UNIVERSITY OF CALIFORNIA

Radiation Laboratory

Contract No. W-7405-eng-48

THE MASSES OF THE HEAVY ISOTOPES

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April 14, 1952

Berkeley, California

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ABSTRACT

Radioactive decay data are used to calculate the atomic masses of the heavy isotopes, $A \geq 203$. The four radioactive families are then connected by means of neutron binding energies known from (n,γ), (γ,n) and (d,p) reactions on various target isotopes. Finally, all the masses are collectively adjusted for the best fit with mass spectrographic information available in this region. The masses so calculated are presented in Table III. Differences between masses of isotopes are estimated to have an error of ± 0.00020 mass units or about 200 Kev; the position of the masses taken collectively is in doubt by about 1.5 Mev.

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Introduction

In a previous paper[1] the author calculated the atomic masses of more than a hundred heavy isotopes from more or less known data about their modes of decay. At that time it was, however, impossible to interconnect the four radioactive families on a firm basis, inasmuch as no experimental evidence was, as yet, available. The procedure adopted was to fit the mass differences between isotopes of the four decay chains in the thorium-uranium region to those calculated by means of a semi-empirical mass formula[2]. The mass of Pb^{208} was finally fixed to give what was thought to be a reasonable packing fraction.

In the present paper, many of the uncertainties present in Reference 1 could be removed. As new decay data became known, some of the assumed decay schemes could be replaced by more definite ones, and over twenty new masses were added. In Reference 1 many isotopes were connected to the main decay chains only through electron capture. In that case, their masses remained undetermined to within an unknown amount of energy ν_i carried off by the neutrino. Some of these masses have now become known, as a different mode of decay connecting them to the main chains has been discovered. Those that still remain undetermined have been omitted from the new table altogether. Furthermore, as explained below, it is now

1. Martin O. Stern, Rev. Mod. Phys. 21, 316 (1949)

2. N. Metropolis and G. Reitwiesner, NP-1980 (March, 1950)

possible to interconnect the four families to very good precision, and to place the masses on an absolute scale with improved accuracy. Finally, the Chemistry Group of the Radiation Laboratory has made a thorough study of the systematics of alpha decay[3] which permits one to predict with fair reliability the decay energy of an alpha emitting nuclide if one knows that of its neighbor isotopes. A number of species have been included on the basis of such predictions.

Procedure

Various experimenters[4-14] have obtained neutron binding energies by observing (γ,n), (d,t), (n,γ) or (d,p) reactions in various targets, some of them in the region of interest here. It is easy to see[10] that since a (γ,n) or (d,t) reaction may result in an excited final nucleus, such a reaction can only put an

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upper bound on the neutron binding energy, whereas an (n,γ) or (d,p) reaction will give a lower bound. If a (γ,n) or (d,t) reaction can be observed on a target nucleus Z_N^A, and a (d,p) or (n,γ) reaction on a target nucleus Z_{N-1}^{A-1}, and both sets of reactions give the same value for the neutron binding energy, this must then be the true binding energy of one neutron in the nucleus Z_N^A. This true value has been determined only for Pb^{207} and Pb^{208}. The neutron binding energies, nb, in millimass units (0.001 mass unit or 0.9314 Mev) adopted for connecting the four decay families are:

$$Pb^{207}: nb = 7.230 \pm 0.009$$

$$Pb^{208}: nb = 7.923 \pm 0.009$$

$$Pb^{209}: nb \geqslant 4.151 \pm 0.054$$

where it is assumed that the inequality for Pb^{209} can be replaced by the limiting equality. The neutron binding energy measured in Bi^{210} is in conflict with that for Pb^{209}; it has been assumed that the established decay values connecting Bi^{210} to Pb^{206} and Pb^{209} to Bi^{209} are correct, and that it is the binding energy for one neutron in Bi^{210} that is in error. If one uses[15] for the masses of

He^4	: 4.00387
He^2	: 2.01473
H	: 1.00814
n	: 1.00898,

one obtains the following mass differences:

