The Masses of Ne^{20} and B^{11}. The Mass of Ne^{22} and the Disintegration of F^{19}.[1]

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The mass of Ne^{20} measured from ten spectra is 19.9967 ±0.0009. This value is outside the limit of error of Aston's measurement and an explanation for his high mass value is suggested. The mass of B^{11} was measured from two spectra as a test of the method used to determine the mass of Ne^{22}. The mass of B^{11} from these measurements is 11.0107±0.001. The mass of Ne^{22} from five spectra is 21.9947±0.0009. The maximum value for the mass of Ne^{22} is 21.9925±0.0015 calculated from Aston's value for F^{19} and from the F^{19} disintegration experiments of Chadwick and Constable. The discrepancy between the two values for the mass of Ne^{22} is discussed.

THE determination of the masses of the isotopes of certain light elements has been valuable, in conjunction with disintegration experiments, as a check on the relationship $\Delta E = c^2 \Delta m$.[2] Possible errors in the measurement of the energies of the products of disintegration, stated in terms of the equivalent mass, are in general small compared to the errors involved in the direct measurements of the masses of atoms. Accepting the equivalence of mass and energy it has been possible to obtain a value for the mass of a neutron.[3] In several cases the evidence for a particular mode of disintegration and synthesis has been clarified and reinforced.[4] The evidence from investigation of the disintegration of F^{19} by α-particle bombardment[5, 6] points to the formation of Ne^{22} by the process $F^{19}+\alpha \rightarrow Ne^{22}$ +proton. If the provisional value for the mass of Ne^{22} reported by Aston[7] is correct, the disintegration of F^{19} and the synthesis of Ne^{22} would be impossible as a result of α-particle bombardment, unless there can exist for Ne^{22} in the simplest case two distinct nuclear conformations whose mass defects differ by 0.0123 mass units, equivalent to 11.4×10^6 electron-volts.

The present work was undertaken to obtain a reliable figure for the mass of Ne^{22} to aid in the interpretation of the mode of disintegration of F^{19}. At the same time the masses of Ne^{20} and B^{11} were determined, and as the measurement of the mass of Ne^{22} to some extent is dependent upon them, these measurements will be reported first.

THE MASS OF Ne^{20}

The mass of Ne^{20} was measured by comparison of the position of its line on a spectrum in relation to the lines of the hydrides of carbon, oxygen and the carbon molecule C_2. Spectrum *A*, Fig. 1, shows in the upper spectrum the lines due to the ions CH_3, O^{16}, CH_4, OH_1, Cl^{35++}, OH_2, Cl^{37++}, OH_3, Ne^{20}, $Ne^{20}H$ and Ne^{21} (?), Ne^{22}, Na (?), C_2, C_2H, etc.

To a first approximation the mass scale is linear[8] so that $D+E=KM$, where D is the distance from the fiducial line to any line of mass M, and E is the distance from the fiducial line to the source. Accordingly two lines of known masses, CH_3 and C_2, or CH_3 and OH_3 are selected to solve for E and K. With E and K known the

[1] This paper was presented before the American Physical Society at the Atlantic City meeting, December 28, 1932.

[2] R. T. Birge, Phys. Rev. **37**, 841 (1931). $B^{10}+\alpha \rightarrow C^{13}$ +proton.

[3] J. Chadwick, Proc. Roy. Soc. **A136**, 701 (1932). $B^{11}+\alpha \rightarrow N^{14}+$neutron.

[4] For example Li^7+proton$\rightarrow 2\alpha$, $F^{19}+$proton$\rightarrow O^{16}+He^4$. J. D. Cockcroft and E. T. S. Walton, Proc. Roy. Soc. **A137**, 229 (1932).

[5] Radiations from Radioactive Substances. Rutherford, Chadwick and Ellis, p. 307. E. Rutherford and J. Chadwick, Proc. Camb. Phil. Soc. **25**, 186 (1929); J. Chadwick, J. E. R. Constable and E. C. Pollard, Proc. Roy. Soc. **A130**, 463 (1931).

