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A COMPILATION OF INFORMATION ON GAMMA-RAY SPECTRA RESULTING FROM THERMAL-NEUTRON CAPTURE

E. Troubetzkoy
H. Goldstein

OAK RIDGE NATIONAL LABORATORY
operated by
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ORNL-2904 ERRATA

"A Compilation of Information on Gamma-Ray Spectra from Thermal-Neutron Capture," E. Troubetzkoy and H. Goldstein.

Table 1, pages 5-8, should be revised as follows:

Target Nucleus	
5 B^{10}	.....Under column heading "0 - 1 Mev" change 0 to 0*.
11 Na	.....Change ref. 27 to 27^{g}.
17 Cl	.....Change ref. 27^{f} to 27^{g}.
22 Ti	.....Change ref. 57^{d} to 57.
23 V	.....Change ref. 132^{g} to 132^{f}.
50 Sn	.....Delete ref. 10.
51 Sb	.....Delete ref. 10.

On page 8, add footnote* as follows:

*The dominant $B^{10}(n,\alpha)$ reaction, resulting in a 0.478-Mev gamma ray in 93% of the reactions, is not considered a "capture" reaction and thus is not included here.

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E. Troubetzkoy and H. Goldstein
Nuclear Development Corporation of America

Date Issued

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Oak Ridge, Tennessee
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Abstract

This report consists of a compilation of thermal-neutron capture gamma-ray spectra of various nuclei which are useful for reactor shielding applications. The bulk of the data is taken from two groups: a Chalk River group, originally led by B. B. Kinsey and later by G. A. Bartholomew, and a group headed by L. V. Groshev at the Institute of Atomic Energy of the Academy of Sciences USSR. All the data are presented in tabular form for seven energy intervals from 0 to above 9 Mev. In addition, figures illustrating the appearance of the spectra are given, including continuous differential spectra for 50 nuclei and line spectra for 15 nuclei. The line spectra consist of vertical lines having heights proportional to intensities.

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Introduction and Discussion

A considerable number of compilations of capture gamma-ray spectra have by now appeared. Some, such as those by Mittelman-Liedtke[1] and Deloumé,[2] have been written primarily with the interests of reactor shields in mind. Others, such as those by Bartholomew[3] and Groshev et al.,[4] have been aimed in the main at the nuclear physicist concerned with problems of nuclear structure. The compilation presented here belongs most emphatically to the former, "shielding" class, and is in structure an outgrowth of the Mittleman-Liedtke compilation. As in that paper, the heart of the compilation is a table which is presented in Section I and lists the intensities of the capture gamma rays in seven energy intervals from 0 to above 9 Mev for various nuclei. For nuclei in which the capture spectra consist entirely of discrete lines, the main table is supplemented by tables in Section II listing the energies and intensities of the lines.

In addition to the tabular matter, figures illustrating the appearance of the spectra have been prepared. Section III, for example, contains miniature graphs showing the continuous differential spectra for some 50 nuclei. Line spectra are illustrated in Section IV for 15 nuclei, the vertical lines having a height proportional to intensity. Only the stronger lines ($>$0.05 photons per capture) are shown.

Section I also includes a detailed bibliography of the sources quoted. As the bibliography indicates, many investigators have studied capture gamma-ray spectra. The overwhelming bulk of the recent data, however, comes from only two groups. One is at Chalk River, initiated by B. B. Kinsey and

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1. P. S. Mittelman and R. A. Liedtke, Nucleonics 13, 50 (1955).
2. F. E. Deloumé, Gamma Ray Energy Spectra from Thermal Neutron Capture, APEX 407 (1958).
3. G. A. Bartholomew and L. A. Higgs, Compilation of Thermal Neutron Capture Gamma Rays, CRGP-784, Chalk River (1958).
4. L. V. Groshev, A. M. Demidov, V. N. Lutsenko and V. I. Pelikov, Atlas of the Spectra of Gamma Rays from the Radiative Capture of Thermal Neutrons, Pergamon Press, London and New York, 1959.

continued in recent years by G. A. Bartholomew. They have so far studied the spectra from about 60 elements, using mainly a magnetic pair spectrometer in the gamma-ray range from $\sim$ 3 to $\sim$12 Mev. The other group, under L. V. Groshev, is at the Institute of Atomic Energy of the Academy of Sciences USSR. Using a magnetic Compton spectrometer, they have investigated the spectra of some 50 elements in the range from 0.3 to 12 Mev, but with primary interest in the lower energy range. Both groups have issued comprehensive compilations of their results,[3,4] and almost all the data presented here are taken from these compilations. Exceptions are Cs and I data recently measured in Switzerland, and some new work of the Russian group not included in their compilation.

The energy ranges covered by the two main groups have considerable overlap. Where data are thus available from both sources, there is unfortunately often considerable discrepancy in measured intensity, at times greater than a factor of two. For rather arbitrary reasons of convenience, preference in such disagreements has always been given to the Chalk River group. The composite spectrum for a given element was constructed by joining the Russian data below 3 Mev as smoothly as possible to the Chalk River results at higher energies.

While the table in Section I is gratifyingly longer than those in the predecessor compilations, it is clear that much remains to be done. There are a few nuclei of interest to reactor applications for which no capture spectra have been reported. Notable are the fissionable isotopes such as U^{235} and Pu^{239}. Many of the uninvestigated rare earths are also of interest, e.g., germanium. In many cases the spectrum has been measured only above 3 Mev. Zirconium is a notable example where data below 3 Mev are needed.

The frequent intensity discrepancies between the two main groups active in the field clamor for resolution. These disagreements occur most often in the 3- to 4-Mev region -- where the gamma rays are the most penetrating in many shielding applications.

Finally, all the data summarized here are for the capture of thermal neutrons. Recent evidence indicates clearly that there may be substantial differences in the spectra of neutrons captured in the resonance region or

at higher energies. The changes are not likely to be large for the "continuous" spectra, but discrete transitions, especially to the ground state or its vicinity, may show significant changes. The variations are of two kinds. One is merely statistical fluctuation of the partial radiation widths from resonance to resonance. The expected variance is unity or less. The other, and possibly more serious, results from the operation of selection rules if the capturing resonances have different spin states. A prominent line in the thermal capture spectrum may be completely suppressed in capture at a resonant energy.

Experiments at other than thermal energies are quite difficult, especially with the light nuclei for which the changes are expected to be the most significant, and it is not likely that any large volume of information of such fluctuations will become available in the near future. The shield designer should, however, be aware of the possibilities of differences from the capture spectra listed here.

I. Tabulation of Integrated Spectral Intensities

Table 1 in format is similar to the table given in Ref. 1. The energy region is divided into seven intervals and the composite spectra for each element are integrated to give the total number of photons emitted, per 100 captures, in the various energy intervals. Often, capture leads to a nucleus decaying radioactively with accompanying gamma-ray emission. Where the radioactive half-life is the order of hours or less the intensity of the decay gamma rays has been added to the appropriate interval. With longer half-lives saturation of the decay activity may not always be reached in a given application, and there is no practical way to include the contribution of the decay gamma rays so as to suit all needs.

Table 1 also gives the most energetic gamma ray observed in each spectrum, and, where available, the directly measured value of the multiplicity, i.e., the number of photons per capture. The multiplicity data all stem from a rather old experiment reported in 1950 by Muehlhause.[5] Integration of the complete spectra measured subsequently often gives considerably different multiplicities. Despite the doubt thus cast upon the direct experiment, the values are none the less listed here because they occasionally help to estimate contributions from portions of the spectrum not yet measured.

A certain amount of information given in the comparable table of the Mittelman-Liedtke compilation has been omitted. For example, thermal-neutron capture cross sections and details of decay schemes have been left out, because such data are available from many sources and also tend to obsolesce at a different rate than information on capture gamma-ray spectra.

The bibliography of Table 1 lists all the primary references to significant work on the capture gamma-ray spectra of the various elements. In a few instances the original investigators revised their data somewhat for inclusion in the compilations of Refs. 3 or 4. The revised data have been used in all such cases.

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5. C. O. Muehlhause, Phys. Rev. 79, 277 (1950).

Table 1. Tabulation of Gamma-Ray Spectra from Thermal-Neutron Capture

Target Nucleus	σ_a	Photons/100 Captures 0 - 1 Mev	1 - 2 Mev	2 - 3 Mev	3 - 5 Mev	5 - 7 Mev	7 - 9 Mev	>9 Mev	Highest Energy Gamma Ray (Mev)	Average Number of Photons Per Capture[a]	References[b]
1 H	.332	0	0	100	0	0	0	0	2.230		3, 16, 36, 65
1 D	[illegible]	0	0	0	0	100	0	0	6.244		43
2 He	.007										
3 Li	71.					~40	~60	0	7.26		7
4 Be	.01	0	0	0	54	73	0	0	6.80		27, 45, 50, 54
5 B^{10}	755	0	0	0	>110	>28	≥6	0.8	11.43		7
6 C	[illegible]	0	0	0	100	0	0	0	4.95	1.3	30, 44, 45, 50
7 N^{14}	1.88				>54	≥11	15	12	10.833		7, 30, 50
8 O	2×10^{-4}										
9 F	.01		>100[c]			≥111	0	0	6.600		19, 30
10 Ne	<2.8										
11 Na	.53	>96	127	187	70	31	0	0	6.41	<2	10, 17, 18, 27, 30, 51[d], 61, 64
12 Mg	.07			>28	>72	10	3.3	0.57	11.089		17, 19, 30, 46, 59
13 Al	.241	>236	195[e]	69	62	19	19	0	7.724	~2	10, 17, 28, 34, 37, 45, 49, 51[d], 53
14 Si	.16	>100	63	30	89	11	4.1	0.1	10.59		2, 17, 45, 49, 53, 59
15 P	.20	>290	97	55	98	27	7.2	0	7.94		10, 17, 30, 53[d], 59
16 S	.52	> 70	32	72	70	44	6.5	0	8.64		10, 17, 27, 49, 53[d], 59, 78, 79
17 Cl	33.8	> 49	85	41	47	55	24	0	8.55	3.1	10, 17, 27, 30, 34, 37, 38, 53[d], 58, 61, 68, 69, 74, 78, 79, 80
18 A	.66										
19 K	2.07	>100	81	57	106	37	4.7	0	9.36		3, 10, 11, 12, 17, 38, 53[d], 58
20 Ca	.44	> 14	191	77	85	64	1.8	0	7.83		3, 10, 17, 38, 49, 53[d], 78, 79
21 Sc	24	> 52	59	38	65	29	12	0	8.85		10, 14[d], 30, 38
22 Ti	5.8	> 54	160	16	24	78	1.3	0.2	10.47		2, 9, 17, 38, 57, 63, 70, 72, 78, 79
23 V	5	>83	132[f]	11.4	21	67	16	0	7.98	2.5	10, 14[d], 15[d], 17, 28, 38, 70
24 Cr	3.1	>85	41	21	12	23	39	6.4	9.716	>2	10, 17, 30, 38, 48[d], 70, 78, 79
25 Mn	13.2	>125[h]	91[i]	60[j]	50	34	17	0	7.261	2.6	10, 14[d], 28, 35, 37, 38, 58, 66, 70
26 Fe	2.62	>75	60	27	23	25	38	2.1	10.16	1.7	2, 10, 34, 35, 37, 38, 48[d], 58, 60, 70, 78, 79
27 Co	38	>61	26	17	42	52	8.5	0	7.486		10, 14[d], 26, 28, 35, 38, 58, 68, 70

Table 1 (continued)

Target Nucleus	Photons/100 Captures 0 - 1 Mev	1 - 2 Mev	2 - 3 Mev	3 - 5 Mev	5 - 7 Mev	7 - 9 Mev	>9 Mev	Highest Energy Gamma Ray (Mev)	Average Number of Photons Per Capture[a]	References[b]
28 Ni 4.6	>84	40	23	23	34	62	0.8	8.997		3, 10, 17, 38, 48[d], 78, 79
29 Cu	>68	47	26	30	27	43	0	7.914	2.6	10, 14[d], 30, 58, 60, 70, 76, 78, 79
30 Zn	>156	93	67	48	29	16	1	9.51		10, 48[d]
31 Ga				57	34	0.2	0	7.73		19
32 Ge										
33 As				47	22	1	0	7.30	2.7	13
34 Se				65	27	9	1.7	10.483		47
35 Br				79	41	6.4	0	7.879		19, 34
36 Kr										
37 Rb										
38 Sr				69	51	14	0.1	9.22		47
39 Y	>71	23	6	50	59	0	0	6.850		8
40 Zr				113	35	4	0	8.66		47
41 Nb				54	14	0.4	0	7.19	2.6	13
42 Mo	>137	>18		84	26	3	0.03	9.15		41, 47
43 Tc										
44 Ru										
45 Rh	>91	99	61	38	10	0	0	6.792		13, 23, 24, 26, 30, 38
46 Pd										
47 Ag	>92	87	64	70	17	0.5	0	7.27	2.9	13, 23, 24, 25, 30, 35, 41, 58, 76
48 Cd	>135	92	96	73	17	1	0.1	9.046	4.1	1[f], 4, 17, 23, 30, 31, 34, 35, 38, 40, 47, 58, 61, 62, 64, 67, 69, 77, 80
49 In	>102[k]	197[ℓ]	78[m]	36	4	0	0	5.86	3.3	13, 23, 30, 35, 38, 76
50 Sn	>216	153	67	139	33	4	0.4	9.35		[illegible], 32, 47
51 Sb	150	99	58	36	12	0	0	6.80		[illegible], 13, 23, 24, 25, 32
52 Te	>58									23, 24, 38, 41
53 I	>30			97	22	0	0	6.71		5, 6, 23, 24, 26, 55, 58, 70
54 Xe										
55 Cs	>46			61	25	0	0	6.702		5, 6, 41, 55
56 Ba				75	14	1.4	0.1	9.23		47

Table 1 (continued)

Target Nucleus	Photons/100 Captures 0 - 1 Mev	1 - 2 Mev	2 - 3 Mev	3 - 5 Mev	5 - 7 Mev	7 - 9 Mev	> 9 Mev	Highest Energy Gamma Ray (Mev)	Average Number of Photons Per Capture[a]	References[b]
57 La	> 21.7	8.2		> 35	> 12.5	0	0	5.045		30, 34, 38
58 Ce										
59 Pr				34	8	0	0	5.83		13
60 Nd	>105									21, 41
61 Pm										
62 Sm	> 167	150	109	45	5	1	0	7.89	5.6	1[f], 23, 26, 30, 31, 40, 47, 58
63 Eu	106	153	109	56	6.5	0	0	6.05		23, 30, 75
64 Ga	194	117	100	23	34	.3	0	7.33	3.9	22, 23, 24, 20, 31, 47, 56, 58, 75
65 Tb	> 7									23
66 Dy	90	102	106	43	10	0	0	5.87		23, 24, 29, 31, 40, 75
67 Ho		98	77	49	8	0	0	6.1		23, 24, 33, 75
68 Er	225	145	133	103	14	0	0	6.680		23, 29, 75
69 Tm		91	73	55	10	0	0	6.5		23, 24, 33, 75
70 Yb										
71 Lu										
72 Hf	>137	137	85	52	12	0.5	0	7.62		19, 23, 29, 75
73 Ta	>137	99	66	55	5	0	0	6.04		9, 13, 23, 24, 29, 75
74 W	> 68	82	59	53	15	.5	0	7.42		30, 34, 47, 58
75 Re	124	88	62	51	10.5	0	0	6.14		23, 30
76 Os										
77 Ir	98	85	58	51	19.6	0	0	6.088		5, 6, 23, 30, 55, 58
78 Pt	> 109	92	64	45	15	1	0	7.920		23, 24, 27, 30
79 Au	> 100	69	33	68	38	.1	0	6.494	3.5	13, 23, 26, 30, 34, 39, 58, 70, 71
80 Hg	> 94	122	55	86	41	0	0	6.446	3.3	1[f], 26, 30, 34, 47, 58, 73
81 Tl				76	62	0	0	6.54		13
82 Pb	0	0	0	0	7	93	0	7.38		1, 52, 60
83 Bi	0	0	0	100	0	0	0	4.17		30, 52, 55
84 Po										

Table 1 (continued)

Target Nucleus	Photons/100 Captures 0 - 1 Mev	1 - 2 Mev	2 - 3 Mev	3 - 5 Mev	5 - 7 Mev	7 - 9 Mev	>9 Mev	Highest Energy Gamma Ray (Mev)	Average Number of Photons Per Capture[a]	References[b]
85 At										
86 Em										
87 Fr										
88 Ra										
89 Ac										
90 Th	>118	140	64	17	0	0	4.92			18, 30
91 Pa										
92 U^{238}	254	178	91	34	0	0	4.062			20, 42
93 Np										
94 Pu										

a. All values in this column are taken from C. O. Muehlhause, Phys. Rev. 79, 277 (1950). They may therefore differ from the multiplicities deduced from the spectra directly.
b. See bibliography. The Chalk River compilation (Ref. 10) and Soviet compilation (Ref. 30) are referred to only in those cases when either new or revised data are reported there.
c. Includes a 100%, 1.63-Mev gamma ray in Ne^{20} following 11s decay of F^{20}.
d. The data have been revised by the authors; revised data are given in Ref. 10.
e. Includes a 100%, 1.78-Mev gamma ray in Si^{28} following 2.3m decay of Al^{28}.
f. Includes a 99.75%, 1.43-Mev gamma ray in Cr^{52} following 3.8m decay of V^{52}.
g. The data have been revised by the authors; revised data are given in Ref. 30.
h. Includes a 99%, 0.85-Mev gamma ray in Fe^{56} following 2.6h decay of Mn^{56}.
i. Includes a 23%, 1.80-Mev gamma ray in Fe^{56} following 2.6h decay of Mn^{56}.
j. Includes a 15%, 2.13-Mev gamma ray in Fe^{56} following 2.6h decay of Mn^{56}.
k. Includes a 5%, 0.41-Mev and an 8%, 0.82-Mev gamma ray in Sn^{116} following 54m decay of In^{116}.
l. Includes a 36%, 1.09-Mev and a 63%, 1.29-Mev gamma ray in Sn^{116} following 54m decay of In^{116}.
m. Includes an 11%, 2.12-Mev gamma ray in Sn^{116} following 54m decay of In^{116}.

* The dominant $B^{10}(n,d)$ reaction, resulting in a 0.478-Mev gamma ray in 93 % of the reactions is not considered a "capture" reaction and thus is not included here!

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II. Tabulation of Line Spectra

Table 2 lists the energies and intensities of the discrete gamma rays emitted where the capture spectra consist for the most part of resolved lines. The two main sources of information, the Chalk River and Russian groups, usually agree well enough, for shielding purposes, on the energy of the lines. However, the intensities they report often disagree by large factors. Preference has always been given to the values published by the Chalk River group. However, the existence of such discrepancies for reasonably intense lines ($>$ 5 photons per 100 captures) may have significant effect on some practical applications. Hence asterisks have been put on lines of this intensity where the disagreement between the different groups is a factor of two or more. In some cases investigations other than those in the two main groups have shown lines at very low energies not elsewhere reported; these are included in Table 2.

Table 2. Energies and Intensities of Discrete Gamma Rays Resulting from Thermal-Neutron Capture

E (Mev)	I (Photons/100 Captures)
$_4Be$	
3.41	50
6.797	75
$_5B$	
11.43	0.8
8.91	6
6.98	18
6.74	10
4.73	30
4.47	80
$_6C$	
3.68	30
4.948	70
$_7N$	
10.833	11
9.152	1
9.03	0.2
8.54	0.2
8.313	4
7.305	9
7.164	≥ 0.8
6.323	17
$_7N$ (continued)	
5.559	14
5.530	18
5.293	35
5.263	22
4.497	16
3.669	17
3.520	15
3.267	$\doteq 6$
$_9F$	
6.600	30
6.019	16
5.54	24
5.28	27
5.10	14
4.50	15
1.36	40
$_{11}Na$	
6.96	<0.1
6.41	13
5.61	5
5.13	1
4.90	1.2

Table 2 (continued)

E (Mev)	I (Photons/100 Captures)	E (Mev)	I (Photons/100 Captures)
$_{11}Na$ (continued)		$_{12}Mg$	
4.70	0.9	11.089	0.03
4.50	2.1	10.08	0.04
4.30	0.5	9.282	0.5
4.18	2.1	8.93	0.06
3.96	8*	8.55	0.06
3.85	5	8.149	3
3.68	1.3	7.36	0.06
3.60	7	7.16	0.11
3.56	8	6.735	1.2
3.30	5	6.440	0.9
3.10	9.5	6.358	2.4
2.84	7	5.76	0.6
2.68	8.5	5.51	0.6
2.52	21	5.442	3
2.41	10.5	5.05	1.7
2.21	7.5	4.93	2.7
2.020	11.5	4.77	0.6
1.95	4	4.21	2.5
1.87	5.5	3.918	47
1.66	7.5	3.552	8
1.35	6.5	3.408	5
0.875	44	3.290	9
0.790	4.3	3.054	9
0.710	5	2.816	24
0.475	74	2.43	5
		1.83	11
		1.07	13

Table 2 (continued)

E (Mev)	I (Photons/100 Captures)
$_{13}Al$	
7.724	20
7.34	0.45
6.98	0.5
6.77	0.8
6.61	0.23
6.50	0.3
6.33	0.9
6.22	0.3
6.13	1.5
6.01	0.44
5.89	0.5
5.78	0.8
5.60	1.2
5.41	1.2
5.32	0.55
5.21	1.5
5.14	3.9
4.94	0.8
4.79	4.3
4.66	2.5
4.45	1.4
4.29	4.3
4.16	3
4.06	2
3.88	4.4

E (Mev)	(Photons/100 Captures)
$_{13}Al$ (continued)	
3.80	1.3
3.62	2.5
3.46	1.5
3.29	2
3.02	10
2.96	8*
2.84	4.6
2.61	5
2.28	5.1
2.12	3
1.78[a]	100
0.97	10
$_{14}Si$	
10.601	0.2
8.468	2
7.79	0.8
7.36	0.7
7.18	8
6.88	0.4
6.76	1.5
6.40	11
6.11	2.5
5.70	1
5.52	1

a. Al^{28} beta-decay line.

Table 2 (continued)

E (Mev)	I (Photons/100 Captures)
$_{14}Si$ (continued)	
5.242	0.8
5.11	8
4.933	75*
4.60	2.5
4.20	10
3.976	4.2
3.8	3
3.667	3.2
3.540	60
2.65	11
2.10	12.8
1.95	3.4
1.7	3
1.5	3
1.28	16
$_{15}P$	
7.94	0.3
7.85	0.9
7.62	1
7.42	4
6.76	14
6.33	0.6
6.14	0.9
6.02	1

E (Mev)	I (Photons/100 Captures)
$_{15}P$ (continued)	
5.71	3
5.41	1
5.27	5.5
4.92	3
4.68	17
4.49	3
4.38	8*
4.20	5*
3.92	16
3.55	16*
3.28	8*
3.04	5
2.93	2.2
2.87	3.4
2.60	3.6
2.46	2.7
2.10	13
1.95	4.5
1.72	5
1.60	3
1.07	20
0.93	8
0.51	28
0.43	70

Table 2 (continued)

E (Mev)	I (Photons/100 Captures)	E (Mev)	I (Photons/100 Captures)
$_{16}S$		$_{17}Cl$	
8.64	1.2	7.77	7
7.78	1.6	7.42	6*
7.42	0.3	6.98	2
7.19	0.25	6.62	9
6.64	0.25	6.12	14
5.97	0.8	5.72	6
5.43	60	5.51	3
5.03	2.7	5.01	9
4.84	11	4.46	5*
4.60	2.7	4.06	7*
4.38	7	3.62	4
3.69	4	3.40	3.6
3.36	7	3.08	4.5
3.21	20	3.02	3.5
3.10	2	2.88	9.5
2.94	20	2.83	2
2.82	4	2.71	2
2.70	2	2.51	1
2.55	4.4	1.950	29
2.415	30	1.72	1
2.29	5	1.67	1
2.00	3	1.60	2.4
1.52	1	1.165	36
0.84	47	0.79	23
		0.51	$\lesssim$ 26

Table 2 (continued)

E (Mev)	I (Photons/100 Captures)
$_{19}K$	
9.39	0.08
8.45	0.1
7.757	4
7.34	0.4
6.994	2
6.31	0.4
5.740 }	12
5.66 }	
5.38	6
5.06	4
4.39	9
4.18	7
3.92	6
3.67	9
3.55	2
3.40	4
3.15	1.5
3.05	3
2.75	4
2.60	4
2.55	4
2.42	2
2.37	3
2.30	3
2.06	9

E (Mev)	I (Photons/100 Captures)
$_{19}K$ (continued)	
2.02	7
1.95	4
1.85	3
1.75	3
1.61	13
1.51	5
1.40	2
1.27	2
1.18	7
0.90	2
0.77	26
0.625	3
$_{20}Ca$	
7.83	0.4
7.43	0.6
6.42	40
5.89	6*
5.66	3
5.49	4
4.95	5
4.76	4
4.45	18
3.62	10
2.810	$\gtrsim 3.6$
2.660	$\gtrsim 2.0$

Table 2 (continued)

E (Mev)	I (Photons/100 Captures)
$_{20}Ca$ (continued)	
2.004	12.7
1.944	39
1.844	6.4
1.790	≳3.6
1.48	≳3.2
1.2	≳4.8
0.532	≳5
0.463	≳9
$_{22}Ti$	
10.621	0.03
9.376	0.08
9.189	0.08
8.342	0.05
8.252	0.17
7.996	0.08
7.844	0.03
7.736	0.03
7.628	0.08
7.55	0.04
7.386	0.3
7.319	0.4
7.149	0.3
6.996	0.3
6.947	0.17

E (Mev)	I (Photons/100 Captures)
$_{22}Ti$ (continued)	
6.753	41
6.550	5.9
6.413	29
6.07	0.17
5.98	0.08
5.89	0.17
5.644	0.5
5.460	0.4
4.957	3.4
4.871	5.0
4.706	1.3
4.38	0.3
4.22	0.3
3.916	1.4
3.733	1.8
3.55	0.7
3.460	1.1
3.23	0.7
3.028	1.8
2.95	1.5
2.730	1.5
2.165	0.6
1.793	1.7
1.760	5
1.589	5

Table 2 (continued)

(Mev)	I (Photons/100 Captures)
$_{22}Ti$ (continued)	
1.583	5
1.497	4
1.438	1.4
1.378	87
1.320	0.5
1.119	1.5
0.984	1.6
0.3408	31
0.2530	0.35
0.2348	0.8
0.2260	0.45
0.2160	0.5
0.2040	0.7
0.1860	0.8
0.1805	0.8
$_{23}V$	
7.98	0.2
7.83	0.6
7.67	0.13
7.305	7
7.154	10
6.868	8
6.62	0.24
6.508	16
5.879	2

E (Mev)	I (Photons/100 Captures)
$_{23}V$ (continued)	
5.744	7
5.511	8
5.21	5
4.98	2
4.85	1.6
4.45	2
4.15	3
3.73	2.4
3.59	2.4
3.36	3
3.05	0.4
2.85	0.6
2.44	1
2.30	0.5
2.13	3.4
2.02	1.1
1.93	1.6
1.77	3.8
1.65	1.3
1.55	5.8
1.434[b]	100
0.84	6
0.79	3
0.652	9.0
0.42	7

b. V^{52} beta decay.

