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Photon Production Assessment for the MCNP™ Data Libraries

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by

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ABSTRACT

The goal of the Multispectral Neutron Logging project was to estimate minimum detection thresholds for environmental contaminants using nuclear well-logging techniques. The specific method was to identify and quantify contaminants from the discrete photons from thermal neutron capture reactions in the formation. Computer simulations using MCNP4A were used to benchmark the computer code against experimental data, and then to predict minimum detection thresholds for other contaminants. High quality photon-production data for MCNP was required for this project. The goal of this work was to assess photon production at thermal neutron energies. This work was extended to include higher energy neutron reactions, E_n=1-14 MeV. Additionally, the assessment was expanded to include all nuclides and not only the contaminants of interest. This report documents the results of the assessment, and makes general recommendations for the user. Ultimately, it is the responsibility of all users to ensure that the data they are using is appropriate for their particular application. This assessment process reinforced the need for higher quality photon-production spectra for use in the Multispectral Neutron Logging project, as well as for other applications.

I. INTRODUCTION

The assessment of photon production for the Recommended and ENDF60 neutron data libraries was originally begun for the Multispectral Neutron Logging (MSL) project at Los Alamos National Laboratory (LANL).[1-2] The goal of the MSL project was to estimate minimum detection thresholds for environmental contaminants using nuclear well-logging techniques. In particular, the goal was to determine the identity and concentration of nuclides present in a formation using the discrete photons from thermal-neutron capture reactions. While it is possible to build physical models to experimentally determine minimum detection thresholds for a few contaminants, it is not practical to use this procedure on a large scale because of expense and regulatory concerns. By benchmarking a computer simulation code against experimental data, one can extend the determination of detection thresholds to a large number of possible contaminants.[3-5] The computer simulation code chosen for this project was the Monte Carlo N-Particle transport code version 4A (MCNP4A),[6] maintained by the Transport Methods group at LANL. The assessment that is the subject of this report initially focused on the specific needs of the MSL project: photon production from thermal neutrons for a set of important nuclides. This assessment has since expanded to include photon production at both thermal and 14-MeV incident neutron energies for all nuclides available in the Recommended and ENDF60 neutron data libraries.

The MSL project's well-logging tool was comprised of a pulsed neutron generator (14 MeV) with a High-Purity Germanium (HPGe) detector. The acquired photon spectra were separated into the inelastic, or high energy, spectrum acquired during the neutron pulse and the thermal spectrum acquired between pulses. The determination of detection thresholds using the discrete photons from the thermal capture reactions required that the computer simulations be able to reproduce the acquired HPGe spectra, showing both the background and discrete photons from interactions in the formation and tool. Cross section libraries having high quality photon-production data were therefore needed for the computer simulation code. After a number of computer simulations were performed, it was evident that high quality photon production was not available in the evaluations or data libraries for some nuclides, though such data had previously been measured. A systematic review of the available data libraries was needed to assess the quality of photon production for elements of interest for the MSL project and was expanded to include all nuclides for which the Recommended and ENDF60 libraries had photon production data. This report documents the computer simulations performed during this assessment process (Section II), and the resulting photon-production spectra produced by the data libraries (Section III). Section IV discusses the use of compilations of thermal neutron capture data in nuclear well-logging applications. It should be noted that this report uses the term *photon-production spectra* loosely; it is actually the photon leakage spectrum resulting from the transport of neutrons through a thin shell of material. It therefore contains photons which have interacted in the material as well as the uncollided photons from the source and downscattered neutrons, but it still allows users to assess the quality of the photon production data for their specific applications.

II. COMPUTER SIMULATIONS

Two neutron data libraries were chosen for the assessment; the MCNP4A Recommended data library (based on ENDF/B-V or LANL evaluations) and the newly available ENDF60 library (based on ENDF/B-VI evaluations).[7] The individual data files that comprise the Recommended neutron data library are ENDF/B-V based or from the Applied Nuclear Theory and Applications group (T-2) at LANL, and are indicated in Appendix G of the MCNP4A manual. Simulations were only performed for the Recommended data files when there was a corresponding data file having photon production data for the ENDF60 library. Therefore, simulations were not performed for the recommended library for Ar, ^{75}As, ^{89}Y, Sn, Xe, Eu, Gd, Re, Pt, $^{239-240}$U, and ^{243}Pu which are from the Lawrence Livermore National Laboratory's (LLNL) Evaluated Nuclear Data Library (ENDL). This is also true for ^{245}Cm for which the recommended library is not ENDF/B-V based. The ENDF60 data library was released to the Radiation Shielding Information Center (RSIC) in the fall of 1994.[6] The general characteristics of the ENDF60 data library are listed in Table 1, which has been revised from that previously reported.[7-8] The individual data files which make up the ENDF60 library were processed at 300°K, as is true for *most of* the data files of

Table 1: The ENDF60 Neutron Data Library for MCNP

ZAID	Filename	Evaluation	Type	Revision	Photon
1001.60c	h1001	LANL	N [a]	6.1 [b]	yes [c]
1002.60c	d1002	LANL,AWRE	N	-	-
1003.60c	t1003	LANL	T	-	no
2003.60c	he2003	LANL	N	6.1	no
2004.60c	he2004	LANL	T	-	no
3006.60c	li3006	LANL	N	6.1	-
3007.60c	li3007	LANL	N	-	-
4009.60c	be4009	LLNL	N	-	-
5010.60c	b5010	LANL	N	6.1	-
5011.60c	b5011	LANL	N	-	-
6000.60c	c6000	ORNL	N	6.1	-
7014.60c	n7014	LANL	N	LANL	-
7015.60c	n7015	LANL	N	-	-
8016.60c	o8016	LANL	N	-	-
8017.60c	o8017	BNL	T	-	no
9019.60c	f9019	ORNL	N	-	-
11023.60c	na11023	ORNL	T	6.1	-
12000.60c	mg12000	ORNL	T	-	-
13027.60c	al13027	LANL	T	-	-
14000.60c	si14000	ORNL	T	-	-
15031.60c	p15031	LLNL	T	-	-
16000.60c	s16000	BNL	T	-	-
16032.60c	s16032	LLNL	T	-	-
17000.60c	cl17000	GGA	T	-	-
19000.60c	k19000	GGA	T	-	-
20000.60c	ca20000	ORNL	N	-	-
21045.60c	sc21045	BNL	N	6.2	-
22000.60c	ti22000	BRC,ANL	T	-	-
23000.60c	v23000	ANL,LLNL,+	N	-	-
24050.60c	cr24050	ORNL	N	6.1	-
24052.60c	cr24052	ORNL	N	6.1	-

a N or T indicates a new or translated evaluation respectively, relative to the ENDF/B-V evaluation.

b All revisions are 6.0 of ENDF/B-VI unless otherwise specified. LANL indicates that modifications were performed.

c All nuclides have photon production unless otherwise noted.

Table 1 (cont.) The ENDF60 Neutron Data Library for MCNP

ZAID	Filename	Evaluation	Type	Revision	Photon
24053.60c	cr24053	ORNL	N	6.1	-
24054.60c	cr24054	ORNL	N	6.1	-
25055.60c	mn25055	ORNL	N	-	-
26054.60c	fe26054	ORNL	N	6.1	-
26056.60c	fe26056	ORNL	N	6.1	-
26057.60c	fe26057	ORNL	N	6.1	-
26058.60c	fe26058	ORNL	N	6.1	-
27059.60c	co27059	ANL	N	6.2	-
28058.60c	ni28058	ORNL	N	6.1	-
28060.60c	ni28060	ORNL	N	6.1	-
28061.60c	ni28061	ORNL	N	6.1	-
28062.60c	ni28062	ORNL	N	6.1	-
28064.60c	ni28064	ORNL	N	6.1	-
29063.60c	cu29063	ORNL	N	6.2	-
29065.60c	cu29065	ORNL	N	6.2	-
31000.60c	ga31000	LLNL,LANL	T	-	-
39089.60c	y39089	ANL,LLNL	N	-	-
40000.60c	zr40000	SAI,BNL	T	6.1	no
41093.60c	nb41093	ANL,LLL	N	6.1	-
42000.60c	mo42000	LLNL,HEDL	T	-	-
43099.60c	tc43099	HEDL,BAW	T	-	no
47107.60c	ag47107	BNL,HEDL	N	-	no
47109.60c	ag47109	BNL,HEDL	N	-	no
49000.60c	in49000	ANL	N	-	-
53127.60c	i53127	HEDL,RCN	N	LANL	-
53129.60c	i53129	HEDL,RCN	T	-	no
55133.60c	cs55133	HEDL,BNL,+	T	-	no
55134.60c	cs55134	ORNL,HEDL	N	-	no
55135.60c	cs55135	HEDL	T	-	no
55136.60c	cs55136	HEDL	T	-	no
55137.60c	cs55137	HEDL	T	-	no

a N or T indicates a new or translated evaluation respectively, relative to the ENDF/B-V evaluation.

b All revisions are 6.0 of ENDF/B-VI unless otherwise specified. LANL indicates that modifications were performed.

c All nuclides have photon production unless otherwise noted.

Table 1 (cont.) The ENDF60 Neutron Data Library for MCNP

ZAID	Filename	Evaluation	Type	Revision	Photon
56138.60c	ba56138	ORNL,HEDL	T	-	-
63151.60c	eu63151	LANL	N	-	-
63153.60c	eu63153	LANL	N	-	-
64152.60c	gd64152	BNL	T	-	no
64154.60c	gd64154	BNL	T	-	no
64155.60c	gd64155	BNL	T	-	no
64156.60c	gd64156	BNL	T	-	no
64157.60c	gd64157	BNL	T	-	no
64158.60c	gd64158	BNL	T	-	no
64160.60c	gd64160	BNL	T	-	no
67165.60c	ho67165	LANL	N	-	-
72000.60c	hf72000	SAI	T	-	no
73181.60c	ta73181	LLNL	T	-	-
73182.60c	ta73182	AI	T	-	no
74182.60c	w74182	LANL,ANL,+	N	-	-
74183.60c	w74183	LANL,ANL,+	N	-	-
74184.60c	w74184	LANL,ANL,+	N	-	-
74186.60c	w74186	LANL,ANL,+	N	-	-
75185.60c	re75185	ORNL,LANL	N	-	no
75187.60c	re75187	ORNL,LANL	N	-	no
79197.60c	au79197	LANL	N	6.1	-
82206.60c	pb82206	ORNL	N	-	-
82207.60c	pb82207	ORNL	N	6.1	-
82208.60c	pb82208	ORNL	N	-	-
83209.60c	bi83209	ANL	N	-	-
90230.60c	th90230	HEDL	T	-	no
90232.60c	th90232	BNL,ANL,+	T	-	-
91231.60c	pa91231	HEDL	T	-	no
92232.60c	u92232	HEDL	T	-	no
92233.60c	u92233	LANL,ORNL	T	-	-
92234.60c	u92234	BNL,GGA	T	-	no

a N or T indicates a new or translated evaluation respectively, relative to the ENDF/B-V evaluation.

b All revisions are 6.0 of ENDF/B-VI unless otherwise specified. LANL indicates that modifications were performed.

c All nuclides have photon production unless otherwise noted.

Table 1 (cont.) The ENDF60 Neutron Data Library for MCNP

ZAID	Filename	Evaluation	Type	Revision	Photon
92235.60c	u92235	ORNL,LANL	N	6.2	-
92236.60c	u92236	HEDL	N	-	no
92238.60c	u92238	ORNL,LANL,+	N	6.2	-
93237.60c	np93237	LANL	N	6.1	-
93238.60c	np93238	SRL	N	6.2	no
93239.60c	np93239	ORNL	N	-	no
94236.60c	pu94236	HEDL,SRL	T	-	no
94237.60c	pu94237	HEDL	T	-	no
94238.60c	pu94238	HEDL,AI,+	T	-	no
94239.60c	pu94239	LANL	N	6.2	-
94240.60c	pu94240	ORNL	N	6.2	-
94241.60c	pu94241	ORNL	N	6.1	-
94242.60c	pu94242	HEDL,SRL,+	T	-	-
94243.60c	pu94243	BNL,SRL,+	N	6.2	-
94244.60c	pu94244	HEDL,SRL	T	-	no
95241.60c	am95241	CNDC	N	LANL	-
95242.60c	am95242	SRL	T	6.1	no
95243.60c	am95243	ORNL,HEDL,+	N	-	-
96241.60c	cm96241	HEDL	T	-	no
96242.60c	cm96242	HEDL,SRL,+	T	-	-
96243.60c	cm96243	HEDL,SRL,+	T	-	-
96244.60c	cm96244	HEDL,SRL,+	T	-	-
96245.60c	cm96245	SRL,LLNL	T	6.2	-
96246.60c	cm96246	BNL,SRL,+	T	6.2	-
96247.60c	cm96247	BNL,SRL,+	T	6.2	-
96248.60c	cm96248	HEDL,SRL,+	T	-	-
97249.60c	bk97249	CNDC	N	-	no
98249.60c	cf98249	CNDC	N	LANL	no
98250.60c	cf98250	BNL,SRL,+	T	6.2	-
98251.60c	cf98251	BNL,SRL,+	T	6.2	-
98252.60c	cf98252	BNL,SRL,+	T	6.2	-

a N or T indicates a new or translated evaluation respectively, relative to the ENDF/B-V evaluation.

b All revisions are 6.0 of ENDF/B-VI unless otherwise specified. LANL indicates that modifications were performed.

c All nuclides have photon production unless otherwise noted.

the Recommended library. Forty-five percent of the ENDF60 data files are from translated ENDF/B-V evaluations for which there should be only slight differences due to processing. The remaining 55% are from new evaluations which have sometimes changed significantly. [9] Each data file is referenced by a file name of the format EEZZAAA, where EE is the elemental symbol, ZZ is the atomic number, and AAA is the isotope or 000 indicating a natural element file. The ZAID, file name, evaluation group, evaluation type, revision number, and photon production availability are given for each nuclide. The evaluation group is identified by the laboratory participants who performed the evaluation, and the evaluation type indicates whether the ENDF/B-VI evaluation is a new (N) or translated (T) evaluation, relative to the ENDF/B-V revision 0 evaluations used for the previous MCNP libraries. The corresponding revision number for the ENDF/B-VI release is specified, where (-) indicates release 6.0. If the evaluation has been modified at Los Alamos, to add in photon production for instance, the revision number has been specified as LANL. Note that the ENDF60 data file for ^{242}Am is for the ground state, whereas all others referenced in Appendix G of the MCNP4A manual are for the metastable state of ^{242}Am.

The simulation geometry was a spherical void region of radius 1 cm, with a thermal-neutron (0.025 eV) or 14-MeV point-source at the center. This was enclosed by a spherical shell of the element or nuclide of interest, with inner radius of 1 cm and an outer radius of 1.5 cm. Another spherical shell void region, with outer radius of 2 cm, was used to perform an F4-tally for the photon flux as a function of energy. The photon flux was tallied over the energy region E_γ=0.0-14.0 MeV and binned in 5 keV energy bins. The density of the element of interest was increased to 10 g/cm^3 if the natural density was less than 5 g/cm^3, allowing the simulations to be performed in a timely manner for the lower density elements without significantly affecting the photon flux tally. A low-energy neutron cutoff of E_n=1.0 MeV was used in the high energy simulations. An F4-tally of the neutron flux was also performed to ensure that all energies were represented. The computer simulations were performed using the natural isotopic composition for each element, or for the individual isotope if there is no naturally occurring element, at 300°K. Table 2 gives the actual material specification, ZAID and atom fraction, for each MCNP simulation.[10]

Table 2: Material Specifications for the MCNP4A Recommended and ENDF60 Libraries

Element	Recommended Specification		ENDF/B VI Specification	
H	1001.50c	1.0000	1001.60c	1.0000
D	1002.55c	1.0000	1002.60c	1.0000
Li	3006.50c	0.0750	3006.60c	0.0750
	3007.55c	0.9250	3007.60c	0.9250
Be	4009.50c	1.0000	4009.60c	1.0000
B	5010.50c	0.1990	5010.60c	0.1990
	5011.56c	0.8010	5011.60c	0.8010
C	6000.50c	1.0000	6000.60c	1.0000
N	7014.50c	0.9963	7014.60c	0.9963
	7015.55c	0.0037	7015.60c	0.0037
O	8016.50c	1.0000	8016.60c	1.0000
F	9019.50c	1.0000	9019.60c	1.0000
Na	11023.50c	1.0000	11023.60c	1.0000
Mg	12000.50c	1.0000	12000.60c	1.0000
Al	13027.50c	1.0000	13027.60c	1.0000
Si	14000.50c	1.0000	14000.60c	1.0000
P	15031.50c	1.0000	15031.60c	1.0000
S	no Recommended		16000.60c	1.0000
^{32}S	16032.50c	1.0000	16032.60c	1.0000
Cl	17000.50c	1.0000	17000.60c	1.0000
K	19000.50c	1.0000	19000.60c	1.0000
Ca	20000.50c	1.0000	20000.60c	1.0000
Sc			21045.60c	1.0000
Ti	22000.50c	1.0000	22000.60c	1.0000
V	23000.50c	1.0000	23000.60c	1.0000
Cr	24000.50c	1.0000	24050.60c	0.0435
			24052.60c	0.8379
			24053.60c	0.0950
			24054.60c	0.0236
Mn	25055.50c	1.0000	25055.60c	1.0000
Fe	26000.55c	1.0000	26054.60c	0.0580
			26056.60c	0.9172
			26057.60c	0.0220
			26058.60c	0.0028
Co	27059.50c	1.0000	27059.60c	1.0000
Ni	28000.50c	1.0000	28058.60c	0.6827
			28060.60c	0.2610
			28061.60c	0.0113
			28062.60c	0.0359
			28064.60c	0.0091
Cu	29000.50c	1.0000	29063.60c	0.6917
			29065.60c	0.3083
Ga	31000.50c	1.0000	31000.60c	1.0000
Y	not ENDF or LANL		39089.60c	1.0000
Nb	41093.50c	1.0000	41093.60c	1.0000

Table 2 (cont.) Material Specifications for the MCNP4A Recommended and ENDF60 Libraries

Element	Recommended Specification	ENDF60 Specification
Mo	42000.50c 1.0000	42000.60c 1.0000
In	no Recommended	49000.60c 1.0000
I	no photon production	53127.60c 1.0000
Ba	56138.50c 1.0000	56138.60c 1.0000
Eu	63151.55c 0.4780 63153.55c 0.5220	63151.60c 0.4780 63153.60c 0.5220
Ho	67165.55c 1.0000	67165.60c 1.0000
Ta	73181.50c 1.0000	73181.60c 1.0000
W	74182.55c 0.2633 74183.55c 0.1432 74184.55c 0.3071 74186.55c 0.2864	74182.60c 0.2633 74183.60c 0.1432 74184.60c 0.3071 74186.60c 0.2864
Au	79197.56c 1.0000	79197.60c 1.0000
Pb	82000.50c 1.0000	82206.60c 0.2444 82207.60c 0.2241 82208.60c 0.5314
^{209}Bi	83209.50c 1.0000	83209.60c 1.0000
^{232}Th	90232.50c 1.0000	90232.60c 1.0000
^{233}U	no photon production	92233.60c 1.0000
U	92235.50c 0.0073 92238.50c 0.9927	92235.60c 0.0073 92238.60c 0.9927
^{237}Np	no photon production	93237.60c 1.0000
^{239}Pu	94239.50c 1.0000	94239.60c 1.0000
^{240}Pu	94240.50c 1.0000	94240.60c 1.0000
^{241}Pu	94241.50c 1.0000	94241.60c 1.0000
^{242}Pu	94242.50c 1.0000	94242.60c 1.0000
^{243}Pu	not ENDF or LANL	94243.60c 1.0000
^{241}Am	95241.50c 1.0000	95241.60c 1.0000
^{243}Am	95243.50c 1.0000	95243.60c 1.0000
^{242}Cm	96242.50c 1.0000	96242.60c 1.0000
^{243}Cm	no Recommended	96243.60c 1.0000
^{244}Cm	96244.50c 1.0000	96244.60c 1.0000
^{245}Cm	not ENDF or LANL	96245.60c 1.0000
^{246}Cm	no Recommended	96246.60c 1.0000
^{247}Cm	no Recommended	96247.60c 1.0000
^{248}Cm	no Recommended	96248.60c 1.0000
^{250}Cf	no Recommended	98250.60c 1.0000
^{251}Cf	no Recommended	98251.60c 1.0000
^{252}Cf	no Recommended	98252.60c 1.0000

III. RESULTS OF THE COMPUTER SIMULATIONS

The results of the computer simulations were quite interesting, and all photon tally results from the simulations described above are documented in Appendices A and B. Appendix A contains coplots of photon production from thermal neutron capture, and Appendix B contains coplots of photon production at 14-MeV (high) incident neutron energies. In all cases, the plots compare the results from the MCNP4A Recommended and ENDF60 neutron data libraries. Both Appendix A and Appendix B provide results in order of increasing mass of the target material. Although the two appendices contain all of the information for the comparison simulations, the rest of this section will focus on specific examples showing the types of photon production data provided in the evaluations and libraries, and the dramatic differences between the two libraries for some nuclides. The following notation is used to denote the element and library corresponding to a particular spectra; the RUNTPE filename is written as XXb5run, XXb6run, or XXt2run for the element XX and the ENDF/B-V, ENDF60, or Group T-2 based libraries respectively. For individual isotopes, the notation used was ###XXb5r, ###XXb6r, or ###XXt2r, where XX still specifies the element and ### identifies the mass number of the isotope.

Some general characteristics of photon production in the data libraries can be observed. Photon production data in the evaluations is generally given in four types of formats; discrete gamma-ray lines, histogram bins with widths of up to 250-500 keV, a continuous photon production background, or a combination of these. Figures 1-3 illustrate these formats for Al, Cu, and U which primarily show the discrete, histogram, and continuous representation for photon production respectively. Note that for all figures and coplot, there will be a prominent line at E_γ=0.511 MeV from photon pair production/annihilation.

The photon production spectra from the ENDF/B-V and B-VI libraries were equivalent for most elements, though there were a number of remarkable differences. The greatest changes in photon production for the ENDF60 library occurred for the series of new evaluations for the isotopes of ^{19}F, V, Cr, Mn, Fe, Ni, Co, and Cu. Most of these new evaluations were performed primarily by Oak Ridge National Laboratory.

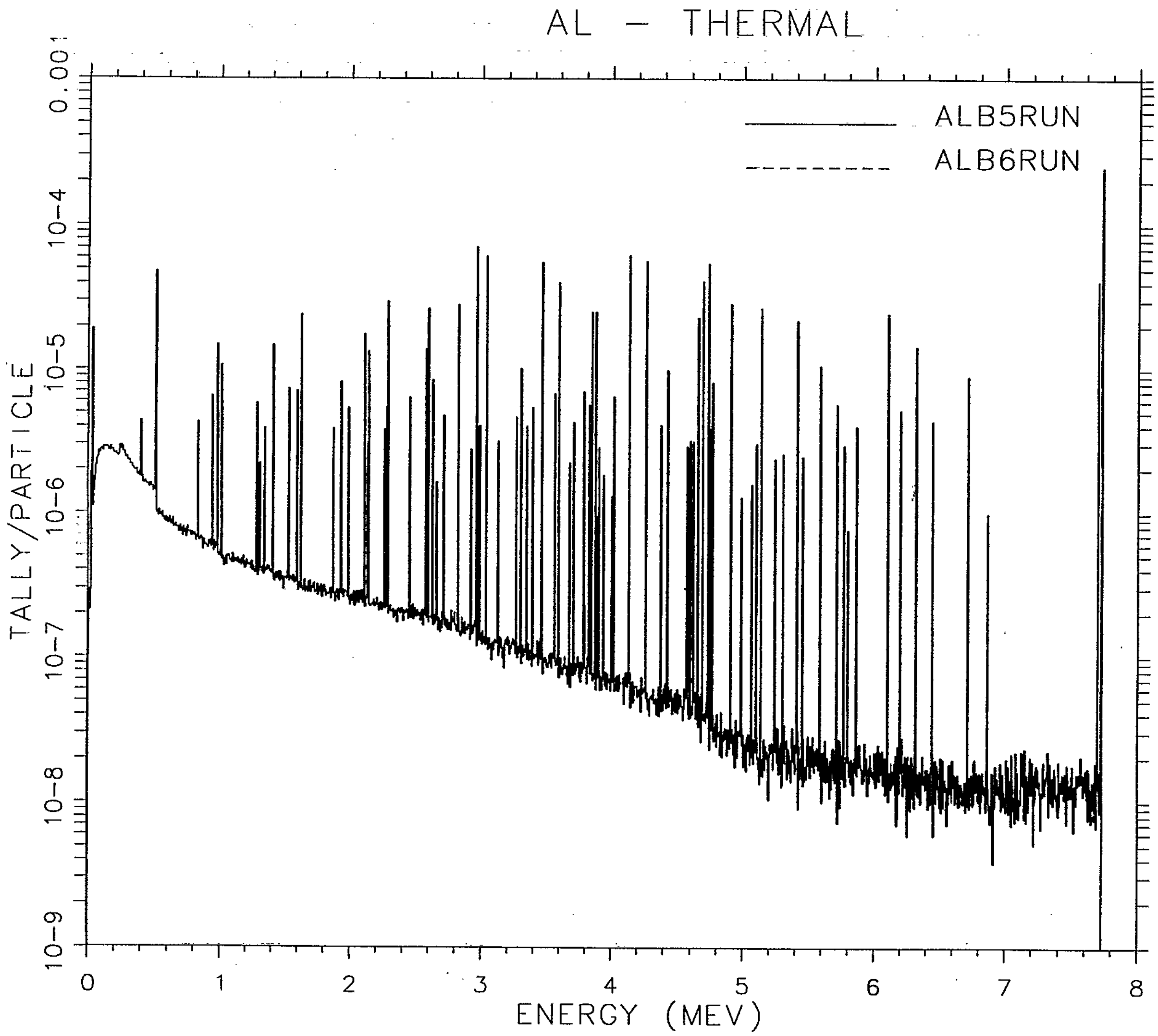

Figure 1: Photon Production for Al at Incident Thermal Neutron Energies.

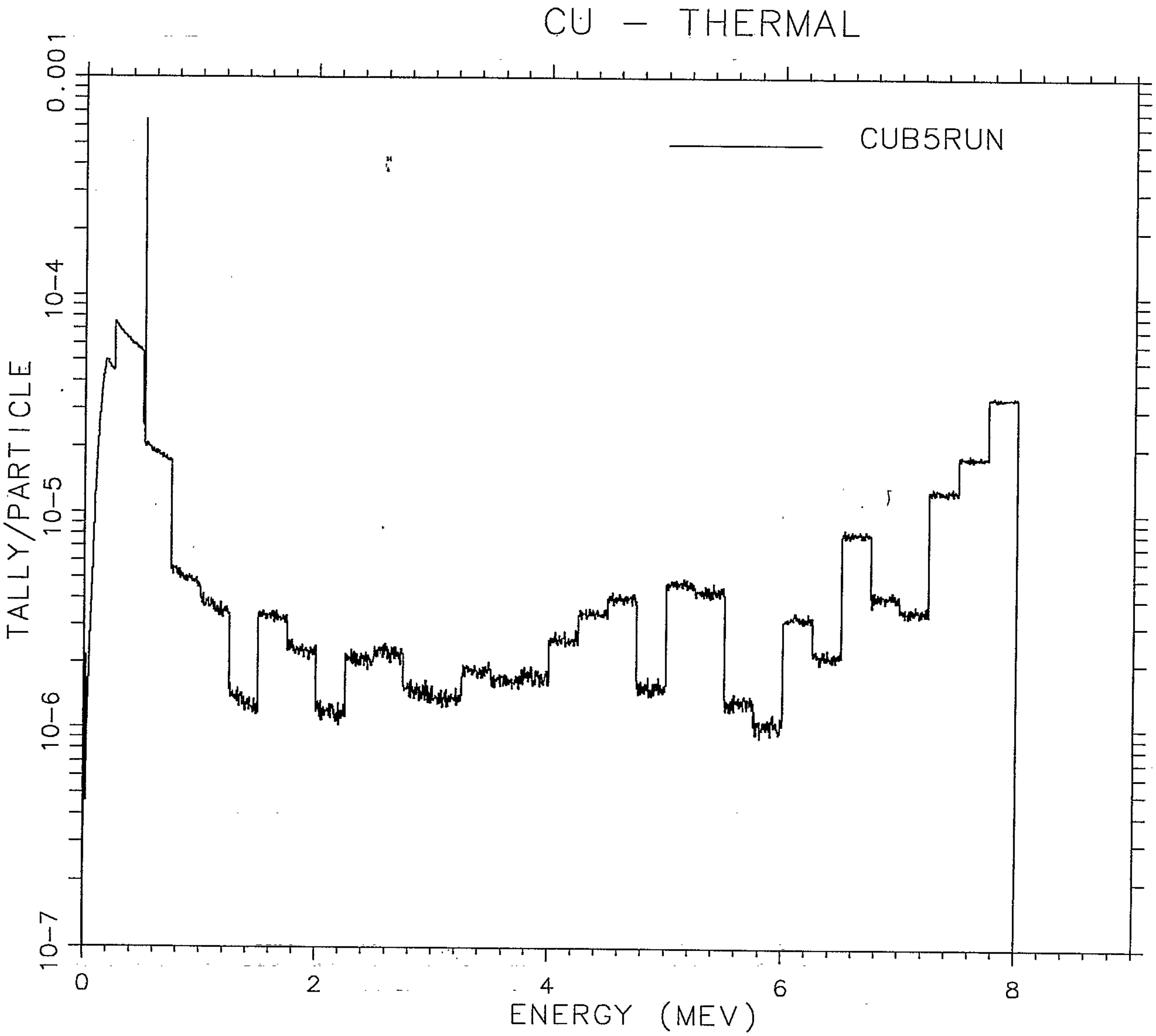

Figure 2: Photon Production for Cu at Incident Thermal Neutron Energies.

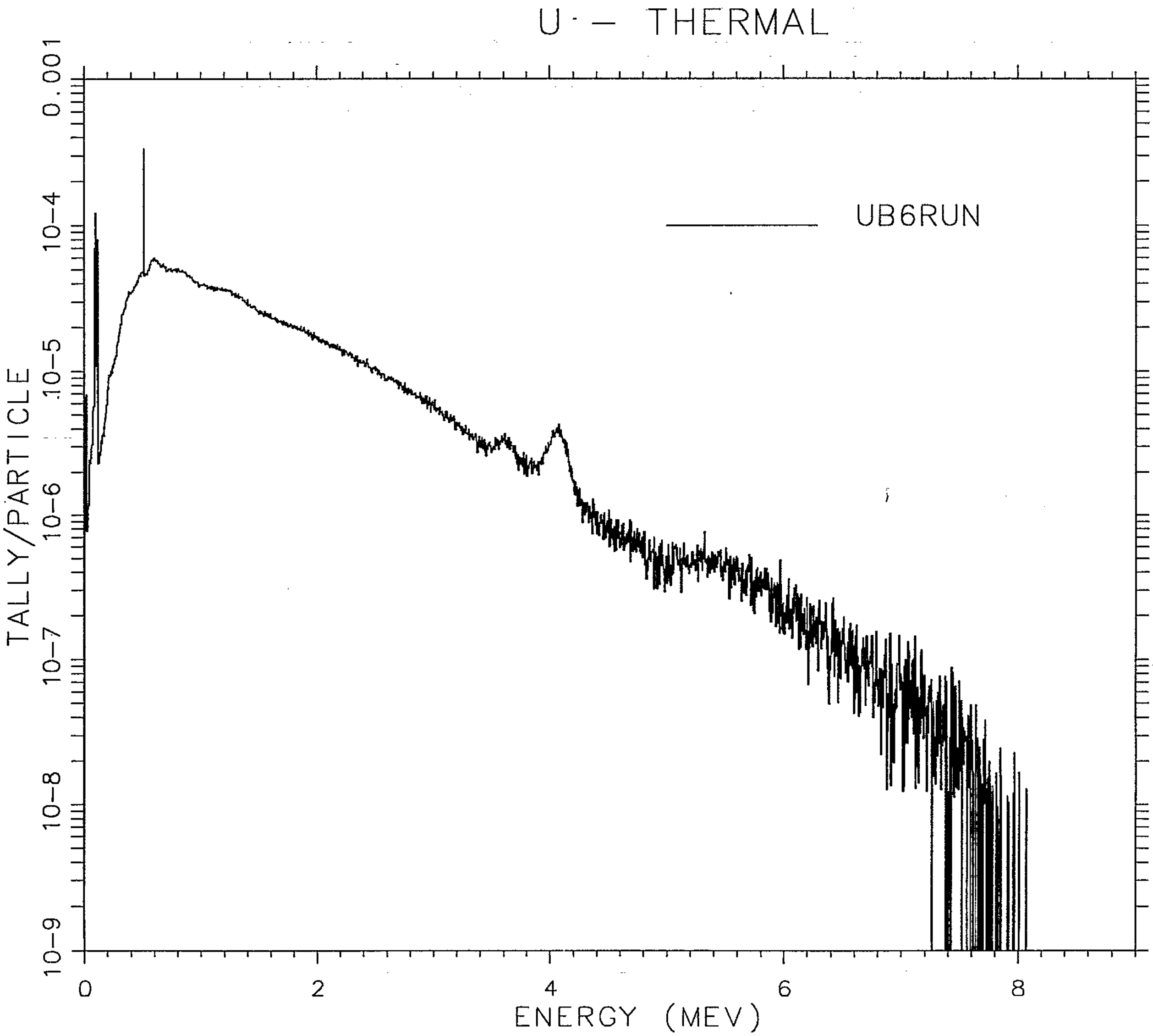

Figure 3: Photon Production for U at Incident Thermal Neutron Energies.

Figures 4 and 5 illustrate the dramatic changes in the ^{19}F evaluation for thermal and higher incident neutron energies respectively over the photon energy range E_γ =2.0-5.0 MeV. As one can see, the ENDF60 library has a much more detailed representation of photon production from the higher energy inelastic reactions, but a far less detailed representation of photon production from thermal capture reactions.

Photon production from thermal neutron capture reactions remains unchanged for V, Fe, and Co, but changes dramatically for the higher energy reactions. In particular, photon production for the ENDF60 Fe does not have the same resolution as for the T-2 evaluation as shown in Figure 6. For applications where this is important, the user is recommended to continue using the T-2 based library for natural Fe.

Both thermal and high energy photon production has changed for Cr, Mn, and Ni. Figure 7 illustrates the combination of discrete and histogram photon production at higher energies for Cr that is common for these nuclides. Although this is an improvement from the ENDF/B-V evaluations, it may in fact make it more difficult for some applications to use this type of data. Figures 8-12 show the comparison between the ENDF/B-V and B-VI based data libraries for Sc, Cr, Mn, Ni, and Cu at thermal neutron energies. For the ENDF60 library, photon production for the Cr and Ni nuclides has decreased in bin width from 250 keV to 100 keV, and Mn decreased in bin width to 25 keV. The Cu nuclides show no decrease in bin width, but the strength of each energy bin has changed. Although a decrease in bin width generally improves the quality of the photon-production spectra, it does not necessarily have the detail required for projects such as the MSL project. Additionally, the photon-production spectra for Sc and Mn show unphysical behavior at thermal energies. The photon-production spectra from the Mg and Fe nuclides, commonly found elements in well-logging tools and in the formation, have bin widths of 250 keV and 50 keV respectively at thermal energies for both libraries.

Photon-production spectra with discrete capture lines at thermal exist for H, D, Li, Be, B, C, N, O, ^{19}F, Na, Al, Si, Cl, K, Ca, Pb, and Bi. However, a number of these evaluations are translations from previous ENDF releases (Na, Al, Si, Cl, and K) sometimes dating back to the early 1970's. We have found discrepancies between experimental data and evaluations for some of these elements such as Al and Cl. The discrepancies in Al are discussed in greater detail in the following section.

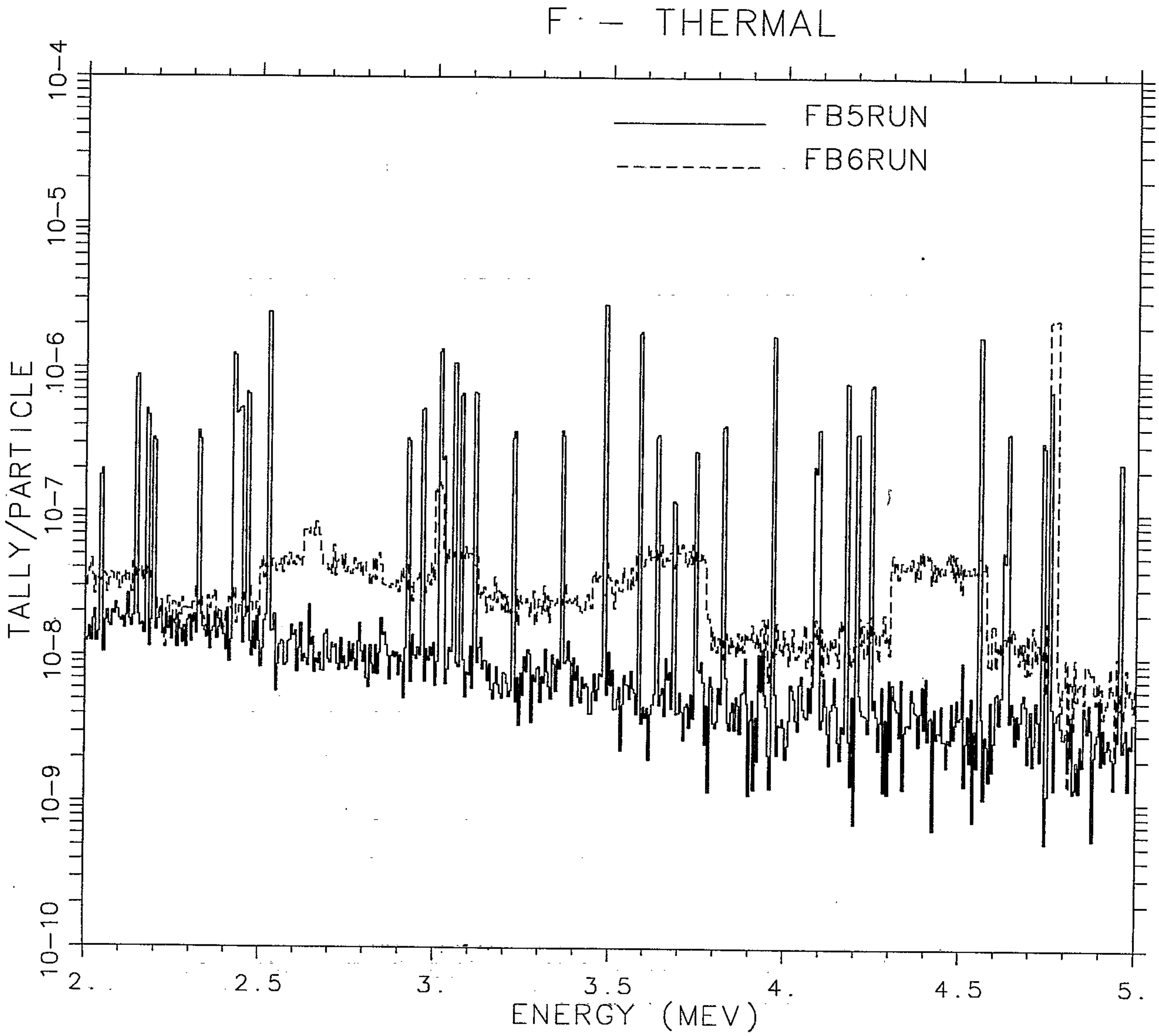

Figure 4: Photon Production for ^{19}F at Incident Thermal Neutron Energies.

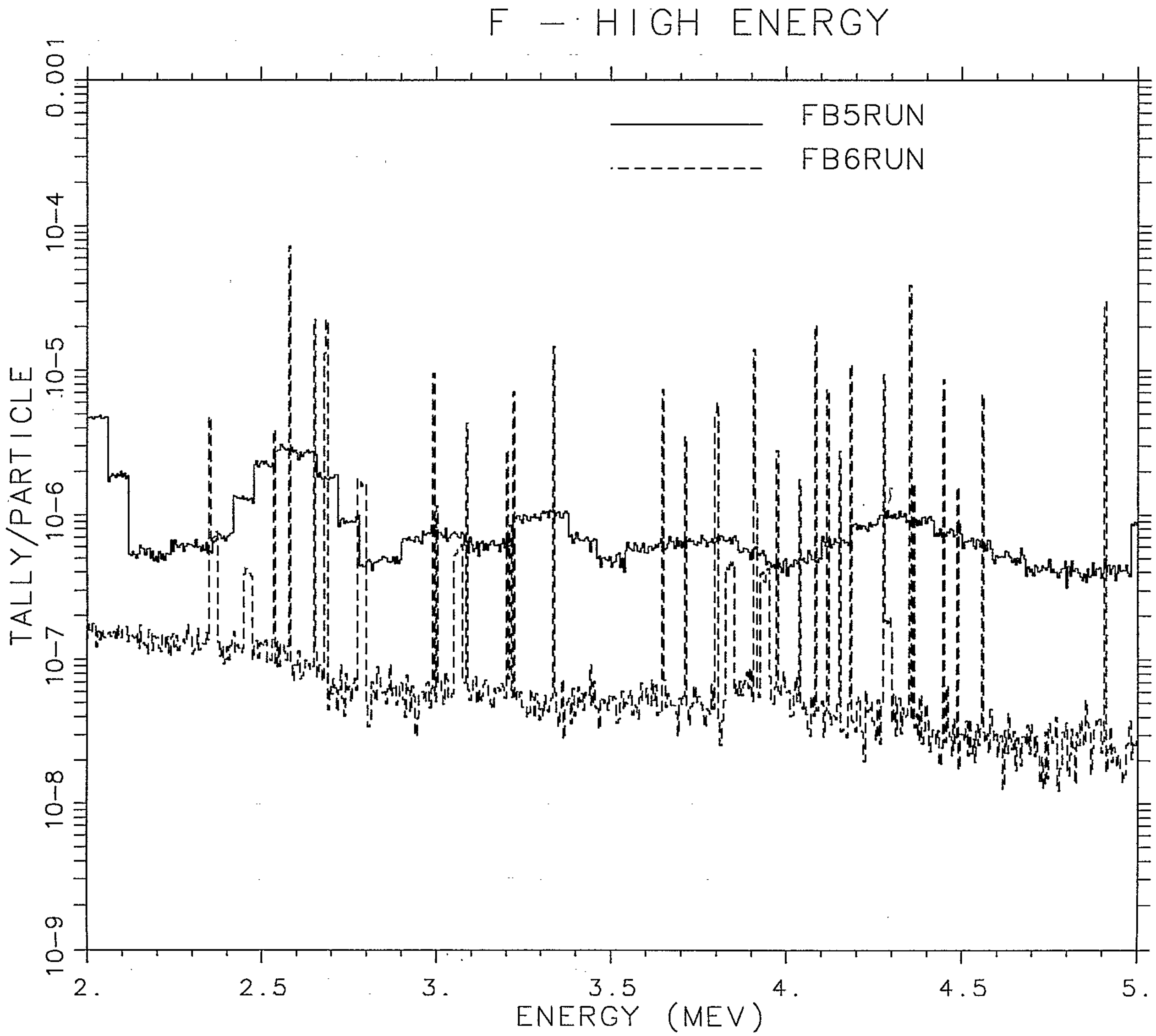

Figure 5: Photon Production for ^{19}F at 14-MeV Incident Neutron Energies.

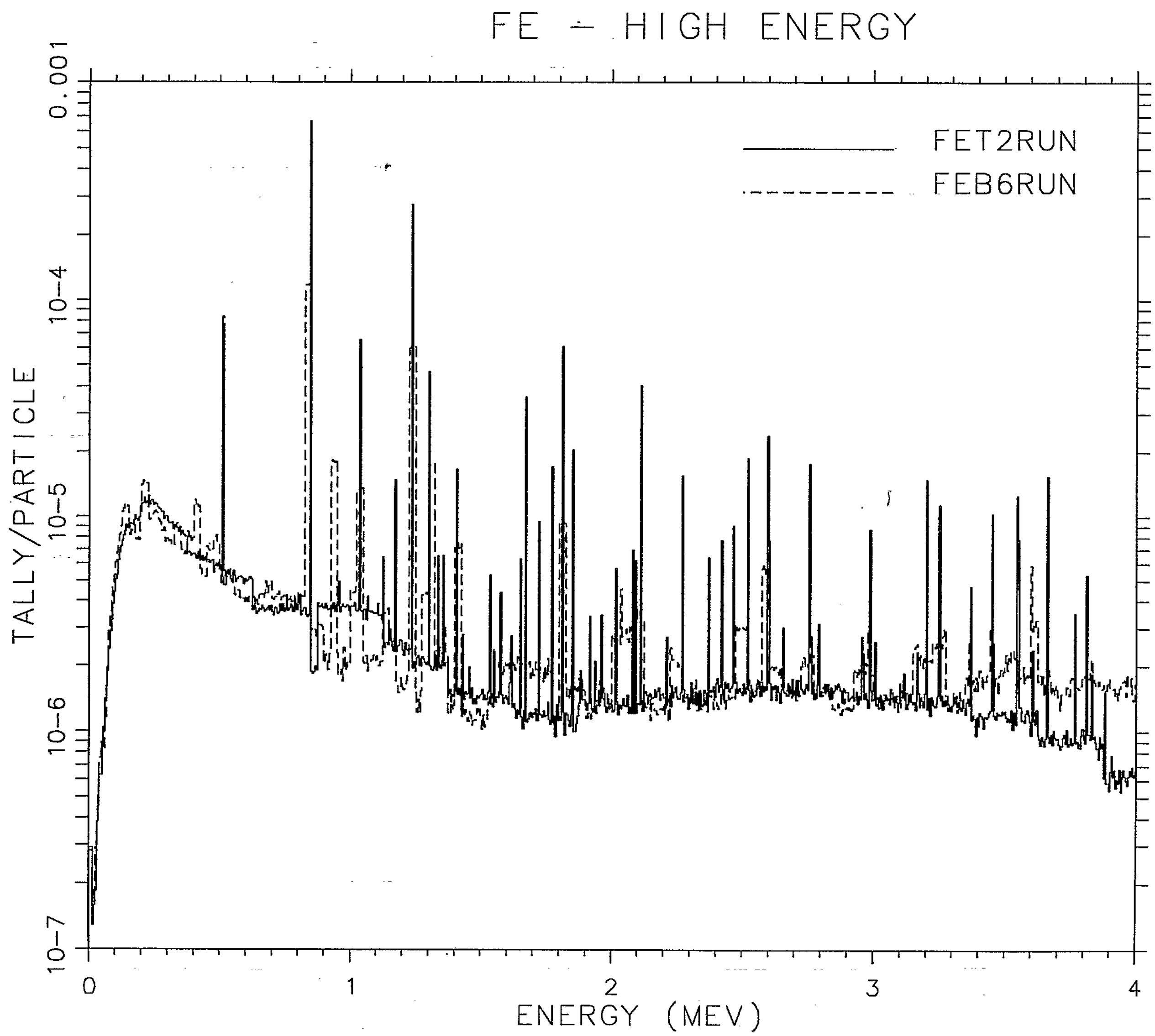

Figure 6: Photon Production for Fe at 14-MeV Incident Neutron Energies.

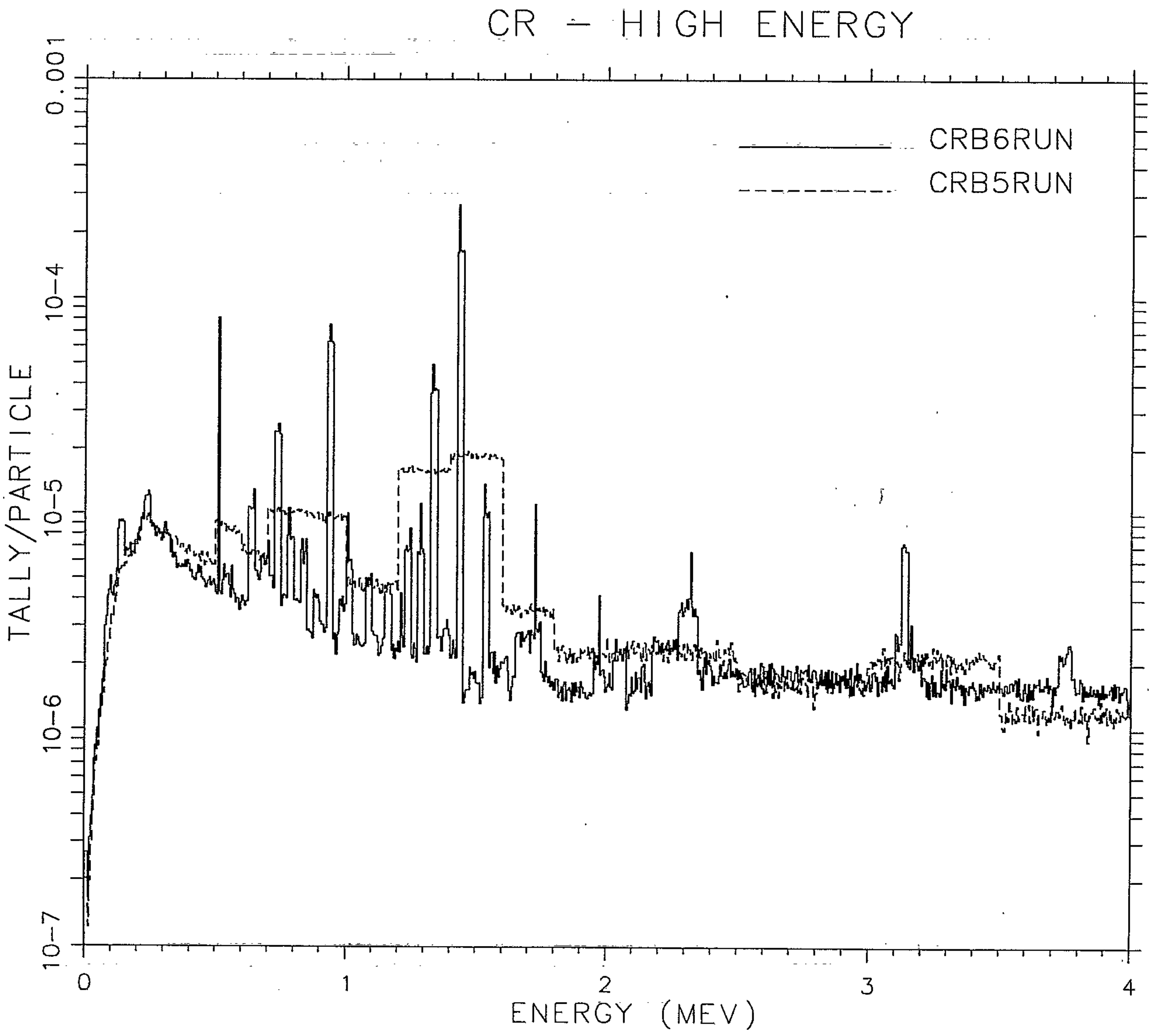

Figure 7: Photon Production for Cr at 14-MeV Incident Neutron Energies.

