho58) that

$$\Gamma_{S_{1}} = \Gamma_{1} \sqrt{\Gamma_{2}^{2} + \Gamma_{3}^{2}} / \sqrt{\Gamma_{1}^{2} + \Gamma_{2}^{2} + \Gamma_{3}^{2}}$$

where the Γ 's are the energy widths of the various γ -ray peaks in a cascade (Γ_1 and Γ_2), of the sum-coincidence peak (Γ_S), and of the γ -ray peak appearing in the sum-gated spectrum (Γ_{S1}). For γ -rays of equal energy this improvement in resolution approached a factor of $\sqrt{2}$, which could make a considerable difference in NaI(T1) spectra.

Despite these advantages, the sum-coincidence technique never really became popular. Probable reasons for this can be seen fairly easily by considering its major disadvantages:

> a) The method was cumbersome. Some insight into the nature of a decay scheme was needed before sum-window gates could be set intelligently. As a result, often as much or more time was spent in running sum-coincidence experiments as in running standard $\gamma - \gamma$ coincidence experiments.

b) In order to achieve the improvement in resolution -indeed, in order to prevent the actual broadening of the sum peaks or their becoming split into several components -- the gains and energy zeros of the two detectors had to be matched as closely as possible. This, of course, could be a very tedious procedure.

c) The gates on the sum-coincidence peaks had to be set very carefully in order to avoid distortions in the peaks appearing in the final spectra. This introduced an added degree of uncertainty in determining γ -ray intensities and energies and made any stripping of peaks in complex spectra very difficult.

d) False peaks could be generated from the underlying Compton background. Because of the poor detector resolution involved, these peaks were difficult to distinguish from those originating from bona fide γ -rays.

The necessity of having prior knowledge concerning a decay scheme before being able to set gates intelligently was emphasized in an adaptation of the sum-coincidence method called the "integral-bias" summing spectrometer (Ka62). Here one set of lower-level discriminators (the "integral bias") or windows on the outputs of the individual detectors and used these to gate the sum spectrum itself. The appearance of a particular sum peak in a sum spectrum gated by, say, windows m and n thus indicated that its components lay in energy regions m and n in the respective singles spectra. In principle, with this method a clever setting of three or four gates could furnish all the coincidence information needed to unravel a reasonably complex decay scheme. In

practice, however, one almost never succeeded in setting the windows "cleverly" before he already knew the specific locations of states in a major portion of the decay scheme.

The main application, then, of the sum-coincidence methods was for neutron-capture γ rays (Dr60), where any technique that might simplify the spectra was welcomed. They have also found occasional uses in total absorption spectroscopy (Ka62a), directional correlation experiments (Ha68), and some g-factor measurements (Bo68). And with the advent of Ge(Li) detectors the sum-coincidence methods might reasonably be expected to become quite obsolescent, for their operational difficulties appear to outweigh their advantages rather quickly. The problem of matching the gains of the detectors, for example, becomes all the more difficult and critical. A recent paper by Kantele and Suominen (Ka70), does extend the "integral-bias" sum-coincidence method to Ge(Li)-Ge(Li) systems, but in all fairness it must be concluded that their results show it to be more of a curiosity than a viable laboratory technique.

Recently, however, a variant of the sum-coincidence method has been used in our laboratory, using Ge(Li)-Ge(Li) detector systems, and has been found to be quite useful in helping to clarify complex spectra and decay schemes. Its usefulness depends critically on the fact that the sum-coincidence method is used only for off-line, afterthe-fact analysis of the recorded data from two-dimensional "megachannel" $\gamma-\gamma$ coincidence experiments. The spectra are obtained later by sorting the two-dimensional data with the program EVENT RECOVERY which is described in Section 3.1.

During the sorting process, the sums can easily be calculated so little or no additional experimental effort is required to add the sum-coincidence method to the other methods of analysis. Also, since the data are available in *digital* rather than analog form, the computer can be made to perform some of the routine tasks that made the older sum-coincidence techniques so unwieldy. For example, it can correct for the energy calibration of the detectors after the experiment has been completed, making it no longer necessary to match the detector gains exactly. Or, since a record is available of which events originated from which detectors, one can immediately obtain meaningful sum spectra even without bothering to convert from channel number to energy, providing that the gains were only moderately mismatched (cf. Sec. 4.2.2.)

In other words, having a complete digital record of the data from a Ge(Li)-Ge(Li) $\gamma-\gamma$ coincidence experiment on hand and then performing sum-coincidence analyses on these data makes the sumcoincidence method a worthy supplement and complement to the standard $\gamma-\gamma$ coincidence analyses, especially for very complex spectra. Its various advantages and disadvantages are discussed and some results from its use on a moderately complex spectrum (63 Zn) and a very complex spectrum (205 Bi) (Ko71) are presented.

4.2.1. Experimental Methods

Our sum-coincidence experimental set-up differs very little in concept from a standard two-dimensional $\gamma-\gamma$ "megachannel" coincidence

experiment. This is shown dramatically in Figure 23 where the only difference is the addition of a summing network to a $\gamma-\gamma$ coincidence block diagram in order to obtain the sum-coincidence block diagram -- and this summing network is simply a modification of the off-line recovery program. It should be pointed out that all of the data presented had been taken prior to the decision to try a sum-coincidence analysis. The experimental methods used to record these data were developed strictly to optimize the $\gamma-\gamma$ coincidence results; yet the data could be analyzed quite successfully by sum-coincidence methods.

A description of the two-dimensional megachannel coincidence system used to obtain the data is given in Section 2.1.2.B. The detectors used to obtain the 63 Zn spectra were the 2.5% efficient and the 2.0% efficient Ge(Li) detectors. The 2.5% detector was also used to obtain the 205 Bi spectra, along with the 3.6% efficient, Ge(Li) detector.

The EVENT RECOVERY program was used to perform sum-coincidence gating as well as the normal $\gamma-\gamma$ coincidence gating. The additional limitation on the sum of X>Y or X<Y was performed because the gains of the detectors were not perfectly matched. In this way two peaks appearing for the same sum were prevented from appearing without having to go through the procedure of converting the addresses to γ -ray energies.

4.2.2. Analysis of a Moderately Simple Spectrum: ⁶³Zn

As an example of the power of the sum-coincidence method to reduce a large background under weak peaks, some results obtained on the decay of 38-min 63 Zn are presented. In Figure 24 portions of the spectra obtained from a two-dimensional $\gamma-\gamma$ coincidence experiment are



Y-SUM COINCIDENCE

Fig. 23. Block diagram of the sum-coincidence experiment. The addition of the "summing network" is the only way in which this differs from a standard two-dimensional megachannel coincidence experiment, and the "summing network" is merely an addition to the offline computer recovery program.



shown. The integral or "any" coincidence spectra, which were obtained by adding up all the listed events recorded by the 2.5% and the 2.0% detectors singly, are shown at the top as X and Y, respectively. All that need be said about the decay scheme, which is described in Chapter 5, is that the first and second excited states of ⁶³Cu lie at 669.7 and 962.1 keV, both decay exclusively to the ground state, and the weak 449.9-keV y feeds the 962.1-keV state from a state 1412.1 keV. The 669.7-, 962.1-, and 1412.1-keV states are all strongly β^+ fed. The cascade nature of the 449.9-keV Y is demonstrated by the gated spectra appearing in the lower half of Figure 24. Placing a gate on the 450keV region causes an enhancement of the 962.1-keV γ over the 669.7-keV γ , although the latter is more intense in most of the other spectra. Also, placing a gate on the 962-keV region results in an enhancement of the 449.9-keV γ . It can be seen, however, that the background interference from the γ^{\pm} (in true coincidence with 962.1-keV γ) is quite severe in this last spectrum.

The spectrum resulting from summing each pair of X and Y addresses together is shown in Figure 25. Two types of peaks appear in this spectrum, sum peaks, as indicated, and Compton scattered peaks. The Compton scattered peaks are those that result from a Compton scattered photon from one detector being captured by the second detector. The peaks at 511.0, 669.7, 962.1, and 1115.4 keV are examples of this type. The peak at 1412.1 keV is mostly a sum peak but contains a Compton scattered component.





Figure 26 shows examples of gating on each type of peak. At the top is shown the X and Y components of all sums with $y>\chi$. The result is that the Y axis shows a relatively normal integral coincidence spectrum, although skewed toward higher energies, while the χ axis shows a spectrum whose intensity is greatly reduced at the higher energies. Gating on the 669.7-keV peak (a Compton scattered peak) as displayed in Figure 25, the following results appear: A sharp peak appears at 511 keV in the Y-axis spectrum, and it appears to be in coincidence with a peak at *160 keV in the X-axis spectrum. What is appearing is a true coincidence between the 511-keV photopeak from one detector with that portion of the γ [±] Compton distribution from the other detector that is required to add up to the 670-keV gate. The peak at ~160 keV is narrow only because the gate on the 670-keV region was also quite narrow.

In the 670-keV gated spectra three broader peaks also appear. The Compton edge from the 669.7-keV γ in the Y spectrum is in coincidence with the backscatter peak from the same γ ray in the X spectrum. And the broad Gaussian-looking peak that is split between the X and Y spectra represents those portions of the Compton continuum from the γ^{\pm} in each detector that, in true coincidence, add up to \approx 670 keV.

The spectra gated on the 511+670-keV sum start to show the advantages of the sum-coincidence method. First, notice the welcome reduction in the Compton background in these spectra. Then notice the clean appearance of the 669.7-keV photopeak in the ¥ spectrum and the 511.0keV photopeak in the ¥ spectrum. The 962.1-keV peak (weak) in the ¥



Fig. 26. Sum-coincidence spectra for 63 Zn. All of the spectra shown were taken with the limitation Y>X, and the X-axis spectra are displayed on the left opposite their corresponding Y-axis spectra.

spectrum arises from chance coincidences, as does the backscatter peak from the 669.7-keV γ in the X spectrum.

In Figure 27 the results of gating on the 1412-keV sum peak are shown. The 449.8- and 962.1-keV peaks are very strongly enhanced, demonstrating conclusively that they are a cascade adding up to 1412 keV. The 511.0- and 669.7-keV peaks are present because of being in coincidence with the underlying Compton background. The fact that there is a 1412.1-keV ground-state transition is evidenced by the Compton edge of this transition appearing in coincidence with its backscatter peak. Subtracting a weighted background from each side of the sum peak improves the peak-to-Compton ratios further and removes some of the 511.0- and 669.7-keV peaks. Perhaps the strongest statement that can be made in favor of the sum-coincidence technique is "compare the 449.8-keV peak in the lower part of Figure 27 with the same peak in the 962-keV gated spectrum in Figure 24." The reader is reminded that both spectra were extracted from the same set of magnetic tapes.

4.2.3. Analysis of a Complex Spectrum: ²⁰⁵Bi

(in conjunction with K. Kosanke)

A second example of how the sum-coincidence method can aid in resolving a weak, closely spaced triplet peak in the complex spectrum is the results from the decay of 14.6-d 205 Bi. The 205 Bi singles spectrum presented in Figure 28 with its myriad of weak peaks, illustrates the complexity of the decay -- a total of 99 γ rays have been identified as belonging to this decay. The peak of interest here is the weak peak near 1002 keV. Figure 29, which shows only that small portion of the decay scheme (Ko71) necessary for the present discussion,









COUNTS PER CHANNEL



Fig. 29. A small portion of the ²⁰⁵Bi decay scheme showing those states and transitions of interest to the present discussion. The three components of the ²¹⁰²-keV triplet are drawn as larger arrows to aid the eye in locating them. indicates the reason for selecting this peak. All of the previous studies of this decay (Ru71) concluded that the 1002-keV peak represents a single γ -ray that feeds the 262.9-keV state. And although a slight broadening of the 1002-keV peak was noted, even the best Ge(Li) detectors did not have the ability to resolve the peak even partially. In our studies, however, considerable Ge(Li)-Ge(Li) γ - γ coincidence data suggested a triplet with the placements indicated in Figure 29.

To substantiate the tentative placements of the transitions in the ~1002-keV triplet, sum-coincidence gates were set on the regions corresponding to the 1264.5-, 1705.0-, and 1764.5-keV states. The integral or "any" sum spectrum is shown in Figure 30. There are relatively few clearcut sum peaks in this spectrum, considering the wealth of cascade γ -rays resulting from ²⁰⁵Bi decay. In fact, examining the positions of the three sum-coincidence gates does not lead to much initial optimism. The position of the 1264.5-keV gate shows no sign of an obvious sum peak -- all that is present is a Compton-type background. At the location of the 1705.0-keV gate there is only a weak peak. Only at the location of the 1764.5-keV gate is the sum peak obviously present.

The spectra resulting from these three sum-coincidence gates is shown in Figure 31. Only the composite spectra from the Y axis (the 3.6% detector) is displayed, with the small arrows indicating where X>Yends and Y>X begins. Even though the sum peaks were small in Figure 30, the gated spectra in Figure 31 show many well-defined peaks. A closer examination of each of these indicates that only a few are in coincidence with other γ rays, while most of them result from Compton Bcattering.



Fig. 30. Total or "any" sum-coincidence spectrum for ^{205}Bi .





In the top spectrum, resulting from a gate on the 1264-keV region, the 1001.8-keV γ is shown definitely to be in coincidence with the 260.6-262.9-keV doublet. Also present is the 576.5-keV and 685.5keV coincidence pair. Both the 561.6- and the 221.2-keV γ 's are too weak to stand out from the background in this spectrum. Also present in the spectrum are strong γ rays such as those at 549.8, 570.9, 703.4, and 1043.7 keV, which are present because of chance coincidences and because of Compton scattering, as discussed in Section 4.1. The other peaks in the spectrum are caused almost solely by Compton scattering, as was verified by increasing the gate widths and observing the resulting changes in the intensities and shapes of these peaks.

The middle spectrum, resulting from a gate on the 1705-keV region, is considerably simpler. The 1001.6-keV and 703.4-keV coincident pair is definitely established, and so is the 717.4-keV and 987.5-keV pair. Both the 661.3- and the 205.8-keV γ 's are too weak to stand out in this spectrum.

A few more peaks are present in the bottom spectrum, gated on the 1764-keV region. The 1003.1-keV and 759.1-761.4-keV and the 720.6-keV 1043.7-keV coincident pairs are readily observed. Also present are the 703.4- and 987.5-keV γ 's, here only in coincidence with the Compton background in the gate, for their intensities are much lower than in the 1705-keV spectrum. In the spectrum drawn at the bottom of Figure 31, the 1501.6-keV and 262.9-keV coincident pair is not seen even though it is moderately intense. However, when using a wider gate width (~20 keV), this pair was easily seen. This result points out one of the problems that has not been completely solved here --

that of unmatched gains for the two detectors. These peaks were far enough away in energy from the other two coincident pairs that their sum peak produced simply by adding channel numbers was excluded from the narrow sum gate based on the other two pairs. In this instance the apparent difference in sum energy was almost 10 keV. Thus, although one can and does use detectors without perfectly matched gains, he must be on the lookout for this sort of sum-peak "jitter". That is, unless he is willing to convert the spectra from channel numbers to γ -ray energies before setting the sum-coincidence gates, a somewhat tedious procedure but one that can be performed readily by the computer.

Accordingly, the presence of the 260.6-262.9- & 1001.8-keV, the 703.4- & 1001.6-keV, and the 759.1-761.4 & 1003.1-keV pairs in the sum gates set both confirm the existence of the ~1002-keV peak as a triplet and also the placements of its components. Perhaps it is worth noting that the sum-coincidence method also added a confirmation of the new state at 1705.0 keV and by removing ambiguities in the $\gamma-\gamma$ coincidence results has allowed the definite placement of the 720.6-keV transition, the center member of a quite weak 717.4-720.6-723.6-keV triplet.

4.2.4. Conclusion

It has been shown that the sum-coincidence technique as applied to the digitally-stored data from a two-dimensional Ge(Li)-Ge(Li) $\gamma-\gamma$ "megachannel" coincidence experiments is a viable and useful tool for the nuclear spectroscopy laboratory. When thus applied, using sum-coincidence gates to complement the standard $\gamma-\gamma$ coincidence gates in the off-line sorting of the spectra, the sum-

coincidence method is quite useful for pulling weak peaks out of a strong Compton background. The analysis of spectra must be made carefully and cautiously, however, for the spectra resulting from sumcoincidence gates are not quite so easily interpreted as those resulting from standard $\gamma-\gamma$ coincidence gates. This is particularly true when there is significant Compton scattering between the detectors. Nevertheless, when used to supplement and complement these $\gamma-\gamma$ coincidence experiments and not as a stand-alone technique, the sumcoincidence method should find considerable use in high-resolution γ -ray spectroscopy.