Table 2 (continued)

E (Mev)	I (Photons/100 Captures)
$_{26}Fe$	
10.16	0.06
9.298	2
8.872	0.3
8.345	0.6
7.639	29
7.285	3
6.369	0.3
6.015	6
5.914	6
5.51	0.6
4.968	0.6
4.81	1
4.44	1
4.21	2
3.86	0.7
3.43	2
3.725	1.1
3.552	1.4
3.43	3.9
3.24	2.9
3.146	2.1
2.837	2.1
2.730	2.9
2.672	1
2.143	1.4
1.802	2.3

E (Mev)	I (Photons/100 Captures)
$_{26}Fe$ (continued)	
1.72	6.4
1.626	6.1
1.53	1.9
1.236	1.5
0.454	4.1
0.364	6.7
0.313	3.2
$_{24}Cr$	
9.716	5
8.881	14
8.499	5
7.929	6
7.67	0.2
7.54	0.2
7.364	3
7.21	0.2
7.097	2.4
6.872	0.5
6.644	3
6.358	0.4
6.28	0.9
6.12	0.8
6.00	1
5.61	2
5.26	1

Table 2 (continued)

E (Mev)	I (Photons/100 Captures)
$_{24}Cr$ (continued)	
4.83	0.8
3.72	2
3.02	2
2.32	2
1.88	2
1.75	2
0.840	20
0.75	3
0.52	2
$_{28}Ni$	
8.997	26
8.532	11
8.119	2.5
7.817	6
7.528	4
7.22	0.4
7.05	0.6
6.839	9
6.58	2
6.34	1
6.10	1.3
5.99	0.4
5.82	3
5.70	0.6
5.31	1.3

E (Mev)	I (Photons/100 Captures)
$_{28}Ni$ (continued)	
4.20	≥ 0.7
4.05	≥ 1
3.67	≥ 1
3.17	≥ 1
3.03	≥ 1
2.15	≥ 2
1.74	≥ 1
1.53	≥ 1
1.10	≥ 2
0.467	≥ 6
0.436	≥ 3
0.330	≥ 7
0.280	≥ 3.5
ϵ $_{29}Cu$	η
7.914	.17
7.634	8
7.296	5
7.16	2
7.01	2
6.69	3
6.41	1
6.05	1
5.75	0.2
5.64	0.6
5.43	1

Table 2 (continued)

E (Mev)	I (Photons/100 Captures)
$_{29}Cu$ (continued)	
5.31	1
5.18	0.6
5.07	0.5
4.75	0.3
4.67	0.7
4.51	1.1
4.36	1.5
3.44	0.5
3.11	0.7
2.65	0.7
2.52	0.8
0.276	20
0.205	4
0.180	6
0.155	19
0.092	2.3
$_{39}Y$	
6.850	0.3
6.646	0.8
6.590	0.8
6.072	45
5.631	2
4.108	9
2.800	0.9
2.270	1
1.382	3

E (Mev)	I (Photons/100 Captures)
$_{39}Y$ (continued)	
1.335	1.8
1.281	1.6
1.240	2.9
1.215	1.5
0.7767	39
0.5747	10
0.247	0.3
0.2024	9
$_{82}Pb$	
7.380	1
6.734	0.077
$_{83}Bi$	
4.170	100
$_{U}238$	
4.062	7
3.662	2
3.576	2
0.637	8
0.628	8
0.611	2
0.589	6
0.577	8
0.552	10
0.540	9

III. Graphs of Differential Capture Spectra

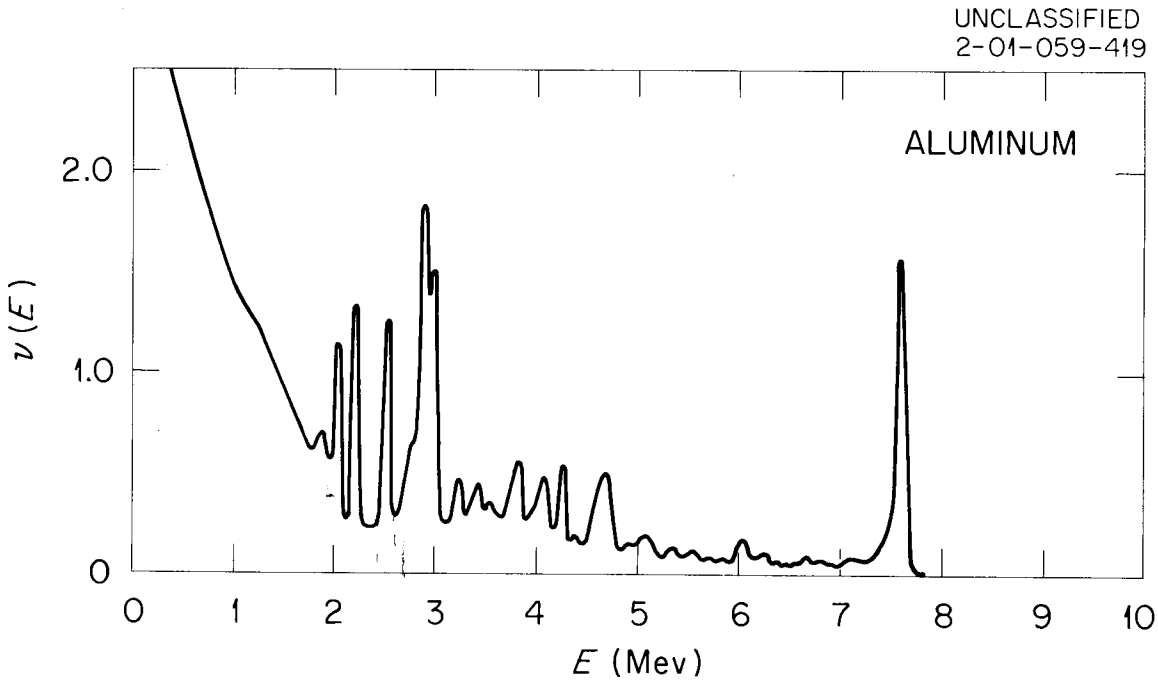
Figures 1 through 50 illustrate the appearance of the observed capture spectra containing a continuous component. Intensity, in photons per Mev and per capture, is plotted against gamma-ray energy in Mev. It is to be emphasized that the purpose of the graphs is to provide the reader with a general idea of the character of the spectra; the plots should not be used to obtain quantitative information. One reason is that the final reproduced size of the figures is too small for accurate reading. Because of this very large reduction, it is often impossible to reproduce all the structure that has been observed in the spectra. In drawing the curves, many of the narrow, closely spaced lines have been fused together by eye, as if the spectrometers were of much poorer resolution than in actuality. Bumps on the side of prominent lines are at times used to indicate weaker narrow lines often well resolved in the experiment. In the 3- to 4-Mev region where the two groups provided overlapping data, discrepancies had to be resolved in an often arbitrary manner so as to impose a smooth transition from the Russian data below 3 Mev to the Chalk River results at higher energies. The instruments used by the two groups are not the same and produce different line shapes. The lines observed by the Russian group are nearly symmetrical, while the lines reported from Chalk River have a characteristically unsymmetrical shape, with a steep drop above the maximum, and a long tail below. Being composites, the plotted spectra show both shapes in different energy regions of the curve.

Many observed spectra have prominent annihilation radiation lines when the decay products are positron emitters. These have been omitted as not part of the capture spectra per se. Radioactive decay gamma-ray lines are also generally omitted although the practice may not have been completely consistent. Occasionally a spectrum has some low-energy lines so intense that when reproduced on any reasonable scale the rest of the spectrum would be completely dwarfed. In such cases the peaks of the lines are not shown, but the line is simply stopped at the top frame line of the plot.

It is believed that Tables 1 and 2 contain all the quantitative information needed for most practical applications. If more quantitative detail is needed on the capture spectra, the reader is advised to refer to the original data in the bibliography of Table 1 or in Refs. 3 and 4.

The data shown in Figs. 1 through 50 are for the following materials:

Material	Fig. No.	Pg. No.	Material	Fig. No.	Pg. No.
Aluminum	1	28	Cadmium	26	45
Silicon	2	28	Indium	27	46
Phosphorus	3	29	Tin	28	47
Potassium	4	30	Antimony	29	48
Calcium	5	31	Iodine	30	49
Scandium	6	32	Cesium	31	49
Titanium	7	32	Barium	32	50
Vanadium	8	33	Paraseodymium	33	50
Chromium	9	34	Samarium	34	51
Manganese	10	35	Europium	35	52
Iron	11	35	Gadolinium	36	53
Cobalt	12	36	Dysprosium Oxide	37	54
Nickel	13	37	Holmium	38	55
Copper	14	37	Erbium Oxide	39	56
Zinc	15	38	Hafnium	40	57
Gallium	16	39	Tantalum	41	58
Arsenic	17	39	Tungsten	42	59
Selenium	18	40	Rhenium	43	60
Bromine	19	40	Iridium	44	60
Strontium	20	41	Platinum	45	61
Zirconium	21	41	Gold	46	62
Niobium	22	42	Mercury	47	63
Molybdenum	23	42	Thallium	48	64
Rhodium	24	43	Thorium	49	65
Silver	25	44	U^{238}	50	66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ν(E)
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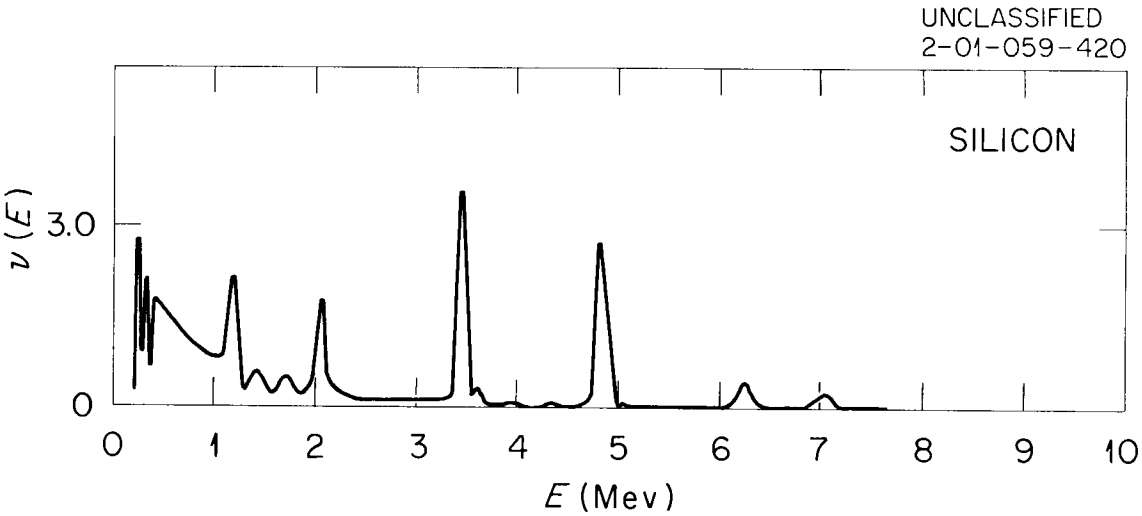
E (Mev)

Fig. 1.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E (Mev)

Fig. 2.

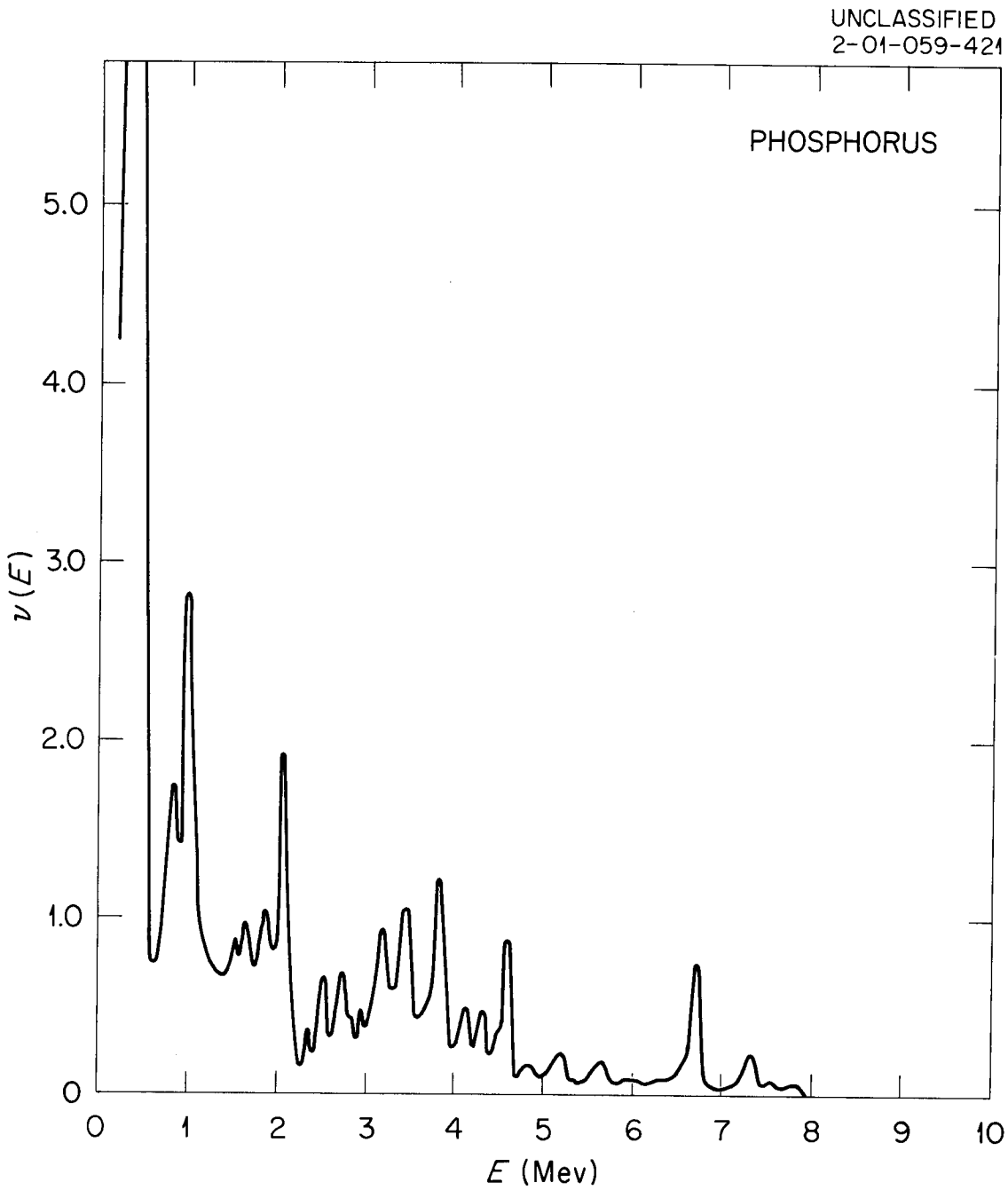
UNCLASSIFIED
2-01-059-421
PHOSPHORUS
5.0
4.0
3.0
2.0
1.0
0
ν(E)
0
1
2
3
4
5
6
7
8
9
10
E (Mev)

Fig. 3.

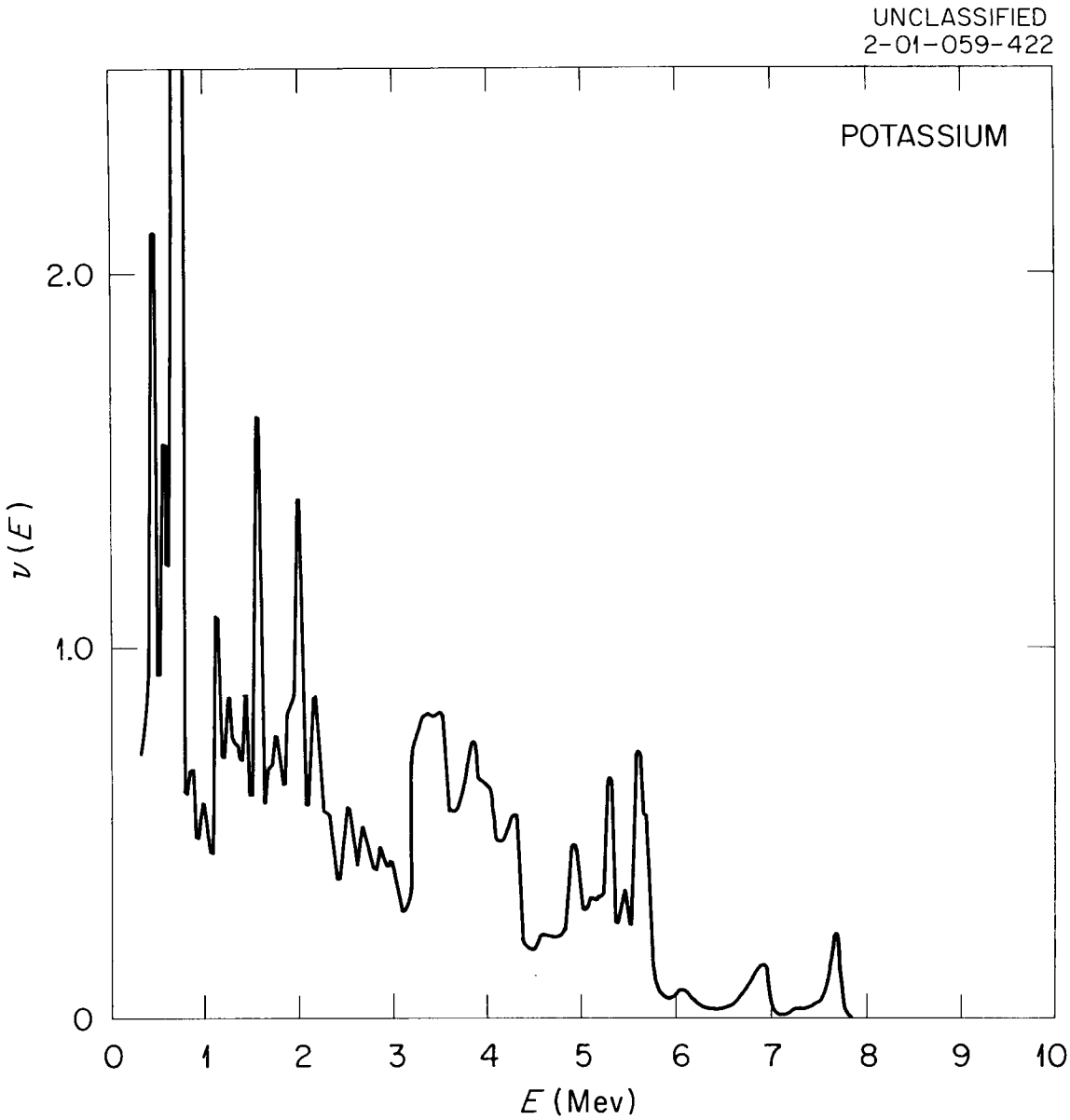
UNCLASSIFIED
2-01-059-422
POTASSIUM
2.0
1.0
0
ν(E)
0
1
2
3
4
5
6
7
8
9
10
E (Mev)

Fig. 4.

UNCLASSIFIED
2-01-059-423

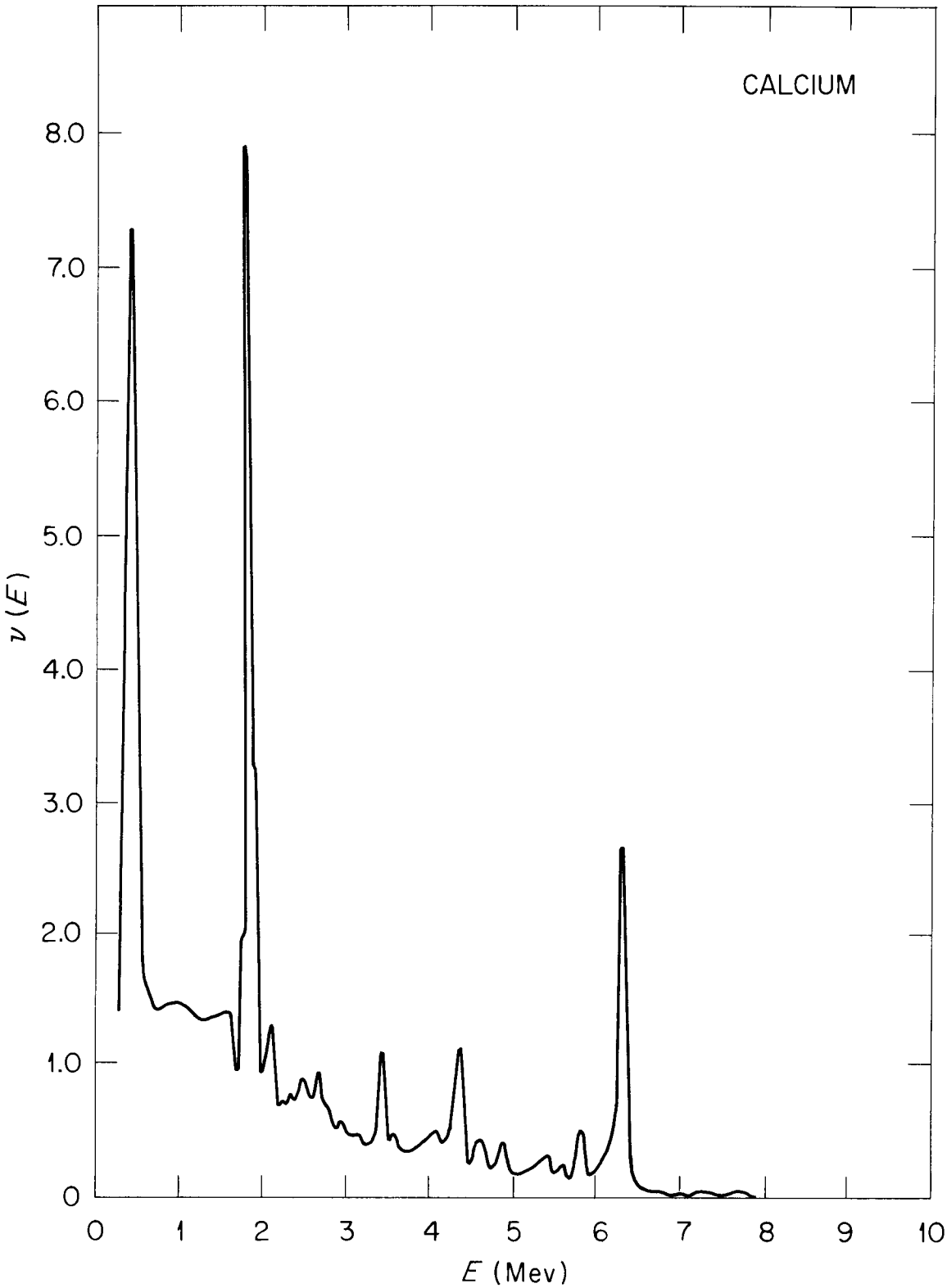

Fig. 5.

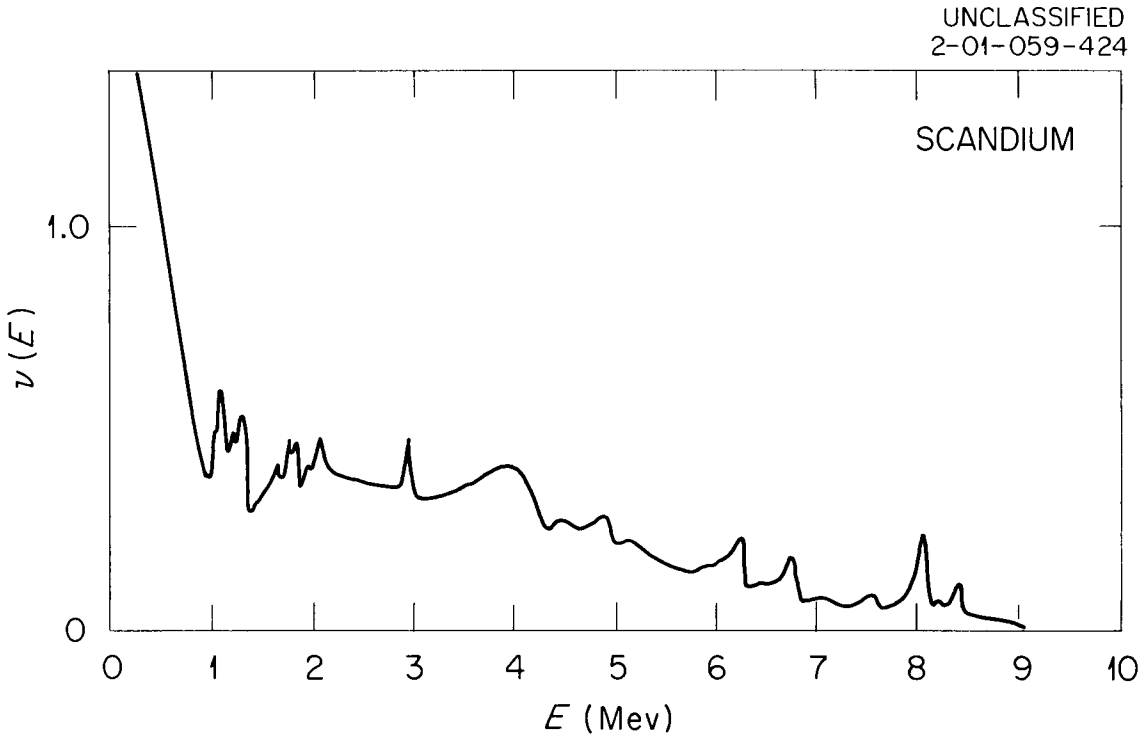
UNCLASSIFIED
2-01-059-424
SCANDIUM
1.0
0
ν(E)
0
1
2
3
4
5
6
7
8
9
10
E (Mev)

Fig. 6.

