HEAVY NUCLEI,
SUPERHEAVY NUCLEI,
AND
NEUTRON STARS

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PREFACE

It could be argued that the trigger which set off the explosion of interest in the physical sciences since the second World War was the possibility of harnessing the enormous energy released in nuclear fission. Yet despite the pioneering work of Bohr and Wheeler a long time elapsed before it became possible to explain the detailed fission mechanism, and only in recent years have many of the outstanding questions in this field been clarified. At the same time the whole question of nuclear stability and the possible existence of relatively long-lived superheavy elements has been the subject of deep scrutiny. Many of the experiments suggested to test the new theories involve heavy ion reactions at energies close to, or above, the Coulomb barrier and the consequent need to design and build a new generation of heavy ion accelerators with which to carry out these experiments.

Paralleling these developments in terrestrial nuclear physics the discovery of pulsars and the suggestion that they may well be neutron stars has once more emphasized the importance of understanding nuclear processes in astrophysics. It thus appears a timely exercise to prepare a brief, unified introduction to these matters. Many of the ideas related to the topics discussed are in state of flux. Thus in no way is this presentation intended to be definitive. I have enclosed a few references, and by and large these are not original research papers but rather reviews which I have found particularly readable and through which the reader will find a more extensive bibliography of original material.

I would like to acknowledge many helpful discussions with my colleagues in Manchester and in particular Dr. C. Pwu. Most of the results presented in Chapter 7 are taken from his Ph.D. thesis and the results in Chapters 8 and 9 relied heavily on computer codes for which he was responsible. I am grateful to Miss V. Harney for the most efficient way she translated my often unintelligible scrawl into a legible typescript.

Finally, I would like to dedicate this book to Ritchie Middlemass, a patient and considerate teacher.

Manchester 1974. J. M. I.

CONTENTS

1

INTRODUCTION

Our topic is the structure of heavy, superheavy, and ultra-superheavy (i.e. neutron-star) nuclei. That is, we are interested in *nuclear matter.* Not in the rather academic sense of an infinite equal number of neutrons and protons in which the Coulomb force has mysteriously been switched off, which technically is the meaning of the term 'nuclear matter', but rather in the sense of the possible states of matter composed of nucleons at densities comparable to, or greater than, those found in terrestial atomic nuclei (Bethe 1971; Irvine 1972).

Where we draw the line between what is heavy and what is not, is, of course, rather arbitrary. We shall draw the line at ^{208}Pb, and our study will concentrate on nuclei with $A \geqslant 208$ and $Z \geqslant 82$. We shall be particularly interested in those phenomena which are essentially statistical in origin, reflecting the participation of very many particles, e.g. collective rotations, fission, shape isomers, superfluidity, etc. This is not to say that some or all of these effects are not seen in lighter nuclei. In particular, the discussion of collective rotations would be applicable to an account of the rare-earth nuclei. Indeed we shall briefly discuss the phenomena of the 'back-bending' of moments of inertia (Sorensen 1973) which to date have only been observed in the rare-earth nuclei but which, if our current ideas have any validity, should also be displayed in the heavy actinides.

In our region of interest there are only ten naturally occurring elements,† although there are many more isotopes, and if this was all there was to discuss we would indeed be severely restricted. However, since the detonation of the first atomic bomb man has been manufacturing new nuclei, and there are currently fourteen man-made elements and their associated isotopes which can be added to our catalogue. One of the subjects we shall discuss concerns the stability of these very heavy nuclei and of the possible existence of an 'island' of stability of superheavy elements (Nix and Swiatecki 1965). This leads naturally to the suggestion that there might exist a continent of ultra-superheavy elements whose mass is so great that their self-gravitational interaction is the dominant stabilizing influence. In order to produce such enormous gravitational potentials these giant nuclei would require to be of stellar masses. Extrapolating from the growing neutron excess in heavy nuclei we conclude that these giant nuclei would be composed mostly of neutrons, and hence the term 'neutron stars' (Harrison, Thorne, Wakano, and Wheeler 1965). Although the existence of such strange objects was postulated by Landau in 1932 and has been strongly advocated by Zwicky since 1934, it was not until the discovery by Hewish in 1968 of 'pulsars' that a

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†Most of which are short lived decay products of longer lived uranium isotopes.

possible identification of neutron stars with any observed astronomical object became likely.

Thus our subject matter covers a wide range of physical phenomena. Such short volume as this cannot attempt to be definitive. Instead we have attempted to outline some of the more outstanding properties of the known heavy nuclei and to develop the theories which have been used to describe them. We have then used those theories to discuss some of the possible properties of superheavy elements and neutron stars.

The possible production of superheavy elements has not been discussed. Great hopes have been pinned on producing superheavies in heavy-ion fusion reactions and these require high-energy heavy-ion accelerators which are only now under construction. In fairness it should be stated that at present the indications are that the fusion cross-sections are likely to be disappointingly small. It is just possible that superheavy elements may be synthesized in neutron stars and may subsequently be found in meteorites or cosmic rays.

Our discussion of neutron stars is extremely brief. Much current work is extremely speculative. However, it is probably true to say that there is a greater richness of physical phenomena possibly associated with neutron stars than with any other objects in nature. We have not discussed star quakes nor pulsing mechanisms.

What we have attempted to do is to develop certain central ideas and provide the reader with the necessary introduction which will allow him to follow the current literature. There are many variations on the theories we have developed and, with apologies to the authors of these variations, we have claimed that these are minor perturbations on our main theme. In order not to confuse the reader we have not developed all the variations simultaneously. The path we have followed involves a personal view of the subject, but as always this is the author's perogative.

2

THE OBSERVED SYSTEMATICS OF HEAVY NUCLEI

Fig. 2.1 shows a chart of the observed nuclides in the plane of the neutron number N and the proton number Z. In this Figure we indicate the naturally occurring isotopes and the principal decay modes of the short-lived isotopes. It is immediately obvious that the region of heavy nuclei is characterized by three novel features not typical of the remainder of the chart:

(1) alpha decay becomes the dominant decay mechanism for an increasing number of nuclei;

(2) amongst the heaviest observed nuclei spontaneous fission becomes important, and in a few cases it rivals alpha decay as the dominant decay mechanism;

(3) the density of naturally occurring nuclides falls off rapidly with increasing mass number.

