

ASSEMBLY AND CALIBRATION OF A GE(LI)
SPECTROMETER SYSTEM FOR ANALYSIS OF GEOLOGICAL SAMPLES

by 6402

PATRICK FRANKLIN ERVIN

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Approved by:

N. Dean Eckhoff
Major Professor

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NOMENCLATURE

<u>Symbol</u>	<u>Explanation</u>
b'	estimator of β
e	error vector
E	energy of gamma ray, keV
E'	expectation operator
FWHM	full width at half maximum
FWHM(E)	FWHM as a function of energy, keV
n	neutron
p	proton
t	time, seconds
t_1	time sample is in the neutron flux, seconds
X	target nuclide
$X_0(t)$	time dependent target nuclide, nuclei/cm ³
X_0	non-time dependent target nuclide, nuclei/cm ³
$\underline{X}$	independent variable matrix
$\underline{X}^T$	transpose matrix of $\underline{X}$
Y	product nuclide
$Y(t)$	time dependent product nuclide, nuclei/cm ³
$\underline{Y}$	dependent variable vector
$\underline{V}$	variance co-variance matrix
$\underline{V}^{-1}$	inverse matrix of $\underline{V}$
α	alpha particle
β	solution vector
γ	gamma ray

NOMENCLATURE (cont'd)

<u>Symbol</u>	<u>Explanation</u>
λ	characteristic decay constant of product nucleus, second ⁻¹
σ	microscopic cross section for interaction, cm ² /nucleus
σ_p^2	a proportionality constant
$\phi(t)$	time dependent neutron flux, n/cm ² -second
ϕ_0	non-time dependent neutron flux, n/cm ² -second

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1.0 INTRODUCTION

The neutron activation analysis (NAA) of geological specimens for more than 45 elements can be performed by the use of gamma-ray spectroscopy (1,2,3,4,5,6,7). The applications of NAA vary from the detection of only one or two elements in a complex matrix (7,8,22) to the multi-elemental analysis of geological specimens (1,2,3,9,10,11). The complexity of the gamma-ray spectrum from a geological specimen results in a rigorous test of the analysis technique.

Gamma-ray spectroscopy has improved in capability and versatility since 1950 due to a series of improvements in the technique (24). These were the development of: 1) the NaI(Tl) scintillation detector, 2) the single channel pulse height analyzer, 3) the 20-channel pulse height analyzer (based on discriminators), 4) the amplitude-to-time-conversion multi-channel pulse height analyzer, 5) a multielement purely instrumental method of performing NAA, based upon gamma-ray spectroscopy, 6) small Cockcroft-Walton (drift-tube and now sealed tube) and Van de Graaff accelerators for thermal-neutron and fast-neutron NAA at moderate fluxes, 7) an intrinsically safe research nuclear reactor especially designed for efficient NAA work, 8) computers and computer techniques for effective NAA data processing, 9) commercial activation analysis service laboratories, 10) high-intensity reactor pulses for improved sensitivity for elements with short-lived induced activities, 11) the high-resolution Ge(Li) detector with 4096-channel pulse height analyzers and fast magnetic tape readouts, 12) and the availability of ^{252}Cf neutron sources.

The advent of the Germanium Lithium-drifted (Ge(Li)) semiconductor detector resulted in a major improvement in NAA techniques. The Ge(Li)

detector has the chief advantage of improved resolution; currently as good as 1.3 keV, full width at half maximum (FWHM) of the 1332 keV ^{60}Co peak (12) contrasted with a FWHM of 60 to 80 keV for a 3 inch by 3 inch NaI(Tl) detector. The chief disadvantage of the Ge(Li) detector is that it is only 2 to 6 per cent as efficient as a 3 inch by 3 inch NaI(Tl) detector when the source is 10 cm from the detector. This efficiency disadvantage is primarily due to the smaller size of current Ge(Li) detectors which have a maximum volume of 35 to 45 cc (14). A second disadvantage in some applications is that the detector must be cooled by liquid nitrogen to prevent the loss of the drifted lithium by thermal diffusion. The use of 1024 to 4096 channel pulse height analyzers is necessary to fully use the superior resolution of the Ge(Li) detector. Therefore, large quantities of data are produced and the "hand-calculation" of the abundances of elements in a sample is both laborious and tedious except in the very simplest of analyses.

A system was designed and assembled to perform routine non-destructive multielemental analysis of samples by NAA using a 25 cc trapezohedral Ge(Li) detector. This consisted of three phases: 1). A library of reference spectra was collected using a standard irradiation and counting geometry. 2). A computer code, HIRES, was developed to locate photopeaks, assign energies to these photopeaks, and search among a list of gamma-ray energies to determine possible contributors to the observed spectrum. 3). A computer code, GELAOI, was developed to unfold the concentrations of the isotopes present in the specimens using Area-of-Interest (AOI) unfolding (15). The system was evaluated by analyzing two U. S. Geological Survey standards, G-1 and W-1 (16).

2.0 THEORY

2.1 Isotope Production and Decay

When a sample is placed in a neutron field a variety of nuclear reactions occur. Four reactions of primary importance to activation analysis are designated as $X(n,\gamma)Y$, $X(n,p)Y$, $X(n,\alpha)Y$ and $X(n,2n)Y$. These notations represent the absorption of a neutron (1_0n) by a nucleus and the subsequent emission of a prompt gamma ray, proton, alpha particle or two neutrons, respectively. The resulting nucleus is in an excited state.

A mass balance on these reactions can be written as

accumulation = production - disappearance

$$\frac{dY(t)}{dt} = \phi(t)\sigma X_0(t) - \lambda Y(t), \quad (1)$$

where $Y(t)$ = time dependent product nuclei (nuclei/cm³),

σ = microscopic cross section for interaction (cm²/nucleus),

$\phi(t)$ = time dependent neutron flux (1_0n /cm²-sec),

λ = characteristic decay constant of the product nucleus (sec⁻¹),

$X_0(t)$ = time dependent target nuclei (nuclei/cm³).

The following assumptions are usually made:

$$\phi(t) = \phi_0 \quad (\text{a constant}),$$

$$X_0(t) = X_0 \quad (\text{a constant}).$$

Incorporating these assumptions into Eq. (1) yields

$$\frac{dY(t)}{dt} = \sigma \phi_0 X_0 - \lambda Y(t). \quad (2)$$

The solution of Eq. (2) is

$$Y(t) = \frac{\sigma \phi_0 X_0}{\lambda} (1 - e^{-\lambda t}). \quad (3)$$

After a time t_1 , the sample is removed from the neutron flux. The number of converted atoms is given by Eq. (3) with t_1 substituted for t .

Since there is no more production after removal from the neutron flux, Eq. (2) becomes

$$\frac{dY(t)}{dt} = -\lambda Y(t) \quad , \quad (4)$$

$$Y(t) = \frac{\sigma \phi X_0}{\lambda} (1 - e^{-\lambda t_1}) e^{-\lambda t} \quad , \quad (5)$$

where t is measured from the time of removal from the neutron flux.

The activity of the sample is defined as the product of $Y(t)$ and λ . It must be realized the previous development is for a very simple case of isotope production. Complications can arise from competing reactions, isotope decay feeding the isotope of interest, and other mechanisms not taken into consideration in this development.

The decay scheme of the isotope ^{24}Na is shown in Fig. 1. Information on decay schemes can be found in reference (16). Precise gamma-ray energy determinations are becoming available (13). The response of the Ge(Li) spectrometer system to a source of ^{24}Na is shown in Fig. 2. Gamma rays interact in the Ge(Li) crystal by three mechanisms; Photoelectric effect, Compton scattering, and pair production. The contributions of each to the spectrum are noted in Fig. 2.

2.2 Data Analysis

The analysis of data from gamma-ray spectrometer systems requires the assumption of certain properties of these data. The counts in each channel are generally assumed to be normally distributed. The variance of these counts is approximated by the value of the counts. Finally, the correlation between counts of different channels is assumed to be zero,

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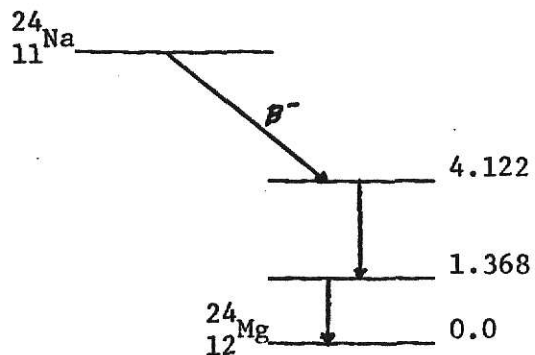


Figure 1. Decay Scheme of ^{24}Na .

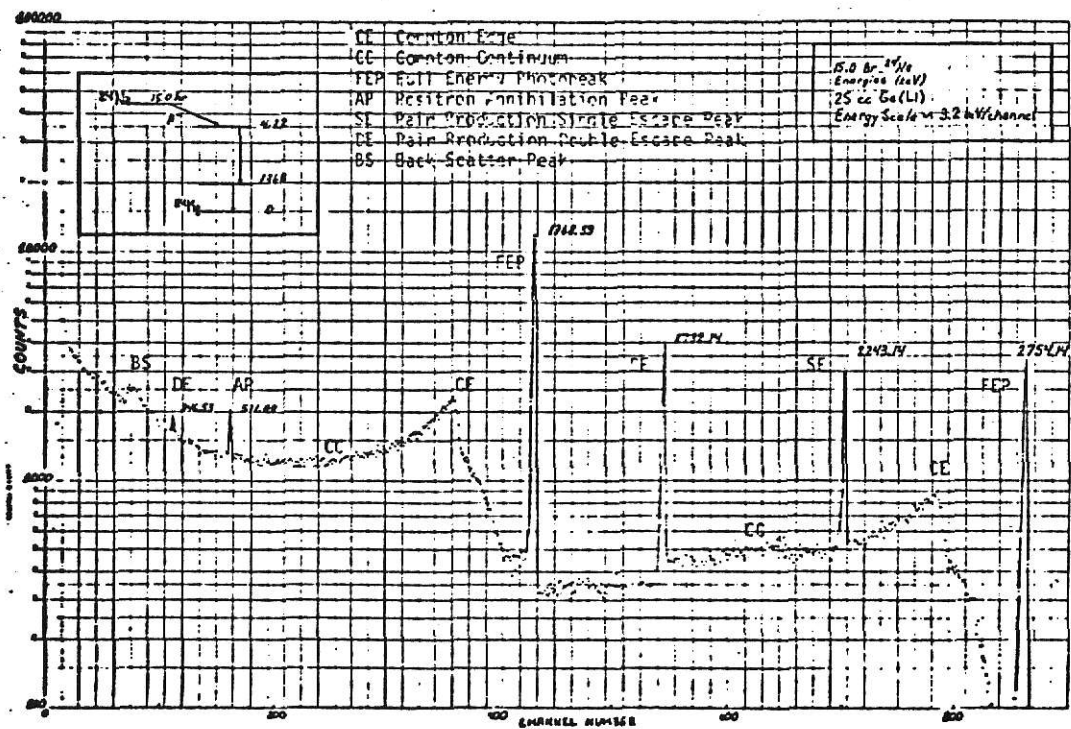


Figure 2. Ge(Li) Detector Response to ^{24}Na Source.

i. e., the counts are assumed to be statistically independent. The validity of these assumptions has been examined (17,18) and they will be retained in this work.

Assume the following model

$$\underline{Y} = \underline{X}\underline{\beta} + \underline{e}, \quad (6)$$

$$E'[\underline{e}] = 0, \quad (7)$$

$$V[\underline{e}] = \sigma_p^2 \underline{V}, \quad (8)$$

where

$\underline{Y}$ = (n x 1) dependent variable vector,

$\underline{X}$ = (n x m) independent variable matrix,

$\underline{\beta}$ = (m x 1) solution vector,

$\underline{e}$ = (n x 1) error vector,

$\underline{V}$ = (n x n) variance-covariance matrix,

σ_p^2 = a proportionality constant.

According to the Gauss-Markoff theorem (19), minimum variance unbiased estimators result from the least squares technique if the errors have a mathematical expectancy of zero and have homoscedastic variances. The least squares solution to Eq. (6) is

$$\underline{b}' = (\underline{X}'\underline{V}^{-1}\underline{X})^{-1}\underline{X}'\underline{V}^{-1}\underline{Y}, \quad (9)$$

where $\underline{b}'$ equals the estimators for $\underline{\beta}$.

Complex gamma-ray spectra from Ge(Li) detectors are typically 1024 to 4096 channels in length. The technique of Area-of-Interest (AOI) unfolding was developed to reduce the amount of data manipulation necessary. As its name implies, AOI deals only with the portion of interest of the data, nominally some energy range around the spectral photopeaks. A computer code, GELAOI, was developed to perform the least squares analysis of these spectral data using the AOI technique.

3.0 EXPERIMENTAL

3.1 Sample Preparation and Irradiation

In 1949, at the Massachusetts Institute of Technology a granite labeled G-1 and a diabase labeled W-1 were produced to be used by the geological community as universal standards. Seventy-four elements have been detected in G-1 and W-1. By 1965 the analysis of these standards had been the subject of 256 papers originating in 105 laboratories in 22 countries (16). These analyses exhibit high accuracy with variable precision. The samples of G-1 and W-1 used in this work were obtained from Dr. D. G. Brookins, Department of Geology, Kansas State University.

The samples were placed into clean 8 cc polyethylene sample vials (obtained from Olympic Plastics Co.). A small amount of copper powder, nominally 10-30 mgms, contained in a gelatin capsule was placed in the bottom of the standard KSU Triga Mark II Nuclear Reactor polystyrene irradiation vial (supplied by Gulf General Atomic). The polyethylene sample vial was placed at the top and inside the polystyrene irradiation vial. The samples were irradiated after manual insertion into the rotary specimen rack (RSR) of the KSU Triga Mark II Nuclear Reactor (20). Each sample received fluences ranging from 10^{14} to 2.5×10^{16} neutrons/cm² to allow the detection of various elements.

3.2 Sample Counting Geometry and Techniques

The irradiated samples, nominally 0.1 to 10 μ Ci, were transferred to clean, weighed polyethylene sample vials for two reasons. First, the ⁴¹Ar produced from the irradiation of the air in the sample vial is vented removing the argon interference; Second, external contamination of the irradiated vial, normally Na and Cl from handling, remains behind on the

irradiated vials. The irradiated vials are disposed of as dry radioactive waste.

All samples were monitored for radiation hazard upon removal from the reactor and during transfer to the counting vials. All personnel involved were equipped with film badges or pocket dosimeters. All samples were processed within the regulations of 10CFR20 and the State of Kansas Radilological Regulations.

The samples were allowed to decay for different intervals before counting using a 25 cc Ge(Li) detector. For instance, if a sample has a high aluminum content (many geological samples contain as much as 10 to 15 per cent Al_2O_3) a decay period of approximately 30 minutes will remove the interference caused by the ^{28}Al . If the prime interference is manganese then a decay period of approximately 24 hours is required. Removal of sodium interferences requires a 6-10 day decay period.

The Ge(Li) detector with bias applied is normally a p-i-n device as shown in Fig. 3. A gamma ray causing ionization in the intrinsic (i) region results in a pulse of ions being swept across the crystal and received at the pre-amplifier. The drifted lithium contained in the germanium crystal is very mobile and at room temperatures (20°C) will diffuse out of the detector. The detector is housed at the end of a gooseneck type dipstick with the dipstick immersed in liquid nitrogen. The liquid nitrogen consumption is 25 liters/ 10 days. Routinely the liquid nitrogen is replenished once per week.

The specimen to be counted is placed on a polystyrene stage mounted on the gooseneck. To correct for geometry effects due to source positioning the stage is adjustable vertically by plastic (to reduce scattering) screws. The stage is in contact with a $3/8$ inch thick poly-

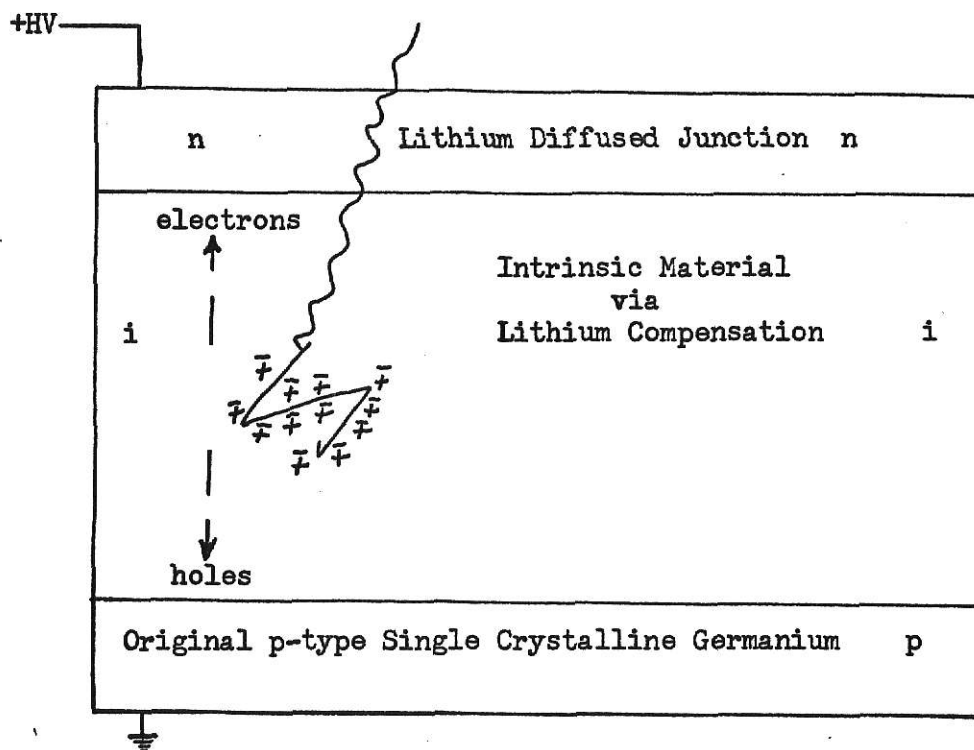


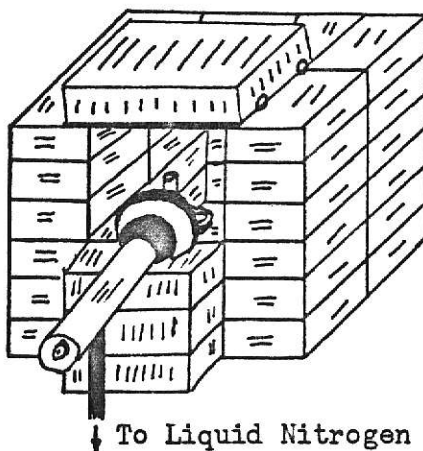
Figure 3. A Schematic Diagram of a Planar-type Lithium-drifted Germanium Detector.

styrene beta shield. The counting stage and gooseneck are enclosed by a lead shield. The interior of the cavity is 8 inches on a side. Access to the stage is provided by a 8" X 8" X 2" lead door. The detector is shielded by 2 inches of lead in either vertical direction, by 4 inches of lead at right angles to the gooseneck and by 8 inches of lead on the direction facing the stage, and by 4 inches of lead for the lower half of the side of the cavity towards the dewar (see Fig. 4). The inside of the cavity is sheathed with cadmium to remove the lead X-rays produced by interactions in the cavity walls. The beta shield covers a 0.5 mm thick aluminum window. The 25 cc trapezohedral Ge(Li) detector is approximately 0.5 cm behind the aluminum window. The complete dipstick-detector assembly is under vacuum.

The signals from the detector, amplified by a Nuclear Diodes Pre-Amplifier, Model 101, undergo considerable amplification and pulse shaping in the Tennelec TC-200 Amplifier. The TC-200 supplies bias voltage for the detector and power for the pre-amplifier. Normal operation uses a bias voltage of -850 V. and the following time constants: First differentiator 0.8 μ sec; Second differentiator 0.8 μ sec; and integrator 12.8 μ sec.

Since all samples are not of the same volume, corrections must be made for sample height. This is done by adjusting the stage so that the center line of the sample is on the horizontal center line of the detector. The copper reference data are accumulated with the capsule as close to the detector as possible. All data are taken with an indicated live-time greater than 80 per cent. At live times of less than 80 per cent the high count rate results in sufficient pulse distortion to render the stored information unreliable. All counting is performed in the live time mode of the TMC 4096 multiparameter system.

