11. USEFUL NUCLEAR DATA FOR NDA

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1. Principal NDA Gamma-Ray Signatures

Isotope	Energy keV	Activity γ/g-s	Mean Free Path High-Z, ρ	Low-Z, ρ
^{234}U	120.9	9.35×10^{4}	0.23	69
^{235}U	143.8	8.40×10^{3}	0.36	73
	185.7	4.32×10^{4}	0.69	80
^{238}U	766.4	2.57×10^{1}	10.0	139
	1001.0	7.34×10^{1}	13.3	159
^{238}Pu	152.7	5.90×10^{6}	0.40	75
	766.4	1.387×10^{5}	9.5	139
^{239}Pu	129.3	1.436×10^{5}	0.27	71
	413.7	3.416×10^{4}	3.7	106
^{240}Pu	45.2	3.80×10^{6}	0.07	25
	160.3	3.37×10^{4}	0.45	76
	642.5	1.044×10^{3}	7.4	127
^{241}Pu	148.6	7.15×10^{6}	0.37	74
	208.0	2.041×10^{7}	0.86	83
^{241}Am	59.5	4.54×10^{10}	0.14	38
	125.3	5.16×10^{6}	0.26	70

2. Major Gamma-Rays from Common Calibration Sources

Isotope	Half-Life	Energy (keV)	Remarks
^{241}Am	433 y	59.54	Many much weaker others
^{137}Cs	29.9 y	661.64	Mono-energetic source
^{133}Ba	10.9 y	81.0, 276.40, 302.85, 356.00, 383.85	Other weaker lines
^{60}Co	5.3 y	1173.23, 1332.51	
^{22}Na	2.8 y	511.01	Annihilation radiation
		1274.51	
^{55}Fe	2.7 y	5.9, 6.5	Mn K x rays for low energy cal
^{109}Cd	1.2 y	88.04	Mono-energetic source
^{54}Mn	312 d	834.8	Mono-energetic source
^{65}Zn	244 d	511.01	Annihilation radiation
		1115.5	
^{57}Co	271 d	122.06, 136.47	
^{75}Se	120 d	121.12, 136.00, 264.65, 279.53, 400.65	

3. Major K x rays of uranium and plutonium

X Ray	Levels (Final-Initial)	Energy (keV) Uranium	Energy (keV) Plutonium	Intensity Uranium	Intensity Plutonium
$K_{\alpha 2}$	$K - L_2$	94.67	99.55	61.9	62.5
$K_{\alpha 1}$	$K - L_3$	98.44	103.76	100	100
$K_{\beta 1}$	$K - M_3$	111.30	117.26	22.0	22.2
$K_{\beta 2}$	$K - N_{2\text{-}5}$	114.5	120.6	12.3	12.5
$K_{\beta 3}$	$K - M_2$	110.41	116.27	11.6	11.7

4. Gamma Rays of ^{238}Pu

	Energy	Intensity	Error	Energy	Intensity	Error
	43.447	3.93×10^{-4}	0.3	200.98	9.56x10-6	0.5
U $K_{\alpha 2}$	94.658	1.05x10-6	1.4	705.6	5.03x10-10	40.0
U $K_{\alpha 1}$	98.442	1.69x10-6	1.0	708.4	5.00x10-9	10.0
	99.846	7.24x10-5	0.2	742.82	5.17x10-8	1.0
$K_{\beta 3}$	110.421	2.00x10-7		766.41	2.19x10-7	0.6
$K_{\beta 1}$	111.300	3.90x10-7		786.3	3.28x10-8	1.0
$K_{\beta 4}$	114.333			805.4	1.29x10-9	15.0
$K_{\beta 2}$	114.561	1.58x10-7		808.2	8.00x10-9	3.0
$K_{\beta x}$	115.400			851.7	1.29x10-8	2.0
	152.680	9.56x10-6	0.5			

R. Gunnink, J. E. Evans, and A. L. Prindle, “A Reevaluation of the Gamma-Ray Energies and Absolute Branching Intensities of ^{237}U, $^{238, 239, 240, 241}$Pu, and ^{241}Am,” Lawrence Livermore Laboratory report UCRL-52139, October 1976.

