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14-Mev NEUTRON REACTIONS

J. E. Strain
W. J. Ross



OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
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U.S. ATOMIC ENERGY COMMISSION

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ANALYTICAL CHEMISTRY DIVISION

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J. E. Strain and W. J. Ross

JANUARY 1965

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
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14-Mev NEUTRON REACTIONS

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ABSTRACT

Reactions observed when pure, naturally occurring elements ($Z = 1$ to $Z = 30$) are irradiated with unmoderated 14-Mev neutrons produced by the $^3\text{T}(d,n)^4\text{He}$ reaction are listed. Cross sections are calculated where possible, and normalized standard gamma spectra are collected. These standard spectra are equivalent to the gamma radioactivity that will be produced when 1 g of the pure element is irradiated for a given length of time at a 14-Mev neutron flux of 5×10^8 neutrons $\text{cm}^{-2} \text{ sec}^{-1}$. If more than one radionuclide is produced, a spectral decay is presented. These spectra may be used to predict accurately the sensitivity of nondestructive spectral analysis of almost any sample.

INTRODUCTION

In order to predict neutron-activation-analysis sensitivity using direct gamma spectral techniques, one needs to know, in addition to the cross section and half-life, the decay scheme and shape of the gamma spectra of all radionuclides produced in the sample. Since there is considerable uncertainty in both the decay schemes and 14.7-Mev cross sections available in the literature, experimentally determined standard gamma spectra are being collected and cataloged. These spectra are normalized for element weight, counting geometry, and neutron flux. Separated isotopes were used to identify reaction products and assist in cross-section calculations, but only spectra produced by the irradiation of elements of the natural isotopic abundance were included in the catalog.

This compilation of spectra was collected using as nearly pure fast-neutron flux as possible to: (1) demonstrate the potential of this type of analysis, (2) determine activation cross sections, and (3) separate the fast-neutron reactions from the mixed thermal and fast-neutron reactions that take place in a moderated system. It is hoped that these curves will help explain some of the interferences encountered in activation analysis using moderated 14-Mev neutrons. Although the calculation of cross sections and collected spectra cannot survive rigorous physical analysis, the spectra can be used by the chemist to predict the possibility of direct gamma spectral analysis.

This first section covers the elements from $Z = 1$ to $Z = 30$ which produce detectable gamma-emitting radionuclides when exposed to unmoderated 14-Mev neutrons from the $\text{T}(d,n)\text{He}$ reaction. When data are available, the same type of information will be published on the remaining stable elements.

EXPERIMENTAL ARRANGEMENTS

The source of 14-Mev neutrons is a 150-kv Cockcroft-Walton accelerator manufactured by the Texas Nuclear Corporation. The terminus of the pneumatic sample transport system is positioned against the target holder and cooling jacket (Fig. 1). There is no deliberate moderation of the fast neutrons.

The neutron production of the generator is monitored by means of a $^{10}\text{BF}_3$ detector located 5 m from the generator target, as shown in Fig. 2. The sample is transferred, after irradiation, to a counting shield (Fig. 3). To eliminate interference from β^- radiation, a 2.54-cm Lucite absorber was interposed between the rabbit-stopping device and the 3- by 3-in. NaI(Tl) detector.

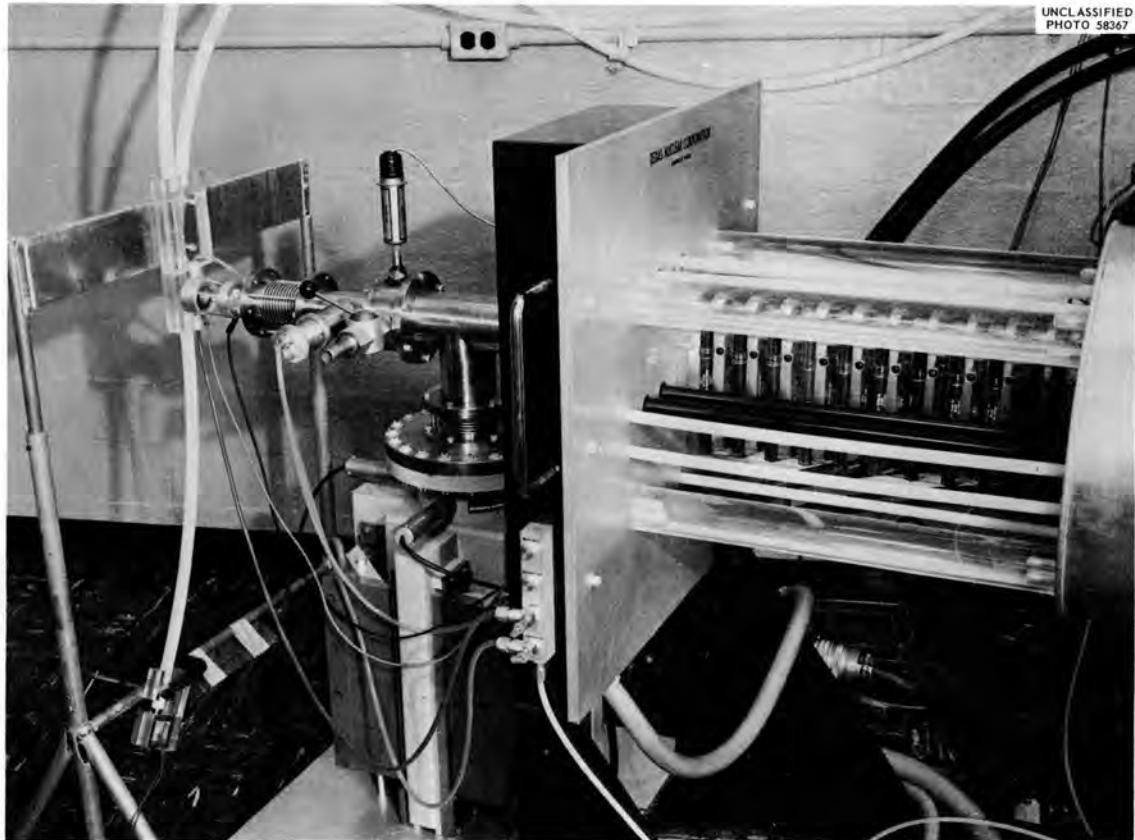


Fig. 1. Target Holder Relation to Neutron Source.

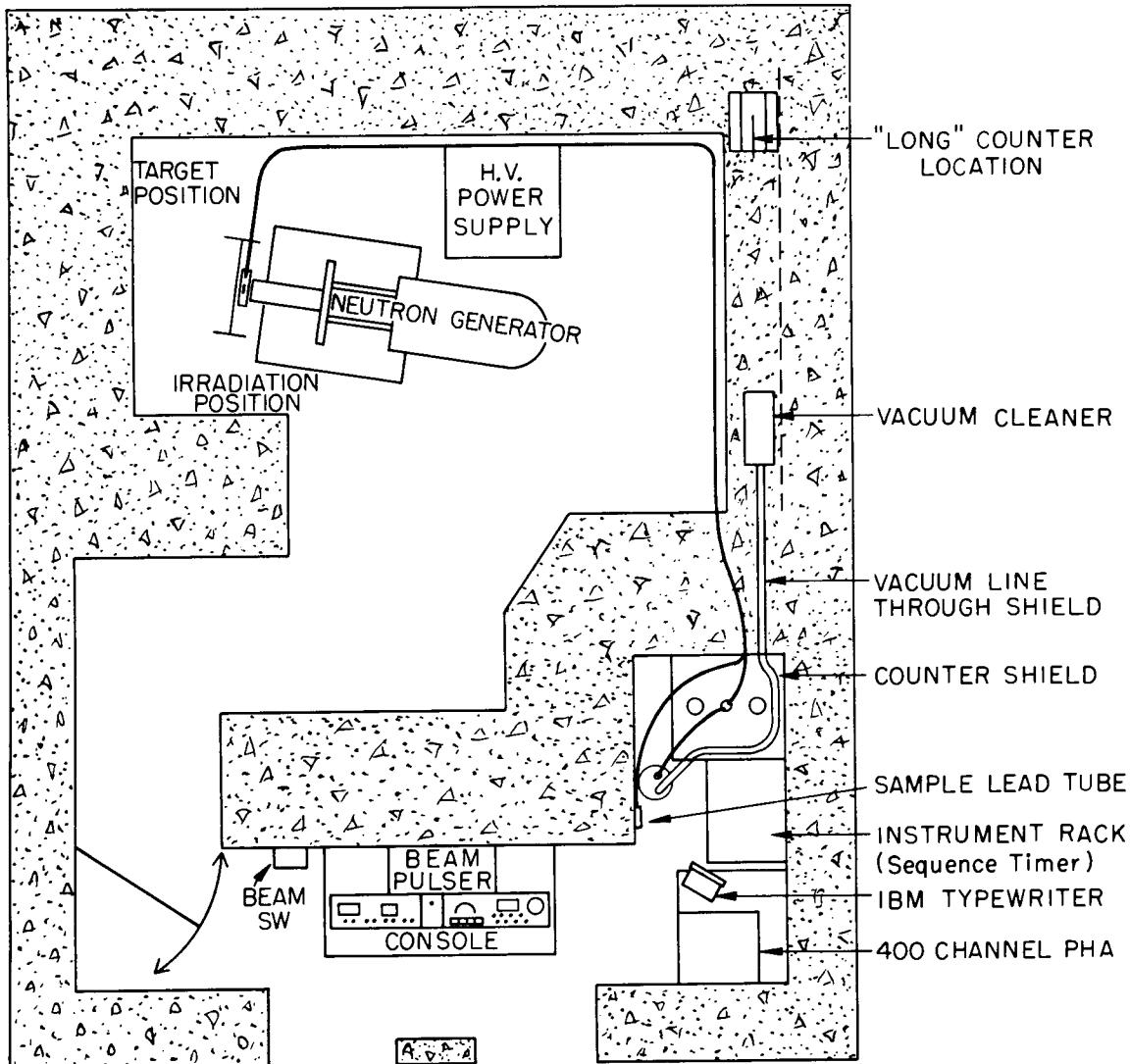
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Fig. 2. Plan View of Generator Installation.

The ratio of neutron flux to neutron count rate, recorded by the BF_3 counter, was determined using the 14.7-Mev neutron reactions:

$$^{28}\text{Si}(n,p)^{28}\text{Al} , \quad \sigma = 250 \text{ mb} ,$$

$$^{63}\text{Cu}(n,2n)^{62}\text{Cu} , \quad \sigma = 550 \text{ mb} ,$$

$$^{27}\text{Al}(n,\alpha)^{24}\text{Na} , \quad \sigma = 118 \text{ mb} .$$

Irradiation times were short in comparison to the half-lives of the reaction products. The neutron counter, which is operated during an irradiation, records a count rate that may be converted

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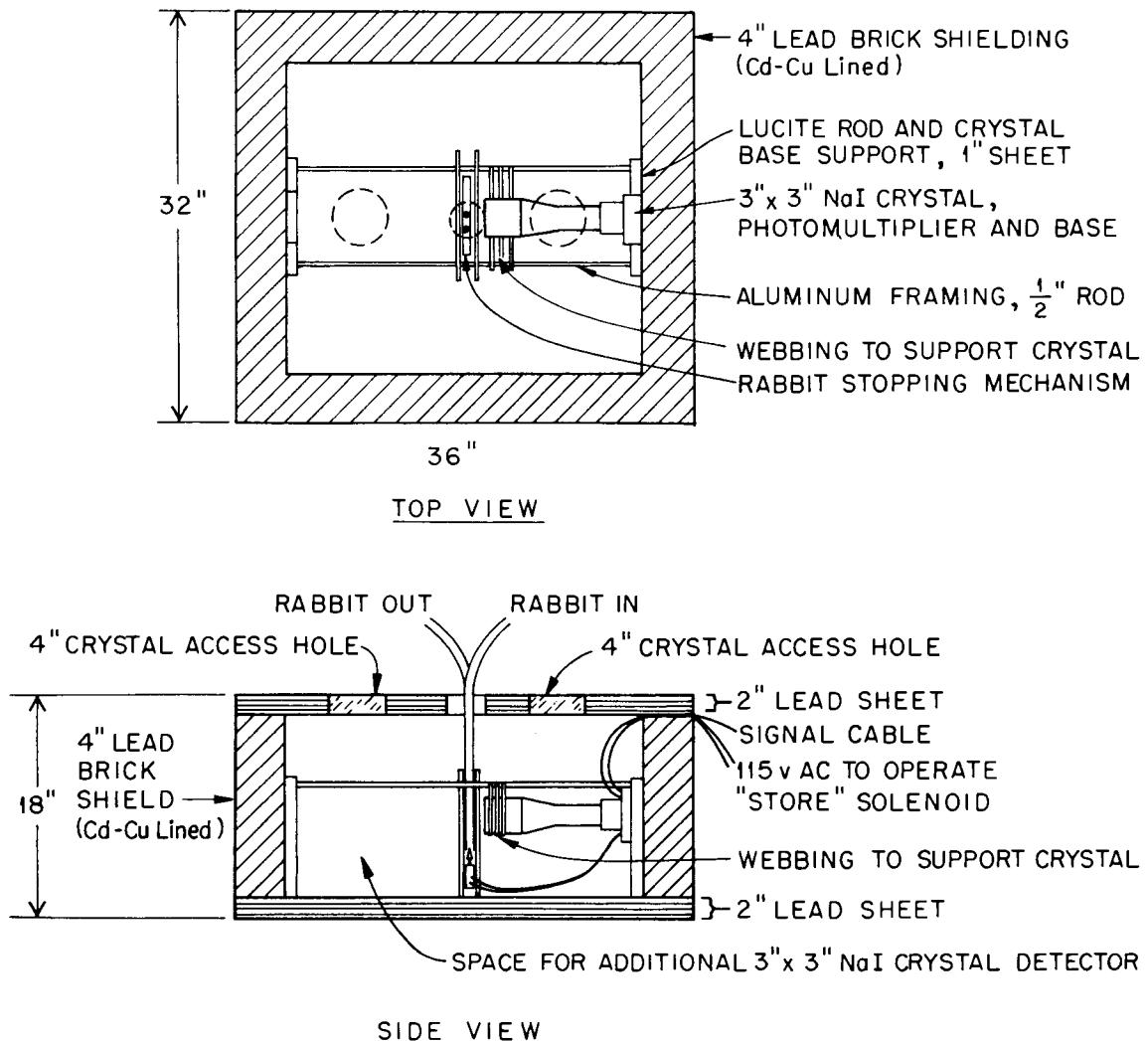


Fig. 3. Diagram of Counting Shield.

to neutron flux by use of a simple empirical factor.¹ The factor was verified by the irradiation of standard silicon samples with each element investigated.

The efficiencies of the 3- by 3-in. NaI(Tl) crystal and analyzer were determined with ¹³⁷Cs, ⁵⁸Co, and ⁶⁰Co radionuclides of known disintegration rates. The calculated absorber thickness was 4.0 cm (Lucite absorber + stopping mechanism + the polyethylene rabbit). The distance from

¹J. E. Strain, J. W. Hampton, and G. W. Leddicotte, *The ORNL Analytical Chemistry Division's 150-kv Cockcroft-Walton Generator*, ORNL-TM-362 (Sept. 10, 1962).

the crystal face to the center line of the rabbit was 4.2 cm. The method of Heath² was used to determine peak area, absolute total efficiency, and peak-to-total ratio. The mass absorption coefficient used to calculate absorption in the Lucite was interpolated from graphs appearing in the *Radiological Health Handbook*.³

When the counting interval was an appreciable fraction ($> \frac{1}{10}$) of the half-life, the count rate at the beginning of the counting interval was determined from the relationship

$$A_{t_1} = \frac{C \times (0.693/t_{1/2})}{1 - \exp(-0.693t/t_{1/2})},$$

where

A_{t_1} = activity at the beginning of the counting interval (counts/sec),

C = total count recorded in the counting interval,

$t_{1/2}$ = radionuclide half-life (sec),

t = counting interval (sec).

EXPERIMENTAL PROCEDURE

The following sequence was used to accumulate data for the standard curves:

1. A portion of pure element or compound that would produce a measurable amount of activity was weighed into a polyethylene rabbit. The weights ranged from 0.5 to 5 g of material.
2. The possible reactions were tabulated, and an irradiation time (or times) was chosen dependent upon the half-lives of the expected products.
3. Gamma spectral decays were run on the samples following irradiation. The flux during irradiation was calculated from the neutron counter reading. The curves were plotted on three-cycle semilogarithmic paper, and the peak area was measured for cross-section calculation and decay plots.
4. The most useful decay spectra were then normalized to represent an irradiation of 1.00 g of the element being studied at a 14-Mev neutron flux of 5×10^8 neutrons $\text{cm}^{-2} \text{ sec}^{-1}$. These are included in this report.

Table 1 presents the reactions observed and their calculated cross sections. The last column contains sensitivity figures for the pure elements. In each case the height of the major photopeak has been normalized to 1 g of the natural element.

The omissions in the table indicate either that insufficient activity was produced to calculate a cross section or that no literature value was available. The elements H, Li, C, S, and Ca produced no detectable gamma activity. The elements Ne, Ar, He, and Sc could not be obtained in a form suitable for irradiation.

²R. L. Heath, *Scintillation Spectrometry Gamma-Ray Spectrum Catalogue*, IDO-16408 (July 1, 1957).

³Simon Kinsman (ed.), *Radiological Health Handbook*, PB-121784, p. 142 (1957).

