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ON THE STRUCTURE OF ATOMIC NUCLEI

AAGE BOHR

Professor of Theoretical Physics at the University of Copenhagen (Denmark)

SVMMARIVM — Ad nuclei atomici structuram examinandam, initium sumere oportet ex descriptione motus, quem singulares nucleones in communi campo nucleari habent.

Huic motui quidam relationis effectus superponuntur, quorum nonnulli, magni sane momenti ac ponderis, efficiunt ut complures eaeque variae nucleares proprietates facilius intellegantur.

In the exploration of the structure of atomic nuclei we are studying a part of nature far removed from the domain of experience of our daily life. In the physical phenomena which govern our normal environment and which also determine the structure of the organisms, the atomic nuclei behave as indivisible particles whose only relevant properties are their mass and electric charge.

When subjected to sufficiently violent conditions, however, the nucleus can be excited and transmuted, and it then exhibits

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Die 13 mensis octobris in Academiae Sessione Plenaria anni 1963 clarissimus vir Professor AAGE BOHR de Academicorum consensu meruit ut coronam auream, vulgo « Medaglia d'oro Pio XI », e manibus Summi Pontifici PAVLI Papae VI acciperet.

Idem post habitas laudes, coram Academicorum Coetum eodem die hanc orationem dixit de studiis suis.

an internal structure of great richness. Such conditions exist in the interior of stars where the temperature reaches millions of degrees. In this environment the nuclei that form the atoms of the various elements present on earth appear to have been formed themselves, billions of years ago, from their basic constituents.

The first key to the exploration of nuclear phenomena was provided by the fact that matter, such as we find it, after it has cooled off, is not in a stage of thermal equilibrium. Certain special quantum processes are inhibited to such an extent that their time scale is comparable with the period which has elapsed since the formation of the elements. These processes manifest themselves in the natural radioactivity which, about half a century ago, gave Rutherford the tool to initiate the study of nuclear reactions.

In the decades which have passed since this new field of research was opened, a great development has taken place. Powerful apparatus have been constructed in countries all over the world, providing beams of particles with energies even much greater than those obtaining in stars. The particles are able to penetrate into the atomic nuclei and produce a large variety of nuclear processes, and highly refined equipment is available for the study of the products arising from such reactions. These investigations have provided an enormous body of data from which a rather detailed picture of the nuclear structure and its dynamics is emerging.

The basic nuclear constituents are the nucleons, which occur in two varieties, the protons and the neutrons. In nuclear reactions of not excessively high energies (induced by particles accelerated to energies up to a few hundred million electron volts) the nucleons behave as elementary particles. At still higher energies, they themselves are transmuted and a new world again opens. We shall consider here only phenomena at the lower energies where the nucleus can be approximately described as an assembly of nucleons. The number of these depends on the nuclear species; the heaviest known contain about 250 nucleons.

The forces that bind together the nucleons in a nucleus represent a novel type of interaction, much stronger than the électromagnetic or gravitational forces known from classical physics. The nuclear forces can be studied most conveniently in scattering or binding processes involving only two nucleons. They are found to have a great complexity in their dependence on the distance between the particles, as well as on their velocities and spin. This complexity is related to the composite structure of the nucleons themselves.

In the development of the theory of atomic constitution, the basic issue was the establishment of the new laws of mechanics which govern the binding of the electrons to the nucleus. These same dynamical principles, known as quantum mechanics, have been found to apply also to the nuclear structure. Thus the basic equations governing nuclear dynamics appear to be well established, which is, of course, a very great aid in the exploration of this new field. Still, these equations in their entireness are far too complex to yield to a direct attempt at solution. Our insight into nuclear structure has therefore come from a close cooperation between experimental and theoretical studies. Again and again experimental discoveries have revealed quite unsuspected new facets of the nuclear structure, which have then been incorporated into the theoretical framework on the basis of which one attempts to predict new phenomena or point to new promising lines of investigation.