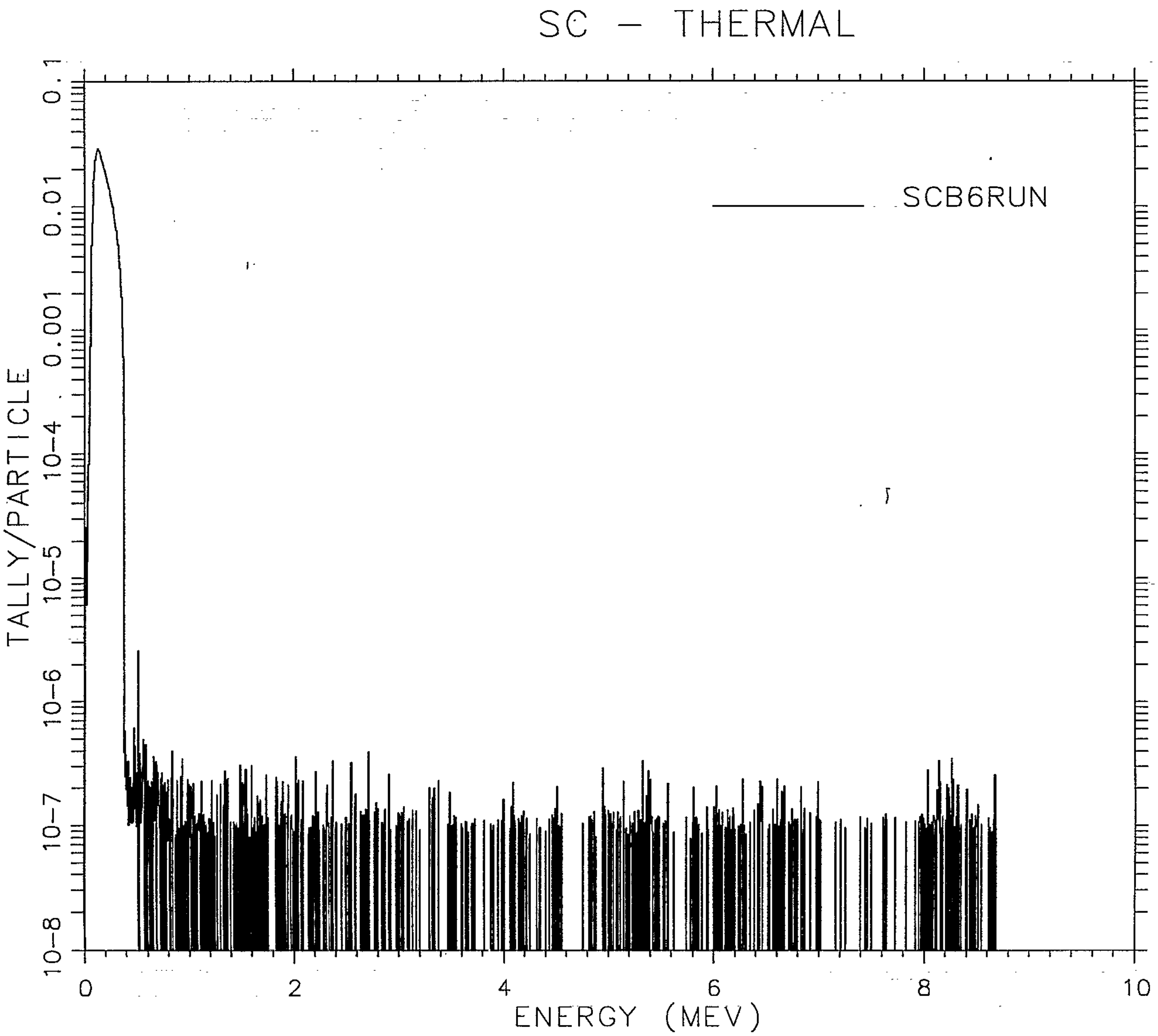

Figure 8: Photon Production for Sc at Incident Thermal Neutron Energies.

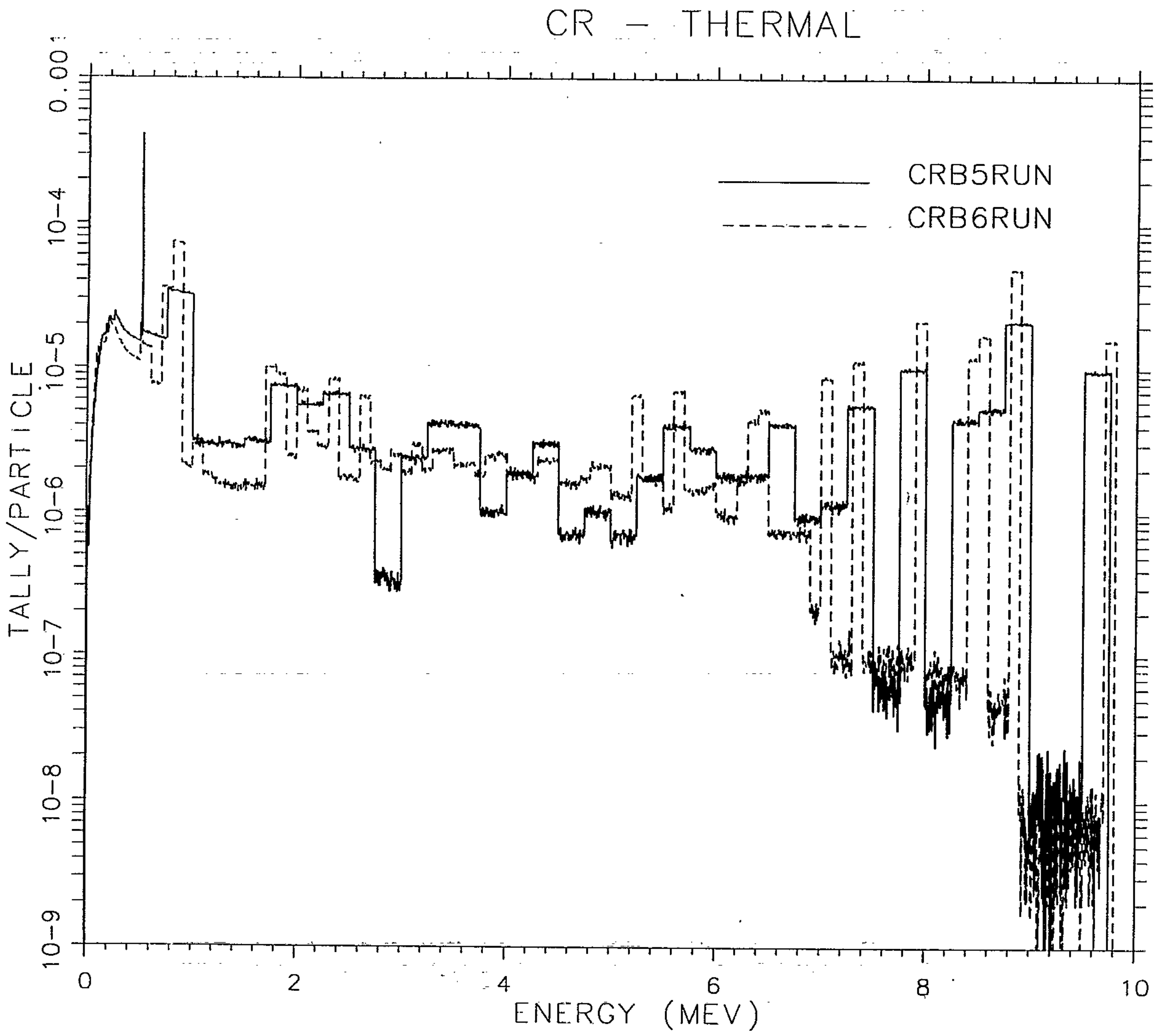

Figure 9: Photon Production for Cr at Incident Thermal Neutron Energies.

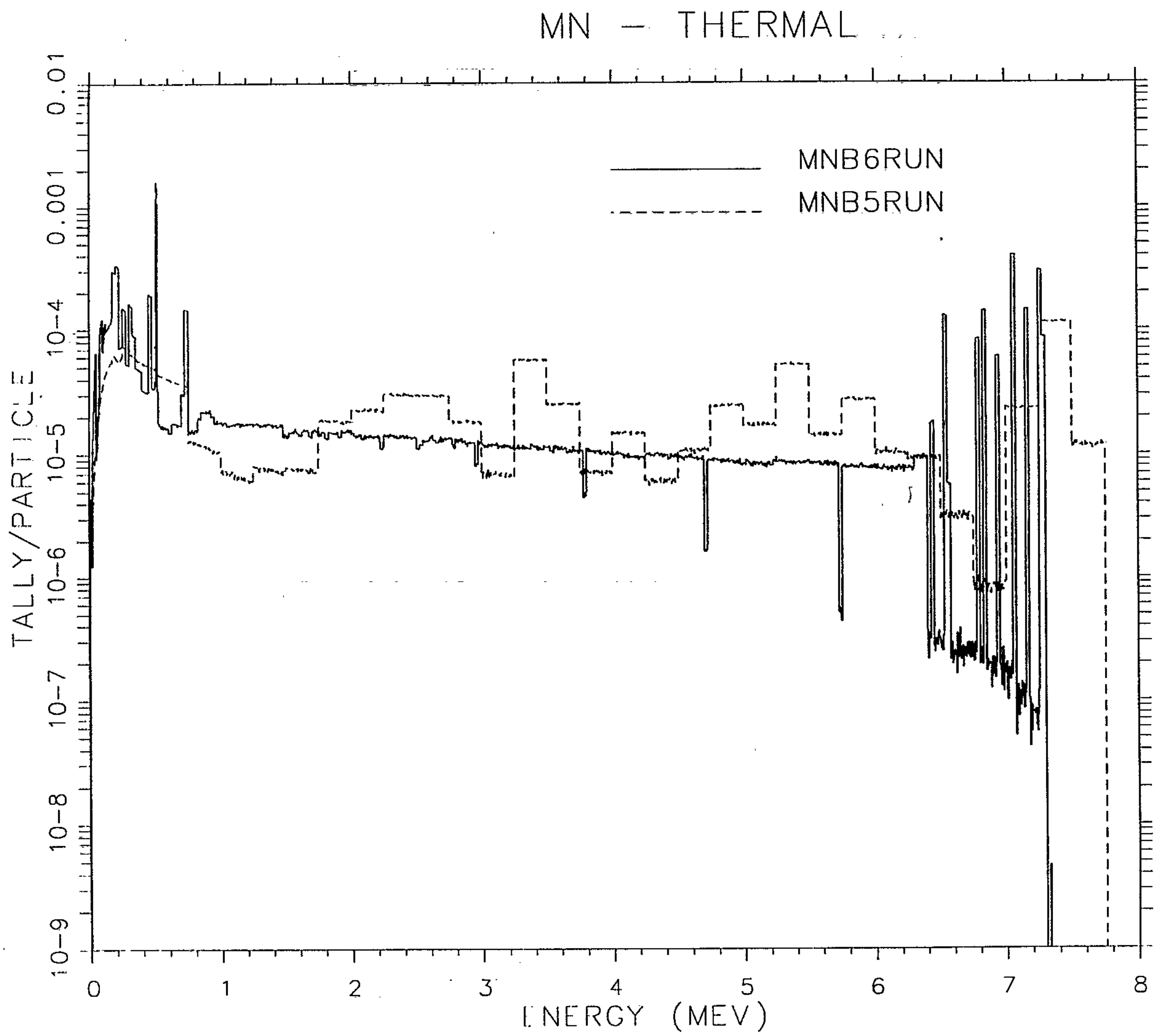

Figure 10: Photon Production for Mn at Incident Thermal Neutron Energies.

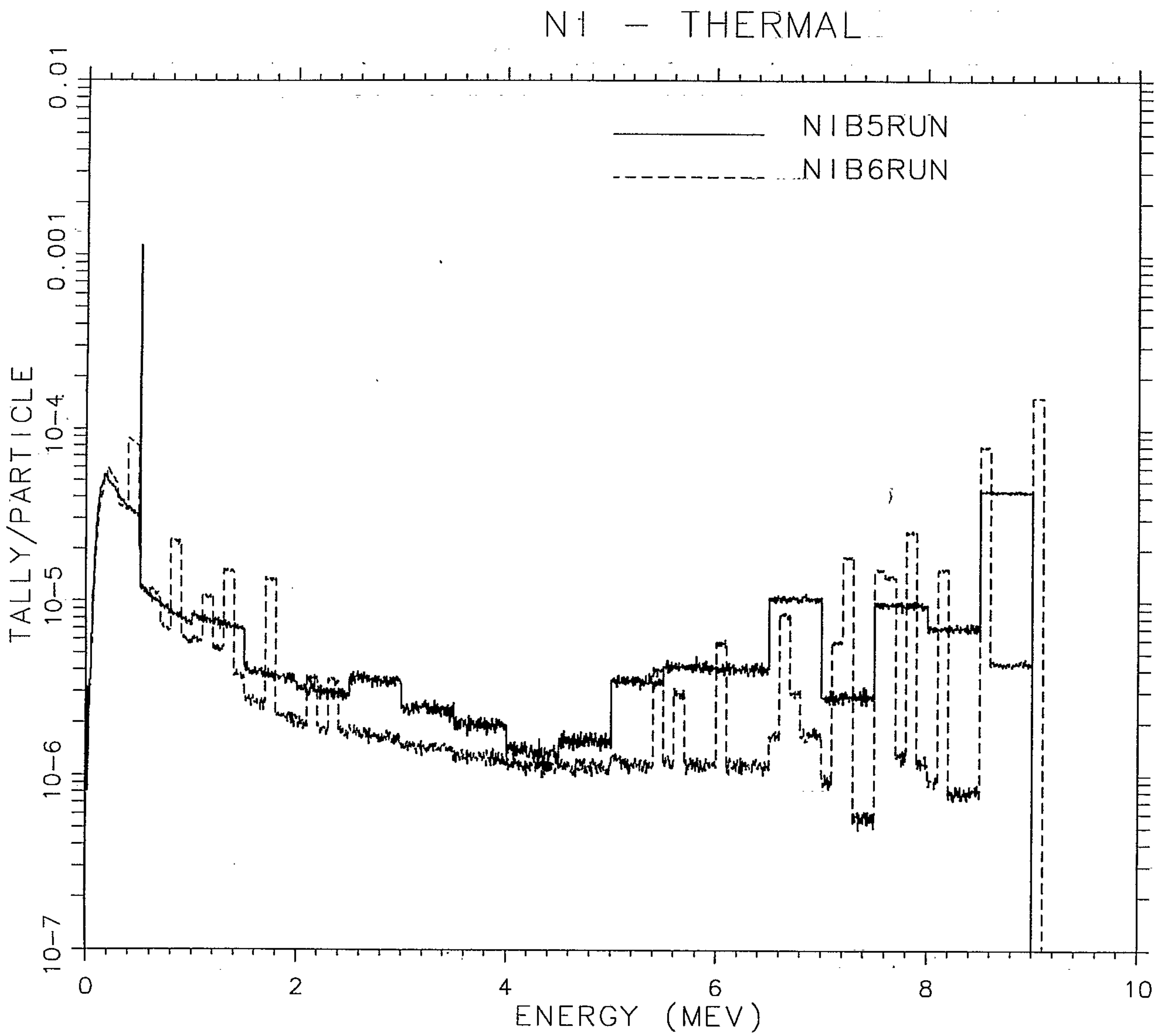

Figure 11: Photon Production for Ni at Incident Thermal Neutron Energies.

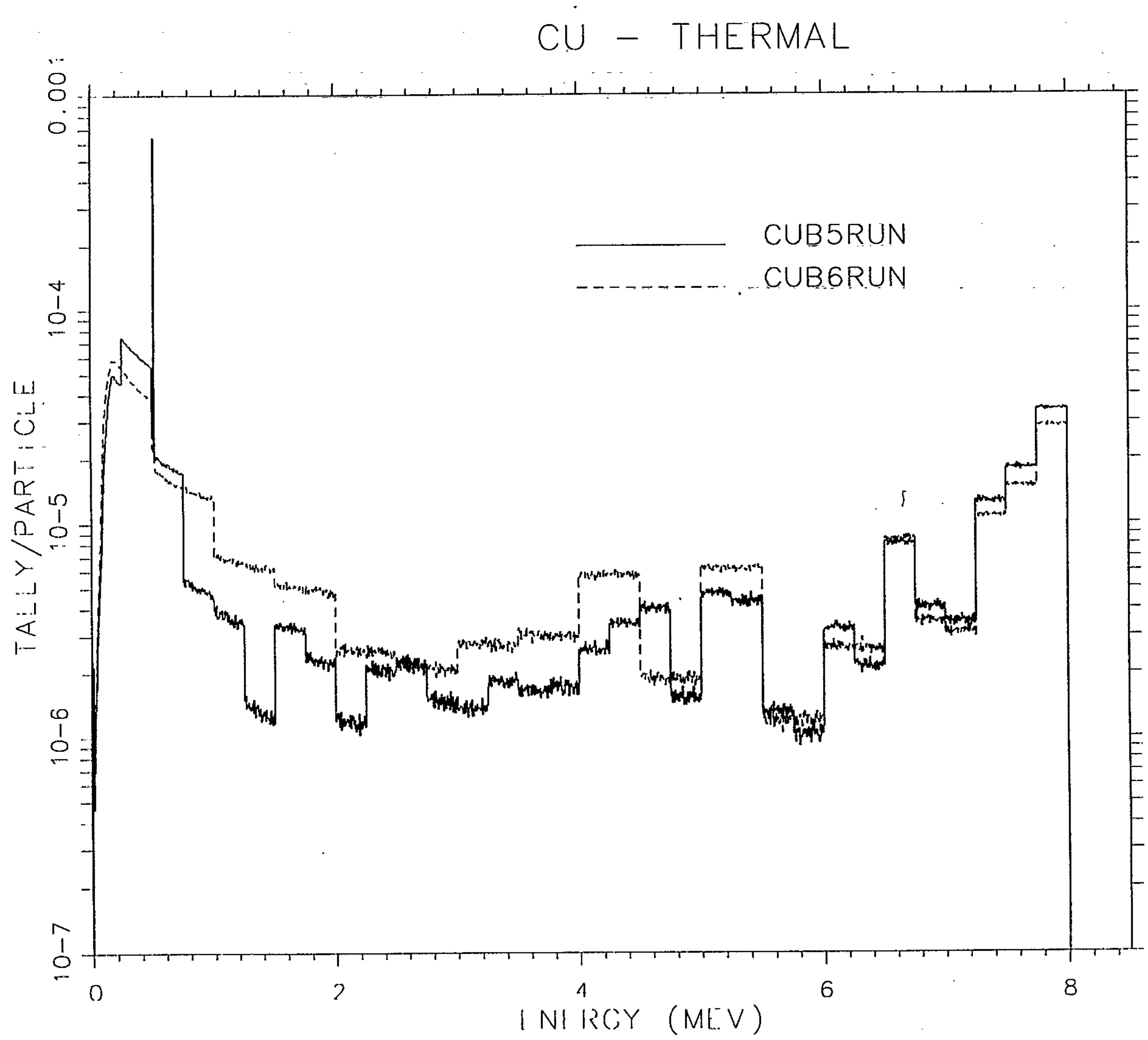

Figure 12: Photon Production for Cu at Incident Thermal Neutron Energies.

In general, the ENDF60 library is equivalent to, or moderately better than, the Recommended data libraries. This equivalence, however, does not always hold true. For those nuclides where photon production has substantially changed, Table 3 lists the library with the most detailed treatment of photon-production data at thermal and higher neutron energies, where a '-' indicates that the libraries are equivalent for that energy region. Users must be aware of all the difficulties discussed whenever they are attempting to model an experimental setup requiring high resolution data of any kind. It is up to the users to ensure that the data they are using is appropriate for their particular application.

Table 3: A More Detailed Treatment for Photon Production for Thermal and Higher Energy Neutron Reactions

Element	Thermal Neutron Reactions	Higher Energy Reactions
B	- [a]	ENDF60
N	ENDF60	ENDF60
F	Recommended	ENDF60
Ca	-	ENDF60
Sc	(none) [b]	ENDF60
V	ENDF60	ENDF60
Cr	ENDF60	ENDF60
Mn	Recommended	ENDF60
Fe	-	Recommended
Co	ENDF60	ENDF60
Ni	ENDF60	ENDF60
Cu	ENDF60	ENDF60
Nb	ENDF60	ENDF60
Ho	ENDF60	-
Pb	ENDF60	ENDF60
Bi	-	ENDF60

a A '-' indicates that the libraries are essentially equivalent.
b There is no library with proper photon production at thermal energies for Sc.

IV. COMPARISON OF SIMULATED SPECTRA WITH EXPERIMENTAL DATA

The compilations "Prompt Gamma Rays from Thermal-Neutron Capture" [11] by Lone et al. and "Line and Continuum Gamma-ray Yields from Thermal-Neutron Capture in 75 Elements" [12] by Orphan et al. are standard references for identifying thermal-neutron capture lines in experimental well-logging data. It was determined that there were a number of differences between the compilations and the simulated spectra containing discrete capture lines. A comparison was made for aluminum between the ENDF evaluation, the compilations, and two publications of experimental data, Hardell (1969) and Schmidt (1982). [13-14] Recall that the ENDF/B-VI evaluation for Al is a translation from ENDF/B-V.

In most cases, the compilations do not include a number of gamma-rays that are present in the ENDF and experimental data. As an example, consider the energy region E_γ=1.0-1.5 MeV in Al. Table 4 lists the capture lines identified by Lone, Orphan, ENDF, Hardell, and Schmidt over this energy region and the corresponding line intensity. The line intensity is the number of photons of a particular energy produced for every 100 neutron capture reactions. As shown in Table 4, the capture lines at 1.284, 1.306, and 1.342 are not present in the compilations. However, these lines are reported by references cited in both compilations. A complete comparison between the latest compilation and the experimental data of Hardell and Schmidt for Aluminum can be found in Appendix C.

While the Orphan and Lone compilations do not list all thermal capture lines reported experimentally, they do list the lines of greatest intensity. Since only the strongest lines are seen in typical well-logging data, these compilations are probably still viable options for identifying thermal capture lines for that application.

Table 4: Comparison of Thermal Neutron Capture Lines in Aluminum for E_γ=1.0-1.5 MeV

Lone,1981 (Energy; Intensity)	Orphan, 1970 (Energy; Intensity)	ENDF (Energy; Intensity)	Hardell, 1969 (Energy; Intensity)	Schmidt, 1982 (Energy; Intensity)
		1.284; 0.8	1.284; 0.6	
		1.317; 0.272	1.306; 0.3	1.305; 0.2
		1.342; 0.51	1.342; 0.5	1.342; 1
				1.365; 0.4
				1.373; 0.2
1.409; 1.08	1.41; 0.81	1.409; 2.1	1.409; 0.6	1.408; 3.1
[Energy (MeV); Intensity (# per 100 captures]				

V. SUMMARY

A systematic review of the Recommended and ENDF60 neutron data libraries for MCNP has been performed to assess the quality of the photon-production data for applications which require high-resolution data such as the MSL project. Where possible, simulations were performed with the MCNP4A recommended and ENDF60 libraries, based primarily on ENDF/B-V and ENDF/B-VI evaluations respectively, for all elements. The photon-production spectra for these libraries are often binned in wide histogram energy bins whose strength, or amplitude, is proportional to the sum of the gamma-ray intensities over that energy bin. Photon-production spectra with discrete capture lines were available for most of the lighter nuclides H, D, Li, Be, B, C, N, O, ^{19}F, Na, Al, Si, Cl, K, and Ca, as well as for Pb and Bi. Coplots showing comparisons between the results for Recommended and ENDF60 libraries at thermal and 14-MeV incident neutron energies were documented. The results for ^{19}F, V, Cr, Mn, Fe, Co, and Cu were discussed. The ENDF/B-VI evaluation for ^{19}F showed more detailed treatment for photon production at higher energies but a far less detailed treatment for thermal capture reactions than ENDF/B-V. We have also found discrepancies between experimental data and evaluations for some elements, such as Al and Cl. . Additionally, the photon-production spectra for Sc and Mn show unphysical behavior at thermal energies. Users must be aware of these kinds of difficulties whenever they are attempting to model an experimental setup requiring high resolution data of any kind. It is up to the users to ensure that the data they are using is appropriate for their particular application.

This assessment process reinforced the need for higher quality photon-production spectra for use in the MSL project, as well as for any simulation primarily interested in discrete photons from neutron reactions. We are currently working with T-2 to modify the available libraries to include discrete photons for thermal-neutron capture reactions for Cl, V, Cr, Mn, Fe, Co, Ni, Cu, Cd and Hg. This modification will enable the project to better estimate minimum detection thresholds for a variety of environmental contaminants which have not been experimentally determined.

VI. ACKNOWLEDGMENTS

The author gratefully acknowledges the support and encouragement from the Multispectral Neutron Logging project leader John Conaway, and from the my colleagues Patrick Soran and Robert Little. The help of Ann Nagy and Patricia Mendius in preparing the final document is also gratefully acknowledged.

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10. "Chart of the Nuclides," 13th Edition, General Electric Company, (1984).

11. Lone *et al.*, "Prompt Gamma Rays from Thermal-Neutron Capture," Atomic Data and Nuclear Data Tables **26**, p. 511-559 (1981).

12. Orphan *et al.*, "Line and Continuum Gamma-ray Yields from Thermal-Neutron Capture in 75 Elements," Gulf General Atomic, Inc., GA-10248 (1970).

13. Hardell *et al.*, "Thermal-Neutron Capture Gamma Rays from the $^{27}Al(n,\gamma)^{28}Al$ Reaction," Nucl. Phys. **A126**, p. 393, (1969).

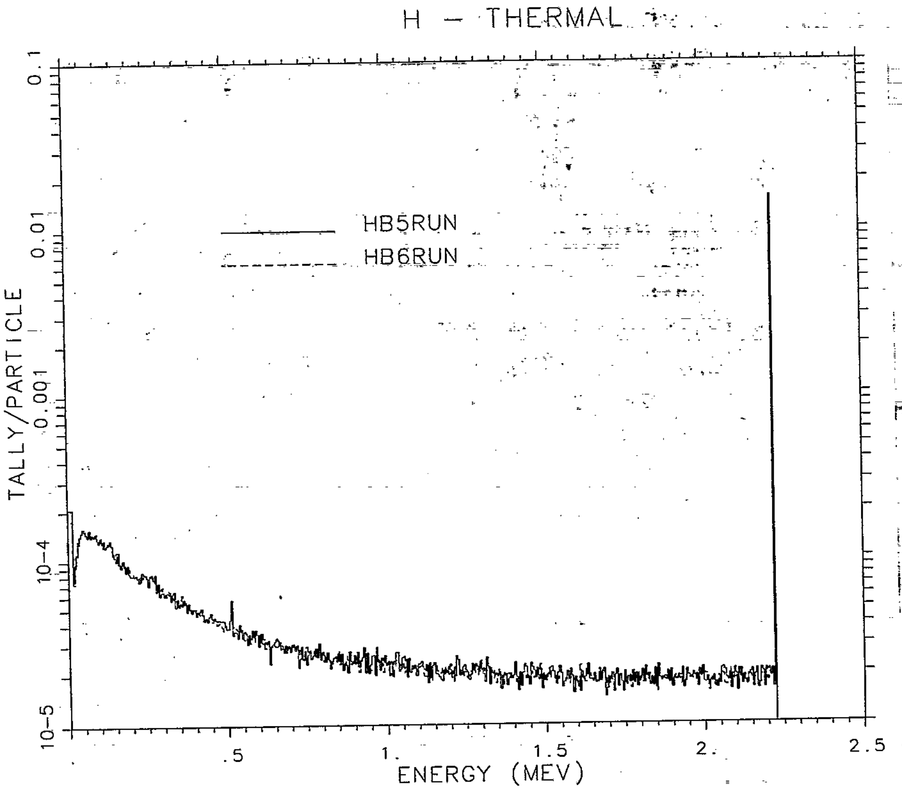
14. Schmidt *et al.*, "Levels and Gamma Energies of ^{28}Al Studied by Thermal Neutron Capture," Phys. Rev. C **25**, p. 2888, (1982).

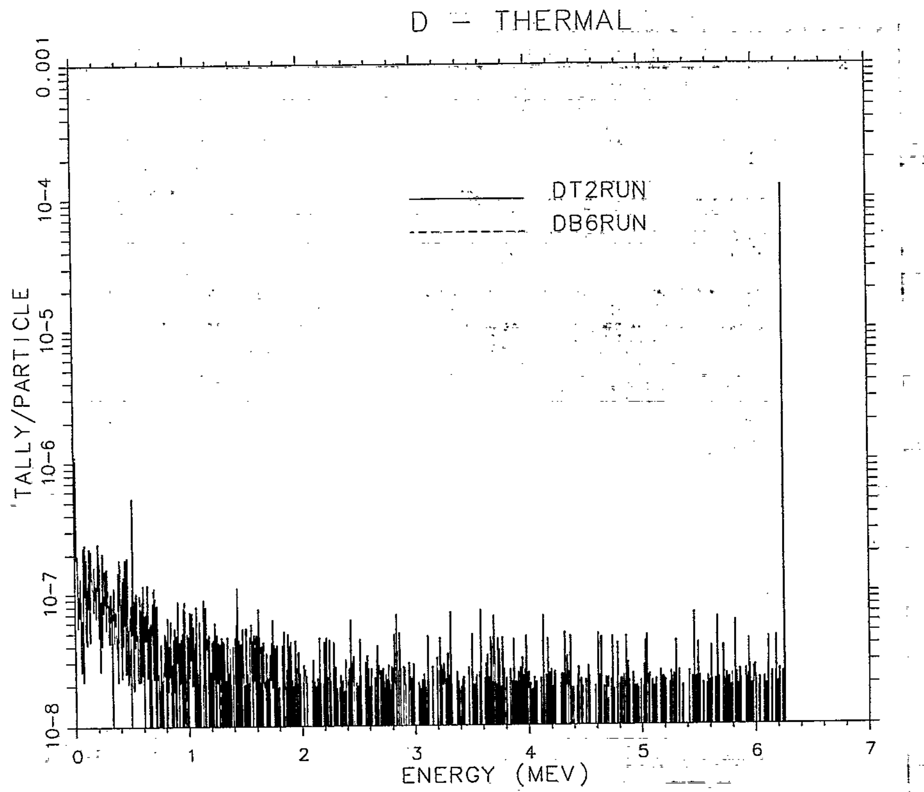
APPENDIX A

Simulated Photon-Production Spectra at Thermal Incident Neutron Energies for the MCNP4A Recommended and ENDF60 Data Libraries

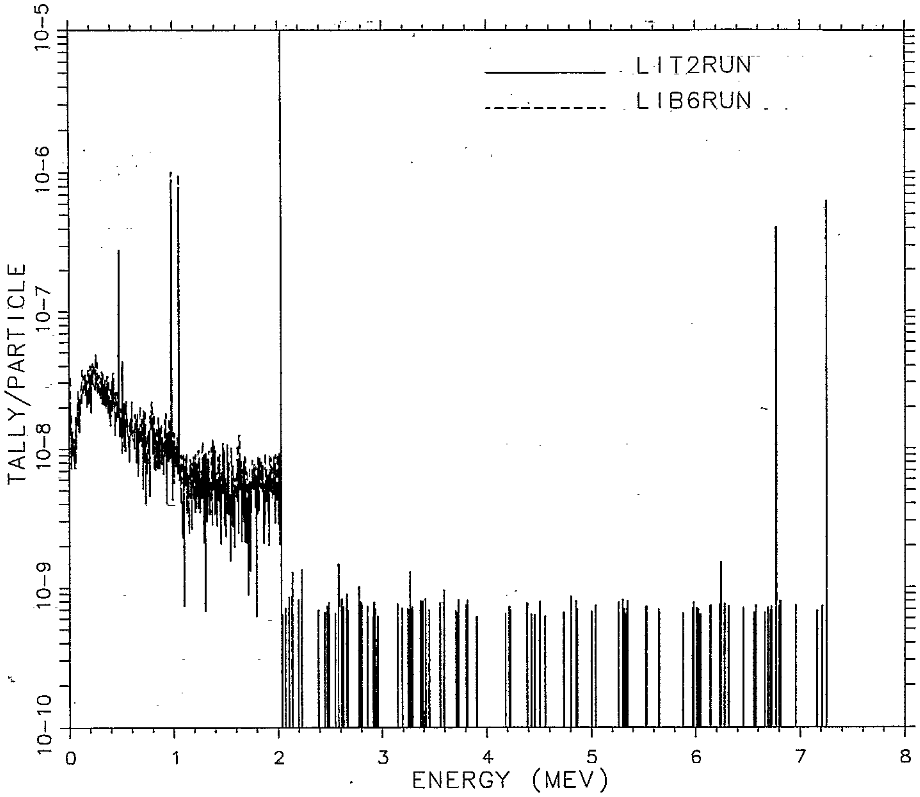
The following notation is used to denote the element and library corresponding to a particular spectra; the filename is written as XXb5run, XXb6run, or XXt2run for the element XX and the ENDF/B-V, ENDF60, or Group T-2 based libraries respectively. For individual isotopes, the notation used was ###XXb5r, ###XXb6r, or ###XXt2r, where XX still specifies the element and ### identifies the mass number of the isotope.

See Table 2 for the precise material specifications for each MCNP run.

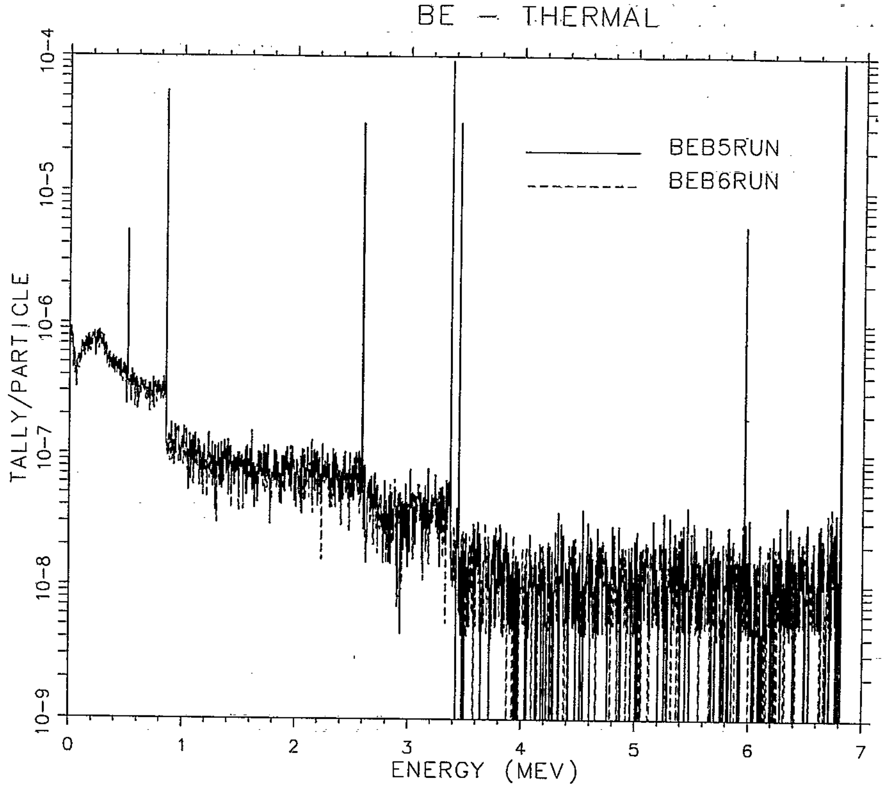

H — THERMAL
TALLY/PARTICLE
0.1
0.01
0.001
10-4
10-5
HB5RUN
HB6RUN
.5
1.
1.5
2.
2.5
ENERGY (MEV)

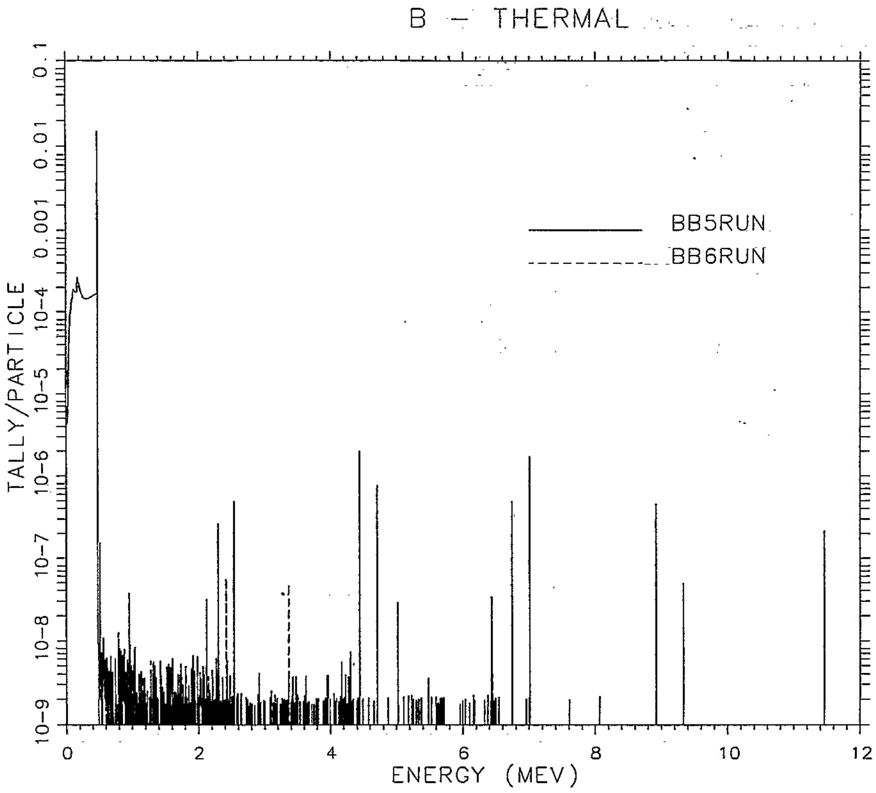

D — THERMAL
TALLY/PARTICLE
0.001
10-4
10-5
10-6
10-7
10-8
DT2RUN
DB6RUN
0
1
2
3
4
5
6
7
ENERGY (MEV)

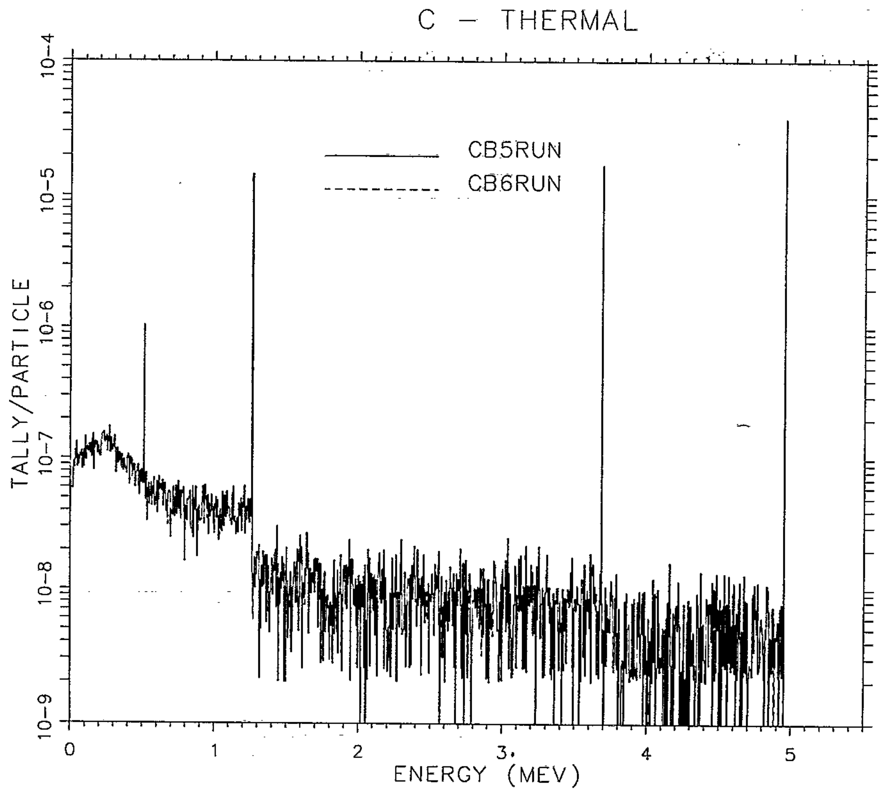
LI — THERMAL

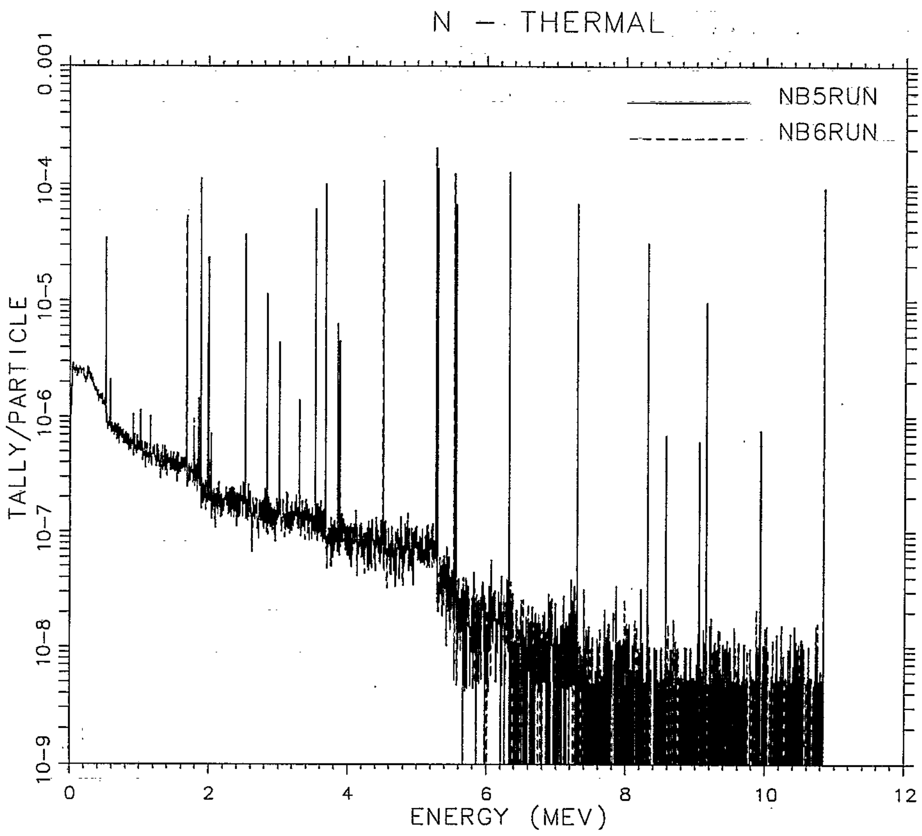


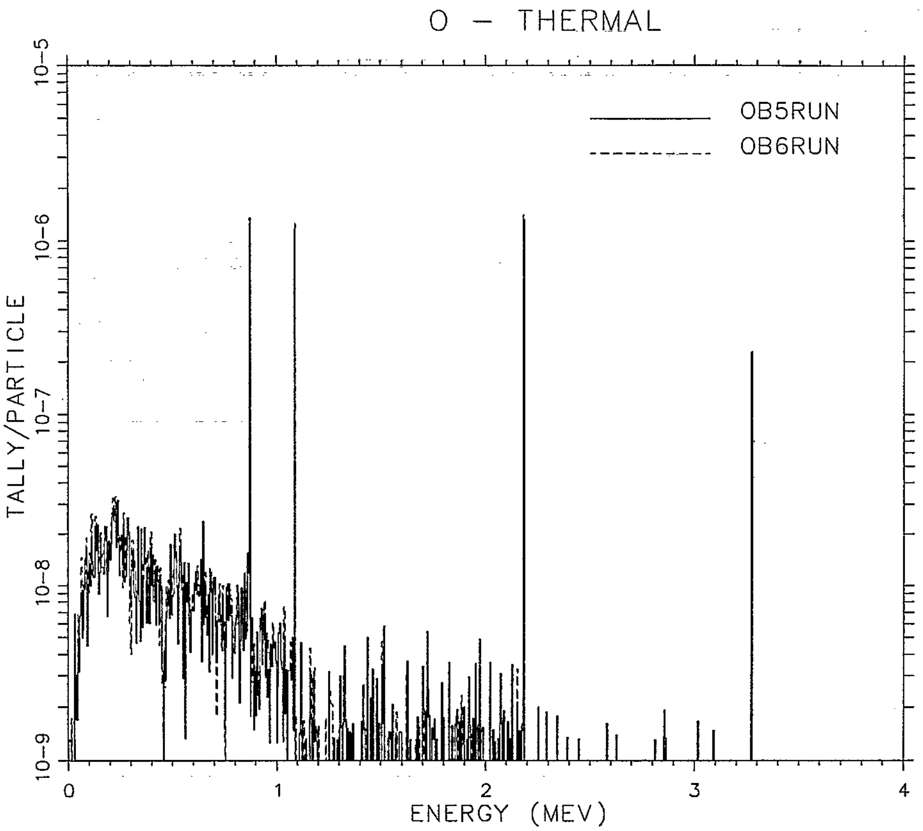
BE — THERMAL

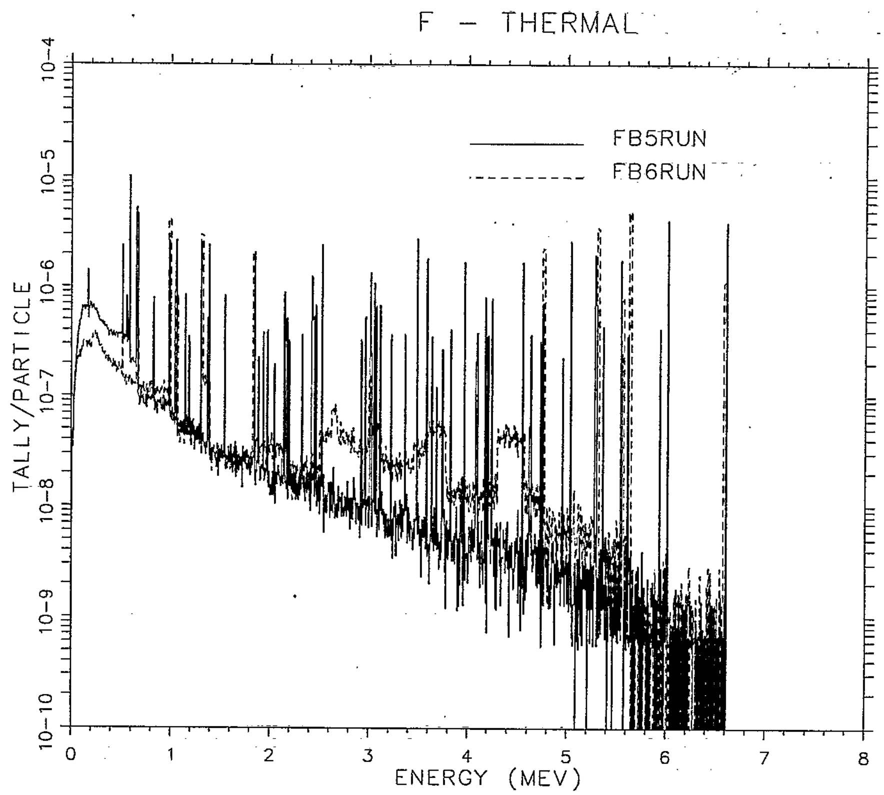



B – THERMAL
BB5RUN
BB6RUN
TALLY/PARTICLE
ENERGY (MEV)


C – THERMAL
CB5RUN
CB6RUN
TALLY/PARTICLE
ENERGY (MEV)


N — THERMAL
NB5RUN
NB6RUN
TALLY/PARTICLE
0.001
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
12
ENERGY (MEV)


O — THERMAL
OB5RUN
OB6RUN
TALLY/PARTICLE
10-5
10-6
10-7
10-8
10-9
0
1
2
3
4
ENERGY (MEV)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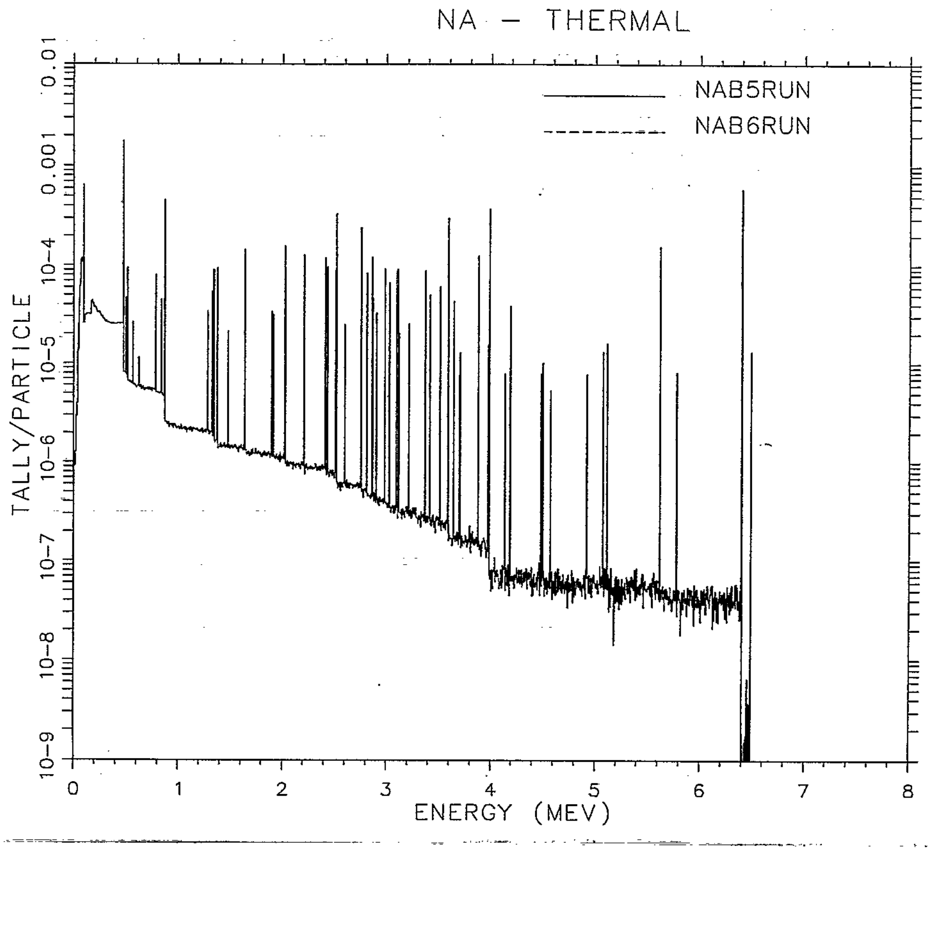
FB5RUN
FB6RUN
TALLY/PARTICLE
ENERGY (MEV)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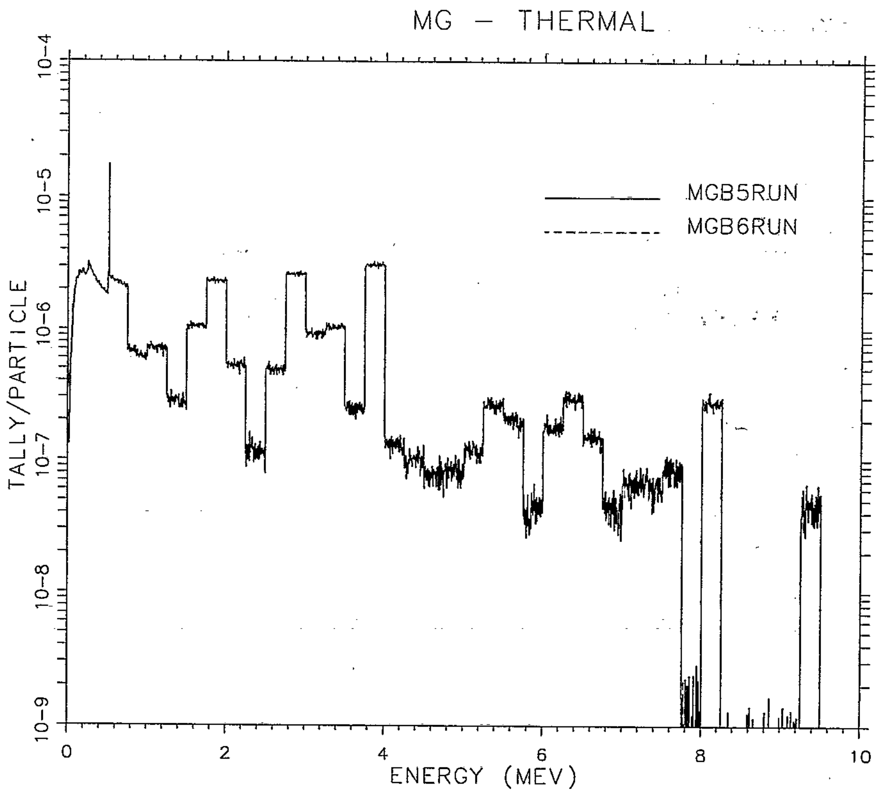
NAB5RUN
NAB6RUN
TALLY/PARTICLE
ENERGY (MEV)


