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DECAY-ENERGY SYSTEMATICS OF THE HEAVY ELEMENTS

Isadore Perlman and Frank Asaro

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I. Summary of Decay Energies

Figures 1 and 2 summarize total decay energies for the four radioactive series. The alpha-decay energy obtained by measuring the energy of the alpha particle leading to the ground state includes the energy of the recoil nucleus. The legends indicate the meaning of superscripts attached to some of the energy values.

The curve shown in Figure 3 defines in broad outline the conditions and regions of alpha instability. A great deal more is to be learned from a more detailed examination of the region where alpha radioactivity is prominent.

Of great value to the experimentalist is that he is able to predict alpha energies, and the agreement between predicted and measured values often serves as a criterion for isotopic assignment. A number of systems for correlating alpha decay energies have been employed, and that perhaps most widely used is illustrated in Fig. 4. Here the isotopes of each element on a mass number vs. energy plot are joined, resulting in a family of curves which over a wide region comprise a series of nearly parallel lines. It will be noted that in this region (above mass number about 212) alpha energies decrease with increasing mass number for each element, i.e., with increasing neutron number. The dramatic inversion in the alpha-energy trend around mass number 212 is a consequence of the major closed shells in this region at 126 neutrons and 82 protons.

II. Complex Alpha Spectra

Table I is a compilation of all alpha-particle energies and abundances in the heavy-element region. Recent absolute energy measurements indicate all the alpha particle energies based upon the Po^{214} (RaC') absolute energy measurements by G. H. Briggs[2] should be revised upward about 0.1%. Pending further clarification of this issue, however, we have used the Briggs value

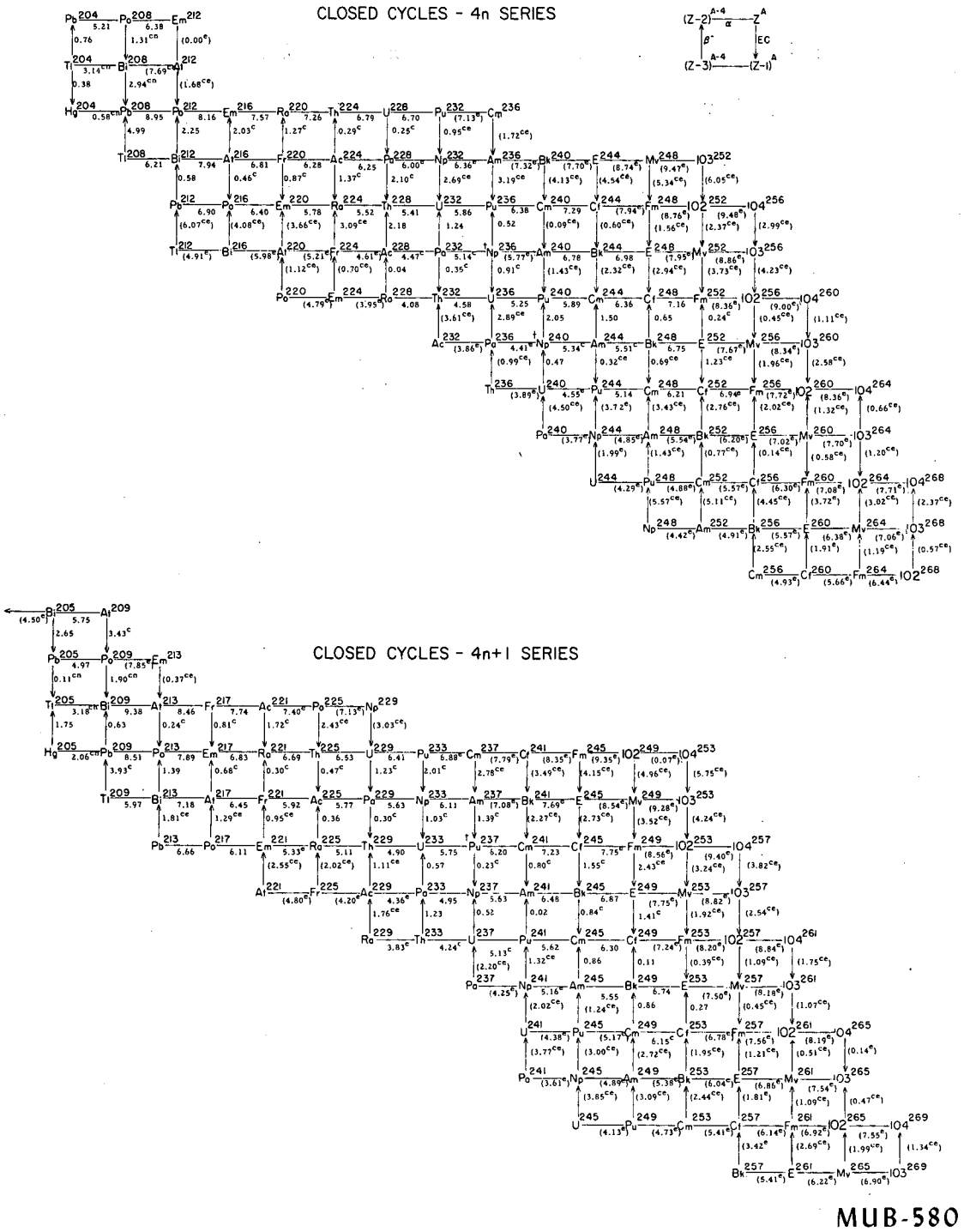


Fig. 1. Closed decay energy cycles for the 4n and 4n + 1 series: No superscript, measured energy; c, calculated; cn, calculated with neutron binding energies; e, estimated; ce, calculated from a cycle containing estimated energies; ( ), uncertain by more than about 0.1 Mev; †, isomers.

