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by

Darrell M. Drake
Edward D. Arthur
Myron G. Silbert

LOS ALAMOS NATIONAL LABORATORY
3 9338 00374 4264

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

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MORE 14-MeV, NEUTRON-INDUCED GAMMA-RAY PRODUCTION CROSS SECTIONS

by

Darrell M. Drake, Edward D. Arthur, and Myron G. Silbert

LOS ALAMOS NATL. LAB. LIBS.
3 9338 00374 4264

ABSTRACT

A pulsed 14.2-MeV neutron source and NaI(Tl) gamma-ray spectrometer were used to measure gamma-ray production cross sections for beryllium, carbon, magnesium, aluminum, silicon, calcium, titanium, vanadium, chromium, iron, copper, niobium, molybdenum, thorium, and ^{238}U.

INTRODUCTION

Gamma-ray production cross sections were measured for samples of beryllium, carbon, magnesium, aluminum, silicon, calcium, titanium, vanadium, chromium, iron, copper, niobium, molybdenum, thorium, and ^{238}U that were bombarded with a pulsed 14.2-MeV neutron beam obtained from the $^{2}H(t,n)^{4}He$ reaction. A first set of such measurements was reported in LA-5662-MS. Cross sections for five of the LA-5662-MS samples were measured several months later for the present report, and these data can be used as a check for consistency.

Data were taken at 90°, 110°, and 130° for most of the samples.

EXPERIMENTAL ARRANGEMENT

Figure 1 shows the experimental arrangement. A chopped beam of tritons (10-ns time width at 2-mHz repetition rate) was accelerated to 2.3 MeV by the Los Alamos Scientific Laboratory vertical Van de Graaff. The triton beam pulses were compressed to a time width of 1 ns by a Mobley bunching system and directed into a deuterium gas target. In this experiment, the triton beam was stopped in the deuterium gas, whereas in the arrangement described in LA-5662-MS the tritons passed through the gas and impinged on a gold beam stop with an energy of about 400 keV. When the beam is stopped in the deuterium gas, the number of neutrons per microampere approximately doubles, and the neutron energy spread is slightly increased.

Emitted neutrons, at 90° to the triton beam and having a mean energy of 14.2 MeV, interacted with one of the samples placed about 100 mm from the neutron source. The energy spread of the neutrons intercepted by the samples was about ± 0.5 MeV. Gamma rays produced from the bombarded samples were collimated and pulse-height analyzed by a heavily shielded NaI(Tl) crystal and photomultiplier system.

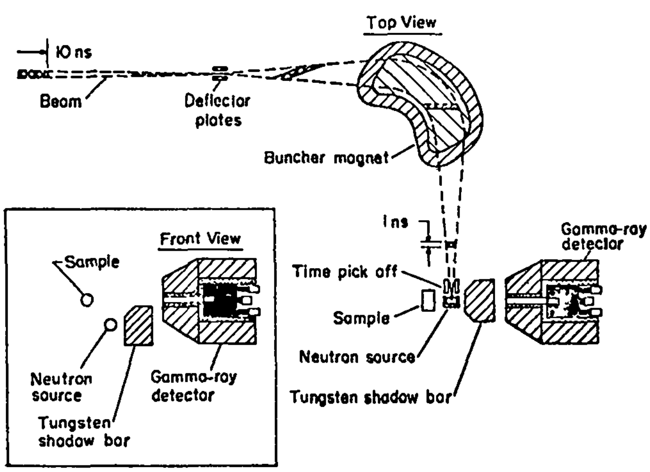

Fig. 1. Experimental arrangement for the measurements of gamma-ray spectra. The detector and sample are about 100 mm above the plane defined by the beam path.

An anti-Compton NaI(Tl) scintillator surrounding the center crystal was used to suppress further the background events and to improve the response functions. The pulsed neutron beam allowed time-of-flight (TOF) discrimination by separating the desired gamma rays from neutron-related and other background events in the crystal.

Angles were changed by rotating the sample about the beam line and moving the gamma-ray spectrometer forward or backward to compensate for the change in sample-to-crystal distance.

DATA REDUCTION

Procedures for background subtraction, response functions, flux measurements, multiple scattering, and the formula for cross-section calculations were the same as those given in Sec. III of LA-5662-MS. The technique used for estimation of errors is described in Sec. IV of that report.

RESULTS

Cross sections are listed in Table I for gamma-ray production by all samples except beryllium and carbon. In Table I, cross sections are listed as millibarns per steradian in 100-keV gamma-ray energy intervals from 200 to 4000 keV, and in 500-keV intervals above 4000 keV.

No gamma rays were observed from beryllium except for the 0.48-MeV gamma-ray from $^{9}Be(n,t)^{7}Li^{*}$, with a cross section of 0.7 $\pm$ 0.2 mb/sr. Table II lists observed cross sections for beryllium gamma rays from 0.5 to 5.0 MeV in 0.5-MeV intervals, along with corresponding standard deviations.

For the lighter elements (carbon through iron), cross sections for separable gamma rays are given in Table III. Some of these cross sections might include contributions from nearby gamma rays. For example, the 0.85-MeV gamma-ray cross section listed for iron probably contains the 0.93-MeV gamma rays from the $^{56}Fe(n,2n)^{55}Fe$ reaction. There are some peaks in the spectra for heavier elements, but no attempt was made to analyze them as single gamma rays.

Table IV lists the energy-weighted integral cross sections, $4\pi \int E_{\gamma}\sigma(\theta,E_{\gamma})\, dE_{\gamma}$ from $E_{\gamma} = 0.3$ to 8.5 MeV, for all elements included in this report.