A main issue in the development of nuclear theory has been to achieve a proper balance between a description in terms of the collective properties of the nucleus (i.e. in terms of modes of motion of the system as a whole), and a description in terms of the motion of individual particles. This theme was first brought into focus by the development of the liquid drop model of the nucleus to which my father was led about 25 years ago. The model stressed the important role of collective aspects of nuclear dynamics and especially gave an understanding of many features of nuclear reactions. About ten years later, new experimental evidence on the properties of nuclear quantum states led MAYER, and HAXEL, JENSEN and SUESS to the establishment of an apparently radically different nuclear model, which describes the nuclear properties in terms of the motion of single nucleons. Much of the work in the group in Copenhagen with which I have been associated has been devoted to the development of a unified description of nuclear dynamics, which attempts to integrate the collective and individual particle aspects. In this connection, I would like especially to mention how much inspiration our whole group, and I myself in particular, have derived from the co-operation with professor BEN R. MOTTELSON.

The starting point for the description of nuclear structure, as we see it today, is the observation that, although the nuclear forces are very strong as compared with the electromagnetic forces, they are actually rather weak when expressed in the natural energy units appropriate to nuclear phenomena, defined by the mass of the nucleon, the range of the force, and PLANCK's constant. Thus, the forces are only barely able to form a bound state of two nucleons. This gives rise to a great simplicity in the structure of nuclei consisting of a larger number of nucleons. In these systems the main effect of the forces is to generate an average smoothly varying binding field. The individual nucleons move in stationary orbits in this binding field, and actual collisions between the nucleons are infrequent. Such an independent-particle description, or FERMI gas model, also applies to many other quantum systems, in particular to the electron structure of atoms, molecules, and of macroscopic bodies.

To a first approximation, the nuclear binding field possesses spherical symmetry which implies that the particle orbits may be grouped into degenerate « shells », each consisting of a set of orbits differing only in orientation and therefore having the same energy. This shell structure manifests itself in characteristic periodicities in the dependence of nuclear properties on the number of nucleons (for an example, see Fig. 1), similar to those which are the basis for the arrangement of the elements in the periodic system, and which are associated with the electronic shell structure.

The very simple approach which reduces the nuclear dynamics to the solution of a one-body problem provides an immediate explanation of many qualitative features of the nuclear structure. Still, the more detailed pattern of the nuclear properties, such as energy spectra and the probabilities for the various nuclear processes, depends in an essential manner on the correlations in the nucleonic motion which are superimposed on the independent-particle motion, as a result of the nucleonic interactions.

It has gradually become clear that, among these correlations, there are two types which play an especially important role in the low energy nuclear phenomena. The first may be described as a tendency, first recognized by RAINWATER, on the part of those nucleons which are not grouped into closed shells, to produce an ellipsoidal distortion of the nuclear shape. A configuration of closed shells, as in the atomic structure, gains its special stability as a result of its spherical symmetry. However, the « valence » nucleons possess a freedom in the orientation of their orbits and, on account of the attractive forces acting between them, these nucleons tend to align their orbits and at the same time to make the shape of the whole nucleus conform to their own density distribution. It may seem surprising, at first sight, that a structure like the nucleus, in its most stable state, may have a non-spherical shape. It is a quantum effect, directly associated with the fact that the system organizes itself in terms of the quantum orbits of individual particles. The atoms show no similar effect on account of the repulsive nature of the forces between the electrons. It must be added that not all nuclei are « deformed », since there are other effects, to be mentioned later, which tend to preserve the spherical symmetry.

Nuclei with non-spherical equilibrium shapes are easily recognized by the fact that their spectra show a rotational band structure somewhat similar to that of molecular spectra. For a spherical nucleus, one cannot talk about a direction of orientation, and therefore not define a rotational motion. One might argue that a spherical object, as for instance a billiard ball, may well be set into a spinning motion; however, this system, although seemingly spherical, has a microstructure (a lattice) which is highly anisotropic, and which, at each moment, may be said to point in a definite direction. A spherical nucleus, however, has no sense of direction, whatsoever. In contrast, an ellipsoidal nucleus has an orientation, and so can rotate, by performing a collective motion of the nucleons, resulting in a gradual change of orientation of the system as a whole.

Rotational spectra have been observed for a large class of nuclei. From the study of these spectra one can derive information about the nuclear shape as well as about the structure of the collective rotational motion (see Fig. 2). This motion is different from that of a rigid body and has features reminiscent of a wave travelling around the surface of a liquid drop.

