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Masses of Light Atoms

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The mass differences of 33 doublets have been measured with a modified Bainbridge-Jordan type mass spectrograph, which has an experimental resolving power of about 60 000. In general, the values obtained are in good agreement with other mass spectroscopic data and with those calculated from nuclear disintegration energies. However, for the $C^{12}(H^1)_4-O^{16}$ doublet, the discrepancy between the present value 364.19 ± 0.06 ($\times 10^{-4}$ amu) and the value 363.72 ± 0.19 obtained from nuclear data does not seem to be negligible. The author calculated the atomic mass of C^{12}, one of the mass substandards, from the four different doublet sets, one with the $C^{12}(H^1)_4-O^{16}$ doublet and the others without. The four values of the C^{12} mass obtained were found to be in good agreement with one another, and their weighted average, 12.003844 ± 6, was adopted as the atomic mass of C^{12}. Other mass substandards H^1 and D^2 were calculated from the $(H^1)_2-D^2$ doublet and the $(D^2)_3-\frac{1}{2}C^{12}$ doublet using the above C^{12} mass, and the atomic masses of H^1 and D^2 were obtained to be $H^1=1.008145\pm 2$, $D^2=2.014741\pm 3$. The atomic masses of other isotopes were determined by using these mass substandards.

I. INTRODUCTION

RECENTLY, Q-value determinations of many nuclear reactions have been made with great accuracy, especially for light nuclei, and in the low mass region, the atomic masses may be determined from the reaction data only without any mass spectroscopic data. The old mass difference values measured by the mass spectrograph were not in good agreement with those calculated from the nuclear reactions. For instance, Mattauch's value of the $(H^1)_2-D^2$ mass difference, 15.39 ± 0.021 ($\times 10^{-4}$ amu),[1] differs from the (1951) nuclear reaction value, 15.494 ± 0.024.[2] The difference between the two values is about four times the probable error in the latter. As for the $(D^2)_2-He^4$ doublet, the Bainbridge-Jordan value, 256.1 ± 0.4,[3] of 1937 is larger than the nuclear reaction value, 255.0 ± 0.23,[4] calculated from the available (1950) data by Bainbridge, by about four times the probable error in the latter value. (In the latter case improved Q determinations[2] brought agreement with the mass spectrographic value.) However, about two or three years ago mass difference redeterminations of light atomic mass doublets were started by Ewald,[5] Mattauch,[6] and Nier[7] and their collaborators, and the discrepancy between mass spectroscopic data and nuclear data has tended to become small, except for the $C^{12}(H^1)_4-O^{16}$ doublet.

In Osaka University, since 1939, mass determinations with the double-focusing mass spectrograph of the Bainbridge-Jordan type have been carried on for about thirty isotopes.[8] However, at that time, the experimental resolving power of the apparatus was about 7–8000, and close doublets, for example $(C^{12})_n(H^1)_m-(C^{12})_{n-1}C^{13}H_{m-1}$ ($n>2$), could not be resolved with it. So, since 1947, in order to obtain higher resolving power, the apparatus has been remodeled, and remeasurement of mass differences was started towards the end of 1950.

II. APPARATUS

A detailed description of the present modified Bainbridge-Jordan type mass spectrograph has been reported previously,[9] but the authors wish to introduce in this paper a brief description of the main points of the improvement. In Fig. 1, a schematic view of the

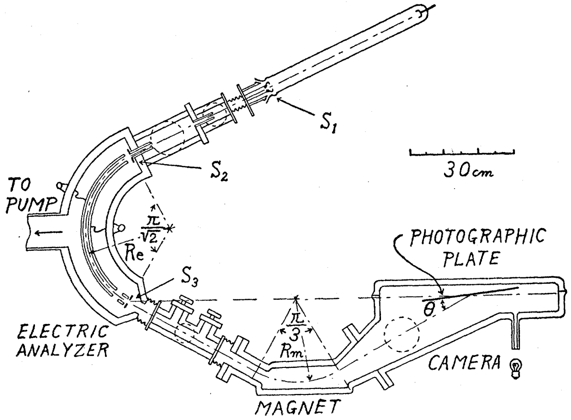

FIG. 1. Schematic drawing of modified Bainbridge-Jordan type mass spectrograph. The radius of the central beam in the electric and magnetic field, r_e and r_m, are both 25 cm. S_1 is a hole with a diameter of 0.5 mm, and S_2 is the principal slit, whose width is 0.005–0.008 mm and length about 0.2 mm, and the distance between them is about 45 cm. S_3 is the energy selecting slit with a width of about 0.08 mm. The inclination angle θ of the photographic plate relative to the central beam is about 24°.