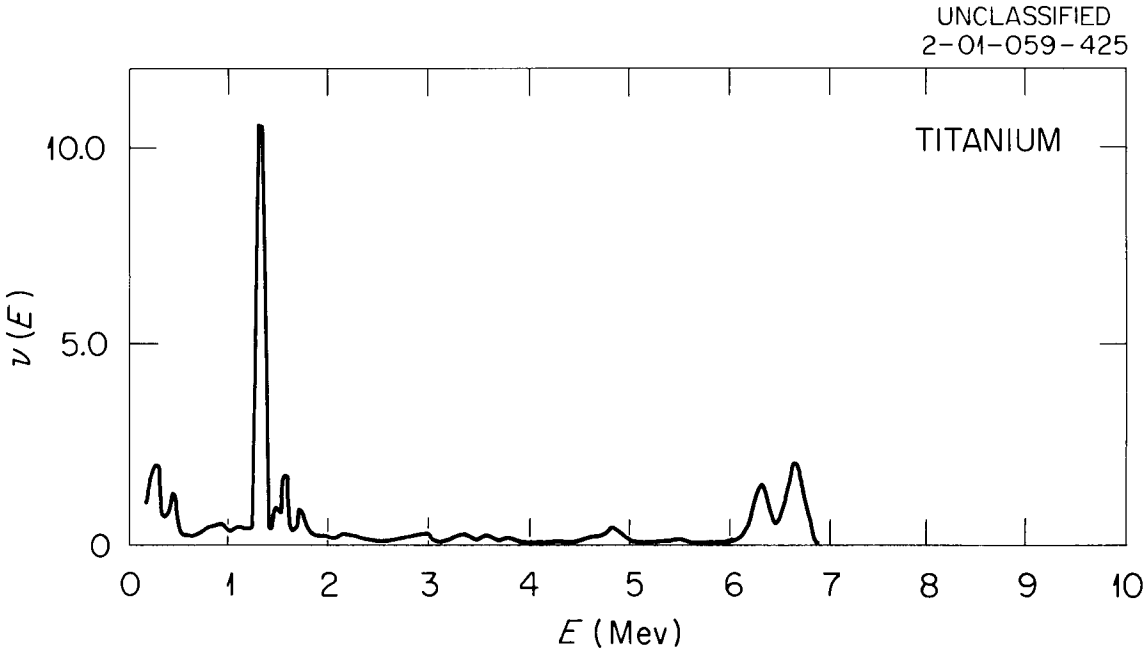
UNCLASSIFIED
2-01-059-425
TITANIUM
10.0
5.0
0
ν(E)
0
1
2
3
4
5
6
7
8
9
10
E (Mev)

Fig. 7

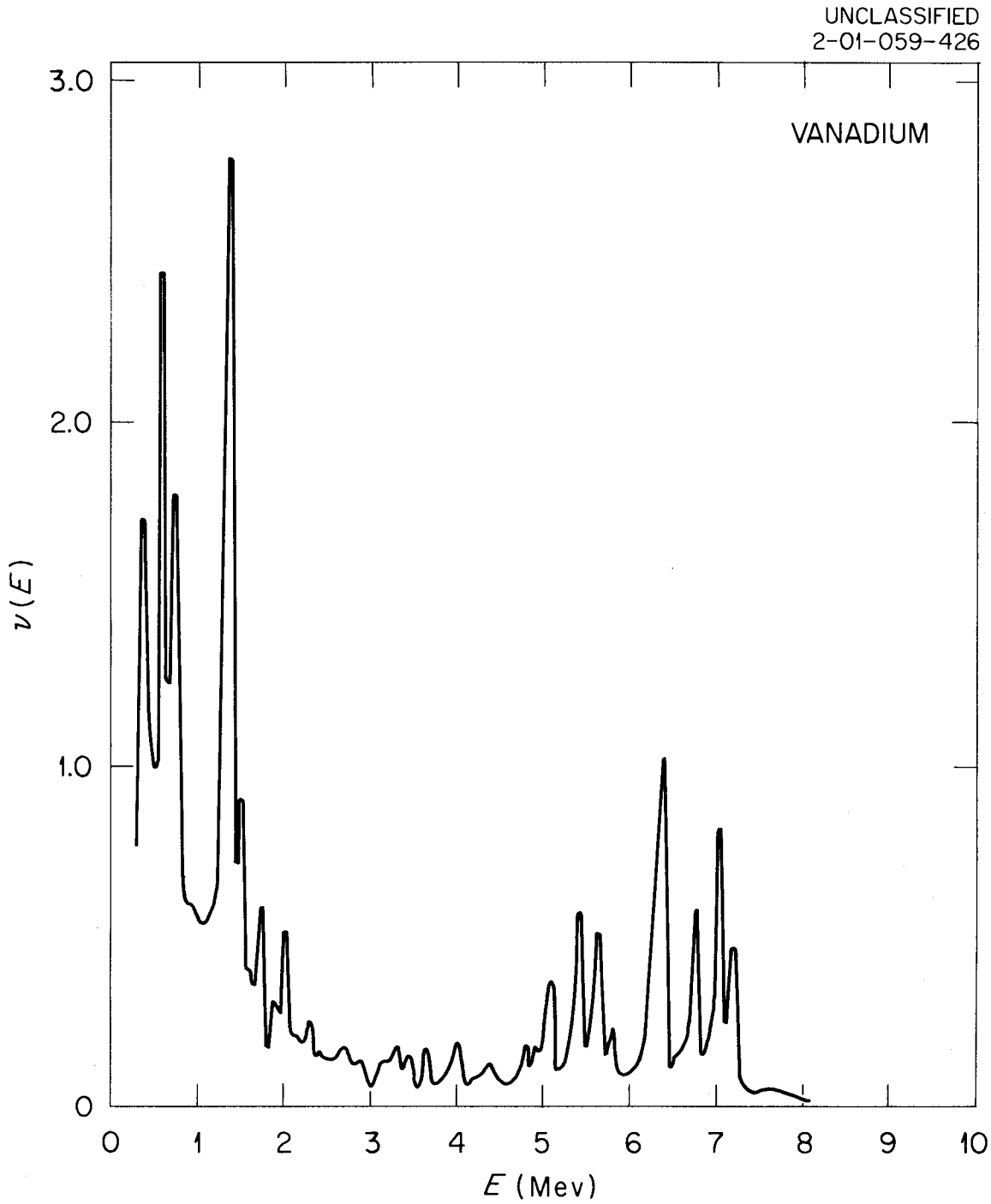
UNCLASSIFIED
2-01-059-426
VANADIUM
3.0
2.0
1.0
0
ν(E)
0
1
2
3
4
5
6
7
8
9
10
E (Mev)

Fig. 8.

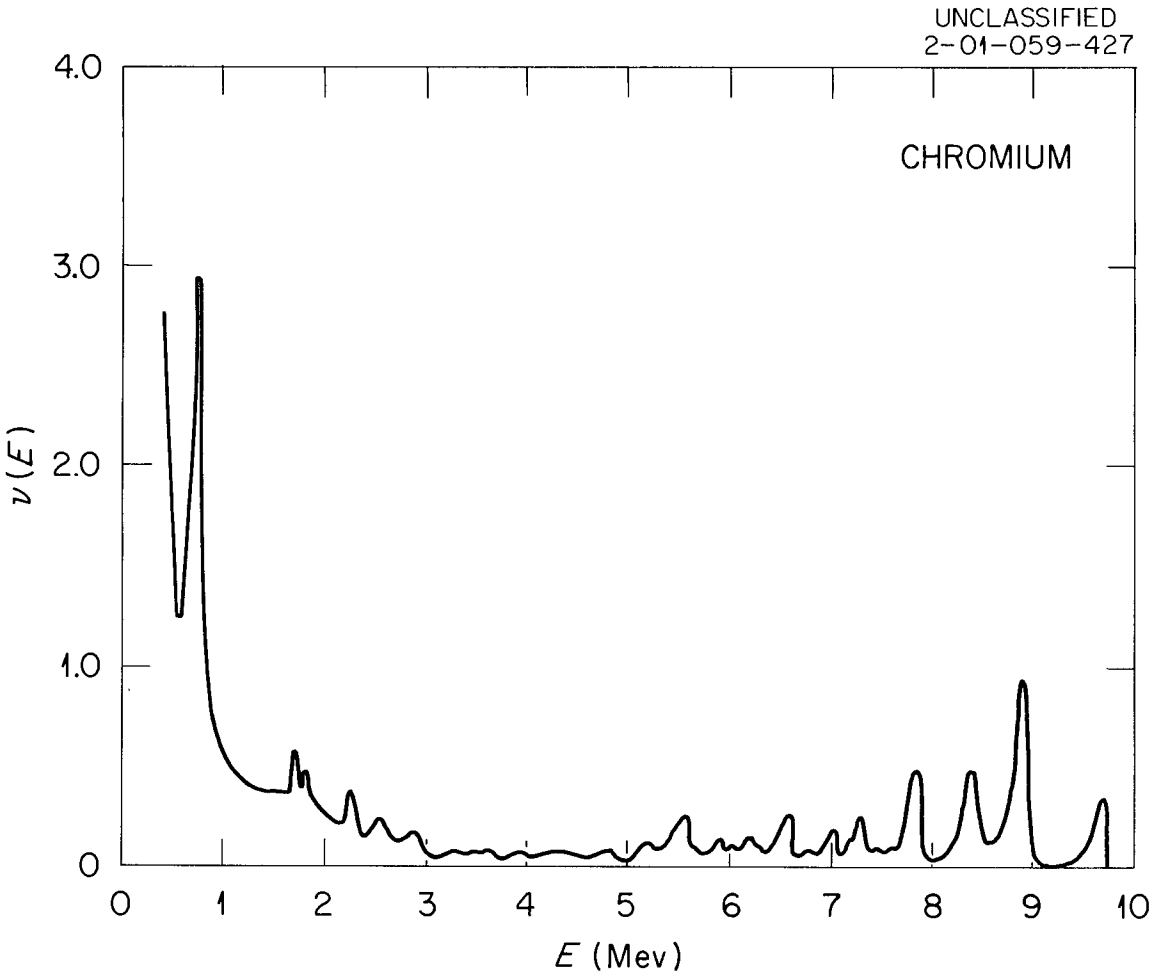
UNCLASSIFIED
2-01-059-427
CHROMIUM
4.0
3.0
2.0
1.0
0
ν(E)
0
1
2
3
4
5
6
7
8
9
10
E (Mev)

Fig. 9.

UNCLASSIFIED
2-01-059-428

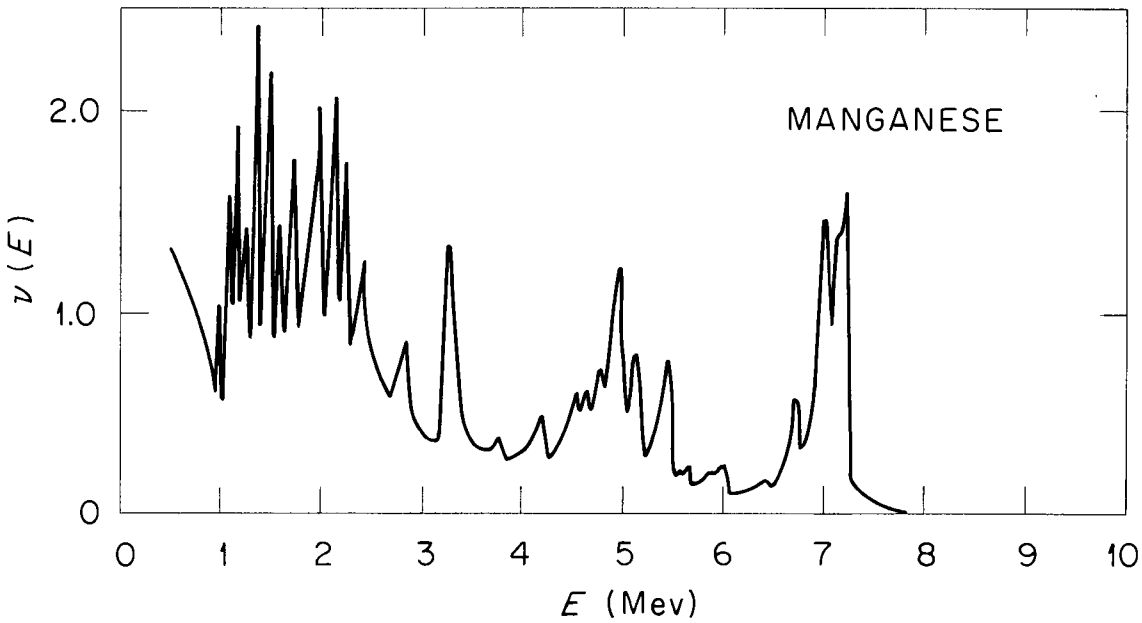

Fig. 10.

UNCLASSIFIED
2-01-059-429

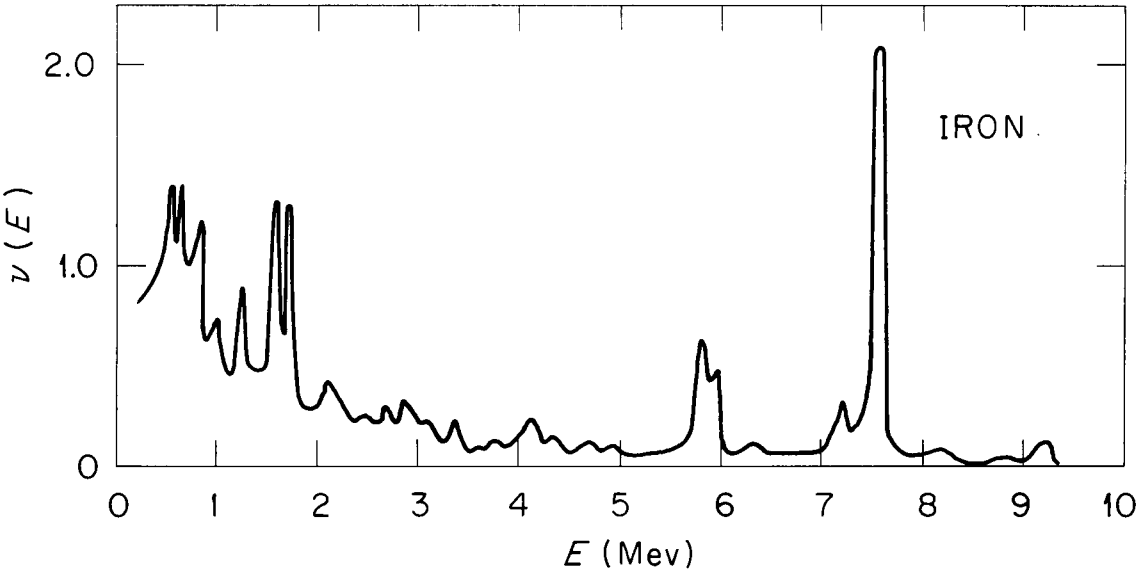

Fig. 11.

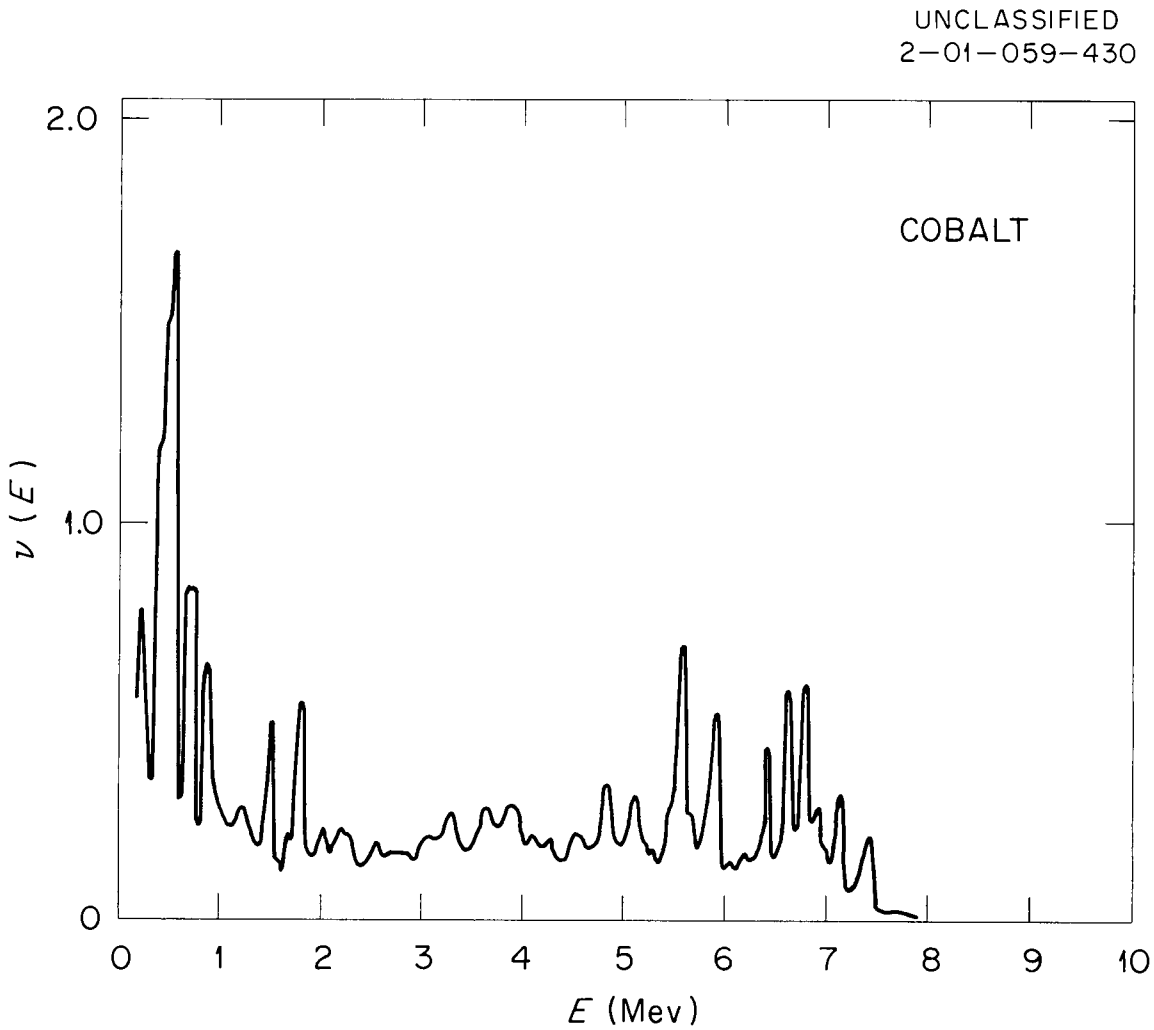
UNCLASSIFIED
2-01-059-430
COBALT
2.0
1.0
0
ν (E)
0
1
2
3
4
5
6
7
8
9
10
E (Mev)

Fig. 12.

UNCLASSIFIED
2-01-059-431

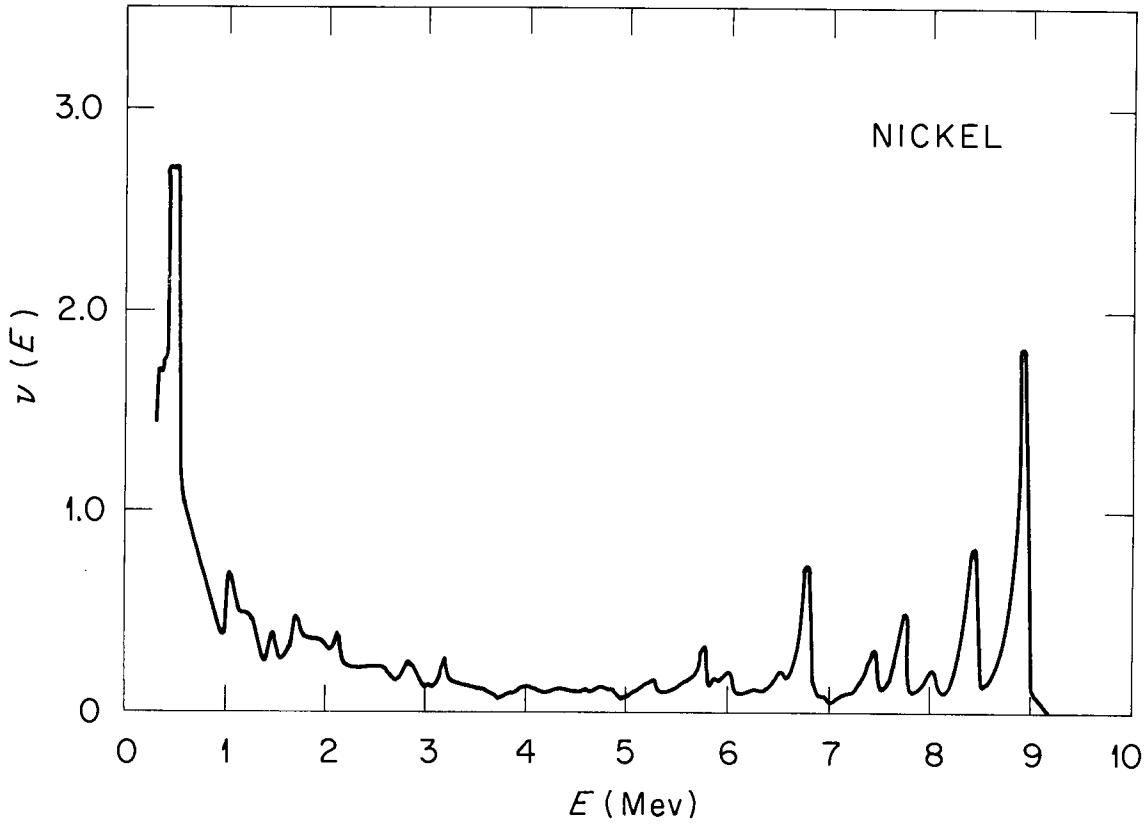

Fig. 13.

UNCLASSIFIED
2-01-059-432

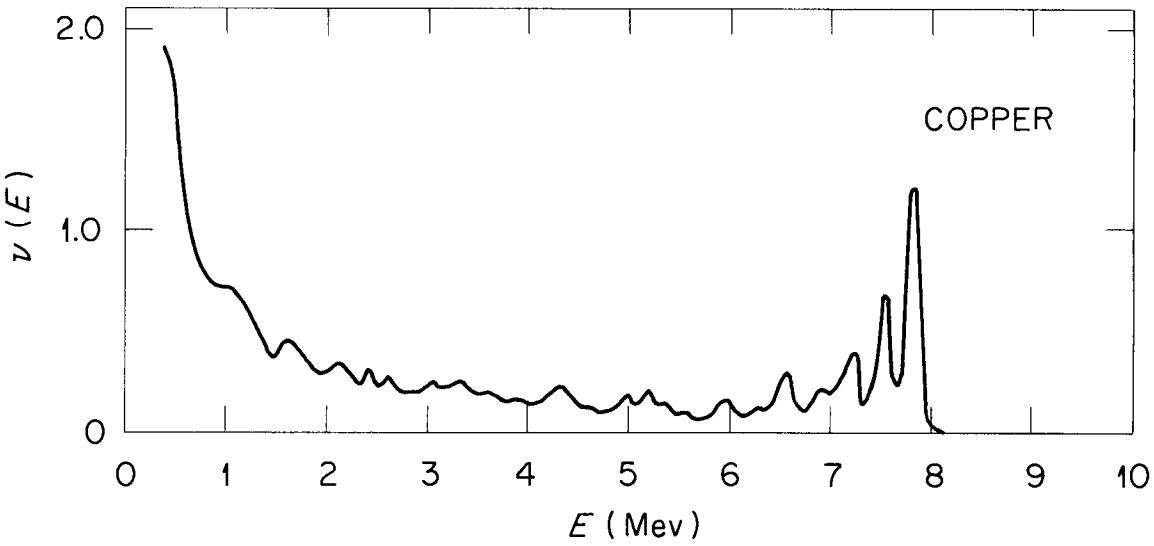

Fig. 14.

UNCLASSIFIED
2-01-059-433

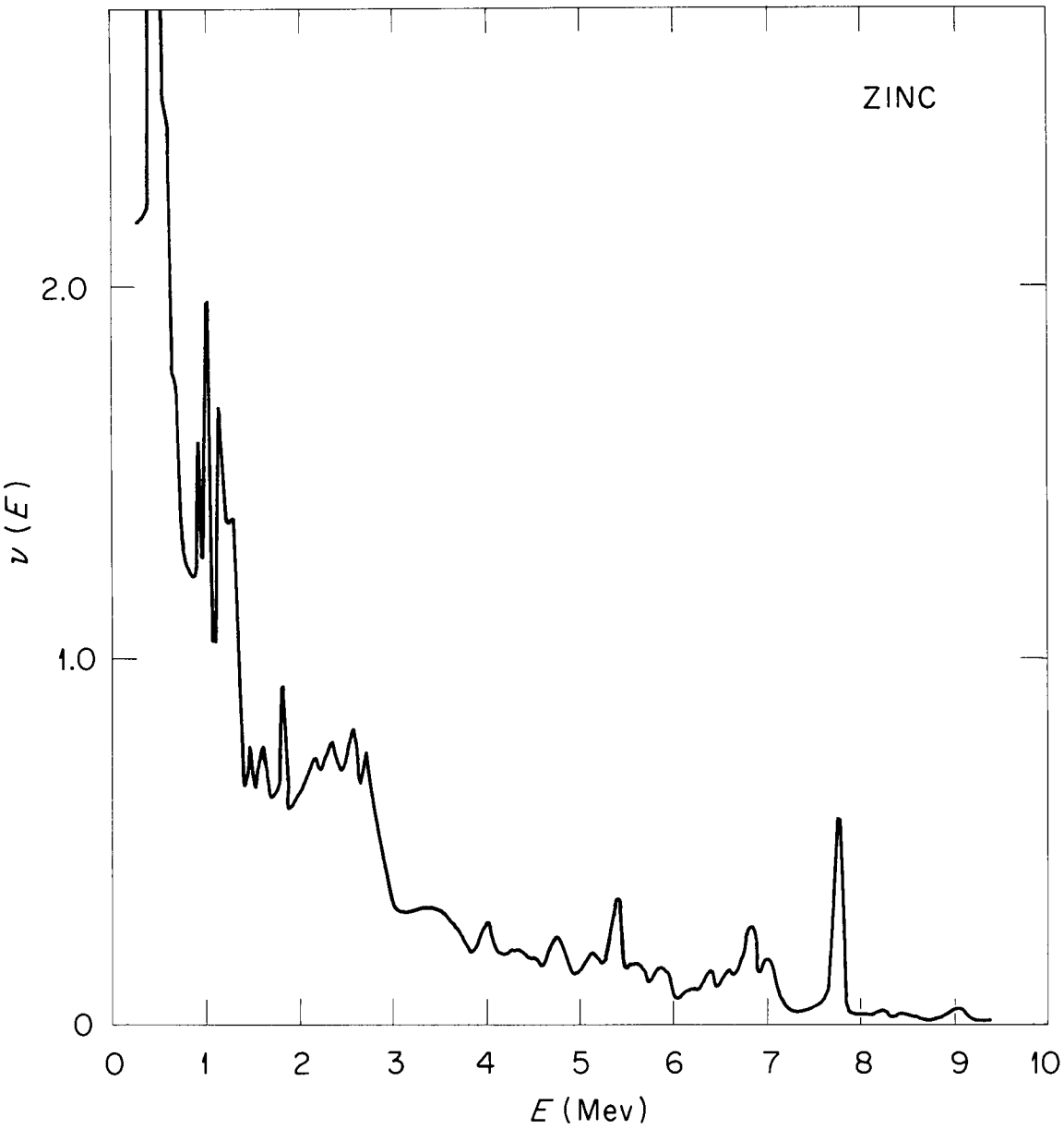

Fig. 15.

UNCLASSIFIED
2-01-059-434

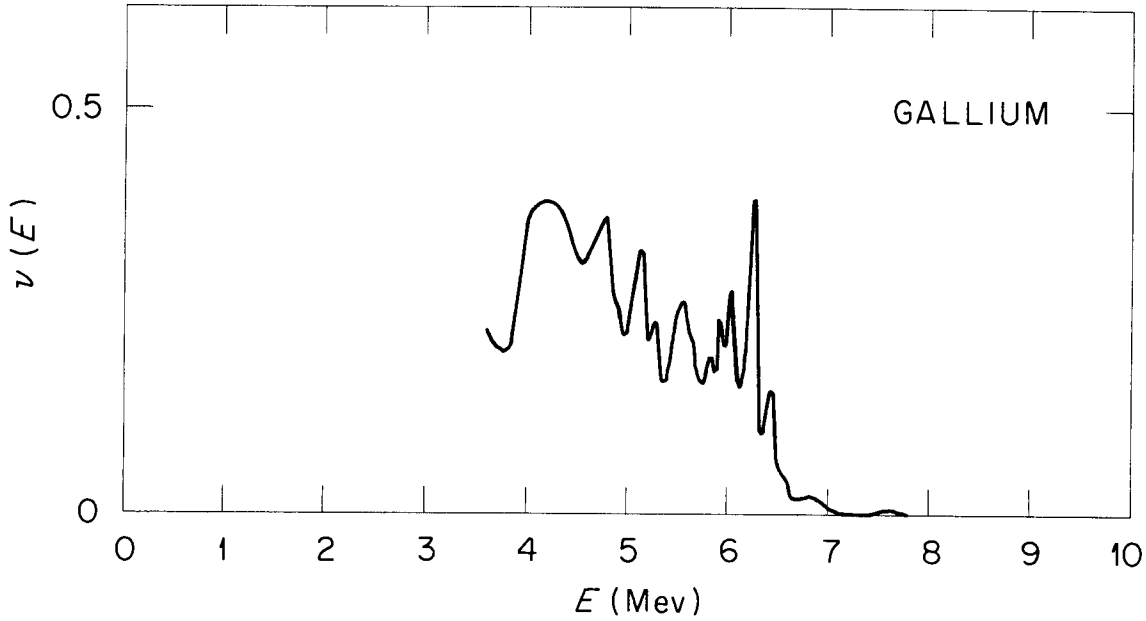

Fig. 16.