Table 1. Nuclear Reactions Obtained with Unmoderated 14-Mev Neutrons

Element Irradiated	Reaction Observed	$t_{1/2}$ Product	ΔT Irrad.	ΔT Decay	ΔT Count	σ (mb)		Major Photoppeak Height ^b (counts/g)
						Calculated	Literature ^a	
B	$^{11}\text{B}(n,p)^{11}\text{Be}$	13.7 s	10 s	1.6 s	18 s	5.5		250
	$^{11}\text{B}(p,n)^{11}\text{C}^c$	20.4 m	5 m	1.6 s	1 m	0.9		2,000
N	$^{14}\text{N}(n,2n)^{13}\text{N}$	10.1 m	5 m	1.6 s	1 m	6.7	5.7	40,000
O	$^{16}\text{O}(n,p)^{16}\text{N}$	7.4 s	10 s	1.6 s	24 s		$49 \pm 50\%$	2,500 ^d
F	$^{19}\text{F}(n,\alpha)^{16}\text{N}$	7.4 s	10 s	1.6 s	18 s			1,500
	$^{19}\text{F}(n,p)^{19}\text{O}$	29 s	10 s	1.6 s	18 s	109	135	3,800
	$^{19}\text{F}(n,2n)^{18}\text{F}$	112 m	2 m	60 m	1 m	60	61	4,700
Na	$^{23}\text{Na}(n,p)^{23}\text{Ne}$	40 s	40 s	80 s	18 s	53	34	4,300
	$^{23}\text{Na}(n,\alpha)^{20}\text{F}$	11.6 s	10 s	1.6 s	12 s	104		11,000
Mg	$^{24}\text{Mg}(n,p)^{24}\text{Na}$	15 h	1 m	18 m	1 m	189	191	210
	$^{25}\text{Mg}(n,p)^{25}\text{Na}$	60 s	1 m	35 s	30 s	144	45	800
	$^{26}\text{Mg}(n,\alpha)^{23}\text{Ne}$	40 s	1 m	35 s	30 s			e
Al	$^{27}\text{Al}(n,p)^{27}\text{Mg}$	9.5 m	5 m	1 m	1 m	78	52.4	60,000
	$^{27}\text{Al}(n,\alpha)^{24}\text{Na}$	15 h	5 m	2 h	5 m	115	$79 \pm 20\%$	2,300
Si	$^{28}\text{Si}(n,p)^{28}\text{Al}$	2.3 m	2 m	1 m	1 m	221	220	66,000
	$^{29}\text{Si}(n,p)^{29}\text{Al}$	6.56 m	2 m	1 m	1 m	83	$101 \pm 30\%$	500
P	$^{31}\text{P}(n,\alpha)^{28}\text{Al}$	2.3 m	1 m	2.4 s	1 m	124	$146 \pm 20\%$	45,000
	$^{31}\text{P}(n,2n)^{30}\text{P}$	2.5 m	1 m	2.4 s	1 m	10.5		27,000
Cl	$^{35}\text{Cl}(n,2n)^{34}\text{Cl}$	32.4 m	5 m	60 m	5 m	5.2	$3.5 \pm 45\%$	5,000
	$^{37}\text{Cl}(n,p)^{37}\text{S}$	5.0 m	5 m	1 m	1 m	28	$33 \pm 20\%$	1,100
K	$^{39}\text{K}(n,2n)^{38}\text{K}$	8.0 m	10 m	1 m	1 m	4	$10 \pm 55\%$	14,000
	$^{41}\text{K}(n,\alpha)^{38}\text{Cl}$	37.5 m	20 m	20 m	10 m	26	$31 \pm 35\%$	2,900
	$^{41}\text{K}(n,p)^{41}\text{Ar}$	1.8 h	20 m	20 m	10 m	42	$81 \pm 40\%$	5,000
Ti	$^{46}\text{Ti}(n,p)^{46m}\text{Sc}$	20 s	1 m	1 s	18 s	72		f

Table 1 (continued)

Element Irradiated	Reaction Observed	$t_{1/2}$ Product	ΔT Irrad.	ΔT Decay	ΔT Count	σ (mb)		Major Photopeak Height ^b (counts/g)
						Calculated	Literature ^a	
Ti	$^{48}\text{Ti}(n,p)^{48}\text{Sc}$	44 h	1 m	1 h	10 m	132	$93 \pm 35\%$	360
	$^{50}\text{Ti}(n,p)^{50}\text{Sc}$	1.7 m	1 m	1 m	1 m	27		210
	$^{46}\text{Ti}(n,2n)^{45}\text{Ti}$	3.1 h	1 m	1 h	10 m	54		800
V	$^{51}\text{V}(n,p)^{51}\text{Ti}$	5.8 m	5 m	20 m	1 m	48	27	10,000
	$^{51}\text{V}(n,\alpha)^{48}\text{Sc}$	44 h	5 m	5 h	10 m	34	29	720
	$^{51}\text{V}(n,\gamma)^{52}\text{V}$	3.8 m	5 m	1 m	1 m	18	24^e	5,200
Cr	$^{52}\text{Cr}(n,p)^{52}\text{V}$	3.76 m	0.5 m	7 m	0.5 m	82	77	880
	$^{50}\text{Cr}(n,2n)^{49}\text{Cr}$	42 m	5 m	1 h	5.0 m	27		660
Mn	$^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$	2.58 h	30 s	2 m	1 m	26	25^e	1,200
	$^{55}\text{Mn}(n,\alpha)^{52}\text{V}$	3.76 m	30 s	72 m	10 m	27	30 ± 12^h	650
Fe	$^{56}\text{Fe}(n,p)^{56}\text{Mn}$	2.58 h	1 m	70 m	10 m	104	110	6,200
	$^{54}\text{Fe}(n,2n)^{53}\text{Fe}$	9 m	1 m	3 s	1 m	21	10	750
Co	$^{59}\text{Co}(n,\alpha)^{56}\text{Mn}$	2.58 h	5 m	100 m	1 m	42	27-39	750
	$^{59}\text{Co}(n,2n)^{58}\text{Co}$	72 d	5 m	119 h	20 m	1040		900
Ni	$^{58}\text{Ni}(n,p)^{58}\text{Co}$	72 d	5 m	140 h	20 m	281	310	120
	$^{58}\text{Ni}(n,2n)^{57}\text{Ni}$	37 h	5 m	25 m	5 m	35	22	400
	$^{62}\text{Ni}(n,p)^{62}\text{Co}$	13.9 m	5 m	1 m	1 m	106		400
Cu	$^{63}\text{Cu}(n,2n)^{62}\text{Cu}$	9.9 m	20 s	30 s	1 m	560	450-550	40,000
	$^{65}\text{Cu}(n,2n)^{64}\text{Cu}$	12.8 h	20 m	17 h	20 m	950	970	35,000

Table 1 (continued)

Element Irradiated	Reaction Observed	$t_{1/2}$ Product	ΔT Irrad.	ΔT Decay	ΔT Count	σ (mb)		Major Photopeak Height ^b (counts/g)
						Calculated	Literature ^a	
Zn	$^{64}\text{Zn}(n,p)^{64}\text{Cu}$	12.8 h	5 m	23 h	20 m	163	216-590	1,700
	$^{64}\text{Zn}(n,2n)^{63}\text{Zn}$	38 m	5 m	1 m	1 m	157	150	30,000
	$^{66}\text{Zn}(n,p)^{66}\text{Cu}$	5.1 m	5 m	1 m	1 m	101	80	$\sim 1,000$
	$^{67}\text{Zn}(n,p)^{67}\text{Cu}$	59 h	5 m					

^aR. J. Howerton, *Tabulated Neutron Cross Sections .001-14.5 Mev*, UCRL-5226 (1959).

^bNeutron flux of 5×10^8 neutrons $\text{cm}^{-2} \text{ sec}^{-1}$, 3- by 3-in. NaI crystal, 4.0-cm Lucite β^- absorber, 4.2-cm source-crystal distance.

^c H_3BO_3 irradiated.

^d5.6-Mev pair peak.

^e $^{23}\text{Ne} \pm ^{25}\text{Na} \approx 2500$ counts/g at 0.41 Mev.

^f $^{46m}\text{Sc} \pm ^{47}\text{Sc} \approx 9600$ counts/g at ≈ 9.16 Mev.

^gD. J. Hughes and R. B. Schwartz, *Supplement to BNL-325* (1957).

^hD. J. Hughes and J. A. Harvey, *Neutron Cross Sections*, BNL-325 (1955).

ELEMENTAL GAMMA SPECTRA

The spectra (Appendix A) have been normalized to a 14-Mev neutron flux of 5×10^8 neutrons $\text{cm}^{-2} \text{ sec}^{-1}$ and an elemental sample weight of 1 g.

Counting was performed using the following conditions for all spectra:

Detector	3- by 3-in. cylindrical NaI(Tl), 8.8% ^{137}Cs resolution
Source-crystal distance	4.2 cm
Absorber	4.0 cm Lucite ($\rho = 1.19 \text{ g/cm}^3$)
Counter shield	24 \times 26 \times 14 in. ID, Cu-Cd lined 4-in.-thick lead
Counter	400-channel RIDL mod 34-12 pulse-height analyzer

USE OF THE SPECTRA FOR PREDICTING ANALYSIS POSSIBILITIES

This section illustrates the use of the fast-neutron reaction product spectra to calculate the limits of detection of a selected element in a multicomponent sample.

It is necessary to know the concentrations of all macro elements present in the sample before the standard spectra can be used to predict the feasibility of direct gamma spectral analysis. A study of the spectra and conditions of accumulation for each element present and for the element sought will make it possible to select the irradiation time, decay time, and counting interval to be used for maximum sensitivity. Since the analysis sensitivity is affected by that portion of the macro element spectra corresponding to the channels beneath the measured photopeak, these channels are normalized to the same irradiation time, decay time, and counting interval used to accumulate the standard spectrum of the element sought.

The normalization is performed using the following equation:

$$\text{counts/channel/time} \times f \times \frac{I}{I_s} \times \frac{D}{D_s} \times \frac{C}{C_s} = \text{corrected interference due to major constituent ,}$$

where the counts/channel/time is read from spectrum produced by irradiation of 1 g of major constituent at the energy to be used in spectral analysis of the element sought, and

f = grams of the macro element in 1.0 g of sample,

I = irradiation time chosen as optimum for element to be determined,

I_s = irradiation time used to compile the standard spectrum of the macro element,

D = decay time chosen as optimum,

D_s = decay time used to compile the standard spectrum,

C = counting interval chosen as optimum,

C_s = counting interval used to compute the standard spectrum.

To be strictly accurate, I , D , and C must be exponential functions of time; but if the times involved are short relative to the half-life, I and C may be expressed as simple time ratios. D is expressed as a decay exponential ($e^{-\lambda t}$).

This process is repeated with each of the major constituents. A final summation of the calculated values will yield the net activity expected in the vicinity of the desired impurity photopeak. This level will determine the ultimate sensitivity of direct gamma-spectral analysis. In no case will it be possible to determine the peak area produced by a sought impurity if its value is less than three times the standard deviation of this summation of counts.

Dividing this 3σ value by the peak counts per channel per gram will yield the number of grams of sought element necessary to produce this minimum detectable activity.

Example 1. Assume that one wants to determine silicon in an aluminum alloy using rapid, nondestructive gamma-spectral analysis. If a 1-g aluminum sample and a 2-min irradiation at a flux of 5×10^8 neutrons $\text{cm}^{-2} \text{ sec}^{-1}$ are used, the activity produced in the aluminum at 1.78 Mev will be due to the second pair peak of ^{24}Na (Fig. A.15). Expected activity may be calculated as follows:

$$\text{counts/channel/gram/min} \times f \times \frac{D}{D_s} \times \frac{C}{C_s} \times \frac{I}{I_s} = \text{normalized counts ,}$$

$$105 \text{ counts/min} \times \frac{1 \text{ g}}{\text{g}} \times \frac{1 \text{ min}}{1 \text{ min}} \times \frac{1 \text{ min}}{1 \text{ min}} \times \frac{2 \text{ min}}{5 \text{ min}} = 42 \text{ counts/min .}$$

To be statistically significant, the activity produced by the neutron reaction on silicon must be greater than three times the standard deviation or $3 \times \sqrt{42} = 18$ counts/min. The amount of silicon that will produce this much activity is calculated from the information obtained from the irradiation of silicon (Fig. A.17):

$$18 \text{ counts/min} \times \frac{1 \text{ g Si}}{66,000 \text{ counts/min}} = 2.7 \times 10^{-4} \text{ g} = 270 \mu\text{g Si} .$$

Therefore, 270 ppm is the minimum amount of silicon that can be detected in an aluminum matrix using nondestructive spectrometry.

Example 2. What is the lower limit of detection for sodium in potassium? The activity produced in the 1.63-Mev peak area of the potassium spectrum after 1 g is irradiated for 10 sec is calculated, from data obtained from the spectrum in Fig. A.21, as follows:

$$\text{counts/min} \times I/I_0 \times D/D_s \times C/C_s ,$$

$$550 \text{ counts/min} \times \frac{10 \text{ sec}}{10 \times 60 \text{ sec}} \times 1 \times \frac{12 \text{ sec}}{60 \text{ sec}} = \sim 1.8 \text{ counts in peak channel in 12 sec.}$$

The amount of sodium necessary to produce this activity is calculated from the spectrum in Fig. A.9:

$$\frac{1.8 \text{ counts}/12 \text{ sec}}{1.06 \times 10^4 \text{ counts}/12 \text{ sec}} = 1.7 \times 10^{-4} \text{ g} = 170 \mu\text{g Na per K} .$$

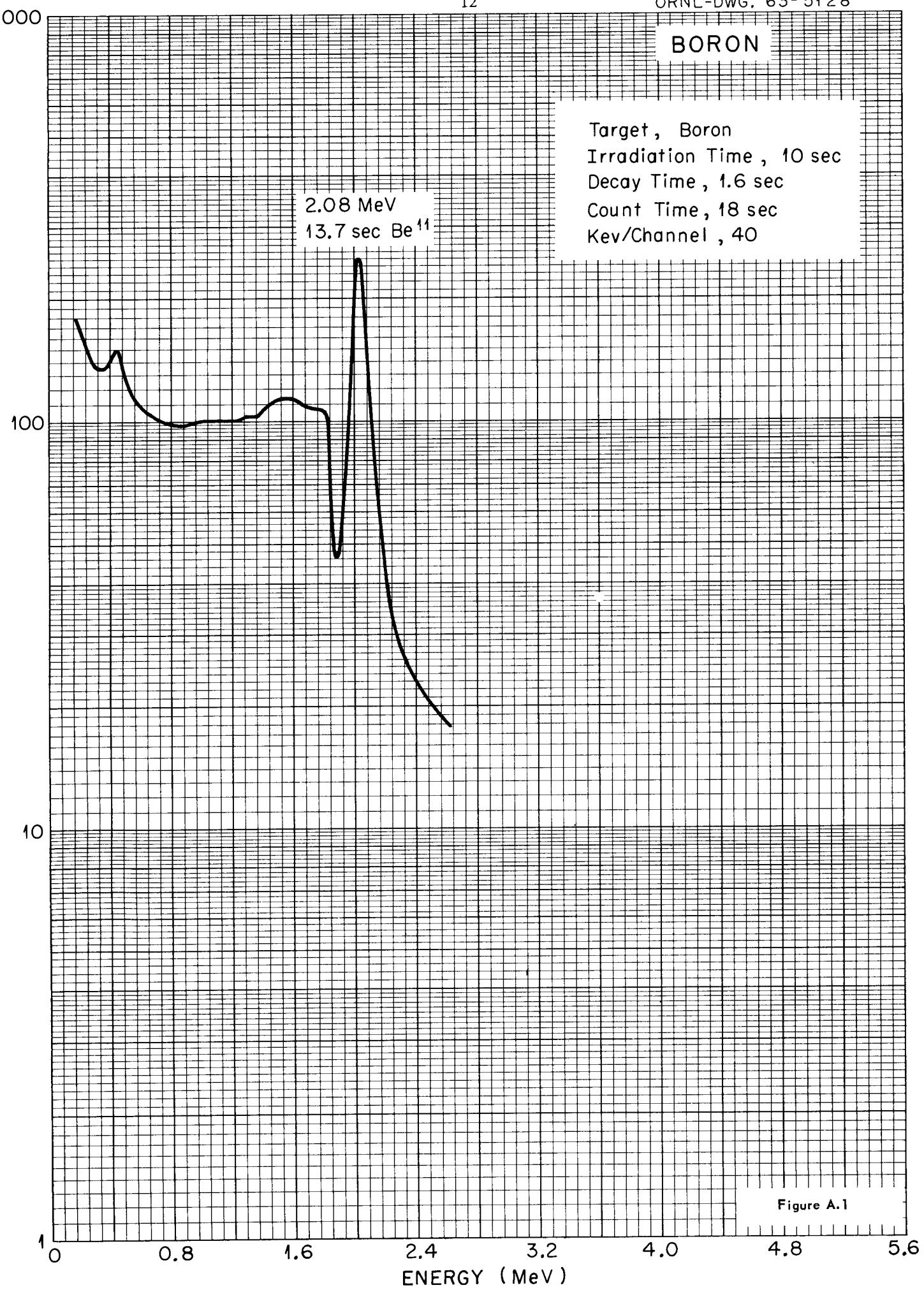
Therefore, assuming no other interferences, 170 μg of sodium can be detected in 1 g of potassium with a 10-sec irradiation at 5×10^8 neutrons $\text{cm}^{-2} \text{ sec}^{-1}$ and an immediate 12-sec count.

Appendix A**GAMMA SPECTRA FOR ELEMENTS $Z = 1$ TO $Z = 30$**

BORON

Target, Boron
Irradiation Time, 10 sec
Decay Time, 1.6 sec
Count Time, 18 sec
Kev/Channel, 40

COUNTS / CHANNEL



10,000

BORON

Target, H_3BO_3
Irradiation Time, 5 min
Decay Time, 1.6 sec
Counting Time, 1 min
Kev / Channel, 20

0.51 MeV β^+
20 min C^{11} β^+

COUNTS / CHANNEL

1000

100

10

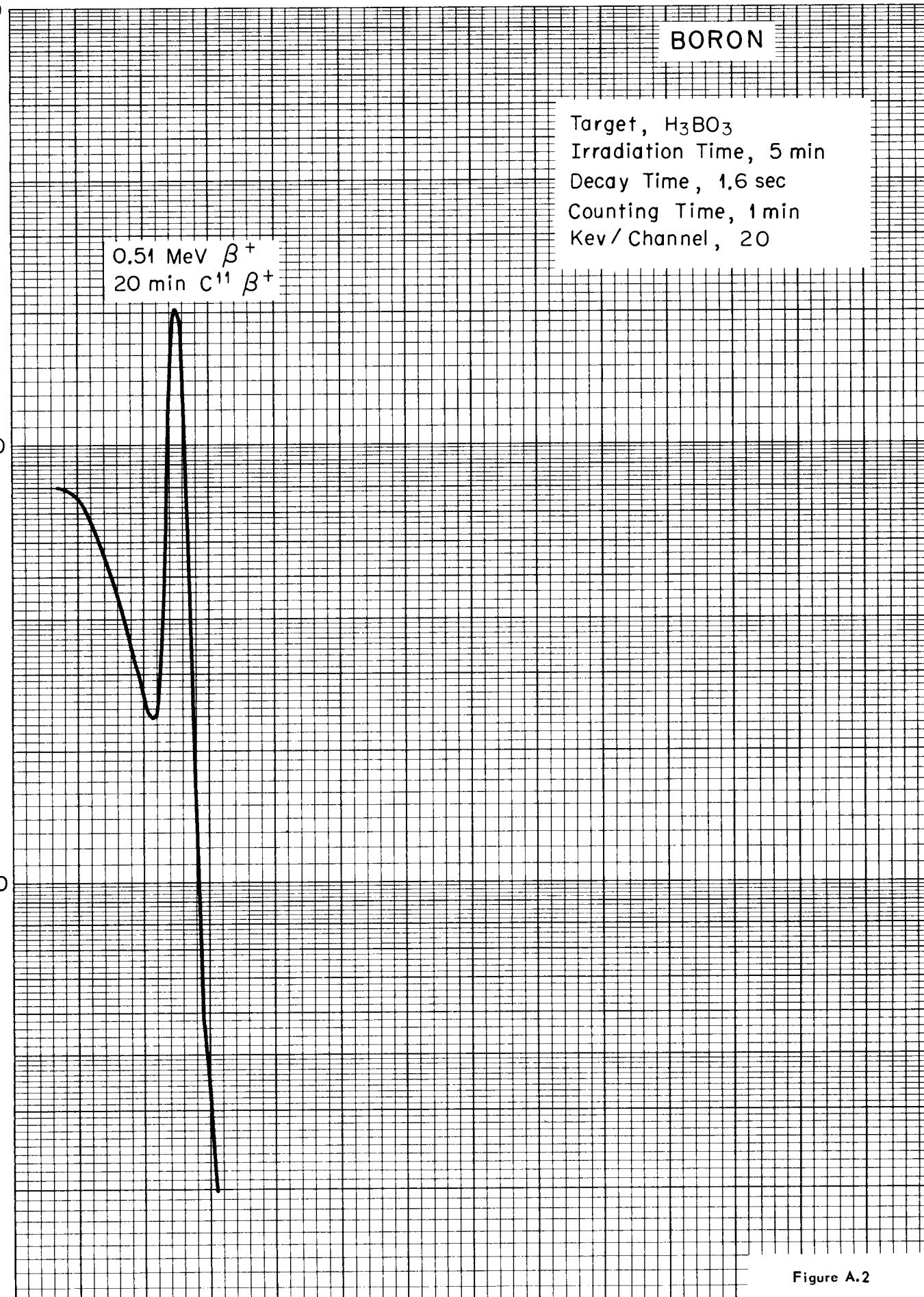


Figure A.2

100,000

0.51 MeV
 $\text{40.1 min } \text{N}^{13} \beta^+$

10,000

Target, NH_4NO_3
Irradiation Time, 5 min
Decay Time, 30 sec
Counting Time, 1 min
Kev/Channel, 20

