Mass Spectroscopic Atomic Mass Differences. II.*†

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I. INTRODUCTION

A BRIEF description is given of the mass spectroscopic methods in current use for the determination of atomic masses. The agreement between atomic masses so-derived and those obtained by studying the energy balance in nuclear reactions is also lightly touched upon, with particular reference to the mass of C^{12}. Finally, a table is given of the atomic mass differences which have been obtained mass spectroscopically during the past three years. This table supplements (and occasionally amends) a similar table which appeared[1] in the October, 1954, issue of this Journal.

II. PRECISION MASS SPECTROSCOPY

The mass spectroscopes employed in the study of atomic masses are necessarily high resolution instruments. With a single exception, those under construction or now in use are deflection instruments which take advantage of the double-focusing property which may be achieved by appropriately combining electrostatic and magnetic fields. The exception is the "mass synchrometer" of L. G. Smith[2] at the Brookhaven National Laboratory, in which measurements are made of the cyclotron frequencies of the motions of ions in a homogeneous magnetic field.

In a mass spectroscope, depending upon whether photographic or electrical detection is employed, "lines" or "peaks" are recorded. As a rule, in mass comparison work, *two* such lines or peaks are observed, representing two groups of ions whose specific charges are nearly equal. These constitute a "doublet," and it is the concern of the mass spectroscopist to ascertain, in terms of mass, the doublet spacing. Indeed, most of the data given in Table II, which is the principal *raison d'être* of this review, are simply mass differences for various doublets.

The precision with which such a mass difference can be determined is dependent upon the precision with which a line or peak may be located. Let us designate the mass width of a line or peak by Δm, a quantity which is directly proportional to the resolution ($\Delta m/m$)

of the mass spectroscope. In the case of photographic recording, the position of a mass spectral line may be determined to some fraction of its width, say 1/50 for an observer who is neither unduly optimistic nor unduly conservative. Thus, if a resolution of 1/20 000 be available, the mass of an atom may be determined with a precision of one part in a million. In practice the grain size ($\sim 10^{-4}$ cm) of the photographic plate sets a lower limit to the *actual* line width, with the result that, for a given size of mass spectroscope, the resolution cannot be improved beyond a certain point. This limit has been approximately reached by Mattauch and his collaborators[3] and by Ewald[4] who have achieved resolutions of 1/100 000 with mass spectrographs possessing dispersions of only 0.2 cm/1% mass difference. This corresponds to an actual line width of 2×10^{-4} cm.

With electrical recording, it has been demonstrated that it is possible to locate a peak with a precision of approximately 1/500 of its width, a tenfold improvement over the photographic case. This is done by the "peak-matching" technique introduced by Smith[5] and also employed, in a modified form, by Nier and his collaborators.[6] In this technique, by taking advantage of rapidly-responding detector systems, the two doublet peaks are made to appear on an oscilloscope screen on alternate sweeps. These two peaks are then brought into coincidence by adjustment of some circuit parameter (in Smith's case, a frequency; in Nier's case, a resistance) whose value gives the doublet mass difference. The peaks are thus "matched" by the human eye, an organ which can discern lack of coincidence with exceptionally keen discrimination. This peak-matching scheme is perhaps the most important single advance in precision mass spectroscopy since the discovery of the double-focusing principle in the mid-1930's. By this device, stated precisions have been regularly achieved of one part in 2×10^7 and, occasionally, of even one part in 10^8.

Partly because of the grain-size limitation in the case of photographic detection instruments but, even more, because of the difficulty of making and aligning the diminutive slits needed in small instruments if high resolution is to be attained, the current trend in precision mass spectroscopes is toward the bigger-and-better variety. Such instruments are larger than their predecessors by roughly an order of magnitude and are

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[1] Duckworth, Hogg, and Pennington, Revs. Modern Phys. 26, 463 (1954).

[2] L. G. Smith and C. C. Damm, Rev. Sci. Instr. 27, 638 (1956).

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[3] F. Everling, *Proceedings of the Mainz Conference on Atomic Masses* (Pergamon Press, New York, 1957).

[4] H. Ewald, Natl. Bur. Standards Circ. 522, 37 (1953).

[5] L. G. Smith and C. C. Damm, Phys. Rev. 90, 324 (1953).

[6] Quisenberry, Scolman, and Nier, Phys. Rev. 102, 1071 (1956).

TABLE I. Recent values for the mass of C^{12}.