TABLE I - DIFFERENTIAL GAMMA-RAY PRODUCTION CROSS SECTIONS AS A FUNCTION OF GAMMA-RAY ENERGY

Element →		MAGNESIUM						ALUMINUM					
Angle →		90°		110°		130°		90°		110°		130°	
Energy Interval (MeV)		Cross Section (mb/sr)	Estimated Uncer-tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer-tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer-tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer-tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer-tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer-tainty (mb/sr)
0.2	0.3	9.1	3.3	6.4	2.3	6.1	2.1	6.9	2.1	4.1	1.2	3.0	0.9
0.3	0.4	10.0	3.6	7.0	2.2	6.1	1.8	5.9	1.8	2.7	0.9	2.4	0.8
0.4	0.5	4.3	0.9	3.4	0.7	3.9	0.8	4.3	0.9	3.2	0.6	3.1	0.6
0.5	0.6	2.2	0.23	2.0	0.2	1.15	0.14	1.8	0.2	1.4	0.2	1.3	0.2
0.6	0.7	1.03	0.12	1.06	0.12	0.94	0.11	1.09	0.12	1.01	0.11	0.74	0.09
0.7	0.8	1.6	0.2	1.5	0.2	1.7	0.2	2.8	0.3	2.6	0.3	2.8	0.3
0.8	0.9	2.8	0.3	2.7	0.3	2.8	0.3	4.4	0.4	3.7	0.4	4.2	0.4
0.9	1.0	2.9	0.3	2.2	0.2	2.1	0.2	6.2	0.6	5.6	0.6	5.6	0.6
1.0	1.1	2.3	0.3	2.2	0.2	2.4	0.3	5.5	0.6	5.0	0.5	4.2	0.4
1.1	1.2	3.2	0.3	2.8	0.3	2.5	0.3	2.7	0.3	2.1	0.2	2.1	0.2
1.2	1.3	4.3	0.4	4.7	0.5	7.1	0.7	1.8	0.2	1.6	0.2	1.7	0.2
1.3	1.4	13.3	1.3	14.6	1.5	16.3	1.6	2.1	0.2	1.8	0.2	1.7	0.2
1.4	1.5	10.9	1.1	10.0	1.0	8.1	0.8	2.2	0.2	1.9	0.2	1.7	0.2
1.5	1.6	3.0	0.3	3.4	0.4	2.0	0.2	1.9	0.2	2.0	0.2	1.9	0.2
1.6	1.7	2.3	0.2	2.1	0.2	2.1	0.2	2.8	0.3	2.6	0.3	3.4	0.3
1.7	1.8	3.0	0.3	3.2	0.3	3.3	0.3	5.9	0.6	5.9	0.6	6.8	0.7
1.8	1.9	3.9	0.4	3.5	0.4	3.7	0.4	7.3	0.7	6.6	0.7	6.5	0.7
1.9	2.0	2.2	0.2	2.0	0.2	1.8	0.2	4.3	0.4	3.8	0.4	3.4	0.3
2.0	2.1	1.24	0.14	1.25	0.14	1.21	0.14	2.4	0.3	2.2	0.2	2.6	0.3
2.1	2.2	0.94	0.11	0.78	0.09	1.11	0.13	3.7	0.4	4.0	0.4	4.9	0.5
2.2	2.3	1.11	0.13	1.21	0.14	1.03	0.12	5.2	0.5	5.1	0.5	5.3	0.5
2.3	2.4	1.00	0.12	1.18	0.13	1.3	0.1	3.9	0.4	3.6	0.4	3.1	0.3
2.4	2.5	1.4	0.2	1.22	0.14	1.7	0.2	2.5	0.3	2.2	0.2	2.1	0.2
2.5	2.6	1.22	0.14	1.4	0.2	1.7	0.2	1.9	0.2	1.7	0.2	1.7	0.2
2.6	2.7	1.5	0.2	1.6	0.2	2.0	0.2	1.6	0.2	1.5	0.2	1.5	0.2
2.7	2.8	1.6	0.2	1.8	0.2	2.0	0.2	1.3	0.1	1.4	0.1	1.4	0.2
2.8	2.9	1.7	0.2	1.5	0.2	1.7	0.2	1.8	0.2	1.9	0.2	2.7	0.3
2.9	3.0	1.11	0.12	1.4	0.2	1.10	0.13	2.9	0.3	3.1	0.3	3.5	0.4
3.0	3.1	0.95	0.11	0.93	0.11	0.85	0.11	3.2	0.3	2.9	0.3	2.8	0.3
3.1	3.2	0.89	0.11	1.07	0.13	0.75	0.10	2.2	0.2	2.1	0.2	1.8	0.2
3.2	3.3	0.77	0.10	0.75	0.09	0.80	0.10	1.5	0.2	1.26	0.14	1.10	0.12
3.3	3.4	0.70	0.09	0.68	0.08	0.80	0.10	0.94	0.11	0.86	0.10	0.87	0.10
3.4	3.5	0.68	0.09	0.67	0.09	0.92	0.11	0.83	0.10	0.75	0.09	0.82	0.10
3.5	3.6	0.83	0.10	0.83	0.10	0.91	0.11	0.84	0.10	0.67	0.08	0.74	0.09
3.6	3.7	0.78	0.10	0.90	0.11	1.12	0.14	0.79	0.09	0.70	0.08	0.88	0.10
3.7	3.8	1.15	0.14	1.01	0.12	1.14	0.14	0.94	0.11	0.80	0.09	0.80	0.09
3.8	3.9	1.06	0.13	1.15	0.14	0.94	0.12	0.91	0.10	0.88	0.10	0.89	0.10
3.9	4.0	0.90	0.11	0.98	0.12	1.38	0.16	0.77	0.09	0.76	0.09	1.02	0.12
4.0	4.5	1.00	0.13	1.12	0.14	1.16	0.15	0.90	0.11	0.81	0.10	0.88	0.11
4.5	5.0	0.79	0.11	0.82	0.11	0.72	0.10	0.86	0.11	0.83	0.10	0.79	0.10
5.0	5.5	0.56	0.09	0.54	0.08	0.51	0.08	0.74	0.10	0.73	0.10	0.65	0.09
5.5	6.0	0.61	0.09	0.67	0.10	0.80	0.12	0.52	0.08	0.50	0.07	0.26	0.08
6.0	6.5	0.46	0.08	0.56	0.09	0.61	0.10	0.57	0.09	0.60	0.09	0.61	0.09
6.5	7.0	0.55	0.09	0.58	0.10	0.58	0.10	0.49	0.08	0.41	0.06	0.50	0.08
7.0	7.5	0.58	0.10	0.49	0.09	0.54	0.10	0.48	0.08	0.47	0.08	0.45	0.08
7.5	8.0	0.41	0.08	0.38	0.08	0.45	0.09	0.39	0.07	0.33	0.06	0.33	0.06
8.0	8.5	0.40	0.08	0.42	0.09	0.41	0.09	0.32	0.06	0.28	0.56	0.27	0.06