CHAPTER V

DECAY OF ⁶³Zn

5.1. Introduction

The first report of the decay of 63 Zn was by Bothe et al. (Bo37) in 1937, who produced it by the 64 Zn $(n, 2n){}^{63}$ Zn reaction. Since then it has been studied by many groups. Most of the γ -ray work has been performed by stripping γ -ray spectra obtained from NaI(T1) detectors and comparing the results to the more precisely measured levels obtained from charged particle reactions. Since the advent of Ge(Li) detectors, several authors (Ho66, De67, Bo69) reported γ -ray spectra obtained with Ge(Li) detectors a few cubic centimeters in size, each reporting more and more precisely measured γ transitions than the previous authors. Kiuru et al. (Ki70) presented results obtained using a relatively large Ge(Li) detector that are in good agreement with previous results. The only coincidence results reported on 63 Zn are from a NaI(T1)-Ge(Li) coincidence experiment performed by Borchert (Bo69).

Many charged particle scattering reactions have also been performed to study the excited states of 63 Cu. Since 63 Cu is stable as are many of its neighbors, a large variety of reactions have been performed. Some of the reactions performed were 63 Cu(p,p') (Ma57), 62 Ni(τ,d) (B165), 64 Zn(t,α) (Ba67), 62 Ni(α,t) (Ro68), and 62 Ni(d,n) (Ma71). A comparison of the results from the different reactions and the γ -ray studies is shown in Figure 32.



5.2. Source Preparation

The 63 Zn sources were prepared by bombarding natural Cu foils (69.09% 63 Cu, 30.91% 65 Cu) with protons from the Michigan State University Sector-Focused Cyclotron; these protons were degraded from higher energies to 12 MeV by the use of Al absorbers to induce the 63 Cu(p,n) 63 Zn reaction. Typically, 10-mil Cu foils were bombarded for \approx 3 minutes with a typical beam current of \approx 2 μ A. The sources were allowed to decay for several minutes before being counted for several half-lives. More source was added with the passage of time to retain a relatively constant counting rate. To insure that only radiations from 63 Zn were observed the γ -ray spectrum was confirmed by counting sources that had been chemically separated according to the procedure in Section 2.3.

5.3. Experimental Results

5.3.1. Y-Ray Singles Results

Energies and intensities of 63 Zn γ rays were determined using the 10.4% efficient Ge(Li) detector. The energies of the prominent γ rays were measured by counting 63 Zn sources simultaneously with ${}^{110^{m}}$ Ag and 56 Co. The energies of most of the weaker 63 Zn γ rays were then determined by using the energies of the prominent 63 Zn γ rays as secondary standards. The centroids and areas of the photopeaks were determined using the computer program SAMPO.

A typical γ -ray spectrum is shown in Figure 33. Forty-four γ transitions were assigned to the 63 Zn decay, and their energies and intensities are listed in Table 5 along with those of other authors (Ho66, De67, Bo69, Ki70). Also included in the table are the levels observed in the (p,p') reaction (Ma57). The uncertainties in the energies listed in


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Decay
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Intensities
Y-Ray
Relative
and
B nergi es
Table 5.

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Present Wor	لد	Bolmberg, 6 Lund	Spring án	DeFrenne	et al.	Bor cher t		Kiuru 6 Bolm	berg	fazari et al.	
Ra	I	64	۹.,	Na	٩.,	Pa	۹	Ng.	.	Ng	
					i i	3645 542 0	0 3+0 1				
4 50 0 + 0 3	2 7 +0.2						2.0+0.5	440 R +1 0	1+ c		
511.0	2188	511	≡1600	511	2110	511.0	=2190	511.0 ±0.2	=2060	į	
585.2 ±0.5	0.22±0.10										
624.1 ±0.6	0.18±0.05			ļ	ļ						
669.71±0.1	100	670±1	100	668±1	100±5	669. 6±0.2	100 ±3.9	699.75±0.2	100±2	668±5	
	1					684.7±1.7	0.45±0.16			İ	
742.5 ±0.5	0.76±0.13					742.5±0.5	0.86±0.13	742.0 ±1.0	0.7±0.4	i	
754.4 ±0.7	0.33±0.15	1			ļ					1	
899.2 ±0.6	0.16±0.06	900±20	veak		ļ						
924.6 ±0.6	0.13±0.06	1				923.5±1.0	0.25±0.09				- u
962.14±0.1	79.8 ±3.2	962±2	84.0	961±1	79±5	961.9±0.2	78.8±2.2	962.1 ±0.2	80±2	961±5 ⊢	
	8					1087 ±2	0.32±0.11	1			
1123.8 ±0.6	1.3 ±0.2				ļ	1123.7±0.3	1.5 ±0.3	1123.6 ±1.0	1.6±0.4	8	
1130.6 ±0.5	0.13±0.04							3 8 8			
1149.6 ±0.3	0.21±0.05	8				1150 ±2	0.30±0.05	*		*	
	1					1168 ±3	0.20±0.04		8		
						1189 ±3	0.2 ±0.1				
1208.6 ±0.8	0.17±0.06					1208 ±2	0.15±0.04	1209.1±1.0	0.3±0.1		
1327.0 ±0.4	0.84±0.06			1327±4	0.7±0.4	1326.4±0.3	0.98±0.12	1327.1 ±1.0	0.8±0.2	1327±5	
8								1340.0 ±1.0	0.6±0.2		
1374.4 ±0.3	0.41±0.06					1374.3±0.3	0.48±0.09	1374.4 ±1.0	0.4±0.2		
1389.5 ±0.6	0.44±0.09)			120046	1 040 5						
1392.3 ±0.5	1.24±0.12			#104CT	C.Uio.L	1391.5±0.4	1.8±0.1	1392.1 ±1.0	1.8±0.3		
1412.07±0.2	9.3 ±0.4 ́	1411±2	4.8	1412±1	10. ±0.8	1411.9±0.2	8.8±0.3	1412.1 ±1.0	9.6±1.0	1412±5	
1546.8 ±0.6	1.6±0.1	1550±10	2.2	1548±1	1.5±0.2	1546.9±0.2	1.4±0.2	1546.6 ±1.0	1.8±0.3	1547±5	
1573.4 ±0.5	0.19±0.07			1573±4	0.2 ± 0.1	1574.0±2.0	0.14±0.04	1573.3 ±1.0	0.25±0.1		
		1650±20	0.72	1700±4	0.3±0.1					1	
1825.4 ±0.6	0.11±0. 04	1800±10	weak	1822±4	0.2±0.1	1816.9±1.0	0.031±0.003	1825.6 ±1.0	<0.09	8	

tinued
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Table 5

		Holmberg, Sp	ring							
Present Wor	¥	6 Lundán		Defrenne e	t al.	Borchert		Kiuru & Holmh	oerg Ma	zari et al.
62	I	60	9 .	50	۹.	64)	I.a	8	e .1	lic;
1860.9 ±0.6	0.24±0.05					1865 240 2	0 3840 03	1 144 2301	16 0426 0	106745
1865.7 ±0.6	0.2640.05					C.UZ3.CUD1	CU-UIOC-U	0.124.COOT	77.0-00.0	C±2001
1926.8 ±0.8	0.062±0.025					1926.4±2.0	0.07±0.01			
2012.0 ±0.5	0.14±0.03				ļ	2012.0±0.5	0.12±0.02	2010.9±1.0	0.15±0.05	2012±5
2026.9 ±0.3	0.7840.05					2027.2±0.5	0.66±0.11	2026.7±1.0	0.8±0.2	
2047.2 ±0.8	0.041±0.14					2048.6±1.5	0.08±0.01			
2062.3 ±0.5	0.41 ± 0.06			2059±4	0.4±0.1	2062.0±0.8	0.35±0.08	2062.7±1.0	0.4±0.4	2063±5
2081.4 ±0.7	0.21+0.05	208 0±10	1.2	2082±5	0.3±0.2	2082.0±0.5	0.16 ± 0.04	2082.1±1.0	0.2±0.1	2082±5
2092.5 ±0.8	0.057±0.025			ļ			i			2093±5
2103.3 ±1.2	0.069±0.030					2103.2±3.0	0.03±0.02			ļ
2110.6 ±0.6	0.087±0.022	-		ļ			i			
		2180±20	0.80							2210±6
2336.8 ±0.3	0.99±0.08	2350±20	1.3	2337±2	0.84±0.08	2336.5±0.2	1.0±0.07	2336.7±1.0	0.9±0.2	2337±6
		I		2394±4	0.11±0.05					2405±6
2497.5 ±0.6	0.25±0.03			2497±4	0.16±0.05	2497.7±0.4	0.25±0.02	2497.1±1.0	0.3±0.2	2497±6
2512.5 ±0.5	0.12±0.03			2516±4	<0.08	2512.0±0.5	0.14±0.02	2512.1±1.0	0.09±0.05	2504±6
				ł						2510±6
2536.2 ±0.4	0.80±0.05	2540±10	0.6	2535±2	0. 7±0.2	2535.9±0.2	0.84±0.04	2536.2±1.0	0.9±0.2	2535±6
								-		254 3±10
										2673±8
2697.0 ±0.4	0.4870.04	2700±20	veak	2694±2	0.3±0.1	2696.7±0.2	0.47±0.09	2696.7±1.0	0.5±0.2	2694±8
2717.2 ±0.5	0.140.012	8				2717.0±0.5	0.13±0.02	2716.8±1.0	0.16±0.05	2716±8
				2767±4	0.09±0.05					2761±8
2780.6 ±0.3	0.18±0.015	2770±10	0.4	2781±4	0.11±0.05	2780.1±2.0	0.20±0.02	2780.1±1.0	0.19±0.05	2778±8
2807.1 ±0.6	0.03940.007			2805±4	0.05±0.02	2806.5±0.4	0.030±0.007	28 07 ±2	0.05±0.02	2805±8
		ļ						*		2831±8
2857.8 ±0.7	0.0320.006			2856±4	0.03±0.01	2857.4±1.0	0.036±0.008	2856 ±2	0.04±0.02	2856±8
1			ļ		8				1	2869±8
1				2880±4	0.026±0.011	2882.1±2.0	0.011±0.003			
2889.5 ±0.5	0.02年0.003					2891.1±1.5	0.026±0.005	28 90 ±2	0.03±0.01	2888±8
										2958±8
										2974±8
		1		3032±6	<0.04					3032±8
3044.0 ±0.7	0.058±0.010			3042±6	<0.04	3044.9±1.0	0.055±0.011	3044 ±2	0.06±0.01	304 2±8
						3090.8±2.0	0.004±0.002			
3100.3 ±1.0	0.001-0.004					3100.9±0.7	0.009±0.002	3101 ±2	0.02±0.01	3099±8

a. Intensities renormalized relative to the 669.71-keV γ retaining the original number of significant figures.

Table 5 are based on the uncertainties in the energy standards, the heights of the peaks above the background, and the reproducibility of the calculated energies of the different spectra. The relative intensities listed are averaged from several spectra, and their uncertainties are based on the reproducibilities of the intensities and the uncertainties in our experimentally-determined efficiencies for the detector. They are in general 50% greater than the largest deviation of a value from the average of several runs. The γ -ray intensities of the other authors were renormalized to the 669.71-keV γ while retaining the original number of significant figures.

A comparison of the present results with those of other authors, especially Borchert (Bo69) and Kiuru et al. (Ki70), shows good agreement among the authors. The results of Holmberg et al. (Ho66) and DeFrenne et al. (De67) will not be further discussed since their results have significantly fewer peaks than the others, even though their results are in generally good agreement with the others. Borchert reports seven transitions not observed here or by Kiuru and Holmberg, while Kiuru and Holmberg report only one transition not observed by other authors. In the present work, nine transitions were reported that were not observed by other authors, while five others were observed only by Borchert.

Shown in one inset in Figure 33 is the 1360-1420-keV region of the 63 Zn spectrum. Notice here the broadening of the photopeak at 21390 keV in comparison to the photopeaks on either side. This broadening on the low energy side is better shown in Figure 15. Because even our best detector could not resolve the 1389.5- and the 1392.3-keV components of the doublet, the program SAMPO was used to strip it, and the results are included in Table 5. The other inset shows the two resolved peaks at

1860.9 and 1865.7 keV. These are both full energy γ rays, and neither one of them is the double escape peak of the 2889.5-keV γ , since both are much stronger than any double escape appearing in the spectrum.

5.3.2. Ge(Li)-Ge(Li) Megachannel Coincidence Results

The decay of 63 Zn was also examined using the two-dimensional Ge(Li)-Ge(Li) megachannel coincidence system described in Section 2.1.2.B. For this experiment, the 2.5% efficient and 2.0% efficient Ge(Li) detectors were used as the x and y detectors respectively. The angle between detectors was 2150 degrees. In Figure 34 some of the results are shown, where Figures 34A and 34E are the x and y integral or "any" coincidence spectra, respectively. Table 6 gives the $\gamma-\gamma$ coincidence results, in addition to those of the other coincidence experiments.

Figure 34B shows the results of gating on the 450-keV peak. This gate produces a 962-keV peak greatly enhanced with respect to the 670-keV peak even though the 670-keV peak is stronger in both the singles and integral coincidence spectra. Therefore, the 962-keV γ is clearly in coincidence with the 450-keV γ . Also observed is a peak at 220 keV which results from a Compton scattered γ -ray from one detector being captured in the other. This was discussed further in Section 4.1.

The next gate, 511 keV, is shown in Figure 34C. The γ -rays appearing in this spectrum indicate the states that are β^+ fed. Feeding to other states is too weak to be seen in this spectrum. Further results on β^+ feeding to states are given in Section 5.3.4.

Gating on the 670-keV peak, Figure 34D, shows only the 511-keV γ from the β^+ feeding. Although there is a continuum at energies above 511 keV, no γ transition to the 670-keV level is strong enough to be observed.



Fig. 34 (Part 1). 63 Zn $\gamma-\gamma$ megachannel coincidence spectra. In the top of this Figure and of Part 2 are shown the integral coincidence spectra, and in the lower portions are shown the various selected gates.



Fig. 34 (Part 2).

Experiments
Coincidence
rays in
6 ³ Zn Y
Intensities of
Table 6

				2	lative Int	ensities				
E, (keV)	Singles	Anticoincidence	511-511-y	450-keV gate	S11-keV gate	670-keV gate	962-keV gate	1039-keV gate	1392-keV ga te	1412-keV gate
450.0	2.7	1.72	ł	ł	ł	ł	9.2	ł	ł	ł
511.0	≣2188	1	31.3	2952	2814	≡2188	≡2188	310	1	≡2168
585.2	0.22	!	1	ł	I				!	
624.1	0.18	i		ł	ł	i	!		ł	ł
669.71	≡100	≣100	≣100	≣100	≣100		ł	≣100	≡100	ł
742.5	0.76	0.56	ł	ł	ł	-	ł		1	1
754.4	0.33		1		8	1			ł	ł
899.2	0.16	ł	I	ł	1	ļ	1			ł
924.6	0.13		:	•						;
962.14	79.8	88.4	69.7	212	72.0		!	•	•	1
1123.8	1.3	1.2	l	ł	ł	•		ł		
1130.6	0.13	I	ł	i	1		8	;	!	
1149.6	0.21	0.30	1		ļ	ļ	1		•	
1208.6	0.17	1	1	1			l		ł	ł
1327.0	0.84	0.76	I	ł	1	!		•	ł	ļ
1374.4	0.41	0.44		1	ł	ł	ł	ł	ł	
1389.5	0.44	:	ł	1	I		1	-	i	
1392.3	1.24	11	ł			1	1		1	:
1412.07	9.3	12.5	4.5		5.8				1	
1546.8	1.6	1.8	0.45	ł	:	ł	1	ļ	;	:
1573.4	0.19	0.23					ł	1		
1825.4	0.11	0.21	ł		1	1				ł
1860.9	0.24	0.22	ł	I		ł		-	;	
1865.7	0.26	0.23	ł	I					ł	ł
1926.8	0.082	0.28	!	1				1	ł	ł
2012.0	0.14	0.14	;	ł	ł	ł	1			
2026.9	0.78	0.67		ł	ł	ł		i		
2047.2	0.041	0.038								ļ
2062.3	0.41	0.81	ł	!	ł					
2081.4	0.20	0.19		ł	1				ļ	•
2092.5	0.057	0.043	1					ł	ł	ł
2103.5	0.069	0.062					1	1		!
2110.6	0.087	0.080	1		ł	ł		ļ	ł	•
2336.8	0.99	1.8				1			!	ł
2497.5	0.25	0.46	ł	i	ł	ł				
2512.5	0.12	0.20		ł	ł		ł	:		
2536.2	0.80	1.5			i				ł	ł
2697.0	0.48	0.87		ļ	ł	!	1		l	•
2717.2	0.14	0.25		ł	ł	ł		ł	ł	1
2780.6	0.18	96.0		ł	!	ļ			ļ	
2807.1	0.039	0.091		ł	ļ	!			ł	
2857.8	0.032	0.071					ļ			•
2889.5	0.026	0.057	1		ļ	ļ				1
3044 0	0.058	860.0	ł	ł	ļ		ł	ł	ł	
3100.3	600.0	0.016		1				ļ	:	ļ
	,)) ,)									

П

Figure 34F displays the results of gating on the 962-keV peak. Here the 450-keV γ is greatly enhanced with respect to the 511-keV γ , indicating again the 450-keV γ is in coincidence with the 962-keV γ .