MG — THERMAL
MGB5RUN
MGB6RUN
TALLY/PARTICLE
ENERGY (MEV)
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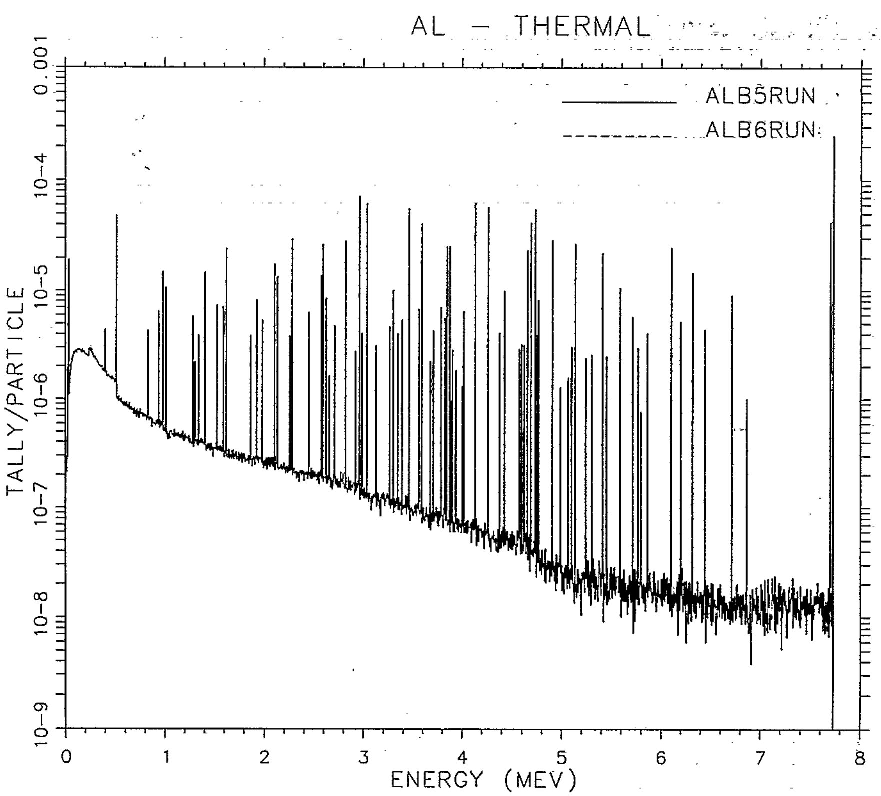
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10


AL — THERMAL
ALB5RUN
ALB6RUN
TALLY/PARTICLE
ENERGY (MEV)
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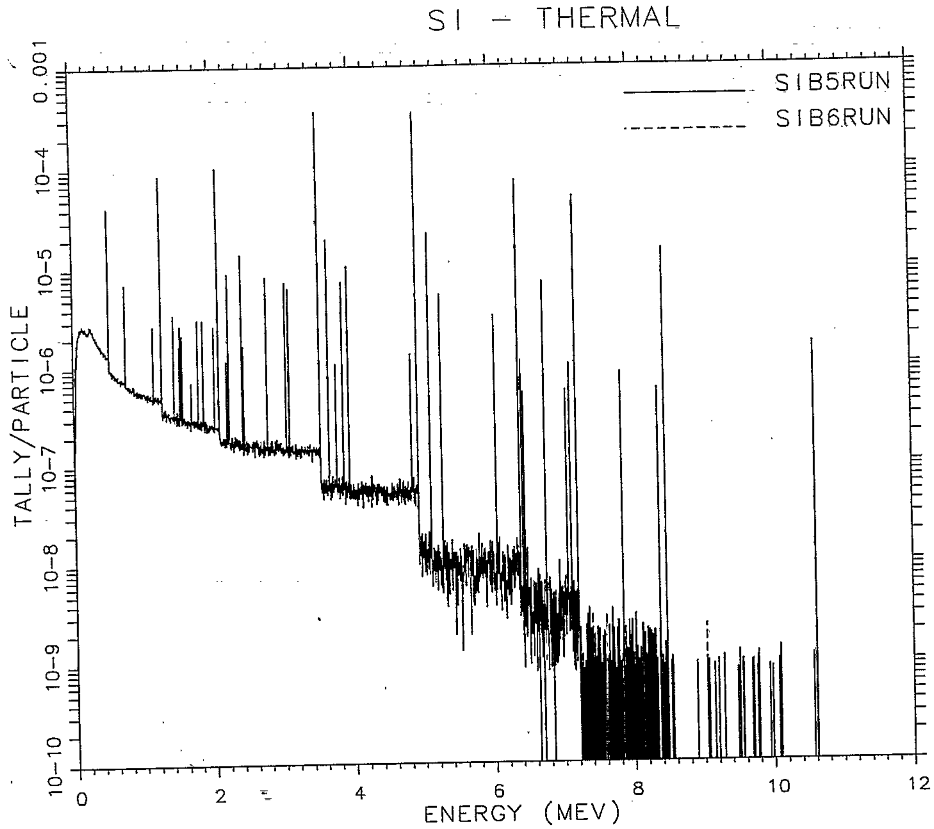
10-4
10-5
10-6
10-7
10-8
10-9
0
1
2
3
4
5
6
7
8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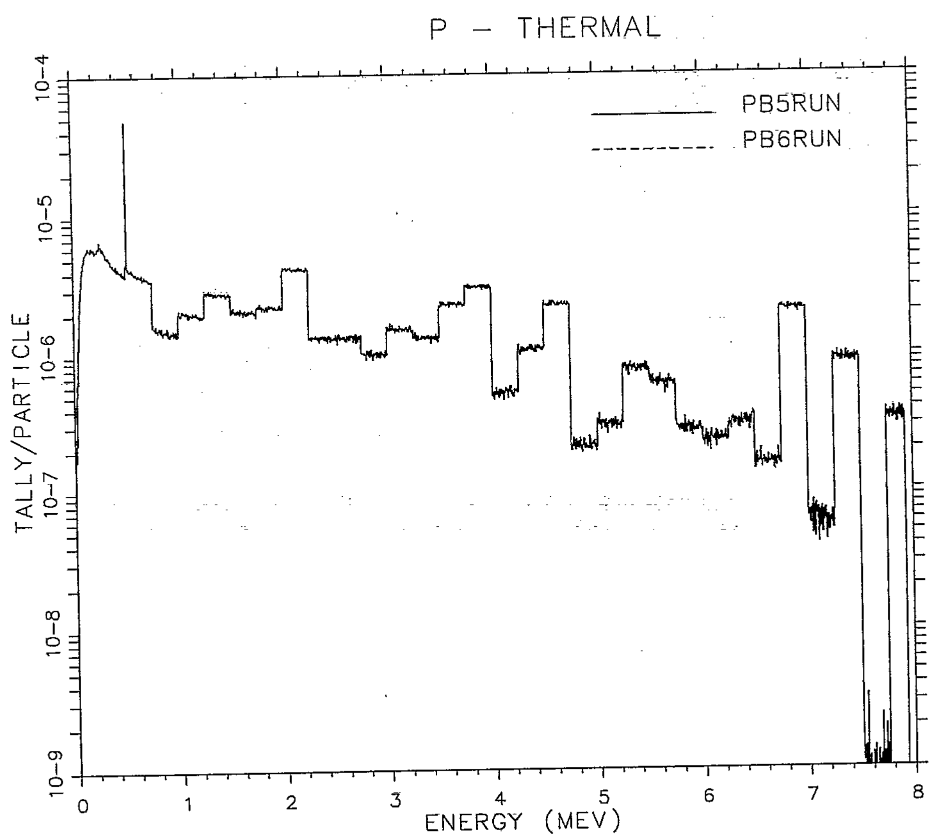
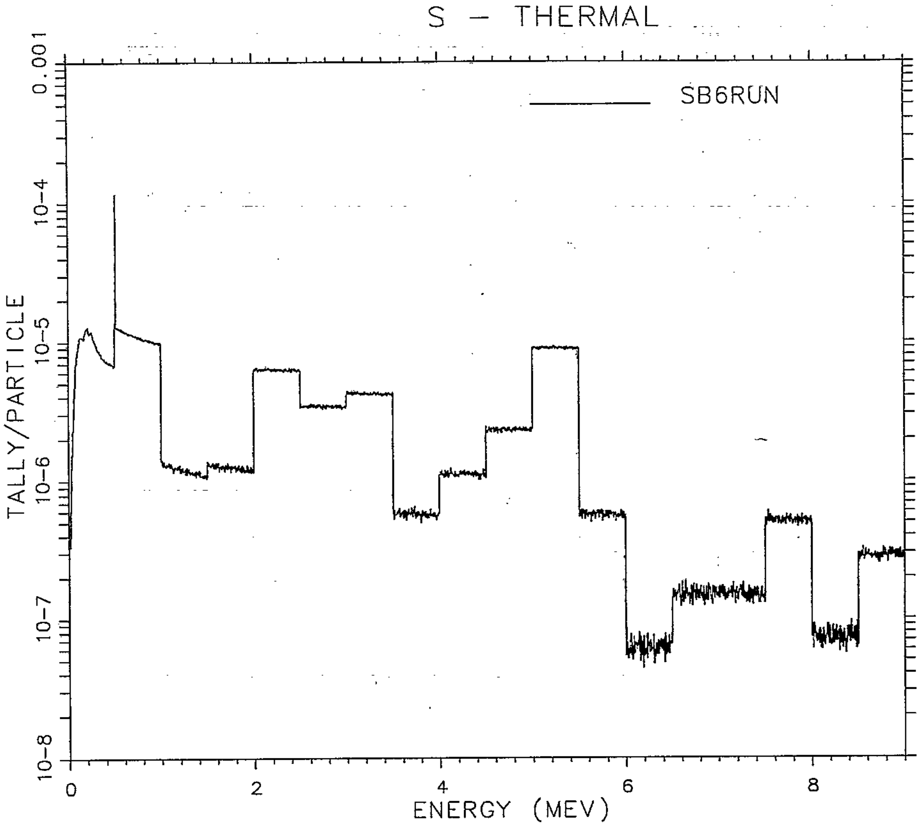
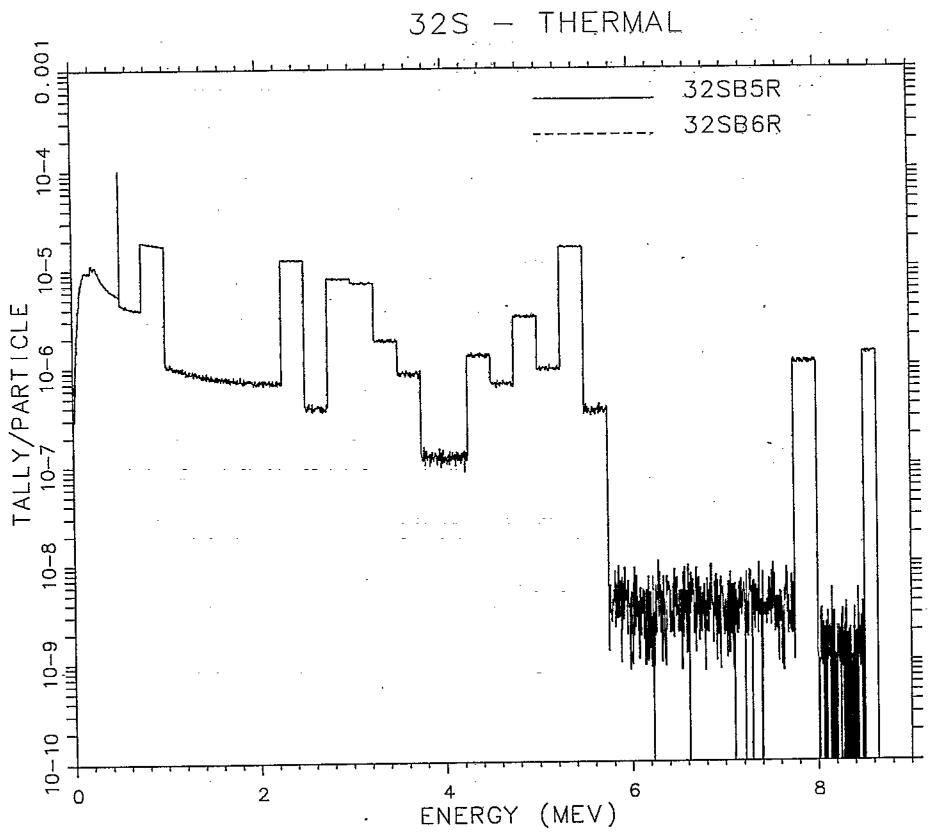
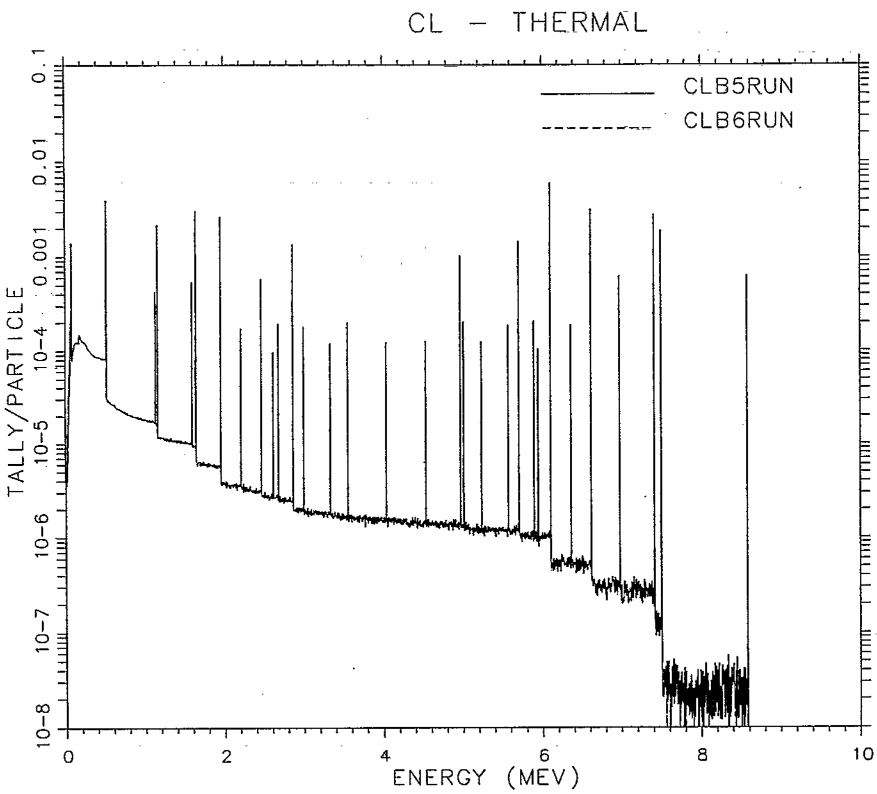
SIB5RUN
SIB6RUN
TALLY/PARTICLE
ENERGY (MEV)


P – THERMAL
PB5RUN
PB6RUN
TALLY/PARTICLE
ENERGY (MEV)


S – THERMAL
SB6RUN
TALLY/PARTICLE
ENERGY (MEV)


32S – THERMAL
32SB5R
32SB6R
TALLY/PARTICLE
ENERGY (MEV)



CL – THERMAL
CLB5RUN
CLB6RUN
TALLY/PARTICLE
ENERGY (MEV)
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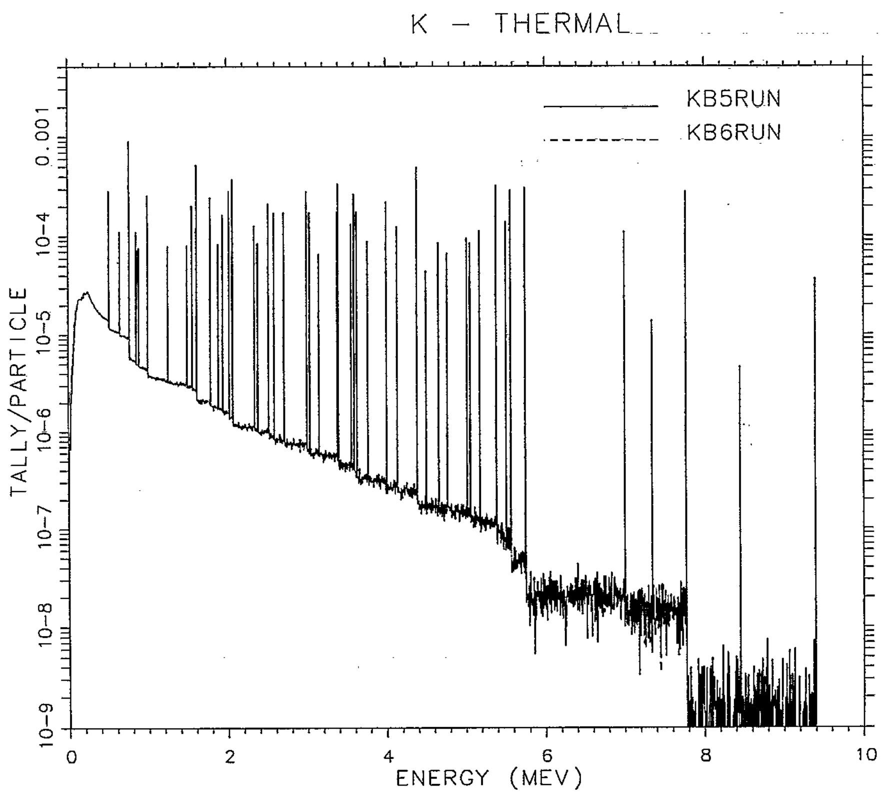
0.001
10-4
10-5
10-6
10-7
10-8
0
2
4
6
8
10



K – THERMAL
KB5RUN
KB6RUN
TALLY/PARTICLE
ENERGY (MEV)
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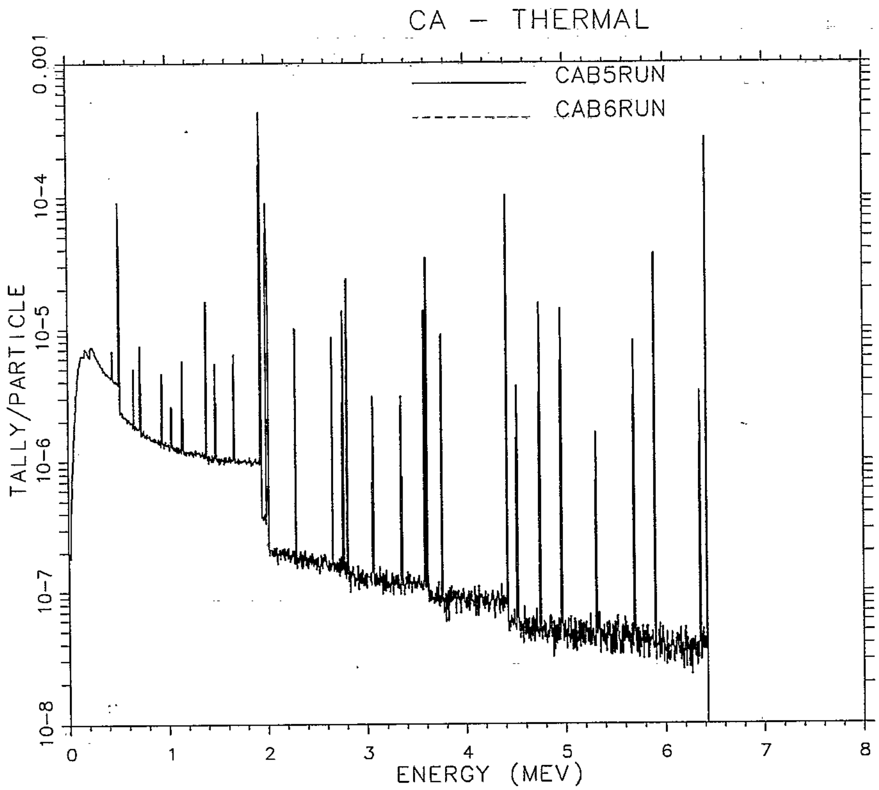
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10


CA – THERMAL
CAB5RUN
CAB6RUN
TALLY/PARTICLE
0.001
10-4
10-5
10-6
10-7
10-8
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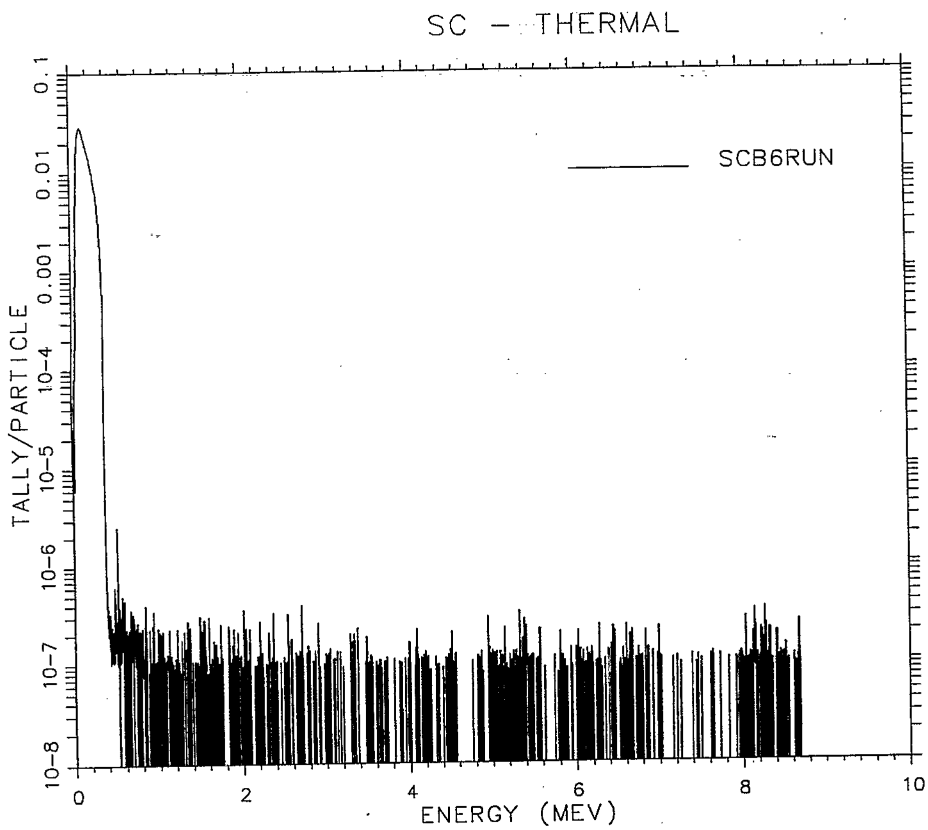
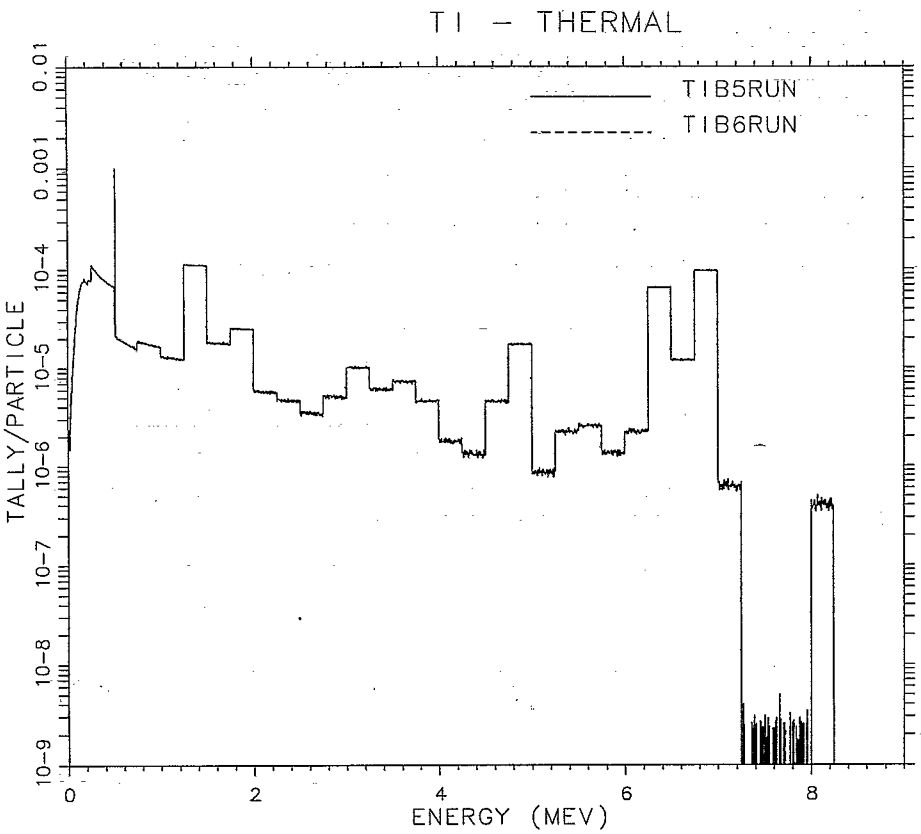
6
7
8
ENERGY (MEV)


SC – THERMAL
SCB6RUN
TALLY/PARTICLE
0.1
0.01
0.001
10-4
10-5
10-6
10-7
10-8
0
2
4
6
8
10
ENERGY (MEV)


TI — THERMAL
TIB5RUN
TIB6RUN
TALLY/PARTICLE
0.01
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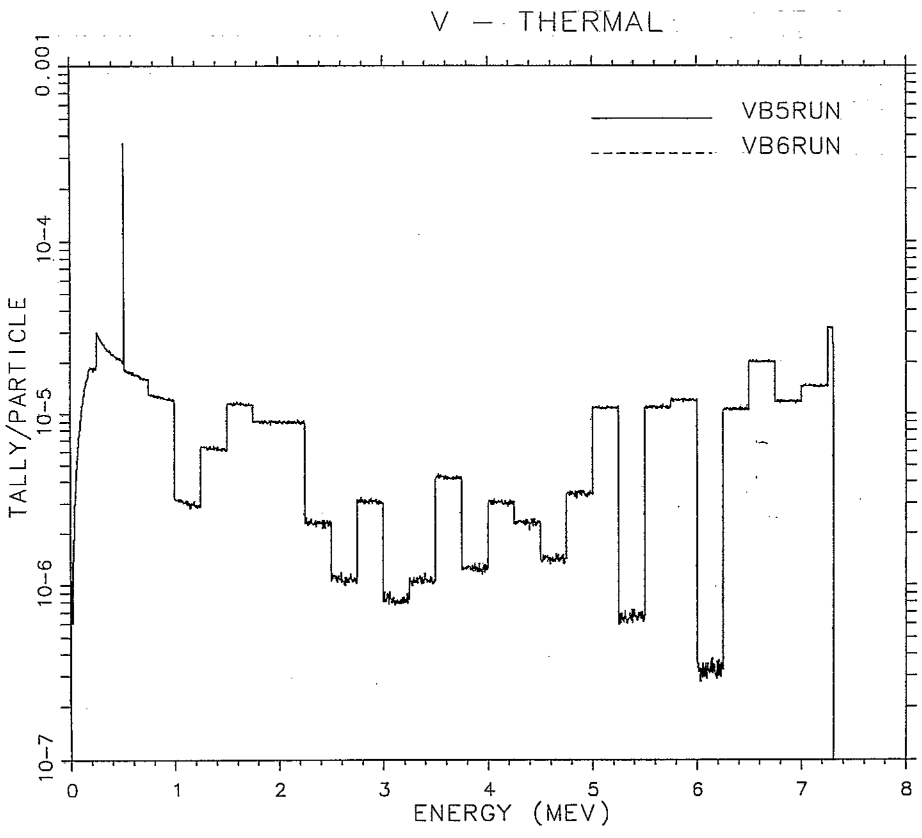
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
ENERGY (MEV)


V — THERMAL
VB5RUN
VB6RUN
TALLY/PARTICLE
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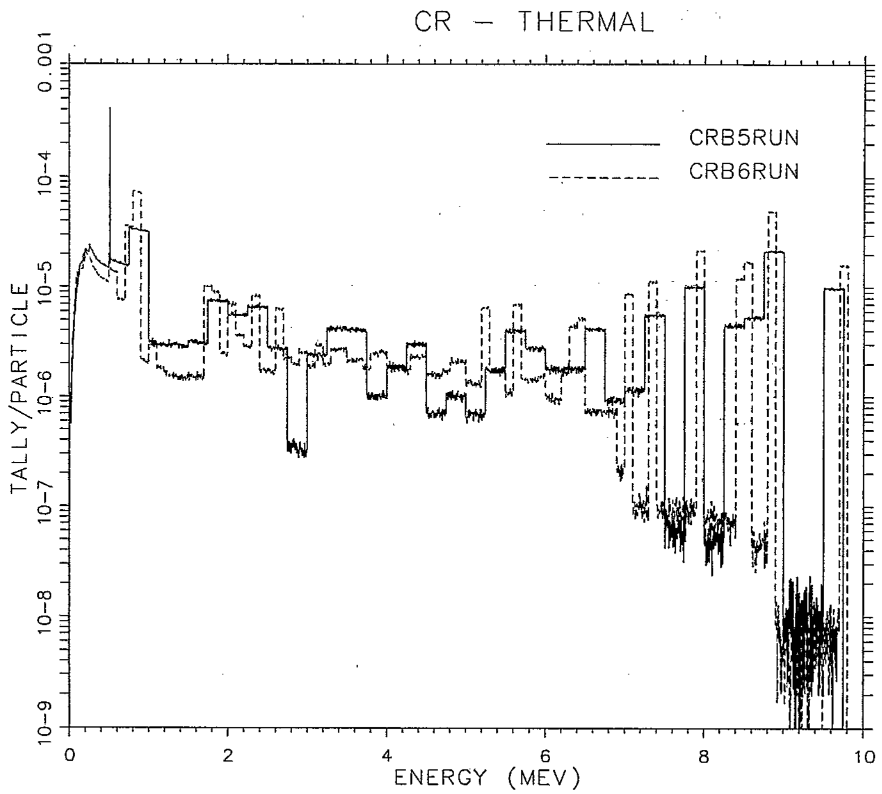
10-4
10-5
10-6
10-7
0
1
2
3
4
5
6
7
8
ENERGY (MEV)


CR — THERMAL
CRB5RUN
CRB6RUN
TALLY/PARTICLE
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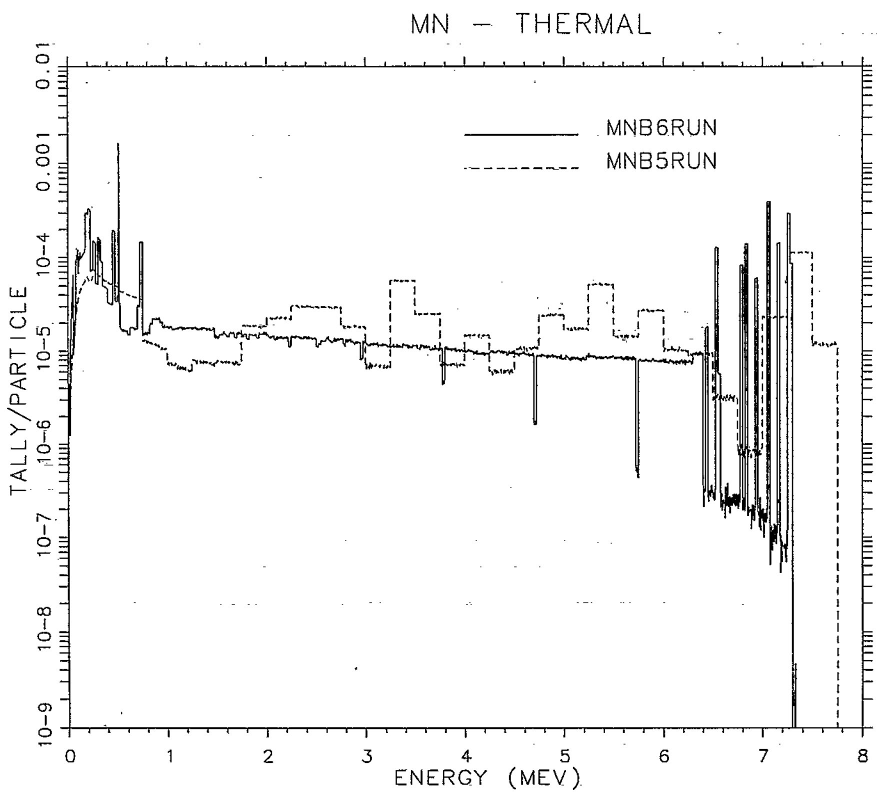
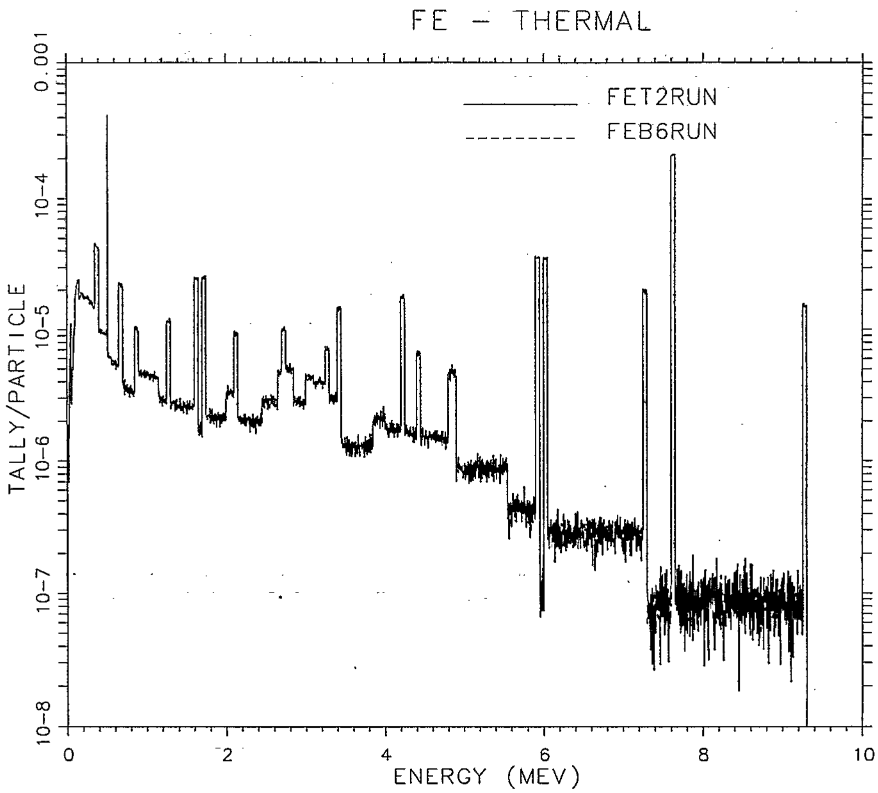
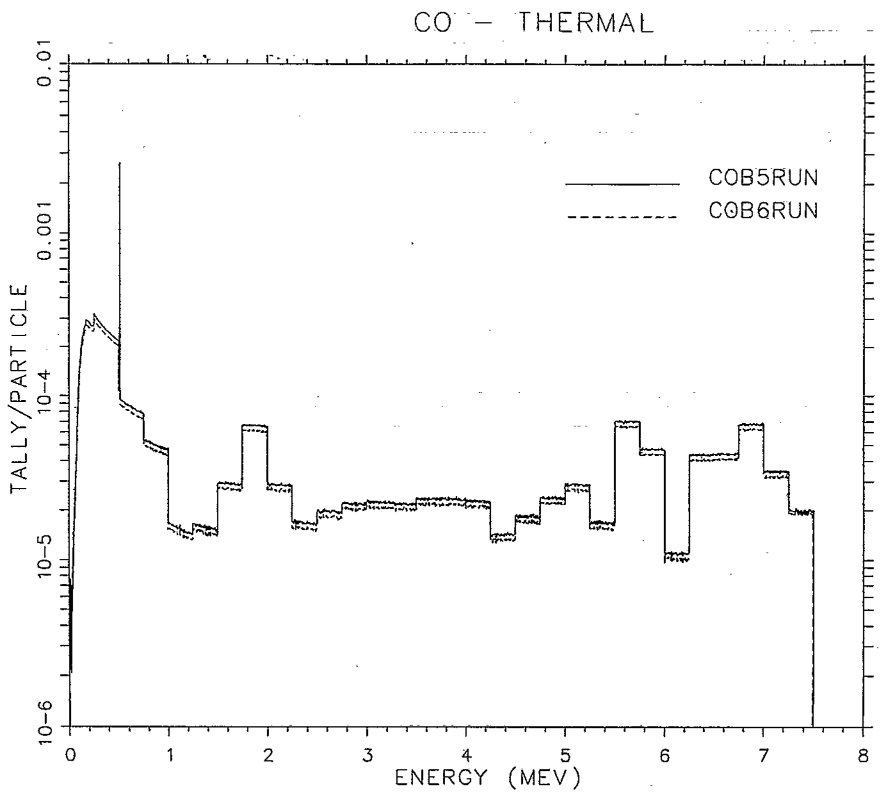
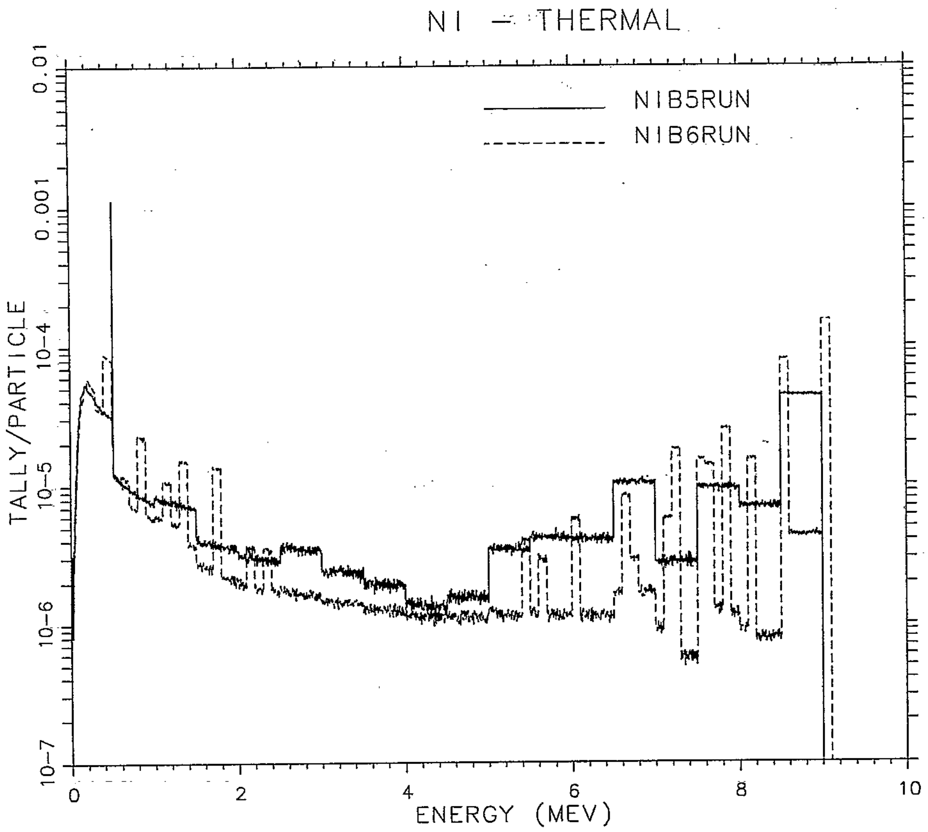
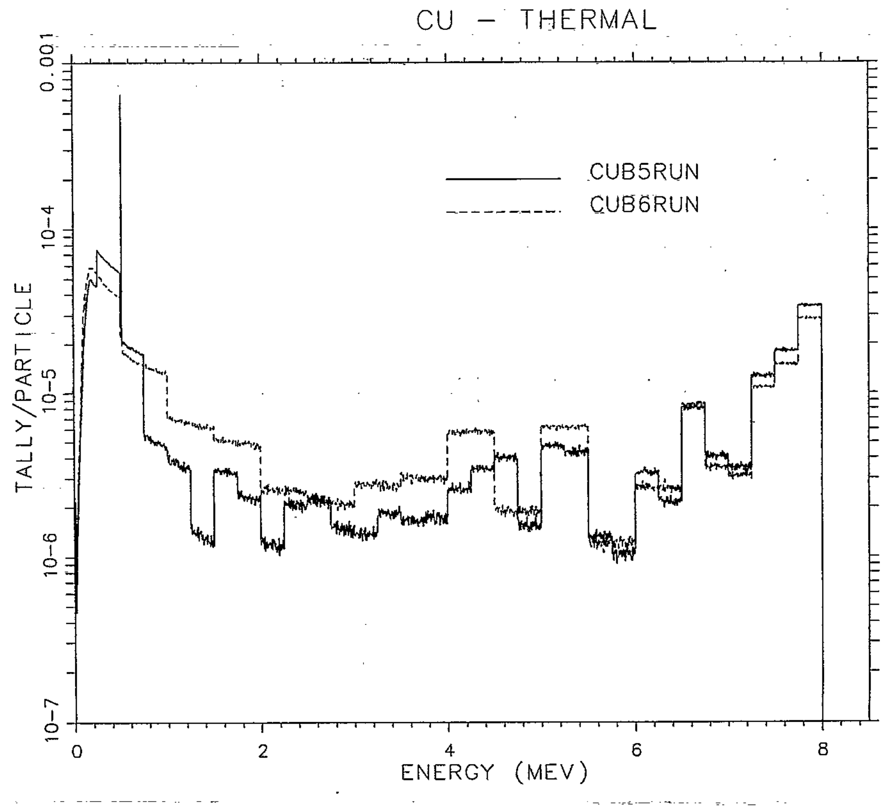
10-8
10-9
0
2
4
6
8
10
ENERGY (MEV)

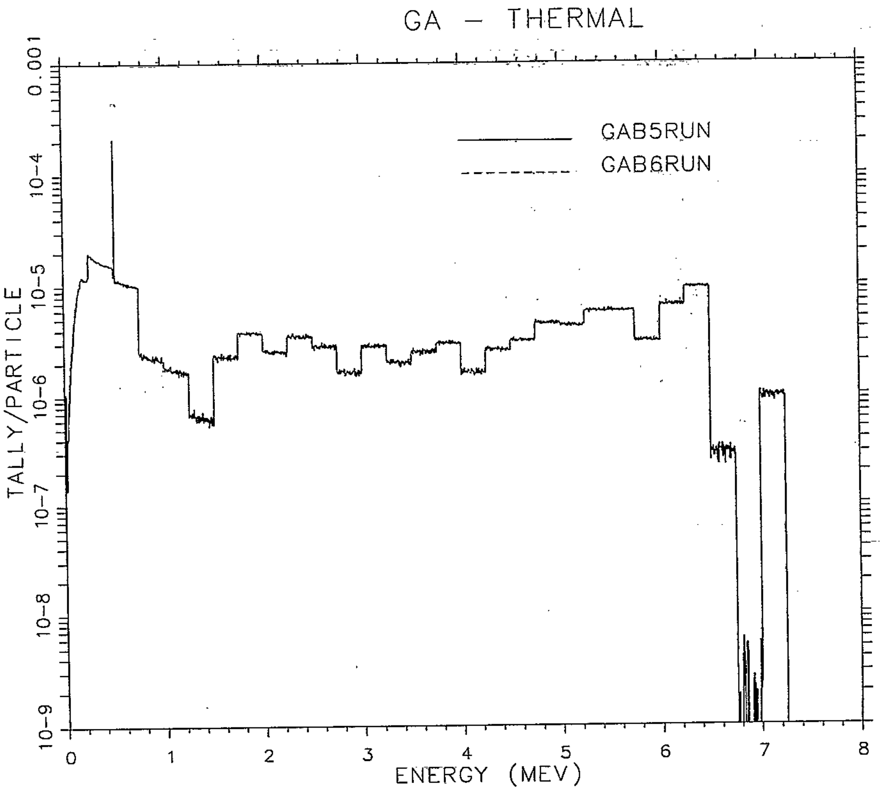

MN — THERMAL
MNB6RUN
MNB5RUN
TALLY/PARTICLE
0.01
0.001
10-4
10-5
10-6
10-7
10-8
10-9
0
1
2
3
4
5
6
7
8
ENERGY (MEV)

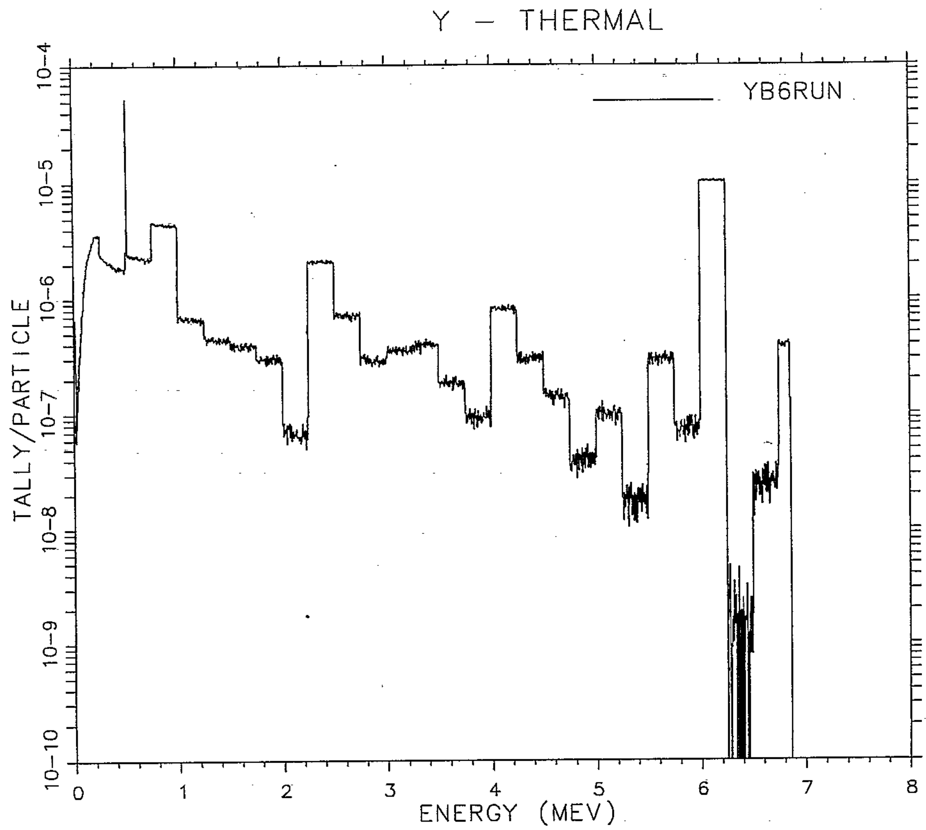

FE – THERMAL
FET2RUN
FEB6RUN
TALLY/PARTICLE
0.001
10-4
10-5
10-6
10-7
10-8
0
2
4
6
8
10
ENERGY (MEV)

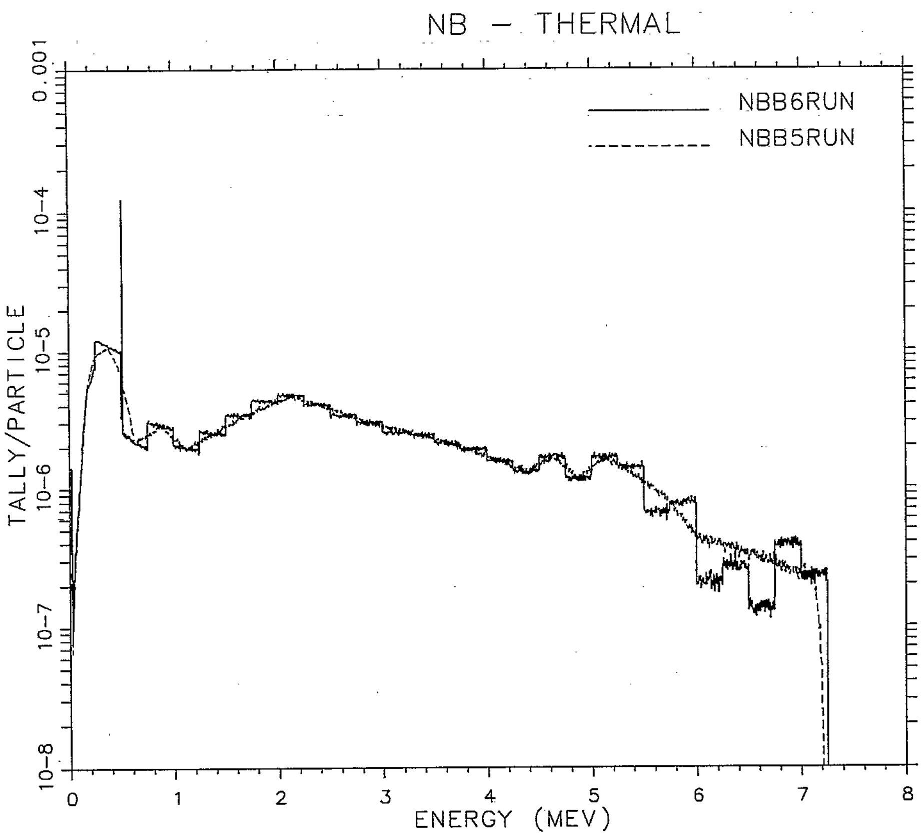

CO – THERMAL
COB5RUN
COB6RUN
TALLY/PARTICLE
0.01
0.001
10-4
10-5
10-6
0
1
2
3
4
5
6
7
8
ENERGY (MEV)

