ALPHA RADIOACTIVITY[1]

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INTRODUCTION

A comparison of the number of α-emitters known at present with those known a few years ago serves as a rough index of the comparative research activity on α-radioactivity and associated problems. By 1944 just 26 α-emitters had been definitely identified and reported, and of these all but one were members of the natural radioactive families. (Some others were found during the war years but publication was delayed.) In 1948 the total number of α-emitters had climbed to nearly 90, and at the end of 1953 there were more than 160 known. The increase in numbers of α-emitters has been accompanied by diversification of the information attainable by the treatment of α-decay data as well as a better insight into those features of α-radioactivity already recognized. It is perhaps worth recalling, however, that the basic α-decay theory (1, 2) was developed in the "days of the natural radioactivities" and precise absolute α-energies were determined during this period (3).

The huge increase in numbers of α-emitters is a result of several stimuli. The wartime military efforts in atomic energy were directly concerned with several new α-emitters, and as a result of their preparation a number of others appeared as by-products. This work stimulated the desire to know the nuclear properties of other isotopes of these elements and developed into a search for higher transuranium elements as well. It is interesting to note that at present there are as many elements known above U as there are between U and Bi. Another important source of α-emitters came with the construction of particle accelerators operating in a new high-energy range. With the use of such instruments (particularly the Berkeley 184-inch cyclotron), exploration into the region of neutron deficient isotopes became possible and resulted in the discovery of a wide range of new α-emitters including a group among the rare earth elements.

This review will be confined in large measure to the development of a few topics which have stemmed from the investigations of the past several years. The classical work on α-radioactivity will not be covered, and no special treatment will be given to the natural α-emitters.

A few brief statements outlining these newer developments are given in the following:

(*a*) Regularities in α-decay energy.—It is possible to correlate decay energies on a semi-empirical basis, and the observed regularities make it possible to predict rather closely the decay energies of unknown species.

[1] The survey of the literature pertaining to this review was concluded in April, 1954.

(*b*) Regularities of decay lifetimes.—It is now known that one-body α-decay theory, not far different in form from that originally proposed, is capable of yielding precise lifetime values for most even-even nuclei but not for other types. Lifetimes can be predicted on a semi-empirical basis for almost all cases.

(*c*) New developments in α-decay theory.—The results to be cited on odd nucleon types and on the complex spectra of all types serve to delimit the applicability of present α-decay theory and to define the problems which must be solved by a more comprehensive theory. Some attempts to build upon the classical theory will be mentioned.

(*d*) Spectroscopic states deduced from alpha decay.—Almost all α-emitters show complex spectra when examined with instruments of high resolution. The mapping of nuclear spectroscopic states populated in the α-decay process has yielded substantial information on the general picture of energy levels in the heavy element region.

Unfortunately, it will not be possible in this review to discuss the important advances in detection and energy determination of α-particles. Also omitted are the means for producing the many α-emitters and any individual discussion of many of the interesting new species.

Alpha Decay Energy

Somewhat beyond the middle of the periodic system α-emission becomes energetically possible for all nuclides along the band of β-stability. Alpha decay lifetimes are, however, strongly dependent upon α-decay energies, and only when the decay energy exceeds a certain value do the lifetimes decrease into the range where radioactivity can be detected. Since the potential barrier against α-decay increases with atomic number, the "critical" α-decay energy increases with atomic number. As a rough gauge of this effect we may say that the energy required for a half life of 10^{12} years is 2 Mev in the region of Sm (atomic number 62) and 4 Mev in the region of U (atomic number 92). The energy dependence in the heavy element region is such that doubling the energy (4 Mev to 8 Mev) decreases the half life by a factor of more than 10^{20}.

The general energy trends along the line of maximum β-stability are indicated in Figure 1 which is similar to a drawing published by Kohman (4). The curve was constructed by making use of available mass data in the region in which α-emission is not discernible. Aside from the smooth curve showing α-decay energies, three other lines are shown. One of these simply shows the line of demarcation between stability and instability toward α-emission, and the other two show the approximate positions at which half lives would be 10^8 years and 10^{-4} years ($\sim$1 hr.). As mentioned, the smooth curve goes through the center of β-stability for each mass number. If we also consider neutron deficient isotopes of each element, it will be found that their α-decay energies are greater, a point which will be considered in more detail presently. Two such series of isotopes (for Gd and U) are indicated by points and segments of curves crossing the main curve. The position of shell

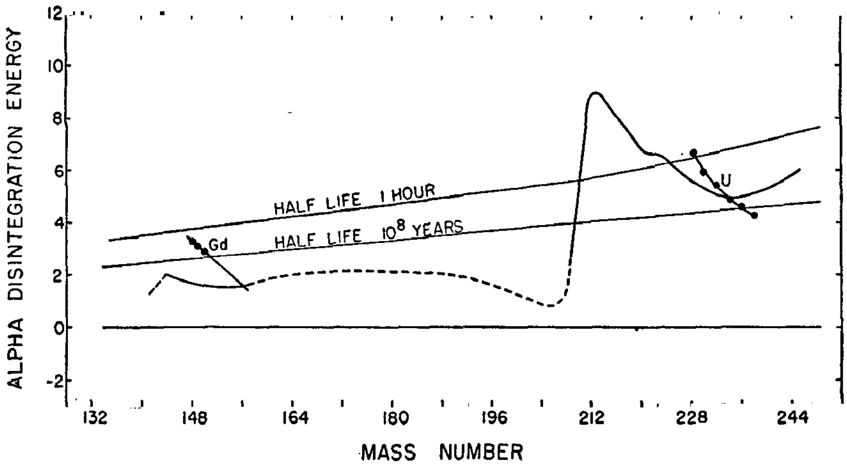

FIG. 1. Alpha decay energy profile. Broken line portion of curve indicates region where direct α-decay measurements are absent. Plotted points on segments of crossing curves pertain to known α-emitters of Gd and U. Half life guide lines indicate positions of applicable lifetimes as a function of mass number.

closures at 82 protons and 126 neutrons is readily seen through its influence on α-decay energy.

The mass data available are not nearly accurate enough to define the curve of Figure 1 with the precision required to be useful as a guide for α-decay properties. Uncertainties of several Mev are present in most of the data while a fraction of a Mev is sufficient to change a lifetime from the region of easy observation to that of extremely long periods. The curve is consistent with known α-decay properties and can be altered in detail as more precise data become available.

Summary of alpha energies.—A compilation of all α-energies in the heavy element region is given in Table I.[2] The data shown for each α-emitter represent what is considered to be the most reliable set. In general, only those α-groups actually measured are included, although from γ-ray and conversion electron data there may be evidence for other α-groups. In a few cases α-γ coincidence measurements showed the presence of a new α-group in coincidence with a specific γ-ray, but the α-energy could be better defined from that of the γ-ray. Where the interpretation was unambiguous such

[2] Most of the references for data shown here and in Figure 2 will be found in the 1953 Table of Isotopes (reference 25). For newer data consult the following: Po^{206} (5), Em^{211} (6), Em^{218} (7), Em^{220} (8), Ra^{222} (7), Ra^{224} (9), Th^{226} (7), Th^{228} (9), Th^{230} (10, 113), Th^{232} (11), Pa^{231} (114), U^{230} (7), U^{232} (8), U^{234} (12), U^{238} (11), Pu^{234} (115), Pu^{238} (13), Pu^{240} (8), Pu^{241} (8), Pu^{242} (8), Am^{241} (14), Am^{243} (14), Cm^{245} (116), Cm^{243} (8, 15), Cm^{241} (16), Bk^{249} (17), Cf^{246} (18), Cf^{248} (19), Cf^{249} (17, 19, 20), Cf^{250} (17, 19, 20), Cf^{252} (17, 19, 20), 99^{247} (21), 99^{253} (19, 20, 22, 23), 100^{254} (19, 22, 23, 24) and 100^{255} (19).

TABLE I

ALPHA PARTICLE ENERGIES AND ABUNDANCES

Alpha emitter	Alpha particle energy (Mev)	Relative abundances (%)	Type of measurement
$Bi^{<198}$ (1.7 m.)	6.2		ion ch
Bi^{198}	5.83		ion ch
Bi^{199}	5.47		ion ch
Bi^{201}	5.15		ion ch
Bi^{203}	4.85		range
Bi^{209}	~3.15		range
Bi^{210} (~10^6 y)	4.93		ion ch
Bi^{211}	6.272	16	spect
	6.618	84	spect
Bi^{212}	5.481	0.016	spect
	5.603	1.1	spect
	5.622	0.15	spect
	5.765	1.7	spect
	6.047	69.9	spect
	6.086	27.2	spect
Bi^{213}	5.86		ion ch
Bi^{214}	5.444	55	spect
	5.505	45	spect
Po^{200}	5.84		ion ch
Po^{201}	5.70		ion ch
Po^{202}	5.59		ion ch
Po^{204}	5.37		ion ch
Po^{205}	5.2		ion ch
Po^{206}	5.064	4	spect
	5.218	96	spect
Po^{207}	5.10		ion ch
Po^{208}	5.108		spect
Po^{209}	4.877		spect
Po^{210}	4.5	weak	α-γ coinc.
	5.299	100	spect
Po^{211} (0.52 s)	6.56	0.53	spect
	6.88	0.50	spect
	7.434	99	range
Po^{211}? (25 s)	7.14		ion ch
Po^{212}	8.776		spect
Po^{213}	8.336		ion ch
Po^{214}	7.680		spect
Po^{215}	7.365		range
Po^{216}	6.774		spect
Po^{217}	6.5		ion ch
Po^{218}	5.998		spect
$At^{<202}$	6.50		ion ch
$At^{<203}$	6.35		ion ch

