ISOTOPIC MASSES AND BINDING ENERGIES OF NUCLEI FOR MASSES BETWEEN 186 AND 196

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Submitted to JETP editor June 4, 1959

J. Exptl. Theoret. Phys. (U.S.S.R.) **37**, 1217-1224 (November, 1959)

Values of the masses and binding energies are presented for the nuclei of isotopes of osmium, iridium, platinum, gold, and mercury. The masses were measured on a mass-spectrograph possessing a resolving power of 60,000 — 80,000. The isotope masses were derived from doublets by direct comparison with the masses of corresponding organic compounds. The masses of 18 stable isotopes were measured and the masses of 18 radioactive isotopes were computed. The data thus obtained were used to evaluate the binding energy of nuclei, the binding energy per nucleon (E/A), the binding energies of the last neutron and proton (B_n and B_p) and the pair energies of neutrons and protons (P_n and P_p). For N = 116, the binding energy of nuclei has been found to vary in a nonmonotonous manner for both odd and even values of Z.

INTRODUCTION

THE masses of isotopes and the coupling energies of nucleons in the nucleus have previously[1] been measured in the region of magic numbers up to 82 protons and 126 neutrons. In the present research, a second series of measurements has been carried out in the mass range $186 \leq M \leq 201$. Measurement of the masses of mercury, gold, platinum, iridium and osmium isotopes was carried out on a mass spectrograph described previously,[2] with a resolving power of 60,000 — 80,000. The measurements were made by means of doublets. A doublet pair was formed from a given isotope with a corresponding organic compound of type C_nH_m, $C_nH_mN_p$ or $C_nH_mO_k$. For high resolving power of the apparatus and dispersion calculations of high accuracy ($\sim 10^5$), this guaranteed a high accuracy of measurement.

Such a method of measurement makes it possible to determine the mass of the nucleus of a given isotope, avoiding intermediate measurements, making use only of the values of the masses of H^1, C^{12}, N^{14} and O^{16} which have been measured with sufficient accuracy previously.[2] Determination of the masses of the isotopes Os^{186}, Os^{187}, Os^{188}, Os^{189}, Ir^{191}, Ir^{193}, Pt^{192} and Au^{197} by the mass-spectrograph method has not been carried out up to the present time. The single research of Johnson and Bhanot, applying to the given mass range,[3] was carried out on a mass spectrometer with a low resolving power ($A_{max} \sim 14{,}000$). In this work mass differences per unit mass were measured for stable isotopes with even Z in the range $64 \leq Z \leq 82$. The value of the isotopic masses was not given in reference 3. Other mass-spectrographic measurements[4,5] were carried out for a small number of isotopes and have a very incomplete character. The values of masses computed in the work of Wapstra[6] from the energy balance of nuclear reactions were obtained with significant error ($\sim 2 - 3$ mMu). In the calculation of the isotopic masses of heavy nuclei the error becomes so large that, as a supporting value, the mass of the isotope Pb^{208} was used in place of O^{16}.[7] With such a large error of measurement, the calculated values of the binding energy of the last neutron or proton do not permit one to make an unambiguous estimate of the nuclear structure.

Ions of the elements thus measured were obtained by introducing vapors of the metal into the gas discharge region of a plasma ion source by means of an evaporator of special construction. The corresponding organic compounds were also introduced into the gas discharge region in the same manner.

As a check for the absence of errors of measurement,[8] determination of the isotopic masses in most cases was carried out with a check for internal consistency, including such cases in which the molecular weight of the organic compound was equal to the weight of the isotope under investigation. In some cases, in addition to this, control of the resultant measurements was obtained by measurement of masses of isotopes of a given element, using as a doublet the lines of isotopes with mass difference of unity.

In each case, the results of measurement were

obtained after analysis of 12 — 15 mass spectra with 4 — 6 photo plates.

MEASUREMENT OF ISOTOPIC MASSES

1. Osmium isotopes Os^{186}, Os^{187}, Os^{188}, Os^{189}, Os^{190} and Os^{192}. For all the osmium isotopes, the measurements were carried out with a check on internal consistency, while different doublet combinations were formed by use of different organic compounds and compounds of osmium. The osmium ions were obtained by introduction into the gas discharge region of a plasma ion source of vapors of OsO_4. The organic compounds perylene ($C_{20}H_{12}$, M = 252) and terphenyl ($C_{18}H_{14}$, M = 230) were used both in molecular form and in the form of fragments of these compounds as the organic compounds for the formation of doublet pairs with ions Os, OsO, OsO_2, OsO_3 and OsO_4. Internal consistency for the masses of the isotopes Os^{186}, Os^{187}, Os^{189} and Os^{192} were determined from three independent doublets for each isotope, Os^{188} from four and Os^{190} from five doublets. The value of the mass of each isotope was computed with account taken of the "weight" of the measurement. The values of the doublets and the masses of the isotopes are given in Table I.

