Atomic Masses from Ruthenium to Xenon*

RICHARD A. DAMEROW,† RICHARD R. RIES,‡ AND WALTER H. JOHNSON, JR.
School of Physics, University of Minnesota, Minneapolis, Minnesota
(Received 14 June 1963)

A sixteen-inch double-focusing mass spectrometer employing the peak matching method of measurement has been used to measure the atomic masses of all stable isotopes in the region ruthenium to xenon. Atomic masses of 53 radioactive nuclei have been calculated from mass differences derived from nuclear reaction and β-decay energies. Nucleon binding and pairing energies have been calculated from the resulting mass table. The effect of the shell closure at $Z=50$ on the systematics of nucleon binding and pairing energies has been investigated in greater detail than has previously been possible. The discontinuity in proton binding energy is shown to be caused by a decrease in binding energy of protons beyond $Z=50$. The main result of the study of nuclear systematics in this region seems to be that the binding energies of both neutrons and protons exhibit smooth behavior except for discontinuities at a shell closure. The presence of doubly charged, diatomic tellurium satellites which interfere with the singly charged ion peaks is also noted.

INTRODUCTION

ATOMIC masses of the stable isotopes of elements from ruthenium through xenon have been measured with the Minnesota 16-inch double focusing mass spectrometer. Improvements to the instrument have been described in the previous paper.[1] The mass results have been combined with disintegration energies and reaction Q values to form a table of 108 stable and radioactive masses. With this table, a study of the nuclear binding energy systematics in the neighborhood of the $Z=50$ shell has been undertaken.

MEASUREMENTS

The procedure of measurement and the analysis of data is similar to that described in the previous paper.[1] Mass doublets have been measured of the narrow hydrocarbon-isotope type and also of the wider isotope-isotope type. In order to resolve the C^{13} satellite ion peak in the hydrocarbon-isotope doublets, a resolution of about 1/60 000 was required. Resultions of 1/60 000 to 1/200 000 were employed, so that the C^{13} satellite was resolved for all measurements.

Metal ions were obtained in most cases by heating the element or one of its compounds in a furnace described in the previous article.[1] The following compounds were employed: $(C_5H_5)_2Ru$, AgCl, $SnCl_2$, and CH_3I. Pure metals were used for rhodium, palladium, cadmium, indium, antimony, and tellurium. The ruthenium and iodine compounds had sufficient vapor pressure at room temperatures to be run as gases. Adequate vapor pressure from rhodium and palladium could not be obtained in the usual way. These materials were vaporized by heating a ribbon of tantalum to which a small sample of rhodium or palladium had been spot welded.

A series of closely spaced satellites were observed near the singly ionized tellurium ion peak. These satellites are illustrated in an oscilloscope photograph shown in Fig. 1. The resolution of the instrument for this illustration was in excess of 1/300 000. The satellite peaks were identified as doubly ionized combinations of other tellurium isotopes, see Fig. 1 for example.

RESULTS

Table I lists the measured doublets. Xenon doublets from Ref. 2 have been included for completeness. The errors listed are standard errors calculated from the statistical spread in the original data together with an estimate of resistor uncertainty. The masses are listed in the mass scale in which C^{12} is exactly 12 units, the symbol for these units being u.

Table II lists atomic masses that may be calculated from the doublets of Table I. Secondary standard masses used in these calculations are found in Table III. Some of the mass values for tin, cadmium, and ruthenium are overdetermined with data from both hydro-

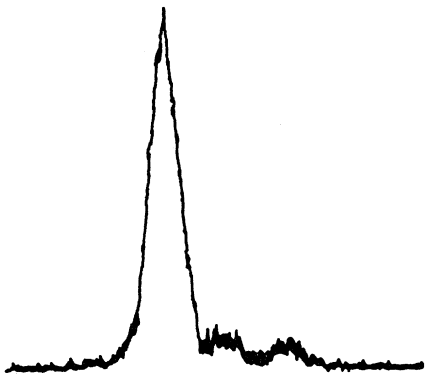

FIG. 1. Tracing the doubly charged, diatomic satellites of the Te^{125} peak. The peaks are, from right to left $(Te^{124}Te^{126})^{++}$, $(Te^{122}Te^{128})^{++}$, Te^{125}, and $(Te^{120}\ Te^{130})^{++}$. The $(Te^{120}\ Te^{130})^{++}$ peak has very low intensity and appears only as a slight broadening of the base of the peak. The Te^{125} and $(Te^{122}\ Te^{128})^{++}$ ions differ in mass by 672 μu.

* Supported in part by contract Nonr-710(18) with the Office of Naval Research.
† Present address: Sandia Corporation, Alburquerque, New Mexico.
‡ Present address: Max Planck Institut für Chemie, Mainz, Germany.
[1] R. R. Ries, R. A. Damerow, and W. H. Johnson, Jr., Phys. Rev. 132, 1662 (1963).
[2] R. A. Damerow, M. S. thesis, University of Minnesota, 1960 (unpublished).

TABLE I. Mass doublets.

Doublet[a]	Mass difference[b] (u)	Error[c]
$C_7H_{12}-Ru^{96}$	0.186 304 6	38
$C_7H_{14}-Ru^{98}$	0.204 263 5	29
$C_7H_{15}-Ru^{99}$	0.211 442 8	30
$C_7H_{16}-Ru^{100}$	0.220 983 8	37
$C_8H_5-Ru^{101}$	0.133 549 5	22
$C_8H_6-Ru^{102}$	0.142 604 8	32
$C_8H_8-Ru^{104}$	0.157 171 5	34
$Ru^{99}-Ru^{98}$	1.000 652	11
$Ru^{100}-Ru^{99}$	0.998 282	11
$Ru^{101}-Ru^{100}$	1.001 368	11
$Ru^{102}-Ru^{101}$	0.998 767	11
$C_8H_7-Ru^{103}$	0.149 263 5	33
$C_8H_6-Pd^{102}$	0.141 324 1	187
$C_8H_8-Pd^{104}$	0.158 612 3	101
$C_8H_9-Pd^{105}$	0.165 356 5	139
$C_8H_{10}-Pd^{106}$	0.174 764 0	43
$C_8H_{12}-Pd^{108}$	0.190 013 5	61
$C_8H_{14}-Pd^{110}$	0.204 388 8	93
$C_8H_{11}-Ag^{107}$	0.180 986 4	31
$C_8H_{13}-Ag^{109}$	0.196 972 1	38
$C_8H_{10}-Cd^{106}$	0.171 789 3	27
$C_8H_{12}-Cd^{108}$	0.189 715 6	29
$C_8H_{14}-Cd^{110}$	0.206 548 4	46
$C_8H_{15}-Cd^{111}$	0.213 184 4	39
$C_8H_{16}-Cd^{112}$	0.222 445 3	39
$C_9H_5-Cd^{113}$	0.134 721 1	39
$C_8H_{18}-Cd^{114}$	0.237 487 6	40
$C_9H_8-Cd^{116}$	0.157 837 4	29
$Cd^{111}-Cd^{110}$	1.001 180	11
$Cd^{112}-Cd^{111}$	0.998 581	11
$Cd^{113}-Cd^{112}$	1.001 642	11
$Cd^{114}-Cd^{113}$	0.998 960	11
$C_9H_5-In^{113}$	0.135 015 3	85
$C_9H_7-In^{115}$	0.150 909 6	79
$C_8H_{16}-Sn^{112}$	0.220 383 6	91
$C_8H_{18}-Sn^{114}$	0.238 092 3	102
$C_9H_7-Sn^{115}$	0.151 411 4	76
$C_9H_8-Sn^{116}$	0.160 860 7	84
$C_9H_9-Sn^{117}$	0.167 485 5	127
$C_9H_{10}-Sn^{118}$	0.176 644 6	71
$C_9H_{11}-Sn^{119}$	0.182 777 6	72
$C_9H_{12}-Sn^{120}$	0.191 709 0	112
$C_8H_{12}N-Sn^{122}$	0.193 541 4	80
$C_7C^{13}H_{13}N-Sn^{124}$	0.202 885 6	83
$Sn^{115}-Sn^{114}$	1.000 573	11
$Sn^{116}-Sn^{115}$	0.998 398	11
$Sn^{117}-Sn^{116}$	1.001 219	11
$Sn^{118}-Sn^{117}$	0.998 662	11
$Sn^{119}-Sn^{118}$	1.001 709	12
$Sn^{120}-Sn^{119}$	0.998 887	11
$Sn^{124}-Sn^{122}$	2.001 838	22
$C_9H_{13}-Sb^{121}$	0.197 910 5	37
$C_8H_{13}N-Sb^{123}$	0.200 580 0	33
$C_9H_{12}-Te^{120}$	0.189 879 0	89
$C_8H_{12}N-Te^{122}$	0.193 924 8	89
$C_8H_{13}N-Te^{123}$	0.200 538 0	155
$C_7C^{13}H_{13}N-Te^{124}$	0.205 336 0	127
$C_7H_6Cl^{35}-Te^{125}$	0.111 363 2	57
$C_{10}H_6-Te^{126}$	0.143 622 5	90
$C_{10}H_8-Te^{128}$	0.158 111 5	86
$C_9H_8N-Te^{130}$	0.159 445 6	101
$C_{10}H_7=I^{127}$	0.150 296 7	62
$C_{11}H_{10}-CH_3I^{127}$	0.150 305 3	34
$Xe^{128}-Xe^{126}$	1.999 226	45
$C_{10}H_8-Xe^{128}$	0.159 068 2	42
$C_{10}H_9-Xe^{129}$	0.165 643 6	36
$C_{10}H_{10}-Xe^{130}$	0.174 743 6	42
$C_{10}H_{11}-Xe^{131}$	0.180 991 6	30
$C_{10}H_{12}-Xe^{132}$	0.189 740 8	33
$C_{10}H_{14}-Xe^{134}$	0.204 155 5	32
$C_{10}H_{16}-Xe^{136}$	0.217 982 0	39
$Xe^{129}-Xe^{128}$	1.001 247	12
$Xe^{130}-Xe^{129}$	0.998 723	12
$Xe^{131}-Xe^{130}$	1.001 574	11
$Xe^{132}-Xe^{131}$	0.999 070	11