Element →		SILICON						CALCIUM					
Angle →		90°		110°		130°		90°		110°		130°	
Energy Interval (MeV)		Cross Section (mb/sr)	Estimated Uncer-tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer-tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer-tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer-tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer-tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer-tainty (mb/sr)
0.2	0.3												
0.3	0.4												
0.4	0.5	4.1	0.8	3.0	0.6	2.5	0.6	4.3	0.9	4.4	1.0	3.4	0.7
0.5	0.6	5.3	0.5	4.9	0.5	4.6	0.5	2.9	0.3	2.4	0.3	2.4	0.3
0.6	0.7	1.7	0.2	1.3	0.2	1.6	0.2	1.8	0.2	2.1	0.2	1.3	0.2
0.7	0.8	1.2	0.1	0.84	0.10	0.46	0.07	6.1	0.6	6.2	0.6	6.2	0.6
0.8	0.9	1.9	0.2	1.4	0.2	1.2	0.1	4.7	0.5	4.5	0.5	4.9	0.5
0.9	1.0	4.5	0.5	3.6	0.4	3.2	0.3	3.4	0.4	1.8	0.2	2.8	0.3
1.0	1.1	2.8	0.3	2.6	0.3	3.0	0.3	2.0	0.2	1.1	0.1	0.7	0.1
1.1	1.2	1.5	0.2	1.06	0.12	0.88	0.10	3.1	0.3	2.3	0.2	2.4	0.3
1.2	1.3	1.8	0.2	1.4	0.2	1.4	0.2	2.2	0.2	1.7	0.2	2.0	0.2
1.3	1.4	2.2	0.2	2.4	0.3	2.5	0.3	2.4	0.3	2.1	0.2	1.9	0.2
1.4	1.5	2.3	0.2	1.7	0.2	2.1	0.2	2.9	0.3	2.5	0.3	2.2	0.2
1.5	1.6	3.4	0.4	3.4	0.4	2.5	0.3	3.3	0.3	3.5	0.4	2.8	0.3
1.6	1.7	6.5	0.7	6.4	0.7	5.3	0.5	4.5	0.5	4.0	0.4	4.1	0.4
1.7	1.8	12.3	1.2	12.8	1.3	12.6	1.3	3.1	0.3	2.2	0.2	2.7	0.3
1.8	1.9	9.9	1.0	11.2	1.1	13.3	1.3	2.8	0.3	1.9	0.2	2.0	0.2
1.9	2.0	3.8	0.4	4.1	0.4	5.6	0.6	2.4	0.3	2.0	0.2	2.5	0.3
2.0	2.1	1.7	0.2	1.9	0.2	2.1	0.2	2.4	0.3	2.3	0.3	2.4	0.3
2.1	2.2	1.8	0.2	1.8	0.2	1.7	0.2	2.4	0.3	2.6	0.3	2.2	0.2
2.2	2.3	2.0	0.2	1.8	0.2	2.1	0.2	2.6	0.3	2.4	0.3	2.7	0.3
2.3	2.4	1.7	0.2	1.6	0.2	1.8	0.2	2.7	0.3	2.2	0.2	2.3	0.2
2.4	2.5	1.4	0.2	1.14	0.13	0.96	0.11	2.4	0.3	2.3	0.2	2.0	0.2
2.5	2.6	1.10	0.12	1.02	0.11	0.96	0.11	2.1	0.2	2.1	0.2	1.7	0.2
2.6	2.7	1.40	0.15	1.29	0.14	1.1	0.1	2.4	0.3	1.9	0.2	2.1	0.2
2.7	2.8	1.9	0.2	2.1	0.2	1.8	0.2	2.2	0.2	2.4	0.3	2.5	0.3
2.8	2.9	2.3	0.2	2.1	0.2	2.4	0.3	2.3	0.3	1.9	0.2	2.2	0.2
2.9	3.0	1.8	0.2	1.8	0.2	2.2	0.2	1.8	0.2	2.0	0.2	1.8	0.2
3.0	3.1	1.25	0.14	1.20	0.14	1.7	0.2	2.2	0.3	1.8	0.2	2.2	0.2
3.1	3.2	1.27	0.14	1.11	0.13	1.0	0.1	1.9	0.2	1.9	0.2	2.2	0.3
3.2	3.3	1.31	0.15	1.03	0.12	0.93	0.11	2.0	0.2	1.7	0.2	1.8	0.2
3.3	3.4	1.20	0.14	1.15	0.13	1.15	0.13	1.8	0.2	1.4	0.2	1.7	0.2
3.4	3.5	1.18	0.13	1.03	0.12	1.07	0.12	1.8	0.2	1.6	0.2	1.7	0.2
3.5	3.6	1.26	0.14	1.08	0.12	1.27	0.15	2.6	0.3	2.8	0.3	2.4	0.3
3.6	3.7	1.12	0.13	1.11	0.13	0.97	0.11	3.9	0.4	3.9	0.4	3.7	0.4
3.7	3.8	1.03	0.12	1.06	0.12	0.99	0.12	3.9	0.4	3.7	0.4	4.0	0.4
3.8	3.9	1.22	0.14	1.02	0.12	1.21	0.14	3.1	0.3	2.6	0.3	3.6	0.4
3.9	4.0	0.96	0.11	0.99	0.12	1.04	0.12	2.0	0.2	1.7	0.2	2.7	0.3
4.0	4.5	1.01	0.13	1.09	0.14	1.03	0.13	1.3	0.2	1.22	0.16	1.22	0.16
4.5	5.0	1.15	0.14	1.17	0.15	1.17	0.15	0.92	0.12	0.92	0.12	0.92	0.13
5.0	5.5	0.75	0.11	0.86	0.12	0.82	0.12	0.63	0.10	0.60	0.09	0.81	0.12
5.5	6.0	0.56	0.08	0.53	0.08	0.59	0.9	0.70	0.11	0.60	0.10	0.80	0.12
6.0	6.5	0.70	0.11	0.68	0.10	0.55	0.9	0.40	0.07	0.50	0.09	0.59	0.10
6.5	7.0	0.86	0.13	0.88	0.13	1.06	0.16	0.60	0.10	0.39	0.07	0.60	0.10
7.0	7.5	0.64	0.11	0.65	0.11	0.74	0.12	0.25	0.06	0.25	0.06	0.23	0.06
7.5	8.0	0.37	0.07	0.44	0.08	0.47	0.09	0.16	0.05	0.19	0.05	0.29	0.07
8.0	8.5	0.56	0.11	0.52	0.10	0.49	0.10	0.15	0.05	0.11	0.04	0.15	0.05