2. Iridium isotopes Ir^{191} and Ir^{193}. Iridium ions were obtained by evaporation of metallic iridium. For the formation of a doublet pair with the isotope Ir^{191}, the splinter ($C_{15}H_{11}$, M = 191) of benzalacetophenone ($C_{15}H_{12}O$, M = 208) was used" and for the isotope Ir^{193}, the splinter ($C_{14}H_9O$, M = 193) of anthrone ($C_{14}H_{10}O$, M = 194). The values of the differences of masses of doublets and the values of the isotopic masses computed from these data are given in Table II.

3. Platinum isotopes Pt^{192}, Pt^{194}, Pt^{195}, Pt^{196} and Pt^{198}. The platinum ions were obtained by evaporation of metallic platinum with successive ionizations of the vapor in the discharge. Testing of internal consistency in the measurements of the isotopic masses of platinum was carried out by utilization of two different organic compounds for the formation of doublet pairs. As organic compounds, benzalphenylhydrazone ($C_{13}H_{12}N_2$, M = 196) was used in one case and a fragment of benzoin ($C_{14}H_{12}O_2$, M = 212) in the other. The values of the mass differences of the doublet and the values of the isotopes are given in Table III. For comparison, data obtained from mass-spectrographic measurements of Hogg and Duckworth[4] are also shown in the table.

4. Gold isotope Au^{197}. Measurement of the mass of the isotope Au^{197} was carried out by comparison of the mass of the gold ion with the mass of benzanilide ($C_{13}H_{11}ON$, M = 197). The value of the doublet $C_{13}H_{11}ON$–Au^{197} and of the mass of the gold isotope are given in Table II. Values of the masses of the isotope Au^{197}, computed in terms of Hg^{198} and $C_{13}H_{10}ON$ (mass differences ~1). The mean value for Au^{197} was computed with account of the "weight" of the measurements.

5. Mercury isotopes Hg^{196}, Hg^{199}, Hg^{200} and Hg^{201}. In the present work, measurements of the mass of the isotope Hg^{196} were carried out and a test for the internal consistency of the masses of the isotopes Hg^{199}, Hg^{200} and Hg^{201} was carried out; the measurements in the latter case were made in a previous research.[1] Use was made of

TABLE I

Mass, A	Doublet	Volume of ΔM, mMu	Value of the mass of the isotope, Mu	Mean value of the mass, Mu
186	$C_{15}H_6$—Os^{186}	92.157±0.150	186.013635±150	186.013246±300
	Os^{187}—Os^{186}	1002.797±0.150	186.012624±220	
	$C_{20}H_{10}$—$Os^{186}O_4$	144.659±0.141	186.013161±140	
187	$C_{13}H_7$—Os^{187}	98.892±0.080	187.015402± 80	187.015370±230
	Os^{188}—Os^{187}	1000.253±0.150	187.015858±220	
	$C_{19}C^{13}H_{10}$—$Os^{187}O_4$	146.481±0.170	187.015010±170	
188	$C_{15}H_8$—Os^{188}	106.549±0.110	188.015887±110	188.015759±200
	Os^{189}—Os^{188}	1002.420±0.150	188.015973±180	
	$C_{16}H_4$—$Os^{188}O_2$	84.948±0.320	188.016380±330	
	$C_{20}H_{12}$—$Os^{188}O_4$	158.472±0.070	188.015632± 70	
189	$C_{13}H_9$—Os^{189}	112.236±0.110	189.018342±110	189.018362± 80
	$C_{16}H_5$—$Os^{189}O_2$	90.949±0.150	189.018521±150	
	$C_{19}H_9$—$Os^{189}O_3$	127.541±0.090	189.018317± 90	
190	$C_{15}H_{10}$—Os^{190}	119.060±0.090	190.019660± 90	190.019176±150
	Os^{190}—Os^{189}	1000.944±0.150	190.019337±160	
	$C_{14}C^{13}H_9$—Os^{190}	115.092±0.080	190.019157± 80	
	$C_{18}H_6$—$Os^{190}O_2$	98.638±0.064	190.018974± 60	
	$C_{19}H_{10}$—$Os^{190}O_3$	135.210±0.240	190.018790±240	
192	$C_{12}N_2H_8$—Os^{192}	107.044±0.110	192.022806±110	192.022529±120
	$C_{18}H_8$—$Os^{192}O_2$	111.363±0.040	192.022533± 50	
	$C_{18}C^{13}H_{11}$—$Os^{192}O_3$	143.323±0.030	192.022490± 40	

