Some Contemporary Advances in Physics—IV

By KARL K. DARROW

Closing the Spectrum Gap Between the Infra-red and the Hertzian Regions

AN electrical circuit having a natural oscillation-frequency anywhere below 10^8 can be constructed by anyone with suitable condensers, inductance-coils, and a few feet of wire at his disposal. It can be set into oscillation by abruptly closing it when the condenser is charged, by coupling it to an audion, or otherwise; and the waves which it radiates while oscillating can be detected and measured, at least when the frequency exceeds 10^4. Thus it is possible to generate perceptible electromagnetic waves of frequencies up to 10^8, and hence of wavelengths down to 3 metres, by methods that may be called *electrotechnical*. Waves shorter than 300 cm., frequencies higher than 10^8 cycles, are not easily produced by any such method; for if one uses excessively small condensers and inductance-coils in the hope of forcing the circuit-frequency much past 10^8, or even omits coils and condensers altogether, it is found that the auxiliary apparatus, the audion, even the wires of the circuit themselves, possess capacities and inductances which can not be annulled and which hold the oscillation-frequency down. By devising oscillating systems which have scarcely any outward resemblance to the circuits of familiar experience (although a formal analogy can be established) Hertz and his successors generated electromagnetic waves of frequencies up to 10^{11} and wavelengths down to 3 mm. Beyond a certain gap there commences, near frequency 10^{12} and wavelength 0.3 mm., the far-flung spectrum of rays emitted by molecules and atoms. This interval is one of the two lacunae in the complete electromagnetic spectrum extending from 10^4 past 10^{20} cycles, which were mentioned in the preceding article of this series. Unlike the gap between the ultra-violet and the X-rays, it is not believed to be populated by rays resulting from important processes occurring within the atoms, nor do we know of any other peculiar type of radiation which should be sought within it; and perhaps the bridging of it, when finally and unquestionably achieved, will be held notable chiefly as a feat of experimental technique or a *tour de force*. On the other hand, so long as the gap remains unspanned, we can hardly dismiss the possibility that something in the order of nature may reserve one range of wavelengths for the "natural" rays resulting from atomic processes, and limit the "artificial" waves generable by electrotechnical

means to a distant range which never can be extended to overlap the other.

The advance into the lacuna from the direction of shorter waves, that is, from the spectrum of natural rays, came almost to a stop in 1911, at a wavelength between 0.3 and 0.4 mm. Rubens and von Baeyer examined the rays emitted by a mercury vapor arc in a quartz tube, operated with a comparatively high expenditure of power; they filtered the radiation through a succession of diaphragms and lenses which cut out a large fraction of the short-wave radiation, but not by any means all of it. At first they analyzed the radiation which came through with an interferometer, like the one which I shall describe in speaking of short artificial waves; the curves indicated that it consisted largely of two waves, one at 0.218 mm. and the other at 0.343 mm. Rubens in 1921 returned to the experiments, and diffracted the transmitted rays with a large-scale wire grating (the wires were a millimetre thick and a millimetre apart). This method of analyzing the radiation, in which it is spread out in a spectrum, is preferable to the other. The results were quite concordant with the earlier ones; the curves of intensity versus wavelength show maxima at 0.210 mm. and 0.325 mm., and extend out as far as 0.4 mm.[1] There is no sign that this is a definite physical limit; it is merely the point at which the rays become too feeble to produce an unmistakable deflection of the micro-radiometer. Nichols and Tear also have observed these long natural waves.

To advance into the lacuna from the region of artificial waves, it was found necessary first of all to remodel the oscillator or "doublet" by means of which Hertz had generated the first waves of this kind. The original oscillators of Hertz were rather large; some for example, consisted of pairs of metal plates 40 cm. square or pairs of spheres 30 cm. in diameter with arms projecring from each toward the other and carrying knobs several mm. or cm. in diameter; their natural frequencies were of the order $10^7 - 10^8$. Their successors were made progressively smaller, and the latest oscillators are comparatively minute—in dealing with a less exact science, one would describe them as microscopic; for Möbius before the war used a doublet of

[1] It is not necessarily to be assumed that the mercury arc is unique in sending out rays of so great a wavelength with so great an intensity; these rays may not be more intense than a black body of the same temperature as the arc would emit in this portion of its spectrum (although this interpretation would involve a rather high estimate of the arc temperature, many thousands of degrees). But if we had a black body of this temperature available, we might not be able to detect these rays because of the flood of light of higher frequencies which could not be completely deflected from the path of the long waves. Thus we are led to the paradoxical conclusion that the mercury arc may be unique not in furnishing these rays, but in not emitting so much radiation of lesser wavelengths that the rays desired cannot be isolated.

platinum cylinders each 1 mm. long [2] and 0.5 mm. thick, while Nichols and Tear in 1922 succeeded in making and using tungsten cylinders 0.2 mm. long and 0.2 mm. thick.   To appreciate this feat it is necesnary to realize that the cylinders must be sealed into a sheet of glass *with both ends projecting*; as they are shown in Fig. 1, which like the remaining figures (unless otherwise mentioned) comes from the work of Nichols and Tear.