5. Gamma Rays of ^{239}Pu

	Energy	Intensity	Error
	30.040	2.17x10-6	3.0
	38.664	1.05x10-4	1.0
	40.410	1.62x10-6	10.0
	42.060	1.65x10-6	3.0
	46.210	7.37x10-6	10.0
	46.690	5.80x10-7	6.0
	51.629	2.70x10-4	0.2
	54.040	2.00x10-6	1.4
	56.838	1.13x10-5	1.0
	65.741	4.53x10-7	4.0
	67.670	1.61x10-6	2.0
	68.720	5.10x10-6	1.0
	77.607	3.90x10-6	0.7
	78.420	1.52x10-6	1.4
	89.590		
U $K_{\alpha 2}$	94.660	4.22x10-5	0.3
	96.130	2.23x10-7	20.0
	98.441	6.76x10-5	0.3
U $K_{\alpha 1}$	98.780	1.22x10-5	3.0
	103.020	2.17x10-6	1.6
	110.421	7.95x10-6	0.8
	111.300	1.55x10-5	0.6
	111.890	3.07x10-7	10.0
$K_{\beta 2}$	114.333	6.28x10-6	2
$K_{\beta 4}$	114.561		
$K_{\beta x}$	115.380	6.49x10-6	1.5
	116.260	5.97x10-6	1.5
	119.708	3.00x10-7	2

Energy	Intensity	Error
123.62	1.97x10-7	6.0
124.51	6.13x10-7	3.0
125.21	7.11x10-7	2.0
129.294	6.26x10-5	0.2
141.657	3.20x10-7	2.0
143.35	1.73x10-7	4.0
144.211	2.83x10-6	0.6
146.077	1.190x10-5	0.6
158.1	1.00x10-8	10.0
160.16	6.20x10-8	20.0
161.45	1.20x10-6	0.4
167.81	2.93x10-8	25.0
171.344	1.105x10-6	0.8
173.7	3.05x10-8	25.0
179.19	6.58x10-7	1.0
184.55	2.12x10-8	30.0
188.23	1.09x10-7	10.0
189.32	8.30x10-7	2.0
193	8.87x10-8	10.0
195.66	1.064x10-6	0.5
196.87	3.70x10-8	12.0
203.537	5.60x10-6	0.2
225.37	1.56x10-7	4.0
227		
237.38	1.44x10-7	4.0
242.08	7.31x10-8	7.0
243.38	2.53x10-7	2.0
244.92	5.10x10-8	10.0
248.95	7.24x10-8	10.0
255.38	8.05x10-7	2.0
263.93	2.61x10-7	3.0

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5. Gamma Rays of ^{239}Pu

Energy	Intensity	Error	Energy	Intensity	Error
265.7	1.58x10-8	25	428.4	1.00x10-8	10
281.2	2.15x10-8	15	430.08	4.30x10-8	3
285.3	1.91x10-8	20	445.72	8.70x10-8	2
297.49	5.02x10-7	2	446.82	8.45x10-9	15
402.87	5.13x10-8	8	451.474	1.89x10-6	0.3
307.85	5.47x10-8	7	457.61	1.49x10-8	1
311.74	2.58x10-7	2	461.25	2.27x10-8	1
316.41	1.36x10-7	3	463.9	2.78x10-9	10
319.68	4.80x10-8	10	473.9	5.36x10-10	50
320.88	5.36x10-7	1	481.54	4.60x10-8	0.6
323.81	5.42x10-7	1	487.06	2.65x10-9	8
332.838	5.060x10-6	0.2	493.08	8.68x10-9	3
336.107	1.134x10-6	0.3	497	4.61x10-10	50
341.51	6.62x10-7	0.4	526.4	5.72x10-10	30
345.014	5.592x10-6	0.2	538.8	3.05x10-9	6
350.8	1.75x10-8	20	550.5	4.22x10-9	6
354	7.31x10-9	40	557.3	3.82x10-10	50
361.89	1.22x10-7	5	579.4	8.58x10-10	20
367.05	8.65x10-7	0.3	582.89	6.15x10-9	3
368.55	9.03x10-7	0.3	586.3	1.53x10-9	10
375.042	1.570x10-5	0.1	596	3.90x10-10	50
380.166	3.051x10-6	0.2	597.99	1.67x10-8	3
382.751	2.587x10-6	0.2	599.6	1.99x10-9	12
392.53	5.527x10-6	0.2	606.9	1.20x10-9	10
393.14			608.9	1.16x10-9	10
399.51	6.10x10-8	4	612.83	9.46x10-9	5
406.9	6.35x10-9	40	617.1	1.34x10-8	5
411.15	6.8x10-8	50	618.28	2.04x10-8	3
413.712	1.489x10-5	0.1	619.21	1.21x10-8	6
422.586	1.193x10-6	0.4	624.78	4.57x10-9	4
426.68	2.328x10-7	1.5	633.15	2.53x10-8	1.2

