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THE STUDY OF NUCLEAR STATES OBSERVED IN ALPHA DECAY

F. S. Stephens, Jr.

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THE STUDY OF NUCLEAR STATES OBSERVED IN ALPHA DECAY

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March 1958

INTRODUCTION

Alpha decay occurs at an appreciable rate in only two regions of the periodic table. The first of these, located in the rare earth elements around gadolinium, is quite limited in extent and includes only about a dozen known alpha-emitting nuclides. The second region, however, extends from lead upwards to the heaviest elements yet discovered, and contains at present over 160 alpha emitters. Only in the latter of these two regions has the study of alpha emitters thus far yielded any data of importance to nuclear spectroscopy and for this reason the discussions in this chapter will be confined almost exclusively to the heaviest elements.

Almost all the data available on nuclear energy levels in the heavy element region have come from the study of radioactive decay schemes. Alpha decay and beta decay have probably contributed about equally in this regard. In many cases the levels of a nucleus are populated by both modes of decay. The energy levels of Pu^{239}, for example, have been studied following the alpha decay of Cm^{243} (1,2), the beta decay of Np^{239} (3-6), and the electron capture decay of Am^{239} (7). The wealth of data thus accumulated has been invaluable in identifying and interpreting the levels of Pu^{239}. The study of alpha decay schemes is very similar to the study of beta decay schemes, which has been discussed in the preceding chapter. There are, however, at least two rather fundamental differences relating particularly to the study of nuclear energy levels. The first of these is the fact that alpha particles from a given

nucleus are emitted with one of a few discreet energies, each of which corresponds to a transition between the parent and a particular state in the daughter nucleus. In beta decay, on the other hand, the essentially undetectable neutrino carries off a varying portion of the transition energy; so that, although each transition is of a discreet energy, a continuum of beta particle energies always results. For this reason in complicated decay schemes it is essentially impossible to pick out levels in the daughter nucleus by analysis of the beta spectrum, whereas this is usually not difficult in alpha decay, provided instruments of sufficient resolving power are available. Alpha decay also differs from beta decay in that the initial and final nuclei in an alpha emission are of the same nuclear type (even-even, odd-even , etc.). This fact is of more significance than it might at first seem to be, since it raises the possibility of alpha transitions occurring between states of the same configuration. Such transitions not only occur, but comprise a large part of alpha decay data at the present time. There are also a number of differences between alpha and beta decay in regard to the selection rules and energy dependence governing the population of various states in the final nucleus, but since these will be discussed in some detail in later sections, they will not be mentioned further here.

The aim of this chapter is not to present a comprehensive review of any particular aspect of the study of alpha emitters, but rather to provide a general picture (with a few specific illustrations) of the energy levels populated in the alpha-decay process and to show how this information is related to theories of nuclear structure. Toward these ends the chapter has been divided into three main sections. The first section deals with the apparatus and experimental techniques used in studying nuclear states observed from alpha decay. The second short section covers a few considerations on the alpha decay process *per se*

which will be essential in understanding the experimental data, and the third section presents some of these data together with their interpretation. It should be emphasized that in this chapter the primary interest will be in alpha decay as a means of studying nuclear energy levels. For more general discussions of alpha radioactivity, several recent review articles are available (8-10).

I. EXPERIMENTAL TECHNIQUES

A. The Study of Alpha Spectra.

A number of techniques have been developed for the detection of alpha particles and the study of alpha particle spectra. These range from extremely sensitive methods (nuclear emulsions) which can detect a very few alpha disintegrations occurring over a period of months and measure their energy to within about 10%, to methods of high resolution (magnetic spectrographs) capable of measuring the energy of an alpha group to about 0.01%, but in doing so can detect less than 0.1% of the alpha particles. The selection of a particular detection method depends, of course, on the experimental requirements. In the study of energy levels populated by alpha decay the interest is usually centered in doing two sorts of things. One of these is determining the exact time (and possibly direction) of the alpha particle emission, so that the gamma rays associated with the decay can be identified and studied. Techniques for doing this will be considered in Part B of this section. The other measurement of general interest is the identification of energy levels directly from analysis of the alpha particle spectrum into its various energy groups. This requires instruments of high resolution, since the average spacing of energy levels in the region of the heaviest elements is somewhere around 50 kev. Of the

techniques yet developed, only the magnetic spectrographs have sufficient resolving power to be very satisfactory in this regard, and for this reason further discussion along this line will be limited to this means of detection. Nevertheless, some important information has been obtained using ionization chambers with pulse height selection (see Ref. 10).

Although a number of magnetic alpha particle spectrographs have been put into operation from time to time, only a few are now being extensively used in the study of radioactive alpha emitters. These differ considerably in their magnetic field properties, as will be described; however, they are quite similar in overall operation. In each case a thin alpha-emitting sample, deposited or masked as a narrow line, is placed at the source position of the instrument with the sample line parallel to the magnetic field (vertical). The alpha particles travel in vacuum through the magnetic field and strike a photographic plate. The field characteristics are such that at the photographic plate, the alpha particles are caused to focus into a vertical line (an approximate image of the source). Upon development, the plates are scanned under a low-power microscope in vertical columns (scans) and the individual alpha tracks are counted. A plot of counts per scan versus horizontal position of the scan along the plate then corresponds to a plot of intensity versus alpha particle energy. Usually the energy of an alpha group is only measured relative to that of another group. The use of photographic plates permits the simultaneous accumulation of data over a rather wide energy region, which is of great help considering the low transmission of these spectrographs.

Two of the most important characteristics of an alpha particle spectrograph, particularly in regard to the study of nuclear energy levels, are its transmission and its resolution. Transmission, as used here, will refer

to that fraction of the total number of alpha disintegrations occurring in the source line which is recorded at the detector. It is important to note that the transmission is not related to the total alpha activity on the source plate if a masking slit is used, but only to the part of this activity which is exposed to the spectrograph. The resolution will be expressed as the full width of an alpha group at one-half its maximum height, and will be referred to as the "half-width". This definition is somewhat arbitrary, but corresponds with that most generally used in alpha particle spectroscopy. A high transmission is clearly desirable in a spectrograph, since this reduces the operating time required to study a given sample. Similarly, small half-widths are advantageous, in that close-lying alpha groups can be resolved, and also more precise energy separations for all the observed groups can be calculated. Resolution and transmission are not independent of each other, however, and with a particular sample and instrument one of the two can usually be improved only at the expense of the other; so that in practice some kind of a compromise must be reached. The exact compromise made is governed by the objectives of each particular experiment, but normally in studying nuclear energy levels half-widths around 8 kev at 6 Mev particle energy are sufficiently good. For this reason, in the following discussion of the various spectrographs, the transmissions mentioned are those at which the above resolution can be obtained.

Two of the first spectrographs used for systematic study of complex alpha spectra are those built by Rosenblum (11,12) at Bellevue, France and by Reynolds, Asaro, and Perlman (13,14) at Berkeley, California. The Bellevue instrument is a large permanent magnet giving a field of 12,500 gauss in which a 180° focusing spectrograph has been built. Figure 1a gives a schematic view of the optics of this instrument. The permanent magnet is a distinct improvement

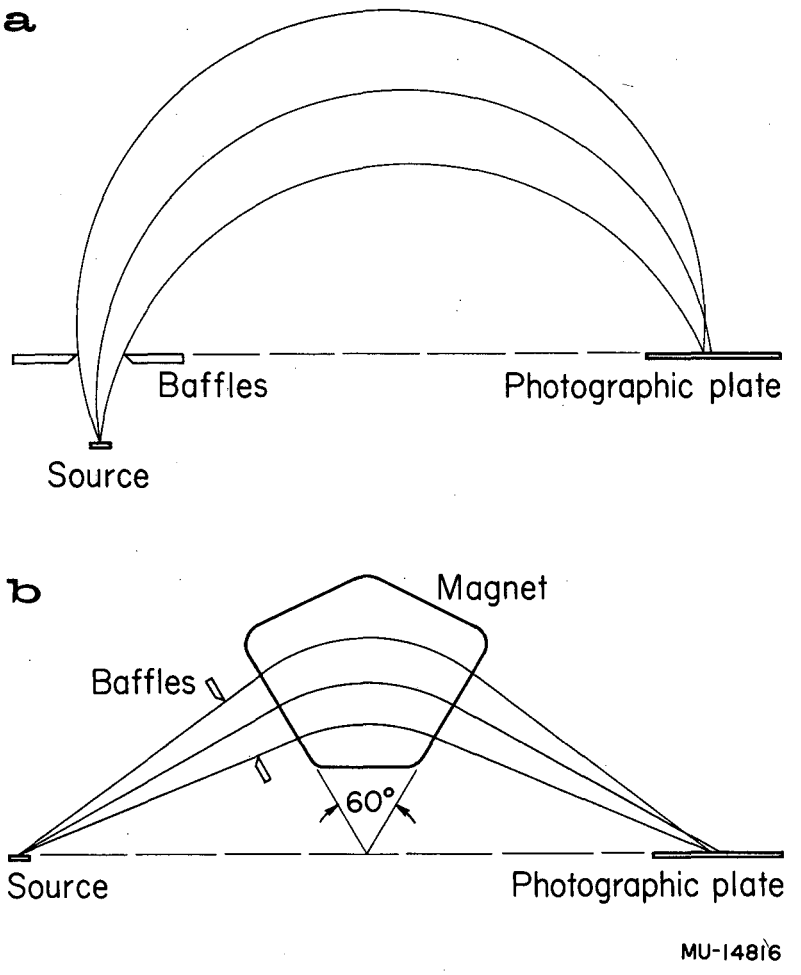

Fig. 1. Schematic view of the optics of (a) the Bellevue permanent-magnet alpha particle spectrograph and (b) the Berkeley electromagnetic alpha particle spectrograph. In (a) the entire assembly is in the magnetic field, whereas in (b) the magnet is indicated.

over the electromagnets as far as field stability is concerned, so that for weak samples or samples of low specific activity where long exposures are required this instrument is quite desirable. Half-widths as low as 8 kev have been reported. The Berkeley spectrograph employs a 60° sector electromagnet having a radius of curvature of 75 cm. Figure 1b gives a sketch of the optics of this instrument. Although the magnetic field shapes of the two instruments are quite different, the focusing characteristics are very similar. Half-widths of 8 kev have been achieved on the Berkeley spectrograph at a transmission of 5×10^{-5}. Considerably smaller half-widths have been obtained at the expense of transmission, as will be discussed presently.

Both of the spectrographs discussed above have flat magnet pole pieces, so that uniform magnetic fields are produced. From the analogy to electron spectrometers it was realized some time ago that considerably better transmission at a given resolution could be achieved by using a non-uniform magnetic field such that without destroying the focusing in the horizontal plane shown in Fig.1 a similar focusing occurs simultaneously in the vertical plane. Such an instrument is said to be "double-focussing". Two electromagnetic double-focusing spectrographs, used principally for studying radioactive alpha emitters, have recently been built; one in Moscow by Goldin, Novikova, and Tretyakov (15,16) and the other in Berkeley by Asaro and Perlman (17,18). The Russian machine is in the form of an annular ring having a radius of 50 cm, and both source and receiver are located inside the magnetic field. Focusing occurs after $\sqrt{2}\ \pi$ radians or about 250°. Half-widths of 7.5 kev have been reported at a transmission of 2×10^{-4}, or about four times larger transmission than the Berkeley uniform field instrument at about the same resolution. The magnet of the Berkeley double-focusing spectrograph is in the form of a semi-

circle, and both the source and receiver are located outside the magnetic field. The alpha particles are brought to a focus after being bent through 180°. The normal radius of this instrument is 35 cm. Half-widths of about 8 kev have been obtained on this machine at a transmission of 1×10^{-3}, which is around 20 times larger than the Berkeley uniform field instrument. The advantage of double focusing is evident; however, these transmissions should not be considered as figures of merit for the spectrographs. Other important considerations closely related to transmission are (1) the permissable source area, (2) the energy range over which the stated resolution can be obtained, and (3) the stability of the instrument. Any relative evaluation of the instruments would have to take all these factors into account, and would be very difficult to make.

