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Atomic Masses in the Heavy Mass Region*

V. B. Bhanot,† W. H. Johnson, Jr., and A. O. Nier
School of Physics, University of Minnesota, Minneapolis, Minnesota

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A six-inch double-focusing mass spectrometer has been employed to determine 61 mass doublets in the region of gadolinium to gold. The present results and other Minnesota mass data have been combined with nuclear reaction, β-decay, and α-decay energies in order to construct a mass table for more than 200 stable and radioactive isotopes in the region from samarium to radon. Total atomic binding energies as well as nucleon separation and pairing energies have been computed, wherever possible.

The present data confirm with greater detail the previously reported anomalies in the nucleon separation and pairing energies in the regions around 90 neutrons and 116 neutrons. The proton pairing energies are found to show rather pronounced "maxima" around $N=88$ and $N=116$, a behavior similar to the previously reported behavior of neutron pairing energies. The nature of the discontinuities in these two regions does not appear to follow the patterns found at major shell closures but seems to be caused by a change in the nuclear structure in these regions. It is known that such a change is indicated also by other nuclear properties.

Major discontinuities connected with the shell closures at $Z=82$ and $N=126$ are brought out in greater detail than has previously been possible.

The mass data have also been employed for the study of isotopic assignments for several nuclear reactions in this region.

INTRODUCTION

THIS paper presents the results of some mass measurements, made with a six-inch double-focusing mass spectrometer, in the region of gadolinium to gold. The study is an extension of the recent investigations[1,2] made with this spectrometer in the heavy mass region. A total of 63 doublets are reported here. By combining these results with the 32 doublets of Johnson and Bhanot,[2] a mass spectroscopic value may be determined for the mass of almost every stable nuclide in the region of gadolinium to gold. No previous mass spectroscopic masses are available for five of these elements, viz., terbium, thulium, lutetium, rhenium, and iridium. The only previous value for gold is an old value due to Dempster.[3] In the case of even-Z elements, no previous mass doublets were available for Gd^{152}, Dy^{256}, Dy^{158}, Er^{162}, Yb^{168}, Yb^{176}, Hf^{176}, W^{180}, and Os^{186}.

A mass table for more than 200 stable and radioactive isotopes in the region from samarium to radon is constructed from these results and other Minnesota mass data, in combination with Q values, beta-decay energies, and alpha-decay energies. Where disagreements exist between the mass spectroscopic results and the Q values and decay energies, various somewhat arbitrary adjustments have been made to minimize or eliminate the inconsistencies.

MEASUREMENTS

Virtually all mass determinations by the mass spectroscopic method employ the doublet technique. In this technique, the mass difference between an ion of unknown mass and a neighboring ion of known mass is determined. With this mass difference the mass of the unknown ion may be calculated in terms of the known mass.

Hydrocarbon molecular or fragment ions serve as convenient known masses because they exist at practically every mass number and because the masses of C^{12} and H^1 are precisely known. Use of hydrocarbon ions, however, has one serious disadvantage. When using the hydrocarbon ion $\mathrm{C}_m{}^{12}\mathrm{H}_n{}^1$, the rare (abundance $\sim 1\%$) isotope C^{13} introduces a fragment $\mathrm{C}_{m-1}{}^{12}\mathrm{C}^{13}\mathrm{H}_{n-1}{}^1$ which has almost the same mass as $\mathrm{C}_m{}^{12}\mathrm{H}_n{}^1$. In most mass spectrometers used for mass measurement the resolution is sufficient in the light mass region to resolve the $\mathrm{C}_m{}^{12}\mathrm{H}_n{}^1$ ion from the $\mathrm{C}_{m-1}{}^{12}\mathrm{C}^{13}\mathrm{H}_{n-1}{}^1$. This may not be the case, however, in the heavy mass region. It is possible to overcome this disadvantage by a correction procedure if the intensity of the C^{13} satellite is small.

The mass spectrometer used in the present measurements has been described previously.[4,5] It has the property that the mass of the ion collected is proportional to the resistance of a circuit element which determines the electric fields in the instrument. Experience has shown that the proportionality is accurate over a wide range and thus ions differing in mass by as much as several percent may be accurately compared. The ability of the mass spectrometer to measure wide doublets has been utilized previously[1,2] to determine the mass differences between isotopes of the same element differing by one mass number. These "isotopic doublets" were then employed as consistency tests for atomic masses determined with hydrocarbon doublets and also to determine neutron separation energies and pairing energies.

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† Now at Department of Physics, Panjab University, Chandigarh 3, India.

[1] W. H. Johnson, Jr., and A. O. Nier, Phys. Rev. **105**, 1014 (1957).

[2] W. H. Johnson, Jr., and V. B. Bhanot, Phys. Rev. **107**, 1669 (1957).

[3] A. J. Dempster, Phys. Rev. **53**, 64 (1938); **53**, 869 (1938).

[4] A. O. Nier, in *Mass Spectroscopy in Physics Research*, National Bureau of Standards Circular No. 522 (U. S. Government Printing Office, Washington, D. C., 1953).

[5] A. O. Nier, in *Nuclear Masses and Their Determinations* (Pergamon Press, London, 1957), p. 185.

In the present investigation, the measurement of isotopic doublets has been extended to isotopes differing by two mass numbers. By this extension, one can measure the mass differences between all of the stable isotopes of an element. The masses of all of the stable isotopes of an element may thus be determined by the measurement of the mass of any one isotope of that element by means of a hydrocarbon doublet, since the masses of the other isotopes can be calculated from the isotopic doublet differences. Fortunately, hydrocarbon ions having small C^{13} corrections were found for at least one mass number for practically every element in the region under consideration.

RESULTS

Table I lists the hydrocarbon type of doublets and the mass differences obtained. In the case of the last two doublets of Table I, Au^{197} was compared with an isotope of mercury. The error quoted for a particular doublet is the square root of the sum of the squares of the various contributing errors. These contributing errors include the errors resulting from resistance calibration uncertainties, the standard error of the mean of the runs taken and an error equal to the corresponding C^{13} satellite correction, if any. This latter effect was never a major source of error since, as mentioned earlier, the comparison ions employed in the present work were selected to have small C^{13} satellites.

TABLE I. Mass doublets in which mass of one member is known from other data.

Doublet[a]	ΔM in mmu[b, c]
$C_{11}H_{10}N-Gd^{156}$	159.14±0.12
$C^{13}C_9H_{22}O-Tb^{159}$	245.61±0.11
$C_{12}H_{16}-Gd^{160}$	198.11±0.09
$C_{12}H_{16}-Dy^{160}$	200.40±0.11
$C_{12}H_{18}-Dy^{162}$	214.44±0.09
$\frac{1}{2}Ho^{165}-C_6H_{10}$	387.10±0.10
$C_7H_7F_4-Er^{167}$	116.37±0.08
$C_6H_{12}-\frac{1}{2}Er^{168}$	127.78±0.05
$\frac{1}{2}Tm^{169}-C_6H_{12}$	373.39±0.05
$C_{12}H_{26}-Yb^{170}$	268.75±0.07
$C_4H_7O_2-\frac{1}{2}Yb^{174}$	75.09±0.04
$C_{13}H_{19}-Lu^{175}$	207.21±0.16[d]
$C_4H_8O_2-\frac{1}{2}Yb^{176}$	81.07±0.07
$C^{13}C_{12}H_{19}-Yb^{176}$	209.36±0.06
$C^{13}C_{12}H_{19}-Hf^{176}$	210.31±0.04
$C_8H_{10}F_4-W^{182}$	123.75±0.04
$C^{13}C_7H_{10}F_4-W^{183}$	125.15±0.04
$C_{12}H_{27}N-Re^{185}$	261.83±0.08
$C^{13}C_{11}H_{27}N-W^{186}$	263.49±0.13
$C^{13}C_{11}H_{27}N-Os^{186}$	264.33±0.18
$C_{14}H_{22}-Os^{190}$	213.77±0.10[d]
$C^{13}C_{13}H_{22}-Ir^{191}$	216.15±0.19[d]
$C_7H_{14}-\frac{1}{2}Pt^{196}$	127.18±0.06
$Hg^{198}-Au^{197}$	1000.27±0.08
$Hg^{199}-Au^{197}$	2002.33±0.20

[a] Throughout this paper C, H, N, O, and F refer to C^{12}, H^1, N^{14}, O^{16}, and F^{19}, respectively.
[b] Throughout this paper all masses or mass differences are calculated on the basis $O^{16}=16$ exactly.
[c] All calculations in this paper have been carried out with more significant figures than are indicated by the magnitude of the error. Results listed in many tables have been rounded off to conform with the size of the error.
[d] These doublets were not employed for the calculation of masses listed in Table VII. The nuclear data available at present indicate that these may be incorrect by 0.5 mmu to 1.0 mmu. See Appendix for details.

TABLE II. Mass differences obtained for isotopic doublets.

Doublet	Results (amu)[a]		Adopted values (amu)
	Present	Previous[b]	
$Kr^{84}-Kr^{83}$	0.997 684± 45		
$Xe^{132}-Xe^{131}$	0.999 394± 50		
$Gd^{154}-Gd^{152}$	2.001 740± 90		2.001 740± 80
$Gd^{155}-Gd^{154}$		1.002 149± 60	1.002 099± 40
$Gd^{156}-Gd^{155}$		0.999 899± 60	0.999 849± 40
$Gd^{157}-Gd^{156}$	1.002 155± 45	1.002 196± 60	1.002 155± 40
$Gd^{158}-Gd^{157}$	1.000 475± 45	1.000 535± 60	1.000 475± 40
$Gd^{158}-Gd^{156}$	2.002 630± 90[c]		
	2.002 636± 90	2.002 731±120[c]	
$Gd^{160}-Gd^{158}$	2.003 619± 90		2.003 619± 80
$Dy^{158}-Dy^{156}$	2.000 837±100		2.000 837± 80
$Dy^{160}-Dy^{158}$	2.001 503±100		2.001 503± 80
$Dy^{161}-Dy^{160}$		1.002 100± 60	1.002 050± 40
$Dy^{162}-Dy^{161}$		1.000 208± 60	1.000 158± 40
$Dy^{162}-Dy^{160}$	2.002 201±100	2.002 308±120[c]	
$Dy^{163}-Dy^{162}$		1.002 264± 60	1.002 214± 40
$Dy^{164}-Dy^{163}$		1.000 794± 60	1.000 744± 40
$Dy^{164}-Dy^{162}$	2.002 964±100	2.003 058±120[c]	
$Er^{164}-Er^{162}$	2.001 145± 94		2.001 145± 80
$Er^{166}-Er^{164}$	2.001 795± 90		2.001 795± 80
$Er^{167}-Er^{166}$		1.002 062± 60	1.002 052± 40
$Er^{168}-Er^{167}$		1.000 653± 60	1.000 643± 40
$Er^{168}-Er^{166}$	2.002 695± 94	2.002 715±120[c]	
$Er^{170}-Er^{168}$	2.003 758± 95		2.003 758± 80
$Yb^{170}-Yb^{168}$	2.001 617± 90		2.001 627± 80
$Yb^{171}-Yb^{170}$		1.001 884± 60	1.001 874± 40
$Yb^{172}-Yb^{171}$		1.000 397± 60	1.000 387± 40
$Yb^{172}-Yb^{170}$	2.002 254± 93	2.002 281±120[c]	
$Yb^{173}-Yb^{172}$		1.002 177± 60	1.002 167± 40
$Yb^{174}-Yb^{173}$		1.000 976± 60	1.000 966± 40
$Yb^{174}-Yb^{172}$	2.003 117± 90	2.003 153±120[c]	
$Yb^{176}-Yb^{174}$	2.004 332± 90		2.004 342± 80
$Lu^{176}-Lu^{175}$	1.002 256± 56		1.002 256± 60
$Hf^{176}-Hf^{174}$	2.002 123± 90		2.002 123±100
$Hf^{177}-Hf^{176}$	1.002 158± 50	1.002 252± 60	1.002 158± 50
$Hf^{178}-Hf^{177}$	1.000 810± 50	1.000 880± 60	1.000 810± 50
$Hf^{179}-Hf^{178}$	1.002 427± 50	1.002 358± 60	1.002 427± 50
$Hf^{180}-Hf^{179}$	1.001 089± 50	1.001 133± 60	1.001 089± 50
$W^{182}-W^{180}$	2.002 156± 93		2.002 136± 80
$W^{183}-W^{182}$	1.002 298± 48	1.002 237± 60	1.002 288± 40
$W^{184}-W^{183}$	1.000 984± 47	1.000 996± 60	1.000 974± 40
$W^{186}-W^{184}$	2.004 003± 90		2.003 983± 80
$Re^{187}-Re^{185}$	2.003 368± 90		2.003 368± 90
$Os^{186}-Os^{184}$	2.002 018± 90		2.002 018± 80
$Os^{187}-Os^{186}$		1.002 126± 60	1.002 136± 40
$Os^{188}-Os^{187}$		1.000 314± 60	1.000 324± 40
$Os^{188}-Os^{186}$	2.002 474±100	2.002 440±120[c]	
$Os^{189}-Os^{188}$		1.002 535± 60	1.002 545± 40
$Os^{190}-Os^{189}$		1.000 523± 60	1.000 533± 40
$Os^{190}-Os^{188}$	2.003 052±100	2.003 058±120[c]	
$Os^{192}-Os^{190}$	2.003 485±100		2.003 485± 80
$Ir^{193}-Ir^{191}$	2.003 012± 94		2.003 000±100
$Pt^{194}-Pt^{192}$	2.002 178±120		2.002 178±100
$Pt^{195}-Pt^{194}$		1.002 446± 60	1.002 446± 40
$Pt^{196}-Pt^{195}$		1.000 480± 60	1.000 480± 40
$Hg^{199}-Hg^{198}$		1.001 814± 60	1.001 824± 40
$Hg^{200}-Hg^{199}$		1.000 315± 60	1.000 325± 40
$Hg^{200}-Hg^{198}$	2.002 156± 90	2.002 129±120[c]	
$Hg^{201}-Hg^{200}$		1.002 259± 60	1.002 269± 40
$Hg^{202}-Hg^{201}$		1.000 642± 60	1.000 652± 40
$Hg^{202}-Hg^{200}$	2.002 944± 90	2.002 901±120[c]	
$Pb^{207}-Pb^{206}$		1.001 742± 60	1.001 742± 40
$Pb^{208}-Pb^{207}$		1.001 070± 60	1.001 070± 40

[a] Throughout this paper, whenever masses are given in amu, the errors refer to the last significant figure of the particular result.
[b] See reference 2.
[c] These double mass units are calculated values obtained by adding the two single mass units given immediately above in the respective columns.