TABLE I—*Continued*

Alpha emitter	Alpha particle energy (Mev)	Relative abundances (%)	Type of measurement
At^{203}	6.10		ion ch
At^{205}	5.90		ion ch
At^{207}	5.75		ion ch
At^{208} (1.7 h)	5.65		ion ch
At^{209}	5.65		ion ch
At^{210}	5.355	37	spect
	5.437	31	spect
	5.519	32	spect
At^{211}	5.862		spect
At^{213}	9.2		range
At^{214}	8.78		ion ch
At^{215}	8.00		ion ch
At^{216}	7.79		ion ch
At^{217}	7.02		ion ch
At^{218}	6.63		range
At^{219}	6.27		ion ch
Em^{208}	6.138		spect
Em^{209}	6.02		ion ch
Em^{210}	6.036		spect
Em^{211}	5.605	~1.5	spect
	5.778	67	spect
	5.847	33	spect
Em^{212}	6.262		spect
Em^{215}	8.6		ion ch
Em^{216}	8.01		ion ch
Em^{217}	7.74		ion ch
Em^{218}	6.53	weak	α-γ coinc
	7.127	100	spect
Em^{219}	6.214	4	spect
	6.434	12	spect
	6.559	15	spect
	6.824	69	spect
Em^{220}	5.747	~0.3	spect
	6.282	100	spect
Em^{222}	5.486		spect
Fr^{212}	6.339	24	spect
	6.387	39	spect
	6.409	37	spect
Fr^{217}	8.3		range
Fr^{218}	7.85		ion ch
Fr^{219}	7.30		ion ch
Fr^{220}	6.69		ion ch
Fr^{221}	6.05	~25	ion ch
	6.30	~75	ion ch
Ra^{213}	6.90		ion ch

TABLE I—*Continued*

Alpha emitter	Alpha particle energy (Mev)	Relative abundances (%)	Type of measurement
Ra^{219}	8.0		ion ch
Ra^{220}	7.43		ion ch
Ra^{221}	6.71		ion ch
Ra^{222}	6.23	weak	α-γ coinc
	6.554	100	spect
Ra^{223}	5.419	3	spect
	5.487	2	spect
	5.528	9	spect
	5.596	24	spect
	5.704	53	spect
	5.730	9	spect
	5.860	weak	spect
Ra^{224}	5.445	5.2	spect
	5.681	95	spect
Ra^{226}	4.592	5.7	spect
	4.777	94	spect
Ac^{221}	7.6		range
Ac^{222}	6.96		ion ch
Ac^{223}	6.64		ion ch
Ac^{224}	6.17		ion ch
Ac^{225}	5.80		ion ch
Ac^{227}	4.942		spect
Th^{223}	7.55		ion ch
Th^{224}	7.13		ion ch
Th^{225}	6.57		ion ch
Th^{226}	6.037	0.6	spect
	6.100	1.8	spect
	6.228	21	spect
	6.336	77	spect
Th^{227}	5.651	~2	spect
	5.704	15	spect
	5.728	~1	spect
	5.749	17	spect
	5.796	2	spect
	5.860	4	spect
	5.922	~2	spect
	5.952	13	spect
	5.972	21	spect
	6.001	5	spect
	6.030	19	spect
Th^{228}	5.173	0.2	spect
	5.208	0.4	spect
	5.338	28	spect
	5.421	71	spect

TABLE I—*Continued*

Alpha emitter	Alpha particle energy (Mev)	Relative abundances (%)	Type of measurement
Th^{229}	4.85	~70	ion ch
	4.94	~20	ion ch
	5.02	~10	ion ch
Th^{230}	4.437	0.07	spect
	4.471	0.2	spect
	4.613	23.4	spect
	4.682	76.3	spect
Th^{232}	(3.93)	24	γ energy
	3.994	76	ion ch
Pa^{226}	6.81		ion ch
Pa^{227}	6.46		ion ch
Pa^{228}	5.85	25	ion ch
	6.09	75	ion ch
Pa^{229}	5.69		ion ch
Pa^{231}	4.660	1–3	spect
	4.720	11	spect
	4.838	3	spect
	4.938	25	spect
	4.998	23	spect
	5.015	23	spect
	5.042	11	spect
U^{227}	6.8		ion ch
U^{228}	6.67		ion ch
U^{229}	6.42		ion ch
U^{230}	5.662	0.8	spect
	5.819	31	spect
	5.888	68	spect
U^{231}	5.45		ion ch
U^{232}	5.132	0.3	spect
	5.261	32	spect
	5.318	68	spect
U^{233}	4.731	2	spect
	4.780	15	spect
	4.823	83	ion ch
U^{234}	4.59	~0.3	α-γ coinc
	4.714	26	spect
	4.763	74	ion ch
U^{235}	4.20	4	ion ch
	4.40	83	ion ch
	4.47?	~3	ion ch
	4.58	10	ion ch
U^{236}	(4.45)	27	γ energy
	4.499	73	ion ch
U^{238}	(4.135)	23	γ energy

TABLE I—*Continued*

Alpha emitter	Alpha particle energy (Mev)	Relative abundances (%)	Type of measurement
	4.182	77	ion ch
Np^{231}	6.28		ion ch
Np^{233}	5.53		ion ch
Np^{235}	5.06		ion ch
Np^{237}	4.77		ion ch
Pu^{232}	6.58		ion ch
Pu^{234}	(6.14)	14	γ energy
	6.19	86	ion ch
Pu^{235}	5.85		ion ch
Pu^{236}	(5.71)	20	γ energy
	5.75	80	ion ch
Pu^{238}	5.352	0.1	spect
	5.452	28	spect
	5.495	72	spect
Pu^{239}	5.099	11	spect
	5.137	20	spect
	5.150	69	spect
Pu^{240}	5.014	0.1	spect
	5.118	24	spect
	5.162	76	spect
Pu^{241}	4.848	25	spect
	4.893	75	spect
Pu^{242}	4.854	20	spect
	4.898	80	spect
Am^{237}	6.01		ion ch
Am^{239}	5.75		ion ch
Am^{241}	5.379	1.4	spect
	5.433	13.6	spect
	5.476	84	spect
	5.503	0.2	spect
	5.535	0.3	spect
Am^{243}	5.171	~3	spect
	5.225	13	spect
	5.267	84	spect
Cm^{238}	6.50		ion ch
Cm^{240}	6.25		ion ch
Cm^{241}	5.95		ion ch
Cm^{242}	5.965	0.035	spect
	6.066	26.3	spect
	6.110	73.7	spect
Cm^{243}	5.679	3	spect
	5.732	13	spect
	5.777	78	spect
	5.985	6	spect

TABLE I—*Continued*

Alpha emitter	Alpha particle energy (Mev)	Relative abundances (%)	Type of measurement
Cm^{244}	5.755	25	spect
	5.798	75	spect
Cm^{245}	5.34		ion ch
Bk^{243}	6.20	17	ion ch
	6.55	53	ion ch
	6.72	30	ion ch
Bk^{245}	5.90	34	ion ch
	6.15	48	ion ch
	6.33	18	ion ch
Bk^{249}	5.4		ion ch
Cf^{244}	7.15		ion ch
Cf^{246}	6.711	22	spect
	6.753	78	spect
Cf^{248}	6.26		ion ch
Cf^{249}	5.82	90	ion ch
	6.00	10	ion ch
Cf^{250}	6.04		ion ch
Cf^{252}	6.13		ion ch
99^{247}	7.35		ion ch
99^{253}	6.62		ion ch
100^{254}	7.20		ion ch
100^{255}	7.1		ion ch

α-groups are included. Similarly, an α-group may be included which is not directly observed because it cannot be resolved from a neighboring intense group, but for which γ-rays or conversion electrons define this group unambiguously. Such α-energies are enclosed in parentheses and the type of measurement designated as "γ energy." We have arbitrarily omitted the so-called "long range α-particles" of Po^{212} and Po^{214} (even though they do appear in low abundance in the spectra) since these are not transitions from the ground states or from measurable metastable states.

It is difficult to assign meaningful limits of error for the individual measurements and they are omitted. In general, those made with a spectrograph may be in error by as much as 15 kev, but a large number are perhaps accurate to less than 5 kev; those made by the ionization chamber method will vary in accuracy from 10 to 75 kev; and range measurements in photographic emulsions are even more difficult to assess. Energy differences between groups in a particular spectrum are in general more accurate than the absolute α-energy. Most energies determined are not absolute but depend upon comparison with standards, so a list of some of the most accurate values (absolute and comparative) suitable for standards are shown in Table II.

TABLE II

ABSOLUTE ALPHA PARTICLE ENERGY DETERMINATIONS INCLUDING SOME VALUES MEASURED RELATIVE TO RaC′*

Alpha emitter	Briggs (3)	Sturm and Johnson (27)	Rosen-blum, Dupouy (28)	Lewis, Bowden (29)	Collins, McKenzie, and Ramm (30)	Best value, Briggs (26)
RaC′ (Po^{214})	7.680	7.683				7.680
ThC′ (Po^{212})	8.776†		8.780	8.776†	8.786	8.780
Po^{210}		5.298	5.299	5.299†	5.305	5.301
ThC (Bi^{212})α_0	6.082†		6.087	6.082†	6.090	6.086
ThC (Bi^{212})α_{40}	6.043†		6.048	6.042†	6.050	6.047

* All measurements cited were made with magnetic spectrographs except those of Sturm & Johnson (27) who used an electrostatic device. The values listed for the magnetic measurements were corrected as done by Briggs (26) in terms of slight revisions of fundamental constants used in the conversion of $H\rho$ to energy.

† Measured relative to RaC′.

Alpha decay energy systematics.—The value of a curve such as that in Figure 1 is to help visualize in broad outline the conditions and regions of α-instability. A good deal more is to be learned from a more detailed examination of the regions where α-radioactivity is prominent. It is observed that α-decay energies[3] fall into well behaved patterns, the recognition of which has proved considerably useful for a number of purposes. Two of the functions of these correlations will be mentioned.