TABLE II

Mass, A	Doublet	Value of ΔM, mMu	Value of the mass of the isotope, Mu	Mean value of the mass, Mu
191	$C_{15}H_{11}$—Ir^{191}	125.037±0.201	191.021825±202	191.021825±202
193	$C_{14}H_9O$—Ir^{193}	102.194±0.100	193.024564±104	193.024564±104
197	$C_{13}H_{11}ON$—Au^{197}	117.572±0.200	197.029177±205	197.029181±120
	Hg^{196}—Au^{197}	1000.709±0.240	197.029004±245	
	Au^{197}—$C_{13}H_{10}ON$	890.805±0.278	197.029412±280	

TABLE III

Mass, A	Doublet	Value of ΔM, mMu	Value of the mass, Mu	Value of the isotopic masses of platinum, Mu	
				According to data of the present research	According to mass-spectrographic measurements[4]
192	$C_{12}H_8N_2$—Pt^{192}	107.289±0.221	192.022561±225	192.022561±225	—
194	$C_{13}H_{10}N_2$—Pt^{194}	121.564±0.087	194.024570± 90	194.024604± 96	194.024100±600
	$C_{14}H_{10}O$—Pt^{194}	110.207±0.234	194.024693±236		
195	$C_{13}H_{11}N_2$—Pt^{195}	127.039±0.100	195.027237±102	195.027199± 95	195.026500±600
	$C_{14}H_{11}O$—Pt^{195}	115.924±0.210	195.027118±215		
196	$C_{13}H_{12}N_2$—Pt^{196}	134.529±0.111	196.027889±115	196.027889±115	196.026700±600
198	Pt^{198}(по Hg^{198})	—	198.029880±200	198.029880±200	198.032700±600

TABLE IV

Mass, A	Doublet	Value of ΔM, mMu	Value of the isotopic masses, Mu	Value of the isotopic masses of mercury, Mu	
				According to data of the present research	According to mass-spectrographic measurements[5] (1958)
196	$C_{14}H_{12}O$—Hg^{196}	122.638±0.176	196.028546±180	196.028362±185	196.027260±230
	$C_{13}H_{10}ON$—Hg^{196}	110.251±0.020	196.028356± 32		
199	$C_{16}H_7$—Hg^{199}	85.994±0.079	199.032120± 82	199.031684±460	199.030960±100
	$C_{13}H_{11}O_2$—Hg^{199}	107.674±0.038	199.031548± 45		
200	$C_{16}H_8$—Hg^{200}	94.354±0.043	200.031902± 47	200.031913± 68	200.031270± 80
	$C_{12}C^{13}H_{11}O_2$—Hg^{200}	110.913±0.111	200.031980±115		
201	Hg^{201}—Hg^{200}	1002.254±0.021	201.034167± 71	201.034603±220	201.033510±120
	Hg^{202}—Hg^{201}	1000.398±0.032	201.034564± 62		
	$C_{16}H_9$—Hg^{201}	99.128±0.069	201.035270± 83		

a splinter ($C_{14}H_{12}O$, M = 196) of benzoin ($C_{14}H_{12}O_2$, M = 212) and a splinter ($C_{13}H_{10}ON$, M = 196) of benzanilide ($C_{13}H_{11}ON$, M = 197) for the formation of doublet pairs with the isotope Hg^{196}. For a test of the internal consistency for the isotope Hg^{199}, the doublet $C_{13}H_{11}O_2$–Hg^{199} was measured in addition to the doublet $C_{16}H_7$—Hg^{199} [1] Similarly, additional measurements were carried out of the doublet $C_{12}C^{13}H_{11}O_2$—Hg^{200}, Hg^{201}–Hg^{200} and Hg^{202}–Hg^{201} were also carried out for the isotopes Hg^{200} and Hg^{201}; in this case the organic compound benzoin ($C_{14}H_{12}O_2$, M = 212) and the mercury spectrum were employed. Masses of the isotopes Hg^{196}, Hg^{199}, Hg^{200} and Hg^{201} were determined from these doublets with account of the "weight" of measurement. The value of the mass differences of the doublets and the values of the isotopic masses of mercury computed from these doublets are given in Table IV. For comparison, data are also given in this table obtained from the mass-spectrographic measurements of Kerr and Duckworth.[5]