1000

100

0

0.4

0.8

1.2

1.6

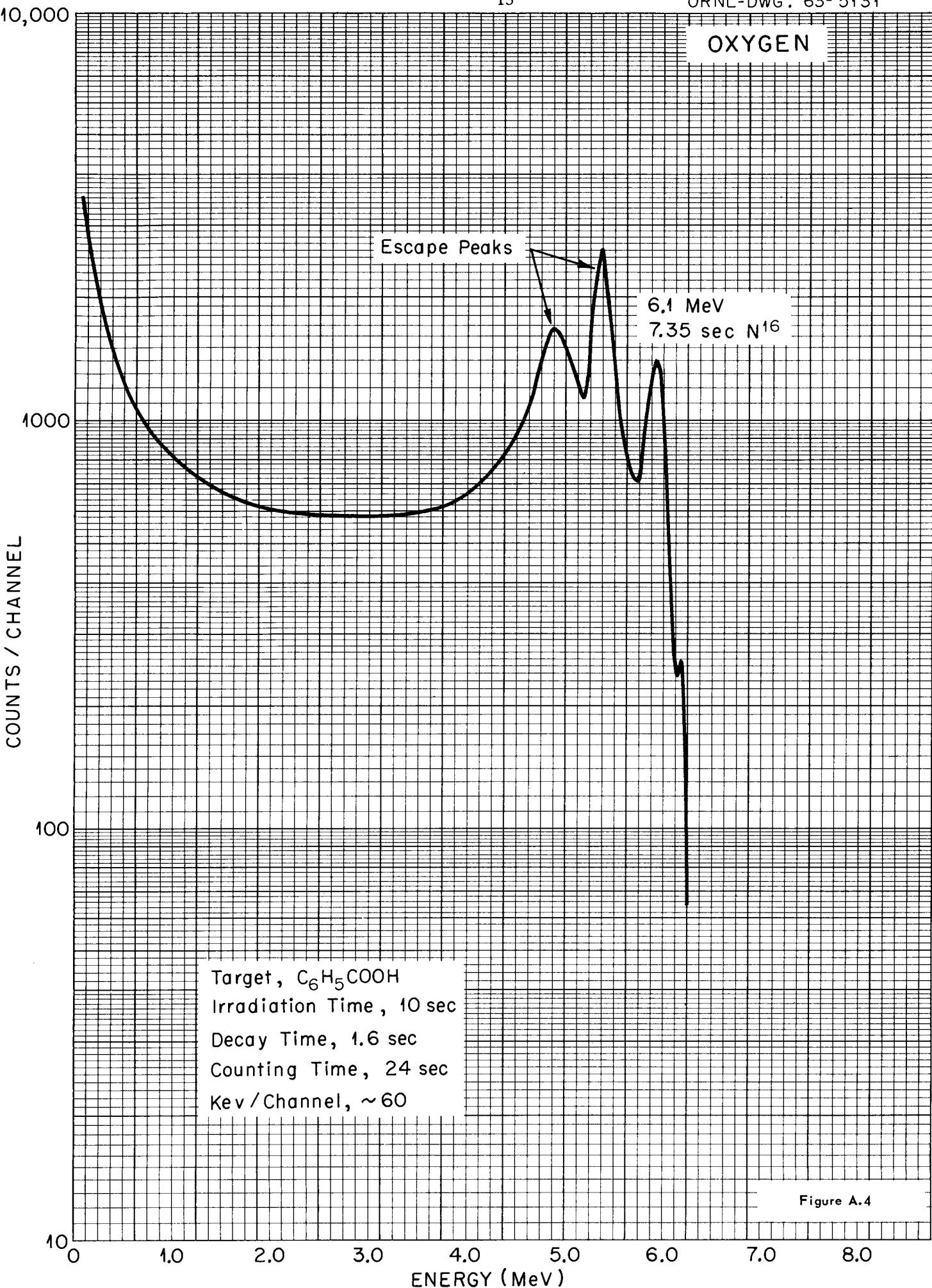
2.0

2.4

2.8

ENERGY (MeV)

Figure A.3



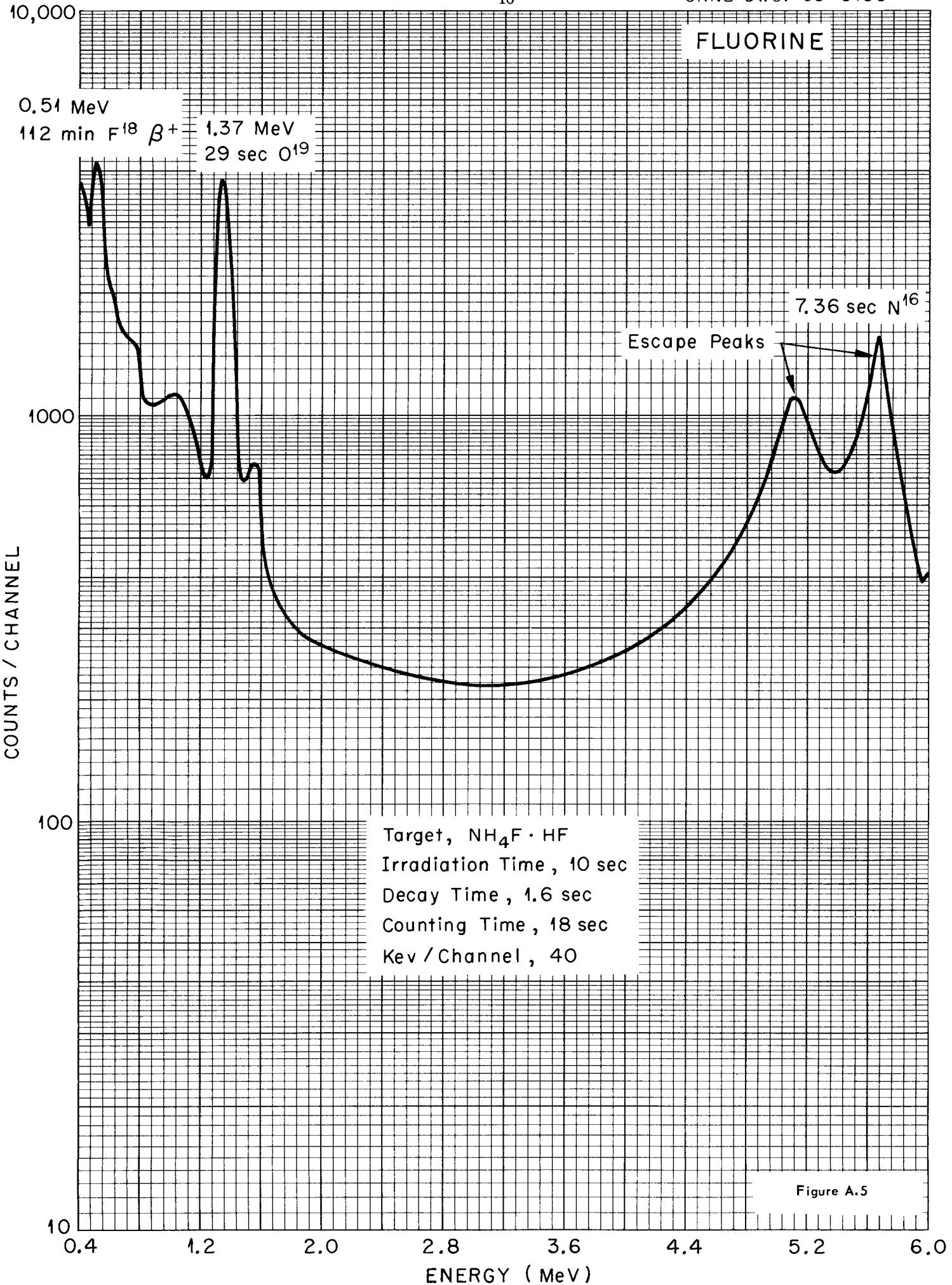
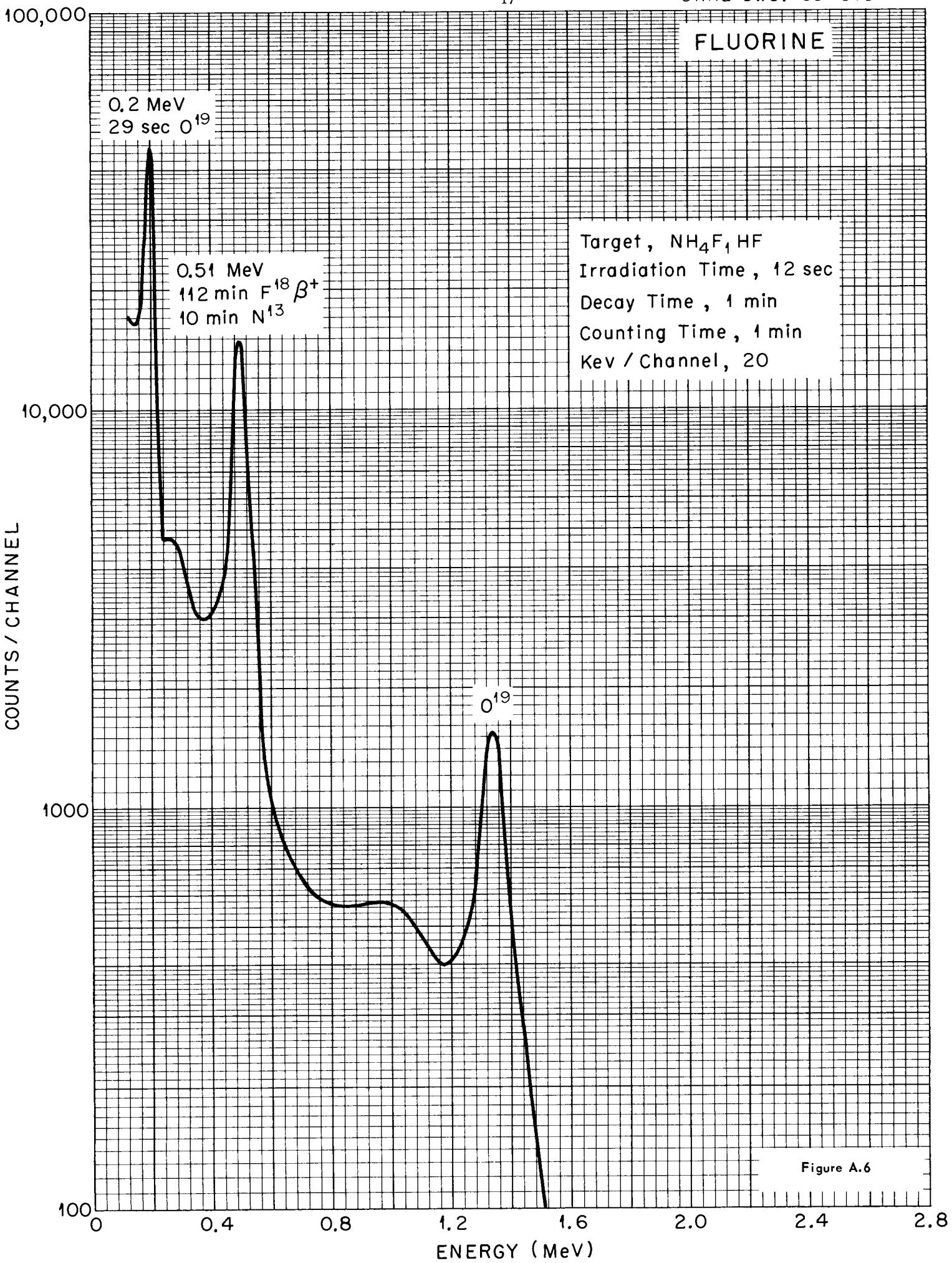


Figure A.5



FLUORINE

Target , $\text{NH}_4\text{F} \cdot \text{HF}$
Irradiation Time, 2 min
Decay Time , 5 min
Count Time , 1 min
Kev / Channel , 20

0.51 MeV
 $112 \text{ min } \text{F}^{18} \beta^+ + 10 \text{ min } \text{N}^{13} \beta^+$

COUNTS / CHANNEL

10,000

1000

100

0 0.4 0.8 1.2 1.6 2.0 2.4 2.8

ENERGY (MeV)

Figure A.7

10,000

FLUORINE0.51 Mev
112 min $F^{18} \beta^+$ Target, $NH_4F \cdot HF$
Irradiation Time, 2 min
Decay Time, 1 hr
Counting Time, 1 min
Kev/Channel, 20

COUNTS / CHANNEL

1000

100

10

0

0.4

0.8

1.2

2.0

2.8

3.6

4.4

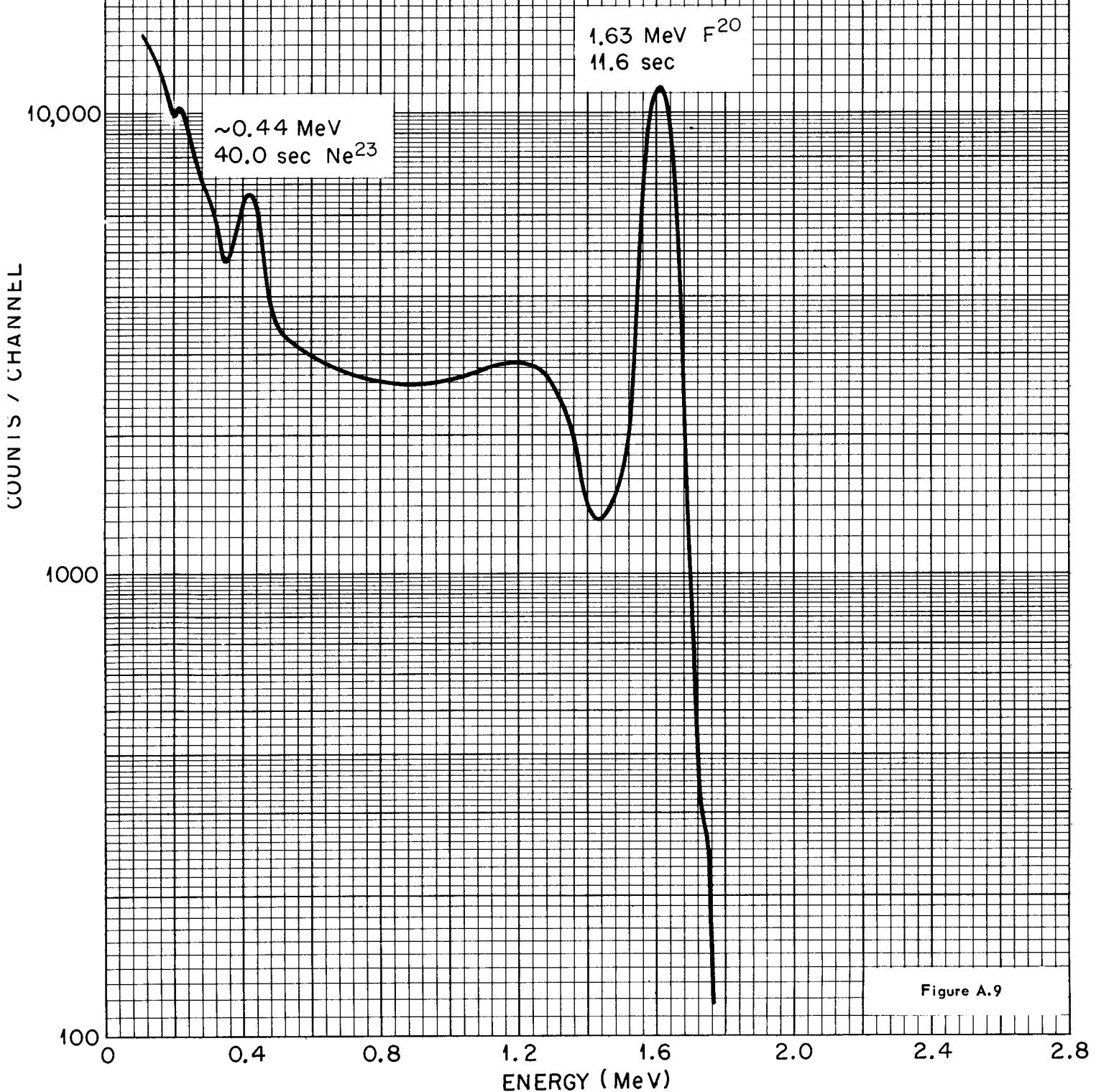
ENERGY (MeV)

Figure A.8

100,000

SODIUM

Target, Na
Irradiation Time, 10 sec
Decay Time, 1.6 sec
Counting Time, 12 sec
Kev / Channel, 20



10,000

SODIUM

0.44 MeV
40 sec Ne²³

Target, Na
Irradiation Time , 40 sec
Decay Time, 80 sec
Counting Time, 18 sec
Kev / Channel , 20

COUNTS / CHANNEL

1000

100

10

0

0.8

1.2

1.6

2.0

2.4

2.8

ENERGY (MeV)

Figure A.10

10,000

MAGNESIUM

0.41 MeV
40 sec Ne^{23} + 60 sec Na^{25}

Target, Mg
Irradiation Time, 1 min
Decay Time, 35 sec
Count Time, 30 sec
Kev / Channel, 20

COUNTS / CHANNEL

1000

0.58 MeV
 Na^{25}

0.97 MeV
 Na^{25}

1.6 MeV
 $\text{Ne}^{23} + \text{Na}^{25}$

1.38 MeV
15 h Na^{24}

2.76 MeV
 Na^{24}

Pair Peak
 Na^{24}

Figure A.11

10

0

0.4

0.8

1.2

1.6

2.0

2.4

2.8

ENERGY (MeV)

MAGNESIUM

Target, Mg
Irradiation Time, 1 min
Decay Time, 2 min
Count Time, 0.5 min
Kev/ Channel, 20

COUNTS / CHANNEL

100

0.41 MeV
40 sec Ne^{23} + 60 sec Na^{25}

0.58 MeV
 Na^{25}

0.93 MeV
 Na^{25}

1.38 MeV
15 hr Na^{24}

1.6 MeV
 Na^{25} + Ne^{23}

2.76 MeV
 Na^{24}

Pair Peak
 Na^{24}

10

1

1000

0.4

0.8

1.2

1.6

2.0

2.4

2.8

ENERGY (MeV)