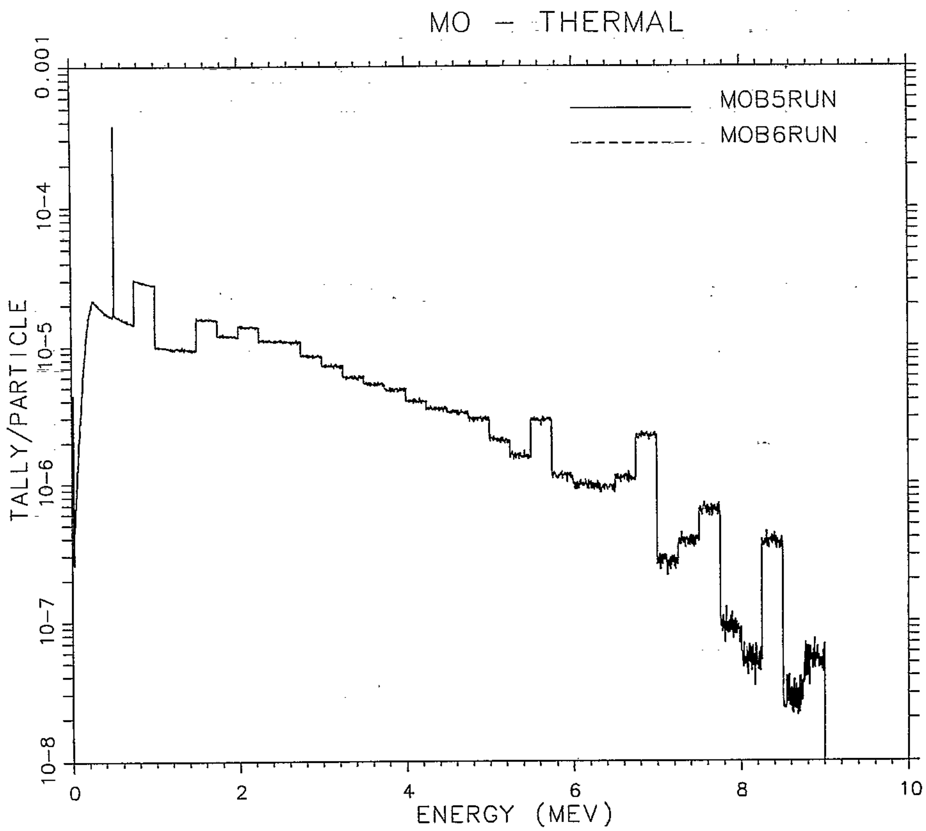

NI – THERMAL
NIB5RUN
NIB6RUN
TALLY/PARTICLE
0.01
0.001
10-4
10-5
10-6
10-7
0
2
4
6
8
10
ENERGY (MEV)

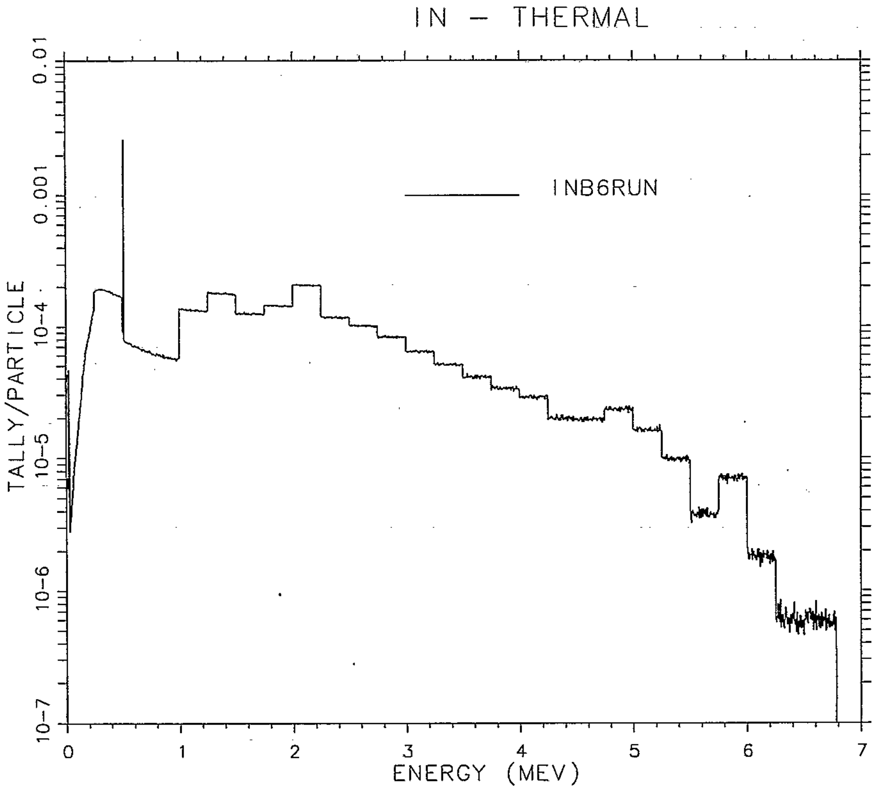

CU – THERMAL
CUB5RUN
CUB6RUN
TALLY/PARTICLE
0.001
10-4
10-5
10-6
10-7
0
2
4
6
8
ENERGY (MEV)

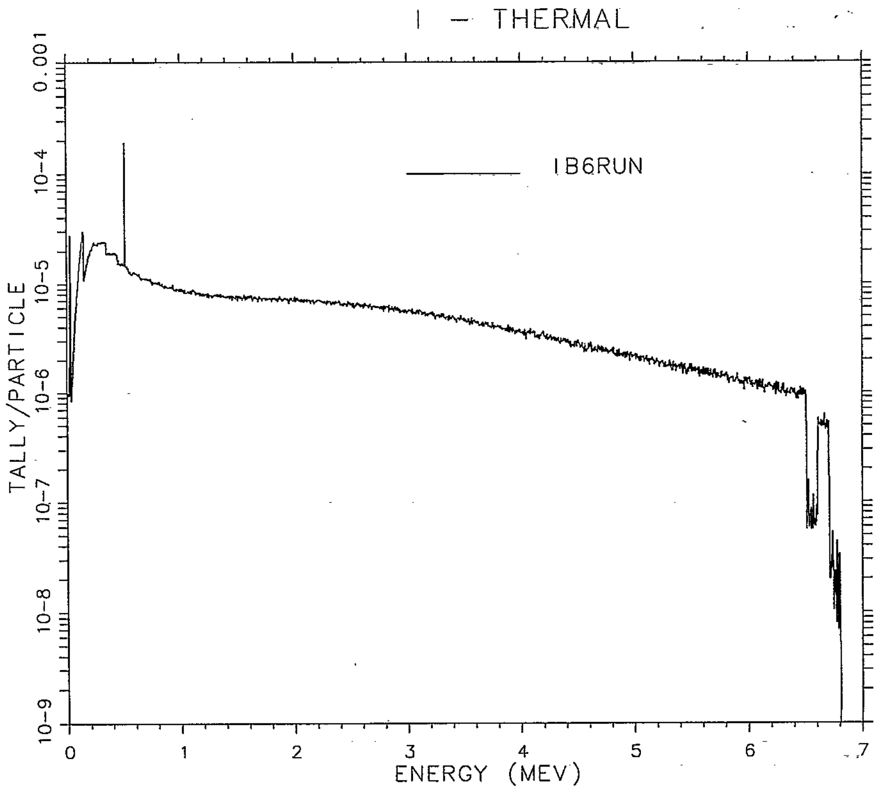

GA – THERMAL
GAB5RUN
GAB6RUN
TALLY/PARTICLE
ENERGY (MEV)
0.001
10–4
10–5
10–6
10–7
10–8
10–9
0
1
2
3
4
5
6
7
8

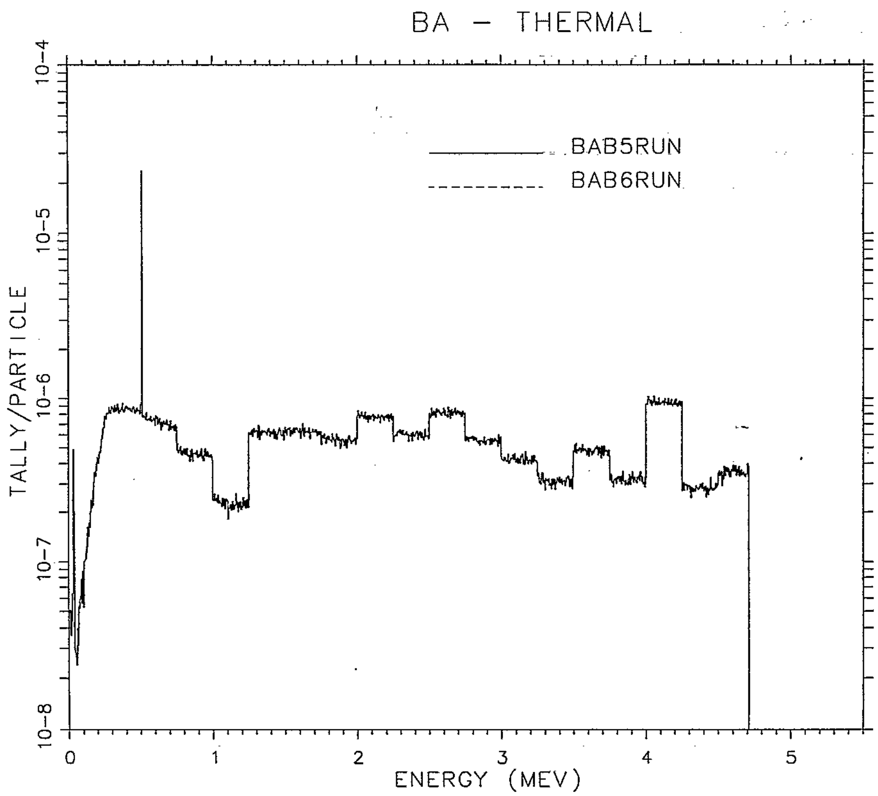

Y – THERMAL
YB6RUN
TALLY/PARTICLE
ENERGY (MEV)
10–4
10–5
10–6
10–7
10–8
10–9
10–10
0
1
2
3
4
5
6
7
8

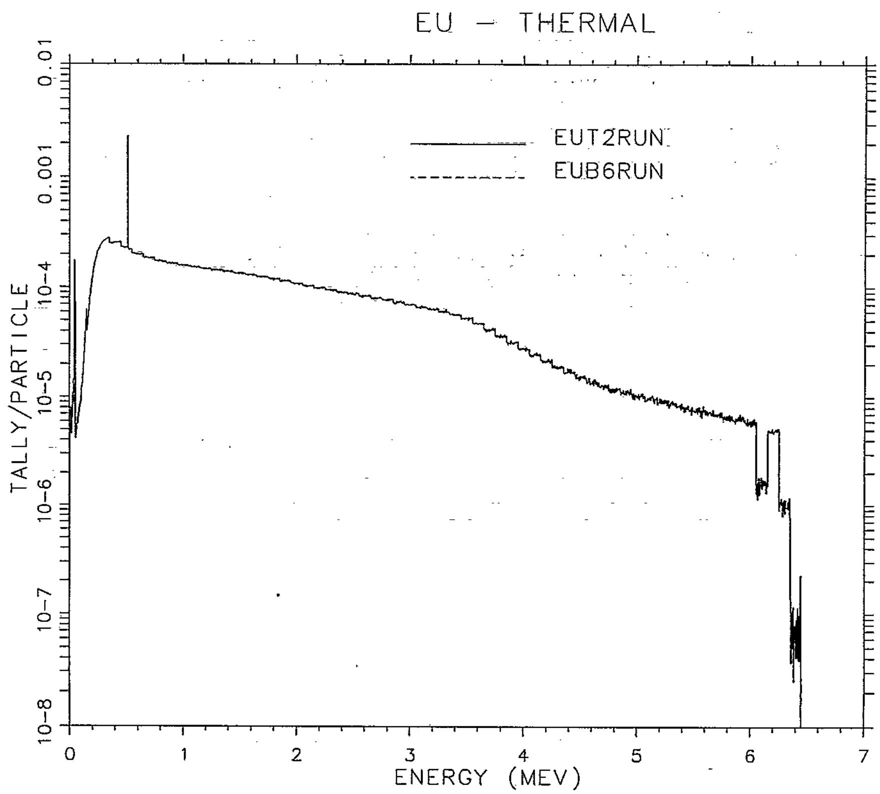

NB – THERMAL
NBB6RUN
NBB5RUN
TALLY/PARTICLE
0.001
10-4
10-5
10-6
10-7
10-8
0
1
2
3
4
5
6
7
8
ENERGY (MEV)

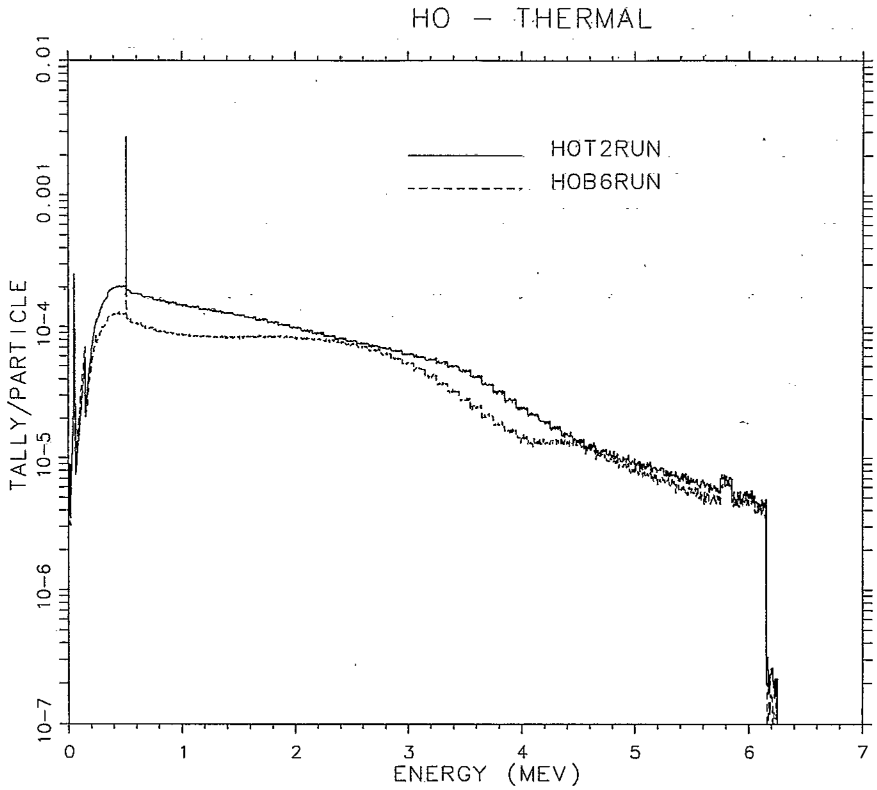

MO – THERMAL
MOB5RUN
MOB6RUN
TALLY/PARTICLE
0.001
10-4
10-5
10-6
10-7
10-8
0
2
4
6
8
10
ENERGY (MEV)

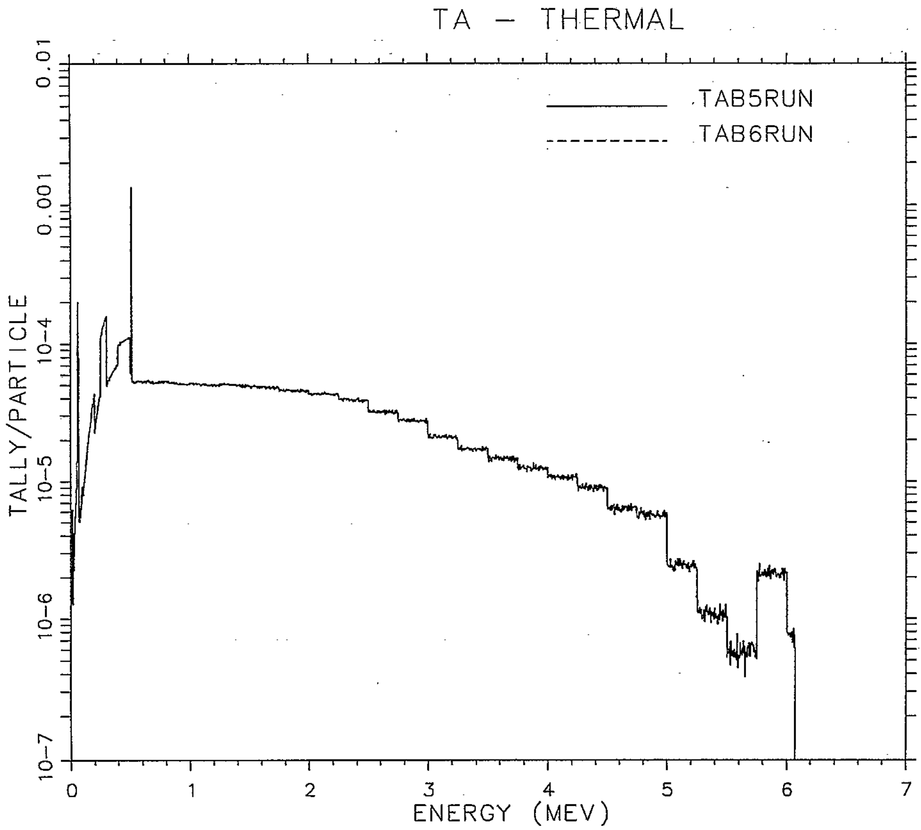

IN – THERMAL
INB6RUN
TALLY/PARTICLE
0.01
0.001
10-4
10-5
10-6
10-7
0
1
2
3
4
5
6
7
ENERGY (MEV)

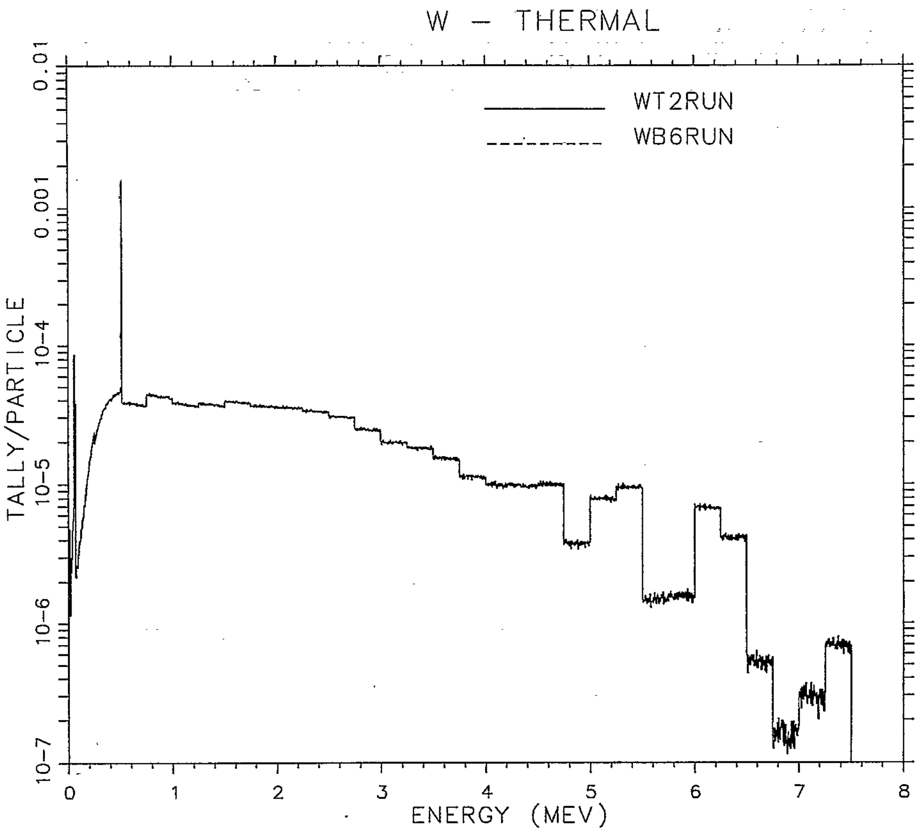

I – THERMAL
IB6RUN
TALLY/PARTICLE
0.001
10-4
10-5
10-6
10-7
10-8
10-9
0
1
2
3
4
5
6
7
ENERGY (MEV)

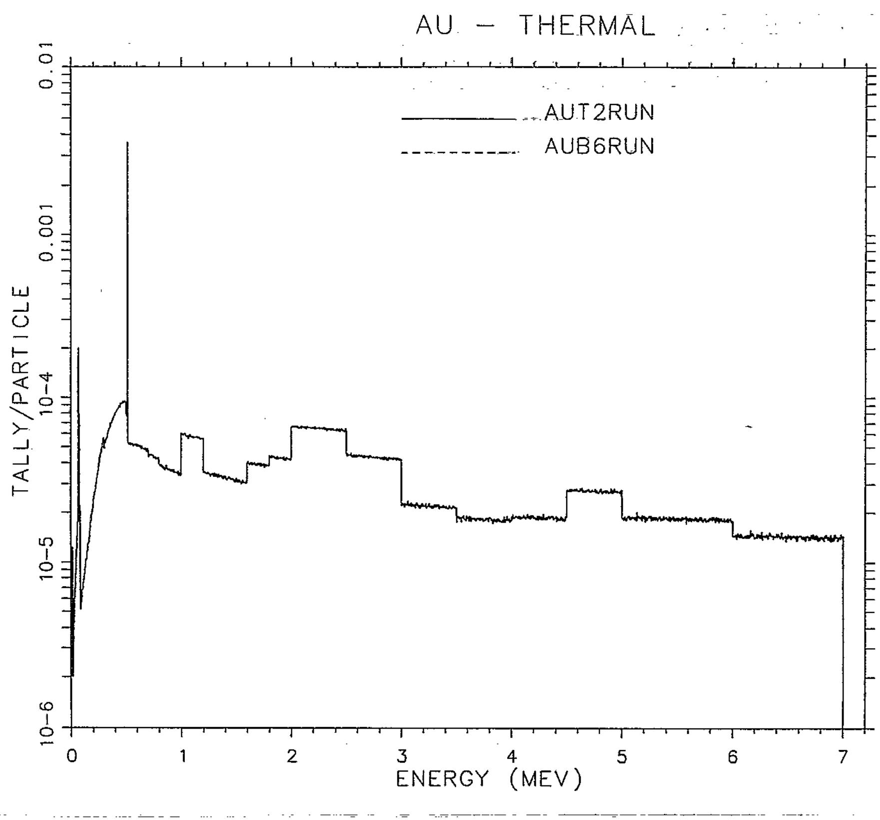

BA – THERMAL
BAB5RUN
BAB6RUN
TALLY/PARTICLE
10-4
10-5
10-6
10-7
10-8
0
1
2
3
4
5
ENERGY (MEV)

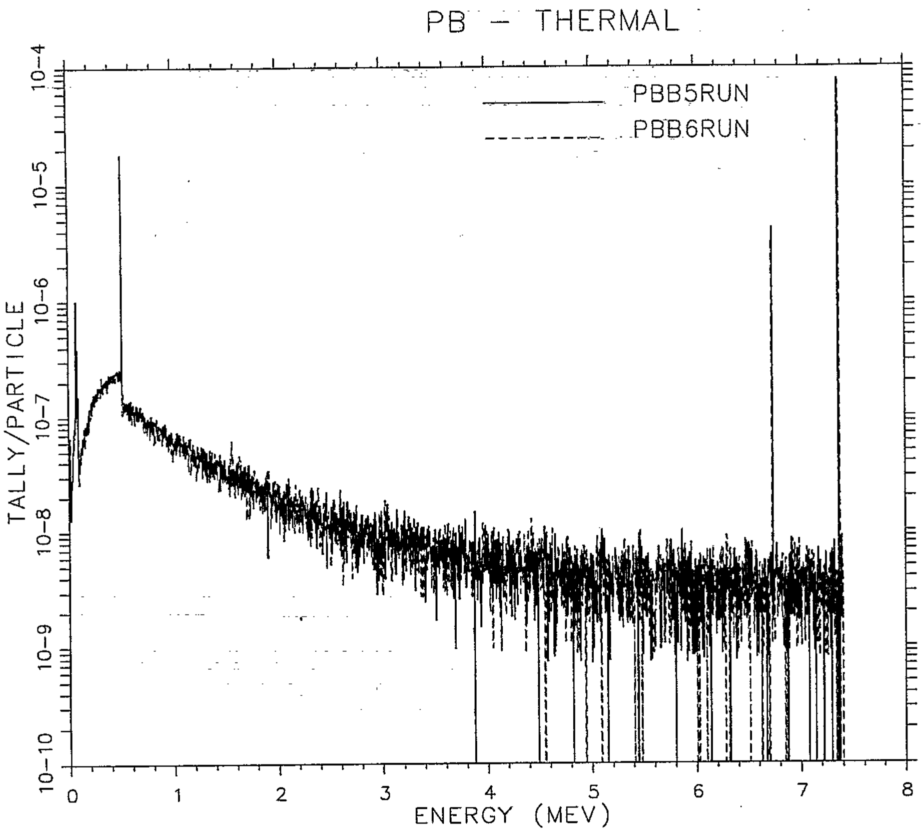

EU – THERMAL
EUT2RUN
EUB6RUN
TALLY/PARTICLE
0.01
0.001
10-4
10-5
10-6
10-7
10-8
0
1
2
3
4
5
6
7
ENERGY (MEV)

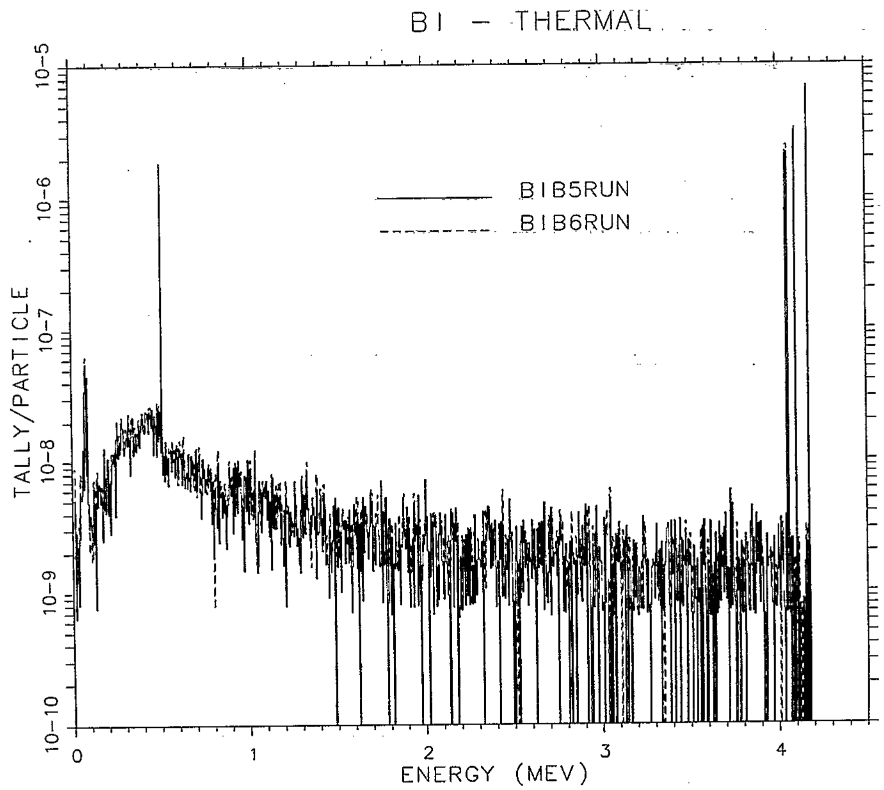

HO — THERMAL
HOT2RUN
HOB6RUN
TALLY/PARTICLE
0.01
0.001
10-4
10-5
10-6
10-7
0
1
2
3
4
5
6
7
ENERGY (MEV)

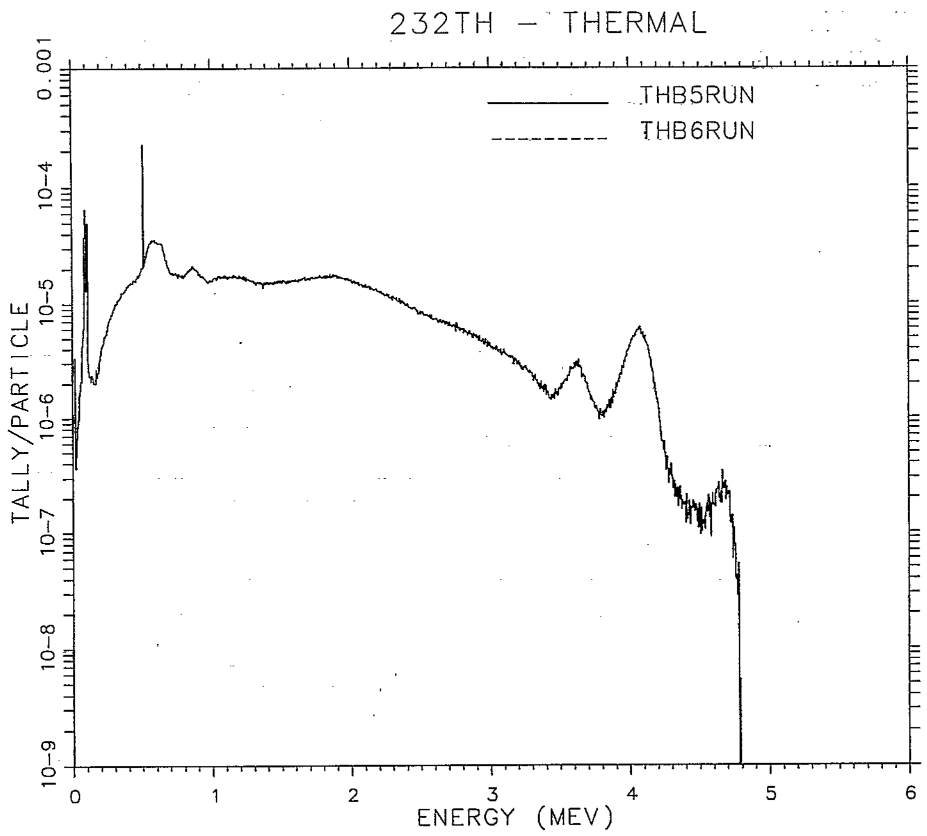

TA — THERMAL
TAB5RUN
TAB6RUN
TALLY/PARTICLE
0.01
0.001
10-4
10-5
10-6
10-7
0
1
2
3
4
5
6
7
ENERGY (MEV)

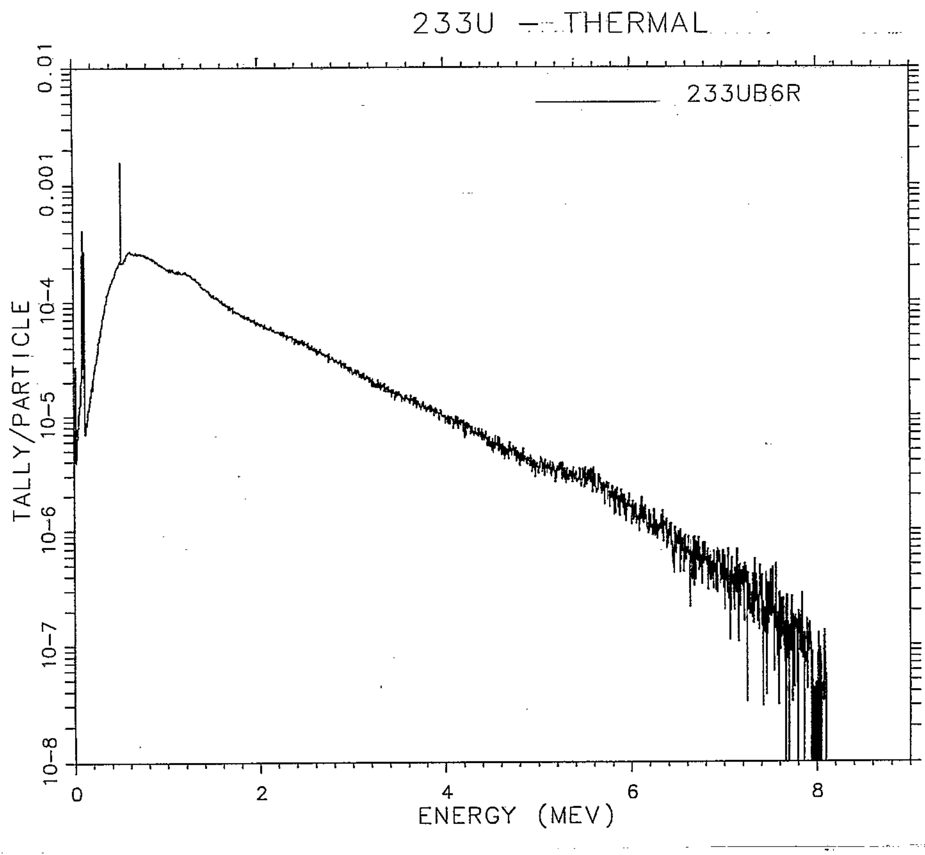

W — THERMAL
WT2RUN
WB6RUN
TALLY/PARTICLE
0.01
0.001
10-4
10-5
10-6
10-7
0
1
2
3
4
5
6
7
8
ENERGY (MEV)


AU — THERMAL
AUT2RUN
AUB6RUN
TALLY/PARTICLE
0.01
0.001
10-4
10-5
10-6
0
1
2
3
4
5
6
7
ENERGY (MEV)

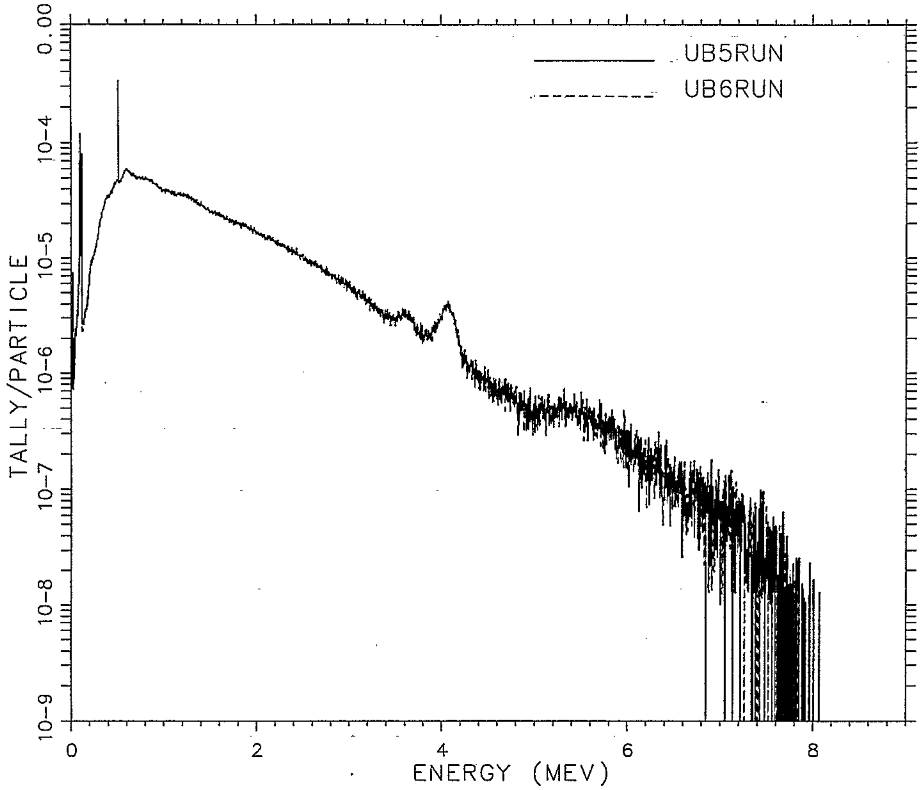

PB - THERMAL
PBB5RUN
PBB6RUN
TALLY/PARTICLE
ENERGY (MEV)


BI - THERMAL
BIB5RUN
BIB6RUN
TALLY/PARTICLE
ENERGY (MEV)

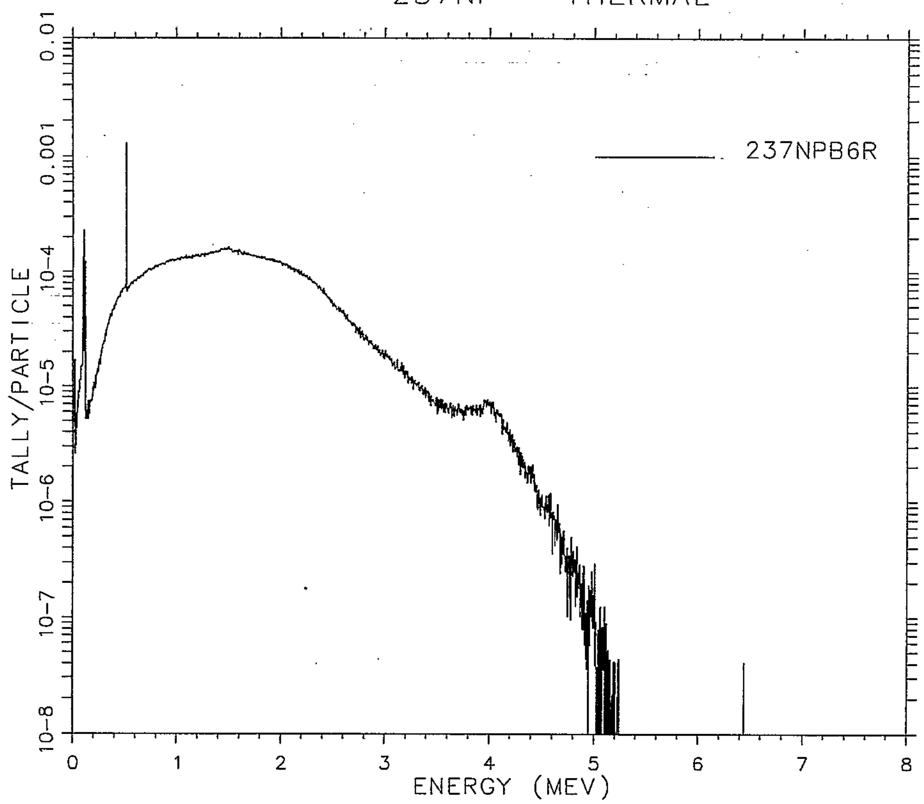

232TH - THERMAL
THB5RUN
THB6RUN
TALLY/PARTICLE
ENERGY (MEV)

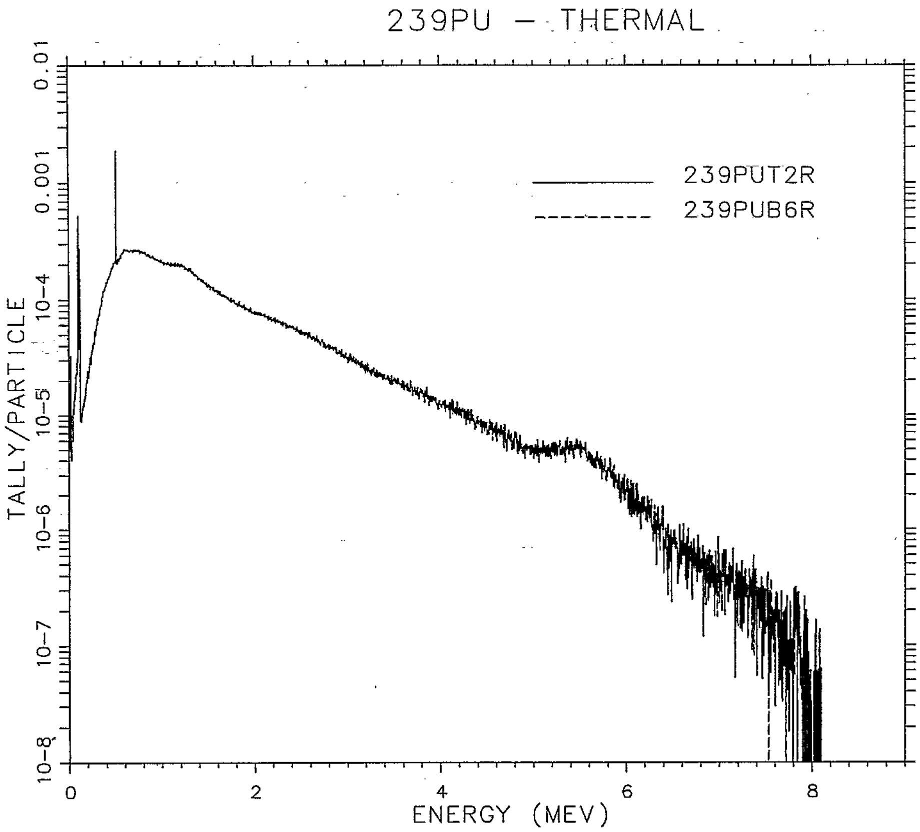

233U - THERMAL
233UB6R
TALLY/PARTICLE
ENERGY (MEV)

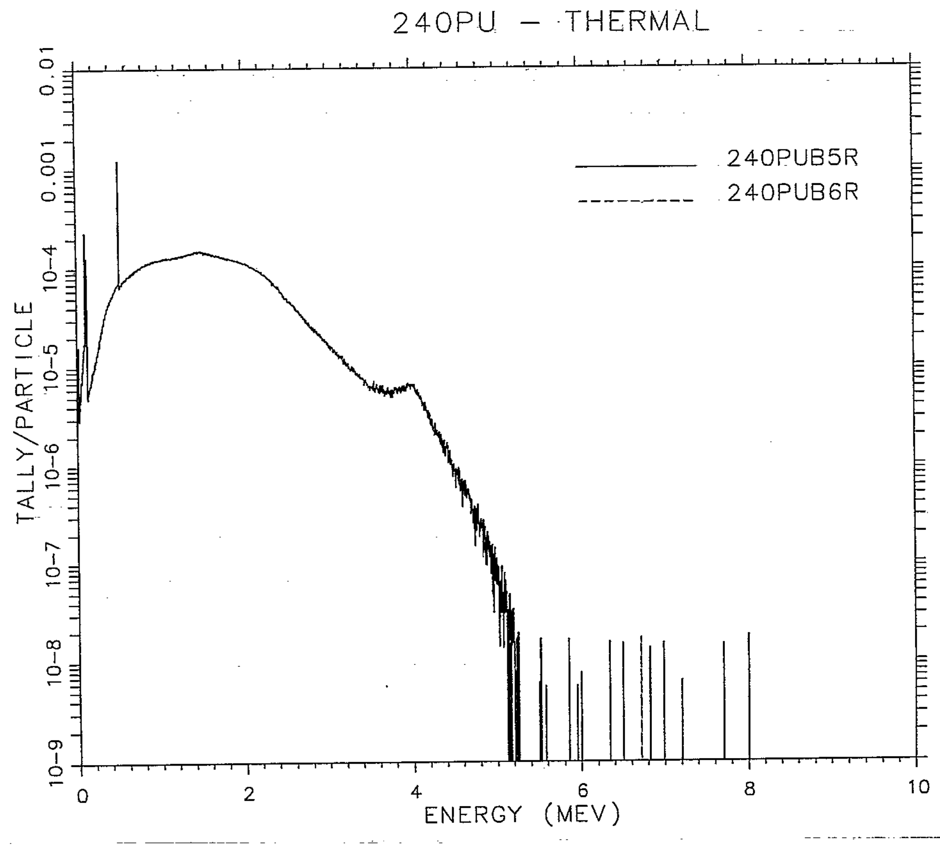
U - THERMAL

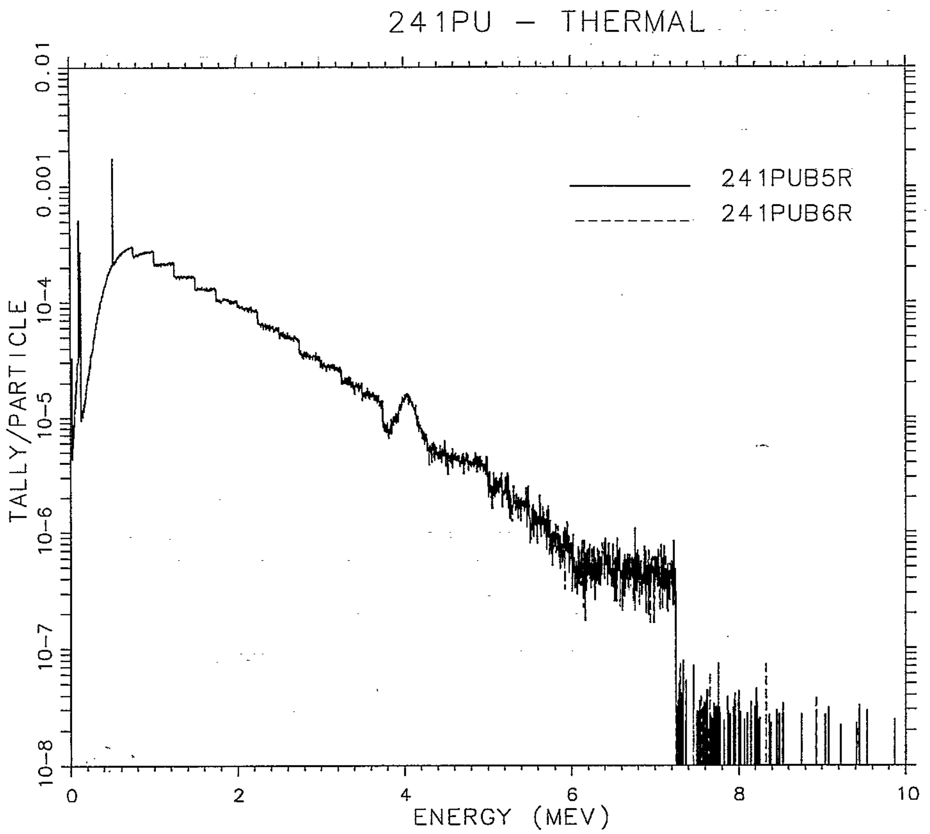


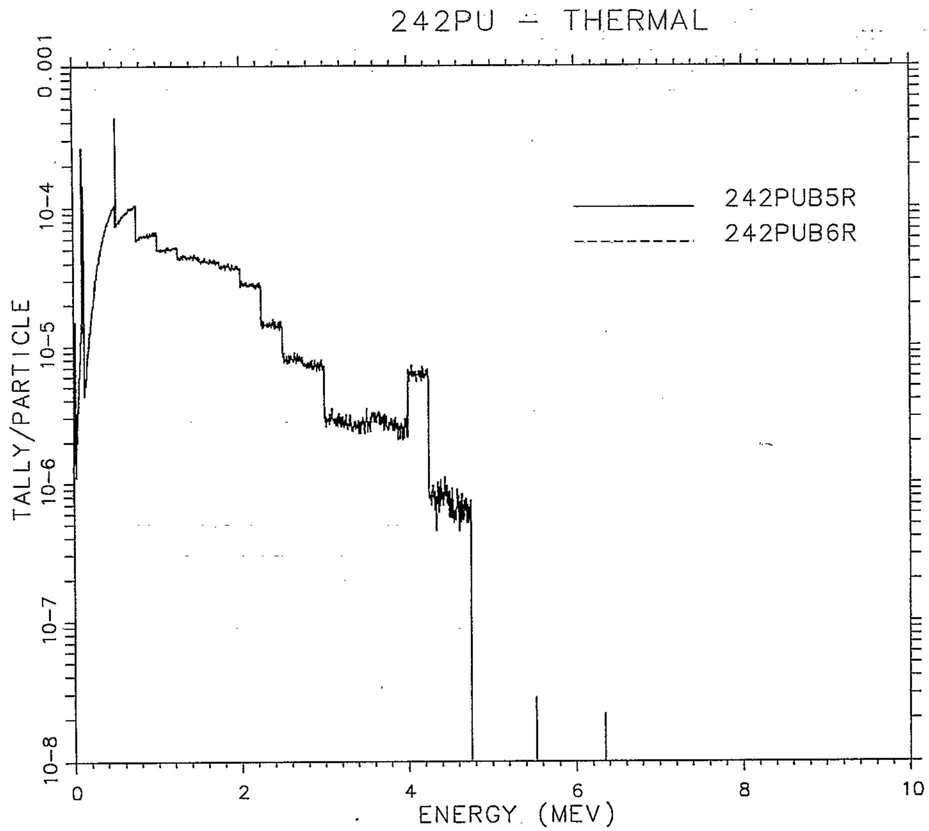
237NP - THERMAL

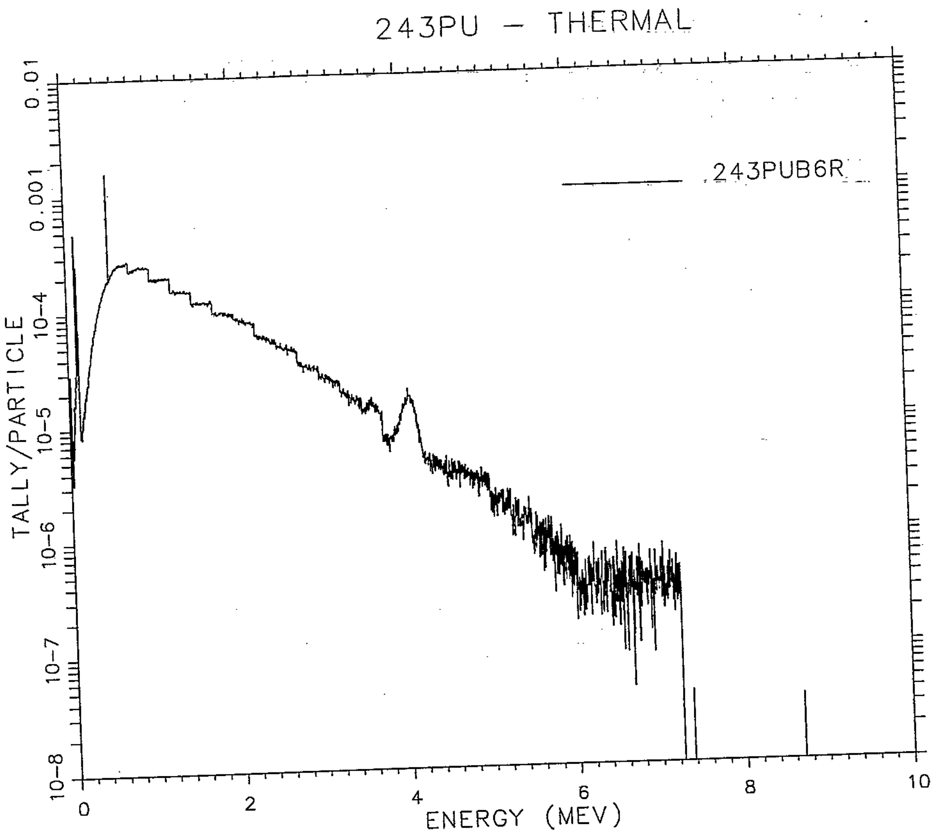


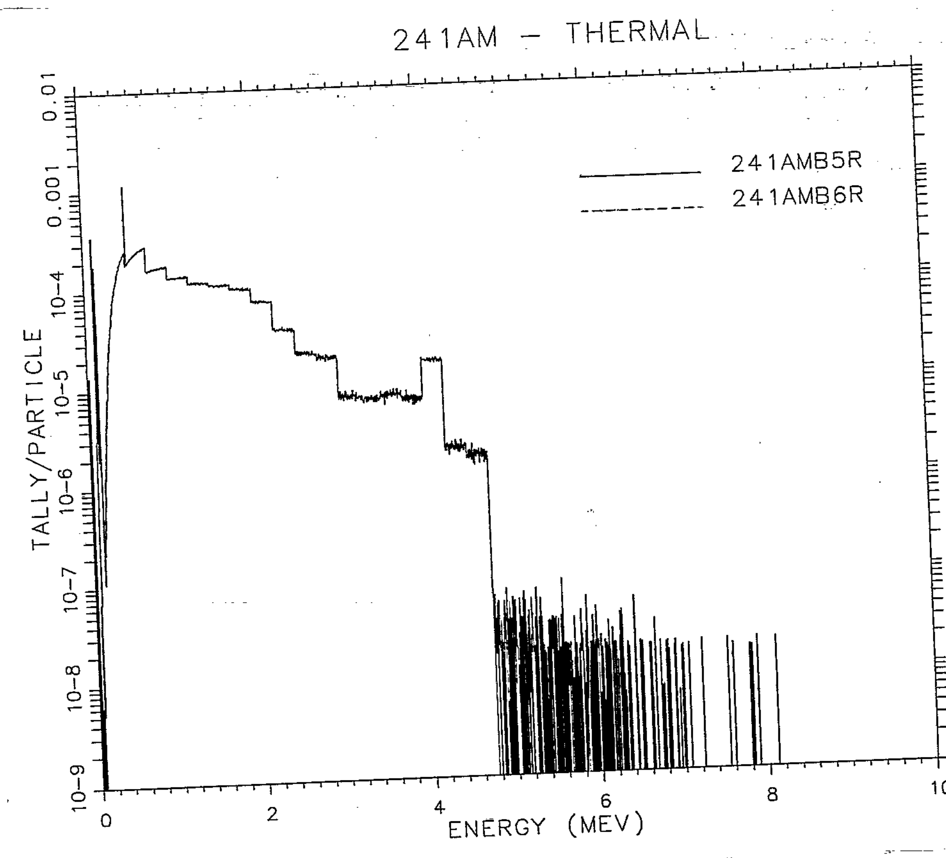

239PU — THERMAL
239PUT2R
239PUB6R
TALLY/PARTICLE
0.01
0.001
10-4
10-5
10-6
10-7
10-8
0
2
4
6
8
ENERGY (MEV)