PERSPECTIVE



TOP VIEW

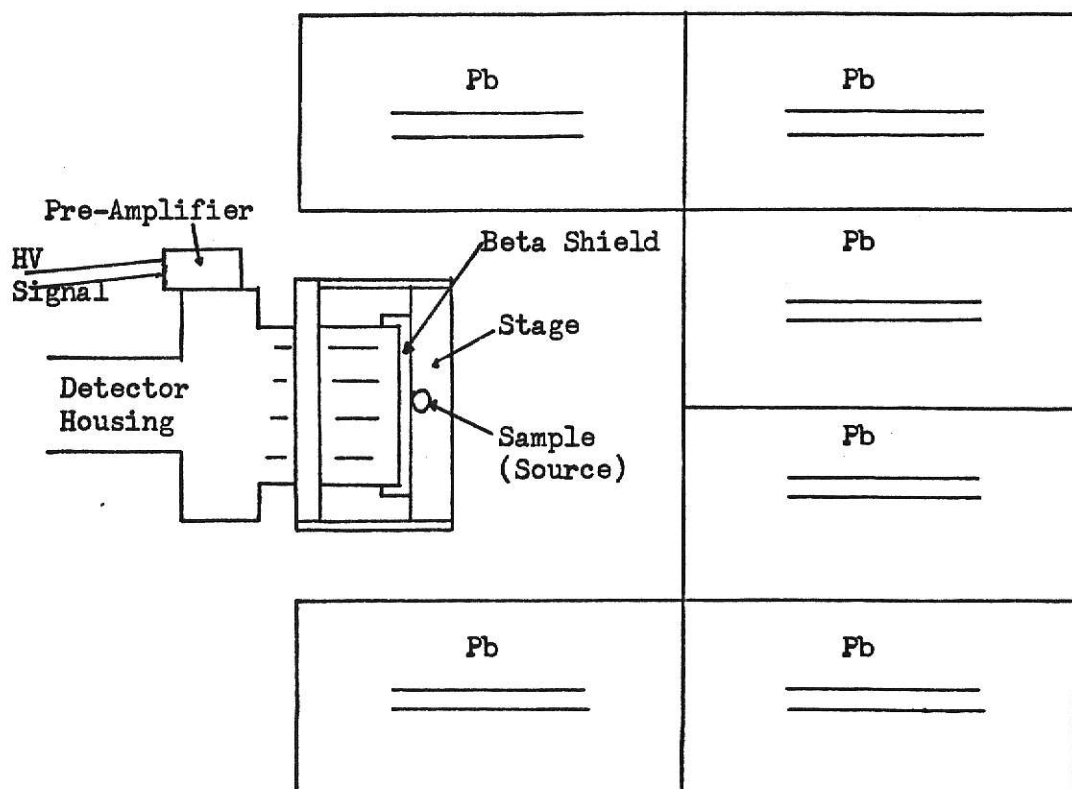


Figure 4. Details of Detector-Source-Shield Configuration.

4.0 RESULTS AND CONCLUSIONS

4.1 Qualitative Analysis

4.1.1 HIRES

The qualitative analysis is performed using the computer code HIRES and manual interpretation of the code output. HIRES is modified version of the code GASPAN (21). HIRES is used to locate photopeaks by examining the first derivative spectrum for changes in sign. If the original spectrum at the point of inflection in the first derivative spectrum is significantly different from the continuum (as determined by a t test), the program is used to compare the full width at half-maximum (FWHM) of the photopeak (as determined by the width of the sign inversion in the first derivative spectrum), to an expected value for the FWHM of the photopeak. If the FWHM width is greater than 0.2 of the expected value, the peak is assumed to be a valid peak and is retained for further analysis. This results in the elimination of spurious "peaks" resulting from electronic noise in the system. The list of approximate peak locations is then passed to a subroutine that performs a fit of a normal (Gaussian) distribution to the photopeak region. The actual function is a Gaussian plus a linear function, i. e., the photopeak is assumed to be a Gaussian superimposed upon a linear base or Compton continuum. The calculated FWHM from the Gaussian fit is then compared with the FWHM from an experimentally determined function of FWHM versus energy (FWHM(E)). Those peaks with an experimental FWHM less than 1.3 times FWHM(E) are assumed to be valid photopeaks. Photopeaks with FWHM greater than 1.3 FWHM(E) are tested to see if they could be backscatter peaks or Compton edges from more energetic peaks in the spectrum. If the photopeak fails that test the photopeak is assumed to be a doublet and is

analyzed as such. The code contains a restriction which prevents the analysis of a particular peak as a doublet more than 5 times. A further restriction prevents the analysis of one peak location as containing more than 4 superimposed peaks. When either restriction is encountered the nature of the restriction and location are printed. The last analysis is retained in the final solution thus yielding some information about that region of the spectrum. These restrictions are normally encountered in the analysis of the single and double escape peaks resulting from the high energy gamma rays of ^{24}Na , ^{37}S , or ^{49}Ca . The escape peaks from many other isotopes appear as only slightly wider than full energy peaks (FEP).

4.1.2 Spectrometer Calibration

The experimental work performed in this work was initially performed under the assumption that the response of the complete system, i. e., Ge(Li) detector--pre-amplifier--main amplifier--4096 multiparameter system, is truly linear. However, evidence (principally the inability of linear fits of various portions of particular spectra to reproduce themselves) indicated that this is not always the case. A ^{226}Ra spectrum was accumulated at a 90 per cent live time and was used in the spectrometer calibration. The ^{226}Ra is a convenient source due to a large number of gamma rays spanning a broad energy range. Therefore ^{226}Ra provides a good calibration spectrum. The energies of the ^{226}Ra gamma rays used in the calibration are listed in Table I. A single precision computer code used to fit, in the least-squares sense, three points to a quadratic function of energy versus channel number did not yield an exact fit. Upon reprocessing these data with a double precision code an exact fit was obtained. It was shown that the 4096 multiparameter system exceeded the manufacturers' integral and

TABLE I

Energies (in keV) of ^{226}Ra used in the Spectrometer Calibration

<u>Number</u>	<u>Energy</u>
1	186.14
2	241.96
3	258.98
4	274.66
5	295.20
6	351.92
7	454.80
8	480.44
9	487.13
10	511.00
11	609.27
12	665.40
13	703.10
14	742.48
15	768.35
16	785.80
17	806.16
18	839.04
19	934.06
20	964.12
21	1051.96
22	1120.28
23	1155.17
24	1207.52
25	1238.13
26	1280.98
27	1401.44
28	1509.22
29	1583.12

differential linearity specifications.

In this work the spectral data from a melanocerite (multiple rare earth oxide mineral) sample were used in determining FWHM as a function of energy. The isotopic identity that results in the particular photopeak energy and the peak parameters are included in Table II. The function obtained is

$$\text{FWHM}(E) = 3.0986 + 0.0026606 E, \quad (10)$$

where E is energy (keV),

FWHM is full width at half-maximum (keV).

4.1.3 A Consistant Set of Gamma-Ray Energies

A consistant set of gamma-ray energies is very important to a Ge(Li) study. The gamma-ray energy set of Gunnick (12), was used in this work. This set of energies was comprised of over 1000 entries of both thermal and fission neutron activation sources. From this large reference gamma-ray energy set a subset was extracted of the isotopes which could be expected from a TRIGA reactor irradiation. Additionally, a series of gamma-ray energies were determined for frequently occurring isotopes that were omitted by Gunnick. Also a series of photopeaks that appear in normal background spectra were calibrated and included in this subset. The uncertainty of the energies determined by Gunnick are generally less than 0.1 keV. The uncertainties of the energies determined in this work are generally less than 1 keV for the reactor produced isotopes and 2-3 keV for the background peaks. In the listing of the gamma-ray energies (Table III), the energy values extracted from the work of Gunnick are listed with no identity in the origin column. The energies of the reactor produced isotopes (not listed by Gunnick) pertinent to this work are listed with a PFE in the origin column. The branching intensities (for the PFE origin) are from reference (16). The

TABLE II

Input Parameters for the Melanocerite Spectrometer Calibration (FWHM(E))

<u>Isotope</u>	<u>Gamma-Ray Energy (keV)</u>	<u>FWHM (keV)</u>
^{140}La	1596.20	7.498 ± 0.363
^{152}Eu	1407.92	6.709 ± 0.674
^{160}Tb	1271.90	6.159 ± 0.671
^{160}Tb	1177.98	6.389 ± 0.273
^{152}Eu	1112.05	5.076 ± 0.454
^{152}Eu	1085.80	6.797 ± 0.304
^{160}Tb	879.31	5.423 ± 0.270
^{140}La ^{152}Eu	867.66 (average)	5.618 ± 0.199
^{140}La	815.80	5.284 ± 0.208
^{152}Eu	778.85	4.826 ± 0.619
^{140}La	751.66	5.172 ± 0.126
^{140}La	574.20	5.243 ± 0.248
^{147}Nd	531.00	4.182 ± 0.361
^{140}La	487.03	4.150 ± 0.086
^{140}La	432.54	3.838 ± 0.098
^{233}Pa	415.75	4.860 ± 0.337
^{233}Pa	398.50	4.149 ± 0.048

TABLE III
Gamma Ray Catalogue

ENERGY KEV	ISOTOPE	HALF LIFE DAYS	NUMBER GAMMAS	BRANCHING INTENSITY	ORIGIN	
53.17	56BA133	2.6300E 03	8	0.01950	ENER	1
57.40	58CE143	1.3750E 00	10	0.12500	ENER	2
65.72	73TA182	1.1500E 02	30	0.03000	ENER	3
66.11	34SE 75	1.2000E 02	9	0.01000	ENER	4
66.90	55CS136	1.3000E 01	15	0.13700	ENER	5
67.75	73TA182	1.1500E 02	30	0.43000	ENER	6
69.66	62SM153	1.9400E 00	4	0.03900	ENER	7
75.28	91PA233	2.7400E 01	15	0.00680	ENER	8
77.35	78PT197	8.3330E-01	2	0.20000	ENER	9
78.00	BACKGND	0.0	0	9.28000	PFE ENER	10
79.59	56BA133	2.6300E 03	8	0.03040	ENER	11
81.00	54XE133	5.2700E 00	1	0.35000	ENER	12
81.01	56BA133	2.6300E 03	8	0.36000	ENER	13
84.67	73TA182	1.1500E 02	30	0.02180	ENER	14
86.43	55CS136	1.3000E 01	15	0.05800	ENER	15
86.61	91PA233	2.7400E 01	15	0.01860	ENER	16
86.79	65TB160	7.2100E 01	18	0.20900	ENER	17
88.83	BACKGND	0.0	0	3.25000	PFE ENER	18
91.00	60ND147	1.1040E 01	12	0.27200	ENER	19
94.66	91PA233	2.7400E 01	15	0.08430	ENER	20
96.73	34SE 75	1.2000E 02	9	0.03400	ENER	21
97.49	62SM153	1.9400E 00	4	0.00900	ENER	22
98.44	91PA233	2.7400E 01	15	0.13500	ENER	23
98.87	78PT195	4.1000E 00	2	0.12000	ENER	24
100.10	73TA182	1.1500E 02	30	0.11900	ENER	25
102.20	52TE131	1.2000E 00	18	0.07500	ENER	26
103.17	62SM153	1.9400E 00	4	0.28400	ENER	27
103.86	91PA233	2.7400E 01	15	0.00810	ENER	28
105.72	52TE129	3.3000E 01	23	0.00230	ENER	29
109.60	57LA140	1.6670E 00	22	0.00220	ENER	30
109.87	55CS136	1.3000E 01	15	0.00450	ENER	31
111.03	91PA233	2.7400E 01	15	0.04850	ENER	32
112.96	71LU177	6.6300E 00	2	0.06500	ENER	33
113.66	73TA182	1.1500E 02	30	0.01770	ENER	34
114.62	91PA233	2.7400E 01	15	0.01680	ENER	35
116.40	73TA182	1.1500E 02	30	0.00430	ENER	36
120.50	60ND147	1.1040E 01	12	0.00350	ENER	37
121.05	34SE 75	1.2000E 02	9	0.17000	ENER	38
121.78	63EU152	5.1170E 03	14	0.33200	ENER	39
122.05	27CO 57	2.7160E 02	2	0.85300	ENER	40
123.10	63EU154	2.8630E 03	23	0.40460	ENER	41
125.40	74 W185	7.4000E 01	1	0.00016	ENER	42
129.53	44RU105	1.8460E-01	17	0.04800	ENER	43
129.65	78PT195	1.8300E 02	2	0.02800	ENER	44
131.15	57LA140	1.6670E 00	22	0.00455	ENER	45

TABLE III (CONTINUED)

ENERGY KEV	ISOTOPE	HALF LIFE DAYS	NUMBER GAMMAS	BRANCHING INTENSITY	ORIGIN
133.05	72HF181	4.5000E 01	4	0.41000	ENER 46
134.24	74 W187	1.0000E 00	14	0.10100	ENER 47
135.89	34SE 75	1.2000E 02	9	0.60600	ENER 48
136.25	72HF181	4.5000E 01	4	0.06900	ENER 49
136.35	77IR192	7.4000E 01	15	0.00150	ENER 50
136.46	27CO 57	2.7160E 02	2	0.08400	ENER 51
142.60	26FE 59	4.5000E 01	5	0.00930	ENER 52
145.22	54XE127	3.6400E 01	4	0.04500	ENER 53
145.44	58CE141	3.2500E 01	1	0.49300	ENER 54
149.04	44RU105	1.8460E-01	17	0.01550	ENER 55
149.80	52TE131	1.2000E 00	18	0.24200	ENER 56
151.10	36KR 85	1.8300E-01	2	0.76000	ENER 57
152.44	73TA182	1.1500E 02	30	0.07100	ENER 58
153.38	55CS136	1.3000E 01	15	0.08200	ENER 59
155.00	75RE188	7.0830E-01	8	0.15000	ENER 60
156.39	73TA182	1.1500E 02	30	0.02720	ENER 61
158.91	52TE129	3.3000E 01	23	0.00150	ENER 62
160.62	56BA133	2.6300E 03	8	0.00760	ENER 63
164.04	55CS136	1.3000E 01	15	0.04500	ENER 64
165.85	56BA139	5.7640E-02	1	0.22000	ENER 65
166.67	55CS136	1.3000E 01	15	0.00650	ENER 66
170.82	12MG 27	6.5970E-03	3	0.00700	ENER 67
172.10	54XE127	3.6400E 01	4	0.26000	ENER 68
172.17	78PT191	3.0000E 00	7	0.10200	ENER 69
172.79	62SM153	1.9400E 00	4	0.00065	ENER 70
176.75	55CS136	1.3000E 01	15	0.13200	ENER 71
179.00	78PT191	3.0000E 00	7	0.03200	ENER 72
179.39	73TA182	1.1500E 02	30	0.03170	ENER 73
180.97	42MO 99	2.7500E 00	4	0.05800	ENER 74
182.40	52TE131	1.2000E 00	18	0.02100	ENER 75
187.30	55CS136	1.3000E 01	15	0.00550	ENER 76
188.32	BACKGND	0.0	0	0.65100	PFE ENER 77
188.40	63EU154	2.8630E 03	23	0.00210	ENER 78
189.90	49IN114	5.0000E 01	4	0.17700	ENER 79
191.31	78PT197	8.3330E-01	2	0.05700	ENER 80
192.30	26FE 59	4.5000E 01	5	0.02800	ENER 81
196.60	60ND147	1.1040E 01	12	0.00200	ENER 82
197.04	65TB160	7.2100E 01	18	0.06500	ENER 83
198.30	73TA182	1.1500E 02	30	0.01530	ENER 84
198.36	34SE 75	1.2000E 02	9	0.01400	ENER 85
200.70	52TE131	1.2000E 00	18	0.07600	ENER 86
201.20	77IR192	7.4000E 01	15	0.00450	ENER 87
202.84	54XE127	3.6400E 01	4	0.69400	ENER 88
205.81	77IR192	7.4000E 01	15	0.03300	ENER 89
206.40	74 W187	1.0000E 00	14	0.00150	ENER 90

TABLE III (CONTINUED)

ENERGY KEV	ISOTOPE	HALF LIFE DAYS	NUMBER GAMMAS	BRANCHING INTENSITY	ORIGIN
208.34	71LU177	6.6300E 00	2	0.11000	ENER 91
208.95	52TE129	3.3000E 01	23	0.00300	ENER 92
215.62	65TB160	7.2100E 01	18	0.05000	ENER 93
222.11	73TA182	1.1500E 02	30	0.07980	ENER 94
229.26	73TA182	1.1500E 02	30	0.03800	ENER 95
231.42	48CD115	2.2080E 00	4	0.00702	ENER 96
231.60	58CE143	1.3750E 00	10	0.02130	ENER 97
239.10	74 W187	1.0000E 00	14	0.00090	ENER 98
240.98	BACKGND	0.0	0	2.90000	PFE ENER 99
240.90	52TE131	1.2000E 00	18	0.08400	ENER100
241.91	57LA140	1.6670E 00	22	0.00555	ENER101
244.70	63EU152	5.1170E 03	14	0.07200	ENER102
246.30	74 W187	1.0000E 00	14	0.00140	ENER103
248.04	63EU154	2.8630E 03	23	0.06600	ENER104
248.30	91PA233	2.7400E 01	15	0.00075	ENER105
249.65	54XE135	3.8330E-01	1	0.92000	ENER106
250.57	52TE129	3.3000E 01	23	0.00465	ENER107
254.30	40ZR 97	7.0080E-01	10	0.01300	ENER108
260.87	48CD115	2.2080E 00	4	0.01850	ENER109
262.84	44RU105	1.8460E-01	17	0.06550	ENER110
264.07	73TA182	1.1500E 02	30	0.03760	ENER111
264.50	34SE 75	1.2000E 02	9	0.58000	ENER112
266.53	57LA140	1.6670E 00	22	0.00510	ENER113
271.54	91PA233	2.7400E 01	15	0.00330	ENER114
273.40	35BR 82	1.4700E 00	10	0.08700	ENER115
273.76	55CS136	1.3000E 01	15	0.12500	ENER116
275.40	60ND147	1.1040E 01	12	0.00720	ENER117
276.29	56BA133	2.6300E 03	8	0.07500	ENER118
278.40	52TE129	3.3000E 01	23	0.00695	ENER119
279.17	80HG203	4.7000E 01	1	0.81000	ENER120
279.43	34SE 75	1.2000E 02	9	0.25000	ENER121
281.15	52TE129	3.3000E 01	23	0.00224	ENER122
293.20	58CE143	1.3750E 00	10	0.46500	ENER123
295.94	77IR192	7.4000E 01	15	0.29200	ENER124
296.58	BACKGND	0.0	0	1.05000	PFE ENER125
298.54	65TB160	7.2100E 01	18	0.35000	ENER126
300.11	91PA233	2.7400E 01	15	0.06600	ENER127
302.71	56BA133	2.6300E 03	8	0.19600	ENER128
303.80	34SE 75	1.2000E 02	9	0.01300	ENER129
305.00	36KR 85	1.8300E-01	2	0.13300	ENER130
308.44	77IR192	7.4000E 01	15	0.30600	ENER131
309.49	65TB160	7.2100E 01	18	0.01100	ENER132
311.90	91PA233	2.7400E 01	15	0.38000	ENER133
312.85	19 K 42	5.1300E-01	3	0.00200	PFE ENER134
316.49	77IR192	7.4000E 01	15	0.85800	ENER135

TABLE III (CONTINUED)