In Fig. 1, the oscillator-cylinders are shown at c and c_1; they are sealed into the tips of hard-glass tubes T and T_1, and project outwards
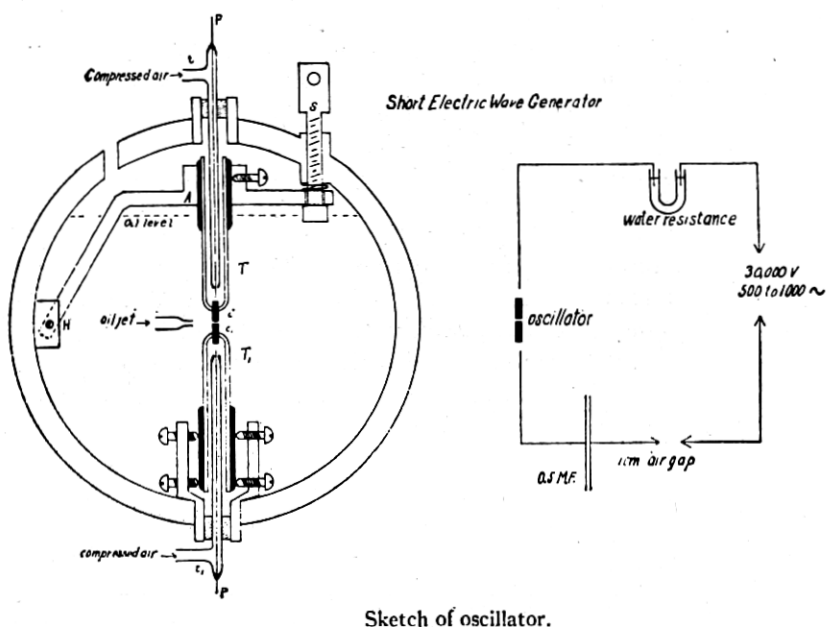

Sketch of oscillator.

Fig. 1—Diagrams of the Oscillator and the Circuit Used by Nichols and Tear. (*Physical Review*)

into kerosene oil which fills the entire cylindrical container up to the level indicated by the dashed line.[3]   The oscillator is excited by the voltage-impulses in the secondary of an induction-coil, resulting from

[2] The figure given by Möbius is 1.98 mm. (last column on p. 317, *l.c.infra*) which he says (on p. 302) applies to the *Gesamtlange* of the doublet.   Theory indicates that the wavelength of the fundamental oscillation is about twice the length of the cylinders, but the exact value of the factor is in doubt.

[3] The kerosene, the "oil-jet" for keeping it circulating rapidly through the region between the cylinders and the blasts of compressed air into the tubes T and T_1 (note the spark-gaps in the leading in wires in these tubes) are all empirical devices for improving the efficiency of the apparatus.

abrupt breaks of the primary circuit produced by a mechanical inter-
rupter at the rate of a thousand per second.   Each of these voltage-
impulses excites a spark between the doublet-cylinders, accompanied
by a highly-damped oscillation which radiates what the authors
describe as "a very short wave-train with from 60 to 80% of the
energy concentrated in the first half-wavelength."   This high damping
is deplorable, as the waves are inconvenient to measure and must be
regarded as mixtures of sine-waves of different frequencies.   The
gap between the cylinders is of the order 0.01–0.02 mm.; it changes
rapidly and irregularly as the opposing surfaces are eaten away by
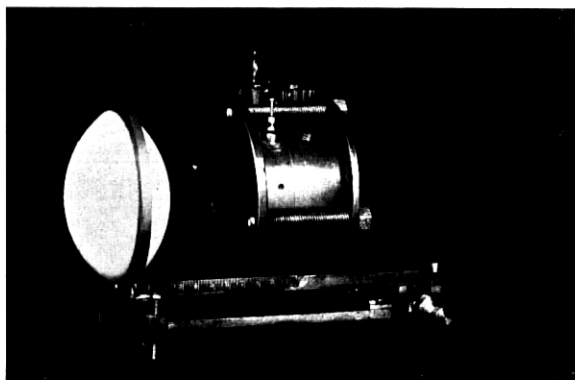

Fig. 2—Photograph of the Oscillator Used by Nichols and Tear.   (*Physical Review*)

the sparks (tungsten was chosen by Nichols and Tear instead of
platinum in the hope, justified by the event, of diminishing this
trouble).

The rays issue through a mica window in the front of the containing-
cylinder and are formed into a plane-parallel beam by an enormous
double-convex paraffin lens (these objects are shown in the photo-
graph, Fig. 2).   Paraboloidal mirrors can be and have been used
instead of the lens.   In the sketch of Fig. 3, L_1 represents the lens;
the plane-parallel beam proceeds to the mirror A and thence to the
mirror B, which is really the pair of mirrors on the left-hand end of
the apparatus of which Fig. 4 is a photograph.   In this apparatus,
the "Boltzmann interferometer," the upper mirror slides backward
and forward (left to right and right to left, in the picture) along the
guides, controlled by the screw; it remains always parallel to the
lower and stationary mirror.   Half of the plane-parallel beam falls
upon each mirror, and the two reflected halves travel side by side

to the lens L_3 which merges them in a common focus at M, where the receiver stands.[4]

The intensity at M depends, by virtue of the principle of interference of periodic waves in its simplest conceivable application, on the ratio of the distance between the planes of the two mirrors to the
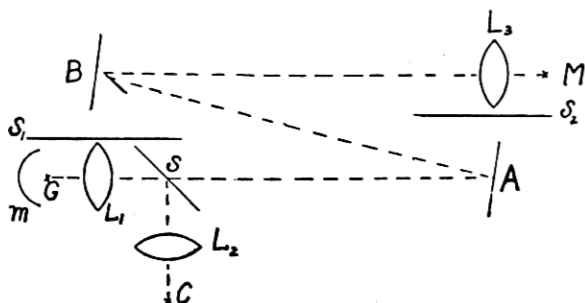

Diagram for wave-length measurements.