UNCLASSIFIED
2-01-059-435

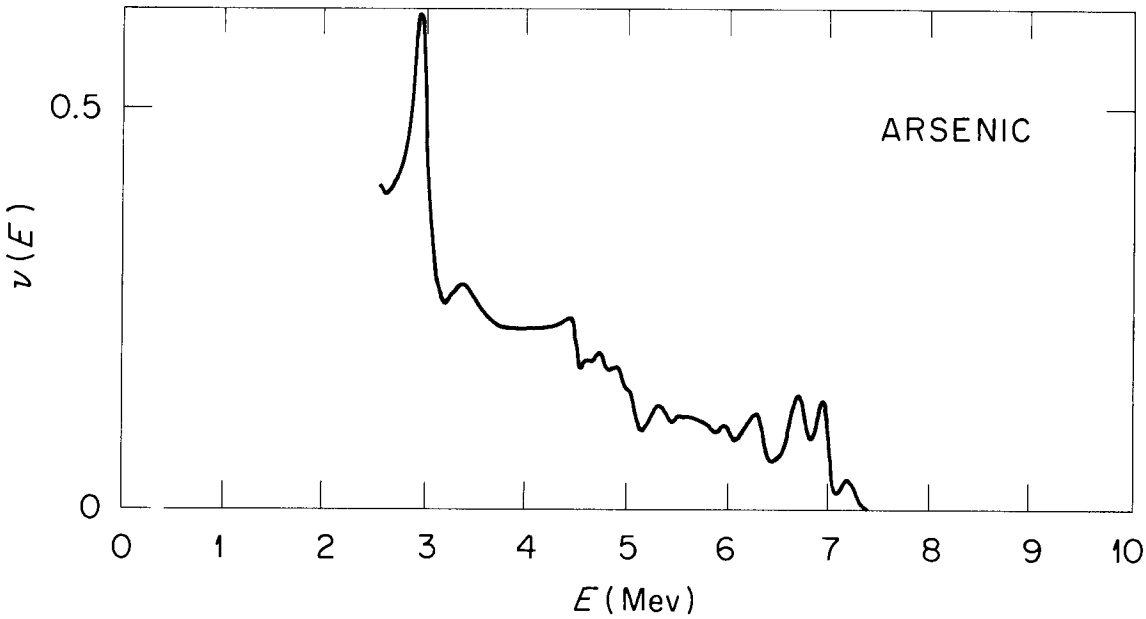

Fig. 17.

UNCLASSIFIED
2-01-059-436

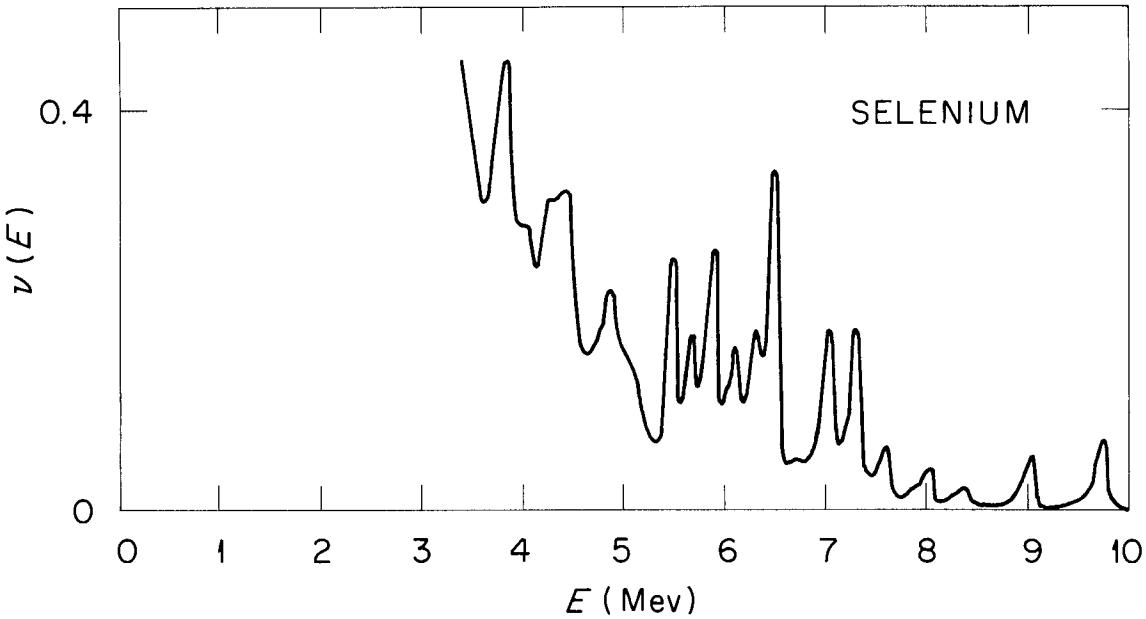

Fig. 18.

UNCLASSIFIED
2-01-059-437

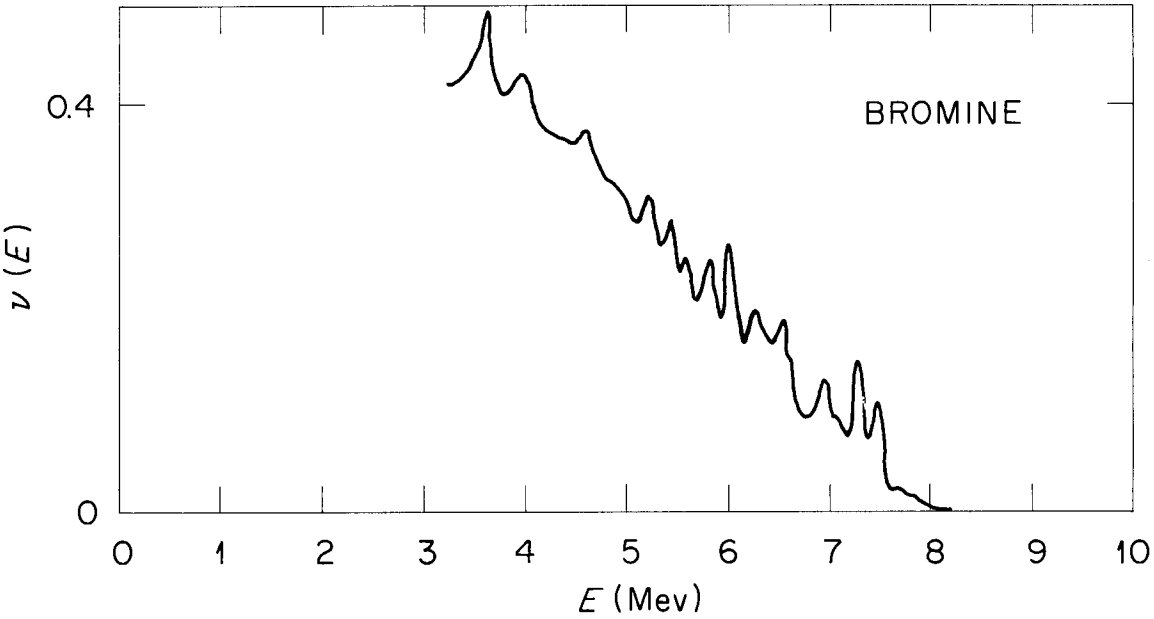

Fig. 19.

UNCLASSIFIED
2-01-059-438

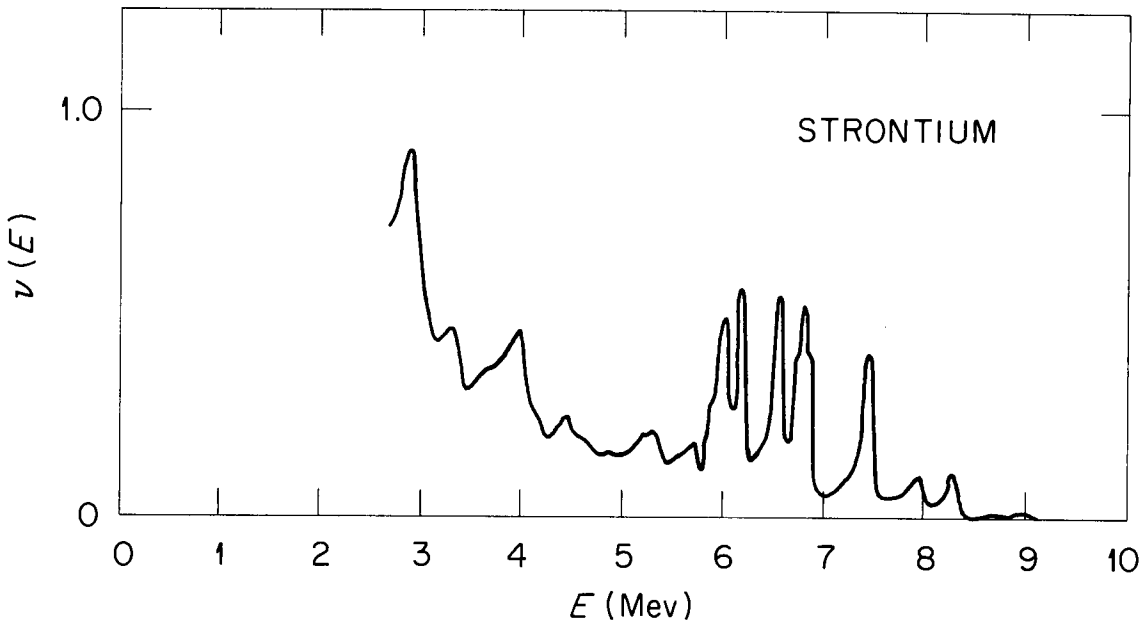

Fig. 20.

UNCLASSIFIED
2-01-059-439

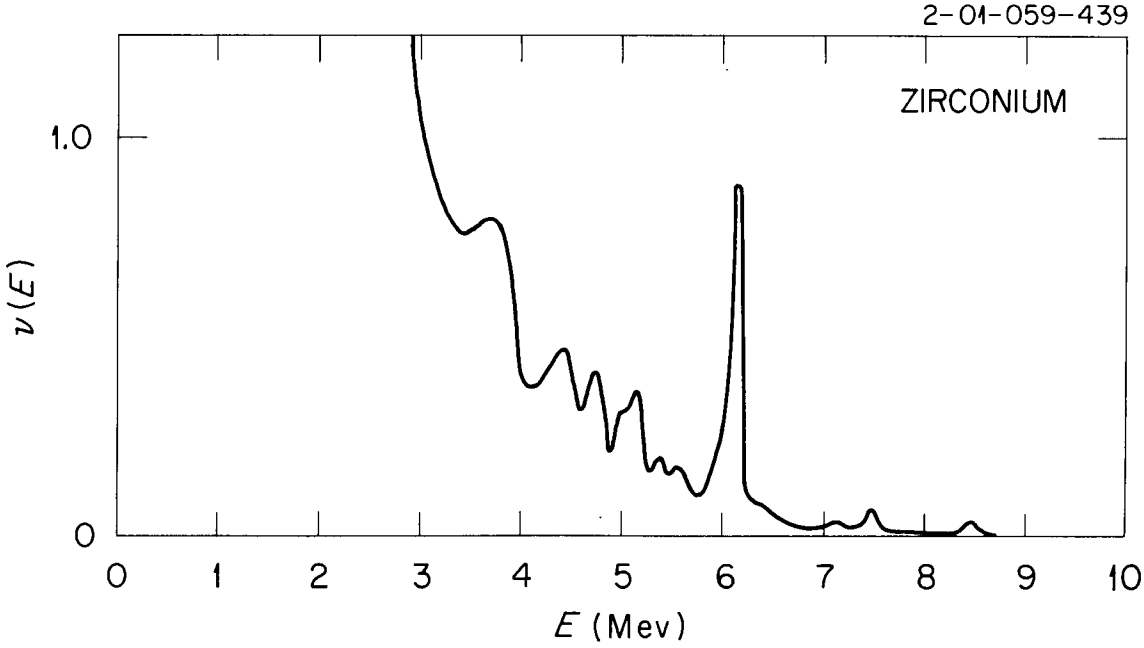

Fig. 21.

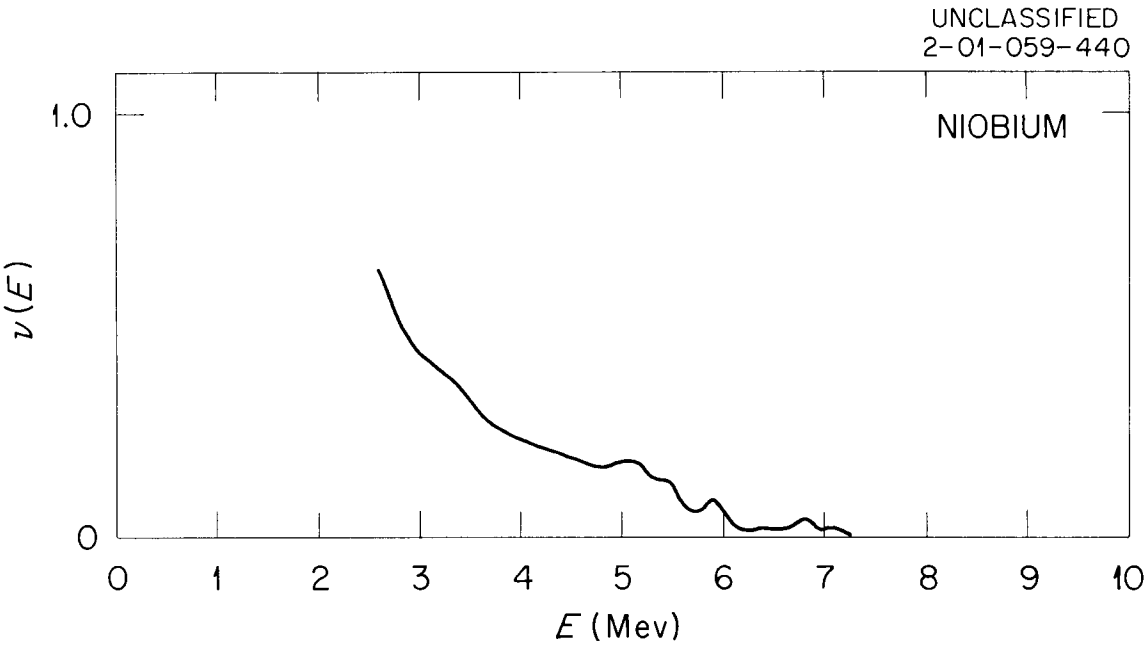
UNCLASSIFIED
2-01-059-440
NIOBIUM
1.0
0
ν(E)
0 1 2 3 4 5 6 7 8 9 10
E (Mev)

Fig. 22.

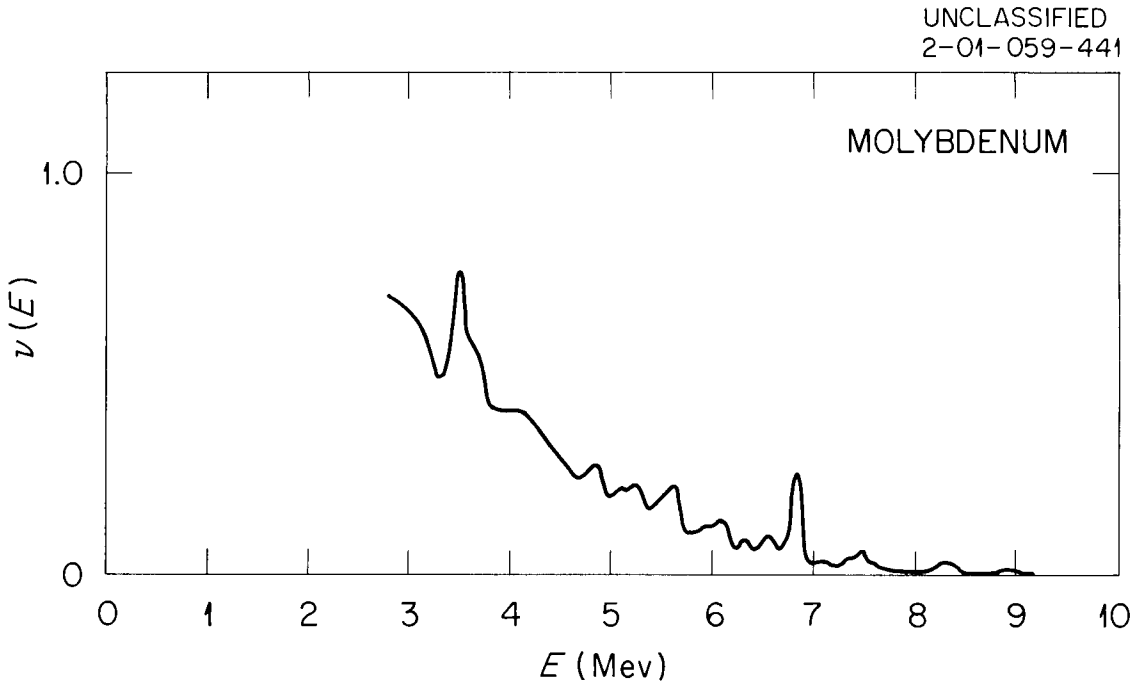
UNCLASSIFIED
2-01-059-441
MOLYBDENUM
1.0
0
ν(E)
0 1 2 3 4 5 6 7 8 9 10
E (Mev)

Fig. 23

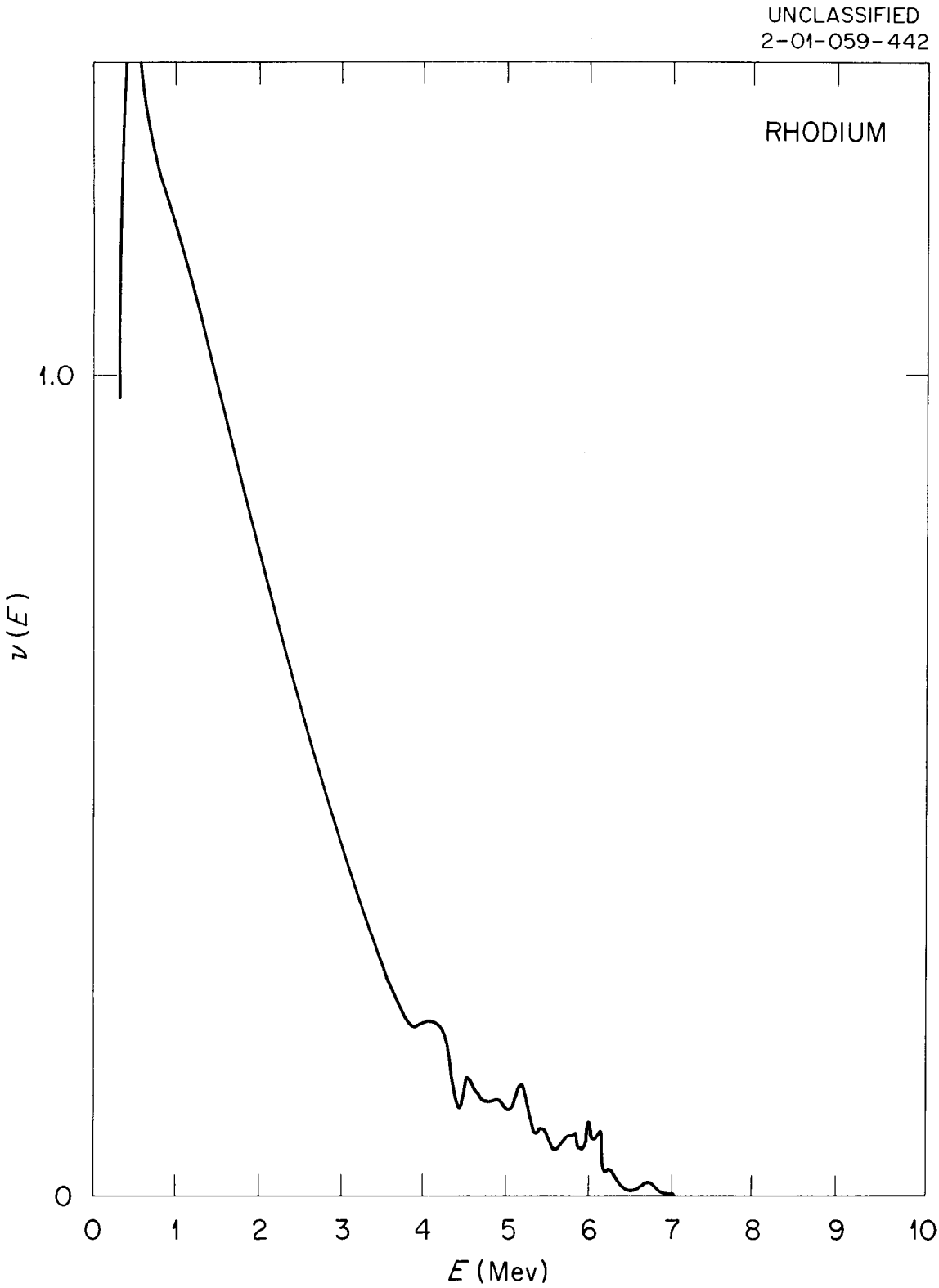

Fig. 24.

UNCLASSIFIED
2-01-059-443

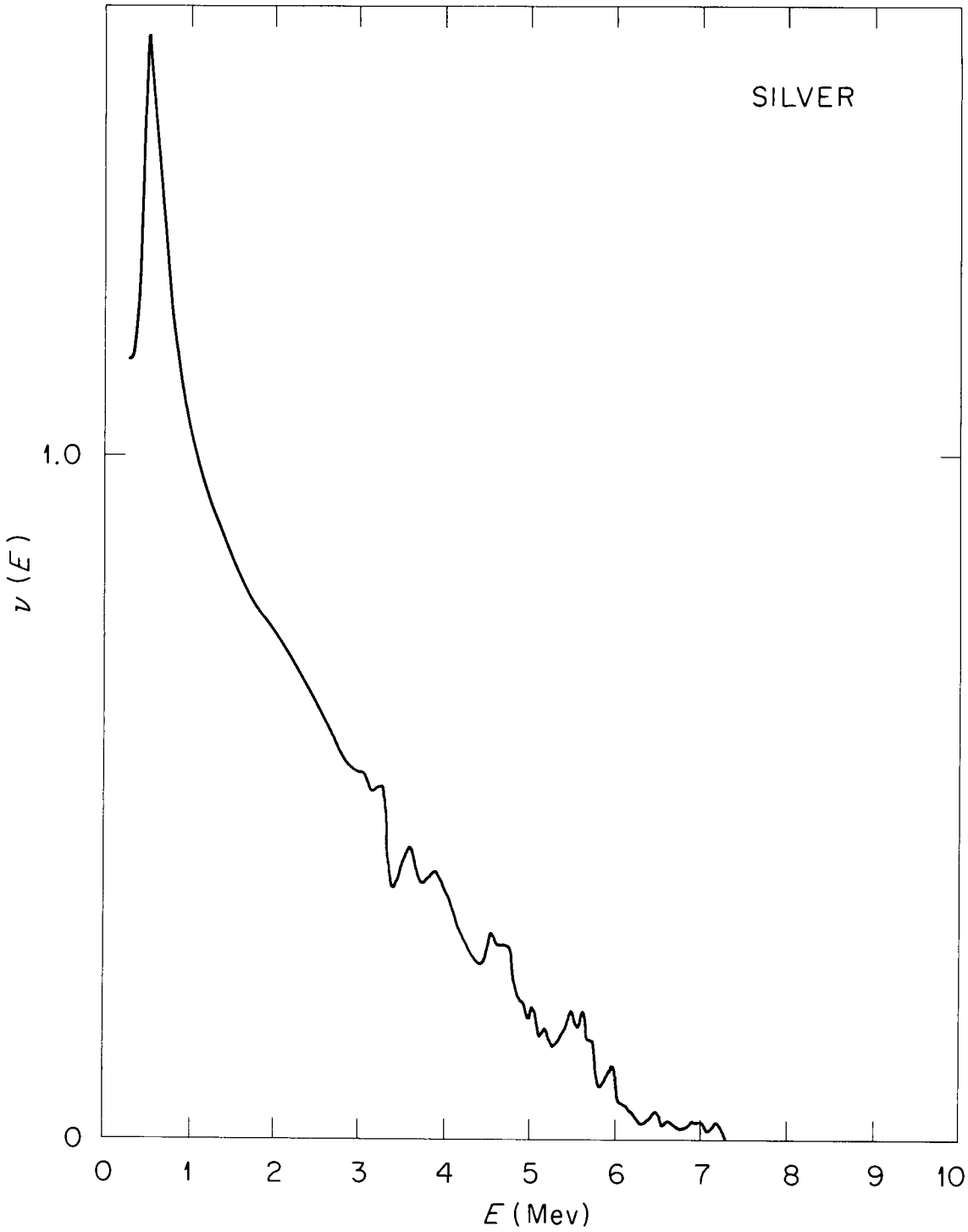

Fig. 25.

UNCLASSIFIED
2-01-059-444

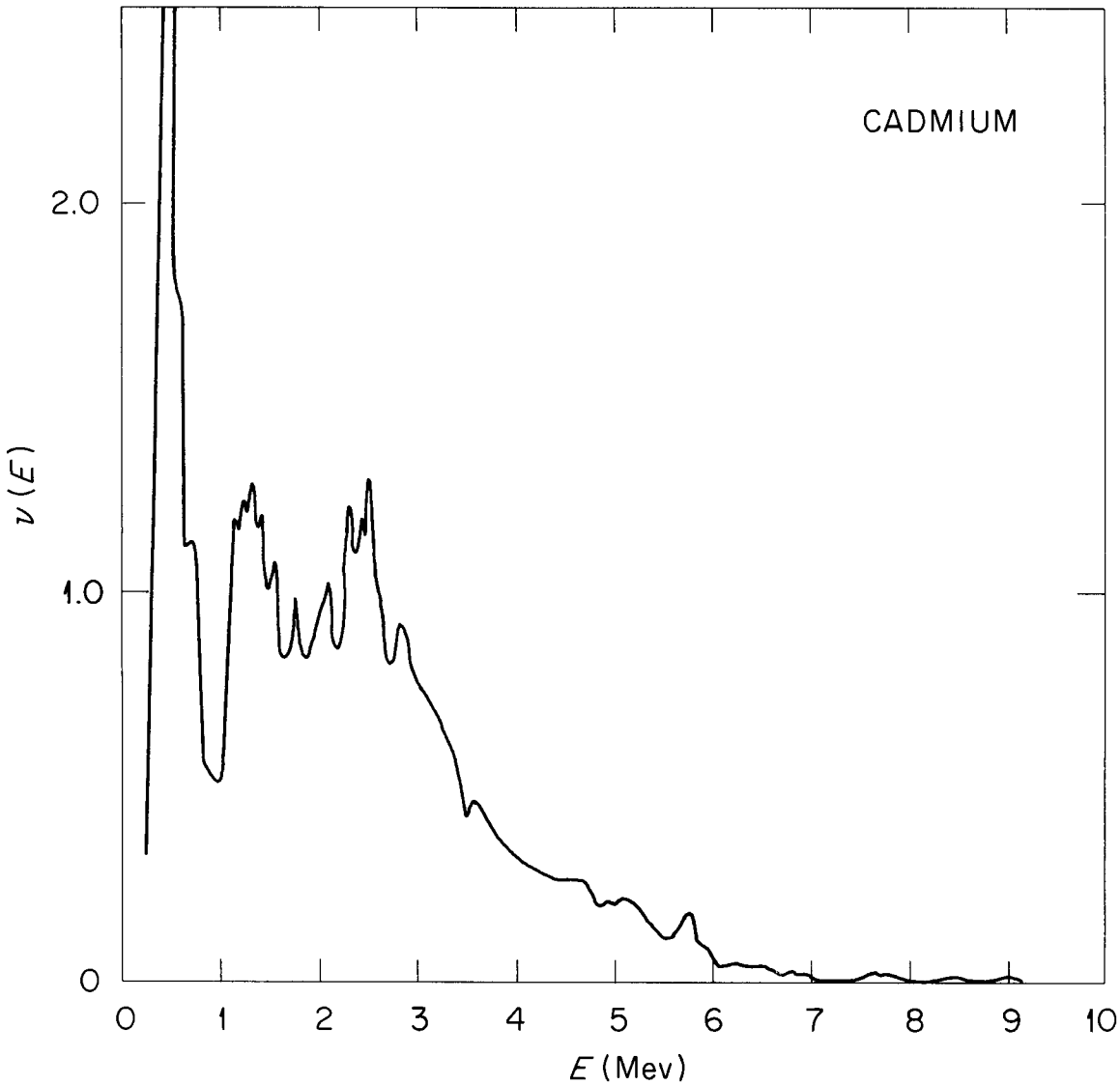

Fig. 26.