Gating on the 1040-kev γ shows, in Figure 34*G*, a spectrum similar to the singles spectrum, but greatly reduced. The appearance of the 1040-keV γ in the singles spectrum is debatable, since it would appear on a Compton edge. It also does not fit anywhere in the decay scheme and is probably a strong background peak that is in chance coincidence with the strong peaks in ⁶³Zn.

The gate on the 1392-keV peak, Figure 34H, shows a coincidence with only one γ , the one at 670 keV. This confirms the placement of it as feeding from the 2062-keV level to the 670-keV level.

Finally, Figure 34*I* shows the results of gating on the 1412-keV peak. Only the 511-keV γ from the β^+ feeding appears. No other feeding to this level is strong enough to be seen.

Gating on the remaining peaks in the x and y integral coincidence spectra show very little if anything. The 1472-keV gates show possible coincidences with 270- and 511-keV γ 's. The 1547-keV gate shows only random coincidences and no firm indication of its β^+ feeding. All the counts in this gate were below 550 keV. The other gates are similar in that all the counts appear below 1000 keV. No channel in any of these gates has more than one count in it, and the channels with counts are randomly spaced. The peak at 2754 keV in the integral coincidence spectra could be from ²⁴Na in room background and the Pb collimator.

5.3.3 Anticoincidence Results

An anticoincidence experiment was performed using a 20.3×20.3cm NaI(T1) split annulus, a 7.6×7.6-cm NaI(T1) detector, and the 10.4%

efficient Ge(Li) detector, with the latter two detectors placed in opposite ends of the annulus tunnel. The γ rays observed by the Ge(Li) detector were counted only when there were no γ rays observed in any of the NaI(T1) detectors. A description of the system and the electronics was given in Section 2.1.2.A. A spectrum obtained using this system is shown in Figure 35, and the results are included in Table 6.

Most of the ground state transitions observed in this experiment were enhanced over their singles intensities. One of those not enhanced is the 1327-keV γ . This is because the 1327-keV state has no β feeding because of the large difference in spin between it and the ⁶³Zn parent. As a result this state is fed completely by γ transitions from higherlying states.

Other ground-state transitions not enhanced were at 1861, 1866, 2012, 2081, and 2092 keV. All these transitions were weak in the singles and were very weak in the anticoincidnece results. Of special interest are the 1861- and 1865-keV γ peaks. It was expected that one of the peaks would be enhanced over the other to indicate which is a ground-state transition from a state at the same energy and which is a possible cascade transition. However, even though neither was enhanced, the relative intensities of the two to each other remained near that of the singles spectrum, indicating both transitions are of the same type, either ground state or cascade. Since other weak ground-state transitions of similar energies showed similar enhancements to this pair, these two peaks both appear to be ground-state transitions.

5.3.4. 511-511-keV-y Triple Coincidence Results

A 511-keV-511-keV-any γ triple coincidence experiment was performed using the 20.3×20.3-cm NaI(T1) split annulus and the 2.5% efficient



Fig. 35. An anticoincidence spectrum from the decay of $^{6\,3}{\rm Zn}.$

Ge(Li) detector. The two halves of the annulus were operated separately and each was gated on the 511-keV region. A triple coincidence was required between the two annulus halves and the Ge(Li) detector in order to count the γ -ray observed by the Ge(Li) detector. A further description was given in Section 2.1.2.A. A spectrum obtained from this experiment is shown in Figure 36, and the results are included in Table 6.

The experimental results show β^+ feeding to the 670-, 962-, 1412-, and 1547-keV states. An upper limit of 0.02% has been placed on the β^+ feeding to the 1327-keV state. All states above 1547 keV are fed too weakly to be observed in this spectrum. A comparision of the measured β^+ feeding to the states to those predicted from calculated $\epsilon_K^{\ }/\beta^+$ ratios (Le66) is given in Table 7. The experimental values were normalized to the predicted $\epsilon_K^{\ }/\beta^+$ ratio for the ground state and the ratio of the 670-keV γ intensity to the 511-keV intensity as measured by Borchert (Bo69). The differences between the experimental and theoretical values for the first two excited states is small, but it is very large for the other two β^+ -fed states. This is another case where the apparently allowed β decay is "hindered" as indicated by the lower than predicted β^+ feeding. A further discussion of the nature of these levels is given in Section 5.6.

5.4. Decay Scheme

Figure 37 shows the decay scheme deduced from our experiments. Transition and excited-state energies are in keV, with the adopted energies for the levels being a weighted average of several experimental runs. The Q_{c} of 3364 keV was obtained from 63 Cu(p,n) measurements by Birstein et al. (Bi66). The total transition intensities, in percent of total 63 Zn decay, are given in the decay scheme. Since all the internal



Table 7.

Comparison of Experimental and Theoretical β^+ Feedings for 63 Zn.

Level	β ⁺ Fee	eding	εĸ	/β ⁺
(keV)	Experimental	Theoretical	Experimental	Theoretical
670	7.54%	7.32%	0.0942	0.127
962	5 .2 3%	5.23%	0.232	0.232
1412	0.33%	0.52%	1.91	0.840
1546	0.032%	0.055%	3.19	1.41

Theoretical results are from Le66.

conversion coefficients would be less than 0.5% of the transition intensity, they were ignored. From the measured relative β^+ feedings, the I_{670}/I_{β}^+ ratio measured by Borchert (Bo69), and the theoretical ϵ_{χ}/β^+ ratio for the ground state, the total intensity of the 670-keV γ was calculated. The total feeding intensities for decay to each state were then calculated based on the transition intensities relative to the 670-keV γ . These total feeding are given in the decay scheme to the right of the energy levels with the exponents given in parentheses. Log ft values based on them appear in italics at the extreme right of the levels. A comparison of these results with those of charged particle scattering reactions was shown in Figure 32. Three weak γ rays were not placed.

5.5. Spin and Parity Assignments

Ground State

The ground state of stable 63 Cu is assigned $I^{\pi}=3/2^{-}$ on the basis of the results of many charged particle scattering experiments as well as those of many other types of experiments, e.g., atomic beams, etc. The log ft for the feeding to this state is 5.4, which agrees well with an allowed decay from the $3/2^{-}$ ground state of the 63 Zn parent. 669.71-, 962.14-, and 1327.0-keV States

These states have been observed many times in scattering reactions and have been assigned $I^{\pi}=1/2^{-}$, $5/2^{-}$, and $7/2^{-}$, respectively. The log ft's for the first two excited states are well within the range of allowed β decay. This is expected from the scattering results. No decay is observed to the 1327-keV state, this in keeping with it being a second-forbidden decay, which would have a log ft in the range 10-14. A detailed comparison with results predicted by a number of calculations for these states is given in Section 5.6.



Fig. 37. Proposed decay scheme for 63Zn.

1412.07-keV State

The results of many scattering experiments suggest $I^{\pi}=5/2^{-}$ for this state. The log ft of 5.6 which falls in the range of an allowed transition supports this assignment. Although the evidence is not conclusive, this assignment is supported by the existence of the strong 450-keV transition to the 962-keV (5/2⁻) state, a weak 742-keV transition to the 670-keV (1/2⁻) state, and a very strong transition to the ground state (3/2⁻).

1546.8-keV State

decay to this state has a log ft of 6.5 suggesting an allowed decay or a fast first-forbidden transition. Since the only positive parity orbital in this shell, the $1g_{9/2}$, is at ~2510 keV (B165) and the first negative parity state in the 62 Ni core is a 3⁻ state at ~3700 keV, it is expected that positive parity levels should be first observed somewhere above 2 MeV. This state is therefore fed by what appears to be an allowed transition. Although not commonly observed in scattering reactions, 64 Zn(τ, α) and 63 Cu(d, d') (Ba65) results indicate $I^{\pi}=3/2^{-}$. In addition to the decay to the ground state this state has a weak γ transition to the 962-keV state. Thus, the γ -ray data are consistant with the $3/2^{-}$ assignment for this state.

1860.9- and 1865.7-keV States

These two states are considered together, since previously only one state has been reported in this region. That state was described as $7/2^{-}$ from the 64 Zn (τ, α) results. However, the log ft's of 6.8 and 7.0, respectively, indicate a slow, allowed (eliminating first-forbidden as above) β transition to each state, which would limit the spins to 5/2 at most. The 1860-keV state is observed to decay almost equally to the ground and second excited states, while the 1865-keV state appears to decay to the ground state. This suggests an $I^{\pi}=(1/2^{-})$, $(3/2^{-})$, $5/2^{-}$ for the 1860-keV state and $1/2^{-}$, $3/2^{-}$, $5/2^{-}$ for the 1865-keV state.

2012.0-keV State

A log ft of 7.0 indicates a slow allowed β transition to this state, which is observed to decay solely to the ground state. Scattering reactions assign $I^{\pi}=1/2^{-}$ to this state. The present work is consistent with this assignment.

2062.3-keV State

This state decays to the 670-keV state with about three times the intensity of that to the ground state. The log ft for β feeding to this state is 6.0. The assignment of $I^{\pi}=1/2^{-}$ agrees with scattering results.

2081.4-keV State

The ß feeding to the 2081-keV state produces a log ft of 6.5. The state in turn decays about twice as fast to the 1327-keV state as to the ground state. Since the 1327-keV state has $I^{\pi}=7/2^{-}$, the 2081-keV state is limited to $I^{\pi}=3/2^{-}$ or $5/2^{-}$. Although there is no observed decay to either $5/2^{-}$ state (a transition to the 1412-keV state would fall under the 670-keV), this state is assigned $I^{\pi}=5/2^{-}$.

2092.5-keV State

The decay of this state to the 962-keV state $(5/2^{-})$ is about three times the intensity of the decay to the ground state $(3/2^{-})$. In addition, this state receives no observable β feeding. The ⁶⁴Zn(τ , α) results indicate $I^{\pi}=7/2^{-}$. The present results agree with this assignment, although $I^{\pi}=5/2^{-}$ would also be possible.

2336.8-keV State

The 2337-keV state has a transition to the ground state $(3/2^{-})$, a transition with half the intensity to the 962-keV state $(5/2^{-})$, and an even weaker one to the 1412-keV state $(5/2^{-})$. The log ft for β decay to this state is 5.8, indicating most likely an allowed transition. This limits I^{π} to $1/2^{-}$, $3/2^{-}$, or $5/2^{-}$. The 64 Zn (t,α) results indicate a $3/2^{+}$ state, while the 62 Ni (τ,d) results indicate it to be $5/2^{-}$. Since there is no agreement in the scattering results, I^{π} of $3/2^{-}$ or $5/2^{-}$ is assigned to this state.

2497.5-keV State

β decay to this state has a log ft of 6.4 suggested an allowed or first forbidden ε decay to it. This state decays to the ground state and perhaps to the 670-keV level $(1/2^{-})$. The second transition has been placed by the energy difference even though the agreement was ~2.5 keV. This state is therefore assigned $I^{\pi}=1/2^{\pm}$, $3/2^{\pm}$, or $5/2^{\pm}$. We are now in the region where positive parity states might be expected.

2512.5-keV State

This state has a single decay to the ground state and a log ftof 6.7 from ϵ feeding. These place few limits on the assignment of this state, only that it is $1/2^{\pm}$, $3/2^{\pm}$, or $5/2^{\pm}$. The results of many different scattering experiments shown in Figure 32 indicate a $9/2^{+}$ state at ~2510 keV. Although this assignment would be incompatible with the feeding to and decay from this level, it is consistent with the overall 63 Cu results, since Mazari et al. (Ma57) report two states in this region, at 2504 and 2510 keV. The state observed in scattering could be the 2504-keV one, while the one observed in β decay experiments could be their 2510-keV level. The present assignment for the 2512-keV state is $1/2^{\pm}$, $3/2^{\pm}$, or $5/2^{\pm}$.

2536.2-keV State

This state has a multitude of γ transitions proceeding from it. In addition to the ground state decay (3/2⁻), there is a γ transition of twice the intensity to the 1412-keV state (5/2⁻), and two, each with ~1/4 the intensity, to the 1327- (7/2⁻) and 962-keV (5/2⁻) states. The log *ft* to this state is 5.4, indicating a strongly allowed transition. The assignment for this state is $I^{\pi}=5/2^{-}$.

2697.0-keV State

This state has a ε feeding with a log ft of 5.4 to it and three γ transitions proceeding from it. In addition to the ground-state decay, there is a γ transition of about 1.7 times the intensity to the 670-keV (1/2⁻) state and one with about half the intensity to the 1547-keV (3/2⁻) state. The $^{62}Ni(\tau,d)$ reaction indicates $I^{\pi}=1/2^{-}$. γ -ray results are consistent with this assignment, although the 3/2⁻ and 5/2⁻ possibilities cannot be excluded.

2717.2-keV State

This state has, in addition to its ground-state decay, a decay to the 1327-keV (7/2⁻) state of three times the intensity, one with the same intensity to the 2092-keV state, and one with one-third the intensity to the 670-keV (1/2⁻) state. The log ft of 5.7 indicates an allowed ε transition. All of this limits the assignment to $I^{\pi}=3/2^{-}$ or $5/2^{-}$, with $5/2^{-}$ being the more probable based on γ ray intensities.

2780.6-keV State

This state decays to the 670-keV $(1/2^{-})$ state with about half the intensity of the ground-state decay. The log ft from the feeding is 6.1. This suggests an assignment of $I^{\pi}=1/2^{-}$, $3/2^{-}$, or perhaps $5/2^{-}$. Although a positive parity is possible, it is not probable. The results of the $^{62}Ni(\tau,d)$ reaction indicate an assignment of $3/2^{-}$.

2807.1- and 2857.8-keV States

Both states are ε fed with a log ft of 6.9 and have only a ground-state γ transition. They are therefore assigned $I^{\pi}=1/2^{\pm}$, $3/2^{\pm}$, or $5/2^{\pm}$, since both allowed and first forbidden ε decay are possible. 2889.5-keV State

The 2889-keV state has a γ transition to the 962-keV (5/2⁻) state that is about three times the intensity of its ground-state transition. The log ft of 6.3 suggests an allowed transition but with a first forbidden decay not ruled out. The assignment for this state is most likely I^{π} =5/2⁻ or perhaps 3/2⁻. The ⁶²Ni(τ ,d) data indicate a 1/2⁻ state at [≈]2880 keV.

3044.0-keV State

This state has an ε feeding with a log ft of 6.2 and only a ground-state γ transition. An assignment of $7/2^-$ is indicated from the results of the 64 Zn (t,α) reaction but could be for the level at 3032 keV reported by Mazari et al. (Ma57), since the low log ft would suggest an allowed transition. This state is therefore assigned $I^{\pi}=1/2^{\pm}$, $3/2^{\pm}$, or $5/2^{\pm}$.