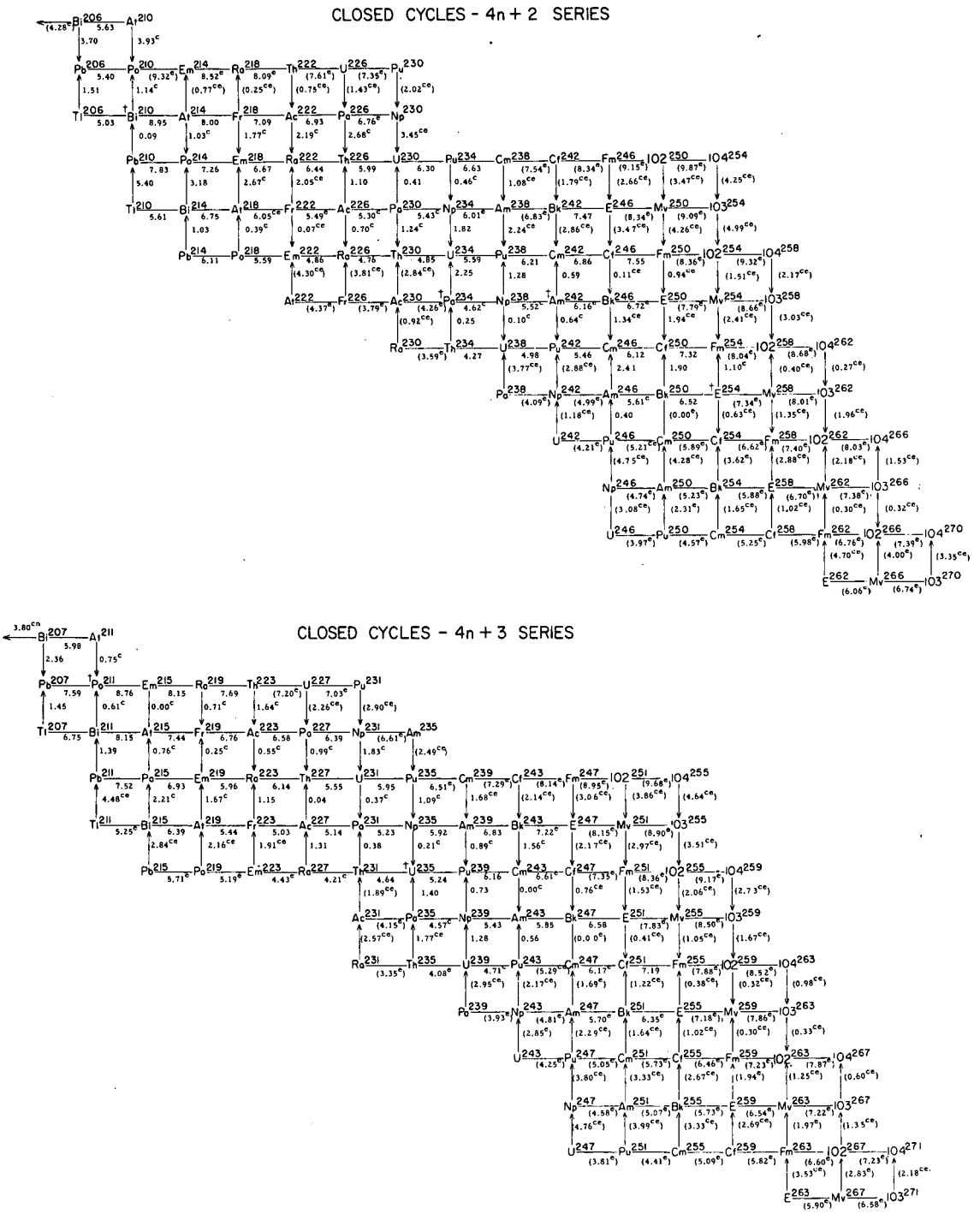


Fig. 2. Closed decay energy cycles for the 4n + 2 and 4n + 3 series: No superscript, measured energy; c, calculated; cn, calculated with neutron binding energies; e, estimated; ce, calculated from a cycle containing estimated energies; ( ), uncertain by more than about 0.1 Mev; †, isomers.

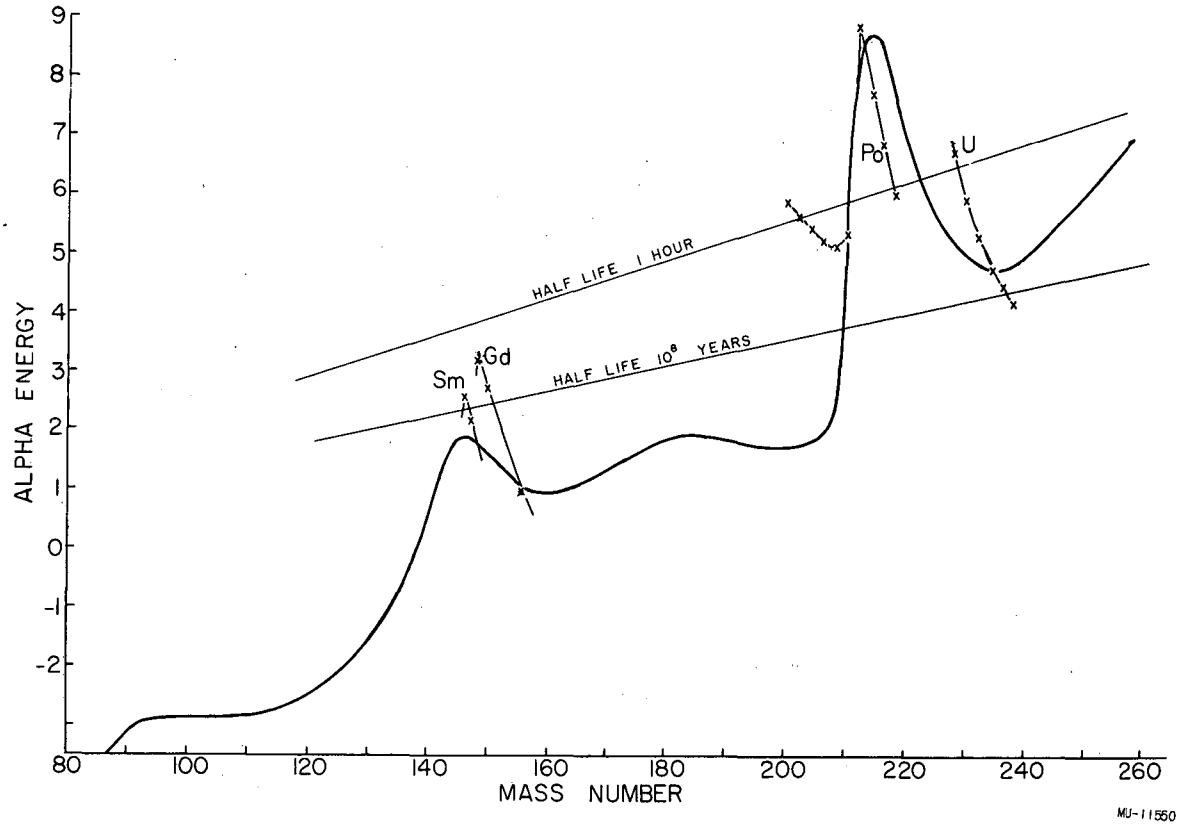
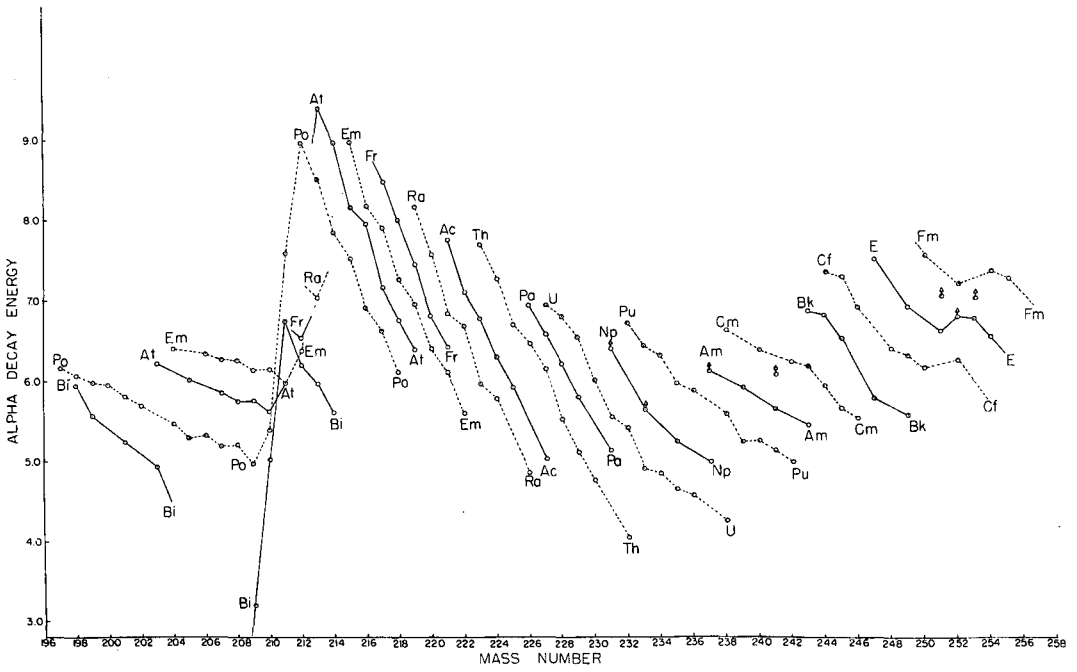


Fig. 3. Alpha-decay energy profile. The segments connecting isotopes of uranium, polonium, gadolinium, and samarium indicate the effects of change in neutron number for these elements. The half-life guide lines denote the alpha energies (Mev) which would be required to provide these half lives. All species which are beta-stable and which lie below the "10^8 years" curve are sufficiently long lived to have persisted since the creation of the element.