Method	Investigator(s)	C^{12}	Error	Reference
Mass spectroscopic	Collins, Nier, and Johnson (1952)	12.003842	4	a
	Ogata and Matsuda (1953)	12.003844	6	b
	Mattauch and Bieri (1954)	12.0038231	33	Ma 54
	Smith (1955)	12.0038212	38	c
	Quisenberry, Scolman, and Nier (1955)	12.0038174	18	d
	Liebl and Ewald (1956)	12.003819	2	Li 56
	Kettner (1956)	12.003814	6	Ket 56
	Quisenberry, Scolman, and Nier (1956)	12.0038167	8	Qu 56
	Demirkhanov et al. (1956)	12.003820	5	De 56
	Smith (1957)	12.00381458	11	Sm 57
	Quisenberry, Giese, and Benson (1957)	12.0038156	4	Qu 57
Nuclear reactions	Li et al. (1951)	12.003804	17	e
	Wapstra (1955)	12.003803	5	f
	Mattauch et al. (1956)	12.0038000	39	g

a Collins, Nier, and Johnson, Phys. Rev. 86, 408 (1952).
b K. Ogata and H. Matsuda, Phys. Rev. 89, 27 (1953).
c L. G. Smith, Third Annual Meeting, Am. Soc. Testing Materials Committee E-14 on Mass Spectrometry (1955).
d Quisenberry, Scolman, and Nier, Phys. Rev. 100, 1245(A) (1955).
e Li, Whaling, Fowler, and Lauritsen, Phys. Rev. 83, 512 (1951).
f A. H. Wapstra, Physica 21, 367 (1955).
g Mattauch, Waldmann, Bieri, and Everling, Z. Naturforsch. 11a, 525 (1956).

under construction at Osaka University,[7,8] Harvard University,[9] the Max Planck Institute for Chemistry[10] and McMaster University.[11]

Although doublets are the traditional objects of study in precision mass spectroscopy, Johnson and Nier[12] have shown that electrical recording makes possible the determination of mass differences that are *much* larger than doublet spacings. This, with photographic detection, would require a knowledge of the dispersion of the mass spectrograph over a considerable range, a knowledge which no mass spectroscopist to date has had the temerity to aver that he possesses. With electrical recording, however, the ion groups are brought in turn to the same collector, say, by altering a resistance that determines the voltage across the electrostatic analyzer, as in Nier's case. Here the ions have each traveled identical paths at the time of detection, and the mass change in moving from one peak to another is proportional to the corresponding resistance change. The accuracy of this dispersion law has been repeatedly verified by determining directly the H^1 mass as, for example, from the $C_5H_8-C_5H_7$ mass difference. These "mass unit" (MU) mass differences do not carry with them the same precision as a doublet difference but they have already proved[13] an important means of determining neutron binding energies among the heavy atoms.

[7] K. Ogata and H. Matsuda, Z. Naturforsch. 10a, 843 (1955).
[8] K. Ogata and H. Matsuda, *Proceedings of the Mainz Conference on Atomic Masses* (Pergamon Press, New York, 1957).
[9] K. T. Bainbridge and T. L. Collins, *Proceedings of the Mainz Conference on Atomic Masses* (Pergamon Press, New York, 1957).
[10] Everling, Hintenberger, König, Mattauch, Müller-Warmuth, and Wende, *Proceedings of the Mainz Conference on Atomic Masses* (Pergamon Press, New York, 1957).
[11] Duckworth, Kerr, and Bainbridge, *Proceedings of the Mainz Conference on Atomic Masses* (Pergamon Press, New York, 1957).
[12] W. H. Johnson and A. O. Nier, Phys. Rev. 105, 1014 (1957).
[13] W. H. Johnson and V. B. Bhanot, Bull. Am. Phys. Soc. Ser. II, 2, 224 (1957).

III. MASS SPECTROSCOPIC *VERSUS* NUCLEAR REACTION MASSES—C^{12}

Three years ago, at the time the first compilation was prepared, the lack of agreement between the mass of C^{12} as determined mass spectroscopically and as derived from reaction data was a source of concern. In the interval, the absolute value of this discrepancy has been greatly reduced, in fact, from $\sim 40\,\mu$ MU to $\sim 15\,\mu$ MU. The discrepancy which remains, however, is still a real one which, statistically-speaking, is more significant than before. The evidence is presented in Table I.