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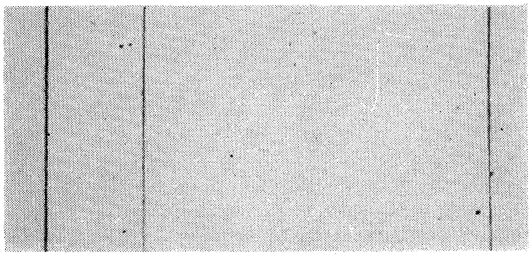
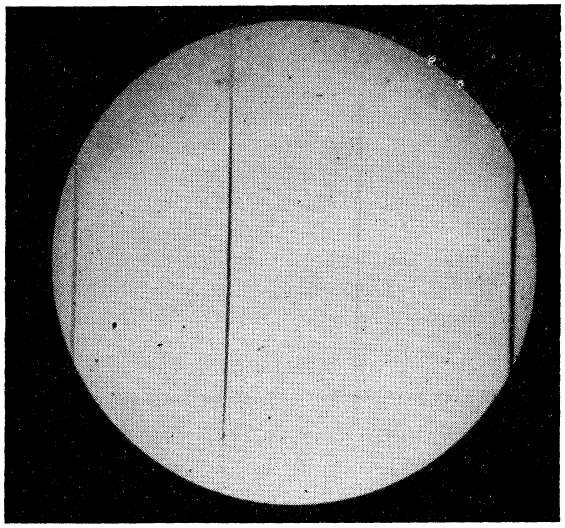
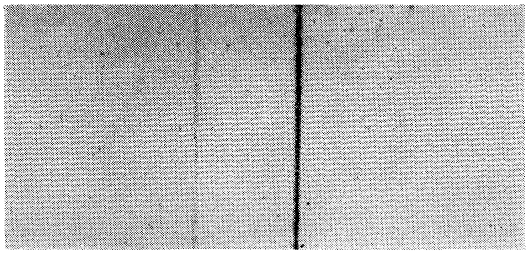
[9] K. Ogata and H. Matsuda, Symposium on Mass Spectroscopy, National Bureau of Standards (1951) (to be published).



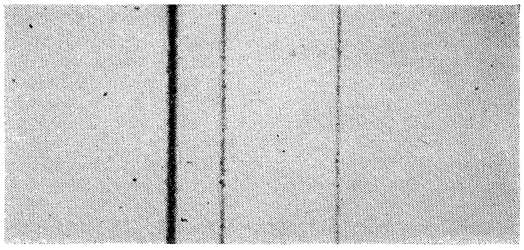
(a) $(D^2)_2-He^4$ doublet. (×20)



(b) $(D^2)_2O^{16}-Ne^{20}$ doublet. (×20)



(c) $(H^1)_2-D^2$ doublet. (×30)



(d) $C^{12}(H^1)_4-(N^{14})_2-C^{12}O^{16}$ triplet. (×30)

FIG. 2. Some typical doublets.

apparatus is given. The main parts of the apparatus, electric field and magnetic field, are quite similar to those of the old Bainbridge-Jordan type; that is, the angle of the electric field and that of the magnetic field are $\pi/(2)^{\frac{1}{2}}$ and $\pi/3$, respectively, and the radius of the center beam is 25 cm in both fields. However, the collimating system and the location of the photographic plate were modified as shown in the figure. The collimating system consists of a hole S_1 and a slit S_2. The diameter of the hole S_1 is about 0.5 mm, the width of the slit S_2 is 0.005–0.008 mm, and the length 0.2 mm; and the distance between S_1 and S_2 is about 45 cm. S_3 is the energy selecting slit, whose width is 0.08–0.13 mm. Under these collimating conditions, the focal depth of the energy focusing is ten times greater than that of the direction focusing, and so the photographic plate is set along the directional focal plane, that is, at 24° to the central beam. Under this condition, the length of the sharp focusing region is about 6 cm on the photographic plate, and the center of the region is slightly on the lower mass side from the double focusing point.

The dry cells are used as the voltage supply to the electric field and their middle point is on the ground potential, and a 6–18 volt 100-amp hr storage battery is used as the magnetic field current supply. Their stability is completely sufficient during the exposure period, which is a few minutes in general. Under these conditions, a maximum experimental resolving power of about 60 000 was obtained.

The ion source is a discharge tube of ordinary Wien-type, whose diameter is 5 cm and length 50 cm, and whose discharge voltage is about 20 kv. The photographic plates now used are of Schumann-type prepared in our laboratory. In Fig. 2, some typical doublets are shown

III. DETERMINATION OF DOUBLET MASS DIFFERENCES

When the mass difference of a doublet is determined from its line separation, the following relation is as-

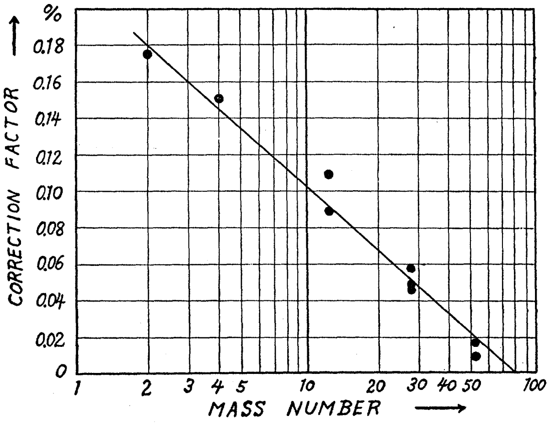


FIG. 3. Correction curve for mass dispersion referred to the Br—HBr line pair as the mass calibration standard.