Alpha decay series (containing relatively few β-decay steps) provide a continuous series of energy increments from the region of the element Pb to the highest elements possible. The many decay chains either combine through decay or can be related energetically by measured neutron binding energies. By analyzing these data, it is possible to obtain a rather detailed picture of the energy surface[4] in the heavy element region. The shape of the

[3] Alpha decay energy or simply decay energy will refer to the Q value for the α-emission process and is therefore immediately transferable into a mass of energy difference between ground states of parent and daughter. The actual α-particle measured for the ground state transition is of appreciably lower energy because of the energy carried off by the recoil atom. Of course, the α-groups leading to excited states are of still lower energy. The measured energies of α-groups will be referred to as "α-particle energies" or "particle energies" to distinguish them from "decay energies."

[4] "Energy surface" refers to a surface defined by the energy contents or masses of the nuclides.

energy surface is readily delineated from these data, and regions of greater or lesser stability stand out clearly. A schematic representation of such a surface, exaggerated for purposes of illustration, was given by Perlman, Ghiorso & Seaborg (31). A complete and critical compilation of all decay energy data, and the atomic masses calculated from these has been made by Seaborg & Glass (32). The data include masses of nuclides not yet prepared and these were derived from decay energies estimated by methods which will be indicated below.

Of great value to the experimentalist has been the ability to predict α-energies, and the agreement between predicted and measured values often serves

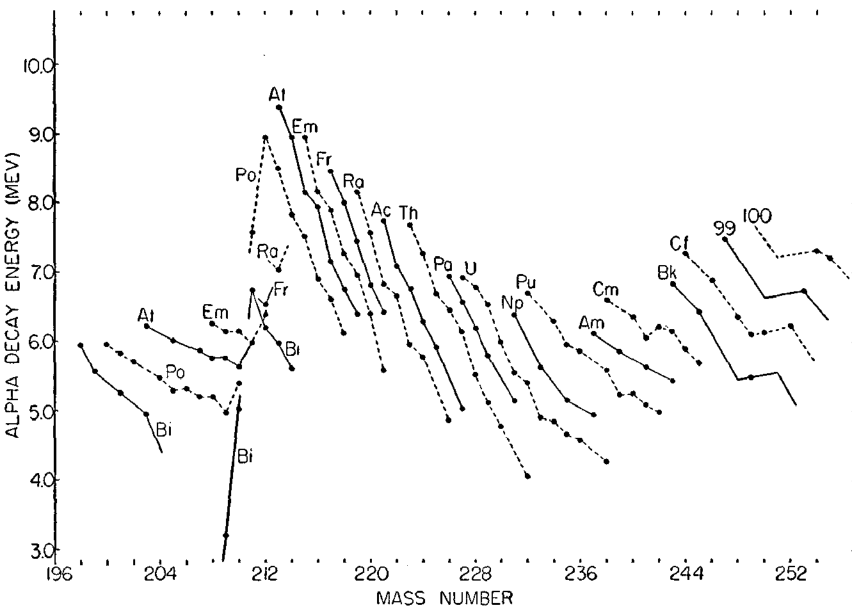

FIG. 2. Alpha decay energy versus mass number.

as a criterion for isotopic assignment. Furthermore, if the energy can be predicted, the half life can be calculated. The forecasting of both α-energy and half life has been of inestimable value in the preparation and identification of higher and higher elements.

A number of systems for correlating α-decay energies have been employed and perhaps that most widely used is illustrated in Figure 2. Here, the isotopes of each element on a mass number versus 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 $\sim$212) α-energies decrease with increasing mass number for each element; that is, with increasing neutron number. This system in some modification has been used by a number of workers (31, 33 to 37), while others have used contour map presentation (38, 39) and still different methods (40).

Before turning to the regions in Figure 2 where sharp changes in the lines occur, let us consider the broad region of regular behavior. The semi-empirical method of calculating atomic masses of Weizsäcker (41), as developed further by Bethe & Bacher (42) and by Bohr & Wheeler (43), pictures the energy surface as a trough having parabolic sections at constant mass number, A. The bottom of the trough goes through the β-stable nuclides and if the energy coordinate is expressed in terms of the mass defect, the line along the bottom becomes the familiar "best" mass defect curve. It can be shown graphically (31) or analytically (4) that the observed trend of α-energy with mass number (Fig. 2) is to be expected from this picture. Differences in slope and spacing of the lines can be interpreted in terms of departures from extreme regularity of the trough such as small changes in curvature of the trough or of its slope.

The dramatic inversion in the α-energy trend around mass number 212 is a consequence of the major closed shells in this region (37, 44). We can see what happens more precisely by following the curve for the Po isotopes. From Po^{218} down to Po^{212} the curve follows the normal trend; then Po^{211} is seen to have considerably lower α-energy than Po^{212}. This can readily be shown to be a reflection of the fact that the binding energy of the 126th neutron in Pb (Pb^{207}–Pb^{208}) is greater than that of the 128th neutron in Po (Po^{211}–Po^{212}). Similarly, since the binding energy of the 125th neutron in Pb (Pb^{206}–Pb^{207}) is greater than that of the 127th neutron in Po (Po^{210}–Po^{211}), the α-energy of Po^{210} is lower than that of Po^{211}. After the neutron shell of 126 is well passed and the neutron binding energies change monotonically for both parents and daughters, the regular trend of increasing α-energy with decreasing neutron number is resumed (see region between Po^{208} and Po^{203}).

The curve for Bi is seen to parallel the Po curve with a wide energy spacing between them. This energy spacing is presumably a consequence of the 82 proton shell. The reappearance of α-radioactivity in highly neutron deficient isotopes of Bi (45) was the clue needed to establish the generalness of this effect of crossing the region of 126 neutrons (44 to 52).

It will be noted that the α-energies for the isotopes with 128 neutrons would be expected to become progressively greater for each higher proton number. Half lives will accordingly be very short in this region so that preparation and identification of such nuclides would be difficult. However, more neutron deficient isotopes should be more stable just as Po^{210} is more stable than Po^{212}. Such a region has been found for At, Em, and even for Ra, showing that the effect of 126 neutrons extends at least this high (51, 52). Undoubtedly these points shown on Figure 2 join to those of higher neutron number by going through sharp peaks higher than those shown for Po and At.

The question arises as to whether or not there is evidence for other closed shells or subshells on the basis of α-decay data. A situation similar to that at 126 neutrons, but considerably more subdued, seems to occur at neutron number 152 (19). The evidence comes principally from the α-energy trend of Cf isotopes (element 98) as seen in Figure 2 showing that the Cf isotope with 154 neutrons has a higher energy than those of the next few isotopes of lower mass number. The fragmentary data on elements 99 and 100 are not out of line with this concept and the lines are drawn in Figure 2 according to expectations. As will be explained later, the positions of closed shells can be correlated with energy level spacings between certain excited states and their ground states but, in this respect, the single nuclide known with 152 neutrons (Cm^{248} from α-decay of Cf^{252}) does not reflect a closed shell configuration (53, 54).

It will be noted in Figure 2 that the energy increments from isotope to isotope along many of the curves are not very uniform. Aside from the marked inversion in trend in the region of Pb and the probable small inversion in con-

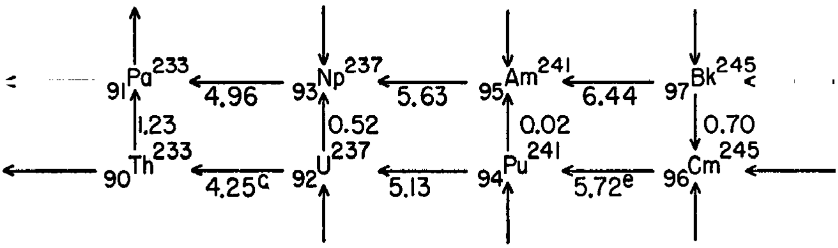

FIG. 3. Decay cycles for part of $4n+1$ family. Code: ← α-decay, ↑ negative β-decay, ↓ electron capture decay. Numerals indicate energies in Mev; those with superscript "c" are calculated by closing the cycles; those with superscript "e" are estimated as by the use of Figure 2; those unmarked are measured values.

junction with 152 neutrons, it is seen that in some places the isotopes seem bunched and in others relatively spread out. It has been suggested that there are subshells at 92 protons (55, 56) and at 88 protons (56) in explanation of some of these irregularities. Other inferences of α-decay energies on possible subshells have been discussed by Broneiwski (57).

Decay energies from energy-balance cycles.—As a guide in research on new heavy isotopes, the ability to predict decay properties is of great value. By interpolation and extrapolation, the curves of Figure 2 may be used to estimate α-energies and these as well as measured values can be used in constructing a self-consistent system of energy-balance cycles which can be used in turn to calculate degrees of β^- instability and other α-energies.

To illustrate this method of correlating decay energies (32), a segment of the decay cycle representation of $4n+1$ type[5] nuclei is shown in Figure 3. A few examples of the uses of these cycles will be mentioned. It is noted that by making use of three measured decay energies the α-energy of the 6.8 day

[5] The type "$4n+1$" means that all mass numbers are divisible by 4 with remainder 1. All nuclei connected by α- and β-decay processes are of the same type.

β^- emitter U^{237} is calculated to be 4.25 Mev. This is almost identical with the decay energy of U^{238} which has a half life of 4.5×10^9 years. The partial α-decay half life of U^{237} would be expected to be at least as long. Accordingly, the α-branching of U^{237} would be only of the order of 10^{-12} so that this mode of decay would be most difficult to observe. On the contrary, the α-branching of Pu^{241} was similarly estimated to be about 10^{-5} which was within reach for measurement and the α-energy as subsequently measured is shown in Figure 3.