Element →		TITANIUM						VANADIUM					
Angle →		90°		110°		130°		90°		110°		130°	
Energy Interval (MeV)		Cross Section (mb/sr)	Estimated Uncer-tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer-tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer-tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer-tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer-tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer-tainty (mb/sr)
0.2	0.3	10.3	4.2	8.2	3.0	6.9	2.1	20.8	7.6	20.8	7.1	20.4	6.2
0.3	0.4	11.1	3.0	8.4	3.1	7.9	2.5	12.8	3.0	8.4	2.4	7.9	2.4
0.4	0.5	10.4	2.1	8.8	1.8	8.8	1.8	10.3	2.1	9.4	1.9	9.0	1.8
0.5	0.6	5.5	0.6	4.7	0.5	4.6	0.5	5.6	0.6	5.0	0.5	4.6	0.5
0.6	0.7	3.1	0.3	2.9	0.3	2.6	0.3	4.0	0.4	3.8	0.4	3.3	0.3
0.7	0.8	4.7	0.5	4.6	0.5	4.3	0.4	3.1	0.3	2.9	0.3	2.7	0.3
0.8	0.9	10.7	1.1	13.7	1.4	14.8	1.5	7.2	0.7	7.5	0.8	7.3	0.7
0.9	1.0	33.5	3.4	37.2	3.7	40.8	4.1	8.1	0.8	7.0	0.7	6.7	0.7
1.0	1.1	25.8	2.6	23.8	2.4	24.4	2.4	5.2	0.5	5.5	0.6	5.2	0.5
1.1	1.2	10.1	1.0	8.8	0.9	9.4	1.0	4.7	0.5	4.8	0.5	4.8	0.5
1.2	1.3	10.7	1.1	12.5	1.3	13.7	1.4	2.9	0.3	2.5	0.3	2.6	0.3
1.3	1.4	13.7	1.4	13.4	1.4	14.8	1.5	2.5	0.3	2.6	0.3	2.6	0.3
1.4	1.5	8.5	0.9	7.5	0.8	8.1	0.8	4.4	0.5	5.1	0.5	4.6	0.5
1.5	1.6	6.1	0.6	6.4	0.6	5.8	0.6	8.8	0.9	10.9	1.1	10.6	1.1
1.6	1.7	4.8	0.5	4.3	0.4	4.0	0.4	11.1	1.1	10.8	1.1	10.5	1.1
1.7	1.8	4.1	0.4	3.8	0.4	3.4	0.3	7.8	0.8	7.2	0.7	7.2	0.7
1.8	1.9	3.6	0.4	3.0	0.3	2.9	0.3	5.7	0.6	5.2	0.5	5.0	0.5
1.9	2.0	3.0	0.3	2.7	0.3	3.0	0.3	3.4	0.4	2.8	0.3	2.9	0.3
2.0	2.1	2.9	0.3	2.9	0.3	2.7	0.3	2.1	0.2	2.3	0.2	2.1	0.2
2.1	2.2	3.3	0.3	3.0	0.3	3.4	0.3	2.2	0.2	2.0	0.2	2.0	0.2
2.2	2.3	3.6	0.4	4.0	0.4	4.0	0.4	2.0	0.2	2.0	0.2	1.9	0.2
2.3	2.4	4.4	0.5	4.4	0.5	4.3	0.4	2.0	0.2	1.9	0.2	1.9	0.2
2.4	2.5	4.3	0.4	3.6	0.4	3.7	0.4	1.7	0.2	1.5	0.2	1.8	0.2
2.5	2.6	3.1	0.3	3.0	0.3	3.1	0.3	1.4	0.2	1.6	0.2	1.7	0.2
2.6	2.7	2.8	0.3	2.7	0.3	2.6	0.3	1.4	0.1	1.5	0.2	1.3	0.1
2.7	2.8	2.5	0.3	2.6	0.3	2.4	0.3	1.4	0.1	1.30	0.14	1.3	0.1
2.8	2.9	2.6	0.3	2.5	0.3	2.7	0.3	1.5	0.2	1.5	0.2	1.7	0.2
2.9	3.0	2.1	0.2	2.4	0.2	2.3	0.2	1.6	0.2	1.7	0.2	1.6	0.2
3.0	3.1	2.0	0.2	2.1	0.2	2.1	0.2	1.7	0.2	1.9	0.2	1.6	0.2
3.1	3.2	2.0	0.2	2.0	0.2	2.0	0.2	1.7	0.2	2.0	0.2	1.7	0.2
3.2	3.3	2.3	0.3	1.8	0.2	1.9	0.2	2.0	0.2	1.9	0.2	2.1	0.2
3.3	3.4	1.7	0.2	1.8	0.2	1.9	0.2	2.1	0.2	2.2	0.2	2.3	0.3
3.4	3.5	1.8	0.2	1.6	0.2	1.9	0.2	2.1	0.2	2.3	0.2	2.3	0.3
3.5	3.6	1.9	0.2	1.5	0.2	1.9	0.2	2.0	0.2	2.0	0.2	1.9	0.2
3.6	3.7	1.7	0.2	1.5	0.2	1.8	0.2	1.6	0.2	1.8	0.2	1.8	0.2
3.7	3.8	1.7	0.2	1.7	0.2	1.7	0.2	1.5	0.2	1.5	0.2	1.4	0.2
3.8	3.9	1.28	0.15	1.5	0.2	1.4	0.2	1.3	0.2	1.5	0.2	1.5	0.2
3.9	4.0	1.25	0.15	1.3	0.2	1.5	0.2	1.22	0.1	1.26	0.14	1.23	0.14
4.0	4.5	1.25	0.16	1.22	0.15	1.3	0.2	1.10	0.14	1.19	0.15	1.15	0.15
4.5	5.0	1.16	0.15	1.09	0.15	1.02	0.13	0.98	0.14	1.12	0.14	1.03	0.13
5.0	5.5	0.99	0.14	1.03	0.14	0.92	0.13	0.83	0.12	0.87	0.12	0.75	0.11
5.5	6.0	0.96	0.14	0.98	0.15	1.03	0.15	0.69	0.12	0.77	0.11	0.74	0.11
6.0	6.5	0.87	0.13	0.88	0.14	0.98	0.15	0.73	0.11	0.65	0.10	0.67	0.10
6.5	7.0	0.81	0.12	0.73	0.13	0.70	0.11	0.64	0.10	0.56	0.09	0.62	0.10
7.0	7.5	0.62	0.11	0.54	0.11	0.54	0.10	0.46	0.08	0.38	0.07	0.41	0.07
7.5	8.0	0.46	0.09	0.43	0.08	0.38	0.08	0.31	0.06	0.35	0.07	0.30	0.06
8.0	8.5	0.30	0.06	.33	0.07	0.29	0.07	0.31	0.07	0.34	0.07	0.26	0.06