Figure A.12

10,000

MAGNESIUM

Target , Mg
Irradiation Time , 1 min
Decay Time , 18 min
Counting Time , 0.5 min
Kev / Channel , 20

COUNTS / CHANNEL

1000

100

10

1.38 MeV
15 hr Na²⁴

2.76 MeV
Na²⁴

Pair Peaks

Na²⁴

Figure A.13

0

0.4

0.8

1.2

1.6

2.0

2.4

2.8

ENERGY (MeV)

ALUMINUM

Target , Al
Irradiation Time , 10 sec
Decay Time , 1 min
Count Time , 1 min
Kev / Channel , 20

0.84 MeV
9.6 min Mg^{27}

1.01 MeV
 Mg^{27}

COUNTS / CHANNEL

1000

100

10

10,000

0.4

0.8

1.2

1.6

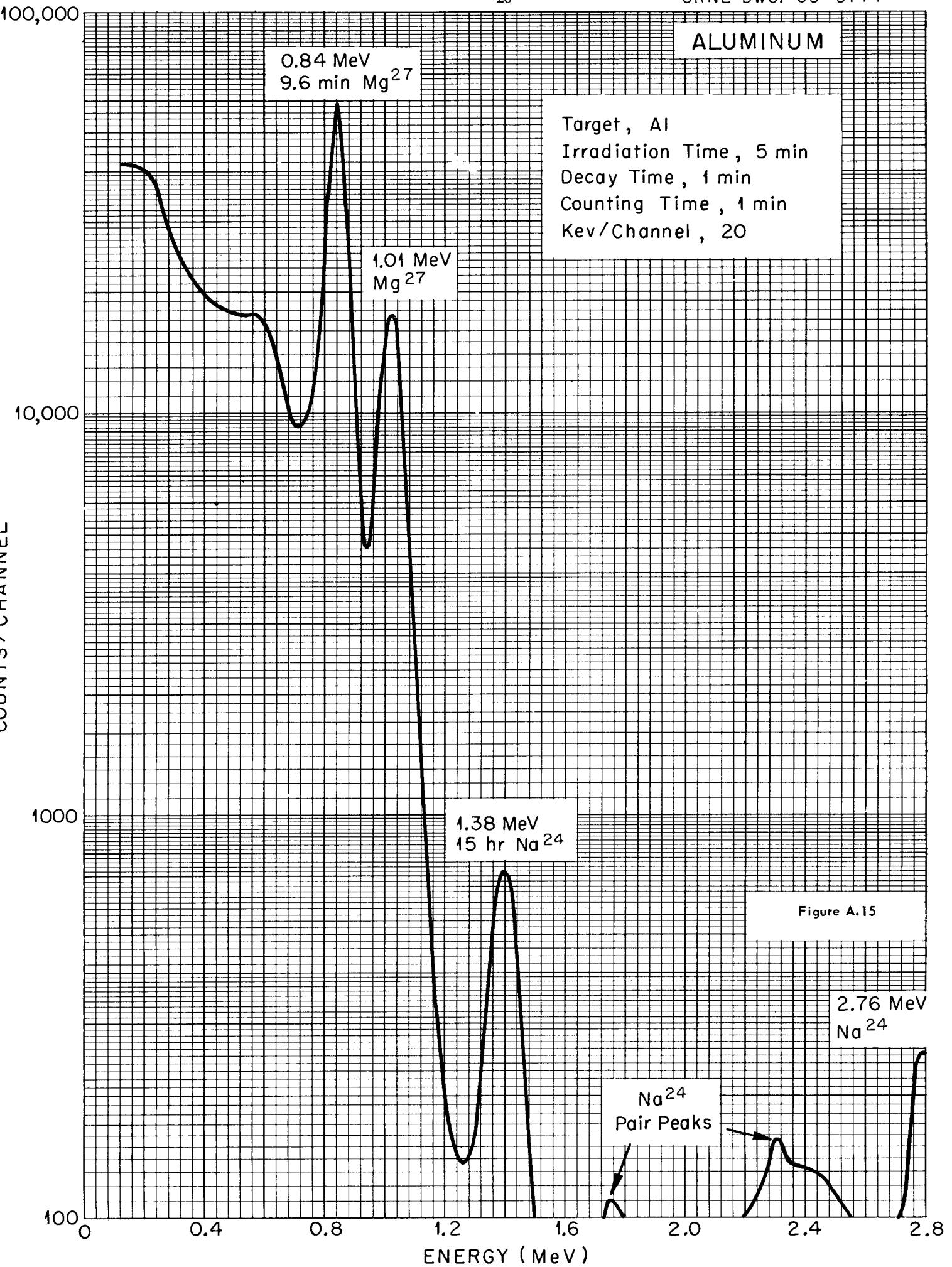
2.0

2.4

2.8

ENERGY (MeV)

Figure A.14



ALUMINUM

10,000

1000

100

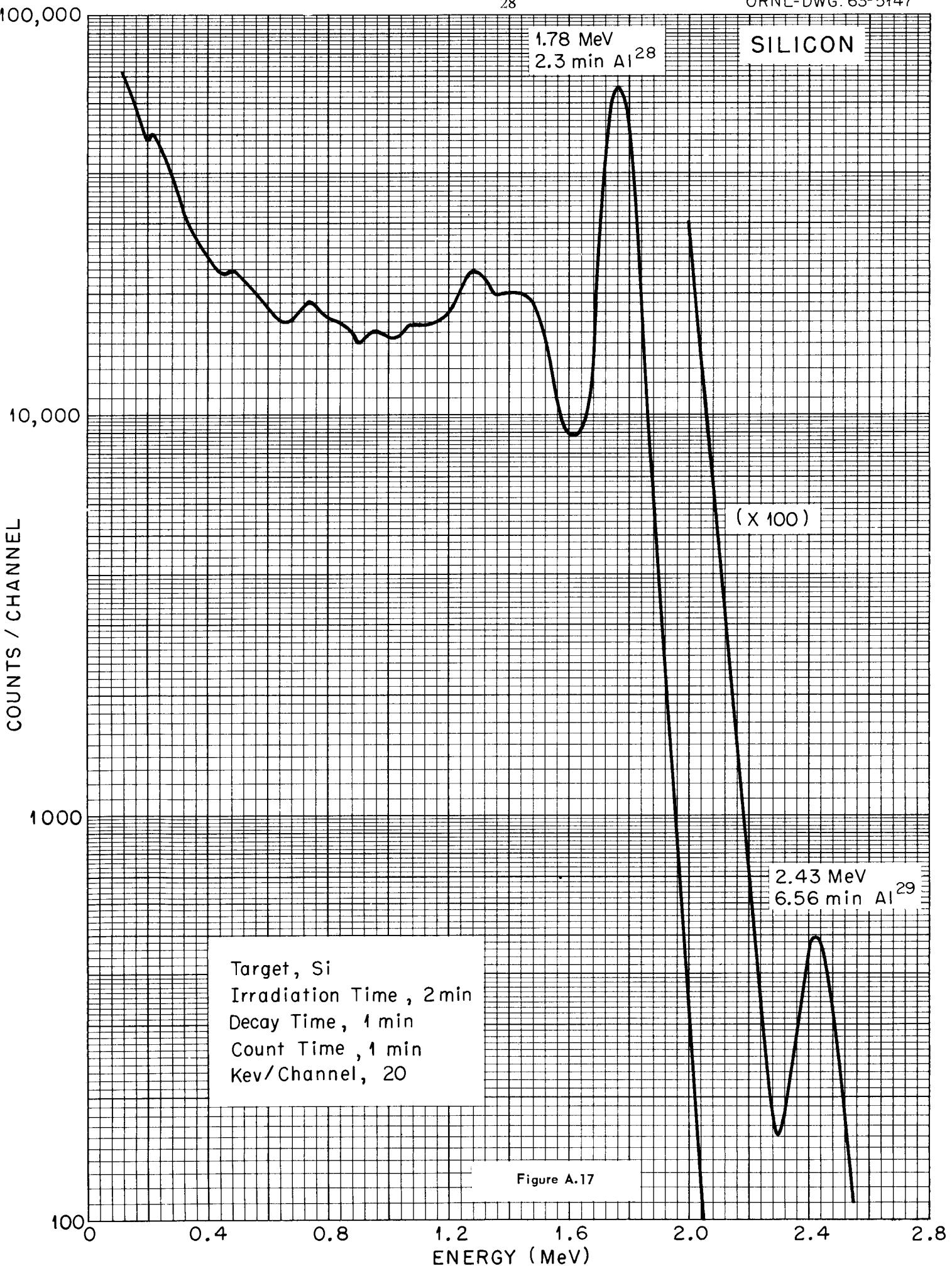
10

1.38 MeV
15 hr Na²⁴Target , Al
Irradiation Time , 5 min
Decay Time , 2 hrs
Count Time , 5 min
Kev / Channel , 202.76 MeV
Na²⁴Na²⁴
Pair Peak

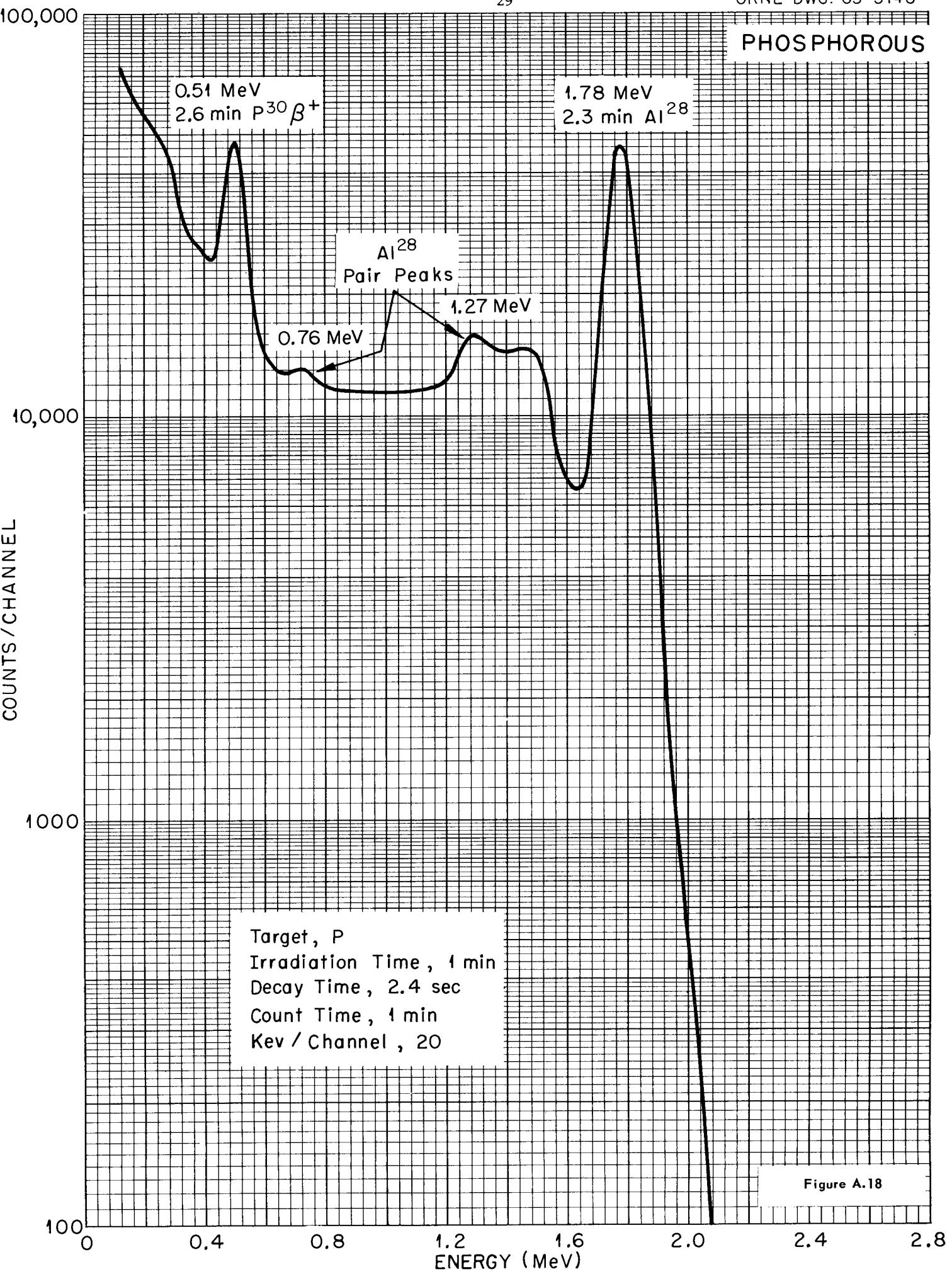
COUNTS / CHANNEL

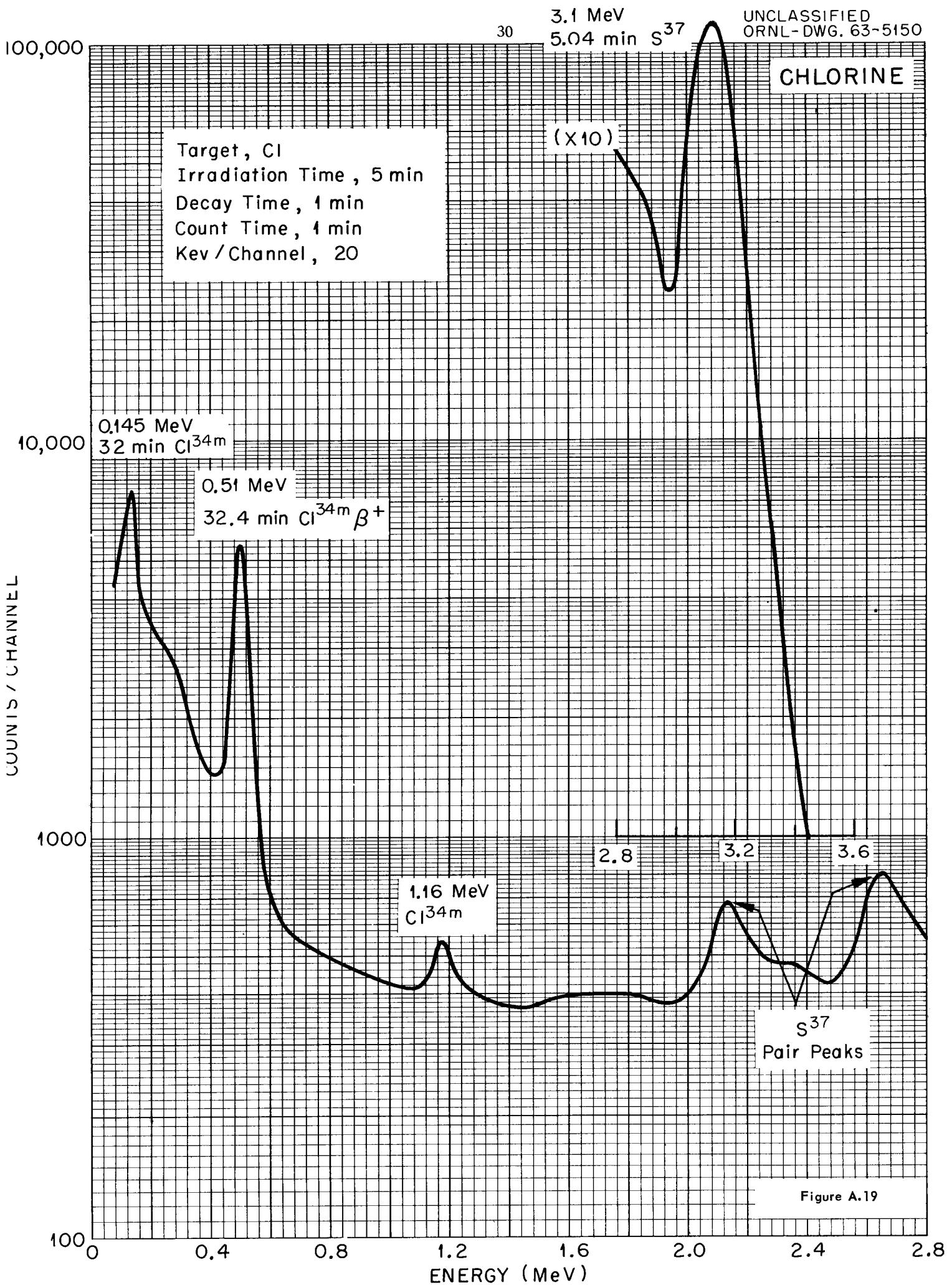
ENERGY (MeV)