Another use of these cycles has to do with predictions of β-stability. If one considers the possibility that Cm^{245} is a β^--emitter and that its preparation would therefore also produce Bk^{245}, the idea should be rejected because it is seen that Bk^{245} is unstable with respect to Cm^{245} by about 0.7 Mev. The estimated α-energy of Cm^{245} which goes into this calculation cannot possibly be in error by an amount to reverse this conclusion.

An extension of these cycles to still higher elements gives a means of making predictions into a region where measurements have not been made, and these predictions serve as an important guide to the experiments. Other cycles can be devised to join different nuclear types through measured binding energies. With a single neutron binding energy measurement joining two series, other neutron binding energies can be calculated (32).

Alpha emitters just below lead.—The removal of neutrons from any element increases the potential toward α-decay and this is the basis for the main trend in Figure 2. Alpha active nuclides of Au and Hg have been prepared by removing many neutrons from the stable isotopes (58). In the case of Au, the stable isotope Au^{197} is estimated to have an α-decay energy of only 1 to 2 Mev, while the isotope observed with an α-energy of 5.1 Mev is believed to lie in the mass number range 183 to 187. As neutrons are removed, successive isotopes become more unstable toward orbital electron capture also, but since α-decay lifetimes are extremely sensitive to energy, this mode of decay should at some point become discernible.

One other α-emitter in this region has been reported (59), a component of natural W. The extremely low specific activity seems out of line with the measured energy (3.2 Mev) if the emitter has the abundance of one of the known W isotopes, so the authors postulate the existence of a rare isotope (W^{178}) in the natural mixture in amounts too small to detect by mass spectroscopy.

Rare earth alpha emitters.—Among the rare earth elements we pass through a region where stable or slightly deficient nuclides can decay by α-emission to the closed shell of 82 neutrons. Such a nuclide with 84 neutrons is Sm^{146} which is β-stable but missing in nature because of its relatively short α-half life ($\sim5\times10^7$ years) (60). The α-energies are summarized in Figure 4 and although the curves are fragmentary as compared with those in the heavy element region, the basic structure as related to the 82 neutron shell is unmistakable. The point assigned to Nd^{144} is of special interest because Nd^{144} is a component of natural Nd (61).

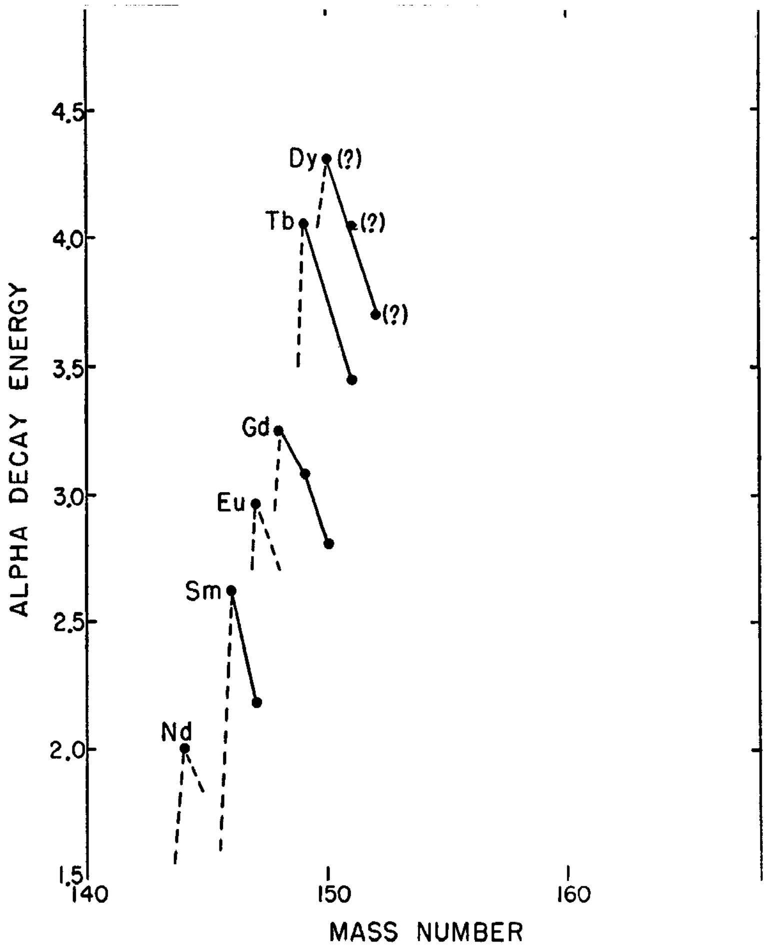

FIG. 4. Alpha decay energy versus mass number in the rare earth region.

COMPLEX ALPHA SPECTRA

As in other decay processes, the appearance of multiple groups in the α-emission process may be considered as the result of competition in populating available energy levels. It will be seen that α-decay lifetimes are influenced by a number of factors and among these is the sharp dependence of lifetime with decay energy. Consequently, it would not be expected that transitions to high-lying levels (say 1 Mev) would be readily observed. There are, however, selection processes operating which can delay the highest energy group and cause lower energy groups to be the most prominent. As yet, there is no systematic formulation of "selection rules" for the α-decay process. The development of α-decay theory with this as an objective is undoubtedly the most important step now faced.

The present discussion will be concerned largely with the regularities which are appearing with respect to the location of energy levels, their spectroscopic designation, and in the degree to which these states are populated. As already stated, only a start has been made in developing reasons for preference in populating certain states.

Even-Even Alpha Emitters

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. In each of the many cases which have been examined in detail, the main α-group is that of highest energy and there is no evidence that the group is followed by γ-radiation. To this extent at least the even-even α-emitters are well behaved according to existing α-decay theory.

In examining a number of even-even α-emitters around U and in the transuranium region, it was noted that each had a second prominent α-group of some 40 to 50 kev lower energy than the ground state transition (62). The abundance of this group was always in the range 15 to 30 per cent.[6] (We shall see presently that the states reached by these α-groups apparently all have spin 2 and even parity and we shall call each the "first even spin state" or simply the "first even state.")[7] When lower elements or lower neutron numbers of a particular element are considered, the same states are identified but the energy level spacings above the ground states become progressively greater and the abundances of the α-groups populating these states progressively lower. A summary of the energy spacings between the ground state and first even state as a function of neutron number and proton number is shown in Figure 5. The points divide into families according to atomic number and appear to reach maxima for nuclei with 126 neutrons. In some cases, the points in Figure 5 were determined from γ-ray spectra rather than from observation of the α-groups.

It has already been deduced by several authors (63, 64, 65) that the first excited states of even-even nuclei in general are 2+ states and this applies to regions other than that of the heavy elements and irrespective of the particular energy spacing of the levels. There is theoretical justification for the 2+ assignment both from modifications of the independent particle model (66, 67) and from the collective model (68, 69). There is also theoretical explanation (67, 69) and empirical proof (62, 65, 70, 71) that the energy

[6] We shall define "abundance" to indicate the number of α-particles in a particular group relative to the total number of α-particles.

[7] It is worth recalling that in conserving parity in the α-decay of an even-even emitter, the even spin states must have even parity and the odd spin states odd parity. A corollary is that γ-ray transitions from any of these excited states to the ground state must be electric transitions and not magnetic.

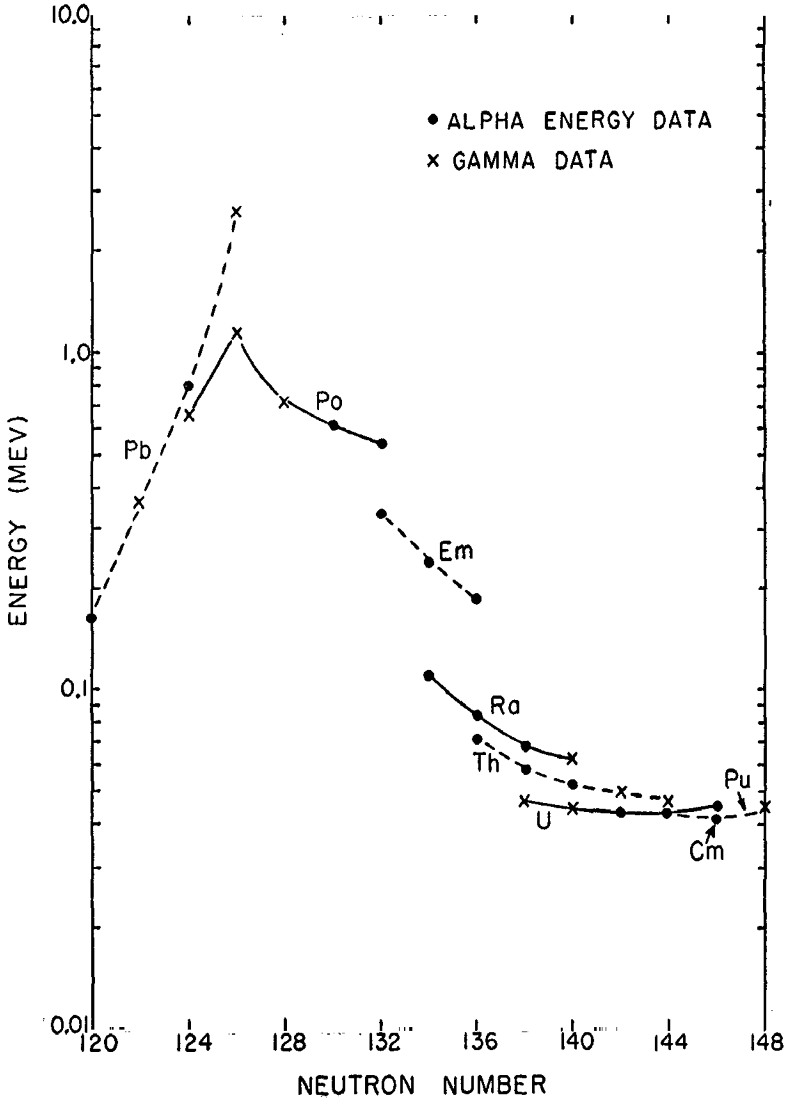

FIG. 5. First excited state energies of even-even nuclei in the heavy element region.

level spacing for the first excited state goes through a maximum at each closed shell as is seen in Figure 5 for the 126 neutron shell.

