derivatives. Consider for instance the Lagrangian $L=\frac{1}{2}\psi(1+\rho^2\varphi/\psi)^{-1}$ with $\psi=\frac{1}{2}F^{\mu\nu}F_{\mu\nu}$, and

$$\varphi=\tfrac{1}{2}(\partial F^{\mu\nu}/\partial x^{\alpha})g^{\alpha\beta}(\partial F_{\mu\nu}/\partial x^{\beta}).$$

The field equations of this Lagrangian are of the 3rd order—and nonlinear. They have a static spherically symmetric singular solution, of finite energy, which reduces for $r\gg\rho$ to a Coulomb field. For this Lagrangian the superposition principle breaks down for

$$p\sim\rho\epsilon^{\frac{3}{2}};\quad p\sim\rho Z^{\frac{1}{2}}\epsilon^{\frac{3}{2}},$$

for impact and radiative losses respectively. More generally, if L involves derivatives of the fields of order n, and gives an electron of finite energy as a singular solution, then the superposition principle breaks down for

$$p_{\text{imp.}}\sim\rho\epsilon^{(n+1)/(n+2)},\quad p_{\text{rad.}}\sim\rho Z^{1/n+2}\epsilon^{(n+1)/(n+2)}.$$

The $\bar{p}=\rho\epsilon$ which we have used as a limit for classical theory in this paper is thus given by a unitary field theory whose field equations are integral equations, for which $n\to\infty$.

We adduce these considerations, not because we believe that the solution to the problem of electronic stability lies in a theory of this type, but because they show that there is, even in classical theory, no inconsistency in the criteria we have used for the validity of electron theory. The discrepancies between theoretical prediction and the experiments can thus be understood on a purely classical basis.

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The Disintegration of the Nuclei of Light Atoms by Neutrons

II. Neon, Fluorine and Carbon

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Neon and fluorine. Quantitative information is presented on the disintegration, by capture of a neutron, of 11 nuclei of neon and 13 of fluorine. The reactions are considered to be:

$$^{20}_{10}\text{Ne}_0+^{1}_{0}n_1\rightarrow{}^{17}_{8}\text{O}_1+^{4}_{2}\text{He}_0$$
$$^{19}_{9}\text{F}_1+^{1}_{0}n_1\rightarrow{}^{16}_{7}\text{N}_2+^{4}_{2}\text{He}_0$$

in which nitrogen 16 is a new isotope of nitrogen. As in the earlier work on nitrogen, it is found that: (1) Neutrons effective in disintegration appear both to come directly from the source and to be scattered by nuclear impact prior to the disintegration. (2) Kinetic energy disappears in the process, or is (rarely) conserved. This kinetic energy decrement may be transformed into mass, if mass increases in the reaction, or into γ-rays; it may also excite the heavier product nucleus and later give rise to an artificial radioactivity. (3) The maximum, minimum and average kinetic energy for the neutrons which in our experiments have been found to disintegrate fluorine, neon and nitrogen are listed below in the table.

Carbon. Mass values obtained in positive ray work give 6.9 m.e.v. as the mass increase in the reaction:

$$^{12}_{6}\text{C}_0+^{1}_{0}n_1\rightarrow{}^{9}_{4}\text{Be}_1+^{4}_{2}\text{He}_0.$$

If the mass values are extremely accurate only neutrons with kinetic energy greater than about 6.9 m.e.v. can therefore disintegrate carbon. Of 6 disintegrations found among 6400 pairs of photographs with ethylene, only 1 involves a neutron which approximates this energy. The other disintegrations may be those of oxygen or nitrogen from the water vapor and trace of air in the chamber. Carbon has therefore not yet been disintegrated with certainty by neutrons. It is of interest that about 20 percent of the neutrons found in this work have extremely high velocities, so that their kinetic energy is from 13.6 to 15.1 m.e.v., and that the energy transformed into γ-rays rises as high as 10 m.e.v.

	No. of disintegrations	Kinetic Energy in m.e.v. Min.	Ave.	Max.
Nitrogen	(28)	1.9	5.4	16.1
Fluorine	(13)	1.9	6.7	13.2
Neon	(11)	3.1	10.6	15.1

I. INTRODUCTION

THE first paper[1] of this series on the disintegration of light atoms by neutrons presented values related to the mechanics of the disintegration of twenty-eight nitrogen nuclei. Further experiments have since been carried out with deuterium, carbon, fluorine and neon. This paper gives the quantitative relations found for the disintegration of 11 neon and 13 fluorine nuclei.[2]

[1] Harkins, Gans and Newson, Phys. Rev. **44**, 529 (1933).