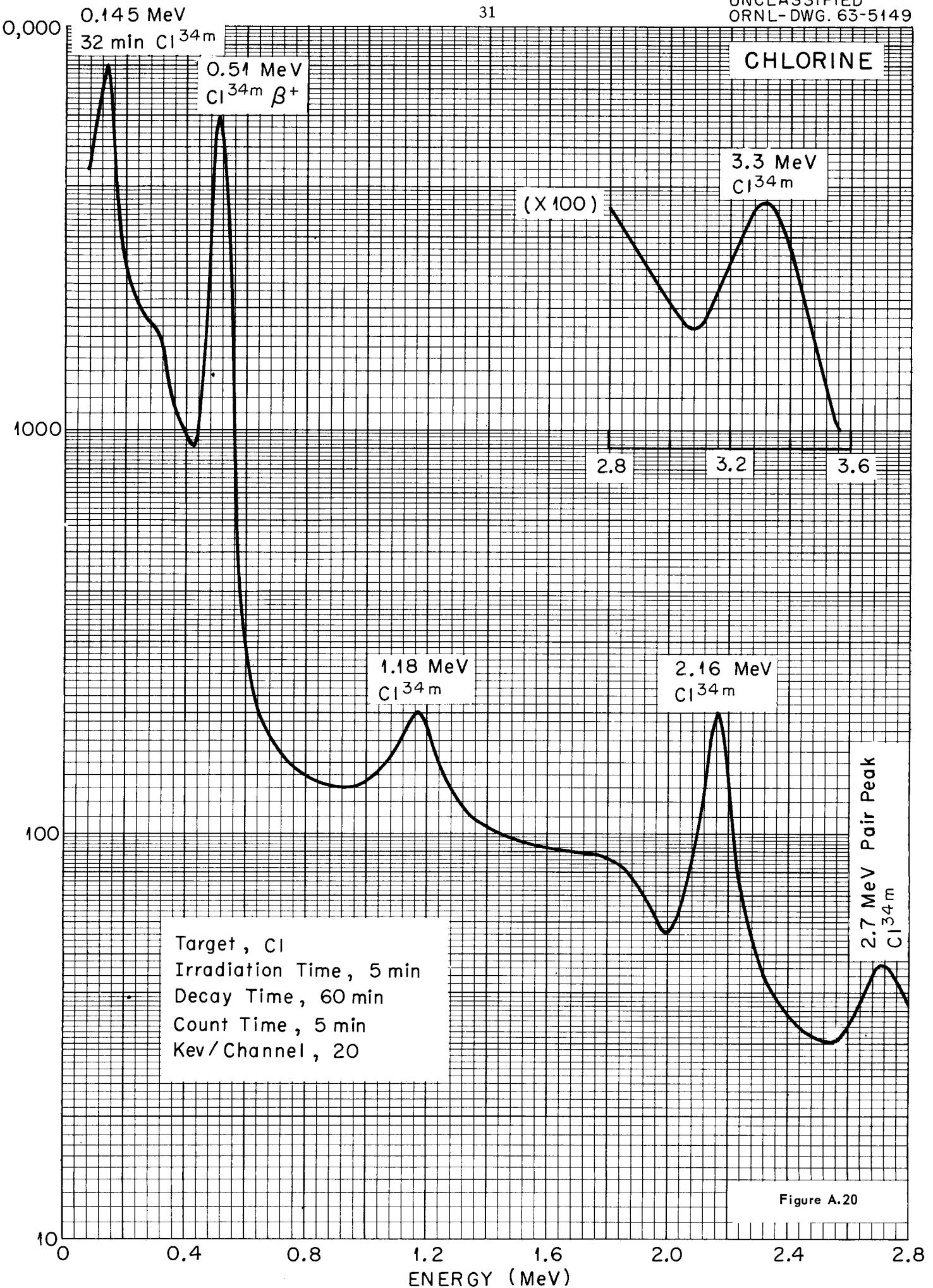
Figure A.16

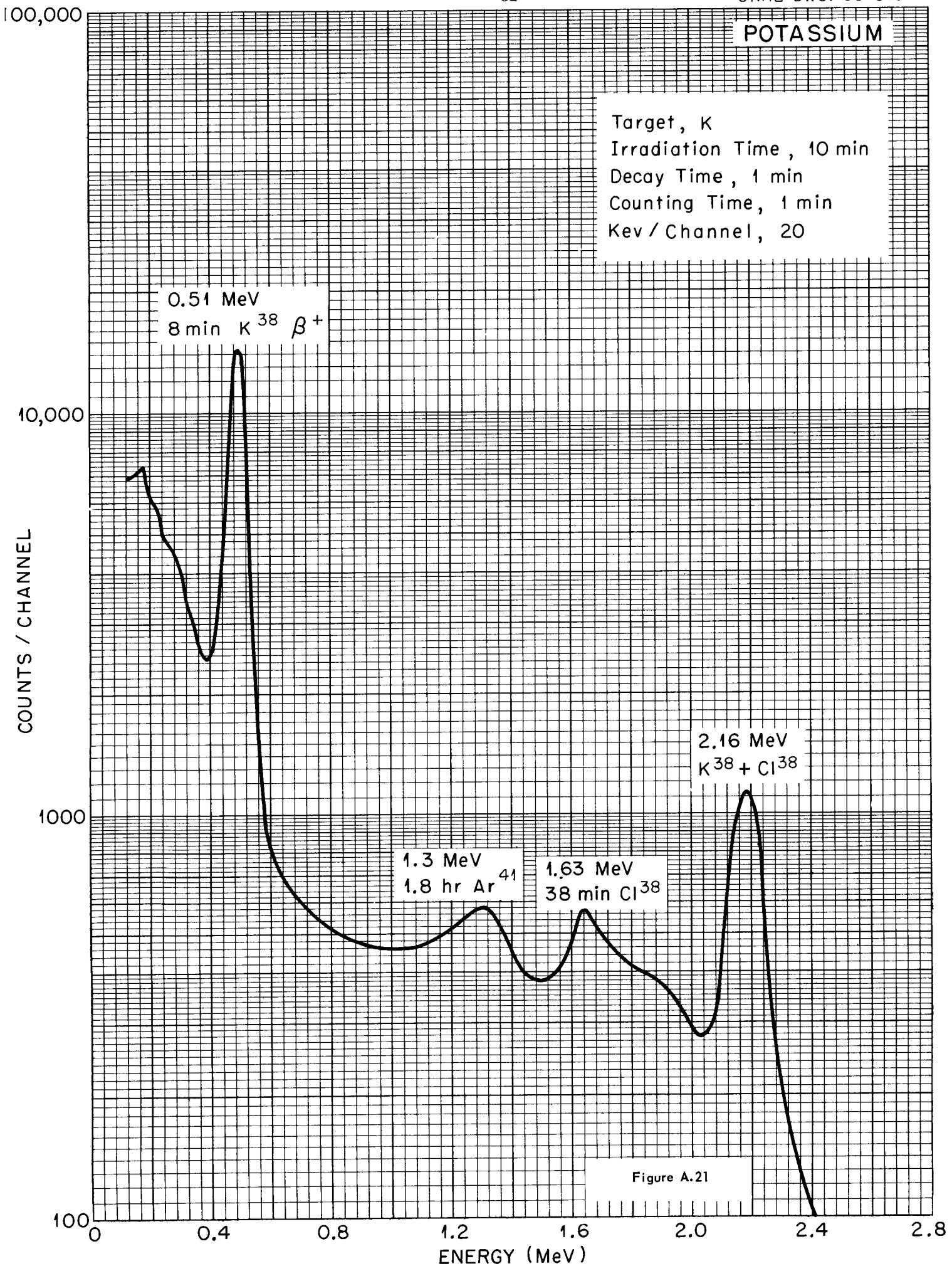


PHOSPHOROUS









POTASSIUM

0.51 MeV
8 min $K^{38}\beta$

Target, K
Irradiation Time, 20 min
Decay Time, 20 min
Count Time, 10 min
Kev / Channel, 20

1.3 MeV
1.8 hr Ar^{41}

1.63 MeV
37.5 min Cl^{38}

2.16 MeV
 $Cl^{38} + K^{41}$

COUNTS / CHANNEL

100 0 0.4 0.8 1.2 1.6 2.0 2.4 2.8

ENERGY (MeV)

Figure A.22

10,000

0.16 MeV
20 sec Sc^{46m} + 3.4 d Sc^{47}

TITANIUM

Target , Ti
Irradiation Time , 1 min
Decay Time , 1.6 sec
Count Time , 18 sec
Kev / Channel , 20

1000

0.51 MeV
3.1 hr Ti^{45} β^+

100

1.17 MeV
1.7 min Sc^{50} 1.58 MeV
 Sc^{50}

10

COUNTS / CHANNEL

0 0.4 0.8 1.2 1.6 2.0 2.4 2.8
ENERGY (MeV)

Figure A.23

TITANIUM

0.16 MeV
20 sec Sc^{46m} + 3.4 d Sc^{47}

0.51 MeV
3.1 hr $\text{Ti}^{45}\beta^+$

1.17 MeV
1.7 min Sc^{50}

1.58 MeV
 Sc^{50}

Target, Ti
Irradiation Time, 1 min
Decay Time, 1 min
Count Time, 1 min
Kev/Channel, 20

COUNTS / CHANNEL

1000

100

10

ENERGY (MeV)

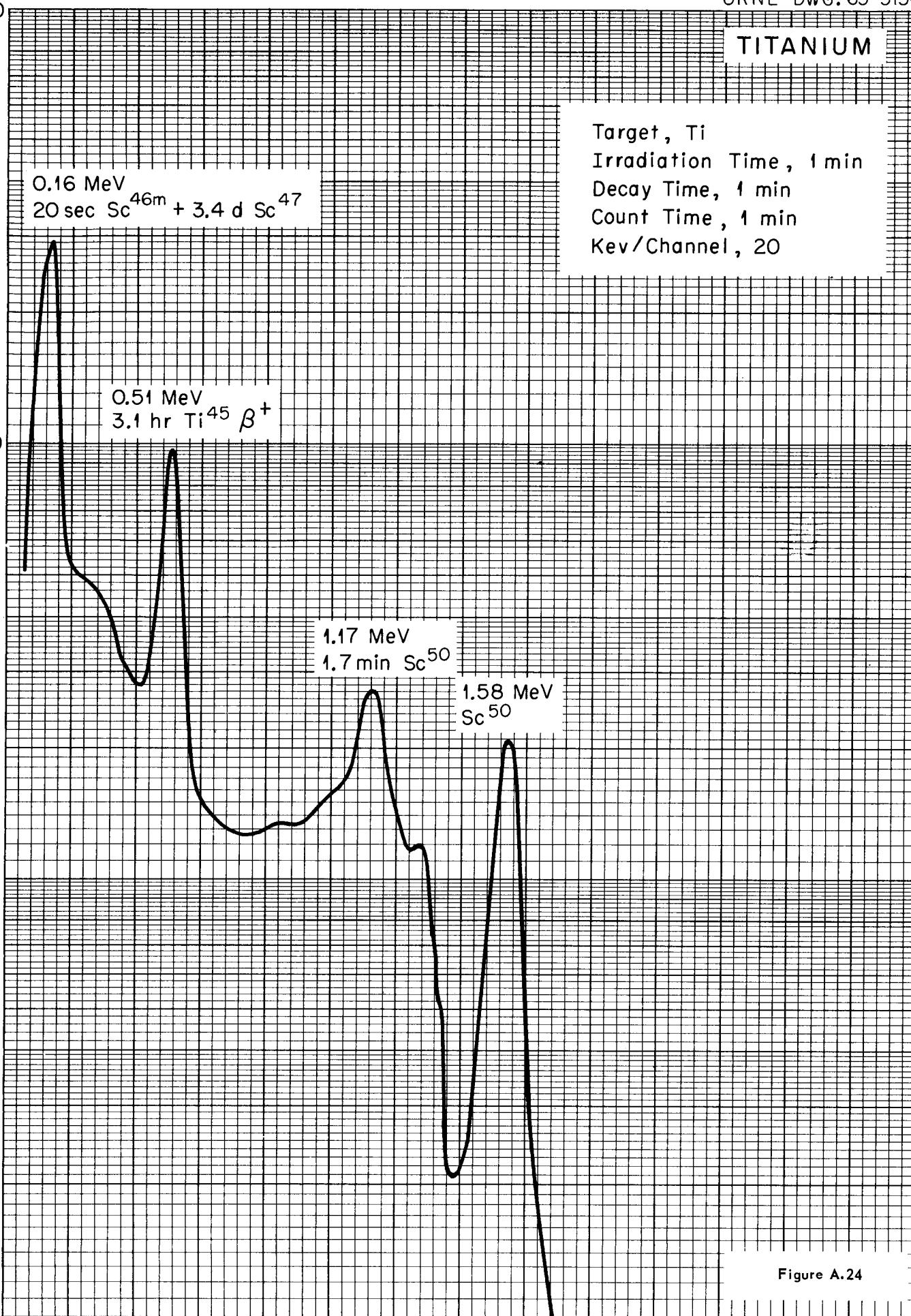


Figure A.24

TITANIUM

Target , Ti
Irradiation Time , 1 min
Decay Time , 1 hr
Count Time , 10 min
Kev/Channel , 20

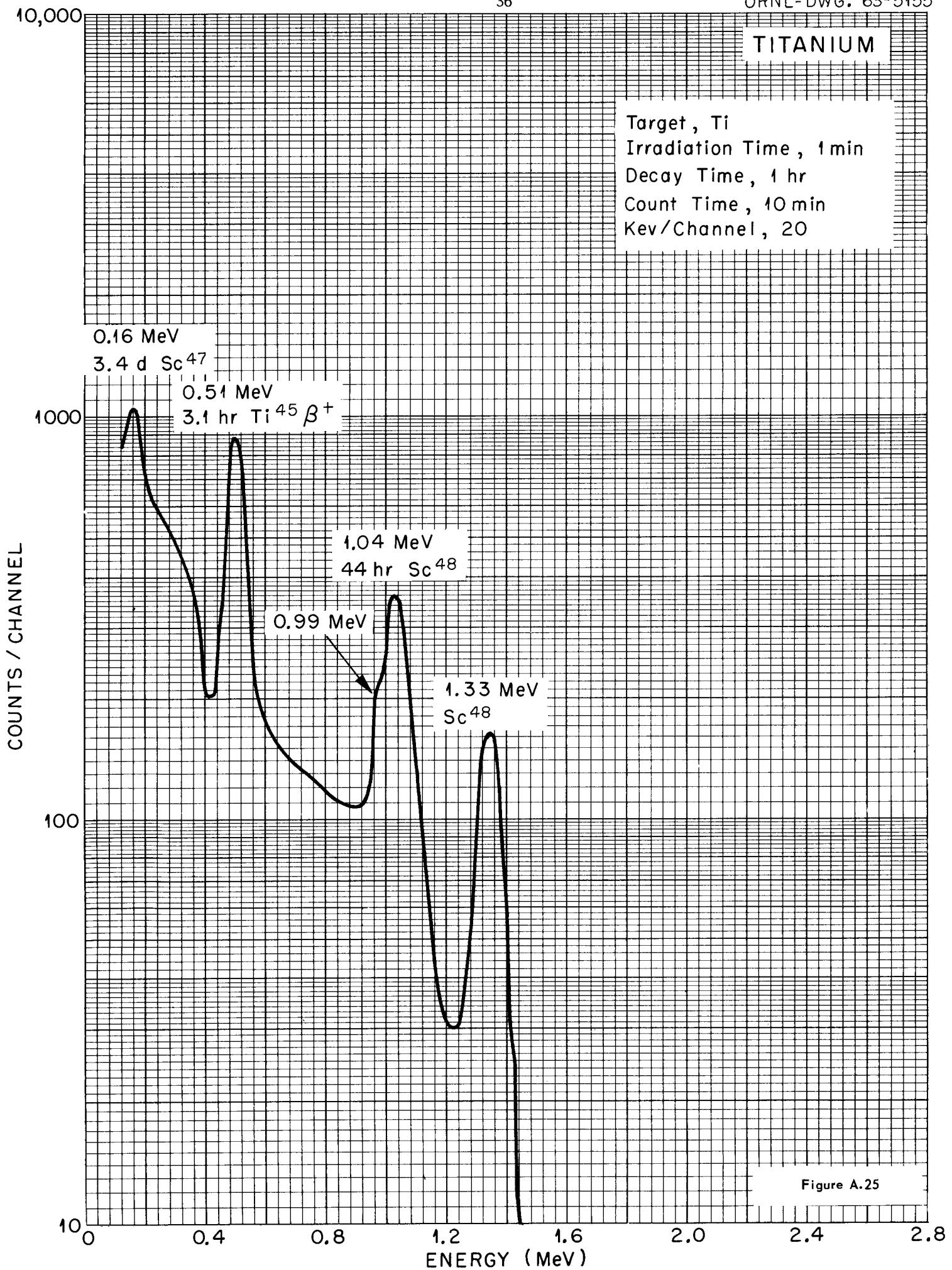


Figure A.25

VANADIUM

Target, V
Irradiation Time, 5 min
Decay Time, 5 hrs
Count Time, 10 min
Kev/Channel, 20