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Fig. 4. Alpha decay energy vs. mass number.

for Po^{214} (RaC') 7.6804 Mev, as the primary energy standard.

As in other decay process, the appearance of multiple groups in the alpha-emission process may be considered as the result of competition in populating available energy levels. Alpha-decay lifetimes are influenced by a number of factors; among these is the sharp dependence of lifetime on decay energy. There are, however, selection process operating which can delay the highest-energy group and cause lower-energy groups to be the most prominent.

Even-even Alpha Emitters. The decay schemes for three typical even-even alpha emitters are shown in Fig. 5. The similarities and differences will be explained below.

PRINCIPAL ALPHA GROUPS (THE GROUND STATE AND FIRST EXCITED STATE): With a high degree of certainty it can be said that the transition to the ground state is the most abundant for this nuclear type. First excited states reached by these alpha groups all have spin 2 and even parity (see Fig. 5). The alpha population to this state is close to theoretical expectations.

A summary of the energy spacings between the ground state and first excited state as a function of neutron number and proton number is shown in Fig. 6. The points divide into families according to atomic number and appear to reach maxima for nuclei with 126 neutrons.

RARE ALPHA GROUPS (HIGHER EVEN STATES AND FIRST ODD STATE): Many of the alpha emitters which have lent themselves to detailed analysis have proven to have one or more additional groups of lower energy and in low intensity.

In each case which could be examined in the necessary detail, there was found a rare alpha group going to a state which decays by an E2 transition only to the 2+ state. From the nature of the gamma ray transition the second state could be 0+, 2+, or 4+. In the alpha decay of Th^{230}, however (see Fig. 5), α-γ and γ-γ angular correlation measurements showed unambiguously the second excited state had spin and parity of 4+. The 4+ assignment is made to nearly all of the remainder of the second excited states (Fig. 6), largely from agreement with energy-level spacings predicted by the Bohr-Mottelson theory of rotational states.

In a few cases a very weak alpha group has been observed which decays to the 4+ state by an E2 transition. These cases, as well as others determined from gamma-ray spectroscopy or coulomb excitation, are those designated as 6+ in Fig. 6a; the 6+ assignment is also made largely from agreement with energy-level spacings predicted by the Bohr-Mottelson theory of rotational states.

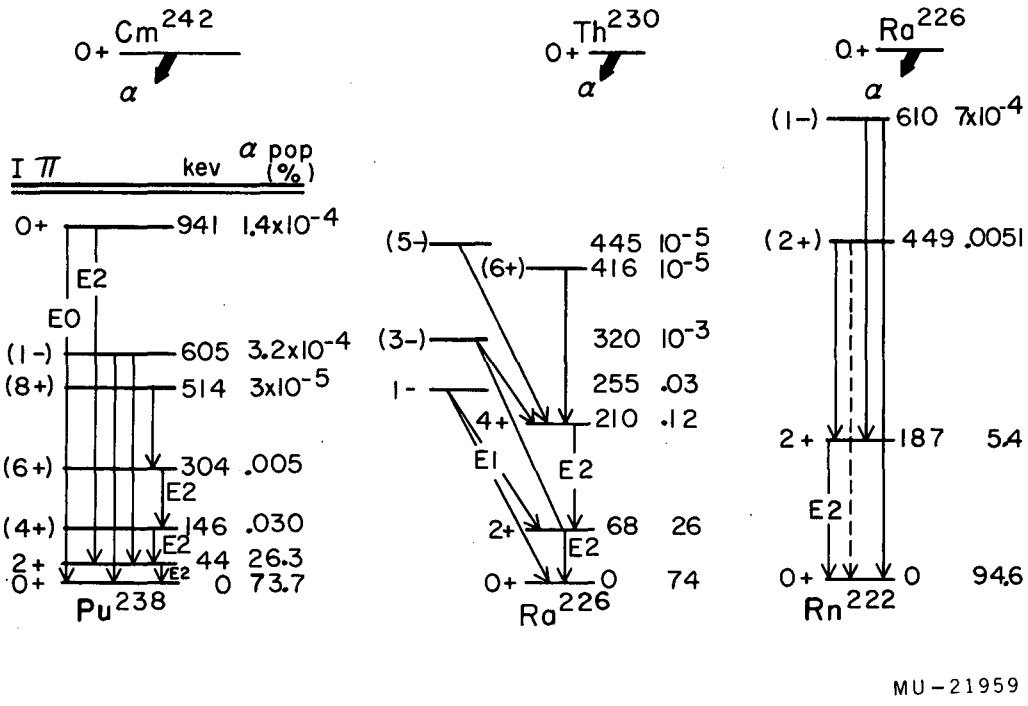


Fig. 5. Decay schemes of Cm^{242}, Th^{230}, and Ra^{226}.

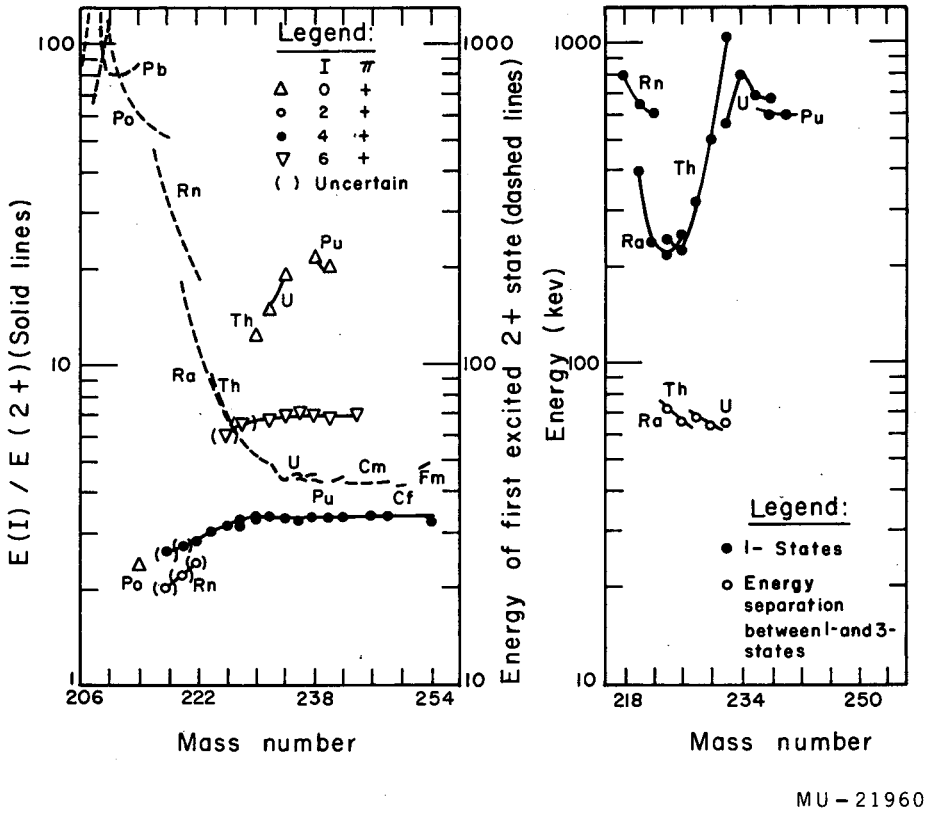


Fig. 6. Energy levels in even-even nuclides:
a. Even spin and parity levels.
b. Odd spin and parity levels.