Fig. 3—Path of the Radiation from Oscillator to Receiver.   (*Physical Review*)
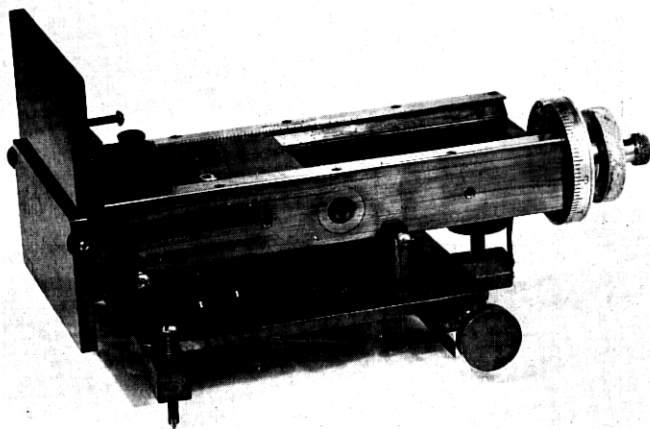

Fig. 4—Photograph of the Boltzmann Interferometer.   (*Physical Review*)

wavelength of the rays.   *If* at M there were a receiver of which the reading was perfectly proportional to the amplitude of the vibration at M and *if* the original wave-train were perfectly sinusoidal and

[4] In the sketch S is a semi-transparent mirror (glass ebonite, or cardboard) which reflects a part of the beam to a lens L_2 and focus C where its intensity can be measured at the same moment as the intensity at M.   The variability of the output of the source makes this control indispensable

very long, then the curve obtained by displacing the movable mirror step by step and plotting the receiver-reading against the mirror-displacement would be a perfect sine-curve; the distance between the positions of the mirror corresponding to two consecutive maxima of the curve would be half the wavelength of the wave-train. Unfortunately neither the receiver nor the wave-train is ever perfect. The wave-train is a heavily-damped sinusoid, and consequently the curve of receiver-reading versus mirror-displacement flattens out before the mirror has been moved very far. Even so, the interpretation might not be uncertain if the receiver gave a reading proportional to the time integral of the intensity of the wave-motion at M. This it rarely does.

The receiver, in this region of the spectrum, must be a thermal receiver—a short thin wire or a narrow band of sputtered metal upon a strip of insulating substance, or sometimes a wire loop. In this the
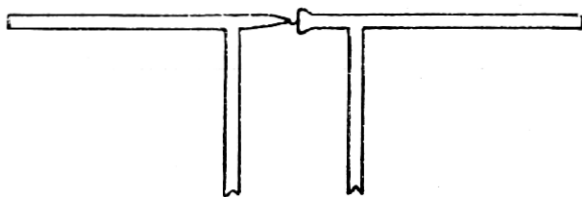

Fig. 5—Thermoelectric Receiver Used by Mobius. (*Annalen der Physik*)

incident waves induce a resonance-current, of which the Joule heat produces the directly-measured effect. A thermojunction may be intercalated in the resonant wire, as in Möbius' apparatus (Fig. 5; in the middle of the transverse piece, 14 mm. long and 0.3 mm. thick, a platinum tip is welded into a tellurium socket). Nichols and Tear, developing a method introduced by G. F. Hull, mounted the thin wire or the sputtered ribbon in front of a radiometer-vane; the Joule heat warmed the front face of the vane, and the rather mysterious agencies sometimes called "radiometer forces" came into play. Four of their receivers are shown in Fig. 6 at b, c, d, and e. In each of these sketches V_1 represents the edge of the radiometer vane; e in sketch b is a wire running from end to end of it, while e_1, e_2, etc., in sketches d and e are short wires mounted vertically or horizontally behind it. The mounting is shown in Fig. 6a; the vanes are seen front-face, one having its wire or wires in front and the other behind, so that the radiometer forces on both will produce torques acting in the same sense. The vanes with the cross-pieces c_1 and c_2 are mounted upon the rod q, which is suspended from a torsion-fibre;

and from the rod is suspended a mirror m to indicate the amount of twist.   The air-pressure is adjusted to produce the maximum torque.

The outstanding defect of a receiver of this type is, that it imprints its own characteristics upon the data.   It will not respond effectively to a wave-train not possessing a frequency agreeing closely with its
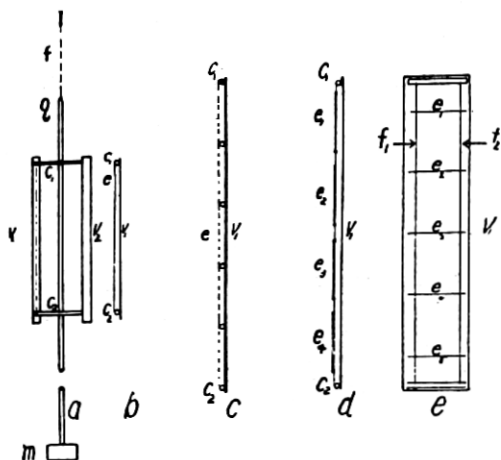

Fig. 6—Radiometer and Radiometer Vanes Used by Nichols and Tear.   (*Physical Review*)

own, or with some harmonic of its own; and has a tendency to exaggerate the apparent proportion of such frequencies in a beam which is a mixture of frequencies, as a damped wave-train is.   In general, the curve of receiver-reading versus mirror-displacement is an unevenly wavy one which, when analyzed into components in Fourier's manner, is found to contain at least two frequencies, one of which is attributed to the receiver and the other to the radiation.   On the other hand, if a receiver having its natural frequency far away from the expected periodicities of the waves is employed, it is found too insensitive.[5]   Worse yet, if the wave-train pursuing the path L_1ABM in Fig. 3 is a short heavily-damped one, while the natural oscillations of the receiver are of comparatively low frequency and slight decrement, the data will suggest that the wave-train is but slightly damped and has the frequency of the receiver.[6]

[5] Thermal receivers having natural frequencies far below those of the incident beams have been employed in studying wave-trains of much greater wavelengths and much more intense than these.