ENERGY KEV	ISOTOPE	HALF LIFE DAYS	NUMBER GAMMAS	BRANCHING INTENSITY	ORIGIN
316.50	44RU105	1.8460E-01	17	0.10200	ENER136
319.40	60ND147	1.1040E 01	12	0.01830	ENER137
319.90	55CS136	1.3000E 01	15	0.00600	ENER138
320.10	24CR 51	2.7800E 01	1	0.09800	ENER139
321.41	22TI 51	4.0278E-03	3	0.95000	PFE ENER140
326.10	44RU105	1.8460E-01	17	0.01070	ENER141
328.75	57LA140	1.6670E 00	22	0.21600	ENER142
330.90	44RU105	1.8460E-01	17	0.00725	ENER143
334.30	52TE131	1.2000E 00	18	0.11100	ENER144
334.90	26FE 59	4.5000E 01	5	0.00260	ENER145
337.30	65TB160	7.2100E 01	18	0.00540	ENER146
339.58	BACKGND	0.0	0	0.28400	PFE ENER147
340.47	91PA233	2.7400E 01	15	0.04430	ENER148
340.60	55CS136	1.3000E 01	15	0.44500	ENER149
342.90	52TE129	3.3000E 01	23	0.00054	ENER150
344.27	63EU152	5.1170E 03	14	0.31400	ENER151
345.95	72HF181	4.5000E 01	4	0.12000	ENER152
350.18	44RU105	1.8460E-01	17	0.01320	ENER153
350.60	58CE143	1.3750E 00	10	0.03550	ENER154
351.10	78PT191	3.0000E 00	7	0.09900	ENER155
352.91	BACKGND	0.0	0	1.74000	PFE ENER156
355.70	40ZR 97	7.0080E-01	10	0.02200	ENER157
355.86	56BA133	2.6300E 03	8	0.67000	ENER158
359.80	78PT191	3.0000E 00	7	0.16600	ENER159
366.30	42MO 99	2.7500E 00	4	0.01180	ENER160
374.40	77IR192	7.4000E 01	15	0.07700	ENER161
374.96	54XE127	3.6400E 01	4	0.17500	ENER162
375.40	91PA233	2.7400E 01	15	0.00655	ENER163
383.70	56BA133	2.6300E 03	8	0.09400	ENER164
388.45	38SR 87	1.1710E-01	1	0.83000	ENER165
392.43	65TB160	7.2100E 01	18	0.01900	ENER166
393.36	44RU105	1.8460E-01	17	0.03860	ENER167
398.10	60ND147	1.1040E 01	12	0.00830	ENER168
398.50	91PA233	2.7400E 01	15	0.01390	ENER169
400.44	34SE 75	1.2000E 02	9	0.11600	ENER170
409.20	78PT191	3.0000E 00	7	0.28800	ENER171
410.40	60ND147	1.1040E 01	12	0.00089	ENER172
411.05	63EU152	5.1170E 03	14	0.02530	ENER173
411.79	79AU198	2.7000E 00	3	0.96800	ENER174
413.51	44RU105	1.8460E-01	17	0.02300	ENER175
415.75	91PA233	2.7400E 01	15	0.01720	ENER176
416.40	77IR192	7.4000E 01	15	0.06900	ENER177
432.54	57LA140	1.6670E 00	22	0.02950	ENER178
432.80	58CE143	1.3750E 00	10	0.00180	ENER179
434.57	47AG108	1.6806E-03	4	0.00450	PFE ENER180

TABLE III (CONTINUED)

ENERGY KEV	ISOTOPE	HALF LIFE DAYS	NUMBER GAMMAS	BRANCHING INTENSITY	ORIGIN
439.80	60ND147	1.1040E 01	12	0.01130	ENER181
442.89	53 I128	1.7360E-02	4	0.17500	ENER182
443.89	63EU152	5.1170E 03	14	0.03300	ENER183
444.00	44RU103	4.0000E 01	4	0.00380	ENER184
444.40	63EU154	2.8630E 03	23	0.00480	ENER185
446.20	47AG110	2.6000E 02	15	0.03500	ENER186
452.40	52TE131	1.2000E 00	18	0.06500	ENER187
456.30	78PT191	3.0000E 00	7	0.09600	ENER188
459.58	52TE129	3.3000E 01	23	0.09000	ENER189
462.79	BACKGND	0.0	0	0.13700	PFE ENER190
468.05	77IR192	7.4000E 01	15	0.50500	ENER191
469.38	44RU105	1.8460E-01	17	0.17500	ENER192
475.34	55CS134	7.6700E 02	10	0.01540	ENER193
478.20	75RE188	7.0830E-01	8	0.01350	ENER194
479.48	74 W187	1.0000E 00	14	0.26600	ENER195
482.16	72HF181	4.5000E 01	4	0.83000	ENER196
484.55	77IR192	7.4000E 01	15	0.03300	ENER197
487.03	57LA140	1.6670E 00	22	0.46500	ENER198
487.38	52TE129	3.3000E 01	23	0.01700	ENER199
489.10	77IR192	7.4000E 01	15	0.00510	ENER200
489.30	60ND147	1.1040E 01	12	0.00160	ENER201
490.40	58CE143	1.3750E 00	10	0.02310	ENER202
492.29	48CD115	2.2080E 00	4	0.08100	ENER203
497.09	44RU103	4.0000E 01	4	0.90000	ENER204
499.28	44RU105	1.8460E-01	17	0.02270	ENER205
501.68	19 K 42	5.1300E-01	3	0.0	PFE ENER206
507.20	55CS136	1.3000E 01	15	0.01000	ENER207
510.95	57LA140	1.6670E 00	22	0.00350	ENER208
511.00	BACKGND	0.0	0	1.11000	PFE ENER209
511.00	11NA 22	9.4170E 02	2	1.80000	ENER210
511.00	21SC 44	1.6300E-01	3	1.92000	ENER211
511.00	27CO 58	7.1000E 01	2	0.29200	ENER212
511.00	29CU 64	5.3750E-01	2	0.38000	PFE ENER213
511.00	30ZN 65	2.4500E 02	2	0.03400	ENER214
511.00	33AS 74	1.7780E 01	4	0.64000	ENER215
511.00	35BR 80	1.2500E-02	3	0.05000	PFE ENER216
511.00	37RB 84	3.2600E 01	2	0.54500	ENER217
511.00	47AG108	1.6806E-03	4	0.00560	PFE ENER218
511.70	74 W187	1.0000E 00	14	0.00770	ENER219
520.43	37RB 83	8.6100E 01	4	0.47000	ENER220
526.62	53 I128	1.7360E-02	4	0.01680	ENER221
527.86	48CD115	2.2080E 00	4	0.27500	ENER222
529.65	37RB 83	8.6100E 01	4	0.30400	ENER223
531.00	60ND147	1.1040E 01	12	0.13100	ENER224
538.70	78PT191	3.0000E 00	7	0.40500	ENER225

TABLE III (CONTINUED)

ENERGY KEV	ISOTOPE	HALF LIFE DAYS	NUMBER GAMMAS	BRANCHING INTENSITY	ORIGIN
551.47	74 W187	1.0000E 00	14	0.06000	ENER226
552.63	37RB 83	8.6100E 01	4	0.16600	ENER227
554.34	35BR 82	1.4700E 00	10	0.72600	ENER228
556.68	52TE129	3.3000E 01	23	0.00225	ENER229
557.07	44RU103	4.0000E 01	4	0.00840	ENER230
558.27	49IN114	5.0000E 01	4	0.04650	ENER231
559.09	33AS 76	1.1040E 00	11	0.44600	ENER232
562.80	33AS 76	1.1040E 00	11	0.01600	ENER233
563.22	55CS134	7.6700E 02	10	0.08820	ENER234
564.08	51SB122	2.8000E 00	4	0.63000	ENER235
569.33	55CS134	7.6700E 02	10	0.15800	ENER236
574.20	57LA140	1.6670E 00	22	0.0	ENER237
575.19	44RU105	1.8460E-01	17	0.01030	ENER238
582.30	63EU154	2.8630E 03	23	0.00770	ENER239
582.72	BACKGND	0.0	0	0.64900	PFE ENER240
587.40	58CE143	1.3750E 00	10	0.00220	ENER241
588.56	77IR192	7.4000E 01	15	0.04600	ENER242
591.70	63EU154	2.8630E 03	23	0.04600	ENER243
594.70	60ND147	1.1040E 01	12	0.00250	ENER244
596.00	33AS 74	1.7780E 01	4	0.59500	ENER245
602.50	40ZR 97	7.0080E-01	10	0.01380	ENER246
602.72	51SB124	6.0200E 01	15	0.98000	ENER247
604.40	77IR192	7.4000E 01	15	0.08900	ENER248
604.70	55CS134	7.6700E 02	10	0.98000	ENER249
608.30	33AS 74	1.7780E 01	4	0.00550	ENER250
608.30	BACKGND	0.0	0	1.36000	PFE ENER251
608.55	22TI 51	4.0278E-03	3	0.01500	PFE ENER252
610.31	44RU103	4.0000E 01	4	0.05600	ENER253
612.44	77IR192	7.4000E 01	15	0.05480	ENER254
616.50	35BR 80	1.2500E-02	3	0.07000	PFE ENER255
618.22	74 W187	1.0000E 00	14	0.07400	ENER256
618.28	47AG108	1.6806E-03	4	0.00180	PFE ENER257
619.06	35BR 82	1.4700E 00	10	0.37400	ENER258
620.10	47AG110	2.6000E 02	15	0.02500	ENER259
620.70	17CL 38	2.5900E-02	5	0.0	ENER260
624.44	52TE129	3.3000E 01	23	0.00109	ENER261
625.37	74 W187	1.0000E 00	14	0.01250	ENER262
632.65	47AG108	1.6806E-03	4	0.01700	PFE ENER263
633.00	75RE188	7.0830E-01	8	0.02000	ENER264
634.90	33AS 74	1.7780E 01	4	0.14800	ENER265
645.82	51SB124	6.0200E 01	15	0.07100	ENER266
656.15	44RU105	1.8460E-01	17	0.01930	ENER267
657.04	33AS 76	1.1040E 00	11	0.06300	ENER268
657.60	47AG110	2.6000E 02	15	0.93000	ENER269
664.59	58CE143	1.3750E 00	10	0.06000	ENER270

TABLE III (CONTINUED)

ENERGY KEV	ISOTOPE	HALF LIFE DAYS	NUMBER GAMMAS	BRANCHING INTENSITY	ORIGIN
665.10	52TE131	1.2000E 00	18	0.05000	ENER271
665.40	33AS 76	1.1040E 00	11	0.00450	ENER272
665.80	35BR 80	1.2500E-02	3	0.01000	PFE ENER273
669.03	51SB124	6.0200E 01	15	0.0	ENER274
671.90	52TE129	3.3000E 01	23	0.00050	ENER275
675.85	79AU198	2.7000E 00	3	0.00760	ENER276
676.32	44RU105	1.8460E-01	17	0.15000	ENER277
677.50	47AG110	2.6000E 02	15	0.12200	ENER278
685.70	74 W187	1.0000E 00	14	0.32000	ENER279
685.80	60ND147	1.1040E 01	12	0.00760	ENER280
686.80	47AG110	2.6000E 02	15	0.07500	ENER281
688.80	63EU152	5.1170E 03	14	0.09100	ENER282
692.50	63EU154	2.8630E 03	23	0.01650	ENER283
692.76	51SB122	2.8000E 00	4	0.03270	ENER284
696.02	52TE129	3.3000E 01	23	0.05700	ENER285
698.36	35BR 82	1.4700E 00	10	0.28200	ENER286
703.80	40ZR 97	7.0080E-01	10	0.01000	ENER287
706.60	47AG110	2.6000E 02	15	0.16000	ENER288
709.31	51SB124	6.0200E 01	15	0.01340	ENER289
713.74	51SB124	6.0200E 01	15	0.02280	ENER290
721.98	58CE143	1.3750E 00	10	0.05600	ENER291
722.78	51SB124	6.0200E 01	15	0.10600	ENER292
723.30	63EU154	2.8630E 03	23	0.19100	ENER293
724.20	40ZR 95	6.5000E 01	2	0.43000	ENER294
724.20	44RU105	1.8460E-01	17	0.44500	ENER295
725.21	49IN114	5.0000E 01	4	0.04550	ENER296
729.69	52TE129	3.3000E 01	23	0.01360	ENER297
739.35	42MD 99	2.7500E 00	4	0.12000	ENER298
741.10	52TE129	3.3000E 01	23	0.00093	ENER299
743.32	53 I128	1.7360E-02	4	0.00169	ENER300
743.37	40ZR 97	7.0080E-01	10	0.94000	ENER301
744.20	47AG110	2.6000E 02	15	0.04330	ENER302
745.23	74 W187	1.0000E 00	14	0.00340	ENER303
751.66	57LA140	1.6670E 00	22	0.04500	ENER304
756.70	63EU154	2.8630E 03	23	0.04100	ENER305
756.72	40ZR 95	6.5000E 01	2	0.54600	ENER306
756.89	13AL 28	1.6000E-03	3	0.0	PFE ENER307
763.80	47AG110	2.6000E 02	15	0.22000	ENER308
765.20	65TB160	7.2100E 01	18	0.01700	ENER309
772.84	74 W187	1.0000E 00	14	0.04800	ENER310
773.70	52TE131	1.2000E 00	18	0.46000	ENER311
776.50	35BR 82	1.4700E 00	10	0.83500	ENER312
777.75	42MD 99	2.7500E 00	4	0.04600	ENER313
778.85	63EU152	5.1170E 03	14	0.15200	ENER314
782.50	52TE131	1.2000E 00	18	0.07600	ENER315

TABLE III (CONTINUED)

ENERGY KEV	ISOTOPE	HALF LIFE DAYS	NUMBER GAMMAS	BRANCHING INTENSITY	ORIGIN
789.19	25MN 56	1.0750E-01	5	0.0	ENER316
790.10	37RB 83	8.6100E 01	4	0.00730	ENER317
790.75	51SB124	6.0200E 01	15	0.00700	ENER318
793.80	52TE131	1.2000E 00	18	0.15900	ENER319
795.79	55CS134	7.6700E 02	10	0.89000	ENER320
801.87	55CS134	7.6700E 02	10	0.09500	ENER321
802.20	52TE129	3.3000E 01	23	0.00244	ENER322
810.50	27CO 58	7.1000E 01	2	0.99500	ENER323
815.60	63EU154	2.8630E 03	23	0.00530	ENER324
815.80	57LA140	1.6670E 00	22	0.24000	ENER325
817.20	52TE129	3.3000E 01	23	0.00170	ENER326
817.90	47AG110	2.6000E 02	15	0.06950	ENER327
818.48	55CS136	1.3000E 01	15	1.00000	ENER328
822.80	52TE131	1.2000E 00	18	0.06700	ENER329
827.79	35BR 82	1.4700E 00	10	0.24300	ENER330
828.00	75RE188	7.0830E-01	8	0.00600	ENER331
833.50	52TE129	3.3000E 01	23	0.00053	ENER332
834.84	25MN 54	3.1400E 02	1	1.00000	ENER333
843.76	12MG 27	6.5970E-03	3	0.72000	ENER334
844.90	52TE129	3.3000E 01	23	0.00072	ENER335
845.60	63EU154	2.8630E 03	23	0.00940	ENER336
846.60	25MN 56	1.0750E-01	5	0.99000	ENER337
846.78	27CO 56	7.7300E 01	18	1.00000	ENER338
852.30	52TE131	1.2000E 00	18	0.25600	ENER339
864.61	74 W187	1.0000E 00	14	0.00400	ENER340
867.42	63EU152	5.1170E 03	14	0.05100	ENER341
867.87	57LA140	1.6670E 00	22	0.05700	ENER342
873.20	63EU154	2.8630E 03	23	0.11300	ENER343
875.80	44RU105	1.8460E-01	17	0.02940	ENER344
879.31	65TB160	7.2100E 01	18	0.40000	ENER345
879.50	74 W187	1.0000E 00	14	0.00280	ENER346
880.40	58CE143	1.3750E 00	10	0.01100	ENER347
882.93	37RB 84	3.2600E 01	2	0.73400	ENER348
884.50	47AG110	2.6000E 02	15	0.71000	ENER349
884.50	77IR192	7.4000E 01	15	0.00170	ENER350
889.30	21SC 46	8.4000E 01	2	1.00000	ENER351
892.80	63EU154	2.8630E 03	23	0.00440	ENER352
904.00	63EU154	2.8630E 03	23	0.00780	ENER353
919.60	57LA140	1.6670E 00	22	0.02500	ENER354
925.25	57LA140	1.6670E 00	22	0.06700	ENER355
927.70	73TA182	1.1500E 02	30	0.00800	ENER356
929.12	22TI 51	4.0278E-03	3	0.05000	ENER357
931.00	75RE188	7.0830E-01	8	0.00800	ENER358
937.30	47AG110	2.6000E 02	15	0.33600	ENER359
951.02	57LA140	1.6670E 00	22	0.00600	ENER360

PFE

TABLE III (CONTINUED)

ENERGY KEV	ISOTOPE	HALF LIFE DAYS	NUMBER GAMMAS	BRANCHING INTENSITY	ORIGIN
959.11	73TA182	1.1500E 02	30	0.00440	ENER361
962.46	65TB160	7.2100E 01	18	0.14000	ENER362
964.00	63EU152	5.1170E 03	14	0.17300	ENER363
966.17	65TB160	7.2100E 01	18	0.34400	ENER364
968.31	51SB124	6.0200E 01	15	0.01720	ENER365
969.40	44RU105	1.8460E-01	17	0.02000	ENER366
969.53	53 I128	1.7360E-02	4	0.00430	ENER367
982.20	52TE129	3.3000E 01	23	0.00028	ENER368
996.30	63EU154	2.8630E 03	23	0.10700	ENER369
1001.66	73TA182	1.1500E 02	30	0.02430	ENER370
1002.90	65TB160	7.2100E 01	18	0.01630	ENER371
1004.80	63EU154	2.8630E 03	23	0.17600	ENER372
1014.40	12MG 27	6.5970E-03	3	0.28000	ENER373
1022.60	52TE129	3.3000E 01	23	0.00041	ENER374
1037.85	27CO 56	7.7300E 01	18	0.12900	ENER375
1038.61	55CS134	7.6700E 02	10	0.01060	ENER376
1043.99	35BR 82	1.4700E 00	10	0.27100	ENER377
1045.10	51SB124	6.0200E 01	15	0.01840	ENER378
1048.10	55CS136	1.3000E 01	15	0.80500	ENER379
1069.20	51SB124	6.0200E 01	15	0.0	ENER380
1078.76	37RB 86	1.8660E 01	1	0.08800	ENER381
1084.00	52TE129	3.3000E 01	23	0.00710	ENER382
1085.30	57LA140	1.6670E 00	22	0.01050	ENER383
1085.80	63EU152	5.1170E 03	14	0.10000	ENER384
1087.64	79AU198	2.7000E 00	3	0.00156	ENER385
1090.59	25MN 56	1.0750E-01	5	0.0	ENER386
1099.32	26FE 59	4.5000E 01	5	0.56200	ENER387
1111.80	52TE129	3.3000E 01	23	0.00274	ENER388
1112.05	63EU152	5.1170E 03	14	0.16400	ENER389
1113.18	73TA182	1.1500E 02	30	0.00410	ENER390
1115.16	65TB160	7.2100E 01	18	0.02160	ENER391
1115.52	30ZN 65	2.4500E 02	2	0.49000	ENER392
1119.70	BACKGND	0.0	0	0.28200	PFE ENER393
1120.50	21SC 46	8.4000E 01	2	1.00000	ENER394
1121.19	73TA182	1.1500E 02	30	0.37000	ENER395
1125.50	52TE131	1.2000E 00	18	0.14800	ENER396
1128.40	63EU154	2.8630E 03	23	0.01100	ENER397
1132.80	75RE188	7.0830E-01	8	0.00140	ENER398
1140.60	51SB122	2.8000E 00	4	0.00660	ENER399
1140.90	63EU154	2.8630E 03	23	0.00195	ENER400
1145.60	17CL 38	2.5900E-02	5	0.0	ENER401
1148.00	40ZR 97	7.0080E-01	10	0.02620	ENER402
1156.98	21SC 44	1.6300E-01	3	0.99000	ENER403
1157.41	73TA182	1.1500E 02	30	0.01100	ENER404
1167.91	55CS134	7.6700E 02	10	0.01850	ENER405

TABLE III (CONTINUED)

ENERGY KEV	ISOTOPE	HALF LIFE DAYS	NUMBER GAMMAS	BRANCHING INTENSITY	ORIGIN
1173.23	27CO 60	1.9210E 03	2	1.00000	ENER406
1175.08	27CO 56	7.7300E 01	18	0.02250	ENER407
1177.98	65TB160	7.2100E 01	18	0.20600	ENER408
1188.95	73TA182	1.1500E 02	30	0.17100	ENER409
1199.92	65TB160	7.2100E 01	18	0.03300	ENER410
1206.60	52TE131	1.2000E 00	18	0.11800	ENER411
1212.90	63EU152	5.1170E 03	14	0.01700	ENER412
1213.30	33AS 76	1.1040E 00	11	0.01600	ENER413
1216.25	33AS 76	1.1040E 00	11	0.03400	ENER414
1221.31	73TA182	1.1500E 02	30	0.28900	ENER415
1228.63	33AS 76	1.1040E 00	11	0.01650	ENER416
1230.93	73TA182	1.1500E 02	30	0.12100	ENER417
1235.41	55CS136	1.3000E 01	15	0.19700	ENER418
1238.29	27CO 56	7.7300E 01	18	0.66600	ENER419
1246.60	63EU154	2.8630E 03	23	0.00640	ENER420
1251.30	65TB160	7.2100E 01	18	0.00170	ENER421
1256.83	51SB122	2.8000E 00	4	0.00650	ENER422
1257.34	73TA182	1.1500E 02	30	0.01600	ENER423
1267.89	13AL 28	1.6000E-03	3	0.0	PFE ENER424
1271.90	65TB160	7.2100E 01	18	0.10300	ENER425
1273.67	73TA182	1.1500E 02	30	0.00690	ENER426
1274.55	11NA 22	9.4170E 02	2	0.89800	ENER427
1274.80	63EU154	2.8630E 03	23	0.33600	ENER428
1276.10	40ZR 97	7.0080E-01	10	0.00900	ENER429
1289.07	73TA182	1.1500E 02	30	0.01470	ENER430
1291.62	26FE 59	4.5000E 01	5	0.43500	ENER431
1292.00	29AR 41	7.6250E-02	1	0.99000	PFE ENER432
1299.20	63EU152	5.1170E 03	14	0.01900	ENER433
1300.20	49IN114	5.0000E 01	4	0.00180	ENER434
1307.90	75RE188	7.0830E-01	8	0.00500	ENER435
1312.17	65TB160	7.2100E 01	18	0.04000	ENER436
1317.43	35BR 82	1.4700E 00	10	0.26500	ENER437
1325.50	51SB124	6.0200E 01	15	0.01580	ENER438
1332.51	27CO 60	1.9210E 03	2	1.00000	ENER439
1342.60	73TA182	1.1500E 02	30	0.00280	ENER440
1345.76	29CU 64	5.3750E-01	2	0.00480	ENER441
1354.90	51SB124	6.0200E 01	15	0.00640	ENER442
1360.22	27CO 56	7.7300E 01	18	0.04200	ENER443
1362.70	40ZR 97	7.0080E-01	10	0.01080	ENER444
1365.13	55CS134	7.6700E 02	10	0.03000	ENER445
1368.30	51SB124	6.0200E 01	15	0.02450	ENER446
1368.53	11NA 24	6.2500E-01	4	1.00000	ENER447
1373.80	73TA182	1.1500E 02	30	0.00240	ENER448
1384.30	47AG110	2.6000E 02	15	0.24000	ENER449
1387.20	73TA182	1.1500E 02	30	0.00081	ENER450