Table II lists the isotopic doublets measured and the mass differences obtained. Also listed are the values reported earlier by Johnson and Bhanot.[2] The procedure for the calculation of the listed errors is the same as the one employed for the doublets of Table I. However, as pointed out before,[2] the predominant errors in the case of isotopic doublets arise from resistance calibration uncertainties.

In all precision mass determination work at Minnesota, one of the methods employed to test the accuracy of the dispersion relation for the mass spectrometer has consisted in the determination of what is known as a hydrogen mass unit. These mass units are wide doublets of the type $C_mH_n - C_mH_{n-1}$, the mass difference being that of the hydrogen atom. The average value of the hydrogen mass units determined during the present investigation is 1.008 17±5 amu, which is in good agreement with the carefully determined value of 1.008 1451±2 amu.[6] For a similar purpose, isotopic doublets of krypton and xenon were also determined several times during the course of the present work. The results are included in Table II and compared with other Minnesota values in Table III. The present value for the krypton mass unit is in excellent agreement with the very precise values of Ries.[7] The present value for the xenon mass unit is in excellent agreement with the value of Johnson and Nier[1] as well as with the very precise value of Damerow.[8] These comparisons indicate that the error, if any, in the dispersion relation employed in the present work is well within the limits set by other experimental errors.

The good agreement, in general, between the newer and older values for the isotopic doublets, listed in Table II, gives further confidence in the extensive use of isotopic doublets. There is some disagreement between the two sets in the case of gadolinium and dysprosium, but the disagreement is not bad. The newer values are considered more reliable and more accurate.

For the older data, hafnium oxide was employed as the source of hafnium ions, whereas metallic hafnium was used in the case of the newer data. Ion intensities were quite poor in the former case. For this reason, all single mass units were redetermined as a part of the present work. The newer values disagree with the older values but in no case by more than the combined error for the two sets. The newer values are considered more reliable.

TABLE III. Comparison of some of the present isotopic mass differences with other available mass spectroscopic results.

Mass difference	Present results (mmu)	Other Minnesota values (mmu)	Other results (mmu)
$Kr^{84}-Kr^{83}-1$	−2.316±0.045	−2.317±0.010[a]	
		−2.23 ±0.07[b]	
$Xe^{132}-Xe^{131}-1$	−0.606±0.048	−0.61 ±0.01[c]	
		−0.59 ±0.07[d]	
		−0.7 ±0.4[e]	
$Hg^{199}-Hg^{198}-1$	1.834±0.040	1.795±0.013[f]	1.86±0.09[h]
		1.816±0.011[g]	
$Hg^{200}-Hg^{199}-1$	0.325±0.040	0.425±0.009[f]	0.33±0.07[h]
$Hg^{201}-Hg^{200}-1$	2.269±0.040	2.281±0.012[f]	2.66±0.08[h]
		2.297±0.011[g]	2.24±0.14[i]
$Hg^{202}-Hg^{201}-1$	0.662±0.040	0.652±0.011[f]	0.39±0.08[h]
$Hg^{204}-Hg^{202}-2$		3.483±0.012[f]	4.09±0.07[h]
		3.487±0.022[g]	
$Pb^{206}-Pb^{204}-2$		1.993±0.015[f]	1.88±0.08[h]
$Pb^{207}-Pb^{206}-1$	1.742±0.040	1.766±0.013[f]	1.34±0.09[h]
$Pb^{208}-Pb^{207}-1$	1.070±0.040	1.084±0.013[f]	1.09±0.08[h]

[a] See reference 7.
[b] T. L. Collins, W. H. Johnson, Jr., and A. O. Nier, Phys. Rev. **94**, 398 (1954).
[c] See reference 8.
[d] See reference 1.
[e] R. E. Halsted, Phys. Rev. **88**, 666 (1952).
[f] Derived from the hydrocarbon mass doublets of reference 9.
[g] Isotopic doublet of reference 9.
[h] See reference 10. The values for C^{12} and H^1 were taken from reference 12.
[i] See reference 11. The values for the mass of the lighter component of the mass doublet were taken from reference 12.

TABLE IV. Mass differences derived from isotopic doublets of Table II compared with similar mass differences derived from doublets of Table I.

Mass difference	Value derived from isotopic doublets of Table II[a] (amu)	Value derived from doublets of Table I[a] (amu)
$Gd^{160}-Gd^{156}$	4.006 25± 8	4.006 19±15
$Dy^{162}-Dy^{160}$	2.002 21± 6	2.002 25±14
$Er^{168}-Er^{167}$	1.000 64± 6	1.000 57±12
$Yb^{174}-Yb^{170}$	4.005 39± 8	4.005 57±11
$Yb^{176}-Yb^{174}$	2.004 34± 6	2.004 30±10
$W^{183}-W^{182}$	1.002 29± 4	1.002 27± 5
$W^{186}-W^{182}$	4.007 24±10	4.007 41±14
$Hg^{199}-Hg^{198}$	1.001 83± 4	1.002 06±22

[a] The errors refer to the last significant figure of the particular result.

On the basis of the two sets of data and the considerations given above, a "best" value was adopted for the mass differences between neighboring stable isotopes, wherever possible. Some of these adopted mass differences are compared in Table III with the other mass spectroscopic results. The agreement with the very precise values of Benson et al.[9] is excellent, except for the case of $Hg^{200}-Hg^{199}$. Even here, the discrepancy is not very large. The agreement with the values reported by Demirkhanov et al.[10] and by Kerr and Duckworth[11] is not as good.

In Table IV, a comparison is made, wherever possible, between some mass differences derived from the adopted values of isotopic doublets with similar mass differences derived from the hydrocarbon types of doublets of Table I. It is seen that the two sets agree in all cases to within the "sum" of the corresponding errors. Not all the doublets of Table I could be compared in this manner. This comparison indicates, however, that the systematic errors in the data reported in Table I are not large.

MASS TABLE

A table of atomic masses is a very valuable tool in the field of nuclear physics. Many such tables[12–15] have been prepared in the past. The region from gadolinium

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TABLE V. Some new and corrected mass differences derived from reaction, beta-decay and alpha-decay data.

Mass difference	Adopted value (mmu)	Reference
$Pm^{145}-Nd^{145}$	0.150±11	a
$Sm^{145}-Pm^{145}$	0.693±15	a
$Eu^{152}-Sm^{152}$	2.00 ± 2	b
$Eu^{152}-Gd^{152}$	1.94 ± 2	b
$Gd^{152}-Sm^{148}-4$	1.88 ±10	c,d
$Gd^{152}-Sm^{152}$	0.060±15	b,e
$Sm^{153}-Eu^{153}$	0.873±20	f
$Eu^{154}-Gd^{154}$	2.116±10	g
$Gd^{159}-Tb^{159}$	1.015±10	h
$Tb^{159}-Tb^{158}-1$	0.225±50	i,j
$Tb^{160}-Tb^{159}-1$	2.0 ± 4	k
$Tb^{161}-Dy^{161}$	0.623±20	l
$Dy^{165}-Ho^{165}$	1.37 ± 1	m
$Ho^{165}-Ho^{163}-2$	0.9 ± 5	j,n
$Ho^{165}-Ho^{164}-1$	0.29 ± 5	i,j
$Dy^{166}-Ho^{166}$	0.26 ± 3	l
$Ho^{166}-Ho^{165}-1$	2.33 ±43	k
$Ho^{166}-Er^{166}$	1.975± 5	f
$Tm^{169}-Tm^{168}-1$	0.39 ± 5	i
$Lu^{175}-Lu^{174}-1$	0.64 ± 5	o
$Re^{180}-W^{180}$	3.14 ±10	p
$Ta^{181}-Ta^{180}-1$	0.74 ± 5	i
$W^{181}-Ta^{181}$	0.20 ± 3	l
$Os^{191}-Ir^{191}$	0.336± 2	q
$Os^{193}-Ir^{193}$	1.192±10	r
$Pt^{193}-Ir^{193}$	0.05 ± 5	l
$Au^{197}-Au^{196}-1$	0.397±56	s
$Au^{200}-Hg^{200}$	2.42 ±10	t
$Pb^{204}-Hg^{200}-4$	6.72 ±10	u,d
$Hg^{205}-Tl^{205}$	1.72 ±15	v
$Pb^{207}-Pb^{206}-1$	1.754±21	w
	1.748±32	x
$Po^{207}-Bi^{207}$	3.120± 9	y
$Pb^{208}-Pb^{207}-1$	1.039±32	x
$Pb^{209}-Pb^{208}-1$	4.761±21	w
$Bi^{210}-Tl^{206}-4$	9.233±60	z
$At^{210}-Po^{210}$	4.40 ±10	aa

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[s] This is weighted average of the value given in reference i and previous values.

[t] J. C. Roy and L. P. Roy, Can. J. Phys. **37**, 385 (1959).

[u] W. Riezler and G. Kauw, Z. Naturforsch. **13a**, 904 (1958).

[v] B. Burson, J. M. Cork, and W. Jordon, Argonne National Laboratory Report ANL-5140, 1953 (unpublished), p. 36.

[w] M. T. McEllistrem, H. J. Martin, D. W. Miller, and M. B. Sampson, Phys. Rev. **111**, 1636 (1958).

[x] B. P. Ad'yasevich, L. V. Groshev, and A. M. Demidov, *Proceedings of the Conference of the Academy of Sciences of the U.S.S.R. on the Peaceful Uses of Atomic Energy, Moscow, July, 1955* (Akademiia Nauk, S.S.S.R., Moscow, 1955), [Translation by Consultants Bureau, New York: Atomic Energy Commission Report TR-2435, 1956, p. 270].

[y] E. Arbman, J. Burde, and T. R. Gerholm, Arkiv Fysik **13**, 501 (1958).

[z] Bi^{210}(2.6×10^6yr) has been arbitrarily considered to be 40 kev higher than the 5.0-day level of Bi^{210}.

[aa] Lower limit given by Lidofsky has been adopted here.

to lead, however, has been represented rather poorly in all previous mass tables. Mass spectroscopic as well as nuclear data were sparse in the case of these elements and wherever available were, relatively speaking, less reliable and less accurate. By combining the doublets reported in this study with the isotopic mass units of Johnson and Bhanot,[2] it is now possible to determine almost all stable atomic masses for the elements gadolinium to gold. Many new alpha-decay, beta-decay, and nuclear reaction Q values in this region have also recently become available. It was, therefore, considered worthwhile to prepare a new atomic mass table for both stable and radioactive nuclei in this region. In order to provide continuity with the trans-lead region and for the purpose of providing some masses beyond the doubly magic isotope of Pb^{208}, isotopic masses for the elements bismuth, polonium, astatine, and radon have also been computed. For similar reasons the isotopic masses of the elements samarium and europium are also included.

In a project of this nature, it is not unusual to run into difficulties because of incompatibility of input data, since values from several different sources have to be employed. Several inconsistencies were discovered when comparisons were made between different values for the same mass or mass difference. An attempt was made to examine each case in some detail in order to locate the more likely source of discrepancy. In most of the cases, more than one experimental value seemed likely to be in error. To resolve these discrepancies, somewhat arbitrary selection of data has been made and not too large but arbitrary adjustments have been employed. General considerations utilized for this purpose are listed below.

Except for the new values listed in Table V, the nuclear data are taken from the excellent compilations[16–20] that have recently become available. Q values marked as doubtful in these compilations were not employed. In the case of beta-decay energies, King[18] as well as Lidofsky[19] have listed for many cases a lower limit as well as an upper limit. Whenever the difference between these limits was less than 100 kev an average was arbitrarily taken as the beta-decay energy. There were only a few such cases. These are listed in Table V.

In general, beta-decay energies were considered as more reliable except in the trans-thallium region where alpha-decay Q values with well-established isotopic assignments were considered equally reliable. Consideration was given to the fact that for several nuclear reaction Q values the isotopic assignments are somewhat doubtful and that in certain cases the reported Q values

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[16] D. M. VanPatter and W. Whaling, Revs. Modern Phys. **26**, 402 (1954).

[17] D. M. VanPatter and W. Whaling, Revs. Modern Phys. **29**, 757 (1957).

[18] R. W. King, Revs. Modern Phys. **26**, 327 (1954).

[19] L. J. Lidofsky, Revs. Modern Phys. **29**, 773 (1957).

[20] D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 585 (1958).

may not represent ground-state transitions. It should be pointed out that the procedure followed here is somewhat similar to the procedure followed by Wapstra[15] in the intermediate and heavy mass regions.

Steps for Calculations of the Mass Table

A. As a first step, a table of unadjusted mass spectroscopic masses for stable isotopes was prepared. This was done in the region from gadolinium to gold by adopting for each element, except tantalum, one of the isotopes of that element as a reference. The masses of these selected isotopes were computed by combining adopted isotopic mass differences of Table II with each doublet listed for that particular element in Table I. These calculated masses are given in the second column of Table VI and will be referred to as Minnesota values. For these calculations, the following secondary standard masses, listed in amu, were employed:[12] H^1, 1.008 1451±2; C^{12}, 12.003 8156±4; C^{13}, 13.007 4900±9; N^{14}, 14.007 5257±3; and F^{19}, 19.004 4431±24.