In Fig. 2.2 is shown the region for $A > 208$ in considerably more detail, and we immediately notice that it is populated almost entirely by unstable nuclei. The only exceptions to this are ^{208}Pb which is completely stable and ^{209}Bi which, although we might expect it to be alpha-particle unstable (see p. 113), has an observed half-life in excess of 2×10^{18} years and hence, to all intents and purposes, may be considered to be completely stable. We can consider these two isotopes to be anomalies in our region of interest, and their principal value to us will be as sources of information which may provide us with a key to the understanding of their heavier neighbours.

It is well known that the measured masses of nuclei are not equal to the sum of the masses of the particles of which they are composed. The missing mass is interpreted as the binding energy of the nucleus $B(A,Z)$,

$$B(A, Z) = \Delta M(A, Z)c^2 = (Nm_\mathrm{n} + Zm_\mathrm{p} - M(A,Z))c^2 \qquad (2.1)$$

In Fig. 2.3 we plot the observed value of B_max/A as a function of mass number A, where B_max is the binding energy of the most stable nucleus of a given value of A. We see that for nuclei with masses greater than ^{56}Fe there is a general trend towards a declining binding energy per particle. This decline shows a marked acceleration beyond ^{208}Pb. In Table 2.1 we present some more detailed information on the binding energies, lifetimes, and decay modes of the heavy nuclei.

Fig. 2.4 is a contour diagram of the binding energy per particle of the nuclides in the N, Z-plane. We see that the diagram resembles a peninsula in which the naturally occurring isotopes form a mountain ridge with peaks corresponding to particularly stable nuclei, and the artificially produced radioactive isotopes

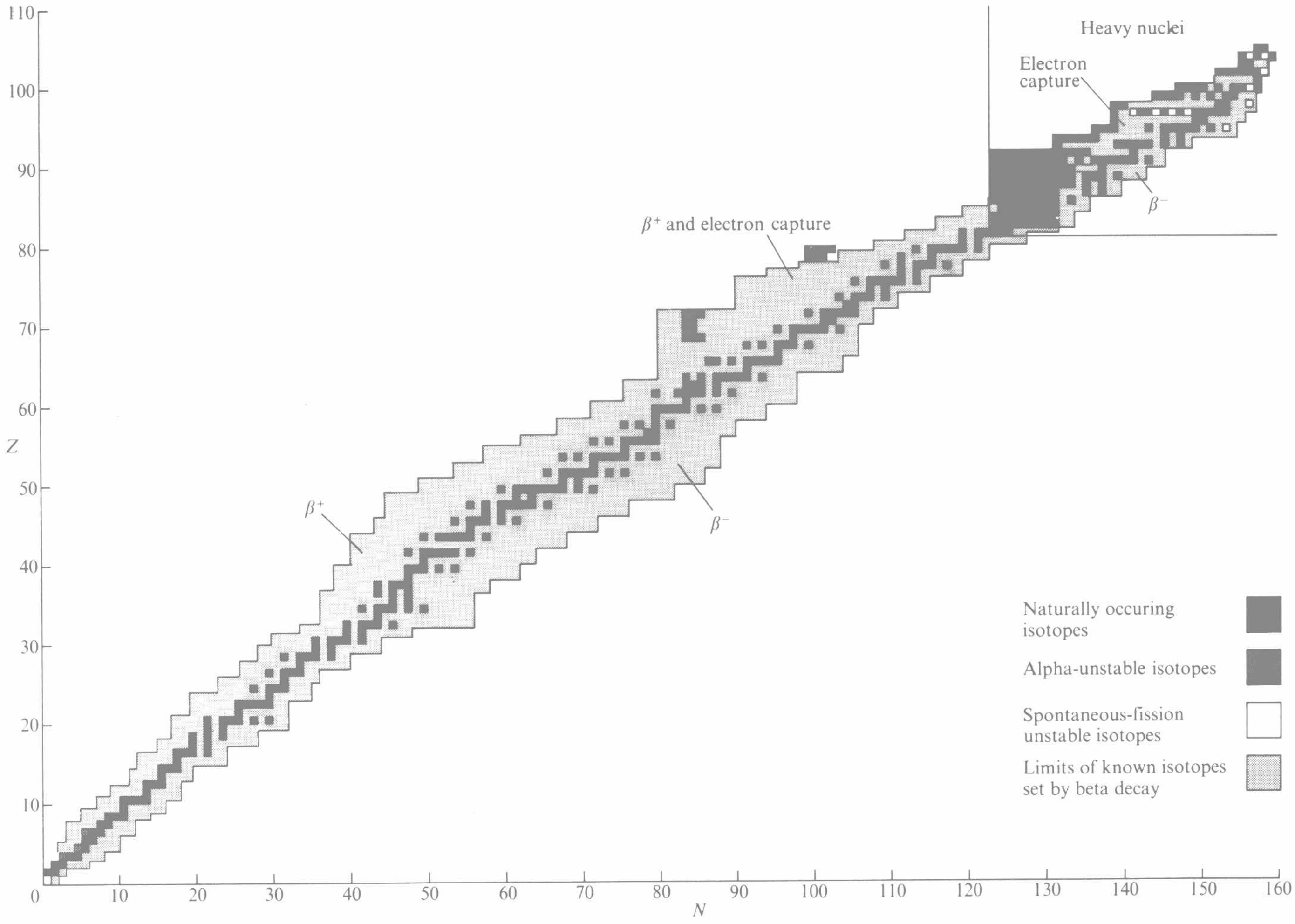


FIG. 2.1. Chart of the nuclides.

appear at progressively greater depths as their binding energies decrease. A central problem in modern nuclear physics concerns the possible existence of off-shore islands, i.e. either stable or near-stable exotic nuclei, with neutron excesses which are much greater or much less than those observed along the peninsula, or superheavy elements which appear as off-shore continuations of the peninsula. If we assume that pulsars are indeed neutron stars then we could claim to have observed a reappearance of the peninsula of stability at $A \gtrsim 10^{55}$. Rather a new continent, dominated by gravitational effects, than another island in the archipelego.