3100.3-keV State

The ε feeding to this state has a log ft of 6.8, and the state has only a ground-state γ transition. It is therefore assigned $I^{\pi} = 1/2^{\frac{1}{2}}$, $3/2^{\frac{1}{2}}$, or $5/2^{\frac{1}{2}}$.

5.6. Systematics

Many authors have performed calculations on the ⁶³Cu nucleus. The most commonly used approach is using a quadrupole-quadrupole interaction to couple the odd proton to the ground state and the first excited state, a 2^+ state, at 1172 keV in 62 Ni. Configuration admixing of the $2p_{3/2}$, $2p_{1/2}$, and $1f_{5/2}$ single particle proton states also needs to be included. Results of calculations including those using other approaches are shown in Figure 38. The percent single particle admixtures are shown when available. A percentage of zero indicates the particular single-particle state that could mix was not used in the calculations. The experimental admixtures are from the 62 Ni(τ ,d) 63 Cu reaction of Blair (B165).

Lawson and Uretsky (La57) applied the "center of gravity" theorem of atomic j-j coupling to the 63 Cu nucleus by assuming that the nucleus was a $2p_{3/2}$ proton coupled to the 62 Ni even-even core. The first four excited states of 63 Cu were then considered to be the quartet formed by coupling the proton to the 2⁺ vibrational first excited state of 62 Ni. By applying this formalism and using the 1412-keV state in 63 Cu as the $3/2^-$ member of the quartet, a center of gravity for the 2⁺ level was obtained at 1167 keV which compared well with the experimentally determined energy of 1172 keV. Later experiments showed the 1412-keV state to be $5/2^$ and the necessary $3/2^-$ state has not been found below 2 MeV. No single particle admixtures were used in the calculations.

A "unified" model was used by Bouten and Van Leuvén (Bo62). The ⁶²Ni core was allowed quadrupole surface oscillations with no more than two phonons. The odd proton was in the $2p_{3/2}$, $2p_{1/2}$, or $1f_{5/2}$ states and coupled to the surface oscillations. The ground state and first two excited states were used as input parameters to obtain the single-particle level spacings. Good agreement was reached between calculated and experimental values for the electric quadrupole moment and for the $\tau(E2)$, the transition half-life, for the first two excited states. Althrough agreement



Fig. 38. Results of calculations of excited states in $^{63}\mathrm{Cu.}$

within a factor of two was also reached for the $\tau(M1)$ for these transitions, poor agreement was reached for the magnetic dipole moment.

Gove (Go63) applied the calculations of Bayman and Silverberg (Ba60) for coupling a j=3/2 particle to quadrupole surface oscillations to the case of 63 Cu. These calculations are in good agreement with the observed B(E2)'s. Harvey (Ha63) extended the Bayman-Silverberg model to the magnetic dipole moment and transition probabilities. He obtained good agreement for the dipole moment and for the B(M1) for the transition from the 962-keV state, but his results were a factor of four faster than the B(M1) experimentally obtained for the 670-keV transition.

A strong coupling model was used by Thankappan and True (Th65). The even-even 62 Ni core which performs quadrupole surface oscillations was coupled by a quadrupole interaction with a dipole element added to the single proton in the $2p_{3/2}$, $2p_{1/2}$, and $1f_{5/2}$ orbitals. Only the 0⁺ ground state and 2⁺ first excited state of 62 Ni were considered in this calculation. Parameters also used were the orbital spacings of Bouten and Leuvén (Bo62), however, these were adjusted for better agreement of the calculations with the experimental results. The agreement for the calculated B(E2)'s with experimental results is good, but the fits of the B(M1)'s vary from good to very bad. Also, the quadrupole moment is in good agreement as is the dipole moment.

Beres (Be66) used a very different model, namely he described the core as a quasiboson of angular momentum 2^+ and the odd proton as a quasiproton of spins $1/2^-$, $3/2^-$, and $5/2^-$. The core and the quasiproton were coupled by a quadrupole interaction. The resulting calculated B(E2)'s were in general agreement with experimental results. He also calculated the case of two quasineutrons interacting via a quadrupole

interaction with the quasiproton. This method gives a large number of low lying levels, and the collective quartet appears very closely spaced at about 2 MeV with the B(E2) values for this quartet in agreement with those of the other method. This method, however, gives much better agreement for the higher lying positive parity states in 63 Cu, and good agreement is also obtained between the calculated inelastic α scattering cross sections and those observed experimentally.

The model used by Kisslinger and Kumar (Ki67) is a modified phenomenological vibrational model with its microscopic description in terms of the pairing-plus-quadrupole model. This involves the coupling of the vibrational phonon with a quasiparticle with a quasirandom phase approximation.

Simons and Sundius (Si69) used a vibrational core with up to three phonons coupled to a single particle in the $2p_{3/2}$, $2p_{1/2}$, and $1f_{5/2}$ states. They treated the phonon energy as a free parameter and obtained values somewhat greater than those of Bouten and Van Leuvén. They obtained a reasonable fit for the magnetic dipole and electric quadrupole moments, and the fits to the B(E2) and B(M1) for the 670-keV transition are reasonable. However, the B(M1) for the 962-keV transition does not fit well at all.

A semimicroscopic model of coupling the proton to a quadrupole vibrator was used by Paar (Pa70). The vibrator was allowed up to three phonons and the proton states included the $2p_{3/2}$, $2p_{1/2}$, $1f_{5/2}$, and $1f_{7/2}$ states. The $1f_{7/2}$ was included since experimental results indicate that the $1f_{7/2}$ is not a good closed shell in this case but is partially empty producing a partially filled $2p_{3/2}$ state. Reasonably good fits were obtained for the B(M1) and B(E2) values and for the magnetic dipole and



The results shown are from ND.

electric quadrupole moments.

Wong (Wo70) performed shell model calculations for the 63 Cu using a weak coupling model with the $2p_{3/2}$, $2p_{1/2}$, and $1f_{5/2}$ orbitals for the proton. The energy levels produced by the shell model calculations are in poor agreement with the experimentally determined energy levels. The fits for the B(M1)'s and B(E2)'s were only fair, although better agreement was reached for the magnetic dipole and electric quadrupole moments.

The intermediate coupling model developed by Thankappan and True (Th65) was used by Larner (La70) to calculated the states $in^{63}Cu$. For the calculations, Larner coupled the 0⁺ ground state and 2⁺ first excited state of ^{62}Ni to the $2p_{3/2}$, $2p_{1/2}$, and $1f_{5/2}$ orbitals with an interaction that contained both dipole and quadrupole terms. For the first case, he used the experimental energy levels and single-particle strengths as input parameters, while the second case used the experimental energy levels and B(E2) values. The results of both cases gave similar good fits to the energy levels, and the first case also gave good fits to the B(E2)'s.

Although most of the calculations agree on single particle admixtures, they are in disagreement with the experimental results. In particular, everyone except Paar (Pa70) assumes that the $1f_{7/2}$ shell is a good closed shell. The experimental results indicate the 1327-keV 7/2⁻ state has a 6% single particle admixture which would come from the $1f_{7/2}$ closed shell. This agrees with the results of Goode et al. (Go69) which indicate that ⁵⁶Ni is only 94% a doubly closed nucleus.

Figure 39 shows a comparison of the levels of the odd mass Cu isotopes. A comparison with the other Cu isotopes indicates the 1400-keV level in 59 Cu may be an unresolved doublet of a $5/2^-$ and a $7/2^-$ level. In general, the excited states rise in energy with neutron number.

CHAPTER VI

DECAY OF ⁶²Zn

6.1. Introduction

The odd-odd nuclide, ${}^{62}_{29}$ Cu₃₃, contains a single proton and five neutrons outside the doubly closed $1f_{7/2}$ shell. Consequently, its states should be amenable to interpretation in fairly straightforward shell-model terms. Also, many states and trends in nearby odd-mass nuclei are known, providing reasonably trustworthy input for predicting the properties of its odd-odd states. Unfortunately, relatively few states are known in 62 Cu itself, and even fewer have been well characterized. Here, the decay of 9.3-h 62 Zn to 62 Cu has been reexamined using the largest Ge(Li) detectors the laboratory has been able to obtain in order to pick up weak β feedings that previously have gone undetected. The findings are then correlated with those of previous investigators and with the data from scattering reactions in an attempt to obtain a more coherent understanding of the structures of the 62 Cu states.

Since the discovery of 62 Zn by Miller et al.(Mi48), it has been studied by many other groups. Hayward (Ha50) determined the end-point energy of its β^+ spectrum to be 0.66±0.01 MeV and observed K and L conversion electrons from the 41.8±0.8-keV transition, the K/L ratio indicating it to be El or M1. Nussbaum et al. (Nu54) determined that the first excited state of 62 Cu lies at 41.3±0.3 keV and that 36±3% of the 62 Zn feeding passes through this state. From α_{K} and K/(L+M) they assigned the 41.3-keV transition an M1 multipolarity.

The first reasonably complete decay scheme was formulated by Brun et al. (Br57) who performed extensive electron and NaI(T1) γ -ray spectroscopy, including coincidence and $\gamma-\gamma$ angular correlation

experiments. They deduced states in 62 Cu at 0, 0.042, 0.30, 0.55, 0.63, and 0.70 MeV.

In the last few years there has been a flurry of activity about the neutron-deficient members of the N=62 mass chain. Four groups (An67, Ro67, Ba68, Ho69) have reported Ge(Li) γ -ray studies on the decay of 62 Zn, and two other groups (Jo69, Va70) have reported on the decay of 9.9-min 62 Cu itself. Antman et al. (An67) performed the first high-resolution Ge(Li) γ -ray experiments (in conjunction with electron experiments), and they and Roulston et al. (Ro67) demonstrated conclusively the doublet nature of the \approx 245-keV γ -ray peak and the existence of a 507.6-keV γ . These data were essential to the construction of a correct decay scheme, and the two groups arrived at almost identical decay schemes containing the first five excited states in 62 Cu that are populated by 62 Zn decay. The most precise half-life determination for ⁶²Zn, 9.2±0.1 h, is also the work of Antman et al. Bakhru (Ba68) also performed high-resolution Ge(Li) γ -ray spectroscopy, including coincidence experiments, and he measured the half-life of the 42-keV state to be 2.5±0.1 nsec. His decay scheme, however, differs in several placements from the others. The most recent paper on ⁶²Zn decay, by Hoffman and Sarantites (Ho69), again includes results from $\gamma-\gamma$ coincidence experiments and shows a decay scheme almost identical to those of An67 and Ro67.

Nuclear reaction and in-beam studies have been reported, also. Davidson et al. (Da70) have used the ${}^{62}Ni(p,n\gamma)$ reaction to study the decay of the excited states in ${}^{62}Cu$. They performed γ -ray angular correlations in addition to γ -ray singles measurements at various excitation energies in order to learn something about spins and parities as well as placements of the states. Fanger et al. (Fa70) report on similar

techniques using the $^{61}Ni(n,\gamma)$ reaction to study states in ^{62}Ni .

The points yet to be clarified are clear: 1) None of the groups studying 62 Zn decay was able to detect any γ rays with energies above 637 keV, although $Q_{_{\rm E}}$ is ~1620 keV. Part of this problem came from the interference of γ rays from 62 Cu itself, which quickly grows into the sources. But now that the decay of 62 Cu is known (Jo69, Va70, Fa70) with some assurance, weak γ rays from 62 Zn can perhaps be distinguished more readily. Also, the larger Ge(Li) detectors now available, having very good peak-to-Compton ratios, should allow one to detect very weak higher-energy γ rays. 2) Very little in the way of interpretation of the structures of the 62 Cu states has been done. Both sides of the problem have been attacked with the following results. 1) Six new weak γ -rays that deexcite four new excited states in 62 Cu can be reported. 2) The structures of the 62 Cu states have been examined in terms of shell model states and the trends observed in this nuclear region, and this very straightforward method has been found to explain much of what is observed.

6.2. Source Preparation

The 62 Zn sources were prepared by irradiating natural Cu foils (69.17% 63 Cu, 30.83% 65 Cu) with 25-MeV protons accelerated by the MSU Sector-Focused Cyclotron. The reaction of interest was 63 Cu $(p,2n){}^{62}$ Zn. Typically, ${}^{\approx}$ 150-mg targets were bombarded with a 1-µA beam for 30-45 min. The only Zn contaminant of any consequence was 38-min 63 Zn, which was essentially eliminated by waiting 4 hours before counting the 62 Zn sources. All other possible contaminants were removed using the chemical separation described in Section 2.3.

6.3. γ -Ray Spectra

Many γ -ray spectra were taken over a long period of time, always using the largest Ge(Li) detectors at our disposal. Spectra were taken with the 2.5% and 3.6% efficient detectors, although most of the spectra were taken with the 10.4% efficient Ge(Li) detector. A typical spectrum taken with the 10.4% efficient detector is shown in Figure 40. As it was mandatory that the higher-energy portion of the spectra be optimized yet maintain a high counting rate in order to minimize stray background peaks that could mask the weak 62 Zn peaks, the spectra were taken through a set of absorbers and with the geometry shown in Figure 41.

Each sample was counted for several consecutive 6-h periods to insure that the peaks observed came indeed from 62 Zn decay. In addition to the normal procedures, however, an on-the-spot efficiency calibration with 110 Mag and a background count of at least 12 h were performed for each sample. A spectrum obtained in 6 h with the 10.4% detector using the absorbers is shown in Figure 42. Note that six very weak higherenergy γ rays attributed to 62 Zn decay can be seen in this spectrum.

The centroids and areas of the photopeaks were determined by using the computer program SAMPO. The secondary energy calibration was performed using the stronger peaks of 62 Zn, its 62 Cu daughter, and the 40 K present in the natural background. The efficiency calibration for the spectra obtained both with and without the absorbers was performed using the method described in Section 2.1.3. The energies and relative intensities of the 62 Zn $_{\rm Y}$ rays are listed in Table 8, where they are compared with the results of the other investigations that used Ge(Li) detectors. Since the point of the investigation was specifically to obtain new information about weak transitions, no coincidence experiments







Fig. 41. A diagram of the sample and absorber placement used to study ⁶²Zn decay.





Tnis Work		Antman, Pette and Suarez (1	ersson An67)	Roulston, and Brown	Becker, (Ro67)	Bakhru (Ba68)		Hoffman and Sarantites (Ho69)
E_{γ} (keV)	+ 2-	Ξ _、 (keV)	r Y	E_{γ} (keV)	$I_{\gamma}^{a}(\pm 10\%)$	$E_{\gamma}(\text{keV})$	I _Y	$E_{\gamma}({\sf keV})$	- -
40.94±0.06	104±10	40.38=0.09	(102) ⁵	41.5±0.2	(192)	42	100±5	40.84±0.13	99.4 ±3.5
243.44±0.03	11.1±0.5	243.40±0.05	= 7]	243.7±0.5	15			243.43±0.2 0	10.3±0.5
247.04=0.04	8.3=0.4	247.02-0.09	:4 11.0±0.9	247.2±0.5	12	245	10±1	247.02 0.20	8.2 0.3
260.50.0. 06	5.9=0.3	260.44=0.10	2.6±0.5	260.7±0.5	8	260	4±1	260.39±0.08	5.9±0.1
305.0 0±0.07	1.24±0.1	1	1	305.5±1. 0	0.8		1	304.80±0.2 0	1.32±0.07
349.59±0.07	1.83±0.1	349.69±0.25	:1	349.5±1.0	1.5			349.34±0.11	1.59±0.16
394.06±0.04	9.2±0.4	394.12=0.18	6.2±1.0	394.5±0.5	10.7	395	5±1	393.8 0±0.06	9.16±0.12
507.5 ±0.4	58 ±10	<u>507.57=0.13</u>	60±15	507.5±1.0	77	505	40±3	507.41±0.15	65 ± 15
548.41±0.04	60.8=1.0	548.33=0.22	59±5	548.7±0.5	65	547	60±4	548.25±0.11	62.2=0.9
596.65±0.04	≡ 1 00	596.68±0.20	100±8	597.0±0.5	100	595	100±5	596.6 0±0.11	≡100 ±
637.53 ±0.06	0.96±0.06	636.9=0.5	1 ∼1	638.5±1.0	1.5	1	8	637.20±0.12	3.45±0.25
	1	1	1	1	1	682	≈4±2	5	8
881.4±0.8	0.08:0.03	5		1	8	8	8 8 8	8	1
915.6±0.6	0.08=0.03	8	1	2 1 8	8	1	8	7	8
1142.5±0.2	0.13±0.03	8	-	L 8 9	1	8	1 8 1	-	2
1280.8±1.5	0.03±0.01	3	1	8	2	8	8 8 8		2
1389.1±0.5	0.05±0.02	8	8	1			-	8	
1429.9±0.3	0.13=0.02	;		;		1			1

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³Normalized to $^{-}$ 597.0 $^{\pm}$ 100, retaining original number of significant figures 5 Calculated from the adopted value for an %1 transition.