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5. Gamma Rays of ^{239}Pu

Energy	Intensity	Error	Energy	Intensity	Error
640.075	8.20x10-8	0.6	786.9	8.61x10-10	10
645.969	1.489x10-7	0.4	788.5	3.52x10-10	20
649.321	7.12x10-9	7	792.9	2.00x10-10	20
650.529	2.70x10-9	15	796.9	1.49x10-10	20
652.074	6.55x10-8	0.6	803.2	6.37x10-10	7
654.88	2.25x10-8	1.2	805.9	2.76x10-10	15
658.929	9.69x10-8	0.7	808.4	1.21x10-9	5
664.587	1.657x10-8	1.6	813.7	4.51x10-10	10
668.2	3.93x10-10	30	816	2.41x10-10	15
670.8	8.60x10-11	50	821.3	5.52x10-10	10
674.05	5.15x10-9	3	826.8	1.80x10-10	30
685.97	8.73x10-9	3	828.9	1.33x10-9	6
688.1	1.11x10-9	10	832.5	2.96x10-10	12
690.81	5.57x10-9	5	837.3	1.91x10-10	20
693.2	5.00x10-10	30	840.4	4.81x10-10	10
697.8	7.35x10-10	20	844	1.34x10-9	5
699.6	7.91x10-10	20	879.2	3.61x10-10	10
701.1	5.12x10-9	3	891	7.93x10-10	10
703.73	3.95x10-8	0.4	895.4	7.49x10-11	30
712.96	5.16x10-10	12	898.1	1.75x10-10	20
714.71	7.85x10-10	10	905.5	7.51x10-11	30
717.72	2.74x10-8	0.4	911.7	1.37x10-10	25
720.3	4.85x10-10	10	918.7	8.44x10-11	35
727.9	1.24x10-9	5	931.9	1.27x10-10	35
736.5	3.00x10-10	30	940.3	4.96x10-10	10
742.7	3.75x10-10	30	955.6	3.09x10-10	10
747.4	8.07x10-10	20	957.6	3.20x10-10	10
756.4	3.47x10-8	0.4	979.7	2.76x10-10	15
763.7	3.24x10-10	50	982.7	1.08x10-10	25
766.6	2.75x10-9	5	986.9	2.09x10-10	20
777.1	2.78x10-10	25	992.7	2.66x10-10	15
779.61	1.36x10-9	6	1005.7	1.78x10-10	15
			1009.4	1.40x10-10	20

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6. Gamma Rays of ^{240}Pu

	Energy	Intensity	Error		Energy	Intensity	Error
	45.232	4.53x10-4	0.2	$K_{\beta 4}$	114.333	9.32x10-8	
U $K_{\alpha 2}$	94.658	6.36x10-7	5	$K_{\beta 2}$	114.561		
U $K_{\alpha 1}$	98.422	1.02x10-6	5	$K_{\beta x}$	115.4		
	104.224	6.98x10-5	0.4		160.28	4.02x10-6	0.7
$K_{\beta 3}$	110.421	1.18x10-7			642.48	1.245x10-7	1
$K_{\beta 1}$	111.3	2.30x10-7			687.7	3.55x10-8	1.5