[a] Throughout this work C, H, and N refer to C^{12}, H^1, and N^{14}.
[b] All masses are measured in a scale in which the atomic mass of C^{12} is exactly equal to 12 units (symbol u). The symbols mu and μu refer to one milliunit and one microunit, respectively.
[c] Throughout this work the errors refer to the last figure of the particular result. The errors given in this table are from the original experimental data. The resulting error in an atomic mass calculation will be rounded off to the nearest μu.

carbon doublets and isotopic doublets. In these cases, a weighted least-squares fit of the data was made. The result listed in Table II is the adjusted value of the mass. Errors in these cases are those derived from the least-square adjustment.

Table II also gives, for comparison purposes, the results of previous measurements. In this region, most of the mass spectroscopic results that were used in the 1961 Mass Table[3] are from previous Minnesota work by Halsted[4] on a smaller instrument. For this reason, no attempt will be made to make detailed comparisons with the 1961 Mass Table. The errors for Halsted's measurements are, in most cases, more than ten times larger than the present quoted errors. Thus, no significant test of the present data can be made by a comparison of these masses. One observes that there is no general tendency for Halsted's results to be higher or lower than the present results.

Comparison of the present results with the precise results of Barber *et al.*[5,6] for tin and antimony isotopes indicate that in all cases Barber's masses are higher than the present masses. The agreement would not be as good if the $Cl^{37}-Cl^{35}$ mass difference which may be obtained from the 1961 Mass Table is employed rather than the value derived from chlorine masses in Table III. The agreement with Barber's results is satisfactory.

Many of the results for ruthenium, tin, and antimony may be compared with results of Demirkhanov *et al.*[7,8] The measurements of Demirkhanov have errors that are about 10 times larger than the errors for the present results. In all cases, the masses listed by Demirkhanov

[3] L. A. König, J. H. E. Mattauch, and A. H. Wapstra, Nucl. Phys. **31**, 18 (1962).
[4] R. E. Halsted, Phys. Rev. **88**, 666 (1952).
[5] R. C. Barber, R. L. Bishop, L. A. Cambey, W. McLatchie, and H. E. Duckworth, Can. J. Phys. **40**, 1496 (1962).
[6] R. C. Barber, L. A. Cambey, J. H. Ormrod, R. L. Bishop, and H. E. Duckworth, Phys. Rev. Letters **9**, 16 (1962).
[7] R. A. Demirkhanov, V. V. Dorokhov, and M. I. Dzkuya, Zh. Eksperim. i Teor. Fiz. **40**, 1572 (1961) [translation: Soviet Phys.—JETP **13**, 1104 (1961)].
[8] R. A. Demirkhanov, T. I. Gutkin, O. A. Samadashvili, and I. K. Karpenko, Bull. Acad. Sci. USSR, Phys. Se.., **25**, 882 (1961).

TABLE II. Atomic masses computed from doublet data in Table I together with a comparison with previous mass spectroscopic values.

Isotope	Present results[a] u	error	1961 Mass Table[b] u	error	Other results[c] u	error
Ru^{96}	95.907 592	4	95.907 600	700	95.907 377	15[d]
Ru^{98}	97.905 282	4	97.905 500	800	97.904 754	60[d]
Ru^{99}	98.905 928	4	98.906 080	490	98.905 668	50[d]
Ru^{100}	99.904 210	5	99.903 020	300	99.904 186	74[d]
Ru^{101}	100.905 574	2	100.904 120	210	100.905 167	44[d]
Ru^{102}	101.904 343	3	101.903 720	200	101.904 021	72[d]
Ru^{104}	103.905 426	4	103.905 530	400	103.905 084	23[d]
Rh^{103}	102.905 509	4	102.904 800	200	102.905 49	10[e]
Pd^{102}	101.905 624	19	101.904 940	190	101.904 87	8[f]
Pd^{104}	103.903 985	10	103.903 560	200	103.903 29	10[f]
Pd^{105}	104.905 066	14	104.904 640	270	104.904 83	14[f]
Pd^{106}	105.903 483	5	105.903 200	120	105.902 92	18[f]
Pd^{108}	107.903 883	6	107.903 920	120	107.903 48	10[f]
Pd^{110}	109.905 157	10	109.904 500	320	109.904 49	12[f]
Ag^{107}	106.905 085	4	106.904 970	110	106.905 00	10[g]
Ag^{109}	108.904 749	4	108.904 700	110	108.904 64	10[g]
Cd^{106}	105.906 458	3	105.905 950	370	105.905 94	14[f]
Cd^{108}	107.904 181	4	107.904 000	120	107.904 08	10[f]
Cd^{110}	109.902 998	5	109.902 970	110	109.903 41	12[f]
Cd^{111}	110.904 184	4	110.904 150	190	110.904 29	8[f]
Cd^{112}	111.902 752	5	111.902 840	110	111.903 06	10[f]
Cd^{113}	112.904 401	4	112.904 610	100	112.904 48	9[f]
Cd^{114}	113.903 357	5	113.903 570	100	113.903 56	13[f]
Cd^{116}	115.904 760	3	115.905 010	320	115.905 00	12[f]
In^{113}	112.904 108	9	112.904 280	100	112.904 32	10[f]
In^{115}	114.903 863	8	114.904 070	100	114.903 62	10[f]
Sn^{112}	111.904 812	10	111.904 940	110		
Sn^{114}	113.902 763	9	113.902 960	100		
Sn^{115}	114.903 349	6	114.903 530	110	114.903 36	25[f]
Sn^{116}	115.901 737	6	115.902 110	190	115.902 20	16[f]
					115.901 747	7[h]
					115.901 679	50[i]
Sn^{117}	116.902 944	8	116.903 060	190	116.903 11	9[f]
					116.902 963	6[h]
					116.902 940	40[i]
Sn^{118}	117.901 601	6	117.901 790	190	117.902 08	22[f]
					117.901 611	6[h]
					117.901 448	45[i]
Sn^{119}	118.903 298	6	118.903 390	200	118.903 16	11[f]
					118.903 320	5[h]
					118.903 150	40[i]
Sn^{120}	119.902 186	9	119.902 130	140	119.902 19	7[f]
					119.902 207	5[h]
					119.902 077	45[i]
Sn^{122}	121.903 428	8	121.903 410	140	121.903 47	14[f]
					121.903 453	6[h]
					121.903 180	40[i]
Sn^{124}	123.905 264	9	123.905 240	130	123.905 24	10[f]
					123.905 287	7[h]
					123.905 025	70[i]
Sb^{121}	120.903 811	4	120.903 750	140	120.903 822	4[h]
					120.903 652	40[i]
Sb^{123}	122.904 214	4	122.904 150	140	122.904 215	5[h]
					122.903 938	50[i]
Te^{120}	119.904 017	9	119.904 510	400	119.904 51	15[f]
Te^{122}	121.903 045	9	121.903 000	130	121.902 91	8[f]
Te^{123}	122.904 256	16	122.904 180	130	122.904 34	40[f]
Te^{124}	123.902 814	13	123.902 760	130	123.903 12	10[f]
Te^{125}	124.904 438	6	124.904 420	130	124.904 62	32[f]
Te^{126}	125.903 326	9	125.903 242	37	125.903 87	6[f]
Te^{128}	127.904 486	9	127.904 710	140	127.905 56	12[f]
Te^{130}	129.906 225	10	129.906 700	140	129.906 96	8[f]
I^{127}	126.904 471	5	126.904 352	23	126.904 66	12[f]
Xe^{126}	125.904 303	45	125.904 169	32	125.904 45	14[f]
Xe^{128}	127.903 529	4	127.903 538	10	127.903 52	7[f]
Xe^{129}	128.904 779	4	128.904 784	10	128.904 78	12[f]
Xe^{130}	129.903 503	5	129.903 510	9	129.903 51	3[j]
Xe^{131}	130.905 080	4	130.905 087	7	130.905 08	4[j]
Xe^{132}	131.904 156	4	131.904 162	8	131.904 17	5[j]
Xe^{134}	133.905 390	4	133.905 398	8	133.905 41	5[j]
Xe^{136}	135.907 213	5	135.907 221	10	135.907 210	25[j]