Table 8. Energies and Intensitivs of , Rays Following the Decay of $^{\tilde{n}\,2}\text{Zn}$


were performed.

A decay scheme which includes the present work is shown in Figure 43. The levels, spins and parities, and transition placements below 950 keV are from Davidson et al. (Da70), which are consistent with the other results, and the energy levels above 950 keV are from the 61 Ni(τ ,d) reaction (Mo67). The percent feedings were determined from the percent ground state feeding determined by Hoffman et al. (Ho69) and the relative γ -ray intensities and are found on the right of the decay scheme. The log ft's based on these feedings are on the extreme right.

6.4. Discussion

 $_{29}Cu_{33}^{62}$ is an odd-odd nucleus one proton and five neutrons removed from the doubly closed shell at Z=N=28. The simplest approach is to extend the the odd-group model, as normally applied to oddeven and even-odd nuclei. In this model the properties of the nuclear states are assumed to be determined primarily by the odd group of particles. In extending it to odd-odd nuclei it is assumed that the wave functions for the states and the odd-odd nuclei are simple vector-coupled product of wavefunctions of the two odd groups. If it is assumed that the residual p-n interactions are weak compared with spin orbit forces (De61) jj coupling can be used with its simplifications. With the assumption of jj coupling, a given proton and neutron configuration $| {}^{\iota}_{p} j_{p} {}^{\iota}_{n} j_{n} >$, can take on all integral spins, $|j_p - j_n| \leq I \leq j_p + j_n$, where the nature of the residual p - n interaction will determine the ordering of these spins. The modified Nordheim coupling rules proposed by Brennan and Bernstein (Br60) can be useful in predicting the ordering of the spins resulting from a given

configuration. Here j_p and j_n are the single-particle total angular momenta obtained from the adjacent odd-mass nuclei, while l_p and l_n (assumed to be pure) are the orbital angular momenta obtained from the standard shell model assignments.

Examining the systematics of the odd mass Cu isotopes, Figure 39, and the odd mass N=33 nuclei, Figure 44, the 62 Cu ground state is assumed to be a $(\pi_{p_{3/2}})(\nu_{p_{3/2}})^{-1}$ configuration for which the coupling rules would predict a ground state of 2^+ with a 1^+ first excited state. However, it is found that these two states are reversed with the 1^+ being the ground state. If the ground state configuration were $(\pi_{p_{3/2}})(\nu_{p_{1/2}})$, the coupling rules would predict the states in correct order. It has been found (Ph68) that there is considerable configuration mixing between these two configurations as well as others which would explain these results.

Table 9 gives the possible proton-neutron configurations in 62 Cu and the spins they would produce in approximate order of increasing energy. The individual proton and neutron orbitals are given in order of increasing energy as determined by the odd mass Cu and odd mass N=33 nuclei. Although the proton orbitals remain well behaved, the neutron orbitals are closely spaced and can change ordering rather easily. As a result, the relative positioning of the levels in 62 Cu is difficult to predict and considerable configuration mixing can occur. Therefore, a further explanation of the higher-lying states of 62 Cu will require more calculations on the orbitals as well as further experimental results. A comparison of the levels in 62 Cu with those of other odd-odd Cu isotopes is shown in Figure 45.



Table	29
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States	Produced	l by	v Some	Lc	w-Lyi	ng
Configu	irations	in	0dd-00	bb	⁶² Cu.	

Proton Orbital	Neutron Orbital	States Produced
^{mp3} /2	$vp_{1/2}^{vp_{3/2}}$ $vp_{1/2}^{vf_{5/2}}$	$2^+_{1+}, 1^+_{+}, 3^+, 0^+_{1+}, 2^+_{1+}, 3^+, 4^+_{1+}$
^{πp1} / ₂	vp 3/2 vp 1/2 vf 5/2	$1^+_{+}, 0^+_{+}$ $1^+_{+}, 2^+_{+}$ $3^+, 2^+$
^{πf5} /2	$v_{p_{1/2}}^{v_{p_{3/2}}}$ $v_{p_{1/2}}^{v_{p_{1/2}}}$ $v_{f_{5/2}}^{v_{f_{2}}}$	4 ⁺ ,5 ⁺ ,3 ⁺ ,2 ⁺ ,1 ⁺ ,0 ⁺ 3 ⁺ ,2 ⁺ 1 ⁺ ,2 ⁺ ,3 ⁺ ,4 ⁺

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CHAPTER VII

DECAY OF ⁶³Ga

7.1. Introduction

The first report of the production of 63 Ga occurred only recently, in 1965, by Nurmia and Fink (Nu65). It was discovered in their search for β -delayed α emission in the light Ga isotopes. However, the only information they reported was that it had a 33-sec half-life, and they estimated its decay energy at 5.3 MeV. Since then, a study of its decay scheme was reported by Dulfer et al. (Du70).

Other studies of the excited states of 63 Zn have been performed by charged particle reactions. Birstein and coworkers have reported results from 63 Cu (p,n_{γ}) (Bi66) and 60 Ni (α,n_{γ}) (Bi67) reactions and have reported the results of γ -ray angular distribution experiments from these reactions (Bi68). Also reported have been other 63 Cu(p,n) (Br55a, An62, Mc66, Ta70), 64 Zn(p,d) (Jo68), 64 Zn(d,t) (Ze60), and 64 Zn (τ,α) (Be67, Fo67) results. A composite comparison of these results giving both ℓ and I^{π} values with the present work is shown in Figure 46. The 63 Cu(p,n)results have not been reported above 1440 keV.

7.2. Experimental Procedure

The sources for the study of 63 Ga decay were produced by irradiating 6-mil and 10-mil thick natural Zn foils (64 Zn 48.89%, 66 Zn 27.81%, 67 Zn 4.11%, 68 Zn 18.57%, 70 Zn 0.62%) with 30-MeV protons from the Michigan State University Sector-Focused Cyclotron. This beam energy was chosen to maximize the production ratio of 63 Ga to 64 Ga, the principle contaminant. Figure 47 shows this ratio as a function of incident beam energy. The various energies were obtained by degrading either 40-Mev or 34-Mev





Fig. 47. Relative production of 63 Ga to 64 Ga as a function of incident beam energy.

Proton beams with the appropriate thickness Al absorbers. A typical **irradiation was a 1-2 second burst of an** $^{2}0.5_{-\mu}A$ proton beam. The **targets were then moved quickly (** $^{2}7$ sec) from the irradiation area to **a distant counting area by a pneumatic rabbit system (Ko70).** The samples were counted with either the 4.6% efficient or 10.4% efficient Ge(Li) detector and using the Ge(Li)-time coincidence system described in Section 2.1.2.C. The time length of the ramp was varied from 120 to 1560 seconds, depending on the particular experiment. In the search for low energy γ -rays, a Si(Li) x-ray detector was used in place of the Ge(Li) detector. Along with each γ -time coincidence experiment, a γ -ray singles spectrum was obtained. A typical experiment involved adding together the spectra from as many as 250 Zn foils.

An energy calibration of the stronger γ rays in the spectrum was performed by counting the Zn foils with ²⁴¹Am, ¹⁵²Eu, and ¹⁹²Ir as internal standards. Also used for the calibration were the γ rays from ⁶³Zn and the 1332-keV and 1791-keV γ 's of ⁶⁰Cu which were internally present. Table 101ists those strong γ rays from sources other than ⁶³Ga that were counted concurrently. These γ rays were then used as internal secondary standards to calibrate the weaker γ rays in the spectra. The intensity calibration was obtained from the procedure described in Section 2.1.3. The centroids and areas of the peaks were determined by the computer program SAMPO.

7.3. Experimental Results

A typical γ -ray spectrum is shown in Figure 48. Sixteen γ transitions were assigned to the 63 Ga decay, and their energies and intensities are listed in Table 11 along with the decay scheme results of Dulfer et al. (Du70) and the 63 Cu($p,n\gamma$) results of Birstein et al. (Bi66).

Table 10

Measured y-Ray Energies

Isotope	Energy
⁶⁰ Cu	826.05±0.15 909.32±0.15 1035.12±0.20
⁶⁴ Ga	807.85±0.10 918.77±0.12 991.50±0.10 1387.35±0.10
⁶⁵ Ga	114.97±0.10 152.93±0.15 751.68±0.10 932.05±0.15 1047.23±0.20 1354.22±0.20

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Table 11

Present Work		Dulfer et al	l. Bin	Birstein et al.	
E	I	<i>E</i> (Du70)	Ι	E(B166)	
193.0±0.2	51.4±3.5	192.9±0.2	49	190±2	
248.0±0.2	30.6±2.0	247.8±0.2	32	246±2	
389.8±0.7	3.4±1.7			390	
415.0±1.3	2.6±1.5			412	
457.9±0.6	5.4±1.4			459	
627.1±0.15	92.1±4.5	627.1±0.2	91	627±2	
637.0±0.15	=100.	637.1±0.2	=100.	636±2	
650.1±0.15	44.0±2.5	649 .9 ±0.2	44	649±2	
768.5±0.2	19.0±2.3	768.2±0.5	12		
1054.6±0.9	2.3±1.2				
1065.2±0.4	19.9±4.0	1065.1±0.6	18	1061±4	
1147.0±0.8	3.1±0.7				
1203.4±2.0	2.4±1.2				
1395.4±0.3	37.0±7.0	1395.5±0.5	41		
1498.5±0.6	2. 9±1.5				
1691.7±0.5	27.4±5.0	1691.8±1.0	28		

 $\gamma\text{-Ray}$ Energies and Relative Intensities from the Decay of ^{63}Ga

The uncertainties in the energies in Table 11 are based on the uncertainties in the energy standards, the height of the peaks above the background, and the reproducibility of the calculated energies from the different spectra. The relative intensities listed are the average from several spectra and their uncertainties are based on the reproducibility of the intensities and the uncertainties in our experimentally determined efficiencies for the detectors. The errors are in general 50% greater than the largest deviation of a value from the average of several runs.

There is quite good agreement between the present results and those of Dulfer et al. (Du70). Seven γ rays were observed in the present study that they did not observe. An upper limit of 2.5 in the units of Table 11 has been placed on the intensity of any unreported γ rays below 511 keV and a limit of 2.0 on those above 511 keV. A search for γ rays from 63 Ga in the energy range 1700 - 4000 keV was performed, but none was observed. A similar search for γ rays below 100 keV was performed using the x-ray detector, but none was observed in this region either. A half-life of 32.4 ± 0.5 sec was determined for 63 Ga by using 12 spectra from the γ -time coincidence system to measure the half-life of the 193-, 627-, 637-, and 650-keV γ transitions.

7.4. Decay Scheme

The decay scheme produced from the present results is shown in Figure 49. Transition and excited state energies are given in keV with the adopted energies for the states being a weighted average of several experimental runs. The $Q_{\rm E}$ of ~5.6 MeV was obtained from the mass table of Garvey et al. (Ga69). The total transition intensities, in percent of total ⁶³Ga decay, are given in the decay scheme. Since all of the internal conversion coefficients would be less than 1% of the individual γ



 $Q_{e} \approx 5.6 \text{ MeV}$

intensities, they were ignored. Using the ratio of the 511-keV γ to the 627-637-650-keV γ -ray triplet measured by Dulfer et al. (Du70), with which these results are consistent, and the theoretical ε/β^+ ratios for the levels (Le66), the total relative feedings to each state were calculated. These total feedings are given in the decay scheme to the right of the energy levels. The log ft values based on them appear at the extreme right of the levels. The spin and parity assignments discussed in the next section are on the left of the levels. A comparison of these results with those of charged particle reactions was shown in Figure 46.

7.5. Spin and Parity Assignments

Ground State

The ground state of 63 Zn is assigned $I^{\pi}=3/2^{-}$ on the basis of charged particle scattering experiments and decay scheme systematics from its decay to states in 63 Cu (cf. Section 5.5.). From scattering reactions an l=1 transfer is indicated, limiting this state to $1/2^{-}$ or $3/2^{-}$. It has an allowed β decay to the $3/2^{-}$ ground state, $1/2^{-}$ first excited state, and $5/2^{-}$ second excited state in 63 Cu, thus limiting the assignment to $3/2^{-}$. The log ft of 5.3 indicated an allowed β decay from the 63 Ga.

193.0-keV State

Scattering results suggest an assignment of $5/2^{-}$. The γ -ray directional correlation experiments of Birstein et al. (Bi68) indicate the 193-keV γ to be a $5/2^{-}$ to $3/2^{-}$ transition. The log ft of 6.3 indicates an allowed transition from the $^{6.3}$ Ga and supports the assignment. 248.0-keV State

The log ft of 6.5 suggests probably allowed β decay which would limit the assignment to 1/2⁻, 3/2⁻, or 5/2⁻. This state decays solely to the ground state. Although the ⁶³Cu(p,n) results report this level, none of the other charged particle experiments observed it. Examining the systematics of the odd-mass Zn isotopes as shown in Figure 50 and the systematics of the N=33 isotopes shown in Figure 45, a $1/2^{-1}$ level in the region below 400 keV is strongly suggested. Since this is the only level that could fit these systematics, it is therefore assigned $I^{\pi}=1/2^{-1}$.

The ground state of 63 Ga is assigned I^{π} -3/2⁻ since allowed β transitions are observed to the 3/2⁻ ground state, the 5/2⁻ first excited state, and the 1/2⁻ second excited state in its 63 Zn daughter. This assignment is consistent with the systematics of the light odd-mass Ga isotopes and the shell model (the odd proton being in the $2p_{3/2}$ orbital). 627.1-, 637.0-, 650.1-keV States

The ß feeding to these states has log ft's of 5.9, 5.7, and 6.1, respectively, all allowed transitions. Results from all the scattering experiments indicate l=1 transfers, most likely $3/2^-$ states. The probability of l=3 transfer was considered small. The 627-keV state decays solely to the ground state, while the 637-keV state also decays to the 248-keV state and the 650-keV state also decays to the 193-keV state. The 627-keV state is therefore assigned $I^{\pi}=(1/2^-, 3/2^-)$, the 637-keV state $I^{\pi}=1/2^-, (3/2^-)$, and the 650-keV state $I^{\pi}=(3/2^-)$.

1065.2-keV State

This state has a β feeding with a log ft of 6.2 and decays to the ground state and the 650-keV state. Results from ${}^{63}Cu(p,n)$ also indicate a level at 1028 keV. Scattering results indicate both $\ell=1$ and $\ell=3$ transfers in this region for presumably a doublet with $\ell=1$, $I^{\pi}=3/2^{-1}$ dominant. This state is therefore assigned $I^{\pi}=3/2^{-1}$.

1395.4-keV State

This state has more γ branching than any other state in $^{6.3}$ Ga.

It decays to the ground state $(3/2^{-})$, the 193-keV state $(5/2^{-})$, the 248keV state $(1/2^{-})$ and the 627-keV state $((1/2^{-}, 3/2^{-}))$. It also is populated by an allowed β transition, as indicated by a log ft of 5.6. The ${}^{64}\text{Zn}(p,d)$ results suggest a $3/2^{-}$ state in this region. The ${}^{63}\text{Cu}(p,n)$ results indicate two states here, with the 1395-keV state the closer to the state observed in the (p,d) results. An I^{π} assignment of $3/2^{-}$, $(1/2^{-})$ is suggested for this state.