[6] This can be seen by considering an extreme case.   Imagine that the wave is a single infinitely thin pulse, while the natural oscillations of the receiver are quite undamped.   The pulse will be divided by the Boltzmann mirrors, so that two pulses

Clear smooth sine-like curves with the periodicity of the wave-train are obtained by using a receiver of which the natural frequency agrees with the fundamental frequency (or its octave) of the oscillator. Such curves are seen in Fig. 7; the two fundamental frequencies were
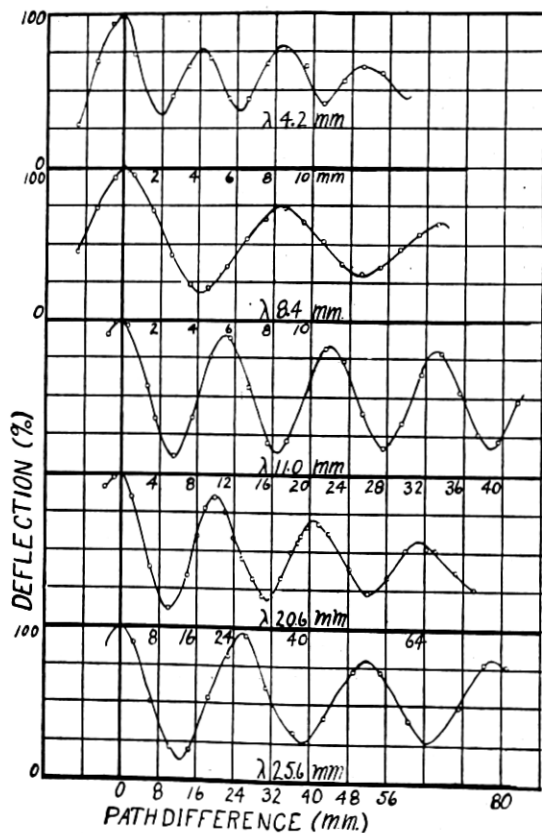
Set of curves, λ 4.2 to λ 27.

Fig. 7—Curves Obtained with a Receiver in Tune with the Oscillator (Topmost Curve with Receiver Tuned One Octave Below the Oscillator).   (*Physical Review*)

will strike the receiver at a time-interval T; there will be nothing of the nature of interference.   But if T happens to be an even-integer multiple of the half-period of the receiver, the second pulse will reinforce the oscillations started by the first; if it is an odd-integer multiple of the half-period, the second pulse will annul the vibration started by the first.   Thus as the Boltzmann mirror is moved along, the receiver-reading will pass through maxima and minima with a spacing imposed by the characteristics of the receiver.   In actual experiment this might happen if the frequency and the damping of the wave-train were much higher than those of the natural vibration of the receiver.   On the other hand it does not appear that a frequency much higher than that of the wave-train could be simulated by any effect due to the receiver—an important point, in view of what follows.

in close agreement for all except the topmost of the curves, for which
the fundamental of the oscillator corresponded to wavelength 4.2 mm.
and that of the receiver to wavelength 8.4 mm.

The lowest wavelength mentioned by Nichols and Tear as having
been manifested and visualized in this lucid fashion is 4.2 mm.; while,
replacing the two mirrors of the Boltzmann interferometer by a set
of eight mirrors forming an evenly-rising staircase or echelon, they
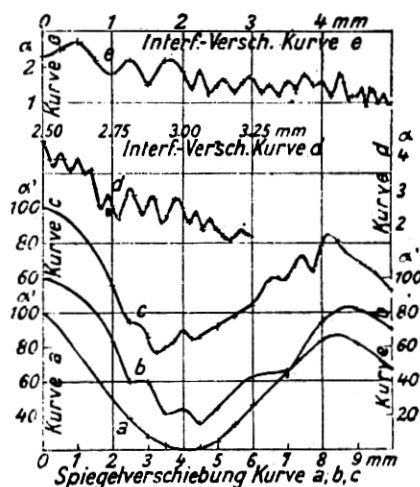obtained curves which in one instance indicated a fundamental of

Fig. 8—Serrated Curves Indicating Very Short-Waved Components of the Wave
Train.   (*Annalen der Physik*)

1.8 mm.   It would be a conservative, perhaps a too conservative,
policy to regard this as the present limit of the spectrum of artificial
electromagnetic waves.

Whether we may believe that rays lying beyond this limit have
actually been generated depends upon the interpretation of certain
narrow sharp serrations observed upon curves of the more uneven
sort; for example, those of Fig. 8 (Möbius) and curves *A* and *C* of
Fig. 9 (Nichols and Tear).   If these are reliable indices of waves of
corresponding wavelength in the mixed radiation from the oscillator,
the frequencies in question must be considerably higher than the
fundamental frequencies of the oscillators heretofore made; wave-
lengths ranging down to 0.1 mm., corresponding to frequencies ranging
up to $3 \cdot 10^{12}$, have been inferred from such curves.   If these are over-
tones emitted by the oscillator along with its fundamental, there would
be little objection to extending the spectrum to cover them (although

it would be equivalent to considering a tenor's range as extending to the highest overtone which could be detected in any of his notes, which would certainly lead to astonishing results). Or they may be radiated by oscillations within particles of metal torn from the electrodes by the violence of the discharge—an idea suggested because
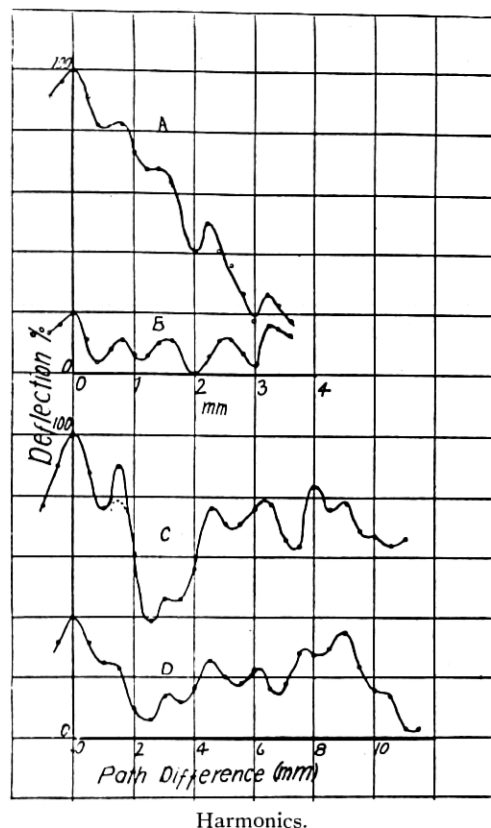
Harmonics.