In order to obtain the resolution and transmission of which the magnetic spectrographs are capable several factors must be considered. Most important of these are magnetic-field control, pressure, and source conditions. The first two of these represent no particular problem. It may readily be estimated, for example, that in order to confine the spread in energy to one kev or less, the magnetic field must be held constant to about one part in 10^{4}. Even for the electromagnets this stability is not difficult to achieve over reasonably short periods (several days), and, in fact, it would probably be possible to obtain equipment that could control the field somewhat better than this if necessary. For very long periods, however, this stability is difficult to maintain and the permanent magnet is a distinct advantage. Similarly one can estimate that a spread in energy of one kev, would require a pressure of a few microns of mercury. Pressures much lower than this are relatively easy to obtain, and for the Berkely spectrographs the operating pressures are a few tenths of a micron or less even

though a spread in energy of one kev would not usually be detectable. The preparation of satisfactory sources, however, can be quite a difficult problem. There are three aspects, in particular, which require careful attention. The first of these is the thickness of the layer of material in which the sample is desposited. If this thickness is too large, some of the alpha particles will lose enough energy in traversing the layer to cause serious broadening of the peaks. Some specific cases will be considered below; however, in general the thickness must be less than a few $\mu gm/cm^2$ of material. Since the line focused on the photographic plates is an approximate image of the source, the source width is also critical. For the Berkeley uniform field spectrograph, a source width of a millimeter would give a line width corresponding to about 8 kev for an alpha particle group of energy 5 or 6 Mev. The allignment of the source is also important in this regard since any deviation of the line from the vertical contributes to the apparent source width. The third aspect requiring attention has to do with a broad "tail" which extends from alpha particle peaks toward lower energies. Unless precautions are taken this continuum is about 0.02% of the height of the peak, and this represents a rather serious disadvantage since low intensity alpha groups which may be present in this region cannot be detected. This tailing is thought to be due largely to alpha particles that have been scattered off the backing plate, slit system, and other objects which may be in the vicinity of the source. Rosenblum (19) has reported that by using very thin backing materials and taking other precautions the effect can be reduced at least two orders of magnitude below the figure quoted above.

It is perhaps of interest to mention the present capabilities of alpha particle spectroscopy when the best possible account is taken of the considerations

in the preceeding discussion. Of interest will be (1) the best resolution that can be obtained with an optimum sample and (2) the weakest samples for which analysis is possible. In both cases thin uniform samples are needed and are at present most satisfactorily prepared by high temperature vacuum sublimation from a tungsten filament onto a cold platinum plate. For case (1) above, the samples were masked to widths of 1-5 mils, and no more than 2-3 $\mu gms/cm^2$ of the radioactive material were vaporized onto the sample plate. The measurements were made on the Berkeley uniform field instrument at transmissions of about 10^{-5}. Half-widths of 2.5 kev (out of 5-6 Mev) have been almost routinely achieved, and the alpha particle spectrum of Th^{227} (20,21) taken at about this resolution is shown in Fig. 2. It is not difficult to see the need for high resolution in studying this particular spectrum. In test runs on Cm^{242} half-widths as small as about one kev were measured (22). The limiting factor may be source thickness, since 5-6 $\mu gm/cm^2$ of a heavy element or ~1 $\mu gm/cm^2$ of a light element impurity would be sufficient to give the above width. With the present equipment it is estimated that half-widths of a few tenths of a kev should be attainable, provided the lines are not made broader than this by some effect accompanying alpha emission, such as the ejection of orbital electrons (23,24). Probably the weakest sample that has been studied on a spectrograph is one of U^{235} containing 250 alpha disintegrations per minute (25,21). The problem in this case has to do with the specific activity of U^{235} which is only 4.5 disintegrations/minute/μgm. To obtain half-widths of 10-15 kev, the maximum amount of uranium that can be on the source plate is around 50 $\mu gm/cm^2$, and, since the area of the sample used was 1/8" wide x 1" long (~0.8 cm^2), only a total of 50 μgm or ~250 disintegrations per minute of U^{235} could be used. This was run in the Berkeley double-focusing spectrograph for about two weeks at a transmission of 0.1%, and the resulting

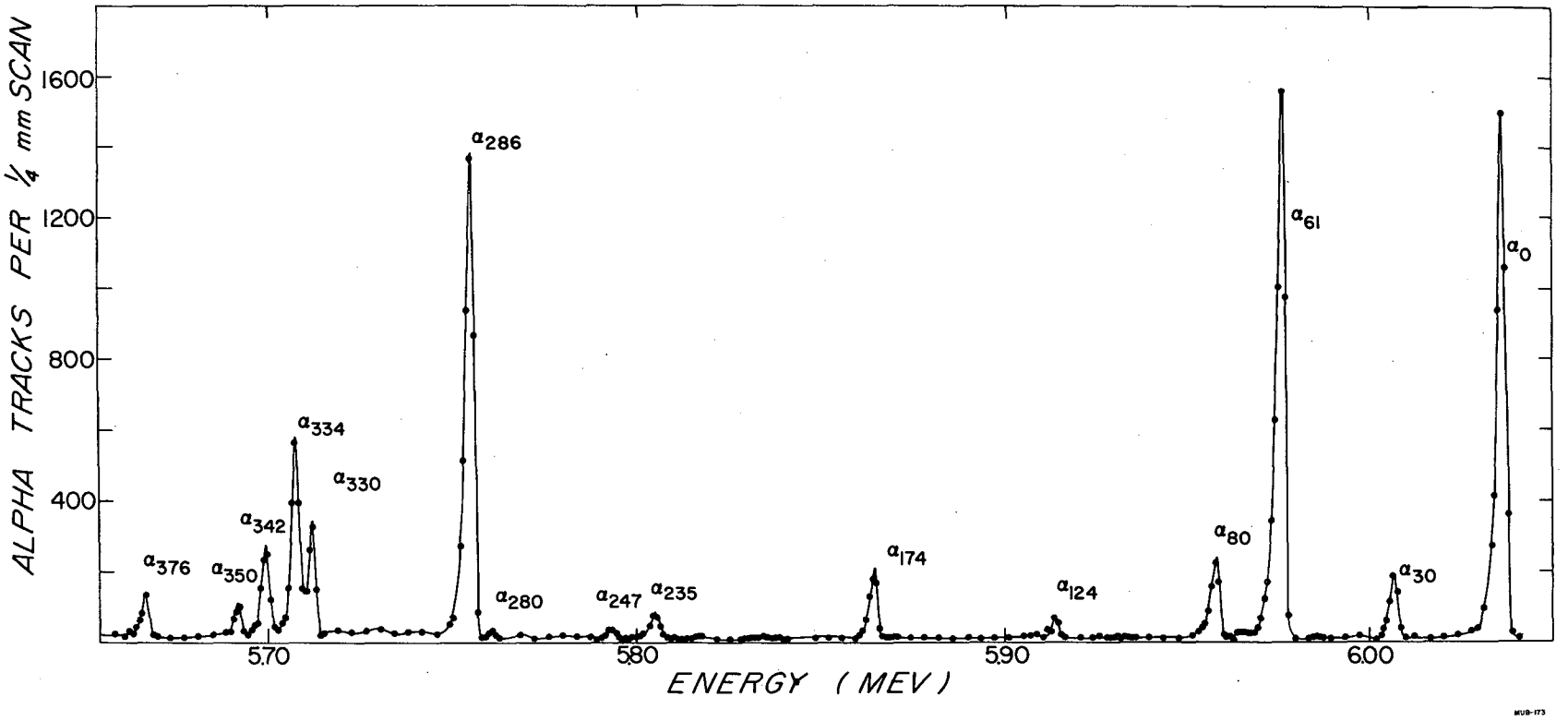

Fig. 2. Alpha particle spectrum of Th^{227} taken by Pilger et al.[20,21] α_x indicates the alpha group populating a state x kev above the ground state of Ra^{223}. The full width of the peaks at half their maximum height is about 2.5 kev.

spectrum is shown in Fig. 3. The half-widths of the peaks are around 15-20 kev, and unfortunately the statistical variation of the counts is rather large. This spectrum has been quite useful in the study of the decay scheme of U^{235} (26), however. Certainly at the present time samples this weak are not very convenient to study on the magnetic spectrographs, and a limit which would permit reasonably convenient study is probably in the vicinity of 1000 alpha disintegrations per minute.

B. Supplementary Techniques.

The study of nuclear states observed from alpha decay by no means ends with the study of alpha particle spectra. The elucidation of a decay scheme always requires that the gamma rays and conversion electrons associated with the alpha emission be studied, and in many cases energy levels can be detected by these means which receive either no direct alpha population or an amount insufficient to be observed directly. Almost all the techniques of gamma-ray and beta-ray (conversion electron) spectroscopy are applicable to the study of alpha emitters, and have been rather extensively used in such studies. Since these subjects are considered in detail in other chapters, however, they will not be reviewed here. Instead, a few coincidence methods which make use of the properties of alpha particles will be described. In this discussion, a general familiarity with the detection methods for gamma rays and alpha particles will be assumed.

The simple measurement of gamma ray spectra in coincidence with gross alpha particles is a considerably more powerful tool than is the analogous measurement with beta emitters. Not only does such a measurement establish that the gamma rays are associated with an alpha emitter, but also in many

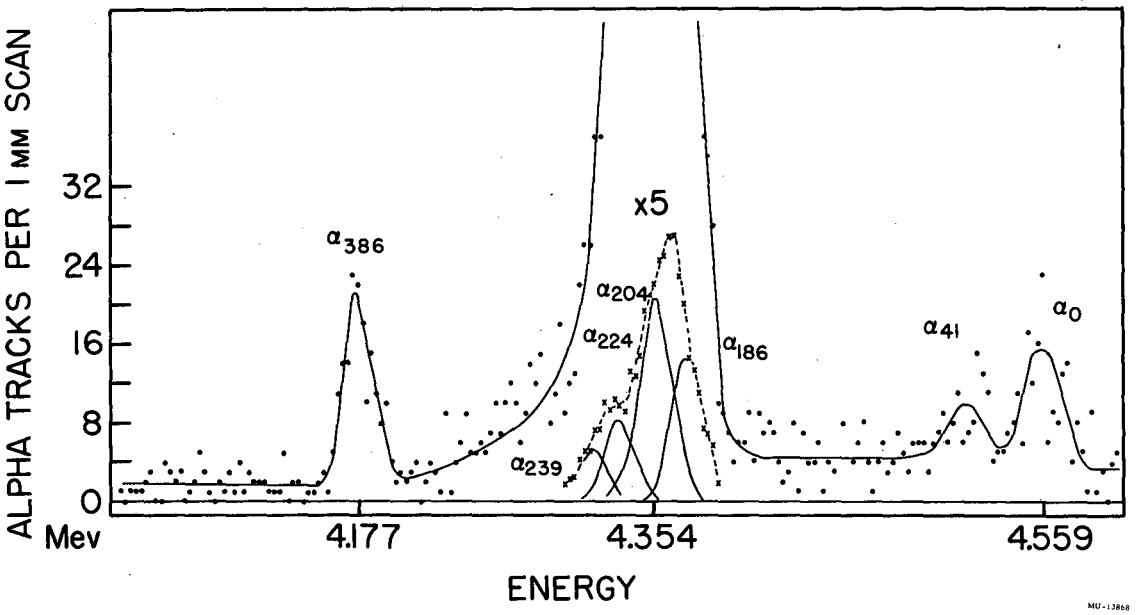

Fig. 3. Alpha particle spectrum of U^{235} taken by Pilger et al.[21,25,26] The full width of the peaks at half their maximum height is 15-20 kev. The peak at 4.354 Mev is complex and consists of three or more alpha groups.

cases photons can be observed which are much too weak to be detected by any other means. The reason for this is that it is extremely easy to detect alpha particles with high efficiency and to differentiate them from all other radiations given off by radioactive nuclei (with the possible exception of spontaneous fission fragments where some energy discrimination is required). For example, a thin layer of zinc sulfide deposited onto a photomultiplier tube can detect about half of the alpha particles given off by a sample (geometrical considerations) and is practically completely insensitive to gamma or beta radiation. The use of pulses from such a detector to "gate on" a gamma ray multi-channel pulse-height analyzer can reduce stray background gamma radiations by a factor of 10^5 or more, while reducing the overall detection efficiency for gamma rays associated with an alpha emitter by only a factor of two. This enormous increase in sensitivity becomes quite important where there are limitations on the amount of sample available. This relatively simple coincidence arrangement, with no alpha-particle energy discrimination, has a variety of other uses ranging from gamma ray abundance measurements to the determination of alpha-particle gamma-ray angular distributions.

In coincidence measurements, however, it is often necessary to discriminate among alpha particles of different energies, and a number of detection methods have been used for this purpose. The only requirement not previously considered for alpha detectors is that an electronic pulse must be produced within a very short time after the arrival of an alpha particle. Usually this time is a few microseconds or less. Scintillation counters using a variety of scintillators have been used for this purpose (10), but the best half-widths that can be obtained in this manner are 150-200 kev (27,28), and this is not sufficiently good for most purposes. Much better results have

been obtained with ionization chambers (10,29), where half-widths of 25-30 kev can be achieved with transmissions of up to 30%. Nevertheless, the complexity of energy levels encountered in heavy-element nuclei is such that frequently even this method leaves something to be desired in the way of resolution. One is thus led again to the magnetic spectrographs as the only means of obtaining really satisfactory resolution. These instruments have not previously been used very extensively for coincidence measurements because of problems associated with their low transmission. This situation should be largely remedied with the double-focusing spectrographs, however, and on the basis of preliminary results (21,30) this method promises to be quite useful in the study of complex decay schemes. A sketch of the arrangement using the Berkeley double-focusing spectrograph, is shown in Fig. 4. A particular alpha group is focused by the spectrograph onto a narrow slit in front of a ZnS screen and those alpha particles which strike the screen produce an electronic pulse in the photomultiplier. The gamma rays from the sample are simultaneously detected with a NaI crystal and those which occur in coincidence with the alpha pulses are then analyzed on a multi-channel pulse-height analyzer. Thus it is possible to observe separately the gamma rays which de-excite each particular level that receives direct alpha population. This represents an extremely powerful tool for studying nuclear energy levels.