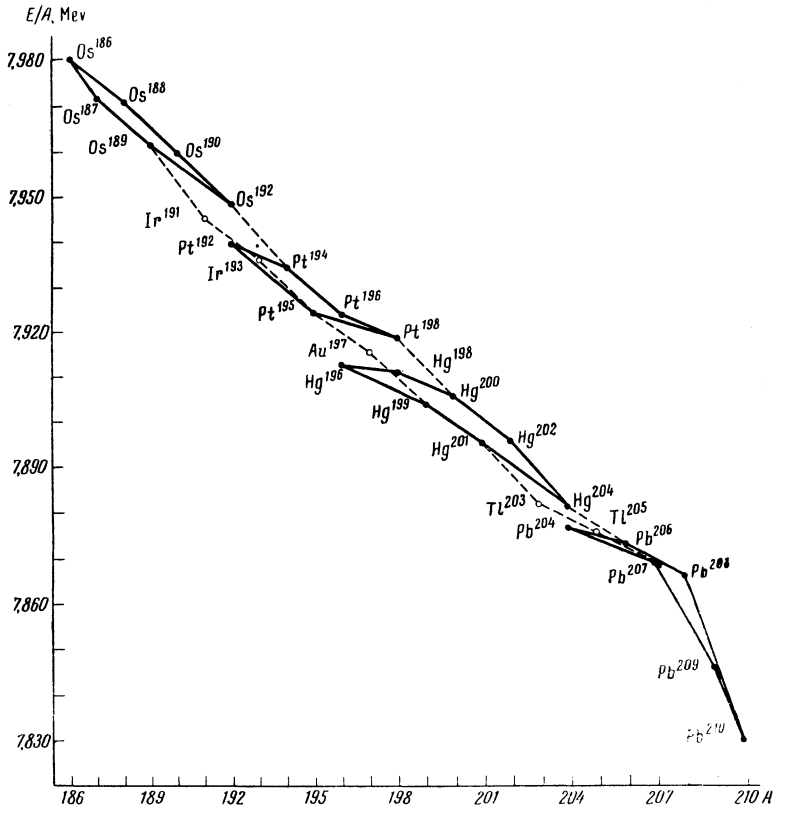
MEASUREMENT RESULTS

By comparing the values of the isotopic masses obtained in the present research with the corresponding data computed from nuclear reactions (see Table V), one can see that they are generally in agreement within the limits of error. However, this agreement is obtained at the cost of a very large error in the determination of the masses of the isotopes in terms of the values of Q obtained from nuclear reactions. In the final analysis, the mass of the isotope O^{16} was used as a supporting value for these isotopes, and consequently a large error of measurement is obtained as the result of the use of a large number of steps with corresponding values of Q. The most significant divergences in the

TABLE V

Isotope	Value of the isotopic mass M from the data of the present research, Mu	Values of the isotopic mass M′ according to data from nuclear reactions,[6] Mu	Δ = M − M′, mMu
Os^{186}	186.013246±200	186.009550±2300	3.696
Os^{187}	187.015370±150	187.011045±2200	4.325
Os^{188}	188.016058±140	188.014100±2000	1.958
Os^{189}	189.018362± 50	189.018120±2000	0.242
Os^{190}	190.019127±110	190.017400±2000	1.727
Os^{192}	192.022470±160	192.022500±3000	−0.030
Ir^{191}	191.021825±202	191.021240±2100	0.585
Ir^{193}	193.024564±104	193.025200±2000	−0.636
Pt^{192}	192.022561±225	192.023100±2050	−0.539
Pt^{194}	194.024604± 96	194.024000±1500	0.604
Pt^{195}	195.027199± 95	195.026400±1500	0.799
Pt^{196}	196.027889±115	196.026880±1500	1.009
Pt^{198}	198.029880±200	198.029000±2000	0.880
Au^{197}	197.029181±120	197.028470±3000	0.717
Hg^{196}	196.028362±185	196.027350±3010	1.012
Hg^{199}	199.031684±460	199.030550±3050	1.134
Hg^{200}	200.031913± 68	200.031910±3010	0.003
Hg^{201}	201.034603±220	201.034000±3000	0.603