Throughout the periodic table it is observed than even–even nuclei are more stable than either their odd-A or odd–odd neighbours. In addition, the ground-state spins and parities are invariably 0^+. This relative stability is even more pronounced in the heavy nuclei (see Table 2.1). The observed low-lying spectra of the most stable even–even nuclei as a function of mass number A is plotted in Fig. 2.5. This Figure shows the truly remarkable result that for $A \gtrsim 230$ the spectra becomes independent of mass number. There is no other region of the periodic table where such an independence holds for such a wide range of mass numbers.

It is usual in a weakly interacting many-fermion system to think of adding particles to states at the top of the Fermi sea and to consider the low-lying excitation spectrum to be provided by the interaction between such particles near the Fermi surface. If this were the case the spectra would depend critically on the mass number, as indeed it does for $A \lesssim 220$ and for all odd-A nuclei. However, for a strongly interacting system it is possible to spontaneously generate collective excitations of the system in which a large fraction of the particles behave coherently. Such a spectrum would then be insensitive to small fluctuations in the mass number (note that in going from $A = 230$ to $A = 250$ the mass number has changed by less than 10 per cent). This view of the nature of the excitation spectrum of the heavy nuclei is reinforced by the observation that the spectrum closely resembles that of a quantal rigid rotator,

$$E_J = J(J + 1)\hbar^2/2\mathscr{I}_{\text{eff}}, \tag{2.2}$$

where E_J is the excitation energy of the state of angular momentum J and $\mathscr{I}_{\text{eff}}$ is the effective moment of inertia. The constancy of the spectra for $A \gtrsim 230$ indicates that the effective moment of inertia is constant. With $E_2 = 0{\cdot}04$ MeV we deduce that $\mathscr{I}_{\text{eff}}$ has the value

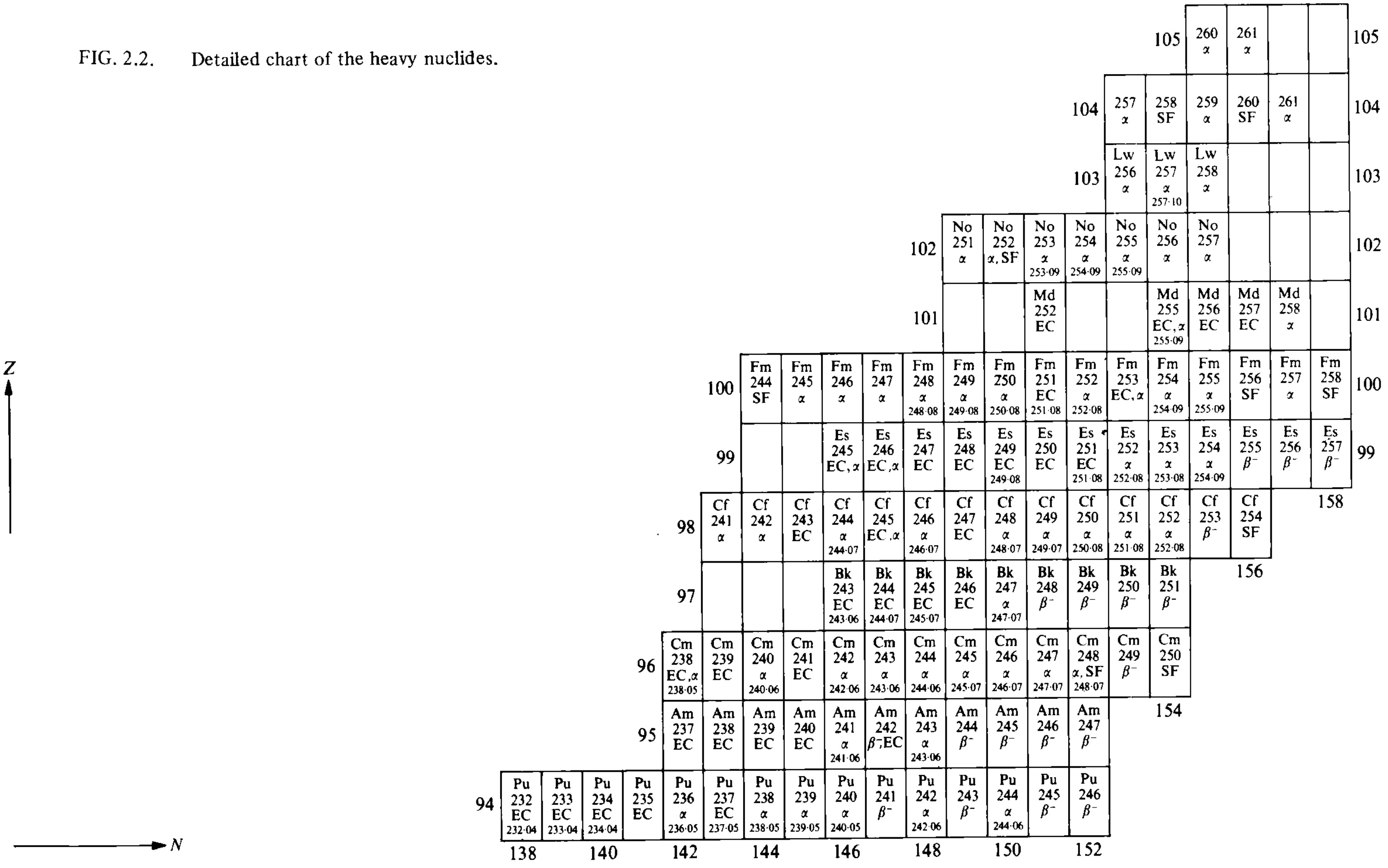
$$\mathscr{I}_{\text{eff}} = 6\hbar^2/2E_2 = 3{\cdot}25 \times 10^{-41} \text{ MeV s}^2. \tag{2.3}$$