TABLE I. Mass doublets.

Row	A	Doublet	No. of doublets (plates)	ΔM in 10^{-4} amu	Previous work
1	2	$(H^1)_2-D^2$	85(4)	15.492±0.008[a]	15.519±0.017[c]
					15.45 ±0.08[d]
					15.503±0.015[e]
					15.489±0.043[f]
2	4	$(D^2)_2-He^4$	36(3)	256.03 ±0.06	256.12 ±0.09[g]
					256.04 ±0.08[h]
3	6	$(D^2)_3-\frac{1}{2}C^{12}$	44(4)	423.01 ±0.09[a]	422.92 ±0.12[e]
4	10	$B^{10}-\frac{1}{2}Ne^{20}$	39(3)	167.22 ±0.08	
5	11	$B^{11}-\frac{1}{2}Ne^{22}$	18(2)	136.20 ±0.08	
6	11	$B^{10}H^1-B^{11}$	11(1)	114.47 ±0.14	
7	30	$B^{10}H^1F^{19}-B^{11}F^{19}$	18(2)	114.50 ±0.15	
		Weighted Average		114.48 ±0.10	
8	12	$B^{10}D^2-C^{12}$	16(2)	270.16 ±0.20	
9	12	$B^{11}H^1-C^{12}$	41(3)	171.15 ±0.06	
10	14	$C^{12}(H^1)_2-N^{14}$	36(4)	125.84 ±0.05[b]	125.97 ±0.21[g]
					125.64 ±0.10[e]
11	28	$(C^{12})_2(H^1)_4-(N^{14})_2$	37(4)	251.61 ±0.11[a]	251.70 ±0.25[g]
		Weighted Average		125.83 ±0.04	125.86 ±0.13[g]
12	15	$C^{12}(H^1)_3-N^{15}$	45(2)	233.77 ±0.06[b]	233.08 ±0.20[i]
13	16	$C^{12}(H^1)_4-O^{16}$	75(4)	364.15 ±0.08[b]	364.80 ±0.63[g]
14	28	$(C^{12})_2(H^1)_4-C^{12}O^{16}$	72(6)	364.23 ±0.08[a]	364.43 ±0.22[g]
		Weighted Average		364.19 ±0.06	363.71 ±0.12[e]
					364.52 ±0.10[f]
					364.27 ±0.08[j]
15	20	$(D^2)_2O^{16}-(H^1)_2O^{18}$	18(2)	83.09 ±0.18	83.12 ±0.12[e]
16	20	$(D^2)_2O^{16}-Ne^{20}$	31(3)	307.10 ±0.11	307.21 ±0.39[g]
					306.88 ±0.10[e]
17	20	$(D^2)_2O^{16}-\frac{1}{2}A^{40}$	24(2)	419.18 ±0.14	419.67 ±0.18[g]
					419.53 ±0.12[e]
18	27	$(C^{12})_2(H^1)_3-C^{12}C^{13}H^1$	20(2)	44.84 ±0.10	44.10 ±0.08[i]
19	27	$(C^{12})_2(H^1)_3-Al^{27}$	25(4)	420.14 ±0.18	
20	28	$(N^{14})_2-C^{12}O^{16}$	38(3)	112.54 ±0.09	112.73 ±0.14[g]
21	28	$C^{12}O^{16}-Si^{28}$	34(4)	180.18 ±0.14	180.15 ±0.30[e]
					180.6 ±0.8[k]
22	29	$C^{13}O^{16}-Si^{29}$	19(2)	218.00 ±0.17	
23	29	$B^{10}F^{19}-C^{13}O^{16}$	17(2)	130.49 ±0.15	
24	30	$B^{11}F^{19}-Si^{30}$	18(2)	339.48 ±0.20	
25	32	$(O^{16})_2-S^{32}$	88(5)	177.25 ±0.08[a]	177.16 ±0.20[e]
					177.64 ±0.07[j]
26	34	$S^{32}(H^1)_2-S^{34}$	64(5)	198.47 ±0.22[a]	
27	35	$S^{33}(H^1)_2-S^{34}H^1$	27(3)	113.77 ±0.32	
28	36	$(C^{12})_3-S^{34}(H^1)_2$	44(4)	165.45 ±0.22[a]	
29	36	$(C^{12})_3-H^1Cl^{35}$	21(2)	233.23 ±0.12	233.41 ±0.44[j]
30	37	$(C^{12})_3H^1-Cl^{37}$	22(2)	420.01 ±0.14	
31	38	$(C^{12})_3(H^1)_2-H^1Cl^{37}$	20(2)	420.03 ±0.14	420.14 ±0.46[j]
		Weighted Average		420.02 ±0.10	
32	40	$(C^{12})_3(H^1)_4-A^{40}$	22(3)	689.37 ±0.28	688.77 ±0.35[g]
33	48	$(C^{12})_4-S^{32}O^{16}$	32(4)	331.22 ±0.22[b]	331.32 ±0.13[j]