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7. Gamma Rays of ^{241}Pu

	Energy	Intensity	Error		Energy	Intensity	Error
	44.2	4.18x10-8		$K_{\beta 3}$	110.421	5.90x10-7	1.5
	44.86	8.36x10-9		$K_{\beta 1}$	111.3	1.09x10-6	1
	56.32	2.50x10-8		$K_{\beta 5}$	111.89	3.31x10-8	
	56.76	9.75x10-9		$K_{\beta 2}$	114.34	1.60x10-7	
	71.6	2.86x10-8	10	$K_{\beta 4}$	114.56	3.64x10-7	
	77.1	2.22x10-8	3	$K_{\beta x}$	115.4	1.34x10-7	
U $K_{\alpha 2}$	94.658	3.03x10-6	0.5		121.2	6.85x10-9	
U $K_{\alpha 1}$	98.442	4.85x10-6	0.5		148.567	1.87x10-6	0.3
	103.68	5.90x10-7	0.6		159.955	6.74x10-8	

8. Gamma Rays of ^{237}U

	Energy	Intensity	Error		Energy	Intensity	Error
	26.34	2.43x10-2	0.5	$K_{\beta x}$	118.43	8.23x10-3	
	33.19	1.30x10-3	1.6		164.58	1.84x10-2	0.5
	43.43	2.40x10-4	7		208.000	2.17x10-1	0.2
	51.005	3.40x10-3	2		221.73	2.12x10-4	2
	59.536	3.45x10-1	0.2		234.24	2.05x10-4	2
	64.832	1.30x10-2	0.5		267.54	7.40x10-3	0.5
$K_{\alpha 2}$	97.071	1.58x10-1	0.4		332.354	1.21x10-2	0.3
$K_{\alpha 1}$	101.066	2.52x10-1	0.3		335.405	9.70x10-4	1
$K_{\beta 3}$	113.3	3.04x10-2	0.5		337.75	8.90x10-5	5
$K_{\beta 1}$	114.23	5.85x10-2	0.3		340.45	1.65x10-5	20
$K_{\beta 5}$	114.95	3.35x10-3	10		368.605	4.29x10-4	2
$K_{\beta 2}$	117.34	7.90x10-3			370.934	1.103x10-3	1.4
$K_{\beta 4}$	117.58	1.56x10-2					

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9. Gamma Rays of ^{241}Am

Energy	Intensity	Error	Energy	Intensity	Error
26.344	2.45x10-2	0.1	203.87	2.90x10-8	6
32.183	1.74x10-4	1	208.000	7.91x10-6	0.5
33.197	1.26x10-3	0.3	221.73	4.24x10-7	1
59.536	0.359		233.87	4.64x10-8	6
97.072	1.18x10-5	2	234.33	6.57x10-9	40
98.951	2.03x10-4	0.5	246.7	2.42x10-8	10
101.066	1.90x10-5	1.4	260.9	1.21x10-8	15
102.966	1.95x10-4	0.5	264.85	9.04x10-8	4
			267.54	2.63x10-7	2
113.300	2.37x10-6		271.58	6.37x10-9	30
			275.68	6.57x10-8	5
114.23	4.72x10-6		291.21	3.08x10-8	10
			292.78	1.42x10-7	3
114.95			304.23	1.01x10-8	20
117.34	2.30x10-6		322.503	1.518x10-6	0.6
			332.354	1.490x10-6	0.3
117.58			335.405	4.960x10-6	0.3
118.43			337.72	4.29x10-8	5
			350.56	1.19x10-8	20
122.994	1.00x10-5	0.8	358.36	1.20x10-8	20
125.292	4.09x10-5	0.5	368.605	2.17x10-6	0.3
139.530	5.34x10-8	20.0	370.934	5.23x10-7	0.8
146.557	4.61x10-6	1	376.595	1.383x10-6	0.7
150.11	7.40x10-7	2	383.74	2.82x10-7	1.5
169.06	1.4x10-8	30	390.54	5.90x10-8	4
164.580	6.67x10-7	3.0	406.37	1.45x10-8	15
165.93	2.32x10-7	4	419.24	2.87x10-7	2
169.557	1.73x10-6	1	426.39	2.46x10-7	2
175.09	1.82x10-7	5	429.84	1.15x10-8	20
190.4	2.19x10-8		442.75	3.52x10-8	7
191.9	2.16x10-7	4	452.21	2.40x10-8	10