$Pb^{207} - Pb^{206}$	: 1.00175
$Pb^{208} - Pb^{207}$	: 1.00106
$Pb^{209} - Pb^{208}$	: 1.00483

Additional data on neutron binding energies are also available. These constitute

15. Experimental Nuclear Physics, edited by E. Segrè, J. Wiley and Sons, Inc., New York (in press)

upper or lower limits, depending on the reaction used to measure them. They can serve either of two purposes. If it is assumed that the inequalities can be replaced by the limiting equalities, the masses of some species can be found which would otherwise, for lack of decay information, have to be omitted from the table. This is true for several species of Tl, Pb and Bi. In four more cases, the measured mass differences from binding energies can be compared with those obtained from decay data, once the lead isotopes have been adjusted relative to each other as discussed above. The results of this comparison are shown in Table I, and lead one to believe that the good agreement is probably not fortuitous,

Table I

A comparison of mass differences for certain species that are listed in the first column; the second column gives the differences D obtained from masses based on the lead masses and decay energy values as adopted in this paper; the third column shows the same differences nb calculated from measured neutron binding energies.

Isotope Differences	D, mass units	nb, mass units	(D-nb), mass units
$Th^{233} - Th^{232}$	1.00348	1.00372 ± 0.00022	-0.00024
$Th^{232} - Th^{231}$	1.00217	1.00216 ± 0.00004	0.00001
$U^{239} - U^{238}$	1.00376	1.00401 ± 0.00016	-0.00025
$U^{238} - U^{237}$	1.00262	1.00259 ± 0.00010	0.00003

but that the inequalities in the neutron binding energy values can be replaced by equalities within the errors quoted, and that the differences obtained from Table III can be assigned errors of ± 0.00020 mass units or about 200 kev.

The masses can finally be put on an absolute basis with the help of some mass spectrographic measurements by Stanford, et al.[16], on Pb^{208}, Th^{232}, U^{234} and U^{238}. To this end the mass differences of Table III were assumed correct and fixed.* A comparison between Stanford's masses and ours so adjusted is presented in Table II, and leads one to assign an error of about ± 0.0015 MU or 1.5 Mev to the absolute masses of Table III.**

Table II

A comparison of the masses of four species as measured mass spectrographically, MS, by Stanford, et al., and as adopted in this paper, D, underlined, with the mass of Pb^{208} taken as 208.04140.

Isotope	D, mass units	MS, mass units	D-MS, mass units
Pb^{208}	208.04140	208.0434 ± 0.0012	-0.0020
Th^{232}	232.11034	232.1092 ± 0.0010	+0.0011
U^{234}	234.11387	234.1133 ± 0.0011	+0.0006
U^{238}	238.12493	238.1234 ± 0.0010	+0.0015

Richards, Hays, and Goudsmit[17] have measured the masses of Pb^{208}, Bi^{209} and the difference between them in their magnetic time of flight spectrograph. Their mass values: Pb^{208}, 208.0416 ± 0.0015; Bi^{209}, 209.0466 ± 0.0015; Bi^{209} - Pb^{208}, 1.0050 ± 0.0015, agree well with those of this paper: Pb^{208}, 208.0414; Bi^{209}, 209.0455; Bi^{209} - Pb^{208}, 1.0041.

16. G. S. Stanford, H. E. Duckworth, B. G. Hogg, and J. S. Geiger, Bull. Am. Phys. Soc., 27, 1 (1952)

* The masses D of all four species were displaced *in toto* until the sum of the squares of the differences, $\Sigma(D-MS)^2$, between them and the masses MS as measured mass spectrographically, was a minimum.

** This error is almost entirely due to the uncertainty in fitting the mass spectrographic data to the disintegration data. Thus a change in the mass of Pb^{208} by 1 - 2 Mev could be expected; such a change would entail a change of the same amount of all other masses, but leave their differences unaltered.