[a] The weighted average of the value determined by the new calibration method and that by the stray field correction on the previous data (see references 9 and 10).
[b] Determined by the stray field correction on the previous data (see references 9 and 10).
[c] T. R. Roberts, Phys. Rev. **81**, 624 (1951).
[d] Sommer, Thomas, and Hipple, Phys. Rev. **82**, 697 (1951).
[e] H. Ewald, Z. Naturforsch. **6a**, 293 (1951).
[f] See reference 6.
[g] A. O. Nier and T. R. Roberts, reference 7.
[h] H. Ewald, Z. Naturforsch. **5a**, 1 (1950).
[i] H. Ewald, Z. Naturforsch. **1**, 131 (1946).
[j] T. L. Collins, *et al.*, reference 7.
[k] H. E. Duckworth and R. S. Preston, Phys. Rev. **79**, 402 (1950).

sumed for a wider line pair (suffix 2) and a narrower doublet (suffix 1) corresponding to the required mass difference at its center:

$$\left(\frac{\Delta m_1}{m_1}\right)\Big/\Delta D_1=\left(\frac{\Delta m_2}{m_2}\right)\Big/\Delta D_2.$$

From this equation, if the fractional mass difference $\Delta m_2/m_2$ is known as the calibration standard, $\Delta m_1/m_1$ could be calculated by measuring the line separations ΔD_1 and ΔD_2.

In previous papers,[9,10] the Br−HBr line pair was used as the mass calibration standard. However, it was later found that with this mass calibration some systematic errors (about 0.2 percent at most) might be introduced to the mass differences of the doublets, especially in the light mass region. The cause of this systematic error may be attributed to the difference in the stray magnetic field, due to the difference between the field strength required for the calibration standard

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[10] K. Ogata and H. Matsuda, Phys. Rev. **83**, 180 (1951).

and that for the doublet. In this case the above relation may not hold as accurately as it should, due to the difference in the dispersion constant for the doublet and for the standard line pair. Therefore, some corrections may be necessary for the mass differences previously reported.[9,10] The correction factor was obtained in the following way. First, two different sets of line pairs of the same fractional mass differences, such as $C_nH_m - C_nH_{m+1}$ and $C_{2n}H_{2m} - C_{2n}H_{2m+2}$ were recorded at the same position on a photographic plate by changing the magnetic field strength, and then the line separations for those two different sets were compared; from these the ratio of the dispersion constant could be obtained. Such an examination was performed for various fields, and the correction curve obtained is shown in Fig. 3, referring to the BrH−Br lines. The percentage correction read off from Fig. 3 should be reduced from the previous data.[9,10] The mass differences corrected with the above correction curve were found to be in good agreement with the mass differences obtained by the following calibration method.

In this paper, a new calibration method is described, in which complicated corrections such as those mentioned above are carefully avoided by using as the calibration standards the hydrocarbon lines which could be recorded with the same magnetic field strength as for the doublets to be measured. However, when the C_1-group is used for calibration standards, a correction of about +0.02 percent is necessary in the dispersion constant because of the wide separation. For the doublets of isotopes lighter than $M=12$, the above stray field correction may be necessary because no hydrocarbon lines could be used.

The systematic errors from other causes have been investigated; these are: (1) a possible effect of the shift of the center potential of the electric field from the ground potential, (2) an effect of the difference in line intensity of the doublet, (3) an effect depending on whether the atomic-molecular doublet or the molecular-molecular doublet is used. As already reported,[9] the errors of the above type have been proved to have no serious effects on the results for the conditions under which the measurements were made.

TABLE II. Zero cycles of mass doublets.

Cycle	$\Delta 10^{-4}$ amu
$(B^{10}D^2 - C^{12}) - (B^{10}H^1 - B^{11}) - (B^{11}H^1 - C^{12}) + [(H^1)_2 - D^2]$	$+0.02 \pm 0.24$
$[C^{12}(H^1)_2 - N^{14}] + \frac{1}{2}[(N^{14})_2 - C^{12}O^{16}] - \frac{1}{2}[C^{12}(H^1)_4 - O^{16}]$	0.00 ± 0.07
$[(D^2)_3 - \frac{1}{2}C^{12}] - \frac{3}{2}[C^{12}(H^1)_4 - O^{16}] - \frac{1}{2}[(O^{16})_2 - S^{32}] + \frac{1}{2}[(C^{12})_4 - S^{32}O^{16}] + 3[(H^1)_2 - D^2]$	$+0.18 \pm 0.16$
$[C^{12}(H^1)_4 - O^{16}] - [(C^{12})_4 - S^{32}O^{16}] - [S^{32}(H^1)_2 - S^{34}] + [(C^{12})_3 - S^{34}(H^1)_2]$	-0.05 ± 0.32
$\frac{1}{2}[(D^2)_2O^{16} - Ne^{20}] - (B^{10} - \frac{1}{2}Ne^{20}) + (B^{10}H^1 - B^{11}) + (B^{11}H^1 - C^{12}) - \frac{1}{2}[C^{12}(H^1)_4 - O^{16}] + \frac{1}{2}[(C^{12})_3 - S^{34}(H^1)_2] - \frac{1}{2}[S^{32}(H^1)_2 - S^{34}] - \frac{1}{2}[(O^{16})_2 - S^{32}] + [(H^1)_2 - D^2]$	$+0.21 \pm 0.23$
$(B^{10} - \frac{1}{2}Ne^{20}) - \frac{1}{2}[(D^2)_2O^{16} - Ne^{20}] - (B^{10}D^2 - C^{12}) + [(D^2)_2O^{16} - \frac{1}{2}A^{40}] - \frac{1}{2}[(C^{12})_3(H^1)_4 - A^{40}] + \frac{1}{2}[C^{12}(H^1)_4 - O^{16}]$	$+0.25 \pm 0.30$
$[(D^2)_2O^{16} - \frac{1}{2}A^{40}] - \frac{1}{2}[(C^{12})_3(H^1)_4 - A^{40}] + 2[(H^1)_2 - D^2] - \frac{1}{2}[(H^1)_2S^{32} - S^{34}] + \frac{1}{2}[(C^{12})_3 - S^{34}(H^1)_2] - \frac{1}{2}[(O^{16})_2 - S^{32}]$	$+0.33 \pm 0.25$