Element →		CHROMIUM						IRON					
Angle →		90°		110°		130°		90°		110°		130°	
Energy Interval (MeV)		Cross Section (mb/sr)	Estimated Uncer- tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer- tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer- tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer- tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer- tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer- tainty (mb/sr)
0.2	0.3							10.4	4.5	10.6	3.8	9.2	2.9
0.3	0.4							11.7	4.7	11.3	3.5	9.9	3.0
0.4	0.5	10.1	1.7	7.7	1.6	7.6	0.16	10.2	2.7	11.3	2.3	11.4	2.5
0.5	0.6	9.8	1.0	9.3	0.9	9.1	0.9	6.3	0.7	5.7	0.5	5.5	0.6
0.6	0.7	10.7	1.1	9.5	1.0	9.3	0.9	4.3	0.5	3.8	0.4	3.4	0.4
0.7	0.8	11.1	1.1	11.1	1.1	10.3	1.0	15.3	1.5	15.8	1.6	17.4	1.7
0.8	0.9	9.9	1.0	9.5	1.0	9.6	1.0	38.6	3.7	39.1	3.9	42.2	4.2
0.9	1.0	13.4	1.4	13.0	1.3	14.5	1.5	14.9	1.5	14.0	1.4	15.3	1.5
1.0	1.1	6.1	0.6	5.5	0.6	6.8	0.7	7.4	0.7	7.4	0.8	7.6	0.8
1.1	1.2	5.9	0.6	4.9	0.5	4.9	0.5	9.8	1.0	10.3	1.1	11.1	1.1
1.2	1.3	11.3	1.1	10.0	1.0	9.6	1.0	19.8	2.0	20.2	2.0	22.7	2.3
1.3	1.4	22.5	2.3	22.6	2.3	22.2	2.2	13.3	1.3	13.3	1.3	14.9	1.5
1.4	1.5	31.9	3.2	33.5	3.4	37.2	3.7	5.8	0.6	5.5	0.6	5.7	0.6
1.5	1.6	16.1	1.6	16.5	1.7	21.2	2.1	3.4	0.4	3.2	0.3	3.4	0.4
1.6	1.7	6.4	0.7	5.8	0.6	7.7	0.8	3.9	0.4	3.8	0.4	4.4	0.5
1.7	1.8	4.2	0.4	3.8	0.4	4.6	0.5	5.0	0.5	4.7	0.5	5.1	0.5
1.8	1.9	3.2	0.3	2.8	0.3	3.0	0.3	4.9	0.5	4.9	0.5	5.1	0.5
1.9	2.0	3.0	0.3	2.5	0.3	2.7	0.3	3.9	0.4	3.5	0.4	3.9	0.4
2.0	2.1	2.8	0.3	2.5	0.3	3.1	0.3	3.2	0.3	3.2	0.3	3.4	0.5
2.1	2.2	2.8	0.3	2.2	0.2	2.4	0.3	3.2	0.3	3.0	0.3	3.1	0.4
2.2	2.3	2.6	0.3	2.4	0.3	3.0	0.3	2.8	0.3	2.6	0.3	3.0	0.3
2.3	2.4	3.1	0.3	2.8	0.3	3.0	0.3	2.8	0.3	2.4	0.3	2.4	0.3
2.4	2.5	2.6	0.3	2.3	0.2	2.3	0.2	2.7	0.3	2.7	0.3	2.9	0.3
2.5	2.6	2.3	0.2	2.2	0.2	2.2	0.2	3.4	0.4	3.4	0.4	3.1	0.3
2.6	2.7	2.2	0.2	1.9	0.2	2.1	0.2	3.5	0.4	3.1	0.3	3.1	0.3
2.7	2.8	2.0	0.2	1.9	0.2	2.1	0.2	2.6	0.3	2.5	0.3	2.5	0.3
2.8	2.9	2.1	0.2	1.5	0.2	2.2	0.2	2.1	0.2	2.0	0.2	2.2	0.2
2.9	3.0	2.1	0.2	1.8	0.2	2.0	0.2	2.2	0.2	2.3	0.3	2.2	0.2
3.0	3.1	2.8	0.3	2.3	0.3	2.8	0.3	2.4	0.3	2.2	0.2	2.2	0.2
3.1	3.2	2.9	0.3	2.6	0.3	2.8	0.3	2.0	0.2	2.3	0.2	2.4	0.3
3.2	3.3	2.5	0.3	2.2	0.2	2.4	.03	2.3	0.3	2.1	0.2	2.0	0.2
3.3	3.4	2.1	0.2	2.0	0.2	2.1	0.2	1.9	0.2	2.1	0.2	2.2	0.3
3.4	3.5	1.9	0.2	1.9	0.2	2.0	0.2	2.0	0.2	2.2	0.3	2.5	0.3
3.5	3.6	1.8	0.2	1.9	0.2	1.7	0.2	2.2	0.3	2.1	0.2	1.9	0.2
3.6	3.7	1.7	0.2	1.7	0.2	1.7	0.2	2.0	0.2	1.7	0.2	1.7	0.2
3.7	3.8	1.7	0.2	1.6	0.2	1.4	0.2	1.7	0.2	1.6	0.2	1.34	0.16
3.8	3.9	1.5	0.2	1.5	0.2	1.8	0.2	1.6	0.2	1.4	0.2	1.20	0.15
3.9	4.0	1.3	0.2	1.28	0.15	1.4	0.2	1.14	0.15	1.29	0.16	1.34	0.16
4.0	4.5	1.5	0.2	1.4	0.2	1.4	0.2	1.28	0.17	1.28	0.17	1.19	0.16
4.5	5.0	1.3	0.2	1.16	0.15	1.3	0.7	1.07	0.15	1.12	0.15	0.94	0.13
5.0	5.5	1.25	0.18	1.10	0.16	1.18	0.17	0.92	0.14	1.03	0.16	0.91	0.14
5.5	6.0	1.12	0.16	1.07	0.15	1.16	0.17	0.95	0.15	1.08	0.16	0.98	0.15
6.0	6.5	1.01	0.16	1.01	0.15	1.00	0.16	1.03	0.17	0.99	0.16	1.08	0.17
6.5	7.0	0.91	0.14	0.86	0.13	0.84	0.13	0.90	0.15	0.88	0.15	0.76	0.12
7.0	7.5	0.83	0.15	0.73	0.13	0.69	0.13	0.61	0.12	0.59	0.12	0.60	0.11
7.5	8.0	0.72	0.13	0.72	0.13	0.76	0.14	0.63	0.12	0.57	0.12	0.54	0.11
8.0	8.5	0.51	0.11	0.56	0.11	0.58	0.12	0.40	0.09	0.41	0.10	0.34	0.08