[a] Computed by combining the doublet data in Table I with the appropriate auxiliary masses given in Table III. The overdetermined masses of Sn, Cd, and Ru are obtained by a least-squares adjustment of the data. The mass of I^{127} is a weighted average of the two determinations.
[b] Ref. 3.
[c] The original doublet values of these authors have, where necessary, been converted to the C^{12} scale and then combined with the appropriate masses from Table III.
[d] Ref. 7.
[e] Obtained from the $\frac{1}{2}Pb^{206}-Rh^{103}$ doublet value of B. G. Hogg and H. E. Duckworth [Can. J. Phys. 30, 637 (1952)] combined with the Pb^{206} value (converted to C^{12}) from J. L. Benson, R. A. Damerow, and R. R. Ries [Phys. Rev. 113, 1105 (1959)].
[f] Ref. 4.
[g] W. H. Johnson, Jr. (private communication).
[h] Refs. 5 and 6.
[i] Ref. 8.
[j] W. H. Johnson, Jr., and A. O. Nier, Phys. Rev. 105, 1014 (1957).

TABLE III. Standard masses.

Isotope	Mass u	error
C^{13}	13.003 355 4	10[a]
Cl^{35}	34.968 853 1	19[b]
Cl^{37}	36.965 903 4	12[b]
H^1	1.007 824 7	2[c]
H^2	2.014 102 2	1[d]
n	1.008 665 4	4[d]
N^{14}	14.003 073 1	4[a]
O^{16}	15.994 914 2	5[c]

[a] T. T. Scolman, K. S. Quisenberry, and A. O. Nier, Phys. Rev. 102, 1076 (1956).
[b] C. F. Giese and J. L. Benson, Phys. Rev. 110, 712 (1958).
[c] K. S. Quisenberry, C. F. Giese, and J. L. Benson, Phys. Rev. 107, 1664 (1957).
[d] Ref. 3.

are smaller than the present results. The source of the large discrepancies in several of these comparisons is unknown.

Table IV lists the unstable masses which may be calculated using the present data combined with nuclear reaction Q values and β-decay energies. (Only results

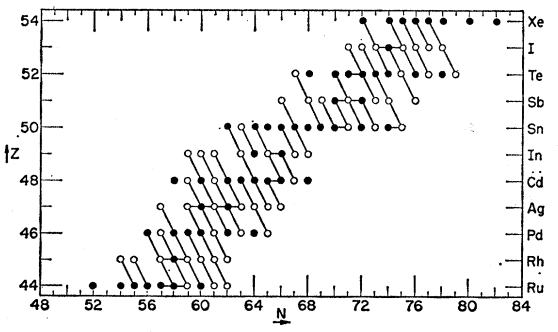

FIG. 2. Nuclear reaction and β-decay paths that were employed to calculate atomic masses of the radioactive isotopes. Solid circles represent stable nuclei, open circles represent radioactive nuclei, and connecting lines indicate nuclear reaction and β-decay mass differences.

TABLE IV. Atomic masses of radioactive nuclei.[a]