17. P. I. Richards, E. E. Hays, and S. A. Goudsmit, Phys. Rev. 85, 630 (1952)

Table of Masses

The calculated masses are presented in Table III, the isotopic atomic mass being given relative to 16.00000 for that of O^{16}. The great majority of the masses were determined relative to others in the table by known decay properties. References for the decay of a given species are given in a column to the right of that species. As in Reference 1, only the number of references needed to make plausible the decay values adopted have been listed. The literature has been checked for new decay values and revisions of old ones, and as a result many new references (to February, 1952) have been included, and some old ones omitted.

Some nuclear species have been included for the sake of completeness, although their decay relations to the main chains could only be estimated. Such estimated masses are in parentheses. SG in the reference column indicates that their alpha decay energies were guessed from alpha systematics[2] by G. T. Seaborg and R. A. Glass. Such estimates are often reliable to 100 Kev, but the building with their help of long decay chains was avoided.

The letters SPH in the reference column designate decay data communicated privately by G. T. Seaborg, I. Perlman and J. Hollander, who are at present engaged in preparing for publication a new table of isotopes. Some of the data in question were obtained by the Chemistry Group in this Laboratory, while others were in turn communicated to the Group by workers in other laboratories. More detailed references will be found in the new table of isotopes when it is published.

Table III

Column 1 gives Z, the atomic number; Column 2, the chemical symbol; Column 3, the integer atomic weight; Column 4, the exact atomic weight; Column 5, references for the decay properties of the species in the same row.

Z	Symbol	A	Mass, in mass units	References
80	Hg	203	203.03550	L3
		205	205.03980	L3
81	Tl	203	203.03499	nb, stable
		204	204.03697	nb
		205	205.03792	nb, stable
		206	206.04021	A1
		207	207.04189	C1, S1, B2, M3
		208	208.04676	M3, N1
		209	209.05044	H1, H2
		210	210.05537	C4
82	Pb	204	204.03612	stable
		205	205.03831	nb
		206	206.03859	nb, stable
		207	207.04034	nb, stable
		208	208.04140	assumed, stable
		209	209.04623	nb, H1, M3
		210	210.04958	B7
		211	211.05450	R2, S1
		212	212.05791	SPH
		213	(213.06268)	SG
		214	214.06633	R2, C1, S2
83	Bi	207	(207.04285)	
		208	208.04451	nb
		209	209.04550	stable
		210	210.04951	M3
		211	211.05300	M3
		212	212.05728	M3
		213	213.06072	H1, SPH
		214	214.06526	C4, SPH
84	Po	208	208.04558	B5, K2
		209	209.04750	B5, K2
		210	210.04826	R2
		211	211.05234	N1
		212	212.05487	M3
		213	213.05922	H1, M3
		214	214.06185	R2
		215	215.06643	L1
		216	216.06919	B1, R2

Z	Symbol	A	Mass, in mass units	References
84	Po	217	(217.07354)	SG
		218	218.07676	B1, R2
		219	(219.08168)	SG
		220	(220.08482)	SG
85	At	211	(211.05317)	N1
		212	(212.05675)	
		213	(213.05925)	SG
		214	214.06299	M3
		215	215.06562	M3
		216	216.06967	M3
		217	217.07225	H1
		218	218.07638	K1
		219	(219.07928)	SG
		220	(220.08372)	SG
86	Em	212	212.05621	P4
		213	(213.06061)	
		214	(214.06220)	SG
		215	215.06562	M4
		216	216.06750	M3
		217	217.07155	M3
		218	218.07351	S3
		219	219.07776	L1
		220	220.07993	B1
		221	(221.08385)	SG
		222	222.08663	B1
		223	(223.09112)	SG
		224	(224.09381)	SG
87	Fr	217	(217.07221)	
		218	218.07544	M3
		219	219.07747	M3
		220	220.08086	M3
		221	221.08301	H1
		222	(222.08674)	SG
		223	223.08917	P1, P2, P3
		224	(224.09318)	SG
		225	(225.09528)	SG
		226	(226.09913)	SG
88	Ra	219	219.07824	M4
		220	220.07950	M3
		221	221.08276	M3
		222	222.08450	S3
		223	223.08788	SPH
		224	224.09001	B1
		225	225.09344	H1
		226	226.09574	L1
		227	227.09982	SPH
		228	228.10212	L2
		229	(229.10588)	SG