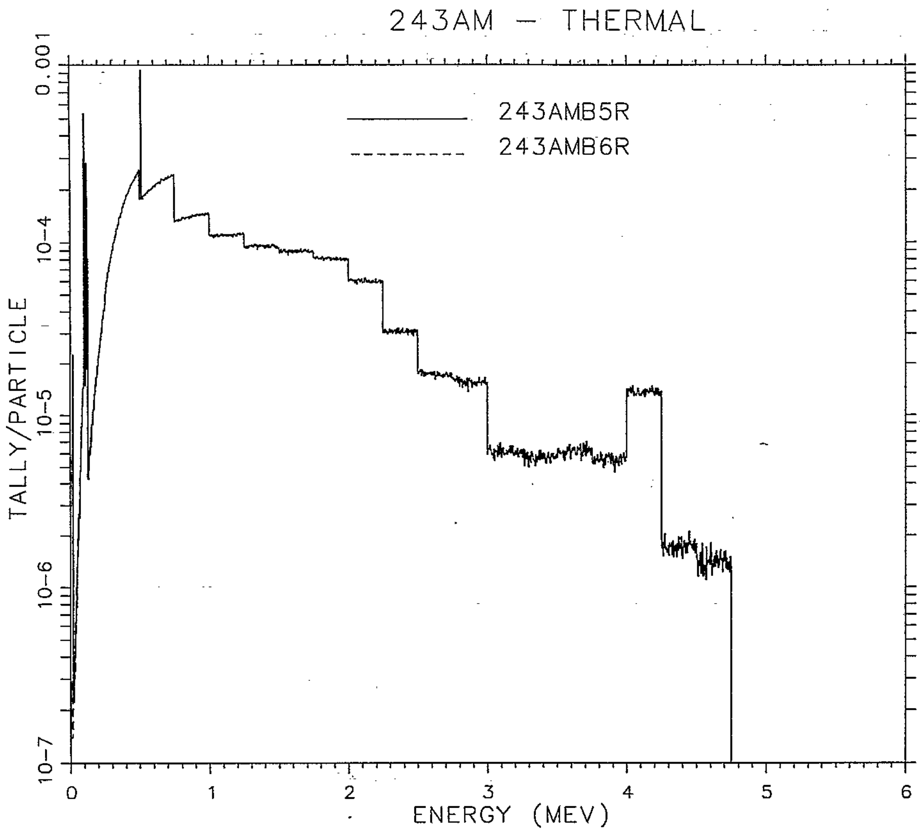

240PU — THERMAL
240PUB5R
240PUB6R
TALLY/PARTICLE
0.01
0.001
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
ENERGY (MEV)

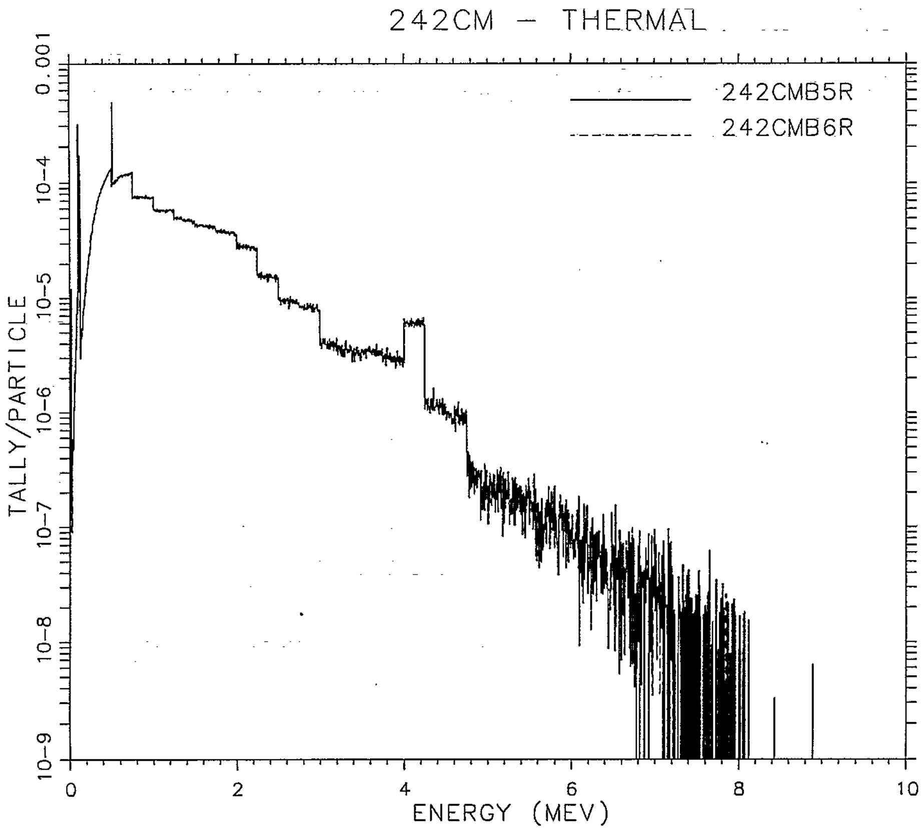

241PU – THERMAL
241PUB5R
241PUB6R
TALLY/PARTICLE
0.01
0.001
10-4
10-5
10-6
10-7
10-8
0
2
4
6
8
10
ENERGY (MEV)

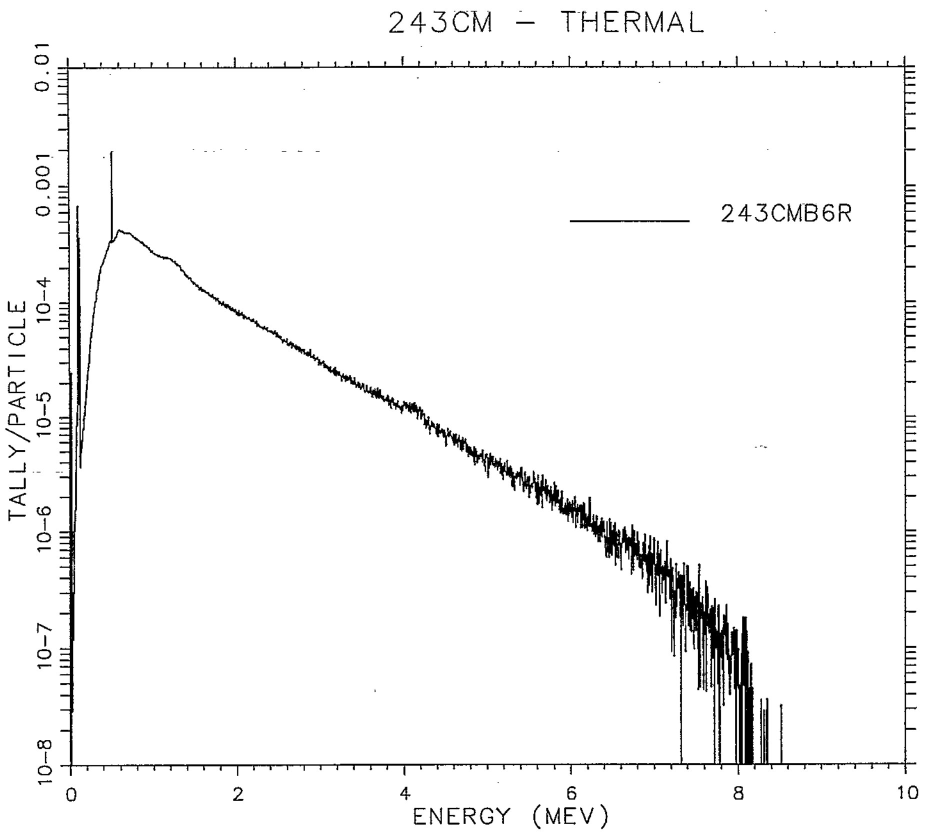

242PU – THERMAL
242PUB5R
242PUB6R
TALLY/PARTICLE
0.001
10-4
10-5
10-6
10-7
10-8
0
2
4
6
8
10
ENERGY (MEV)

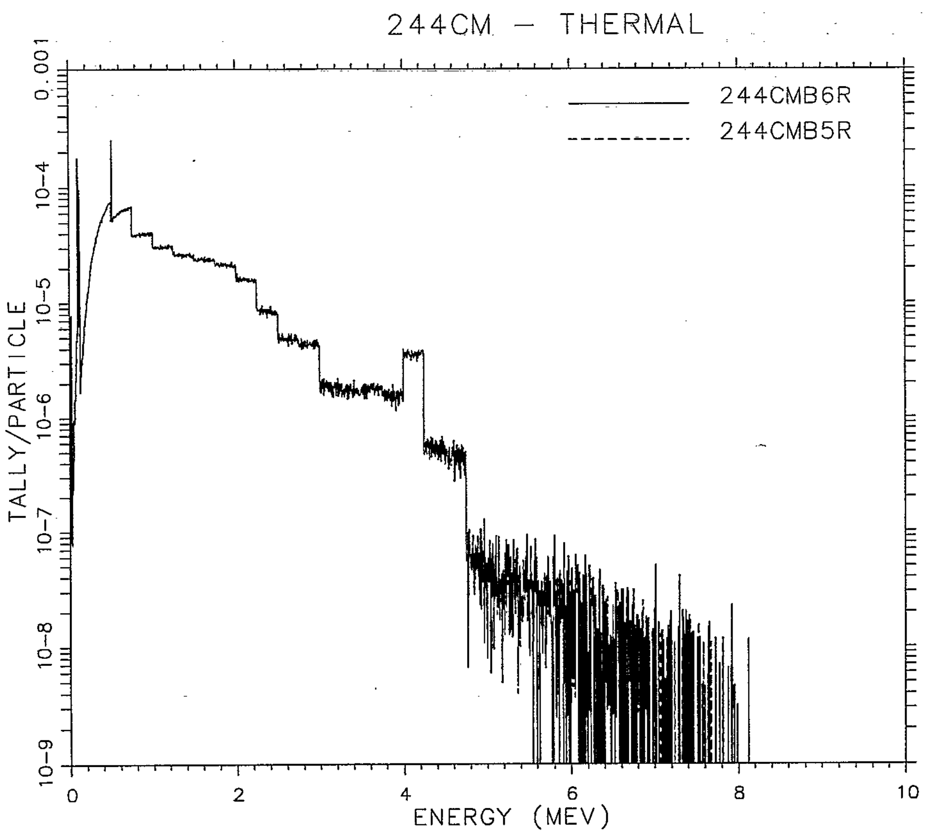

243PU – THERMAL
243PUB6R
TALLY/PARTICLE
ENERGY (MEV)
0.01
0.001
10−4
10−5
10−6
10−7
10−8
0
2
4
6
8
10

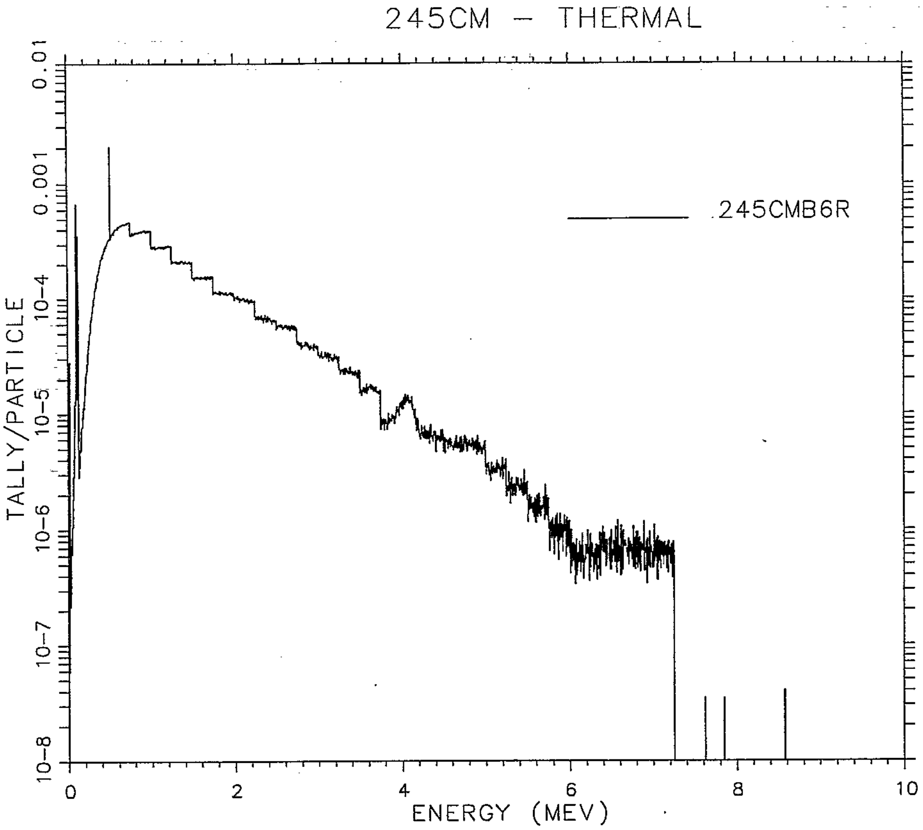

241AM – THERMAL
241AMB5R
241AMB6R
TALLY/PARTICLE
ENERGY (MEV)
0.01
0.001
10−4
10−5
10−6
10−7
10−8
10−9
0
2
4
6
8
10

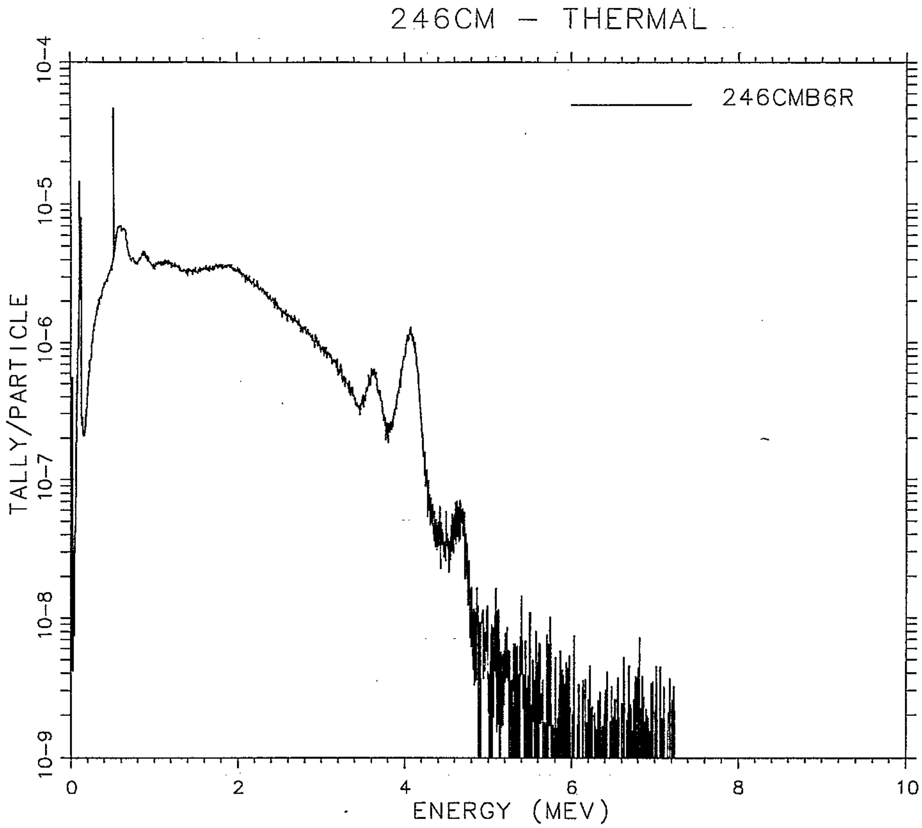

243AM — THERMAL
243AMB5R
243AMB6R
TALLY/PARTICLE
0.001
10-4
10-5
10-6
10-7
0
1
2
3
4
5
6
ENERGY (MEV)

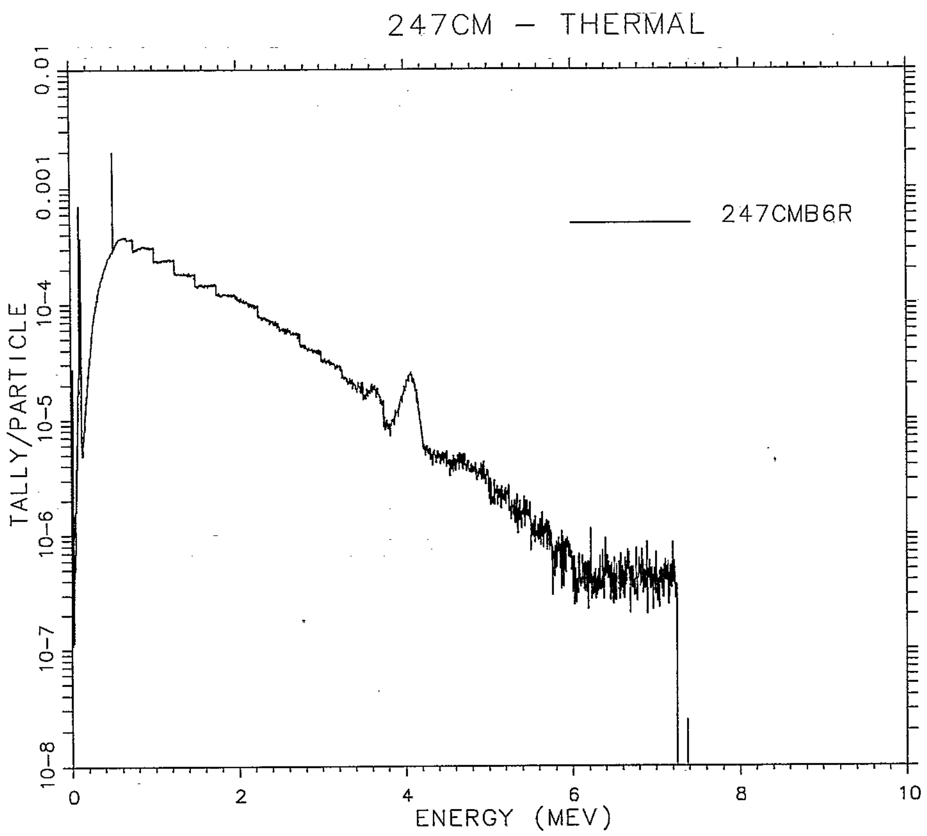

242CM — THERMAL
242CMB5R
242CMB6R
TALLY/PARTICLE
0.001
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
ENERGY (MEV)

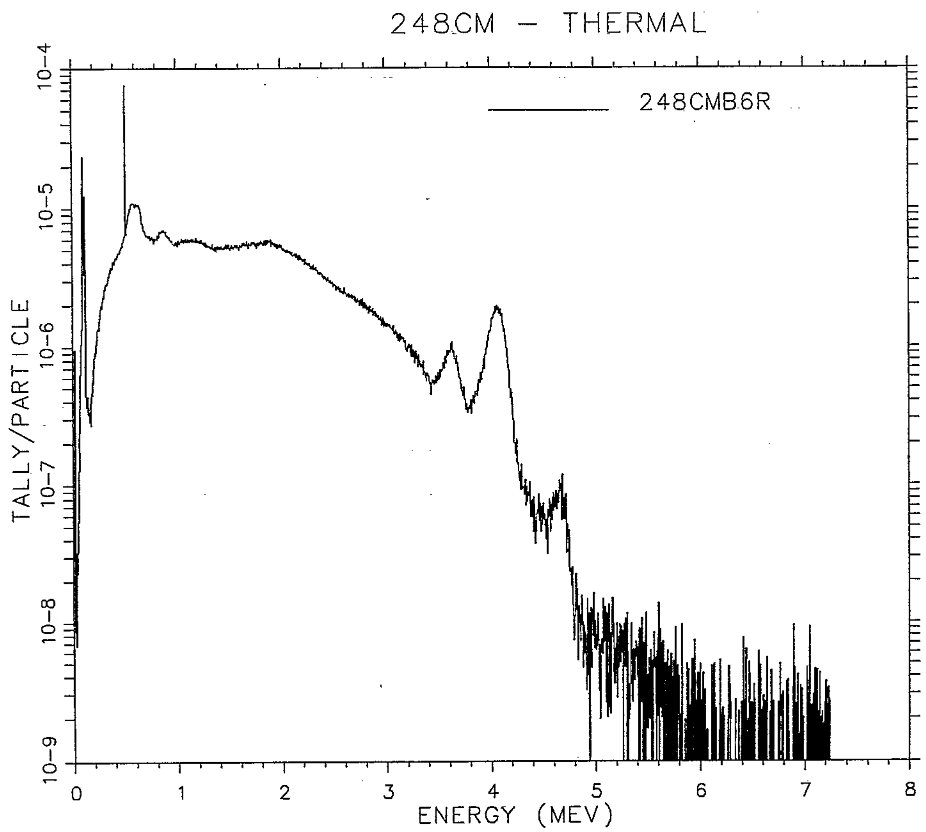

243CM — THERMAL
243CMB6R
TALLY/PARTICLE
ENERGY (MEV)
0.01
0.001
10-4
10-5
10-6
10-7
10-8
0
2
4
6
8
10

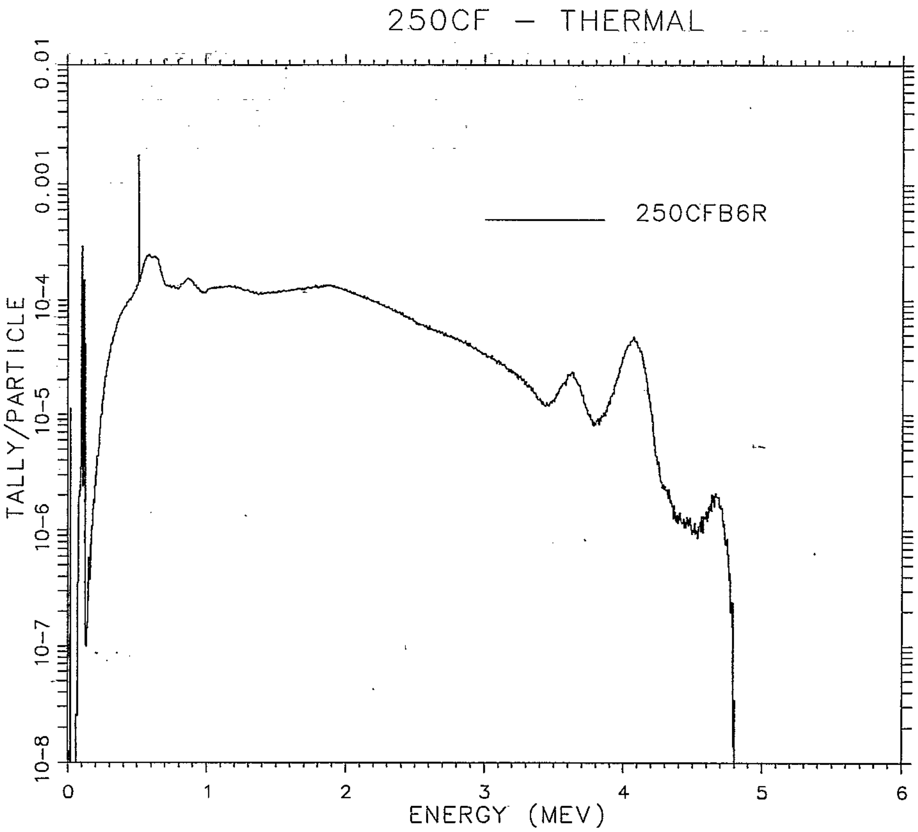

244CM — THERMAL
244CMB6R
244CMB5R
TALLY/PARTICLE
ENERGY (MEV)
0.001
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10

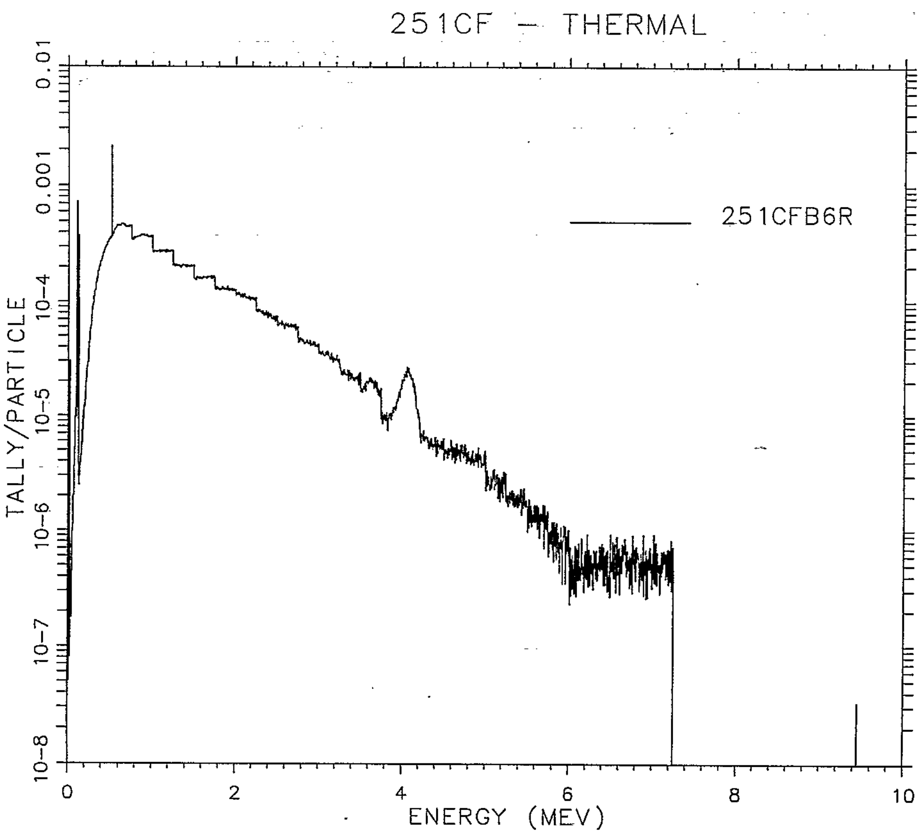

245CM — THERMAL
245CMB6R
TALLY/PARTICLE
0.01
0.001
10−4
10−5
10−6
10−7
10−8
0
2
4
6
8
10
ENERGY (MEV)

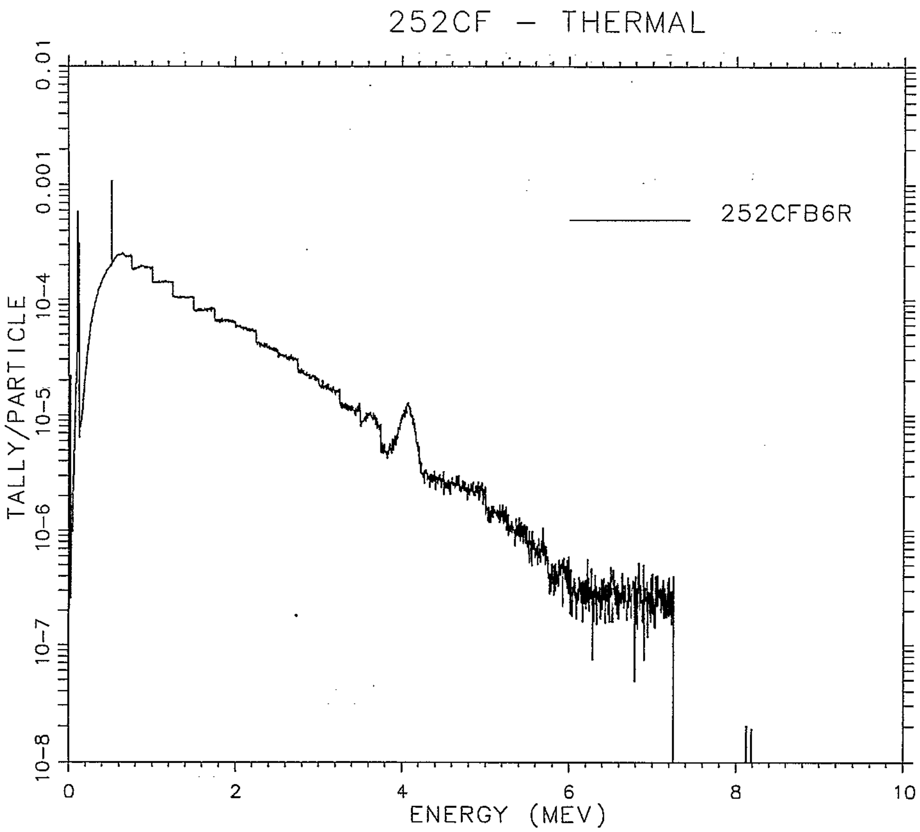

246CM — THERMAL
246CMB6R
TALLY/PARTICLE
10−4
10−5
10−6
10−7
10−8
10−9
0
2
4
6
8
10
ENERGY (MEV)


247CM — THERMAL
247CMB6R
TALLY/PARTICLE
0.01
0.001
10-4
10-5
10-6
10-7
10-8
0
2
4
6
8
10
ENERGY (MEV)


248CM — THERMAL
248CMB6R
TALLY/PARTICLE
10-4
10-5
10-6
10-7
10-8
10-9
0
1
2
3
4
5
6
7
8
ENERGY (MEV)


250CF – THERMAL
250CFB6R
TALLY/PARTICLE
ENERGY (MEV)
0.01
0.001
10-4
10-5
10-6
10-7
10-8
0
1
2
3
4
5
6


251CF – THERMAL
251CFB6R
TALLY/PARTICLE
ENERGY (MEV)
0.01
0.001
10-4
10-5
10-6
10-7
10-8
0
2
4
6
8
10

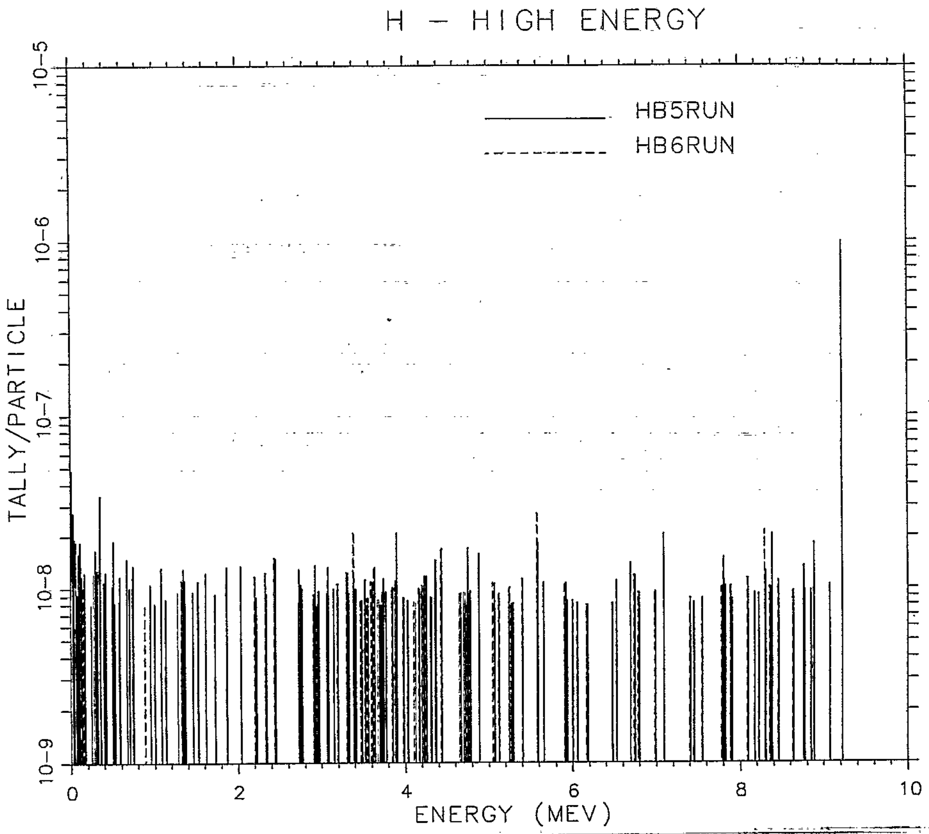

252CF - THERMAL
252CFB6R
TALLY/PARTICLE
0.01
0.001
10-4
10-5
10-6
10-7
10-8
0
2
4
6
8
10
ENERGY (MEV)

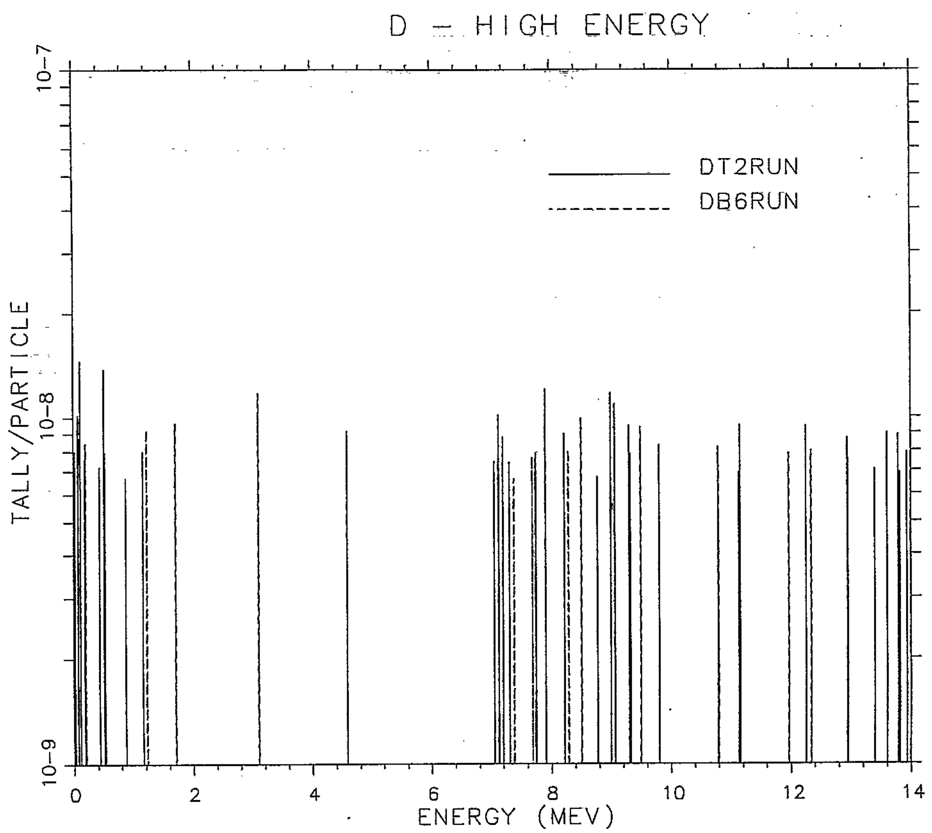
APPENDIX B

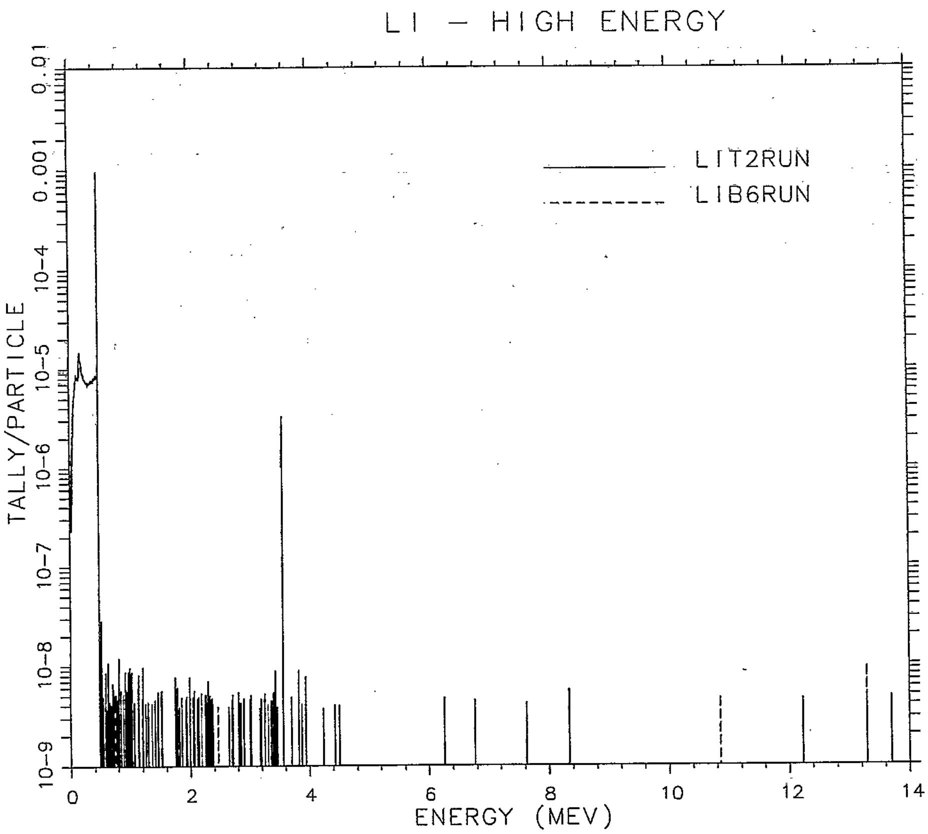
Simulated Photon-Production Spectra at 14-MeV Incident Neutron Energies for the MCNP4A Recommended and ENDF60 Data Libraries

The photon-production spectra include photons from neutron reactions from the 14-MeV source as well as those that downscatter to a lower limit of 1 MeV. The following notation is used to denote the element and library corresponding to a particular spectra; the filename is written as XXb5run, XXb6run, or XXt2run for the element XX and the ENDF/B-V, ENDF60, or Group T-2 based libraries respectively. For individual isotopes, the notation used was ###XXb5r, ###XXb6r, or ###XXt2r, where XX still specifies the element and ### identifies the mass number of the isotope.

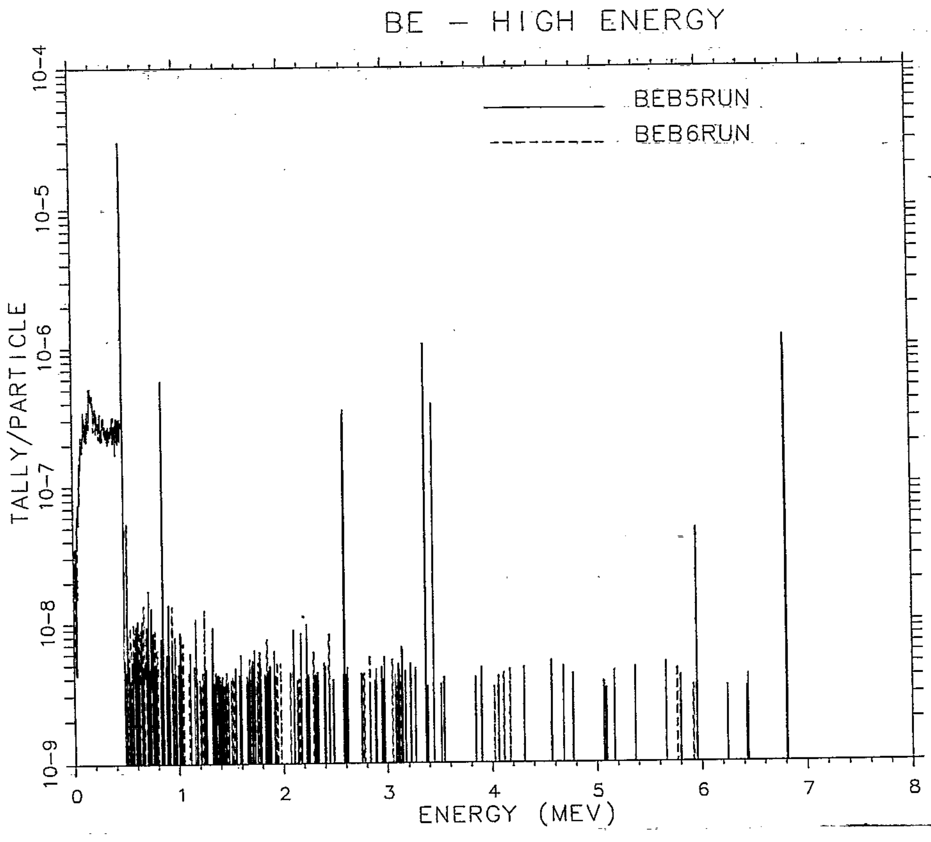
See Table 2 for the precise material specifications for each MCNP run.


H — HIGH ENERGY
HB5RUN
HB6RUN
TALLY/PARTICLE
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
ENERGY (MEV)

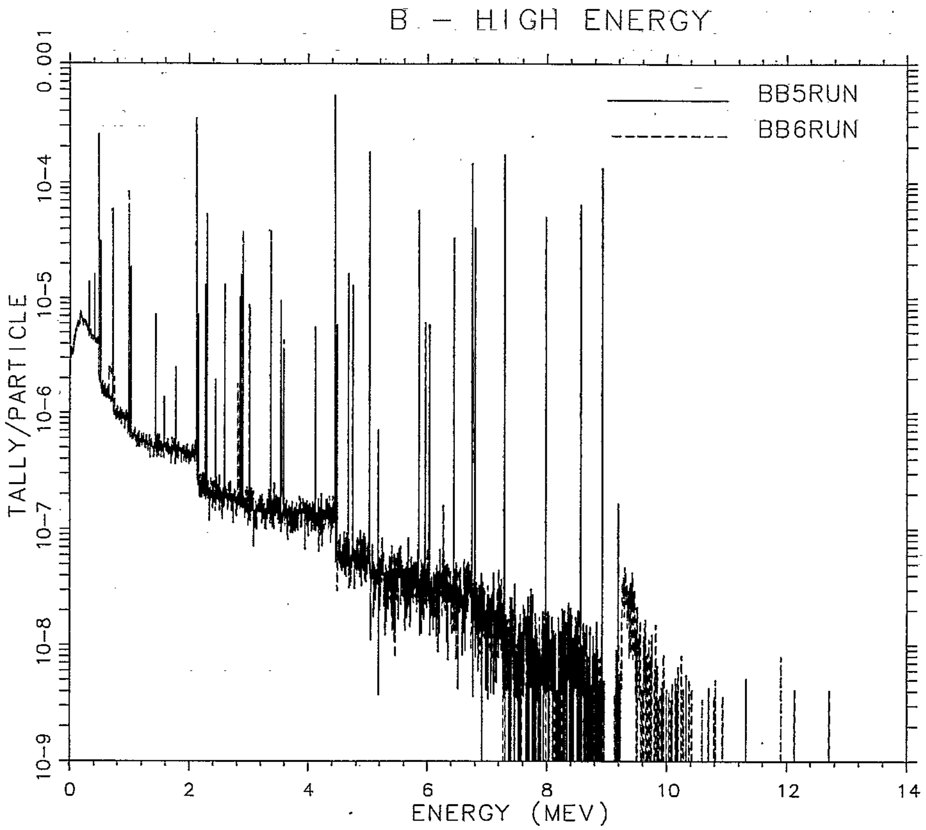

D — HIGH ENERGY
DT2RUN
DB6RUN
TALLY/PARTICLE
10-7
10-8
10-9
0
2
4
6
8
10
12
14
ENERGY (MEV)



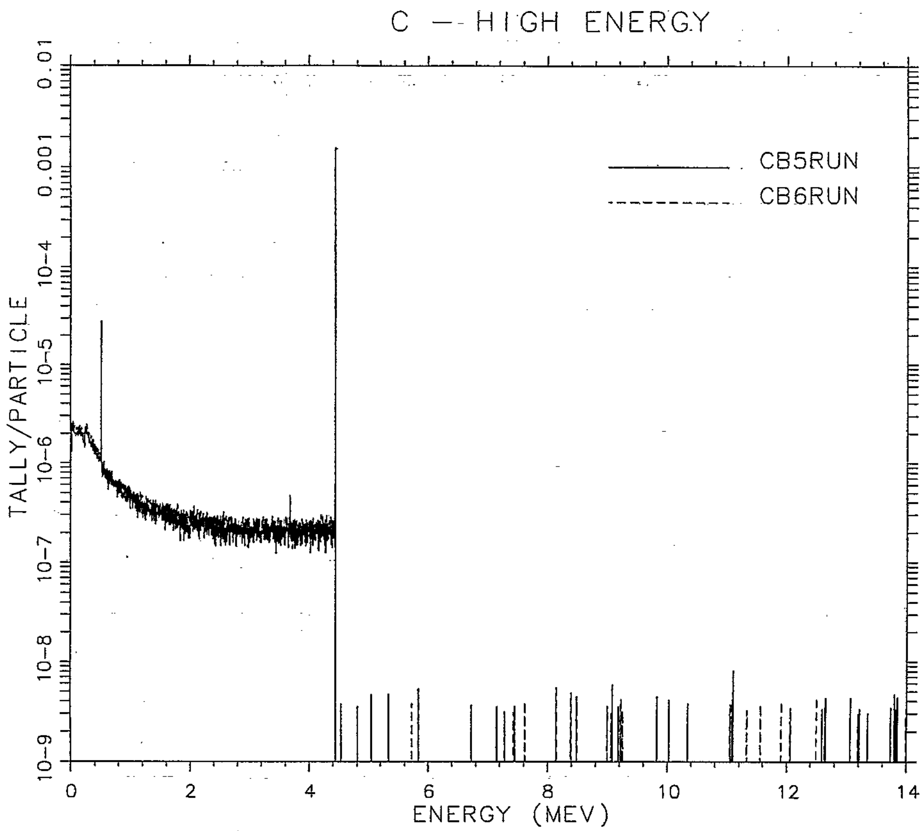
LI - HIGH ENERGY
TALLY/PARTICLE
ENERGY (MEV)
LIT2RUN
LIB6RUN
10-9
10-8
10-7
10-6
10-5
10-4
0.001
0.01
0
2
4
6
8
10
12
14



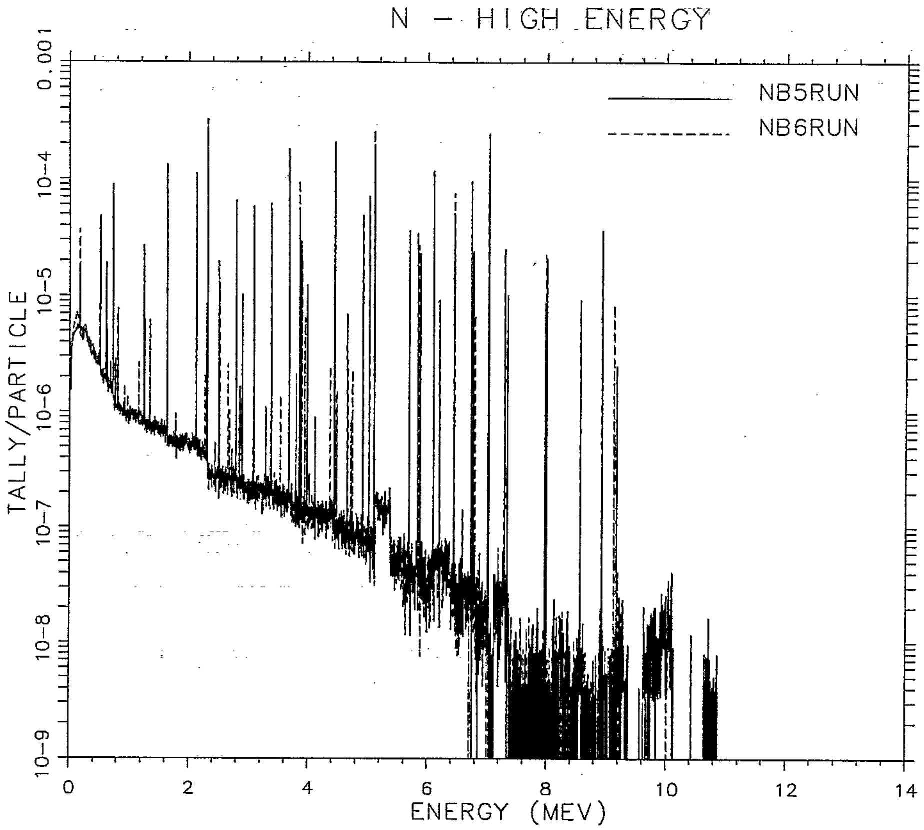
BE - HIGH ENERGY
TALLY/PARTICLE
ENERGY (MEV)
BEB5RUN
BEB6RUN
10-9
10-8
10-7
10-6
10-5
10-4
0
1
2
3
4
5
6
7
8