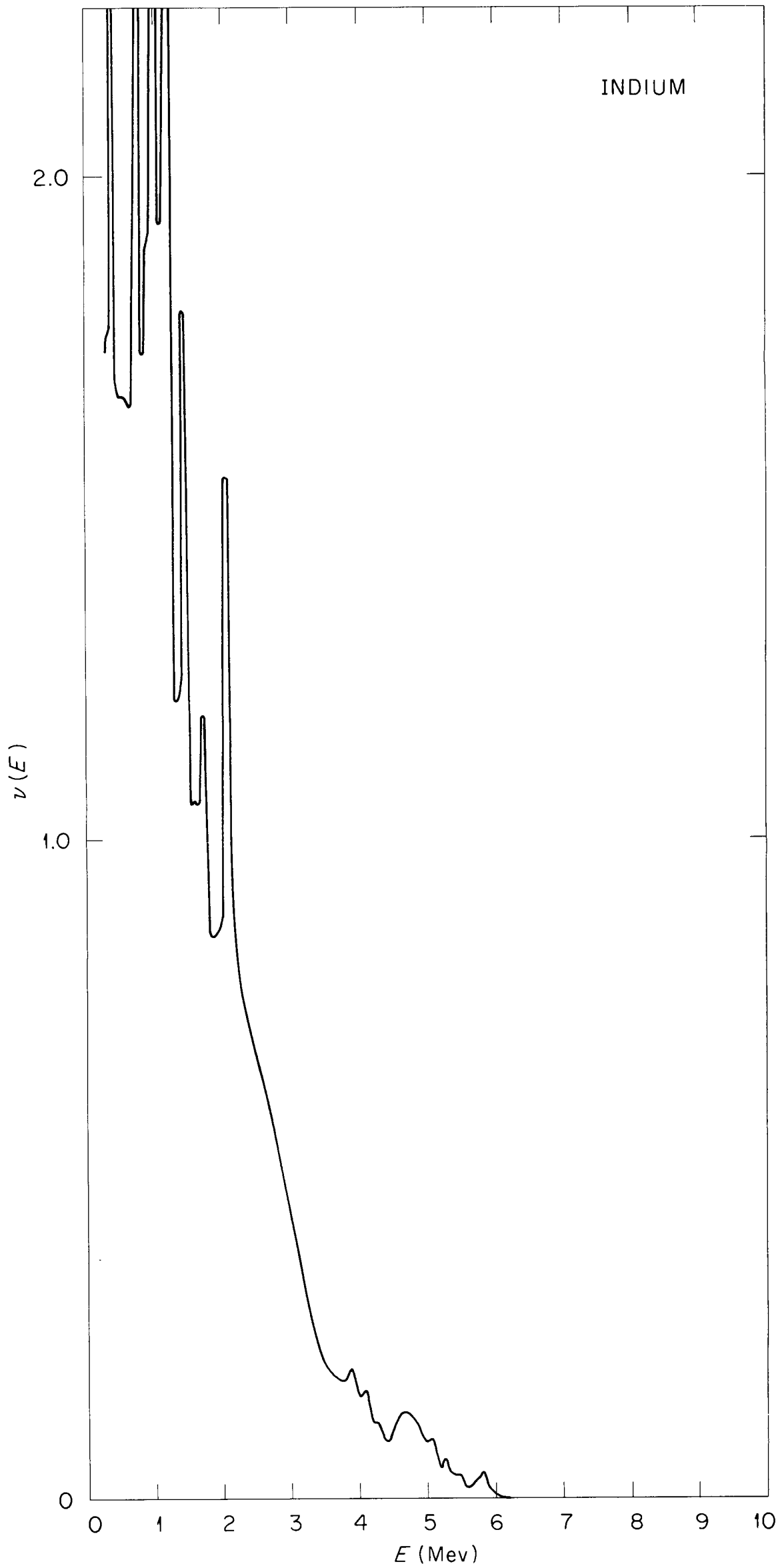

Fig. 27.

UNCLASSIFIED
2-01-059-446

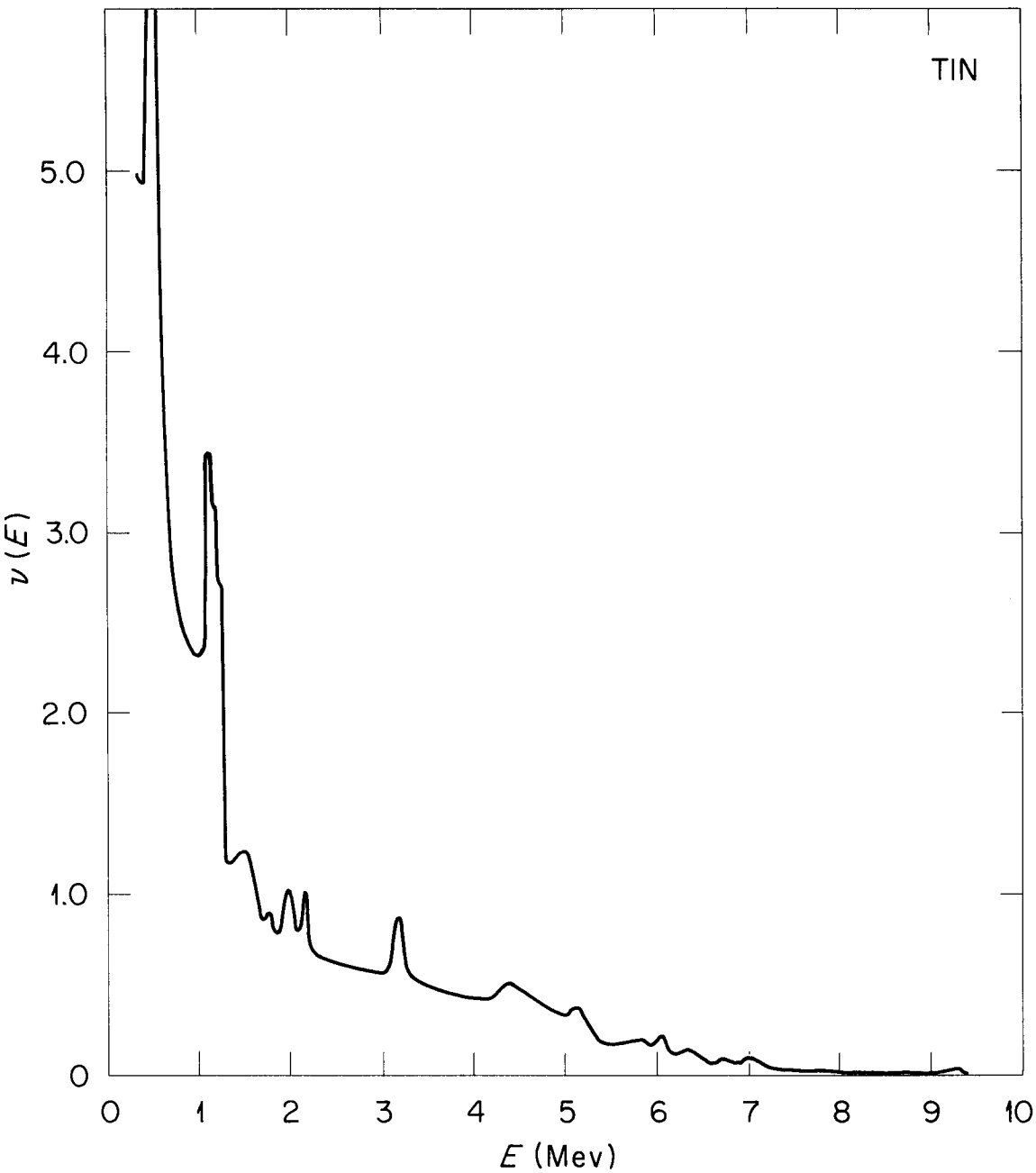

Fig. 28

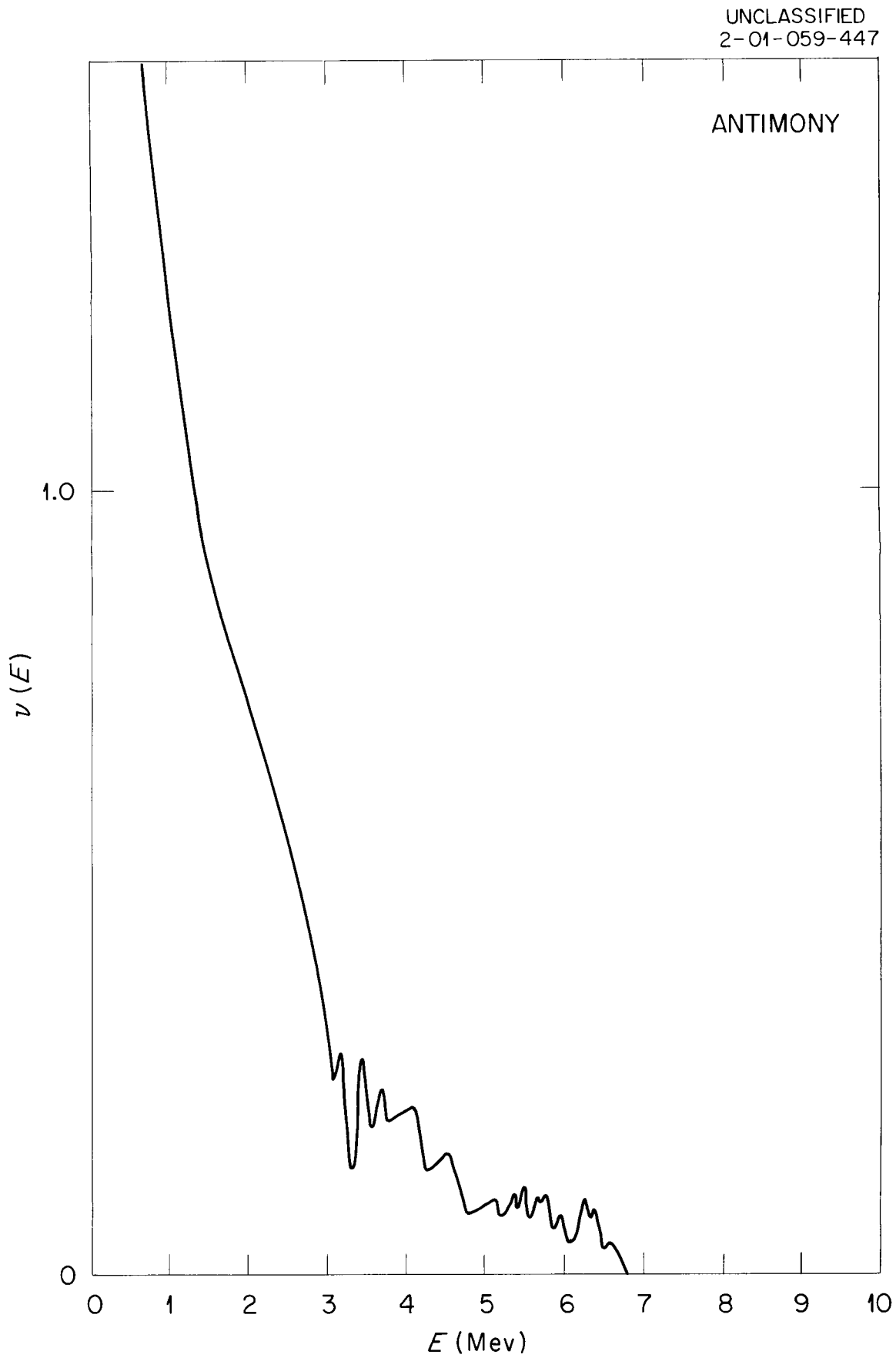
UNCLASSIFIED
2-01-059-447
ANTIMONY
1.0
0
ν (E)
0
1
2
3
4
5
6
7
8
9
10
E (Mev)

Fig. 29.

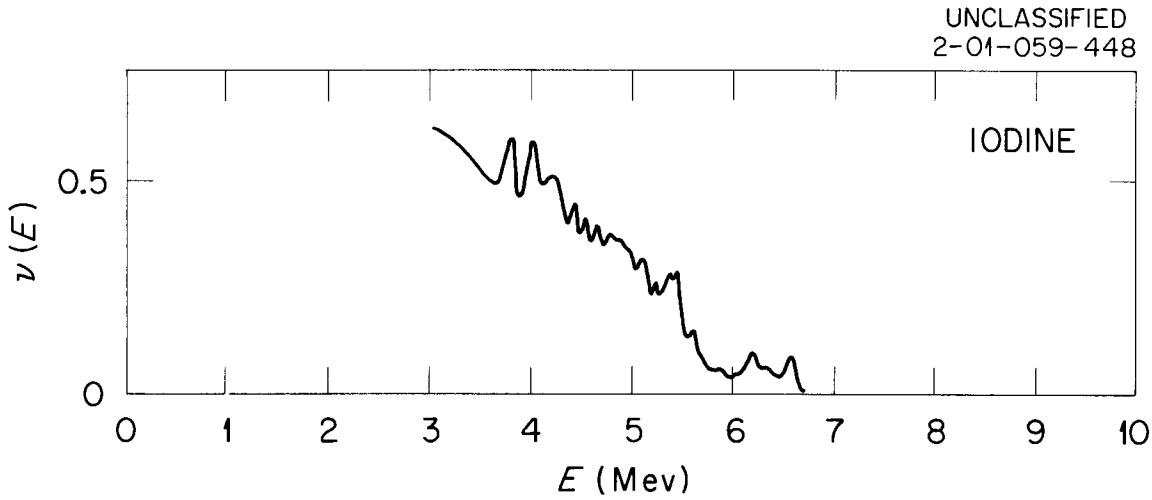
UNCLASSIFIED
2-01-059-448
IODINE
0.5
0
ν(E)
0
1
2
3
4
5
6
7
8
9
10
E (Mev)

Fig. 30.

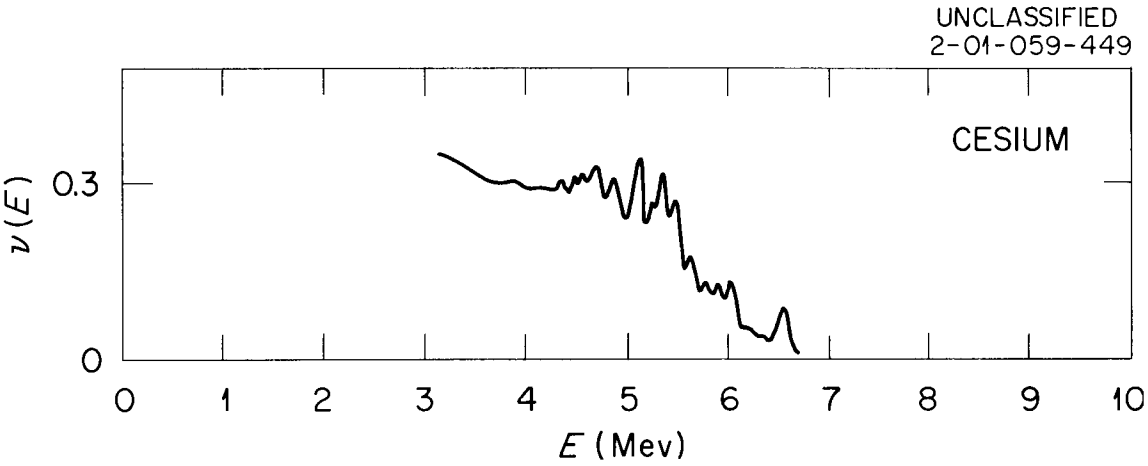
UNCLASSIFIED
2-01-059-449
CESIUM
0.3
0
ν(E)
0
1
2
3
4
5
6
7
8
9
10
E (Mev)

Fig. 31.

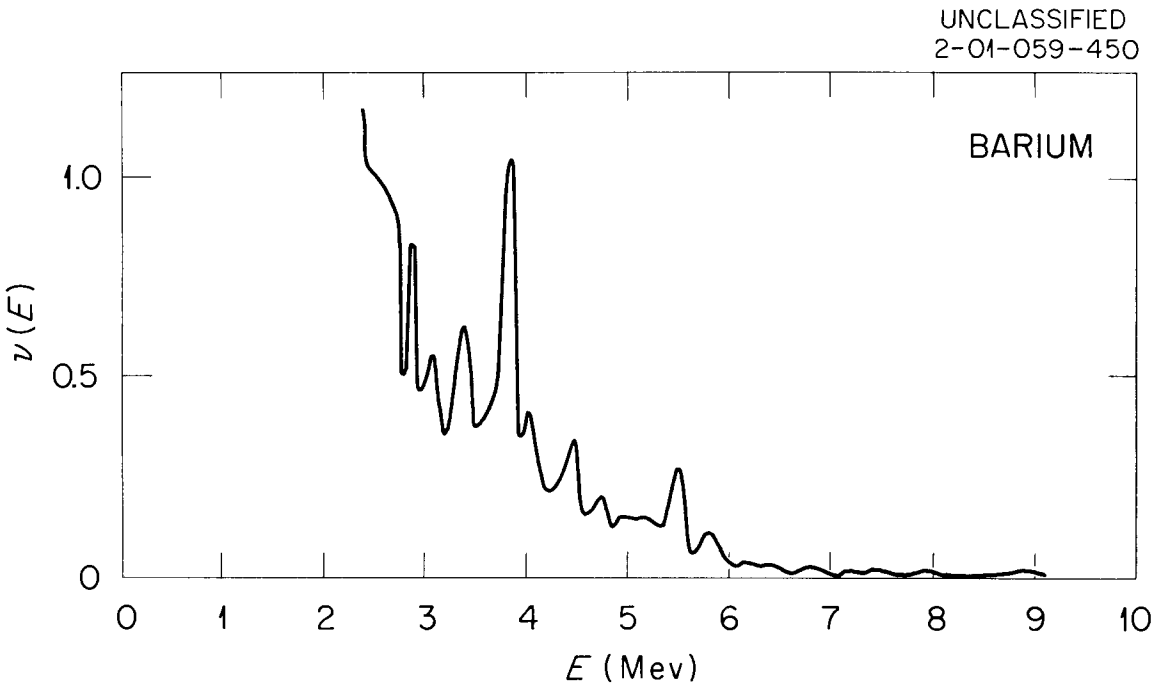
UNCLASSIFIED
2-01-059-450
BARIUM
1.0
0.5
0
ν(E)
0
1
2
3
4
5
6
7
8
9
10
E (Mev)

Fig. 32

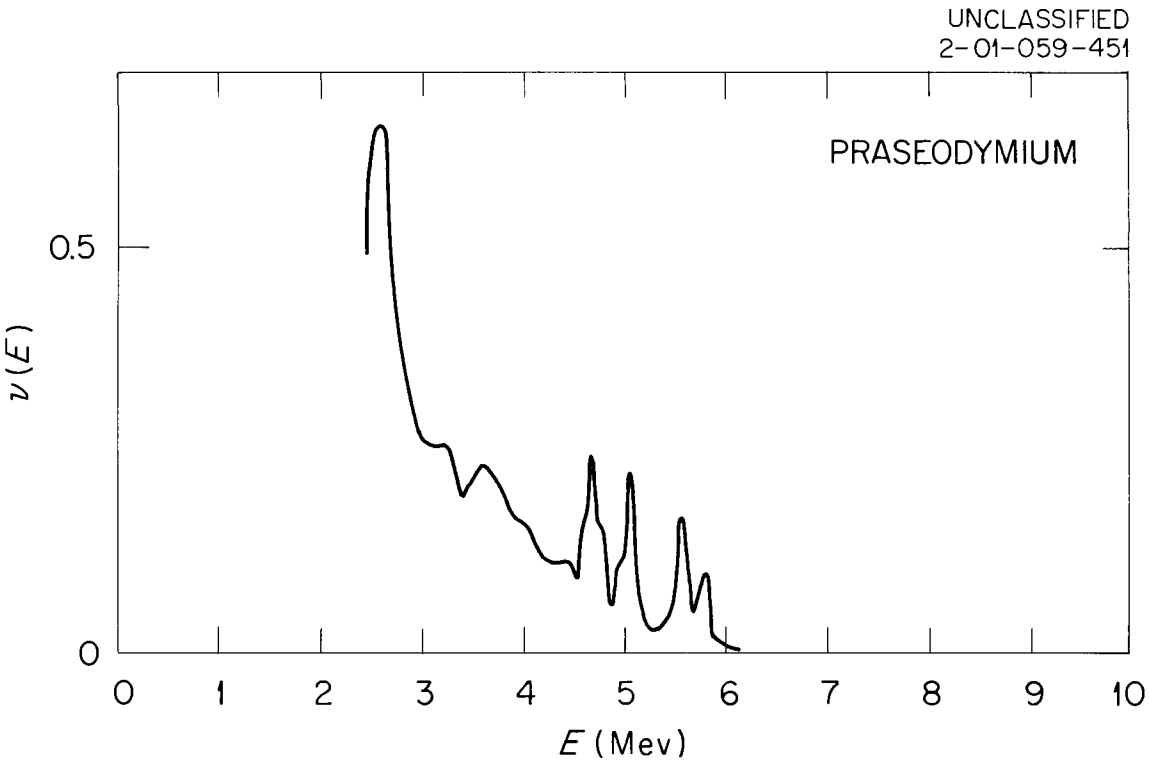
UNCLASSIFIED
2-01-059-451
PRASEODYMIUM
0.5
0
ν(E)
0
1
2
3
4
5
6
7
8
9
10
E (Mev)

Fig. 33.

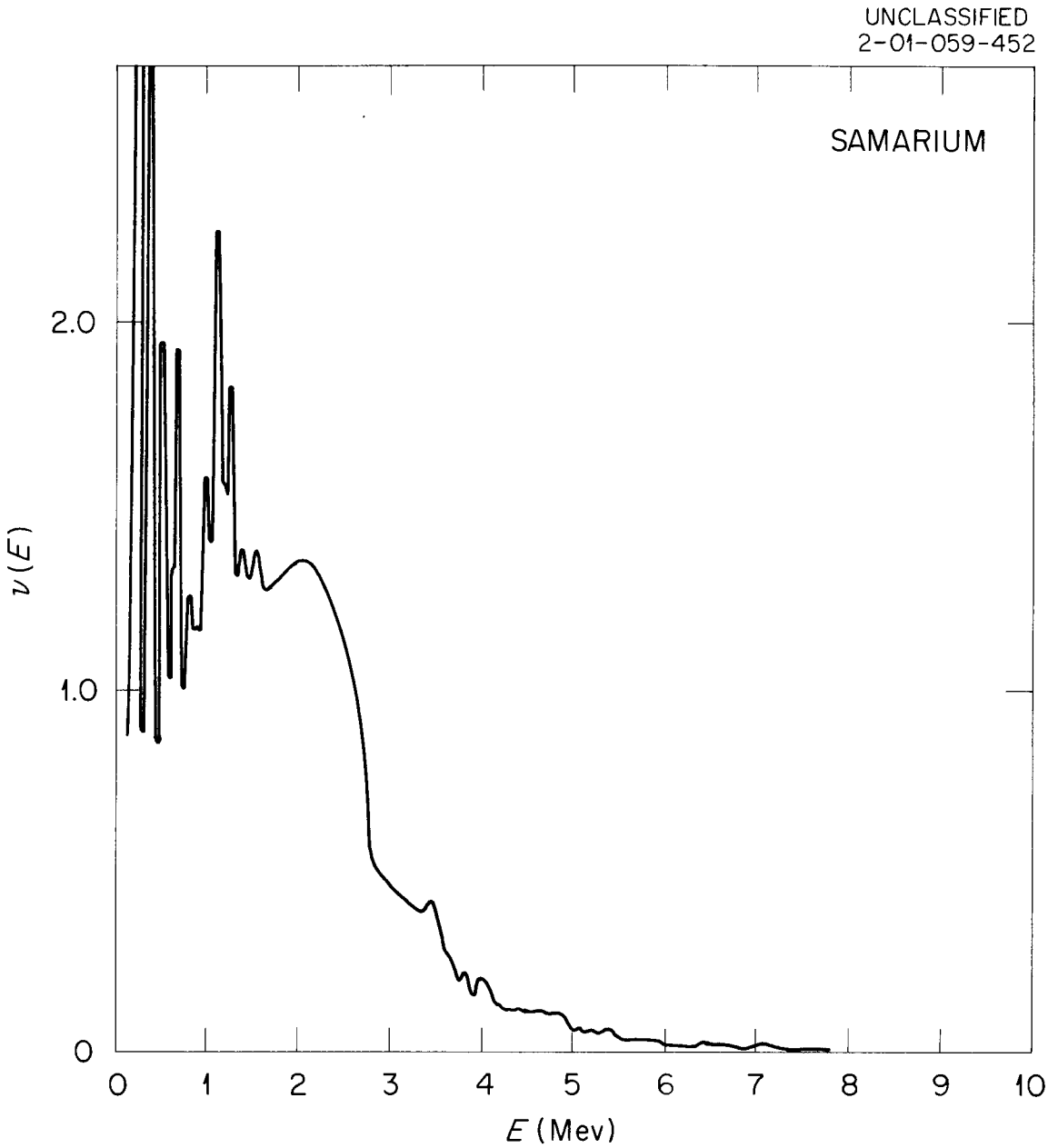
UNCLASSIFIED
2-01-059-452
SAMARIUM
2.0
1.0
0
$\nu(E)$
0
1
2
3
4
5
6
7
8
9
10
E (Mev)

Fig. 34.

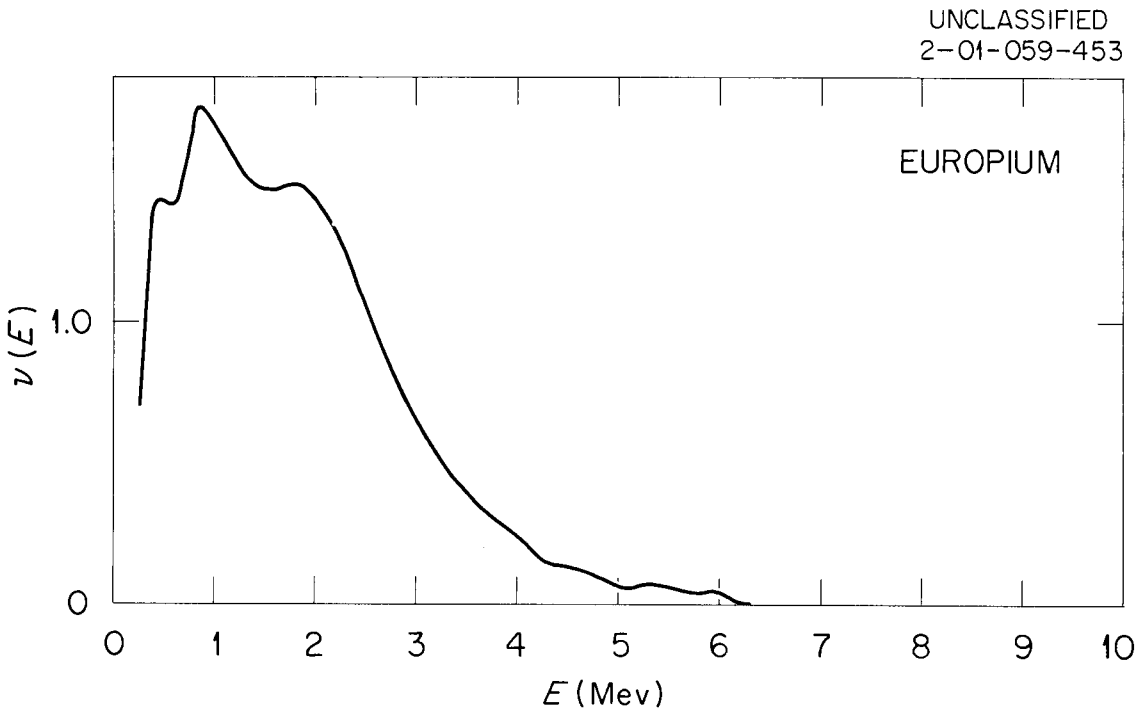
UNCLASSIFIED
2-01-059-453
EUROPIUM
ν(E)
1.0
0
0
1
2
3
4
5
6
7
8
9
10
E (Mev)

Fig. 35.