IV. DOUBLET MASS DIFFERENCE

The mass differences determined with particular attention to the above-mentioned points are summarized in Table I. In the table some of the values of the mass differences recently reported by others are also included for reference. The errors given in the table include not only the purely statistical errors and errors due to the deviation of the dispersion constant, about 0.03 percent, but also the errors due to the stray field correction, about 0.02 percent. In general, the present values are in good agreement with the recent values reported by others. However, for the $C^{12}(H^1)_4 - O^{16}$ doublet the discrepancy between our present result and that of Ewald[5] is about five times as large as his error, and for the $(O^{16})_2 - S^{32}$ doublet, the recent result of Collins *et al.*,[7] is greater than ours by six times their error. The mass difference for the $S^{33}(H^1)_2 - S^{34}H^1$ doublet, calculated from the results obtained by Collins *et al.* for the $(C^{12})_4H^1 - S^{33}O^{16}$ and $(C^{12})_4(H^1)_2 - S^{34}O^{16}$ doublets, is 115.15±0.61, while the result obtained by the authors by direct measurement is 113.77±0.32.

In order to check the reliability of the results obtained, several zero-cycles were calculated, and are given in Table II. The consistency between the results obtained could be considered to be satisfactory.

In Table III(a), the present values are compared with the mass differences calculated from the Q-values of Li *et al.*'s table,[2] and in Table III(b), Q-values computed from our mass data are compared with those from nuclear reactions. As may be observed in Table III(a), the mass differences from the present mass spectroscopic measurements are in good agreement with those from nuclear reactions except for the $C^{12}(H^1)_4 - O^{16}$ doublet, in which the difference is about two times as large as the error. In Table III(b), the Q-value, 3.116 ±0.004 Mev, for $O^{16}(d, \alpha)N^{14}$ is greater than that calculated from our mass data by about three times the error of the difference

V. ATOMIC MASS

To calculate the atomic masses from the doublets obtained above, the mass substandards H^1, D^2, and C^{12} must first be determined. These masses, in general, are computed from the so-called fundamental doublets, $(H^1)_2 - D^2$, $(D^2)_3 - \frac{1}{2}C^{12}$, and $C^{12}(H^1)_4 - O^{16}$. However, the agreement between the mass spectroscopic value for $C^{12}(H^1)_4 - O^{16}$ and the nuclear reaction value is not satisfactory, while for $(H^1)_2 - D^2$ and $(D^2)_3 - \frac{1}{2}C^{12}$ consistant values are obtained with either method. For

Table III. Comparison with nuclear reaction data.

(a) Doublet mass differences

Doublet	From Table I ΔM_1, 10^{-4} amu	Calculated from nuclear data ΔM_2, 10^{-4} amu[a]	$(\Delta M_2-\Delta M_1)$ in 10^{-4} amu
$(H^1)_2-D^2$	15.492±0.008	15.494±0.024	+0.002±0.025
$(D^2)_2-He^4$	256.03 ±0.06	255.96 ±0.08	−0.07 ±0.10
$(D^2)_3-\frac{1}{2}C^{12}$	423.01 ±0.09	423.02 ±0.16	+0.01 ±0.18
$B^{10}H^1-B^{11}$	114.48 ±0.10	114.66 ±0.09[b]	+0.19 ±0.14
$B^{10}D^2-C^{12}$	270.16 ±0.20	270.44 ±0.15[c]	+0.28 ±0.25
$B^{11}H^1-C^{12}$	171.15 ±0.06	171.27 ±0.11[d]	+0.12 ±0.13
$C^{12}(H^1)_2-N^{14}$	125.83 ±0.04	125.73 ±0.12[e]	−0.10 ±0.13
$C^{12}(H^1)_3-N^{15}$	233.77 ±0.06	233.68 ±0.11[f]	−0.09 ±0.12
$C^{12}(H^1)_4-O^{16}$	364.19 ±0.06	363.72 ±0.19[g]	−0.47 ±0.20
$(C^{12})_2(H^1)_3-C^{12}C^{13}(H^1)_2$	44.84 ±0.10	44.74 ±0.09[h]	−0.10 ±0.13

(b) Q-values.