Discrepancies exist elsewhere as well, but these are not so sharply defined, as the nuclides in question have not been the subject of such intense investigation. Giese and Benson,[14] at the University of Minnesota, have recently concluded a mass spectroscopic study of atomic masses in the region $31 \leqslant A \leqslant 55$. These results, when compared with the masses derived from nuclear reactions, show a discrepancy whose magnitude appears to be linearly dependent upon the distance by which the nuclide is removed from O^{16}. Such a discrepancy could be explained by assuming small errors in the determination of nuclear reaction Q's. These errors would be cumulative and, consequently, the total error would increase with the number of reaction stages connecting the nuclide in question to O^{16}. On the other hand, it is hard to imagine a systematic error in the mass spectroscopic work that could lead to this steadily-increasing type of discrepancy. True, an error in the mass of C^{12} is potentially present, but this is much smaller than the inconsistencies here referred to. In each case the mass of the atom is found by studying some particular doublet, that is, by a one-stage operation. Furthermore, the doublets employed by Giese and Benson are such that they do not

[14] C. F. Giese and Benson, Bull. Am. Phys. Soc. Ser. II, 2, 223 (1957).

TABLE II. Mass spectroscopic atomic mass differences.[a]

Element Z	A	Doublet	ΔM in mMU	Error	Reference
1 H	1	H_2-D	1.5483	10	De 56
		CH_2-N	12.5803	4	Qu 56
		CH_4-O	36.388	4	De 56
			36.3931	9	Qu 56
		NH_2-O	23.8164	5	Qu 56
		CH_4-NH_2	12.5804	5	Qu 56
		NH_3-OH	23.833	8	Ket 56
			23.8159	6	Qu 56
		NH_3-NDH	1.5478	4	Qu 56
		$C^{13}H_4-OH$	31.943	11	Ket 56
			31.9253	7	Sco 56
		H_2O-DO	1.5476	5	Qu 56
		H_2O-O^{18}	11.4033	21	Qu 56
		$N^{15}H_3-H_2O$	13.019	5	Ket 56
			13.0234	4	Sco 56
		$H_3O-H_2O^{17}$	3.601	6	Ket 56
		H_3O-HO^{18}	11.405	8	Ket 56
		$D_2O-H_2O^{18}$	8.3102	4	Qu 56
		D_2O-HF^{19}	16.8944	5	Sco 56
		C_2H_4-CO	36.3934	8	Qu 56
			36.3960	5	Qu 57
		$C_2H_4-N_2$	25.1585	6	Sco 56
		CH_3OH-O_2	36.3958	12	Qu 57
		$\frac{1}{2}C_4H_2O-O^{17}O$	11.224	9	Ket 56
		$\frac{1}{2}C_4H_4O-H_2S$	25.3926	9	Qu 56
		$\frac{1}{2}C_4H_4O-H_2O_2$	7.6312	8	Qu 57
		$\frac{1}{2}C_4H_4O-O^{18}O$	19.040	13	Ket 56
			19.0367	8	Qu 56
		$C_3H_4-A^{40}$	68.9344	13	Qu 56
			68.9346	11	Qu 57
		$C_3H_8-CO_2$	72.7870	16	Qu 56
			72.7932	16	Qu 57
D	2	H_2-D	1.5483	10	De 56
		D_2-He^4	25.600	2	De 56
		$D_3-\frac{1}{2}C$	42.298	7	De 56
		NH_3-NDH	1.5478	4	Qu 56
		H_2O-DO	1.5476	5	Qu 56
		CD_4-D_2O	33.29453	11	Sm 57
		ND_3-D_2O	22.26447	10	Sm 57
		CD_4-ND_3	11.03006	10	Sm 57
		CD_4-Ne^{20}	63.97896	13	Sm 57
		ND_3-Ne^{20}	52.94890	12	Sm 57
		D_2O-Ne^{20}	30.6872	7	Sco 56
			30.68443	12	Sm 57
		$CD_4-\frac{1}{2}A^{40}$	75.22626	17	Sm 57
		$D_2O-\frac{1}{2}A^{40}$	41.9390	13	Qu 56
			41.93173	15	Sm 57
		$ND_3-\frac{1}{2}A^{40}$	64.19620	16	Sm 57
		$C_3D_8-C_4D_2$	84.62526	22	Sm 57