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Gamma Rays of ^{241}Am

Energy	Intensity	Error	Energy	Intensity	Error
454.62	9.70x10-8	3	737.29	9.00x10-8	3
459.59	3.63x10-8	7	755.91	7.60x10-8	3
467.98	2.88x10-8	7	759.46	1.67x10-8	5
486.3	1.00x10-8	30	763.4	1.96x10-9	30
512	1.15x10-8	20	766.92	5.00x10-8	3
514.2	2.58x10-8	10	770.58	4.74x10-8	4
522	9.46x10-9	30	772.13	2.66x10-8	5
574	1.25x10-8	15	777.2	6.10x10-10	50
582.6	2.32x10-9	50	780.5	2.50x10-9	20
586.52	1.31x10-8	15	788.8	3.88x10-9	15
590.28	2.86x10-8	7	801.9	1.36x10-8	10
587.42	7.41x10-8	4	811.8	6.05x10-9	12
619.001	5.94x10-7	1	819.3	4.00x10-9	15
627.2	5.64x10-9	30	822.6	2.18x10-9	25
633.01	1.26x10-8	15	828.5	2.43x10-9	25
641.42	7.10x10-8	4	851.5	3.77x10-9	15
652.96	3.77x10-7	2	854.7	2.00x10-9	20
662.421	3.64x10-6	0.3	859.2	816x10-10	30
669.9	3.80x10-9	30	862.6	5.34x10-9	10
675.8	6.40x10-9	20	887.5	2.22x10-9	20
680.06	3.13x10-8	5	898.4	7.22x10-10	40
688.77	3.25x10-7	1.5	902.5	3.00x10-9	15
693.49	3.68x10-8	4	912.4	2.50x10-9	20
696.44	5.34x10-8	3	922.2	1.91x10-9	20
709.41	6.41x10-8	2	928.8	5.52x10-10	50
721.991	1.96x10-6	0.4	945.7	5.60x10-10	50
729.52	1.33x10-8	10	955.7	5.78x10-9	10
731.5	4.70x10-9	30			