A second major correlation effect can be described as a tendency of the nuclear forces to form bound pairs of nucleons. The paired particles are not locally bound to each other, but correlations are set up which imply that the particles come together, within the range of their interaction, with increased frequency. Between these encounters, the particles move each in its orbit. The pair correlations are thus but a ripple on the independent particle motion, but they give to the low energy states of the system a peculiar added stability, of quantum mechanical origin. Pair correlations of very similar nature characterize the electron motion in the superconducting metallic phase, where they also stabilize the electron system and thereby give rise to the many striking properties of superconductors.

The pairing effect is clearly revealed by the precision determinations of nuclear masses, which are a measure of nuclear binding energies. Nuclei with an even number of particles are found to be systematically more strongly bound than those with an odd number, in which one particle must remain unpaired (see Fig. 3). The pair correlation also greatly affect many nuclear reactions involving pairs of particles.

The nucleon pairs have the largest binding in an isotropic nuclear potential, and the pair correlations therefore provide a stabilization of the spherical shape, counteracting the above mentioned distortion effect of the individual nucleons in unfilled shells. This competition between pairing and deformation effects is, in fact, a prominent feature of the nuclear dynamics and provides the key to the interpretation of many of the low energy nuclear properties. For nuclei with relatively few particles in unfilled shells, the distortion effect is too weak to break the spherical symmetry favoured by the pairs, but as more particles are added in unfilled shells, the spherical shape becomes less and less stable and finally the nuclear equilibrium configuration acquires a spheroidal shape (see Fig. 4).

The analysis of the nuclear dynamics in terms of the above mentioned components, i.e. the individual particle motion on which are superimposed the collective distortion effects and the pair correlations, leads to a description of the low energy nuclear properties in terms of a few simple degrees of freedom, sometimes referred to as the elementary modes of excitation. These fall into two categories.

On the one hand, we have the particle degree of freedom; with each unpaired nucleon are associated states corresponding to the various quantum orbits of this particle. The lowest state of the nucleus is characterized by a maximum pairing, but excited states can be formed by breaking one or more pairs.

On the other hand, we have collective degrees of freedom.

A special type of these, and the best studied one, is the rotational excitations of deformed nuclei. Additional collective modes are associated with fluctuations of the nuclear field about its equilibrium shape. For example, the nuclei with near instability of the spherical shape exhibit low energy vibrations with large amplitudes of the nuclear eccentricity. In recent years many additional vibrational modes of nuclei have been recognized, but it is likely that still further types may be discovered in the coming years.

In terms of these simple modes of excitation it seems possible to interpret the main pattern of the low energy nuclear spectra. But, of course, the picture described is a highly simplified one and only represents a starting point for a more detailed analysis. Thus, the neglected interaction effects manifest themselves in the coupling between the elementary excitons. Like all physical particles, these excitons only to a first approximation can be treated as independent entities. In higher order one must take into account that they interact with each other, in the process of which they may exchange energy and momentum and may transform themselves into other modes of excitation. These couplings are intimately interwoven with the structure of the excitons themselves; thus a particular kind of excitation may often be described in terms of bound states of other modes.

Some of the couplings are weak, notably the coupling to the rotational motion, and can be treated by perturbation theory; others are stronger and much less understood. We have here a rich field of study, the exploration of which is only in its early stage and which may lead to a greatly added insight into the nuclear structure.

The physical problems which confront us in the study of nuclear phenomena bear many deep relationships to those met with in other domains of physics. Indeed, the study of the almost inexhaustible structural possibilities of many-particle systems is one of the central themes of present day physics.

Not only the atomic and molecular structure exhibits close resemblances to that of the nucleus, but also in the analysis of macroscopic systems such as solid bodies, on the basis of their atomic constitution, the characterization of the elementary modes of excitation and the analysis of their couplings is a focal point of interest.

In the high energy « subnuclear » phenomena, associated with the structure of the nucleons themselves, the elementary excitations are the various families of particles, such as the nucleons, the hyperons, mesons, etc., which constitute the different quantum forms of matter. These may be regarded as the modes of excitation of the system referred to as the vacuum, the substratum on which all physical phenomena display themselves.

Thus, in spite of the growing specialization which characterizes the present-day development of physics, there remain many unifying features and in fact new ideas engendered in one branch of physics very often provide direct inspiration for efforts in other branches.