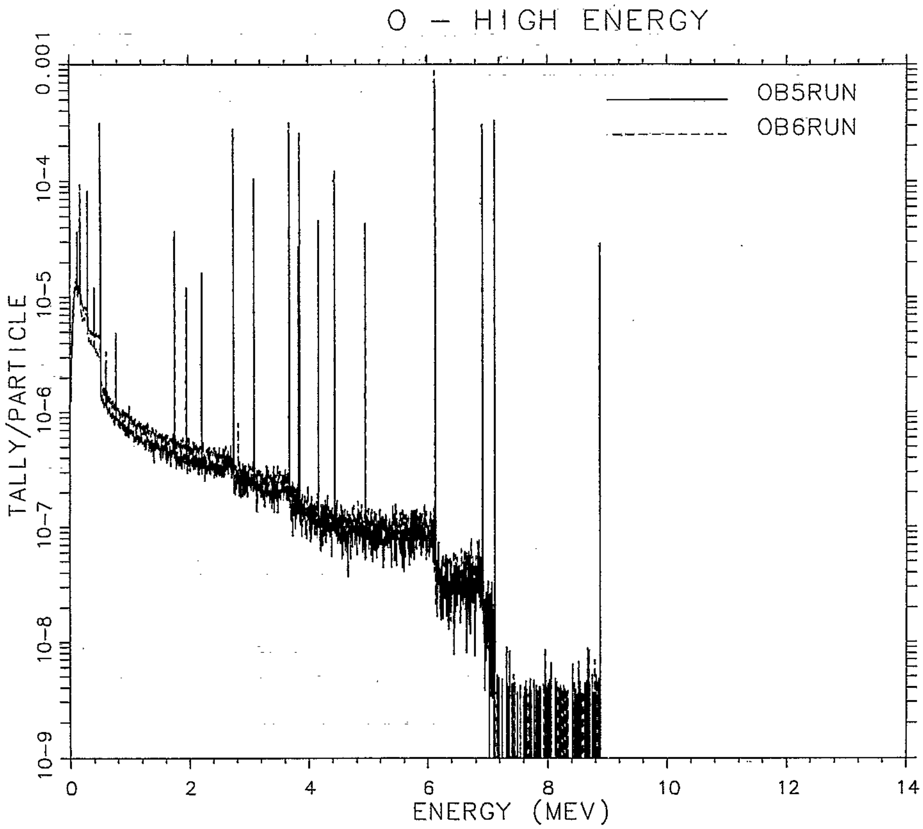


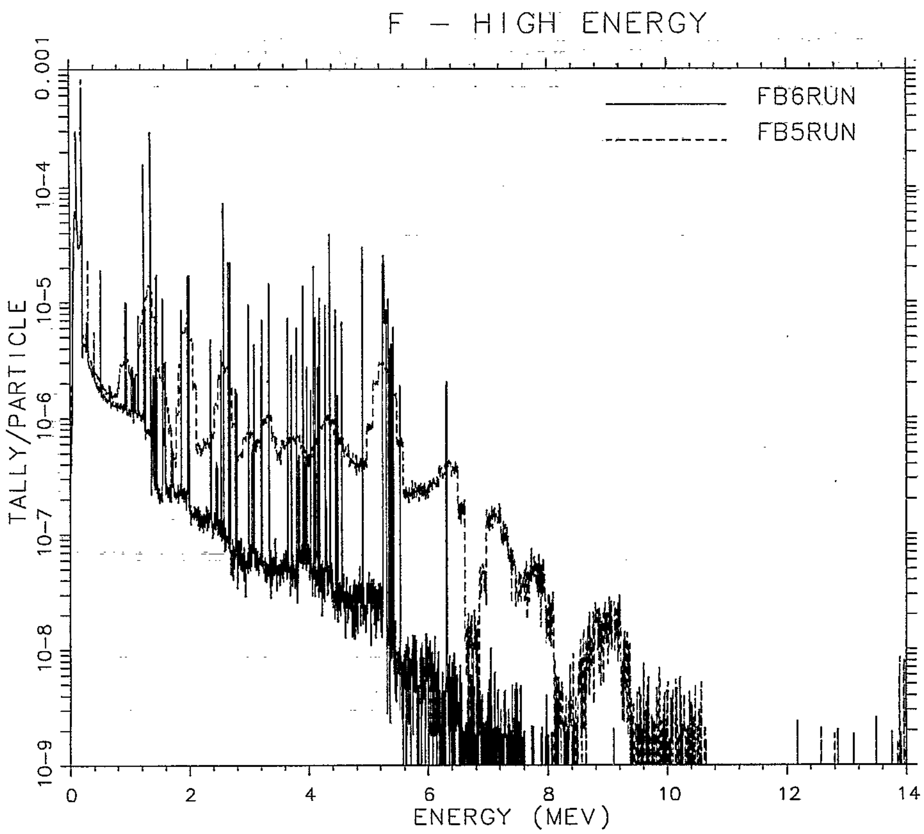
B – HIGH ENERGY
BB5RUN
BB6RUN
TALLY/PARTICLE
ENERGY (MEV)
0.001
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
12
14

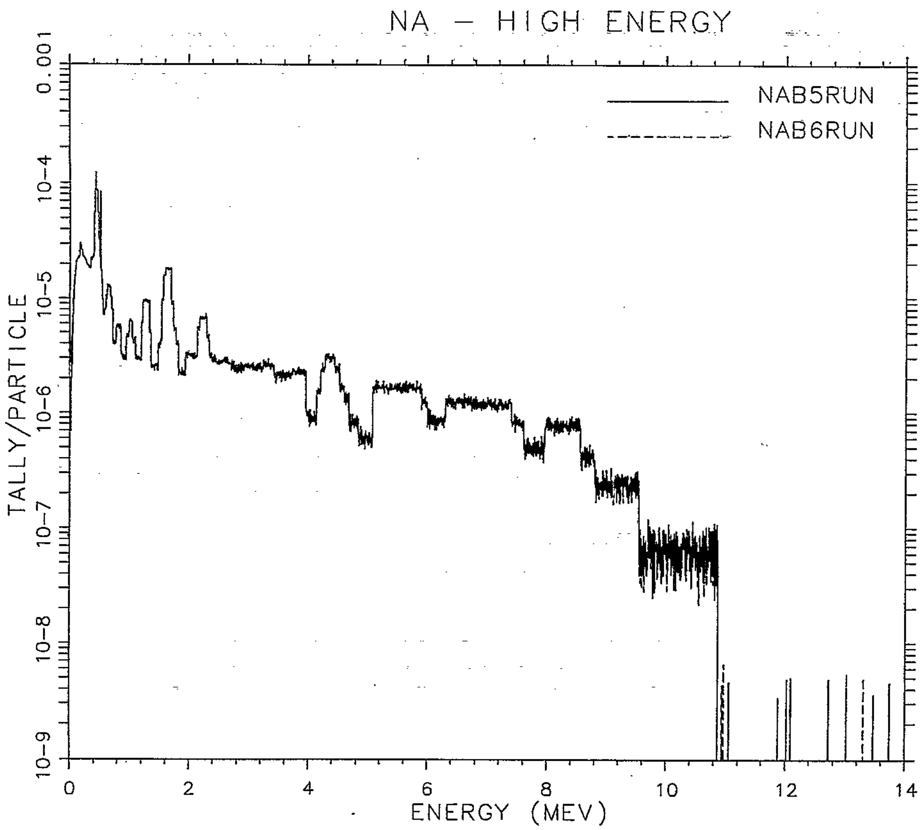


C – HIGH ENERGY
CB5RUN
CB6RUN
TALLY/PARTICLE
ENERGY (MEV)
0.01
0.001
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
12
14

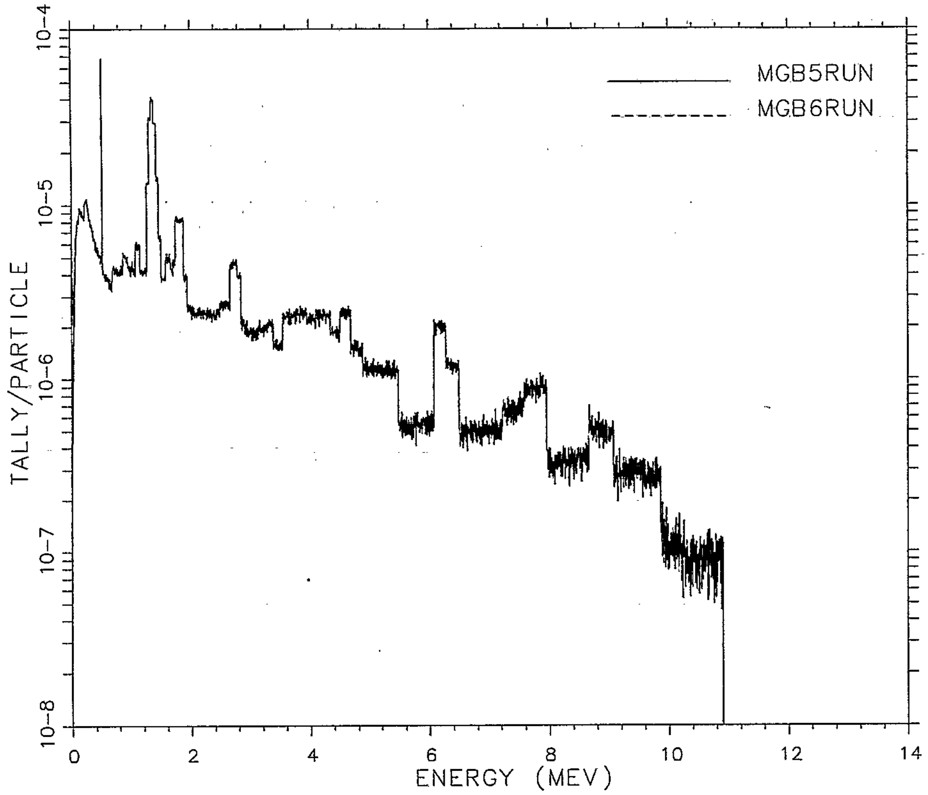

N – HIGH ENERGY
NB5RUN
NB6RUN
TALLY/PARTICLE
0.001
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
12
14
ENERGY (MEV)


O – HIGH ENERGY
OB5RUN
OB6RUN
TALLY/PARTICLE
0.001
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
12
14
ENERGY (MEV)

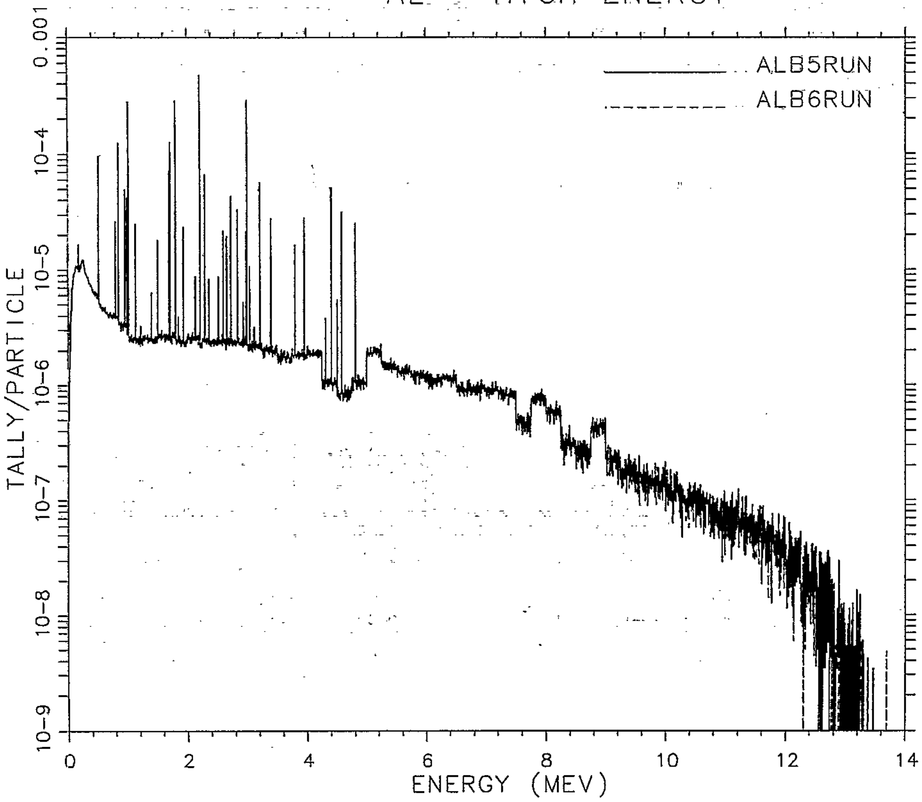

F – HIGH ENERGY
FB6RUN
FB5RUN
TALLY/PARTICLE
ENERGY (MEV)
0.001
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
12
14

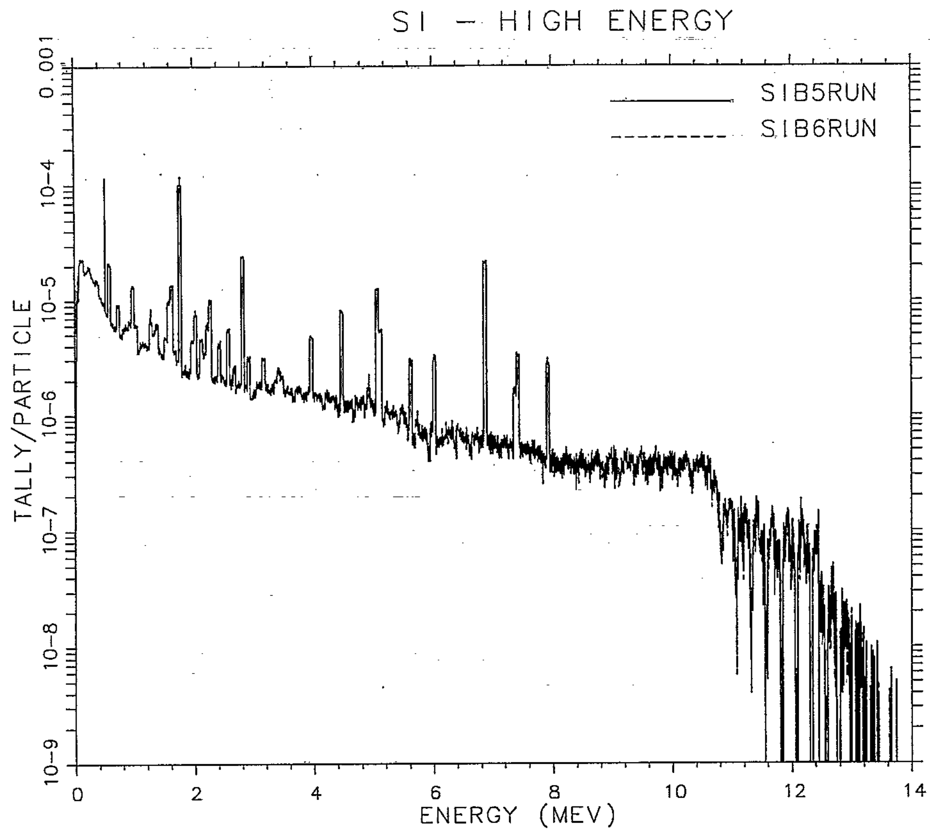

NA – HIGH ENERGY
NAB5RUN
NAB6RUN
TALLY/PARTICLE
ENERGY (MEV)
0.001
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
12
14

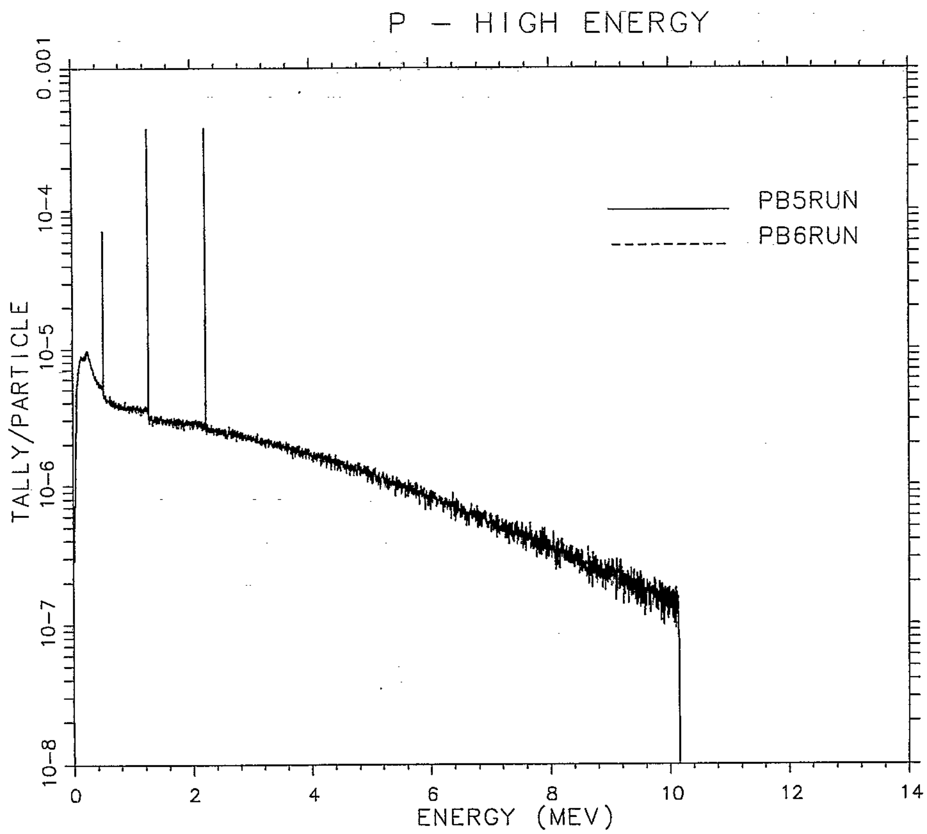
MG – HIGH ENERGY



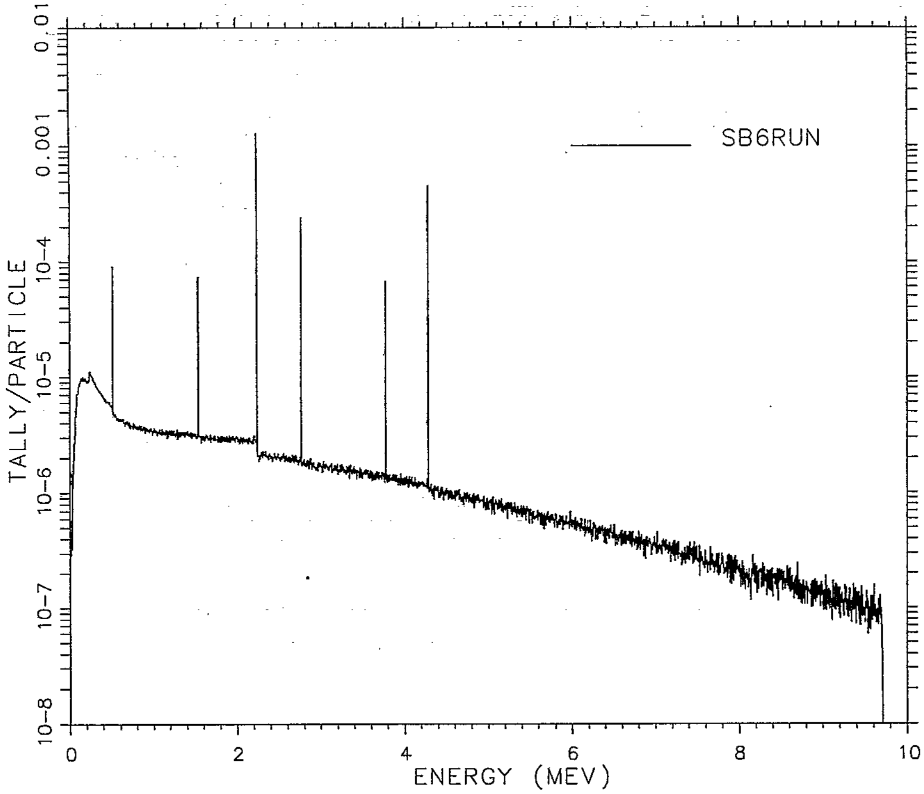
AL – HIGH ENERGY



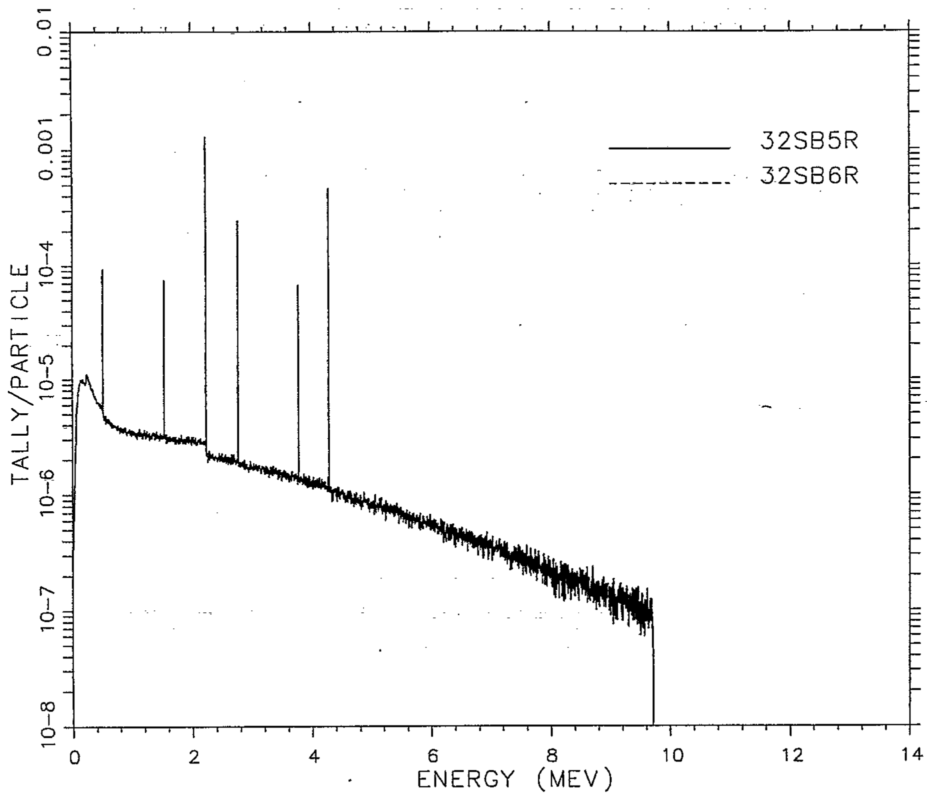

SI – HIGH ENERGY
SIB5RUN
SIB6RUN
TALLY/PARTICLE
0.001
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
12
14
ENERGY (MEV)

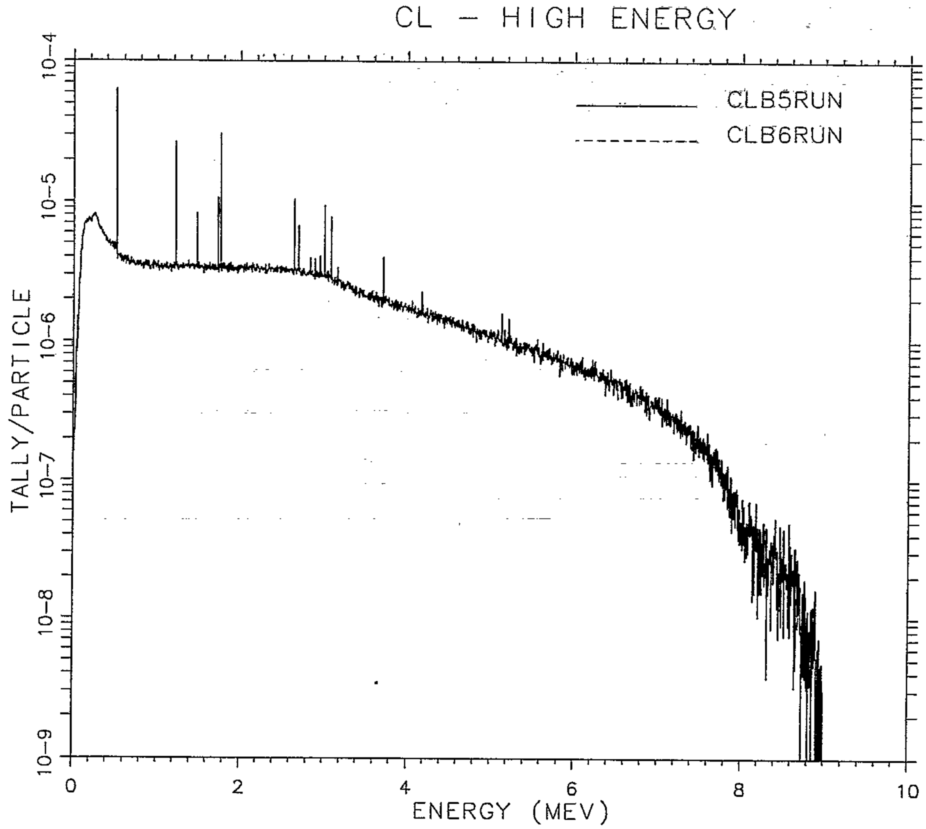

P – HIGH ENERGY
PB5RUN
PB6RUN
TALLY/PARTICLE
0.001
10-4
10-5
10-6
10-7
10-8
0
2
4
6
8
10
12
14
ENERGY (MEV)

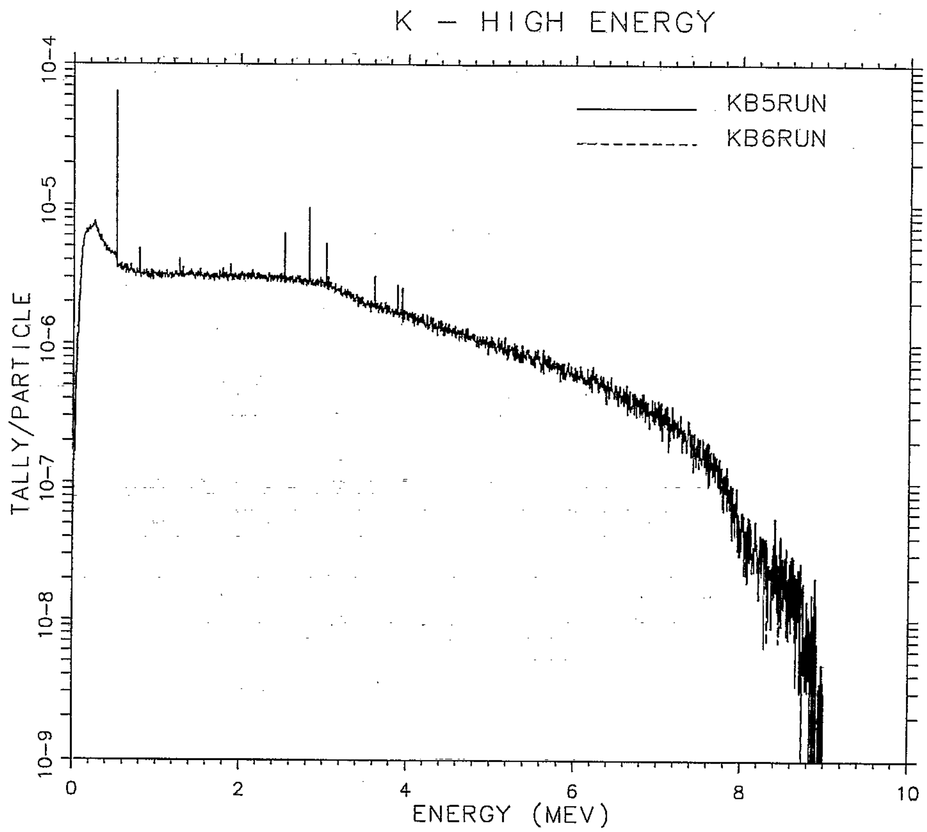
S – HIGH ENERGY

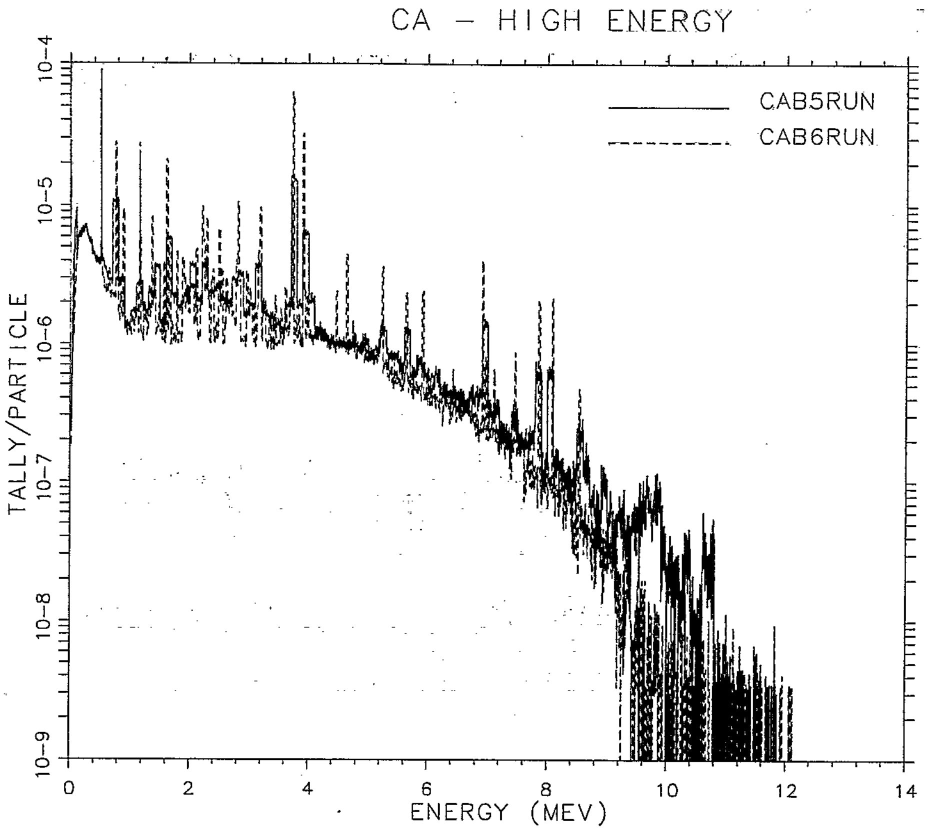


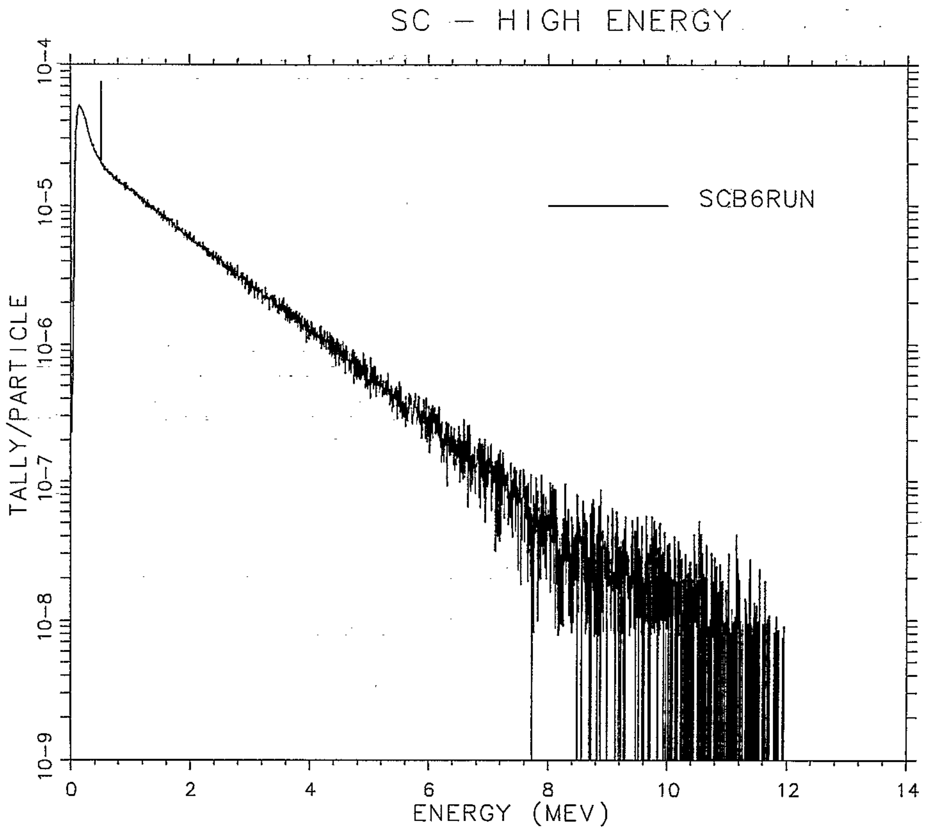
32S – HIGH ENERGY

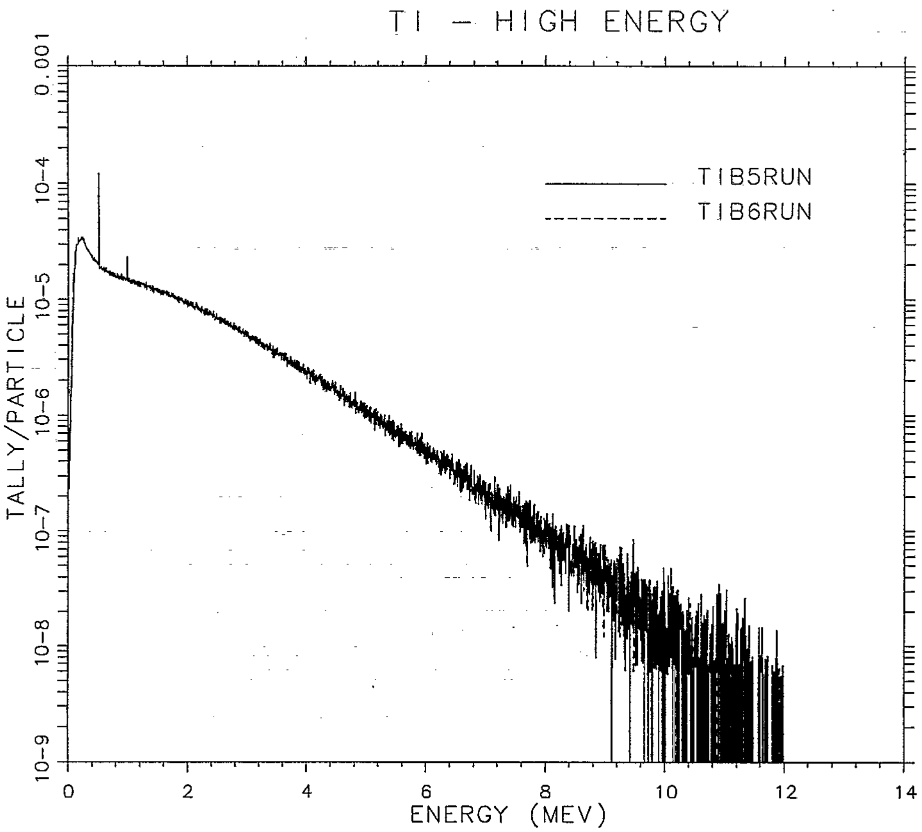


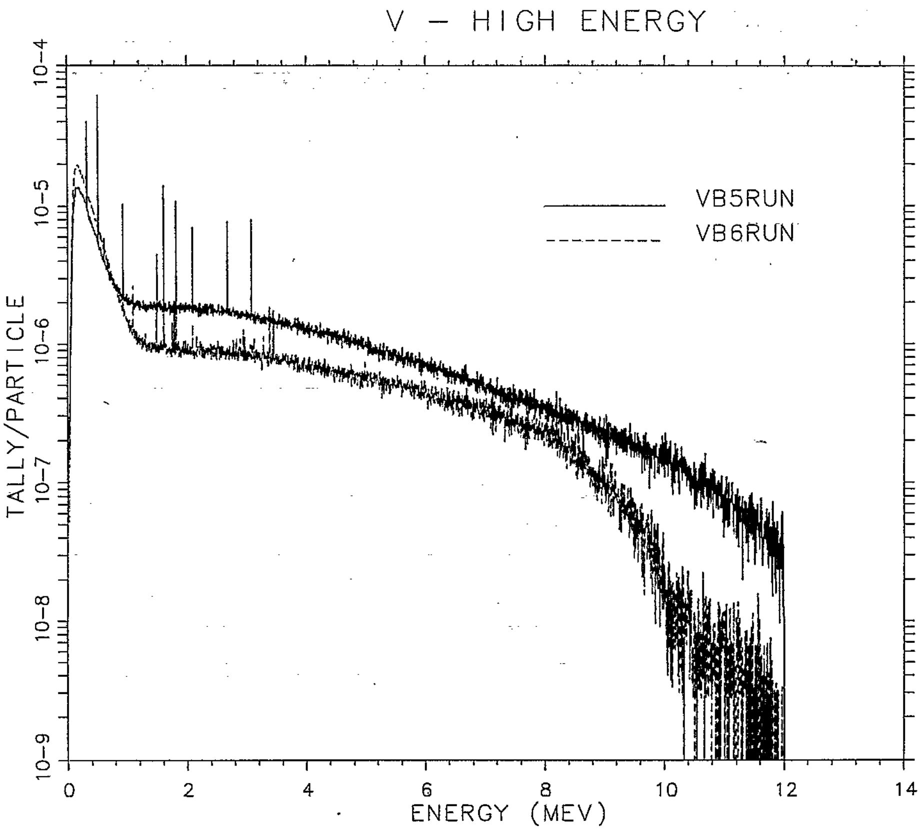

CL – HIGH ENERGY
CLB5RUN
CLB6RUN
TALLY/PARTICLE
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
ENERGY (MEV)

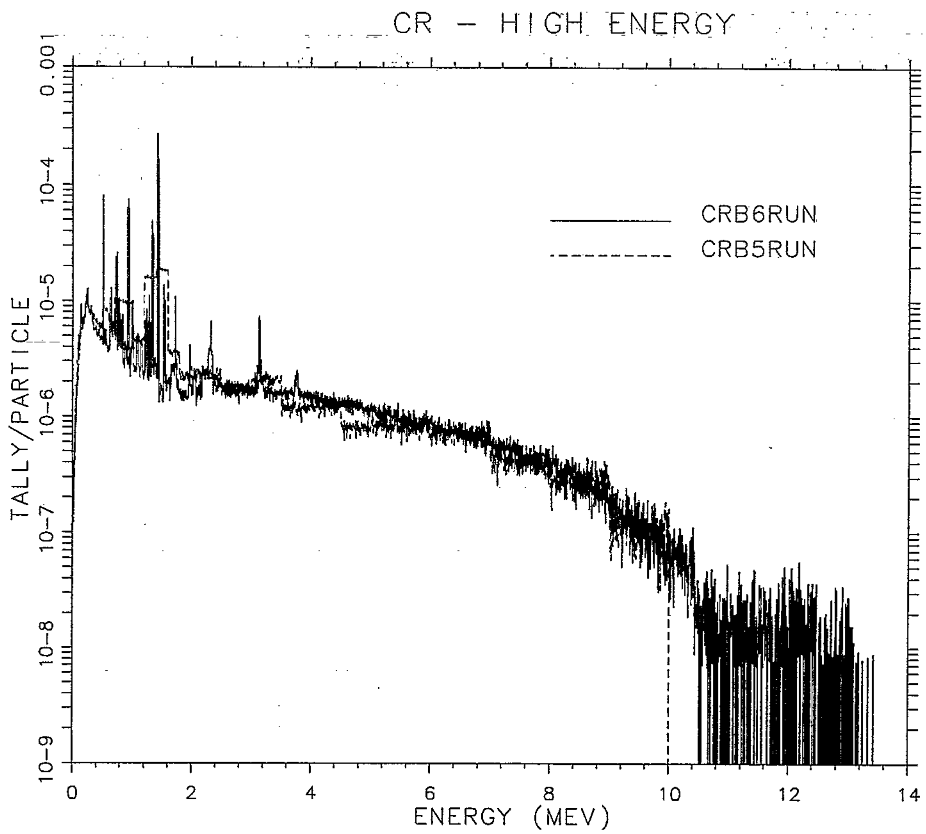

K – HIGH ENERGY
KB5RUN
KB6RUN
TALLY/PARTICLE
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
ENERGY (MEV)

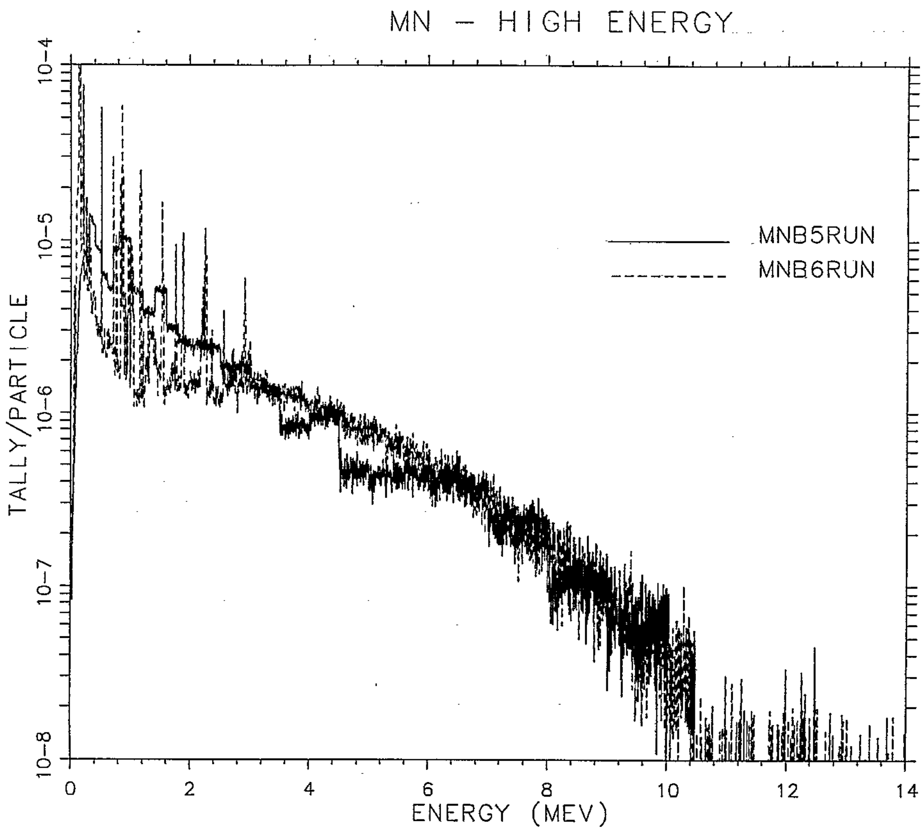

CA - HIGH ENERGY
CAB5RUN
CAB6RUN
TALLY/PARTICLE
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
12
14
ENERGY (MEV)

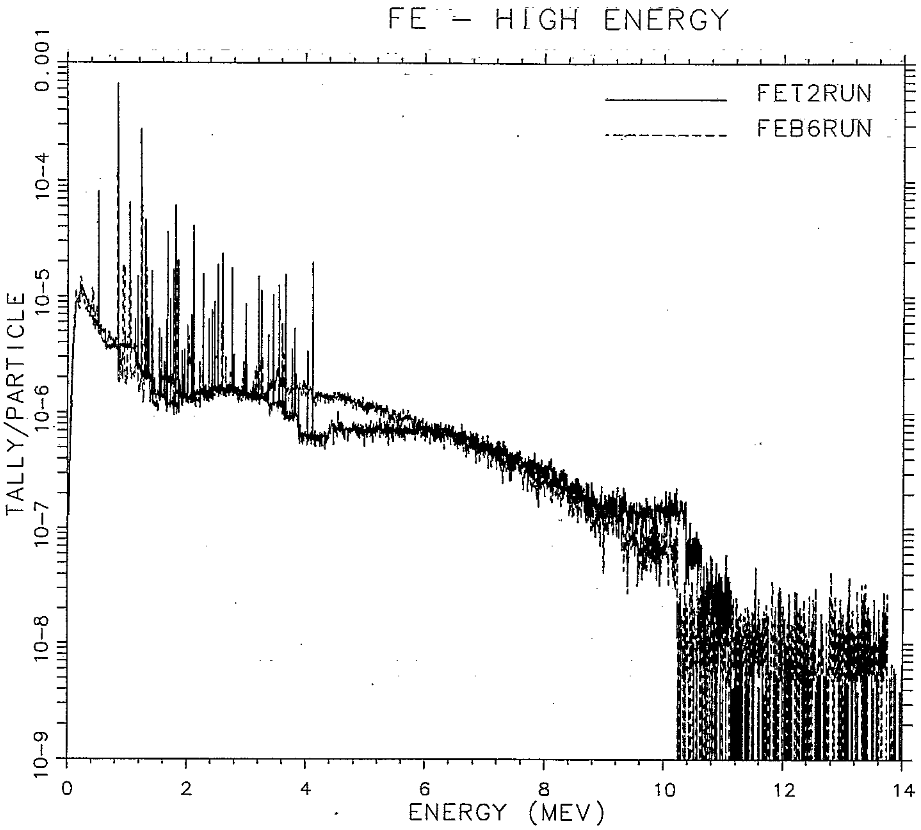

SC - HIGH ENERGY
SCB6RUN
TALLY/PARTICLE
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
12
14
ENERGY (MEV)

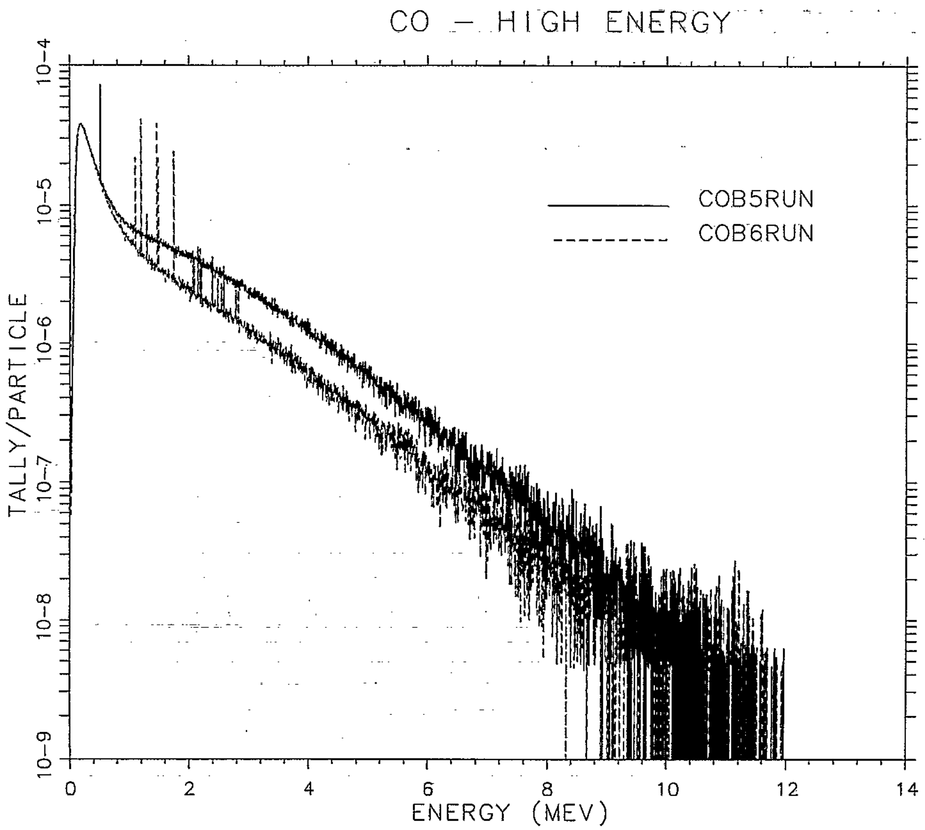

TI - HIGH ENERGY
TIB5RUN
TIB6RUN
TALLY/PARTICLE
ENERGY (MEV)

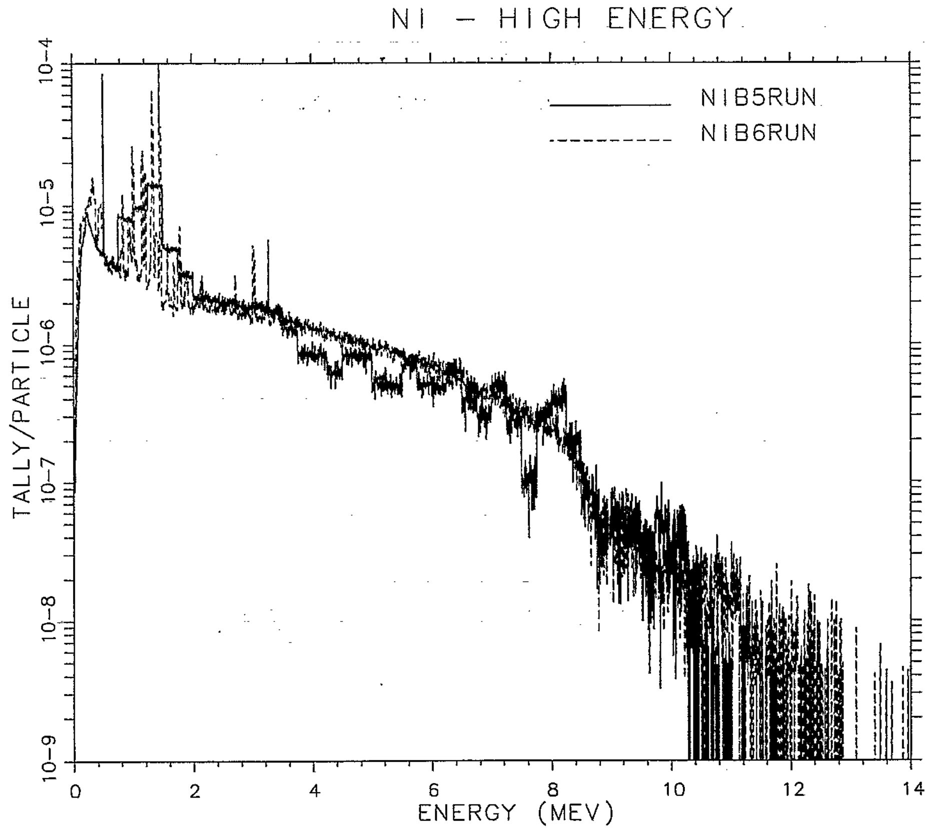

V - HIGH ENERGY
VB5RUN
VB6RUN
TALLY/PARTICLE
ENERGY (MEV)