This may be compared with the classical rigid-body moment of inertia obtained by considering the nucleus to be a sphere of mass M and radius $R = A^{\frac{1}{3}} r_0$,

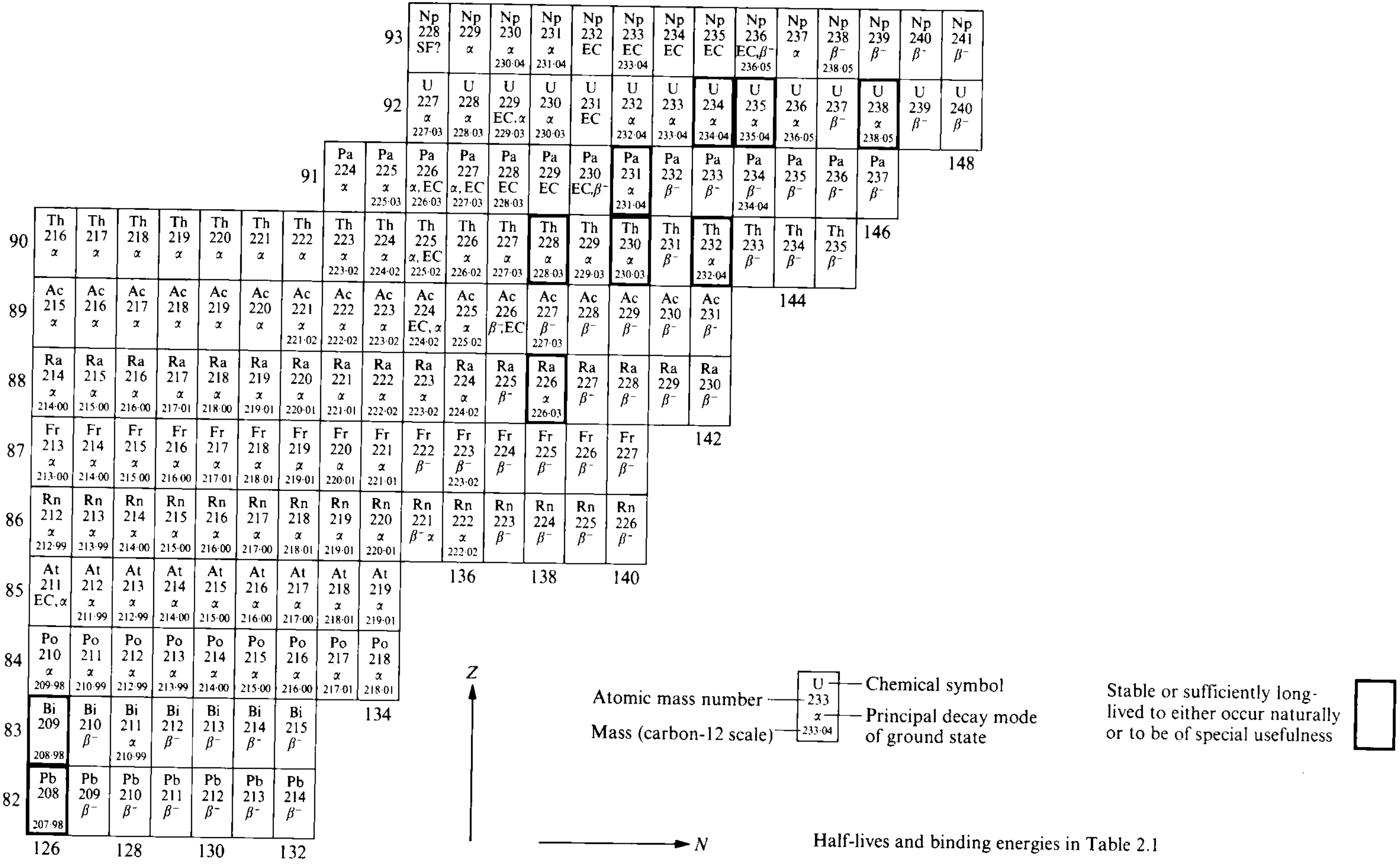
$$\mathscr{I}_{\text{rigid}} \simeq A^{\frac{5}{3}} \times 10^{-44} \text{ MeV s}^2. \tag{2.4}$$

For $A \approx 250$ we find that $\mathscr{I}_{\text{rigid}} \approx 3 \ \mathscr{I}_{\text{eff}}$. In Chapter 5 we shall use this discrepancy between the rigid-body value of the moment of inertia and the effective

FIG. 2.2. Detailed chart of the heavy nuclides.