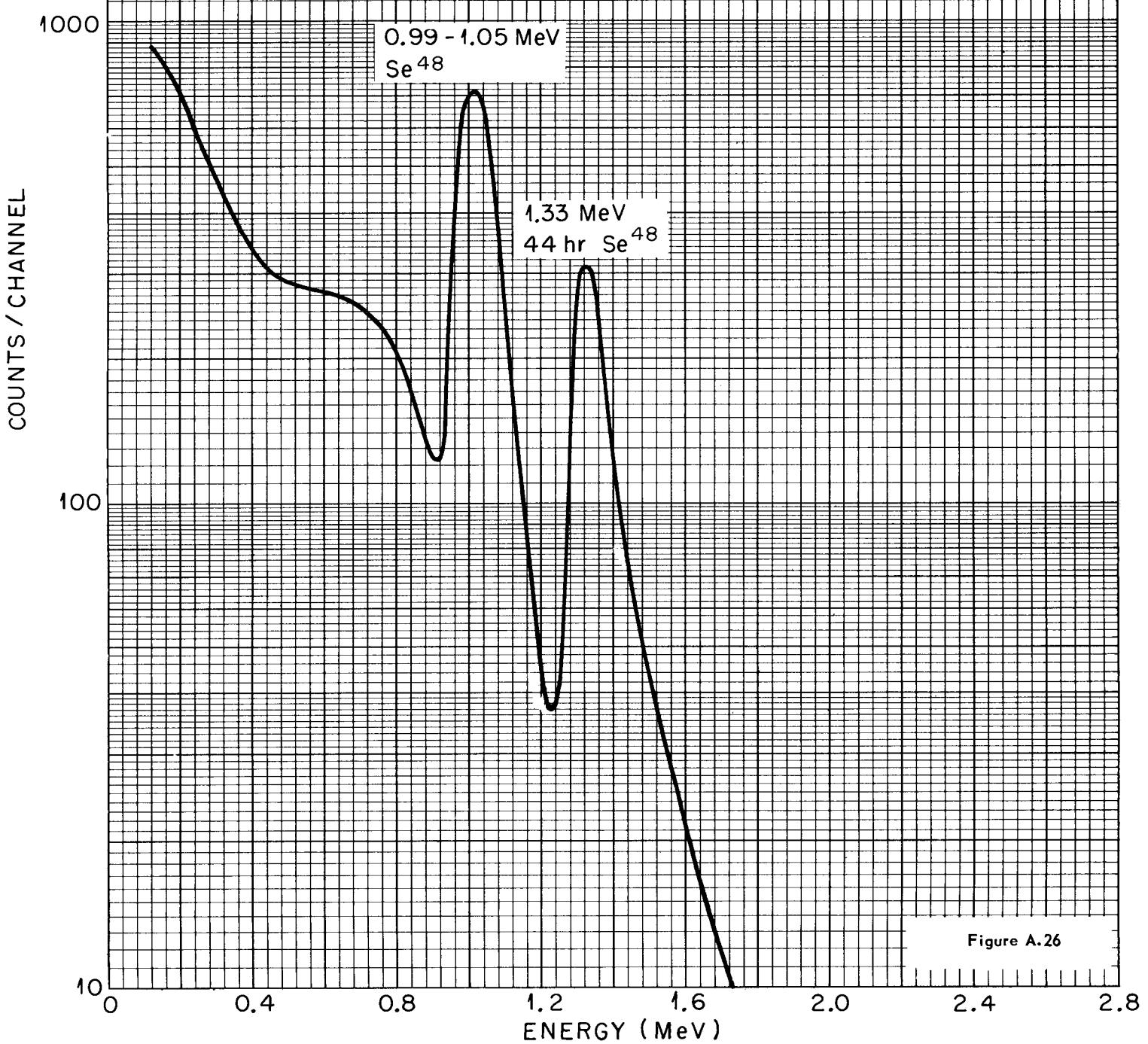
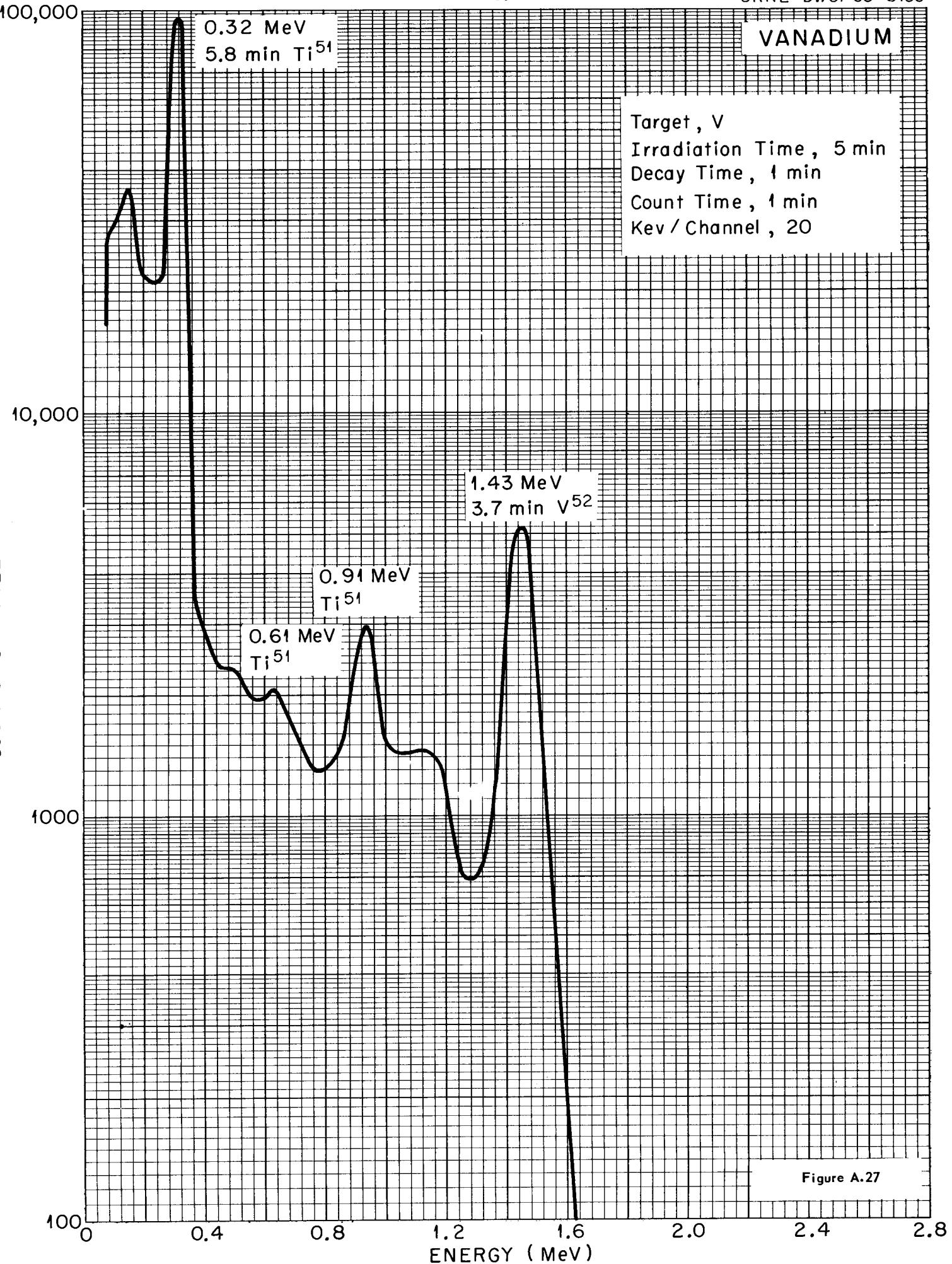
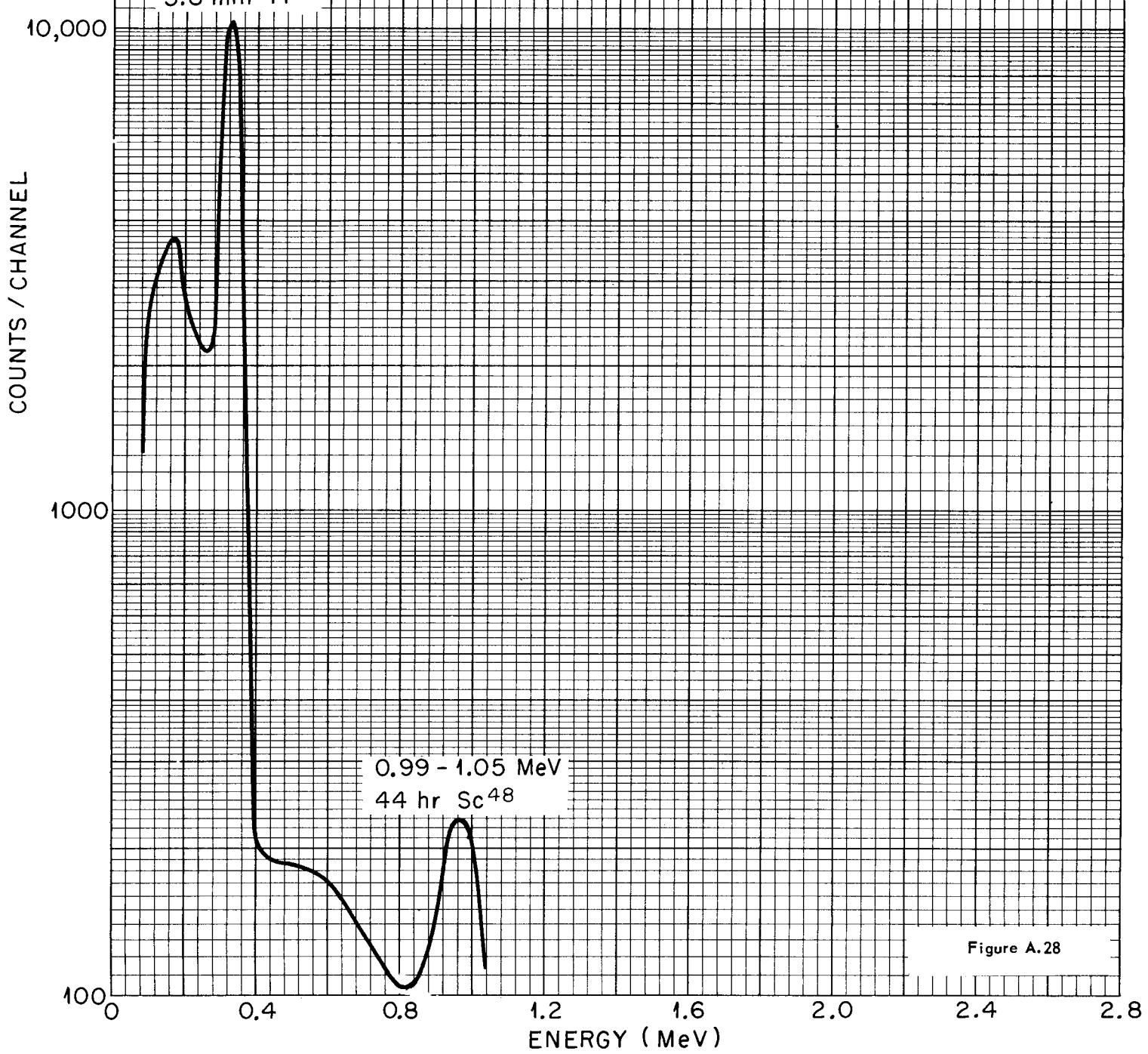


Figure A.26



VANADIUM

Target, V
Irradiation Time, 5 min
Decay Time, 20 min
Count Time, 1 min
Kev / Channel, 20



UNCLASSIFIED
ORNL-DWG.63-5160

1.44 MeV

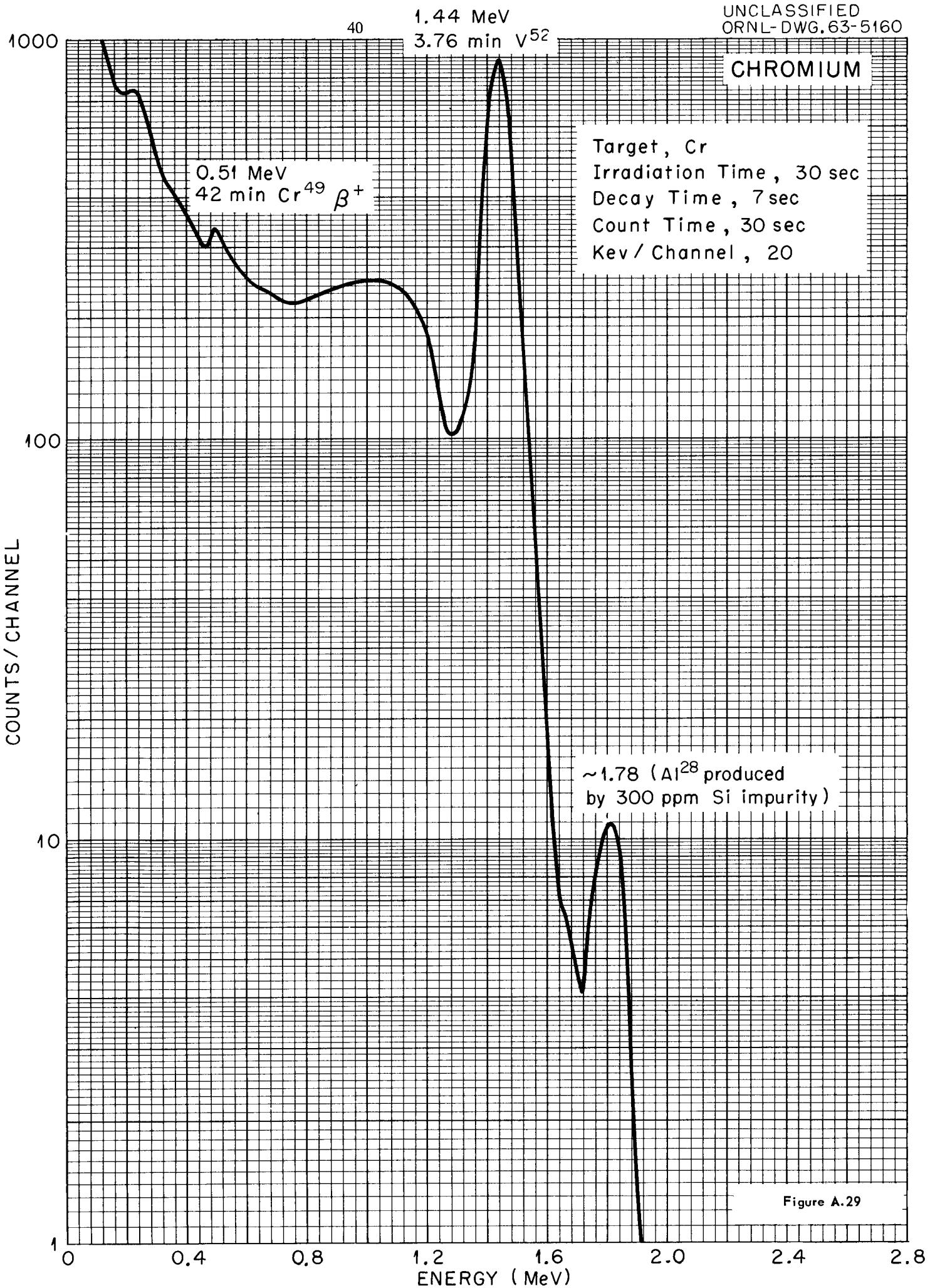
3.76 min $\sqrt{52}$

CHROMIUM

Target, Cr
Irradiation Time, 30 sec
Decay Time, 7 sec
Count Time, 30 sec
Kev / Channel, 20

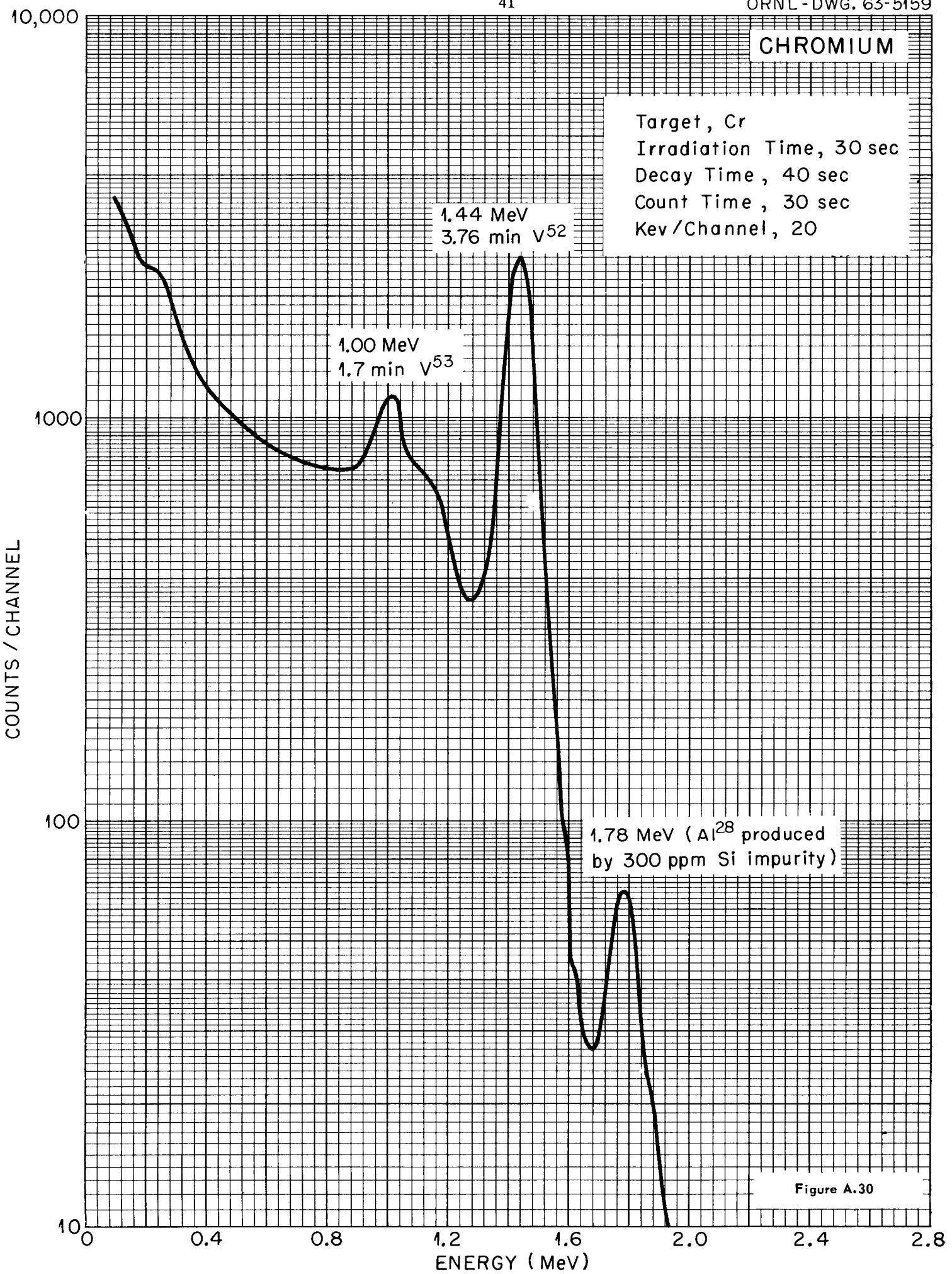
0.51 MeV
42 min Cr⁴⁹ β⁺

~ 1.78 (Al^{28} produced
by 300 ppm Si impurity)



CHROMIUM

Target, Cr
Irradiation Time, 30 sec
Decay Time, 40 sec
Count Time, 30 sec
Kev / Channel, 20



10,000

CHROMIUM

Target, Cr

Irradiation Time, 5 min

Decay Time, 60 min

Count Time, 5 min

Kev/Channel, 5

COUNTS / CHANNEL

1000

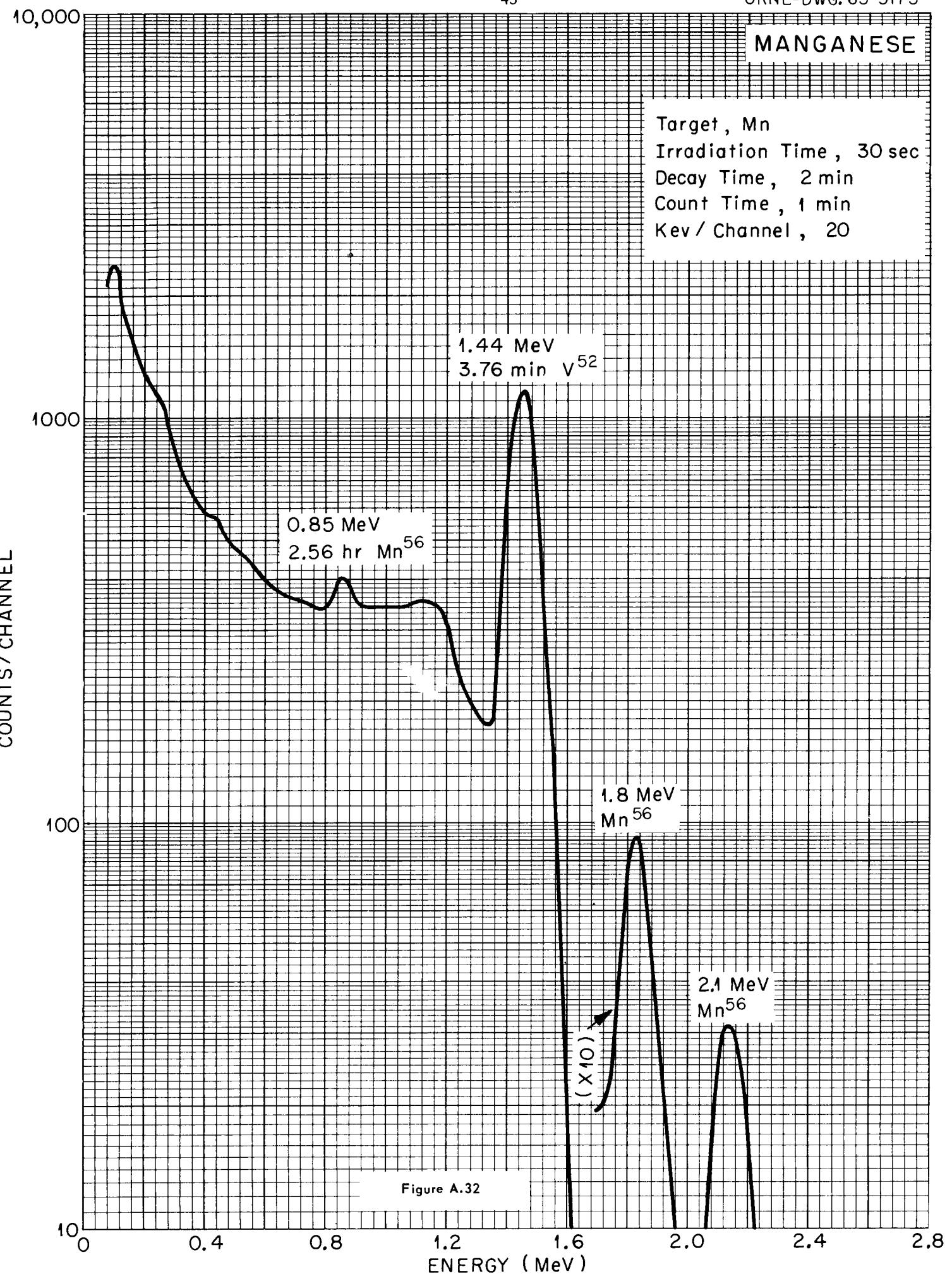
0.06 MeV
42 min Cr⁴⁹0.15 MeV
Cr⁴⁹0.51 MeV
Cr⁴⁹ β^+