Reaction	Q_1 calculated from Table I, in Mev[i]	Q_2 from nuclear reaction in Mev	(Q_1-Q_2) in Mev
$B^{10}(d,p)B^{11}$	9.217±0.014	9.234±0.009[j]	−0.017±0.017
$C^{12}(d,p)C^{13}$	2.733±0.009	2.723±0.004[j]	+0.010±0.010
$C^{13}(d,\alpha)B^{11}$	5.171±0.013	5.163±0.005[j]	+0.008±0.014
$N^{14}(d,p)N^{15}$	8.609±0.007	8.608±0.007[j]	+0.001±0.010
$N^{15}(p,\alpha)C^{12}$	4.957±0.008	4.961±0.005[j]	−0.004±0.009
$N^{15}(d,\alpha)C^{13}$	7.693±0.012	7.684±0.006[j]	+0.009±0.013
$O^{16}(d,\alpha)N^{14}$	3.088±0.009	3.116±0.004[j]	−0.028±0.010
$S^{32}(d,p)S^{33}$	6.445±0.036	6.422±0.011[k]	+0.023±0.038
$Si^{28}(d,p)Si^{29}$	6.254±0.023	6.246±0.008[k]	+0.008±0.024
$Si^{29}(d,p)Si^{30}$	8.379±0.030	8.388±0.013[l]	−0.009±0.033
$Si^{29}(d,\alpha)Al^{27}$	6.018±0.032	5.994±0.011[l]	+0.024±0.034

1 amu=931.152 Mev.

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[a] These mass differences are calculated from the Q-values listed in the paper of C. W. Li *et al.*, reference 2.
[b] $B^{10}(d,p)B^{11}$, $(2p-d)$.
[c] $C^{12}(d,p)C^{13}$, $C^{13}(d,\alpha)B^{11}$, $B^{10}(d,p)B^{11}$ and $(2d-\alpha)$.
[d] $C^{12}(d,p)C^{13}$, $C^{13}(d,\alpha)B^{11}$, $(2d-\alpha)$.
[e] $N^{14}(d,p)N^{15}$, $N^{15}(p,\alpha)C^{12}$, $(2p-d)$, $(2d-\alpha)$.
[f] $N^{15}(p,\alpha)C^{12}$, $(2p-d$, $(2d-\alpha)$.
[g] $O^{16}(d,\alpha)N^{14}$, $N^{14}(d,p)N^{15}$, $N^{15}(p,\alpha)C^{12}$, $(2d-\alpha)$, $(2p-d)$.
[h] $C^{12}(d,p)C^{13}$, $(2p-d)$.
[i] Doublets used in the calculation:

Reaction	Row No. in Table I.
$B^{10}(d,p)B^{11}$	(1), (6), (7)
$C^{12}(d,p)C^{13}$	(1), (18)
$C^{13}(d,\alpha)B^{11}$	(1), (2), (9), (18)
$N^{14}(d,p)N^{15}$	(1), (10), (11), (12)
$N^{15}(p,\alpha)C^{12}$	(1), (2), (12)
$N^{15}(d,\alpha)C^{13}$	(1), (2), (12), (18)
$O^{16}(d,\alpha)N^{14}$	(1), (2), (10), (11), (13), (14)
$S^{32}(d,p)S^{33}$	(1), (26), (27)
$Si^{28}(d,p)Si^{29}$	(1), (18), (21), (22)
$Si^{29}(d,p)Si^{30}$	(1), (6), (7), (22), (23), (24)
$Si^{29}(d,\alpha)Al^{27}$	(1), (2), (13), (14), (19), (21), (22)

[j] See reference 2.
[k] E. N. Strait *et al.*, Phys. Rev. **81**, 747 (1951).
[l] D. M. Patter *et al.*, Phys. Rev. **85**, 142 (1952).

the determination of the C^{12} mass, the following four doublets sets could be used; one of these is the ordinary fundamental doublets, while the others do not contain the $C^{12}(H^1)_4-O^{16}$ doublet.