Isotope	Reaction	Q value keV	error	Ref.[b]	Mass u	error[c]
Ru^{103}	$(\beta^-)Rh^{103}$	750	20	61-3-65	102.906 314	22
	$Ru^{102}(d,p)$	4110	60	61-3-66	102.906 208	65
					102.906 261[d]	27
Ru^{105}	$(\beta^-)Rh^{105}$	1871	10	61-4-20	104.907 682	18
Ru^{106}	$(\beta^-)Rh^{106}$	39	1	60-4-47	105.907 325	12
Rh^{99}	$(\beta^+)Ru^{99}$	2100	20	61-1-60	98.908 182	22
Rh^{100}	$(\beta^+)Ru^{100}$	3640	20	61-1-69	99.908 118	22
Rh^{102}	$(\beta^+)Ru^{102}$	2300	12	61-2-42	101.906 812	13
	$(\beta^-)Pd^{102}$	1150	6	61-2-42	101.906 859	20
	$Rh^{103}(\gamma,n)$	−9307	32	61-3-67	101.906 836	34
					101.906 836[d]	13
Rh^{104}	$Rh^{103}(d,p)$	4786	20	61-4-5,9	103.906 648	22
	$(\beta^-)Pd^{104}$	2440	30	61-4-8	103.906 604	34
	$Ru^{104}(p,n)$	−2340	30	61-4-9	103.907 097[e]	32
					103.906 626[d]	22
Rh^{105}	$(\beta^-)Pd^{105}$	565	3	61-4-22	104.905 673	14
Rh^{106}	$(\beta^-)Pd^{106}$	3540	10	60-4-48	105.907 283	12
Rh^{107}	$(\beta^-)Pd^{107}$	1500	50	58-5-44	106.906 733	54
Pd^{103}	$(\epsilon)Rh^{103}$	560	30	61-3-68	102.906 110	32
Pd^{107}	$(\beta^-)Ag^{107}$	35	1	60-5-140	106.905 123	4
Pd^{109}	$(\beta^-)Ag^{109}$	1116	2	[f]	108.905 947	5
Pd^{111}	$(\beta^-)Ag^{111}$	2190	50	60-2-81	110.907 662	55
Ag^{104}	$(\beta^+)Pd^{104}$	4270	10	61-4-3	103.908 569	15
Ag^{106}	$(\beta^+)Pd^{106}$	2980	10	60-4-52	105.906 682	12
	$Ag^{107}(\gamma,n)$	−9578	70	60-5-142[g]	105.906 703	75
					105.906 692[d]	12
Ag^{108}	$Ag^{107}(n,\gamma)$	7270	20	58-3-53	107.905 945	22
	$(\beta^-)Cd^{108}$	1650	40	5-1-9	107.905 952	43
	$(\beta^+)Pd^{108}$	1902	25	[h]	107.905 925	28
	$Ag^{109}(\gamma,n)$	−9196	26	60-2-55	107.905 956	28
	$Ag^{107}(d,p)$	4974	10	5-1-11	107.906 022[e]	11
					107.905 944[d]	22
Ag^{110}	$(\beta^-)Cd^{110}$	2869	8	60-2-65	109.906 078	10
	$Ag^{109}(d,p)$	4585	5	60-2-69	109.906 104	7
					109.906 091[d]	7
Ag^{111}	$(\beta^-)Cd^{111}$	1050	10	60-2-82	110.905 311	11
Ag^{112}	$(\beta^-)Cd^{112}$	4040	30	60-2-93	111.907 089	33
Ag^{113}	$(\beta^-)Cd^{113}$	2000	40	60-2-102	112.906 548	43
Cd^{107}	$(\beta^+)Ag^{107}$	1417	4	[i]	106.906 606	6
Cd^{109}	$(\epsilon)Ag^{109}$	158	4	60-2-56	108.904 919	6
Cd^{115}	$(\beta^-)In^{115}$	1450	10	60-3-108	114.905 420	13
In^{108}	$(\beta^+)Cd^{108}$	5110	50	5-1-13	107.909 667	54
In^{109}	$(\beta^+)Cd^{109}$	2020	10	60-2-57	108.907 088	12
In^{110}	$(\beta^+)Cd^{110}$	3960	40	60-2-75	109.907 249	43
In^{112}	$(\beta^-)Sn^{112}$	656	6	60-2-95	111.905 516	12
In^{112}	$(\beta^+)Cd^{112}$	2582	20	[j]	111.905 524	22
					111.905 520[d]	12
In^{114}	$(\beta^+)Cd^{114}$	1419	24	60-3-96	113.904 880	26
	$(\beta^-)Sn^{114}$	1984	4	60-3-96	113.904 893	10
	$In^{115}(\gamma,n)$	−9024	29	60-3-111	113.904 886	32
					113.904 886[d]	10
In^{116}	$(\beta^-)Sn^{116}$	3290	60	60-3-121	115.905 269	65
In^{117}	$(\beta^-)Sn^{117}$	1470	10	60-3-135	116.904 522	13
Sn^{113}	$(\epsilon)In^{113}$	684	4	60-2-106	112.904 842	10
Sn^{121}	$Sn^{120}(d,p)$	3920	70	60-4-78	120.904 256	76
	$(\beta^-)Sb^{121}$	383	5	60-4-78	120.904 222	7
					120.904 239[d]	9
Sn^{123}	$(\beta^-)Sb^{123}$	1420	10	60-6-66	122.905 738	11
Sn^{125}	$(\beta^-)Sb^{125}$	2340	10	60-6-93	124.907 763	14
	$Sn^{124}(d,p)$	3520	70	60-9-95	124.907 762	76
					124.907 762[d]	14
Sb^{117}	$(\beta^+)Sn^{117}$	1820	30	60-3-137	116.904 898	33
Sb^{119}	$(\epsilon)Sn^{119}$	579	20	60-4-62	118.903 920	22
Sb^{120}	$(\beta^+)Sn^{120}$	2720	20	60-4-70	119.905 106	23
Sb^{122}	$(\beta^-)Te^{122}$	1971	4	60-4-88	121.905 161	10
	$(\beta^+)Sn^{122}$	1590	30	60-4-88	121.905 135	33
	$Sb^{123}(\gamma,n)$	−8980	50	60-6-68	121.905 190	54
	$Sb^{121}(n,\gamma)$	6780	20	60-4-90	121.905 197	22
					121.905 171[d]	18
Sb^{124}	$(\beta^-)Te^{124}$	2916	3	60-6-79	123.905 945	13
Sb^{125}	$(\beta^-)Te^{125}$	757	6	60-6-96	124.905 251	9
Sb^{127}	$(\beta^-)Te^{127}$	1570	3	61-1-75	126.906 896	10
Te^{119}	$(\beta^+)Sb^{119}$	2294	2	60-4-63	118.906 383	22
Te^{127}	$(\beta^-)I^{127}$	689	7	61-1-76	126.905 211	9
Te^{129}	$(\beta^-)I^{129}$	1480	5	61-1-99	128.906 571	9
Te^{131}	$(\beta^-)I^{131}$	2280	20	61-2-53	130.908 570	22
I^{124}	$(\beta^+)Te^{124}$	3170	30	60-6-85	123.906 217	35
I^{125}	$(\epsilon)Te^{125}$	150	30	60-6-99	124.904 599	33
I^{126}	$(\beta^+)Te^{126}$	2151	5	60-6-109	125.905 635	10
	$(\beta^-)Xe^{126}$	1251	5	60-6-109	125.905 646	45
	$I^{127}(\gamma,n)$	−9135	22	61-1-77	125.905 613	24
					125.905 631[d]	10
I^{128}	$(\beta^-)Xe^{128}$	2120	10	61-1-88	127.905 805	11
	$(\beta^+)Te^{128}$	1267	12	[k]	127.905 846	16
	$I^{127}(n,\gamma)$	6785	22	61-1-90[l]	127.905 852	24
	$I^{127}(d,p)$	4350	50	61-1-90	127.906 078[e]	54
					127.905 834[d]	15
I^{129}	$(\beta^-)Xe^{129}$	189	5	61-1-101	128.904 982	7
I^{130}	$(\beta^-)Xe^{130}$	2950	20	61-3-73	129.906 670	22
I^{131}	$(\beta^-)Xe^{131}$	970.4	0.6	61-2-56	130.906 122	4

[a] The conversion factor 931.476±0.004 MeV/u [E. R. Cohen, Bull. Am. Phys. Soc. **7**, 305 (1962)] has been used in these calculations.
[b] References have usually been given to the year, the set, and the page numbers of the *Nuclear Data Sheets*; for example, 60-2-56. Recent editions of these sheets specify the volume number rather than the year; for example, 5-1-13.
[c] The error assigned to the average is the larger of the following quantities: (1) The error of the most precise value, and (2) A number chosen so that twice its value covers all measurements.
[d] Unweighted average.
[e] Not included in the average.
[f] H. W. Brandhorst, Jr., and J. W. Cobble, Phys. Rev. **125**, 1323 (1962).
[g] This is a particular value rather than the average given in the sheets.
[h] L. Frevert, Z. Physik **169**, 456 (1962).
[i] N. L. Lark, P. F. A. Goudsmit, J. F. W. Jansen, J. E. J. Oberski, and A. H. Wapstra, Nucl. Phys. **35**, 582 (1962).
[j] J. Ruan and Y. Yoshizawa, Nucl. Phys. **36**, 431 (Z962).
[k] H. Langhoff, P. Kilian, and A. Flammersfeld, Z. Physik **165**, 393 (1961).
[l] An unassigned gamma ray (0.075 MeV) has been added to the value given in the *Nuclear Data Sheets*.

with errors smaller than 75 keV are used.) The nuclear reaction and β-decay paths that were employed to calculate atomic masses of the radioactive isotopes are pictured in Fig. 2. A check on the present data may be obtained from the thirteen overdetermined Q value masses. It should be pointed out, however, that such studies cannot detect with any certainty small systematic errors ($5-10\,\mu$u). In general, the different determinations of the same mass agree quite well, and this agreement is taken to be a confirmation of the accuracy of the present data. In three cases, one of the individual masses disagreed markedly with the remainder and was eliminated from the average. Only in the case of the rejected Q values will a specific comment be made.

The reaction $Ru^{104}(p,n)Rh^{104}$ has been rejected because the Rh^{104} mass value derived from it is approximately 470 μu higher than the other values. It should be mentioned, however, that the Ru^{104} value of Demirkhanov *et al.*[7] would reduce this disagreement by a factor of three. The $Ag^{107}(d,p)Ag^{108}$ Q value appears to be wrong in view of the excellent agreement of the four other determinations. Similarly, the agreement of three of the four determinations of I^{128} is considered grounds for rejecting the $I^{127}(d,p)I^{128}$ Q value.

