Neutrons in the Nucleus. I

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It is supposed that the nucleus consists of α-particles, neutrons and zero or one proton, instead of the former structure scheme, α-particles, electrons and 0, 1, 2, 3 protons. The calculated mass defects Δm of the isotopes of a single element show an exact linear increase of Δm with the mass number (instead of the fluctuating function in the former structure scheme). The Δm-difference of the isotopes of each element is rather constant throughout the periodic system for even elements. The absolute values of the mass defects give a potential energy curve decreasing uniformly with increasing atomic number (instead of showing a minimum at the element No. 50 in the former structure scheme). In the region of the radioactive substances the energy curve seems to turn up again. All of this helps the model that the isotopes of an element differ only by the number of neutrons incorporated by them, the binding energy per neutron being rather constant throughout the periodic system and about 0.009 in mass units for even elements. In several cases the isotopes give a picture of the construction of a complete outer shell of 8 or 12 neutrons and indications that also in other cases there is a shell structure of the neutron arrangement, but none of the α-particles. The empirical rule that odd elements have no isotopes with even mass numbers can be explained, together with its exceptions, by help of the neutron structure scheme.

FOLLOWING Heisenberg,[1] who has explained several facts about the existence and stability of isotopes by help of neutrons and protons, we assume that the building stones of the nucleus consist of α-particles, zero or one loose proton, and neutrons. It may be of interest to support this model from some other points of view throughout the periodical table, stressing more than does Heisenberg the rôle of the α-particles in the whole nuclear structure.

I. Isotopes of a Single Element

There are only a few elements with several isotopes whose atomic weights have been measured to three decimals, so that one can calculate their mass defects with sufficient accuracy. These are Kr 36 (6 isotopes), Sn 50 (11 isotopes), Xe 54 (9 isotopes), Hg 80 (9 isotopes). Now the former theory interprets the structure of the Xe-isotopes $Z=54$ in the following way:

$$Xe^{124}=31\alpha+8\text{ el},$$

Xe^{125}, missing,

$$Xe^{126}=31\alpha+10\text{ el}+2\text{ pr},$$

Xe^{127}, missing,

$$Xe^{128}=32\alpha+10\text{ el},$$

$$Xe^{129}=32\alpha+11\text{ el}+1\text{ pr},$$

etc.

assuming four different numbers of α-particles from 31 to 34. This scheme gives the following values for the mass defects of the nine isotopes (compare the mass-spectrum of Xe in Table II): 0.133, —, 0.150, —, 0.137, ?, 0.154, 0.162, 0.141, —, 0.158, —, 0.154, which are seen to fluctuate with increasing mass of the isotope (compare Gamow's Table II of reduced weights with He = 4.000).

Now since Aston's weights[2] of the Xe-isotopes increase from 123.867 to 135.855 in almost exactly equal steps (passing over the missing isotopes) it is rather unsatisfactory to account for this linear rise by a fluctuating function. One has rather to explain it by a linear sequence of equal binding processes. In the scheme of neutrons (ν) the Xe-isotopes are to be described by

$$Xe^{124}=27\alpha+16\nu \quad \text{to} \quad Xe^{136}=27\alpha+28\nu.$$

Here the mass defect of Xe^{124} becomes $27\times 4.000+16\times 1.0075+16\times 0.0005-m_{\text{observed}}=0.261$, representing the energy required to split up the nucleus into 27 α-particles and 16

[1] W. Heisenberg, Zeits. f. Physik **78**, 150 (1932).

[2] G. Gamow, *Atomic Nuclei and Radioactivity*, Oxford, 1931.

neutrons and break up each neutron into its components. The last part could be separated if we knew the exact atomic weight of the neutron. If one calculates in the same way the mass defects of all Xe-isotopes, one gets the results: 0.261, —, 0.279, —, 0.297, ?, 0.315, 0.324, 0.333, —, 0.351, —, 0.369, indicating a *linear increase* of the defect by equal steps of 0.009 each, parallel to the observed linear steps of the atomic weights. This result is based on the assumption that all of the Xe-isotopes consist of 27 α-particles and 16 to 28 neutrons, the energy required to split off each neutron from the nucleus of Xe and to break it up into a proton and an electron being exactly constant, equal to 0.009 in mass units.

II. Isotopes of Various Elements

If one carries out the same calculations for the isotopes of other elements insofar as their atomic weights are sufficiently determined, one obtains in all cases the same exact linearity of the mass defects, parallel to the fact that the observed atomic weights of the isotopes form a linear set. We have then merely to report the constant intervals between subsequent mass defects for various elements, among them 0.009 for Xe. These are given in Table I for those

Table I. *Mass defect differences.*

6 C	0.008	54 Xe	0.009
10 Ne	0.006	80 Hg	0.008
18 Ar	0.009	3 Li	0.009
36 Kr	0.008	5 B	0.013
42 Mo	0.008	17 Cl	0.011
50 Sn	0.009	35 Br	0.010

elements with more than one isotope, whose atomic weights are known up to 3 decimals.