$$\left.\begin{aligned}(H^1)_2-D^2\\(D^2)_3-\tfrac{1}{2}C^{12}\\C^{12}(H^1)_4-O^{16}\end{aligned}\right\}\quad C^{12}=12.003840\pm\ 8 \tag{1}$$

$$\left.\begin{aligned}(O^{16})_2-S^{32}\\(C^{12})_4-S^{32}O^{16}\end{aligned}\right\}\quad C^{12}=12.003849\pm\ 6 \tag{2}$$

$$\left.\begin{aligned}B^{10}-\tfrac{1}{2}Ne^{20}\\(D^2)_2O^{16}-Ne^{20}\\B^{10}D^2-C^{12}\\(D^2)_3-\tfrac{1}{2}C^{12}\end{aligned}\right\}\quad C^{12}=12.003829\pm 27 \tag{3}$$

$$\left.\begin{aligned}(D^2)_2O^{16}-\tfrac{1}{2}A^{40}\\(C^{12})_3(H^1)_4-A^{10}\\(D^2)_3-\tfrac{1}{2}C^{12}\\(H^1)_2-D^2\end{aligned}\right\}\quad C^{12}=12.003827\pm 15 \tag{4}$$

Since the four different values of the C^{12} mass thus obtained were found to be in good agreement with one another, the weighted average of those four values was adopted as the atomic mass of C^{12}, and then the atomic masses of H^1 and D^2 were calculated from this C^{12} value and the mass differences of the $(H^1)_2-D^2$, $(D^2)_3-\frac{1}{2}C^{12}$ doublets. The masses of H^1, D^2, and C^{12} thus determined are given in Table IV together with those reported by others. The masses of other isotopes are computed from the doublet mass differences given in Table I with these masses of H^1, D^2 and C^{12} and are given in Table V.

In Table VI, some mass differences obtained in the

TABLE IV. Mass substandards.

	H^1	D^2	C^{12}
Ewald[a]	$1.008141 \pm 2\times10^{-6}$	$2.014732 \pm 4\times10^{-6}$	$12.003807\pm 11\times10^{-6}$
Collins *et al.*[b]	$1.008146 \pm 3\times10^{-6}$	$2.014740 \pm 6\times10^{-6}$[e]	$12.003842\pm 4\times10^{-6}$
Li *et al.*[c]	$1.008142 \pm 3\times10^{-6}$	$2.014735 \pm 6\times10^{-6}$	$12.003804\pm 17\times10^{-6}$
Bainbridge[d]	$1.0081386\pm 3.2\times10^{-6}$	$2.0147252\pm 5.7\times10^{-6}$	$12.003895\pm 19\times10^{-6}$
Present work	$1.008145 \pm 2\times10^{-6}$	$2.014741 \pm 3\times10^{-6}$	$12.003844\pm 6\times10^{-6}$

[a] H. Ewald, Z. Naturforsch. **6a**, 293 (1951).
[b] T. L. Collins *et al.*, reference 7.
[c] See reference 2.
[d] See reference 4.
[e] Computed from H^1 and $(H^1)_2-D^2=15.519\pm0.017$ [T. R. Roberts, Phys. Rev. **81**, 624 (1951)].

TABLE V. Atomic masses.

$C^{12}=12.003844\pm 6$
$D^2=2.014741\pm 3$
$H^1=1.008145\pm 2$
$He^4=4.003879\pm 9$
$B^{10}=10.016110\pm 10$[a]
$B^{11}=11.012811\pm 9$[b]
$C^{13}=13.007505\pm 12$
$N^{14}=14.007550\pm 5$
$N^{15}=15.004902\pm 9$
$O^{18}=18.004883\pm 20$
$F^{19}=19.004444\pm 22$
$Ne^{20}=19.998772\pm 13$
$Ne^{22}=21.998382\pm 24$
$Al^{27}=26.990109\pm 23$
$Si^{28}=27.985825\pm 16$
$Si^{29}=28.985705\pm 21$
$Si^{30}=29.983307\pm 31$
$S^{32}=31.982274\pm 8$[c]
$S^{33}=32.981941\pm 37$
$S^{34}=33.978709\pm 19$[d]
$Cl^{35}=34.980064\pm 22$
$Cl^{37}=36.977675\pm 21$
$A^{40}=39.975148\pm 24$[e]

[a] Weighted average of the masses from Row (4) and (8) in Table I.
[b] From (6) and (9).
[c] From (25) and (33).
[d] From (26) and (28).
[e] From (17) and (32).

above manner are compared with those calculated from recent nuclear disintegration data as well as with those from other mass spectroscopic data. The sulfur mass difference ratio, $(S^{32}-S^{32})/(S^{34}-S^{32})$, calculated from the present results is 0.500727±20, which is in good agreement with the microwave value, 0.500714±30;[11] while the value, 0.50082±3, for the sulfur mass difference ratio is calculated from the data of Collins *et al.*[7] The mass ratio of Cl^{35}/Cl^{37} calculated from the present data is 0.9459779±9, which is in agreement with the values obtained by others.[7]

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TABLE VI. Mass differences (amu) of nuclides comparing with other data.