TABLE III (CONTINUED)

ENERGY KEV	ISOTOPE	HALF LIFE DAYS	NUMBER GAMMAS	BRANCHING INTENSITY	ORIGIN
1397.80	63EU154	2.8630E 03	23	0.01600	ENER451
1400.50	55CS134	7.6700E 02	10	0.00080	ENER452
1407.92	63EU152	5.1170E 03	14	0.24300	ENER453
1410.00	73TA182	1.1500E 02	30	0.00047	ENER454
1434.19	23 V 52	2.6200E-03	1	1.00000	PFE ENER455
1439.40	33AS 76	1.1040E 00	11	0.00260	ENER456
1453.00	73TA182	1.1500E 02	30	0.00033	ENER457
1460.00	BACKGND	0.0	0	3.46000	PFE ENER458
1474.88	35BR 82	1.4700E 00	10	0.16700	ENER459
1475.90	47AG110	2.6000E 02	15	0.03700	ENER460
1494.60	63EU154	2.8630E 03	23	0.00670	ENER461
1499.20	21SC 44	1.6300E-01	3	0.01000	ENER462
1499.67	57LA140	1.6670E 00	22	0.0	ENER463
1505.20	47AG110	2.6000E 02	15	0.12600	ENER464
1523.68	19 K 42	5.1300E-01	3	0.18000	PFE ENER465
1562.50	47AG110	2.6000E 02	15	0.01100	ENER466
1576.56	27CO 56	7.7300E 01	18	0.0	ENER467
1591.75	BACKGND	0.0	0	0.20300	PFE ENER468
1596.20	57LA140	1.6670E 00	22	0.96500	ENER469
1597.30	63EU154	2.8630E 03	23	0.01700	ENER470
1609.80	75RE188	7.0830E-01	8	0.00500	ENER471
1642.70	17CL 38	2.5900E-02	5	0.35000	ENER472
1645.80	52TE131	1.2000E 00	18	0.01500	ENER473
1650.20	35BR 82	1.4700E 00	10	0.07200	ENER474
1656.60	17CL 38	2.5900E-02	5	0.0	ENER475
1691.03	51SB124	6.0200E 01	15	0.45700	ENER476
1732.13	11NA 24	6.2500E-01	4	0.0	ENER477
1750.60	40ZR 97	7.0080E-01	10	0.01080	ENER478
1771.33	27CO 56	7.7300E 01	18	0.16200	ENER479
1778.89	13AL 28	1.6000E-03	3	1.00000	PFE ENER480
1787.80	33AS 76	1.1040E 00	11	0.00320	ENER481
1811.20	25MN 56	1.0750E-01	5	0.30000	ENER482
1852.00	40ZR 97	7.0080E-01	10	0.00260	ENER483
1887.70	52TE131	1.2000E 00	18	0.01700	ENER484
2001.00	52TE131	1.2000E 00	18	0.02700	ENER485
2010.40	57LA140	1.6670E 00	22	0.00430	ENER486
2015.30	27CO 56	7.7300E 01	18	0.03200	ENER487
2034.90	27CO 56	7.7300E 01	18	0.07900	ENER488
2062.49	20CA 49	6.1200E-03	3	0.0	PFE ENER489
2079.55	16 S 37	3.5400E-03	3	0.0	PFE ENER490
2091.20	51SB124	6.0200E 01	15	0.05200	ENER491
2096.60	33AS 76	1.1040E 00	11	0.00600	ENER492
2111.10	33AS 76	1.1040E 00	11	0.00330	ENER493
2112.60	25MN 56	1.0750E-01	5	0.15500	ENER494
2167.60	17CL 38	2.5900E-02	5	0.47000	ENER495

TABLE III (CONTINUED)

ENERGY KEV	ISOTOPE	HALF LIFE DAYS	NUMBER GAMMAS	BRANCHING INTENSITY	ORIGIN
2180.17	27CO 56	7.7300E 01	18	0.0	ENER496
2231.60	27CO 56	7.7300E 01	18	0.0	ENER497
2243.13	11NA 24	6.2500E-01	4	0.0	ENER498
2251.15	27CO 56	7.7300E 01	18	0.0	ENER499
2348.20	57LA140	1.6670E 00	22	0.00820	ENER500
2429.28	27CO 56	7.7300E 01	18	0.0	ENER501
2521.83	57LA140	1.6670E 00	22	0.03250	ENER502
2547.70	57LA140	1.6670E 00	22	0.00090	ENER503
2573.49	20CA 49	6.1200E-03	3	0.0	PFE ENER504
2590.55	16 S 37	3.5400E-03	3	0.0	PFE ENER505
2598.52	27CO 56	7.7300E 01	18	0.17200	ENER506
2754.14	11NA 24	6.2500E-01	4	1.00000	ENER507
3084.49	20CA 49	6.1200E-03	3	0.89000	PFE ENER508
3101.55	16 S 37	3.5400E-03	3	0.90000	PFE ENER509
3202.18	27CO 56	7.7300E 01	18	0.03120	ENER510
3253.61	27CO 56	7.7300E 01	18	0.07400	ENER511
3273.16	27CO 56	7.7300E 01	18	0.01700	ENER512
3451.29	27CO 56	7.7300E 01	18	0.00900	ENER513

background peaks are labeled BACKGND (the half life entries equal zero). The branching intensity is the net cpm in the photopeak as determined by a 60 hour accumulation of background data. The consistant set of gamma-ray energies used is listed in Table III.

4.1.4 Deficiencies of the Gamma-Ray Catalogue (GRC)

There are three main difficulties involved in the calibration or identification of photopeaks using this GRC. First, a significant number of shorter lived isotopes are not included in the catalogue at this time. Secondly, there is a basic lack of comprehensive information in the energy region between 50 and 400 keV. A significant portion of the rare earth elements (REE) decay schemes are quite complicated in this energy region. The problem of obtaining high purity stable compounds of particular elements combined with the complex decay schemes of the various REE isotopes results in the precise calibration of a particular isotope being a formidable task. Third, the calibration of background peaks is complicated by the fact that the background source is so weak that very long counting times are required in order to obtain good counting statistics.

4.1.5 Qualitative Analysis Results

The geological sample W-1 was irradiated for 1 minute at 250 kWt in the KSU TRIGA Mark II Nuclear Reactor. The spectrum accumulated at 23 minutes decay is shown in Fig. 5. The results of the analysis performed by HIRES are given in Table IV. In the spectrum only one peak (the 1090 keV double escape (DE) peak from ^{56}Mn) was overlooked in the region examined. As a result the quantitative analysis of the sample would not have been affected since four other ^{56}Mn peaks were detected. At the present time no attempt has been made to resolve the 511 keV photopeak into its component isotopes.

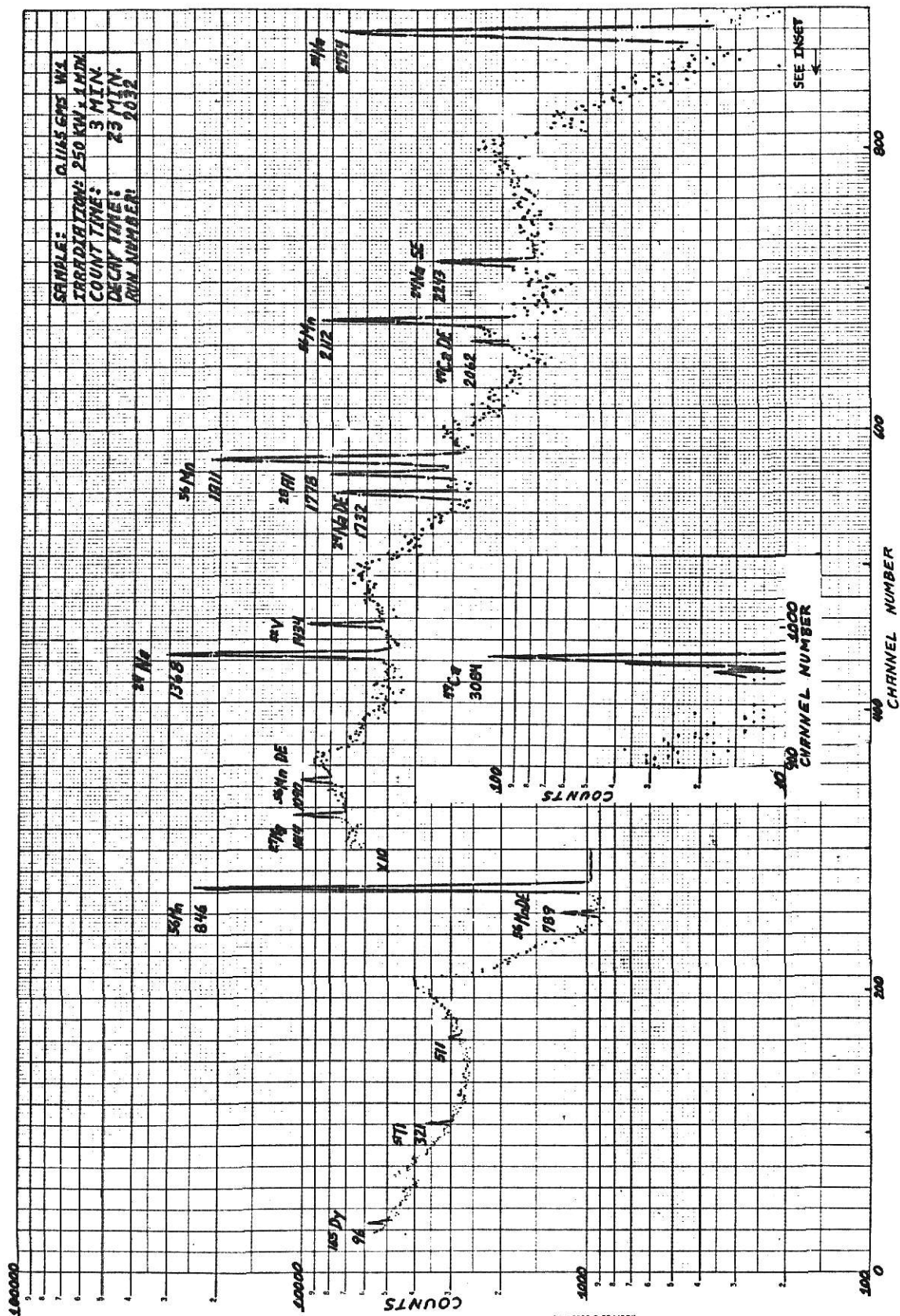


Figure 5 Ge(Li) Detector Response to Sample W-1, 23 Minute Decay.

TABLE IV

Qualitative Analysis Results for Run # 2032, Sample W-1, 1 Minute Irradiation.

Isotope	Half Life	Gamma-Ray Energy from HIRES keV	Gamma-Ray Energy from Gunnick keV	Energy Difference (HIRES-Gunnick) keV
⁴⁹ Ca	8.8 min	3084.16	3084.39	-0.33
²⁴ Na	15.0 hr	2754.14	2754.14	----- ^a
²⁴ Na SE ^b	15.0 hr	2242.55	2243.13	-0.58
⁵⁶ Mn	2.58 hr	2113.05	2112.60	0.45
⁴⁹ Ca DE ^c	8.8 min	2064.27	2062.49	1.78
⁵⁶ Mn	2.58 hr	1810.54	1811.20	-0.66
²⁸ Al	2.3 min	1778.92	1778.89	0.03
²⁴ Na DE	15.0 hr	1730.76	1732.13	-1.37
²⁴ Na DE	15.0 hr	1723.89	1732.13	-8.24
⁵² V	3.77 min	1433.87	1434.19	-0.32
²⁴ Na	15.0 hr	1368.53	1368.53	----- ^a
⁵⁶ Mn DE	2.58 hr	1090. ^d	1090.59	NC ^e
²⁷ Mg	9.5 min	1014.21	1014.40	-0.19
²⁷ Mg	9.5 min	846.60	843.76	NC ^e
⁵⁶ Mn	2.58 hr	846.60	846.60	0.00
⁵⁶ Mn DE	2.58 hr	788.87	789.19	-0.32
		511.00	511.00	-----
⁵¹ Ti	5.80 min	320.47	321.41	-0.94
¹⁶⁵ Dy	2.35 hr	96. ^f	NE ^g	NC ^e

^a Energy Difference was defined to be zero in HIRES (a calibration photo-peak).

TABLE IV (contd)

b	Single Escape photopeak.
c	Double Escape photopeak.
d	This peak rejected by HIRES as non significant.
e	Energy difference not calculated, since photopeak energy was estimated.
f	This peak was not examined by HIRES and the energy was estimated.
g	No entry in Gamma-Ray Catalogue.

It is realized that all photons energetic enough to interact by pair production will contribute to the peak along with ^{64}Cu and other positron emitters. The 96 keV peak of ^{165}Dy was not in the region of the spectrum examined by HIRES and was identified by hand calculating the energy of the photopeak and performing a decay study on the peak.

The geological standard G-1 was irradiated for 1 minute in the KSU Triga reactor at 10 kWt. The spectrum accumulated after a 14 minute decay period is plotted in Fig. 6 and the HIRES output is given in Table V. All significant photopeaks of the spectrum were identified as such in the region examined by HIRES. The 167 keV peak was not identified. It appears to be composed of several interfering gamma rays.

The sample of W-1 that was irradiated for 15 minutes at 250 kWt was accumulated for 1280 minutes after a decay period of 36,225 minutes (approximately 25 days). The spectral data are shown in Fig. 7 and the HIRES results in Table VI. Problems in the use of HIRES appeared in the analysis of these data. First, the code failed to reject the peaks located in channel 420 as being a Compton edge. It was reported as two separate peaks.

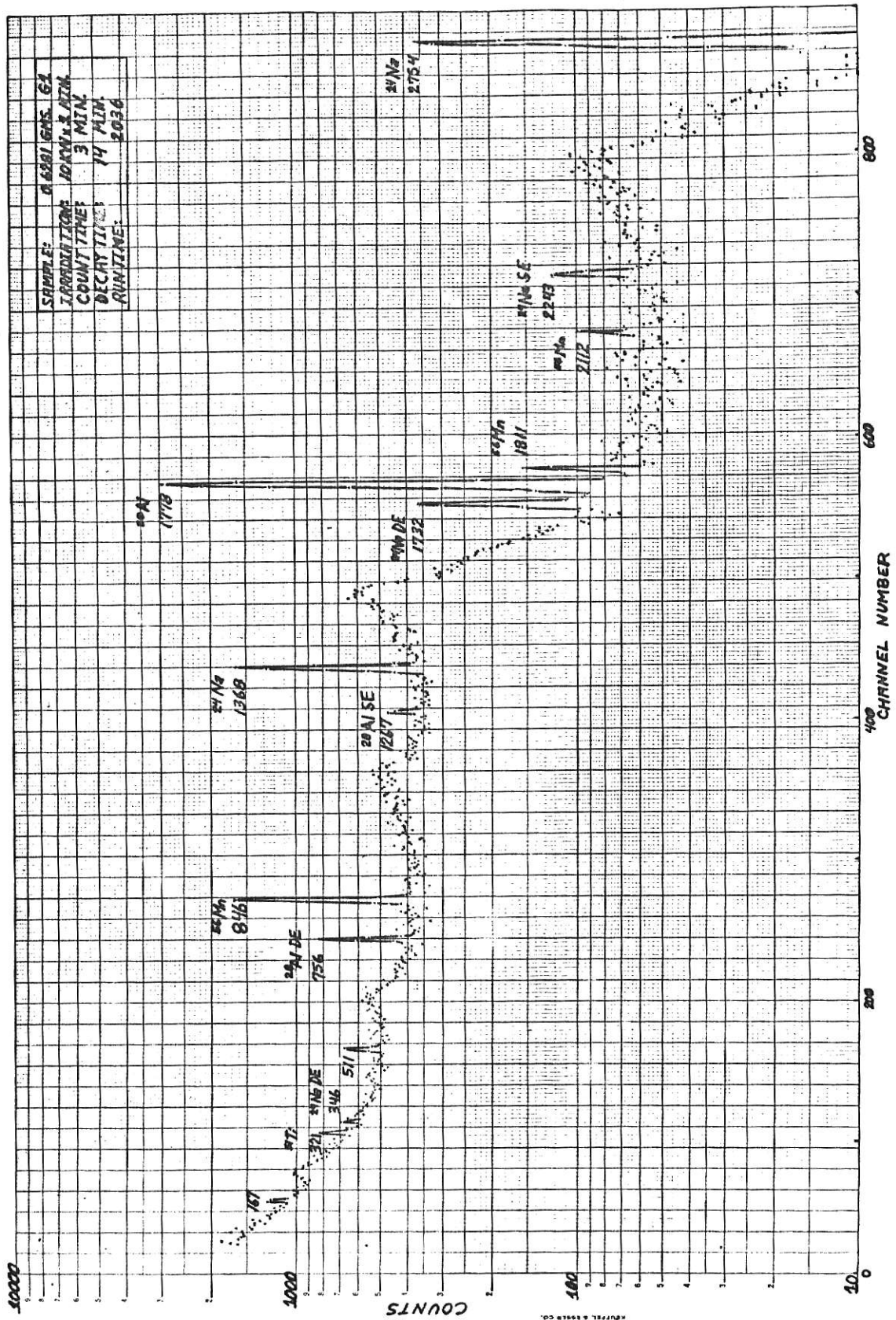


Figure 6. Ge(Li) Detector Response to Sample G-1, 14 Minute Decay.

TABLE V

Qualitative Analysis Results for Run # 2036, Sample G-1, 1 min irradiation.

Isotope	Half Life	Gamma-Ray Energy from HIRES keV	Gamma-Ray Energy from Gunnick keV	Energy Difference (HIRES-Gunnick) keV
^{24}Na	15.0 hr	2754.14	2754.14	----- ^a
^{24}Na SE ^b	15.0 hr	2242.23	2243.13	-0.90
^{56}Mn	2.58 hr	2112.84	2112.60	0.24
^{56}Mn	2.58 hr	1810.98	1811.20	-0.22
^{28}Al	2.3 min	1778.89	1778.89	----- ^a
^{24}Na DE ^c	15.0 hr	1732.00	1732.13	-0.13
^{24}Na	15.0 hr	1368.85	1368.53	0.32
^{28}Al SE	2.3 min	1268.16	1267.89	0.27
^{56}Mn	2.58 hr	846.60	846.60	----- ^a
^{28}Al DE	2.3 min	757.61	756.89	0.72
		511.16	511.00	0.16
^{24}Na	15.0 hr	346.09	346.53	-0.44
^{51}Ti	5.8 min	321.18	321.41	-0.23
NI ^d		167. ^e		

^a Energy Difference was defined to be zero in HIRES (a calibration photopeak).^b Single Escape photopeak.^c Double Escape photopeak.^d This peak was not identified.^e This peak was not in the region examined by HIRES and the energy was estimated.