In conclusion I would like to point to the increasingly important role which international cooperation is playing in the field of nuclear physics, as in so many other branches of science. This is indeed an aspect of the work which gives it added scope. Thus, to the development described above, important contributions have been made by physicists in countries all over the world. Personally, I have had the stimulating experience of working directly together with colleagues from many different countries; in recent years, it has been especially gratifying that again it has been possible to establish close personal cooperation across borders which for a time were closed. At the Institute in Copenhagen we are fortunate to be able to build upon the traditions for international cooperation which go back to the very early days of atomic theory, and in which my father placed such great hopes.

FIG. 1 — *Excitation energies for even-even nuclei* (*).

In even-even nuclei the ground state always has the symmetry O^+ (angular momentum O and parity +), and the first excited state almost always is of 2^+ type. Its excitation energy is shown in the figure, as a function of the numbers of neutrons (N) and protons (Z) and exhibits large « periodic » variations. The greatest values are reached if N or Z (and especially if both N and Z) is equal to 2, 8, 20, 50, 82, or 126. For these nucleon numbers, the configurations form closed shells and have a special stability, and the excitation requires a nucleon to be shifted from one shell to the next. When additional particles are present, the excitation is associated with a rearrangement of the particles in unfilled shells. For relatively few extra particles, this excitation can be described as a vibration around a spherical equilibrium shape. As the number of particles in unfilled shells increases, the equilibrium becomes less stable with a resulting decrease in the vibrational energy. For the nuclei with especially large numbers of nucleons outside closed shells, the equilibrium shape is spheroidal, and the lowest excitation is a rotational motion (see Fig. 4).

In the electronic structure of atoms, the closed shell configurations correspond to the noble gases, which also have especially large excitation energies.

(*) Reproduced from K. ALDER, A. BOHR, T. TUUS, B. MOTTELSON, and A. WINTER, « Revs. Mod. Phys. », 28, 432 (1956).

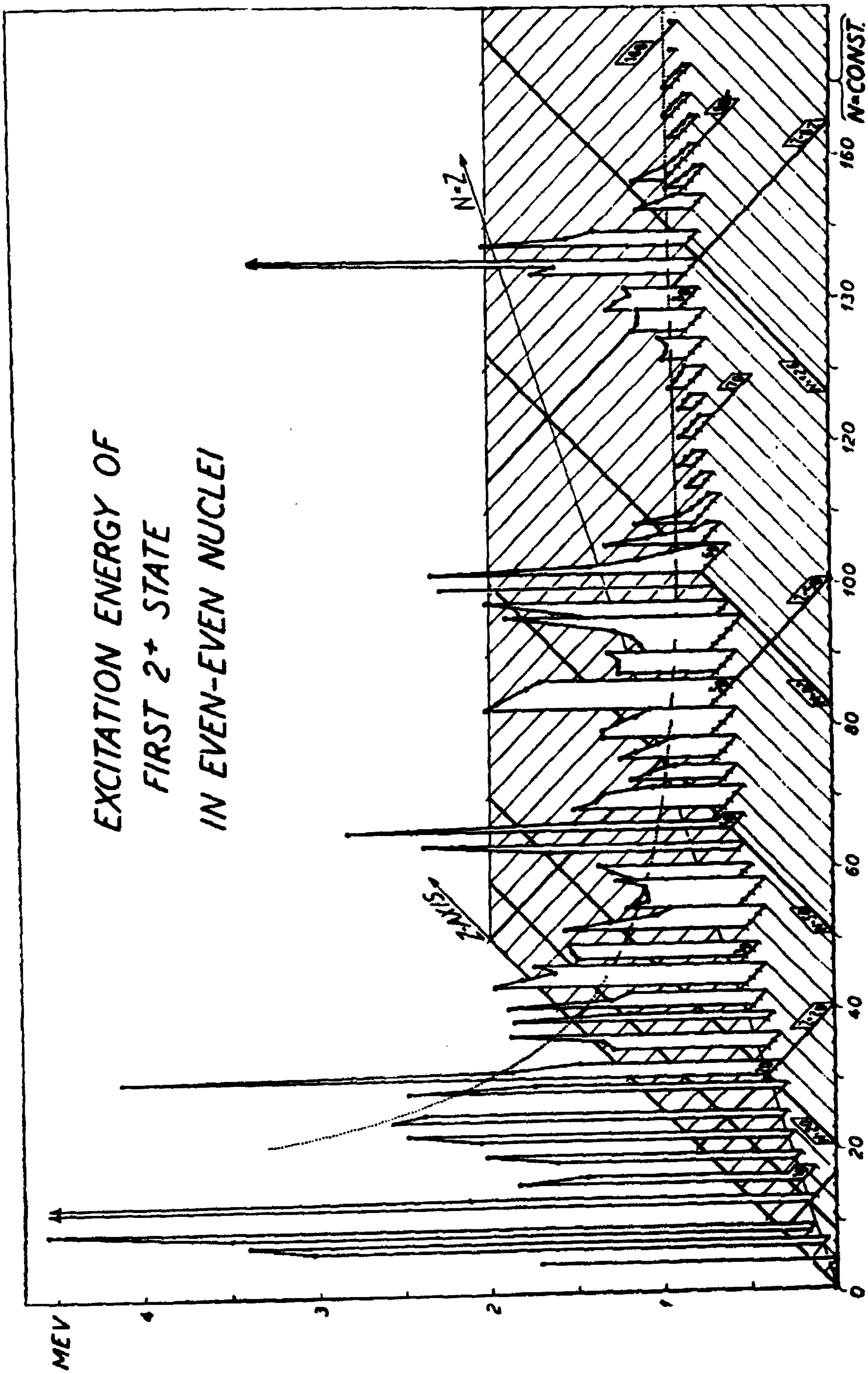
EXCITATION ENERGY OF
FIRST 2+ STATE
IN EVEN-EVEN NUCLEI
MEV
0
1
2
3
4
N=Z
N=CONST.
0
20
40
60
80
100
120
130
160