Element →		COPPER		NIOBIUM						MOLYBDENUM					
Angle →		110°		90°		110°		130°		90°		110°		130°	
Energy Interval (MeV)		Cross Section (mb/sr)	Estimated Uncertainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncertainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncertainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncertainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncertainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncertainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncertainty (mb/sr)
0.2	0.3	15.2	6.1	25.	9.	23.	8.	23.	7.	27.	8.	26.	8.	22.	8.
0.3	0.4	16.6	6.2	30.	9.	26.	8.	29.	8.	25.	7.	21.	6.	22.	8.
0.4	0.5	15.7	3.1	31.	6.	28.	6.	33.	6.	31.	6.	29.	5.	33.	7.
0.5	0.6	11.3	1.1	18.9	1.9	17.4	1.8	19.	2.	27.	3.	26.	3.	27.	3.
0.6	0.7	11.4	1.2	12.7	1.3	12.1	1.2	13.4	1.4	35.	4.	36.	4.	40.	4.
0.7	0.8	8.2	0.8	15.9	1.6	14.0	1.4	16.1	1.6	52.	5.	55.	5.	61.	6.
0.8	0.9	10.8	1.1	15.1	1.5	14.5	1.5	17.0	1.7	43.	4.	45.	5.	51.	5.
0.9	1.0	19.8	2.0	24.0	2.4	21.	2.	23.	2.3	27.	3.	24.	2.	25.	3.
1.0	1.1	16.8	1.7	15.6	1.7	14.6	1.5	15.0	1.5	21.	2.	21.	2.	23.	2.
1.1	1.2	21.7	2.2	10.8	1.1	10.0	1.0	11.3	1.1	17.6	1.8	17.	2.	19.	2.
1.2	1.3	16.5	1.7	8.8	0.9	7.5	0.8	7.7	0.8	13.2	1.3	11.9	1.2	12.3	1.3
1.3	1.4	13.0	1.3	8.6	0.9	7.8	0.8	8.0	0.8	10.6	1.1	9.9	1.0	10.8	1.1
1.4	1.5	10.4	1.0	8.4	0.9	7.6	0.8	9.0	0.9	12.6	1.3	11.9	1.2	14.3	1.5
1.5	1.6	7.2	0.7	8.6	0.9	7.6	0.8	7.7	0.8	13.4	1.4	12.9	1.3	14.6	1.5
1.6	1.7	5.6	0.6	6.7	0.7	6.4	0.7	7.4	0.8	9.5	1.0	9.1	0.9	10.8	1.1
1.7	1.8	5.1	0.5	6.0	0.6	4.8	0.5	5.7	0.6	7.2	0.7	7.0	0.7	7.3	0.8
1.8	1.9	5.1	0.5	5.9	0.6	6.1	0.6	6.2	0.6	6.1	0.6	6.4	0.7	6.7	0.7
1.9	2.0	4.4	0.5	6.7	0.7	5.4	0.6	6.1	0.6	6.1	0.6	5.7	0.6	5.8	0.6
2.0	2.1	3.8	0.4	6.4	0.7	5.9	0.6	7.0	0.7	5.5	0.6	4.4	0.5	5.2	0.5
2.1	2.2	3.0	0.3	6.8	0.7	6.6	0.7	7.1	0.7	4.6	0.5	4.3	0.5	4.5	0.5
2.2	2.3	2.5	0.3	5.5	0.6	5.8	0.6	5.9	0.6	4.2	0.4	3.9	0.4	3.3	0.4
2.3	2.4	2.0	0.2	4.9	0.5	4.5	0.5	5.4	0.6	3.8	0.4	3.3	0.4	3.7	0.4
2.4	2.5	2.0	0.2	3.9	0.4	2.9	0.3	3.5	0.4	3.0	0.3	3.0	0.3	2.7	0.3
2.5	2.6	1.9	0.2	2.9	0.3	2.9	0.3	3.5	0.4	3.3	0.4	3.0	0.3	3.5	0.4
2.6	2.7	1.9	0.2	3.0	0.3	2.7	0.3	3.1	0.3	3.1	0.3	2.6	0.3	3.4	0.4
2.7	2.8	1.8	0.2	2.9	0.3	2.2	0.2	2.8	0.3	2.7	0.3	2.2	0.2	2.7	0.3
2.8	2.9	1.8	0.2	2.3	0.3	2.1	0.2	2.7	0.3	2.3	0.3	2.2	0.2	2.6	0.3
2.9	3.0	1.5	0.2	2.4	0.3	2.0	0.2	2.4	0.3	2.1	0.2	1.9	0.2	1.7	0.2
3.0	3.1	1.5	0.2	2.7	0.3	1.7	0.2	2.0	0.2	2.5	0.3	1.9	0.2	1.9	0.2
3.1	3.2	1.8	0.2	1.3	0.2	1.5	0.2	1.4	0.2	1.6	0.2	1.6	0.2	1.29	0.16
3.2	3.3	1.4	0.2	1.6	0.2	1.8	0.2	1.6	0.2	1.7	0.2	1.8	0.2	2.3	0.3
3.3	3.4	1.6	0.2	1.6	0.2	1.4	0.2	1.7	0.2	1.7	0.2	1.28	0.16	1.19	0.15
3.4	3.5	1.4	0.2	1.8	0.2	0.95	0.12	.15	.02	1.6	0.2	1.29	0.16	1.8	0.2
3.5	3.6	1.7	0.2	1.5	0.2	1.16	0.14	1.27	0.16	1.29	0.16	1.14	0.15	1.5	0.2
3.6	3.7	1.11	0.13	1.23	0.16	1.13	0.14	1.12	0.14	0.99	0.13	1.15	0.15	1.18	0.16
3.7	3.8	1.17	0.14	1.08	0.15	0.97	0.12	1.14	0.15	1.20	0.16	1.01	0.13	0.74	0.11
3.8	3.9	0.79	0.10	0.82	0.12	1.24	0.15	0.80	0.11	1.29	0.17	0.82	0.12	0.97	0.13
3.9	4.0	1.15	0.14	0.40	0.07	1.14	0.14	1.04	0.14	0.76	0.11	0.96	0.13	0.61	0.10
4.0	4.5	0.92	0.12	0.86	0.13	0.70	0.10	0.83	0.13	0.97	0.14	0.73	0.11	0.92	0.14
4.5	5.0	0.75	0.10	0.48	0.09	0.41	0.07	0.30	0.07	0.50	0.09	0.52	0.09	0.71	0.12
5.0	5.5	0.70	0.10	0.22	0.08	0.32	0.07	0.38	0.08	0.25	0.07	0.25	0.06	0.31	0.09
5.5	6.0	0.58	0.09	0.14	0.06	0.17	0.05	0.28	0.08	0.18	0.07	0.42	0.08	0.37	0.10
6.0	6.5	0.48	0.08	0.11	0.08	0.22	0.07	0.12	0.08	0.34	0.10	0.31	0.09	0.07	0.09
6.5	7.0	0.25	0.05	0.18	0.08	0.14	0.06	0.24	0.08	0.40	0.09	0.13	0.08	0.16	0.09
7.0	7.5	0.31	0.06	0.03	0.07	0.05	0.05	0.09	0.07	0.17	0.07	0.06	0.06	0.23	0.08
7.5	8.0	0.18	0.05	0.11	0.07	0.08	0.05	0.07	0.03	0.11	0.06	0.07	0.05	0.12	0.08
8.0	8.5	0.14	0.04	0.05	0.05	0.08	0.04	0.06	0.05	0.08	0.06	0.11	0.06	0.07	0.07