TABLE V. Total nuclear binding energy, TNBE; and the average binding energy per nucleon, TNBE/A.

Isotope	TNBE[a] mu	TNBE/A mu	error
$_{44}Ru_{52}^{96}$	887.181	9.2415	3
Ru_{54}^{98}	906.821	9.2533	3
Ru_{55}^{99}	914.841	9.2408	3
Ru_{56}^{100}	925.224	9.2522	3
Ru_{57}^{101}	932.526	9.2329	3
Ru_{58}^{102}	942.422	9.2394	3
Ru_{59}^{103}	949.169	9.2152	4
Ru_{60}^{104}	958.670	9.2180	3
Ru_{61}^{105}	965.079	9.1912	3
Ru_{62}^{106}	974.102	9.1896	3
$_{45}Rh_{54}^{99}$	91.739	9.2095	3
Rh_{55}^{100}	920.468	9.2047	3
Rh_{57}^{102}	939.081	9.2067	3
Rh_{58}^{103}	949.074	9.2143	3
Rh_{59}^{104}	956.622	9.1983	3
Rh_{60}^{105}	966.240	9.2023	3
Rh_{61}^{106}	973.296	9.1820	3
Rh_{62}^{107}	982.511	9.1823	6
$_{46}Pd_{56}^{102}$	939.447	9.2103	3
Pd_{57}^{103}	947.626	9.2003	4
Pd_{58}^{104}	958.416	9.2155	3
Pd_{59}^{105}	966.001	9.2000	3
Pd_{60}^{106}	976.249	9.2099	3
Pd_{61}^{107}	983.275	9.1895	3
Pd_{62}^{108}	993.180	9.1961	3
Pd_{63}^{109}	999.781	9.1723	3
Pd_{64}^{110}	1009.237	9.1749	3
Pd_{65}^{111}	1015.397	9.1477	6
$_{47}Ag_{57}^{104}$	952.985	9.1633	3
Ag_{59}^{106}	972.192	9.1716	3
Ag_{60}^{107}	982.465	9.1819	3
Ag_{61}^{108}	990.271	9.1692	3
Ag_{62}^{109}	1000.132	9.1755	3
Ag_{63}^{110}	1007.455	9.1587	3
Ag_{64}^{111}	1016.900	9.1613	3
Ag_{65}^{112}	1023.788	9.1410	4
Ag_{66}^{113}	1032.994	9.1415	5
$_{48}Cd_{58}^{106}$	971.580	9.1658	3
Cd_{59}^{107}	980.097	9.1598	3
Cd_{60}^{108}	991.188	9.1777	3
Cd_{61}^{109}	999.115	9.1662	3
Cd_{62}^{110}	1009.701	9.1791	3
Cd_{63}^{111}	1017.181	9.1638	3
Cd_{64}^{112}	1027.278	9.1721	3
Cd_{65}^{113}	1034.295	9.1531	3
Cd_{66}^{114}	1044.004	9.1579	3
Cd_{67}^{115}	1050.606	9.1357	3
Cd_{68}^{116}	1059.932	9.1373	3
$_{49}In_{59}^{108}$	984.854	9.1190	6
In_{60}^{109}	996.098	9.1385	3
In_{61}^{110}	1004.603	9.1328	5
In_{63}^{112}	1023.662	9.1398	3
In_{64}^{113}	1033.740	9.1481	3
In_{65}^{114}	1041.627	9.1371	3
In_{66}^{115}	1051.316	9.1419	3
In_{67}^{116}	1058.575	9.1256	6
In_{68}^{117}	1067.988	9.1281	3
$_{50}Sn_{62}^{112}$	1023.522	9.1386	3
Sn_{63}^{113}	1032.157	9.1341	3
Sn_{64}^{114}	1042.902	9.1483	3
Sn_{65}^{115}	1050.981	9.1390	3
Sn_{66}^{116}	1061.258	9.1488	3
Sn_{67}^{117}	1068.717	9.1343	3
Sn_{68}^{118}	1078.725	9.1417	3
Sn_{69}^{119}	1085.694	9.1235	3
Sn_{70}^{120}	1095.471	9.1289	3
Sn_{71}^{121}	1102.083	9.1081	3
Sn_{72}^{122}	1111.560	9.1111	3
Sn_{73}^{123}	1117.915	9.0887	3
Sn_{74}^{124}	1127.055	9.0892	3
Sn_{75}^{125}	1133.222	9.0658	3
$_{51}Sb_{66}^{117}$	1065.915	9.1104	4
Sb_{68}^{119}	1084.224	9.1111	3
Sb_{69}^{120}	1091.703	9.0975	3
Sb_{70}^{121}	1101.664	9.1047	3
Sb_{71}^{122}	1108.969	9.0899	3
Sb_{72}^{123}	1118.592	9.0942	3
Sb_{73}^{124}	1125.526	9.0768	3
Sb_{74}^{125}	1134.885	9.0791	3
Sb_{76}^{127}	1150.571	9.0596	3
$_{52}Te_{67}^{119}$	1080.913	9.0833	3
Te_{68}^{120}	1091.945	9.0995	3
Te_{70}^{122}	1110.247	9.1004	3
Te_{71}^{123}	1117.702	9.0870	3
Te_{72}^{124}	1127.809	9.0952	3
Te_{73}^{125}	1134.851	9.0788	3
Te_{74}^{126}	1144.628	9.0843	3
Te_{75}^{127}	1151.408	9.0662	3
Te_{76}^{128}	1160.799	9.0687	3
Te_{77}^{129}	1167.379	9.0494	3
Te_{78}^{130}	1176.391	9.0492	3
Te_{79}^{131}	1182.711	9.0283	3
$_{53}I_{71}^{124}$	1123.558	9.0610	4
I_{72}^{125}	1133.841	9.0707	4
I_{73}^{126}	1141.474	9.0593	3
I_{74}^{127}	1151.300	9.0654	3
I_{75}^{128}	1158.602	9.0516	3
I_{76}^{129}	1168.120	9.0552	3
I_{77}^{130}	1175.097	9.0392	3
I_{78}^{131}	1184.310	9.0405	3
$_{54}Xe_{72}^{126}$	1141.954	9.0631	5
Xe_{74}^{128}	1160.058	9.0630	3
Xe_{75}^{129}	1167.474	9.0502	3
Xe_{76}^{130}	1177.415	9.0570	3
Xe_{77}^{131}	1184.504	9.0420	3
Xe_{78}^{132}	1194.093	9.0462	3
Xe_{80}^{134}	1210.190	9.0313	3
Xe_{82}^{136}	1225.698	9.0125	3

[a] No errors for total binding energy are specified. For most purposes, the difference in two TNBE values is employed. For these cases, the errors in TNBE may be considered to be equal to the errors given for the corresponding atomic mass. In other words, one may assume the errors associated with the neutron mass and the hydrogen mass to be negligible.

Three nuclear reactions linking stable isotopes are also shown in Fig. 2. The reaction linking Ru^{101} and Ru^{102} (Ref. 9) yields a mass difference which is 831±64 μu greater than the present value. The value of this difference obtained from Ref. 7 is in substantial agreement with the present result and would seem to indicate that the Q value does not represent a ground-state transition. The $Cd^{113}(n,\gamma)Cd^{114}$ reaction[10] yields a mass difference of 0.998, 954±9 u which agrees very well with the present value of 0.998, 956±6 u. The $Te^{123}(n,\gamma)Te^{124}$ reaction[11] gives a mass difference of 0.998, 573±22 u which compares well with the value 0.998, 558±21 u calculated from the present data.

[9] P. Mason, F. C. Flack, and G. Parry, Proc. Phys. Soc. (London) **73**, 138 (1959).

[10] B. B. Kinsey and G. A. Bartholomew, Can. J. Phys. **31**, 1051 (1953).

[11] K. Way, G. Anderson, F. Everling, G. H. Fuller, N. B. Gove, R. Levesque, J. B. Marion, C. L. McGinnis, R. Nakasima, and M. Yamada, in *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C., 1960), set 6, p. 84.