In the decay of Cm^{242} and Pu^{238} a very rare gamma ray has been seen which is in coincidence with the 6+ → 4+ transition. Since the energy of the state defined by the gamma ray corresponds closely with expectations if it were the 8+ member of the Bohr-Mottelson rotational band, it has been so designated (see Cm^{242} spectrum Fig. 5).

In a number of cases a state with spin and parity, 1-, (see Fig. 6b) has entered among the low lying even states. This state, as is shown in Fig. 5, decays to both the ground state and first excited state by E1 transitions. The multipolarities of most of these transitions have been determined by conversion coefficient and angular correlation measurements. An additional characteristic feature of all of these E1 transitions concerns the ratio of the gamma-ray intensities to the ground and first excited state. After removing the third power energy dependence, this ratio is found to be 0.50, within experimental error. This particular value conforms with one of the expectations of Bohr-Mottelson theory and has been used to tentatively identify the 1- states where other means were not available. As shown in Fig. 6b there seems to be a minimum in the energy of the 1- states at 136 neutrons. There is no suitable explanation for this effect.

As shown in Fig. 5, 3- and 5- states have been tentatively assigned in Ra^{226}. The assignments were based on the choice of states populated by the gamma rays de-exciting these levels and the agreement of the energy separation between the 3- and 5- states with that predicted by the Bohr-Mottelson theory of rotational states. The 3- states (in Ra^{224} and Ra^{226}) detected by alpha emission as well as several determined by beta decay are shown in Fig. 6b.

As seen in the decay of Ra^{226} to Rn^{222} (Fig. 5) a second state has been tentatively assigned spin and parity 2+. This state is characterized by gamma ray de-excitation to the first excited 2+ state with a much weaker tentative crossover transition to the ground state. A seen in Fig. 6a this 2+ assignment is also made for states in Rn^{220} and Rn^{218}. Analogous states have been observed in the rare earth region where the spin and parity assignments were more definitely determined.

In a few cases a second state with spin and parity 0+ has been identified near 1 Mev excitation energy. This state is de-excited by an E0 electron transition to the ground state and an E2 transition to the first excited 2+ state. Fig. 6a shows the excited 0+ states populated by the alpha decay of

Cm^{242}, Pu^{238}, and U^{234} as well as others populated by beta decay.

Odd-nucleon alpha emitters. In contrast to the even-even nuclides, the ground state transition of an odd nucleon alpha emitter is usually not the most abundant, as can be seen from Table 1. Indeed its abundance is often orders of magnitude smaller than the theoretical value. An exception to this general rule is shown in Fig. 7, the decay scheme of E^{253}. This decay scheme, however, demonstrates another significant difference in that the odd-nucleon alpha emitters have considerably more complex alpha spectra than the even-even type.

In many cases, however, it has been found that a complex spectra can be broken down into simpler components. In Fig. 7, for example, the 15 alpha groups have been divided into three subgroups. The states within any subgroup all have the same parity, and their nuclear spins bear a simple relation to one another, usually increasing one unit for each excited state at higher energy. These subgroups bear a marked resemblance to the rotational bands discussed for even-even nuclides and have been interpreted in terms of the Bohr-Mottelson theory for odd-nucleon rotational states. Indeed some of the spin and parity assignments shown in Fig. 7, were made because of the good agreement of the energies of these states with the theoretical expectations.

Not all of the odd-nucleon alpha spectra can be interpreted as readily as that of E^{253}. The spectrum of Th^{227}, for example, is one which still defies similar analysis.

III. Alpha decay Lifetimes and Theory

It is possible to correlate alpha-decay lifetimes empirically and to arrive at systems which can be used to predict half lives.

Even-even alpha Emitters— Ground-state Transitions. Figure 8 shows a plot of the half life vs. energy relationship as a family of curves. The curves are defined by the experimental half lives and are in this respect empirical. If, however, we were to calculate half lives by using the measured alpha energy for each point and assuming a function for the nuclear radius, $1.5 \times 10^{-13} A^{1/3}$, the resulting curves would lie close to those of Fig. 8.

In summary it can be said that the basic one-body theory of alpha decay applied to the ground-state transitions of even-even alpha emitters gives a remarkably consistent picture. When reasonable and consistent assumptions for the values of the nuclear radii are used, the theory explains observed half lives which differ by a factor of 10^{24}. It should be pointed out that