A similar procedure was adopted wherever possible for previous mass spectroscopic doublets listed by Duckworth et al.[21] These values are given in the fourth column of Table VI. Doublets determined before 1950, except those for the ytterbium isotopes, have not been included because the associated errors are rather large. Wherever necessary, the masses of the lighter isotopes in these previous mass doublets were taken from the mass table of Johnson et al.[12] The values in the fourth column for a particular isotopic mass are seen to have, in general, a spread of more than one milli-mass-unit and are on the average lower than the corresponding Minnesota values listed in the second column. These latter values are considered more reliable. Accordingly, the preliminary table of stable atomic masses was based only on the unweighted averages of the Minnesota values listed in the second column. These averages were combined with the adopted values given in Table II in order to prepare the aforesaid mass table.

B. As a second step, adjustments were made in this preliminary mass table on the basis of a comparison with the nuclear data. This was done by adjusting the reference masses that were employed in step A. The details of the adjustment are given in the Appendix. The adjusted values are given in the third column of Table VI. This procedure ensured that the adopted mass differences of Table II were not changed. Only the data of Table I are adjusted. This procedure was employed for several reasons. First, doublet values of Table I have errors that are much larger than the errors associated with the isotopic mass differences of Table II. Second, the doublet values of Table I are more subject to systematic errors then the isotopic doublet values of Table II. Third, as new, more reliable, and more precise atomic masses become available for some stable isotopes in this region, a simple revision of the mass table, in the form of suitable additive factors at the appropriate places, may become possible.

TABLE VI. The present experimental values, the adopted values and the previous mass spectroscopic values for the mass of the "reference" isotopes.

Isotope	Present values[a] (amu)	Adopted values[b] (amu)	Previous mass spectroscopic results[c] Mass (amu)	Previous mass spectroscopic results[c] Δ,[d] mmu
Gd^{156}	155.971 81±12	155.971 42±20	155.971 87±22	+0.45
	155.971 75±13		155.971 50±40	+0.08
			155.971 84±22	+0.42
			155.970 90±22	−0.52
			155.971 72±24	+0.30
Tb^{159}	158.975 41±10	158.975 41±15		
Dy^{162}	161.977 91±12	161.977 93±18	161.977 1± 8	−0.8
	161.977 95± 9		161.977 1± 6	−0.8
			161.976 4± 8	−1.5
Ho^{165}	164.982 89±21	164.982 70±15	164.981 5± 9	−1.2
Er^{168}	167.985 77± 8	167.985 85±15	167.986 4± 4	+0.55
	167.985 70±10		167.984 2± 3	−1.65
			167.985 8± 8	−0.05
Tm^{169}	168.988 06±10	168.988 06±15		
Yb^{174}	173.994 20±11	173.994 32±10	173.983 0±26	−11.3
	173.994 38± 8		173.980 9±24	−13.4
	173.994 36±16			
	173.994 34±10			
Lu^{176}	175.999 41±17	175.998 79±15		
Hf^{176}	175.997 72± 4	175.997 72±10	175.993 1± 8	−4.6
			175.996 7± 6	−1.0
			175.990 6± 8	−7.0
			175.996 4± 6	−1.3
			175.997 1± 6	−0.6
			175.997 8± 6	+0.1
			175.996 3± 6	−1.4
W^{183}	183.008 29± 6	183.008 29±10	183.006 3± 8	−2.0
	183.008 27± 4		183.006 2± 6	−2.1
	183.008 46±16		183.006 8± 4	−1.5
			183.007 4± 8	−0.9
			183.006 4± 6	−1.9
			183.007 1± 4	−1.2
			183.004 8± 9	−3.5
Re^{185}	185.011 40± 8	185.011 40±15		
Os^{186}	186.012 58±18	186.012 58±20	186.014 3± 9	+1.7
	186.013 30±10		186.013 6± 9	+1.0
			186.013 1± 6	+0.5
			186.015 6± 7	+3.0
			186.012 9± 5	+0.3
Ir^{191}	191.020 14±19	191.021 19±30		
Pt^{196}	196.027 12±12	196.027 12±15	196.030 9± 6	+3.8
			196.027 9± 4	+0.8
			196.026 7± 6	−0.4
			196.025 8± 3	−1.3
			196.029 1±21	+2.0
			196.029 4± 6	+2.3
Au^{197}	197.029 42± 8	197.029 29±10		
	197.029 16±20			

[a] Every doublet of Table I was employed in combination with the relevant isotopic mass differences of Table II for obtaining a mass for the reference isotope of the particular element. The masses have been listed in the same order as that used in Table I for listing the corresponding doublets.

[b] The values in this column have been adopted on the basis of a comparison between the present mass spectroscopic values and the nuclear reaction and decay energies available in this region. Several somewhat arbitrary adjustments had to be employed in order to minimize or eliminate the inconsistencies between the two sets. Details are given in the Appendix. The quoted errors may be considered as standard errors. The limit of error is estimated to be three times the quoted error.

[c] Masses listed in this column have been calculated by employing the data of Table II and the previously known mass doublets compiled in the review article of Duckworth et al. (reference 21). Doublets published before 1950 were not employed, except those for the ytterbium isotopes. The masses for Zr^{94}, Zr^{96}, Ru^{96}, Ru^{98}, and Ru^{99} are not known and the mass difference Pt^{198}−Pt^{196} was not determined in the present study. For these two reasons, three doublets for osmium isotopes and three doublets for platinum isotopes could not be employed. Except for these omissions, all relevant doublets listed in reference 21 were employed. The masses are listed in the same order as that of the corresponding doublets in reference 21.

[d] Δ stands for the previous mass spectroscopic mass minus the adopted value.

C. As a third step, these Minnesota values of the stable atomic masses for the elements from samarium to lead, adjusted in a manner explained in the Appendix, were combined with nuclear Q values for the purpose of computing masses for a large number of radioactive nuclides as well as for a few stable nuclides. The "paths" employed are shown in Fig. 1(a) and 1(b), except for

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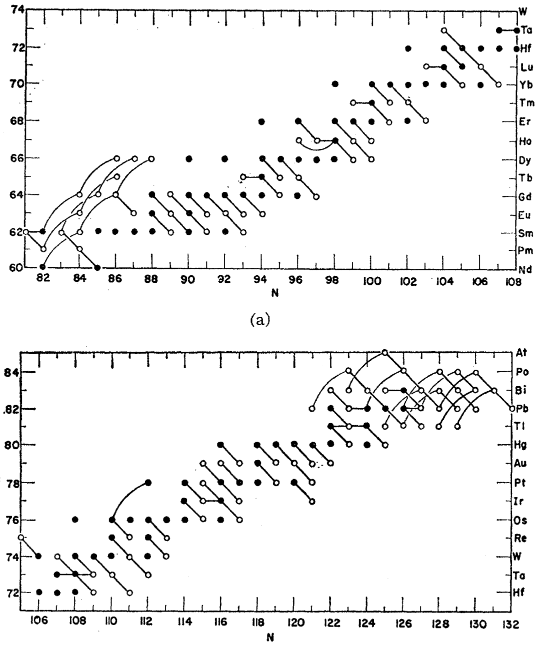
[21] H. E. Duckworth, B. G. Hogg, and E. M. Pennington, Revs. Modern Phys. 26, 463 (1954).



(a)

(b)

FIG. 1. Nuclear reaction, beta-decay, and alpha-decay paths that were employed to calculate atomic masses of the radioactive isotopes and the "stable" isotopes Lu^{176}, Ta^{180}, Ta^{181}, and Pt^{190}. Solid circles indicate the "stable" isotopes. Open circles indicate the radioactive isotopes.

some omissions in the region above bismuth. These omissions are for the isotopes of polonium, astatine, and radon whose masses could be computed directly by combining alpha-decay energies with the masses of the nuclides included in Fig. 1.

The $Sm^{144}(\gamma,n)$ threshold of Silva and Goldemberg[22] and the $Ho^{165}(\gamma,2n)$ threshold of Gove et al.[23] appear to be incorrect. The masses of Ho^{163}, Tb^{151}, Eu^{147}, and Sm^{143}, calculated by employing these two Q values, have been rejected.

The mass of Pt^{198}, the only remaining stable nuclide in this region, could not be computed in the manner described above. The mass spectroscopic value for Pt^{198} derived from the doublet $\frac{1}{3}Pt^{198}-Zn^{66}$ of Duckworth et al.[24] appears to be too low by more than 3 mmu and was therefore rejected. For the sake of completeness, an estimated mass of Pt^{198} has been included. This was calculated from that of Pt^{197} by using an estimated value for $S_n(Pt^{198})$.

In the region beyond lead, several "cycles," each comprised of two alpha decays and two beta decays, do not "close" as they should. It became necessary to resort to somewhat arbitrary selection of data in these cases.

The masses of the five heavier "stable" nuclides, viz., Ra^{226}, Th^{232}, U^{234}, U^{235}, and U^{238}, have been computed by combining experimental alpha-decay and beta-decay energies with the masses of Pb^{214}, Pb^{212}, Ra^{226}, Pb^{211}, and U^{234}, respectively.

The final adopted values for the atomic mass of 208 nuclides are given in Table VII. The quoted errors may be considered as standard errors. The limit of error is estimated to be three times the quoted error. Errors larger than 1 mmu are considered very unlikely.

BINDING ENERGIES

The systematic study of trends in the binding energies of nuclei is one of the important applications of mass data. Quantities often studied are the average binding energy per nucleon of a given nucleus, the separation energy of the last proton or neutron, the pairing energies for the last pair of protons or neutrons, and the separation energy of the last pair of protons or neutrons added to form a nucleus. It is convenient for the calculation of these quantities to employ the total atomic binding energy. This term includes not only the total nuclear binding energy but also the binding energy of the orbital electrons of the atom. The total atomic binding energy, $\mathrm{TBE}(Z,N)$, may be calculated with

$$\mathrm{TBE}(Z,N)=Z(m_p+m_e)+N(m_n)-M(Z,N). \quad (1)$$

In this equation the mass of the atom with Z protons and N neutrons is $M(Z,N)$. The masses of the proton, electron, and neutron are indicated by m_p, m_e, and m_n, respectively. The sum of m_p and m_e can be replaced by the mass of the hydrogen atom. The resulting error is insignificant in the present work.

The total binding energies for atoms are given in Table VII. A negligible error is made by using these quantities for the calculation of the various binding energy terms because the orbital electron binding energy is very small compared with the total nuclear binding energy and also is slowly varying.

One obtains the average binding energy per nucleon by dividing the total binding energy by the mass number A. The values of the average binding energy per nucleon for all stable isotopes of this investigation are listed in Table VII and are plotted against the mass number A in Fig. 2. The even-A points for a particular even-Z element have been joined by a solid curve which is approximately a parabola for most of the cases. The odd-A points for all elements have been joined by a dashed curve.

The most prominent feature of this plot is a sharp break in the region of the doubly magic nuclide Pb^{208}. The points for thorium and uranium are approximately on a straight line extrapolation of the part of the curve below about $A=180$. With respect to such an imaginary line, the average binding energy per nucleon curve rises slowly to a maximum around the region of Pb^{208} and falls gradually thereafter. This behavior is in contrast

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[22] E. Silva and J. Goldemberg, Nuovo cimento 3, 12 (1956).

[23] N. B. Gove, R. W. Henry, L. T. Dillman, and R. A. Becker, Phys. Rev. 112, 489 (1958).

[24] H. E. Duckworth, H. A. Johnson, R. S. Preston, and R. F. Woodcock, Phys. Rev. 78, 386 (1950).

TABLE VII. Atomic mass; total atomic binding energy, TBE; the average binding energy per nucleon, TBE/A; the separation energy of the last neutron, S_n; the separation energy of the last two neutrons, S_{2n}; and the neutron pairing energy, P_n, of the heavy nuclei.