Fig. 9—Serrated Curves (*A* and *C*) Indicating Very Short-Waved Components of the Wave Train. (*Physical Review*)

they are prone to appear after the spark-gap has been widened and the electrode-surfaces corroded by a succession of sparks. Or they might result from an excitation of molecules or atoms, in which case they should be regarded as belonging to the spectrum of natural rays, in the sense of my previous distinction.[7] Even so, if the serra-

[7] It is interesting to note that the opposite idea was put forward by Rubens—*i.e.*, that the rays of wavelengths 0.1 mm. and thereabouts emitted by the mercury arc might be due to oscillations in droplets of liquid mercury.

tions are truly due to waves issuing from the doublet and not to some unhappy peculiarity of the receiver—and the former alternative is considered the more probable one—then there is good reason for believing that the spectrum of artificial waves has been prolonged to overlap the spectrum of natural waves, and the lacuna is closed.[8]

THE DISCOVERY OF ISOTOPES

Thirteen additional elements having been analyzed into isotopes by Aston, the moment is opportune for restating the two great series of discoveries which have disclosed the hidden law and the underlying unity of the chemical elements. Twenty-five years ago, the labors of chemists had resulted in setting apart about seventy-five distinct, unchangeable, non-interconvertible substances as "the elements"; and the ancient ambition to describe all forms of matter as combinations or modifications of a single, truly fundamental element must have seemed to be definitely frustrated. It is true that there were undeniable signs of a family relationship among the elements. They could be classified into groups of elements more or less alike in their properties; and when they were arranged in the order of their combining weights, there was distinctly a periodic variation of chemical

[8] Dr. Ernest Fox Nichols died suddenly on the twenty-ninth of April, 1924. A few days earlier he had very graciously offered to inform me of his latest work in extending the spectrum of artificial waves, hitherto unpublished except in brief reports before the Physical Society. He discussed the matter with his collaborator Dr. Tear, and to present his final formulation of his great achievement I can do no better than to quote verbatim a letter which Dr. Tear kindly wrote to me on April 29th:
"The most satisfactory data we have at present has been obtained with receivers whose fundamental wavelengths are long compared with those to be measured. The electrodes of our smallest oscillators are 0.1 mm. in diameter and 0.1 mm. long. The glass seal covers approximately one-half their length. The fundamental wavelength of such an oscillator is of the order of 1 mm. The distribution of the dielectric and the means of excitation are such however as to accent certain harmonics and to suppress the fundamental and other frequencies. The interference curves show then the presence of one high frequency, usually the second or fourth harmonic, plus the low frequency of the receiver. The interference persists for three or four cycles and is reproducible, although the construction of such minute seals introduces the element of chance, frequently making it necessary to construct several oscillators before finding one having the right proportions of bare and glass-covered electrode-surface to bring out one frequency and suppress the remainder.
"It is in a way perplexing that although chance proportions of glass and metal bring out one harmonic to a greater or less degree, the fundamentals of these smallest oscillators do not show up at all. It is of interest, too, to note that a sheet of glass 0.2 mm. thick, such as the seals are made of, transmits but 25% of the 0.32 mm.-radiation from the mercury arc. We have been led to the interpretation that the particular standing waves which can exist upon these small oscillators are determined by the location of the glass-oil boundary-surface, and that the predominant wavelength is the fundamental wavelength of that part of the oscillator which is in oil between the two glass-oil surfaces. *The wavelengths which we have isolated in this way extend to the 0.22 mm. limit* which we reported at Boston." (That is, at the Boston meeting of the Physical Society, December, 1922. Italics mine.— K. K. D.)

and physical properties in passing along the line.   Indeed the periodicity was so clear that in three instances when the order of two consecutive elements was such as to damage the periodic law, chemists simply reversed the order—putting argon before potassium, cobalt before nickel, tellurium before iodine, thus testifying to a faith that there must be something governing the nature of the chemical elements more fundamental than combining weights.   Furthermore, in several instances where the periodic law implied that there ought to be an additional element between two apparently consecutive ones, chemists left a vacant space between the two for an element presumed to be existent but unknown; and some of these elements were subsequently discovered, thus justifying the faith in the most impressive way.   But of the nature of this fundamental something, there was no inkling.

It had been suggested at one time that all atoms are built up of hydrogen atoms.   But the most accurate measurements placed it beyond doubt that the chemical combining weights of the elements are not, in every case, integer multiples of the combining weight of hydrogen, nor of any other common divisor large enough to have a physical meaning.   As it was universally assumed that the weight of the ultimate particles of an element is equal to its combining weight multiplied by some universal factor, this fact seemed to disprove the suggestion.   Yet on the other hand the measurements established a rule that the combining weight of many of the elements —far too many to be explained as due merely to chance—are integer multiples of a common unit which is $\frac{1}{16}$ of the combining weight of oxygen.   This can be illustrated from any group of elements, for example from the first ten of the periodic table:

H	He	Li	Be	B	C	N	O	F	Ne
1.008	4.00	6.94	9.02	10.83	12.00	14.01	16.00	19.0	20.20

out of which group of numbers eight are integer multiples of the unit 1.00, within observational error; while four—the combining weights of hydrogen, lithium, boron and neon—certainly are not.   We are confronted with a manifest rule restricted by undeniable exceptions— the most stimulating situation which can arise in a science.