[6] J. Chadwick and J. E. R. Constable, Proc. Roy. Soc. **A135**, 48 (1932).

[7] F. W. Aston, Proc. Roy. Soc. **A115**, 487 (1927).

[8] K. T. Bainbridge, Phys. Rev. **40**, 130 (1932), and a paper shortly to appear in the Journal of the Franklin Institute.

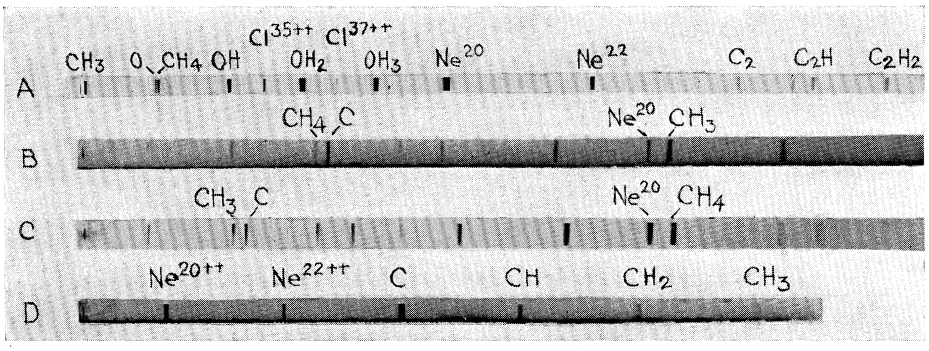

FIG. 1. Mass-spectra of Ne^{20} and Ne^{22}. Natural size.

masses corresponding to all the other lines are evaluated. The deviation of the mass scale from absolute linearity is easily found by comparison of the positions of the known masses CH, CH_2, CH_3, CH_4, OH, OH_2, OH_3, C_2H, C_2H_2 with their positions as calculated under the assumption of strict linearity. The mass of any intermediate line, such as Ne^{20}, may be derived from the position of the line *E*, *K*, and the correction curve. The deviations from linearity range from one part in 10,000 over the first 8 cm of the plate to 10 parts in 10,000 near the other extremity of the plate.

TABLE I. *Mass determinations of* Ne^{20}.

19.99792	19.99672
19.99292	19.99619
20.00154	19.99370
20.00081	19.99444
19.99600	19.99686

Table I lists the measurements of the mass of Ne^{20} from ten different spectra taken on five different plates. The mass[9] of Ne^{20} is 19.9967 $\pm$0.0009 referred to O^{16}, a value much lower than the 20.0004$\pm$0.0007 reported by Aston[7] and outside of the confines of his limit of error, $\pm$0.002 mass units. The probable error in the present determination is $\pm$0.0006. When the effective proportional uncertainty in the mass of C^{12} is included, the probable error of the mass of Ne^{20} referred to O^{16} becomes $\pm$0.0009.

It is suggested that the high value of the mass of Ne^{20} obtained by Aston may be traced to the experimental conditions. The ratio Ne^{20} : O was evaluated in terms of the ratio CH_3 : C. Under the conditions of the experiment CH_4 may have been present in an abundance very nearly equal to that of O.[10] If the O$-CH_4$ doublet was in the region of lowest dispersion, or if the resolving power of the apparatus was below par at the time, the Kostinsky and related effects[11] might tend to increase the separation of the O$-CH_4$ traces and in consequence depress the position of the O trace and so raise the Ne : O ratio. This hypothesis should be easy to test if the ratios Ne : CH_4 :: CH_3 : C or Ne : CH_3 :: CH_4 : C are used with the oxygen line weak or absent.[12] Spectra *B* and *C*, Fig. 1, are of this type. To account for the difference between the present value of the mass of Ne^{20} and that reported by Aston would only require a shift in the position of O, because of the Kostinsky or other effects of about 0.005 cm.[13]

Aston[7] measured the mass of A^{40} by means of the ratios A^{++} : O^+ :: CH_3^+ : C^+, a method identical with that used for Ne^{20}; accordingly the

[9] All mass values refer to the masses of neutral atoms.