105																		260 α	261 α		
104																257 α	258 SF	259 α	260 SF	261 α	
103																Lw 256 α	Lw 257 α 257·10	Lw 258 α			
102												No 251 α	No 252 α, SF	No 253 α 253·09	No 254 α 254·09	No 255 α 255·09	No 256 α	No 257 α			
101														Md 252 EC			Md 255 EC, α 255·09	Md 256 EC	Md 257 EC	Md 258 α	
100							Fm 244 SF	Fm 245 α	Fm 246 α	Fm 247 α	Fm 248 α 248·08	Fm 249 α 249·08	Fm 250 α 250·08	Fm 251 EC 251·08	Fm 252 α 252·08	Fm 253 EC, α	Fm 254 α 254·09	Fm 255 α 255·09	Fm 256 SF	Fm 257 α	Fm 258 SF
99									Es 245 EC, α	Es 246 EC, α	Es 247 EC	Es 248 EC	Es 249 EC 249·08	Es 250 EC	Es 251 EC 251·08	Es 252 α 252·08	Es 253 α 253·08	Es 254 α 254·09	Es 255 β^-	Es 256 β^-	Es 257 β^-
98						Cf 241 α	Cf 242 α	Cf 243 EC	Cf 244 α 244·07	Cf 245 EC, α	Cf 246 α 246·07	Cf 247 EC	Cf 248 α 248·07	Cf 249 α 249·07	Cf 250 α 250·08	Cf 251 α 251·08	Cf 252 α 252·08	Cf 253 β^-	Cf 254 SF		
97									Bk 243 EC 243·06	Bk 244 EC 244·07	Bk 245 EC 245·07	Bk 246 EC	Bk 247 α 247·07	Bk 248 β^-	Bk 249 β^-	Bk 250 β^-	Bk 251 β^-				
96					Cm 238 EC, α 238·05	Cm 239 EC	Cm 240 α 240·06	Cm 241 EC	Cm 242 α 242·06	Cm 243 α 243·06	Cm 244 α 244·06	Cm 245 α 245·07	Cm 246 α 246·07	Cm 247 α 247·07	Cm 248 α, SF 248·07	Cm 249 β^-	Cm 250 SF				
95					Am 237 EC	Am 238 EC	Am 239 EC	Am 240 EC	Am 241 α 241·06	Am 242 β^-, EC	Am 243 α 243·06	Am 244 β^-	Am 245 β^-	Am 246 β^-	Am 247 β^-						
94	Pu 232 EC 232·04	Pu 233 EC 233·04	Pu 234 EC 234·04	Pu 235 EC	Pu 236 α 236·05	Pu 237 EC 237·05	Pu 238 α 238·05	Pu 239 α 239·05	Pu 240 α 240·05	Pu 241 β^-	Pu 242 α 242·06	Pu 243 β^-	Pu 244 α 244·06	Pu 245 β^-	Pu 246 β^-						
	138		140		142		144		146		148		150		152		154		156		158



93										Np 228 SF?	Np 229 α	Np 230 α 230·04	Np 231 α 231·04	Np 232 EC	Np 233 EC 233·04	Np 234 EC	Np 235 EC	Np 236 EC,β^- 236·05	Np 237 α	Np 238 β^- 238·05	Np 239 β^-	Np 240 β^-	Np 241 β^-
92										U 227 α 227·03	U 228 α 228·03	U 229 EC,α 229·03	U 230 α 230·03	U 231 EC	U 232 α 232·04	U 233 α 233·04	U 234 α 234·04	U 235 α 235·04	U 236 α 236·05	U 237 β^-	U 238 α 238·05	U 239 β^-	U 240 β^-
91								Pa 224 α	Pa 225 α 225·03	Pa 226 α, EC 226·03	Pa 227 α, EC 227·03	Pa 228 EC 228·03	Pa 229 EC	Pa 230 EC,β^-	Pa 231 α 231·04	Pa 232 β^-	Pa 233 β^-	Pa 234 β^- 234·04	Pa 235 β^-	Pa 236 β^-	Pa 237 β^-		
90	Th 216 α	Th 217 α	Th 218 α	Th 219 α	Th 220 α	Th 221 α	Th 222 α	Th 223 α 223·02	Th 224 α 224·02	Th 225 α, EC 225·02	Th 226 α 226·02	Th 227 α 227·03	Th 228 α 228·03	Th 229 α 229·03	Th 230 α 230·03	Th 231 β^-	Th 232 α 232·04	Th 233 β^-	Th 234 β^-	Th 235 β^-			
89	Ac 215 α	Ac 216 α	Ac 217 α	Ac 218 α	Ac 219 α	Ac 220 α	Ac 221 α 221·02	Ac 222 α 222·02	Ac 223 α 223·02	Ac 224 EC, α 224·02	Ac 225 α 225·02	Ac 226 β^-;EC	Ac 227 β^- 227·03	Ac 228 β^-	Ac 229 β^-	Ac 230 β^-	Ac 231 β^-						
88	Ra 214 α 214·00	Ra 215 α 215·00	Ra 216 α 216·00	Ra 217 α 217·01	Ra 218 α 218·00	Ra 219 α 219·01	Ra 220 α 220·01	Ra 221 α 221·01	Ra 222 α 222·02	Ra 223 α 223·02	Ra 224 α 224·02	Ra 225 β^-	Ra 226 α 226·03	Ra 227 β^-	Ra 228 β^-	Ra 229 β^-	Ra 230 β^-						
87	Fr 213 α 213·00	Fr 214 α 214·00	Fr 215 α 215·00	Fr 216 α 216·00	Fr 217 α 217·01	Fr 218 α 218·01	Fr 219 α 219·01	Fr 220 α 220·01	Fr 221 α 221·01	Fr 222 β^-	Fr 223 β^- 223·02	Fr 224 β^-	Fr 225 β^-	Fr 226 β^-	Fr 227 β^-								
86	Rn 212 α 212·99	Rn 213 α 213·99	Rn 214 α 214·00	Rn 215 α 215·00	Rn 216 α 216·00	Rn 217 α 217·00	Rn 218 α 218·01	Rn 219 α 219·01	Rn 220 α 220·01	Rn 221 β^- α	Rn 222 α 222·02	Rn 223 β^-	Rn 224 β^-	Rn 225 β^-	Rn 226 β^-								
85	At 211 EC,α	At 212 α 211·99	At 213 α 212·99	At 214 α 214·00	At 215 α 215·00	At 216 α 216·00	At 217 α 217·00	At 218 α 218·01	At 219 α 219·01														
84	Po 210 α 209·98	Po 211 α 210·99	Po 212 α 212·99	Po 213 α 213·99	Po 214 α 214·00	Po 215 α 215·00	Po 216 α 216·00	Po 217 α 217·01	Po 218 α 218·01														
83	Bi 209 208·98	Bi 210 β^-	Bi 211 α 210·99	Bi 212 β^-	Bi 213 β^-	Bi 214 β^-	Bi 215 β^-																
82	Pb 208 207·98	Pb 209 β^-	Pb 210 β^-	Pb 211 β^-	Pb 212 β^-	Pb 213 β^-	Pb 214 β^-																
	126		128		130		132		134		136		138		140		142		144		146		148

Half-lives and binding energies in Table 2.1

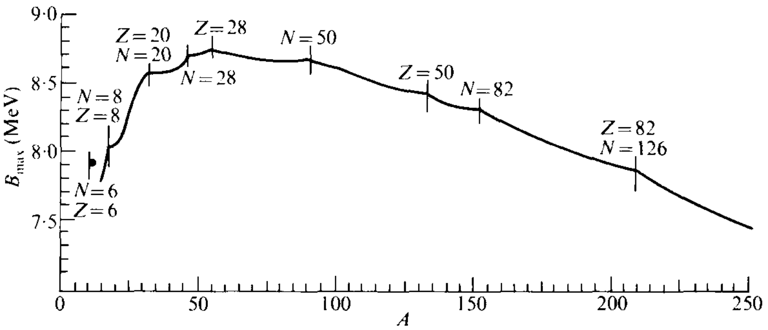


FIG. 2.3. Binding energy per particle for the most stable nuclei as a function of mass number A.