UNCLASSIFIED
2-01-059-454

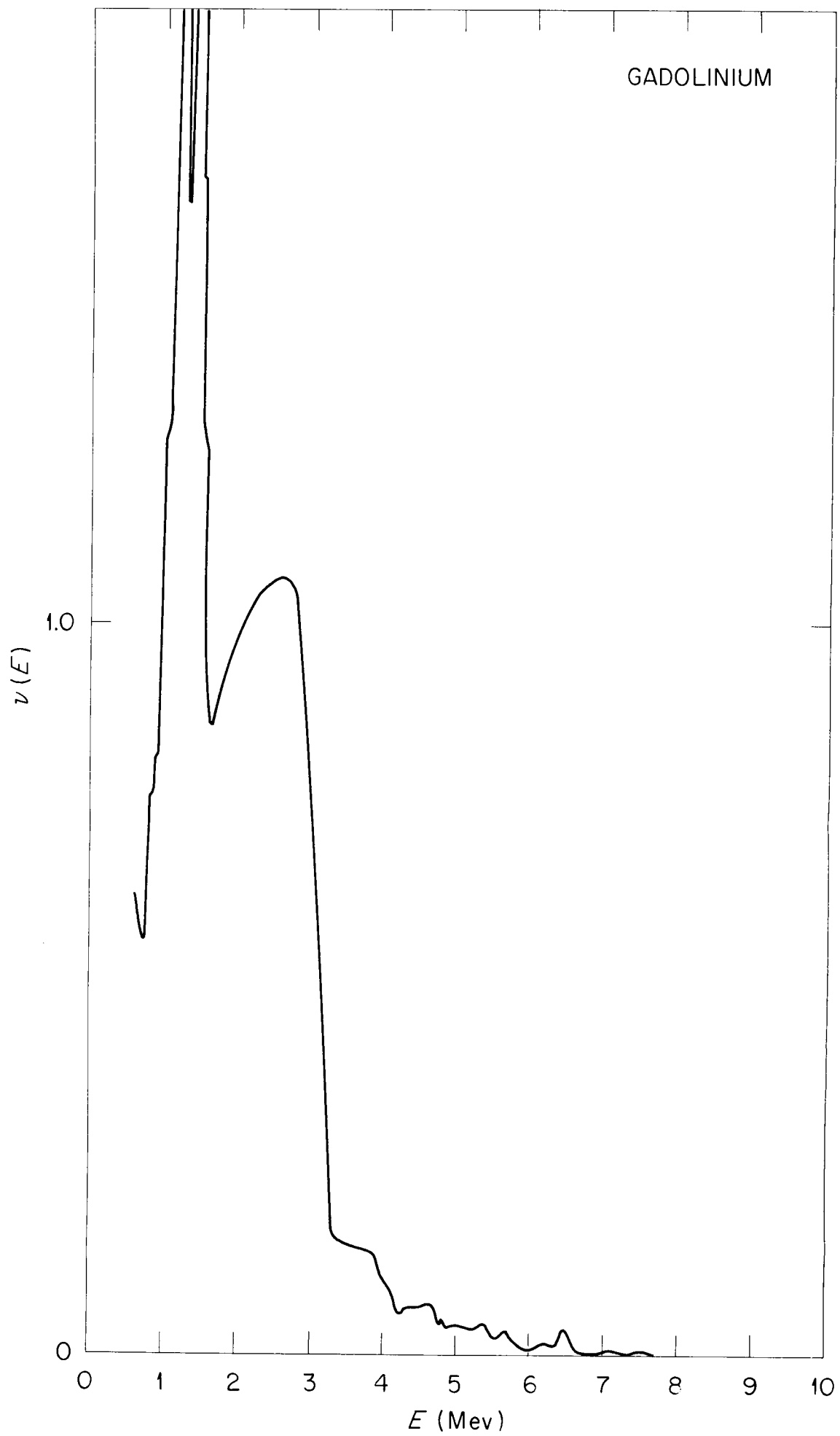

Fig. 36.

UNCLASSIFIED
2-01-059-455

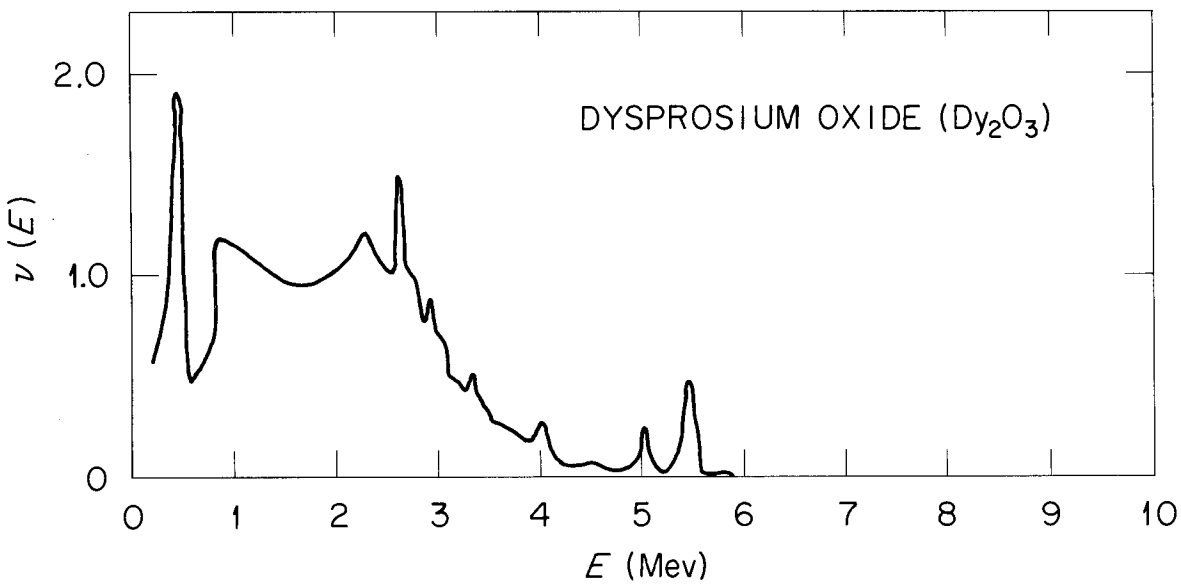

Fig. 37.

UNCLASSIFIED
2-01-059-456

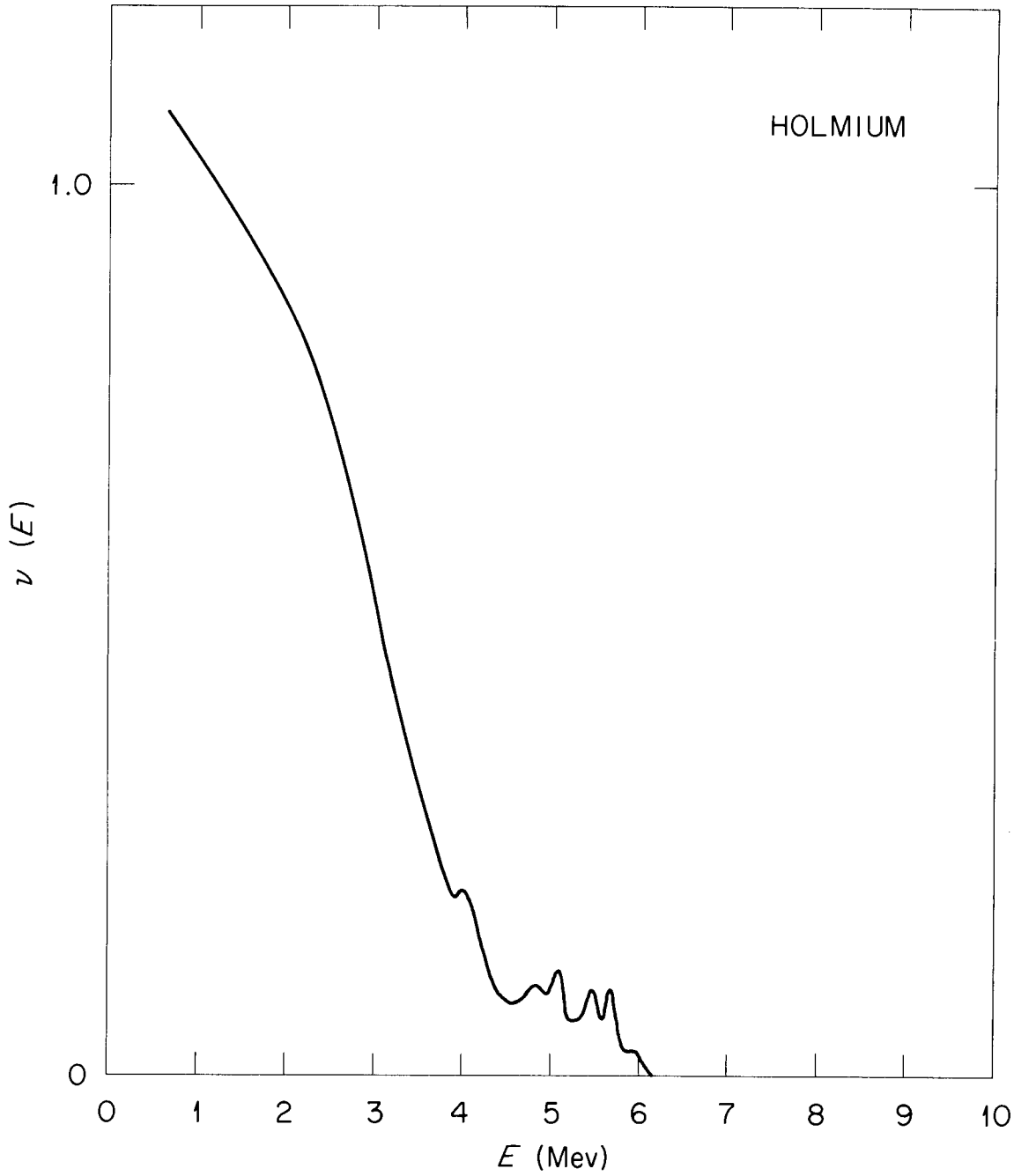

Fig. 38.

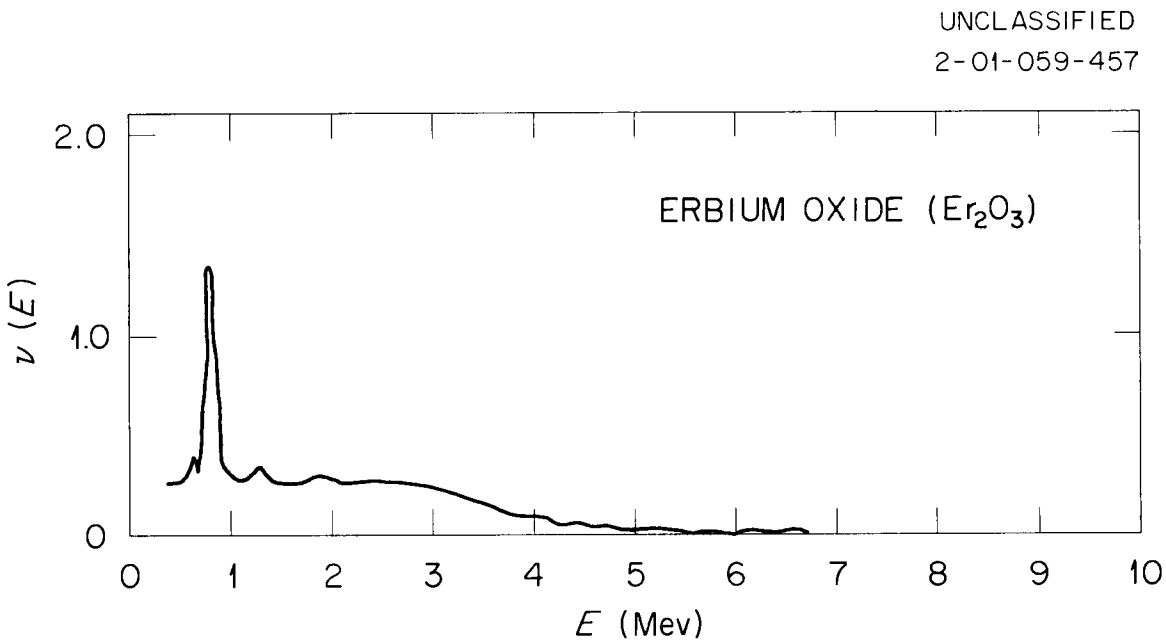
UNCLASSIFIED
2-01-059-457
ERBIUM OXIDE (Er_2O_3)
2.0
1.0
0
ν (E)
0
1
2
3
4
5
6
7
8
9
10
E (Mev)

Fig. 39.

UNCLASSIFIED
2-01-059-458

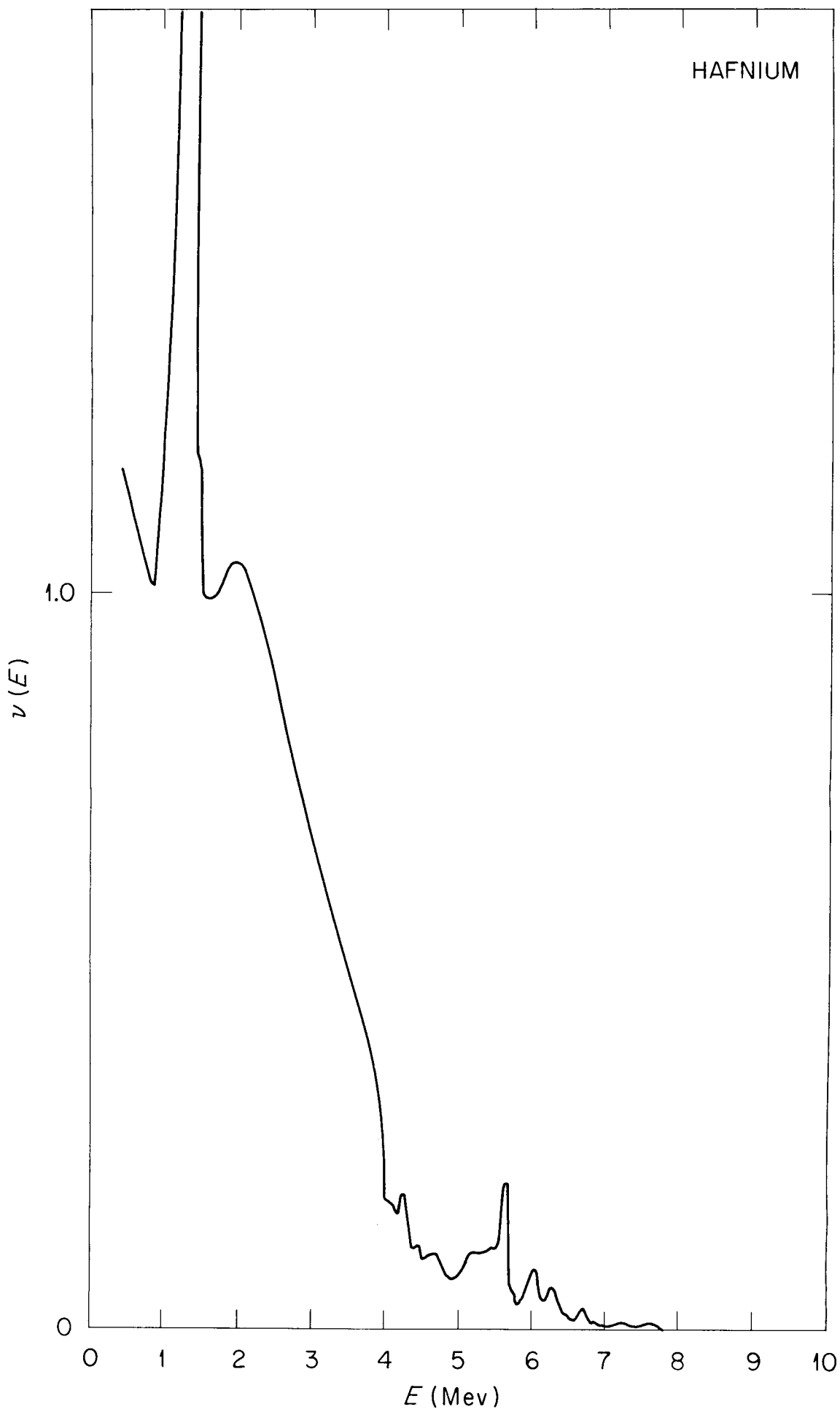

Fig. 40.

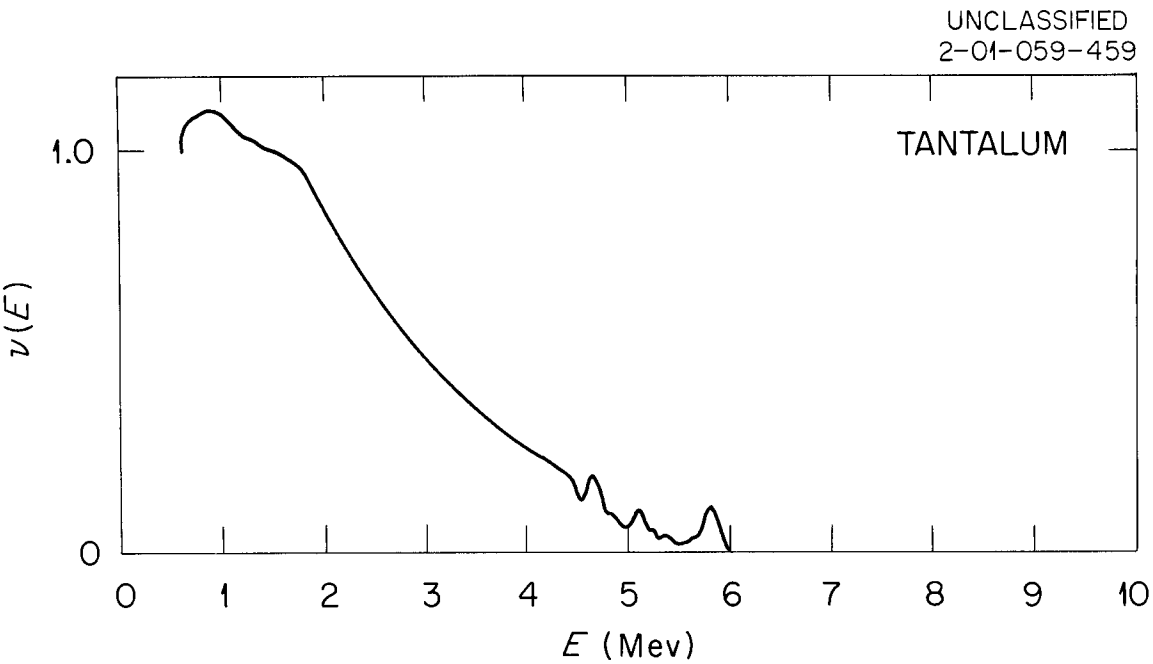
UNCLASSIFIED
2-01-059-459
TANTALUM
1.0
0
ν(E)
0
1
2
3
4
5
6
7
8
9
10
E (Mev)

Fig. 41.

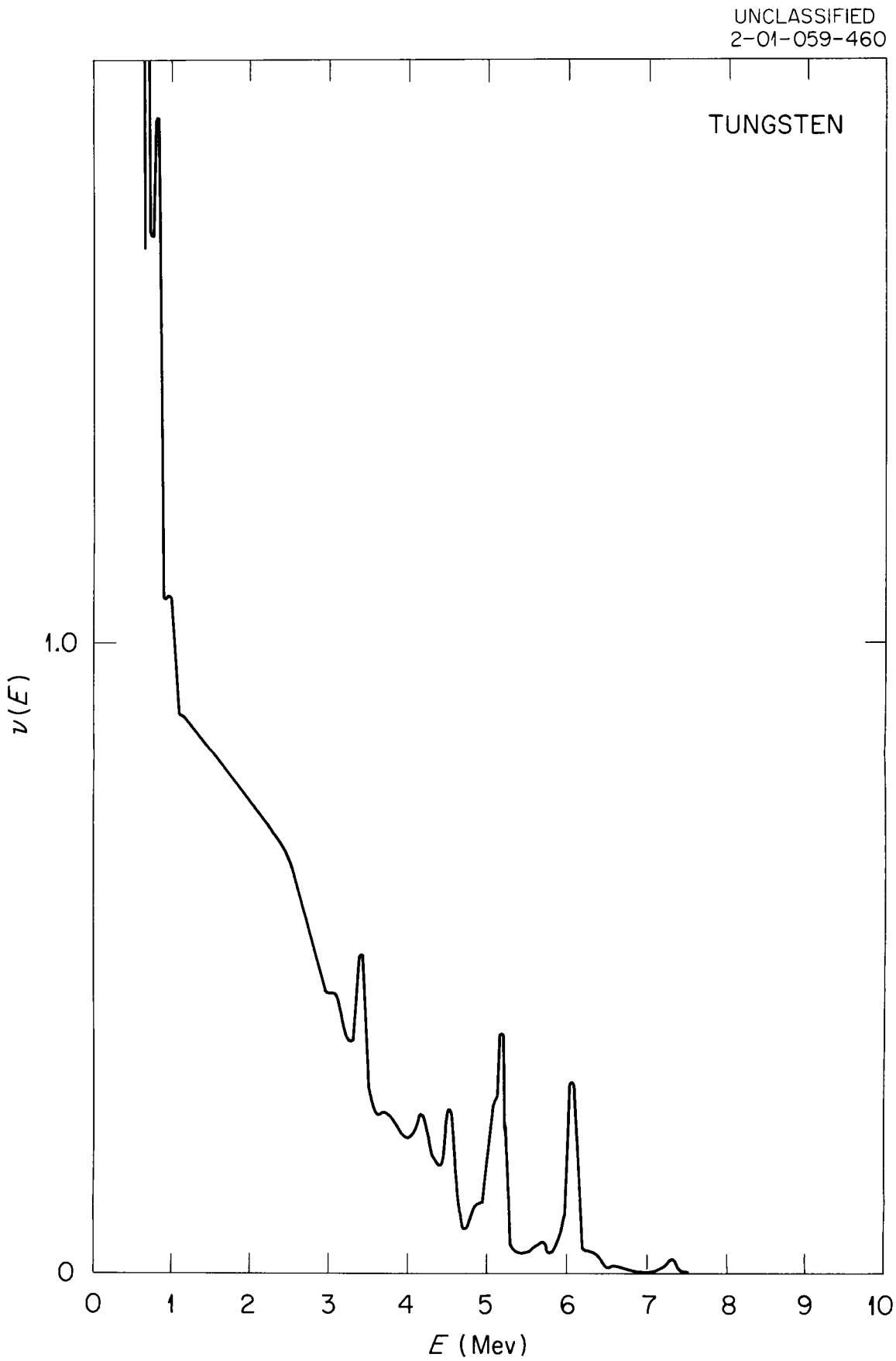
UNCLASSIFIED
2-01-059-460
TUNGSTEN
1.0
0
ν(E)
0
1
2
3
4
5
6
7
8
9
10
E (Mev)

Fig. 42.

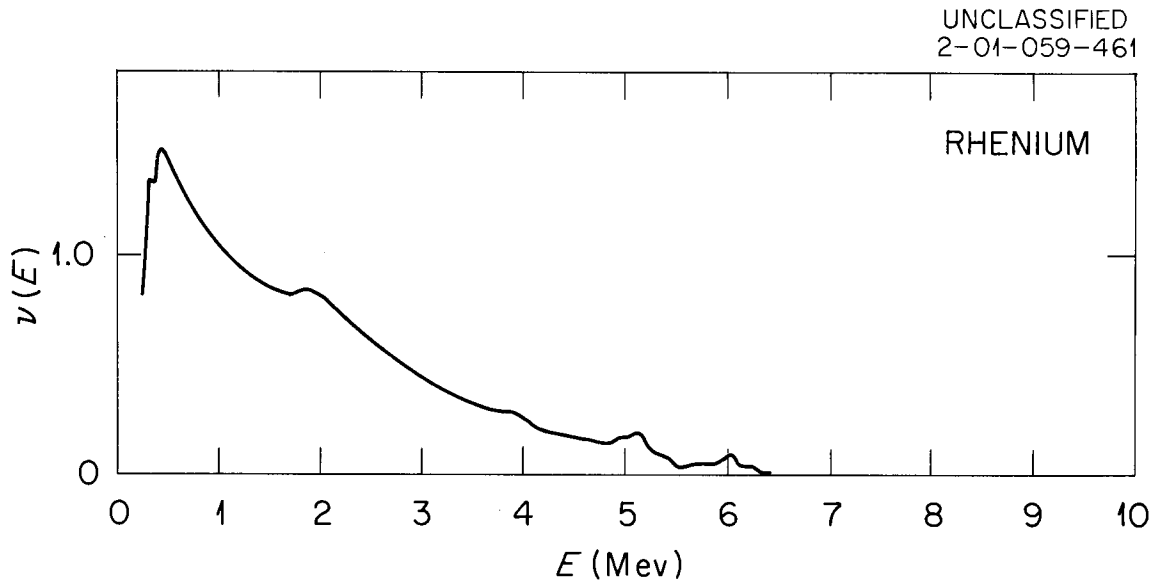
UNCLASSIFIED
2-01-059-461
RHENIUM
ν(E)
1.0
0
0
1
2
3
4
5
6
7
8
9
10
E (Mev)

Fig. 43.

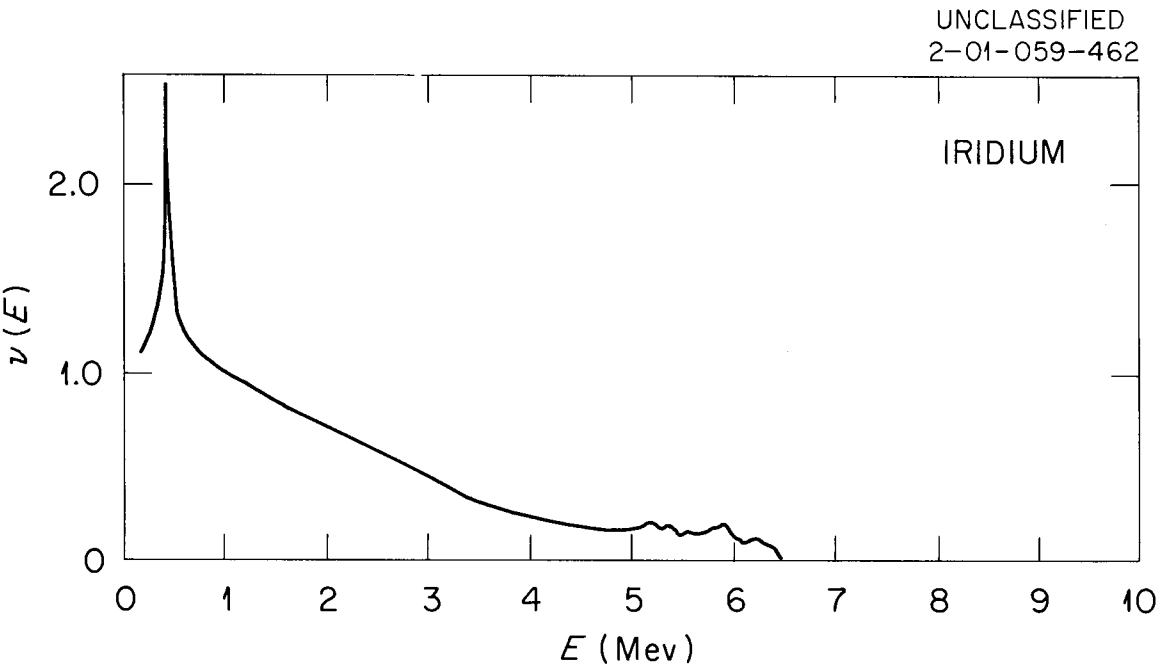
UNCLASSIFIED
2-01-059-462
IRIDIUM
ν(E)
2.0
1.0
0
0
1
2
3
4
5
6
7
8
9
10
E (Mev)

Fig. 44.