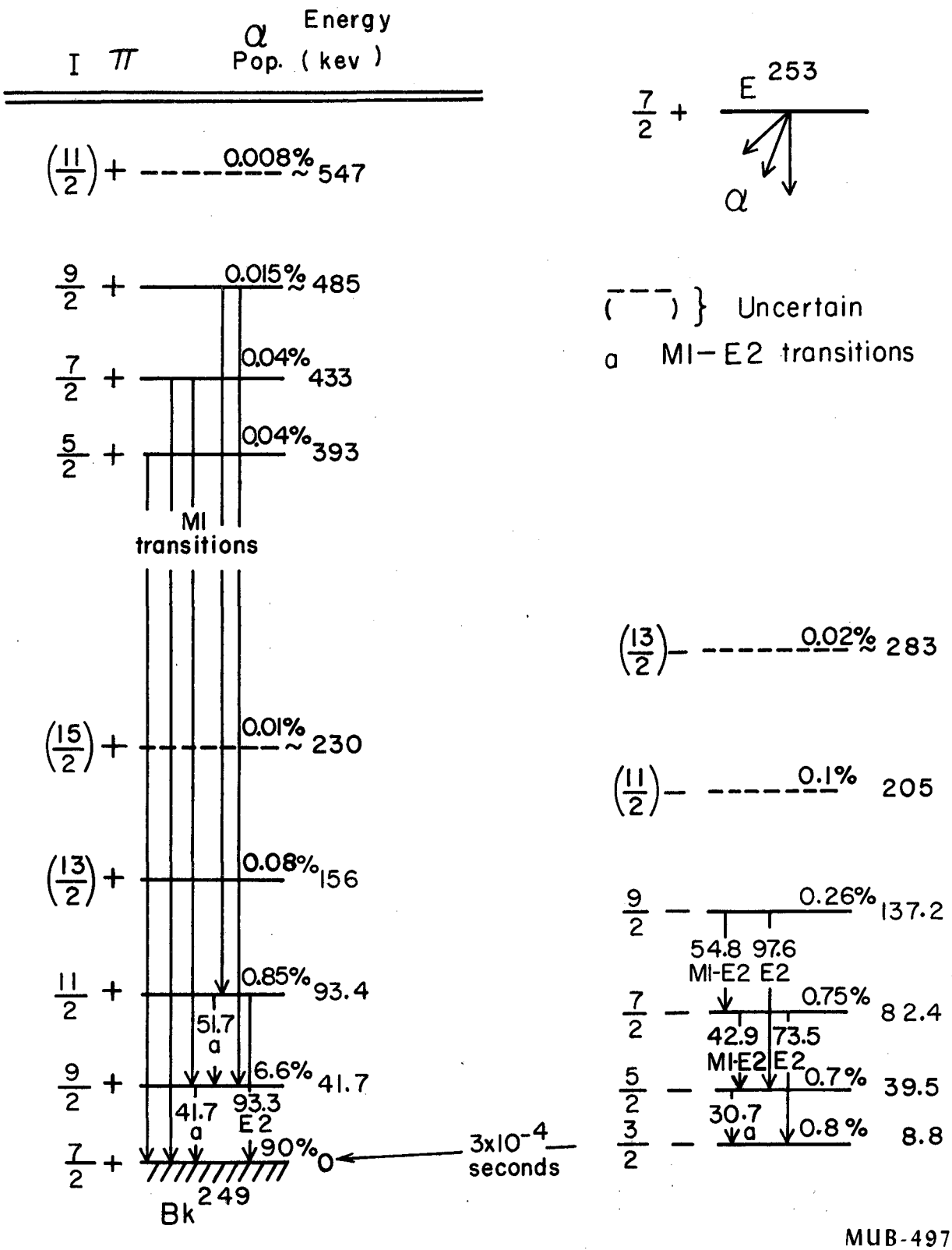


Fig. 7. Decay scheme of E^{253}.

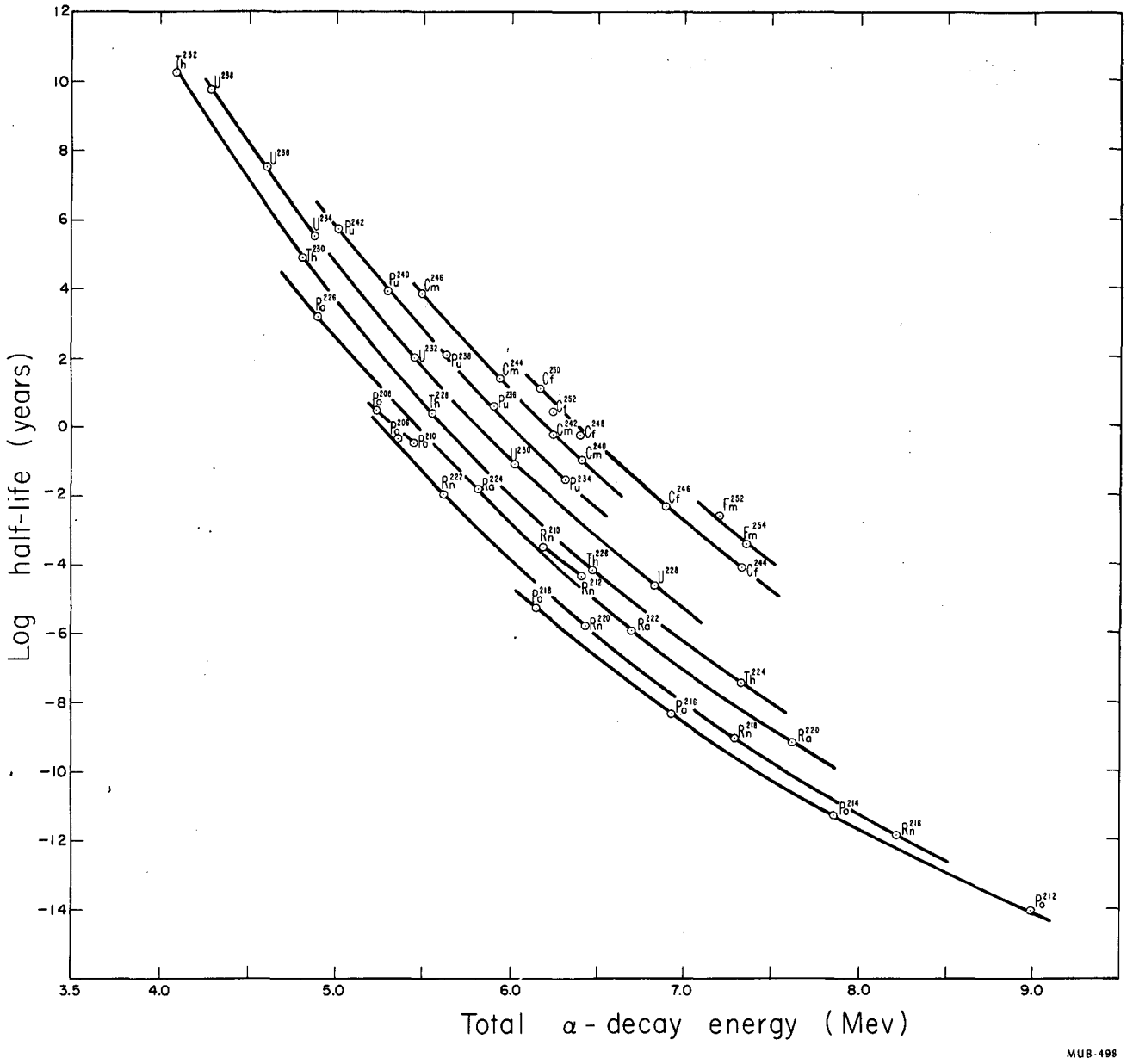


Fig. 8. Experimental values of log half life vs. effective alpha energy ("Effective alpha energy" includes correction of particle energy for recoil and electron screening).

different formulations of the theory will give somewhat different "best values" for the radius parameter, but each is internally consistent. It will be noted that some points (e.g., Po^{210}, Po^{208}, Em^{210}, Em^{212}) lie off their respective curves. These are the alpha emitters with 126 neutrons or fewer which have abnormally long lifetimes.

Even-even Alpha Emitters— Transitions to Excited States. For any particular case, one can calculate the partial half-life to any excited state under the assumption that the only factor influencing the relative decay rates is the energy function. It is found that the populations of the first excited 2+ states are not far from the calculated values while the populations to the higher spin even-parity rotational members are quite hindered and show considerable variation as shown in Fig. 9a. An explanation for the variation in population of these states has been developed in terms of the interaction of the emitted alpha particle wave with the nuclear quadrupole moment.

The hindrance factors (ratio of experimental half-life to calculated value) for the odd-parity states are shown in Fig. 9b. An explanation for the variation with mass number has not yet been developed.

Odd-nucleon alpha emitters. One of the most obvious questions about this category is why the ground state transition is often highly hindered and why the hindrance is so irregular. Although a completely satisfactory answer has not yet been obtained, some promising leads have been uncovered. It has been shown, for example, that the alpha population to the various members of the rotational band populated by the least hindered alpha transition (usually the most abundant) can be calculated from the Bohr, Fröman and Mottelson theory for unhindered alpha decay. The nuclear configuration of the band receiving this type of alpha decay is assumed to be the same as the parent alpha emitter. The alpha populations are then calculated semi-empirically by analogy with even-even emitters. In general, the ground states of the parent and daughter in an alpha decay do not have the same type of nuclear configuration; hence, the ground state alpha transition would generally not be the most abundant. The decay scheme of E^{253} shown in Fig. 7 illustrates one of the few cases where the parent and daughter ground states do have the same nuclear configuration.