2 He	4	D_2-He^4	25.600	2	De 56
		$He_2^4-\frac{1}{2}O$	‡7.7543	44	Ma 54
5 B	10	$B^{10}H-B^{11}$	11.450	12	Li 56
		$B^{10}B^{11}H_2-Na^{23}$	48.130	10	Li 56
		$B^{10}F_2^{19}-S^{32}O$	42.7730	17	Sco 56
	11	$B^{11}H-B^{11}$	11.450	12	Li 56
		$B^{11}H-C$	17.139	7	Li 56
		$B^{10}B^{11}H_2-Na^{23}$	48.130	10	Li 56
		$C_4H_4O-B^{11}F_3^{19}$	21.7052	13	Sco 56
6 C	12	$D_3-\frac{1}{2}C$	42.298	7	De 56
		CH_2-N	12.5803	4	Qu 56
		CH_4-NH_2	12.5804	5	Qu 56
		CH_4-O	36.388	4	De 56
			36.3931	9	Qu 56
		CD_4-D_2O	33.29453	11	Sm 57
		CD_4-ND_3	11.03006	10	Sm 57
		CD_4-Ne^{20}	63.97896	13	Sm 57
		$CD_4-\frac{1}{2}A^{40}$	75.22626	17	Sm 57
6 C	12	C_2H_4-CO	36.3934	8	Qu 56
			36.3960	5	Qu 57
		$C_2H_4-N_2$	25.1585	6	Sco 56
		N_2-CO	11.2355	6	Sco 56
		CH_3OH-O_2	36.3958	12	Qu 57
		$\frac{1}{2}C_4H_2O-O^{17}O$	11.224	9	Ket 56
		$\frac{1}{2}C_4H_4O-H_2S$	25.3926	9	Qu 56
		$\frac{1}{2}C_4H_4O-H_2O_2$	7.6312	8	Qu 57
		$\frac{1}{2}C_4H_4O-O^{18}O$	19.040	13	Ket 56
			19.0367	8	Qu 56
		$C_3H_4-A^{40}$	68.9344	13	Qu 56
			68.9346	11	Qu 57
		$C_3H_8-CO_2$	72.7870	16	Qu 56
			72.7932	16	Qu 57
		N_2O-CO_2	11.244	10	Kr 57
		C_4-SO	33.0269	13	Qu 56
		$C_3D_8-C_4D_2$	84.62526	22	Sm 57
	13	$C^{13}H_4-HO$	31.943	11	Ket 56
			31.9253	7	Sco 56
7 N	14	CH_2-N	12.5803	4	Qu 56
		NH_2-O	23.8164	5	Qu 56
		NH_3-OH	23.833	8	Ket 56
			23.8159	6	Qu 56
		CD_4-ND_3	11.03006	10	Sm 57
		ND_3-D_2O	22.26447	10	Sm 57
		ND_3-Ne^{20}	52.94890	12	Sm 57
		$ND_3-\frac{1}{2}A^{40}$	64.19620	16	Sm 57
		$C_2H_4-N_2$	25.1585	6	Qu 56
		N_2-CO	11.2355	6	Sco 56
		N_2O-CO_2	11.244	10	Kr 57
	15	CH_3-N^{15}	23.3652	9	Sco 56
		$N^{15}H_3-H_2O$	13.019	5	Ket 56
			13.0234	4	Sco 56
8 O	17	$OH-O^{17}$	3.6077	5	Sco 56
		$H_3O-H_2O^{17}$	3.601	6	Ket 56
		$\frac{1}{2}C_4H_2O-O^{17}O$	11.224	9	Ket 56
	18	H_2O-O^{18}	11.4033	21	Qu 56
		H_3O-HO^{18}	11.405	8	Ket 56
		$D_2O-H_2O^{18}$	8.3102	4	Qu 56
		$H_2O^{18}-HF^{19}$	8.582	2	Ket 56
		$H_2O^{18}-Ne^{20}$	22.392	5	Ket 56
			22.3770	6	Sco 56
		$HDO^{18}-Ne^{21}$	27.2482	7	Sco 56
		$\frac{1}{2}COO^{18}-Na^{23}$	7.2592	20	Sco 56
		$\frac{1}{2}C_4H_4O-O^{18}O$	19.040	13	Ket 56
			19.0367	8	Qu 56
9 F	19	$HDO-F^{19}$	18.4380	14	Sco 56
		$H_2O^{18}-HF^{19}$	8.582	2	Ket 56
		D_2O-HF^{19}	16.8944	5	Sco 56
		$B^{10}F_2^{19}-SO$	42.7730	17	Sco 56
		$C_4H_4O-B^{11}F_3^{19}$	21.7052	13	Sco 56
		$C_5H_9-CF_3^{19}$	75.2462	20	Sco 56
		$C_6H_{13}-Si^{28}F_3^{19}$	129.625	4	Sco 56
		$C_6H_{14}-Si^{29}F_3^{19}$	137.889	7	Sco 56
		$C_4H_7O_2-Si^{30}F_3^{19}$	75.6590	36	Sco 56
10 Ne	20	CD_4-Ne^{20}	63.97896	13	Sm 57
		ND_3-Ne^{20}	52.94890	12*	Sm 57
		D_2O-Ne^{20}	30.6872	7	Sco 56
			30.68443	12	Sm 57
		$H_2O^{18}-Ne^{20}$	22.392	5	Ket 56
			22.3770	6	Qu 56
		$Ne^{20}-\frac{1}{2}A^{40}$	11.24730	18	Sm 57
	21	$\frac{1}{2}C_2H_2O-Ne^{21}$	11.429	5	Ket 56
		$HDO^{18}-Ne^{21}$	27.2482	7	Sco 56
	22	$\frac{1}{2}CO_2-Ne^{22}$	3.521	12	Ket 56
			3.5307	6	Sco 56

[a] Special symbols appearing in this table are defined in the second last paragraph of Sec. IV.