Element →		THORIUM				^{238}U			
Angle →		90°		130°		90°		130°	
Energy Interval (MeV)		Cross Section (mb/sr)	Estimated Uncer- tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer- tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer- tainty (mb/sr)	Cross Section (mb/sr)	Estimated Uncer- tainty (mb/sr)
0.2	0.3								
0.3	0.4								
0.4	0.5	83.	18.	78.	15.	108.	22.	111.	25.
0.5	0.6	63.	6.	63.	6.	104.	10.	105.	11.
0.6	0.7	44.	4.	41.	4.	72.	7.	80.	9.
0.7	0.8	43.	4.	35.	4.	56.	6.	60.	7.
0.8	0.9	30.	3.	31.	3.	47.	5.	51.	6.
0.9	1.0	30.	3.	27.	3.	43.	4.	45.	5.
1.0	1.1	30.	3.	26.	3.	38.	4.	41.	4.
1.1	1.2	25.	3.	25.	3.	32.	3.	34.	4.
1.2	1.3	23.4	2.4	22.5	2.3	28.	3.	31.	3.
1.3	1.4	19.5	2.0	20.1	2.1	25.	3.	26.	3.
1.4	1.5	23.8	2.4	22.5	2.3	23.	2.	23.3	2.5
1.5	1.6	21.0	2.2	20.1	2.1	19.6	2.0	20.6	2.2
1.6	1.7	20.8	2.1	20.9	2.2	20.6	2.1	21.2	2.3
1.7	1.8	20.4	2.1	19.0	2.0	20.5	2.1	20.0	2.0
1.8	1.9	19.1	2.0	18.7	1.9	18.2	1.9	18.0	1.8
1.9	2.0	18.1	1.9	17.9	1.9	17.2	1.8	16.9	1.7
2.0	2.1	13.4	1.4	15.2	1.6	13.7	1.4	14.1	1.5
2.1	2.2	13.6	1.4	11.6	1.2	12.5	1.3	13.0	1.4
2.2	2.3	12.2	1.3	11.6	1.2	12.5	1.3	11.6	1.1
2.3	2.4	10.6	1.1	10.0	1.1	11.2	1.2	10.7	1.1
2.4	2.5	9.9	1.1	9.1	1.0	9.8	1.0	10.0	1.1
2.5	2.6	8.3	0.9	5.8	0.6	8.4	0.9	8.3	0.9
2.6	2.7	7.0	0.8	6.3	0.7	7.2	0.8	7.1	0.8
2.7	2.8	7.0	0.8	3.5	0.4	6.2	0.7	6.3	0.7
2.8	2.9	4.9	0.6	3.9	0.5	6.1	0.7	5.9	0.6
2.9	3.0	4.0	0.5	4.6	0.5	4.8	0.5	5.3	0.6
3.0	3.1	4.5	0.5	5.6	0.7	4.7	0.5	4.5	0.5
3.1	3.2	4.2	0.5	3.7	0.5	4.4	0.5	4.1	0.5
3.2	3.3	4.2	0.5	1.8	0.3	3.3	0.4	3.0	0.3
3.3	3.4	2.7	0.3	2.7	0.4	2.9	0.3	2.7	0.3
3.4	3.5	2.7	0.3	2.4	0.3	3.4	0.4	3.1	0.3
3.5	3.6	3.1	0.4	2.2	0.3	2.8	0.3	2.6	0.3
3.6	3.7	2.4	0.3	1.3	0.2	2.6	0.3	2.3	0.3
3.7	3.8	1.3	0.2	0.74	0.14	2.4	0.3	2.2	0.3
3.8	3.9	1.3	0.2	1.43	0.24	1.26	0.18	1.6	0.2
3.9	4.0	0.30	0.1	0.66	0.20	0.85	0.14	0.88	0.15
4.0	4.5	1.1	0.2	1.21	0.23	1.14	0.18	0.85	0.13
4.5	5.0	0.84	0.17	0.36	0.15	0.89	0.15	0.70	0.13
5.0	5.5	0.27	0.14	0.28	0.17	0.29	0.11	0.35	0.12
5.5	6.0	0.67	0.17	0.71	0.21	0.42	0.11	0.37	0.12
6.0	6.5	0.54	0.20	0.43	0.23	0.33	0.14	0.20	0.11
6.5	7.0	0.32	0.17	0.01	0.22	0.54	0.14	0.30	0.16
7.0	7.5	0.27	0.14	0.09	0.16	0.23	0.11	0.15	0.13
7.5	8.0	0.09	0.13	0.25	0.18	0.11	0.10	0.17	0.11
8.0	8.5	0.14	0.13	0.07	0.19	0.04	0.09	0.18	0.12