TABLE VI. Neutron separation and pairing energies.

Isotope	S_n mu	error	S_{2n} mu	error	P_n mu	error
$_{44}Ru_{54}^{98}$			19.640	3		
Ru_{55}^{99}	8.020	2				
Ru_{56}^{100}	10.383	3	18.403	3	2.363	4
Ru_{57}^{101}	7.302	3				
Ru_{58}^{102}	9.896	3	17.198	3	2.594	4
Ru_{59}^{103}	6.747	27				
Ru_{60}^{104}	9.501	27	16.248	4	2.754	54
Ru_{61}^{105}	6.409	18				
Ru_{62}^{106}	9.023	21	15.432	12	2.614	37
$_{45}Rh_{55}^{100}$	8.729	31				
Rh_{58}^{103}	9.993	13				
Rh_{59}^{104}	7.548	22				
Rh_{60}^{105}	9.618	26	17.166	14	2.070	46
Rh_{61}^{106}	7.056	18				
Rh_{62}^{107}	9.215	55	16.271	56	2.159	60
$_{46}Pd_{57}^{103}$	8.179	37				
Pd_{58}^{104}	10.790	34	18.969	21	2.611	68
Pd_{59}^{105}	7.585	17				
Pd_{60}^{106}	10.248	14	17.833	11	2.663	29
Pd_{61}^{107}	7.026	4				
Pd_{62}^{108}	9.905	6	16.931	7	2.879	8
Pd_{63}^{109}	6.601	7				
Pd_{64}^{110}	9.456	10	16.057	11	2.855	13
Pd_{65}^{111}	6.160	56				
$_{47}Ag_{60}^{107}$	10.273	12				
Ag_{61}^{108}	7.806	22				
Ag_{62}^{109}	9.861	22	17.667	3	2.055	44
Ag_{63}^{110}	7.323	8				
Ag_{64}^{111}	9.445	13	16.768	11	2.122	18
Ag_{65}^{112}	6.888	34				
Ag_{66}^{113}	9.206	54	16.094	45	2.318	78
$_{48}Cd_{59}^{107}$	8.517	5				
Cd_{60}^{108}	11.091	5	19.608	2	2.574	10
Cd_{61}^{109}	7.927	5				
Cd_{62}^{110}	10.586	6	18.513	4	2.659	11
Cd_{63}^{111}	7.480	5				
Cd_{64}^{112}	10.097	4	17.577	5	2.617	7
Cd_{65}^{113}	7.017	4				
Cd_{66}^{114}	9.709	4	16.726	4	2.692	8
Cd_{67}^{115}	6.602	13				
Cd_{68}^{116}	9.326	13	15.928	3	2.724	26
$_{49}In_{60}^{109}$	11.244	55				
In_{61}^{110}	8.505	45				
In_{64}^{113}	10.078	15				
In_{65}^{114}	7.887	13				
In_{66}^{115}	9.689	13	17.576	11	1.802	23
In_{67}^{116}	7.259	65				
In_{68}^{117}	9.413	67	16.672	18	2.154	130
$_{50}Sn_{63}^{113}$	8.635	13				
Sn_{64}^{114}	10.745	13	19.380	13	2.110	23
Sn_{65}^{115}	8.079	13				
Sn_{66}^{116}	10.277	11	18.356	13	2.198	19
Sn_{67}^{117}	7.459	15				
Sn_{68}^{118}	10.008	15	17.467	11	2.549	27
Sn_{69}^{119}	6.969	10				
Sn_{70}^{120}	9.777	13	16.746	13	2.808	19
Sn_{71}^{121}	6.612	14				
Sn_{72}^{122}	9.477	12	16.089	13	2.865	22
Sn_{73}^{123}	6.355	13				
Sn_{74}^{124}	9.140	13	15.495	11	2.785	24
Sn_{75}^{125}	6.167	16				
$_{51}Sb_{68}^{119}$			18.309	41		
Sb_{69}^{120}	7.479	33				
Sb_{70}^{121}	9.961	24	17.440	23	2.482	53
Sb_{71}^{122}	7.305	18				
Sb_{72}^{123}	9.623	18	16.928	3	2.318	36
Sb_{73}^{124}	6.934	11				
Sb_{74}^{125}	9.359	14	16.293	8	2.425	27
Sb_{76}^{127}			15.686	12		
$_{52}Te_{68}^{120}$	11.032	24				
Te_{70}^{122}			18.302	12		
Te_{71}^{123}	7.455	18				
Te_{72}^{124}	10.107	20	17.562	15	2.652	34
Te_{73}^{125}	7.042	13				
Te_{74}^{126}	9.777	10	16.819	15	2.735	18
Te_{75}^{127}	6.780	12				
Te_{76}^{128}	9.391	12	16.171	12	2.611	21
Te_{77}^{129}	6.580	11				
Te_{78}^{130}	9.012	13	15.592	13	2.432	20
Te_{79}^{131}	6.320	24				
$_{53}I_{72}^{125}$	10.283	48				
I_{73}^{126}	7.633	34				
I_{74}^{127}	9.826	11	17.459	33	2.193	39
I_{75}^{128}	7.302	16				
I_{76}^{129}	9.518	16	16.820	7	2.216	31
I_{77}^{130}	6.977	23				
I_{78}^{131}	9.213	22	16.190	6	2.236	44
$_{54}Xe_{74}^{128}$			18.104	45		
Xe_{75}^{129}	7.416	4				
Xe_{76}^{130}	9.941	4	17.357	5	2.525	7
Xe_{77}^{131}	7.089	4				
Xe_{78}^{132}	9.589	2	16.678	4	2.500	5
Xe_{80}^{134}			16.097	2		
Xe_{82}^{136}			15.508	3		

NUCLEAR SYSTEMATICS

The total nuclear binding energy (TNBE) and the average binding energy per nucleon (TNBE/A) for 108 stable and radioactive nuclei in this region are given in Table V. The total nuclear binding energy is defined as follows:

$$\text{TNBE}(Z,N)=ZM_{\text{H}}+NM_n-{}_ZM_N{}^A-E_b(Z,N)/c^2, \quad (1)$$

where M_n and M_{H} are the neutron mass and hydrogen atomic mass, and ${}_ZM_N{}^A$ is the mass of the atom characterized by Z protons and N neutrons. The Coulomb binding of the electrons $[E_b(Z,N)/c^2]$ has been calculated by means of an expression given in Ref. 12. The value of this correction ranged from 115 μu for ruthenium to 186 μu for xenon, with a stated accuracy of 10%. The expression for TNBE ignores the binding energy of the electron in the hydrogen atom. The

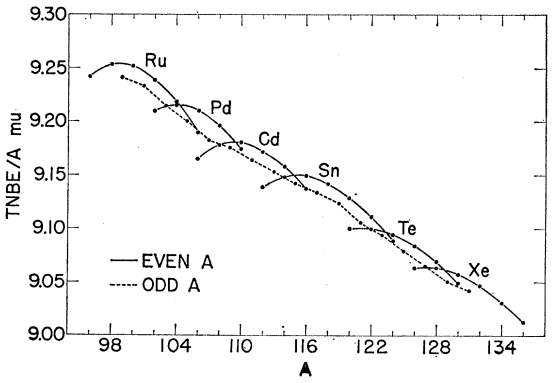

FIG. 3. Average binding energy per nucleon for stable isotopes.

[12] L. L. Foldy, Phys. Rev. 83, 397 (1951).

TABLE VII. Proton separation and pairing energies.