Isotope	Atomic mass[a] (amu)	TBE[b] (mmu)	TBE/A[c] (mmu)	S_n (mmu)	S_{2n} (mmu)	P_n (mmu)
${}_{62}\mathrm{Sm}_{82}^{144}$	143.957 410±90	1284.438	8.920			
Sm_{83}^{145}	144.958 983±190	1291.851		7.41±21		
Sm_{84}^{146}	145.959 288±100	1300.532		8.68±22	16.09±14	1.27±30
Sm_{85}^{147}	146.961 200±80	1307.606	8.895	7.07±13		
Sm_{86}^{148}	147.961 450±100	1316.342	8.894	8.74±6	15.81±14	1.66±14
Sm_{87}^{149}	148.964 150±100	1322.628	8.877	6.29±6		
Sm_{88}^{150}	149.964 570±80	1331.194	8.875	8.57±6	14.85±12	2.28±8
Sm_{89}^{151}	150.967 633±130	1337.117		5.92±15		
Sm_{90}^{152}	151.967 670±150	1346.066	8.856	8.95±20	14.87±17	3.03±25
Sm_{91}^{153}	152.970 473±250	1352.249		6.18±29		
Sm_{92}^{154}	153.970 870±150	1360.838	8.837	8.59±29	14.77±21	2.41±40
Sm_{93}^{155}	154.974 199±220	1366.495		5.66±27		
${}_{63}\mathrm{Eu}_{87}^{150}$	149.967 297±140	1327.626				
Eu_{88}^{151}	150.967 530±130	1336.379	8.850	8.75±19		
Eu_{89}^{152}	151.969 671±150	1343.224		6.85±20		
Eu_{90}^{153}	152.969 600±250	1352.281	8.838[d]	9.06±29	15.90±28	2.21±35
Eu_{91}^{154}	153.971 588±200	1359.279		7.00±32		
Eu_{92}^{155}	154.971 836±200	1368.017		8.74±4	15.74±28	1.74±32
Eu_{93}^{156}	155.974 148±210	1374.691		6.67±6		
Eu_{94}^{157}	156.975 401±220	1382.424		7.73±11	14.41±12	1.06±13
${}_{64}\mathrm{Gd}_{84}^{148}$	147.964 817±130	1311.293				
Gd_{85}^{149}	148.966 171±220	1318.925		7.63±26		
Gd_{86}^{150}	149.966 148±140	1327.934		9.01±26	16.64±19	1.38±37
Gd_{88}^{152}	151.967 732±170	1344.322	8.844		16.39±22	
Gd_{89}^{153}	152.969 826±250	1351.214		6.89±30		
Gd_{90}^{154}	153.969 472±200	1360.554	8.835	9.34±32	16.23±8	2.45±44
Gd_{91}^{155}	154.971 571±200	1367.441	8.822	6.89±4		
Gd_{92}^{156}	155.971 420±200	1376.578	8.824	9.14±4	16.02±8	2.25±5
Gd_{93}^{157}	156.973 575±200	1383.409	8.812	6.83±4		
Gd_{94}^{158}	157.974 050±210	1391.920	8.810	8.51±4	15.34±8	1.68±5
Gd_{95}^{159}	158.976 429±150	1398.527		6.61±26		
Gd_{96}^{160}	159.977 669±220	1406.273	8.789	7.75±27	14.35±8	1.14±37
Gd_{97}^{161}	160.980 439±180	1412.489		6.22±23		
${}_{65}\mathrm{Tb}_{93}^{158}$	157.975 189±160	1389.941				
Tb_{94}^{159}	158.975 414±150	1398.702	8.797	8.76±5		
Tb_{95}^{160}	159.977 681±150	1405.421		6.72±21		
Tb_{96}^{161}	160.978 399±150	1413.689		8.27±5	14.99±21	1.55±22
${}_{66}\mathrm{Dy}_{86}^{152}$	151.972 729±170	1337.644				
Dy_{87}^{153}	152.973 890±240	1345.469		7.82±29		
Dy_{88}^{154}	153.973 738±170	1354.607		9.14±29	16.96±24	1.31±40
Dy_{90}^{156}	155.973 386±200	1372.931	8.801		18.32±4	
Dy_{92}^{158}	157.974 223±180	1390.066	8.798		17.14±8	
Dy_{94}^{160}	159.975 726±160	1406.535	8.791		16.47±8	
Dy_{95}^{161}	160.977 776±160	1413.471	8.779	6.94±4		
Dy_{96}^{162}	161.977 934±150	1422.299	8.780	8.83±4	15.76±8	1.89±5
Dy_{97}^{163}	162.980 148±160	1429.071	8.767	6.77±4		
Dy_{98}^{164}	163.980 892±160	1437.313	8.764	8.24±4	15.01±8	1.47±5
Dy_{99}^{165}	164.984 070±150	1443.121		5.81±22		
Dy_{100}^{166}	165.985 388±160	1450.789		7.67±22	13.48±23	1.86±30
${}_{67}\mathrm{Ho}_{97}^{164}$	163.982 411±160	1434.953				
Ho_{98}^{165}	164.982 700±150	1443.650	8.749	8.70±5		
Ho_{99}^{166}	165.985 130±160	1450.206		6.56±22		
Ho_{100}^{167}	166.986 281±190	1458.041		7.84±11	14.39±24	1.28±25
${}_{68}\mathrm{Er}_{94}^{162}$	161.980 215±180	1418.336	8.755			
Er_{96}^{164}	163.981 360±160	1435.163	8.751		16.83±8	
Er_{98}^{166}	165.983 155±160	1451.340	8.743		16.18±8	
Er_{99}^{167}	166.985 207±160	1458.274	8.732	6.93±4		
Er_{100}^{168}	167.985 850±150	1466.617	8.730	8.34±4	15.28±8	1.41±5
Er_{101}^{169}	168.988 423±150	1473.030		6.41±21		
Er_{102}^{170}	169.989 608±180	1480.831	8.711	7.80±24	14.21±8	1.39±32
Er_{103}^{171}	170.992 479±120	1486.946		6.12±22		
${}_{69}\mathrm{Tm}_{99}^{168}$	167.987 669±160	1463.957				
Tm_{100}^{169}	168.988 059±150	1472.553	8.713	8.60±5		
Tm_{101}^{170}	169.989 963±130	1479.635		7.08±20		
Tm_{102}^{171}	170.990 910±120	1487.674		8.04±4	15.12±19	0.96±20
${}_{70}\mathrm{Yb}_{98}^{168}$	167.987 299±150	1463.486	8.711			
Yb_{100}^{170}	169.988 926±130	1479.831	8.705		16.34±8	
Yb_{101}^{171}	170.990 800±120	1486.943	8.700	7.11±4		
Yb_{102}^{172}	171.991 187±120	1495.542	8.695	8.60±4	15.71±8	1.49±5
Yb_{103}^{173}	172.993 354±110	1502.361	8.684	6.82±4		
Yb_{104}^{174}	173.994 320±100	1510.381	8.680	8.02±4	14.84±8	1.20±5

TABLE VII.—*Continued.*

Isotope	Atomic mass[a] (amu)	TBE[b] (mmu)	TBE/A[c] (mmu)	S_n (mmu)	S_{2n} (mmu)	P_n (mmu)
Yb_{105}^{175}	174.997 036±160	1516.651		6.27±19		
Yb_{106}^{176}	175.998 662±130	1524.011	8.659	7.36±21	13.63± 8	1.09±28
Yb_{107}^{177}	177.001 895±120	1529.764		5.75±18		
$_{71}\mathrm{Lu}_{103}^{174}$	173.995 894±170	1507.966				
Lu_{104}^{175}	174.996 534±160	1516.312	8.665	8.35± 5		
Lu_{105}^{176}	175.998 790±150	1523.042	8.654	6.73± 6		
Lu_{106}^{177}	177.000 413±110	1530.405		7.36± 5	14.09± 8	0.63± 8
$_{72}\mathrm{Hf}_{102}^{174}$	173.995 602±140	1507.417	8.663			
Hf_{104}^{176}	175.997 725±100	1523.266	8.655		15.85±10	
Hf_{105}^{177}	176.999 883±110	1530.094	8.645	6.83± 5		
Hf_{106}^{178}	178.000 693±120	1538.270	8.642	8.18± 5	15.00±10	1.35± 7
Hf_{107}^{179}	179.003 120±130	1544.829	8.630	6.56± 5		
Hf_{108}^{180}	180.004 209±140	1552.726	8.626	7.90± 5	14.46±10	1.34± 7
Hf_{109}^{181}	181.006 487±110	1559.434		6.71±18		
Hf_{111}^{183}	183.011 800±220	1572.093				
$_{73}\mathrm{Ta}_{104}^{177}$	177.001 118±120	1528.018				
Ta_{107}^{180}	180.004 652±120	1551.442	8.619			
Ta_{108}^{181}	181.005 392±110	1559.688	8.617	8.25± 5		
Ta_{109}^{182}	182.007 862±110	1566.204		6.52± 3		
Ta_{110}^{183}	183.009 437±100	1573.615		7.41± 4	13.93±15	0.90± 5
Ta_{112}^{185}	185.013 686±180	1587.338			13.72±21	
$_{74}\mathrm{W}_{106}^{180}$	180.003 866±130	1551.387	8.619			
W_{107}^{181}	181.005 592±120	1558.647		7.26±18		
W_{108}^{182}	182.006 002±110	1567.223	8.611	8.58±16	15.84± 8	1.32±24
W_{109}^{183}	183.008 290±100	1573.921	8.601	6.70± 4		
W_{110}^{184}	184.009 264±110	1581.933	8.597	8.01± 4	14.71± 8	1.31± 5
W_{111}^{185}	185.011 863±150	1588.320		6.39±19		
W_{112}^{186}	186.013 247±130	1595.922	8.580	7.60±20	13.99± 8	1.22±28
W_{113}^{187}	187.016 180±180	1601.975		6.05±22		
$_{75}\mathrm{Re}_{105}^{180}$	180.007 006±170	1547.406				
Re_{110}^{185}	185.011 403±150	1587.939	8.583			
Re_{111}^{186}	186.013 725±200	1594.603		6.66±10		
Re_{112}^{187}	187.014 771±180	1602.543	8.570	7.94± 5	14.60± 9	1.28±11
Re_{113}^{188}	188.017 309±210	1608.991		6.45± 5		
$_{76}\mathrm{Os}_{108}^{184}$	184.010 561±220	1578.955	8.581			
Os_{110}^{186}	186.012 579±200	1594.909	8.575		15.95± 8	
Os_{111}^{187}	187.014 715±200	1601.759	8.566	6.85± 4		
Os_{112}^{188}	188.015 039±210	1610.421	8.566	8.66± 4	15.51± 8	1.81± 5
Os_{113}^{189}	189.017 584±210	1616.862	8.555	6.44± 4		
Os_{114}^{190}	190.018 117±220	1625.315	8.554	8.45± 4	14.89± 8	2.01± 5
Os_{115}^{191}	191.021 526±300	1630.892		5.58±37		
Os_{116}^{192}	192.021 602±230	1639.802	8.541	8.91±37	14.49± 8	3.33±50
Os_{117}^{193}	193.025 382±250	1645.008		5.21±34		
$_{77}\mathrm{Ir}_{114}^{191}$	191.021 190±300	1630.387	8.541[d]			
Ir_{115}^{192}	192.023 580±220	1636.983		6.60±22		
Ir_{116}^{193}	193.024 190±250	1645.359	8.525	8.38±20	14.97±10	1.58±42
Ir_{117}^{194}	194.026 597±160	1651.938		6.58±22		
$_{78}\mathrm{Pt}_{112}^{190}$	190.020 072±220	1621.678	8.535			
Pt_{114}^{192}	192.022 021±190	1637.701	8.530		16.02±29	
Pt_{115}^{193}	193.024 240±250	1644.468		6.77±20		
Pt_{116}^{194}	194.024 199±160	1653.495	8.523	9.03±22	15.79±10	2.26±30
Pt_{117}^{195}	195.026 645±160	1660.035	8.513	6.54± 4		
Pt_{118}^{196}	196.027 125±150	1668.541	8.513	8.51± 4	15.05± 8	1.97± 5
Pt_{119}^{197}	197.029 844±100	1674.808		6.27±18		
Pt_{120}^{198}	(198.031 000±300)[e]	(1682.638)[e]	(8.498)[d, e]	(7.83±30)[e]		
Pt_{121}^{199}	199.033 918± 80	1688.706				
$_{79}\mathrm{Au}_{115}^{194}$	194.026 955±160	1649.898				
Au_{116}^{195}	195.026 935±160	1658.904		9.01± 5		
Au_{117}^{196}	196.028 888± 40	1665.937		7.03±16		
Au_{118}^{197}	197.029 290±100	1674.521	8.500	8.58± 8	15.62±18	1.55±18
Au_{119}^{198}	198.031 187± 20	1681.610		7.09± 6		
Au_{120}^{199}	199.032 006± 30	1689.777		8.17± 4	15.26± 7	1.08± 7
Au_{121}^{200}	200.034 307±100	1696.462		6.68±10		
Au_{122}^{201}	201.035 803±100	1703.952		7.49±14	14.18±10	0.80±20
$_{80}\mathrm{Hg}_{116}^{196}$	196.028 136± 20	1665.848	8.499			
Hg_{118}^{198}	198.029 712± 25	1682.244	8.496			
Hg_{119}^{199}	199.031 517± 30	1689.425	8.490	7.18± 4		
Hg_{120}^{200}	200.031 891± 25	1698.037	8.490	8.61± 4	15.79± 4	1.43± 6
Hg_{121}^{201}	201.034 192± 20	1704.722	8.481	6.68± 3		
Hg_{122}^{202}	202.034 845± 20	1713.055	8.480	8.33± 3	15.02± 3	1.65± 4
Hg_{123}^{203}	203.037 314± 40	1719.572		6.52± 5		
Hg_{124}^{204}	204.038 328± 20	1727.544	8.468	7.97± 5	14.49± 3	1.46± 6
Hg_{125}^{205}	205.041 403±190	1733.455		5.91±20		