1691.7-keV State

This state decays to the 193-keV state $(5/2^{-})$ and the 637-keV state $(1/2^{-}, (3/2^{-}))$ in addition to the ground state. The log ft of 5.7 for feeding to this state indicates an allowed decay. The results from charged particle scattering suggest an $\ell=3$, $I^{\pi}=7/2^{-}$ state. Since a $7/2^{-}$ assignment would not permit allowed β decay, this state is assigned $I^{\pi}=5/2^{-}$, which is consistent with all results.

7.6. Discussion

The 63 Zn is in the region above the doubly closed shell occurring at 56 Nf. In this region the active particle states for both neutrons and protons are the $2p_{3/2}$, $2p_{1/2}$, $1f_{5/2}$, and $1g_{9/2}$. Since both $1g_{9/2}$ orbitals are well above 2 MeV (cf. Figures 39 and 50), they will be ignored. The odd nucleon in 63 Zn is a neutron found in the $2p_{3/2}$ orbital. In contrast to its 63 Cu daughter where the low-lying states are from the odd proton coupling to a core vibrational state, the first two excited states in 63 Zn appear to be primarily single particle states, the first being the $1f_{5/2}$ and the second the $2p_{1/2}$. These three single particle states remain rather closely spaced in the lighter Zn isotopes with the $1f_{5/2}$ being the ground state for 65 Zn and 67 Zn.

The triplet of the 627-, 637-, and 650-keV states appear to be



core coupled states. Since the log ft's to these states fall between that of the ground state decay and those to the first two excited states, these states would therefore result from the coupling of the odd neutron in the $2p_{3/2}$ orbital to a 62 Zn core excitation. However, since little is known about the excited states in 62 Zn, the details of these states must be left to a later time. Not enough is known about the higher-lying states in 63 Zn since they occur above the pairing gap and could result from several different sources, so therefore little can be said about them here.

The ß decay from 63 Ga to the states in 63 Zn presents some very interesting problems. The ground state of 63 Ga apparently has the odd proton in the ${}^{\pi}p_{3/2}$ orbital. The ground state of 63 Zn appears to be $(\pi p_{3/2})^2 (vf_{5/2})^2 (vp_{3/2})^3$ or some similar neutron configuration since it has five neutrons outside a closed shell and an $I^{\pi}=3/2^{-}$. While a neutron configuration of $(vp_{1/2})^2 (vp_{3/2})^3$ might appear to more easily explain the ground state of 63 Zn and the nonobservance of its 248-keV (1/2⁻) state in all the scattering reactions, it is not a probable configuration since it would require the lower spin state of an ℓ to be below the higher spin state, and this does not occur in nuclear level systematics.

The more probable configuration suggests that the $vp_{3/2}$ and $vf_{5/2}$ states are degenerate so that both may be partially filled. The decay from the ⁶³Ga indicates a normal allowed transition to the ⁶³Zn ground state with its suggested degeneracy, while unexpectedly slow β transitions feed the supposedly pure single particle 5/2 and 1/2 states. A much more detailed study of this region **is** necessary before these states in ⁶³Zn can be fully explained.

CHAPTER VIII

62 Ga AND β -DELAYED α EMISSION

8.1. Introduction

The occurance of β -delayed α emission has been known for a long time. In 1935, Crane et al. (Cr35) reported the β -delayed α decay of 850-msec ⁸Li. Alvarez (A150) in 1950 expanded the list when he reported similar decays for 774-msec ⁸B, 11.0-msec ¹²N, and 405-msec ²⁰Na. Further searches for β -delayed α emission in the light elements have produced 20.4-msec ¹²B, 7.13-sec ¹⁶N, 2.09-sec ²⁴Al, and 297-msec ³²Cl. All of these nuclei are of the type $N=Z\pm 2$, where Z is odd, β decaying to excited states in N=Z even-even nuclei. The excited states immediately decay by emitting an α particle rather than by the usual γ emission.

In their report of the discovery of 33-sec 63 Ga, Nurmia and Fink (Nu65) reported their purpose was to look for delayed α 's from 62 Ga, but they did not observe any. Their search was based on calculations by Taagepera and Nurmia (Ta61) which indicated the possibility of β -delayed α emission in the nuclei just above the 56 Ni doubly closed shell, among other places. Fengés and Rupp (Fe68) used these calculations and the Myers and Swiatecki mass tables (My65) to predict the onset of β -delayed α and proton emission for all elements through N=84. Their results indicate that 64 Ga would be the heaviest possible β -delayed α emitter for Ga, with delayed proton emission expected to start with 62 Ga and direct proton emission expected to start with 60 Ga.

Figure 51 shows the mass equation-based predictions of Myers and Swiatecki (My65) for the light Ga isotopes as well as predictions based on experimental results from the $^{6.3}$ Ga decay described in Chapter 7. The figure indicates α and proton binding energies from both sources. Since





the proton binding energies are close to those for α particles, the lower Coulomb barrier could make β -delayed proton emission competitive with the β -delayed α emission. The general trend of increasing decay energy with decreasing particle binding energy is easily seen both in calculated and experimentally based binding energies. An anomaly is seen in the binding energies of 60 Ga. The β -delayed α emission of 60 Ga would lead to 56 Ni, a doubly closed shell nucleus. However, the experimentally based binding energy is larger than that of 61 Zn, and the proton binding energy is the same as that for 61 Zn. The corresponding calculated values from Myers and Swiatecki (My65) decrease approximately with A. With these results and calculations in mind, a search for β -delayed α emission in the light Ga isotopes was begun.

8.2. Experimental Procedure

The search for β -delayed α emission utilized the He-jet thermalizer and α detectors described in Section 2.2. In addition to the α detector, the 4.6% efficient Ge(Li) detector was also used to count the γ rays from the collected nuclei. The targets used were 0.1-mil thick natural Cu foils. Three foils were used at any one time, each separated by a 0.8 inch thick teflon block with a 1-inch ϕ hole in it. An incident beam of 70 MeV τ of about 0.4 μ A current was used to produce the light Ga isotopes. Lower beam energies were obtained by degrading the beam with Al absorbers. The range of the recoils produced with this beam is 0.035 mil in Cu or 0.74 inches in the 2 atm He used. The ranges were calculated using the results reported by Harvey (Ha60). The recoils were collected on masking tape. The bombardment energies of 70, 55, and 40 MeV were chosen to represent the peak in the production cross section of 61 Ga, 62 Ga, and 63 Ga, respectively.



Fig. 52. An α spectrum from the β -delayed α emission of ²⁰Na (Po67).

In order to insure β -delayed α 's could be observed, the β -delayed α decay of 20 Na (Po67) was examined. For this experiment, the Cu foils were removed and Ne gas was allowed to leak into the target chamber along with the He thermalizer gas. The results of this test are shown in Figure 52. In addition to the 20 Na peaks, there is a peak from 241 Am. This appears to be contamination on the detector face and is seen in other spectra including those with no source present. For this experiment, the recoils were collected on a cooled Al block.

8.3. Results

In Figure 53, the results of the search for β -delayed α emission in the light Ga isotopes are shown. Incident beams of 70-, 55-, and 40-MeV τ were used to bombard the Cu targets, and the results from each beam energy are shown. The only peak observed in all three spectra is the 5.545-MeV α peak from the ²⁴¹Am contamination on the detector. Only in the 70-MeV spectrum is there any sign of α activity. Four single channels in the region from channel 500 to channel 1000 have more than one count in them. The peak at about channel 550 has about 4 counts and the one at 905 has 3 counts, whereas the other two have only the two counts in the one channel. No counts were observed at these locations in other α spectra.

The γ -ray spectra corresponding to the α spectra shown in Figure 53 are shown in Figures 54, 55, and 56. Several isotopes appear here that were not observed in the 63 Ga studies. In general, the shorter lived species will not be observed since the collection tape was changed hourly and therefore allowed a buildup of the long lived species.

Examining the spectra, the 66 Ga is found to increase by about one third going from 40 MeV τ to 55 MeV τ and increased by about one half















again going to 70 MeV τ . The 65 Ga in turn decreased by about 40% from 40 MeV to 55 MeV, and decreased slightly further going to 70 MeV. Both of these isotopes are only weakly seen above 40 MeV and are hard to measure accurately because the 66 Ga is obscured by stronger nearby γ rays from other isotopes present and the 65 Ga is overwhelmed by the underlying Compton background. An increase by a factor of 2.7 is noted in the 64 Ga intensity going from 40 to 55 MeV. The increase was reduced to only a factor of 2 for 70 MeV as compared to 40 MeV.

The 63 Zn daughter of 63 Ga increases by about one fifth from 40 to 55 MeV and increases by another half at 70 MeV, while the 62 Zn daughter of 62 Ga increases by one half at 55 MeV then drops to only about five sixths at 70 MeV. A doubling of intensity from 40 MeV to 55 MeV is noted for 61 Cu, with an additional increase of one half going to 70 MeV. 61 Zn is observed only weakly in the Compton valley from the 511-keV γ but does appear to have the same intensity relations as its more obvious 61 Cu daughter. The 60 Cu, in turn, has about the same intensity at the two lower energies, but an intensity at 70 MeV of more than 4 times that at lower energies.

Some of the peaks present result from beam interactions with the Havar foil separating the evacuated beam line and the pressurized target chamber, the Al collimator and absorbers, and the natural background. Some isotopes occuring from these sources are 56 Co, 52 Mn, 54 Mn, and 24 Na. In addition to the γ rays from these isotopes, several other γ rays, mostly weak, were observed but could not be identified, although their source is believed to be reactions with the Havar foil.

Figures 57 and 58 show the calculated cross sections for 63 Cu and 65 Cu produced by the program CS8N written by T. Sikkeland and D. Lebeck







Fig. 58. The ${}^{65}Cu(\tau, xn)$ cross sections calculated by the program CS8N.

at the University of California, Berkeley, to calculate the results of bombarding heavy elements with heavy ions. The relative cross sections predicted by the curves are in general agreement with the experimental results, taking into account that the interacting beam degraded by the Al absorbers, is not monoenergetic like the incident beam, but has a large range of energies, the range being larger for the thicker absorbers. It should be said that the isotopes of masses 61 and heavier are considered to be daughters of the Ga isotopes produced by the $Cu(\tau, xn)$ reaction. The ⁶⁰Cu and lighter masses are primarily from the Cu($\tau, \alpha x \eta$) reactions. Since ^{61}Cu and ^{61}Zn are observed as well as ^{62}Zn and ^{63}Zn . it appears that the light Ga isotopes, 61 Ga, 62 Ga, and 63 Ga, have been produced. Since the ⁶⁰Cu is present from other reactions and the presence of 60 Zn cannot be determined because its most intense γ rays fall at the same energy as much stronger transitions in the spectra, the production of ⁶⁰Ga is hard to evaluate. However, the large increase in the ⁶⁰Cu intensity from the 70-MeV τ beam gives a strong indication that ⁶⁰Ga was produced with this beam. These isotopes were not observed directly since their half-lives are expected to be seconds or less. However, based on the intensity of the daughter decays and the lack of observed a transitions, an upper limit of about ten parts per million can be placed on the β -delayed α branching of any of these isotopes. This could be due to the Coulomb barrier of the nuclei or the lack of β feeding to states above the α binding energy.

CHAPTER IX

CONCLUSIONS

Although there has been comparitively little work done on it, the region beyond the doubly closed shell at 56 Ni can provide significant information about the structure of the nucleus. Since 56 Ni is not stable and 58 Ni is the lightest stable nucleus in this region, the nuclei just outside the doubly closed shell are not as easily produced as those near the lighter doubly magic nuclei. To add to the difficulty in studying these nuclei, their half-lives are short, minutes or less, making decay scheme studies rather arduous.

One of the purposes of examining this region is the possibility of β -delayed α emission occuring in the light Ga isotopes. An extensive search for this α emission was conducted by producing isotopes as light as ⁶⁰Ga. Although some hints of delayed α emission were observed, the only definite result was the placing of an upper limit on the β -delayed α emission in this region.

Excited states in several other isotopes have also been studied in order to learn more about the systematics in this region. In the investigation of the β decay of 63 Zn a new level and several new γ transitions were observed. The new level is one of the doublet of the 1861and the 1865-keV states. All previous studies of the excited states in 63 Cu report only a single state at ~1863 keV. Several different coinci dence experiments were also performed to help elucidate features of the 63 Zn decay scheme such as the differences in ε_K/β^+ between the strongly collective states and the primarily single-particle states, all supposedly fed by allowed β transitions.

An examination of the decay scheme of ^{62}Zn revealed six new γ

transitions, one of which had been previously observed only in ${}^{62}Ni(p,n_Y)$ reactions. Since ${}^{62}Cu$ is an odd-odd nucleus, the structure of its states is much more complex than other nuclei and requires considerable under-standing in order to interpret it.

Seven new transitions were observed in the β decay of 63 Ga. No transition from this decay was observed above 1700 keV. Since the α binding energy, and therefore the lower energy limit on β -delayed α emission, lies somewhere in the range 1700 to 3300 keV depending on the mass tables used, γ transitions in this region would greatly aid in placing a firmer limit on the α binding energy and the possibility of β -delayed α emission.

Although the results reported here produce some new insights into the systematics of this region just above the doubly closed shell at ⁵⁶Ni, more information is needed before a good understanding of the behavior of the nuclei in this region can be obtained. More results, both experimental and theoretical, must be obtained before a consistent interpretation of the energy levels in these nuclei can be presented. The results presented here represent but a small step on the long road to this end. BIBLIOGRAPHY
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APPENDICES

	EVENT REC	OVERY FORTRAN	and SYMBOL Listi	ng
C EVENT FECAVERY DIMENSIEN SPEC(4096,10), SPEC(4094), TITLF(10,10), T(30), WIL(10), MFL 1(10), VI(10), VF(10), MIR(10), MFR(10), NCHAN(10), NS052(10), NS0(10), NT(210), AL(10), A(10), AR(10), NA(10), NB(10) C9MMEN SPEC C9MMEN SPECTRUM C9MMEN SPECTRUM	20 28 4 U=1,10 READ(105,2,E+C=8)MIL(U),MEL(U),MI(U),MER(U),MER(U),MER(U), 1NA(U),NB(U),T(U),NSQ(U),NSQEZ(U),(TITLE(I,U),I=1,10) 2 FORMAT(715,511,1044) 1 F(NCHAA(U),FR2,0)NCHAM(U)=1024	6:5 6:7 AL(U)=0 AL(U)=0 AL(U)=0 AL(U)=0 AL(U)=0 AL(U)=1 AL	<pre>C A (J)=YF (J)=YI (J)+1 ALAR,A=CHANNELS IN LEFT,RIGHT, AND CENTER SATES AL(U)=A(U)/(AL(U)+2) AR(U)=A(U)/(AR(U)+2) C AL(U)=A(U)/(AR(U)+2) C AL(U)=A(U)/(AR(U)+2) C AL/D=A(U)/(AR(U)+2) C AL/D=A(U)</pre>	<pre>UK=Ji+1C+J IF(UK-LE+C)GF T8 31 IF(UK-LE+C)GF T8 31 IF(U+EC)G8 T8 26 FRINT 25,(NTL(L), YFL(L), YI(L), YFR(L), YFR(L), NCHAN(L), NT(L), 1*A(L), 55(L), 53(L), NS3E2(L), (TITLE((1,L), 1=1,10)), L=1,0) 25 F9RMAT(+2) mild mfL MT VF MIR YFR (CHAN NTAPE XADC NB 1 NSG *5572 TITLE'/(3X,215), F(14,15), 16,515, 4X,10A4)) 28 NFVE:T=2 18 /pre>

APPENDIX A

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·, NSC, SPEC, AL, AR, MIL, MFL, MI, MF, MIR,	CATIBNS FER USE IN SUBRBUTINE DATA				ADC SET USED	PBINTER FAR VB					ALLEN DY AN			CET LP AC DRURLE WADDO	STACK FOR LIVITS
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4	00050	22700000	4		L1,7	()	INITIALIZE 5
ເດ 1	00C5E	35700007			STW,7	ノロイロノー	RESET EVENT
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460				* * *	PERFÜRNS TAPES GEA	CPERATIONS WITH C FRG4 F:139 UP	EVE ^N t RECORDER TAPES TO 50 W0RD RECORDS	
8 9 9				**	NGRAN NGRAN	TRY NITH NLAST I	ADICATING IF LAST TAPE	
010				* * :			GIVING NUMBER OF COINCIVENCE E SINGLE COUNTS TO END ADDRESS &	619 19
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87	00080	41100000	4	٩	DATA	FS.1		
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90	DOCB3	0000000	•.		DATA	11		
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46	00087	0100000	?	RE-11D	GEN, 8, 24	1.F.1.9	REAIND TAPE	
95	00088	J3COCOCO	/		GEN, 8, 24	x.C3. F.109	CHANGE VOLUME CALL	
96	00089	F CCCCCC	٩		GEN,1,31	× 1 ' , × ' C '		
97	000BA	00000000	t.		PZE	2 V.H.F		