TABLE VI

Qualitative Analysis Results for Run # 2096, Sample W-1, 15 Minute Irradiation

Isotope	Half Life	Gamma-Ray Energy from HIRES keV	Gamma-Ray Energy from Gunnick keV	Energy Difference (HIRES-Gunnick) keV
^{40}K	1.3×10^9 yr	1460.83	1460.00	0.83
^{152}Eu	12.4 yr	1407.95	1407.92	0.03
^{60}Co	5.28 yr	1332.51	1332.51	----- ^a
^{59}Fe	45 days	1291.76	1291.62	0.14
^{60}Co	5.28 yr	1173.40	1173.23	0.17
^{46}Sc	83.8 days	1120.73	1120.50	0.23
^{59}Fe	45 days	1099.14	1099.32	-0.18
^{46}Sc	83.8 days	889.30	889.30	----- ^a
D ^b		834. ^c		NC ^d
Compton Edge		688.32		NC
Compton Edge		684.68		NC
		511.00	511.00	----- ^a
^{181}Hf	45 days	482.04	482.16	-0.12
^{152}Eu	12.4 yr	344.22	345.95	-1.73
^{181}Hf	45 days	344.22	344.27	-0.05
^{51}Cr	27.8 days	320.45	320.10	0.35
NI ^b		299.07		NC ^d
NI		295.30		NC
NI		240.23		NC
NI		200.10		NC
NI		194.21		NC

TABLE VI (contd)

Isotope	Half Life	Gamma-Ray Energy from HIRES keV	Gamma-Ray Energy from Gunnick keV	Energy Difference (HIRES-Gunnick) keV
NI ^b		179.17		NC ^d
NI		161.31		NC
C ^e		147.		NC
B ^e		135.		NC
A ^e		125.		NC

a Energy Difference was defined to be zero in HIRES (a calibration photopeak).

b This photopeak was not identified.

c Photopeak energy estimated.

d Energy difference not calculated.

e This photopeak was in a region of the spectrum not examined by HIRES and the energy was estimated.

No peaks are listed in the GRC that would explain the retention of these peaks. Secondly, the peak labeled D in the spectrum was rejected as non significant. It has not been identified but is felt to be significant. All of the peaks that have energies less than the ⁵¹Cr peak (320 keV) are unidentified. This reflects the lack of information in the low energy region of the GRC. The three peaks labeled A, B, and C were in the region of the spectrum not examined by HIRES.

The spectrum of G-1 that was accumulated for 1130 minutes at 26,067 minute decay (approximately 18 days) is shown in Fig. 8. The HIRES analysis

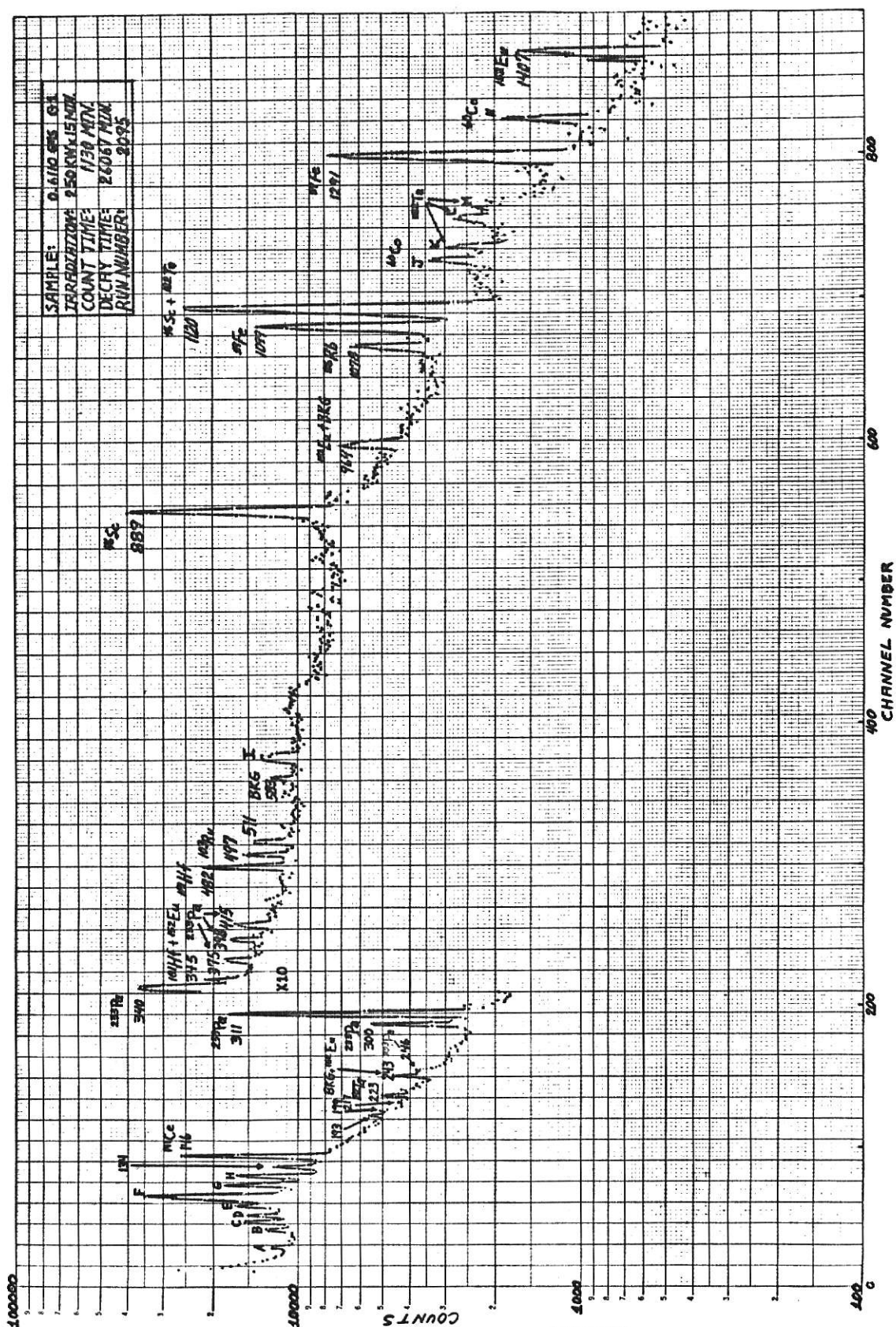


Figure 8. Ge(Li) Detector Response to Sample G-1, 26067 Minute Decay.

is listed in Table VII. This sample was irradiated for 15 minutes at 250 kWt. In this spectrum HIRES failed to analyze the peaks labeled J, K, L, M, and N. This resulted in the failure to recognize ^{60}Co and ^{182}Ta which are present in the sample. The ^{182}Ta peak (223 keV) would probably have been rejected since its associated photopeaks apparently were not present. Also note that all of the peaks of energy less than 223 keV are unidentified. This once again reflects the inadequacy of the GRC at lower energies. The photopeaks labeled A-H were in the region of the spectrum not examined by HIRES.

The region of the spectrum not examined was chosen such that the 145 keV ^{141}Ce photopeak would be detected if present. All photopeaks of lower energies contained in the GRC have associated photopeaks of higher energies. Therefore, usually they can be identified by the higher energy peaks.

The failure of the HIRES code to detect the ^{60}Co and ^{182}Ta photopeaks indicates the need for a high quality plotting technique to allow visual examination of spectra along with the HIRES output to prevent the loss of identification of isotopes.

The energy differences listed in Tables IV-VII are generally less than 1 keV for the photoelectric photopeaks. This small deviation greatly reduces the candidates in an identification process. One constant deviation from Gunnick is the energy (from HIRES) for ^{86}Rb , it is approximately 2 keV less than the value of 1078.76 reported.

TABLE VII

Qualitative Analysis Results for Run # 2095, Sample G-1, 15 Minute Irradiation

Isotope	Half Life	Gamma-Ray Energy from HIRES keV	Gamma-Ray Energy from Gunnick keV	Energy Difference (HIRES-Gunnick) keV
^{152}Eu	12.4 yr	1407.65	1407.92	-0.30
^{60}Co	5.28 yr	N ^a	1332.51	NC ^b
^{59}Fe	45 days	1291.62	1291.62	----- ^c
^{182}Ta	115 days	M ^a	1230.93	NC
^{182}Ta	115 days	L ^a	1221.31	NC
^{182}Ta	115 days	K ^a	1188.95	NC
^{60}Co	5.28 yr	J ^a	1173.23	NC
^{46}Sc	83.8 days	1120.43	1120.50	-0.07
^{182}Ta	115 days	1120.43	1121.19	-0.76
^{59}Fe	45 days	1099.00	1099.32	-0.32
^{86}Rb	18.7 days	1076.76	1078.76	-2.00
^{160}Tb	72 days	969.50	966.17	3.33
^{152}Eu	12.4 yr	964.12	964.00	0.12
^{46}Sc	83.8 days	889.30	889.30	----- ^c
NI ^d		I ^a		
Background		583.23	582.72	0.51
		511.00	511.00	----- ^c
^{103}Ru	40 days	496.18	497.09	-0.91
^{181}Hf	45 days	481.65	482.16	-0.51
^{233}Pa	27.4 days	415.99	415.75	0.24

TABLE VII (contd)

Isotope	Half Life	Gamma-Ray Energy from HIRES keV	Gamma-Ray Energy from Gunnick keV	Energy Difference (HIRES-Gunnick) keV
^{233}Pa	27.4 days	413.26	415.75	-1.49
^{233}Pa	27.4 days	398.14	398.50	-0.36
^{233}Pa	27.4 days	374.34	375.40	-1.06
^{152}Eu	12.4 yr	344.79	344.27	0.52
^{181}Hf	45 days	344.79	345.95	-1.16
^{233}Pa	27.4 days	340.83	340.87	0.36
^{233}Pa	27.4 days	312.11	311.90	0.21
^{233}Pa	27.4 days	299.80	300.11	-0.31
^{233}Pa	27.4 days	246.40	248.30	-1.90
^{152}Eu	12.4 yr	243.82	244.70	-0.88
^{182}Ta	115 days	223.15	222.11	1.04
NI^{d}		216.94		NC^{b}
NI		199.13		NC
NI		193.43		NC
NI		146.47		NC
NI		134.34		NC
H^{e}		124.		NC
G^{e}		112.		NC
F^{e}		99.		NC
E^{e}		88.		NC
D^{e}		76.		NC
C^{e}		69.		NC

TABLE VII (contd)

Isotope	Half Life	Gamma-Ray Energy from HIRES keV	Gamma-Ray Energy from Gunnick keV	Energy Difference (HIRES-Gunnick) keV
B ^e		60.		NC ^b
A ^e		40.		NC

a This photopeak was rejected by HIRES as non significant.

b Energy Difference not calculated.

c Energy Difference was defined to be zero in HIRES (a calibration photopeak).

d This photopeak not identified.

e This photopeak was in a region of the spectrum not examined by HIRES and the energy was estimated.

4.2 Quantitative Analysis

4.2.1 Area of Interest Unfolding

The Area of Interest (AOI) unfolding technique is useful for two reasons: 1.) The results of unfolding by AOI are always as good as others but in some instances more accurate. 2.) Ge(Li) spectrometers with their increased resolution demand the use of 1024 to 4096 channel analyzers. AOI unfolding requires the data of only a portion of the total number of channels; consequently less computer time and core storage is needed for analysis. For instance, a 1024 channel spectrum with 40 photopeaks and a 10 channel area of interest about each photopeak can be processed as a 400 channel spectrum.

4.2.2 Electronic Drift and System Nonlinearity Compensation

Most electronic systems are not stable but in fact exhibit a change

over the long term in their response to identical inputs. This drift combined with start-up irreproducibilities result in spectra from the same source being accumulated at different gains and baselines. It is necessary prior to quantitative analysis to shift these data to the same gains and baselines.

The analysis of gamma-ray spectra from a variety of experiments is commonly performed under the assumption that the analyzer is linear, i. e., the energy represented by the data in channel i is

$$E_i = a + bx_i, \quad (11)$$

where E_i = energy of the i th channel,

a = zero channel intercept (keV),

b = gain of the spectrum (keV/channel).

A widely used technique for the shifting of NaI(Tl) gamma-ray spectral data has been reported by Heath (26). The assumption of linearity for NaI(Tl) is valid for most analyzer systems, because of the comparatively poor resolution (approximately 40 keV for ^{137}Cs).

The improved resolution of Ge(Li) gamma-ray spectra leads to the importance of identifying the nonlinearities in the analyzer system. One method of accounting for the nonlinearity of the analyzer system is to obtain detailed information on the differential nonlinearity of the system (12), store it in a computer memory, and recover the necessary corrections for each datum point as spectra are processed. An alternative algorithm is described below.

Assume that the energy of a data point can be described as

$$E_i = a_{NS} + b_{NS}x_i + c_{NS}x_i^2, \quad (12)$$

where E_i = energy of channel x_i (keV),

a_{NS} = zero channel intercept (keV),

b_{NS} = gain of the spectrum (keV/channel),

c_{NS} = a nonlinearity coefficient (keV/channel²),

x_i = channel number of interest.

If it is desired to shift the spectrum to another nonlinear set of parameters, called a_S , b_S , and c_S , the algorithm is as follows: 1) Select a channel in the shifted data x_S . 2) Calculate E_S from Eq. (12) with the subscript NS replaced by S. 3) Calculate the channel number in the unshifted data x_{NS} from the fact that the energy in the shifted case is identical to that in the unshifted case, i. e.,

$$a_{NS} + b_{NS}x_{NS} + c_{NS}x_{NS}^2 = a_S + b_Sx_S + c_Sx_S^2.$$

The solution for x_{NS} is

$$x_{NS} = \frac{-b_{NS} + \sqrt{b_{NS}^2 - 4c_{NS}(a_{NS} - (a_S + b_Sx_S + c_Sx_S^2))}}{2c_{NS}}. \quad (13)$$

In most cases the term $c_Sx_S^2$ is negligible compared to the others in the radicand of Eq. (13). 4) Interpolate linearly between the two closest channels to x_{NS} in the unshifted spectrum. 5) Store the value obtained in the shifted spectrum for channel x_S . 6) Increment x_S by 1 and return to step 2 until x_S or x_{NS} attain a preselected value.

4.2.3 Reference Spectra Accumulation

The reference spectra used in the AOI unfolding code, GELAOI were collected following a standard procedure which was similar to that procedure used to collect the G-1 and W-1 spectra. First, a clean polyethylene sample vial was filled with the reference material, which is described in Table VIII, so that the activated sample would form a disk source about 1/8 inch in height. Second, a calculation was performed to obtain the power

level for a 5 minute irradiation that would result in an analyzer live time of greater than 80 per cent and preferably less than 95 per cent. In this live time range background sources do not usually interfere with the reference material sources. Also the response in this live time range is not affected by pulse distortion due to pulse pileup in the analyzer. Third, a flux monitor of certain weight was selected by the same considerations. The flux monitor used was copper powder contained in gelatin capsules. The flux monitor was placed at the bottom of the polystyrene irradiation vial; the reference material was suspended at the top of the polystyrene irradiation vial. Figure 9 is a plot of the vertical flux profile along the axis of a polystyrene irradiation vial. The copper flux reference was always located at position four. The reference material was always located between position two and position three. It should be pointed out that the flux across the irradiation vial, as shown in Fig. 9, is approximately constant for positions one, two, and three. Therefore all portions of the sample vial in the irradiation vial was exposed to approximately the same magnitude of flux. Fourth, the sample was irradiated in the KSU TRIGA Mark II Nuclear Reactor for five minutes. After irradiation the sample was transferred to a clean non-irradiated vial to remove any extraneous contamination and ^{41}Ar from the air contained in the vial. Fifth, after the proper decay time a series of spectra was accumulated with the centerline of the reference material at the centerline of the detector. The flux monitor was accumulated with the gelatin capsule in a polyethylene vial with the capsule as close to the detector as possible. Also the flux monitor was positioned with the source centerline on the centerline of the detector.

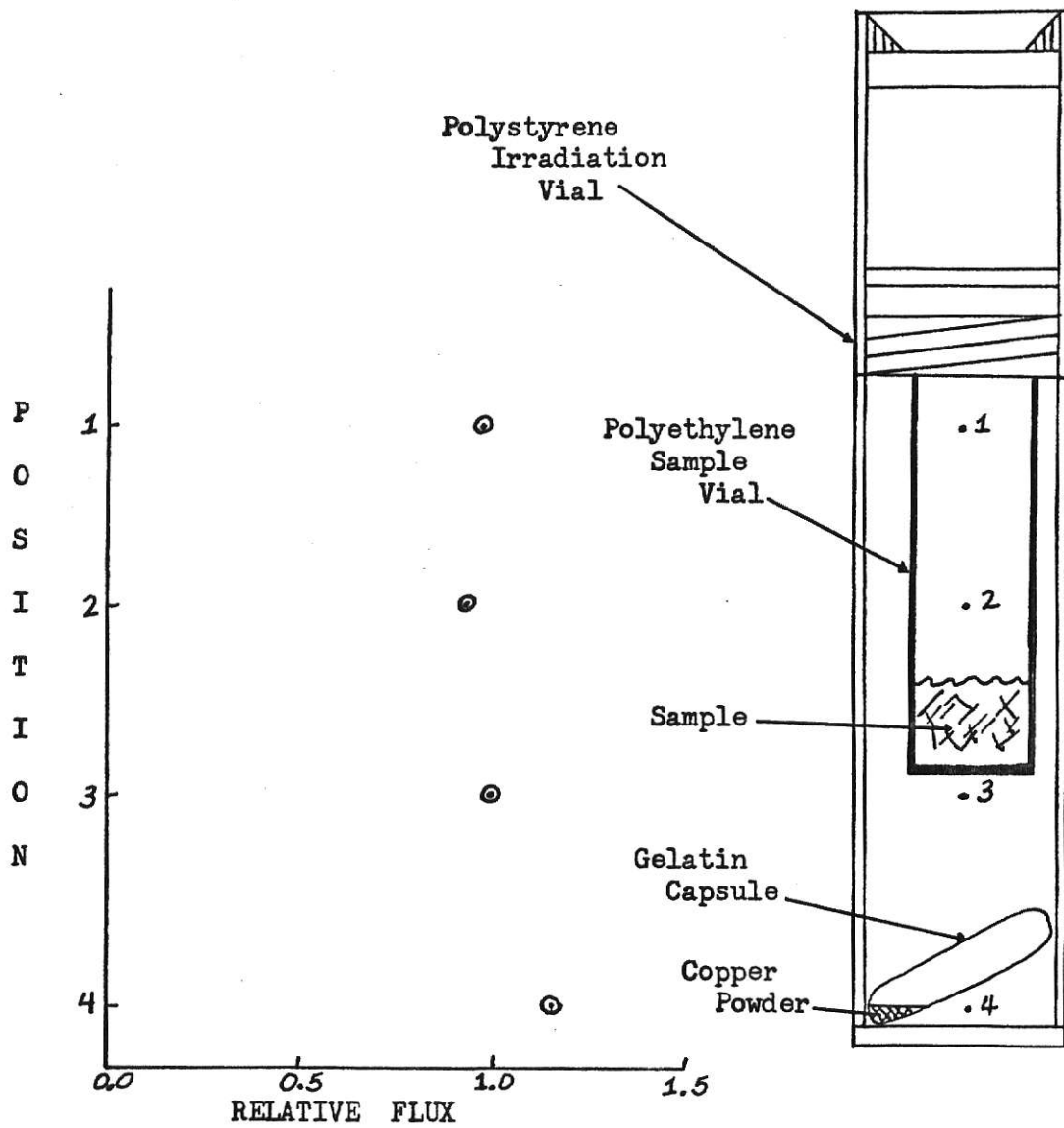


Figure 9. Irradiation Configuration with Normalized Flux Profile.

TABLE VIII
Reference Compound Parameters

Isotope	Reference Compound	Purity or Grade	Source
^{24}Na	Na_2CO_3	.999996	Johnson, Matthey & Co., Limited
^{27}Mg	MgO	.999987	Johnson, Matthey & Co., Limited
^{28}Al	Al_2O_3	.999994	Johnson, Matthey & Co., Limited
^{42}K	K_2CO_3	.999990	Johnson, Matthey & Co., Limited
^{49}Ca	CaCO_3	.999990	Johnson, Matthey & Co., Limited
^{51}Ti	TiO	Reagent	KSU Department of Chemistry
^{52}V	V_2O_5	Technical	Matheson Coleman & Bell
^{56}Mn	MnO	Reagent	KSU Department of Chemistry
^{64}Cu	Cu	.999992	Johnson, Matthey & Co., Limited

The spectra were normalized to obtain a particular isotope with the following units:

$$\frac{\text{counts/minute-gram of element at the time of removal from the reactor}}{10^6 \text{ counts/minute-gram of copper at the time of removal from the reactor}} .$$

The final restriction on the units of the spectra was that of a 15 minute irradiation in the rotary specimen rack. Normalization to 15 minutes was chosen because the majority of the samples processed at the NAA laboratory are 15 minute irradiations. These spectra were then shifted using the algorithm previously described to a baseline of 0 keV and a gain of 3.14 or 1.57 keV/channel depending on the energy and half-life of the isotope involved.