TABLE VII.—*Continued.*

Isotope	Atomic mass[a] (amu)	TBE[b] (mmu)	TBE/A[c] (mmu)	S_n (mmu)	S_{2n} (mmu)	P_n (mmu)
${}_{81}\mathrm{Tl}_{122}^{203}$	203.036 792± 40	1719.253	8.469			
Tl_{123}^{204}	204.038 757± 25	1726.274		7.02± 3		
Tl_{124}^{205}	205.039 683±120	1734.334	8.460	8.06±12	15.08±13	1.04±12
Tl_{125}^{206}	206.041 644± 70	1741.359		7.02±14		
Tl_{126}^{207}	207.043 260± 45	1748.729		7.37± 9	14.40±13	0.34±16
Tl_{127}^{208}	208.048 102± 30	1752.873		4.14± 5		
Tl_{128}^{209}	209.051 757± 45	1758.204		5.33± 6	9.48± 6	1.19± 8
Tl_{129}^{210}	210.056 744±110	1762.203		4.00±12		
${}_{82}\mathrm{Pb}_{121}^{203}$	203.037 939± 50	1717.265				
Pb_{122}^{204}	204.037 935± 25	1726.255	8.462	8.99± 6		
Pb_{123}^{205}	205.039 734± 80	1733.442		7.19± 8		
Pb_{124}^{206}	206.039 947± 20	1742.215	8.457	8.77± 8	15.96± 3	1.59±11
Pb_{125}^{207}	207.041 700± 20	1749.448	8.451	7.23± 1		
Pb_{126}^{208}	208.042 764± 20	1757.370	8.449	7.92± 1	15.16± 1	0.69± 1
Pb_{127}^{209}	209.047 536± 30	1761.584		4.21± 2		
Pb_{128}^{210}	210.050 945± 35	1767.161		5.58± 5	9.79± 4	1.36± 6
Pb_{129}^{211}	211.055 876± 80	1771.216		4.06± 9		
Pb_{130}^{212}	212.059 291± 35	1776.787		5.57± 9	9.63± 5	1.52±13
Pb_{132}^{214}	214.067 781± 80	1786.269			9.48± 9	
${}_{83}\mathrm{Bi}_{122}^{205}$	205.042 580± 80	1729.755				
Bi_{123}^{206}	206.044 099±110	1737.222		7.47±14		
Bi_{124}^{207}	207.044 277± 50	1746.030		8.81±12	16.28±10	1.34±18
Bi_{125}^{208}	208.045 852± 80	1753.441		7.41± 9		
Bi_{126}^{209}	209.046 859± 35	1761.420	8.428	7.98± 5	15.39± 6	0.57±10
Bi_{127}^{210}	210.050 877± 30	1766.388		4.97± 5		
Bi_{128}^{211}	211.054 383± 45	1771.868		5.48± 5	10.45± 6	0.51± 7
Bi_{129}^{212}	212.058 666± 35	1776.571		4.70± 6		
Bi_{130}^{213}	213.062 042± 40	1782.181		5.61± 5	10.31± 6	0.91± 6
Bi_{131}^{214}	214.066 675± 50	1786.534		4.35± 6		
${}_{84}\mathrm{Po}_{123}^{207}$	207.047 397± 50	1742.069				
Po_{124}^{208}	208.047 404± 30	1751.048		8.98± 6		
Po_{125}^{209}	209.048 945± 80	1758.493		7.44± 9		
Po_{126}^{210}	210.049 620± 30	1766.804		8.31± 9	15.76± 4	0.87±12
Po_{127}^{211}	211.053 725± 25	1771.685		4.88± 4		
Po_{128}^{212}	212.056 250± 25	1778.146		6.46± 4	11.34± 4	1.58± 5
Po_{129}^{213}	213.060 549± 35	1782.833		4.69± 4		
Po_{130}^{214}	214.063 228± 40	1789.140		6.31± 5	10.99± 5	1.62± 7
Po_{131}^{215}	215.067 804± 80	1793.550		4.41± 9		
Po_{132}^{216}	216.070 575± 40	1799.765		6.22± 9	10.62± 6	1.80±13
Po_{134}^{218}	218.078 185±130	1810.127			10.36±14	
${}_{85}\mathrm{At}_{124}^{209}$	209.052 629± 80	1753.969				
At_{125}^{210}	210.054 019±100	1761.565		7.60±13		
At_{126}^{211}	211.054 573± 50	1769.997		8.43±11	16.03±10	0.84±17
At_{128}^{213}	213.060 828±150	1781.714			11.72±16	
At_{129}^{214}	214.064 363± 35	1787.165		5.45±15		
At_{130}^{215}	215.067 010± 45	1793.504		6.34± 6	11.79±16	0.89±16
At_{131}^{216}	216.071 067± 40	1798.433		4.93± 6		
At_{132}^{217}	217.073 627± 45	1804.859		6.43± 6	11.36± 6	1.50± 9
At_{133}^{218}	218.077 766±110	1809.706		4.85±12		
${}_{86}\mathrm{Rn}_{125}^{211}$	211.057 672± 50	1766.057				
Rn_{126}^{212}	212.058 130± 35	1774.585		8.53± 6		
Rn_{129}^{215}	215.067 007±150	1792.666				
Rn_{130}^{216}	216.068 887± 35	1799.772		7.11±15		
Rn_{131}^{217}	217.072 896± 40	1804.749		4.98± 5		
Rn_{132}^{218}	218.074 899± 40	1811.732		6.98± 6	11.96± 5	2.01± 8
Rn_{133}^{219}	219.079 131± 80	1816.486		4.75± 9		
Rn_{134}^{220}	220.081 322± 40	1823.281		6.80± 9	11.55± 6	2.04±13
Rn_{136}^{222}	222.088 062±130	1834.513			11.23±14	
${}_{88}\mathrm{Ra}_{138}^{226}$	226.097 184± 80	1859.653	8.229			
${}_{90}\mathrm{Th}_{142}^{232}$	232.111 834± 40	1897.237	8.178			
${}_{92}\mathrm{U}_{142}^{234}$	234.115 259± 80	1910.102	8.163			
U_{143}^{235}	235.118 591± 90	1915.756	8.152			
U_{146}^{238}	238.126 373± 90	1934.932	8.130			

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[a] The errors throughout this table refer to the last significant figure of the particular result. These errors may be considered to be standard errors. The limit of error is estimated to be three times the quoted error.

[b] No errors for total binding energy are specified. For most purposes, the difference in two TBE values is employed. For these cases, the errors in TBE 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. For these calculations a neutron mass of 1.008 9860±8 amu[12] was employed.

[c] The error in this column is ±0.001 mmu unless otherwise specified.

[d] The error for this value is ±0.002 mmu.

[e] This value is estimated from binding energy systematics.

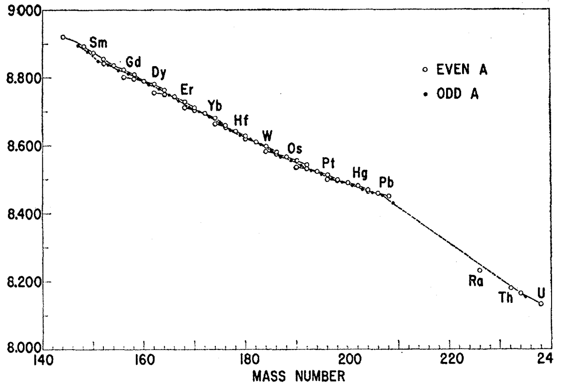

FIG. 2. Average binding energy per nucleon for the stable isotopes.

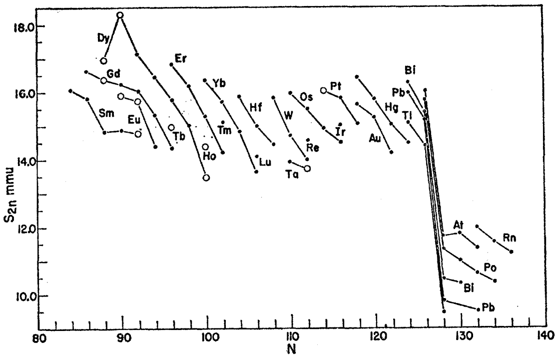

FIG. 4. The separation energy of the last pair of neutrons, S_{2n}. Values having errors larger than 0.2 mmu appear as open circles.

to the behavior in the vicinity of $N=82$ as can be seen from a similar plot drawn for the lighter region by Johnson and Nier.[1]

The mass data of the present investigation can be employed to calculate a large number of separation energies and pairing energies. The neutron separation energy, $S_n(Z,N)$, sometimes known as the binding energy of the last neutron, is easily calculated from the total binding energy data:

$$S_n(Z,N)=\mathrm{TBE}(Z,N)-\mathrm{TBE}(Z,N-1). \tag{2}$$

The separation energy of the last pair of neutrons, S_{2n}, is determined by a similar difference between two total binding energy terms. Proton separation energies are defined in a corresponding manner. A negligible error is made by employing total binding energies instead of total nuclear binding energies. The pairing energy, $P_n(Z,N)$, associated with the last pair of neutrons for a nucleus with an even neutron number, N, is given by

$$\begin{aligned}P_n(Z,N)&=S_n(Z,N)-S_n(Z,N-1),\quad N\text{ even},\\&=\mathrm{TBE}(Z,N)+\mathrm{TBE}(Z,N-2)\\&\quad-2\,\mathrm{TBE}(Z,N-1).\end{aligned}\tag{3}$$

In a similar manner, the pairing energy of the last pair of protons, $P_p(Z,N)$, in a nucleus with even Z can be calculated from

$$\begin{aligned}P_p(Z,N)&=S_p(Z,N)-S_p(Z-1,N),\quad Z\text{ even},\\&=\mathrm{TBE}(Z,N)+\mathrm{TBE}(Z-2,N)\\&\quad-2\,\mathrm{TBE}(Z-1,N).\end{aligned}\tag{4}$$

The definition of pairing energies will be employed for all calculations although it is recognized that the neutron pairing energy for odd Z contains an interaction term between the odd proton and the added neutrons. Similarly, the proton pairing energy for odd N contains an interaction term between the odd neutron and the added protons.

The neutron separation energies, binding energies, and pairing energies that may be calculated from the present data are listed in Table VII while the proton separation energies and pairing energies that may be calculated are listed in Table VIII.[25]

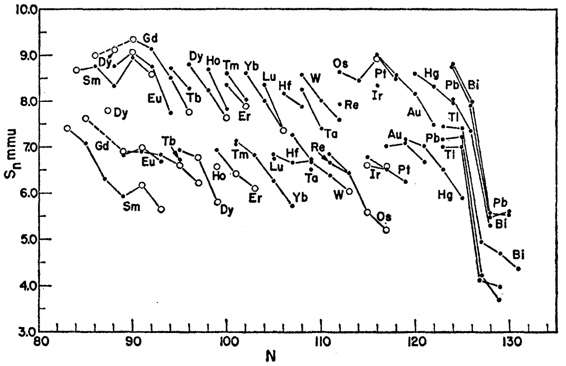

FIG. 3. The neutron separation energies, S_n. Values having errors larger than 0.2 mmu appear as open circles.

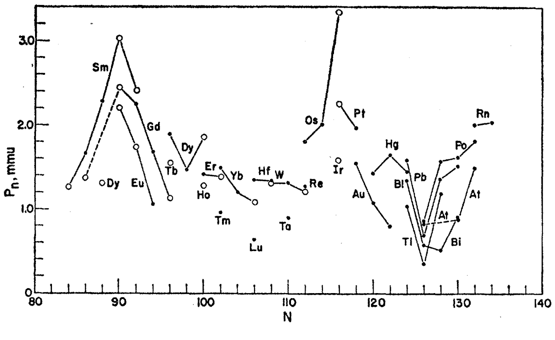

FIG. 5. The neutron pairing energies, P_n. Values having errors larger than 0.2 mmu appear as open circles.

S_n, S_{2n}, and P_n have been plotted as functions of N in Fig. 3, Fig. 4, and Fig. 5, respectively. If an error larger than 0.2 mmu is associated with a particular

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[25] It should be pointed out that the measured mass differences are often more accurate than the corresponding atomic masses listed in Table VII. For this reason, separation energies and pairing energies were computed directly by using the adopted values of the isotopic doublets of Table II and the relevant nuclear data, wherever this procedure could give a value more accurate than the values obtainable by use of the atomic masses.

TABLE VIII. Separation energy of the last proton, S_p, and the proton pairing energy, P_p, for heavy nuclei.