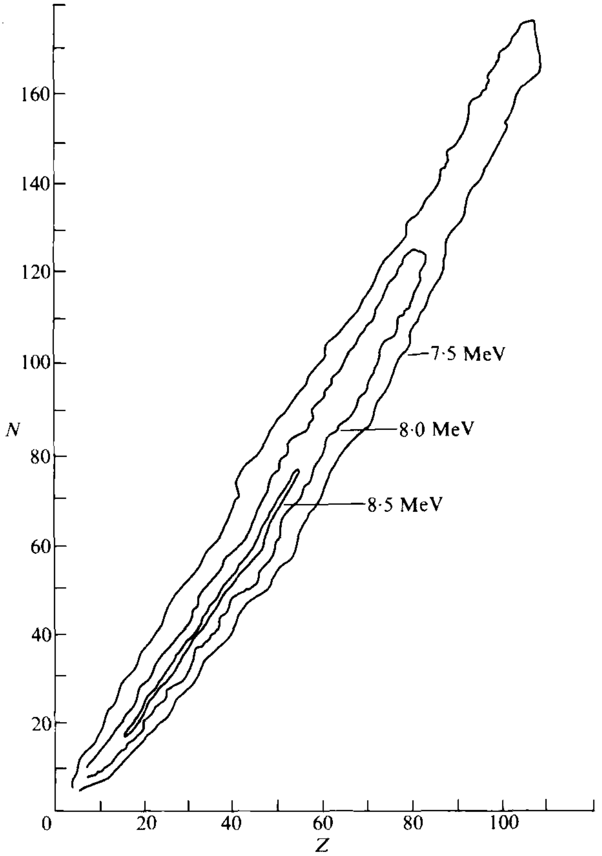


FIG. 2.4. Energy contours for binding energies per particle in the plane of neutron number N and proton number Z.

TABLE 2.1

Binding energies, half-lives, and principal decay modes of the ground states of some heavy nuclei†

Nucleus	Binding energy (MeV)	Half-life	Principal decay
^{210}Po	1645	138·4 days	α
^{211}Po	1650	25 s	α
^{212}Po	1656	45 s	α
^{213}Po	1660	4·2 × 10^{-6} s	α
^{214}Po	1666	1·64 × 10^{-4} s	α
^{215}Po	1670	1·78 × 10^{-3} s	α
^{216}Po	1676	0·15 s	α
^{217}Po	1680	<10 s	α
^{218}Po	1686	3·05 min	α
^{211}At	1648	7·21 hours	Ec, α
^{212}At	1653	0·3 s	α
^{213}At	1659	short	α
^{214}At	1664	2 × 10^{-6} s	α
^{215}At	1670	$\sim 10^{14}$ s	α
^{216}At	1675	3 × 10^{-4} s	α
^{217}At	1681	0·03 s	α
^{218}At	1685	2·0 s	α
^{219}At	1690	0·9 min	α
^{215}Rn	1669	10^{-6} s	α
^{216}Rn	1676	4·5 × 10^{-5} s	α
^{217}Rn	1681	5·4 × 10^{-4} s	α
^{218}Rn	1687	0·04 s	α
^{219}Rn	1692	4 s	α
^{220}Rn	1698	55 s	α
^{221}Rn	1702	25 min	β^-
^{222}Rn	1708	3·82 days	α
^{217}Fr	1679	short	α
^{218}Fr	1684	5 × 10^{-3} s	α
^{219}Fr	1691	0·02 s	α
^{220}Fr	1696	27·5 s	α
^{221}Fr	1703	4·8 min	α
^{222}Fr	1707	14·8 min	β^-
^{223}Fr	1713	22 min	β^-
^{224}Fr	1718	<2 min	β^-
^{219}Ra	1689	10^{-3} s	α
^{220}Ra	1697	0·02 s	α
^{221}Ra	1702	29 s	α
^{222}Ra	1709	37·5 s	α
^{223}Ra	1714	11·4 days	α
^{224}Ra	1720	3·64 days	α
^{225}Ra	1725	14·8 days	β^-
^{226}Ra	1732	$\sim$ 1600 years	α
^{227}Ra	1736	41·2 min	β^-
^{228}Ra	1742	6·7 years	β^-
^{221}Ac	1700	short	α
^{222}Ac	1706	5 s	α
^{223}Ac	1712	2·2 min	α
^{224}Ac	1718	2·9 hours	Ec
^{225}Ac	1725	10 days	α
^{226}Ac	1730	29 hours	β^-, Ec
^{227}Ac	1737	21·5 years	β^-
^{228}Ac	1742	6·13 hours	β^-
^{229}Ac	1748	66 min	β^-
^{230}Ac	1753	<1 min	β^-
^{223}Th	1710	0·9 s	α
^{224}Th	1718	1·05 s	α
^{225}Th	1723	8·0 min	α
^{226}Th	1731	30·9 min	α
^{227}Th	1736	18·2 days	α
^{228}Th	1743	1·91 years	α
^{229}Th	1748	7340 years	α
^{230}Th	1755	8 × 10^{4} years	α
^{231}Th	1760	25·52 hours	β^-
^{232}Th	1767	1·41 × 10^{10} years	α
^{233}Th	1772	22·4 min	β^-
^{234}Th	1778	24·10 days	β^-
^{225}Pa	1720	0·8 s	α
^{226}Pa	1727	1·8 min	α, Ec
^{227}Pa	1734	38·3 min	α, Ec
^{228}Pa	1740	22 hours	Ec
^{229}Pa	1747	1·5 days	Ec
^{230}Pa	1753	17·5 days	Ec, β^-
^{231}Pa	1760	3·25 × 10^{4} years	α
^{232}Pa	1765	1·31 days	β^-
^{233}Pa	1772	27·0 days	β^-
^{234}Pa	1777	6·75 hours	β^-
^{235}Pa	1783	23·7 min	β^-
^{236}Pa	1788	12 min	β^-
^{237}Pa	1794	39 min	β^-
^{228}U	1739	9·1 min	α
^{229}U	1745	58 min	Ec, α
^{230}U	1753	20·8 days	α
^{231}U	1759	4·3 days	Ec
^{232}U	1766	72 years	α
^{233}U	1772	1·62 × 10^{5} years	α