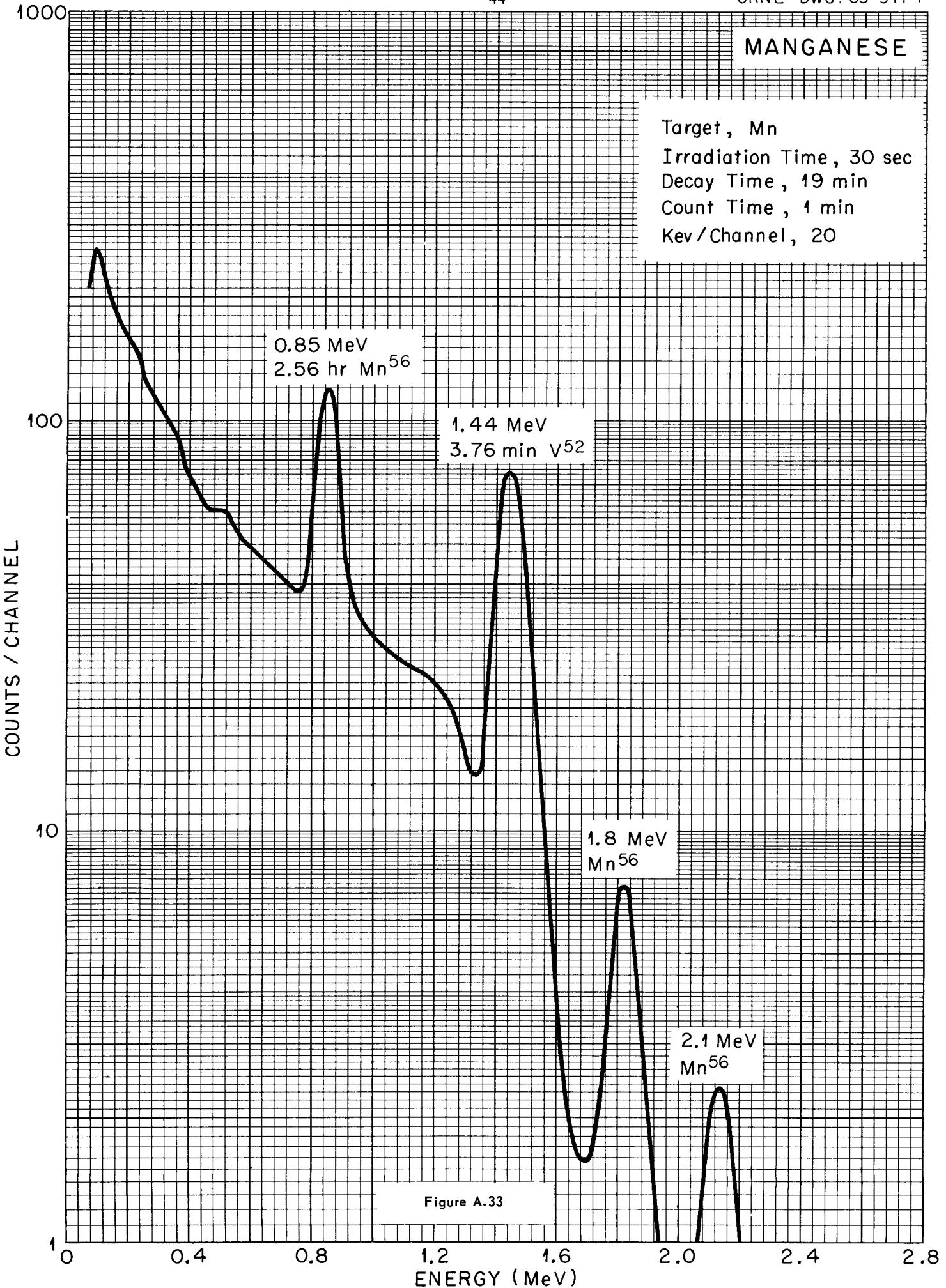
100

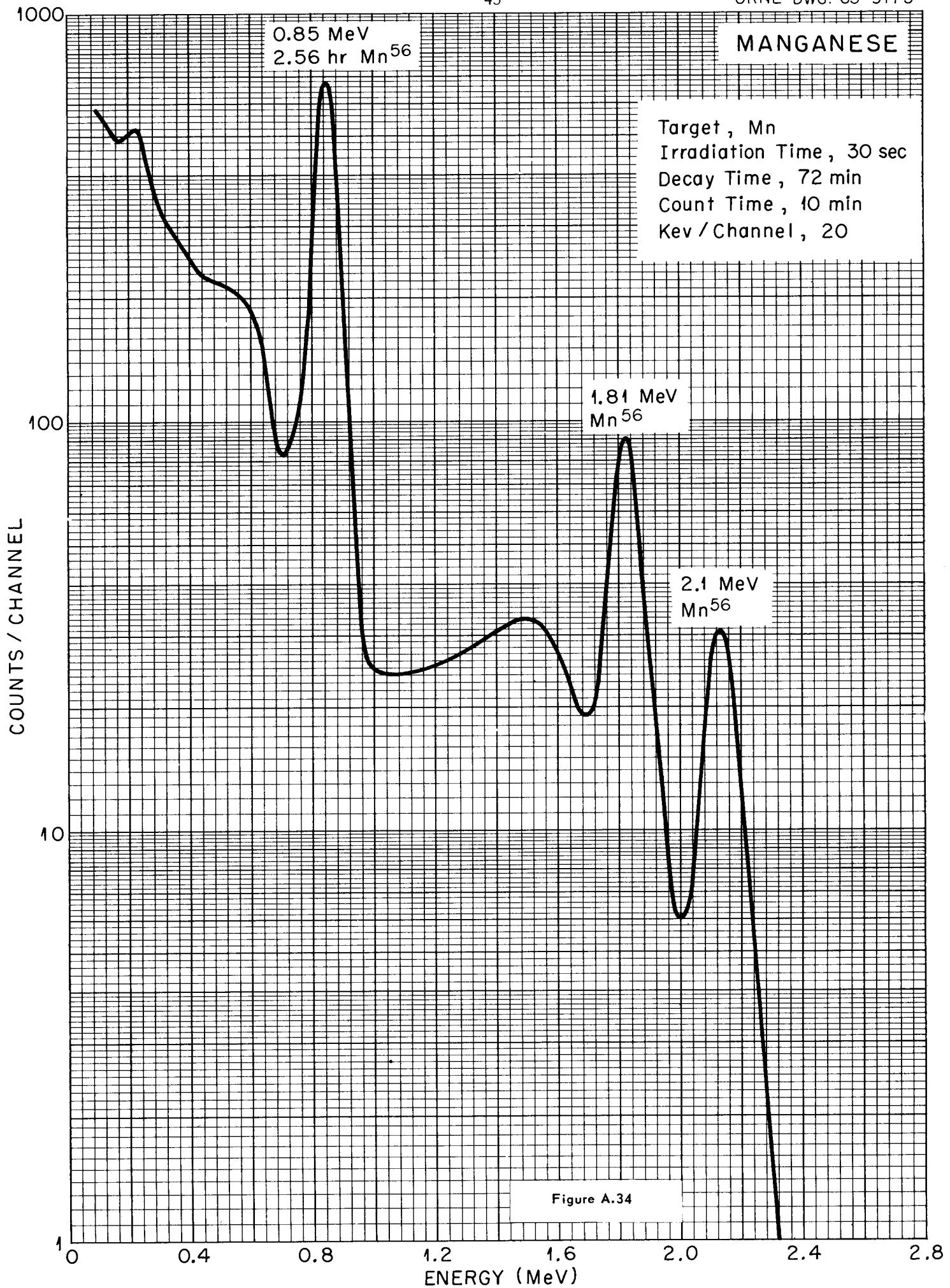
10

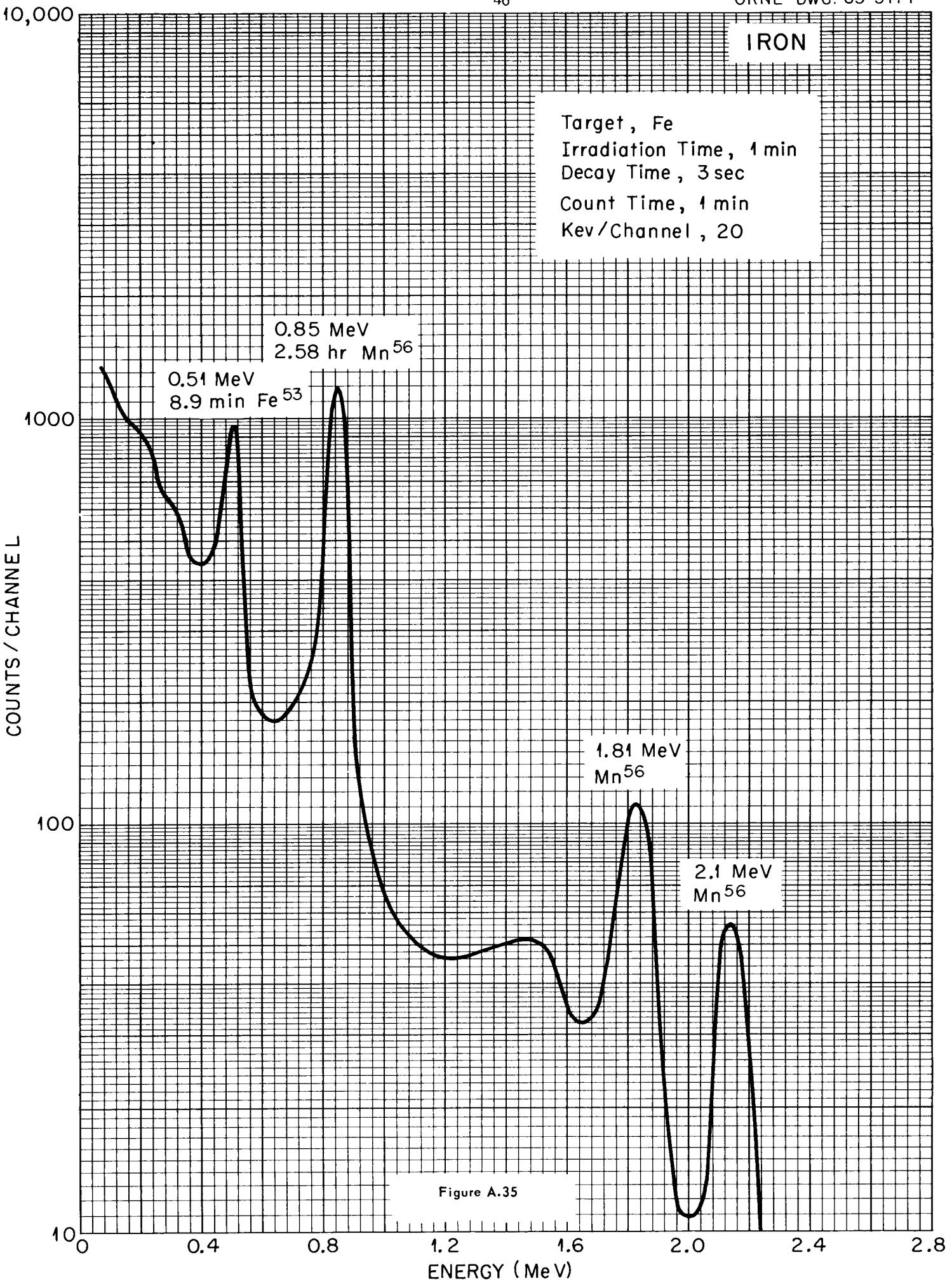
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 ENERGY (MeV)