Suddenly the exceptions to the rule were all explained away, and the mystery vanished with a completeness which we hope that some of the other mysteries of physics will some day emulate.   The trouble was simply that everyone has assumed, with an indifference to the other alternative which now seems strange,[9] that all the atoms of an

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[9] Compare Aston's historical review (*Isotopes*, pp. 1–6).   Crookes very definitely suggested a multiplicity of atomic weights in 1886.

element have the same weight, which (multiplied by the proper universal factor) is the combining weight of the element; whereas now it is known that some of the elements have two or several different kinds of atoms apiece, with different weights, of which the observed combining weight of the element is merely an average. The combining weight of an element as observed in ordinary chemical experiments has no general right to the title of *atomic weight*; only in special instances may the two be identified. The elements of which the combining weights are integers—meaning, integer multiples of $\frac{1}{16}$ of the combining weight of oxygen—consist of atoms of a single kind, the weight of which is truly and accurately given by the combining weight of the substance. The others, or those of them which have been analyzed, are mixtures of atoms of different kinds, the weight of no one of which is given by the combining weight of the element. Wherever it is actually the mass of an atom which is measured by the chemical method, the rule is verified; where the rule is apparently infringed, the quantity measured is merely a misleading average, and not the mass of an atom at all. When, therefore, the rule is restated to apply only to those combining weights which are truly atomic weights, the conspicuous exceptions no longer militate against it, and the supposition that all atoms may be built of hydrogen atoms is strongly reinforced.

When J. J. Thomson developed the technique of his "positive-ray analysis" by which he measured the masses of fast-flying charged atoms and molecules, he was unknowingly preparing the way for ascertaining how many different kinds of atoms belong to a single element. In these classical experiments the ionized particles were those existing in a rarefied gas traversed by an electrical discharge, and drawn to the cathode by the strong field maintaining the discharge; through a narrow perforation in the cathode, a thin pencil of the ions passed into a chamber where it was subject to crossed electric and magnetic fields. These fields resolved it into a number of separated and separately-directed pencils, each containing exclusively atoms (or molecules) of a single uniform mass, which could be deduced from the location of the trace made by the pencil upon a photographic plate.[10] The method was designed by Thomson as a sensitive, indeed a supersensitive, method of chemical analysis, by

[10] The actuality is somewhat more complex, as a distinct pencil is obtained for each value of the charge-mass ratio E/m, and it is this ratio which is deducible from the location of the pencil. However E is either the electron-charge e or a small integer multiple of it (occasionally, but rarely, as great as $8e$), and the multiplicity of pencils corresponding to different values of E and a single value of m seems to be an actual advantage to the experienced interpreter of such data.

which gases present even in small proportions in a discharge-tube could be detected and identified. The first trials were naturally made upon discharge-tubes containing the commoner gases, which as it happens nearly all consist of one kind of atom (or molecule) apiece—oxygen, nitrogen, hydrogen, carbon dioxide, carbon monoxide. This retarded the great discovery. But when neon, a gas of presumed atomic weight 20.2, was introduced into the tube in 1912, Thomson observed two pencils, of atoms of masses about 20 and 22, respectively, where he had expected to see but one consisting of atoms of mass about 20.2.[11]

This observation was not immediately interpreted as we now interpret it. The mysterious pencil might have consisted of molecules of CO_2 of mass 44 bearing a double charge, or of molecules of a hitherto unknown compound NeH_2. These possibilities were tested by appropriate experiments and discarded, and then for a time the gas of atomic mass 22 was apparently regarded as a new element distinct from neon and fortuitously mixed with it.

F. W. Aston undertook the attempt to separate the two gases, but they were so entirely alike in their properties that no success whatever was attained by fractional distillation and little by diffusion. This was Aston's entry into this field, and in a celebrated series of researches, soon interrupted by the war but resumed after six years and still continuing, he associated his name forever with the analysis of elements into the different kinds of atoms of which they consist.

Of the improvements which Aston made in the method of measuring the masses of charged particles, as of the details of Thomson's original method and of Dempster's method, it is hardly necessary to speak; for they have been admirably described, with reproductions of photographs, in several recent books.[12] The problem of generating ions of the elements to be analyzed became progressively harder to solve. The elements gaseous at room-temperature were easily investigated, and those of which a high vapor density could be produced either of the element or of one of its compounds, without overheating the tube, were also tractable; but when these elements had all been tested the resistance to further advance became formidable. Ions of the thirteen elements lately analyzed were formed as *anode rays*: that is, they were charged atoms expelled from the anode of a discharge-tube

[11] Neon by virtue of its well-known chemical inertness has no "combining" weight, but its average molecular weight was determined from its density by Watson, using Avogadro's principle, as 20.200. Thomson's earliest experiments were not delicate enough to distinguish whether the atoms in the former of the two pencils were of mass 20.0 or of mass 20.2, but the difference between either and 22 was unmistakable.

[12] Notably in Aston's own book *Isotopes* and in Andrade's *The Structure of the Atom*.

during the discharge—not ionized atoms of a gas sustaining the discharge, as previously—and drawn to and through the cathode by the entire voltage across the tube. The anode of the tube must be made in a special manner; in Aston's experiments it consists of a "paste" made of graphite, of lithium iodide, of a halogen salt of the metal to be analyzed, and sometimes of other salts as well. Ions of the other elements in the paste and from the gas in the discharge mingle with the desired ions in the pencil which shoots through the cathode perforation, but this is no inconvenience, quite the reverse, as the traces

	I	II	III	IV	V	VI	VII	VIII	0
1	1 H 1.008								2 He 4
2	3 Li 7,6	4 Be 9	5 B 11,10	6 C 12	7 N 14	8 O 16	9 F 19		10 Ne 20,22
3	11 Na 23	12 Mg 24,25,26	13 Al 27	14 Si 28,29,30	15 P 31	16 S 32	17 Cl 35,37		18 A 40,36
4	19 K 39,41	20 Ca 40,44	21 Sc 45	22 Ti 48	23 V 51	24 Cr 52	25 Mn 55	26 Fe 56,54 27 Co 59 28 Ni 58,60	36 Kr 84,86,82 83,80,78
	29 Cu 63,65	30 Zn 64,66 68,70	31 Ga 69,71	32 Ge 74,72,70	33 As 75	34 Se 80,78,76 82,77,74	35 Br 79,81		
5	37 Rb 85,87	38 Sr 88	39 Yt 89	40 Zr	41 Nb	42 Mo	43—	44 Ru 45 Rh 46 Pd	54 Xe 129, 132, 131 134 136, 128 130, 126, 124
	47 Ag 107,109	48 Cd	49 In 115	50 Sn 120, 118, 116, 124 119, 117, 122, 121	51 Sb 121,123	52 Te	53 I 127		