Two typical even-even α-spectra are shown in Figure 6 and for the present we shall focus attention on the two lowest states corresponding to the two α-groups considered. The states assigned $2+$ are the "first even states"

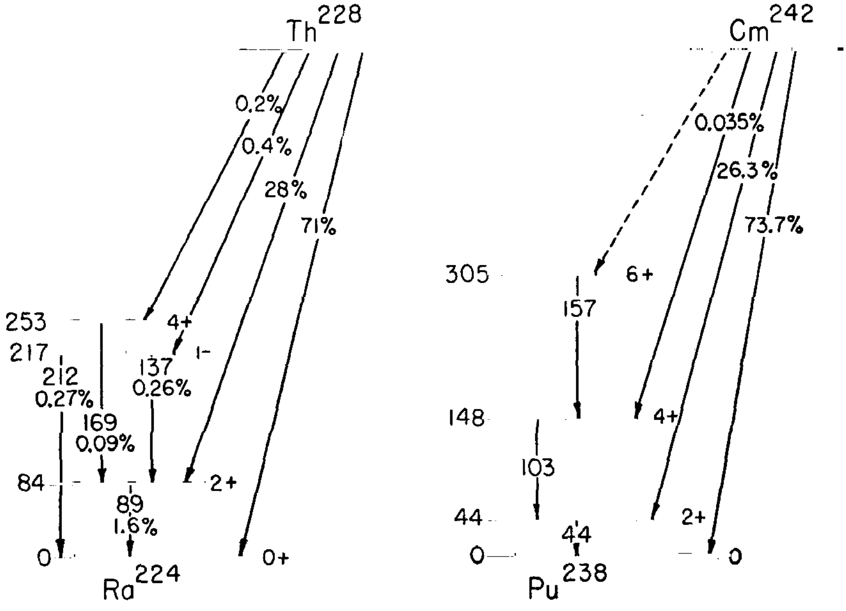

FIG. 6. Decay schemes of Th^{228} and Cm^{242}.

already mentioned and are designated so because they de-excite to the ground state by electric quadrupole (E2) transitions.[8] Since there is no evidence to the contrary, we shall assume that the "first even state" is in each case the "first excited state."

Rare alpha groups (*higher even states and first odd state*).—Many of the α-emitters which have lent themselves to detailed analysis have proved to have one or more additional groups of lower energy and in low intensity. The low intensities of these groups are not attributable alone to lower energy than the two main groups. If we calculate the lifetimes for the ground state transition and that to the first excited state according to current α-decay theory, the results are in substantial agreement with the measured lifetimes. However, the measured partial half lives for the higher transitions are considerably longer than the calculated values and we refer to such transitions as "hindered." This subject will be dealt with under the section on α-decay theory, and for the present we will consider only the energy level spacings and spectroscopic assignments.

In each case which could be examined in the necessary detail, there was

[8] The nature of the transition has been deduced from measurements of absolute conversion coefficients, relative L subshell conversion coefficients and α-γ angular correlations. The cases studied are the α-emitters Po^{210} (72), Ra^{222} (7), Ra^{224} (73, 74, 75), Ra^{226} (75), Th^{226} (7), Th^{228} (9, 76, 77, 78), Th^{230} (77, 79), U^{230} (7), U^{232} (8), U^{234} (8), U^{236} (80), Pu^{238} (13), Cm^{242} (15), and Cf^{246} (89). The excited states in question belong, of course, to the α-decay products.

found a rare α-group going to a state which decays by an E2 transition only to the 2+ state.[9] These states are those designated as 4+ in Figure 6 and will be known as the "second even states." From the nature of the γ-ray transition, the second state could be 0+, 2+ or 4+; the 4+ assignment is made largely from a theory to be mentioned presently which fixes it as a member of a rotational band of states 0+, 2+, 4+ $\cdots$. The fact that no crossover transition is seen from the second even state to the ground state may also be taken as partial evidence for the assignment.

In a few cases, very rare γ-rays have been seen (the α-groups would be below the limits for detection) and are assigned to transitions between the third and second even states (13, 15). In the case of Pu^{238} decay (13), the γ-ray was shown to be in coincidence with that between the 4+ and 2+ states. Since the energy of the state defined by the γ-ray corresponds closely with expectations if it were the third "even state" (6+) of the rotational band, it has been so designated (see Cm^{242} spectrum, Fig. 6). The theory behind these assignments will now be examined.

According to a theory of Bohr and Mottelson (68, 82), collective aspects of nuclear motion and individual particle aspects are coupled. In a "region well removed from a closed shell" there should be a series of energy levels corresponding to a rotational band in which only even states (0+, 2+, 4+ $\cdots$) appear for an even-even nucleus. On this basis, electric quadrupole transitions should predominate. Another requirement of the rotational spectrum in this region is that the states lie at energies proportional to $I_j(I_j+1)$, where I_j is the spin of the jth even state. For the levels 0+, 2+, 4+, 6+, the ratios of 4+/2+ and 6+/2+ would therefore be respectively 3.3 and 7.0. Figure 7 shows an extensive set of these ratios of the first and second even states, and it is seen that the agreement with expectations is excellent for the higher neutron numbers but gradually departs as the region of 126 neutrons is approached. Apparently the same behavior can be noted for even-even nuclei in the rare earth region in reference to the 82 neutron shell (83). The point for Pb^{208} in Figure 7 is of questionable significance since it is not at all certain that the first two excited states as deduced from Tl^{208} β^--decay are indeed 2+ and 4+. As an example of this uncertainty, a number of different measurements concerning the first excited state have resulted in different assignments: 1+ or 2+ (84), 2+ (85, 86, 87), 3− (88). In two cases, Pu^{238} and U^{234}, (α-decay of Cm^{242} and Pu^{238}) where a third even state is inferred, the energy ratio of this level to the 2+ level is indeed close to 7.0. The evidence for the higher state in the case of Pu^{238} decay is that the γ-ray used to define it is in coincidence with the γ-ray from the 4+ to the 2+ states (13).

[9] Conversion coefficient data defining the transition as E2 have been obtained in the α-decay of Cm^{242} (15) Pu^{238} (13, 81), U^{232} (8), Th^{228} (9). For other cases there is no direct information, but other regularities to be discussed presently make it highly likely that comparable states are being considered.

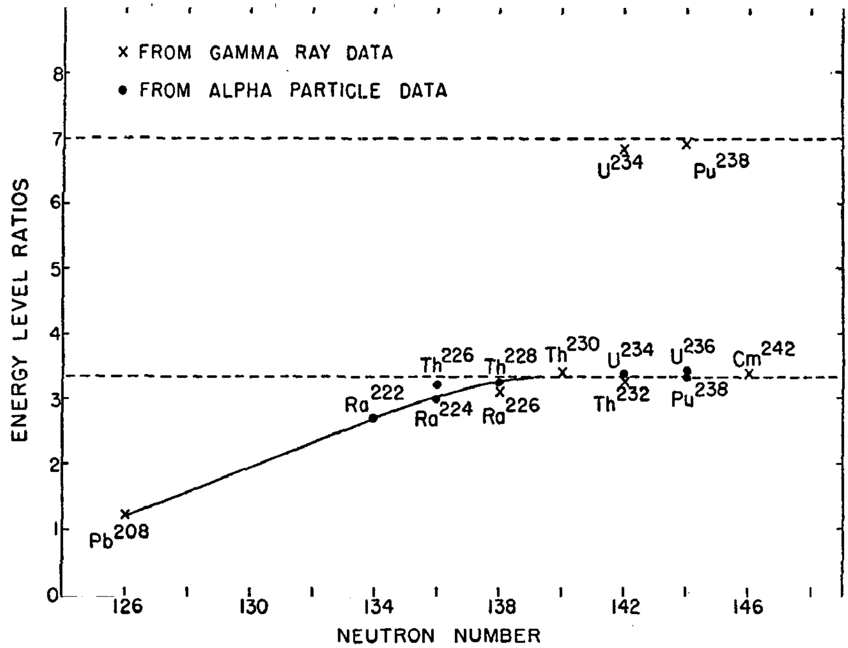

FIG. 7. Ratios of energies of the second and third even spin state to the first excited state. The broken lines represent the expected values from the Bohr-Mottelson theory for rotational levels in regions removed from closed shells.

In a number of cases, a state believed to be 1− has entered among the low-lying even states. The spectrum for Th^{228} which is typical of this type is shown in Figure 6 (9). In contrast to the second even state, this state always decays both to the first even state and to the ground state. The conversion coefficients of both conform with E1 transitions (9) as do more recent α-γ angular correlations made on Th^{226}, Th^{228} and U^{230} (89).

The 1− state has probably been identified in the decay of Th^{230} and U^{232} as well as for the three cases just mentioned. Significantly this state has been identified only among the low-lying excited states of nuclei of neutron numbers in the range 134 to 138 neutrons. From the fragmentary evidence at hand it seems possible that the state has a minimum energy at 136 neutrons and rises at both lower and higher neutron numbers.

With respect to the degree of population of the 1− state in the α-decay process, the data are too few to arrive at any generalizations. In the cases studied, the process seems to be competitive with that leading to the 4+ state for comparable energies.