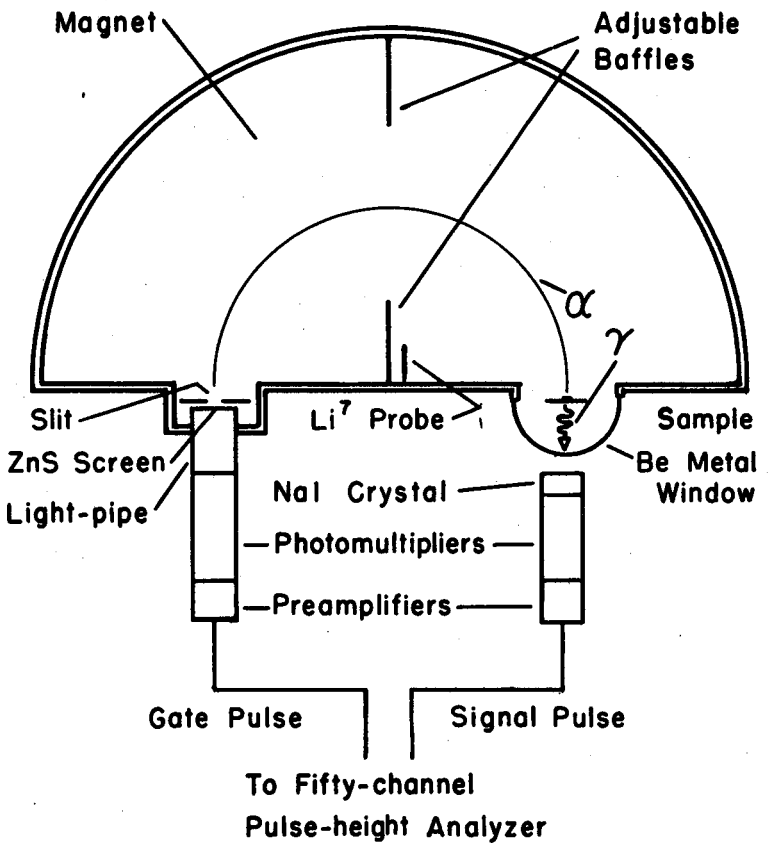

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Fig. 4. Schematic view of the Berkeley double-focusing spectrograph used as a coincidence instrument.

II. ALPHA DECAY ENERGY AND LIFETIME CONSIDERATIONS

A. Alpha Decay Energies.

Around the middle of the periodic table, alpha decay becomes energetically possible for nuclei in the band of beta stability. However, except for a small region around gadolinium, this type of decay does not proceed at an appreciable rate until the elements somewhat heavier than lead are reached. The reason for this is to be found in the Coulomb barrier, which prevents the alpha particles from leaving the parent nucleus until sufficient energy is available. This barrier, incidentally, prevents completely the emission of such particles as C^{12} and O^{16}, which is usually considerably more favorable energetically than alpha emission. The point at which sufficient energy is available for alpha emission to occur at a reasonable rate is determined by the height and thickness of the Coulomb barrier, which in turn depend on the charge (atomic number) of the nucleus. Hence, the requirement goes up as one proceeds upward in the periodic table. Figure 5 illustrates the situation graphically. The two straight lines represent the alpha energy required to give half-lives of 10^8 years and 1 hour as a function of mass number, and the heavy curve corresponds to the alpha decay energy available for nuclei in the region of beta stability. It is evident that, except for nuclei which lie quite a distance from beta stability, alpha emission would not be expected to occur until the heavy elements are reached. The rather large irregularities in alpha decay energy for nuclei around mass number 140 and 210 are caused by the closed shells of 82 neutrons and 82 protons - 126 neutrons which occur respectively in these two regions. The island of alpha emitters in the rare earth elements and the rather sudden onset of alpha radioactivity in the region just above lead are caused by these two irregularities.

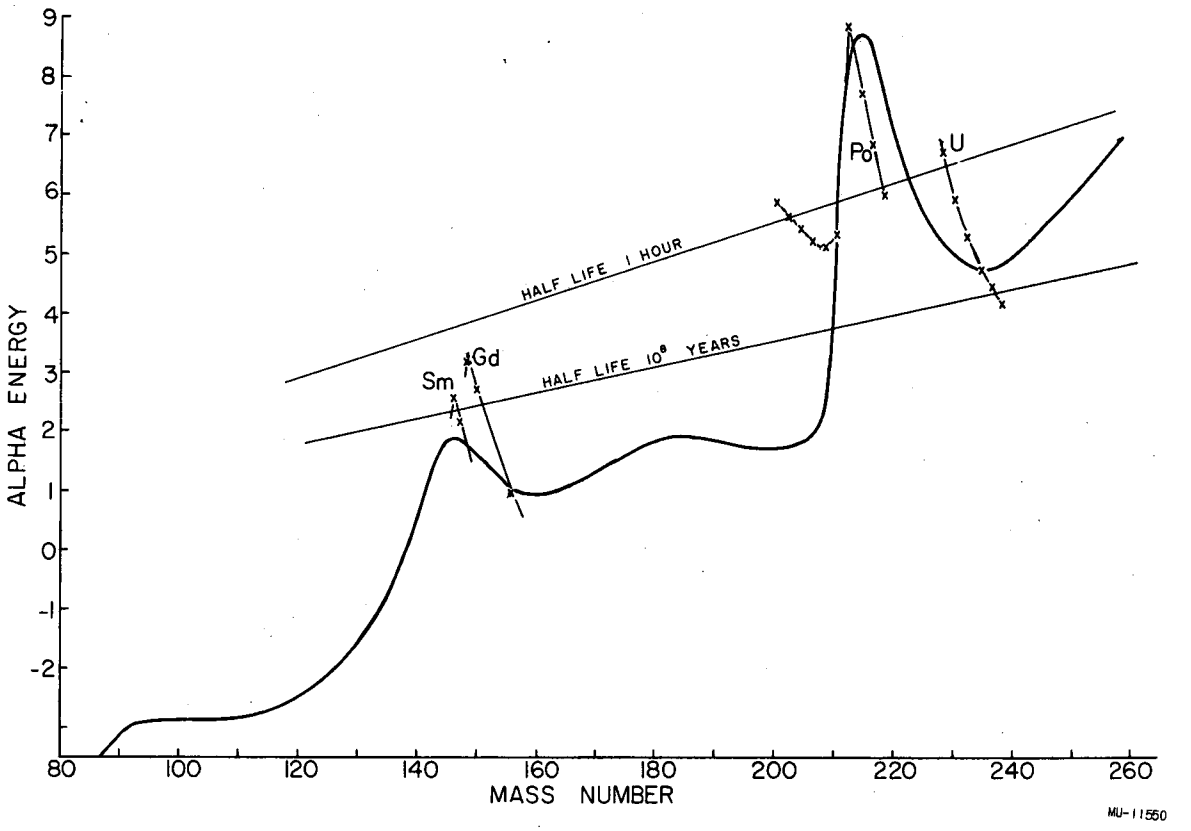

Fig. 5. The heavy line shows the alpha decay energy as a function of mass number for nuclei in the band of beta stability. The two straight lines denote the alpha decay energies necessary to give half-lives of 10^8 years and 1 hour. The isotopes of a few elements have been included to show the effect of varying neutron number.

A more detailed view of the heavy-element section of Fig. 5 is shown in Fig. 6. Here again the closed-shell effects around the region of mass number 210 are evident. Away from this region, however, there is observed for each element a reasonably uniform decrease in alpha decay energy with increasing mass number. That this type of behavior is to be expected has been deduced by a number of authors (31,32) from general considerations of atomic masses. The principal value of a plot like Fig. 6, aside from orientation, is that it permits reasonably good prediction of the alpha decay energies of undiscovered isotopes. This fact has been of great value in the search for new alpha emitters.

B. Lifetime Considerations.

Certainly one of the most impressive facts about alpha decay lifetimes is the wide range they cover. In the heavy elements alone, half-lives vary from less than 10^{-6} seconds (Po^{212}) to over 10^{10} years (Th^{232}) or more than a factor of 10^{24}. That this variation is caused by (or related to) differences in alpha decay energy was recognized as early as about 1907 (33,34); however, an understanding of the quantitative relationship between decay energy and lifetimes had to await the advent of wave mechanics. In 1928 Gamow (35) and Condon and Gurney (36) independently proposed the wave mechanical barrier penetration solution, which is essentially the one used today. Although certain features of this "one-body theory" are unacceptable in terms of present nuclear theory, the results are of such importance to the study of energy levels from alpha decay that a qualitative description of the theory will be presented.

"One-body" alpha decay theory considers the alpha particle to have a continuous existence in the potential of the daughter nucleus. The decay rate

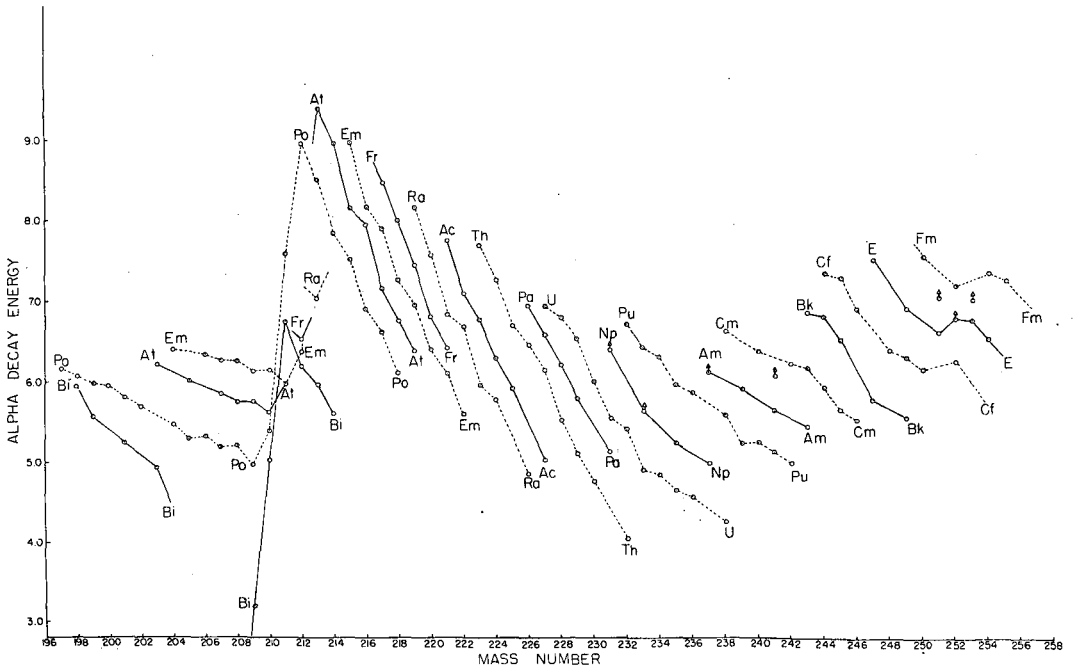

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Fig. 6. Detailed view of alpha decay energy as a function of mass number for the heavy-element region.

is expressed as the product of a "frequency factor", that represents the frequency with which the alpha particle strikes the potential wall, and a "penetration factor" that expresses the probability of the alpha particle penetrating the negative kinetic energy region of the Coulomb barrier. The serious objections to the theory have to do mainly with the frequency factor and the concept of an alpha particle existing for any length of time within a nucleus. Fortunately, it turns out that the lifetimes are not very sensitive to this portion of the treatment; so that the usefulness of the results, in spite of these objections, can be understood. In practice some rather simple approximation of the frequency factor is generally used.

