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Periodic variation in atomic mass of the noble gases

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A correlation between the atomic masses of the most abundant isotopes of the noble gases (ΔM) and the charge in their nuclei (ΔP), expressed by the equation $\Delta M = \Delta P + \sum_{n=0}^{n=(\Delta P/2)^{1/2}} 2n^2$, has been established, and the upper limit of stability for isotopes of element 118, corresponding to mass 316, has been calculated; the structure of neutron orbitals for isotopes of noble gases has been proposed.

The problem of correlation between the atomic mass of an element and its place in the Periodic system or its atomic number has been a key problem since the discovery of the periodic law by D. I. Mendeleev.

Of early investigations, the work by Thomsen[1] is particularly interesting. Thomsen predicted the existence of noble elements and calculated their atomic masses (Table 1). Two of Thomsen's working hypotheses attract attention: (*a*) about the equal changes in atomic masses of elements in paired periods; (*b*) about the existence of particular stable groups of particles consisting of original proto-matter in atoms.

In 1897, Rydberg[2] separated out of the atomic mass of element (M) its ordering number (P) and proposed a numerical row for the ordering numbers of noble gases.

$$M = P + N \tag{1}$$

$$P = 2 \times (1^2 + 1^2 + 2^2 + 2^2 + 3^2 + 3^2 + \ ...) \tag{2}$$

In the actual Periodic table of elements, the first period is not repeated and Rydberg's row looks like this:

$$P \ = \ 2 \times (1^2 + 1^2 + 2^2 + 2^2 + 3^2 + 3^2 + \ ...) - 2 \times 1^2 \tag{3}$$

This exactly defines the ordering numbers of noble gases (Table 1).[2,3]

Table 1 Calculated atomic masses and ordering numbers for noble gases.[1,3]

Element	He	Ne	Ar	Kr	Xe	Rn	ERn
Atomic mass (Thomsen)	4	20	36	84	132	212	292
Ordering number (Rydberg)	2	10	18	36	54	86	118

However, after the discovery of isotopism, the creation of the electromagnetic theory of the atom and successes in quantum mechanics, hardly any attempts to reveal regularities in the variation of atomic masses of the elements have been undertaken.[4]

Although quantum mechanical calculations of the structure of the nucleus led to a model of nuclear shells,[5] this did not settle the problem of periodicity.[6] Only recently, this problem has become of topical interest in relation to the prediction of atomic masses of the most stable isotopes of element 118. A direct extrapolation of changes in atomic masses of the VI period elements to the VII period in accordance with Thomsen's hypothesis gives the value of 314,[7] but Thomsen's hypothesis is not valid for the most stable isotopes of the noble gases in twin periods (Table 2, entry 6).

The atomic mass of the most abundant isotopes of noble gases and the number of neutrons and protons in their nuclei are listed in Table 2. It is evident from these data that the number of added neutrons in paired periods differs by 4:

$$\begin{aligned} &(N_{Ar} - N_{Ne}) - (N_{Ne} - N_{He}) = 12 - 8 = 4; \\ &(N_{Xe} - N_{Kr}) - (N_{Kr} - N_{Ar}) = 30 - 26 = 4; \\ &(N_{ERn} - N_{Rn}) - (N_{Rn} - N_{Xe}) = ? - 58 = 4. \end{aligned} \tag{4}$$

Hence, the gain in mass to a nucleus of element 118 is 62 due to neutrons. Thus, the mass number of the ecaradone isotope satisfying the above regularity is 316.

The series of the increase in mass in period due to neutrons (Table 2, entry 6) is not remarkable. However, if we use Thomsen's hypothesis on the equal atomic mass increase in paired periods and equate these masses (Table 2, entry 7), we obtain a very interesting result. The numbers 2, 10, 28, 60 are a sequence of sums of a well-known quantum mechanical row:

Table 2 Change of isotope mass of noble gases in periods.