PAGE

	SU3REUTINE ENTRY PEINT	ENTRY FOR COINCIDENCE PAIR	SAVE FLOAT MODE	AND SET LIGHTS TO BEF	GET FIRST VALUE	INCREMENT BAD READ COUNTER	SET POINTER TO NEXT VALLE	SET POINTER	IS IT TREFIG	IF AGT, USE IT	ELSE READ ANOTHER RECORD	SET EFFSET FOR ACTUAL RECORD SIZE	AND PICK IT UP	ALISN AS HALFWORD COUNT	AN.) STBRE		RESET POINTER	GET ADCS USED	IS IT BLD EVENT RECARDER	IF ACT, JUMP	SET POINTER	JUNP TE GET CATA	LOAD FIRST HALF WORD	GET ITS ADC	MASK BFF GARBAGE	L ^B AD XADC	CAMPARE TO CHECK IF CORRECT	IF ACTIGET AEW COUNTITACHEMENT SAU COU	LOUX AT YADC	LEAD SECOND HALF WERD	SET ITS ADC	MASK BFF GARBAGE	GET SECEND ADC	COMPARE THESE TAB	IF NOTIGET NEW COUNTIINCREMENT BAD COUT	LEAC Y SIDE	MASK BFF GARBAGE		SET LOCATION OF X EVENT	GET X EVENT
	tri t	,fr	513 13	0	VEXT1	NBAD	VAL	VAL	SIZE	JETIT	U V U V	t	F:109, ARG	-1e	512E	()	VAL	4 2	t -	GETNE.	•1	GE TOLO	BUF, ARG	-14	=X131	۲	11 (r	SEXT2	4	BUF, ARG	-14	= X + 3 +	•-4	56	NENT 2	EUF, ARG	=X • 1 F F F •	ZEKO	-1	014 JUD
PAGE	E J C	EGU	STCF	LCFI	6	MTW.1	MTW.1	L v , ARG	C×, ARG	н Н Н	CAL1,1	LI, ARG	LW, ARG	SLS, ARG	STW, ARG	LIJARG	STU, ARG	LN,R7	C1,R7	BNE	AI, ARG	с	LH,R6	SLS,R6	AND.R6	L 🛚 , R 7	C×, R7	ш ал	ALARC	LH,R6	SLS, R6	A ND . RE	AI,R7	C'A, R7	37E	LH,R7	AND.R7	BLEZ	AI, ARG	L1, R6
4	CATA	NEXT				VEXT2	NEX 1	1			tr L							GETIT					GETVEN													GETULD				
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141	0001	4360000	L		A V D . R A	= X - 1 F C F -	MARK BFF GARBAGF
142	000E2	68200000	. 1.		BLEZ	ZERE	JUMP IF Y=0
143	ODCE3	331000AE			MTN 1	VAL	SET POINTER TO NEXT EVENT
144	00054	33100007			MTW 1		INCREMENT EVENT COUNTER
145	o o	DOE5		EXIT	E G C	\$	NBRYAL EXIT WITH DATA
146	OCCES	7030C00D	4		L L L	110 110	RESTORE FLOAT MODE
147	OCCEÉ	68000000	L		ສ	STORE	UUTP TS STBRAGE RAUTINE
148		-		*	1		
149	00CE7	331000AE		252B	M.Twol	VAL	SET POINTER TO NEXT EVENT
150	000E8	33100007			MTW 1	ノロノロノー	INCREMENT EVENT COUNTER
151	00CE9	68COCCBF			ت ا)	ZEXTI	AND GET NEXT EVENT
152				*			
153				Ŧ	HERE IF	AUNBRIAL CONDITIO	
154	õ	OCEA		V E A	EGC	•	
155	COCEA	19ACC070			CLM, SR3	EBFCBJES	DBES IT LBBK LIKE EBF
156	COCEB	E9900008	۹		BCS,9	* SR1	IGLARE IF NOT
157	OCEC	04100087			CAL1.1	SEE 120	REXIND TAPE
158	OCCED	32700000	٩		L * , × 7	7ET	GET LOCATION OF ARGUMENTS
159	OCCEE	327E0001	٦		L ²⁴ , R7	1,47	GET POINTER FOR NLAST
160	ODCEF	52700007	4		Lv,R7	+ X. /	GET NLAST
161	OUCFC	6820000	L		BLEZ	RETUR	JUMP IF LAST TAPE
162	0001	C410C0B8		CHAIN CHAIN	CAL1,1	CVBL	CHANGE VOLUME CALL
163	ö	OOF2		RETURN	EQU	, 9	RETURN FROM CHANGE VOLUME
164	OUCF2	70300C0D	∢	I	C L	R13	RESTORE FLOAT MODE
165	00CF3	3270000	∢		Lw, R7	RET	GET LOCATION OF ARGUMENTS
166	COCF4	327E0002	Д		L ., R7	2,67	GET POINTER FOR NEVENT
167	OOOFE	32600007			L × , R6		GET NUMBER OF EVENTS
168	OCCF6	B5600007	٩		STW, R6	*R7	AND STURE IT
169	00CF7	3270C00D	4		L*, F7	RET	GET LOCATION OF ARGUMENTS
170	000F8	327ECC03	٩		L 7	3 , R7	GET P91NTER FOR NBAD
171	000F9	32600008			L×, R6	RAD	GET NUMBER OF BAD COUNTS
172	DOOFA	5560CC07	∢		STW, R6	*K7	AND STORE IT
173	OOCFB	3020C05	۹	RETURNI	AX, RET	#RET	GET LAST ARGUMENT (ERROR ADDRESS)
174	OOOFC	BEDGOCCD	٩	1	L * , RE T	* RE T	1
175	OOCFD	ERCOCCCD	4		с С		AND 30 THERE

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						ENTRY TO DATA STORAGE ROUTI	IS X BUFFER FILLER	SKIP IF NOT	IS Y BUFFER FILLER	IF BUTH ARE, GET MEXT EVENT	INITIALIZE CONTROL CARD IND	LOAC X		<pre>CE: #VD: af C+4.40</pre>			DISPLAY X GATE Y	DISPLAY Y GATE X	ANY X	ANY Y	ANY SUM	UISPLAY X GATE SUM	DISPLAY Y GATE SUM	UNUSED CONTROL PARAMETER	UNUSED CONTROL PARAMETER	UNUSED CONTROL PARAMETER			IS Y IN LOWER BACKGROUND	IF BELO, GP TO NEXT CARD	IF ABBVE GC TB PEAK	LOAD ARRAY SIZE	BETALN ARRAY LECATION	ADS CHANNEL ADDRESS	LEAD CHANNEL	SUBIRACT WEIGHTED BACKGRBUN	AND STORE	GE TO VEXT CARD	IS Y I' PEAK	IF AELBY GO TE NEXT CARD
) •	ţĄ	8191	6 + B	8191	VEXT	^	o r		: () ;		5° 5	27S	12S	155	16S	18S	19S	225	17S	17S	17S			LIMITS,4	175	105	4096	1	Q	*SPEC,3	* 4 6 • 4	*SPEC, 3	17S	LIMIT3+23+4	175
PAGE				R7 CHNTA		С С Ш	CI,6	BL	C1,7	53E	۲۱ 4	ر بر ال		ں دور	ר) א א	n	മ	£	G Ì)	ß	ന	α.	ഹ	ന	a	ന			CLM,7	BCS,1	BCS, 8	L1,3	8 ° 1 W	5 4 4 4	L ~ , 1C	FSS,10	STW.1C	ന	CL~,7	3CS,1
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19 20	00110 0011E	69800000 22301000	ו∟ ∢		BC5,8 L1,3	115 4096	IF ABBVE SE TS UPPER BACKGROUND Løad Array Size
	00115	37300004	4		M	t	5BTAIN ARRAY LECATION
20	00120	3030006	-1		A . B	.0	ADJ CHANNEL ADCRESS
53	00121	P246C003			L~,10	*SFEC_3	LBAD CHANNEL
+ N	00122	3DACCCBC			FAS,10	~	ADJ ANE COUNT
ຽວ	00123	B5460003			STW.10	*SPEC_3	AND STERE
26	00124	68000000	LL.		B	175	G8 T5 VEXT CARD
27	00125	1978CC32		119	CL4,7	t «0++SLI~I~	IS Y IN UPPER BACKGROUND
28	00126	69900000	L.		BCS,9	17S	IF LET GO TO NEXT CARD
29	00127	22301000	A		L1,3	4096	LBAC ARRAY SIZE
30	00128	37300004	ત		K4, 3	+	981AIN ARRAY LOCATION
31	00129	30300006	4		A*, 3	¢	ADC CHANNEL ADDRESS
32	0012A	92A6COC3			10 م م ما	*SPEC_3	LBAC CHANNEL
33	00128	PCARCOOS			FSS,10	* AR. 4	SUBTRACT WEIGHTED BACKGROUND
3 4	0012C	B5A6C003			STW, 10	*SPEC, 3	ANJ STORE
32	00120	680000089	L		භ	17S	GB TB NEXT CARD
36				*			
37				*	DISPLAY	Y GATE X	
ათ ულ	0.125	196800A		บ ก + +	4 " M] J	11M11c.4	IS X IN LAWER BACKGROUND
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) 4 + 4		303000CC	۲ ۹				ADJ CHANNEL ADDRESS
ເມ †	00134	3246CCO3			L×,10	*SPEC,3	LBAD CHANNEL
46	00135	PCA82CC4			FSS,10	* 41.04	SU3TRACT WEIGHTED BACKGRBUND
47	00136	E5A60003			STW 10	*SPEC,3	AND STORE
4	00137	683C0C0C	LA .		٢.	175	GE T9 NEXT CARD
б ф	0013 8	1968001E		1 30	CL ~ 16	LIMIT9+2014	IS X IV PEAK
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<u>ה</u> ה	00130	4/30004	ব		5	t	UDTAIN ARRAT LOCATION
រ ហ	00130	20000000	-(A%, 3	/	AD) CHANNEL ADDRESS
ទា	0013E	FZAECC3			LN, 10	+SPEC, 3	LOAD CHANNEL
56	0013F	3DACCEC			FAS,10	4	ADO ENE COUNT
57	00140	B5A6CCC3			STW, 10	+SPEC,3	AND STORE
58	00141	680000089	LL		'n	175	GA TO NEXT CARD
20	00142	19680032		145	CLM, 6		IS X IN UPPER BACKGROUND
60	00143	00000669	١٠		BCS,9	17S	IF LET G9 TO VEXT CARD
61	00144	22301000	7		L1,3	40.96	LCAS ARRAY SIZE

م	00145	37201004	4		5	4	UBTAIN ARRAY LECATISN
) M	00146	30300007	٩		A * . 3	7	ADD CHANNEL ADDRESS
) 4	00147	B2A6003	Ľ			+ CPFC 3	
ى س	00148	BCABOCO5			FSS.1	* AR. +	SUBTRACT WEIGHTED BACKGRBUND
9	00149	B5A6003			STwall	+SPEC,3	AND STORE
2	0014A	6800000	ى		3	17S	GRITP VEXT CARD
00				*			
σc				* *	X Y'A		
,	00148	22301000	٩	153	L1,3	4096	LBAJ ARRAY SIZE
N.	00140	3730004	4	•	(M) (* 12) (* 12)		BBTAIN ARRAY LECATION
e	00140	3030006	٩		A . 3	6	ADD CHAWNEL ADDRESS
4	0014E	32A6C003			L×, 10	*SPEC,3	LPAD CHANNEL
ß	0014F	3DACCOBO			FAS, 10	•	ADJ ENE COUNT
ç	00150	85A6C0C3			STww10	*SPEC,3	AND STORE
~	00151	6800000	L		aı	17S	GO TE NEXT CARD
0 0 (38 3			
ס ת				• *			
.	00152	32301000	٩	1 6 S	L1, 3	4096	LOAD ARAY SIZE
ŝ	00153	3730000	۹		m ¶ ≠ Σ	t	BETAIN ARRAY LECATION
ო	00154	30300007	۸		A*,3	7	ADD CHANNEL ADDRESS
4	00155	BRA6COC3			L ~ م ا	*SPEC,3	LOAD CHANNEL
ທ	00156	30 ACCOBO			FAS.10	4	ADJ ENE COUNT
9	00157	BSA6003			STar10	*SPEC, 3	AND STURE
2	00158	680000C89	L		വ	17S	GE TU NEXT CARD
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) -	• .	00150		00	Ċ	+++	
• N	0 <u>0</u> 159	32800005	-1	0)) 	r 10	GET SUM
m	0015A	92280001			L > 2	+ 18.4	GET TYPE BF SUM
4	00153	21200001	۰٦	180	C1,2		WHAT TYPE OF SUM
S	00150	691CCCC0	L		ыL	18A	IF LESS, 30 TO STORAGE
9	00150	6920000	••		B C	185	IF SREATER, GO TO X <y< th=""></y<>
2	0015E	31600007	A		C×16	7	IS X>Y
00	0015F	68200000	L		3 5	17S	IF NET GR TR NEXT CARD
თ	00160	6 8 JCC PC PC	11		£ 0	18A	BTHERWISE STARE IT
0	0.161	31600007	٩	1 8 J	C *) 6	7	IS X <y< th=""></y<>
	00162	681000CO	L		398	17S	IF NOT GO TO VEXT CARD
S	00163	22301000	۷	184	د,1)	4C96	LEAC ARRAY SIZE
m	00164	37300004	ন		υ « ۲ Σ	4	BETAIN ARRAY LOCATION
4	00165	3000000	٩		A ^ J 3	U L i	ADD CHANNEL ADDRESS

, 3 LOAD CHANNEL Admente Caunt	AND STORE	GE TE NEXT CARD		S. S.		GET TYPE BF SUM	IF VONE 39 TO STARAGE RUUT	IS IT x>Y	IF AGT GR TH XKY	IS X>Y	IF NOT GO TO NEXT CARD	BTHERWISE STORE IT	IS x <y< th=""><th>IF NOT GO TO NEXT CARD</th><th>AJ & IS SUM IN LOVER BACKGROUZD IF DEL AL ADD</th><th></th><th>IF ADUVE OF TU FEAK - F.C. ADUAV CIVE</th><th></th><th>ADD X ADDRESS</th><th></th><th>SUBTRACT WEIGHTED BACKGQOUN</th><th>, 3 AND STORE</th><th>GB TU NEXT CARC</th><th>3+23+4 IS SUM IN PEAK</th><th>IF BELBW GO TO NEXT CARD</th><th>JF AROVE GG TU UPPER 34LKG B 0 482444 0134</th><th>LUAU AKKAY 312E ARtain araay 1 Fratiar</th><th>ADD X ADDRESS</th><th>3 LOAD CHANNEL</th><th>ACO BNE COUNT</th><th>je AMO STBRE</th><th>GE TE VEXT CARD</th><th>3+40,4 IS SUM IN UPPER BACKGRBUND</th><th>IF AUT GO TO NEXT CARD</th><th>LBAD ARRAY SIZE</th><th>BBTAIN ARRAY LOCATION</th><th>ADJ X AJDRESS</th><th></th></y<>	IF NOT GO TO NEXT CARD	AJ & IS SUM IN LOVER BACKGROUZD IF DEL AL ADD		IF ADUVE OF TU FEAK - F.C. ADUAV CIVE		ADD X ADDRESS		SUBTRACT WEIGHTED BACKGQOUN	, 3 AND STORE	GB TU NEXT CARC	3+23+4 IS SUM IN PEAK	IF BELBW GO TO NEXT CARD	JF AROVE GG TU UPPER 34LKG B 0 482444 0134	LUAU AKKAY 312E ARtain araay 1 Fratiar	ADD X ADDRESS	3 LOAD CHANNEL	ACO BNE COUNT	je AMO STBRE	GE TE VEXT CARD	3+40,4 IS SUM IN UPPER BACKGRBUND	IF AUT GO TO NEXT CARD	LBAD ARRAY SIZE	BBTAIN ARRAY LOCATION	ADJ X AJDRESS	
★SPEC,	* SPEC	17S		X GATE	tý	* 28° *	194	-1	1 96	7	175	194	7	17S		n (200 200 200	+ C 7 0	1 t	* SPEC	* 4 - 4	*SPEC	17S	LIMITS	17S	6.1S	1 1 1 1	ç	*SPEC	٩	*SPEC,	17S	LIMIT	17S	4C96	t	¢	
	STE 10	n n		DISPLAN	С С Э Ц	ر × م ۲	BEZ	C1,2	B∧E	C ⊱) €	BLE	C	C 1 6	BGE	5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5) (* 		FSS,10	STW110	æ	CLM, 5	RCS.1	ອິເຈົ້າ ອີ	אר - אר אר	N N N	Lw, 10	FAS,10	STAJIC	n	CL 4, 5	8CS 1 9	L1,3	× × و ع	A., J.	
			*	* 1	195								198		194									20S									ت 1 ت 2					
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305	200	308	309	910 010	312	313	314	315	316	317	318	319	320	321	322	n . 		200	220	328	329	330	331	332	333	4 0 0 0	5 V 7 V 7 V	337	338	339	340	341	342	943	キキの	345	346	347