In the penetration factor the decay constant, λ, depends on the decay energy, the charge of the nucleus, and the effective nuclear radius. The decay energy and the nuclear charge can be determined precisely, but the effective nuclear radius turns out to be some combination of the actual nuclear radius and the alpha particle radius, and is not subject to independent measurement. Several courses could be followed from this point, but the one usually found most fruitful (32, 37-40) is to assume some function for the radius, calculate decay constants using this function, and compare these calculated values with the experimental ones. The results of this type of treatment can be seen in Fig. 7, which is a plot of the logarithm of the alpha half-life <u>versus</u> the decay energy <u>for the alpha transitions from even-even nuclei to the ground states of the daughter nuclei</u>. The points on Fig. 7 correspond to the experimental alpha half-lives, while the curves are those calculated from Preston's treatment of the one-body model (41), using a radius of $1.51 \times 10^{-13} A^{1/3}$ cm, where A is the nuclear mass number. Significant deviations occur for the lighter elements, and become progressively worse for

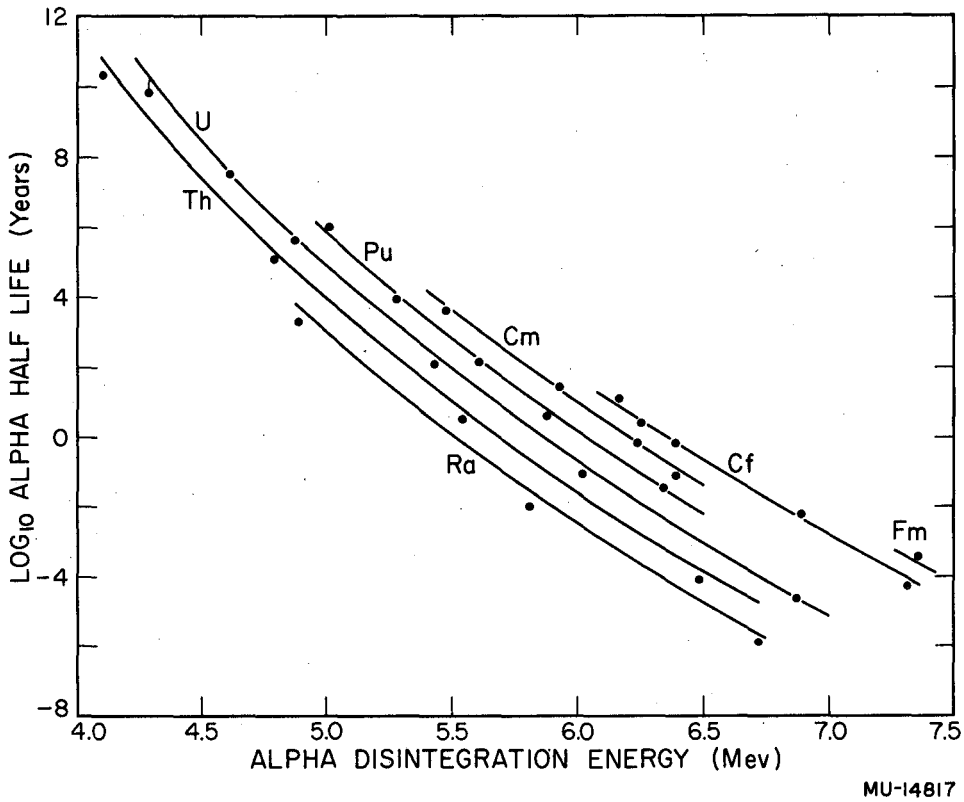

Fig. 7. The logarithm of the alpha half-life has been plotted against the alpha decay energy for the alpha transitions from even-even nuclei to the ground states of the daughter nuclei. The curves are those obtained from Preston's[41] treatment of one-body alpha decay theory, using a nuclear radius of $1.51 \times 10^{-13} A^{1/3}$ cm. The systematic deviations for Th, Ra, and lower elements (not shown) could probably be reduced considerably by using a different value for the radius.

radon and polonium which, for the sake of clarity, have not been included in Fig. 7. Nevertheless, the agreement between the theory and experiment is impressive and could probably be even further improved by using a more complicated function for the radius. It should be kept in mind, however, that this is only for the even-even ground state transitions, and some other types of alpha transitions, as we shall see, are by no means so simply explained.

Since the even-even ground state transitions are so well accounted for by the theory, a logical next step is to try to include excited states for these nuclei. The way to proceed is clear. The radius is expected to be the same as for the ground state transition in the same nucleus, so that the only change should be the reduction of the alpha decay energy by an amount corresponding to the excitation of the state. In some cases this procedure works beautifully. In U^{232} (42,43) decay, for example, an excited state of Th^{228} at an energy of 57.5 kev is populated, for which a decay constant is calculated such that the state is expected to receive 32% of the total alpha decay. This corresponds exactly to the observed situation. On the other hand, in the decay of this same nucleus a state at 326 kev is also populated, but in an amount about a factor of 70 smaller than would correspond to the calculated decay constant. This leads to the introduction of the term "hindrance factor", which will be quite important in later sections. The hindrance factor for decay to an excited state of an even-even nucleus is the ratio of the experimental alpha half-life for decay to that level divided by the half-life calculated as indicated above. This automatically makes the hindrance factors for the even-even ground state transitions nearly unity, and in practice these are all assumed to be exactly unity, so that they serve to define the nuclear radius rather than using the $A^{1/3}$ relationship. Thus for the U^{232} case described

above, hindrance factors for the transitions to the ground, 57.5, and 326 kev states of the daughter nucleus would be 1.0 (by definition), 1.0, and 70 respectively. The concept of hinderance factors is so useful it has been extended to the other nuclear types (besides even-even). In these cases the ground state transitions do not generally give results in agreement with the theory, so that effective nuclear radii cannot be calculated as for the even-even nuclei. The usual procedure, for this reason, is to use the average radius appropriate to the even-even nuclei nearest the nucleus under consideration. In U^{235} decay, for instance, the radius used in the calculation would be the average of those calculated from the ground state transitions of U^{234} and U^{236}. Hindrance factors actually represent the reciprocal of what might be called reduced alpha transition probabilities. Effectively the theory is used only to remove the energy dependence of alpha decay. It is in this regard that the hindrance factors are of considerable importance to the study of nuclear states populated by alpha decay.

III. ENERGY LEVELS POPULATED IN ALPHA DECAY

The study of alpha emitters divides rather naturally into categories according to the nuclear type involved. At the present time sufficient information is available to warrant discussion of only two of the three nuclear types — the even-even and the odd-mass nuclei. The absence of data on odd-odd alpha emitters is due to the added instability of this nuclear type towards beta decay; which usually results in half-lives too short for favorable alpha competition. As our understanding of the energy levels and the alpha decay process in the other nuclear types improves, however, the odd-odd nuclei present a more and more interesting challenge, and it seems likely that in the near future a few of these nuclei will be studied. This section will thus be divided into two parts discussing the data on even-even and odd-mass nuclei respectively. The theory of nuclear energy levels will not be considered in any detail, but a sufficient amount of theory to permit some understanding of the regularities observed in the alpha decay process will be introduced from time to time.

A. Even-Even Nuclei.

The alpha particle has spin zero, even-parity, and no excited states below about 20 Mev (i.e., none that can be reached in even the most energetic alpha decay). This means that any change in angular momentum between the initial and final states in an alpha decay process must be carried off by the alpha particle as orbital angular momentum. For even-even nuclei, whose ground states are all presumed to have zero spin and even-parity (0+) also, the above facts result in a "selection rule". It is possible for each orbital

angular momentum wave (s, p, d, ...) to populate only states of a particular spin and parity in the daughter nucleus (0+, 1-, 2+, ... respectively, for the above waves). States with other spins and parities (0-, 1+, 2-, ...) cannot receive direct alpha population from an even-even nucleus. This rule is not nearly so important as it might be, because it is now rather well established that states with even spin and odd parity (also odd spin and even parity) are missing among the levels of low energy in even-even nuclei. However, a number of spin assignments have been made or confirmed by the use of this selection rule. For odd-mass nuclei no such selection rule results since spins are half integer (eliminating the possibility of spin 0). Consideration of the orbital angular momentum waves involved in the alpha decay of odd-mass nuclei will be of great importance, however.

1. Even-Parity Rotational Band. The excellent agreement of the ground state alpha transitions of even-even nuclei with the one-body model for alpha decay has already been noted. Since the spin and parity of the ground state of every even-even nucleus is thought to be 0+, these must all be s-wave ($\ell = 0$) alpha transitions, which occur between very similar states in the initial and final nucleus. Thus the uniformity of these alpha transitions and the fact that they are "unhindered" (agree with the one-body model) are not particularly unexpected. According to the unified nuclear model of Bohr and Mottelson (44), nuclei in regions removed from closed shells should have spheroidal rather than spherical shapes, and there should then be associated with the ground states of even-even nuclei rotational bands whose members have spins and parities of 0+ (ground state), 2+, 4+, 6+, ... The odd spin members of the rotational band are excluded by symmetry considerations. The energies, E_I, of these states are given by:

$$E_I = W_o + \frac{\hbar^2}{2\mathfrak{J}} (I)(I+1), \qquad (1)$$

Where I is the spin of the level, $\mathfrak{J}$ represents an effective moment of inertia, and W_o is a constant giving the elevation of the entire band above the ground state (for the ground state band under discussion here, W_o is of course zero). In all instances where a closed shell is sufficiently far away and where data are available, such bands have been found. Starting with uranium and progressing through the transuranium elements the value of $\frac{\hbar^2}{2\mathfrak{J}}$ is rather constant and equal to approximately 7 kev. Below uranium the value of $\frac{\hbar^2}{2\mathfrak{J}}$ (i.e., the spacing of the band) becomes larger until, as the closed shell region is approached, the band can no longer be identified. Alpha decay follows distinct patterns in its population to the various band members, and some of the data in this regard will now be examined.

The decay scheme of Pu^{238} (45,46) is shown in Fig. 8. This scheme is typical of that for decay to the ground state (or "even-parity") rotational band in an even-even nucleus. The alpha transitions not inclosed in parentheses in Fig. 8 have been directly observed with a magnetic spectrograph. Those in parentheses are too weak for direct observation on the spectrograph, and have been identified from gamma-ray and gamma-gamma coincidence studies. The spin and parity of the first excited state has been assigned 2+ from the fact that the 43.50 kev transition is E2. The other spin and parity assignments have been made principally on the basis that the energy agreement with equation (1) is good, and the gamma-ray data are consistent with the predicted spins. These data and assignments are typical of the even-even nuclei in this region and are considered

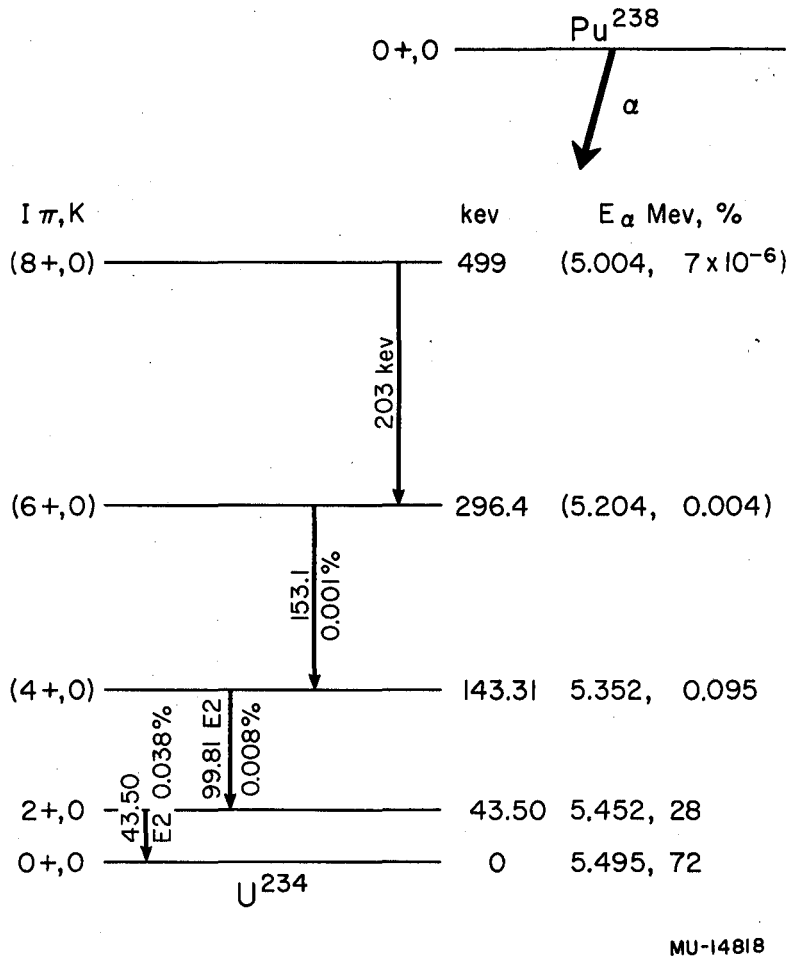

Fig. 8. Decay scheme of Pu^{238}. K, which has not been mentioned in the text, represents the projection of the spin, I, on the nuclear symmetry axis. In all the decay schemes, parentheses around the spins indicates that these are uncertain, whereas parentheses around an alpha energy and intensity mean that the group was not directly observed on an alpha particle spectrograph, but was deduced from gamma ray data. The sequence of levels populated in U^{234} are those of the even-parity rotational band.

well established. However, it should be pointed out that independent spin and parity assignments of states above the 2+ levels are largely absent; in fact, in only one case (47) can a 4+ assignment be considered independently proved for the second excited state. The hindrance factors for alpha decay to the 0+, 2+, 4+, 6+, and 8+ levels of U^{234} are 1.0 (by definition), 1.5, 120, 360, and 15,000 respectively. Comment on these values will be reserved until they are compared with the analogous data for other even-even nuclei.