TABLE II.—*Continued.*

Element Z	A	Doublet	ΔM in mMU	Error	Reference
11 Na	23	$B^{10}B^{11}H_2-Na^{23}$	48.130	10	Li 56
		$\frac{1}{2}COO^{18}-Na^{23}$	7.2592	20	Sco 56
12 Mg	24	C_2-Mg^{24}	14.9621	11	Sco 56
	25	C_2H-Mg^{25}	21.9944	10	Sco 56
	26	$C_2H_2-Mg^{26}$	33.0676	10	Sco 56
13 Al	27	$C_2H_3-Al^{27}$	41.9548	23	Sco 56
14 Si	28	$C_6H_{13}-Si^{28}F_3^{19}$	129.625	4	Sco 56
	29	$C_6H_{14}-Si^{29}F_3^{19}$	137.889	7	Sco 56
	30	$C_4H_7O_2-Si^{30}F_3^{19}$	75.6590	36	Sco 56
15 P	31	$O_2-P^{31}H$	8.2423	6	Ge 57
16 S	32	O_2-S	17.756	10	Sch 56
			17.7599	9	Qu 56
			17.7623	11	Qu 57
		$HS-S^{33}$	8.448	25	Sch 56
		$\frac{1}{2}C_4H_4O-H_2S$	25.3926	9	Qu 56
	33	$HS-S^{33}$	8.448	25	Sch 56
		$C_4H-S^{33}O$	41.4602	15	Ge 57
	34	H_2S-S^{34}	19.851	10	Sch 56
		$C_3-H_2S^{34}$	16.466	10	Sch 56
		$C_4H_2-S^{34}O$	52.9889	15	Ge 57
	36	$C_4H_4-S^{36}O$	69.3175	35	Ge 57
17 Cl	35	$HCl^{35}-A^{36}$	9.1346	9	Ge 57
		$C_5H_{10}-Cl_2^{35}$	140.5850	34	Ge 57
	37	$HCl^{37}-A^{38}$	11.0001	10	Ge 57
		$C_6H_2-Cl_2^{37}$	83.8692	23	Ge 57
18 A	36	$H_2O-\frac{1}{2}A^{36}$	(26.7937	6)	Qu 56
		C_3-A^{36}	(32.4729	20)	Qu 56
		$HCl^{35}-A^{36}$	9.1346	9	Ge 57
	38	$HCl^{37}-A^{38}$	11.0001	10	Ge 57
	40	$CD_4-\frac{1}{2}A^{40}$	75.22626	17	Sm 57
		$ND_3-\frac{1}{2}A^{40}$	64.19620	16	Sm 57
		$D_2O-\frac{1}{2}A^{40}$	41.9390	13	Qu 56
			41.93173	15	Sm 57
		$Ne^{20}-\frac{1}{2}A^{40}$	11.24730	18	Sm 57
		$C_3H_4-A^{40}$	68.9344	13	Qu 56
			68.9346	11	Qu 57
19 K	39	$C_3H_3-K^{39}$	59.762	20	Li 56
			59.7819	15	Ge 57
		C_2HN-K^{39}	‡47.58	8	He 51
	40	$C_3H_4-K^{40}$	67.3178	21	Ge 57
	41	$C_3H_5-K^{41}$	77.331	20	Li 56
			77.3167	19	Ge 57
		$C_2H_3N-K^{41}$	‡65.13	5	He 51
20 Ca	40	$C_3H_4-Ca^{40}$	68.7341	15	Ge 57
	42	$C_3H_6-Ca^{42}$	88.3500	22	Ge 57
	43	$C_3H_7-Ca^{43}$	96.0186	26	Ge 57
	44	CO_2-Ca^{44}	34.3442	24	Ge 57
	46	CSH_2-Ca^{46}	34.0462	39	Ge 57
	48	C_4-Ca^{48}	47.4964	55	Ge 57
21 Sc	45	$CSH-Sc^{45}$	23.9873	18	Ge 57
22 Ti	46	CSH_2-Ti^{46}	35.1026	14	Ge 57
	47	CSH_3-Ti^{47}	43.8035	30	Ge 57
	48	$SO-Ti^{48}$	19.0476	12	Ge 57
	49	C_4H-Ti^{49}	59.9781	15	Ge 57
	50	$C_4H_2-Ti^{50}$	70.8839	18	Ge 57
23 V	50	$C_4H_2-V^{50}$	68.5076	15	Ge 57
	51	$C_4H_3-V^{51}$	79.5223	18	Ge 57
24 Cr	50	$C_4H_2-Cr^{50}$	69.6218	18	Ge 57
	52	$C_4H_4-Cr^{52}$	90.8165	17	Ge 57
	53	$C_4H_5-Cr^{53}$	98.5062	21	Ge 57