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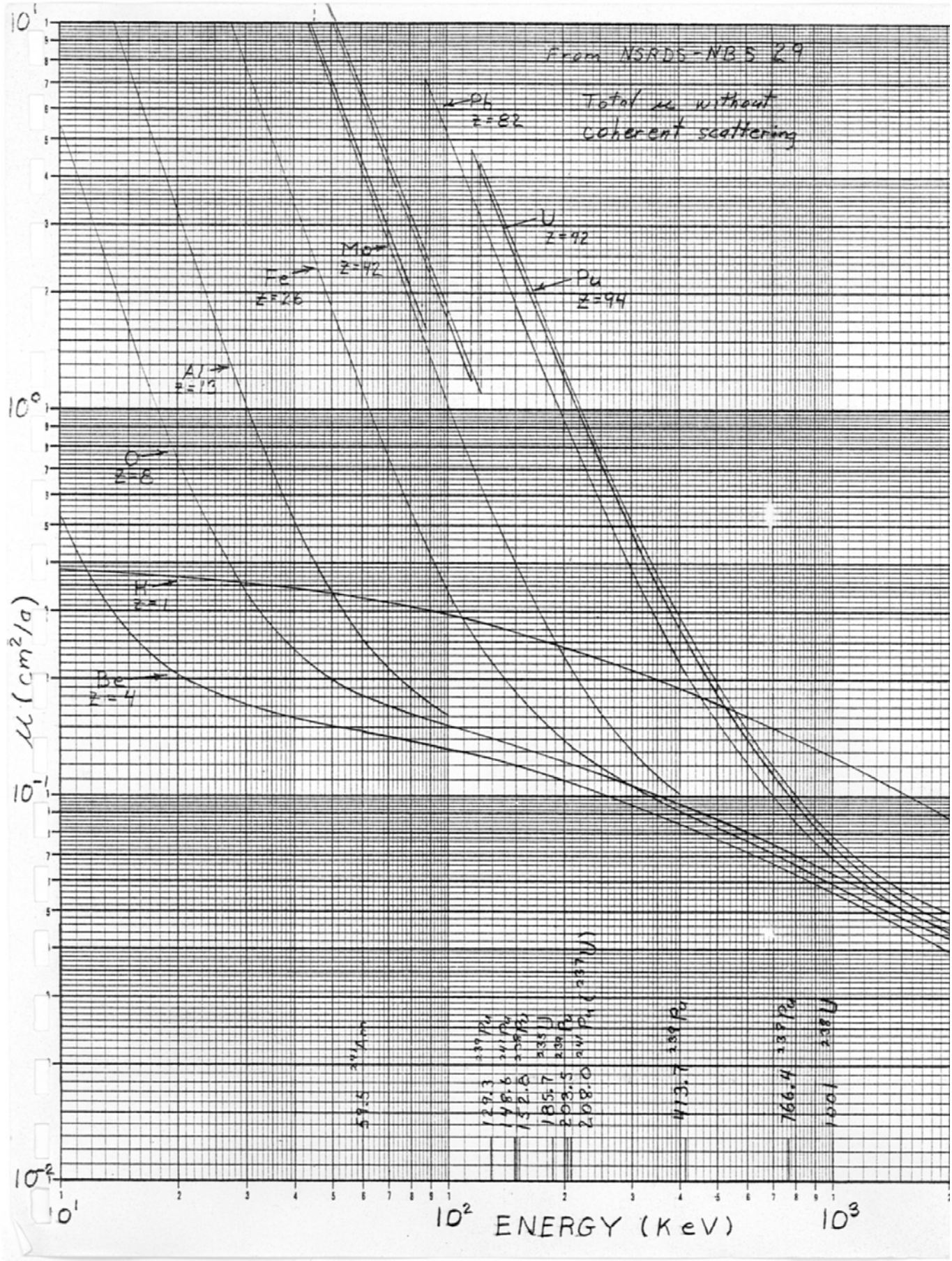
10. Kα x-ray energies, intensities and intrinsic line widths

	Energy	Intensity ratio	Width eV		Energy	Intensity ratio	Width eV
U $K_{\alpha 1}$	94.661	0.625	104	Np $K_{\alpha 2}$	101.066		
U $K_{\alpha 2}$	98.441			Pu $K_{\alpha 1}$	99.531	0.63	112
Np $K_{\alpha 1}$	97.071	0.628	108	Pu $K_{\alpha 2}$	103.748		

11. Mass attenuation coefficients for various elements



12. Spontaneous Fission Neutron Yields

Isotope A	Protons Z	Neutrons N	Half-Life	Fission Yield (n/s-g)	Spontaneous Multiplicity	Thermal Multiplicity
^{232}Th	90	142	1.41×10^{10} y	$>6 \times 10^{-8}$	2.14	1.9
^{232}U	92	140	71.7 y	1.3	1.71	3.13
^{233}U	92	141	1.59×10^{5} y	8.6×10^{-4}	1.76	2.4
^{234}U	92	142	2.45×10^{5} y	5.02×10^{-3}	1.81	2.4
^{235}U	92	143	7.04×10^{8} y	2.99×10^{-4}	1.86	2.41
^{236}U	92	144	2.34×10^{7} y	5.49×10^{-3}	1.91	2.2
^{238}U	92	146	4.47×10^{9} y	1.36×10^{-2}	2.01	2.3
^{237}Np	93	144	2.14 x 106 y	1.14×10^{-4}	2.05	2.70
^{238}Pu	94	144	87.74 y	2.59×10^{3}	2.21	2.9
^{239}Pu	94	145	2.41×10^{4} y	2.18×10^{-2}	2.16	2.88
^{240}Pu	94	146	6.56×10^{3} y	1.02×10^{3}	2.16	2.8
^{241}Pu	94	147	14.35 y	5×10^{-2}	2.25	2.8
^{242}Pu	94	148	3.76×10^{5} y	1.72×10^{3}	2.15	2.81
^{241}Am	95	146	433.6 y	1.18	3.22	3.09
^{242}Cm	96	146	163 d	2.10×10^{7}	2.54	3.44
^{244}Cm	96	148	18.1 y	1.08×10^{7}	2.72	3.46
^{249}Bk	97	152	320 d	1.0×10^{5}	3.40	3.7
^{252}Cf	98	154	2.646 y	2.34×10^{12}	3.757	4.06