Isotope	S_p, mmu	P_p, mmu
${}_{63}\mathrm{Eu}_{87}^{150}$	5.00±17	
Eu_{88}^{151}	5.18±16	
Eu_{89}^{152}	6.11±17	
Eu_{90}^{153}	6.22±28	
Eu_{91}^{154}	7.03±25	
Eu_{92}^{155}	7.18±32	
Eu_{93}^{156}	8.20±12	
${}_{64}\mathrm{Gd}_{88}^{152}$	7.94±21	2.76±26
Gd_{89}^{153}	7.99±29	1.88±34
Gd_{90}^{154}	8.27±32	2.06±43
Gd_{91}^{155}	8.16± 4	1.13±25
Gd_{92}^{156}	8.56± 4	1.38±32
Gd_{93}^{157}	8.72± 7	0.52±14
Gd_{94}^{158}	9.50±11	
${}_{65}\mathrm{Tb}_{93}^{158}$	6.53±26	
Tb_{94}^{159}	6.78±26	
Tb_{95}^{160}	6.89±21	
Tb_{96}^{161}	7.42±27	
${}_{66}\mathrm{Dy}_{94}^{160}$	7.83±22	1.05±34
Dy_{95}^{161}	8.05± 5	1.16±22
Dy_{96}^{162}	8.61± 5	1.19±28
${}_{67}\mathrm{Ho}_{97}^{164}$	5.88±23	
Ho_{98}^{165}	6.34±22	
Ho_{99}^{166}	7.08±22	
Ho_{100}^{167}	7.25±11	
${}_{68}\mathrm{Er}_{98}^{166}$	7.69±22	1.35±31
Er_{99}^{167}	8.07± 4	0.98±22
Er_{100}^{168}	8.58±11	1.32±16
${}_{69}\mathrm{Tm}_{99}^{168}$	5.68±23	
Tm_{100}^{169}	5.94±21	
Tm_{101}^{170}	6.60±20	
Tm_{102}^{171}	6.84±22	
${}_{70}\mathrm{Yb}_{100}^{170}$	7.28±20	1.34±29
Yb_{101}^{171}	7.31± 4	0.70±20
Yb_{102}^{172}	7.87± 4	1.02±22
${}_{71}\mathrm{Lu}_{103}^{174}$	5.60±20	
Lu_{104}^{175}	5.93±19	
Lu_{105}^{176}	6.39± 6	
Lu_{106}^{177}	6.39±17	
${}_{72}\mathrm{Hf}_{104}^{176}$	6.95±19	1.02±27
Hf_{105}^{177}	7.05± 6	0.66± 9
Hf_{106}^{178}	7.86± 5	1.47±18
${}_{73}\mathrm{Ta}_{104}^{177}$	4.75± 7	
Ta_{107}^{180}	6.61±18	
Ta_{108}^{181}	6.96±18	
Ta_{109}^{182}	6.77±16	
${}_{74}\mathrm{W}_{107}^{181}$	7.20±17	0.59±25
W_{108}^{182}	7.54±16	0.57±24
W_{109}^{183}	7.72± 4	0.95±17
W_{110}^{184}	8.32± 4	
W_{112}^{186}	8.58±22	
${}_{75}\mathrm{Re}_{110}^{185}$	6.01±19	
Re_{111}^{186}	6.28±25	
Re_{112}^{187}	6.62±22	
Re_{113}^{188}	7.02±28	
${}_{76}\mathrm{Os}_{110}^{186}$	6.97±25	0.96±31
Os_{111}^{187}	7.16± 4	0.87±25
Os_{112}^{188}	7.88±28	1.26±36
Os_{113}^{189}	7.87± 4	0.86±28
${}_{77}\mathrm{Ir}_{114}^{191}$	5.07±37	
Ir_{115}^{192}	6.09±37	
Ir_{116}^{193}	5.56±34	
Ir_{117}^{194}	6.93±30	
${}_{78}\mathrm{Pt}_{114}^{192}$	7.31±36	2.24±52
Pt_{115}^{193}	7.48±33	1.39±50
Pt_{116}^{194}	8.14±30	2.58±45
Pt_{117}^{195}	8.10± 4	1.17±30
${}_{79}\mathrm{Au}_{115}^{194}$	5.43±30	
Au_{116}^{195}	5.41± 5	
Au_{117}^{196}	5.90±17	
Au_{118}^{197}	5.98±18	
Au_{119}^{198}	6.80±15	
Au_{120}^{199}	(7.14±30)[a]	
Au_{121}^{200}	7.76±13	
${}_{80}\mathrm{Hg}_{116}^{196}$	6.94±16	1.54±17
Hg_{118}^{198}	7.72±10	1.74±21
Hg_{119}^{199}	7.82± 4	1.01±16
Hg_{120}^{200}	8.26± 4	(1.12±30)[a]
Hg_{121}^{201}	8.26±10	0.50±16
Hg_{122}^{202}	9.10±10	
${}_{81}\mathrm{Tl}_{122}^{203}$	6.20± 5	
Tl_{123}^{204}	6.70± 5	
Tl_{124}^{205}	6.79±12	
Tl_{125}^{206}	7.90±20	
${}_{82}\mathrm{Pb}_{122}^{204}$	7.00± 5	0.80± 7
Pb_{123}^{205}	7.17± 8	0.47± 9
Pb_{124}^{206}	7.88±12	1.09±17
Pb_{125}^{207}	8.09± 7	0.18±21
Pb_{126}^{208}	8.64± 5	
Pb_{127}^{209}	8.71± 4	
Pb_{128}^{210}	8.96± 6	
Pb_{129}^{211}	9.01±14	
${}_{83}\mathrm{Bi}_{122}^{205}$	3.50± 8	
Bi_{123}^{206}	3.78±14	
Bi_{124}^{207}	3.82± 5	
Bi_{125}^{208}	3.99± 8	
Bi_{126}^{209}	4.05± 4	
Bi_{127}^{210}	4.80± 4	
Bi_{128}^{211}	4.71± 6	
Bi_{129}^{212}	5.36± 9	
Bi_{130}^{213}	5.39± 5	
${}_{84}\mathrm{Po}_{123}^{207}$	4.85±12	1.07±18
Po_{124}^{208}	5.02± 9	1.20±10
Po_{125}^{209}	5.05±11	1.06±14
Po_{126}^{210}	5.38± 5	1.33± 6
Po_{127}^{211}	5.30± 4	0.49± 6
Po_{128}^{212}	6.28± 5	1.57± 8
Po_{129}^{213}	6.26± 5	0.91±10
Po_{130}^{214}	6.96± 6	1.56± 8
Po_{131}^{215}	7.02± 9	
${}_{85}\mathrm{At}_{124}^{209}$	2.92± 9	
At_{125}^{210}	3.07±13	
At_{126}^{211}	3.19± 6	
At_{128}^{213}	3.57±15	
At_{129}^{214}	4.33± 5	
At_{130}^{215}	4.36± 6	
At_{131}^{216}	4.88± 9	
At_{132}^{217}	5.09± 6	
${}_{86}\mathrm{Rn}_{125}^{211}$	4.49±11	1.42±17
Rn_{126}^{212}	4.59± 6	1.40± 9
Rn_{129}^{215}	5.50±15	1.17±16
Rn_{130}^{216}	6.27± 6	1.90± 9
Rn_{131}^{217}	6.32± 6	1.43±11
Rn_{132}^{218}	6.87± 6	1.78± 9
Rn_{133}^{219}	6.78±14	

[a] This value is calculated using the estimated total binding energy of Pt^{198}.

value, the point appears as an open circle. The points referring to neighboring isotopes of a particular element have been joined together by a solid line. A dashed line is employed to indicate that at least one intermediate point is missing.

All three plots show marked discontinuities corresponding to the major shell closure at $N=126$. The neutron separation energies for neutron numbers beyond $N=126$ have considerably smaller values than the values for $N=83$ to 126. For the case of even N,

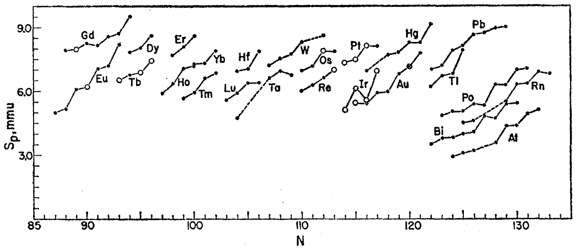

FIG. 6. The proton separation energies, S_p. Values having errors larger than 0.25 mmu appear as open circles. The value indicated by ⊗ is calculated using the estimated total binding energy of Pt^{198}.

$S_n(N=128)$ is, on the average, about 2.2 mmu smaller than $S_n(N=126)$ for the same element. For the case of odd N, this decrease is about 2.8 mmu. Johnson and Nier[1] reported a similar decrease as the shell edge at $N=82$ is crossed. They, however, did not report any difference between the even-N and the odd-N cases. A closer examination of the present data reveals that the neutron separation energies for $N=125$ are in general "anomalously high" by about 0.5 mmu. This anomalous increase is reflected in the values of neutron pairing energies for $N=126$, which have very low values in the case of all five elements represented in Fig. 5. The same anomalous increase for $S_n(N=125)$ appears to be responsible, at least in part, for the increase in average binding energy per nucleon in the vicinity of $Z=82$ and $N=126$, which was pointed out in an earlier paragraph. It may be pointed out that the value of $S_n(N=125)$ for Hg^{205} does not depict this anomalous increase. It may also be noted that the closure of the proton shell at $Z=82$ does not appear to give rise to any significant anomalies for the neutron separation and pairing energies.

The plots in Fig. 3 and Fig. 5 confirm with more completeness the anomalies in the neutron separation energies and the neutron pairing energies, which were reported earlier[1,2] in the regions around $N=90$ and $N=116$. A plot of S_{2n} against N in Fig. 4, which was not reported earlier, substantiates quite clearly the existence of anomalies in both of these regions. $S_{2n}(N=90)$ for Dy^{156} appears to have a particularly high value. In general, the discontinuities present in the region around $N=90$ appear to be more pronounced than the discontinuities present in the region around $N=116$.

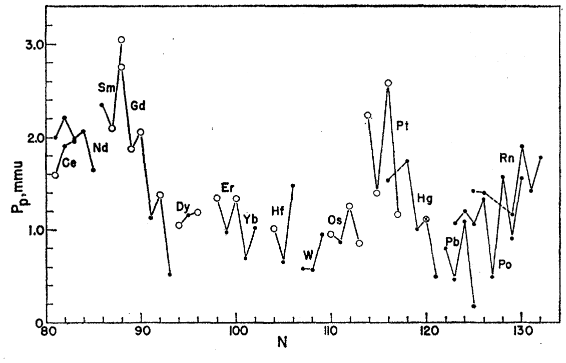

FIG. 7. The proton pairing energies, P_p. Values having errors larger than 0.25 mmu appear as open circles. The value indicated by ⊗ is calculated using the estimated total binding energy of Pt^{198}.

In a manner similar to the above, the proton separation energies, S_p, and the proton pairing energies, P_p, have been plotted as a function of N in Figs. 6 and 7, respectively. In contrast to the plots of neutron binding energies, the open-circle points in Figs. 6 and 7 indicate errors larger than 0.25 mmu. The proton pairing energies for cerium and neodymium have been taken from Johnson and Nier.[1] The plot of S_p depicts a marked discontinuity for the major shell closure at $Z=82$. Among the nuclei with the same neutron number N, the proton separation energies are reduced considerably as the shell edge at $Z=82$ is crossed. The proton pairing energies have a "minimum" for $Z=82$, a behavior similar to that of the neutron pairing energies at $N=126$.

In addition, the proton pairing energies show two pronounced maxima at $N=88$ and $N=116$. As remarked earlier, the neutron pairing energies also show maxima in the same regions at $N=90$ and $N=116$. The nature of this anomalous behavior appears to be different from the discontinuities connected with the major shell closures, where, for instance, the "magic" character of a particular neutron number N does not affect in a significant manner the behavior of the proton separation and pairing energies for nuclei with neutron numbers close to N. The discontinuities near $N=90$ and $N=116$ appear to be caused by a change in the nuclear structure in these regions. Such a change is indicated by other nuclear properties also, such as the isotope shifts, the electric quadrupole moments, and the ratio of the excited state energies. It is now well known that the region around 90 neutrons is the region of transition from a nuclear model characterized by vibrational energy states to one characterized by rotational energy states. The reverse transition takes place in the region around $N=116$. The fact that the nucleon pairing energies are rather large in these regions of transition indicates that the nucleon-nucleon interaction in the outermost shells acquires additional prominence in these regions.

Q VALUES IN THE HEAVY MASS REGION

The calculation of ground-state Q values is another important application of mass data. Comparison of these calculated values with the experimentally determined Q values provides an independent check for the latter value as well as its isotopic assignments. Most of the experimental Q values in the heavy mass region have been obtained by use of materials with natural isotopic abundance. For this reason, the isotopic assignments for these experimental Q values are difficult or impossible. The comparisons that may be made by use of the present mass data are, therefore, valuable in the assignment of these Q values. The following paragraphs discuss some of these comparisons.

Silva and Goldemberg[22] measured a (γ,n) threshold for samarium of -9.6 Mev and assigned it to the reaction $\mathrm{Sm}^{144}(\gamma,n)\mathrm{Sm}^{143}$. This gives a value of 10.3 mmu for $S_n(\mathrm{Sm}^{144})$. From the systematics of Johnson and Nier,[1] $S_n(\mathrm{Sm}^{144})$ may be estimated to be about 11.2 mmu. Sm^{144} has 82 neutrons and is the lightest stable isotope of samarium. The S_n values for all of the other stable isotopes of samarium are less than 9.0 mmu. It would appear, therefore, that the (γ,n) threshold measured by Silva and Goldemberg does not represent a ground-state transition for any stable isotope of samarium. It may, however, be assigned as an excited state transition for a stable isotope of samarium other than Sm^{144}.

Knowles et al.[26] have investigated neutron capture gamma rays from a source of separated isotope Gd^{157} and give a value of 8.509 ± 0.009 mmu for $S_n(\mathrm{Gd}^{158})$. This value is in excellent agreement with the value calculated from the present mass data. Kubitschek and Dancoff[27] assigned a gamma ray of energy 6.8 ± 0.4 mmu to the same reaction. Their value appears to be incorrect or misassigned.

Tobin et al.[28] have reported, on the basis of their photoneutron thresholds, S_n values of 7.20 ± 0.10 mmu and 7.01 ± 0.12 mmu for Hf^{177} and Hf^{179}, respectively. These values are about 0.4 mmu larger than the corresponding S_n values calculated from the present mass data. The differences in the ground-state spins of the initial and final nuclei,[20] for the reactions $\mathrm{Hf}^{177}(\gamma,n)\mathrm{Hf}^{176}$ and $\mathrm{Hf}^{179}(\gamma,n)\mathrm{Hf}^{178}$ are, respectively, 7/2 and 9/2. Under these circumstances, it is likely that their photoneutron thresholds do not represent ground-state transitions. Campion and Bartholomew[29] investigated the neutron capture gamma ray for hafnium. They did not make any isotopic assignments for the six observed gamma rays. A comparison of their results with the values given in Table VII, suggests several assignments. Their gamma ray A of energy equal to 8.18 ± 0.02 mmu should clearly be assigned to the reaction $\mathrm{Hf}^{177}(n,\gamma)\mathrm{Hf}^{178}$, for which the mass data predict a Q value of 8.18 ± 0.05 mmu. The other large value of S_n, predicted from the present mass data, is 7.90 ± 0.05 mmu for Hf^{180}. Gamma ray B reported by Campion and Bartholomew has an energy of 7.872 ± 0.032 mmu and should, therefore, be assigned to the reaction $\mathrm{Hf}^{179}(n,\gamma)\mathrm{Hf}^{180}$. Their gamma ray of energy equal to 6.545 ± 0.011 mmu can be assigned to a neutron capture by Hf^{178}. The present mass data predict an energy of 6.56 ± 0.05 mmu for the reaction $\mathrm{Hf}^{178}(n,\gamma)\mathrm{Hf}^{179}$. Their gamma ray D of energy 6.92 ± 0.02 mmu may possibly be assigned to the reaction $\mathrm{Hf}^{176}(n,\gamma)\mathrm{Hf}^{177}$. The mass data predict a Q value of 6.83 ± 0.05 mmu for this reaction. From the S_n systematics in this region, the gamma rays C and F of Campion and Bartholomew may be assigned to the reactions $\mathrm{Hf}^{174}(n,\gamma)\mathrm{Hf}^{175}$ and $\mathrm{Hf}^{180}(n,\gamma)\mathrm{Hf}^{181}$, respectively. This assignment will yield a value of 6.14 ± 0.09 mmu for $S_n(\mathrm{Hf}^{181})$. The present mass data combined with several Q values and beta-decay energies gives a value of 6.71 ± 0.18 mmu for $S_n(\mathrm{Hf}^{181})$. This value is believed to be in error. The former value derived from (n,γ) spectra appears to fit in better with the systematics of S_n.