Finally, it should be remarked that there is no ready explanation for a low-lying odd parity state such as this. Neither the independent particle model nor the collective model would predict such states in any straightforward manner.

Odd Nucleon Alpha Emitters

The α-spectra of nuclei having odd nucleons are in general considerably more complex than those of even-even nuclei and consequently have not been worked out with the same degree of certainty. Also, they may differ from each other considerably and have not yet yielded to a comprehensive generalized picture such as applies to the even-even nuclei.

Nevertheless, some regularities can be discerned, and among these is the appearance of rotational bands (14, 90) closely similar to those of the even-even nuclei. Interestingly enough, the fundamental state of the rotational band (where such a band shows up distinctly) is that populated in highest abundance, but it need not be the ground state and perhaps usually is not. The important implication of such spectra with respect to α-decay theory is that powerful "selection rules" are in force since the highest energy transition (that to the ground state) is often in very low intensity (91).

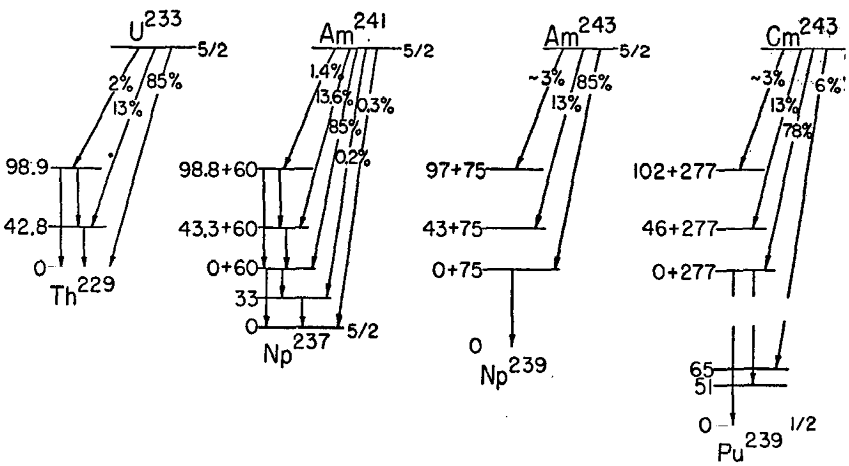

Fig. 8. Decay schemes of some odd-nucleon α-emitters.

Figure 8 shows some spectra which were selected to illustrate some of the regularities noted.[10] (Obviously it is not possible to discuss all spectra of these types and some, such as that for Th^{227} with eleven reported groups (92), are too complex for analysis at present.)

The partial spectrum for U^{233} is not representative of most of those examined in that it looks much like that of an even-even α-emitter. The energy level spacings for these states are much like those of Cm^{242} (see Fig. 6) and the relative populations of the states are roughly comparable, but an important difference to be noted is that the second excited state decays both to the first excited state and directly to the ground state. A possible explana-

[10] The references for the data comprising these α-spectra are Am^{241} (14, 91) Am^{243} (14), Cm^{243} (8, 15), U^{233} (8).

tion of this spectrum lies in its interpretation as a rotational band, the grounds for which are now sketched.

According to Bohr & Mottelson (68), the rotational band for a nucleus with an odd nucleon will have a fundamental state of spin I_0 and higher states of spins I_0+1, I_0+2, $\cdots$, all with the same parity. The spacings of these levels will go as $W+CI(I+1)$, where W and C are constants for a particular level sequence. For the U^{233} case the following equations may be set up:

$$E_{98.9} - E_{42.8} = C(I_0 + 2)(I_0 + 3) - C(I_0 + 1)(I_0 + 2) = 56.1$$
$$2C(I_0 + 2) = 56.1$$
$$E_{42.8} - E_0 = C(I_0 + 1)(I_0 + 2) - CI_0(I_0 + 1) = 42.8$$
$$2C(I_0 + 1) = 42.8.$$

The solution of the simultaneous equations gives $I_0=2.2$ and since the spin must be half integral we take the closest value, $I_0=5/2$. It should be mentioned that this analysis is extremely sensitive to the accuracy of the data; an error of only 0.5 kev in the 42.8 kev level, making it 43.3 kev, would change the calculated value of I_0 to exactly 2.5. If we accept 5/2 for the fundamental state, the spins of the other two levels become 7/2 and 9/2. The cascading γ-ray transitions could then be M1 and/or E2 and the cross over transition E2, which assignments are not out of order with the fact that both crossover and cascade γ-rays are observed.

The spectra for Am^{241}, Am^{243}, and Cm^{243} α-decay show quite similar rotational bands with calculated fundamental state spins of 5/2, but the fundamental states in these cases are not the ground states. Americium 241 and Am^{243} differ only in that this state is respectively 60 and 75 kev above the ground state. For Cm^{243}, the ground state transition has not yet been observed even though it has 277 kev higher decay energy than the main group, a fact established by α-γ coincidence counting (15).

It is perhaps not profitable at present to speculate in detail on the meaning of the complex spectra of the nuclear types under discussion. We believe that rotational bands which can be explained as a consequence of collective modes of nuclear motion are discernible. It is also probable that other important features of the spectra must bring in the concept of single particle states. Just what these states are and what guides the α-decay process to some and not others is still obscure. Some speculations on these matters as they apply to α-decay theory will be brought out in the section on this subject. It is worth reiterating here that no simple criterion or rule is likely to explain the spectra shown in Figure 8 as well as the extremely complex spectrum of Th^{227} and that of Pu^{239} which is a good deal simpler but different from both types.

Alpha Decay Lifetimes and Theory

It is possible to correlate α-decay lifetimes empirically and to arrive at systems which can be used to predict half lives. For example, regularities can be observed in plotting the half life with the mass number for successive elements. However, it is also possible to systematize the half lives in terms of parameters which are involved in current α-decay theory and thereby also obtain some information on the status of the theory.

It will be seen that the ground state transitions of even-even α-emitters are treated with extraordinary precision by basic one-body α-decay theory. However, analysis of the many α-spectra obtained during the past few years has shown clearly that more elaborate theory is required to account for the behavior of other nuclear types as well as for certain of the transitions to excited states of the even-even nuclei. The development of new approaches to cover these cases is currently in a formative stage. It will not be possible in this review to cover in detail either the old theory or the new approaches; rather, we shall emphasize those aspects of α-spectra which appear to require new forms for expression and indicate the direction some of these new forms are taking.

Basis for one body theory.—The initial conception by Gamow (1) and by Condon & Gurney (2) of the α-decay process as a barrier penetration problem has been cast into a number of forms differing in detail but basically all ending up with the decay rate expressed as the product of two factors: (*a*) a "frequency factor" which may be considered as the decay rate without the barrier; and (*b*) a "penetration factor" which expresses the probability of an α-particle emerging through the negative energy region of the coulombic potential barrier. The various solutions to the problem differ in the degree of rigor which is applied, and it might be stated that the sensitive portion is the "penetration factor" which is exponential in form and is handled virtually identically in the several treatments. (See, for example, references 93 to 97.)

The parameters which enter into the penetration factor are those which define the barrier for the α-particle of energy E and these are the nuclear charge and the effective nuclear radius. The frequency factor, likewise, is a function of the energy of the α-particle and nuclear radius and although approximations are introduced in its evaluation, this factor is relatively insensitive and does not strongly influence the results. It is probably here, however that the one body model breaks down as a representation of decay processes, that is, where single particle states are of importance.

It will be noted that of these parameters the nuclear charge has explicit meaning dissociated from the α-decay process and the α-energy and decay constant are subject to precise measurement, but the effective nuclear radius is a quantity which is not obviously meaningful for this process when determined from other nuclear phenomena, nor do such independent methods of measuring the radius give the desired precision for testing α-decay theory. The procedure to test the theory is therefore confined at present to see if calculated nuclear radii fall into a reasonable range and pattern of values or fluctuate in an unreasonable fashion (58, 93 to 100). Conversely, one may assume some function for nuclear radii, from this derive theoretical curves to express the decay constant in terms of the other parameters, and test the agreement with the measured decay constants (31, 98, 99, 101, 102). It is this second approach which has proved most useful in correlating a large number of data. Further discussion of this matter will follow as the data for even-even α-emitters are examined.

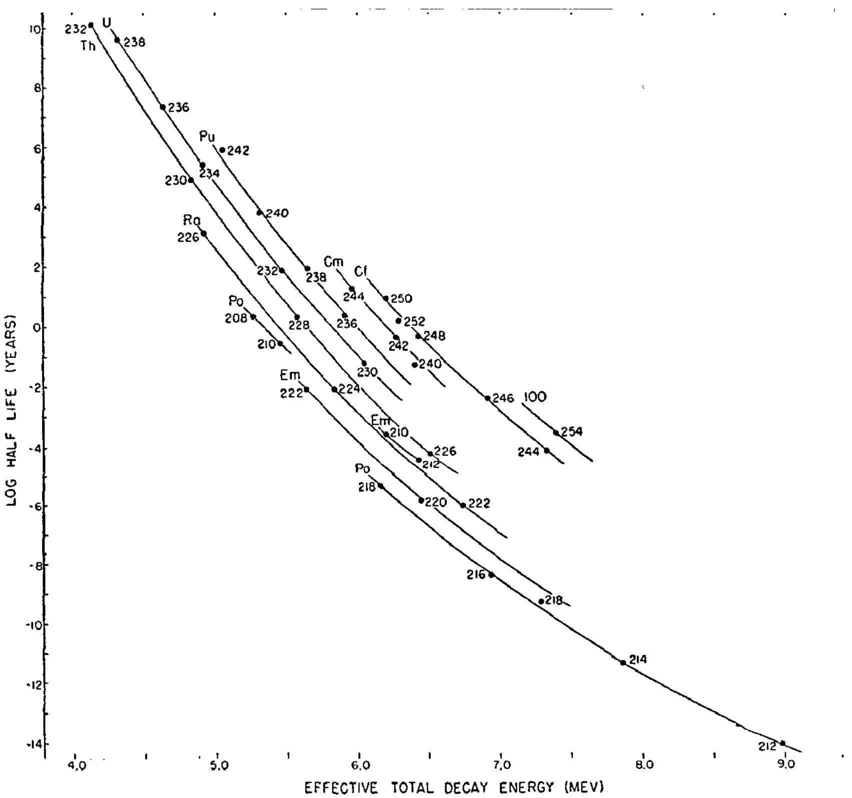

FIG. 9. Experimental values of log half life versus α-energy. ("Effective α-energy" includes correction of particle energy for recoil and electron screening—see text.)

