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The Relationship of Density with the Sizes of Atoms and Their Nuclei

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Annotation. The analysis of the relationship between the density of elements (metals and semimetals) with the parameters of atoms and their nuclei is carried out. It is shown that there is a weak correlation between the density and the diameter of the atom.The relationship between the density and diameter of the atomic nucleus is more significant. A high correlation has been revealed between the density and the ratio of the nuclear volume to the atomic volume.

Density is one of the most important parameters of a substance. Herewith, of great interest is how closethe connection between the density of a substance and the parameters of atoms and their nucleiis. The parameters of the group of substances(metals and semimetals)including the name of the element, its formula, atomic number, atomic weight (*A*), density (ρ), atom diameter (*D*a) and nucleus diameter (*D*n) are given in Table 1. The values of atomic weight, density, (ρ), and atom diameter are compiled according to the reference data[1, 2].

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Different methods give different sizes of atomic nuclei. In the work specially devoted to the theory of the atomic nucleus, methods are listed by which the sizes of the atomic nucleus are determined [3]. For example, according to the method for determining the sectionof nuclear reactions, the radius of the nucleus is

$$R_n = a_0\sqrt[3]{A}\cdot 10^{-15}m, \tag{1}$$

where a_0 = 1.4.

By the method of measuring the electrostatic interaction of protons in the nucleus, it was found that a_0 = 1.5. The scattering of electrons by atomic nuclei made it possible to estimate the coefficient a_0 = 1.2. Using the energy of X-ray radiation of μ-mesons, it was found that a_0 = 1.2. The approach that allows representing the nucleus as a uniformly charged Coulomb sphere gave the value a_0 = 1.23. Similar results are given in[4]. Summarizing the above results, we can obtain the average a_0 = 1.3. Thus, the average atomic nuclei diameter

$$D_n = 2.6\sqrt[3]{A}\cdot 10^{-15}\ m. \tag{1}$$

According to the data in the Table, the density of the group of substances varies from 0.53 g/cm^3 (lithium) to 22.6 g/cm^3 (osmium, iridium). The atomic size range is 2.44□$10^{-10}m$ (germanium) – 5.34□$10^{-10}m$ (cesium). Changes in core diameters are in the range of 4.96□$10^{-15}m$ (lithium) -15.43□$10^{-15}m$ (bismuthum, polonium).

It is known that an atomic massis concentrated in its nucleus [3, 4]. The ratio of the nucleus mass to the sum of the electron masses of the atom is approximately 2000/1. In addition to the mass of atomic nuclei, the density of a substance depends on the distance between its atoms (molecules). This distance is determined by the size of the electron shells of the atoms. The Tableshows that alkali metals have the largest sizes of electron shells at a relatively low density.

The plot, Fig. 1, shows the field of points ρ vs *D*a. From the review of the Table and Fig. 1 one can conclude that substances with a high density, such as osmium, rhenium and gold have small atomic sizes.

Table. Parameters of the group of elements of the periodic table (metals and semimetals)