We interpret then the values of Table I as the energy in mass units to split off one neutron and to break it up. The atoms of even charge number display in general many more isotopes than the odd elements. For even elements the binding energy per neutron seems rather constant throughout the periodic system except for Ne. The binding energy per neutron for odd elements is more variable and on the average a little larger than for even elements. This may be due to the one extra proton which increases the attraction of the neutrons and disturbs the symmetry of the neutron arrangement.

III. Nuclear Stability Throughout the Periodic Table

If one plots the mass defects according to the old theory (α-particles, loose electrons and 0, 1, 2, 3 loose protons) one obtains for the potential energy of the nuclei a distribution having a minimum in the range of element number 50 (compare Gamow's Fig. 16). This minimum is a serious difficulty, because it means that the elements above 50 should be unstable, while in fact they are unstable above 80. If however we plot the mass defects according to the new scheme (α-particles, neutrons and 0 or 1 proton), then we obtain the mass defects given in Fig. 1. Each mass defect dot is marked with the number of neutrons contained in the isotope. The figure shows a *general decrease of the potential energy* with increasing atomic number. Among the radioactive substances the weights of Ra, Th and U are determined to only 2 decimals, in which the last one is not certain. So we have drawn dashes instead of dots in the region of their probable mass defects. Among the lighter elements the measured weights are rather incomplete, and sometimes only one of several isotopes could be used in our figure for that reason. The potential energy seems to have a minimum just in the region of the radioactive substances, where stable elements cease to exist. That our Δm increases uniformly while the curve of Gamow's book bends up after 50 is due to the fact that in the old scheme the number of α-particles is larger than in the neutron theory. For instance Hg 80 with $m = 196$ to 204 has in the old scheme 49 to 51 α-particles, in the neutron scheme only 40.

IV. Existence of Odd Charged Nuclei

The rules of Harkins concerning the relative abundance of the elements and their isotopes throughout the periodic table read in our scheme: Elements with a loose proton (odd charge number) are much rarer than elements without a loose proton (even charge number). Furthermore if we consider first only even elements we find that isotopes with an even number of neutrons are more frequent than those with an odd number of neutrons. Missing isotopes in most cases belong to odd neutron arrangements. *This fact cannot be*

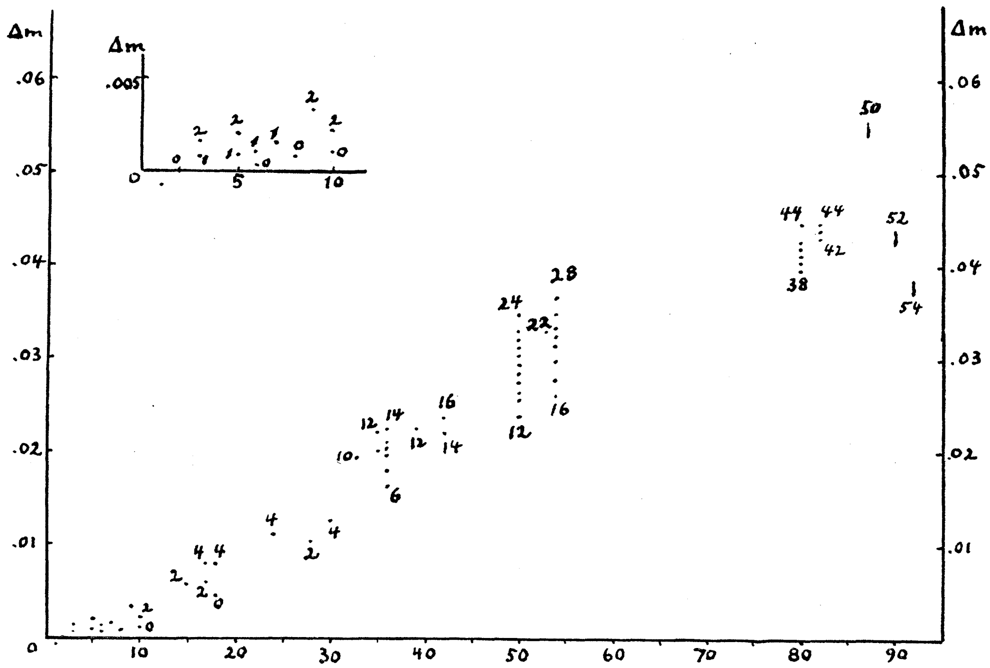

FIG. 1.

explained by energy balances, since we learned in Part I that the successive incorporation of one neutron after the other produces a linear increase of the mass defect without any break, at least for the neutrons added last. We have then to take for granted the preference of even arrangements of neutrons without an explanation by energy balances.

As to the elements of odd charge number one may wonder why they exist at all, both with even and odd numbers of neutrons. For if processes of *β-emission* connected with a transformation of one of the neutrons into a proton are taken into account, then the original loose proton and the new proton should associate with two neutrons to form an α-particle, and the odd element should pass over into an even one. However, though the final product has one α-particle more, it has three neutrons less. Now we learn from Table I that the energy gain 0.032 of building up an α-particle is about the energy loss of separating three neutrons and one β-particle from the nucleus; so these two effects may approximately balance each other, and we expect that minor secondary causes shall give the *decision* whether an element of odd charge number is or is not stable.