FIG. 1

FIG. 2 —*Excitation of rotational spectra in collision processes.*

The left hand figure shows the γ-ray spectrum observed when U^{238} is irradiated with A^{40}—ions with an energy of 190 MeV. (The experimental data is taken from STEPHENS, DIAMOND, and PERLMAN, *Phys. Rev. Letters*, *3*, 435 (1959)). On account of the strong Coulomb repulsion between the colliding nuclei, the A-ion is unable to penetrate into the target nucleus itself, but during the collision, the electrostatic field from the ion produces a torque which sets the U-nucleus into rotational motion (Coloumb excitation process).

The rotational energy spectrum, derived from the measured γ-energies shown in the right hand figure. The angular momentum and parity quantum numbers are given to the left of the levels, while the excitation energies (in keV) are given to the right. These energies follow rather closely the simple rotational expression $E = \frac{\hbar^2}{2\mathfrak{J}} I\,(I+1)$, where I (= 0, 2, 4, 6, ...) is the angular momentum quantum number, while $\mathfrak{J}$ is the effective moment of inertia. These theoretical values are listed in the first column in parentheses. The deviations from the observed values can be well accounted for by an additional energy term $\delta E = -BI^2\,(I+1)^2$ representing the centrifugal distortion produced by the rotation. The calculated values including a term of this type, with a suitably chosen coefficient B, are shown in the second column in parentheses.

From the observed spectra one can conclude that the nuclear shape has axial symmetry (from the dependence of the energy on I) and reflection symmetry (from the absence of levels with odd I). The magnitude of the spheroidal eccentricity can be determined from the intensity of the observed γ-rays.