Element	Formula	Atomic weight$A$	Density ρ, g/cm^3	Atom diameter, Da□$10^{10}$$м$	Nucleus diameter , Dn□$10^{15}$$м$	$Vn/Va\cdot10^{15}$
Lithium	Li	6.94	0.53	2.90	4.96	6.93
Natrium	Na	22.99	0.971	3.80	7.39	7.36
Magnesium	Mg	24.31	1.736	3.20	7.53	13.03
Aluminum	Al	26.98	2.70	2.86	7.79	20.26
Silicium	Si	28.08	2.33	2.64	7.90	26.85
Kalium	K	39.10	0.856	4.70	8.82	6.62
Calcium	Ca	40.08	1.55	3.94	8.90	12.92
Scandium	Sc	44.96	2.99	3.24	9.24	23.23
Titanium	Ti	47.87	4.54	2.94	9.44	33.09
Vanadium	V	50.94	6.11	2.68	9.64	46.50
Chromium	Cr	51.99	7.19	2.60	9.70	52.0
Manganum	Mn	54.94	7.21	2.54	9.88	58.95
Ferrum	Fe	55.84	7.87	2.52	9.94	61.30
Cobaltum	Co	58.93	8.9	2.50	10.12	66.34
Niccolum	Ni	58.69	8.9	2.48	10.10	67.59
Cuprum	Cu	63.55	8.92	2.56	10.38	66.58
Zincum	Zn	65.38	7.13	2.76	10.47	54.65
Gallium	Ga	69.72	5.91	2.82	10.70	54.62
Germanium	Ge	72.63	5.32	2.44	10.85	87.84
Arsenicum	As	74.92	5.73	2.76	10.96	62.11
Rubidium	Rb	85.47	1.532	4.96	11.45	12.31
Strontium	Sr	87.62	2.54	4.30	11.55	19.36
Yttrium	Y	88.90	4.47	3.56	11.60	34.62
Zirconium	Zr	91.22	6.51	3.20	11.70	48.92
Niobium	Nb	92.90	8.57	2.92	11.77	65.55
Molybdaenum	Mo	95.95	10.22	2.76	11.90	80.19
Technetium	Tc	98	11.5	2.72	11.99	85.59
Ruthenium	Ru	101.1	12.4	2.68	12.11	92.26
Rhodium	Rh	102.90	12.4	2.68	12.18	93.92
Palladium	Pd	106.42	12.0	2.74	12.32	90.91
Argentum	Ag	107.86	10.5	2.88	12.38	79.37
Cadmium	Kd	112.41	8.65	3.08	12.55	67.63
Indium	In	114.81	7.31	3.32	12.64	55.14
Stannum	Sn	118.71	7.31	3.24	12.78	61.33
Stibium	Sb	121.76	6.69	3.18	12.89	66.54
Caesium	Cs	132.90	1.873	5.34	13.26	15.34
Barium	Ba	137.32	3.5	4.44	13.41	27.57
Lanthanum	La	138.90	6.17	3.74	13.46	46.66
Cerium	Ce	140.11	6.76	3.62	13.50	51.90
Praseodymium	Pr	140.90	6.77	3.64	13.53	51.33
Neodymium	Nd	144.24	7.01	3.64	13.64	52.56
Promethium	Pm	145	7.26	3.66	13.66	51.97
Samarium	Sm	150.36	7.52	3.62	13.83	55.71
Europium	Eu	151.96	5.24	3.98	13.87	42.37
Gadolinium	Gd	157.25	7.90	3.58	14.03	60.24
Terbium	Tb	158.92	8.23	3.60	14.08	59.86
Dysprosium	Dy	162.50	8.55	3.60	14.19	61.21
Holmium	Ho	164.93	8.79	3.58	14.26	63.18
Erbium	Er	167.25	9.06	3.56	14.32	65.16
Thulium	Tm	168.93	9.32	3.54	14.37	66.92
Ytterbium	Yb	173.05	6.97	3.88	14.49	52.08
Lutetium	Lu	174.96	9.84	3.50	14.54	71.72
Hafnium	Hf	178.48	13.3	3.34	14.64	84.19
Tantalum	Ta	180.94	16.65	2.98	14.71	120.2
Wolframium	W	183.84	19.25	2.74	14.78	157.1
Rhenium	Re	186.20	21.0	2.74	14.85	159.1
Osmium	Os	190.23	22.6	2.70	14.95	169.8
Iridium	Ir	192.21	22.6	2.72	15.00	167.9
Platinum	Pt	195.08	21.3	2.78	15.08	159.6
Aurum	Au	196.96	19.3	2.88	15.13	144.9
Thallium	Tl	204.38	11.85	3.42	15.32	89.80
Plumbum	Pb	207.2	11.34	3.50	15.38	84.94
Bismuthum	Bi	208.98	9.79	3.40	15.43	93.45
Polonium	Po	209	9.20	3.52	15.43	84.22

In general, the distribution of points on the plot field, Fig. 1, shows that the relationship between the diameter of an atom and the density of a substance is very blurred (the regression equation $\rho = -3.98Da + 21.5$ with the coefficient of linear determination $R^2 = 0.226$). A more significant relationship is observed between the diameter of atomic nuclei and the density of substances($\rho = 1.46Dn - 9.55$, $R^2 = 0.403$), Fig. 2.

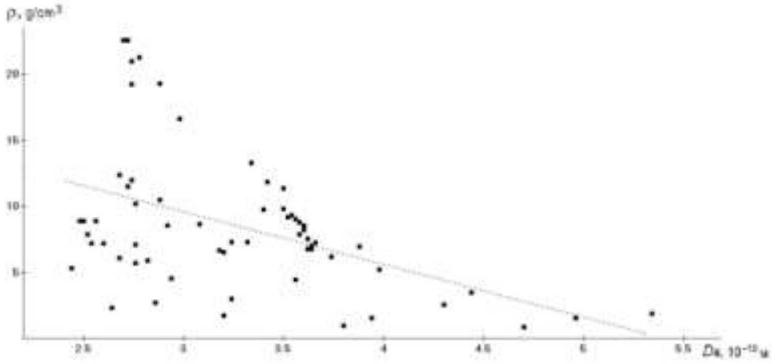

Figure 1. Distribution of the atomic diameters*D*a and the density values ρ of the substances.