values of the mass take place in the isotopes of osmium. For two of them (Os^{186} and Os^{187}, see Table V), the difference in values exceeds twice the value of the very large error of nuclear measurements. According to existing evidence,[9] the values of the masses of these isotopes (Os^{186} and Os^{187}) given in the work of Wapstra,[6] are unreliable. In addition to these isotopes, significant divergences also take place in the value of the masses of the isotopes Os^{188}, Os^{189}, Pt^{192} and Hg^{199}. The most accurate measurements in the region under consideration were made in the work of Johnson and Bhanot.[3] Unfortunately, the work did not cover differences of masses with odd Z, and for elements with even Z several isotopes were not measured (Os^{192}, Pt^{192}, Hg^{198}, etc.). However, comparison of the mass differences obtained in this work with similar data of the present research and nuclear data computed directly from nuclear reactions shows that all comparable values are in excellent agreement within the limits of the errors of measurement. Quite a different picture is obtained for



Binding energies per nucleon in the range 186 ≤ M ≤ 210.

comparison of the same quantities computed from the values of the mass given by nuclear data.[6] The divergences in a number of cases exceed 2 — 2.5 mMu. Analysis of the data of the present research and of reference 3 shows the error of measurements of the masses of the isotopes Os^{186}, Os^{187}, Os^{188}, Os^{189}, and Pt^{192} advanced in reference 6.

Additional measurements of the masses of the isotopes Hg^{199}, Hg^{200}, and Hg^{201} with "internal consistency" for Hg^{200} made it possible to carry out a comparison of the values of Q obtained from nuclear reactions with the corresponding values computed according to the current measurements of isotopic masses. Thus, for example, the value for the mass of the isotope Hg^{200}, according to the data of the present work is equal to $M(Hg^{200}) = 200.031913 \pm 68$ Mu. This quantity is in excellent agreement with data obtained from nuclear reac-

TABLE VI

Isotope	Z	N	Binding energy of the nucleus,* Mev	Binding energies of the nucleon, E/A, Mev	B_n, Mev*	B_p, Mev*	P_n, Mev*	P_p, Mev*
Os^{186}		110	1484.142	7.9792				
Os^{187}		111	1490.530	7.9708	6.388			
Os^{188}		112	1498.256	7.9694	7.726		1.338	
Os^{189}		113	1504.477	7.9602	6.221			
Os^{190}	76	114	1512.056	7.9582	7.579		1.358	
Os^{191}		115	1517.765	7.9464	5.709			
Os^{192}		116	1525.751	7.9466	7.986		2.277	
Os^{193}		117	1531.022	7.9328	5.271			
Ir^{190}		113	1510.015	7.9474		5.538		
Ir^{191}		114	1517.200	7.9435	7.185	5.144		
Ir^{192}		115	1523.438	7.9346	6.238	5.673		
Ir^{193}	77	116	1531.382	7.9346	7.944	5.631	1.706	
Ir^{194}		117	1537.521	7.9254	6.139	6.499		
Ir^{195}		118	1543.566	7.9157	6.045		0.906	
Pt^{192}		114	1524.096	7.9380		6.896		1.752
Pt^{193}		115	1530.549	7.9303	6.453	7.111		1.438
Pt^{194}		116	1538.926	7.9326	8.377	7.544	1.924	1.913
Pt^{195}		117	1544.876	7.9224	5.950	7.355		0.856
Pt^{196}	78	118	1552.600	7.9214	7.724	9.034	1.774	
Pt^{197}		119	1559.014	7.9138	6.414			
Pt^{198}		120	1567.479	7.9166	8.465		2.051	
Pt^{199}		121	1571.945	7.8992	4.466			
Au^{194}		115	1535.590	7.9154		6.142		
Au^{195}		116	1543.820	7.9170	8.230	4.894		
Au^{196}		117	1550.902	7.9128	7.082	6.026		
Au^{197}		118	1558.979	7.9136	8.077	6.379	0.995	
Au^{198}	79	119	1565.357	7.9058	6.378	6.243		
Au^{199}		120	1572.929	7.9042	7.572	5.450	1.194	
Au^{200}		121	1579.234	7.8962	6.305	7.289		
Au^{201}		122	1585.896	7.8900	6.662		0.357	
Hg^{195}		115	1541.861	7.9070		6.271		0.130
Hg^{196}		116	1550.590	7.9112	8.729	6.770		1.876
Hg^{197}		117	1558.000	7.9086	7.410	7.098		1.072
Hg^{198}**		118	1566.100	7.9096	8.100	7.121	0.690	0.742
Hg^{199}		119	1572.596	7.9025	6.496	7.239		0.896
Hg^{200}	80	120	1580.749	7.9037	8.153	7.820	1.657	2.370
Hg^{201}		121	1586.610	7.8936	5.861	7.376		0.087
Hg^{202}**		122	1594.685	7.8945	8.075	8.789	2.214	
Hg^{203}**		123	1600.048	7.8820	5.363			
Hg^{204}**		124	1607.614	7.8805	7.566		2.203	
Hg^{205}**		125	1613.388	7.8702	5.774			