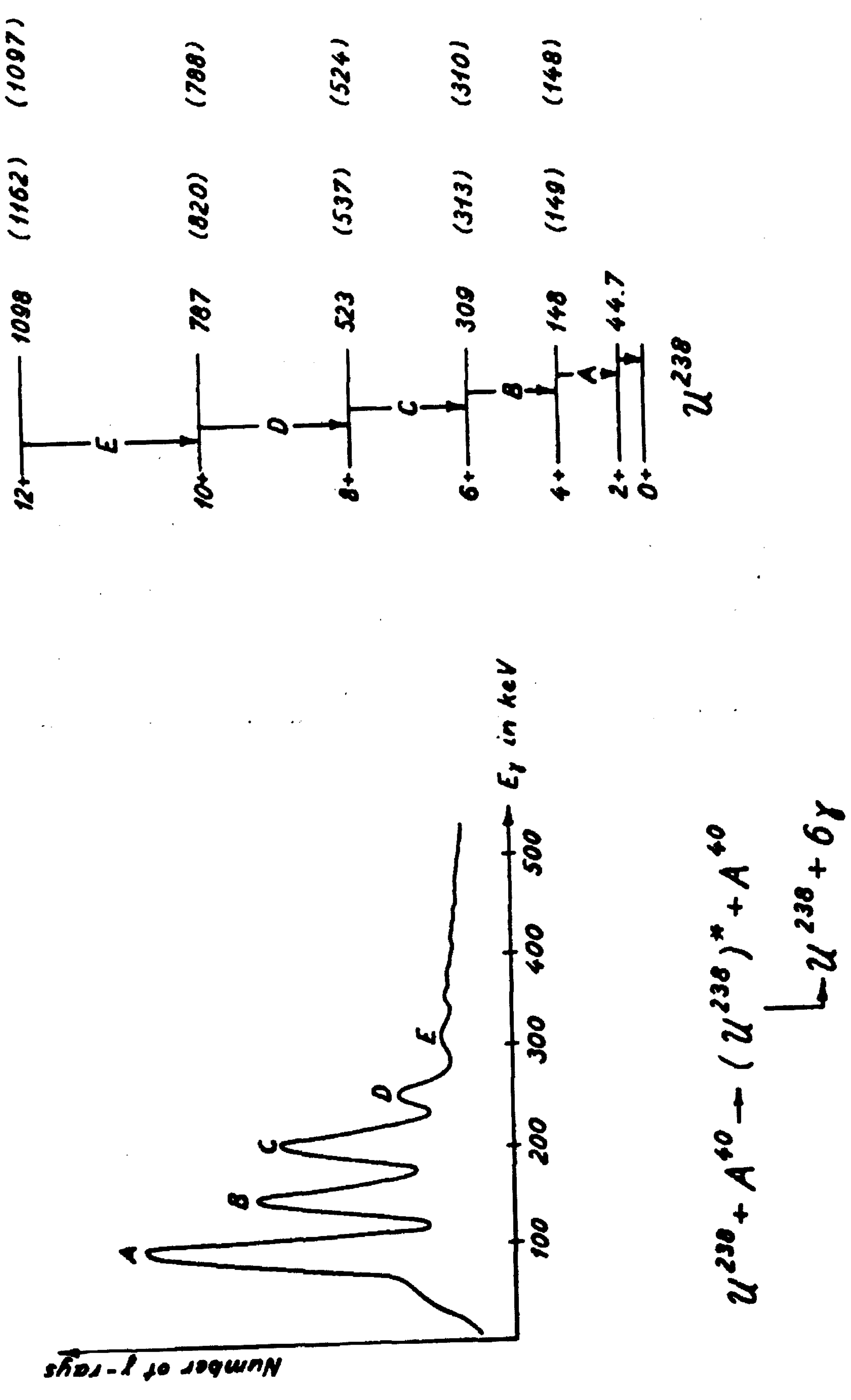
12+ 1098 (1162) (1097)
10+ 787 (820) (788)
8+ 523 (537) (524)
6+ 309 (313) (310)
4+ 148 (149) (148)
2+ 44.7
0+
A
B
C
D
E
U238
Number of γ-rays
Eγ in keV
100
200
300
400
500
U238 + A40 → (U238)* + A40
→ U238 + 6γ

FIG. 2

FIG. 3 — *Pairing effect in nuclear binding energies.*

The figure shows the binding energy of the last neutron in a sequence of nuclei with different N, but constant N-Z. It is seen that the binding energies are systematically greater for even values of N than for odd N, reflecting the extra stability associated with the binding of a neutron pair.

This pairing energy was known already at a rather early stage of nuclear physics. Thus, it may be mentioned that the effect is the main reason for the different fission properties of the two Uranium isotopes (U^{235} and U^{238}), which has had such great practical consequences. Only in recent years, however, the fuller implications of the pair correlations were recognized.