Now experience shows as a rule that odd elements have isotopes with odd mass numbers only, or expressed in our scheme: *Odd elements have no isotopes with an odd number of neutrons.*

We can explain this rule in the following way. The above-mentioned β-emission transforms an odd arrangement of neutrons into an even one. If there is only a small preference of even neutron arrangements before odd ones, this may give the decision mentioned above that the β-emission in this case always will happen, hence odd arrangements of neutrons in odd elements will be unstable. In the reverse case, if an even number of neutrons has only a small tendency to remain even instead of turning odd, this will give the decision that the β-emission is barred, and the isotope is stable.

This consideration does not hold if the odd number of neutrons is just *unity*. For then a β-emission would leave no neutron to form a new α-particle. In fact, there are four exceptions to the rule, namely, the existence of the stable isotopes, H^2, Li^6, B^{10}, N^{14}. But these are just four cases in which our structure scheme gives *one* neutron only, namely:

$$H^2 \ldots\ldots\ldots 0\alpha+1\ \mathrm{pr}+1\nu$$

$$Li^6 \ldots\ldots\ldots 1\alpha+1\ \mathrm{pr}+1\nu$$

$$B^{10} \ldots\ldots\ldots 2\alpha+1\ \mathrm{pr}+1\nu$$

$$N^{14} \ldots\ldots\ldots 3\alpha+1\ \mathrm{pr}+1\nu$$

Thus from the point of view of the neutron scheme the four exceptions prove the rule. The same holds for the exceptions among the radioactive elements giving β-rays.

V. Neutron Shells

It is very tempting but precarious to conclude from the table of the isotopes known up to now details of the arrangement of the neutrons in the nucleus. The existence of closed shells of neutrons is suggested by the fact, so striking at the first view of an isotopic table, of similar isotope sequences repeated in different elements. Consider for instance the following cases of mass-spectra given in Table II. Missing isotopes are indicated by dots. The second line means the charge number of the element, the last line of the table indicates the number of neutrons contained in the isotopes of lowest mass. We interpret this number as the total number in complete or incomplete inner neutron shells, to which neutrons are then attached step by step until an outer shell is completed. The examples of Table II we interpret as the incorporation of an outer shell of 8 or of 12 neutrons. As to the dots we observe that usually odd arrangements of neutrons are missing. With Se, Kr, Mo, Ru and also Sn and Xe, the isotopes with *one* neutron in the outer shell and the isotope with *one* neutron lacking in the outer shell are not observed. Whether this is essential or merely due to small intensity may be judged from the case of Hg. Here Aston's first experiments missed these two isotopes, but in a recent paper he reported them present in small intensity. So if one looks only for the possible population of neutron shells and for quantum rules controlling them, one should consider the missing isotopes more as an intensity problem.

Table II. *Mass-spectra.*

Ge 32	Se 34	Kr 36	Mo 42	Ru 44	Hg 80	Pb 82	Po 84	Sn 50	Xe 54
·	—	—	—	—	—	—	—	—	—
—	·	·	·	·	(—)	·	·	·	·
—	—	—	—	—	—	—	—	—	—
—	·	·	—	—	—	—	—	—	·
—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	·	·	·	—
—	—	—	—	—	—	·	—	—	—
—	·	·	·	·	(—)	—	—	—	—
—	—	—	—	—	—	—	—	—	—
								—	·
								—	—
								·	·
								—	—
6ν	6ν	6ν	8ν	8ν	36ν	42ν	42ν	12ν	16ν

Until the table of isotopes is completed by a table of their exact atomic weights to 3 decimals, it is rather precarious to generalize the idea that *the smallest isotope represents all neutrons in inner shells, and the largest isotope an additional complete outer shell.* This idea may be justified for the group of elements in Table II, since for those of them which are measured the mass defects certainly increase in equal steps, with the step magnitude 0.008 and 0.009. From mere energetic considerations one should expect that the incorporation of the neutrons takes place with decreasing energy steps, until the last neutron is bound with nearly no energy and bars the incorporation of more neutrons. This helps the conclusion that the neutrons are arranged in shells like the outer electrons, subject to Pauli's exclusion principle and Fermi statistics.[3] At the same time one expects for the α-particles, since they consist of an even number of components, *Bose* statistics and no shell structure at all.

Note added in proof: After this paper was sent in, I received an article of E. N. Gapon[4] being rather identical with the contents of Sections I, II and III of the present paper. Compare also with D. Iwanenko[5] who first suggested the nuclear model used here. One may consider, then, these parts as an introduction into Part II.

[3] J. H. Bartlett, Phys. Rev. **41**, 370 (1932); **42**, 145 (1932).

[4] E. N. Gapon, Zeits. f. Physik **79**, 676 (1932).

[5] D. Iwanenko, Comptes Rendus **195**, 439 (1932).