Element Z	A	Doublet	ΔM in mMU	Error	Reference
24 Cr	54	$C_4H_6-Cr^{54}$	108.1099	23	Ge 57
25 Mn	55	$C_4H_7-Mn^{55}$	116.7547	22	Ge 57
		$\frac{1}{3}Ho^{165}-Mn^{55}$	§38.3	3	Ho 54
26 Fe	54	$C_4H_6-Fe^{54}$	107.374	4	Qu 56a
	56	$Si^{28}-\frac{1}{2}Fe^{56}$	§9.30	6	Du 50
		$C_4H_8-Fe^{56}$	127.698	4	Qu 56a
	57	$C_4H_9-Fe^{57}$	135.005	7	Qu 56a
	58	$C_4H_{10}-Fe^{58}$	144.977	4	Qu 56a
27 Co	59	$C_2H_3O_2-Co^{59}$	80.1466	23	Qu 56a
28 Ni	58	$C_4H_{10}-Ni^{58}$	142.941	7	Qu 56a
		$C_3H_6O-Ni^{58}$	106.52	15	Ea 56
	60	$C_2H_4O_2-Ni^{60}$	90.387	6	Qu 56a
			90.82	15	Ea 56
	61	$C_2H_5O_2-Ni^{61}$	97.894	5	Qu 56a
	62	$C_5H_2-Ni^{62}$	87.339	6	Qu 56a
	64	SO_2-Ni^{64}	33.901	5	Qu 56a
29 Cu	63	$C_5H_3-Cu^{63}$	93.909	7	Qu 56a
	65	$C_5H_5-Cu^{65}$	111.377	4	Qu 56a
30 Zn	64	$O_2-\frac{1}{2}Zn^{64}$	25.45	15	Kr 55
			25.2633	26	Qu 56a
		SO_2-Zn^{64}	32.7687	32	Qu 56a
	66	$C_5H_6-Zn^{66}$	120.935	6	Qu 56a
		$\frac{1}{2}Xe^{132}-Zn^{66}$	25.61	15	Kr 55
30 Zn	67	$C_5H_7-Zn^{67}$	127.675	7	Qu 56a
		$\frac{1}{2}Xe^{134}-Zn^{67}$	25.25	20	Kr 55
	68	$C_5H_8-Zn^{68}$	137.781	4	Qu 56a
		$\frac{1}{2}Xe^{136}-Zn^{68}$	27.70	20	Kr 55
	70	$C_5H_{10}-Zn^{70}$	152.953	6	Qu 56a
36 Kr	84	$CH_2Cl_2^{35}-Kr^{84}$	41.849	33	Kr 57
	86	$\frac{1}{2}Xe^{129}-\frac{1}{2}Kr^{86}$	12.969	17	Kr 57
		$CHCl^{35}F_2^{19}-Kr^{86}$	62.733	49	Kr 57
38 Sr	88	$CO_2-\frac{1}{2}Sr^{88}$	§37.00	18	Du 51a
39 Y	89	$C_8H_9-Y^{89}O$	§169.84	11	Co 54
54 Xe	126	$C_5H_3-\frac{1}{2}Xe^{126}$	§71.27	7	Ha 52
	129	$\frac{1}{2}Xe^{129}-\frac{1}{2}Kr^{86}$	12.969	17	Kr 57
	130	$C_6H_{10}O_3-Xe^{130}$	159.53	3	Jo 57
	131	$C_{10}H_{11}-Xe^{131}$	181.05	4	Jo 57
	132	$CO_2-\frac{1}{3}Xe^{132}$	21.762	20	Kr 57
		$\frac{1}{2}Xe^{132}-Zn^{66}$	25.61	15	Kr 55
		$C_{10}H_{12}-Xe^{132}$	189.79	5	Jo 57
	134	$\frac{1}{2}Xe^{134}-Zn^{67}$	25.25	20	Kr 55
		$C_{10}H_{14}-Xe^{134}$	204.20	5	Jo 57
	136	$\frac{1}{2}Xe^{136}-Zn^{68}$	27.70	20	Kr 55
		$C_{10}H_{16}-Xe^{136}$	218.055	25	Jo 57
55 Cs	133	$C_{10}H_{13}-Cs^{133}$	196.66	7	Jo 57
56 Ba	130	$C_6H_{10}O_3-Ba^{130}$	156.24	20	Jo 57
	132	$C_{10}H_{12}-Ba^{132}$	188.84	12	Jo 57
	134	$C_{10}H_{14}-Ba^{134}$	205.36	8	Jo 57
	135	$C^{13}C_9H_{14}-Ba^{135}$	207.40	10	Jo 57
	136	$C_{10}H_{16}-Ba^{136}$	220.89	9	Jo 57
	137	$C^{13}C_9H_{16}-Ba^{137}$	223.08	6	Jo 57
	138	$C_{10}H_{18}-Ba^{138}$	236.03	8	Jo 57
57 La	138	$C_{10}H_{18}-La^{138}$	234.17	20	Jo 57
	139	$C^{13}C_9H_{18}-La^{139}$	238.23	6	Jo 57
58 Ce	136	$C_{10}H_{16}-Ce^{136}$	218.19	20	Jo 57
	138	$C_{10}H_{18}-Ce^{138}$	234.89	20	Jo 57
	140	$C_{10}H_{20}-Ce^{140}$	251.29	6	Jo 57
	142	$C_{10}H_{22}-Ce^{142}$	262.93	7	Jo 57