The neutron capture gamma-ray spectrum for tungsten has been investigated by Kinsey and Bartholomew.[30] They assigned, tentatively, their gamma ray D of energy 6.640 ± 0.008 mmu to the reaction $\mathrm{W}^{182}(n,\gamma)\mathrm{W}^{183}$. The data of Table VII predict a ground-state gamma ray of energy equal to 6.70 ± 0.04 mmu for this reaction. It may be pointed out that the peak D of Kinsey and Bartholomew was complex in shape. Also, a level at 0.05 Mev for W^{184} has been reported.[20] These considerations suggest that the tentative assignment of gamma ray D is correct but the value for its energy may contain a small error. The same authors assigned tentatively their gamma ray A of energy 7.97 ± 0.02 mmu to the reaction $\mathrm{W}^{183}(n,\gamma)\mathrm{W}^{184}$. The mass data predict an energy of 8.01 ± 0.04 mmu. This agreement suggests that the tentative assignment made by Kinsey and Bartholomew is correct. There are also available two (γ,n) thresholds for tungsten at 6.72 ± 0.32 mmu and at 7.69 ± 0.32 mmu, determined by Sher et al.[31] A reference to Table VII indicates that these should be assigned to the reactions $\mathrm{W}^{183}(\gamma,n)\mathrm{W}^{182}$ and $\mathrm{W}^{186}(\gamma,n)\mathrm{W}^{185}$, respectively. Kubitschek and Dancoff[27] investigated the neutron capture gamma-ray spectrum for tungsten and gave a probable S_n value of 7.61 ± 0.3 mmu for W^{187}. The present data indicate that their Q value does not represent a ground-state transition for any isotope of tungsten.

For the element rhenium, Sher et al.[31] observed a (γ,n) threshold at 7.84 ± 0.32 mmu. Their probable assignment of this threshold was for the reaction $\mathrm{Re}^{187}(\gamma,n)\mathrm{Re}^{186}$. The present mass data, combined with the beta-decay energy for Re^{186} predict a threshold value of 7.94 ± 0.05 mmu for this reaction. S_n systematics for this region indicate that the threshold for the reaction $\mathrm{Re}^{185}(\gamma,n)\mathrm{Re}^{184}$ should be greater than the threshold for the reaction $\mathrm{Re}^{187}(\gamma,n)\mathrm{Re}^{186}$. This indicates that the probable assignment made by Sher et al.[31] is correct.

The $S_n(\mathrm{Ir}^{192})$ value obtained from the (n,γ) Q value

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[26] J. W. Knowles, G. A. Bartholomew, and P. J. Campion, Bull. Am. Phys. Soc. **4**, 246 (1959), and private communication.

[27] H. Kubitschek and S. M. Dancoff, Phys. Rev. **76**, 531 (1949).

[28] R. Tobin, J. McElhinney, and L. Cohen, Phys. Rev. **110**, 1388 (1958).

[29] P. J. Campion and G. A. Bartholomew, Can. J. Phys. **35**, 1361 (1957); erratum in Can. J. Phys. **36**, 1721 (1958).

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

[31] R. Sher, J. Halpern, and A. K. Mann, Phys. Rev. **84**, 387 (1951).

of Kubitschek and Dancoff[27] appears to be in error. $S_n(\mathrm{Ir}^{193})$ obtained from (γ,n) threshold of Sher et al.[31] has been considered to be correct. The details are given in the Appendix.

TABLE IX. Mass differences calculated from present values compared with nuclear values.

Mass difference	Present result (mmu)	Nuclear value (mmu)
$\mathrm{Gd}^{152}-\mathrm{Sm}^{148}-4$	6.64 ±20	5.75 ±10[a]
$\mathrm{Gd}^{152}-\mathrm{Sm}^{152}$	0.42 ±20	0.060±20
$\mathrm{Gd}^{155}-\mathrm{Sm}^{154}-1$	1.06 ±20	0.36 ±30[a]
$\mathrm{Gd}^{156}-\mathrm{Gd}^{155}-1$	−0.151±40	0.63 ± 5[a]
$\mathrm{Gd}^{158}-\mathrm{Gd}^{157}-1$	0.475±40	0.477±11[b]
		1.08 ± 5[a, c]
		2.2 ± 4[d]
$\mathrm{Dy}^{160}-\mathrm{Tb}^{159}-1$	0.31 ±15	0.05 ±40
$\mathrm{Gd}^{160}-\mathrm{Dy}^{160}$	2.30 ±20	<1.96 ± 1[e]
$\mathrm{Ho}^{165}-\mathrm{Er}^{164}-1$	1.64 ±25	1.34 ± 7
$\mathrm{Er}^{166}-\mathrm{Ho}^{165}-1$	0.16 ±25	0.35 ±40
$\mathrm{Lu}^{176}-\mathrm{Hf}^{176}$	1.69 ±18	1.07 ± 2
$\mathrm{Hf}^{177}-\mathrm{Hf}^{176}-1$	2.16 ± 5	1.79 ±10[f]
$\mathrm{Hf}^{179}-\mathrm{Hf}^{178}-1$	2.43 ± 5	1.98 ±13[f]
$\mathrm{W}^{183}-\mathrm{W}^{182}-1$	2.288±40	(2.346± 8)[c]
		2.27 ±30[g]
$\mathrm{W}^{184}-\mathrm{W}^{183}-1$	0.974±40	1.02 ± 2
$\mathrm{Re}^{187}-\mathrm{W}^{186}-1$	1.48 ±15	−0.05 ±30[a]
$\mathrm{Re}^{187}-\mathrm{Os}^{187}$	0.05 ±20[h]	<0.01
	−0.68 ±15[i]	
$\mathrm{Os}^{187}-\mathrm{Os}^{186}-1$	2.136±40	2.30 ±30
$\mathrm{Pt}^{192}-\mathrm{Os}^{188}-4$	6.98 ±25[j]	(∼6.7)
$\mathrm{Ir}^{193}-\mathrm{Ir}^{191}-2$	3.00 ± 9	4.06 ±30[a]
$\mathrm{Ir}^{193}-\mathrm{Pt}^{192}-1$	1.12 ±27	2.17 ±20
$\mathrm{Pt}^{194}-\mathrm{Pt}^{192}-2$	2.18 ±10	1.00 ±30[a]
$\mathrm{Pt}^{195}-\mathrm{Pt}^{194}-1$	2.446±40	(2.47 ± 4)[c]
		(2.43 ± 9)[k]
		2.4 ± 2[l]
$\mathrm{Pt}^{196}-\mathrm{Pt}^{195}-1$	0.480±40	0.480±13[c]
		0.18 ±20[g]
		0.43 ±20[l]
$\mathrm{Hg}^{200}-\mathrm{Hg}^{199}-1$	0.325±40	0.36 ± 3[l, m]
		1.4 ± 4[a, d]
		0.35 ±10[n]
$\mathrm{Hg}^{201}-\mathrm{Hg}^{200}-1$	2.269±40	2.09 ±20
$\mathrm{Pb}^{207}-\mathrm{Pb}^{206}-1$	1.742±40	1.754± 8[o]
		1.56 ± 7[k]
		1.79 ± 2[p]
		1.81 ± 5[q]
$\mathrm{Pb}^{208}-\mathrm{Pb}^{207}-1$	1.070±40	1.060± 8[o]
		0.96 ± 9[k]
		1.08 ± 3[l]
		1.08 ± 5[q]

[a] These values are based in part on nuclear reaction Q values whose isotopic assignment appears to be incorrect. See Appendix.

[b] See reference 26.

[c] See reference 30.

[d] See reference 27.

[e] This value is based on the assumption that $\mathrm{Tb}^{160}-\mathrm{Gd}^{160}<0$. Gd^{160} is known to be a stable nuclide.

[f] These values are based on (γ,n) thresholds of Tobin et al.[28] These may not represent ground-state transitions and isotopic assignment may also be wrong.

[g] See reference 31.

[h] This value is based on the doublet $\mathrm{C}^{13}\mathrm{C}_{11}\mathrm{H}_{27}\mathrm{N}-\mathrm{Os}^{186}$ of Table I.

[i] This value is based on the doublet $\mathrm{C}_{14}\mathrm{H}_{22}-\mathrm{Os}^{190}$ of Table I.

[j] The doublet $\mathrm{C}^{13}\mathrm{C}_{11}\mathrm{H}_{27}\mathrm{N}-\mathrm{Os}^{186}$ of Table I was employed to obtain the mass of Os^{188}.

[k] Weighted average of (γ,n) thresholds listed in reference 16.

[l] See reference 32.

[m] B. P. Ad'yasevich, L. V. Groshev, and A. M. Demidov, *Proceedings of the Conference of the Academy of Sciences of the U.S.S.R. on the Peaceful Uses of Atomic Energy, Moscow, July, 1955* (Akademiia Nauk, U.S.S.R., Moscow, 1955) [translation by Consultants Bureau, New York: Atomic Energy Commission Report TR-2435, 1956, p. 270].

[n] T. J. Kennett, L. M. Bollinger, and R. T. Carpenter, Bull. Am. Phys. Soc. **3**, 177 (1958). Error is not specified by the authors.

[o] See reference 37.

[p] M. T. McEllistrem et al., Phys. Rev. **111**, 1636 (1958).

[q] This is derived from (d,t) reaction listed in reference 16.

In the case of platinum, a number of nuclear Q values are available. Sher et al.[31] reported three photoneutron thresholds at −10.20±0.21 mmu, −6.55±0.21 mmu, and −8.81±0.21 mmu, which were assigned, respectively, to the reactions $\mathrm{Pt}^{194}(\gamma,n)\mathrm{Pt}^{193}$, $\mathrm{Pt}^{195}(\gamma,n)\mathrm{Pt}^{194}$, and $\mathrm{Pt}^{196}(\gamma,n)\mathrm{Pt}^{195}$. Harvey[32] reported Q values for $\mathrm{Pt}^{194}(d,p)\mathrm{Pt}^{195}$ and $\mathrm{Pt}^{195}(d,p)\mathrm{Pt}^{196}$. His data give for $S_n(\mathrm{Pt}^{195})$ and $S_n(\mathrm{Pt}^{196})$ the values 6.59±0.21 mmu and 8.55±0.21 mmu, respectively. Kinsey and Bartholomew[30] assigned their gamma rays of energy 6.52±0.04 mmu and 8.51±0.013 mmu to the reactions $\mathrm{Pt}^{194}(n,\gamma)\mathrm{Pt}^{195}$ and $\mathrm{Pt}^{195}(n,\gamma)\mathrm{Pt}^{196}$, respectively. A reference to Table VII indicates that the value for $S_n(\mathrm{Pt}^{195})$ and $S_n(\mathrm{Pt}^{196})$, computed by employing the mass spectroscopic data of Johnson and Bhanot,[2] are in agreement with the values derived from (n,γ) and (d,p) reactions. $S_n(\mathrm{Pt}^{194})$ and $S_n(\mathrm{Pt}^{196})$ derived from the photoneutron thresholds of Sher et al. appear to be too high. The threshold for $\mathrm{Pt}^{195}(\gamma,n)\mathrm{Pt}^{194}$ agrees with the mass spectroscopic as well as with the other nuclear data.

Three nuclear values are available for the mass difference $\mathrm{Hg}^{200}-\mathrm{Hg}^{199}$. These have been compared with the mass data in Table IX. The value of Kubitschek and Dancoff[27] for $\mathrm{Hg}^{199}(n,\gamma)\mathrm{Hg}^{200}$ is clearly incorrect or misassigned. The two other values are in agreement with the present mass data. The mass spectroscopic value for the mass difference $\mathrm{Hg}^{201}-\mathrm{Hg}^{200}$ leads to an S_n value of 6.68±0.03 mmu for Hg^{201}. The (γ,n) threshold of Hanson et al.[33] gives a value of 6.71±0.21 mmu for the same, indicating that their tentative assignment of the observed threshold to the reaction $\mathrm{Hg}^{201}(\gamma,n)\mathrm{Hg}^{200}$ is correct. Parsons and Collie[34] observed a photoneutron threshold for mercury at 7.09±0.21 mmu and assigned it to the reaction $\mathrm{Hg}^{201}(\gamma,n)\mathrm{Hg}^{200}$. A comparison with the mass spectroscopic value and with the photoneutron threshold of Hanson et al. indicates that Parsons and Collie's (γ,n) threshold is incorrect or misassigned. Their value may be assigned to the reaction $\mathrm{Hg}^{199}(\gamma,n)\mathrm{Hg}^{198}$. The present mass data predict a threshold of 7.18±0.04 mmu for this reaction.

Sher et al.[31] observed two thresholds for the (γ,n) reaction with a thallium target. Threshold energies of 9.45±0.21 mmu and 8.11±0.21 mmu were obtained. They assigned these to the reactions $\mathrm{Tl}^{203}(\gamma,n)\mathrm{Tl}^{202}$ and $\mathrm{Tl}^{205}(\gamma,n)\mathrm{Tl}^{204}$, respectively. For the latter reaction, two more nuclear values[20] were available. Both of these agree within the experimental errors with the threshold value given by Sher et al. However, the threshold of Sher et al. for the reaction $\mathrm{Tl}^{203}(\gamma,n)\mathrm{Tl}^{202}$ leads to a value for $S_n(\mathrm{Tl}^{203})$ that appears to be too high when compared to S_n systematics for the region. This

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[32] J. A. Harvey, Phys. Rev. **81**, 353 (1951).

[33] A. O. Hanson, R. B. Duffield, J. D. Knight, B. C. Diven, and H. Palevsky, Phys. Rev. **76**, 578 (1949).

[34] R. W. Parsons and C. H. Collie, Proc. Phys. Soc. (London) **A63**, 839 (1950).

threshold value was, therefore, not employed for the calculation of the mass of Tl^{202}. Harvey [32] investigated (d,p) reactions for a thallium target. Two Q values of 4.29 ± 0.15 Mev and 3.93 ± 0.15 Mev were obtained. These were assigned to the reactions $Tl^{203}(d,p)Tl^{204}$ and $Tl^{205}(d,p)Tl^{206}$, respectively. Neutron separation energies for Tl^{204} and Tl^{206} derived from the (n,γ) reactions are in agreement with the values derived by use of (d,p) Q values. Foreman and Seaborg[35] interchanged, somewhat arbitrarily, the S_n values for Tl^{204} and Tl^{206}. This interchange, however, is found to lead to a value for $S_n(Hg^{203})$ that does not fit in with the S_n systematics. Also, this interchange gives for $S_n(Tl^{203})$ a value that is smaller than $S_n(Tl^{205})$. This is contrary to the trends of S_n systematics for this region. It is believed, therefore, that the isotopic assignments made by Harvey[32] and by Bartholomew and Kinsey[36] are correct. It appears, however, that the Q values assigned to the reactions $Tl^{205}(n,\gamma)Tl^{206}$ and $Tl^{205}(d,p)Tl^{206}$ do not represent ground-state transitions. These two Q values were, therefore, not employed in the present study.