13. (α,n) Neutron Yields

Isotope A	Total Half-Life	Yield (α/s-g)	Mean Energy (MeV)	(α,n) Yield in Oxide (n/s-g)	(α,n) Yield in UF_6/PuF_4
^{232}Th	1.41×10^{10} y	4.1×10^{3}	4.00	2.2×10^{-5}	
^{232}U	71.7 y	8.0×10^{11}	5.30	1.49×10^{4}	2.6×10^{6}
^{233}U	1.59×10^{5} y	3.5×10^{8}	4.82	4.8	7.0×10^{2}
^{234}U	2.45×10^{5} y	2.3×10^{8}	4.76	3.0	5.8×10^{2}
^{235}U	7.04×10^{8} y	7.9×10^{4}	4.40	7.1×10^{-4}	0.08
^{236}U	2.34×10^{7} y	2.3×10^{6}	4.48	2.4×10^{-2}	2.9
^{238}U	4.47×10^{9} y	1.2×10^{4}	4.19	8.3×10^{-5}	0.028
^{237}Np	2.14 x 106 y	2.6×10^{7}	4.77	3.4 x 10-1	
^{238}Pu	87.74 y	6.4×10^{11}	5.49	1.34×10^{4}	2.2×10^{6}
^{239}Pu	2.41×10^{4} y	2.3×10^{9}	5.15	3.81×10^{1}	5.6×10^{3}
^{240}Pu	6.56×10^{3} y	8.4×10^{9}	5.15	1.41×10^{2}	2.1×10^{4}
^{241}Pu	14.35 y	9.4×10^{7}	4.89	1.3	1.7×10^{2}
^{242}Pu	3.76×10^{5} y	1.4×10^{8}	4.90	2.0	2.7×10^{2}
^{241}Am	433.6 y	1.3×10^{11}	5.48	2.69×10^{3}	
^{242}Cm	163 d	1.2×10^{14}	6.10	3.76×10^{6}	
^{244}Cm	18.1 y	3.0×10^{12}	5.80	7.73×10^{4}	
^{249}Bk	320 d	8.8×10^{8}	5.40	1.8×10^{1}	
^{252}Cf	2.464 y	1.9×10^{13}	6.11	6.0×10^{5}	

14. Thick-Target Yields from (α,n) Reactions

Element	Yield per 10^6 α @ 4.7 MeV (^{234}U)	Yield per 10^6 α @ 5.2 MeV (Pu)	Mean n Energy (MeV) for 5.2 MeV α
Li	0.16 ± 0.04	1.13 ± 0.25	0.3
Be	44 ± 4	65 ± 5	4.2
B	12.4 ± 0.6	17.5 ± 0.4	2.9
C	0.051 ± 0.002	0.078 ± 0.004	4.4
O	0.040 ± 0.001	0.059 ± 0.002	1.9
F	3.1 ± 0.3	5.9 ± 0.6	1.2
Na	0.5 ± 0.5	1.1 + 0.5	
Mg	0.42 ± 0.03	0.89 ± 0.02	2.7
Al	0.13 ± 0.01	0.41 ± 0.01	1.0
Si	0.028 ± 0.002	0.076 ± 0.003	1.2
Cl	0.01 ± 0.01	0.07 ± 0.04	

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