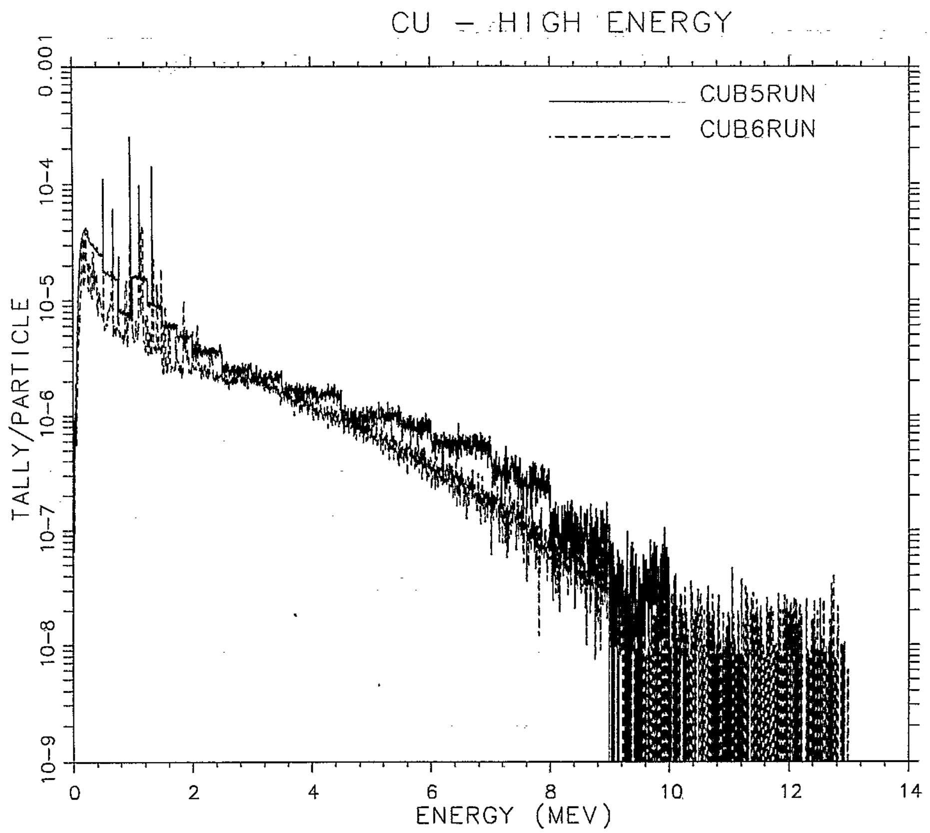

CR – HIGH ENERGY
TALLY/PARTICLE
0.001
10-4
10-5
10-6
10-7
10-8
10-9
ENERGY (MEV)
0
2
4
6
8
10
12
14
CRB6RUN
CRB5RUN

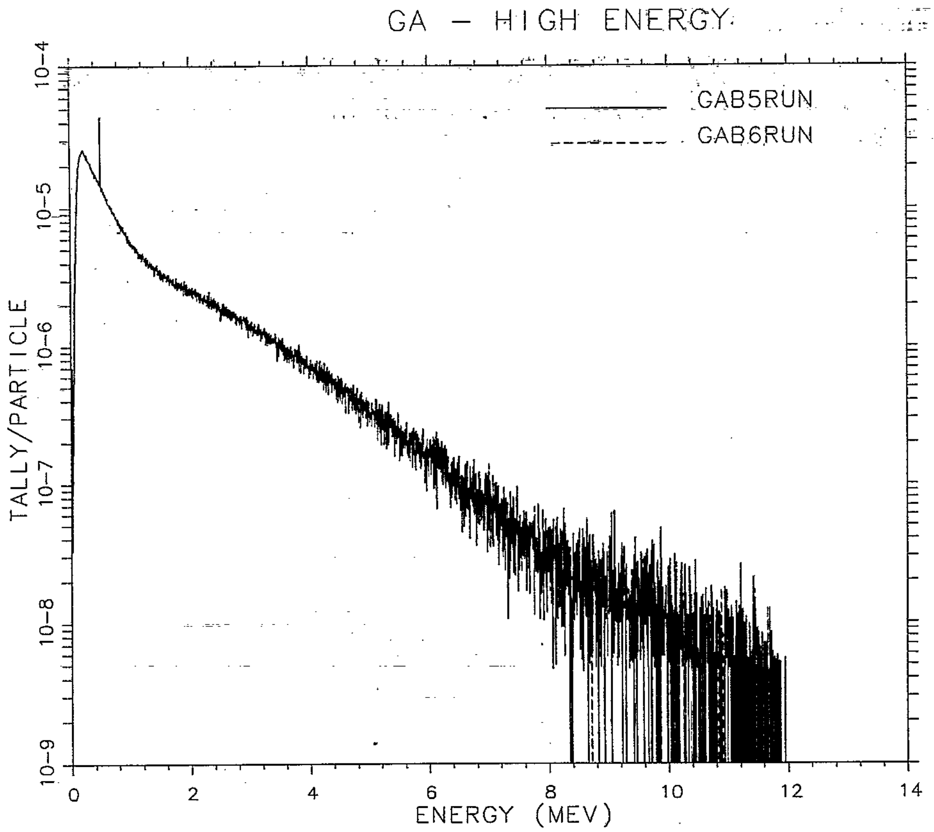

MN – HIGH ENERGY
TALLY/PARTICLE
10-4
10-5
10-6
10-7
10-8
ENERGY (MEV)
0
2
4
6
8
10
12
14
MNB5RUN
MNB6RUN

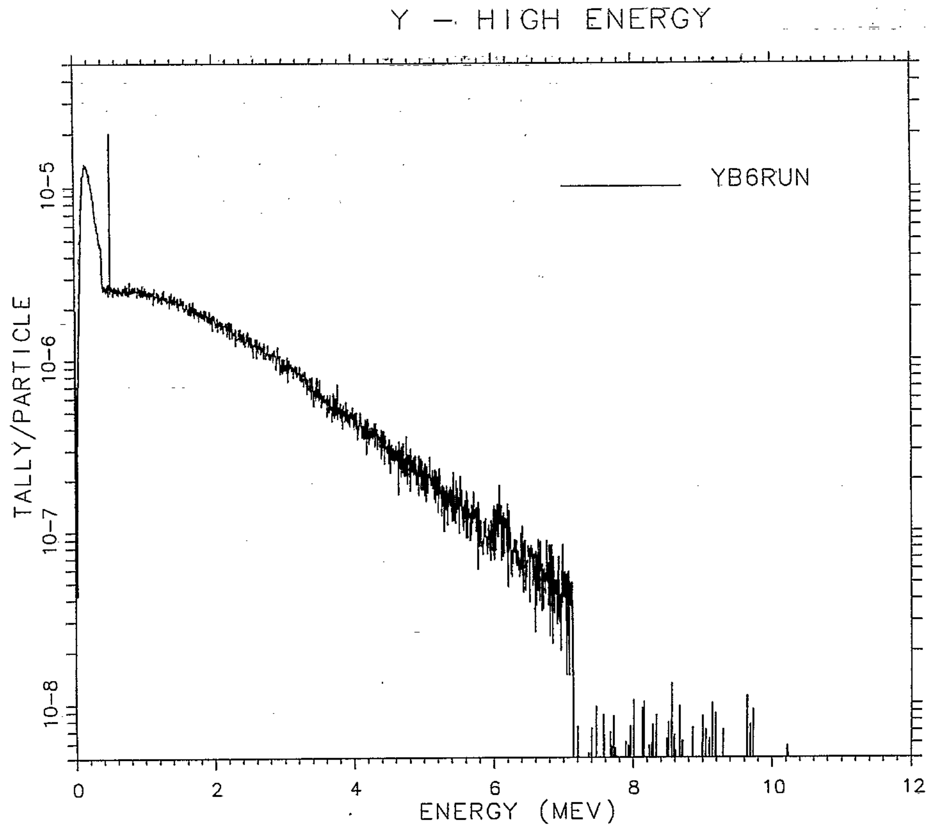

FE – HIGH ENERGY
FET2RUN
FEB6RUN
TALLY/PARTICLE
0.001
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
12
14
ENERGY (MEV)

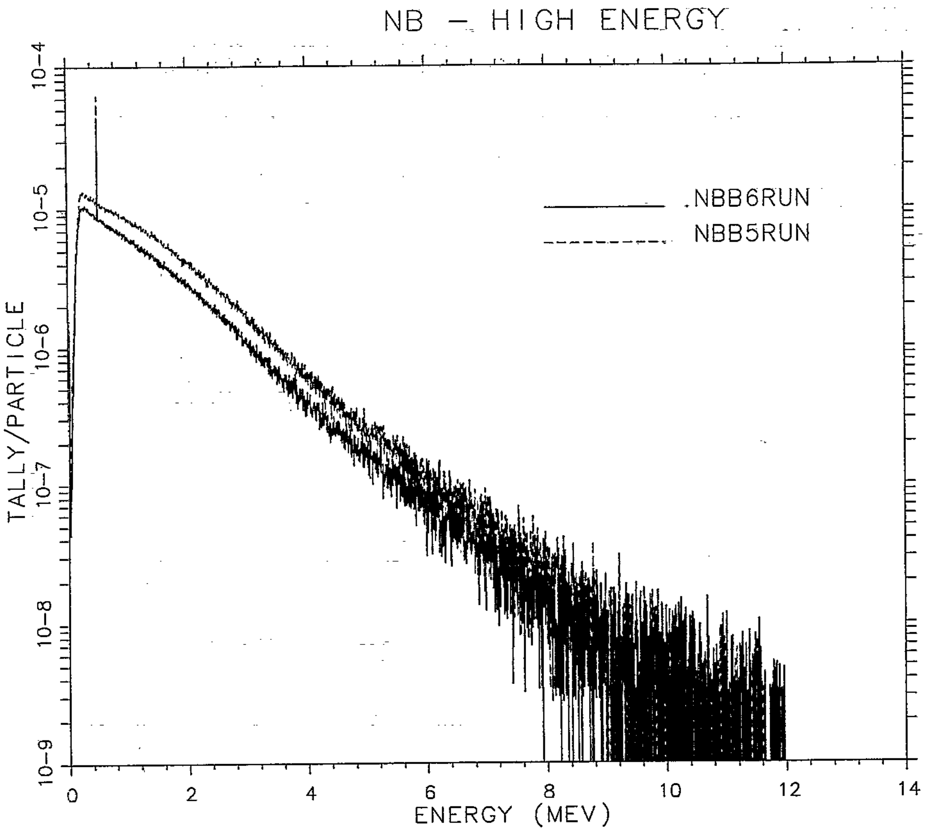

CO – HIGH ENERGY
COB5RUN
COB6RUN
TALLY/PARTICLE
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
12
14
ENERGY (MEV)

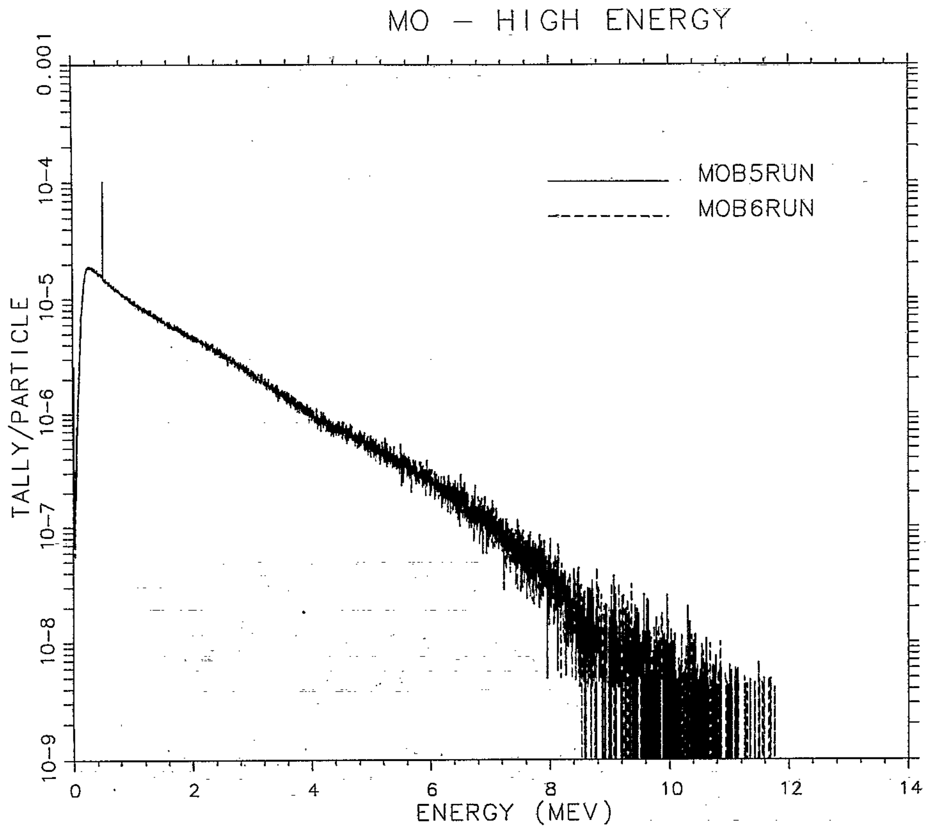

NI - HIGH ENERGY
NIB5RUN
NIB6RUN
TALLY/PARTICLE
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
12
14
ENERGY (MEV)

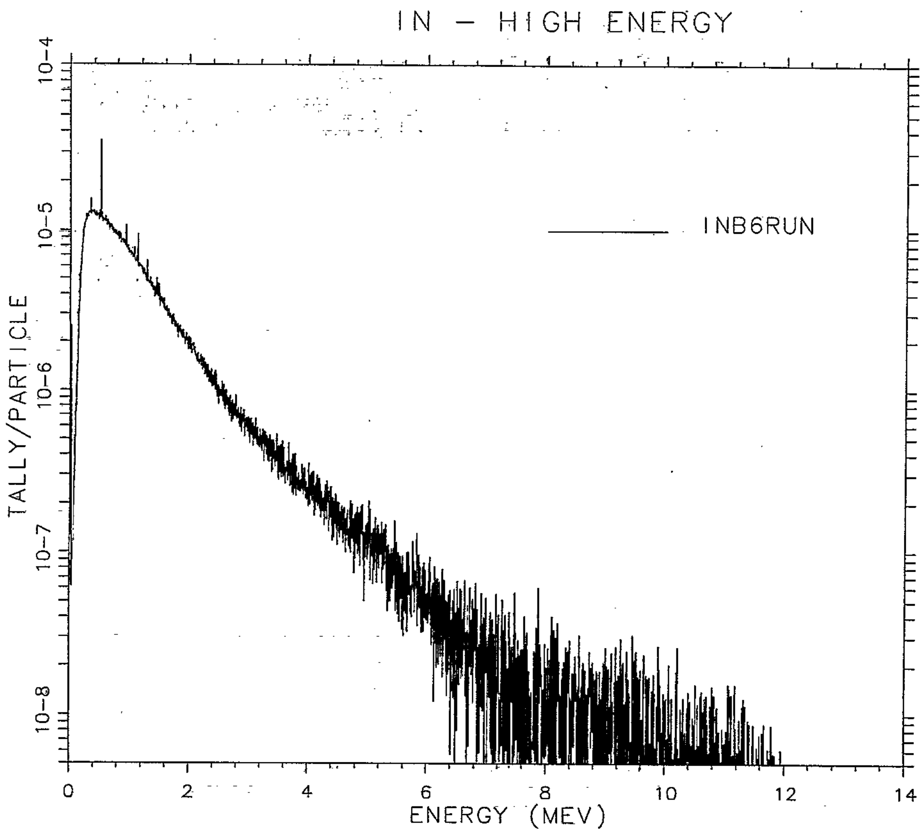

CU - HIGH ENERGY
CUB5RUN
CUB6RUN
TALLY/PARTICLE
0.001
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
12
14
ENERGY (MEV)

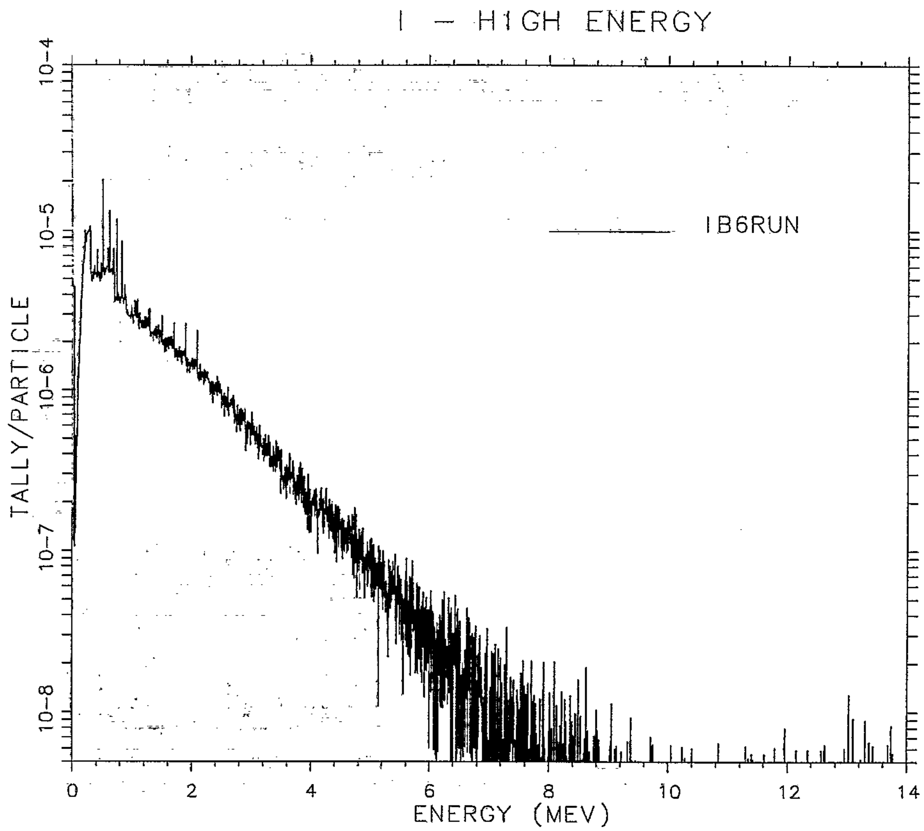

GA - HIGH ENERGY
GAB5RUN
GAB6RUN
TALLY/PARTICLE
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
12
14
ENERGY (MEV)

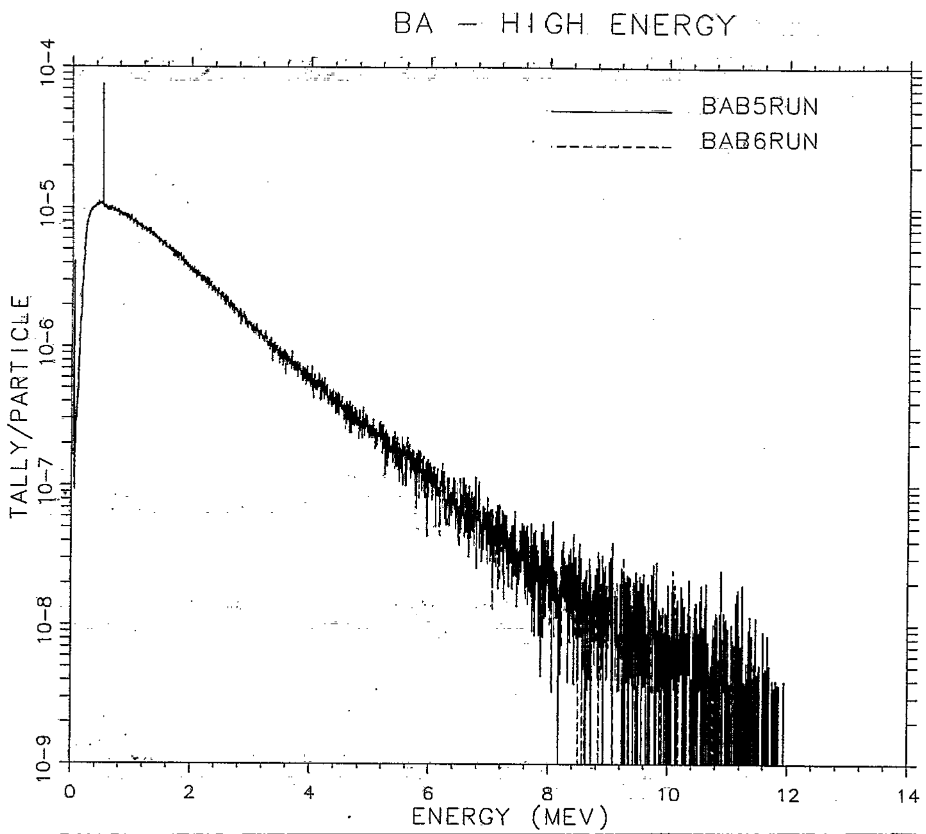

Y - HIGH ENERGY
YB6RUN
TALLY/PARTICLE
10-5
10-6
10-7
10-8
0
2
4
6
8
10
12
ENERGY (MEV)

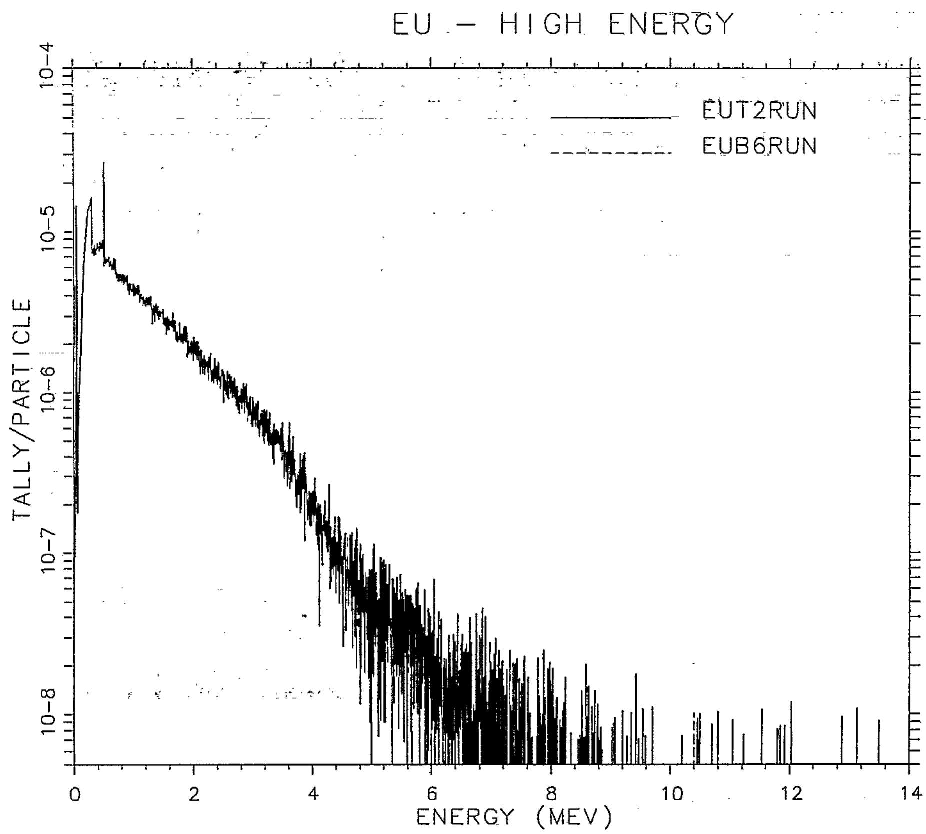

NB – HIGH ENERGY
TALLY/PARTICLE
ENERGY (MEV)
NBB6RUN
NBB5RUN
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
12
14

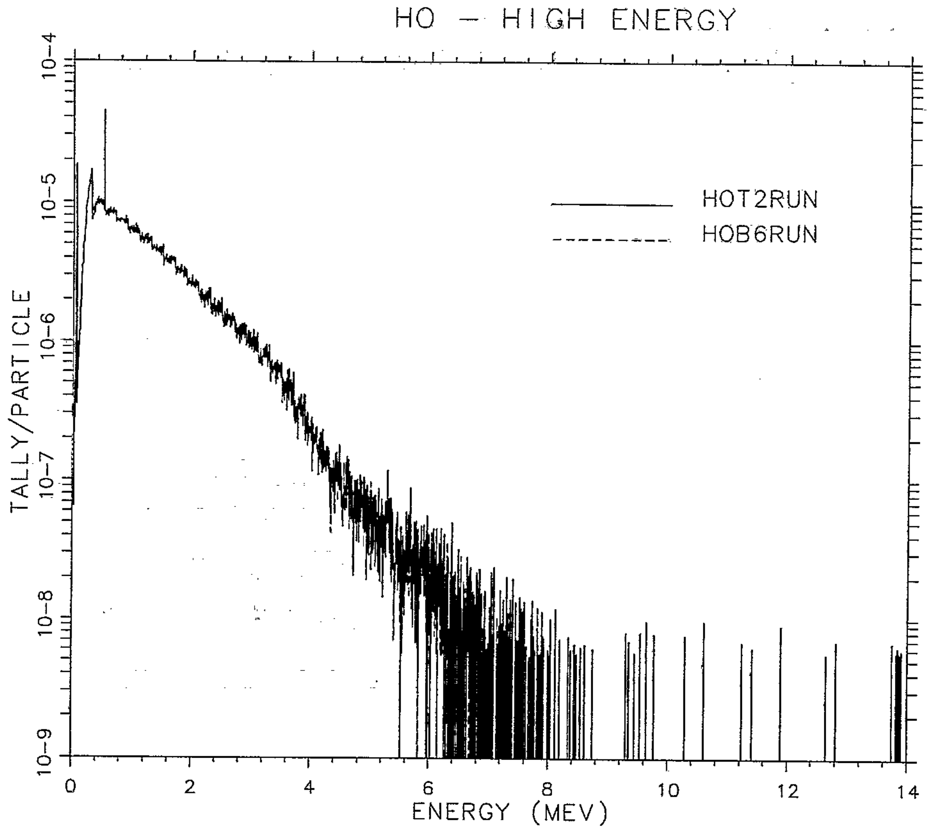

MO – HIGH ENERGY
TALLY/PARTICLE
ENERGY (MEV)
MOB5RUN
MOB6RUN
0.001
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
12
14

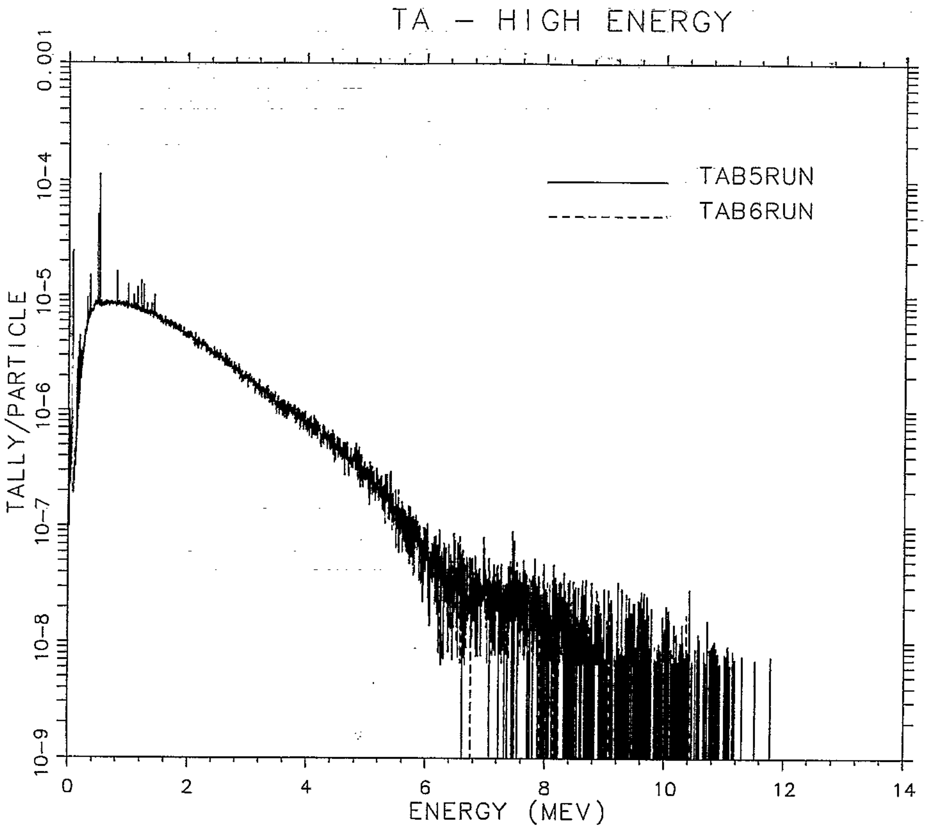

IN – HIGH ENERGY
INB6RUN
TALLY/PARTICLE
10-4
10-5
10-6
10-7
10-8
0
2
4
6
8
10
12
14
ENERGY (MEV)

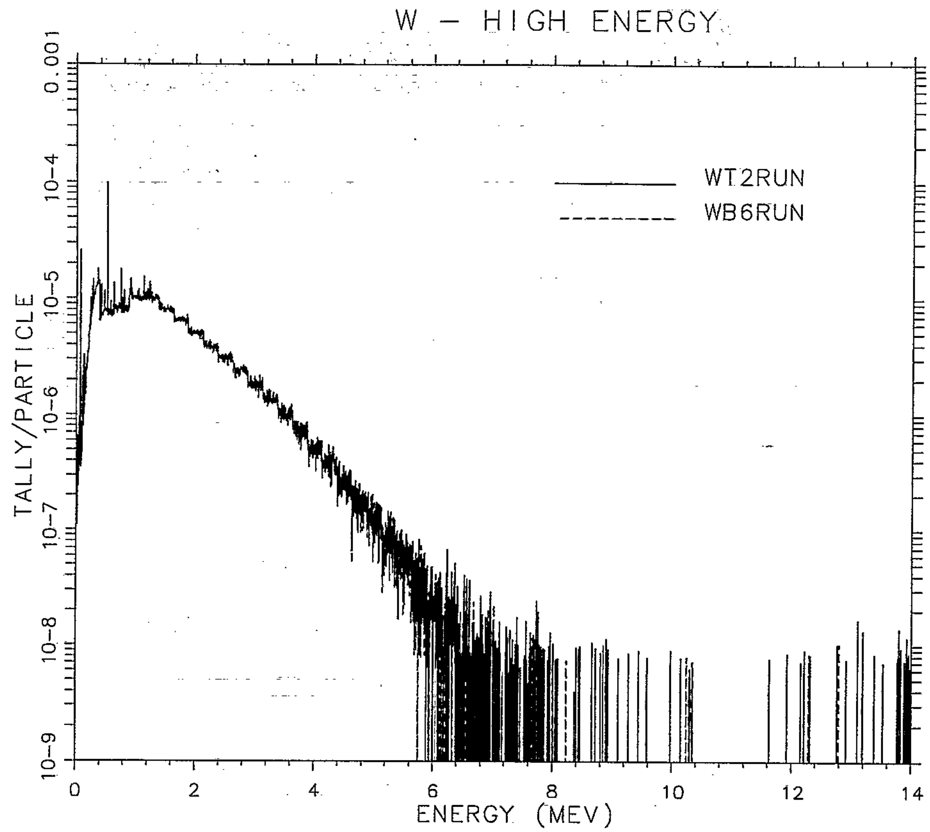

I – HIGH ENERGY
IB6RUN
TALLY/PARTICLE
10-4
10-5
10-6
10-7
10-8
0
2
4
6
8
10
12
14
ENERGY (MEV)

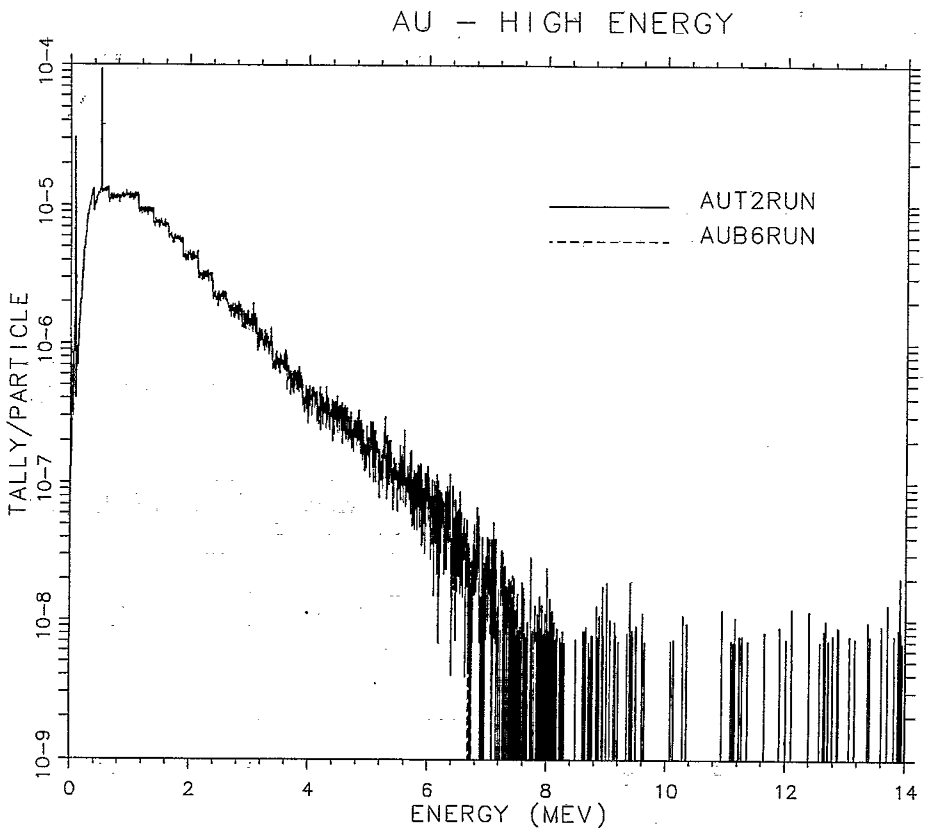

BA – HIGH ENERGY
BAB5RUN
BAB6RUN
TALLY/PARTICLE
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
12
14
ENERGY (MEV)

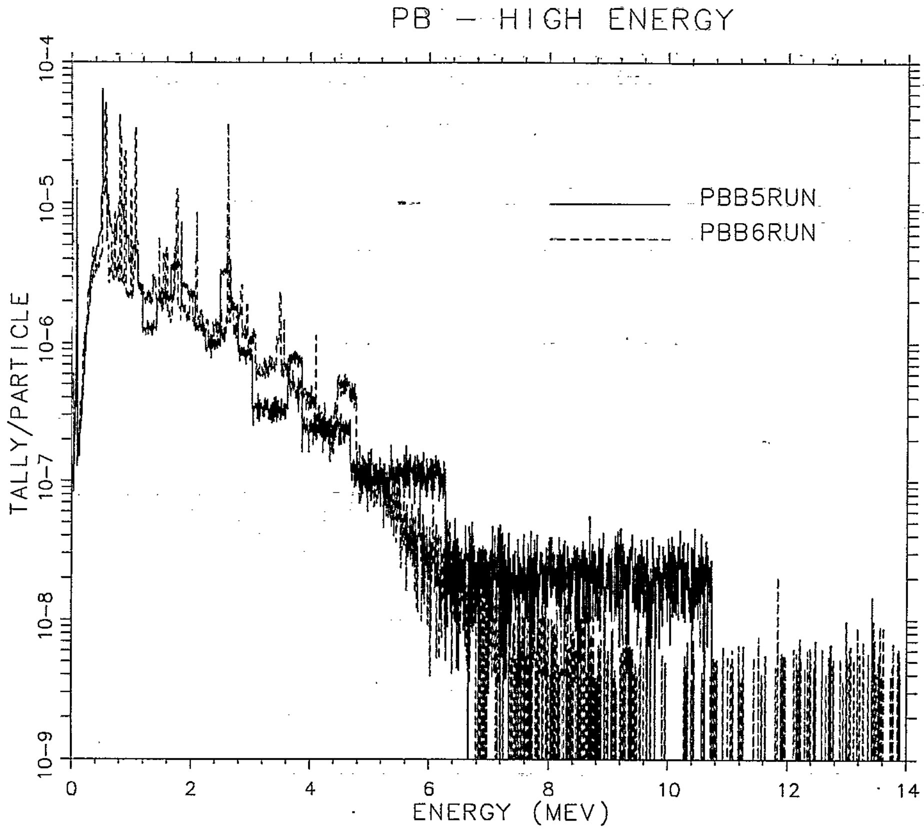

EU – HIGH ENERGY
EUT2RUN
EUB6RUN
TALLY/PARTICLE
10-4
10-5
10-6
10-7
10-8
0
2
4
6
8
10
12
14
ENERGY (MEV)

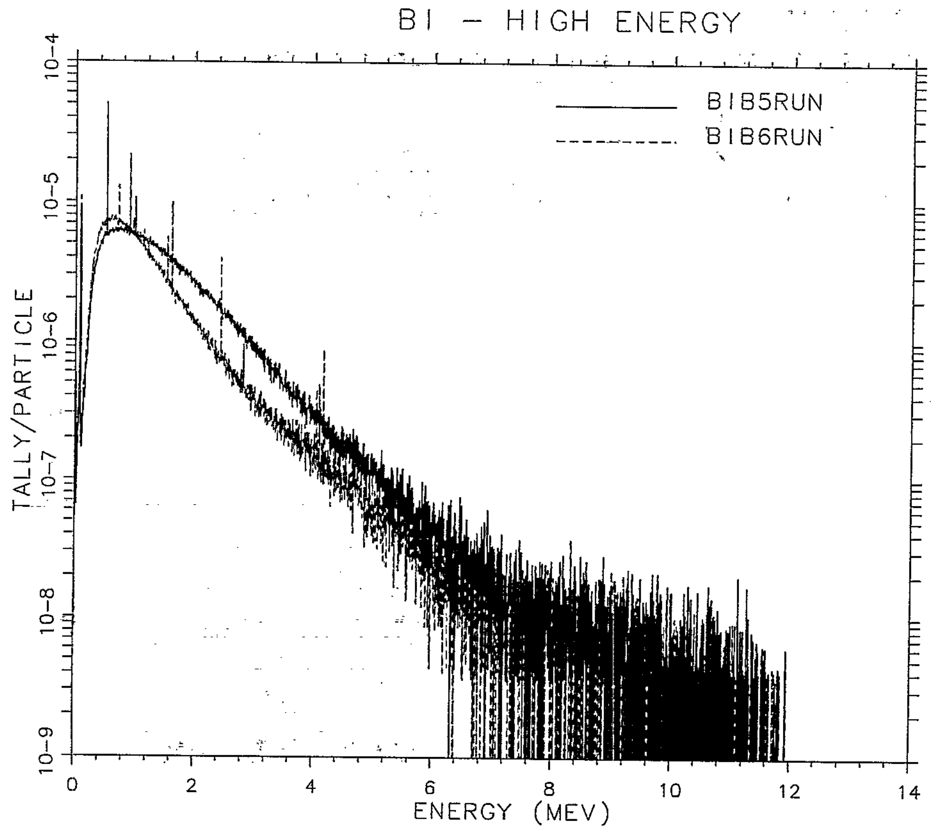

HO – HIGH ENERGY
TALLY/PARTICLE
ENERGY (MEV)
HOT2RUN
HOB6RUN
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
12
14

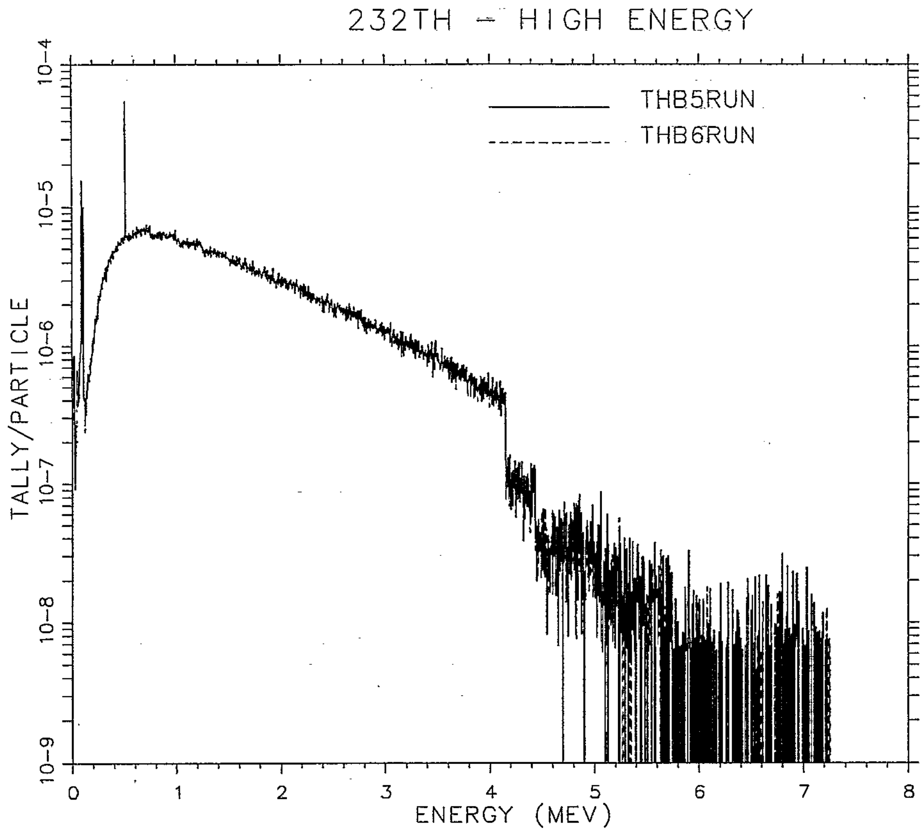

TA – HIGH ENERGY
TALLY/PARTICLE
ENERGY (MEV)
TAB5RUN
TAB6RUN
0.001
10-4
10-5
10-6
10-7
10-8
10-9
0
2
4
6
8
10
12
14

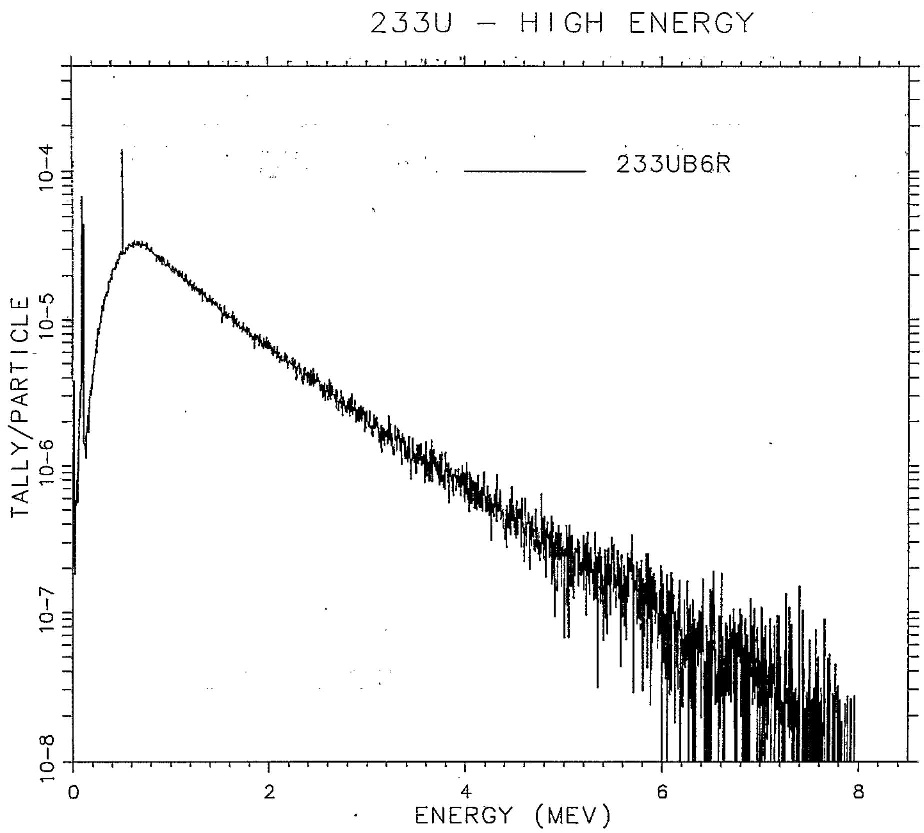

W – HIGH ENERGY
WT2RUN
WB6RUN
TALLY/PARTICLE
0.001
10−4
10−5
10−6
10−7
10−8
10−9
0
2
4
6
8
10
12
14
ENERGY (MEV)

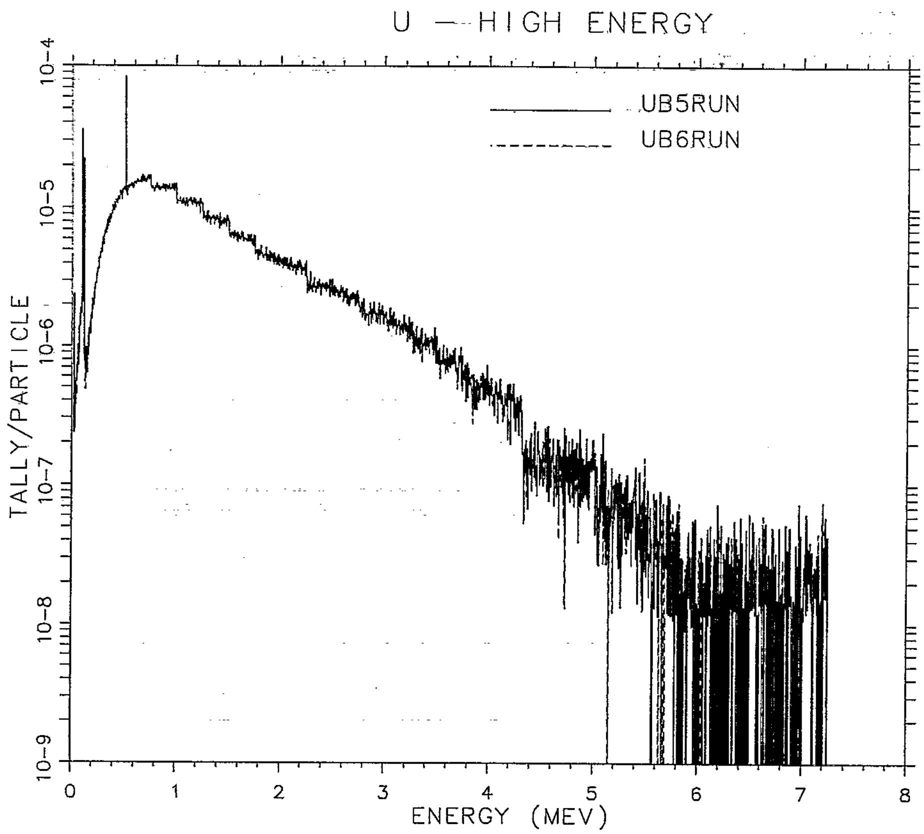

AU – HIGH ENERGY
AUT2RUN
AUB6RUN
TALLY/PARTICLE
10−4
10−5
10−6
10−7
10−8
10−9
0
2
4
6
8
10
12
14
ENERGY (MEV)

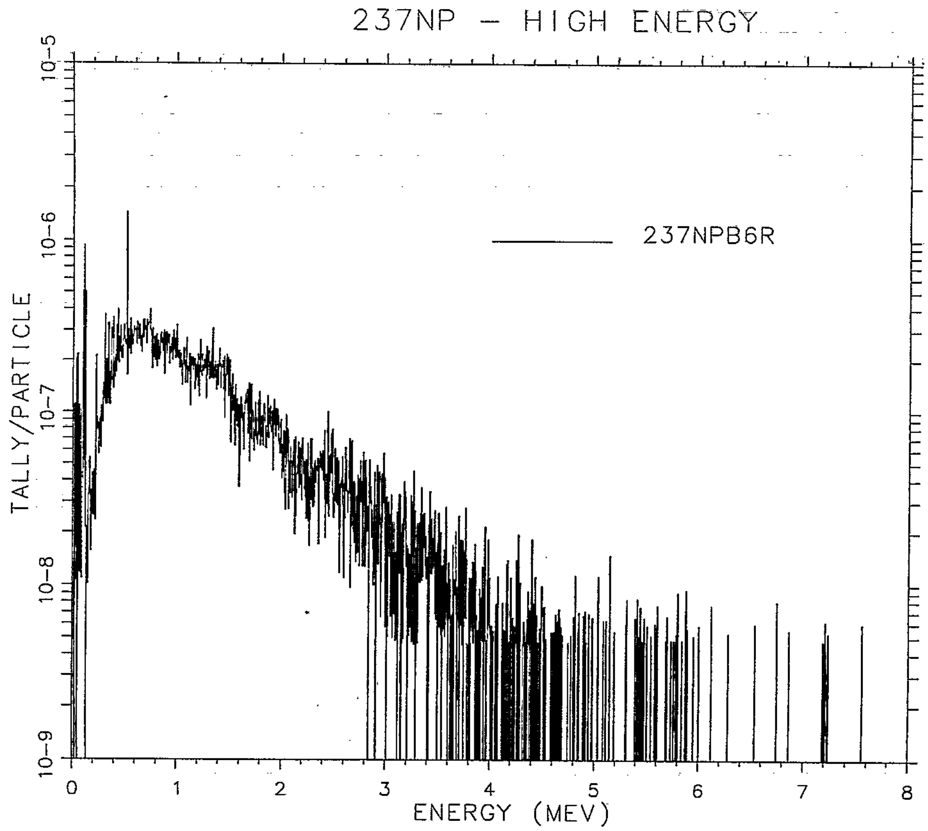

PB – HIGH ENERGY
PBB5RUN
PBB6RUN
TALLY/PARTICLE
ENERGY (MEV)

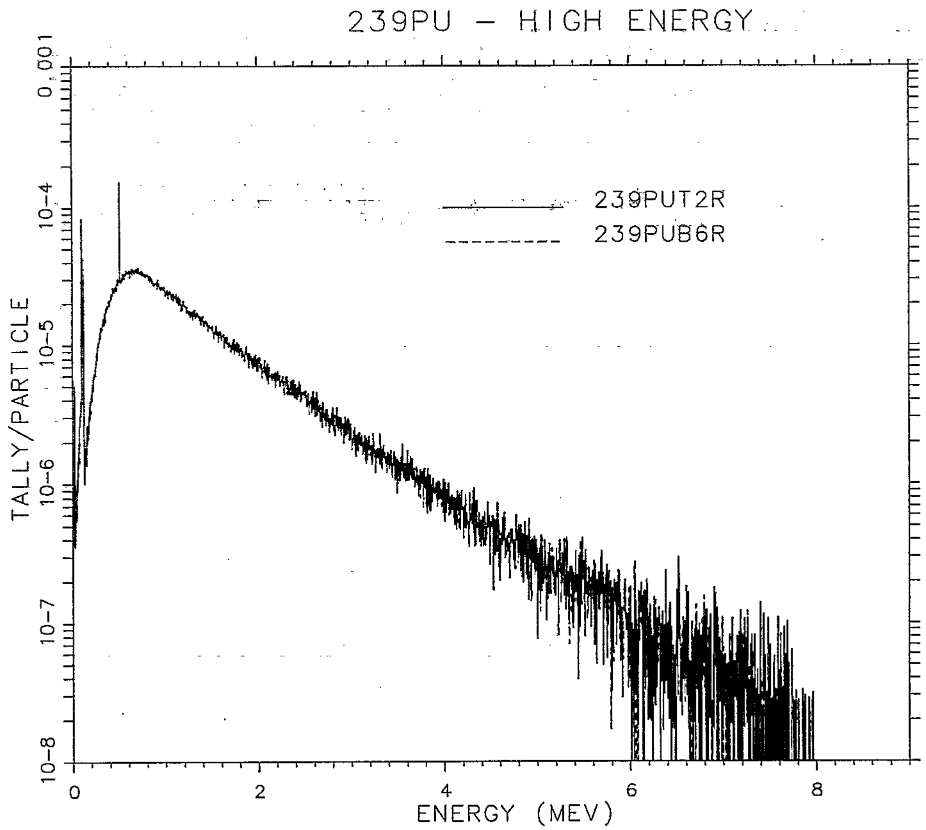

BI – HIGH ENERGY
BIB5RUN
BIB6RUN
TALLY/PARTICLE
ENERGY (MEV)

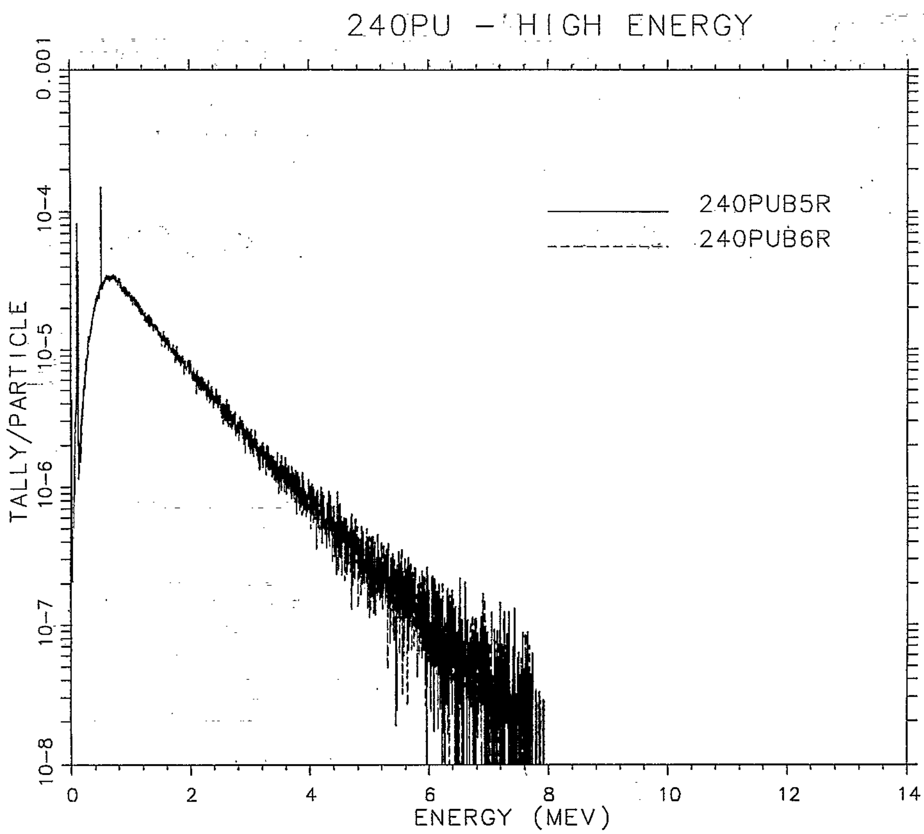

232TH - HIGH ENERGY
THB5RUN
THB6RUN
TALLY/PARTICLE
ENERGY (MEV)