Additional elements: 55 Cs, one isotope at 133
80 Hg, isotopes at 202,204, and in the range 197-200

Fig. 10—The First Six Rows of the Periodic Table of the Elements, Showing the Atomic Masses of the Isotopes of the Elements which Have Been Analyzed. The Data Come from Aston's Tabulations

which they leave on the plate are convenient *points de repère* for fixing the exact location of the traces left by the ions being analyzed. In this manner the elements scandium, titanium, vanadium, chromium, manganese, cobalt, copper, gallium, germanium, strontium, yttrium, silver and indium were studied—thirteen altogether, bringing up to forty-seven the number of elements which have been analyzed in the fourteen years since neon was first discovered to be multiple.

Ali of these forty-seven elements except two lie in the first five periods of the periodic table, and they have been written out in the tabular form in Fig. 10. The symbol of each element is preceded by its atomic number, and below the symbol lies not the combining weight of the element as in the tables one usually sees hanging on the walls of chemical lecture-rooms, but the ensemble of the atomic weights of its various kinds of atoms—the atomic masses of its *isotopes*, as the term is. Where no number or set of numbers is given, the analysis has not yet been made. Of the first fifty-five elements of

the table, all have been analyzed except nine; but of the next twenty-seven elements, only one (mercury) has been analyzed. These heavier elements and their compounds seem generally to be non-volatile and so impregnable by the original method; while they are difficult, if not impossible, to examine by Aston's new scheme, as the traces of the ions upon the plate become fainter with increasing mass, and are already extremely faint for the elements in the fifth row of the table.

Among the eight known elements beyond the eighty-second, every one has atoms of several different kinds, alike in physical and chemical properties but different, it is presumed, in mass; but they differ also in another quality, a much more striking quality—they differ in their degree of instability. Out of a great number of atoms of a radio-active substance, existing at a moment t, one-half will have disintegrated at a subsequent instant $t+T$; the interval T, which is called the *half-period* of the substance, is the measure of its instability. Like the atomic mass, this half-period may vary from one kind of atom to another, though both kinds have almost identical chemical and physical properties and belong to the same element. The three isotopes of the eighty-sixth element, "emanation," have three entirely distinct half-periods: 54 seconds, 3.85 days and 11.2 days. Moreover, not only the rate but the manner of disintegration may be different for different isotopes of a single element. The six kinds of atoms which share the ninetieth place in the periodic table display this diversity of properties:

> *Uranium* X_1 has a half-period of 23.8 days and its atoms emit electrons and electromagnetic waves when breaking up;
> *Uranium Y* has a half-period of 24.6 hours and emits electrons;
> *Ionium* has a half-period of 9×10^4 years and emits helium nuclei;
> *Thorium* has a half-period of 2.2×10^{10} years and emits helium nuclei;
> *Radiothorium* has a half-period of 1.90 years and emits helium nuclei;
> *Radioactinium* has a half-period of 19 days and emits helium nuclei.

Nor must it be supposed that if each of two isotopes is stated to emit helium nuclei, they are in that respect identical; for the energies of the emitted nuclei generally vary from one isotope to another, so that every one of the six kinds of atoms listed above differs from every other not only in the rate but also in the manner of its disintegration—and likewise in its ancestry and its posterity, in the

genealogical line to which it belongs. These are the conspicuous differences between the isotopes comprised in a single element, when the element is one of the eight final ones of the periodic table; and they are so conspicuous and impressive that the individual isotopes
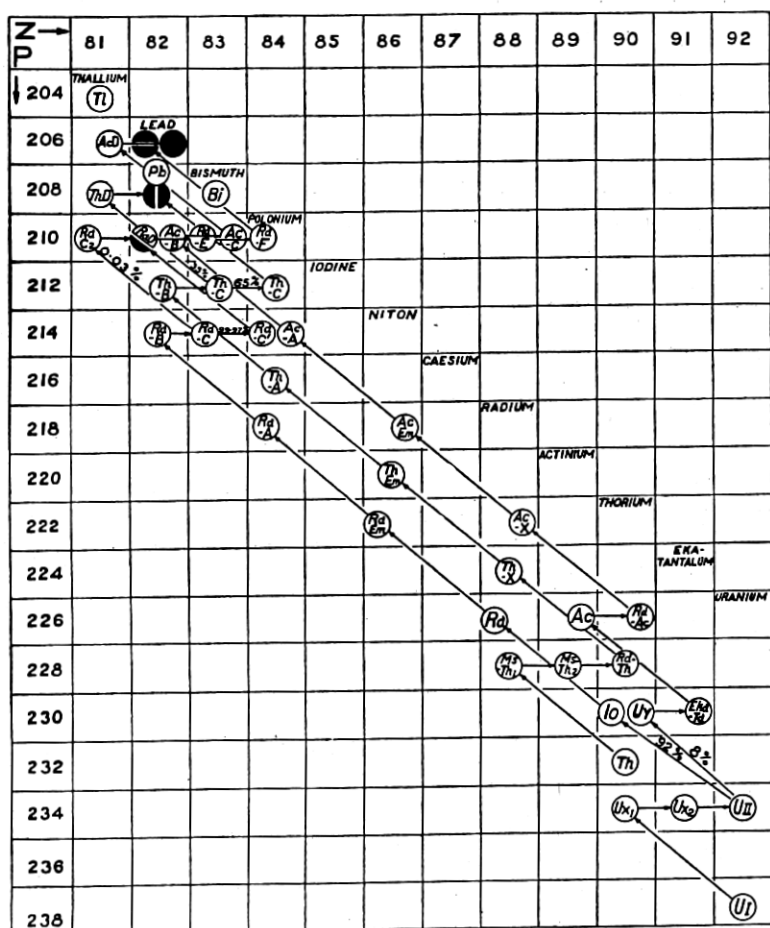
Fig. 11—Table of the Elements from the Eighty-Second to the Ninety-Second (Inclusive) Showing the Names and the Presumed Atomic Masses of Their Isotopes. (Andrade, *The Structure of the Atom*)