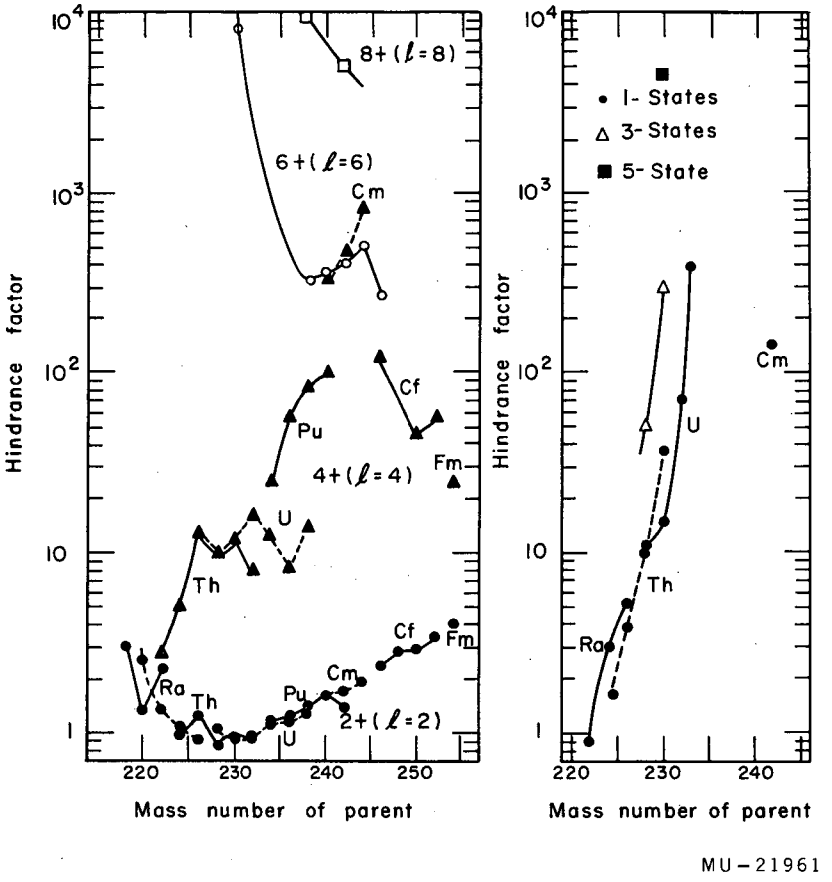


Fig. 9. Hindrance factors for the alpha decay to energy levels in even-even nuclides:

a. Even parity ground state rotational bands.
b. Odd parity rotational bands.

The alpha populations to states with different nuclear configurations than the ground state are not well understood as yet. Some progress is being made, however, by detailed consideration of the nuclear wave functions.

Odd-odd alpha emitters. These types of spectra are extremely complex and as yet very little understood.

REFERENCES

1. The data used in this compilation were originally drawn from many primary sources. Figures 1 to 2 are from B.M. Foreman, Jr. and G.T. Seaborg, Nuclear Thermodynamics of the Heaviest Elements, II, J. Inorg. and Nuclear Chem. 7, 305 (1958). Figures 3 and 4 are from Perlman and Rasmussen, Alpha Radioactivity, Encyclopedia of Physics, Vol. XLII, Springer-Verlag Berlin (1957).

2. G. H. Briggs, Proc. Roy. Soc. (London) 157A, 183 (1936).

TABLE I. ALPHA-PARTICLE ENERGIES AND ABUNDANCES

Alpha emitter			Alpha-particle energy, Mev	Relative abundances, %	Type of measurement
Bi^{198}			5.83		ion ch
Bi^{199}			5.47		ion ch
Bi^{201}			5.15		ion ch
Bi^{203}			4.85		emuls
Bi^{210}	5.0d		4.681	40	spect
			4.644	60	spect
Bi^{210}	2.6×10^{6} y		4.935	60	ion ch
			4.90	30	ion ch
			4.64	10	ion ch
Bi^{211}		(ACC)	6.617	83	spect
			6.273	17	spect
Bi^{212}		(Th C)	6.082	27.1	spect
			6.043	69.7	spect
			5.760	1.78	spect
			5.618	0.165	spect
			5.599	1.19	spect
			5.473	0.014	spect
			5.337	0.001	spect
			5.294	1.1×10^{-4}	spect
			5.184	5×10^{-5}	spect
Bi^{213}			5.86		ion ch
Bi^{214}		(Ra C)	5.507	39.2	spect
			5.443	53.9	spect
			5.263	5.8	spect
			5.179	0.61	spect
			5.018	0.21	spect
			4.936	0.25	spect
$Po^{192,193}$	0.5s		6.58		spect
$Po^{193,194}$	4s		6.47		spect
$Po^{194,195}$	13s		6.38		spect
$Po^{195,196}$	30s		6.26		spect
$Po^{196,197}$	1.8m		6.13		ion ch

$Po^{197,198}$	~ 4m		6.040		spect
$Po^{198,199}$	~ 6m		5.935		spect
$Po^{199,200}$	11m		5.846		spect
$Po^{200,201}$	8m		5.770		spect
Po^{201}			5.671		spect
Po^{202}			5.575		spect
Po^{203}			5.48		ion ch
Po^{204}			5.370		spect
Po^{205}			5.2		ion ch
Po^{206}			5.218	~100	spect
Po^{207}			5.10		ion ch
Po^{208}			5.108	~100	spect
Po^{209}			4.877	99.4	spect
			4.62	0.6	α-γ
Po^{210}		(Ra F)	5.299	100	spect
			4.512	1.07×10^{-3}	spect
Po^{211}	0.52s	(A cC')	7.44	99.0	spect
			6.88	0.53	spect
			6.56	0.50	spect
Po^{211}	25s		8.70	7	ion ch
			7.85	2.5	ion ch
			7.14	90.5	ion ch
Po^{212}		(Th C')	8.776	~100	spect
Po^{213}			8.35	~100	spect
Po^{214}		(RaC')	7.680	100	spect
			6.892	.01	spect
Po^{215}		(AcA)	7.36	~100	spect
Po^{216}		(ThA)	6.775	~100	spect
Po^{217}			6.54		ion ch
Po^{218}		(RaA)	5.998	100	spect
			5.175	.0011	spect
At^{201}			6.348	~100	spect
At^{202}			6.231	36	spect
			6.133	64	spect
At^{203}			6.086	~100	spect
At^{204}	9.3 min		5.950	~100	spect
At^{205}			5.899	~100	spect

At^{206}	22 min		5.699		spect
At^{207}			5.750		spect
At^{208}	1.6 hr		5.65	~97	ion ch
			5.53	~ 3	α-γ
At^{209}			5.642	~100	spect
At^{210}			5.519	32	spect
			5.437	31	spect
			5.355	37	spect
At^{211}			5.862	~100	spect
At^{213}			9.2		emuls
At^{214}			8.78		ion ch
At^{215}			8.00		ion ch
At^{216}			7.79		ion ch
At^{217}			7.05		spect
At^{218}			6.685	94	spect
			6.640	~ 6	spect
At^{219}			6.27		ion ch
Rn^{204}			6.28		ion ch
Rn^{206}			6.25		ion ch
Rn^{207}			6.14		ion ch
Rn^{208}			6.141	~100	spect
Rn^{209}			6.037		spect
Rn^{210}			6.037	~100	spect
Rn^{211}			5.847	33.5	spect
			5.779	64.5	spect
			5.613	2	spect
Rn^{212}			6.264	~100	spect
Rn^{215}			8.6		ion ch
Rn^{216}			8.04	~100	ion ch
Rn^{217}			7.735	~100	spect
Rn^{218}			7.127	99.8	spect
			6.529	0.2	γ
Rn^{219}		(An)	6.813	82	spect
			6.547	13	spect
			6.419	5	spect
			6.807	69	spect
			6.542	15	spect
			6.418	12	spect
			6.197	4	spect