Even-even alpha emitters: ground state transitions.—Figure 9 shows a plot of the half life versus 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 with the Kaplan (99) modification of the Preston (95) formula, by using the measured α-energy for each point and assuming a function for the nuclear radius, $1.52 \times 10^{-13} A^{1/3}$, the resulting curves would lie close to those of Figure 9. In detail, the calculated curves of the lower elements (Po, Em) would lie somewhat below the corresponding curves of Figure 9 and for the higher elements (Cm, Cf) the calculated curves would lie slightly above those shown in Figure 9. (The segments of curves shown for Po^{210} and Po^{208} and for Em^{210} and Em^{208} should be considered as special cases in which effective nuclear radii suffer a discontinuity and these are nuclei with 126 neutrons and fewer.) To bring about more exact agreement one can bring in a second order effect by assuming that the nuclear radius parameter should not be a constant, 1.52, but should vary in some fashion, say with atomic number. To see what is required, a calculation was made for the effective radius of each nucleus using measured values of both energy and half life and the results are shown in Figure 10. The sharp

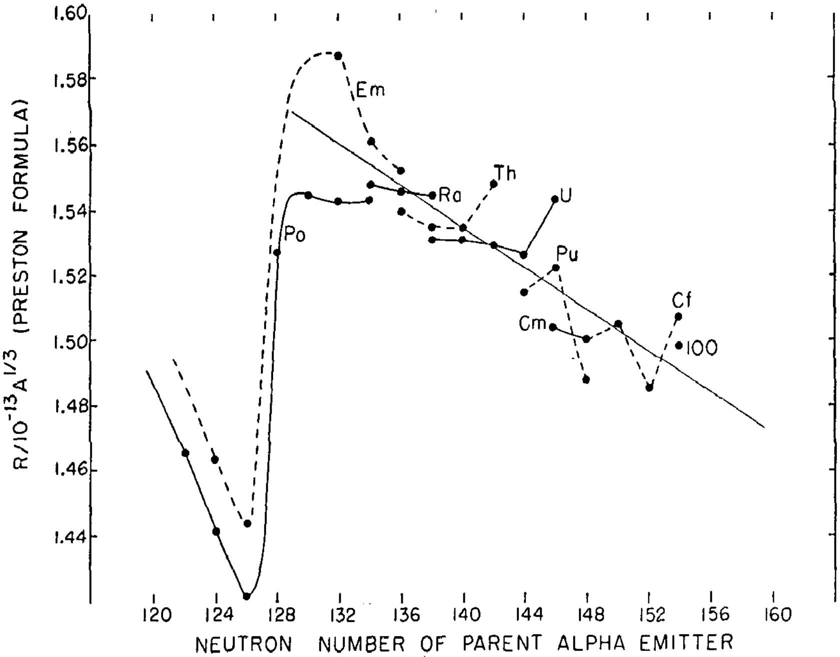

FIG. 10. Nuclear radius parameter.

break at 126 neutrons is apparent but, in addition, there seems to be general decrease in radius parameter with increase in atomic number. This, of course, is a restatement of the relation mentioned between the empirical curves and those calculated on the basis of a single average value for the radius parameter. With reference to the data of Figure 10, it should be pointed out that there is sufficient experimental uncertainty in some of the values which went into these calculations to shift the points by 0.02 unit of radius parameter or even more.

In summary, we can say that the basic one body theory of α-decay applied to the ground state transitions of even-even α-emitters gives a remarkably consistent picture. By using reasonable and consistent assumptions for the values of the nuclear radii, the theory explains observed half lives which differ by a factor of 10^{24}. It should be pointed out that different formulations of the theory will give somewhat different "best values" for the radius parameter, but each is internally consistent.

Two further points should be mentioned with respect to the curves of Figure 9. It may be noted that the energy values listed are somewhat higher than measured particle energies. The α-energy pertinent to α-decay theory is based on its center of mass velocity and therefore the particle energy must be increased by the energy of the recoil nucleus. This correction amounts to ~100 kev for a 6 Mev α-particle in this region.

An additive correction to the α-particle energy so far overlooked has been suggested by Ambrosino & Piatier (103) and has to do with the lowering of the potential barrier by the electron cloud. As discussed by Rasmussen (104) this correction should be applied as an added α-energy amounting to about the difference of total electron binding energies between parent and daughter in the particular α-decay process. This amounts to ~38 kev in the region of U and is smaller for lighter elements. This latter "screening correction" to the particle energies does not have a profound effect on the agreement of theory and experiment which is under discussion, but it does have the effect of giving somewhat smaller values of nuclear radii than if it were ignored.

The other item concerning Figure 9 has to do with the reason that smooth curves can be drawn at all because, in principle, each curve is not continuous if the nuclear radius is an independent variable. However, as seen in Figure 2, α-energies vary more or less monotonically with mass number A and since nuclear radii do so likewise, each value of energy (for a particular element) does localize the mass number and therefore the radius. Where two isotopes within the same energy range do have large differences in effective radii they do not lie on the same curve. This effect is seen for Po and Em curves on the two sides of 126 neutrons.

Even-even alpha emitters: transitions to excited states.—For any particular ground state transition, 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. Let us first consider transitions to the first excited state (2+). The effective radius as determined from the ground state transition process is adopted and it is assumed that the spin change, whether $\Delta I=0$ or $\Delta I=2$, will not affect the decay rates very much. This latter assumption has the theoretical justification of the calculations of Preston (95, 96) which show that contrary to previous treatments, a $\Delta I=2$ transition should be some 1.5 times faster than a $\Delta I=0$ transition and that only when $\Delta I=4$ does the function take the direction of delaying the transition.

The ratios of expected abundances (solely from energy difference) to experimental abundances are shown in Table III. Around Ra, Th, and U the ratios are seen to be close to unity and perhaps to rise significantly for the heavier elements. Some recent ideas on the population of these states will be mentioned below where transitions to the 4+ state are discussed.

One apparent anomaly is Po^{208}, for which no α-group has yet been seen

TABLE III

POPULATION OF FIRST EVEN STATE (2+) BY ALPHA DECAY OF EVEN-EVEN NUCLEI

Alpha emitter	Energy level (kev)*	Departure factor†	Alpha emitter	Energy level (kev)*	Departure factor†
Po^{206}	163	3.1	U^{234}	52	1.2
Po^{208}	374	>32	U^{236}‡	50	1.1
Po^{210}‡	800	1.6	U^{238}‡	45	1.5
Ra^{224}	240	1.2	Pu^{234}‡	45	3.5
Ra^{226}	188	0.9	Pu^{236}‡	47	2.2
Th^{226}	110	1.2	Pu^{238}	43	1.6
Th^{228}	84	0.9	Pu^{240}	44	1.7
Th^{230}	68	1.0	Pu^{242}‡	45	2.2
Th^{232}‡	65	0.8	Cm^{242}	44	1.7
U^{230}	70	1.1	Cm^{244}	43	1.8
U^{232}	58	1.1	Cf^{246}	42	2.7

* Energy level of the 2+ state of the daughter nucleus.

† Ratio of calculated abundance (solely from energy difference) to experimental abundance. A factor of unity means that the lifetime for the decay to this state (in this case 2+) is according to expectations from α-decay theory using the ground state transition to define the nuclear radius and neglecting any effect of spin change.

‡ The experimental abundances or energies may be suspect.

leading to the 374 kev 2+ state, and the partial half life is at least thirty-two-fold greater than that calculated. It is significant that there is other evidence (68, 105) that the first excited state of Pb^{204} is not a rotational state. Here, it seems, is a presently isolated but important item which must be included in a comprehensive α-decay theory. If we may generalize from this single case, we may postulate that a 2+ state of an even-even nucleus is populated "normally" only if it is a collective state of the type discussed.

The examination of transitions to the 4+ state gives a totally different and unique picture (106). Here, if the partial half lives are calculated as above, it is found that they are much shorter than the measured values; that is, the 4+ states are populated much more sparsely than would be expected on the basis of α-energy alone. Furthermore, the ratio of measured half life to calculated half life varies considerably and in a more or less regular way with atomic number as shown in Figure 11. It is seen that for Cm^{242} the second even state is hindered in its population by a factor of 400 (compare with factor 1.7 for first even state, Table III), while for Th isotopes this factor is of the order of 10. There is no a priori justification for plotting the data of Figure 11 in the manner shown; for the present it merely serves the purpose of giving visual expression to the considerable range encountered in the population of apparently identical spectroscopic states.