[10] In general CH_4 is admitted to a discharge tube, and the lines C, CH, CH_2, CH_3, CH_4 appear in approximately equal abundance.

[11] F. E. Ross, Atrophys. J. **53**, 349 (1921).

[12] If the suggested ratios are used a loss in accuracy results because the mass of Ne^{20} no longer is compared with O^{16}. The mass of CH_4 however has been accurately determined (reference 7) and it constitutes a valuable secondary standard of mass.

[13] Two serious objections exist which militate against the Kostinsky effect *per se* as the correct explanation. First, the density of the O$-CH_4$ traces, in the absence of any direct statement, may be assumed to be low, and the Kostinsky effect only attains an appreciable magnitude for high photographic densities. Secondly, it is possible that ethane was used to provide the CH_3 and C lines which would reduce the amount of CH_4 present in the discharge below that which would be present if methane had been used to give the lines C and CH_3.

argon determination might also be in error. The writer made a rough check of the ratio of the masses of A^{40} and Ne^{20} by direct comparison on two adjacent spectra. For the first exposure the discharge tube contained only argon and nitrogen and the lines due to A^{++} and the nitrogen molecule were recorded. Immediately following this exposure the argon was pumped out and the tube was washed out with neon. before admitting a mixture of neon and nitrogen. On an adjacent strip of the recording photographic plate the lines due to Ne^{20}, $Ne^{20}H$, Ne^{22} and $Ne^{22}H$ and the nitrogen molecule were then recorded.[14] The mass of A^{40} was determined provisionally as 39.9724 evaluated in terms of $Ne^{20}=19.9967$. On the basis of this measurement we may say that whatever error appeared in the measurement of the mass of Ne^{20} when the ratios $Ne^{20}:O :: CH_3 : C$ were used by Aston did not occur in the evaluation of the mass of A^{40} from the similar ratios $A^{40++}:O^{+} :: CH_3^{+}:C^{+}$. The close agreement of the value 39.9724 with Aston's value 39.971 may be fortuitous to some extent as the error in a single determination of this type may be as great as one part in 10,000. Even if an error of this magnitude were present, however, it could not invalidate the argument that the present value of the mass of Ne^{20} and Aston's value of the mass of A^{40} are more consistent than are Aston's values for the masses of Ne^{20} and A^{40}.

Mass of B^{11}

A rough determination of the mass of B^{11} was made as a test of the method which was planned for use with Ne^{22++}. Out of 18 spectra taken, with BCl_3 and CH_4 in the discharge tube, two spectra in which the B^{11+} line was photographed together with the lines of the ions C, CH_1, CH_2, CH_3, were suitable for measurement. The latter lines gave the values of E and K in the relationship $D+E=KM$. Then the mass of B^{11+} was evaluated from this equation by substitution of D, the distance from the B^{11+} line to the fiducial line. The two measurements gave for the mass of the neutral B^{11} atom, 11.0098 and 11.0117 or a mean value 11.010_{75}. Aston[7] has reported the value 11.0110 ± 0.0005 from a more extended and exact series of measurements.

Mass of Ne^{22}

Doubly ionized Ne^{22} was compared with Ne^{20++} and C^{+} and its hydrides on five spectra on five different plates of which spectrum D, Fig. 1 is an example. The values obtained were, 21.99468, 21.99583, 21.99309, 21.99488 and 21.99518. The average value is 21.99473 with a probable error[15] in the determination of ±0.00033. On the O^{16} scale $Ne^{22}=21.9947\pm0.0009$ when the effective proportional probable errors of the reference masses are included. Aston[7] has reported the provisional value 22.0048 for Ne^{22} measured in relation to Ne^{20} using the approximate ratios $Ne^{22}:Ne^{20} :: CH : C$.