Rn^{220}	(Tn)	6.282	99.7	spect
		5.747	0.3	spect
Rn^{221}		6.0		ion ch
Rn^{222}	(Rn)	5.486	99.9	spect
		4.982	0.078	spect
Fr^{212}		6.411	37	spect
		6.387	39	spect
		6.342	24	spect
Fr^{217}		8.3		emuls
Fr^{218}		7.85		ion ch
Fr^{219}		7.30		ion ch
Fr^{220}		6.69		ion ch
Fr^{221}		6.33	84	spect
		6.12	16	spect
Fr^{223}	(AcK)	5.34		emuls
Ra^{215}		6.90		ion ch
Ra^{219}		8.0		ion ch
Ra^{220}		7.45	99	ion ch
		6.99	1	α-γ
Ra^{221}		6.754	31	spect
		6.665	20	spect
		6.606	38	spect
		6.583	8	spect
		6.573	3	spect
Ra^{222}		6.551	95.6	spect
		6.233	4.4	α-γ
		5.914	.01	γ-γ
		5.76	.03	γ-γ
		5.72	.002	γ-γ
Ra^{223}	(A cX)	5.867	.96	spect
		5.853	0.3	spect
		5.742	10.5	spect
		5.712	50.4	spect
		5.602	23.6	spect
		5.534	10.3	spect
		5.497	.86	spect
		5.429	2.4	spect
		5.360	0.20	spect
		5.334	0.07	spect
		5.282	0.3	spect
Ra^{224}	(Th X)	5.681	95	spect
		5.444	4.9	spect,γ
		5.16	.01	γ-γ
		5.04	.01	γ-γ

Ra^{226}	(Ra)	4.777	94.6	spect
		4.594	5.4	spect
		4.335	.0051	spect
		4.178	7×10^{-4}	spect, γ
Ac^{221}		7.6		emuls
Ac^{222}		6.96		ion ch
Ac^{223}		6.657	40	spect
		6.643	46	spect
		6.561	14	spect
Ac^{224}		6.17		ion ch
Ac^{225}		5.818	54	spect
		5.782	28	spect
		5.721	9.5	spect
		5.713	2.6	spect
		5.672	0.8	spect
		5.627	3.8	spect
		5.599	0.6	spect
		5.570	0.7	spect
		5.543	0.07	spect
Ac^{227}		4.949	49	spect
		4.936	36	spect
		4.866	6.9	spect
		4.849	5.5	spect
		4.786	1.0	spect
		4.759	1.8	spect
		4.704	0.4	spect
Th^{223}		7.55		ion ch
Th^{224}		7.17	79	ion ch
		7.00	19	ion ch
		6.77	1.5	α-γ
		6.70	0.5	α-γ
Th^{225}		6.793	9	spect
		6.739	7	spect
		6.695	2	spect
		6.645	3	spect
		6.622	3	spect
		6.496	14	spect
		6.473	43	spect
		6.436	15	spect
		6.340	2	spect
		6.307	2	spect
Th^{226}		6.330	79	spect
		6.221	19	spect, e
		6.095	1.7	spect
		6.029	0.6	spect

Th^{227}	(Rd Ac)	6.036	23	spect
		6.007	2.8	spect
		5.976	24	spect
		5.958	3.5	spect
		5.914	0.9	spect
		5.865	3.0	spect
		5.805	1.0	spect
		5.793	0.3	spect
		5.761	0.3	spect
		5.755	21	spect
		5.712	5.0	spect
		5.708	8.7	spect
		5.699	4.0	spect
		5.692	1.5	spect
		5.667	1.9	spect
Th^{228}	(Rd Th)	5.421	71	spect
		5.338	28	spect
		5.208	0.4	spect
		5.173	0.2	spect
		5.137	0.03	spect
Th^{229}		5.048	6.7	spect
		5.028	~0.2	spect
		5.003	~0.1	spect
		4.971	3.4	spect
		4.961	6.0	spect
		4.925	0.25	spect
		4.894	10.7	spect
		4.837	58.2	spect
		4.806	11.4	spect
		4.788	1.0	spect
		4.751	1.5	spect
		4.678	0.4	spect
Th^{230}	(Io)	4.682	74	spect
		4.615	26	spect
		4.476	0.2	spect, γ
		4.433	0.03	γ-γ
		4.368	0.001	γ-γ
		4.273	8×10^{-6}	γ-γ
		4.245	8×10^{-6}	γ-γ
Th^{232}	(Th)	4.007	76	ion ch
		3.949	24	ion ch, α-e
		3.825	0.2	ion ch, α-e
Pa^{226}		6.81		ion ch
Pa^{227}		6.526	2.3	spect
		6.515	0.3	spect
		6.460	50	spect
		6.418	11.5	spect
		6.410	14.8	spect
		6.396	9.3	spect
		6.371	2.6	spect

	6.351	7.8	spect
	6.331	0.7	spect
	6.321	0.4	spect
	6.294	0.8	spect
Pa^{228}	6.138	2.5	spect
	6.114	10	spect
	6.101	12	spect
	6.087	2.3	spect
	6.074	21	spect
	6.062	1.0	spect
	6.037	2.3	spect
	6.024	9	spect
	6.007	0.8	spect
	5.994	0.3	spect
	5.985	1.1	spect
	5.978	2.8	spect
	5.971	2.7	spect
	5.943	0.6	spect
	5.937	0.5	spect
	5.918	0.8	spect
	5.903	1.1	spect
	5.870	1.4	spect
	5.854	0.3	spect
	5.839	0.4	spect
	5.801	7.3	spect
	5.795	11	spect
	5.775	1.4	spect
	5.761	2.0	spect
	5.756	1.4	spect
	5.752	2.5	spect
	5.707	1.0	spect
Pa^{229}	5.665	19	spect
	5.625	10	spect
	5.610	13	spect
	5.586	5	spect
	5.575	37	spect
	5.560	3.9	spect
	5.531	9	spect
	5.512	0.6	spect
	5.496	0.7	spect
	5.474	1.8	spect
	5.417	0.07	spect
	5.408	0.15	spect
	5.315	0.05	spect
Pa^{231}	5.047	10	spect
	5.018	23	spect
	5.002	24	spect
	4.972	2.3	spect
	4.939	22	spect
	4.922	2.8	spect

		4.840	1.4	spect
		4.723	11	spect
		4.697	1.4	spect
		4.667	2.1	spect
U^{227}		6.8		ion ch
U^{228}		6.68	70	ion ch
		6.59	29	ion ch
		6.44	0.7	α-γ
		6.40	0.5	α-γ
U^{229}		6.355	64	spect
		6.327	20	spect
		6.292	11	spect
		6.255	1	spect
		6.218	3	spect
		6.180	1	spect
U^{230}		5.884	67.2	spect
		5.813	32.1	spect
		5.662	0.4	spect { e
		5.658	0.3	spect { γ
U^{231}		5.45		ion ch
U^{232}		5.318	68	spect
		5.261	32	spect
		5.135	0.32	spect, e
		4.998	.01	γ
U^{233}		4.816	84	spect
		4.774	14	spect, e
		4.746	0.3	spect
		4.720	1.9	spect, e
		4.655	0.06	spect, e
		4.503	0.033	spect
		4.457	0.004	e
U^{234}	(U_{II})	4.768	72	spect
		4.717	28	spect
		4.601	0.35	ion ch (α-e)
		4.27	3×10^{-5}	γ
		4.14	1.6×10^{-5}	γ
U^{235}	(AcU)	4.592	~5	spect
		4.578	~1.5	spect
		4.550	~3	spect
		4.496	~1	spect
		4.438	~3	spect
		4.412	~2	spect
		4.394	62	spect
		4.368	6	spect