94 94 94 90	00180 0018E	95 A & C C C S 95 A & C C C G			FSS,10 STw.10	+ AR, + + SPEC , 3	SUJTRACT WEIGHTEC BACKURGUND And Store
350	0018F	6800000	i.		ι Γ	175	GO TA VEXT CARC
351				*			
352 352				* *	21SPLAY	Y GATE SUM	
904 907		00 190		223	С С Ч	•*	
355	00190	B2280001		k k	L v Z	* N.B. • •	GET TYPE BF SUM
356	00191	6830000	ц		BEZ	224	IF NONE GO TO STORAGE ROUTINE
357	00192	21200001	4		C1,2	1	IS IT X _{>} Y
358	00193	6930000	i.		BNE	228	IF NOT GO TO X <y< th=""></y<>
359	00194	31600007	۹		C ~) 6	7	
360	C0195	68200000	L		۲ ۲	17S	IF VET GO TO MEXT CARU
361	C0196	6800000	L		d)	ZZA	BILERWISE STORE IT
362	00197	31600007	4	223	C ×) 6	7	IS x <y< th=""></y<>
363	00198	58100000	L		BGF	17S	IF VOT GO TO NEXT CARD
364	00199	1958C00A		22A	CL < , 5	LIMITS	IS SUM IN LOWER BACKGROUND
365	0019A	6910C0C0	ا م		BCS,1	17S	IF BELGN GO TO NEXT CARU
366	0019B	6980000	L		BCS,8	235	IF ABBVE GO TO PEAK
367	00190	22301000	7		L1,3	4C96	LEAD ARRAY SIZE
368	00190	37300004	4		د ا ا	t	BUTAIN AKRAY LUCATION
369	0019E	30300007	٩		A 10 J	7	ADJ Y ADDRESS
370	0019F	B2A6C003			L 1 10	*SPEC,3	LBAD CHANNEL
371	OC1AC	BCARCOCH			FSS,1C	* 4 L ø 4	SUBTRACT WEIGHTED RACKURDUND L
372	001A1	B5A6CC03			STw.10	+SPEC,3	AND STURE
373	00142	5800000 9	L	ļ	មា	175	GO TO VEXT CARD
374	00143	1958CC1E		2 3 2	CL < , 5	LIMIT3+20.4	IS SUM IN PEAK
375	00 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1	69100000 69800000	և ս		800°1 00°1	17S	IF BELGA GO TO NEXT CARU IF ABAVE GO TO HEPER BACKGROUND
575		00000000000000000000000000000000000000	_ <		1.2	5 - 5 7 - 5 - 5	
378	00147	9790000	(4				JBTAIN ARRAY LOCATIAN
379	001AF	30300007	-1		A A B	7	ADD Y ADDRESS
380	00149	P2A60C03			L×,10	+SPEC,3	LBAD CHANNEL
381	001 A A	3DA000BC			FAS.10	4	ADJ BNE COUNT
382	001AB	85A60003			STw.1C	*SPEC,3	AND ST9RE
383	001AC	68CCCCC0	۱ـ		ť	175	GE TH NEXT CARD
384	001AD	19580032		540	CL" , 5	t Cit+dLIWIT	IS SUM IN UPPER BACKSRUUND
385 0	OC1AE	00000669	۱ ۲		5 CS ,9	17S	IF VET GO TO VEXT CARD
386	JO1AF	22301000	ব		[1]3	4096	LEAD ARRAY SIZE
387	00180	37300004	٩		۳ ۲	t.	BBTAIN ARRAY LACATION
388	CC181	30300007	٩		A ~ J 3	7	ADD Y ADURESS
в В С	00182	32A6CCC3			L ~ 1 J J	*SPEC, 3	LBAD CHANNEL
390	00163	3CARACC5			FSS,10	+ ATS +	SUNTRACT NEIGHTED BACKBARDNU

AND STARE GB TO WEXT CARD			INCREMENT INDER DT 3NE MAS IT LAST CARD	IF NOT LOROOOP At an above that the second	I SC CO IN NEXT EVENT		
STw.10 *SPEC(3 B 175	HERE TO NEXT CARD	th الح		BL 7S	EAD EAD	i	
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CIMENSIEN A(300), SOA(300), Y(300), WEKLE(300), NFKHI(300), 2(300), X(30 10) / E(40), F(40), NEC(40), COFT(4), TITLE(16), U(7) A5E1) MOIRAE E(I) FORTRAN Listing 1 1 .UENPIS.I 20 2 IENUJ300 86 20(105,1,2°D_221)%URUN,A(I),SDA(I),X(I),~PKLP(I),NPKHP(I) 86 40(105,1,2°D_221)%URUN,A(I),SDA(I),X(I),~PKLP(I), ഗ CALCULATED LEAST STUARE GEAL LUG PEAD(105,10,END=12)NPTS,NGECC,NEVC3,X',X',TITLE Permat(312,2F5,2,16A4) Fermat(312,2F5,2,16A4) LI=LI+1 READ 1,NURUN,A(I),SDA(I),X(I),NPAUG(I),NPAHI(I) PRINT 93.20205 (TITLE(L)21=1216) Farmat (11: 9% 1902 2008851 152 198216447) CALIBRATI9 V CALL BESTFIT(E, X, NENCO, NTERM, CEFT) u 7 RINT 96 REMAT(ICIJ5X, ICBEFFICIELTS BIRAE EVERGY AND INTENSITY GP T9 19 READ 99, (MEC(L) JL=1, NENCP) F9RMAT(4012) S **T9** 95 11,0 \TER\=3 1F(\E\C0+LE+2)\TER4=2 ---- × venC Ð -IF (NEC (LL) .NF .L) GP IF (X4. NE.O.) READ IF (NENCP ... E.C.) GB 4 L=1,NPTS 5 LL=1,NENC9 F9RMAT(RF10.0) NENCO=LDTS D9 3 1=1,VPTS I=NELCO+LI F(I)=F(L) Centing C9 3 1=1, E(1)=F(1) CONTINCE CONTINUE ^E₩X=I-1 したり ままし ままし ן ברר **1** 1 1 1 Σ ü L () - a) -50 10 10 10 10 to 10 5 C) 1 C) m ŝ ٥ì ŧ σ١ ч 0 \mathbf{O}

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APPENDIX B

STANDARD DEVIATION IN CALIBRATION EVERGIES . F12.4) DEVIATION IN KEV.) < שי צ 007 FITED ^ Ge JO FBRMAT(1C1,9%, C1,7%, E1,13%, E =',F20.1C) INCHES SD=SJ+DFV+DEV PRINT 92,X(V),E(V),Y(N),JEV FPRMAT(F13+2,F9+2,F18+2,F12+3) Y(N)=Y(\)+CBFT(M)+(X(\)++2A) ာ ပ ဗ CONTINUE SDESAT(SSZ(CECC9-1)) PRINT 6,SS 6 FORMAT(IC STANDARD 16 1 4 4 6 4 6 ¢) ► Ð FERMAT (9X, 1A1, 12, 1 97, 1, COFT (4) IF (NGECC+NE - 1) G9 3+6% DETECT9R IF (NJECC+5G+C) 39 NE#NENCG+1 IF (NE+37+NExx) 38 U+C361465663 X1==2.8481884CC3 X2= 0+668965220 DP 61 VELATERY E 53 M. L. NTERM DE 70 VENEAX Y(N)=0.0 VETIN LEX V=1.VEVCB CEV=E(N)-Y(N) Centinue X1=0.0 **PNTINUE** CENTINUE PRINT 91 SD=0. De 52 /= Y (N)=0. Mam-1 X2=C+C X5=C•C X6=0.0 X7=1.C X 3=0 • C 0 • 0 = 7 X PRINT ວ ຄ e C Ũ × ຕ ທ 0. C 600 Ś 101 5

C

X5= 7.2898702621 X6= -0.3815773129 X7=Exp(90.6825256348+48+1047210693*0+73525+0+18718) X6= -0.4991953175 X7=ExP(81.422289551+45.2146911621-0.78031-1.43676) X7=Exp(81.5283508301+31.3188476563-0.74116-0.48050) (O S ഗ ഗ INCHE INCHE INCH: 1 CHE 4 (U (I) 10 10 10 33 \circ 5 T 5 ₽ TG AT a) ⊷ AT X2==2.2184772491 X3= 0.0094535089 X4==45.1457977295 X4=53.140625000 X5= 9.4473867416 X6= -0.5440230337 SECC.NE. 2) Ge 3.6% DETECTBR IF(NGECC.NE. 3)69 3.6% DETECT08 X1=17.6195983887 IF (NGECC-NE-11) 69 2-5% DETECTOR IF (NGECC-NE-12) G8 2+5% SETECT03 14.C573759079 -1.7552604675 -1-2133836746 C+C528133995 X4=-30.7291870117 X5= 2.8710823059 0.0800320506 = 1C.4776115417 X4==45.8184967041 1990212004.8 4==2.8481884003 5= 0.6668965220 6==0.0361465663 X1=16.3561859131 X2==2.0367994308 X3* 0.0909128785 X6==0.036146566 GA TO 18 IF (NGECC.NE. **1** 1 α) +1 **00** X7= 1.0 X6=0.C **6** 19 e E 68 T9 ***** X X X X X ₩CX ×5. ж? к н Сі × × C C 3 **6**: 00 33 C U J C

50+48•k855133057-C•82155-1+1963C) x7=ExP(96+4995422363+39+1673889167=0+73961=0+24043) AVAILABLE w > AVAILAGL л Х 1700 102 v **⊢**02 Gead :S **1** () | 1.CHES I VCHE S ഗ S n ഗ ഗ ŝ I', CHE INCHE INCH1 I. CHE 1 CHE :0 I. CHF ű ţ 5 5 5 s c e 00 () () () ວ ເປ 4 m (u 35 37 \mathbf{O} າ ເປັ 41 X ÷ 0; 1 1 (0 9 T A 10 ₽1 Ð 4 4 4 4 5 4 AT 10 10 **c** : X2= -2.247324650 X3= -2.247324650 X5= 41.9310455322 X5= 7.3369789124 X6= -0.4129425322 X6= -0.412942864 X6= -0.4129428864 X6= -18 77.8628264 GP -10 -18 X7AY -0.5700 115 (0.5700 - 2.0100 - 100 T T 1 F(NCECC.VE.13)G9 2.55% DETTCT022 1= 17.8550252451 2= -2.24732552451 2= -2.247325509 3= -1011717319 4= +1.93104553222 5= 7.3369729124 6= -C.4129428864 CC+VE+23)64 44 DETECT88 (N3ECC+1E+42)69 4+6% 7ET4CT61 DETECTOR C • \E • 32) 59 DETECT98 T3 17 (NGECC+VE+31)G9 е, (NGECC+NE+P2) G0 XRAY DETECT93 .6% DETECTOR (NGECC . XE . 44) G 7575(0 TO 18 T9 17 T3 17 XRAY * **N** 17 GP 19 18 17 2 200 (NOECC 200 (NGEC ---J) 40 ► 13 3) ۲ 4 т С **a**) (5 e C ф С ал Среч en Co θÛ X Ľ 1. L L 1 L --**6**£ 4e ц: m Ś 37 80 0 **†** C. ň t. J \mathbf{c} \mathbf{U} U \mathbf{O} \mathbf{O} υ \cup \mathbf{O}

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X5≖ 11.4318425040
X6= --6618534923
X7=Exp(117-8≏77503545+13+7962741832+2+41350+5+18760)
                                                                                                                                                                                                                                                                                                                                                                 X7=Exp(117+2r301+14+C4565++35542+.71733)
         INCHES
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1F(NGECC+XE+54)69 T

1C+4% DETECT03 /

1C+4% DETECT03 /
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10.4% SETECTBR A
X1= 2.136800766
X2= -.1194006205
                                                                                                                                                                                                                                                                                                                                      X3= .0733111654
X4=+3.055947376
                                                                                                                                                                                         69 T9 18
IF (NGECC+NE+52) G9
10+4% DETECT93
IF(NGECC.*E.43)G3
4.6% DETECT03
                                                                                                                                                                                                                                        X3= •CC61463341
X4==64•2149871826
                                                                                                                                                                                                                                                                                                                                                         8.2276744221
                                                                          X7=Exp(93.173646
                                                                                                                                                                                                                      X1=2.0880670547
X2=-1455207467
                   3.7981853
-.3336803
.0137885
                                              X4==42.398137
X5= 7.2985811
X6= -.4363828
                                                                                                                                    • C22847
                                                                                                               4.27583
                                                                                                                                                      X5= 11.03314
X6= -.63864
                                                                                                                         --47926
                                                                                                                                            X4==62.71104
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	15	Ge TU 22 END
<mark>ں</mark> ن		SUBR<INE RESTFIT (Y,x,VPT)ATERALCAFT) THIS FBUTTNE CUES A LEAST SQUARES FIT TO THE FBLLPAING FUNCTION= V=CUFT(1)+CQFT(2)*X+COFT(3)*X**2++COFT(NTERM)*X**(NTERM=1) DIMENSIEN Y(NPT)_X(NPT)_COFT(NTERV)
		DeUBLE PRECISIEN A(23,23),YD(200),XD(200),XTERM(41) IF(NTERM-ST-21)Ge Te 3 IF(NPT-GE-NTFRM)3E TE 9 Print (
	16	FORMAT(JCX,FIGT EIGUGH DATA POINTS FOR NUMBER OF TERMSF) GO TO 14
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	N	A(I)-0-000 Fe 4 I=1, PT
U	t-	XU(L)=X(?) YD(l)=Y(l) FILLS X PAXT PF ~ATRIX
		XTERX(1)=0PT DG 5 1=2*70
	ц)	DC 5 (=1,×PT XTERV(1)=XTERV(1)+×((-)++(1+1) A =
U	CX :	A(IJ)=XTERM(IND) FILLS Y PART OF MATRIX
	ЧĴ	A(1)/TER*+1) = A(1)/TEX*+1)+YD(U) De 7 1=20/TEX* De 7 1=20/TEX*
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GESTEIT WEDE EXCEEDED, ZERABS RETURNED.)
                                                                                           05 11 7=10×1
A(Usk)=A(U+1,k+1)=A(U+1,1)*A(N10k+1)
                                                                                                                                                          JE SVEISVENIC
                                                                        A(N1,U)=A(1,U)/A(1,1)
28 11 U=1,NTFRM
                    VATR1X
SETS THE PIVIOT
A(1)ALTER*+2)=1.0
INVERTS THE WATRI)
                                        N2=NTER4+2
00 11 1=1,NTER4
00 10 J=2,N2
                                                                                    UEL NTERG
                                                                                                                DB 12 I=1,NTFRY
                                                                                                                                                                  08 13 1=1,4TFAH
CAFT(1)=1+0
                                                                                                                          CEFT(1)=A(1,1)
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