Now that a rather typical decay scheme has been examined in some detail, the general features of alpha decay to the even-parity rotational bands will be considered. Figure 9 shows the variation in energy of the first excited state (2+) of even-even nuclei as a function of neutron number, where the lines are connecting points for each element. The sharp increase in this energy in the vicinity of the closed shell region (126 neutrons) is apparent. For convenience in discussing energy levels, the heavy elements have been divided into three regions as indicated in Fig. 9. In the immediate vicinity of the closed shell, nuclei are thought to be spherically shaped, and hence this region will be referred to as the spherical region. Similarly, well removed from the closed shell, the spheroidal shapes previously mentioned are thought to be stable, giving rise to the rotational characteristics of this region. Hence this is generally called the spheroidal region. Between these two reasonably well-characterized areas lies the intermediate region, where the properties of the nucleus seem to be changing from spherical to spheroidal. The extent of this region varies somewhat according to the nuclear properties under consideration. These subdivisions are quite important in considering the energy levels of both even-even and odd-mass nuclei. When the energy of the first excited state in even-even nuclei gets as high as about 200 kev (around neutron number 134 in Fig. 9)

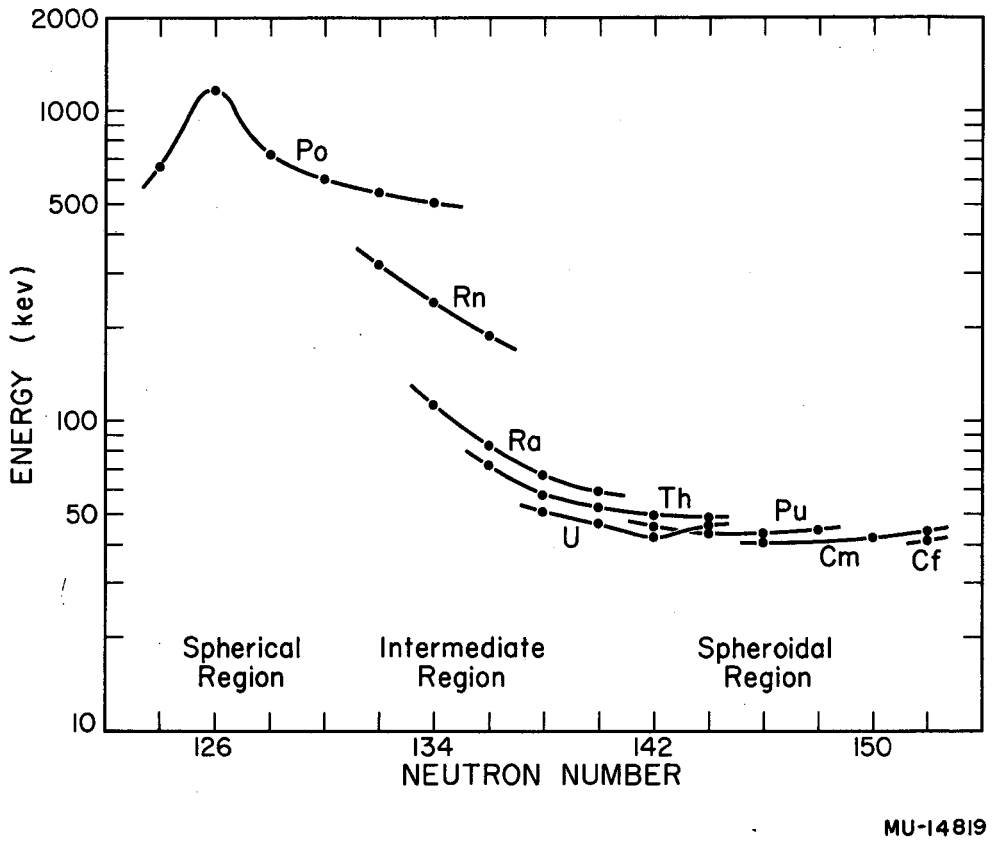

Fig. 9. The first excited state energy of even-even nuclei is shown plotted against neutron number, where the lines connect the points for each element. The spherical, intermediate, and spheroidal regions of the heavy elements are indicated.

the pattern of excited states changes from "rotational", as has been described, to "near-harmonic", which has been discussed by Goldhaber and Weneser (49), and is characteristic of the intermediate region. Thus the regularities in the even-parity rotational band as illustrated for U^{234} extend only down to the vicinity of neutron number 134.

Hindrance factors for alpha decay to the members of the even-parity rotational band are shown in Fig. 10, where they have been plotted against the atomic number of the parent, the wide variation of these hindrance factors is apparent, and it is well to bear in mind that these differences are after the energy dependence of alpha decay has been removed by the one-body theory. The reasons why (1) the higher spin states have such large hindrance factors and (2) there is such a wide variation in hindrance factor to a given level (almost a factor of 100 in the case of the 4+ state) are not very well understood at the present time. It is true that the dependence of the alpha particle emission probability on the angular momentum change in the transition ("spin dependence") has not been included in the hindrance factor, and its inclusion would probably bring down appreciably the values for the higher angular momentum alpha waves. This effect does not seem to be large enough, however, to account for all the hindrance of these waves, nor does it explain the large variation of hindrance factor within a given wave (to a given level). Thus it seems we must look further for the explanation of these hindrance factors, and considerable progress is being made in this direction by Rasmussen (50) and others (51-53). It is worth noting that the spin dependence of alpha decay is enormously less than that of beta decay, so that in regard to spin, alpha decay is much less selective in the levels it populates.

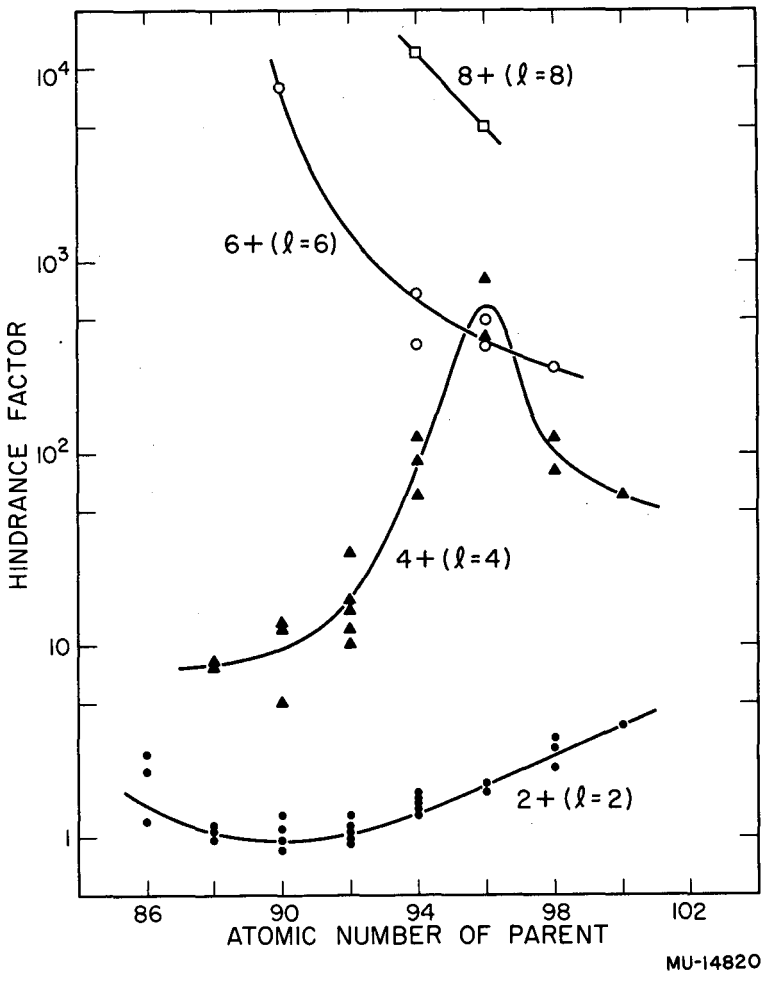

Fig. 10. The hindrance factors for alpha decay to members of the even parity rotational band are shown plotted against the atomic number of the parent alpha emitter. The spins indicated are those of the final state, and the ℓ value is the alpha particle orbital angular momentum wave for each transition.

2. Odd-Parity Rotational Band. In some heavy even-even nuclei, energy levels that are not members of the even-parity rotational band, have been found at excitation energies of only a few hundred kev (54). Ra^{224} (54-61) is such a case, and the level scheme of this nucleus, as populated by the alpha decay of Th^{228}, is shown in Fig. 11. Each of the alpha transitions indicated in Fig. 11 has been observed in studies of the alpha particle spectrum of Th^{228} on the Berkeley uniform field spectrograph. The gamma rays de-exciting the levels have been identified from a combination of gamma-ray, alpha-gamma coincidence, and gamma-gamma coincidence measurements. The spins of the 84 and 217 kev states have been established relative to that of the ground (0+) state by conversion coefficient and angular correlation studies; however, the spins for the highest two states cannot yet be considered certain.

The even-parity rotational band is easily recognized in Ra^{224}, even though the level spacing has become considerably wider than in U^{234} (Fig. 8), and significant deviations from equation (1) have developed. These changes are due to the proximity of the closed-shell region where some of the approximations made in the rotational model are no longer valid. There are also observed in Ra^{224} two levels that are not members of the even-parity band. These occur at energies of 217 and 289 kev and comprise what we shall call the "odd-parity" rotational band. States with spin and parity 1- (the 217 kev level in Ra^{224}) have appeared at low excitation energies in many even-even nuclei in the heavy-element region (54). Recently evidence has been accumulating (56) that there is a rotational band based on this 1- state, where the band members have spins and parities 1-, 3-, 5-, ..., and energies given by equation (1). The 217 and 289 kev levels in Ra^{224} are thought to constitute the first two members of such a band. The odd-parity states seem to de-excite predominately by electric dipole

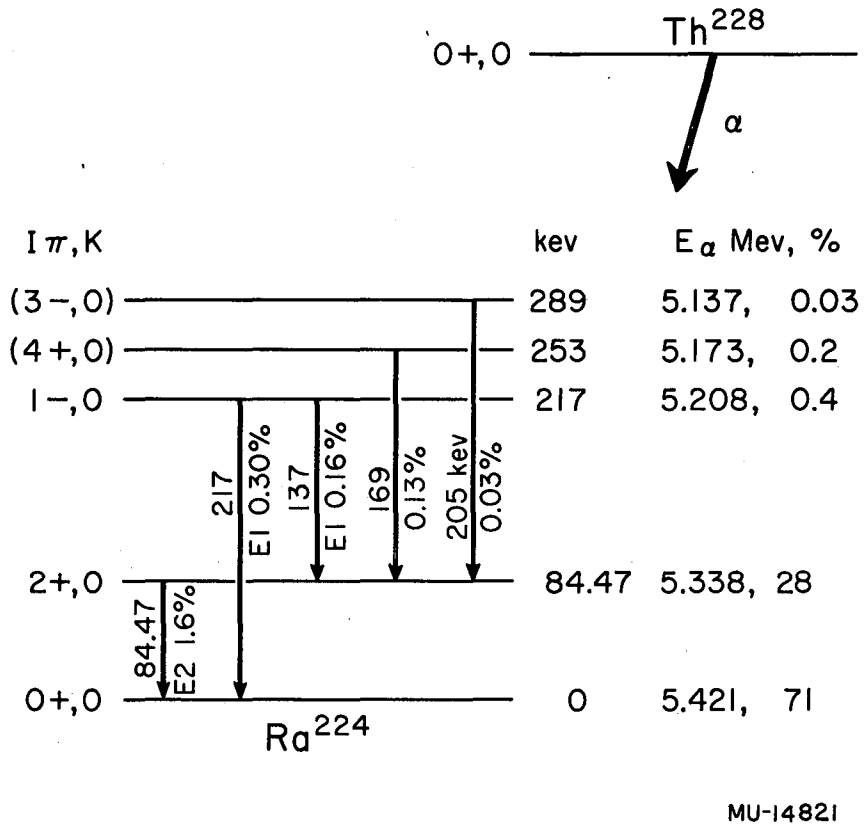

Fig. 11. Decay scheme of Th^{228}, showing both the even- and odd-parity rotational bands.

transitions to the members of the even-parity band. Thus the 1- state of Ra^{224} decays to the 0+ and 2+ states and the 3- state decays to the 2+ state. The absence of the transition from the 3- state to the 4+ state is thought to be due only to its small energy (34 kev) relative to that of the transition to the 2+ state (205 kev). The relative intensity of the two E1 gamma rays de-exciting each odd-parity state has been interpreted in the framework of the unified nuclear model as indicating that the odd-parity band is related to the even-parity band (62), and a suggestion has been made (63) that it represents the members of the even-parity band supposedly absent due to symmetry considerations. Thus the possibility seems to be raised that some of the symmetry conditions within the nucleus are beginning to break down, and it will be of interest to see whether such a conclusion can be confirmed.