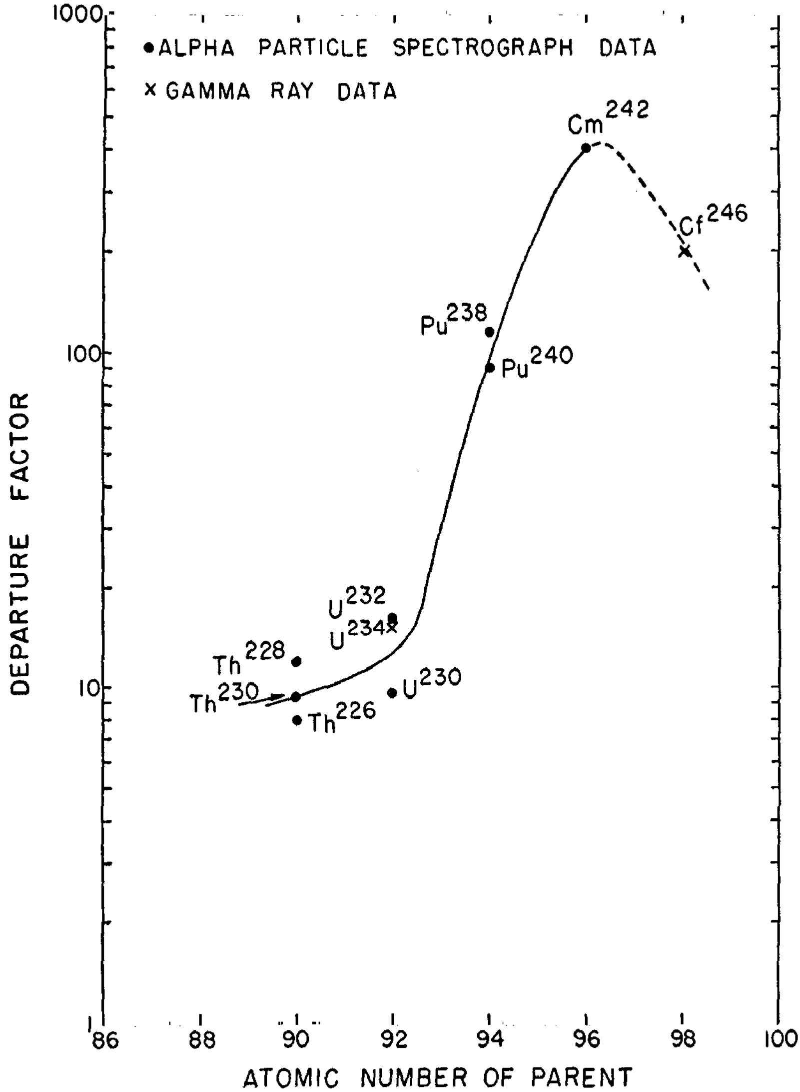

FIG. 11. Departure factors for α-groups to the second even spin state of even-even nuclides.

Recently, an attack has been made on this problem which appears fruitful. The basic idea developed by Preston (107) is that the α-particle emerging through the coulomb potential region and beyond the range of nuclear forces can couple with a noncentral electric field of the nucleus in such a way as to change its energy. Such fields would be associated with spheroidal distortions in nuclei as discussed by Bohr & Mottelson (68) and Hill & Wheeler (108). The distortion would be described by the intrinsic quadrupole moment which Ford (69) has shown by calculations to be increasing with mass number in the region above Pb and would presumably continue until the approach to a new shell is felt.

The mechanism of quadrupole interaction with the emerging α-particle wave to explain the population of the first two excited states in a rotational band has been explored in detail by Rasmussen (109). For the case of Cm^{242} decay, for which approximate numerical integrations have been carried out (assuming an intrinsic quadrupole moment, Q_0, in Pu^{238} of $+17\times10^{-24}$ cm.^{2}), he found that the population of the $2+$ state should be relatively unaffected, but that the population of the $4+$ state should be strongly depressed in essential agreement with the experimental observations. The assumed value for Q_0 seems reasonable for a nucleus in this region in view of the recent measurement of the quadrupole moment of U^{235} as $+8\times10^{-24}$ cm.^{2} (112), which with the spin of 5/2 corresponds to a value for Q_0 of $+22\times10^{-24}$ cm.^{2}. The quadrupole moment for even-even nuclei cannot, of course, be measured by spectroscopic means, but there is the possibility of obtaining information through coulomb excitation cross sections and γ-ray lifetimes.

Since this approach in explaining certain features of α-spectra is in an incomplete state of development, it is not worthwhile to speculate on the possible significance of the downturn of the curve of Figure 11 between Cm^{242} and Cf^{246}, nor to discuss a number of other ramifications of the mechanism.

We shall just recall that other low-lying states in even-even nuclei have been identified, but for which detailed information is lacking. There is the third even state ($6+$?) which is a member of the well-defined rotational band. Also, in a limited region there appear $1-$ states which are populated roughly to the same extent as the $4+$ states in the same region. It is not clear what type of nuclear configuration would give rise to such states.

Odd nucleon alpha emitters.—The most obvious question concerning this category of α-emitters is why the ground state transition is often highly hindered and why the hindrance is so irregular. Table IV shows the data for such α-emitters and the last column contains the "departure factor" which, as before, is the ratio of the measured partial half life for a transition to the half life which would be calculated from one body α-decay theory. We note that for the four species shown in Figure 8 the departure factors for the apparent ground state transitions are: U^{233}—1.4, Am^{241}—1000, Am^{243}—700, Cm^{243}—>26. It is not certain that for each case in Table IV the ground state transition has been identified and where this should prove to be the case the departure factor would be larger.

The first point to be disposed of is the effect of spin change. As already pointed out in a number of instances, both theoretical and experimental appraisal indicates that the lifetime is relatively insensitive to spin change, per

TABLE IV

POPULATION OF GROUND STATE BY ALPHA DECAY OF ODD-NUCLEON EMITTERS

Alpha emitter	Particle energy*	Abundance†	Departure factor‡
Cf^{249}	6.00	0.10	300
Bk^{245}	6.33	0.18	700
Bk^{243}	6.72	0.30	900
Cm^{243}	6.049	<0.5	>26
Am^{243}	5.341	$\gtrsim$0.003	$\lesssim$1000
Am^{241}	5.535	0.0034	700
Pu^{241}	5.01	<0.11	>30
Pu^{239}	5.150	0.69	3
Np^{237}	4.86	<0.15	>50
U^{235}	4.58	0.10	900
U^{233}	4.823	0.83	1.4
Pa^{231}	5.042	0.11	220
Th^{229}	5.02	0.10	100
Th^{227}	6.030	0.19	130
Ra^{223}	5.730	0.09	50
Fr^{212}	6.409	0.37	10
Em^{219}	6.824	0.69	18
Em^{211}	5.847	0.33	8
At^{211}	5.862	1.00	3
At^{210}	5.519	0.32	2
Po^{213}	8.336		1.5
Po^{211}	7.434	0.99	100
Po^{209}	4.877		2

* Particle energy of α-group believed to lead to the ground state. In some instances it is possible that the groups selected are not the ground state transitions in which cases the "departure factors" would be greater than those shown.

† Abundances are based on observed α-groups except where the highest energy group is known to be followed by γ-radiation.

‡ Defined in Table III.

se, certainly within the framework of reasonable spin changes. Conversely, we know that the ground states of Am^{241} and Np^{237} both have spin 5/2 (110, 111) yet the transition between these states is hindered 1000 fold.

Other ideas, not yet formulated quantitatively, appear to be more promising. One suggestion (31) has to do with the breakdown of the one body model in its implication that α-particles exist as discrete entities within the nucleus and that the probability of α-emission depends only upon the frequency factor of this preformed α-particle in encountering the coulomb barrier and upon the rate of barrier penetration. We have seen that for ground state transitions of even-even nuclei the evidence for this extreme simplification indicates that it is substantially correct. For ground state transitions of odd nucleon emitters, however, it is suggested (31) that there can be a considerable time involved in assembling the components of the α-particle. Such would be the description if the mixture of configurations which constitutes the emitting nucleus contained only as a minor component the configuration with the odd particle as a constituent of an incipient α-particle. Rasmussen (90) has pointed out further that nuclear spins need not give a true picture of the nucleon states of the parent and daughter nuclei. In a region well away from a closed shell where large spheroidal distortions are expected, the strong-coupling configurations may predominate and the nuclear spin can be different from and lower than the j-value for the single odd nucleon. On this basis, the spectroscopic state of the odd proton in Am^{241} may be quite different from that in Np^{237} even though both nuclear spins are 5/2. If such were the case, the change in wave functions could properly introduce a hindrance to the α-decay. Only for those transitions where the single particle wave function remains unaltered would one expect unhindered α-decay. Significantly, it appears that such transitions can be found in the spectra of the odd nucleon emitters, but in general these are not the ground state transitions. This subject will now be examined.

In Figure 8 it is seen that the most abundant groups of Am^{241} and Am^{243} lead to states which are 60 and 75 kev respectively above the ground state. Furthermore, for the particular energies of these α-transitions, the hindrance or departure factors are only of the order of unity (in contrast to 1000 for the ground state transitions) and, in this respect, appear to be like the ground state transitions of even-even nuclei. By making certain assumptions it is possible to deduce the spins for these excited states (60 and 75 kev states). The analysis has already been carried out on page 178 and is based on the recognition of three excited states as members of a rotational band from which the spins of these states can be deduced. In this case, the spins for the 60 kev excited state of Np^{237} and the 75 kev state for Am^{243} are deduced to be 5/2 (14, 90). It is suggested (90) then that these states may be those in which the odd particle wave function rearrangement is a minimum and that the transition is therefore relatively unhindered.

As already discussed under even-even nuclei, the splitting of α-groups into a rotational spectrum may involve the effect of electric field interactions. The appearance of what looks like rotational bands in these odd nucleon species implies, of course, that the same mechanism is in play here.

It seems apparent that the past few years have seen a departure from classical α-decay theory as well as a reinforcement in our confidence in some of its aspects. It also seems likely that some of the new ideas when further developed will add appreciably to the explanation of the α-decay process, and that the ramifications of these ideas will provide a better understanding of nuclear structure.

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