1. Isotope	He	Ne	Ar	Kr	Xe	Rn	ERn
2. Mass number	4	20	40	84	132	222	(316)
3. Number of protons	2	10	18	36	54	86	118
4. Number of neutrons	2	10	22	48	78	136	(198)
5. Mass added by protons	2	8	8	18	18	32	32
6. Mass added by neutrons	2	8	12	26	30	58	(62)
7. Mass added by neutrons (Thomsen's hypothesis)	2	10	10	28	28	60	60

$$2, 8, 18, 32, 50, \ ... \ 2n^2; \tag{5}$$

and we have

$$\begin{aligned} &2 = 2; \ 10 = 2 + 8; \ 28 = 2 + 8 + 18; \\ &60 = 2 + 8 + 18 + 32, \ etc. \end{aligned} \tag{6}$$

It is unlikely that this coincidence is casual. More likely, it leads to the conclusion that there is a system of orbitals occupied by neutrons in each period and related to the change in the number of protons in the isotope nuclei of noble gases (ΔP) in each period by the formula:

$$\Delta M = \Delta P + \sum_{n=0}^{n=\sqrt{\frac{\Delta P}{2}}} 2n^2. \tag{7}$$

The second term of equation (7) is the gain in mass due to neutrons. The structure of nucleon orbitals for isotopes of noble gases is presented in Table 3.

These isotopes correspond to the upper boundary of their stability range. In even periods (Ne, Kr, Rn), the mass of the most abundant isotope is less by 2 units. This lack of neutrons is totally compensated in the next twin period (Ar, Xe, ERn). It is evident from Table 3 that for a stable isotope of an element to be obtained, it is necessary to fill additional neutron sublevels in each shell. Table 4 demonstrates the process of filling the additional neutron sublevels for even elements in the VI period (for the middle of the stability range) and in the VII period (for the most stable known isotopes). Both rows coincide through californium and the isotopes of these elements have long decay periods. The higher elements contain fewer neutrons than VI period elements, and their stability decreases sharply. Current methods for synthesising new isotopes of superheavy elements do not allow one to obtain nuclei with a higher number of neutrons. Apparently, this is the reason for their low stability.[7]

The recent synthesis of an element 108 isotope carried out in UINI (Dubna, Russia)[8] gives two isotopes of element 106 with atomic numbers 265 and 266 with half-lives of 2–30 and 10–30 s, respectively. Table 5 presents the half-life periods for the known isotopes of element 106.[8]

The addition of six neutrons leads to an increase in the half-life of the isotopes from 0.3 ms to 10–30 s, although 10–12

Table 3 Structure of nucleon orbitals in the isotopes of noble gases.

Period	I		II		III		IV		V		VI		VII	
	Number of nucleons in sublevels													
Isotope	p	n	p	n	p	n	p	n	p	n	p	n	p	n
He^4	2	2												
Ne^{22}	2	2	8	8 2										
Ar^{40}	2	2	8	8 2	8	8 2								
Kr^{86}	2	2	8	8 2	8	8 2	18	18 8 2						
Xe^{132}	2	2	8	8 2	8	8 2	18	18 8 2	18	18 8 2				
Rn^{224}	2	2	8	8 2	8	8 2	18	18 8 2	18	18 8 2	32	32 18 8 2		
ERn^{316}	2	2	8	8 2	8	8 2	18	18 8 2	18	18 8 2	32	32 18 8 2	32	32 18 8 2

Table 4 Number of neutrons on additional neutron orbitals.

Element(VI)	Xe	Ba	Ce	Nd	Sm	Gd	Dy	Er	Ib	Hf	W	Os	Pt	Hg	Pb	Po	Rn
Δn	0	0	0	0	0	4	4	6	8	9	11	12	14	16	18	18	26
Element (VII)	Rn	Ra	Th	U	Pu	Cm	Cf	Fm	No	104	106	108	110	112	114	116	118
Δn	–2	–2	0	2	4	3	3	2	–3	1	–2	–2					

Table 5 Atomic numbers and half-lives for isotopes of element 106.[8]

Atomic number of isotope	260	263	265	266
Half-life / s	3.6×10^{-3}	0.3–0.9	2–30	10–30

neutrons are still required for reaching the middle of the stability range of element 106 isotopes, and even more neutrons are needed to reach the upper stability limit. A similar picture is observed for elements 104 and 105.[9]

It is unlikely that the proposed structure of the nucleon orbitals can be explained by any of the theories of the atomic nucleus, as all these theories do not take into account the distinction between neutrons and protons, but use instead a common term ‘nucleons’.[10] Although such an approach is quite satisfactory for describing the high-energy states of a nucleus obtained due to collision of particles and for describing several properties of nuclei, the solution of the periodicity problem demands a nuclear model which takes the different structure and properties of neutrons and protons into account.

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