The energies of the 1- states thus far identified in even-even nuclei are shown plotted against mass number in Fig. 12. A distinct minimum in the energy of this state seems to occur around mass number 224 (or neutron number 136). The reason for this is not known; however, in terms of the discussion in the preceding paragraph it is probably related in some manner to the stability of the unsymmetrical deformations of the nucleus. The data on the transuranium elements are fragmentary due to experimental difficulties in this region, and it should not be inferred that the absence of data is due to an absence of 1- states. The hindrance factors for alpha decay to the odd-parity band members are plotted against neutron number of the parent in Fig. 13. The 1- state hinderance factors are seen to follow a rather smooth curve which possibly has a maximum around neutron number 144. In this regard it is interesting to note that no 1- state has been found in the alpha decay of Pu^{238} (144 neutrons),

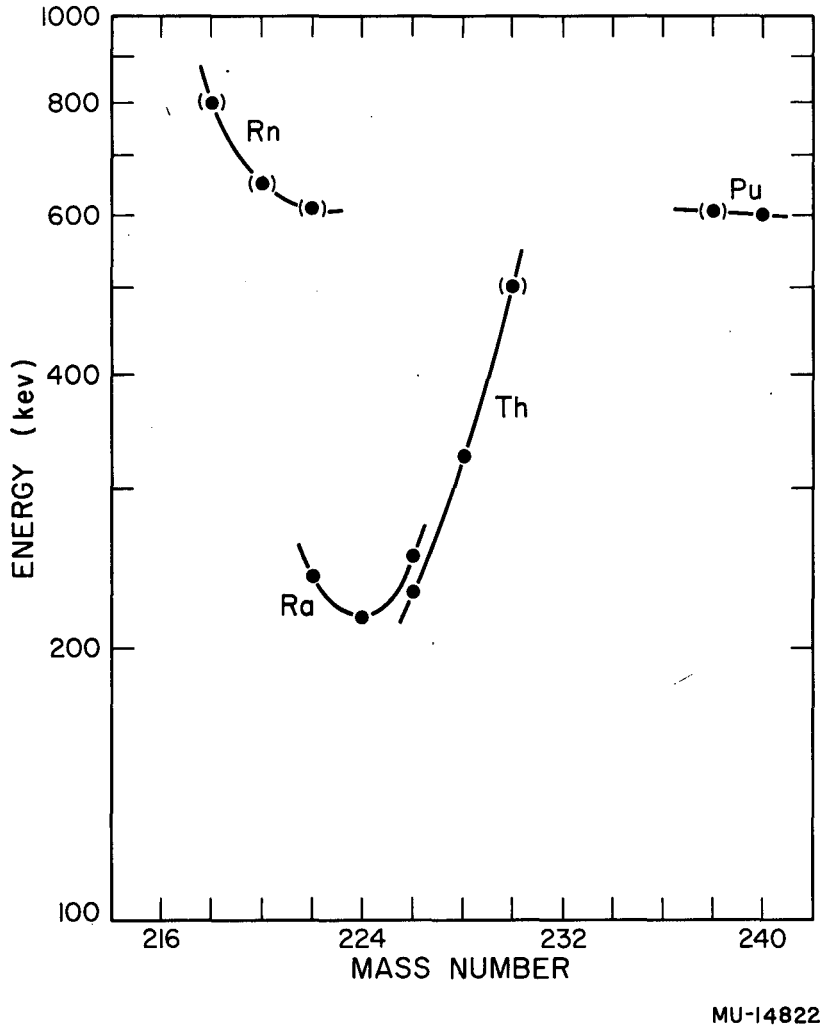

Fig. 12. The energy of the 1- states of even-even nuclei is shown plotted against mass number. The lines connect the points for each element. No 1- states in uranium isotopes have been found.

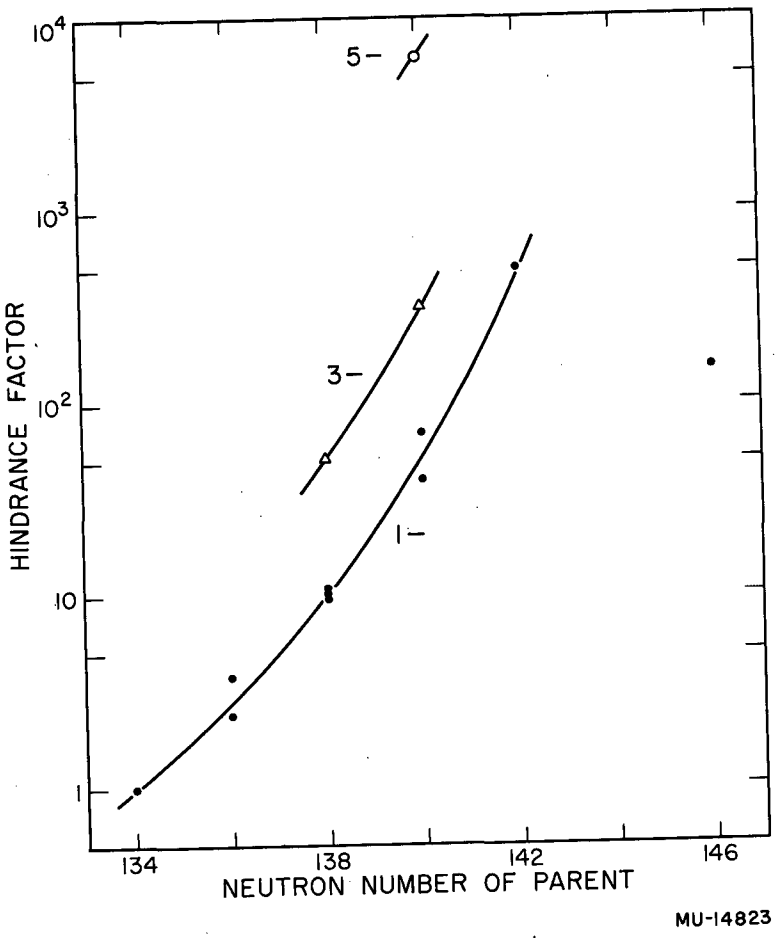

Fig. 13. Hindrance factors for alpha decay to the members of the odd-parity rotational band in even-even nuclei. The point (corresponding to Cm^{242} alpha decay) at 146 neutrons makes it seem that the hindrance factors for decay to the 1- state may go through a maximum around 144 neutrons.

although a careful search has been made (46). This means that either the energy of the 1- state in U^{234} is quite high, which doesn't seem too likely from Fig. 12, or that the hindrance factor for decay to the 1- state is very high, which does seem rather likely considering Fig. 13. Why these hindrance factors vary the way they do is not understood, although, as in the case of the even-parity band, progress in this regard is being made.

3. Higher Energy Levels. Alpha decay is not a very favorable means for studying the higher energy states of even-even nuclei. This is because almost all such levels lie at energies of about 1 Mev or more, and the steep energy dependence of the alpha emission process discriminates rather severely against levels of such high energy. In spite of this difficulty two types of states have been observed which do not belong to the even- or odd-parity rotational bands. These types are illustrated by the decay schemes of Ra^{226} (64-68) and Cm^{242} (69-71) which are shown in Figs. 14 and 15. Rn^{222}, from Ra^{226} decay, lies in the intermediate region, and Goldhaber and Weneser (49) have shown that in this region a second 2+ state is expected at almost twice the energy of the first 2+ state. The 450 kev level in Rn^{222} is believed to be such a level (67). Two other similar levels have been observed from alpha decay (68), and the hindrance factors for the decay to each of these is around 10. The level at 935 kev in Pu^{238} (from the alpha decay of Cm^{242}) is quite interesting in that it decays by an electric monopole transition (71) to the ground state of Pu^{238}. This fixes the spin of the level as 0+, and makes it seem likely that it is the so-called "beta vibrational state" predicted by the unified nuclear model. One other such state has been observed (alpha decay of Pu^{238} to U^{234} (71)), and in both cases the alpha transition is essentially

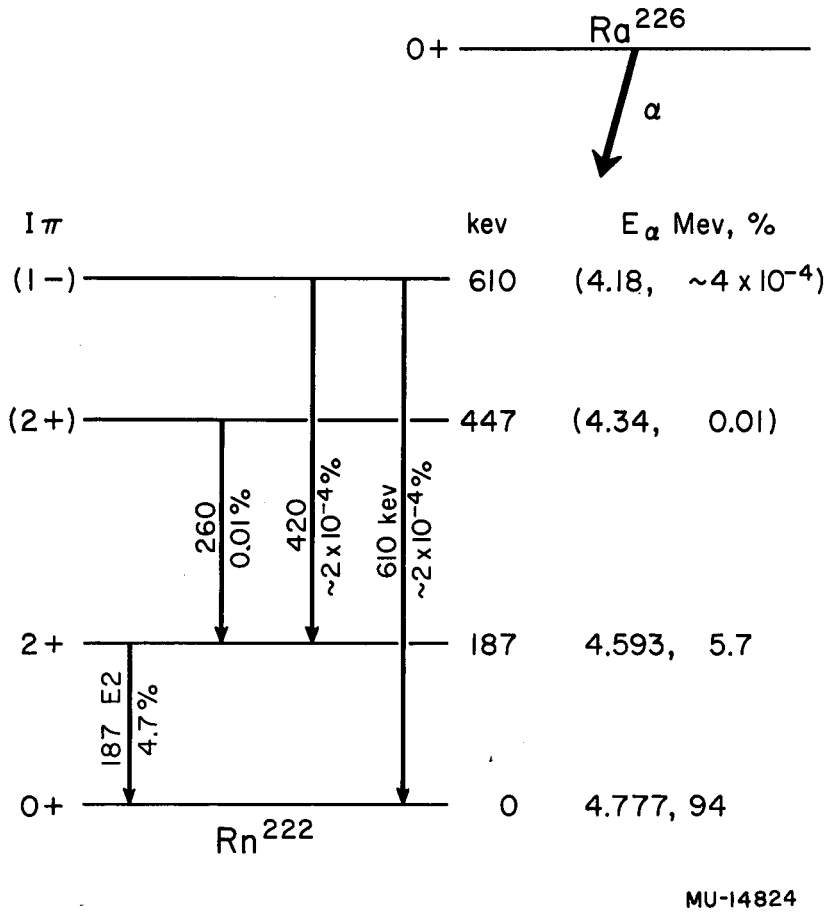

Fig. 14. Decay scheme of Ra^{226}. The (2+) level in Rn^{222} at 447 kev is believed to be characteristic of even-even nuclei in the intermediate region.

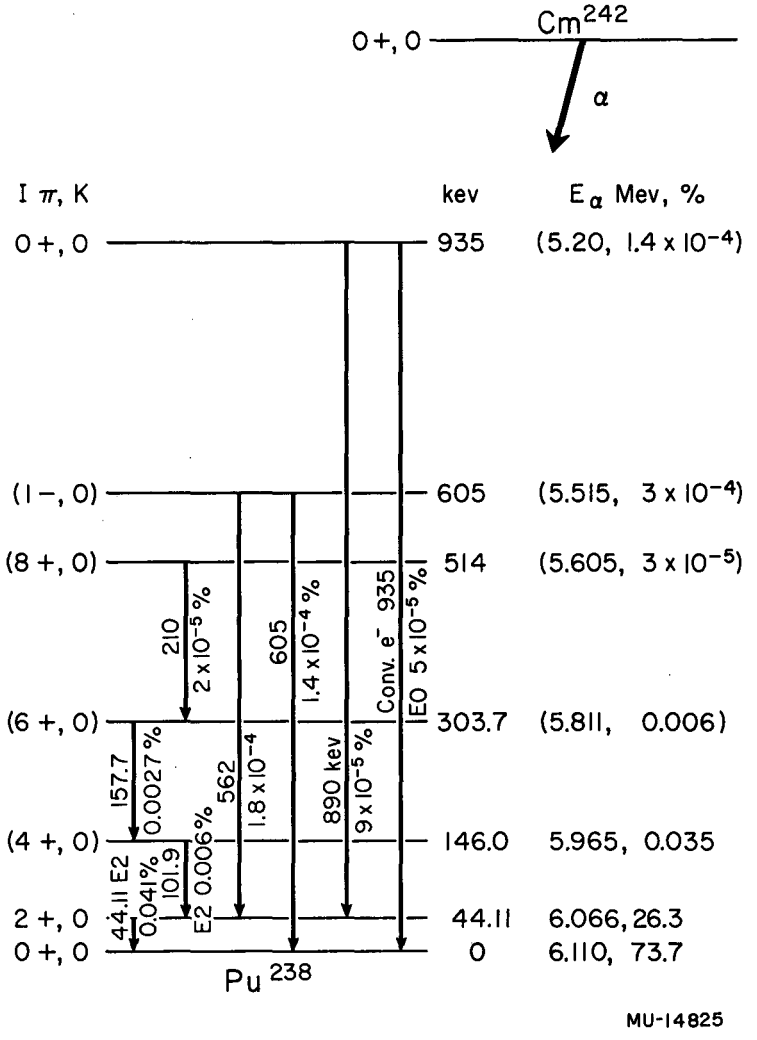

Fig. 15. Decay scheme of Cm^{242}. The 0+ level at 935 kev is believed to be the lowest member of the beta vibrational band. Other levels in Pu^{238} have been observed from the decay of Np^{238} and Am^{238}.

unhindered (similar to the ground, 0+, state). There seems to be little doubt that these weakly populated states in the alpha decay of even-even nuclei will receive considerable attention in the future.