		4.362	11	spect
		4.339	1.5	spect
		4.320	3	spect
		4.214	5.5	spect
U^{236}		4.499	73	ion ch
		4.451	27	α-e (emuls)
		4.339	~0.5	γ
U^{238}	(U_I)	4.195	77	ion ch
		4.148	23	ion ch (α-e)
		4.038	0.23	ion ch (α-e)
Np^{231}		6.28		ion ch
Np^{233}		5.53		ion ch
Np^{235}		5.095	3.8	ion ch
		5.015	83.6	ion ch
		4.925	11.8	ion ch
		4.864	0.8	ion ch
Np^{237}		4.866	3	spect
		4.860	1	spect
		4.810	1.4	spect
		4.798	1.5	spect
		4.781	42	spect
		4.764	28	spect
		4.759	5	spect
		4.726?	0.8	spect
		4.703	2.2	spect
		4.687	1.6	spect
		4.656	5.5	spect
		4.631	6.0	spect
		4.59	0.5%	ion ch
		4.52	0.02%	ion ch
Pu^{232}		6.58		ion ch
Pu^{233}		6.30		ion ch
Pu^{234}		6.196	68	spect
		6.145	32	spect
		6.025	0.4	spect
Pu^{235}		5.85		ion ch
Pu^{236}		5.763	68.9	spect
		5.716	30.9	spect
		5.610	.18	spect
		5.448	.002	α-γ

Pu^{237}	5.65	21	ion ch
	5.36	79	ion ch
Pu^{238}	5.491	71	spect
	5.448	29	spect
	5.350	0.13	spect, e
	5.200	0.0043	e
	5.000	7×10^{-6}	γ-γ
	4.695	1.2×10^{-4}	γ
Pu^{239}	5.147	72.5	spect
	5.134	16.8	spect
	5.096	10.7	spect
	5.064	0.037%	spect
	5.000	0.013%	spect
	4.973	0.005	spect
	4.917	0.005	spect
	4.780	0.002	spect
	4.728	0.005	spect
Pu^{240}	5.159	76	spect
	5.115	24	spect
	5.014	.09	spect
	4.854	.002	spect
Pu^{241}	4.74		γ
	4.747		γ
	4.890	75	spect
	4.845	25	spect
Pu^{242}	4.895	74	spect
	4.851	26	spect
Am^{237}	6.01		ion ch
Am^{239}	5.83		α-γ
	5.78	~100	ion ch
Am^{241}	5.541	0.39	spect
	5.508	0.24	spect
	5.482	85	spect
	5.439	12.8	spect
	5.416	0.008	spect
	5.385	1.7	spect, e
	5.321	.015	spect
	5.241	.004	spect
Am^{242}	5.53		*
	5.201	~100	spect
Am^{243}	5.345	0.17%	spect
	5.314	0.16%	spect
	5.272	87%	spect
	5.230	11.5%	spect
	5.175	1.1%	spect

Cm^{238}	6.50		ion ch
Cm^{240}	6.287	72	spect
	6.243	28	spect
	6.143	.04	spect
Cm^{241}	6.078	< 35	γ
	5.935	70	spect
	5.925	17	spect
	5.879	13	spect
Cm^{242}	6.110	73.7	spect
	6.067	26.3	spect, e
	5.967	0.030	spect
	5.812	0.005	spect
	5.606	3×10^{-5}	spect
	5.515	3.2×10^{-4}	spect
	5.185	1.4×10^{-4}	spect
	5.12	4×10^{-6}	spect
Cm^{243}	6.061	1	spect, e
	6.054	5	spect
	6.005	0.9	spect, e
	5.987	6	spect, e
	5.900	0.1	spect
	5.872	0.5	spect
	5.780	73	spect, e
	5.736	11.5	spect, e
	5.680	1.6	spect
	5.676	0.2	spect
	5.634	0.15	spect
	5.584	0.05	spect
Cm^{244}	5.802	76.7	spect
	5.760	23.3	spect
	5.663	0.017	spect
	5.515	0.004	γ
Cm^{245}	5.53		α-γ
	5.36	~92	ion ch
	5.31	~8	γ-γ
Cm^{246}	5.37		ion ch
Cm^{248}	5.05		ion ch
Bk^{243}	6.72	30	ion ch
	6.55	53	ion ch
	6.20	17	ion ch

Bk^{244}	6.67		ion ch
Bk^{245}	6.37	33	ion ch
	6.17	41	ion ch
	5.89	26	ion ch
Bk^{247}	5.75		α-γ
	5.67	~40	ion ch
	5.51	~60	ion ch
	5.30	~5	ion ch
Bk^{249}	~5.46		α-γ
	5.42	96	ion ch
	5.08	4	ion ch, α-γ
Cf^{244}	7.17		ion ch
Cf^{245}	7.11		ion ch
Cf^{246}	6.733	78	spect
	6.711	22	spect
	6.615	0.3	α-γ
	6.468	0.02	α-γ
Cf^{248}	6.26	82	ion ch
	6.22	18	α-e
Cf^{249}	6.194	1.9	spect
	6.139	1.1	spect
	6.072	0.4	spect
	5.990	0.08	spect
	5.941	3.3	spect
	5.898	1.2	spect
	5.842	3.0	spect
	5.806	84	spect
	5.778	0.5	spect
	5.749	4.4	spect
	5.687	0.4	spect
Cf^{250}	6.024	83	spect
	5.980	17	spect
	5.882	0.32	spect
Cf^{251}	5.844	50	spect
	5.667	50	spect
Cf^{252}	6.112	84	spect
	6.069	15.5	spect
	5.968	0.28	spect
E^{246}	7.3		ion ch
E^{248}	6.87		ion ch
E^{249}	6.76		ion ch

E^{251}		6.48		ion ch
E^{252}		6.64		ion ch
E^{253}		6.633	90	spect
		6.624	0.8	spect
		6.594	0.7	spect
		6.592	6.6	spect
		6.552	0.75	spect
		6.541	0.85	spect
		6.498	0.26	spect
		6.480	0.08	spect
		6.246	0.04	spect
		6.206	0.04	spect
		6.156	0.015	spect
E^{254}	(480d)	6.43		spect
Fm^{248}		7.8		ion ch
Fm^{249}		7.9		emuls
Fm^{250}		7.43		ion ch
Fm^{251}		6.89		ion ch
Fm^{252}		7.04		ion ch
Fm^{253}		6.9		ion ch
Fm^{254}		7.20	85	ion ch, spect
		7.16	14	spect
		7.06	0.9	spect
Fm^{255}		7.12	< 0.4	α-e
		7.09	0.4	spect
		7.03	94	spect
		6.97	5	spect
		6.90	0.8	spect
Mv^{255}		7.34		ion ch
102^{253}		8.8		ion ch
102^{254}		8.3		ion ch

ion ch	= ion chamber
spect	= magnetic spectograph
α-γ, α-e, or γ-γ	= α-γ, α-e, or γ-γ coincidences
emuls	= energy or intensity measurement in an emulsion
γ	= gamma ray energy measurement
e	= conversion electron energy measurement
*	= energy determined from closed decay energy cycles

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