Isotope	S_p mu	error	S_{2p} mu	error	P_p mu	error
$_{45}Rh_{54}^{99}$	4.918	22				
Rh_{55}^{100}	5.627	22				
Rh_{57}^{102}	6.555	13				
Rh_{58}^{103}	6.652	3				
Rh_{59}^{104}	7.453	35				
Rh_{60}^{105}	7.570	14				
Rh_{61}^{106}	8.217	21				
Rh_{62}^{107}	8.409	55				
$_{46}Pd_{56}^{102}$			14.223	19		
Pd_{57}^{103}	8.545	35	15.100	32	1.990	41
Pd_{58}^{104}	9.342	10	15.994	10	2.690	11
Pd_{59}^{105}	9.379	26	16.832	30	1.926	53
Pd_{60}^{106}	10.009	15	17.579	4	2.439	28
Pd_{61}^{107}	9.979	11	18.196	18	1.762	29
Pd_{62}^{108}	10.669	54	19.078	13	2.260	110
$_{47}Ag_{57}^{104}$	5.359	35				
Ag_{59}^{106}	6.191	18				
Ag_{60}^{107}	6.216	4				
Ag_{61}^{108}	6.996	22				
Ag_{62}^{109}	6.952	6				
Ag_{63}^{110}	7.674	8				
Ag_{64}^{111}	7.663	14				
Ag_{65}^{112}	8.391	64				
$_{48}Cd_{58}^{106}$			13.164	10		
Cd_{59}^{107}	7.905	13	14.096	14	1.714	28
Cd_{60}^{108}	8.723	2	14.939	4	2.507	5
Cd_{61}^{109}	8.844	23	15.840	6	1.848	23
Cd_{62}^{110}	9.569	5	16.521	7	2.617	9
Cd_{63}^{111}	9.726	8	17.400	5	2.052	15
Cd_{64}^{112}	10.378	11	18.041	9	2.715	24
Cd_{65}^{113}	10.507	32	18.898	55	2.116	85
Cd_{66}^{114}	11.010	43				
$_{49}In_{59}^{108}$	4.757	54				
In_{60}^{109}	4.910	12				
In_{61}^{110}	5.488	43				
In_{63}^{112}	6.481	12				
In_{64}^{113}	6.462	9				
In_{65}^{114}	7.332	11				
In_{66}^{115}	7.312	8				
In_{67}^{116}	7.969	66				
In_{68}^{117}	8.056	17				
$_{50}Sn_{62}^{112}$			13.821	10		
Sn_{63}^{113}	8.495	15	14.976	10	2.014	26
Sn_{64}^{114}	9.162	13	15.624	10	2.700	19
Sn_{65}^{115}	9.354	12	16.686	8	2.022	22
Sn_{66}^{116}	9.942	11	17.254	8	2.630	17
Sn_{67}^{117}	10.142	66	18.111	18	2.173	130
Sn_{68}^{118}	10.737	18	18.793	7	2.681	134
$_{51}Sb_{66}^{117}$	4.657	35				
Sb_{68}^{119}	5.499	23				
Sb_{69}^{120}	6.009	25				
Sb_{70}^{121}	6.193	11				
Sb_{71}^{122}	6.886	20				
Sb_{72}^{123}	7.032	8				
Sb_{73}^{124}	7.611	17				
Sb_{74}^{125}	7.830	11				
$_{52}Te_{67}^{119}$			12.196	26		
Te_{68}^{120}	7.721	24	13.220	11	2.222	46
Te_{70}^{122}	8.583	9	14.776	14	2.390	15
Te_{71}^{123}	8.733	24	15.619	18	1.847	40
Te_{72}^{124}	9.217	13	16.249	15	2.185	15
Te_{73}^{125}	9.325	14	16.936	12	1.714	28
Te_{74}^{126}	9.743	12	17.573	12	1.913	20
Te_{75}^{127}			18.186	17		
Te_{76}^{128}	10.228	12				
$_{53}I_{71}^{124}$	5.856	38				
I_{72}^{125}	6.032	35				
I_{73}^{126}	6.623	11				
I_{74}^{127}	6.672	10				
I_{75}^{128}	7.194	17				
I_{76}^{129}	7.321	10				
I_{77}^{130}	7.718	23				
I_{78}^{131}	7.919	10				
$_{54}Xe_{72}^{126}$	8.113	56	14.145	47	2.081	80
Xe_{74}^{128}	8.758	6	15.430	9	2.086	13
Xe_{75}^{129}	8.872	15	16.066	9	1.678	31
Xe_{76}^{130}	9.295	7	16.616	9	1.974	15
Xe_{77}^{131}	9.407	22	17.125	8	1.689	44
Xe_{78}^{132}	9.783	2	17.702	10	1.864	10

average binding energy per nucleon, TNBE/A, for stable nuclei is plotted as a function of A in Fig. 3. The effect of the shell closure at $Z=50$ is not evident in this graph. A change in slope of the odd-A curve that is found at other magic numbers may be masked

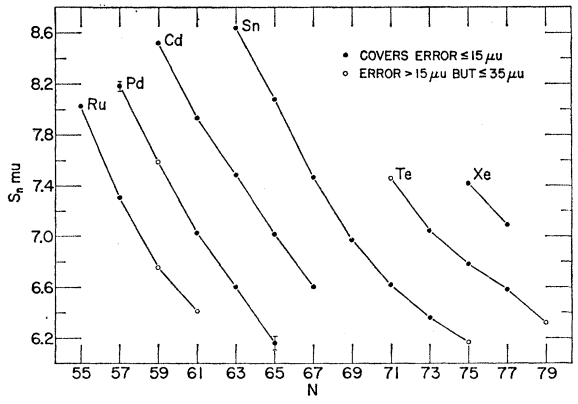

FIG. 4. Neutron separation energy.

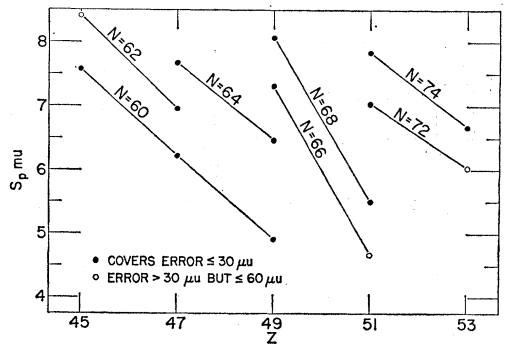

FIG. 5. Proton separation energy.

at $Z=50$ because of the nearness of the next neutron shell closure at $N=82$.

Average quantities, such as TNBE/A, are not particularly sensitive to changes in nuclear structure. For this reason, various differences of the total binding energies are studied. The neutron separation energy, $S_n(Z,N)$; the binding energy of the last two neutrons

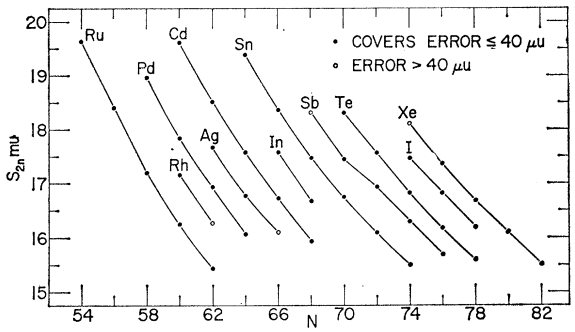

FIG. 6. Binding energy of the last two neutrons.

in a nucleus of even N, $S_{2n}(Z,N)$; and the neutron pairing energy, $P_n(Z,N)$; are given by the following expressions:

$$S_n(Z,N)=\mathrm{TNBE}(Z,N)-\mathrm{TNBE}(Z,N-1), \quad (2)$$

$$S_{2n}(Z,N)=\mathrm{TNBE}(Z,N)-\mathrm{TNBE}(Z,N-2) \quad (3)$$

$$P_n(Z,N)=S_n(Z,N)-S_n(Z,N-1) \quad N \text{ even}$$
$$=\mathrm{TNBE}(Z,N)+\mathrm{TNBE}(Z,N-2)$$
$$-2\,\mathrm{TNBE}(Z,N-1), \quad (4)$$

with similar relations for the proton binding and pairing energies. The energy differences defined above are given in Tables VI and VII.