The Mass of Ne^{22} and the Disintegration of F^{19}

The mass of Ne^{22} is 21.9925 ± 0.0015 calculated from the F^{19} disintegration experiments of Chadwick and Constable.[6, 16] $F^{19}+\alpha+E_\alpha+e\rightarrow Ne^{22}+\rho+E_\rho+E_n$ where α, e, and ρ are the masses of an α-particle, electron, and proton respectively, E_α, E_ρ, and E_n are the kinetic energies of the α-particle, proton and the residual nucleus. This

[14] This method of measurement is one which appears to be peculiarly suited for the spectrographs of the type described by W. R. Smythe, Phys. Rev. **28**, 1275 (1926) and by J. Mattauch, Phys. Zeits. **33**, 899 (1932).

[15] The probable error was calculated on the basis of a theory of errors for small samples. H. Jeffreys, Proc. Roy. Soc. **A138**, 48 (1932).

[16] The calculation of the mass of Ne^{22} from the F^{19} disintegration experiments has been given using earlier and less exact data for the proton and α-particle energies and omitting the kinetic energy of the Ne^{22} nucleus. (Reference 5.) The present calculation has been made on the basis $F^{19}=19.0000\pm0.00127$, $He=4.00216\pm0.00013$ (Aston, reference 7), $H^1=1.007775\pm0.000035$ (Bainbridge, Phys. Rev. **43**, 103 (1933), mass of electron 0.000548 (Birge, Phys. Rev. Supplement **1**, 1 (1929)), energy of incident α-particle 5.25×10^6 e-volts $=0.00564$ mass units, energy of proton of 56 cm range and velocity 3.58×10^9 cm/sec. $=6.82\times10^6$ e-volts $=0.00732$ mass units, all masses referred to the O^{16} scale. The velocity-range data for protons has been given by P. M. S. Blackett, Proc. Roy. Soc. **A135**, 132 (1932).

The kinetic energy of the nucleus was calculated under the assumption that the protons, which had been measured in the forward direction, were, on the average, emitted at 10° from the direction of the projected track of the incident α-particle. Under this assumption the kinetic energy of the nucleus is 0.192×10^6 e-volts $=0.00021$ mass units.

equation does not include the possible loss in mass by γ-ray emission from the residual nucleus and assumes that both the proton before and the α-particle after disintegration occupy the ground states in their respective nuclei.

If the 2×10^6 *e*-volt quanta observed by Webster[17] are attributed to Ne^{22} the mass 21.9925 must be decreased to 21.9903. Consequently on the basis of the disintegration experiments and the mass of F^{19} the mass of Ne^{22} cannot exceed 21.9925 ± 0.0015 and the agreement with the mass-spectrograph value 21.9947 ± 0.0009 is unsatisfactory. Other possible modes of disintegration of F^{19} are eliminated for various reasons.[18]

An explanation which has the benefit of being consistent with the chemical data is that the mass-spectrograph value[7, 19] for the mass of F^{19} is too low by approximately 0.0022 mass units. Moles and Batuecas[20, 21] determined the molecular weight of methyl fluoride as 34.025. If the accepted values 12.0025 and 1.00777 are used for the atomic weights of carbon and hydrogen, the atomic weight of fluorine on the chemical scale is 18.999_2. The mass of F^{19} on the O^{16} scale, assuming no other isotopes, is $19.0034\pm.005$. This is to be compared with the minimum value for the mass of F^{19}, 19.0022, if the disintegration experiments on F^{19} and the present mass-spectrograph determination of the mass of Ne^{22} are taken to be correct.

In conclusion the writer wishes to thank Dr. A. Bramley for his interest and helpful discussions and to thank Professor John A. Miller and the members of the Swarthmore College Observatory for their generous permission to use their measuring instruments.

Note added in proof: The faint lines of mass 17 in spectra *B* and *C*, Fig. 1, are definitely CH_5^+ lines as determined by accurate mass measurements. CH_5^+ only appears rarely and the conditions essential to its formation are not known.

[17] H. C. Webster, Proc. Roy. Soc. **A136**, 428 (1932).