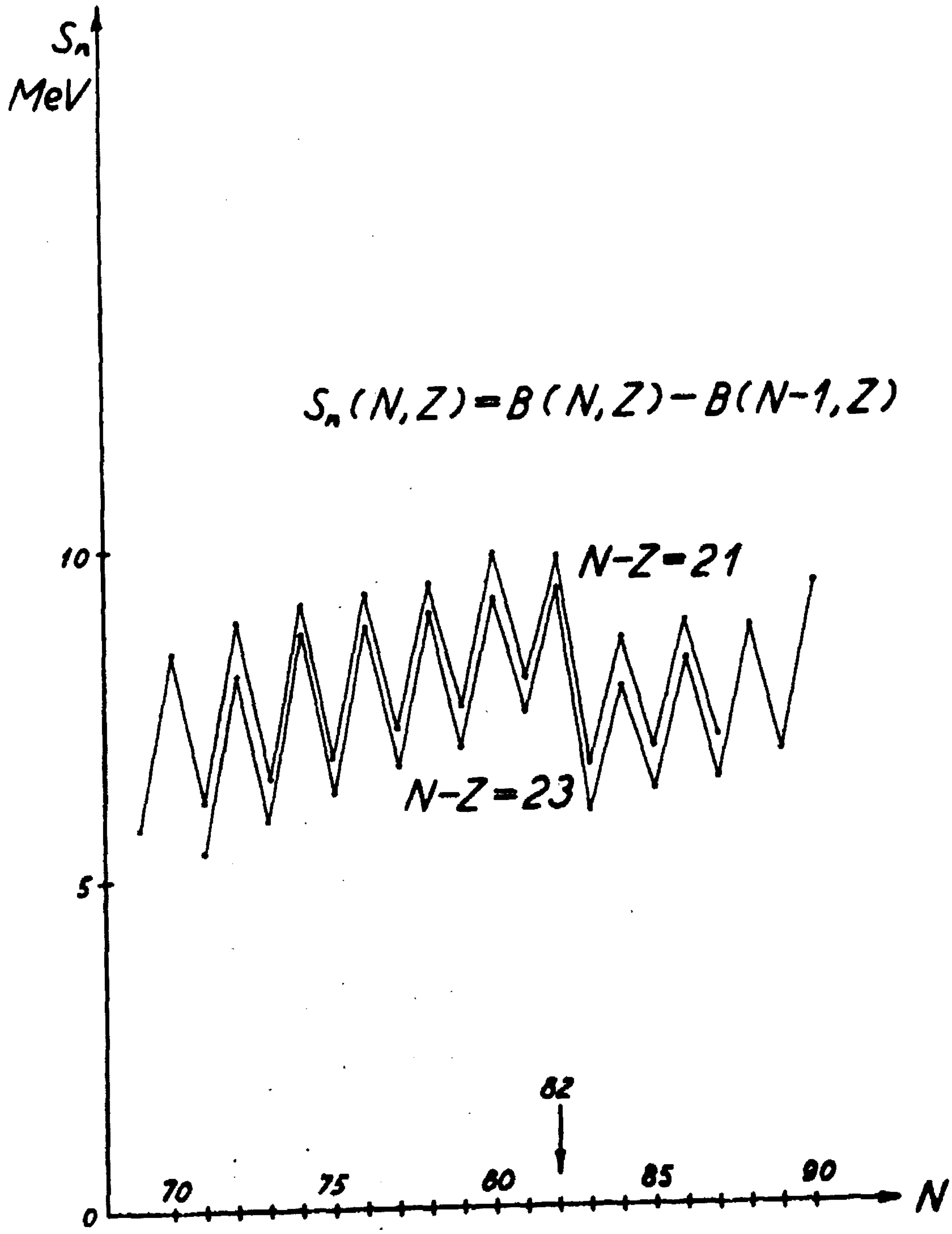

FIG. 3

FIG. 4 — *Regions of nuclear deformation.*

The small squares show the known β-stable nuclear species; those very stable towards α-decay are indicated by black squares, and those less stable by open squares. As one moves away from the β-stability region, the nuclei become radioactive with progressively shorter lifetimes. Finally, when the line $B_n = O$ (or $B_p = O$) is crossed, the nuclei become unstable with respect to neutron (or proton) emission. The domain between the borders $B_n = O$ and $B_p = O$, and limited by the line for « instantaneous » spontaneous fission ($Z^2/A = 41$), may be said to be in principle available to nuclear spectroscopy studies, but only a small region around the β-stability domain has so far been explored.

The vertical and horizontal lines give the closed shell configurations and the hatched domains are those in which the nuclei have been found to (or are expected to) have spheroidal equilibrium shapes. In these regions, the numbers of nucleons in unfilled shells are especially large. (The precise position of the demarcation line between sperical and deformed nuclei depends on a delicate balance between pairing and deformation effects, and may be influenced by rather fine details in the shell structure. The dashed part of the demarcation lines, which represent theoretical extrapolations, only have a qualitative significance).