[2] For preliminary reports, see Harkins, Gans and Newson, Phys. Rev. **44**, 236, 945 (1933).

II. Experimental Details

Most of the photographs were obtained with the modified Wilson cloud chamber described in the first paper. Some of the work, however, was done with a chamber in which the closely fitted piston was sealed gas-tight to the cylinder with a sylphon bellows. For quantitative work, this arrangement appears to be superior to that in which the sylphon itself acts as the wall for the piston, for with a closely fitted piston the stroke required for a given expansion ratio is at a minimum, which lessens the highly undesirable surge in the gas during and after the expansion.

As in the earlier work, two views at an angle of about 73° are obtained for each disintegration, and are transformed by projection into a single photograph in the actual plane of the disintegration. In the photograph only two of the three tracks are visible.

III. Disintegration by Capture or by Non-Capture

The question as to whether the disintegration of N^{14} by neutrons occurs by capture or by non-capture, has been discussed in detail by Harkins and Gans[3] with the conclusion that while evidence for disintegration by capture is very good, there appears to be no evidence which supports disintegration without capture of the neutron.

In the present work, it is found that for about half of the events, the calculated path of the neutron passes through the source in a direction toward the nucleus which is hit. For the other half, the neutron is either scattered by a nuclear collision prior to the disintegrative capture, or is not captured. In the latter case, the details of the disintegration may be analyzed by the equations given by Harkins and Gans.[3] If, however, it is assumed, as is here done, that the reactions occur by capture, then the energies and velocities of the various particles may be calculated as outlined by Harkins, Gans and Newson.[1]

IV. The Disintegration of Neon Nuclei by Neutrons

About 4800 pairs of photographs with neon in the chamber have shown 11 pairs sufficiently good to give useful data concerning the disintegration. It is assumed that the reaction which takes place is

$$\begin{aligned} &{}^{20}_{10}\mathrm{Ne}_0 \qquad\qquad +{}^{1}_{0}n_1 \\ &(19.9967\pm0.0009)+(1.0067-E) \\ &\qquad \rightarrow {}^{17}_{8}\mathrm{O}_1 \\ &\qquad \rightarrow(17.0032\pm0.003-E') \\ &\qquad\qquad +{}^{4}_{2}\mathrm{He}_0 \\ &\qquad\qquad +(4.00216\pm0.0004). \end{aligned} \tag{1}$$

Here E represents the energy (in mass units) converted into a γ-ray in the formation of a neutron from boron, and E' is the similar value for O^{17} formed from N^{14} by capture of an α-particle. If E and E' are both zero, then 0.002 unit of mass or 1.9 m.e.v. (million electron-volts) would be required for this reaction. The actual amount to be supplied is probably greater than 2 m.e.v. since E is probably larger than E'. This calculation is subject to modification by the amount of the unknown error in the mass of the neutron.

The data related to the disintegrations of neon are collected in Table I. The lowest velocity for a neutron which disintegrated a nitrogen nucleus is 1.9×10^9 cm/sec., while for neon the corresponding velocity is 2.4×10^9. The minimum kinetic energy of the neutron is thus 1.9 m.e.v. for nitrogen and 3.1 m.e.v. for neon. For nitrogen, the maximum kinetic energy of the neutron is 16.1 m.e.v., while for neon it is 15.1 m.e.v. The average kinetic energy of the 28 neutrons which disintegrated nitrogen nuclei is 5.4 m.e.v., while that for 11 neon nuclei is 10.6 m.e.v.

As in all earlier work, the kinetic energy of the particles is found to be less after the disintegration, by an amount in the case of neon which varies from $(0.8-0.93\times10^3E')$ to $(11.0-0.93\times10^3E')$ m.e.v.

It is assumed that of the kinetic energy thus lost, the amount in excess of $(1.9-0.93\times10^3E')$ m.e.v. (which difference is the mass increment in the reaction, a value subject to the errors in the mass values) is converted into a γ-ray, or may appear as the energy of an artificial radioactivity. In the disintegration in which the minimum kinetic energy, 0.82 m.e.v., is lost, no γ-ray may be emitted, and the discrepancy between the 0.82 m.e.v. lost and the 1.9 m.e.v.

[3] Harkins and Gans, Phys. Rev. **46**, 397 (1934).

TABLE I.

Quality of photographs: A, Excellent; B, Good; C, Fair
Type of disintegration: D, Neutron direct from source;
S, Neutron scattered by nuclear collision prior to disintegrative impact
X = Heavy product nucleus, O^{17} for Ne; N^{16} for F.