†Where more than one decay mode has a greater than 10 per cent intensity, the decays are listed in order of probability.

Table 2.1 continued

Nucleus	Binding energy (MeV)	Half-life	Principal decay
^{234}U	1779	$2{\cdot}47 \times 10^{5}$ years	α
^{235}U	1784	$7{\cdot}1 \times 10^{8}$ years	α
^{236}U	1790	$2{\cdot}39 \times 10^{7}$ years	α
^{237}U	1796	6·7 days	β^-
^{238}U	1802	$4{\cdot}51 \times 10^{9}$ years	α
^{239}U	1807	23·5 min	β^-
^{240}U	1812	14·1 hours	β^-
^{231}Np	1756	50 min	α
^{232}Np	1763	13 min	Ec
^{233}Np	1770	35 min	Ec
^{234}Np	1776	4·4 days	Ec
^{235}Np	1783	410 days	Ec
^{236}Np	1789	22 hours	Ec, β^-
^{237}Np	1795	$2{\cdot}14 \times 10^{6}$ years	α
^{238}Np	1801	2·10 days	β^-
^{239}Np	1807	2·35 days	β^-
^{240}Np	1812	63 min	β^-
^{241}Np	1818	16 min	β^-
^{234}Pu	1775	9 hours	Ec
^{235}Pu	1781	26 min	Ec
^{236}Pu	1788	2·85 years	α
^{237}Pu	1794	45 days	Ec
^{238}Pu	1801	86·4 years	α
^{239}Pu	1807	24 390 years	α
^{240}Pu	1813	6580 years	α
^{241}Pu	1819	13·2 years	β^-
^{242}Pu	1825	$3{\cdot}79 \times 10^{5}$ years	α
^{243}Pu	1830	4·98 hours	β^-
^{244}Pu	1836	$7{\cdot}6 \times 10^{7}$ years	α
^{245}Pu	1841	10·5 hours	β^-
^{246}Pu	1847	10·85 days	β^-
^{237}Am	1792	1·3 hours	Ec
^{238}Am	1798	1·9 hours	Ec
^{239}Am	1805	12·1 hours	Ec
^{240}Am	1811	51 hours	Ec
^{241}Am	1818	458 years	α
^{242}Am	1824	16·01 hours	β^-, Ec
^{243}Am	1830	$7{\cdot}95 \times 10^{3}$ years	α
^{244}Am	1835	10·1 hours	β^-
^{245}Am	1841	2·07 hours	β^-
^{246}Am	1846	25 min	β^-
^{238}Cm	1796	2·5 hours	Ec, α
^{239}Cm	1803	3 hours	Ec
^{240}Cm	1810	26·8 days	α
^{241}Cm	1817	35 days	Ec
^{242}Cm	1823	162·5 days	α
^{243}Cm	1829	32 years	α
^{244}Cm	1836	17·6 years	α
^{245}Cm	1842	$9{\cdot}3 \times 10^{3}$ years	α
^{246}Cm	1848	$5{\cdot}5 \times 10^{3}$ years	α
^{247}Cm	1853	$1{\cdot}6 \times 10^{7}$ years	α
^{248}Cm	1859	$4{\cdot}7 \times 10^{5}$ years	α, SF
^{249}Cm	1864	64 min	β^-
^{243}Bk	1827	4·5 hours	Ec
^{244}Bk	1833	4·4 hours	Ec
^{245}Bk	1840	4·98 days	Ec
^{246}Bk	1846	1·8 days	Ec
^{247}Bk	1852	$1{\cdot}4 \times 10^{3}$ years	α
^{248}Bk	1858	16 hours	β^-, Ec
^{249}Bk	1864	314 days	β^-
^{250}Bk	1869	193·3 min	β^-
^{244}Cf	1831	25 min	α
^{245}Cf	1838	44 min	Ec, α
^{246}Cf	1845	35·7 hours	α
^{247}Cf	1851	2·5 hours	Ec
^{248}Cf	1858	350 days	α
^{249}Cf	1863	360 years	α
^{250}Cf	1870	13·2 years	α
^{251}Cf	1875	800 years	α
^{252}Cf	1881	2·65 years	α
^{253}Cf	1886	17·6 days	β^-
^{246}Es	1841	7·5 min	Ec, α
^{247}Es	1848	5·0 min	Ec
^{248}Es	1854	25 min	Ec
^{249}Es	1861	2 hours	Ec
^{250}Es	1867	8 hours	Ec
^{251}Es	1874	1·5 days	Ec
^{252}Es	1879	140 days	α
^{253}Es	1886	20·5 days	α
^{254}Es	1891	276 days	α
^{248}Fm	1852	0·6 min	α
^{249}Fm	1858	2·5 min	α
^{250}Fm	1866	30 min	α
^{251}Fm	1872	7 hours	Ec
^{252}Fm	1879	22·7 hours	α
^{253}Fm	1885	3 days	Ec, α
^{254}Fm	1891	3·24 hours	α
^{255}Fm	1896	20·1 hours	α
^{255}Md	1895	0·6 hours	Ec, α
^{253}No	1877	100 s	α
^{254}No	1885	55 s	α
^{255}No	1892	180 s	α
^{257}Lw	1902	~ 20 s	α

moment of inertia to deduce some features of the nuclear structure of these nuclei. Table 2.2 indicates how closely the experimental energy levels correspond to the quantal rotator values predicted by eqn. (2.2) in the case of ^{244}Cm. We see that up to, and including, the 6^+ level the agreement is excellent. However, a discrepancy of a few per cent has appeared by the time we reach the 8^+ state, and the discrepancy increases rapidly thereafter. Such results are typical throughout this region.