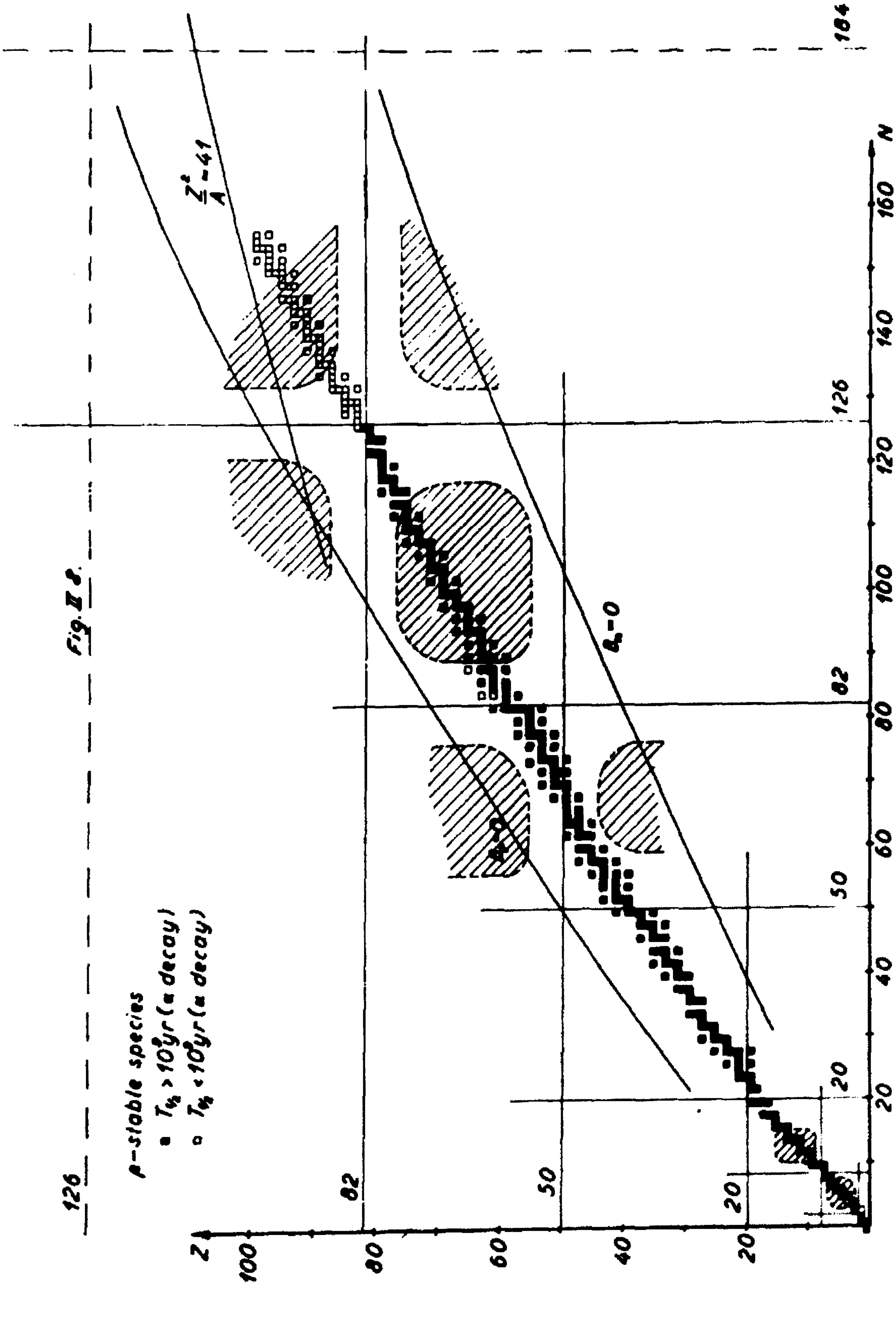
Fig. II 8.
β-stable species
$T_{1/2} > 10^8 yr$ (α decay)
$T_{1/2} < 10^8 yr$ (α decay)
$\frac{Z^2}{A} = 41$
$B_n = 0$
$B_p = 0$
126
82
50
20
184
N
Z

FIG. 4