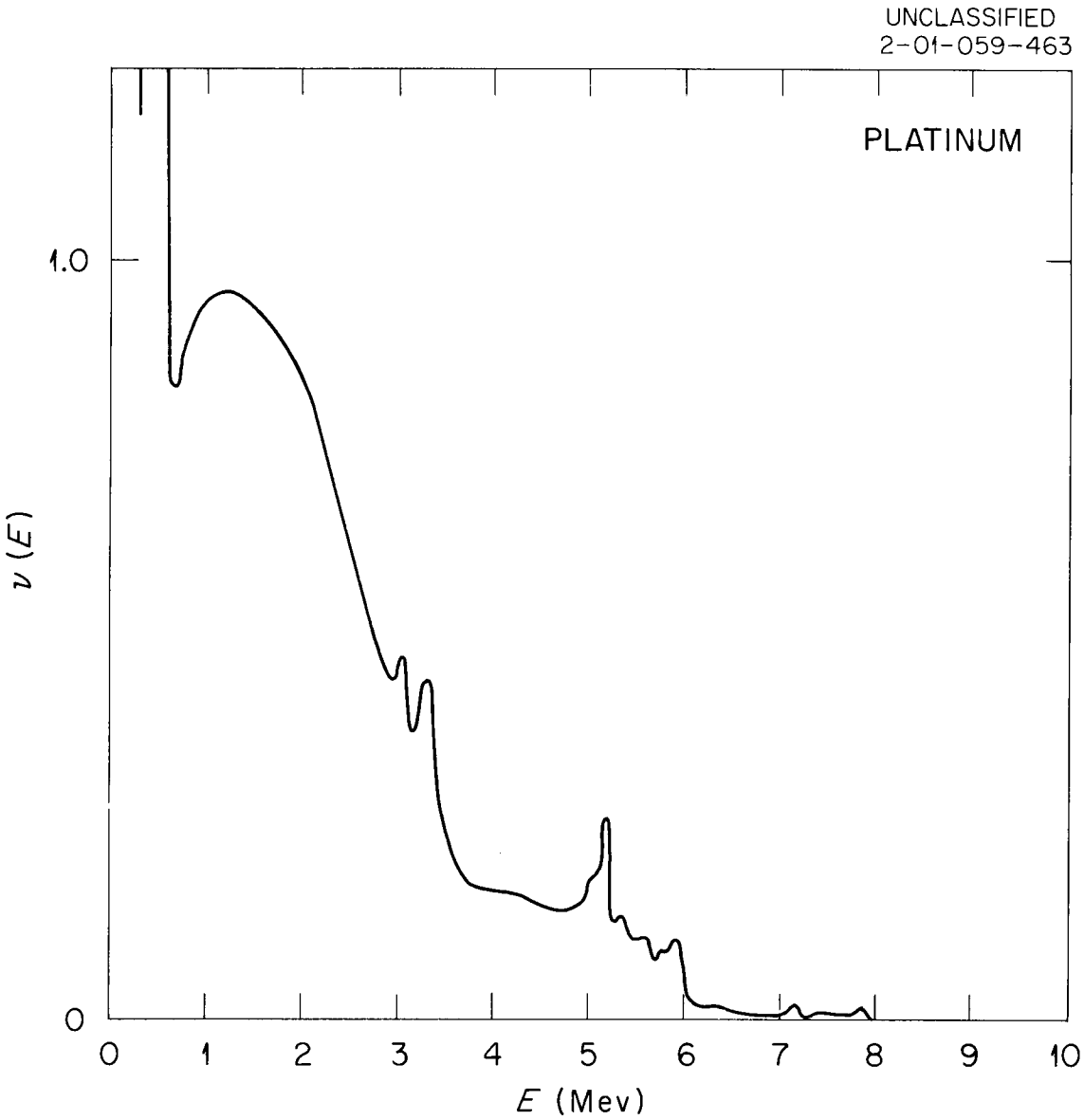
UNCLASSIFIED
2-01-059-463
PLATINUM
1.0
0
ν (E)
0
1
2
3
4
5
6
7
8
9
10
E (Mev)

Fig. 45

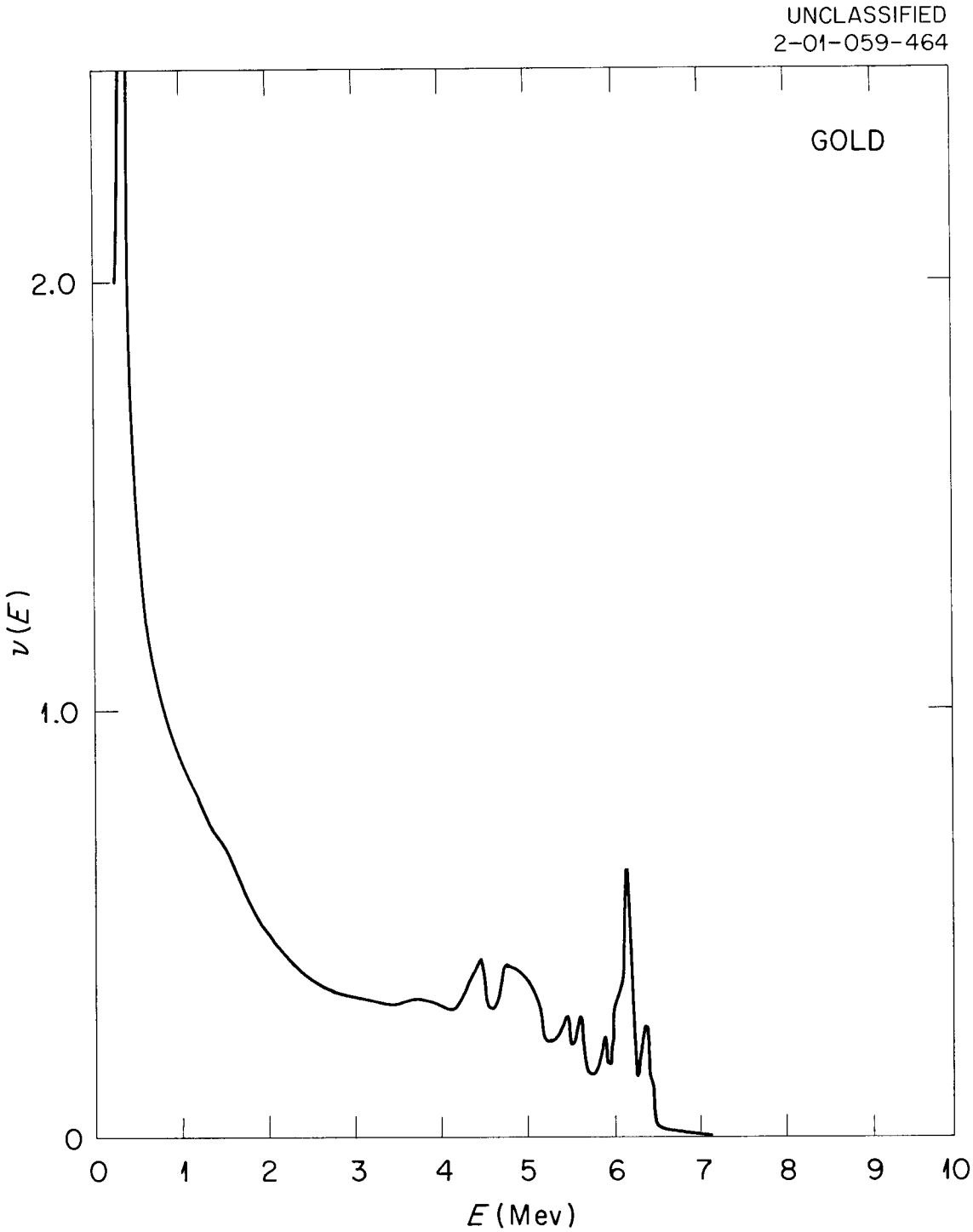

Fig. 46.

UNCLASSIFIED
2-01-059-465

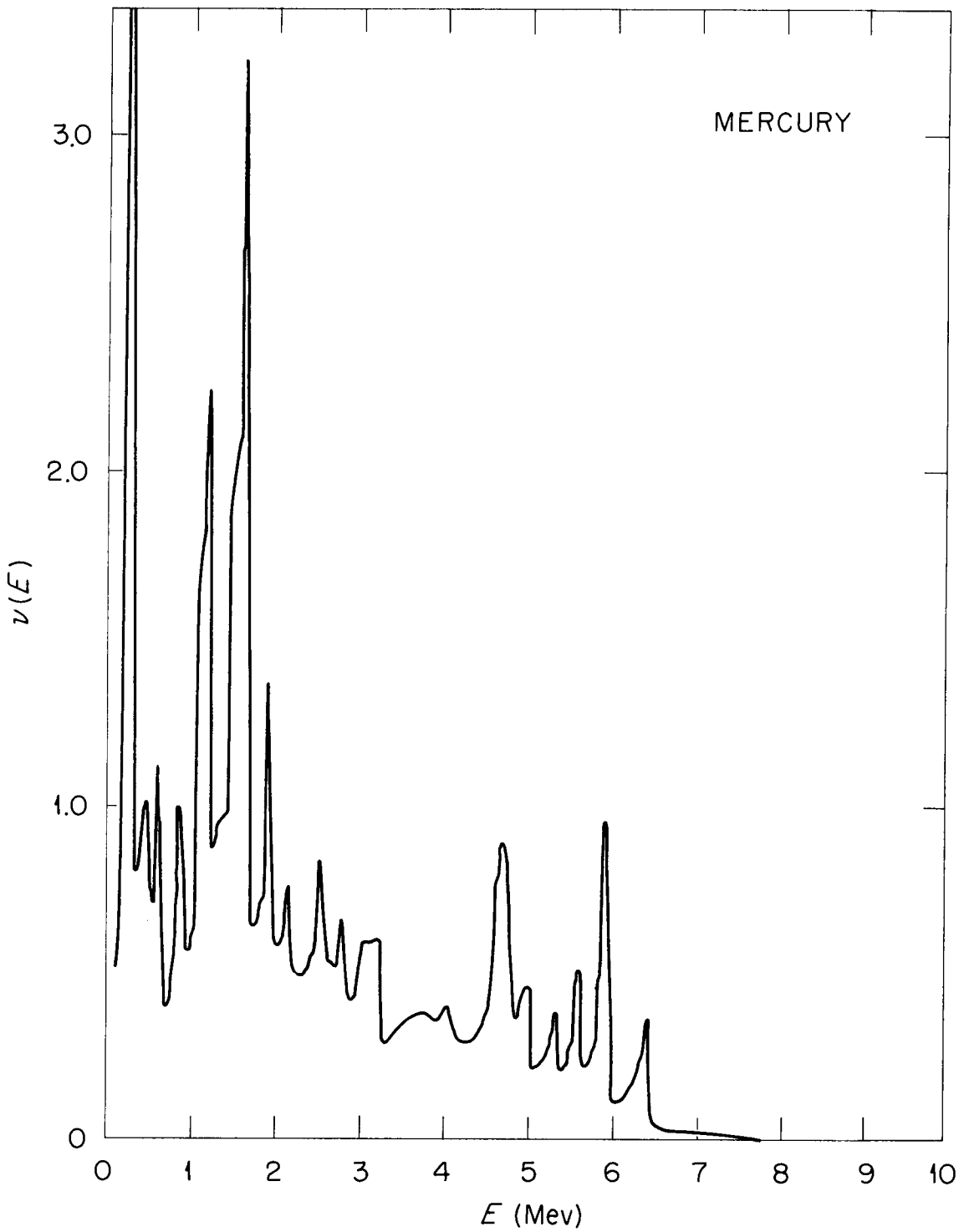

Fig. 47.

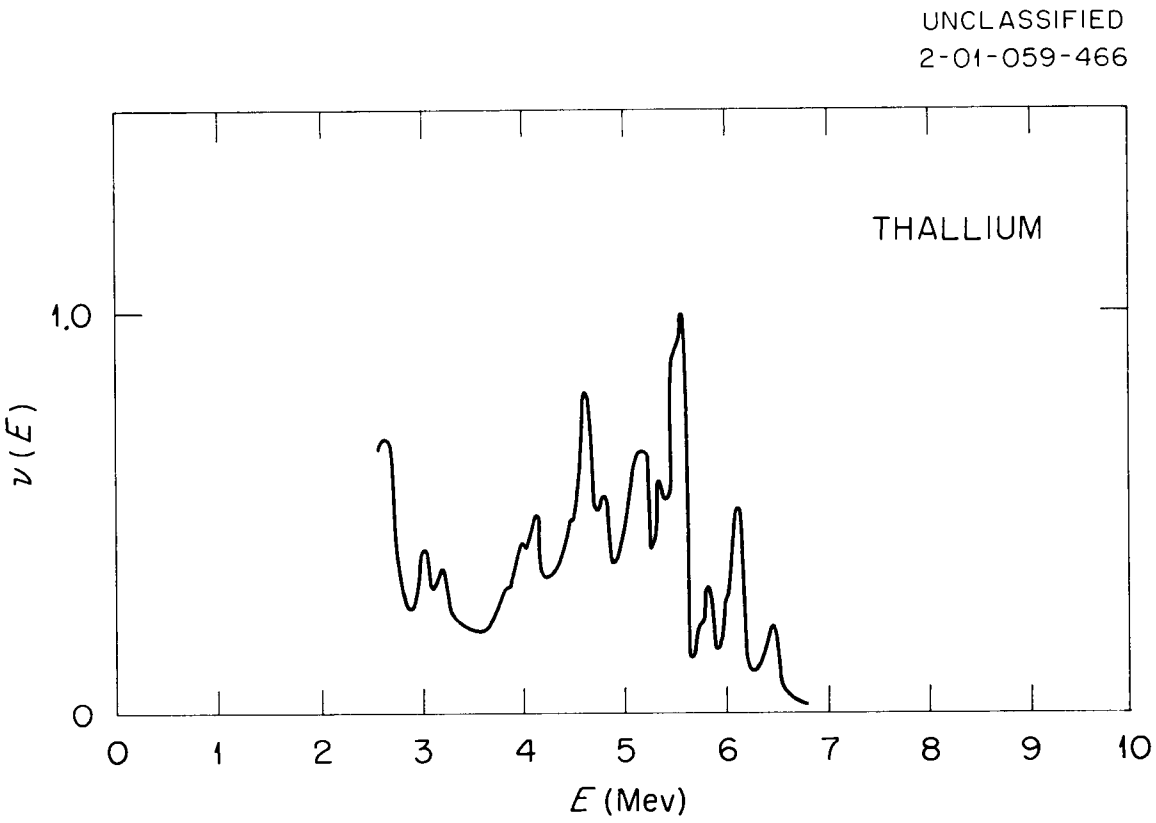
UNCLASSIFIED
2-01-059-466
THALLIUM
1.0
0
ν(E)
0
1
2
3
4
5
6
7
8
9
10
E (Mev)

Fig. 48.

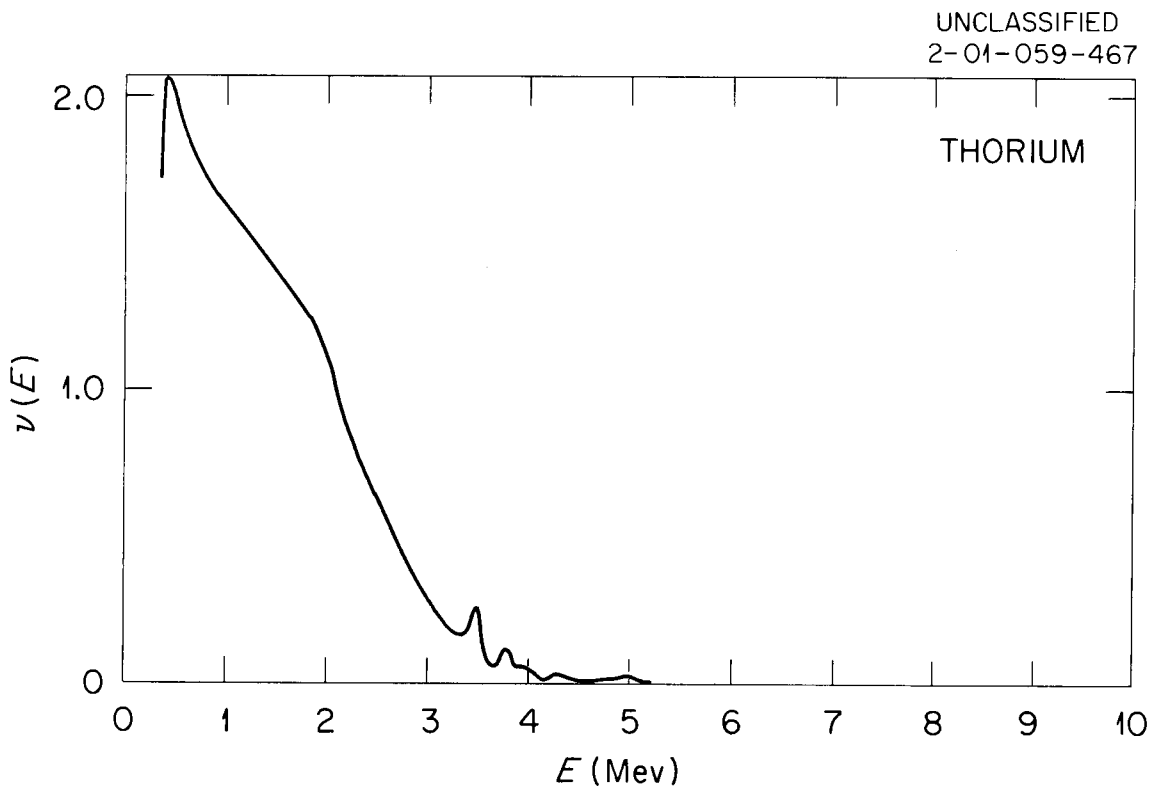
UNCLASSIFIED
2-01-059-467
THORIUM
2.0
1.0
0
ν(E)
0
1
2
3
4
5
6
7
8
9
10
E (Mev)

Fig. 49.

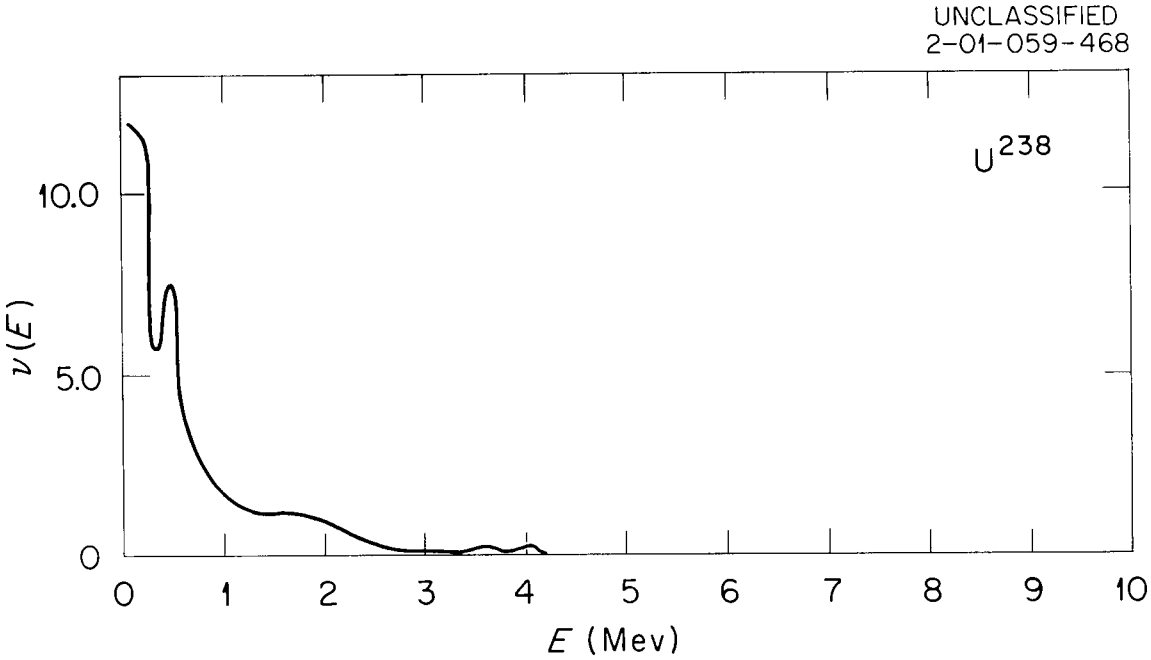

Fig. 50.

IV. Bar Graphs of Line Spectra

Where the capture spectrum consists almost entirely of narrow, well-resolved lines, the observed experimental spectrum gives a poorer idea of the actual spectrum than a bar graph where the height of the vertical bars displays the integrated intensity of lines. Figures 51 through 65 show bar graphs of this type which have been constructed from the data of Table 2. Only lines with intensities of 5 or more photons per 100 captures are included. As with the continuous spectra of the preceding section, annihilation and decay gamma-ray lines have been omitted.

The bar graphs represent the following materials:

Material	Fig. No.	Pg. No.
Hydrogen	51	68
Deuterium	52	68
Li^7	53	69
Beryllium	54	69
B^{10}	55	70
Carbon	56	70
Nitrogen	57	71
Fluorine	58	71
Sodium	59	72
Magnesium	60	72
Sulfur	61	73
Chlorine	62	74
Yttrium	63	74
Lead	64	75
Bismuth	65	75

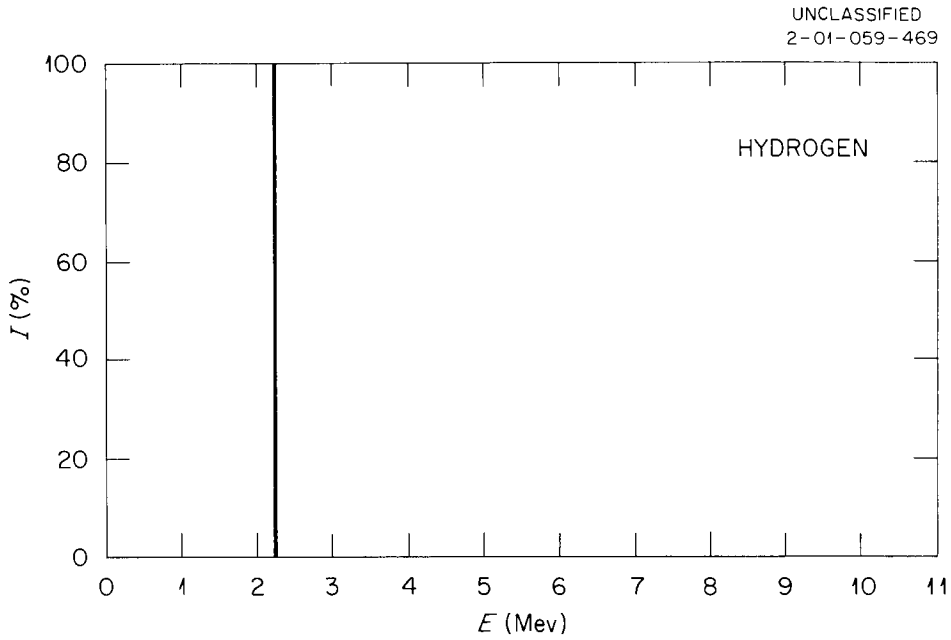
UNCLASSIFIED
2-01-059-469
HYDROGEN
I (%)
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
11
E (Mev)

Fig. 51.

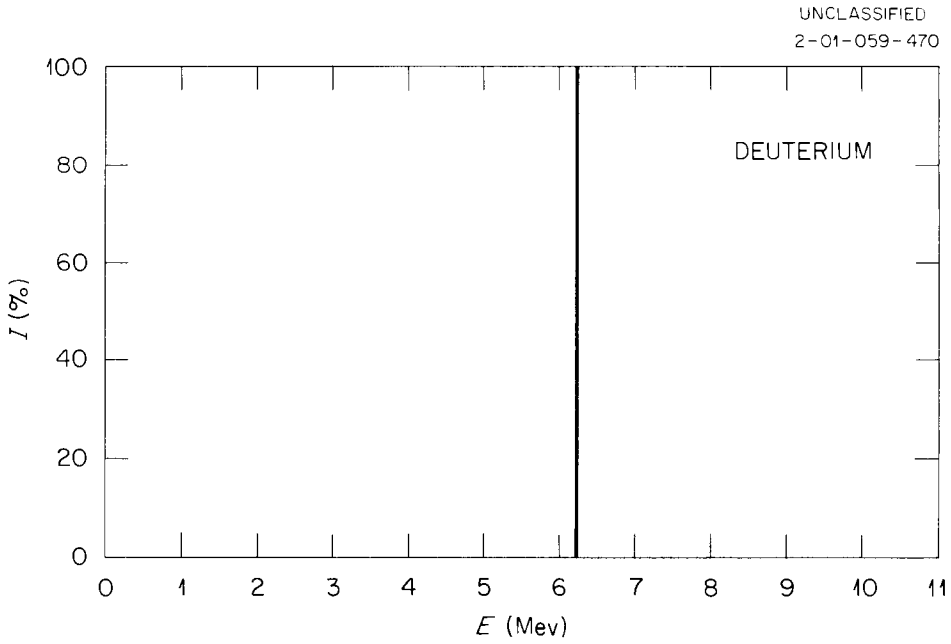
UNCLASSIFIED
2-01-059-470
DEUTERIUM
I (%)
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
11
E (Mev)

Fig. 52.

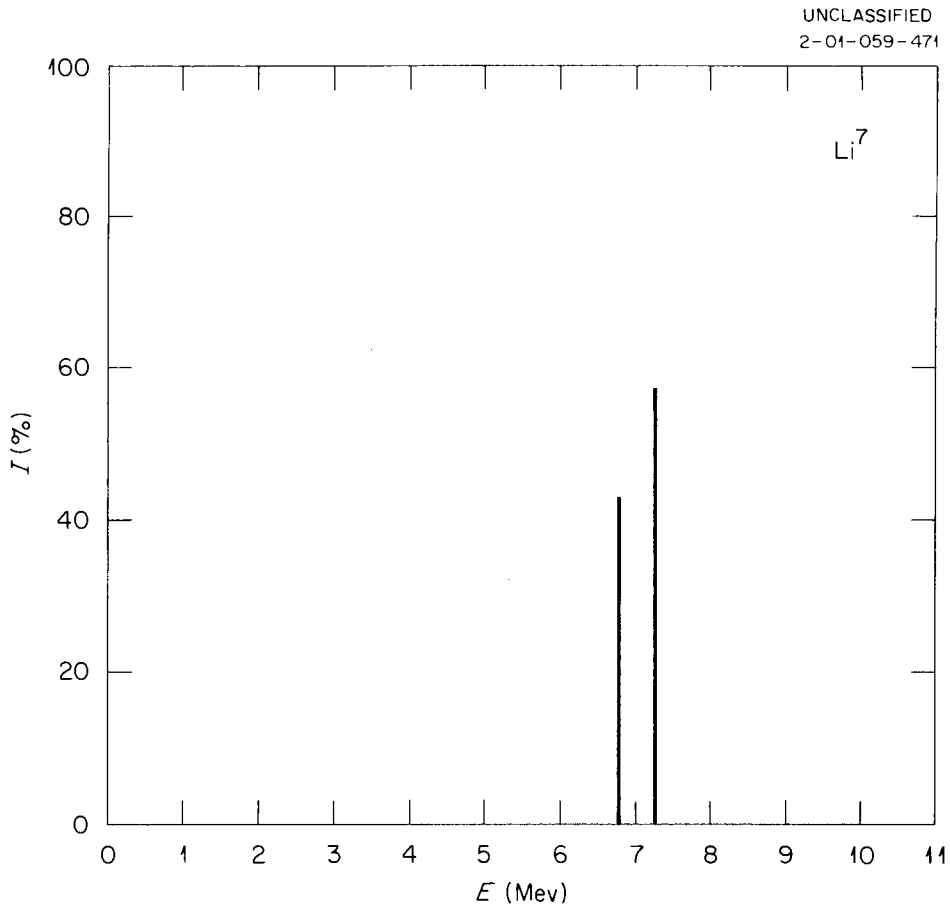
UNCLASSIFIED
2-01-059-471
Li7
I (%)
E (Mev)
0
20
40
60
80
100
0
1
2
3
4
5
6
7
8
9
10
11

Fig. 53.