TABLE II

GAMMA-RAY PRODUCTION CROSS SECTIONS FOR BERYLLIUM

Gamma-Ray Energy Interval (MeV)	90° Differential Cross Section (mb/sr)
0.5 - 1.0	0.01 ± 0.06
1.0 - 1.5	-0.07 ± 0.05
1.5 - 2.0	0.00 ± 0.04
2.0 - 2.5	0.01 ± 0.03
2.5 - 3.0	-0.05 ± 0.03
3.0 - 3.5	0.00 ± 0.03
3.5 - 4.0	0.00 ± 0.02
4.0 - 4.5	-0.01 ± 0.02
4.5 - 5.0	-0.01 ± 0.02

TABLE III

DIFFERENTIAL GAMMA-RAY PRODUCTION CROSS SECTIONS FOR PROMINENT GAMMA RAYS

Element	Gamma-Ray Energy (MeV)	σ (θ) (mb/sr) θ = 90°	θ = 110°	θ = 130°
Carbon	4.4	10.7 ± 1.5	13.6 ± 1.9	18.1 ± 2.5
Magnesium	1.37	22.0 ± 2.6	24.5 ± 2.9	27.6 ± 3.3
Aluminum	0.84 + 1.01	13.8 ± 1.8	11.5 ± 1.3	12.7 ± 1.7
	1.8	11.4 ± 1.5	10.7 ± 1.3	11.4 ± 1.5
	2.2	9.8 ± 1.3	8.8 ± 1.1	8.4 ± 1.1
	3.0	6.3 ± 0.8	6.5 ± 0.8	6.6 ± 0.8
Silicon	1.78	27.5 ± 3.3	29.9 ± 3.6	30.9 ± 3.7
Titanium	0.99	64.8 ± 7.7	70.0 ± 8.4	75.9 ± 9.1
	1.31	19.0 ± 2.3	22.2 ± 2.7	23.2 ± 2.8
Vanadium	1.66	18.2 ± 2.3	20.6 ± 2.7	21.2 ± 2.8
Chromium	1.33 + 1.43	69.8 ± 8.1	74.6 ± 8.6	79.8 ± 9.3
Iron	0.85	51.3 ± 6.2	52.7 ± 6.3	59.5 ± 7.1
	1.24	28.6 ± 3.4	29.8 ± 3.6	33.7 ± 4.0

TABLE IV

ENERGY-WEIGHTED INTEGRAL CROSS SECTIONS

$4\pi \int E_\gamma \sigma(\theta, E_\gamma) dE_\gamma$ (MeV-barn)

Element	90°	110°	130°
Beryllium	0.05		
Carbon	0.59 ± 0.08	0.82 ± 0.11	1.07 ± 0.15
Magnesium	3.9 ± 0.4	3.9 ± 0.4	4.1 ± 0.4
Aluminum	4.3 ± 0.4	4.0 ± 0.4	4.1 ± 0.4
Silicon	4.7 ± 0.5	4.7 ± 0.5	4.8 ± 0.5
Calcium	4.4 ± 0.4	4.0 ± 0.4	4.5 ± 0.4
Titanium	6.7 ± 0.7	6.6 ± 0.6	6.7 ± 0.6
Vanadium	5.0 ± 0.5	5.1 ± 0.5	4.9 ± 0.5
Chromium	7.7 ± 0.7	7.2 ± 0.7	7.7 ± 0.7
Iron	6.5 ± 0.6	6.8 ± 0.7	6.8 ± 0.7
Copper		5.4 ± 0.5	
Molybdenum	6.8 ± 0.7	6.4 ± 0.7	7.0 ± 0.7
Niobium	5.3 ± 0.5	4.9 ± 0.5	5.3 ± 0.5
Thorium	11.8 ± 1.2		12.8 ± 1.3
^{238}U	13.2 ± 1.3		12.8 ± 1.3

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