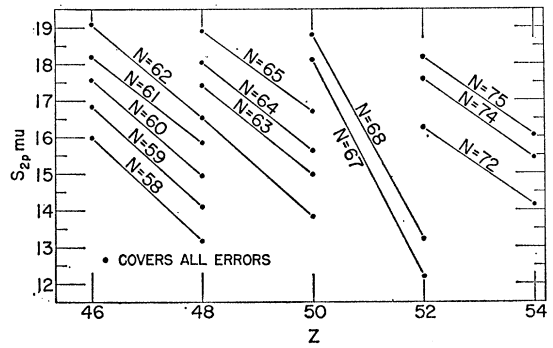

FIG. 7. Binding energy of the last two protons.

In Fig. 4, the neutron separation energy is plotted for even Z and odd N. Such nuclei consist of one odd neutron bound to a zero spin core. The most striking features of this plot are the smooth variation of S_n and the similarity of the curves for the various elements. It is also interesting to note that the proton shell closure at $Z=50$ does not seem to influence the general trend of these curves.

The proton separation energy is plotted in Fig. 5 for odd-Z, even-N nuclei. Unfortunately, there is insufficient information to yield curves as extensive as those for S_n. Nevertheless, one notices that the slopes of the curves are all similar except for the shell closure at $Z=50$. One can also see that the binding of the proton which closes the shell is not anomalously high; rather, the binding of the proton just outside the shell is depressed. The depression in the binding energy is approximately 1.4 MeV.

The binding energy of the last two neutrons is plotted in Fig. 6 for even N and all values of Z. Here again, one is struck by the great regularity of the curves. This regularity is taken to mean that no drastic change in nuclear structure occurs in this region. Here also, the shell closure at $Z=50$ does not seem to affect the neutron systematics in this region. It is interesting to note that the curves for odd Z are not equidistant from the neighboring even-Z curves but are shifted slightly

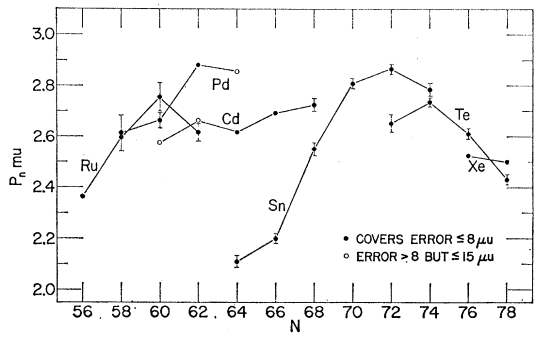

FIG. 8. Neutron pairing energy.

toward the higher-Z curve. This is presumably due to the interaction between the odd proton and the neutron pair.

The binding energy of the last two protons is plotted in Fig. 7 for even Z and all values of N. Once again, the data are too sparse to allow extensive curves to be drawn. The influence of the shell closure is quite obvious, as well as the fact that the slope of the curves seems to be essentially the same on each side of the closure.

Neutron pairing energies and proton pairing energies that may be calculated are listed in Table VI and Table VII, respectively. The P_n values are plotted in Fig. 8 as a function of N. Values for the same element are connected by straight lines. As in the previous paper, an attempt was made to correlate the magnitude

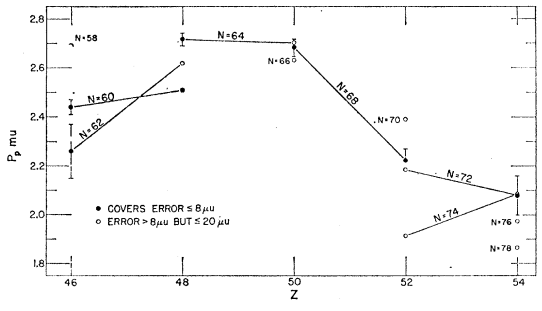

FIG. 9. Proton pairing energy.

of the pairing energy with the j value of the individual nucleons in the pair. In many cases, the common j value for the individual nucleons in the pair is the same as the j value for the preceding odd nucleon. In other cases, the pairing may take place in a higher j value level. This is possible if one follows the assumption of Mayer and Jensen[13] that the pairing energy increases as the j value of the pairing particles increases. In certain circumstances, it would thus be energetically favorable to pair in a high j-value state. Mayer and Jensen have indicated a possible ordering of shell model states in this region. From this ordering, one can determine the j value in which each pair is formed. Attempts have been made to correlate P_n values either to the j value of the odd neutron or to the j value given by the Mayer-Jensen scheme. In neither case are consistent correlations apparent.

[13] M. G. Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure* (John Wiley & Sons, Inc., New York, 1955).

Proton pairing energies are plotted in Fig. 9 as a function of Z. Values with a common neutron number are connected by a straight line. A decrease in the proton pairing energy is noted for values of Z beyond $Z=50$. This change was indicated in the neutron pairing energy at $N=50$ in the previous paper. Over-all correlation to either the j value of the pair or to the j value from the scheme of Mayer and Jensen is poor. The decrease from $Z=50$ to 52 corresponds to a j value decrease. This may indicate that the relationship between pairing energy and j value is good only near a shell closure.

ACKNOWLEDGMENTS

The authors wish to thank Professor A. O. C. Nier for his continued support and encouragement of this work. We wish to acknowledge the aid of J. L. Benson who helped to make some of the measurements. We are also indebted to R. B. Thorness for his aid in design and construction of the mass spectrometer.

PHYSICAL REVIEW VOLUME 132, NUMBER 4 15 NOVEMBER 1963

Properties of Radioactive Re^{189}†

B. CRASEMANN,* G. T. EMERY, W. R. KANE, AND M. L. PERLMAN
Brookhaven National Laboratory, Upton, New York

(Received 3 April 1963; revised manuscript received 19 July 1963)

The new isotope Re^{189} has been produced by fast-neutron irradiation of osmium and by the (α,p) reaction on tungsten. The rhenium was separated chemically from the target material. Beta-ray, gamma-ray, and internal conversion spectra have been measured. The mass assignment is confirmed by the observation of eleven electromagnetic transitions in the Os^{189} daughter, including the 30.8-keV isomeric transition (6h), all of which were known from the decay of Ir^{189}. Rhenium-189 has a half-life of 23.4 ± 1.0 h and emits beta-ray groups with end-point energies 1000, 780, and 725 keV, and probably others. Results of coincidence measurements lead to some new information about the level scheme of Os^{189}. The effects of the expected rotation-particle coupling between low-lying $K=1/2$ and $K=3/2$ bands in Os^{189} are discussed.

I. INTRODUCTION

A CONSIDERABLE number of activities have been tentatively assigned to the isotope Re^{189} in the course of the last several years, but little definite information about this nucleus and its decay has been available. We have conducted experiments leading to the production and identification of this isotope and have studied its decay to levels in Os^{189}.

Previously existing knowledge of some features of the level structure of Os^{189} has been helpful in the identification of Re^{189}. In turn, the results of this work add to the available information about the level scheme of Os^{189}. The decay of Ir^{189} to Os^{189} has been studied by Diamond and Hollander,[1] by Kane,[2] and recently, by Harmatz, Handley, and Mihelich,[3] and by Lerohl.[4] An isomer of Os^{189}, decaying by $M3$ radiation to the ground state, was characterized by Scharff-Goldhaber, Alburger, Harbottle, and McKeown[5] and further investigated by Newton.[6] At least two low-lying levels of Os^{189} have been studied in Coulomb excitation experi-

† Supported by the U. S. Atomic Energy Commission and by the National Science Foundation.

* On leave from the University of Oregon, Eugene, Oregon.

[1] R. M. Diamond and J. M. Hollander, Nucl. Phys. 8, 143 (1958).

[2] W. R. Kane, thesis, Department of Physics, Harvard University, Cambridge, Massachusetts [Technical Report 3-9,1959 (unpublished)].

[3] B. Harmatz, T. H. Handley, and J. W. Mihelich, Phys. Rev. 128, 1186 (1962); referred to as HHM.

[4] J. K. Lerohl, thesis, Ohio State University, Columbus, Ohio, 1962 (unpublished).

[5] G. Scharff-Goldhaber, D. E. Alburger, G. Harbottle, and M. McKeown, Phys. Rev. 111, 913 (1958).

[6] J. O. Newton, Phys. Rev. 117, 1529 (1960).