In the case of lead, many Q values are available.[20] All of these, except one, are found to be in agreement with one another and with the mass spectroscopic data, as shown in Table IX. The value in disagreement with the rest of the data is the threshold for the reaction $Pb^{208}(\gamma,n)Pb^{207}$ reported by Parsons and Collie.[34] It appears that this photoneutron threshold is incorrect. The (n,γ) spectra for "natural" lead as well as for a sample of radiogenic lead were investigated by Kinsey et al.[37] By a comparison of the intensities of the spectra from natural lead and from radiogenic lead, Kinsey et al. assigned their gamma rays of energy 6.734 Mev and 7.380 Mev to neutron capture in Pb^{206} and in Pb^{207}, respectively. They did not assign any gamma ray to a capture in Pb^{204}. They had observed a gamma ray of energy equal to 6.90 ± 0.05 Mev which they stated might be due to an impurity or due to a transition to an excited state of Pb^{208}. In addition, it appeared that the peak for the 6.7-Mev gamma ray in the case of natural lead was enhanced by another gamma ray due to some impurity. The masses given in Table VII lead to a value of 6.70 ± 0.08 Mev for $S_n(Pb^{205})$. This indicates that the contamination of the 6.7-Mev gamma ray was, possibly, a weak gamma ray of an almost equivalent energy due to a neutron capture in Pb^{204}. There is also the possibility that the mass data may contain small errors, and that $S_n(Pb^{205})$ should be close to 6.9 Mev. In that case the gamma ray of energy 6.90 ± 0.05 Mev, observed by Kinsey et al.,[37] may be assigned to a capture in Pb^{204}.

In the case of bismuth, the nuclear Q values[20] for the reactions $Bi^{209}(n,\gamma)Bi^{210}$ and $Bi^{209}(d,p)Bi^{210}$ have not been employed in the present work. It is believed that these do not represent ground-state transitions.

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APPENDIX

The various adjustments made in the preliminary mass spectroscopic mass table will now be discussed. Table IX lists the various nuclear values with the corresponding unadjusted mass spectroscopic values, wherever a comparison could be made. Quite a few listed nuclear values are based on nuclear reaction data for which isotopic assignments are considered to be doubtful. Such nuclear values were not employed as a basis for any adjustments. The remaining comparisons lead to the following considerations.

1. The mass spectroscopic value for the mass difference $Gd^{152}-Sm^{152}$ is found to be higher than the nuclear value which is considered to be quite well established. The mass of Gd^{152} is obtained from that of Gd^{156}. This indicates that either the mass of Gd^{156} is too high or the mass of Sm^{152} is too low or both. It may be noted here that the mass of Tb^{160} obtained from that of Dy^{160} by using the beta-decay Q value is found to be less than that of its stable isobar Gd^{160}. This is considered as an indication that either the mass of Gd^{156} is too high or the mass of Dy^{162} is too low or both. However, the comparison for the mass difference $Dy^{160}-Tb^{159}$ gives some indication that the mass of Dy^{162} may already be too high unless the mass of Tb^{159} is too low or the nuclear value is incorrect. Considering all these factors and in order to introduce a minimum number of arbitrary adjustments, the mass of Gd^{156} has been lowered by 0.36 mmu.
2. The disagreement for the mass difference $Ho^{165}-Er^{164}$ is not poor, considering the errors associated with the experimental data. The mass of Ho^{165} was reduced by about 0.19 mmu and the mass of Er^{168} was increased by about 0.11 mmu in order to eliminate this discrepancy.
3. A somewhat large inconsistency is found for the mass difference $Lu^{176}-Hf^{176}$. Since the mass of Hf^{176} has a smaller error associated with it and the beta-decay energy seems to be well established, the mass of Lu^{176} has been obtained from that of Hf^{176}. The mass for Lu^{175} is calculated from that of Lu^{176} by employment of the isotopic mass unit $Lu^{176}-Lu^{175}$ of Table II. Thus, the doublet value for Lu^{175} has not been employed.
4. The nuclear values for the hafnium isotopes were

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[35] G. M. Foreman, Jr., and G. T. Seaborg, J. Inorg. & Nuclear Chem. 7, 305 (1948).

[36] G. A. Bartholomew and B. B. Kinsey, Can. J. Phys. 31, 1025 (1953).

[37] B. B. Kinsey, G. A. Bartholomew, and W. H. Walker, Phys. Rev. 82, 380 (1951).

calculated from (n,γ) Q values of Tobin et al.[28] It appears that these do not represent ground-state transitions.

5. The next serious discrepancy occurs for one of the values for the mass difference $Re^{187}-Os^{187}$. The second value, which is obtained from the experimental mass of Os^{190} in combination with the osmium isotopic mass units, appears to be incorrect. The ion intensities for both components of this doublet were poor. This doublet has, therefore, been rejected in favor of the doublet $C^{13}C_{11}H_{27}N-Os^{186}$ of Table I, which gives directly the mass of Os^{186}. It is also possible that a part of the error may lie in the mass of Re^{185} or in the mass difference $Re^{187}-Re^{185}$. The choice for the osmium mass is, therefore, rather arbitrary.

6. The iridium masses presented probably the most serious inconsistencies. Several mass spectroscopic as well as nuclear values seem to be in error. The directly determined mass spectroscopic value for $Ir^{193}-Ir^{191}$ is more than 1 mmu lower than the corresponding nuclear value, which is obtained by combining the $Ir^{191}(n,\gamma)$ Q value of Kubitschek and Dancoff[27] with the $Ir^{193}(\gamma,n)$ threshold of Sher et al.[31] There is another discrepancy of about the same magnitude between the mass of Ir^{193} obtained from Ir^{191} via the isotopic doublet $Ir^{193}-Ir^{191}$ and the same mass computed from Pt^{192} via the $Ir^{193}(\gamma,n)$ threshold and the beta-decay energy of Ir^{192}. Both discrepancies could be resolved by assuming that the measured value of the double mass unit $Ir^{193}-Ir^{191}$ is low by about 1 mmu. In view of possible background contamination on both of the iridium peaks, such a large error is possible, but is not considered very likely. It should be noted that the (n,γ) value of Kubitschek and Dancoff leads to a value for $S_n(Ir^{192})$ which appears to be too low when compared to S_n values for similar neighboring nuclei. If this (n,γ) Q value is incorrect by about 1 Mev, the present value of the mass difference $Ir^{193}-Ir^{191}$ should be about correct. That will indicate either that the mass of Pt^{192} and so of Pt^{195} is wrong or that the mass of Ir^{191} is incorrect. With a view to introduce the minimum number of arbitrary changes, the experimental masses of the platinum isotopes were not changed. The mass of Ir^{193} was obtained from that of Pt^{192} by employing the $Ir^{193}(\gamma,n)$ threshold of Sher et al. and the beta-decay energy of Ir^{192}. The experimental value for $Ir^{193}-Ir^{191}$ was employed to obtain the mass of Ir^{191} from that of Ir^{193}. Thus, the doublet $C^{13}C_{13}H_{22}-Ir^{191}$ from Table I was rejected. At the same time the (n,γ) Q value of Kubitschek and Dancoff is adjusted through about 1 mmu.

The mass table was extended to the lighter region by adopting Johnson and Nier's values[1] for stable atomic masses of samarium and europium, except for one major change. Their value for Eu^{153} leads to values of neutron separation energies which do not fit very well with the systematics of the region. The doublet $C^{13}C_{12}H_{12}-Eu^{153}O^{16}$ from which this mass is obtained was a particularly difficult one to measure. This is reflected in its rather large quoted error of 0.4 mmu. The intensities of both ions comprising the doublet were poor. Because the comparison ion had a rather large $(C^{13})_2$ satellite, Johnson and Nier had to apply a correction to the measured value. In addition, the possibility exists that a peak due to $C_{13}H_{13}$, not resolvable with their resolution from $C^{13}C_{12}H_{12}$, may have contaminated the latter peak. Such a contamination, if undetected and so uncorrected for, will cause the measured value of Eu^{153} to be too small. An error in the same direction is indicated, in fact, by the neutron separation energy systematics. An increase of about 0.4 mmu in the mass of Eu^{153} will lead to more plausible trends in neutron separation energy systematics in the region. It may be noted that the quoted error for the measured value is also 0.4 mmu and so such a change is not very unlikely. Tentatively, this arbitrary adjustment has been adopted. Errors quoted by Johnson and Nier have also been changed in a few cases in order to bring them in line with the errors adopted for the heavier region.

The mass table was then extended to the heavier region by adopting the very precise values of Benson et al.[9] for stable atomic masses of mercury and lead (with a few minor changes). Recently, Demirkhanov et al.[10] have also published mass spectroscopic values for stable atomic masses for both of these elements. Their values disagree rather sharply with the values of Benson et al. In addition, several isotopic mass differences calculated from their data disagree rather badly with the nuclear values and with the present isotopic mass differences of Table II. Some of their isotopic mass differences agree with those of Benson et al. and with other values. However, this agreement does not rule out a constant shift in both of the masses from which a particular mass difference is derived. A closer examination of the two sets of data will show that the presence of C^{13} satellites on the "lines" of Demirkhanov et al. can lead to errors in the same direction as indicated by the discrepancies. However, it appears that the mass spectrograph employed by Demirkhanov et al. has a resolution which is sufficiently high to resolve the C^{13} satellites from the reference lines being employed. The reasons for these discrepancies are, therefore, not understood.

In the work of Benson et al., C^{13} satellites were clearly observable on their oscilloscope screen and were completely resolved from the ion peaks employed in their doublets. Isotopic mass differences calculated from their doublets are in excellent agreement with the nuclear values and with the values reported in the present work, except in the case of $Hg^{200}-Hg^{199}$. Even in this case, the disagreements are less than 0.1 mmu.

Recently, Kerr and Duckworth[11] also have published mass spectroscopic masses for Hg^{200}, Hg^{201}, and Hg^{204}.

Their values disagree with the values of Benson et al. It may be noted that Kerr and Duckworth employed only a part of a large mass spectrometer under construction. The employed part has only single-focusing properties. Also, their quoted errors are much larger than those of Benson et al.

In view of these considerations, the masses for mercury and lead isotopes of Benson et al. have been adopted with a few minor changes. These changes were made to obtain atomic masses consistent with the nuclear values for isotopic mass differences, and also consistent with the adopted values of Table II of the present work. The experimental masses of Benson et al. were in no case changed by more than 30 μmu.

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Gamma Rays from the Proton Bombardment of Natural Silicon*

L. W. Seagondollar, Gale I. Harris, and L. Kasturi Rangan
Department of Physics and Astronomy, University of Kansas, Lawrence, Kansas

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The gamma-ray yield curve was observed when thin targets of natural silicon were bombarded with monoergic protons in the energy range of 300 to 1840 kev. In order to take small steps in proton energy, a target potential modulation technique was used. Fifty-five resonances were observed, all but fifteen of which have been observed elsewhere using targets enriched in Si^{29} or Si^{30}. The fifteen resonances at 369, 1096, 1134, 1204, 1290, 1382, 1472, 1484, 1507, 1570, 1598, 1617, 1625, 1630, and 1653 kev are presumed due to the Si^{28} $+p$ reaction.

In an earlier attempt at this laboratory to measure the gamma-ray yield versus proton energy[1] resulting from proton bombardment of natural silicon, it was found that the resonances in the thin-target yield curve were very sharp and extremely small. The agreement of these earlier data with other comparable data[2,3] was generally good but certain discrepancies did exist.

Possible sources of discrepancies seemed to be (1) impurities in targets, (2) the size of steps taken in proton energy, and (3) the statistical accuracy of individual yield points. Detailed checks showed our targets free of contaminants in amounts sufficient to give detectable resonances. Great improvements were desired, however, in counting rates and in the method of taking steps in proton energy. A larger gamma-detector and the energy modulation system developed by Cranberg *et al.*[4] offered attractive improvements.

In the energy modulation system, the potential of the target is swept from 20 kv to -20 kv by a 10-cps "saw-tooth" high-voltage source. A single energy setting of the Van de Graaff is all that is necessary, in principle, to cover a 40 kev range of the yield curve. Correlation of a particular gamma ray with the energy of the proton which caused its emission is done by amplitude modulation of the pulses put out by the single-level, pulse-height discriminator in the gamma detection system. The modulated pulses are then analyzed in a multichannel pulse-height analyzer.

In the present work, protons were accelerated in the University of Kansas Van de Graaff generator, separated from the heavier hydrogen ions, passed through an electrostatic analyzer, and allowed to bombard thin targets. The electrostatic analyzer was a 1-meter radius, 127-degree deflection unit used as a relative instrument. It was calibrated by observation of the gamma resonance at 992-kev proton energy[5] in the aluminum yield curve. Linearity between the voltage across the analyzer gap and the generator voltage was verified by observation of many of the resonances in this same yield curve.

The thin targets were prepared by evaporation onto outgassed tungsten disks in a radio-frequency induction vacuum furnace.[6] Ultra-high purity silicon[7] was used to form targets of several-kev thickness. Several silicon targets, calibration targets, and a viewing disk of quartz were simultaneously mounted in a multiple-target chamber which was so designed that a 3 in.×3 in. NaI(Tl) gamma detector could be placed within $\frac{1}{2}$ inch of the disk being bombarded. A corona-reduction shield surrounded the target chamber.

The method of varying the potential of the target was identical to that developed by Cranberg *et al.* but a somewhat different system of pulse amplitude modu-

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