regularly increase in width as heavier atoms are investigated. If this latter had not been the case, a systematic error that increased with doublet spacing might have provided an explanation for the mounting inconsistencies.

Among heavier atoms, particularly in the iron-nickel-zinc region, certain large discrepancies[15] between mass differences as calculated from mass spectroscopy and as derived from reaction energies have been virtually removed.[16] Large inconsistencies still exist in the 50-neutron region.

In short, the absolute agreement between the results from these two major sources of atomic mass information has much improved in the past three years. The remaining dissonance would be greatly lessened and, incidentally, great joy would be brought to the heart of the mass spectroscopist, if a *small* systematic error were to be found among Q-value determinations.

IV. TABLE OF ATOMIC MASS DIFFERENCES

In Table II are listed the atomic mass differences which have been obtained by mass spectroscopic methods in the past three years. These data supplement those in Tables II, III, and IV of reference 1. Appearing herein is a good deal of information which has not, at the time of writing (June 1957), been published.

In reference 1 the doublets that were used to obtain the masses of the secondary standards H^1, D^2, and C^{12} were tabulated separately. Recently, however, several new doublet cycles that provide means of calculating these masses have been introduced,[17,6,18] with the result that there is now a rather formidable number of "fundamental" doublets, some of which are sacrosanct in one laboratory but not in another. For this reason, and also because a number of heavier atoms are likely to be added[19] to the list of secondary standards, all the mass data are here shown in a single table.

The mass differences in Table II are arranged according to element in order of increasing atomic number, Z, and, within the given element, according to isotope in order of increasing mass number, A. The entries associated with any particular nuclide represent those data which may be useful in calculating the mass of the nuclide in question. As a result there are many double entries, for example, the H_2O-DO mass difference is listed under both H and D. On the other hand, the $C_{12}H_{10}-Sm^{154}$ mass difference is listed only under Sm^{154}. Although it does involve both H and C, this difference is not of practical use in determining the masses of these two atoms.

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TABLE II.—Continued.