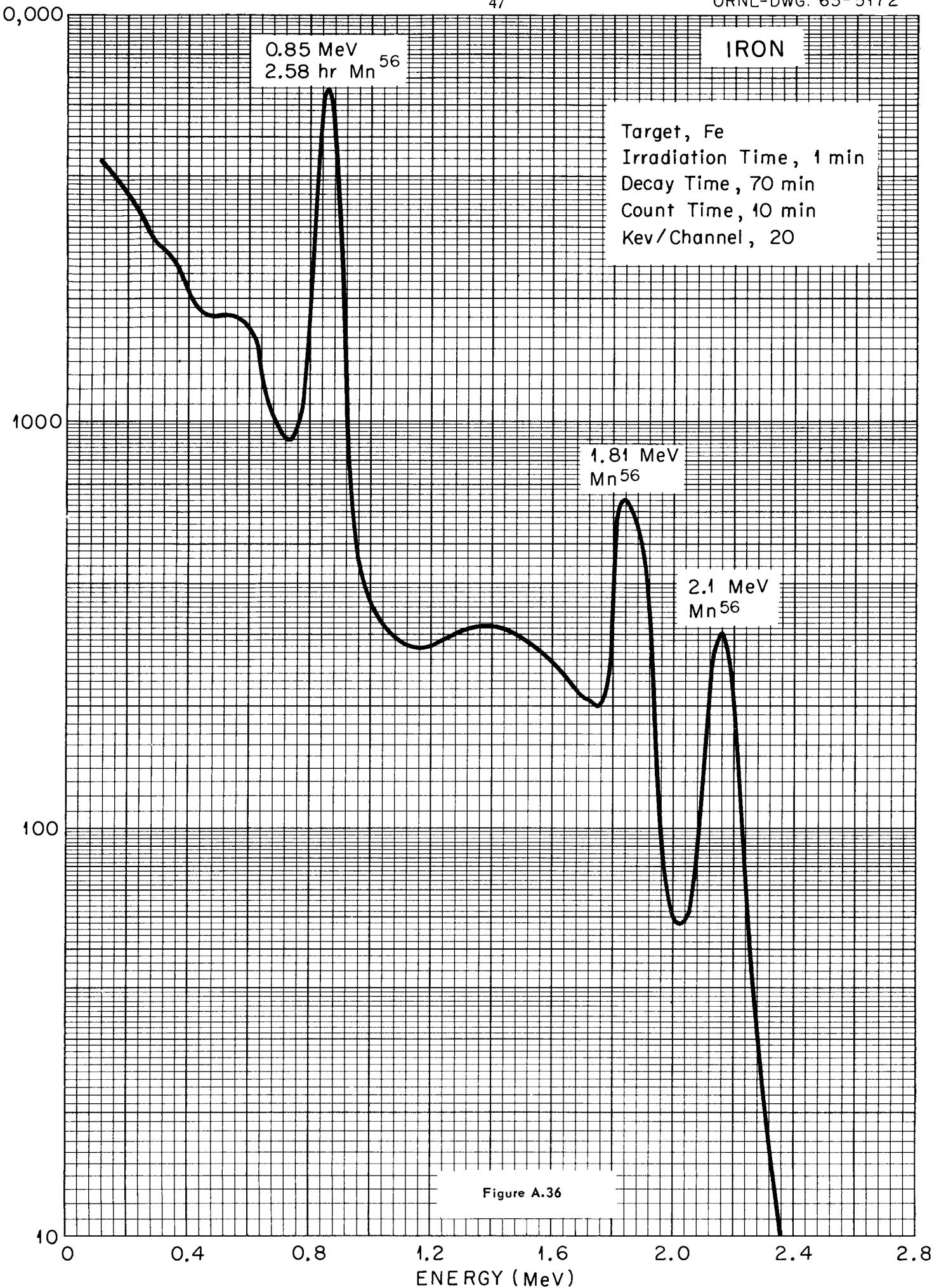
Figure A.31

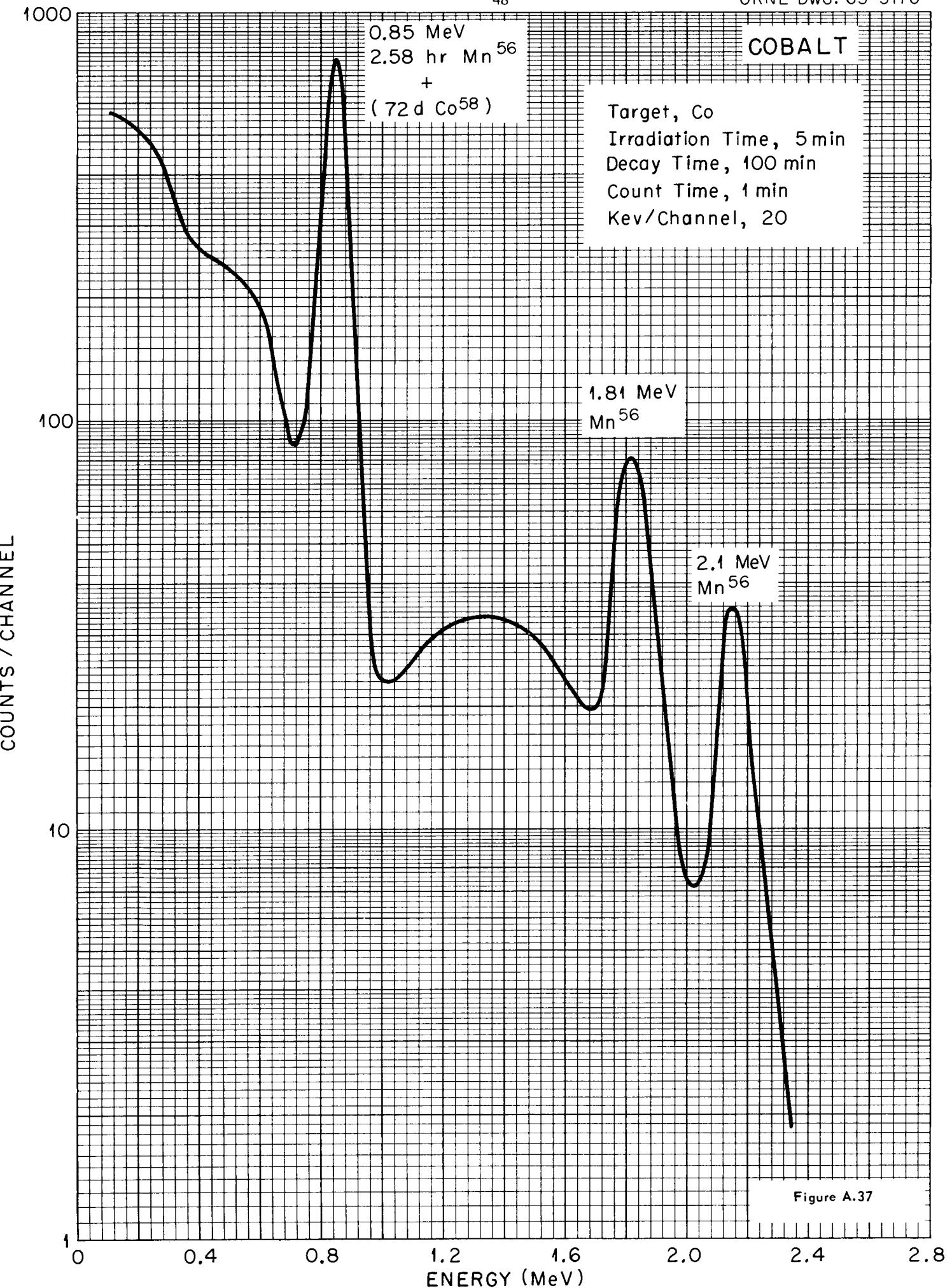


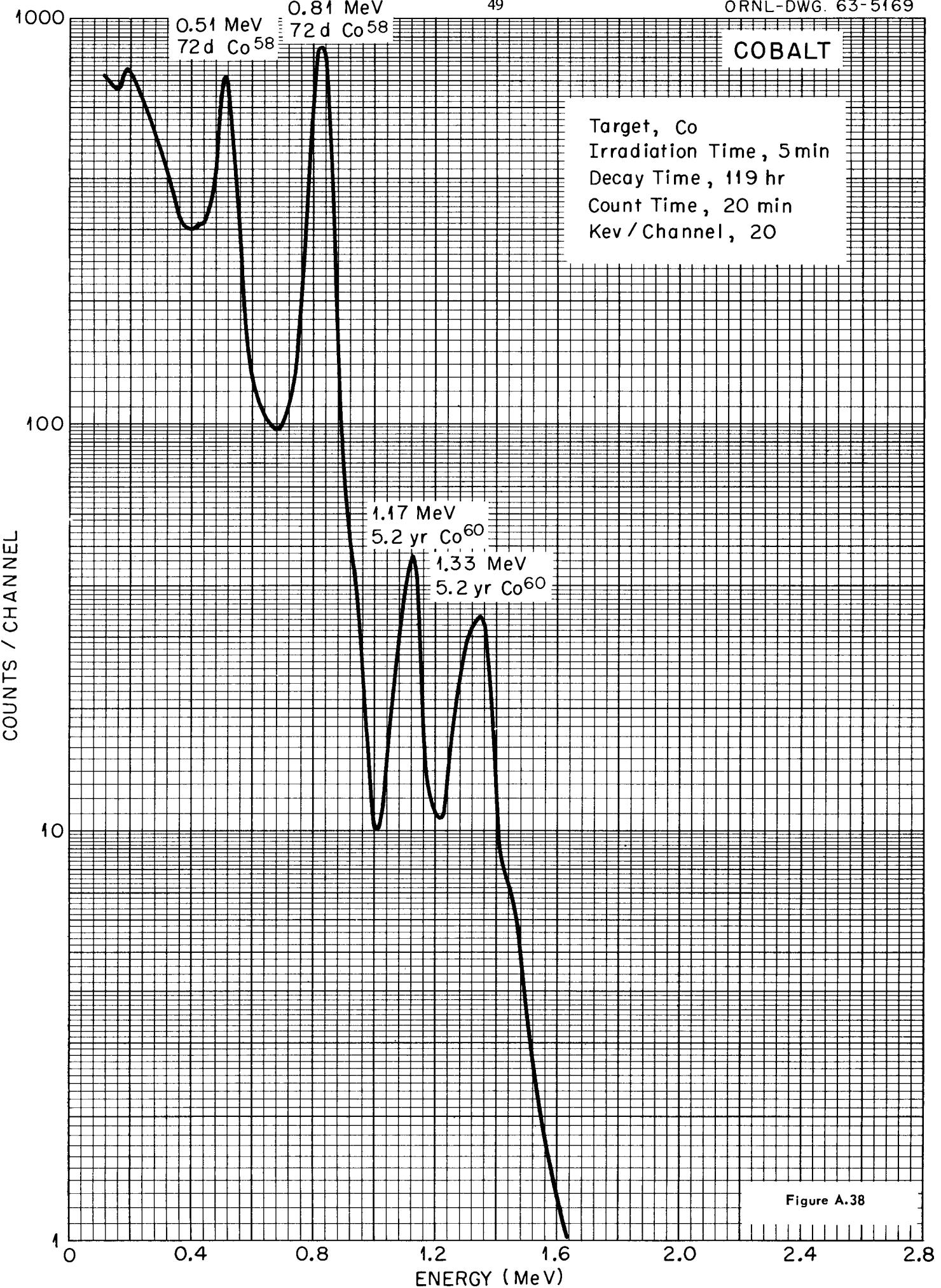












1000

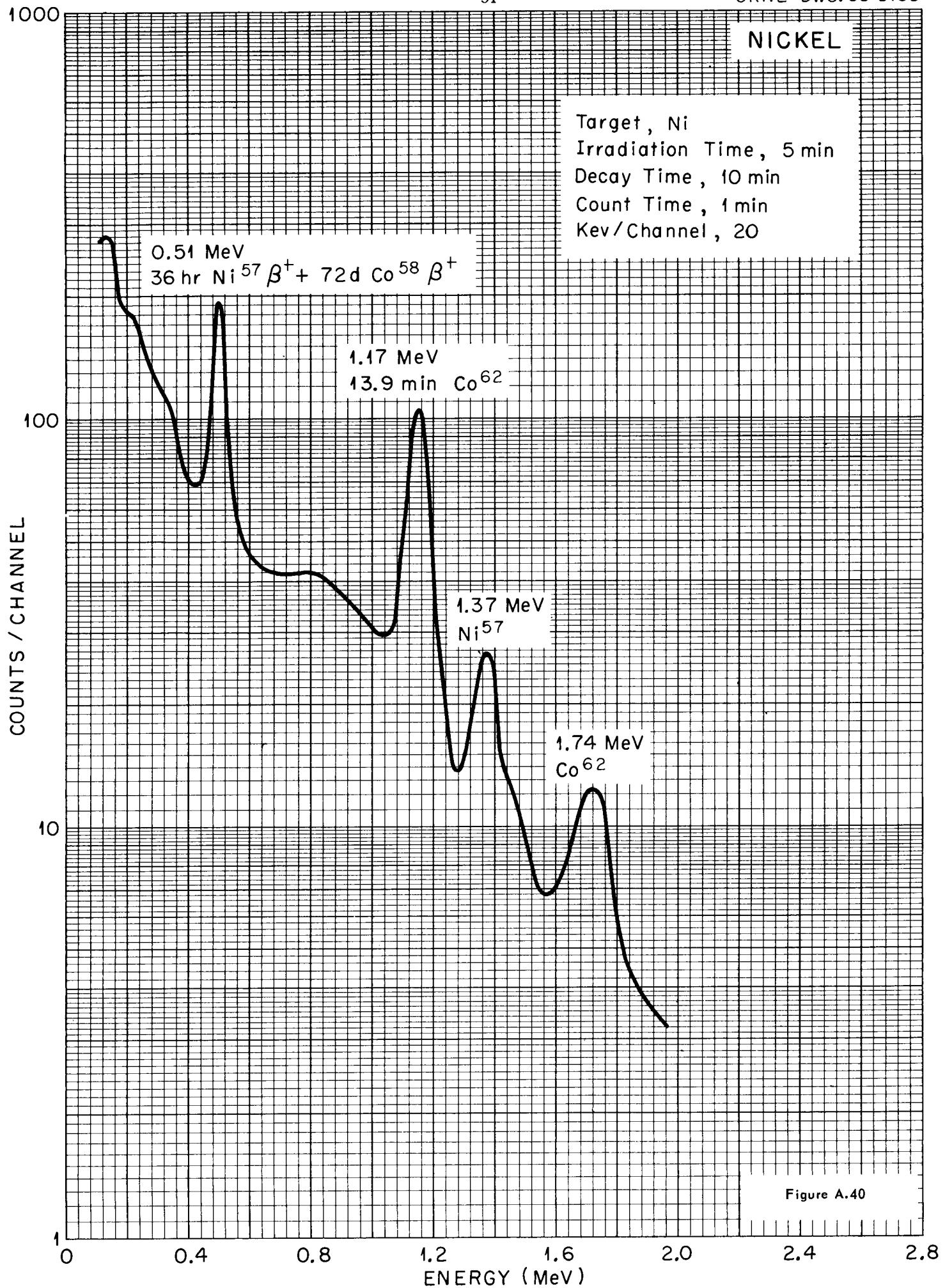
100

10

1

COUNTS / CHANNEL





NICKEL

Target, Ni
Irradiation Time, 5 min
Decay Time, 25 min
Count Time, 5 min
Kev / Channel, 20

1000

COUNTS / CHANNEL

0.51 MeV
72 d Co⁵⁸ + 36 hr Ni⁵⁷

1.17 MeV
13.9 min Co⁶²

0.82 MeV
Co⁵⁸

1.38 MeV
Co⁵⁸ + Ni⁵⁷

100

10

0

0.4

0.8

1.2

1.6

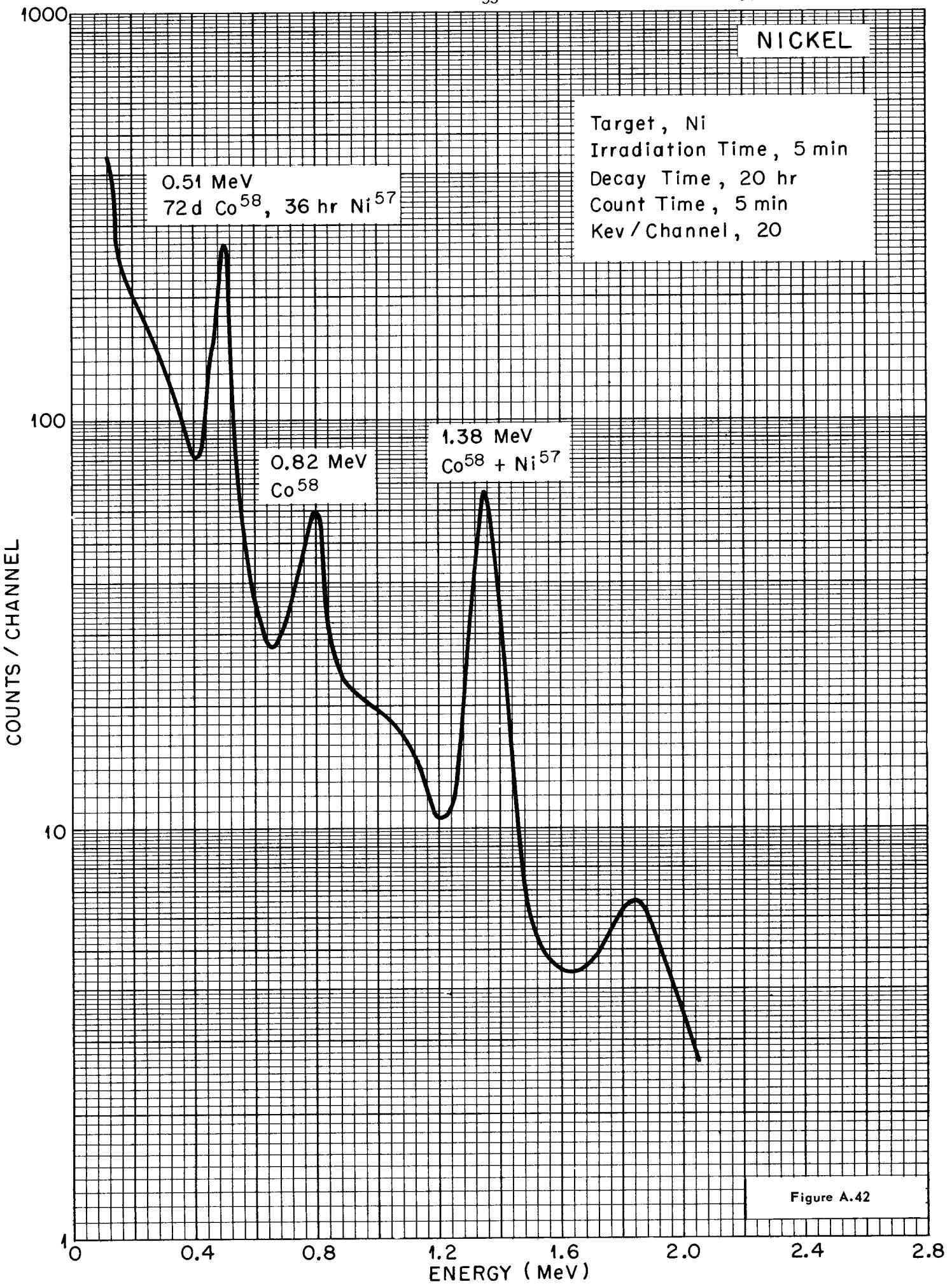
2.0

2.4

2.8

ENERGY (MeV)

Figure A.41



1000

NICKEL

Target, Ni
Irradiation Time, 5 min
Decay Time, 140 hr
Count Time, 20 min
Kev / Channel, 20

0.51 MeV
72 d Co⁵⁸ + 36 hr Ni⁵⁷

0.82 MeV
Co⁵⁸

COUNTS / CHANNEL

100

10

1

Co⁶⁰ ?

1.38 MeV
Co⁶⁰ ? + Co⁶⁰ Sum Peak ?

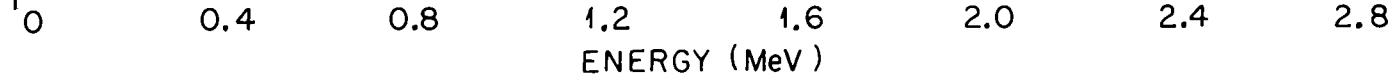


Figure A.43

100,000

COPPER

0.51 MeV
9.8 min
 $\text{Cu}^{62}\beta^+$ annihilation

Target , Cu
Irradiation Time , 20 sec
Decay Time , 30 sec
Count Time , 1 min
Kev/Channel , 20

COUNTS / CHANNEL

10,000

1000

100

ENERGY (MeV)

(X 10)

1.17 MeV
1.6 min
 Co^{62}

Figure A.44

100,000

COPPER

Target , Cu
Irradiation Time , 20 sec
Decay Time , 10 min
Count Time , 1 min
Kev / Channel , 20

0.51 MeV
 β^+ ann. radiation
 Cu^{62}

COUNTS / CHANNEL

10,000

(x 10)

1.19 MeV
 Co^{62} 13.9 min

100

0

0.4

0.8

1.2

1.6

2.0

2.4

2.8

ENERGY (MeV)

Figure A.45

COPPER

0.51 MeV
 $\text{Cu}^{64}\beta^+$ annihilation

Target, Cu
Irradiation Time, 20 min
Decay Time, 17 hr
Count Time, 20 min
Kev/Channel, 20

COUNTS / CHANNEL

10,000

1.35 MeV
 $\text{Cu}^{64}\gamma$

(X 10)

1000

100

0

0.4

0.8

1.2

1.6

2.0

2.4

2.8

ENERGY (MeV)

Figure A.46

100,000

COUNTS / CHANNEL

ZINC

0.51 MeV
38 min $Zn^{63}\beta^+$
+12 hr $Cu^{64}\beta^+$

Target, Zn
Irradiation Time, 5 min
Decay Time, 1 min
Count Time, 1 min
Kev/Channel, 20

10,000

(X 100)

1.8 MeV
 Zn^{63}

 Cu^{63}

0.96 MeV
 Zn^{63}

1.04 MeV
5 min Cu^{66}

1000

100

0

0.4

0.8

1.2

1.6

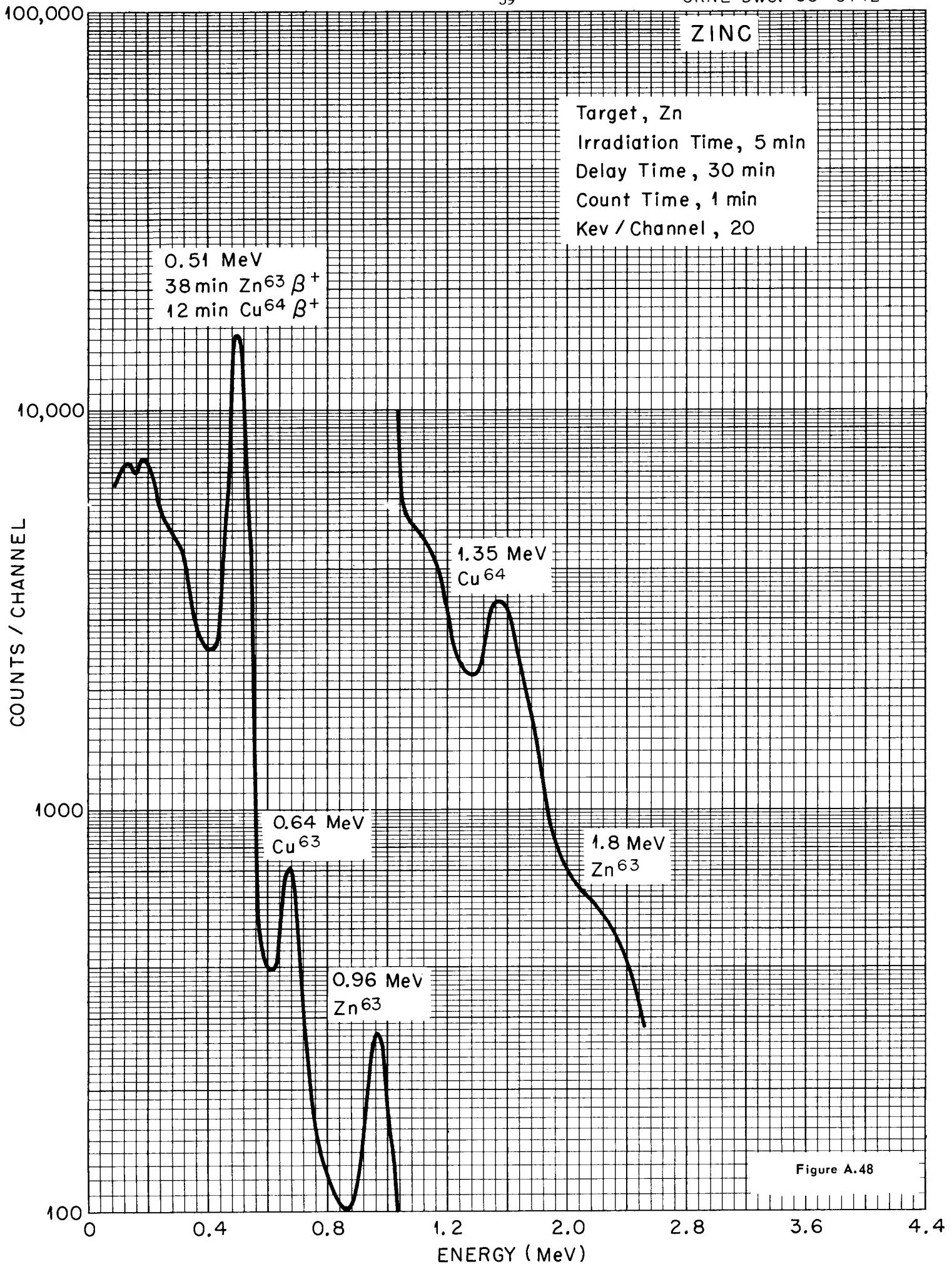
2.0

2.4

2.8

ENERGY (MeV)

Figure A.47



1000

60

ZINC

0.090 MeV
0.182 MeV
59 hr Cu⁶⁷Target, Zn
Irradiation Time, 20 min
Decay Time, 94 hr
Count Time, 20 min
Kev / Channel, 200.51 MeV
12 hr Cu⁶⁴ β^+
250 d Zn⁶⁵ β^+ 0.44 MeV
Zn⁶⁹1.12 MeV
Zn⁶⁵

COUNTS / CHANNEL

1

0 0.4 0.8 1.2 1.6 2.0 2.4 2.8

ENERGY (MeV)

Figure A.49

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