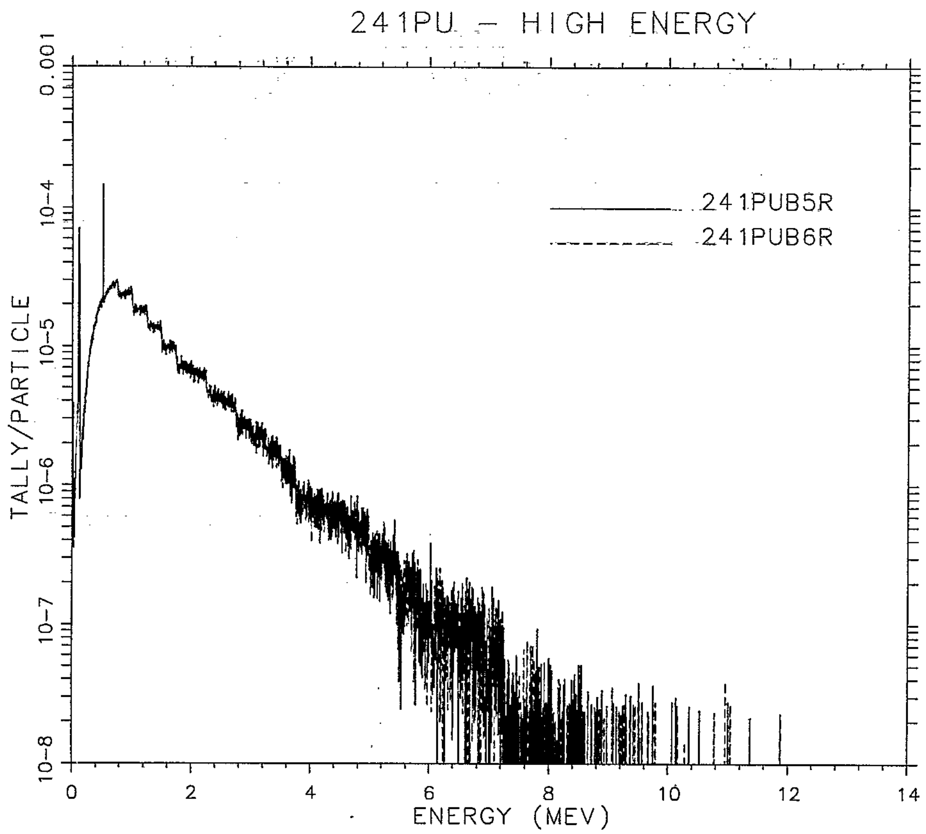

233U - HIGH ENERGY
233UB6R
TALLY/PARTICLE
ENERGY (MEV)


U — HIGH ENERGY
UB5RUN
UB6RUN
TALLY/PARTICLE
ENERGY (MEV)

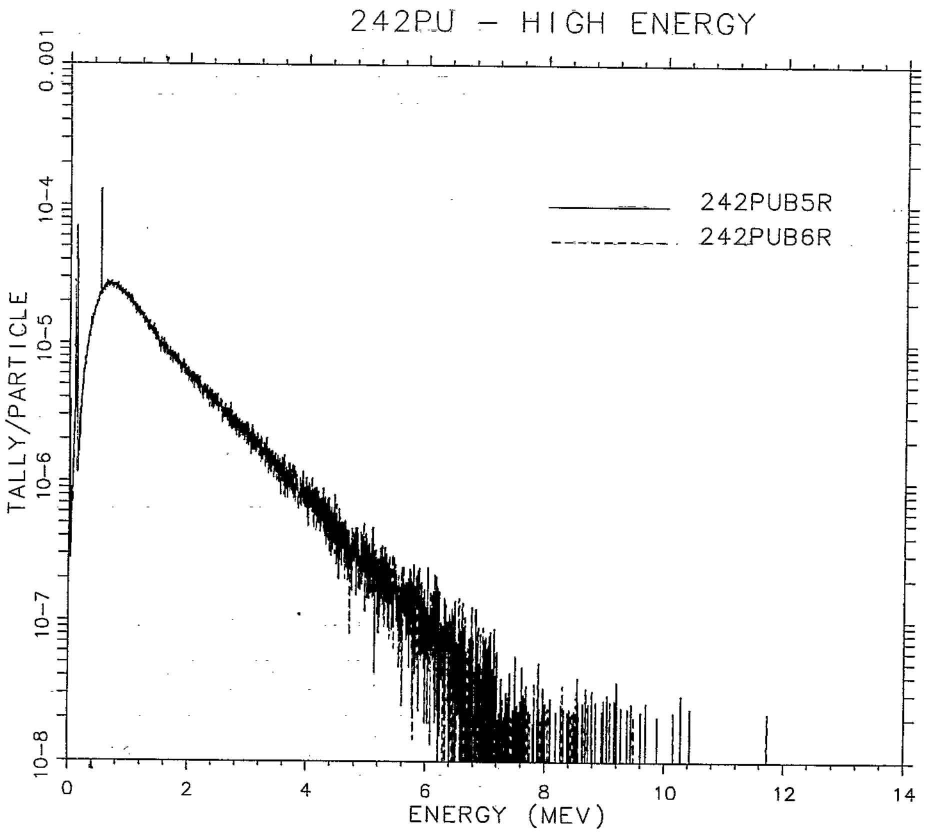

237NP — HIGH ENERGY
237NPB6R
TALLY/PARTICLE
ENERGY (MEV)


239PU - HIGH ENERGY
TALLY/PARTICLE
ENERGY (MEV)
239PUT2R
239PUB6R
0.001
10-4
10-5
10-6
10-7
10-8
0
2
4
6
8

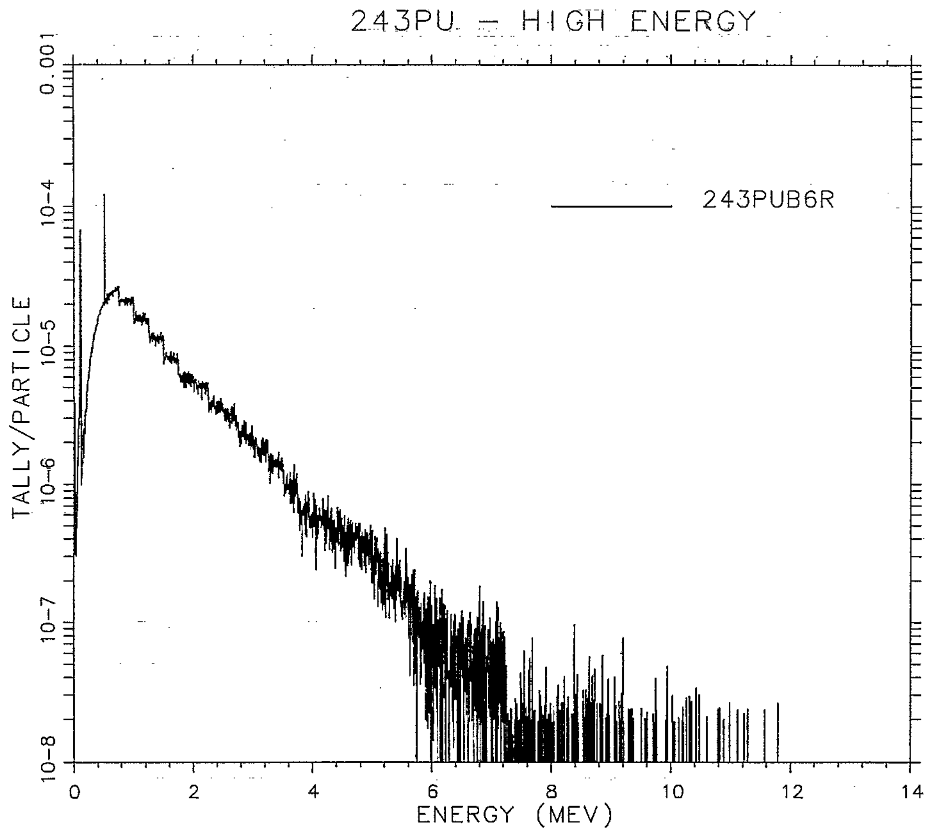

240PU - HIGH ENERGY
TALLY/PARTICLE
ENERGY (MEV)
240PUB5R
240PUB6R
0.001
10-4
10-5
10-6
10-7
10-8
0
2
4
6
8
10
12
14



241PU – HIGH ENERGY
TALLY/PARTICLE
0.001
10-4
10-5
10-6
10-7
10-8
241PUB5R
241PUB6R
0
2
4
6
8
10
12
14
ENERGY (MEV)



242PU – HIGH ENERGY
TALLY/PARTICLE
0.001
10-4
10-5
10-6
10-7
10-8
242PUB5R
242PUB6R
0
2
4
6
8
10
12
14
ENERGY (MEV)


243PU — HIGH ENERGY
243PUB6R
TALLY/PARTICLE
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10-5
10-6
10-7
10-8
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2
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6
8
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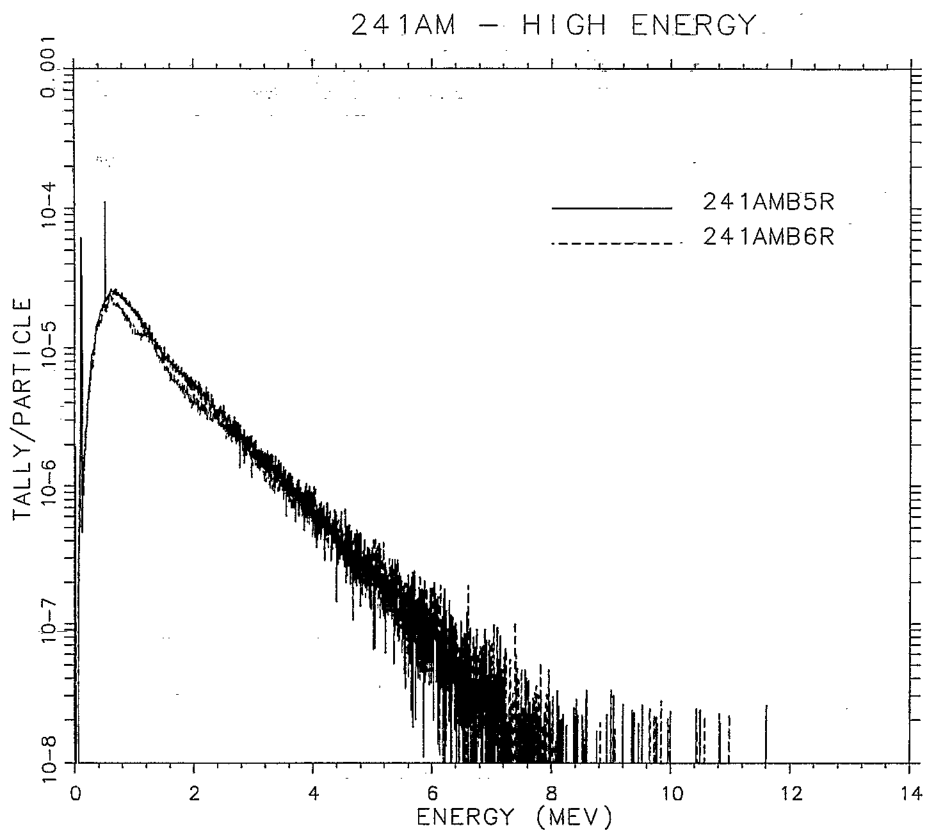
14
ENERGY (MEV)


241AM — HIGH ENERGY
241AMB5R
241AMB6R
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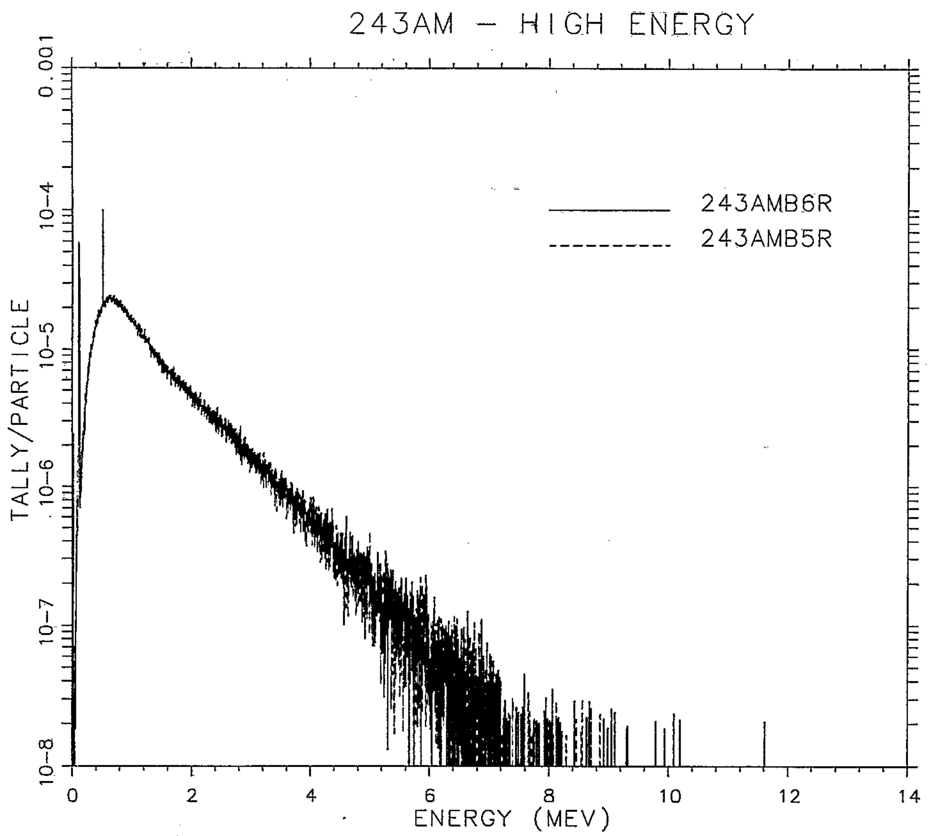
ENERGY (MEV)


243AM – HIGH ENERGY
TALLY/PARTICLE
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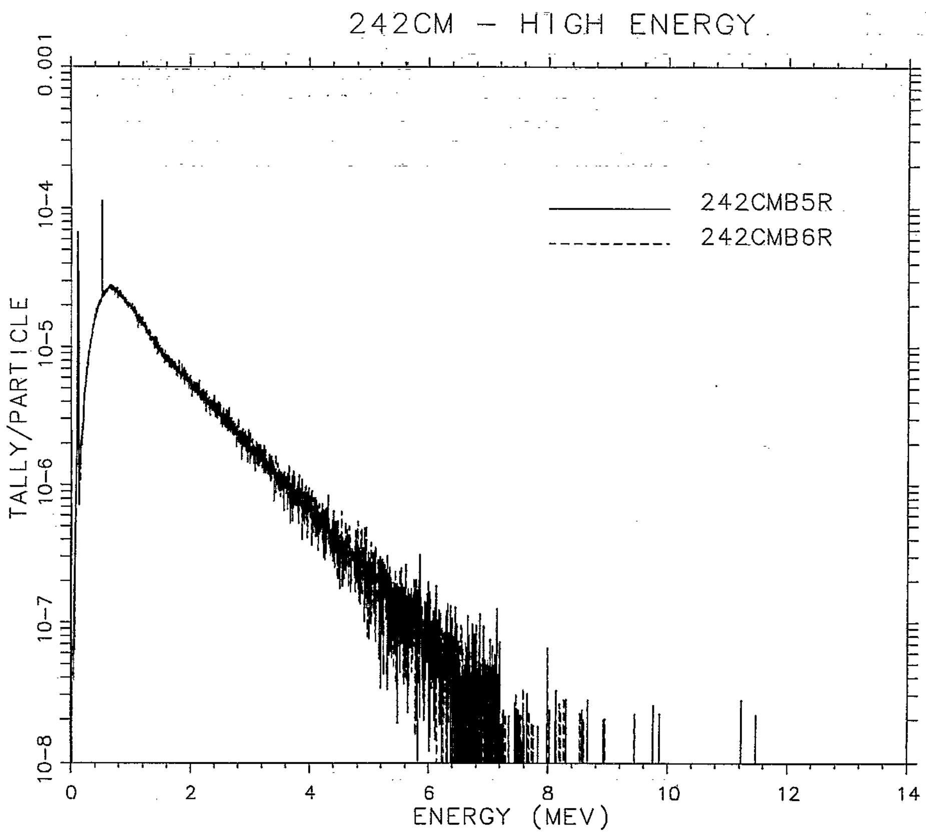
ENERGY (MEV)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TALLY/PARTICLE
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242CMB6R
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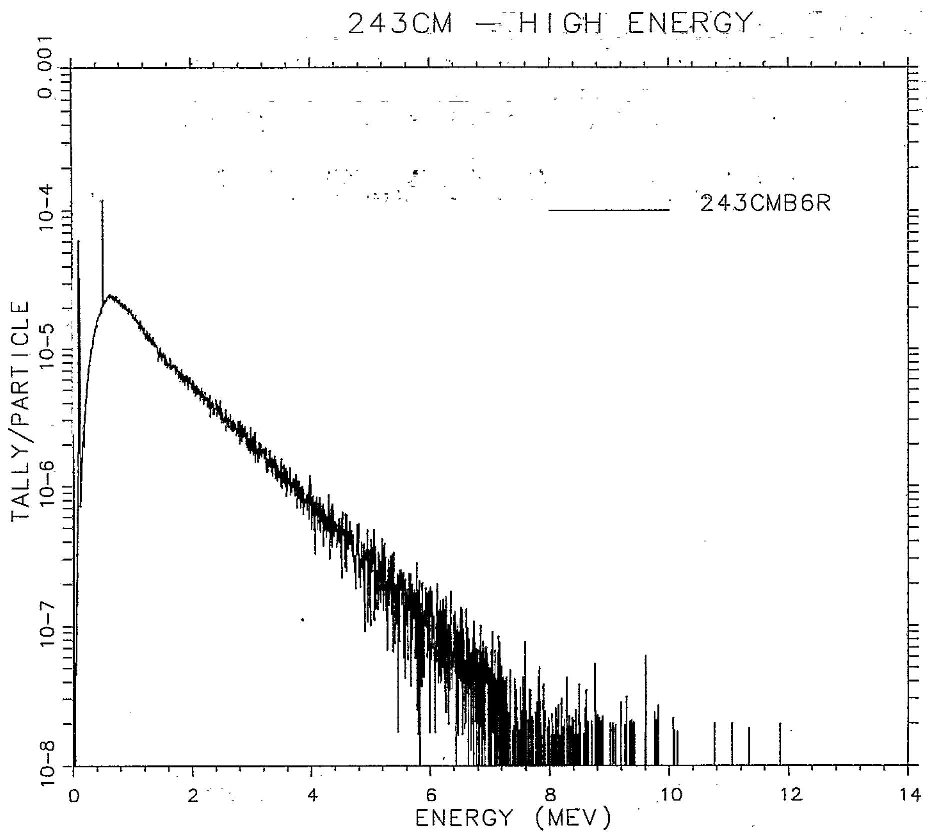
ENERGY (MEV)


243CM — HIGH ENERGY
243CMB6R
TALLY/PARTICLE
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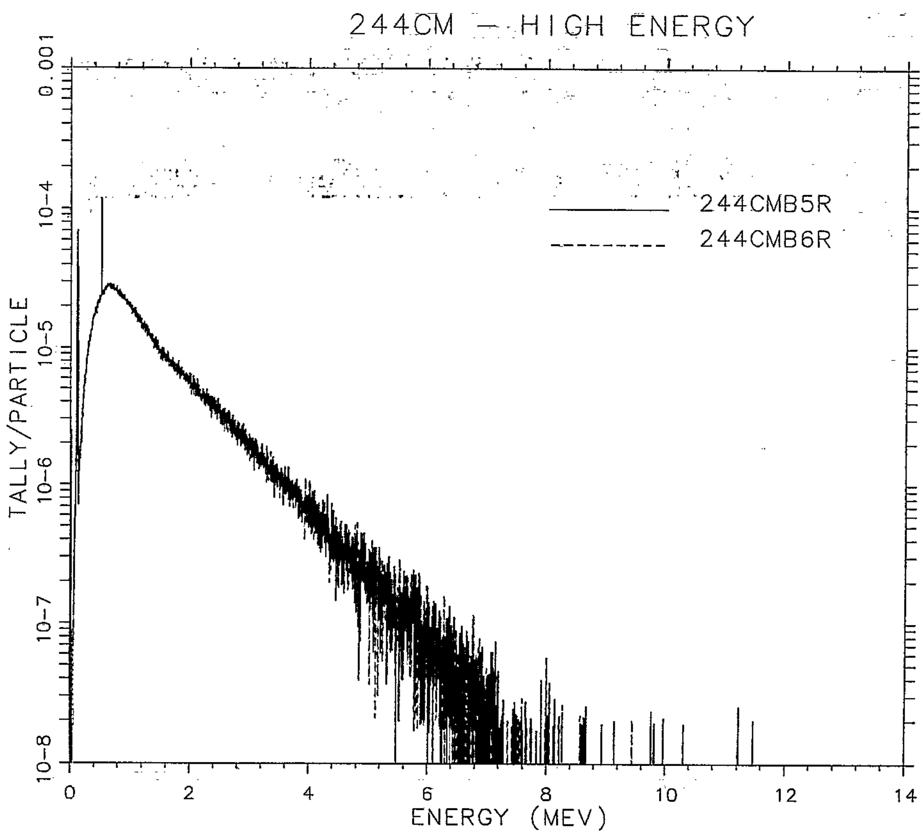
ENERGY (MEV)


244CM — HIGH ENERGY
244CMB5R
244CMB6R
TALLY/PARTICLE
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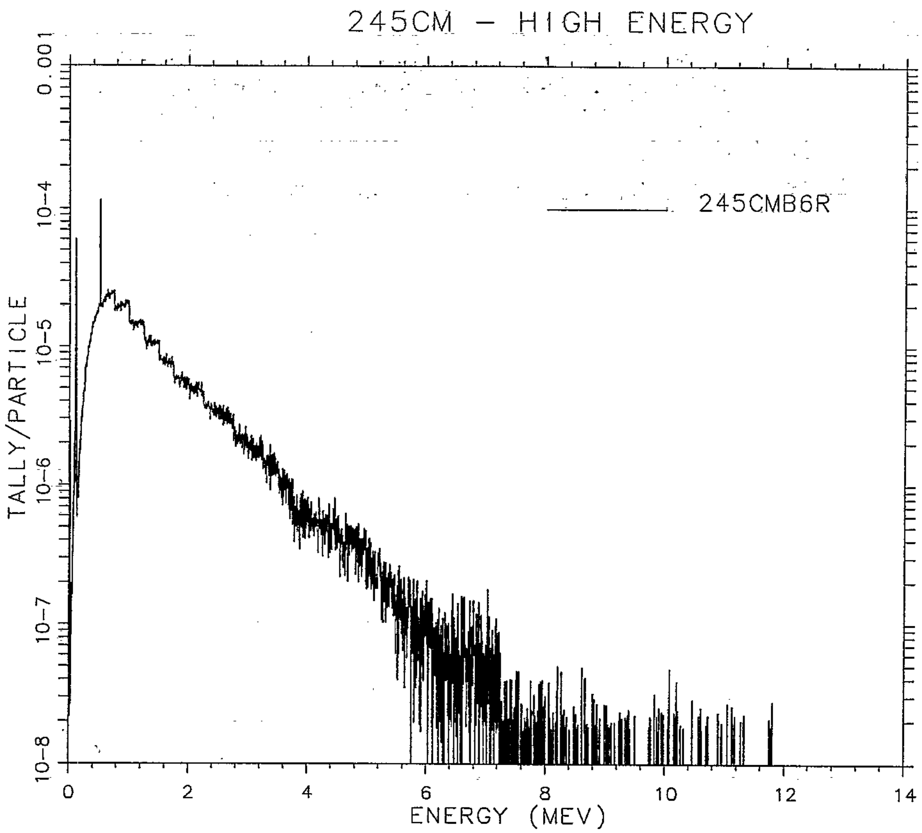
ENERGY (MEV)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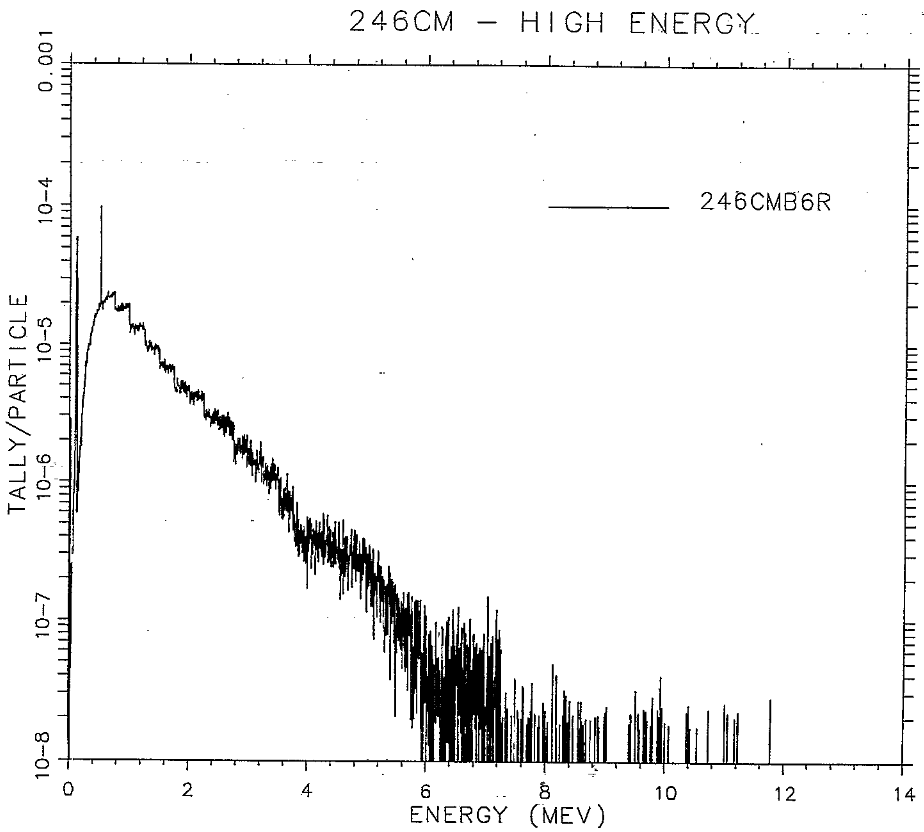
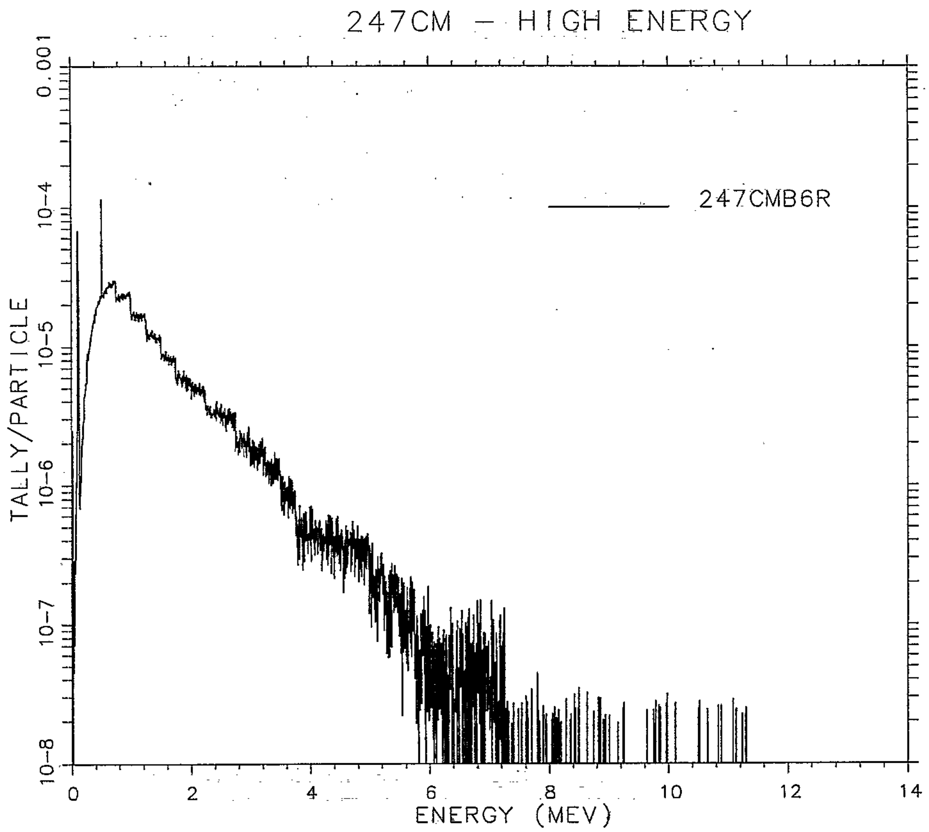
245CMB6R
TALLY/PARTICLE
ENERGY (MEV)


246CM - HIGH ENERGY
246CMB6R
TALLY/PARTICLE
ENERGY (MEV)


247CM – HIGH ENERGY
247CMB6R
TALLY/PARTICLE
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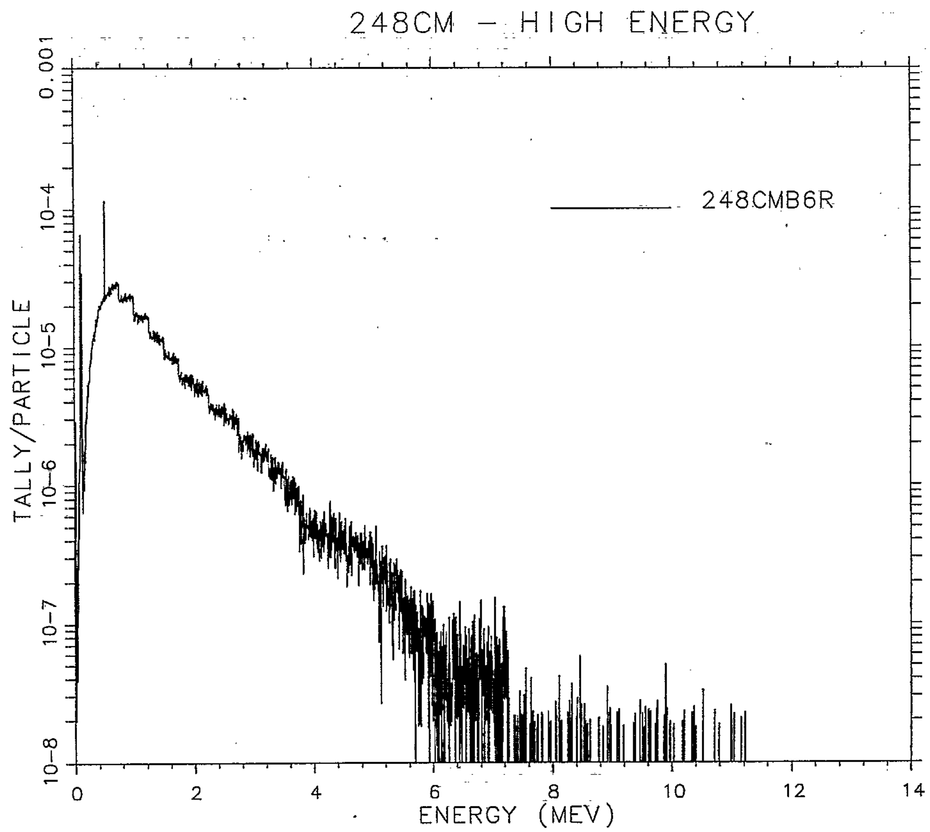
ENERGY (MEV)


248CM – HIGH ENERGY
248CMB6R
TALLY/PARTICLE
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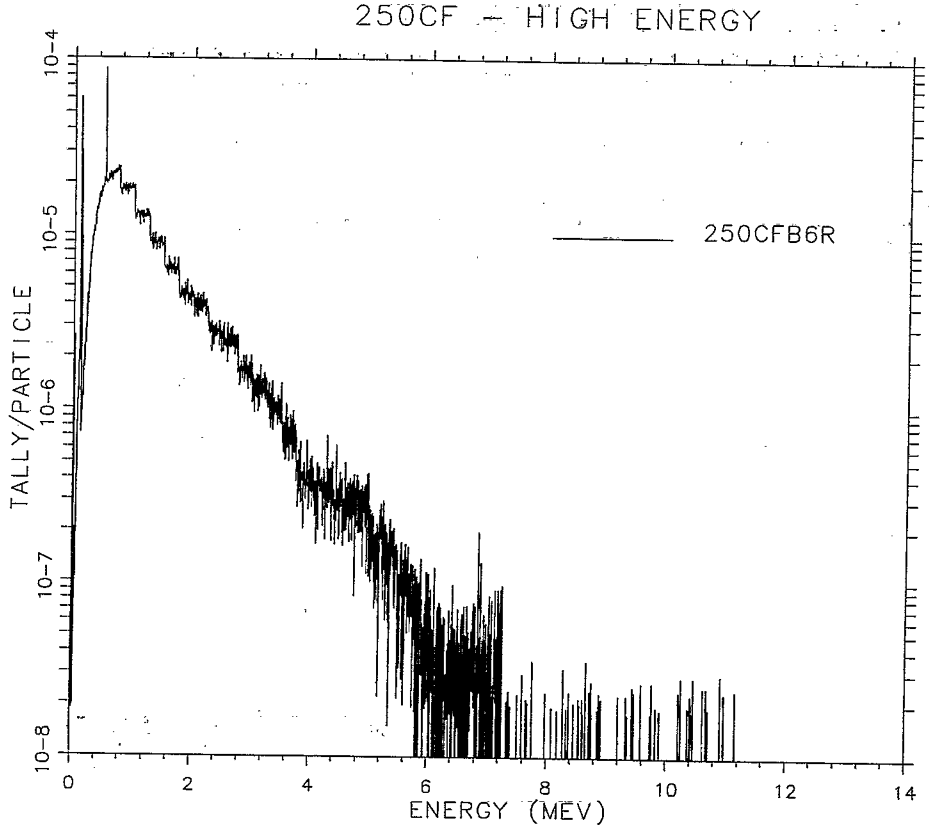
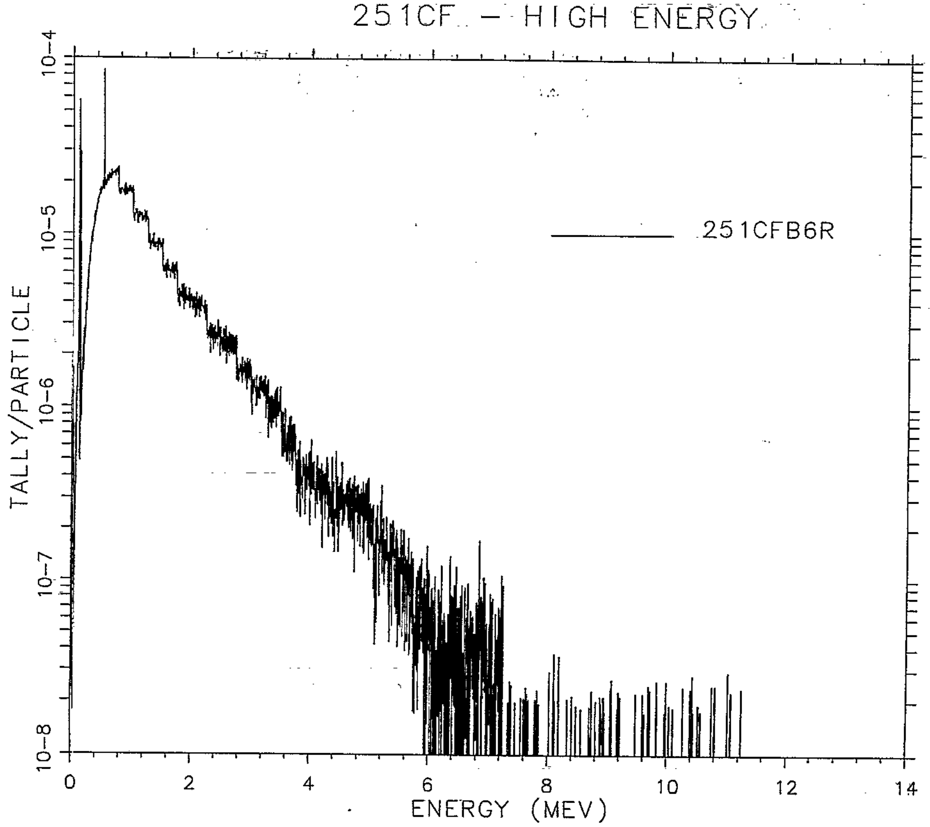
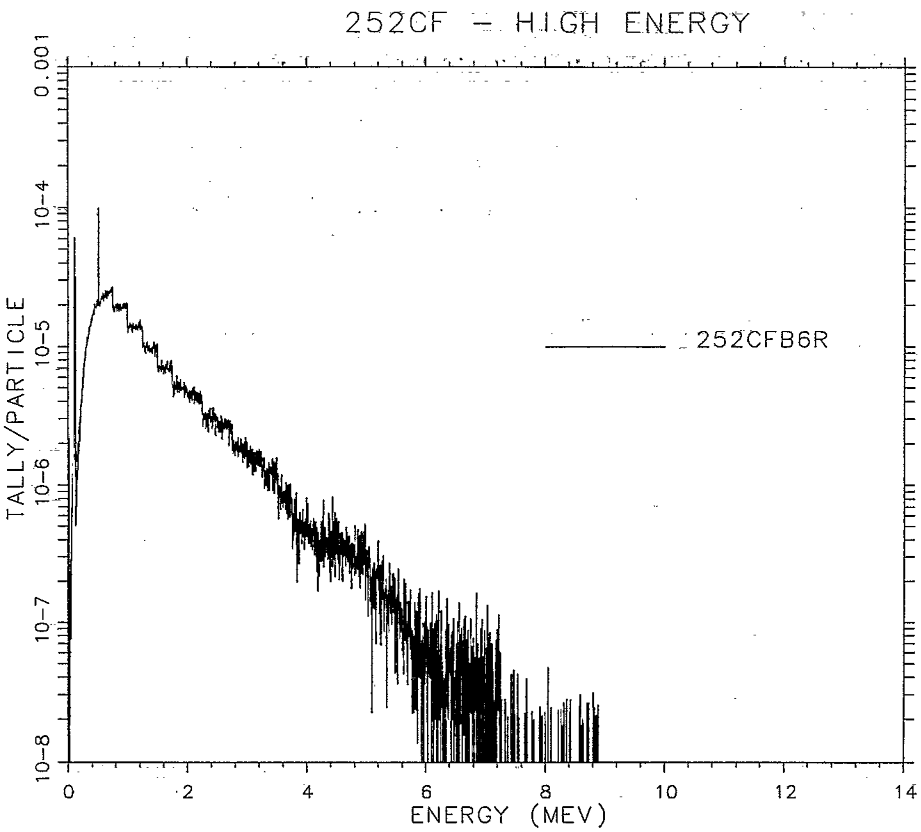
ENERGY (MEV)

250CF - HIGH ENERGY



251CF - HIGH ENERGY




252CF - HIGH ENERGY
TALLY/PARTICLE
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252CFB6R
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ENERGY (MEV)

APPENDIX C

Comparison of Thermal Neutron Capture Gamma-ray Energies and Intensities in Aluminum from Hardell (1969), Lone(1981), and Schmidt (1982)

The following table indicates the photon energy and intensity for each discrete photon from thermal neutron capture reactions. The intensity is the number of photons of a particular energy produced for every 100 neutron capture reactions. Many of the gamma-rays *not* reported by Schmidt (1982), but included in Lone (1981), were concluded to be doubtful Al capture lines by Schmidt.

Hardell (1969)		Lone (1981)		Schmidt (1982)	
Energy (MeV)	Intensity (#/100 Captures)	Energy (MeV)	Intensity (#/100 Captures)	Energy (MeV)	Intensity (#/100 Captures)
		0.249	6.84		
		0.252	5.65		
		0.259	2.58		
0.400	0.50			0.456	0.29
		0.551	0.92	0.549	0.23
		0.559	0.92		
		0.597	1.62		
		0.758	1.79		
0.832	0.50	0.830	1.72	0.831	1.30
0.844	1.50			0.866	0.54
0.942	0.40			0.942	1.30
				0.945	0.24
				0.969	0.42
0.984	1.90	0.984	5.47	0.983	4.40
1.014	4.30			1.014	2.70
				1.074	0.57
				1.102	0.70
				1.126	0.38
				1.173	0.39
1.193	0.30			1.194	0.60
1.284	0.60			1.284	1.10
1.306	0.30			1.305	0.19
1.342	0.50			1.342	1.00
				1.365	0.38
1.409	1.60	1.409	1.08	1.408	3.10
1.526	0.90	1.526	0.80	1.526	1.80
1.590	0.90	1.590	1.00	1.590	1.60
				1.592	0.36
1.623	3.20	1.623	3.35	1.623	4.60
				1.642	0.30
		1.659	0.82	1.673	0.23
				1.705	0.39
1.865	0.40			1.865	0.46
1.927	1.00	1.927	0.80	1.928	1.20
				1.968	0.10
1.983	0.60	1.984	0.70	1.984	1.10
				2.048	0.07
2.108	2.30	2.108	1.80	2.108	2.80
2.128	0.30	2.131	0.35	2.129	0.34
2.138	1.80	2.139	1.75	2.139	2.20
2.170	0.20	2.172	0.25	2.171	0.45
2.212	1.90				
		2.241	3.04		
2.254	0.30	2.256	0.47	2.255	0 55
2.272	1.50	2.272	1.51	2.272	2.10
				2.279	0.08
2.282	3.70	2.283	2.93	2.283	4.70

Hardell (1969)		Lone (1981)		Schmidt (1982)	
Energy (MeV)	Intensity (#/100 Captures)	Energy (MeV)	Intensity (#/100 Captures)	Energy (MeV)	Intensity (#/100 Captures)
		2.298	0.64	2.300	12.00
2.347	0.20	2.347	0.13	2.347	0.16
2.380	0.20	2.381	0.13	2.380	0.21
				2.384	0.03
2.451	0.30	2.420	0.10	2.419	0.14
		2.452	0.43	2.451	0.39
		2.486	0.16	2.486	0.18
		2.503	0.12	2.503	0.16
		2.535	0.06	2.535	0.08
		2.550	0.18	2.548	0.15
				2.552	0.09
		2.566	0.14	2.564	0.10
				2.568	0.70
2.578	1.60	2.578	1.39	2.578	2.20
				2.582	0.05
2.590	3.20	2.590	2.69	2.590	4.20
2.625	1.00	2.626	0.97	2.626	1.37
2.656	0.20	2.657	0.16	2.656	0.16
		2.692	0.05	2.691	0.03
2.709	0.50	2.710	0.48	2.710	0.69
2.731	0.50	2.728	0.23	2.725	0.02
		2.738	0.19	2.728	0.27
		2.755	0.05	2.734	0.38
				2.744	0.05
2.821	3.40	2.821	2.94	2.821	3.90
				2.862	0.04
		2.878	0.15	2.876	0.12
				2.881	0.03
2.887	0.10	2.887	0.23	2.887	0.23
				2.894	0.05
2.921	0.30	2.922	0.22	2.922	0.28
				2.955	0.23
2.960	9.30	2.960	7.99	2.960	9.60
		2.976	0.11	2.974	0.02
2.987	0.40	2.988	0.21	2.988	0.32
				3.017	0.06
				3.020	0.07
				3.024	0.05
3.034	8.00	3.034	7.01	3.034	8.80
		3.075	0.07	3.068	0.08
				3.076	0.08
3.128	0.30	3.129	0.21	3.129	0.24
		3.143	0.21	3.142	0.16
		3.192	0.07	3.191	0.05
		3.207	0.13	3.208	0.09
				3.223	0.05
				3.231	0.03
				3.255	0.02
				3.263	0.10

Hardell (1969)		Lone (1981)		Schmidt (1982)	
Energy (MeV)	Intensity (#/100 Captures)	Energy (MeV)	Intensity (#/100 Captures)	Energy (MeV)	Intensity (#/100 Captures)
3.265	0.40	3.266	0.37	3.265	0.42
3.303	0.90	3.303	1.11	3.303	1.14
				3.317	0.03
3.346	0.40	3.347	0.39	3.347	0.50
				3.375	0.03
3.392	0.50	3.392	0.45	3.392	0.57
				3.409	0.02
				3.448	0.03
3.465	6.80	3.465	6.16	3.465	7.00
				3.472	0.06
		3.481	0.17	3.481	0.12
		3.541	0.04		
3.561	0.80	3.560	0.68	3.561	0.93
				3.570	0.04
3.592	4.60	3.591	4.11	3.591	4.70
				3.599	0.15
		3.624	0.08	3.624	0.09
				3.635	0.01
		3.640	0.08	3.640	0.07
		3.651	0.99		
		3.659	0.08	3.659	0.06
				3.671	0.07
3.678	0.20	3.680	0.51	3.678	0.31
				3.702	0.08
3.709	0.40	3.709	0.51	3.709	0.45
		3.723	0.08	3.722	0.03
				3.725	0.02
				3.751	0.04
		3.754	0.08	3.755	0.04
				3.769	0.01
3.790	0.80	3.789	0.84	3.789	0.87
				3.804	0.01
				3.821	0.03
3.825	0.60	3.824	0.41	3.824	0.56
3.850	3.00	3.849	2.55	3.849	3.10
				3.859	0.05
3.877	2.60	3.875	2.14	3.875	2.70
3.891	0.10	3.890	0.20	3.890	0.23
3.904	0.30	3.902	0.39	3.901	0.23
				3.905	0.20
				3.927	0.02
3.937	0.20	3.935	0.29	3.935	0.33
		3.950	0.06	3.950	0.01
		3.986	0.10		
4.003	0.10	4.003	0.13	4.002	0.14
4.017	0.70	4.016	0.60	4.016	0.73
				4.023	0.14
				4.045	0.02
		4.055	0.31	4.054	0.14

Hardell (1969)		Lone (1981)		Schmidt (1982)	
Energy (MeV)	Intensity (#/100 Captures)	Energy (MeV)	Intensity (#/100 Captures)	Energy (MeV)	Intensity (#/100 Captures)
				4.060	0.03
		4.069	0.12	4.069	0.16
				4.085	0.01
		4.102	0.35	4.102	0.02
				4.120	0.04
				4.125	0.09
4.134	7.20	4.133	6.42	4.133	6.90
				4.162	0.02
		4.169	0.29	4.169	0.12
				4.175	0.03
		4.185	0.06	4.185	0.06
		4.215	0.06	4.213	0.06
				4.218	0.03
		4.240	0.12	4.237	0.06
4.260	6.60	4.260	6.00	4.260	6.80
				4.270	0.05
4.282	0.10	4.280	0.18	4.280	0.17
		4.331	0.06	4.331	0.05
4.378	0.40	4.378	0.48	4.378	0.43
		4.397	0.06	4.396	0.06
				4.424	0.36
4.428	1.20	4.428	0.73	4.428	0.81
				4.447	0.02
		4.460	2.20	4.462	0.04
		4.485	0.08	4.485	0.07
		4.512	0.12	4.512	0.08
				4.566	0.03
4.577	0.40	4.576	0.36	4.576	0.30
				4.582	0.04
4.598	0.10	4.596	0.10	4.596	0.12
				4.613	0.02
				4.618	0.08
4.621	0.30	4.620	0.26	4.621	0.19
4.661	2.70	4.660	2.09	4.660	2.60
4.691	4.70	4.691	3.94	4.691	4.60
4.735	6.10	4.734	5.00	4.734	5.50
				4.737	0.45
4.756	0.40	4.755	0.60	4.754	0.38
4.766	0.90	4.764	0.67	4.764	0.91
				4.770	0.11
				4.783	0.01
				4.813	0.03
		4.868	0.05	4.869	0.06
4.904	3.10	4.903	2.64	4.903	3.10
		4.945	0.72		
4.984	0.10	4.984	0.11	4.984	0.11
		4.997	0.08	4.997	0.06
		5.005	0.05	5.005	0.05
				5.032	0.02

Hardell (1969)		Lone (1981)		Schmidt (1982)	
Energy (MeV)	Intensity (#/100 Captures)	Energy (MeV)	Intensity (#/100 Captures)	Energy (MeV)	Intensity (#/100 Captures)
5.068	0.10	5.069	0.16	5.069	0.17
5.104	0.40	5.104	0.34	5.104	0.39
				5.130	0.11
5.135	3.20	5.134	2.59	5.134	3.00
				5.142	0.02
		5.176	0.08	5.176	0.07
				5.185	0.03
		5.202	0.03	5.204	0.02
		5.210	0.03	5.209	0.02
				5.213	0.01
				5.228	0.01
5.239	0.20	5.238	0.27	5.238	0.26
				5.270	0.06
				5.278	0.02
5.303	0.40	5.302	0.39	5.303	0.47
5.310	0.10			5.315	0.03
		5.343	0.02	5.344	0.02
		5.377	0.11	5.377	0.08
5.412	1.90	5.411	1.82	5.411	2.00
		5.423	0.15	5.427	0.09
		5.443	0.11	5.442	0.02
				5.447	0.04
5.454	0.20	5.452	0.22	5.453	0.17
				5.459	0.02
		5.523	0.07	5.523	0.06
5.586	1.20	5.585	0.88	5.586	1.10
				5.595	0.01
		5.610	0.02		
		5.648	0.01		
5.711	0.50	5.709	0.43	5.710	0.56
				5.719	0.02
				5.730	0.01
				5.761	0.02
5.767	0.40	5.765	0.39	5.766	0.38
5.798	0.10	5.796	0.15	5.797	0.12
				5.803	0.04
		5.829	0.01	5.830	0.01
5.862	0.10	5.859	0.16	5.860	0.16
		5.879	0.04	5.879	0.03
				5.883	0.01
		5.922	0.05	5.923	0.04
		5.969	0.03	5.970	0.02
		5.988	0.02	5.988	0.02
6.019	0.20	6.017	0.21	6.019	0.19
6.102	2.70	6.101	2.28	6.101	2.60
				6.110	0.01
				6.121	0.01
				6.162	0.01
6.199	0.70	6.198	0.57	6.198	0.67

Hardell (1969)		Lone (1981)		Schmidt (1982)	
Energy (MeV)	Intensity (#/100 Captures)	Energy (MeV)	Intensity (#/100 Captures)	Energy (MeV)	Intensity (#/100 Captures)
				6.211	0.01
				6.255	0.01
6.318	2.20	6.316	1.81	6.316	2.00
				6.330	0.01
		6.349	0.11	6.351	0.11
		6.388	0.01	6.390	0.01
6.441	0.60	6.440	0.59	6.441	0.66
		6.459	0.02	6.460	0.02
6.594	0.10	6.590	0.17	6.592	0.16
6.622	0.40	6.619	0.44	6.620	0.24
				6.622	0.19
				6.628	0.01
6.712	0.80	6.710	0.71	6.711	0.90
		6.723	0.10	6.725	0.09
		6.751	0.08	6.752	0.06
		6.800	0.03	6.801	0.02
		6.822	0.06	6.823	0.06
6.864	0.10	6.861	0.19	6.862	0.17
		6.893	0.03	6.894	0.03
6.931	0.10	6.936	0.13	6.937	0.12
		6.953	0.15		
		6.978	0.09		
		7.119	0.08		
		7.135	0.05	7.135	0.05
7.176	0.10	7.175	0.14	7.176	0.13
		7.238	0.07	7.238	0.09
		7.268	0.04	7.268	0.04
		7.341	0.06	7.342	0.06
				7.377	0.02
				7.408	0.07
		7.454	0.16		
		7.657	0.17		
7.695	4.60	7.693	4.14	7.693	3.30
7.726	28.40	7.724	27.43	7.724	26.80

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