Element Z	A	Doublet	ΔM in mMU	Error	Reference
59 Pr	141	$C_{11}H_9-Pr^{141}$	163.00	3	Jo 57
60 Nd	142	$C_{10}H_{22}-Nd^{142}$	264.74	3	Jo 57
	143	$C^{13}C_{10}H_{10}-Nd^{143}$	172.08	10	Jo 57
	144	$C_{10}H_5F^{19}-Nd^{144}$	127.77	7	Jo 57
	145	$C_{10}H_6F^{19}-Nd^{145}$	133.33	19	Jo 57
	146	$C_{10}H_7F^{19}-Nd^{146}$	140.53	6	Jo 57
	148	$C_2^{13}C_8H_7F^{19}-Nd^{148}$	143.46	6	Jo 57
	150	$C_9H_{10}O_2-Nd^{150}$	147.30	7	Jo 57
62 Sm	144	$C_{10}H_5F^{19}-Sm^{144}$	125.92	9	Jo 57
	147	$C^{13}C_9H_7F^{19}-Sm^{147}$	142.09	3	Jo 57
	148	$Sm^{148}-Sm^{147}$	†1000.25		Jo 57
		$Sm^{149}-Sm^{148}$	†1002.71		Jo 57
	149	$Sm^{149}-Sm^{148}$	†1002.71		Jo 57
		$Sm^{150}-Sm^{149}$	†1000.42		Jo 57
	150	$C_9H_{10}O_2-Sm^{150}$	151.23	7	Jo 57
	152	$C_{12}H_8-Sm^{152}$	143.29	13	Jo 57
	154	$C_{12}H_{10}-Sm^{154}$	156.37	15	Jo 57
63 Eu	151	$C_{12}H_7-Eu^{151}$	135.26	17	Jo 57
		$C_{13}H_{11}-Eu^{151}O$	171.69	19	Jo 57
	153	$C^{13}C_{12}H_{12}-Eu^{153}O$	181.8	4	Jo 57
64 Gd	154	$Gd^{155}-Gd^{154}$	†1002.15	6	Jo 57a
	155	$Gd^{156}-Gd^{155}$	†999.90	6	Jo 57a
	156	$Gd^{157}-Gd^{156}$	†1002.20	6	Jo 57a
	157	$Gd^{158}-Gd^{157}$	†1000.53	6	Jo 57a
66 Dy	160	$Dy^{161}-Dy^{160}$	†1002.10	6	Jo 57a
	161	$Dy^{162}-Dy^{161}$	†1000.21	6	Jo 57a
	162	$Dy^{163}-Dy^{162}$	†1002.26	6	Jo 57a
	163	$Dy^{164}-Dy^{163}$	†1000.80	6	Jo 57a
67 Ho	165	$\frac{1}{3}Ho^{165}-Mn^{55}$	§38.3	3	Ho 54
68 Er	166	$Er^{167}-Er^{166}$	†1002.06	6	Jo 57a
	167	$Er^{168}-Er^{167}$	†1000.65	6	Jo 57a
70 Yb	170	$Yb^{171}-Yb^{170}$	†1001.88	6	Jo 57a
	171	$Yb^{172}-Yb^{171}$	†1000.40	6	Jo 57a
	172	$Yb^{173}-Yb^{172}$	†1002.17	6	Jo 57a
	173	$Yb^{174}-Yb^{173}$	†1000.97	6	Jo 57a
72 Hf	176	$Hf^{177}-Hf^{176}$	†1002.25	6	Jo 57a
	177	$Hf^{178}-Hf^{177}$	†1000.88	6	Jo 57a
	178	$Hf^{179}-Hf^{178}$	†1002.36	6	Jo 57a
	179	$Hf^{180}-Hf^{179}$	†1001.13	6	Jo 57a
74 W	182	$W^{183}-W^{182}$	†1002.23	6	Jo 57a
	183	$W^{184}-W^{183}$	†1000.99	6	Jo 57a
76 Os	186	$Os^{187}-Os^{186}$	†1002.14	6	Jo 57a
	187	$Os^{188}-Os^{187}$	†1000.33	6	Jo 57a
	188	$Os^{189}-Os^{188}$	†1002.55	6	Jo 57a
	189	$Os^{190}-Os^{189}$	†1000.52	6	Jo 57a
78 Pt	194	$Pt^{195}-Pt^{194}$	†1002.45	6	Jo 57a
	195	$Pt^{196}-Pt^{195}$	†1000.49	6	Jo 57a
80 Hg	198	$Hg^{199}-Hg^{198}$	†1001.82	6	Jo 57a
	199	$Hg^{200}-Hg^{199}$	†1000.31	6	Jo 57a
	200	$Hg^{201}-Hg^{200}$	†1002.26	6	Jo 57a
	201	$Hg^{202}-Hg^{201}$	†1000.64	6	Jo 57a
82 Pb	206	$Pb^{207}-Pb^{206}$	†1001.74	6	Jo 57a
	207	$Pb^{208}-Pb^{207}$	†1001.06	6	Jo 57a

Symbols appearing in Table II have the following significance: ‡ indicates a datum omitted in the tables of reference 1, § indicates a correction to the tables of

reference 1, and † designates mass differences which are not true doublets but are, rather, mass-unit differences of the type described in the concluding paragraph of Sec. II. A datum in parentheses indicates that the investigator originally responsible for it now views it with suspicion. As before, it should be assumed that later values supersede earlier values from the same laboratory.

The reader should consult the original papers for descriptions of the assigned errors. In most cases these are probable errors based *only* on the internal consistency of the data. The frequency with which two entries for the same doublet agree within the stated errors suggests that systematic errors are roughly comparable in size to the statistical ones.

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