[18] Other possible modes of disintegration of F^{19} are:

1. $F^{19}+\alpha\rightarrow\alpha+p+O^{18}$
2. $F^{19}+\alpha\rightarrow\alpha+n+p+O^{17}$
3. $F^{19}+\alpha\rightarrow\alpha+H^2+O^{17}$
4. $F^{19}+\alpha\rightarrow n+p+Ne^{21}$
5. $F^{19}+\alpha\rightarrow H^2+Ne^{21}$
6. $F^{19}+\alpha\rightarrow n+Na^{22}$
7. $F^{19}+\alpha\rightarrow Na^{23}$

From considerations of the masses and energies involved numbers 1, 2, 3, 4 and 5 may be ruled out. 6 is possible but bears no relation to the observations of Chadwick and Constable (reference 6). The possibility of neutron emission is not definitely ruled out (J. Chadwick, Proc. Roy. Soc. **136**, 705 (1932)) but the observed scarcity of Na^{22} indicates that Na^{22} may be unstable and may not exist (K. Bainbridge, J. Frank. Inst. **212**, 336, 1931). 7 is incompatible with the γ-emission experiments of H. C. Webster (reference 15).

[19] Aston compared the mass of fluorine with that of carbon by means of the progression $C : CH_3 : F : C_2$. The limit of error for carbon was given as ±0.0012 mass units or one part in 10,000. The limit of error of the fluorine determination was also given as one part in 10,000 which, as the mass of fluorine was determined in terms of carbon and hydrogen, does not allow for any error in the fluorine determination itself. Assuming equal accuracy in the fluorine determination the limit of error becomes ±0.0038 instead of ±0.0019 mass units as given by Aston and the probable error is ±0.00127, under the usual convention. If probable errors alone are dealt with, the p.e. in the mass of F^{19} is $(2)^{\frac{1}{2}}(19/30{,}000)=\pm0.0009$. In view of the uncertainty in the mass of F^{19} the value ±0.00127 is indicated.

[20] E. Moles and T. Batuecas, J. Chim. Phys. **18**, 353 (1920). The data used by R. T. Birge, Phys. Rev. **37**, 1669 (1931), was taken from the first paper of Moles and Batuecas, J. Chim. Phys. **17**, 539 (1919).

[21] H. S. Patterson, R. Whytlaw-Gray and W. Cawood, give several reasons for not accepting the results of Moles and Batuecas. It appears however that Patterson, Whytlaw-Gray and Cawood were troubled by systematic errors as their value for the mass of carbon 12.010, derived from the density of ethylene, is high compared to the accepted value 12.0025 and their value for methyl fluoride may also be high in the ratio 28.05108 : 28.03608 or $(\mathbf{C}\,H_2)_2 : (C\,H_2)_2$ where **C** is 12.010 and C is the accepted value 12.0025. Assuming that systematic errors were present of the magnitude indicated above and no other isotopes are present the mass of F^{19}, is 19.0022 on the chemical scale or 19.0064 on the O^{16} scale when the measured molecular weight of FCH_3 is reduced from 34.046 to 34.028 by multiplication by the conversion factor $(CH_2)_2 : (\mathbf{C}\,H_2)_2$.

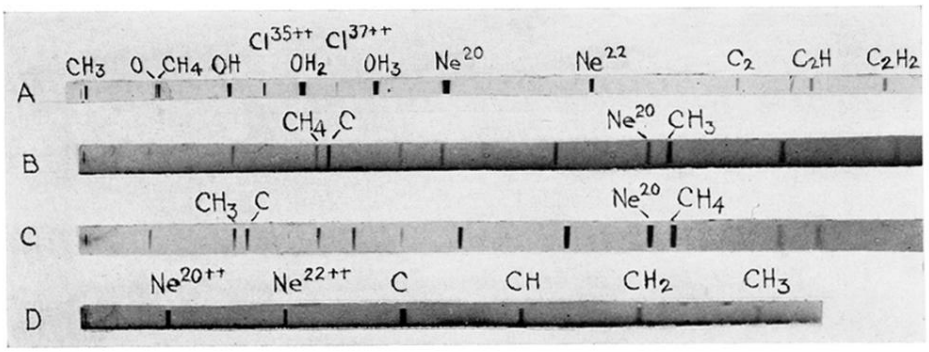

FIG. 1. Mass-spectra of Ne^{20} and Ne^{22}. Natural size.