The points (Fig. 2) corresponding to substances with a high density lie significantly higher than the regression line (for example, the elements aluminum, cuprum, rhodium and osmium). The points of substances (potassium, rubidium, cesium, etc.) with low density are located below this straight line. This is explained, as noted above, by the relatively large size of the outerelectron shells of alkali metals (Table).In order to take into account the effect of the distance between the atoms of an element in the substance, the ratio of the nucleus volume to the atom volume, *V*n/*V*a, was calculated. Assuming the shape of the nucleus in the form of a correctsphere, its volume

$$V_n = \frac{1}{6}\pi D_n{}^3.$$

Taking a similar condition regarding the shape of the atom, we obtain

$$\frac{V_n}{V_a} = \frac{D_n^3}{D_a^3}.$$

This ratio compensates for the effect of different distances between the electron shells of the atomicsubstance. The Table shows the calculated values *V*n/*V*afor the group of elements(metals and semimetals). The plot, Fig. 3, shows the field of points ρ vs $(Dn)^3/(Da)^3$of these elements.

A review of the plot reveals a high correlation between the values of ρ and $(Dn)^3/(Da)^3$. According to the averaging straight line, the dependence between the values ρ and *V*n/*V*a is described by the equation

$$\rho = 1.32\square(Vn/Va)\square10^{14},\ g/cm^3 \qquad (2)$$

with a linear correlation coefficient $R^2 = 0.958$.

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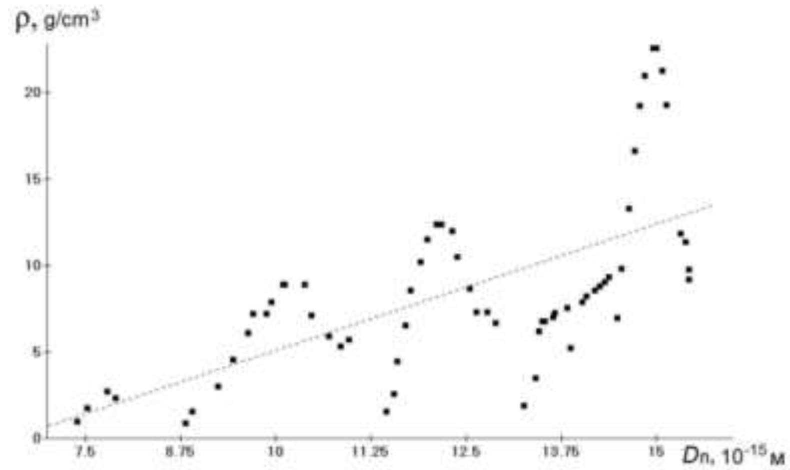

Figure 2. Distribution of the diameters*D*n of the atom nuclei and the values of density ρ of substances.

This is a fairly strict dependence, showing that the density of a substance directly depends on the mass of the nucleus and the volume that the outermost electron shells of atoms occupy in space. It should be noted that the nucleus mass determines its volume [3, 4]. Dependence (2) indicates a tight packing of metal atoms.

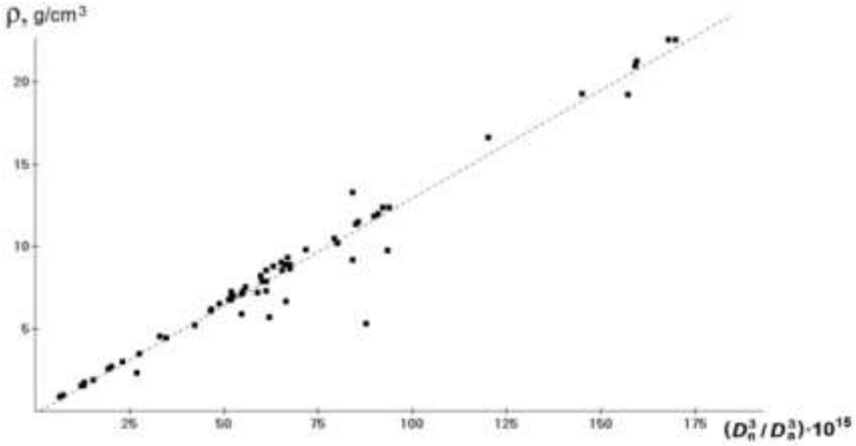

Figure 3. Distribution of the ratios $(Dn)^3/(Da)^3$ and corresponding density valuesρ of substances (metals and semimetals).

Deviations from dependence (2) towards lower density values ρ are observed in arsenicum, stibium, and especially in germanium. Germanium, arsenicum and stibium are semimetals. The positions of individual points of elements that do not lie on the generalized straight line (2) can be explained by non-sphericityof the nucleus and atomshape, the different number of electrons in the outer electron shell of the atom, etc. The dependence (2), as a whole, establishes a causal relationship between the macro value-density, nucleus mass and atom size.

Declaration of competing interest.
The author declares that he has not known competing financial interest or personal relationships that couldappear to influence the work reported in this paper.

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