*Errors in the values of the binding energy do not exceed 0.2 Mev and correspondingly in B_n and B_p — 0.3 Mev and P_n and P_p — 0.4 Mev

**Data taken from reference 1.

tions according to which (see Table V) $M(Hg^{200})$ = 200.031910 ± 3010 Mu. Moreover, the mass difference $Hg^{202} - Hg^{200}$, obtained in the data of reference 1 and in the present work, is ΔM = 2.003039 ± 180, which is in good agreement with the corresponding value obtained from mass-spectrometric measurements by Johnson and Bhanot[3] (ΔM = 2.002900 ± 150). Because of this we can consider that the value for the mass of Hg^{202}, obtained in reference 1, is sufficiently reliable. Moreover, there is good agreement between the values obtained from the cycle of mass-spectrographic measurements[1] and the data of nuclear reactions in the calculation of the mass of Tl^{203} by means of the reaction Hg^{204}–Tl^{203}. The agreement of the value for the mass of Tl^{203} obtained from the reaction $Tl^{203}(\gamma, n)Tl^{202}$ by means of the chain $Hg^{202} \rightarrow Tl^{202} \rightarrow Tl^{203}$ leads to a discrepancy for the mass of Tl^{203} ~ 1.7 mMu. Thus, joint consideration of nuclear and mass-spectrographic measurements leads to the conclusion that in all probability the assumed value of the quantity Q for the reaction $Tl^{203}(\gamma, n)Tl^{202}$ [10] is in error and it would be desirable to repeat the measurement of this quantity Q.

BINDING ENERGY OF NUCLEONS IN THE NUCLEUS

The mass values of the isotopes of osmium, iridium, platinum, gold and mercury obtained in the present research make possible a more accurate determination of the binding energy of nucleons in the nucleus over the mass range $186 \leq M \leq 200$. In addition to the results of the present research, the masses of 18 radioactive isotopes were computed by means of the values of Q obtained from nuclear reactions and beta decay energies. In this case the values of the masses of stable isotopes obtained in the present research were used as standardizing values.

Evidence on the general characteristics of nucleon binding can be obtained from a study of the binding energy per nucleon. The binding energy per nucleon E/A is plotted in the drawing in Mev as a function of A. For completeness of the picture, the region of values of A is expanded over the range of values used in reference 1. In the drawing the solid lines connect the binding energies of stable (measured) isotopes with the same Z. The binding energies of nuclei with odd Z (Ir, Au, Tl) are denoted by circles and are connected with odd A of elements with even Z. As is seen from the figure, a certain periodicity in the binding energy of stable nuclei in this mass region is indicated. The peculiarity noted in reference 1 of the isobaric pair of nuclei Hg^{204} and Pb^{204} is preserved and even expanded to the isobars Pt^{198}–Hg^{198}; Pt^{196}–Hg^{196} and Os^{192}–Pt^{192}. In the isobaric pairs shown, the binding energies of the nucleus in which two protons are replaced by two neutrons is larger than in the opposite case. Values of the binding energy of nuclei, the binding energy of the last neutron B_n, of the last proton B_p, the pair energies of neutrons P_n and protons P_p are shown in Table VI. Analysis of the data of Table VI shows that nuclei having N = 116 for both even and odd Z possess an increased stability. This is evident from the values of B_n and P_n. In contrast to this, nuclei with N = 115 are distinguished by a lower value of coupling energy in comparison with other nuclei of odd N. For even-even nuclei, an increased value of the pair energies of protons P_p occurs for N = 116 ($^{116}_{78}Pt^{194}$ and $^{116}_{80}Hg^{196}$).

In conclusion the authors express their gratitude to E. E. Baroni and their co-workers K. A. Kovyrzina and V. M. Soĭfer for preparation of the organic compounds and also to M. I. Dzkuya and G. A. Dorokhova for help in the research.

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