Figures 10-18 are the normalized spectra used in the unfolding code GELAOI. Spectra of detector responses of isotopes not used in the unfolding are given in the Appendix.

4.2.4 Quantitative Analysis Results

The results obtained from the code GELAOI for a one minute irradiation are listed in Tables IX and X for samples W-1 and G-1 respectively. A space in the table with no entry signifies that the element listed was either not detected in that spectrum or the unfolding technique yielded a non-significant result.

The quality of fit number listed at the head of the entries in the tables is a measure of the goodness of fit of the least squares solution. In general a quality of fit number should range between 0.5 and 2.0 (23). The recommended, maximum and minimum values are those listed in the summary of analyses of W-1 and G-1 of Fleischer (16). Three trends are observed. First, the shorter lived isotopes show larger discrepancies from the recommended values. Second, for longer-lived isotopes large decay times result in better agreement. Third, there is a distinct trend for the NAA values to yield slightly lower values than the recommended values. The disagreement between the copper values indicates the presence of other positron emitters. Any isotope interacting by pair production will contribute to the 511 keV photopeak. The peak is larger than that from the copper alone. Since it is virtually impossible to separate these contributions from all of the positron emitters, the unfolding technique was developed to report copper equivalent values.

It should be realized that the recommended, maximum, and minimum values give a measure of the accuracy of the analyses of these samples since they were obtained from almost independent analyses. The standard deviations

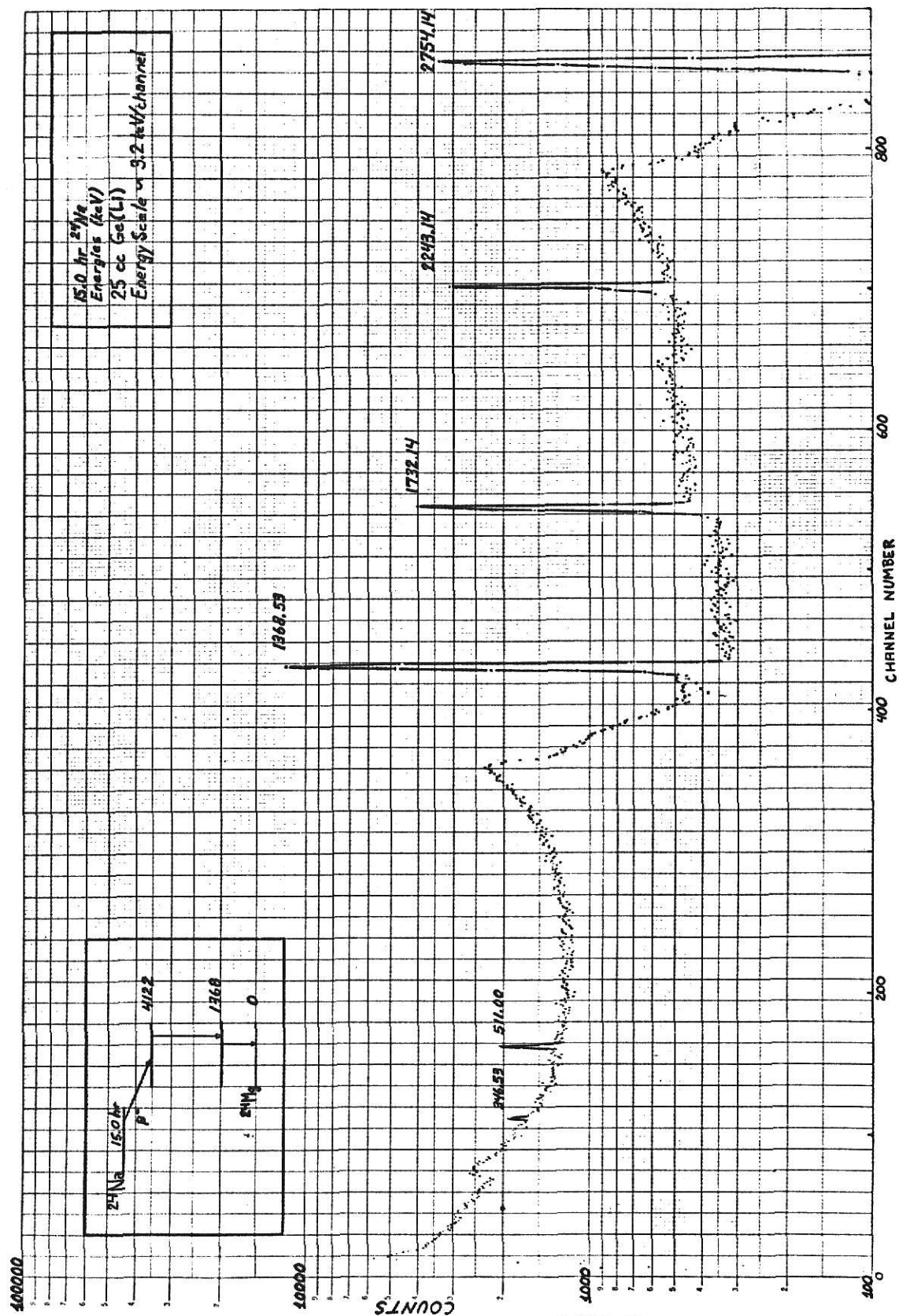


Figure 10. Normalized Spectrum of ^{24}Na .

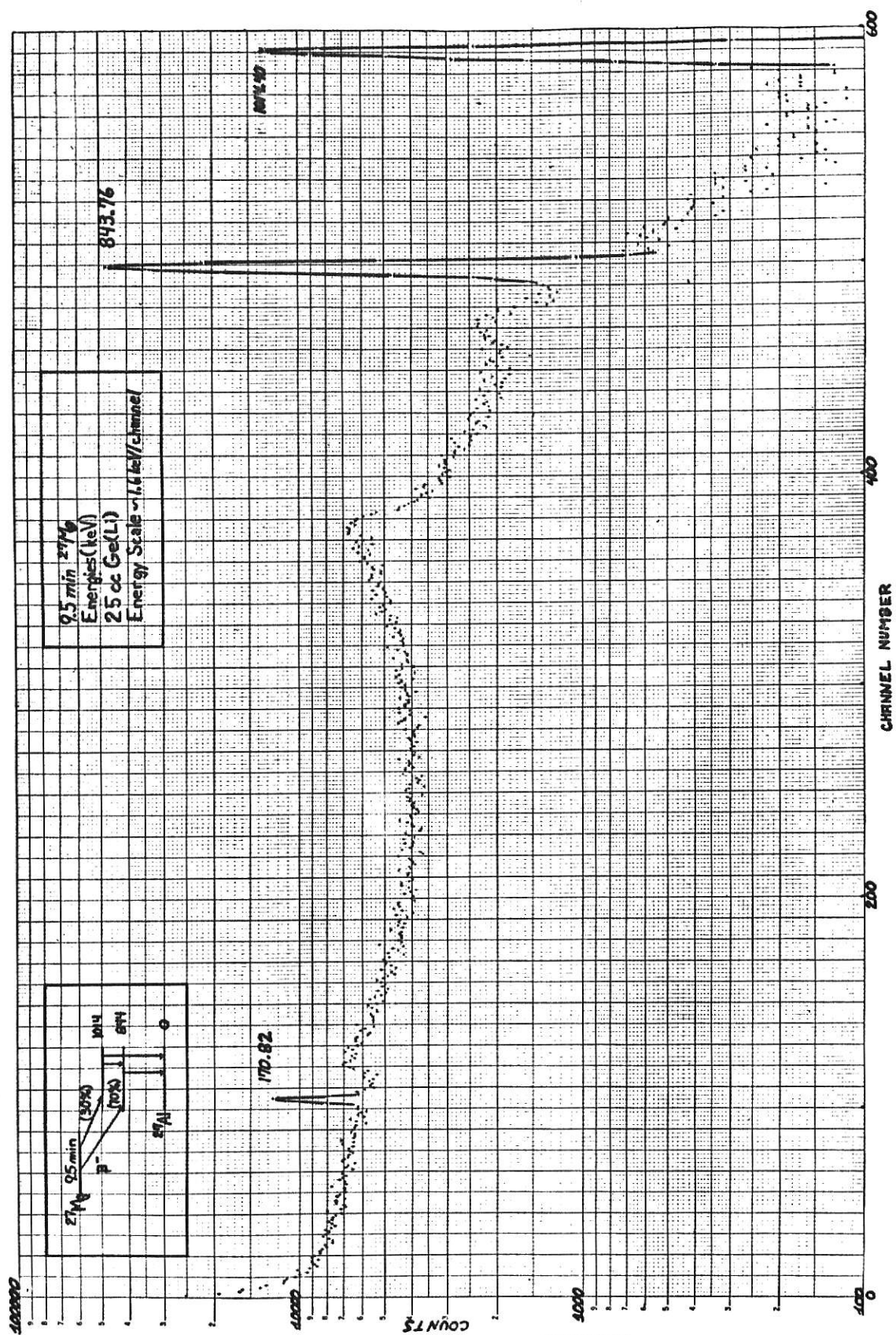
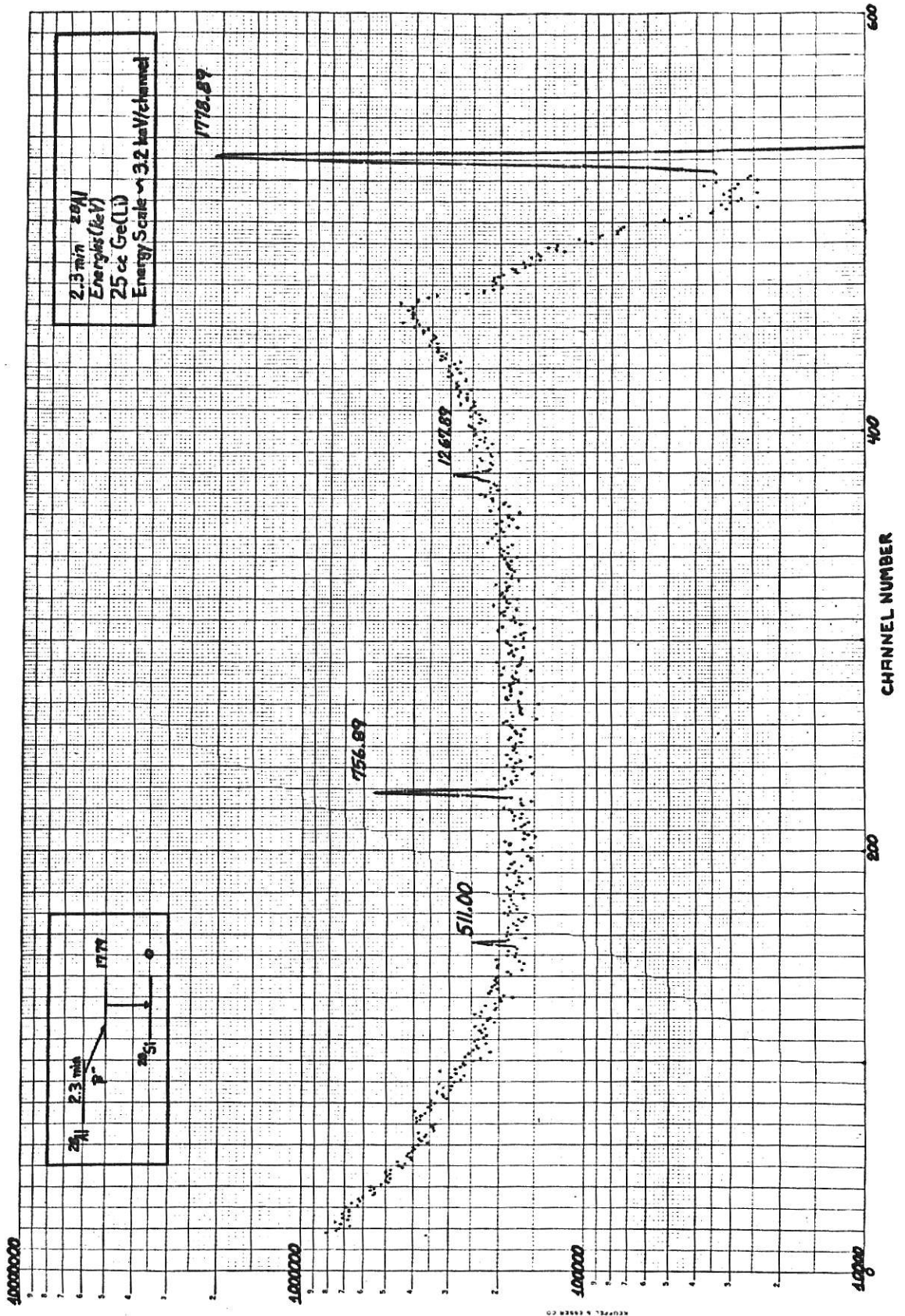


Figure 11. Normalized Spectrum of ^{27}Mg .

Figure 12. Normalized Spectrum of ^{24}Na .

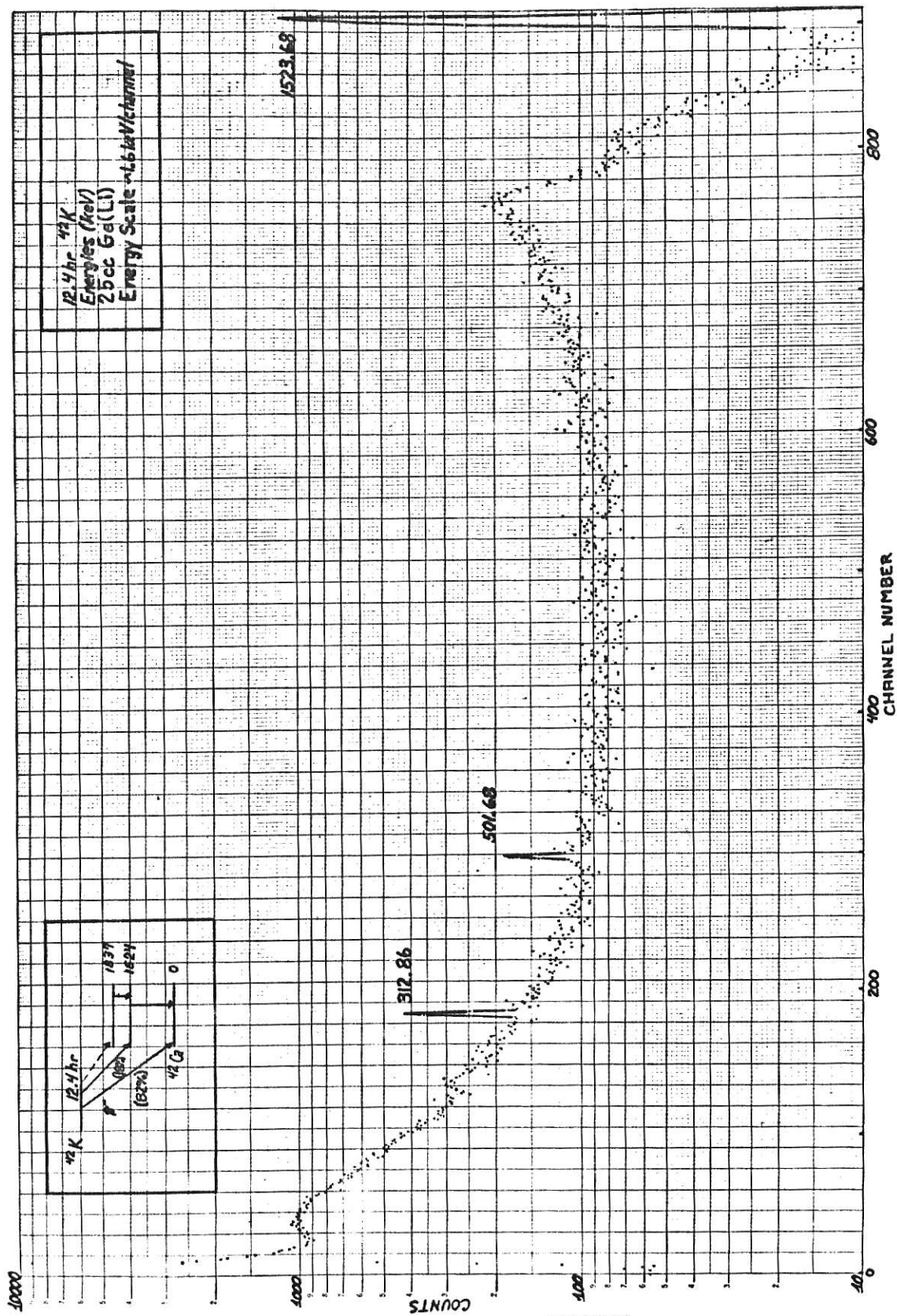
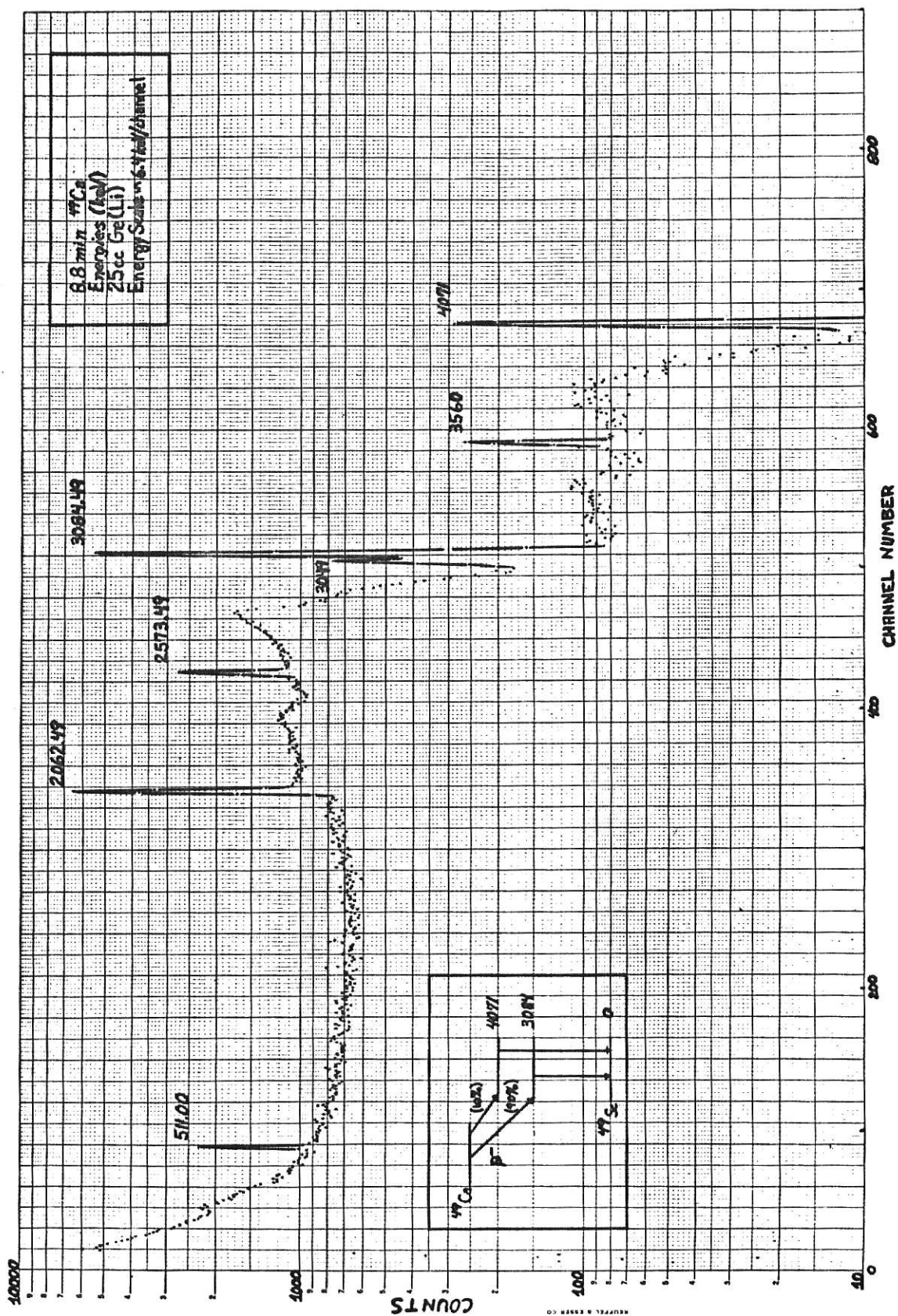
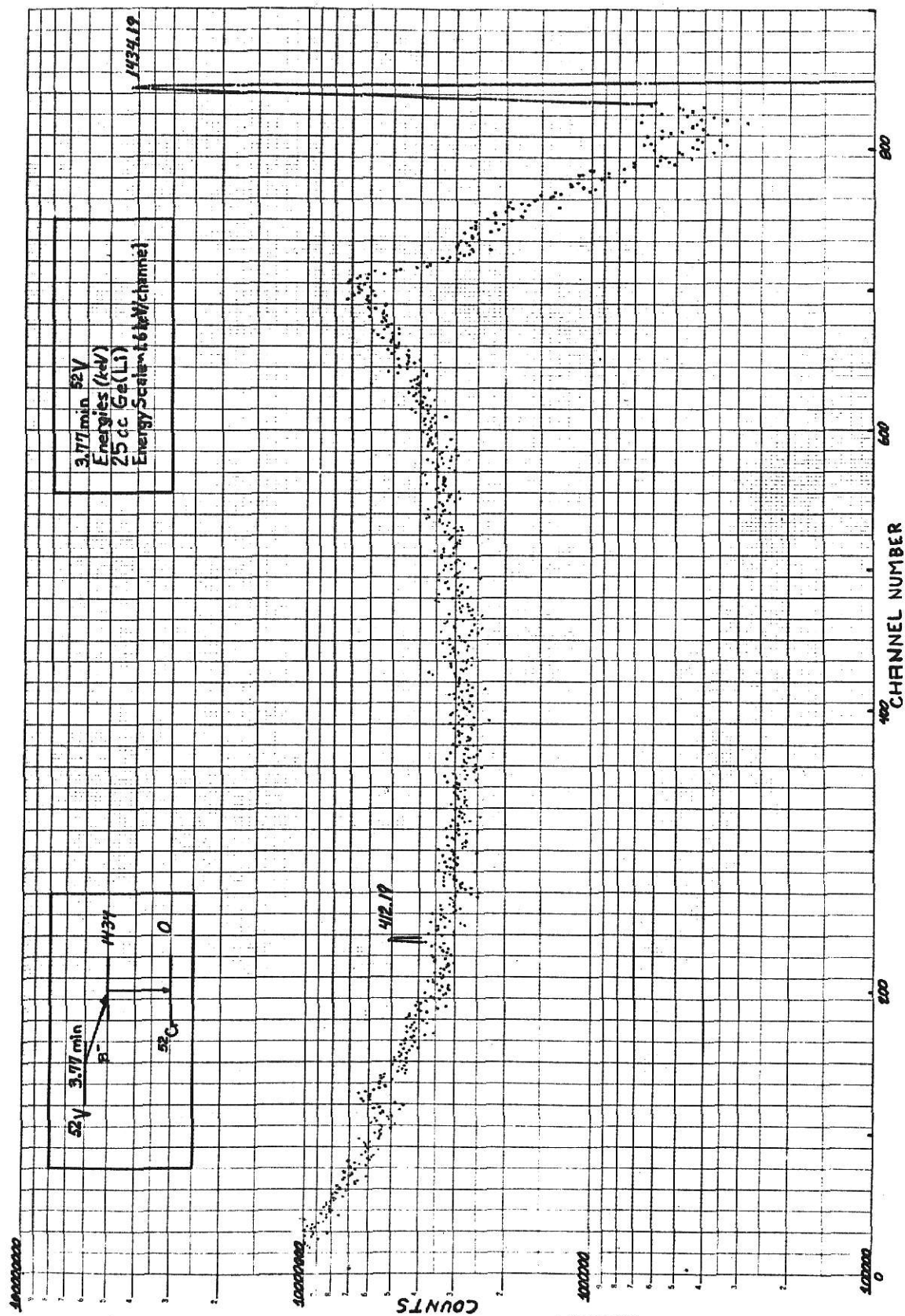
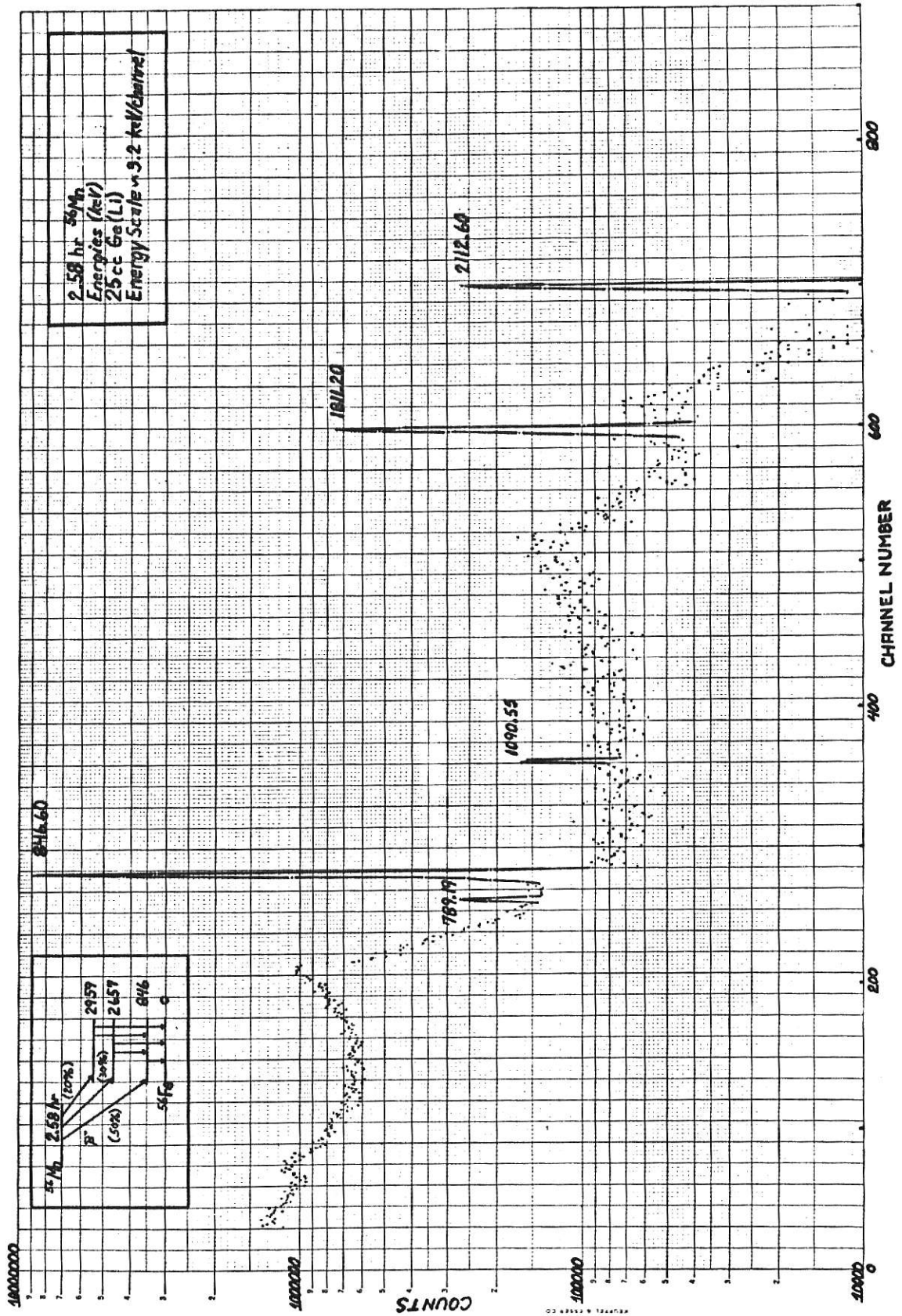