TABLE 2.2

A comparison of the observed 'rotational' energies in ^{244}Cm compared with the predictions of eqn (2.2)

	E_{exp}	E_{rot}
2+	0·0429	0·0429
4+	0·1423	0·1430
6+	0·296	0·3003
8+	0·502	0·5148

Further evidence supporting our interpretation of the 'rotational' bands comes from a study of the gamma-decay spectrum. The sequence of decays . . . $8^+ \rightarrow 6^+ \rightarrow 4^+ \rightarrow 2^+ \rightarrow 0^+$ is characterized by the observation of extremely strong electric quadrupole radiation such as would be expected to arise in large-scale charge-density fluctuations corresponding to collective motion.

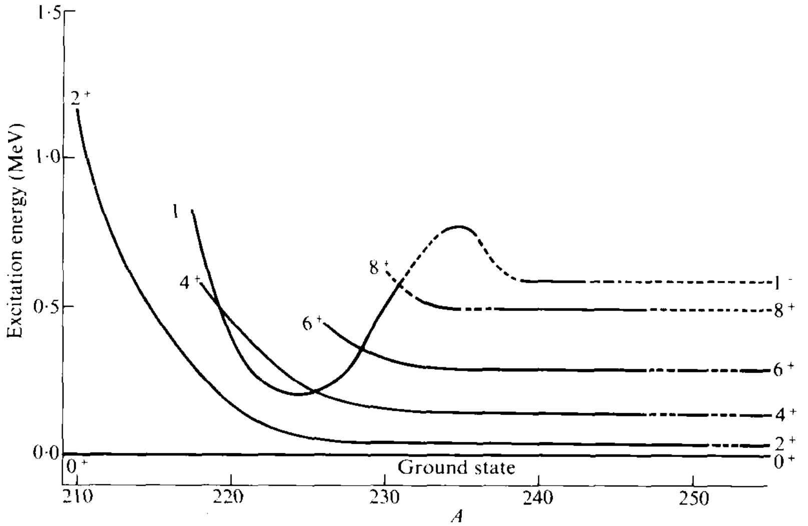


FIG. 2.5. Low-energy excitation spectra of the most stable heavy even–even nuclei as a function of mass number A.

Turning to the spectra of even–even nuclei in the range $210 < A < 230$ the only obvious systematic is that the first excited state is always a 2^+ level and that its energy falls rapidly with increasing mass number. There is always a gap of at least 100 keV between the first 2^+ level and the next excited state, but above this the density of energy levels increases rapidly with excitation energy.

If we study the odd–odd heavy nuclei we find that very little is known about the excitation spectra. Indeed there are fewer than a dozen nuclides throughout the whole region in which confident spin and parity assignments can be made for levels other than the ground state. The only completely unambiguous statement that can be made is that the density of low-lying states is much greater for the odd–odd nuclei than for even–even nuclei. In all cases the first excited state lies within 300 keV of the ground state, and most commonly at less than 100 keV excitation.

Turning to the spectra of odd-*A* nuclei we consider first the odd–even nuclei, i.e. those with even numbers of protons. In Table 2.3 we present a study of the observed ground-state spins of odd–even nuclei. While there is nothing as dramatic as the situation in the even–even nuclei we notice the following regularities:

TABLE 2.3

Ground-state spins and parities of heavy odd–even nuclei

^{209}Pb	$\frac{9}{2}^+$	^{229}Th	$\frac{5}{2}^+$	^{241}Pu	$\frac{5}{2}^+$
^{211}Pb	$\frac{9}{2}^+$	^{229}U	$\frac{3}{2}^+$	^{241}Cm	$\frac{1}{2}^+$
^{211}Po	$\frac{9}{2}^+$	^{231}Th	$\frac{5}{2}^+$	^{243}Pu	$\frac{7}{2}^+$
^{213}Po	$\frac{9}{2}^+$	^{231}U	$\frac{5}{2}^-$	^{243}Cm	$\frac{5}{2}^+$
^{215}Po	$\frac{9}{2}^+$	^{233}U	$\frac{5}{2}^+$	^{245}Cm	$\frac{7}{2}^+$
^{217}Rn	$\frac{9}{2}^+$	^{235}U	$\frac{7}{2}^-$	^{249}Cf	$\frac{9}{2}^-$
^{223}Ra	$\frac{1}{2}^+$	^{237}U	$\frac{1}{2}^+$	^{251}Cf	$\frac{1}{2}^+$
^{225}Ra	$\frac{3}{2}^-$	^{237}Pu	$\frac{7}{2}^-$	^{253}Cf	$\frac{7}{2}^+$
^{225}Th	$\frac{3}{2}^+$	^{239}Pu	$\frac{1}{2}^+$	^{255}Fm	$\frac{7}{2}^+$
^{227}Th	$\frac{3}{2}^+$	^{239}U	$\frac{5}{2}^+$	^{257}Fm	$\frac{9}{2}^+$

(1) a large majority of the nuclei have positive-parity ground states;

(2) the negative-parity ground states have relatively high spin;

(3) the nuclei tend to form groups of neighbours with the same ground-state spin.

Table 2.4 shows a study of the observed ground-state spins of even–odd nuclei. Again there is a tendency for neighbouring nuclei to have the same ground-state spin, and the majority of the states have negative parity.

In both odd–even and even–odd nuclei the density of low-lying states is similar to that exhibited by odd–odd nuclei.

As may be seen from Fig. 2.1, among the lighter nuclei the stability of the ground states is completely determined by the energetics of beta decay. Nuclei