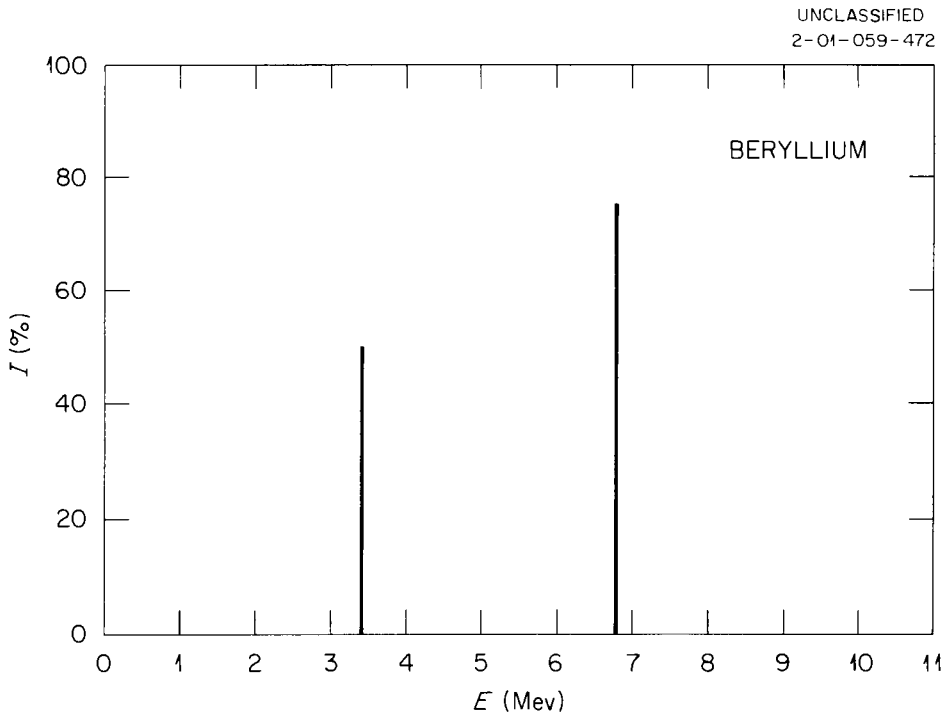
UNCLASSIFIED
2-01-059-472
BERYLLIUM
I (%)
E (Mev)
0
20
40
60
80
100
0
1
2
3
4
5
6
7
8
9
10
11

Fig. 54.

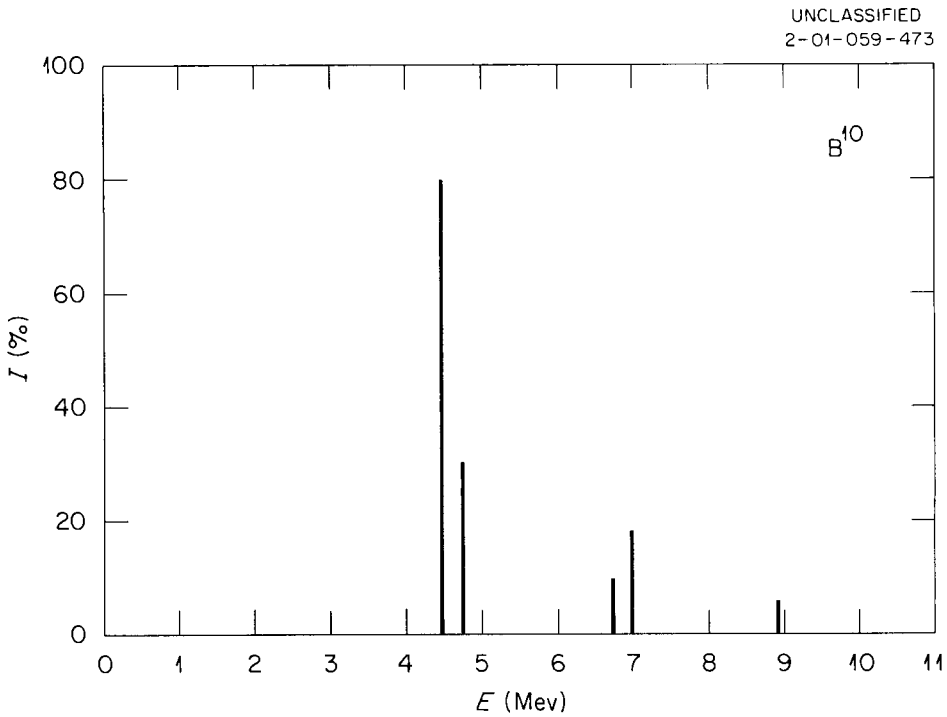
UNCLASSIFIED
2-01-059-473
B^{10}
I (%)
E (Mev)
0
20
40
60
80
100
0
1
2
3
4
5
6
7
8
9
10
11

Fig. 55.

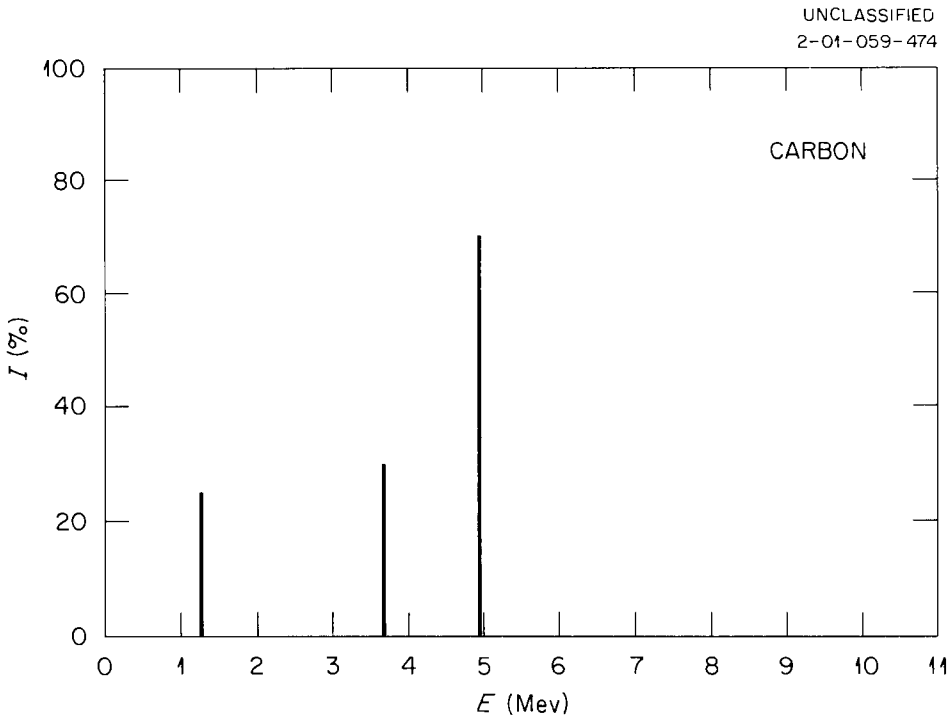
UNCLASSIFIED
2-01-059-474
CARBON
I (%)
E (Mev)
0
20
40
60
80
100
0
1
2
3
4
5
6
7
8
9
10
11

Fig. 56.

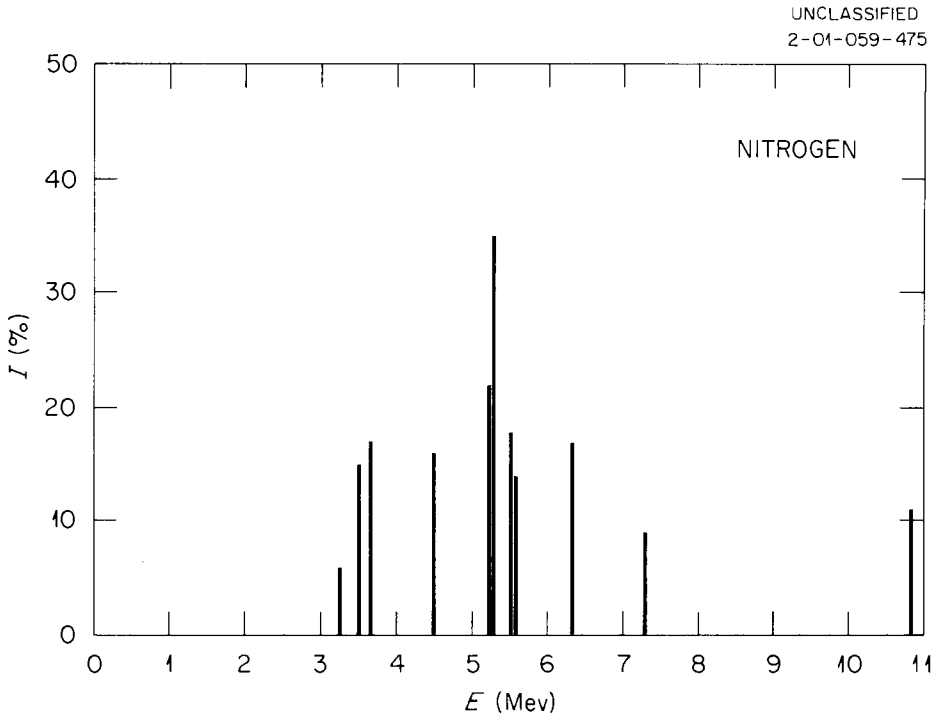
UNCLASSIFIED
2-01-059-475
NITROGEN
I (%)
E (Mev)
0
10
20
30
40
50
0
1
2
3
4
5
6
7
8
9
10
11

Fig. 57.

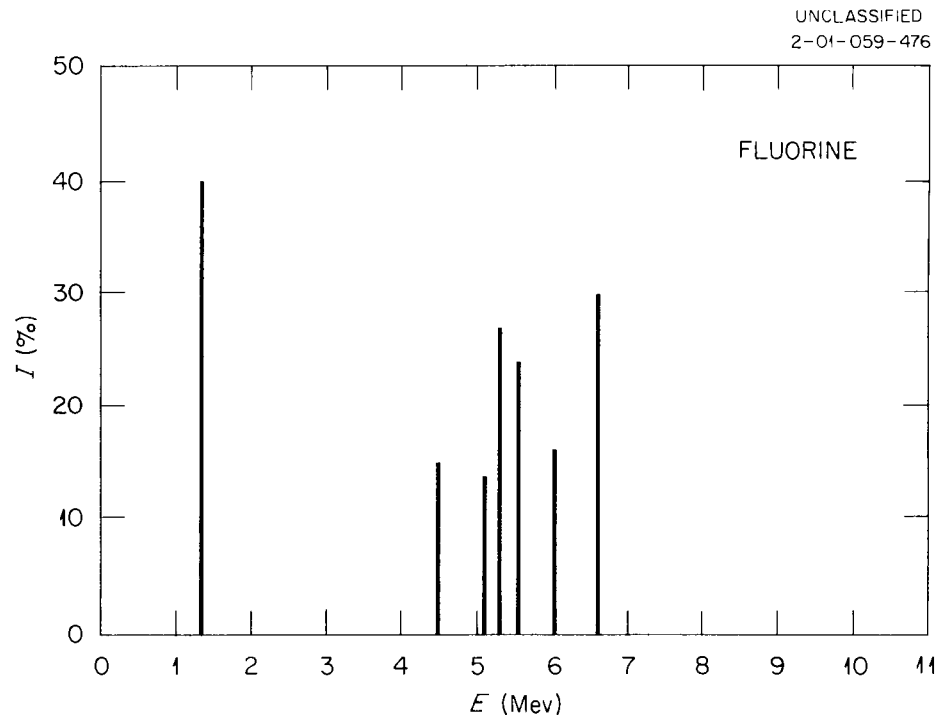
UNCLASSIFIED
2-01-059-476
FLUORINE
I (%)
E (Mev)
0
10
20
30
40
50
0
1
2
3
4
5
6
7
8
9
10
11

Fig. 58.

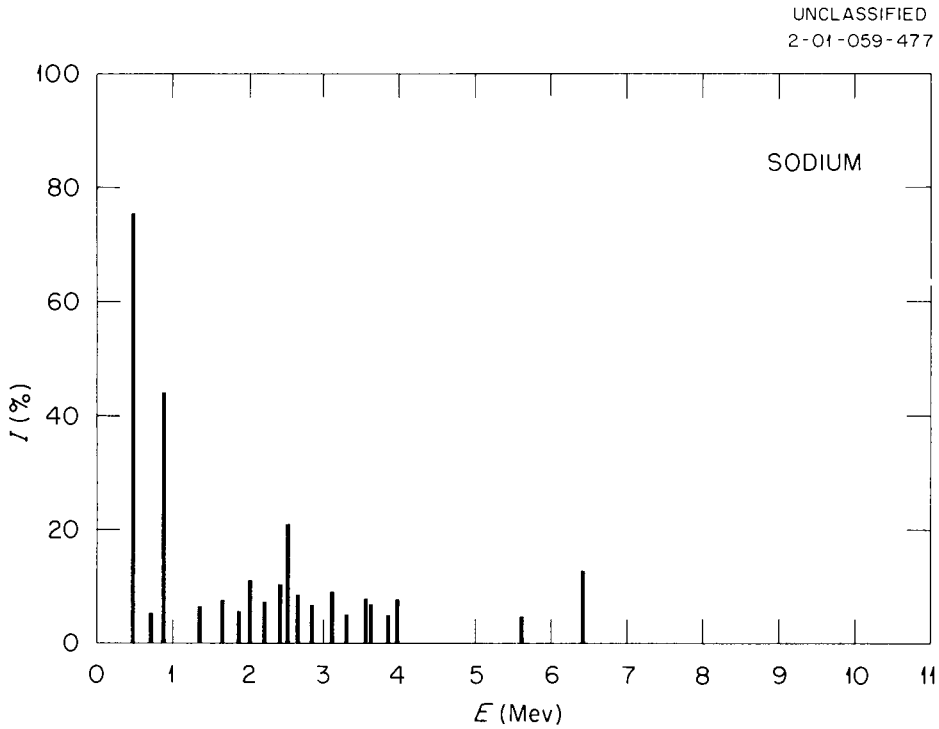
UNCLASSIFIED
2-01-059-477
SODIUM
I (%)
E (Mev)
0
20
40
60
80
100
0
1
2
3
4
5
6
7
8
9
10
11

Fig. 59.

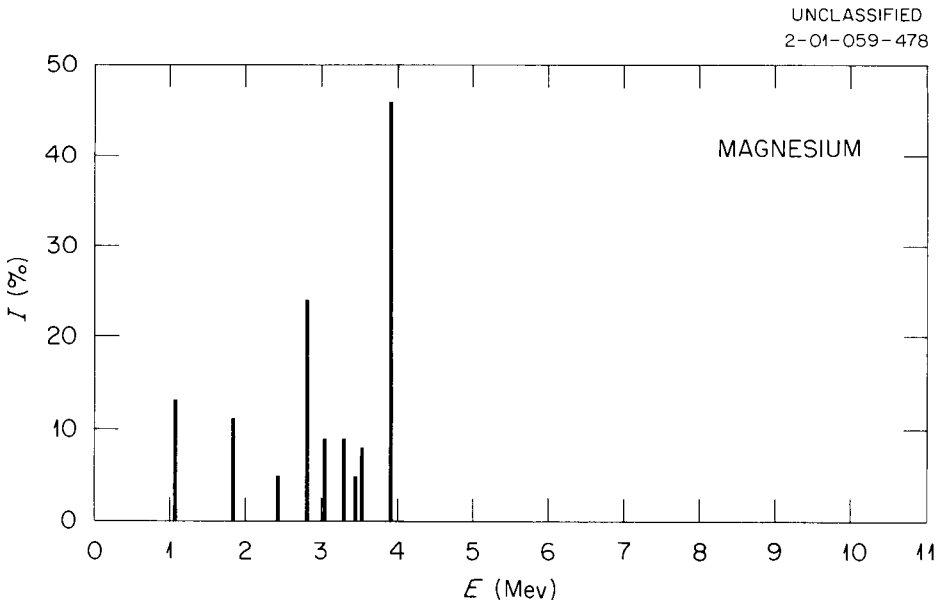
UNCLASSIFIED
2-01-059-478
MAGNESIUM
I (%)
E (Mev)
0
10
20
30
40
50
0
1
2
3
4
5
6
7
8
9
10
11

Fig. 60.

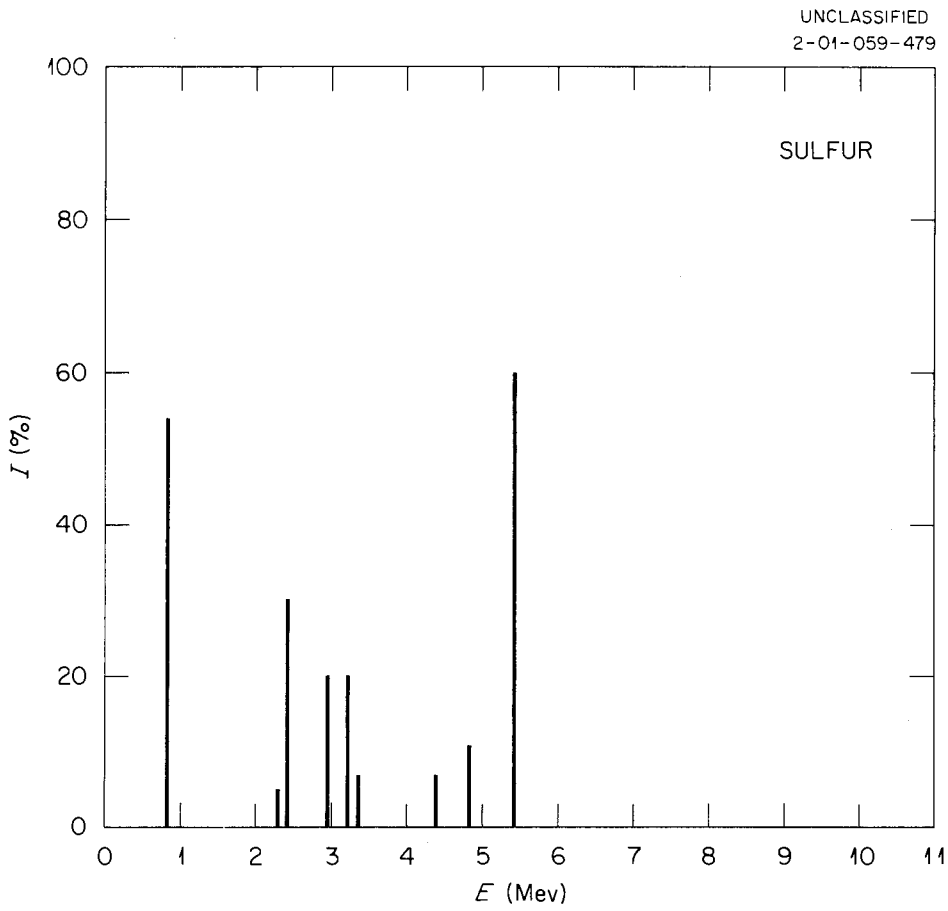
UNCLASSIFIED
2-01-059-479
SULFUR
100
80
60
40
20
0
I (%)
0
1
2
3
4
5
6
7
8
9
10
11
E (Mev)

Fig. 61.

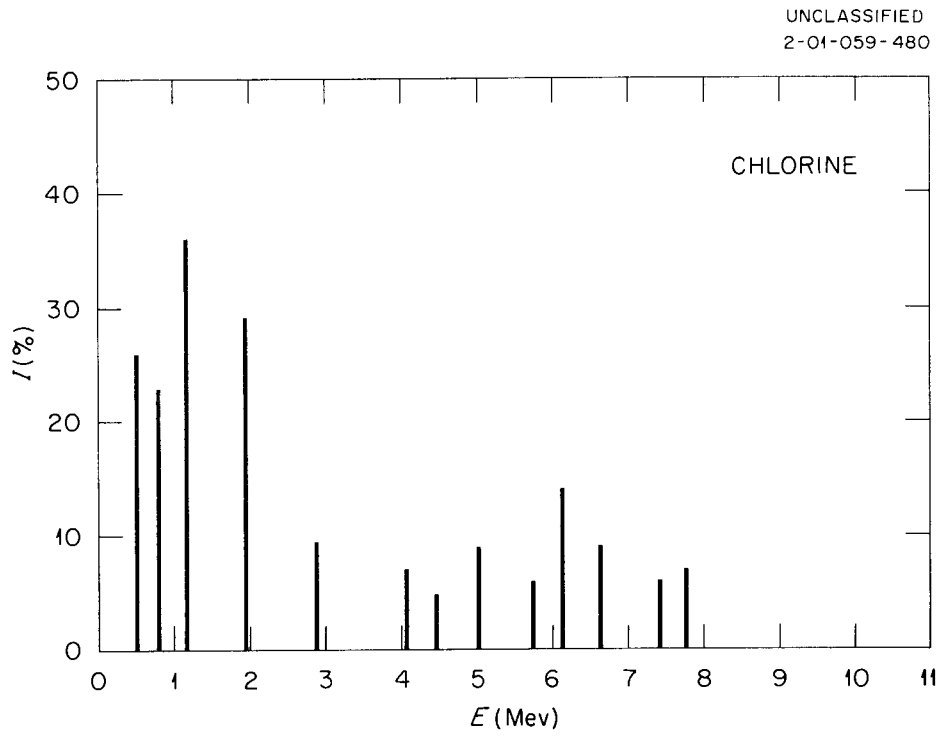
UNCLASSIFIED
2-01-059-480
CHLORINE
I (%)
E (Mev)
0
10
20
30
40
50
0
1
2
3
4
5
6
7
8
9
10
11

Fig. 62.

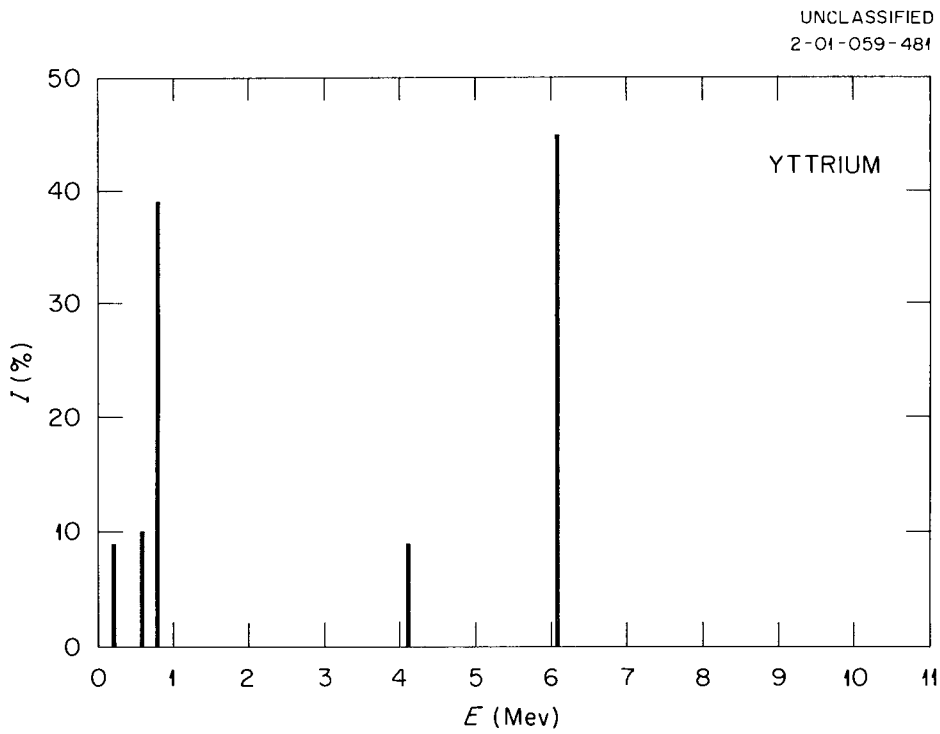
UNCLASSIFIED
2-01-059-481
YTTRIUM
I (%)
E (Mev)
0
10
20
30
40
50
0
1
2
3
4
5
6
7
8
9
10
11

Fig. 63.

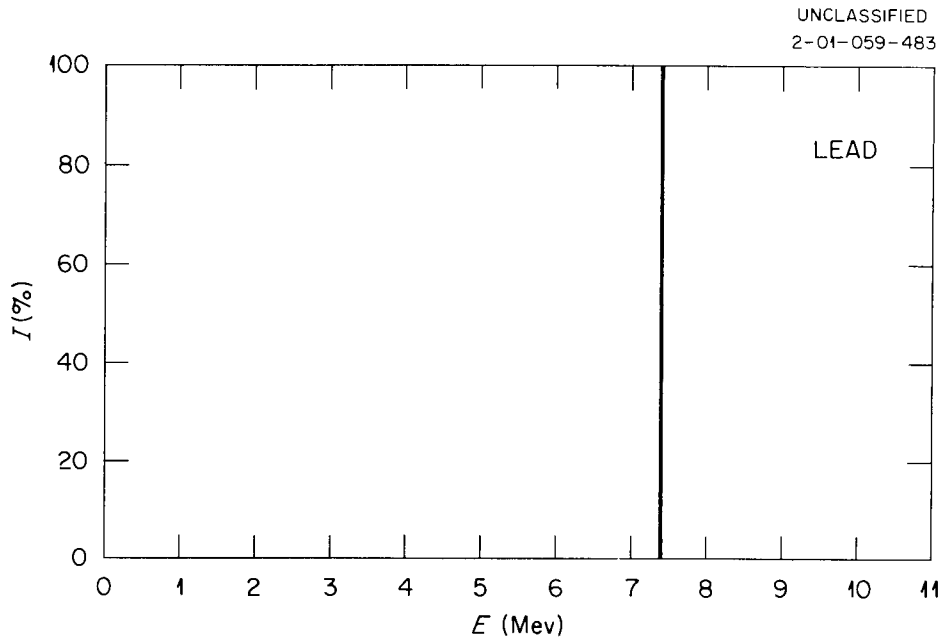
UNCLASSIFIED
2-01-059-483
LEAD
I (%)
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
11
E (Mev)

Fig. 64.

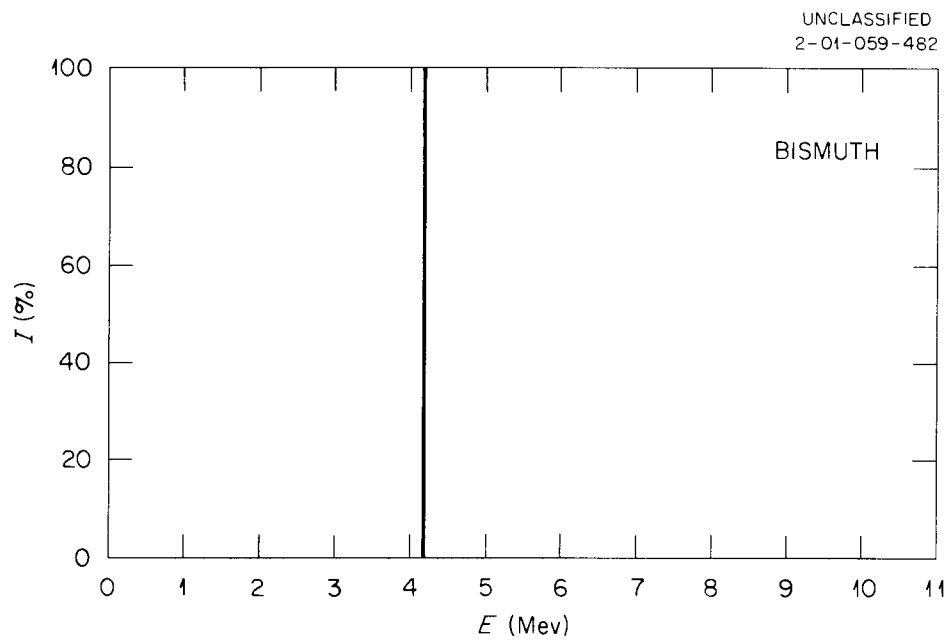
UNCLASSIFIED
2-01-059-482
BISMUTH
I (%)
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
11
E (Mev)

Fig. 65.

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