No.	R_{He} (Mm, Dry air at 15°C, 1 Atm.)	R_X	ϕ	θ	v_{He} (cm/sec. $\times 10^{-9}$)	vX	v_n	$KE\cdot$He (ergs $\times 10^6$)	$KE\cdot X$	$KE\cdot n$	$-\Delta KE$	$KE\cdot$He (electron-volts $\times 10^{-6}$)	$KE\cdot X$	$KE\cdot n$	$-\Delta KE$
							Neon								
101 AS	4.3	1.6	106.4	31.6	0.480	0.207	2.44	0.76	0.60	4.96	3.60	0.48	0.38	3.12	2.26
102 AD	11.8	2.9	81.5	68.3	0.980	0.345	2.74	3.20	1.69	6.19	1.30	2.01	1.06	3.89	0.82
103 AD	8.8	2.7	97.6	39.7	0.915	0.335	3.87	2.77	1.59	12.43	7.91	1.74	1.00	7.81	4.97
104 AS	12.4	2.4	81.0	42.5	1.01	0.296	4.40	3.31	1.21	16.07	11.55	2.08	0.76	10.1	7.26
105 AD	15.0	4.1	132.3	23.7	1.12	0.485	4.50	4.15	3.29	16.87	9.42	2.61	2.07	10.6	5.92
106 BS	6.0	3.2	111.5	22.5	0.630	0.360	4.57	1.32	1.81	17.34	14.21	0.83	1.14	10.9	8.93
107 AD	21.5	4.8	159.3	10.7	1.30	0.585	4.90	5.60	4.90	19.89	9.39	3.52	3.08	12.5	5.90
108 BD	23.9	4.7	129.1	26.9	1.36	0.565	5.10	6.11	4.49	21.64	11.03	3.84	2.82	13.6	6.93
109 AD	13.2	3.7	103.9	32.6	1.04	0.440	5.27	3.56	2.72	23.07	16.80	2.24	1.71	14.5	10.6
110 AS	9.9	4.1	136.0	17.9	0.880	0.485	5.27	2.56	3.29	23.23	17.34	1.61	2.07	14.6	10.9
111 BS	28.9	3.9	75.0	60.5	1.44	0.463	5.36	6.95	2.99	24.03	14.08	4.37	1.88	15.1	8.85
							Fluorine								
201 CD	11.2	2.0	76.3	76.7	1.00	0.25	1.90	3.31	0.83	3.04	− 1.11	2.08	0.52	1.91	− 0.70
202 AD	6.0	2.1	105.7	38.3	0.69	0.27	2.59	1.56	0.94	5.55	3.05	0.98	0.59	3.49	1.91
203 CD	5.9	2.5	126.5	27.5	0.69	0.30	2.59	1.56	1.19	5.55	2.80	0.98	0.75	3.49	1.76
204 BS	6.0	2.0	86.5	43.5	0.69	0.25	2.90	1.56	0.83	6.81	4.42	0.98	0.52	4.28	2.78
205 BD	9.0	2.5	90.8	45.2	0.88	0.31	3.42	2.56	1.27	9.67	5.98	1.61	0.80	6.08	3.76
206 AS	23.8	2.2	57.3	82.7	1.34	0.28	3.44	5.88	1.06	9.80	2.87	3.69	0.66	6.16	1.80
207 AD	14.1	4.1	160.0	11.0	1.08	0.48	3.51	3.85	3.09	10.25	3.32	2.42	1.94	6.44	2.08
208 AS	20.8	2.8	76.1	62.9	1.27	0.35	3.72	5.33	1.59	11.49	4.57	3.35	1.00	7.22	2.87
209 AS	15.6	3.6	110.1	38.4	1.13	0.43	3.77	4.21	2.40	11.81	5.20	2.65	1.51	7.42	3.27
210 AD	20.5	3.1	81.1	56.9	1.26	0.37	4.01	5.24	1.82	13.32	6.27	3.29	1.14	8.37	3.94
211 AS	11.2	2.2	69.2	53.8	0.98	0.28	4.04	3.15	1.06	13.52	9.31	1.98	0.66	8.50	5.85
212 BD	10.6	3.9	124.1	25.9	0.97	0.46	4.42	3.10	2.80	16.09	10.18	1.95	1.76	10.11	6.40
213 BD	11.2	2.5	66.7	45.3	1.00	0.31	5.04	3.31	1.27	21.00	16.42	2.08	0.80	13.20	10.32

required as mass may be due to the experimental error in the measurement of the individual disintegration, to errors in the masses used in the calculation, or to both.

A plot of the data to detect definite nuclear levels, such as those indicated by the corresponding data for nitrogen, would here involve too few events to be of value. To prove or to disprove the existence of such levels requires more extensive and more accurate work.