Figure 13. Normalized Spectrum of ^{42}K .

Figure 14. Normalized Spectrum of ^{49}Ca .

Figure 16. Normalized Spectrum of ^{52}V .

Figure 17. Normalized Spectrum of ^{56}Mn .

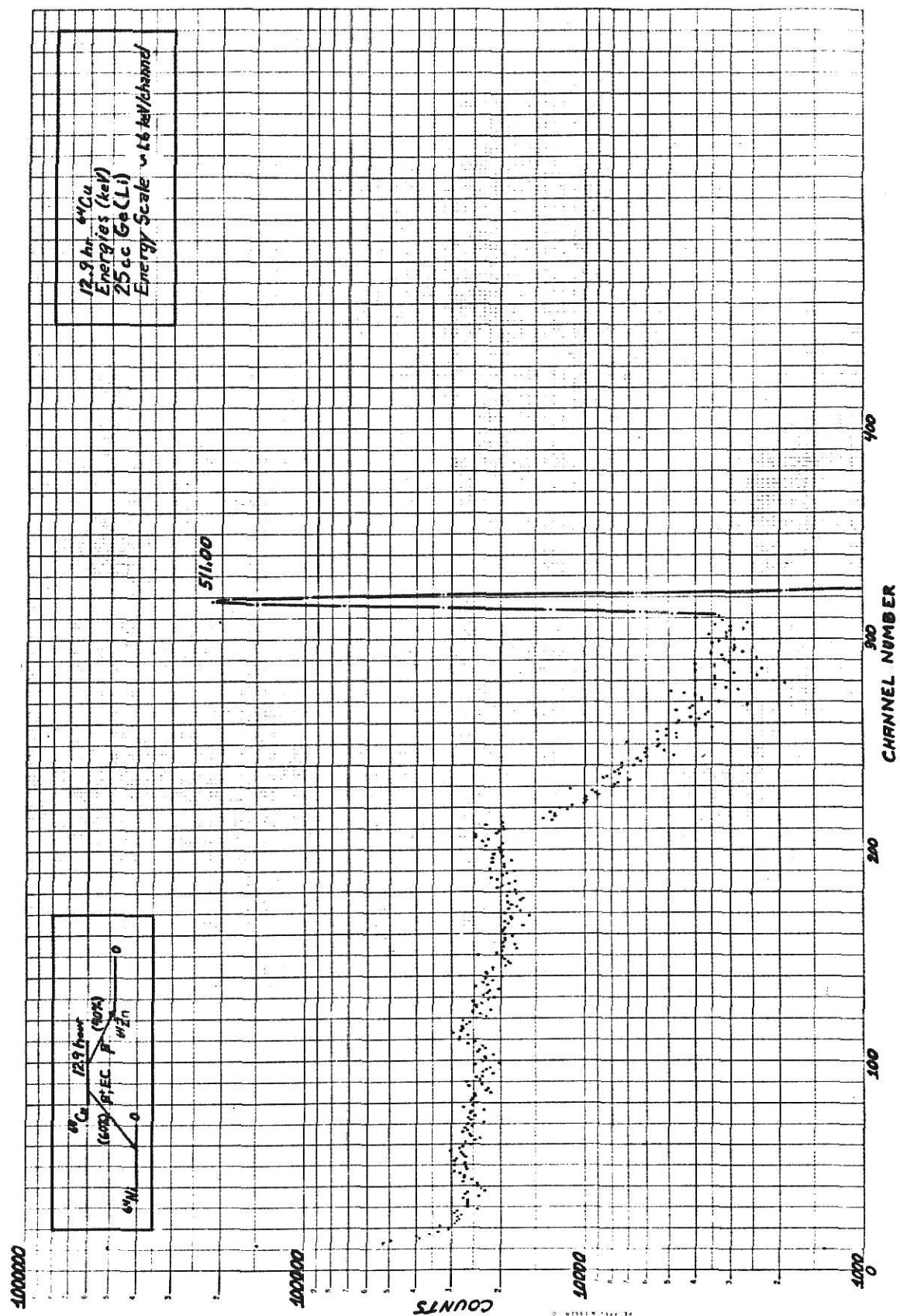


Figure 18. Normalized Spectrum of ^{64}Cu .

TABLE IX

Quantitative Results for Sample W-1, 1 Minute Irradiation

Sample weight 0.1165 grams							
Run Number			2032	2033	2043	2045	
Accumulation time (minutes)			3	3	30	30	
Decay time (minutes)			23	33	361	1141	
Quality of Fit			2.074	1.390	1.148	1.392	
Element	(ALL VALUES ARE PARTS PER MILLION)						
	Recommended	Maximum	Minimum				
Na	15950	17582	14837	14322 <u>+163</u>	13922 <u>+146</u>	15070 <u>+137</u>	14729 <u>+136</u>
Mg	39322	41493	38658	37966 <u>+1723</u>	33941 <u>+2270</u>		
Al	79058	80700	77472	65041 ^a <u>+142</u>			
K	5230	5971	4400			5907 <u>+3947</u>	
Ca	78044	82905	76472	75400 <u>+2122</u>	85450 <u>+2527</u>		
Ti	6400	8200	5400	5859 <u>+254</u>	6224 <u>+475</u>		
V	240	333	224	935 ^a <u>+10</u>			
Mn	1320	1570	1300	1194 <u>+7</u>	1184 <u>+7</u>	1349 <u>+6</u>	1407 <u>+10</u>
Cu ^b	110	152	80	265 <u>+88</u>	538 <u>+395</u>	147 <u>+57</u>	161 <u>+40</u>

a Re-irradiated and hand calculated to be Al= 73018 and V= 231 ppm.

b Copper equivalents.

TABLE X

Quantitative Results for Sample G-1, 1 Minute Irradiation

Sample weight 0.6281 grams						
Run Number			2036		2039	2042
Accumulation time (minutes)			3		15	30
Decay time (minutes)			14		67	261
Quality of Fit			0.369		0.406	0.472
Element	(ALL VALUES ARE PARTS PER MILLION)					
	Recommended	Maximum	Minumum			
Na	24407	25372	22627	22396 +206	22647 +180	24229 +280
Mg	2111	3679	1809	1979 +1241		
Al	74508	76571	73027	72151 +88		
K	45824	48564	43168		45143 +4722	44249 +4635
Ca	9720	10435	9291			
Ti	1500	1680	1100	2093 +129		
V	16	25	14			
Mn	230	248	188	218 +5	204 +3	226 +8
Cu ^a	13	20	7.8	273 +74	32 +51	59 +52

^a Copper equivalents.

reported with the values obtained by GELAOI are a measure of the precision of the data and analysis. The overall agreement of the values is quite satisfactory when one realizes that no particular element was specifically sought, rather the samples were irradiated and the data were taken using a routine analysis scheme. In 3 of the 5 elements considered by Youden (26) for which values were obtained by the author, i. e., K, Na, and Ca the values obtained in this study are clearly within the accepted values of the scatter diagram presented. The scatter diagram for Al is very widely dispersed and the values obtained in this work are clearly on its lower margin. Only the value of Mg for W-1 is significantly different. The Mg value obtained for W-1 is approximately 10 per cent less than the accepted values; while the Mg value obtained for G-1 is well within the scatter diagram. The precision of the analysis for particular elements could be expected to increase if the irradiations would be performed to enhance the determination of specific isotopes (23).

The first trend mentioned above would be expected since the more isotopes present cause interferences to occur. As the shorter-lived isotopes decay the interferences decrease and the second trend mentioned appears. The third trend mentioned could result from samples of W-1 and G-1 absorbing moisture during storage. The resultant normalization would indicate less activity per gram of sample and the unfolded results would reflect these consistently lower values. However, it was noted that in 23 elements reported in Fleischer (16) that were analyzed by different methods that 13 of the 23 had significantly lower values than the currently accepted values. Only three of the remaining 10 analyses had significantly greater values than the recommended values. This seems to be significant,

perhaps implying that some of the other techniques that are currently accepted may suffer from interference from other elements.

4.2.5 Detection Limits for Certain Elements

The detection limits for the nine elements analyzed as reported by Gulf General Atomic (25) in micro-grams of element per sample for an interference free sample are shown in Table XI.

TABLE XI

Interference Free Detection Limits of Elements Determined Quantitatively

Element	Na	Mg	Al	K	Ca	Ti	V	Mn	Cu
Detection Limit gm/gm	0.004	0.5	0.004	0.2	4.0	0.1	0.002	0.0001	0.002

Attention is called to the large deviation reported for K in W-1. This indicated that 5230 ppm is very close to the detection limit for K in the matrix of the composition of W-1. In sample G-1 the values of 9720 ppm for Ca and 16 ppm for V are 2430 and 8000 times respectively, above those listed in Table XI. However in both cases the elements are below their detection limits in the matrix of the composition of G-1 (i.e., these elements were not detected in any analysis of these spectra). This gives an indication of the matrix effects, i. e., the resulting interferences, on the analysis.

5.0 SUGGESTIONS FOR FURTHER STUDY

There are always present a number of appropriate projects using a Ge(Li) spectrometer system. However, with respect to the system developed at Kansas State University there are some suggestions that are more appropriate than others and those are included below.

First, with respect to the continuing analysis of geological samples the GRC needs to be extended to lower energy gamma rays, particularly those of the rare earth elements. The photopeaks resulting from background sources should be identified and calibrated more precisely. The GRC should also be extended to include those short-lived isotopes not presently included. Secondly, the program HIRES should be examined to determine why some peaks are being omitted and this cause eliminated. The unfolding code GELAOI should be modified to reflect the separate contributions to the statistics from the raw spectral data and due to the lack of fit of the least squares solution. Third, there is an obvious extension of the technique to other types of samples; e. g., agricultural products such as grains and feeds, water and air samples for pollution studies, tissue from plant and animals for trace elements and nutritional studies. Fourth, very precise analyses of particular elements may be obtained using chemical separations (either before or after irradiation). Fifth, the application of the ^{252}Cf neutron source to these types of analyses in conjunction with the Ge(Li) detector should be vigorously pursued.