Z	Symbol	A	Mass, in mass units	References
88	Ra	230	(230.10826)	J2
		231	(231.11300)	SG
89	Ac	222	222.08692	M3
		223	223.08860	M1, M3
		224	224.09147	M3
		225	225.09322	H1
		226	226.09651	H3
		227	227.09845	P4
		228	228.10206	C5, SPH
		229	(229.10373)	SG
		230	(230.10719)	J2
		231	(231.11029)	SG
90	Th	223	223.09036	M4
		224	224.09116	M3
		225	225.09381	M3
		226	226.09525	S3
		227	227.09836	L1
		228	228.09981	B6
		229	229.10279	H1
		230	230.10472	R3
		231	231.10817	J1, J4, SPH
		232	232.11034	C3
		233	233.11382	B4
		234	234.11650	B3
		235	235.12037	SPH
91	Pa	226	226.09823	M3
		227	227.09953	M1, M3
		228	228.10200	M3
		229	229.10331	P4
		230	230.10599	SPH
		231	231.10783	R1
		232	232.11095	S4, SPH
		233	233.11250	SPH
		234	234.11586	SPH
		235	235.11854	M2
		236	(236.12130)	SG
		237	(237.12388)	SG
92	U	227	227.10166	M4
		228	228.10232	M3
		229	229.10469	M3
		230	230.10553	S3
		231	231.10818	SPH
		232	232.10947	S4
		233	233.11193	H1
		234	234.11379	J3
		235	235.11704	G2
		236	236.11912	G1, J3
		237	237.12231	SPH
		238	238.12493	C2
		239	239.12869	H5

Z	Symbol	A	Mass, in mass units	References
93	Np	231	231.11026	M1
		232	(232.11236)	SG
		233	233.11322	M1
		234	(234.11568)	SG
		235	235.11723	M1, J4
		236	236.12017	O2
		237	237.12158	M1, H1
		238	238.12514	F1
		239	239.12730	H5
		240	240.13002	SPH
		241	241.13250	SPH
94	Pu	232	232.11338	O1
		233	(233.11555)	SG
		234	234.11616	O1
		235	235.11844	SPH
		236	236.11962	S4
		237	(237.12192)	SG
		238	238.12366	J3
		239	239.12653	J3, H5
		240	240.12862	T2
		241	241.13154	T2
		242	242.13413	T2
		243	243.13740	T3
95	Am	236	(236.12310)	SG
		237	(237.12375)	SG
		238	(238.12602)	SG
		239	239.12740	S5
		240	(240.13023)	SG
		241	241.13151	A2
		242	242.13489	O3
		243	243.13686	S5
		244	(244.13952)	SG
		245	(245.14187)	SG
96	Cm	236	(236.12503)	SG
		237	(237.12698)	SG
		238	238.12713	S4
		239	239.12941	SPH
		240	240.13044	P4
		241	(241.13223)	SG
		242	242.13420	A2
		243	243.13694	A3
		244	244.13880	A3
		245	(245.14159)	SG
		246	(246.14402)	SG
		247	(247.14725)	SG
97	Bk	242	(242.13743)	SG
		243	243.13860	T1
		244	(244.14122)	SG

Z	Symbol	A	Mass, in mass units	References
97	Bk	245	245.14229	H4
		246	(246.14547)	SG
		247	(247.14726)	SG
		248	(248.14977)	SG
		249	(249.15197)	SG
98	Cf	242	(242.13925)	SG
		243	(243.14131)	SG
		244	244.14211	H4
		245	(245.14368)	SG
		246	246.14543	H4
		247	(247.14797)	SG
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ACKNOWLEDGMENTS

The author would like to thank Prof. E. Segrè for continued interest and many discussions. He is also very much indebted, for helpful information, to the University of California Radiation Laboratory Chemistry Group, in particular to Prof. G. T. Seaborg, Dr. Jack Hollander, and Mr. R. A. Glass.

Information Division
4/16/52 bw