V. The Disintegration of Fluorine Nuclei by Neutrons

Out of 1600 pairs of photographs taken to detect the effects of fast neutrons in carbon tetrafluoride and 3200 pairs in difluor-dichlormethane, both diluted with helium, 13 pairs were suitable for measurement. Only eleven pairs, however, were of a quality comparable with those obtained in nitrogen, neon, etc.

The reaction for the disintegration of fluorine by capture is:

$$^{19}_{9}F_1 + ^{1}_{0}n_1 \rightarrow ^{20}_{9}F_2 \rightarrow ^{16}_{7}N_2 + ^{4}_{2}He_0.$$

This reaction is remarkable in that a new isotope of nitrogen of mass 16 and isotopic number 2 appears. In the preliminary announcement of the discovery of this new isotope, the writers[4] considered that it would be likely to be unstable and to emit an electron to form oxygen 16. This has been verified by Fermi[5] who finds nitrogen 16 to be radioactive, and to change to oxygen 16, as was predicted. In disintegration 201, the kinetic energy is found to increase by 0.7 m.e.v. While this case represents the only known instance of an increase of kinetic energy, such an increase is not impossible, and can be accounted for by a decrease in rest mass during the reaction, with conversion of this mass into kinetic energy and possibly in part also into a γ-ray. Since the mass of the N^{16} formed is unknown, this supposition cannot be tested. In any case, however, this particular pair of photographs was rather poor, and the experimental error probably exceeds the 0.7 m.e.v. involved.

The maximum value for the kinetic energy which disappears is 10.3 m.e.v. as shown in

[4] Harkins, Gans and Newson, Phys. Rev. **44**, 945 (1933).
[5] Fermi, Amaldi, D'Agostino, Rasetti and Segré, Proc. Roy. Soc. **A146**, 483 (1934).

Table I. The average value for the kinetic energy of the neutron at impact is 6.7 m.e.v.

The number of disintegrations obtained under similar conditions is much larger for fluorine than for neon nuclei, and is of the same order as for nitrogen nuclei.

VI. The Disintegration of Carbon Nuclei by Neutrons

If carbon 12 is disintegrated by capture:

$$^{12}_{6}C_0+^{1}_{0}n_1\rightarrow^{9}_{4}Be_1+^{4}_{2}He_0$$

the increase of mass in the reaction is equivalent to 6.9 m.e.v. If this energy, in addition to any γ-ray energy liberated in the reaction, is supplied by the decrement in the kinetic energy accompanying the process, it would require a neutron of velocity greater than 3.6×10^9 cm/sec. Since the average velocity of the neutrons which disintegrated nitrogen nuclei is less than this value, it is to be expected that carbon nuclei will be disintegrated much less frequently than nitrogen nuclei by the same source of neutrons.

Of 6400 pairs of photographs taken with ethylene (C_2H_4) in the chamber, 6 pairs showed good photographs of disintegrations. Most if not all of these may, however, be due to the disintegration of oxygen nuclei in the water vapor used to form the cloud tracks in the chamber or of nitrogen nuclei from any residual air in the chamber. Only one disintegration represented a decrease of kinetic energy sufficient to supply the mass increment in the disintegrative-synthesis for carbon. In this disintegration, which was by a neutron directly from the source,

$R_{He}=13.8$ mm	$KE\cdot He=2.24$ m.e.v.
$R_{Be}=3.8$ mm	$KE\cdot Be=1.68$ m.e.v.
$\phi=97.6°$	$Ke\cdot n=10.19$ m.e.v.
$\theta=22.4°$	$-\Delta KE=6.27$ m.e.v.
$_{He}=1.04\times10^9$ cm/sec.	
$_{Be}=0.60\times10^9$ cm/sec.	
$v_n=4.42\times10^9$ cm/sec.	

Possibly this event is also due either to oxygen or nitrogen. It is not yet certain, therefore, that carbon 12 has been disintegrated by neutron impact.

The average energies in millions of electron-volts which have been thus far found to disintegrate light nuclei are:

Element	N	F	0*	Ne	C
No. of disintegrations	28	13	4	11	1
Energy of neutron (m.e.v.)	5.4	6.7	7.0	10.6	High

An important source of error in this work is the uncertainty in the energy-range relations of the heavier nucleus, as has been pointed out by us[1] and by Feather.[6] Fortunately the energy of this nucleus is usually less than that of the lighter one.

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* From the work of Feather, Nature **130**, 237 (1932).
[6] N. Feather, Proc. Roy. Soc. **A142**, 702 (1933).