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APPENDIX

Spectra of Isotopes not used in Unfolding

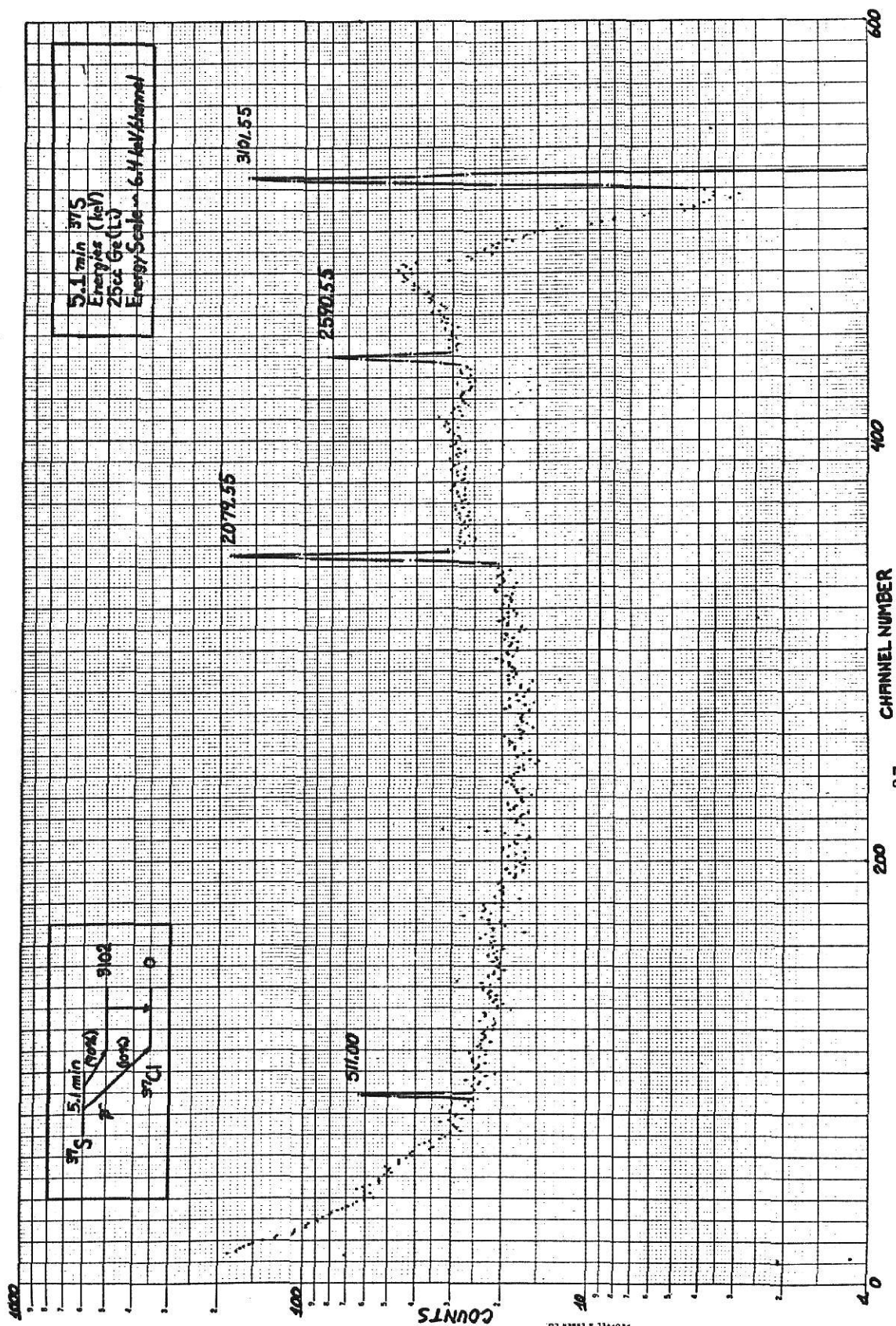
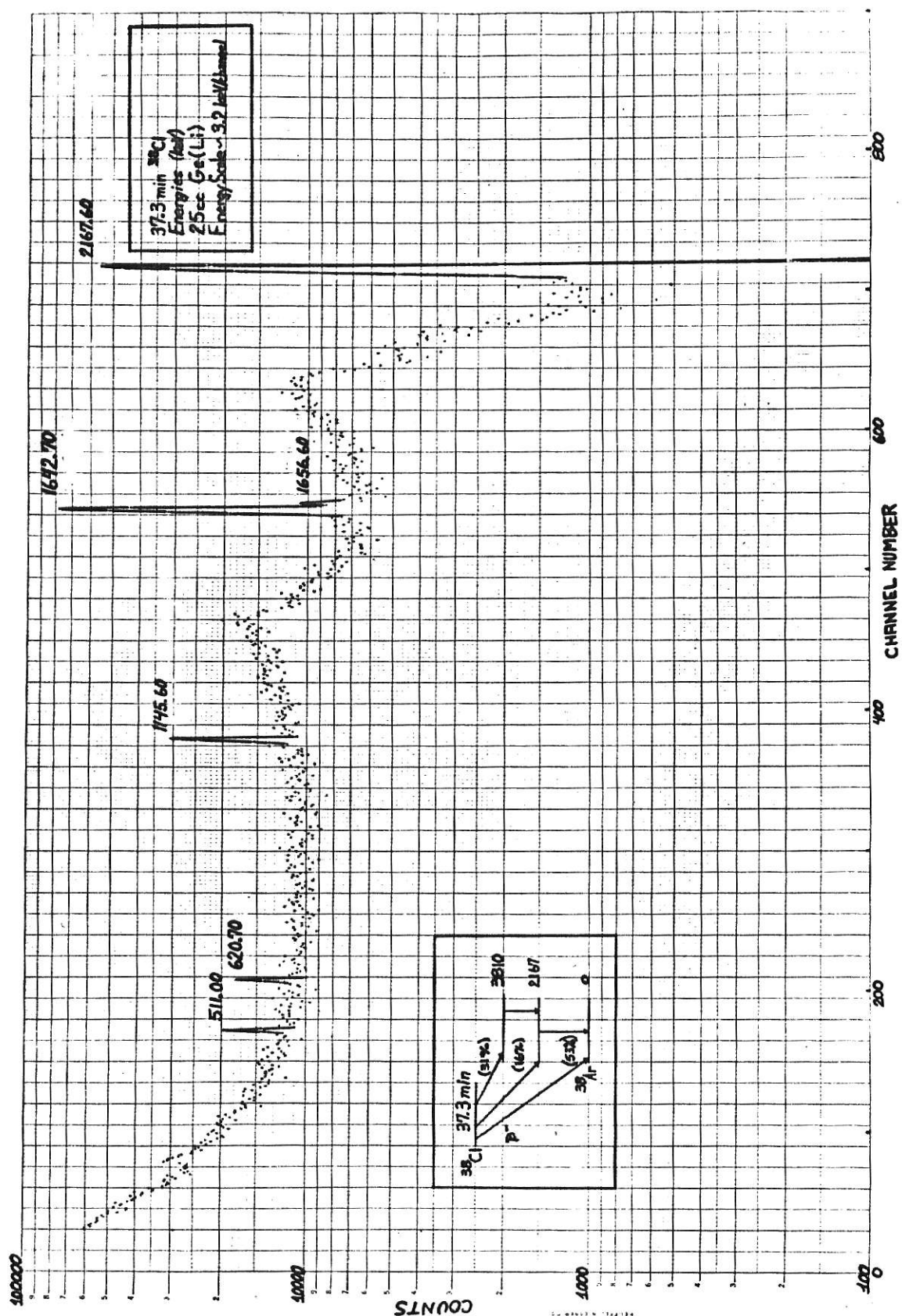
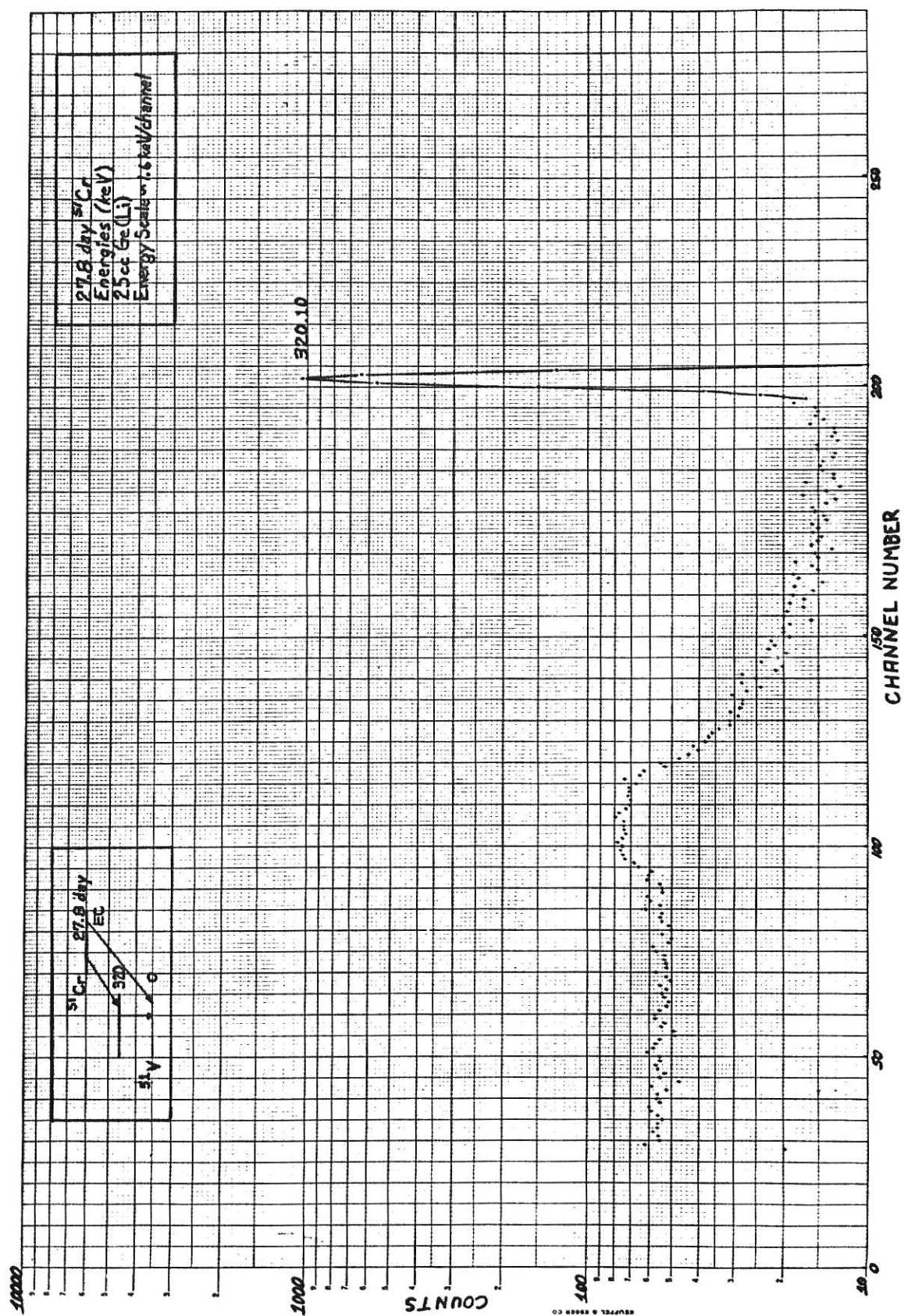
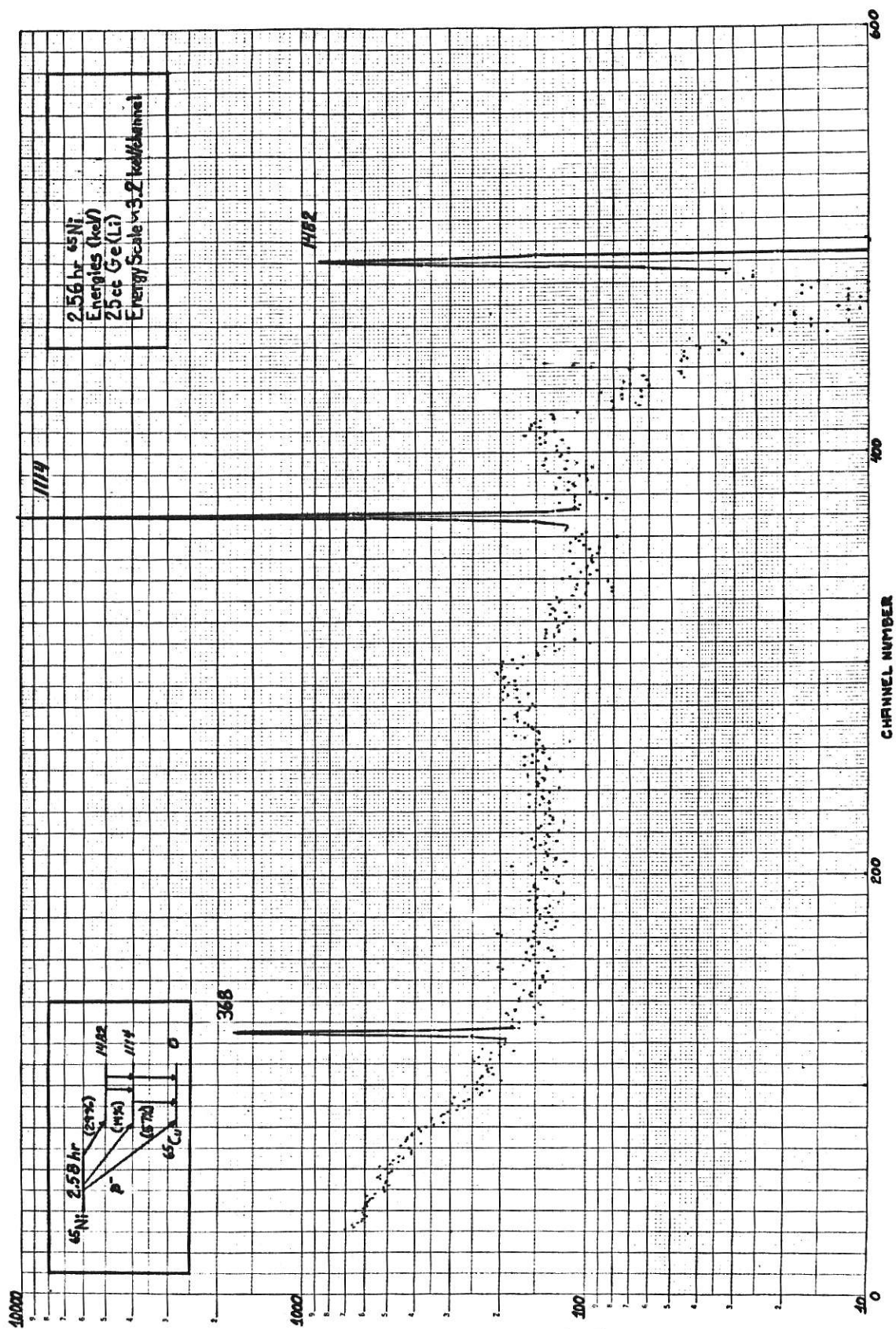
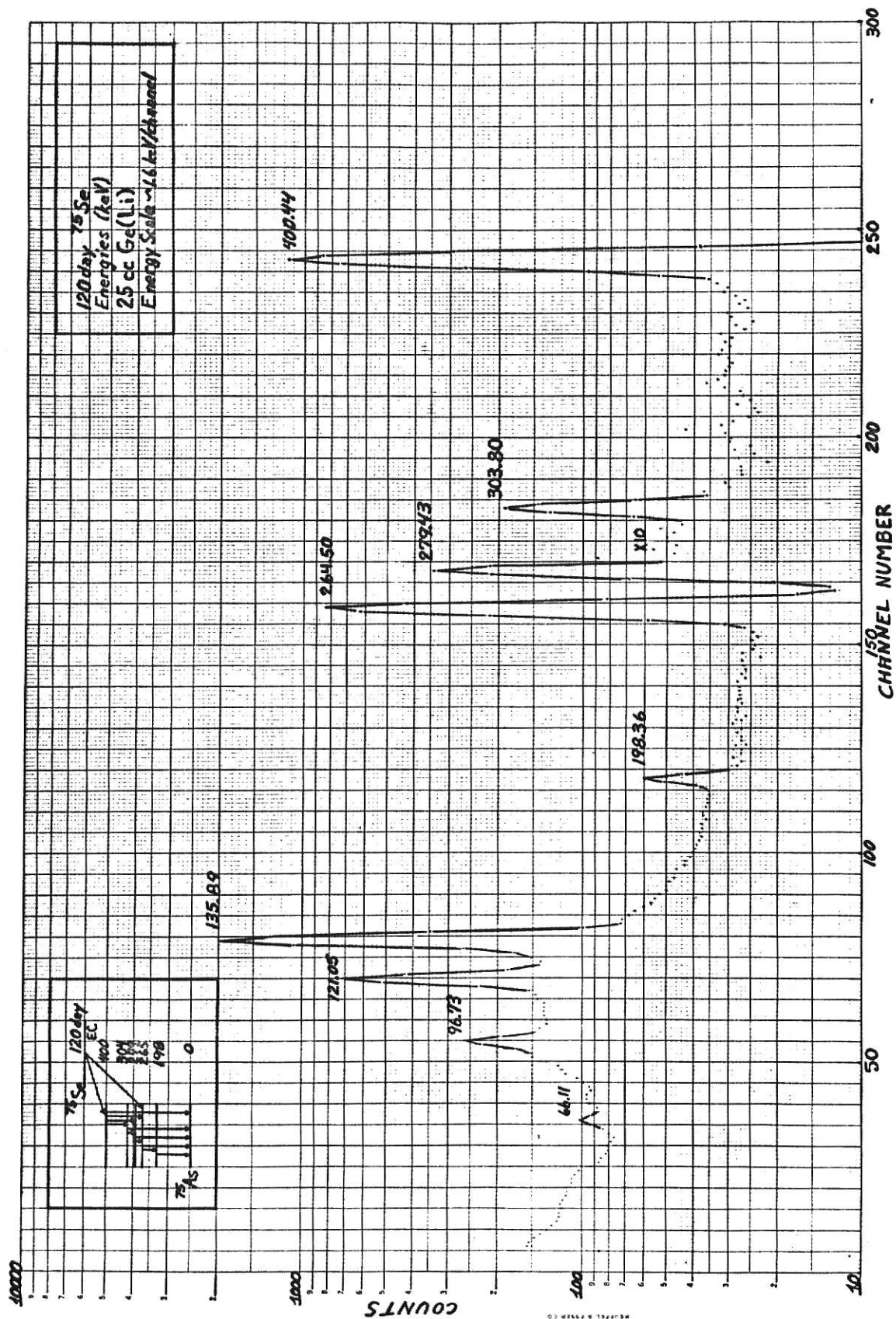


Figure 19. Normalized Spectrum of ^{37}S .

Figure 20. Normalized Spectrum of ^{38}Cl .

Figure 21. Normalized Spectrum of ^{51}Cr .

Figure 22. Normalized Spectrum of ^{65}Ni .

Figure 23. Normalized Spectrum of ^{75}Se .

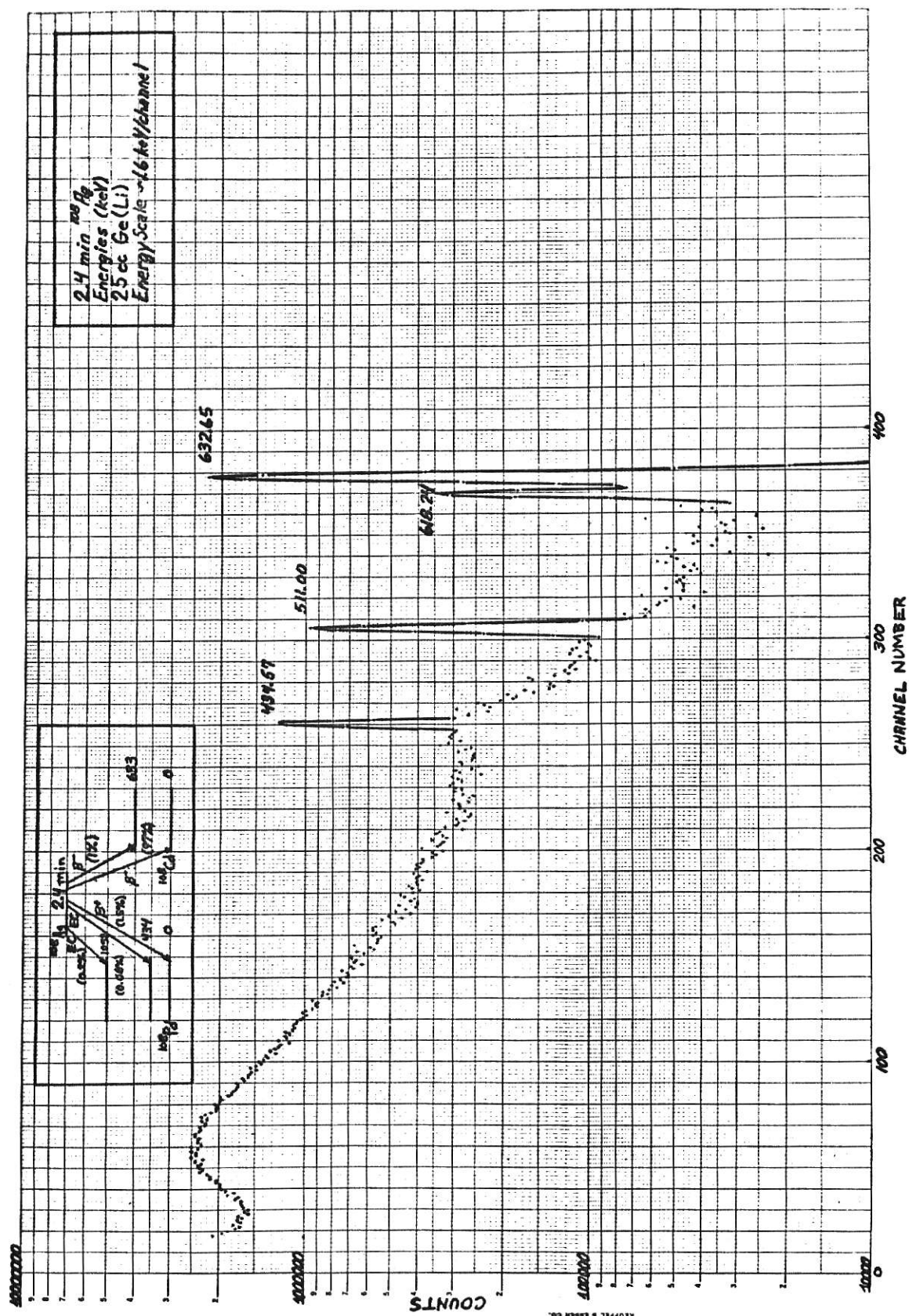


Figure 24. Normalized Spectrum of ^{108}Ag .

ASSEMBLY AND CALIBRATION OF A GE(LI)
SPECTROMETER SYSTEM FOR ANALYSIS OF GEOLOGICAL SAMPLES

by

PATRICK FRANKLIN ERVIN

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ABSTRACT

To perform routine quantitative non-destructive neutron activation analyses of geological samples, a 25 cc Ge(Li) spectrometer system was assembled and calibrated. The spectral response of fifteen elements (Na, Mg, Al, S, Cl, K, Ca, Ti, V, Cr, Mn, Ni, Cu, Ag, La) activated in the KSU Triga Mark II nuclear reactor were collected. Two computer codes, HIRES and GELAOI, for qualitative and quantitative analysis, respectively, were developed using FORTRAN IV for the IBM 360/50 computer. To demonstrate the utility of the techniques developed in this work the U. S. Geological Survey Standards W-1 and G-1 were analyzed for Na, Mg, Al, K, Ca, Ti, V, Mn, and Cu. Seventy-five per cent of the twenty-eight analyses obtained were within 10 per cent of currently established values for those elements.