	Present work (from Table V)	Previous work	Reference
$Si^{29}-Si^{28}$	$0.999880\pm 26\times10^{-6}$	$0.99986 \pm 16\times10^{-5}$	Duckworth[a]
		$0.999885\pm 11\times10^{-6}$	Nuclear reaction[b]
$Si^{30}-Si^{29}$	$0.997602\pm 36\times10^{-6}$	$0.99723 \pm 21\times10^{-5}$	Duckworth[c]
		$0.997593\pm 16\times10^{-6}$	Nuclear reaction[d]
$Si^{28}-Al^{27}$	$0.995717\pm 28\times10^{-6}$	$0.995712\pm 25\times10^{-6}$	Nuclear reaction[e]
$S^{33}-S^{32}$	$0.999667\pm 38\times10^{-6}$	$0.99989 \pm 5\times10^{-5}$	Collins *et al.*[f]
		$0.999696\pm 14\times10^{-6}$	Nuclear reaction[g]
$S^{34}-S^{32}$	$1.996435\pm 21\times10^{-6}$	$1.99652 \pm 5\times10^{-5}$	Collins *et al.*[f]

[a] H. E. Duckworth and R. S. Preston, Phys. Rev. **79**, 402 (1950).
[b] From $Si^{28}(d, p)Si^{29}$ [E. N. Strait *et al.*, Phys. Rev. **81**, 747 (1951)], and H^1, D^2 (reference 2).
[c] Duckworth, Preston, and Woodcock, Phys. Rev. **79**, 188 (1950); and reference a.
[d] From $Si^{29}(d, p)Si^{30}$ [D. M. Patter *et al.*, Phys. Rev. **85**, 142 (1952)], and H^1, D^2 (reference 2).
[e] From $Al^{27}(\alpha, p)Si^{30}$, $Si^{28}(d, p)Si^{29}$ (E. N. Strait *et al.*, reference b), $Si^{29}(d, p)Si^{30}$ (D. M. Van Patter *et al.*, reference d) and H^1, $[(D^2)_2-He^4]$ (reference2).
[f] T. L. Collins *et al.*, reference 7.
[g] From $S^{32}(d, p)S^{33}$ (E. N. Strait *et al.*, reference b) and H^1, D^2 (reference 2).

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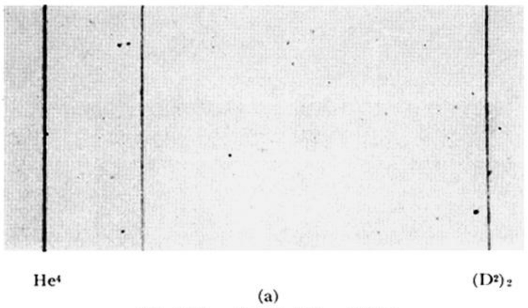
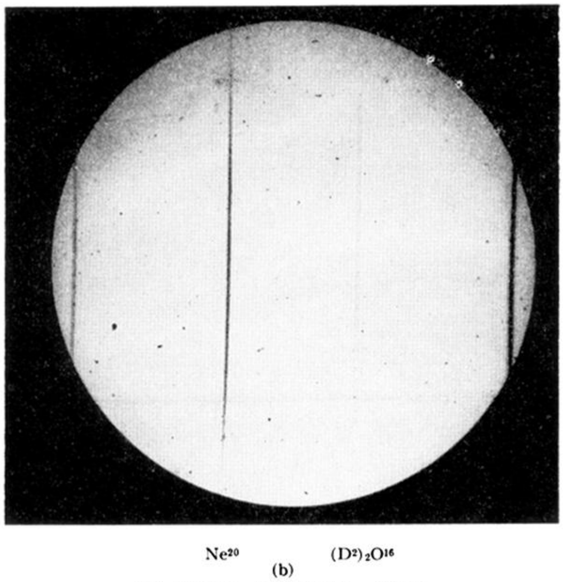
[11] S. Geschwind and R. Gunther-Mohr, Phys. Rev. **81**, 882 (1951).



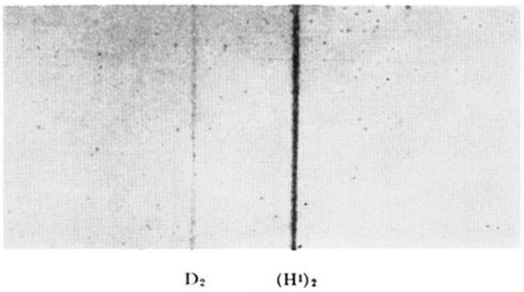
(a)

(a) $(D^2)_2 - He^4$ doublet. (×20)



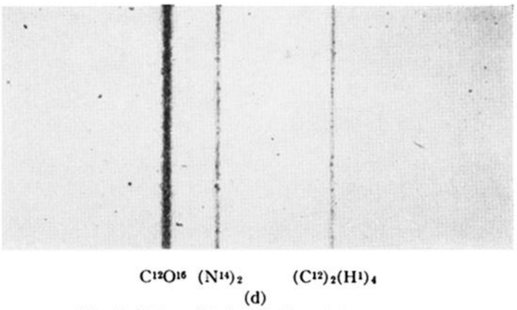
(b)

(b) $(D^2)_2O^{16} - Ne^{20}$ doublet. (×20)



(c)

(c) $(H^1)_2 - D^2$ doublet. (×30)



(d)

(d) $C^{12}(H^1)_4 - (N^{14})_2 - C^{12}O^{16}$ triplet. (×30)

FIG. 2. Some typical doublets.