B. Odd-Mass Nuclei.

Odd-mass nuclei exhibit considerably less regularity in their alpha decay than has been described above for the even-even nuclear type. Consider, for example, that in comparison with the extremely regular behavior of the even-even ground state alpha transitions, those in odd-mass nuclei have hindrance factors varying from about one to well over ten thousand. It is becoming increasingly clear that this apparent irregularity is due to an increased complexity of energy levels in odd-mass nuclei rather than to any change in the alpha decay process. Recent information, in fact, seems to indicate that in the spheroidal region of the heavy elements certain "favored" alpha transitions in odd-mass nuclei are virtually identical with those transitions to the even-parity rotational bands of the adjacent even-even nuclei. These "favored" alpha transitions seem to be one of the first steps in understanding the alpha decay of odd-mass nuclei and will be considered in some detail below. For convenience the following discussion has been divided into a section on the spheroidal region of the heavy elements where most of the work both experimentally and theoretically has centered and a short section outlining the situation in the other regions.

1. Spheroidal Region. An enormous amount of progress has recently been made in understanding the energy levels of odd-mass nuclei in the regions of large spheroidal deformation. The first big step came with the unified nuclear model (44) which predicted the occurrence of rotational bands similar

to those in even-even nuclei. Many such bands have since been found with spins I_o, $I_o + 1$, $I_o + 2$, ..., and energy level spacings in good agreement with equation (1)[a]. The second step was taken by Nilsson (72) and others (73,74) who considered the effect of a spheroidal deformation of the nucleus on the shell model energy levels. The results of Nilsson's calculations for a limited region are shown in Fig. 16. The energy of particular levels has been plotted along the vertical axis in Fig. 16 against the amount of spheroidal deformation given in terms of a parameter, δ (or η). A value of zero for δ corresponds to a spherical nucleus, and here the usual shell model levels are observed. As δ increases, however, these shell model levels split into a number of components, each of which can accomodate two nucleons. These components are designated by a spin and parity, and three "asymptotic quantum numbers" whose significance will not be of importance here. The usefulness of the diagram may be illustrated by considering the nucleus, Np^{237}, which has 144 neutrons and 93 protons. Since, like the shell model, it is the last odd particle which is of importance in determining the properties of the nucleus, the neutrons in Np^{237} need be considered no further. Of the protons, 82 should be contained in the closed shell corresponding to the bottom of the diagram in Fig. 16. The remaining 11 protons should fill in pairs into the lowest unoccupied levels of the diagram until a single proton remains. This proton is expected to be in the next lowest available level, whose characteristics determine those exhibited by the nucleus. Since, in the region of neptunium, δ is expected to be about 0.20-0.25, the

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[a] In the case where $I_o = 1/2$, a second term, $\Delta E_I = a\,(-)^{I + 1/2}\,(I + 1/2)$, must be added to equation (1), where a is a constant for each band.

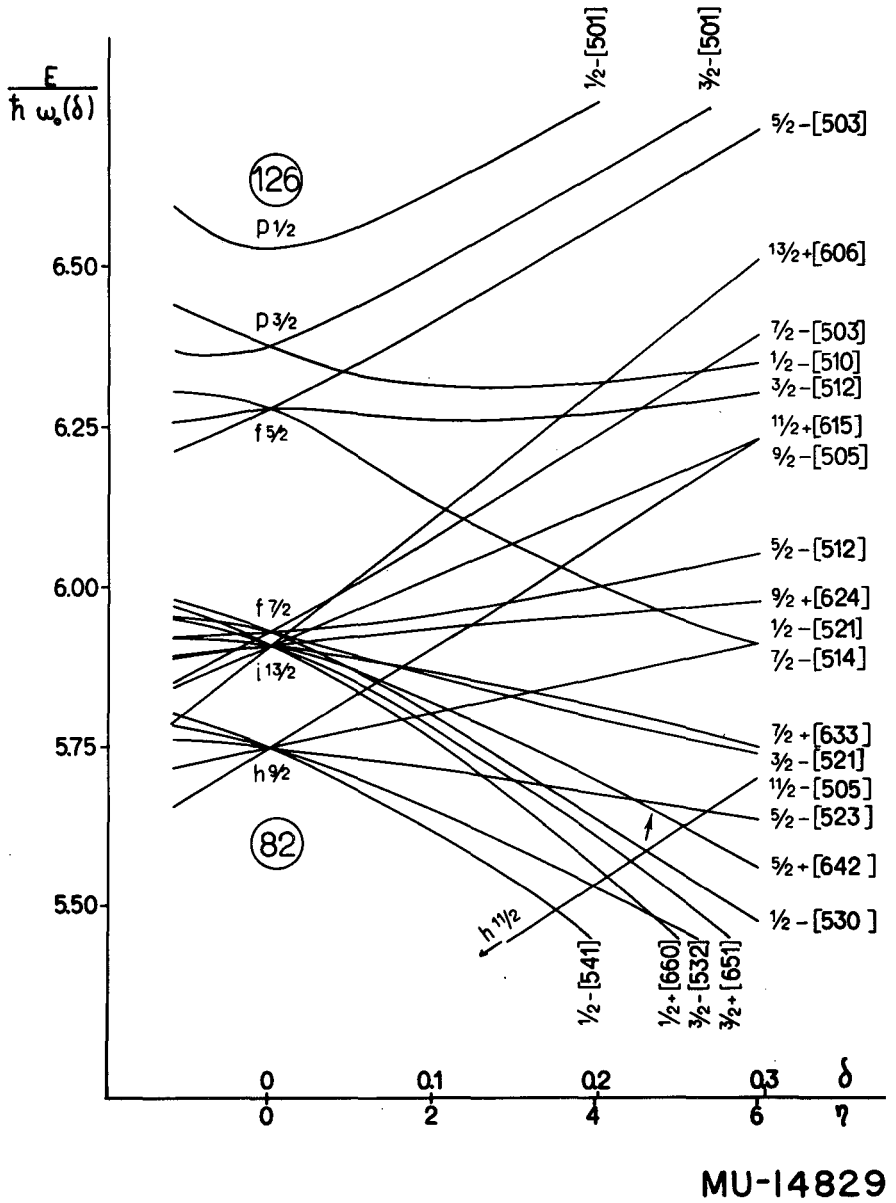

Fig. 16. Nilsson diagram for protons, showing the energy of the levels versus the amount of spheroidal distortion given in terms of the parameter δ (or η). A value of zero for δ corresponds to a spherical nucleus, and here the usual shell model levels are observed. Positive values of δ (toward the right from zero) correspond to prolate distortion. The arrow indicates the level believed to correspond to the ground state of Np^{237}. The levels are identified by the quantum numbers $\Omega\ \pi\ [N\ \eta_z\ \Lambda]$, which represent respectively the symmetry-axis component of total nuclear angular momentum, the parity, the principal oscillator quantum number, the symmetry-axis oscillator quantum number, and the symmetry-axis component of orbital angular momentum.

above procedure puts the last odd proton of Np^{237} into the level indicated by an arrow in Fig. 16. A spin and parity of 5/2+ are thus expected for Np^{237}, and a spin of 5/2 has been experimentally observed (75). Other evidence (76-78) indicates that the last odd proton of Np^{237} is, indeed, in the expected level. Although the energy separations calculated by Nilsson are only approximate, the usefulness of such a diagram in interpreting ground and excited states in odd-mass nuclei in the spheroidal region can hardly be overestimated. This will be further illustrated by the consideration of a particular alpha decay scheme.

One of the most carefully studied decay schemes in the heavy element region is that of Am^{241} (16,76,79-87) which is shown in Fig. 17. The alpha spectrum has been thoroughly investigated (16,80,81,84,87), and the six groups shown in Fig. 17 have all been seen by more than one laboratory. The conversion electron and gamma ray data are quite extensive, so that there seems to be little question about the gamma ray placements and the multipolarities indicated in Fig. 17. In addition, the ground state spins of Np^{237} and Am^{241} represent measured values (75,88), and that of the 59.57 kev level has been determined rather conclusively from alpha-gamma angular correlation measurements (89) and other data (9,90). Some additional energy levels in Np^{237} have been seen from U^{237} beta decay (77,86,91,92), but those will not be of interest here. The levels of Np^{237} shown in Fig. 17 have been interpreted in terms of two rotational bands based on the ground and the 59.57 kev levels. The Nilsson assignment of the ground state has already been discussed and corresponds to the indicated level in Fig. 13. Just above this level in the diagram at $\delta \approx 0.23$ is a 5/2- state which is believed to correspond to the 59.57 kev

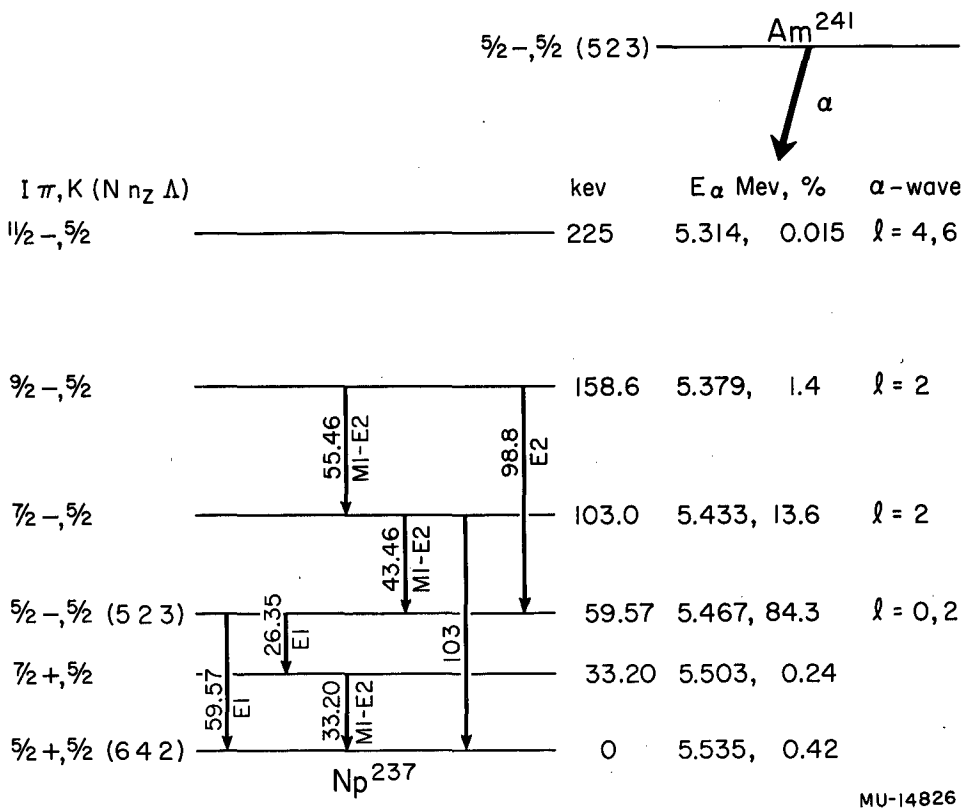

Fig. 17. Decay scheme of Am^{241}, illustrating particularly the favored alpha decay to the 5/2- band. The ℓ values are the alpha waves believed to contribute to the population of each member of the favored rotational band.

level in Np^{237}. The 33.20 kev level is presumably a member of the ground state rotational band, and the remaining levels have been assigned to the rotational band based on the 59.57 kev level. The energy level spacing of this latter band is in good agreement with equation (1). Am^{241} contains two more protons than Np^{237}, and would be expected to have for its ground state the same 5/2- level that corresponds to the 59.57 kev level in Np^{237}. All the available evidence indicates that this is the situation and the almost unhindered alpha decay between these two states (H.F. = 1.2) is thought to be characteristic of alpha transitions between the same Nilsson level in the parent and daughter nuclei. The term, "favored" alpha decay, is usually applied to these transitions. Alpha transitions to other rotational bands in the daughter nucleus, such as the ground state band of Np^{237}, are referred to as "unfavored" or "hindered" alpha decay.

Almost every odd-mass alpha emitter in the spheroidal region of the heavy elements exhibits favored alpha decay to a rotational band of its daughter nucleus. The favored decay is usually the most prominent, since it is essentially unhindered, whereas the unfavored transitions generally have rather large hindrance factors. The position of the favored band in the daughter nucleus varies in different cases. It may be the ground state as in U^{233} (16,84) and E^{253} (93) decay or it might be an excited state as high as around 400 kev as in Cf^{249} decay (94). The current picture of favored alpha decay is that the odd nucleon remains in its particular Nilsson level throughout the process, while the alpha particle is formed from the paired nucleons and emitted in a manner exactly similar to the decay of an even-even nucleus. Bohr, Fröman, and Mottelson (BFM)(95) have considered this process and conclude that, making certain approximations, the total

emission probability for a given alpha wave should be the same for the alpha transitions to the favored band in odd-mass nuclei and the even-parity rotational band in even-even nuclei. A complication arises, however, since in odd-mass nuclei a given alpha wave can generally populate more than one level in the favored rotational band. In the decay of Am^{241} (Fig. 17), for example, the $\ell = 2$ wave can populate the 5/2, 7/2, and 9/2 members of the favored band. This is not true in the even-even analogy, where the $\ell = 2$ wave can only populate the 2+ state of the even-parity band. This aspect of the problem has also been considered by BFM who have shown that the distribution of a given alpha wave among the various band members it can populate is given approximately by certain readily obtained vector addition coefficients. Application of the BFM treatment to calculate the relative populations to the favored band is then as follows: (1) compute the distribution of each wave according to the vector addition coefficients given in BFM, (2) use hindrance factors for each alpha wave similar to the adjacent even-even nuclei (i.e., from Fig. 10), (3) obtain the energy dependence for each level from one-body theory of alpha decay. For Am^{241} decay the above prodecure gives relative intensities to the 5/2, 7/2, 9/2, and 11/2 states of 100, 13, 2.2, and 0.021 respectively (95,10), compared with experimental values of 100, 15, 2.0, and 0.018 (16). The alpha waves to each band member are indicated on Fig. 17, and hindrance factors of 1.0, 1.67, 200, and 300 were used for the $\ell = 0$, 2, 4, and 6 waves respectively (cf. Fig. 10). The contribution of the $\ell = 4$ and 6 waves to the 5/2, 7/2, and 9/2 band members is negligibly small compared with the $\ell = 2$ and $\ell = 0$ waves, and similarly the contribution of the $\ell = 8$ wave can be estimated to be negligible for the 11/2 state. The odd alpha waves are all excluded by parity considerations. The experimental and calculated intensities to the 5/2 state were

normalized, but even so the agreement is rather impressive. A number of other favored alpha decays have been analyzed in this manner (95,9,10), and the agreement is about like that for Am^{241}, although in most cases the experimental data are not so extensive.

Unfavored alpha decay in the spheroidal region of the heavy elements has received very little theoretical attention. This is probably due not only to the absence of an apparent analogy in the even-even nuclei, but also to the small amount of experimental data which, at least until very recently, has been available on this type of decay. This latter problem arises due to the usual low intensity of the unfavored transitions. In the case of Am^{241} (Fig. 17), for example, only about 0.6% of the total alpha decay goes to the unfavored ground state rotational band. A considerably better situation is found in the decay of Cm^{243}, however, which has recently been studied by Asaro et al. (1,2), and whose decay scheme is shown in Fig. 18. The levels of Pu^{239} have also been studied from the beta decay of Np^{239} (3-6), the electron capture decay of Am^{239} (7), and Coulomb excitation of Pu^{239}, itself (96); so that the level scheme shown in Fig. 18 is quite well established. The favored alpha decay of Cm^{243} populates a rotational band 286 kev above the ground state of Pu^{239}, while unfavored decay is seen to two bands, one at the ground state and the other at 392 kev above the ground state. Alpha population to six members of the ground state (spin 1/2) rotational band in Pu^{239} has been observed (2), and this represents considerably more information than is available on any other unfavored alpha transition. Asaro et al. (2) have been able to calculate the relative alpha populations to the members of this band using an approach similar to the BFM method for favored decay. For the unfavored transitions, however, the alpha wave hindrance factors are treated as adjustable

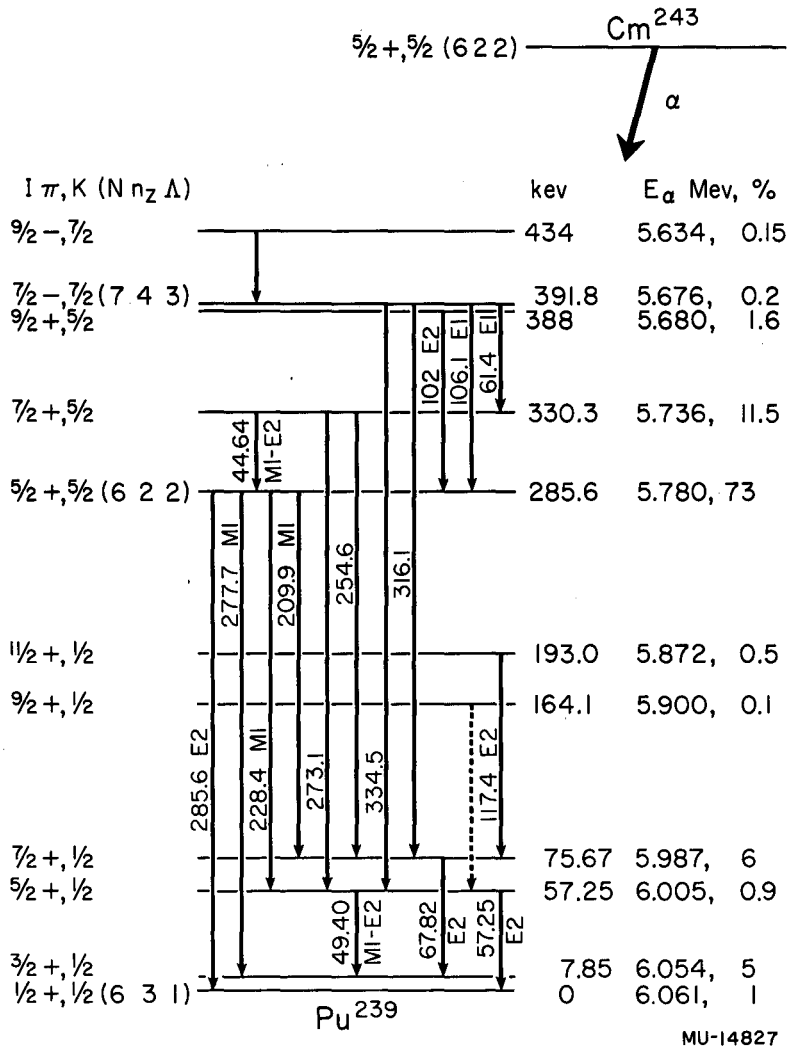

Fig. 18. Decay scheme of Cm^{243}, illustrating particularly the unfavored alpha decay to the ground state rotational band of Pu^{239}.

parameters, and the values required to fit the experimental data seem to bear no relationship to those for the even-even nuclei. There are not yet sufficient data to test the general applicability of this method, but at the present time it seems to offer a rather promising start toward understanding unfavored alpha decay.

2. Non-Spheroidal Regions. Almost all the nuclear spectroscopic data on non-spheroidal odd-mass alpha emitters come from the intermediate region of the heavy elements (Fig. 9), extending very roughly from astatine through actinium. Several alpha decay schemes have been studied in the closed shell region (21,97-104), but at the present time these do not seem to be sufficiently extensive nor informative to warrant discussion here. Perhaps the most outstanding feature of alpha decay schemes in the intermediate region is their complexity. As an example consider decay of Th^{227}, whose alpha spectrum was shown in Fig. 2. The level scheme of Ra^{223}, as populated in this decay, has been the subject of considerable study (105-111), and the recent results of Pilger, Asaro, and Perlman (21,112) are shown in Fig. 19. The complexity is evident, and our present understanding of either the energy levels or the alpha decay process is almost non-existent. This complexity of levels seems to change rather abruptly around thorium into the rotational pattern characteristic of spheroidal nuclei. As one moves toward lower mass numbers the average spacing between levels gets wider until around bismuth and polonium the levels can be interpreted in terms of the spherical-well shell model. As the theory of nuclear energy levels progresses, this intermediate region is becoming of considerable interest, and its elucidation will probable represent one of the next steps in understanding nuclear energy levels. It should perhaps be

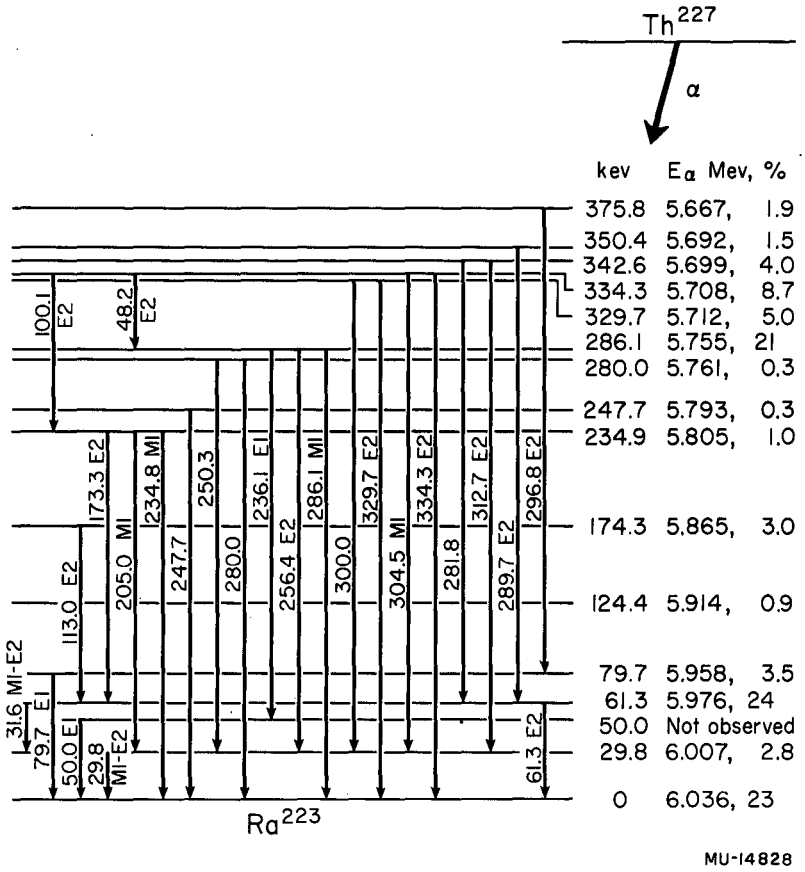

Fig. 19. Decay scheme of Th^{227}. Very little is understood at present about the levels of Ra^{223}. The alpha particle spectrum of Th^{227} was shown in Fig. 2.

pointed out that the study of a complex decay scheme such as that in Fig. 19 is aided immeasurably by the fact that most of the levels can be observed directly in the alpha particle spectrum. If these same levels in Ra^{223} were populated by a beta emitter instead of an alpha emitter, it would have been much more difficult, if not impossible, to establish the decay scheme with equal certainty.

CONCLUSION

There are two essentially different kinds of information that can be obtained from the study of alpha emitters. The first of these might be called simply decay scheme information; that is, the mapping of nuclear energy levels and their decay characteristics. An enormous amount of progress has recently been made in this regard, and has been followed, for the most part, by at least some understanding of the energy levels in terms of nuclear structure. Only in the odd-mass nuclei of the intermediate region is the theory seriously behind the experimental data. Beta decay, as well as a number of other means of exciting nuclear energy levels, can also give information of this kind, and the study of nuclear energy levels represents the combined attack of all these methods. For this purpose, alpha decay differs from the other methods only in that where it occurs it is usually the most convenient to exploit.

The second kind of information has to do with the alpha decay process and, therefore, can only be obtained from the study of alpha emitters. The energy dependence of alpha particle emission should probably be given as the first example of this kind of information, and the theoretical solution of this problem in terms of the quantum-mechanical penetration of the Coulomb barrier

(35.36) contributed enormously not only to the understanding of nuclear phenomena, but also to the then-new concept of quantum mechanics. The hindrance factors (reciprocal of the reduced alpha transition probability) almost undoubtedly represent another example of this kind of information. Although at the present time these are not fully understood, Rasmussen (50,51) has shown that the regular variation of the hindrance factors for the even-parity rotational bands in even-even nuclei (Fig. 10) is probably related to the particular area on the nuclear surface where alpha particle formation is most probable. This area, Rasmussen further suggests, may depend rather sensitively on the wave functions of the most loosely bound nucleons. Thus, as our understanding of the alpha emission process improves, it seems likely that a considerable amount of fundamental information will be derived from its study.

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