enjoy individual names, while the element to which they all belong usually has no all-embracing name of its own,—quite the opposite of the state of affairs among the stable elements, each of which has its own name while the isotopes composing it are known only by the numbers giving their atomic masses. Fig. 11 displays these last

eight elements and the preceding one (lead) each in a column of its own marked with its atomic number (and for identification the name of some element in the same column of the periodic table), while the mass of each kind of atom is given by its elevation above the bottom of the figure (the values are written along the vertical axis).[13]

In these tabulations of Fig. 10 and Fig. 11, all the numbers representing atomic masses are written as integers. The conspicuous post-decimal figures occurring in the sequence of combining weights are absent; the notorious 35.45 of chlorine, the 24.32 of magnesium, the 10.83 of boron have vanished from the scene. Are then the masses of all atoms really integer multiples of $\frac{1}{16}$ of the mass of the oxygen atom, using "really" in its only significant sense of "within the uncertainty of observation?" Or do some of them deviate appreciably from the rule? The trial can be made most exactly upon the lightest elements, as for these a given deviation from an integer value would bulk as a larger percentage of the total mass, which is the measured quantity, than it would for the heavy elements. It is performed by mingling the ions under test with ions of oxygen, or of some other element, preferably one which has previously been compared with oxygen; the locations of the traces of the two pencils of ions upon the photographic plate are compared. Mingling lithium ions with carbon ions, Aston finds that the masses of the two kinds of lithium atoms stand to the mass of the carbon atom as

$$(7.006 \pm .005) : 12.000 \text{ and } (6.008 \pm .005) : 12.000$$

and if the mass of the carbon atom is exactly $\frac{12}{16}$ that of the oxygen atom, then the masses of the lithium atoms are very slightly distinct from $\frac{7}{16}$ and $\frac{6}{16}$ of the oxygen mass (for, little as the difference exceeds the uncertainty of experiment, Aston regards it as real). Beryllium, however, yielded the values 9.003 and 9.001—indistinguishable experimentally from 9.000—in two separate experiments, in terms of the same assumed value 12.000 for carbon. Farther along in the

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[13] The atomic masses of these different kinds of atoms are largely hypothetical. They have been measured for four single isotopes belonging to four distinct elements; radium (number 88, mass 226), radium emanation or niton (number 86, mass 222), thorium (number 90, mass 232), and uranium (number 92, mass 238). Measurements have also been made upon samples of lead believed to be composed almost entirely of a single isotope, giving 206 for one kind of atom and 208 for another). Each of the other atoms is a descendant of one or two of the four first-named atoms, and its atomic mass is calculated by subtracting, from the atomic mass of its ancestor, the masses of all the fragments which dropped away from the earlier atom during its evolution. This procedure is confirmed by comparing the measured values for uranium, radium, radium emanation, and one sample of lead, which all belong to the same line of evolution; and the measured values for thorium and for another sample of lead which is descended from thorium.

procession of elements, comparisons with the oxygen atom become difficult; but adjacent elements can be intercompared. The eight sorts of tin atoms lie next to the nine sorts of xenon atoms, the most massive kind of tin agreeing closely in weight with the least massive kind of xenon. When atoms of gaseous xenon and molecules of a volatile compound of tin are mixed together in the discharge-tube, the beam of ions issuing through the cathode-perforation is resolved into seventeen pencils; and the seventeen traces upon the plate are so placed that the masses of the seventeen atoms cannot all be integer multiples of a common unit of the order of $\frac{1}{16}$ the oxygen mass.[14] Either the tin atoms or the xenon atoms deviate appreciably from the rule, or possibly both do.

So the common history of great sweeping discoveries in science seems to repeat itself; the simplicity of the principle first announced is gradually marred, its sharp lines become a trifle hazy and vague, as experiments are multiplied and refined. Yet the principle does not for that lose its character or its importance; the deviations of the new group of values from integer numbers are small compared to those of the old one, and promise to amplify the physical meaning of the rule instead of restricting it. We should be less prepared to accept them, were there not one of them at the very root of the system of elements; for the mass of the hydrogen atom is not exactly the $\frac{1}{16}$ of the oxygen mass which was taken for the fundamental unit mass of the system of atoms, but is 1.008/16 of it. This seems embarrassing; the bricks of which we intended to say that the atomic structures are built turn out to be smaller than the sample brick. But the embarrassment can be removed; for it can be shown that of the mass of the hydrogen atom is altogether electromagnetic, then the total mass of a group of such atoms crowded closely together must be inferior to the sum of the masses of the individual atoms when far apart. Therefore, small deviations from the rule of integer masses are to be anticipated, and may be expected to serve as a most valuable contrôle of proposed models of atom-nuclei, when the epoch of quantitative spatial models arrives. This epoch may be distant; or we may be upon the verge of it.

We have admitted, then, that the combining weight of an element, being in general not its atomic mass but the average of the masses of several kinds of atoms, and a *weighted* average at that, does not have

[14] The experiment was performed with a tube containing the gaseous compound tin tetramethide $(SnCH_3)_4$ and some xenon from a previous experiment. Eight pencils of $SnCH_3$ ions were observed, consisting of molecules comprising tin atoms of the eight different kinds; molecules containing tin atoms of mass 120 would have a total mass of 135, and hence a pencil containing them would have fallen just midway between the pencils of xenon atoms of masses 134 and 136, respectively; actually it fell distinctly off-centre.

the profound physical significance it once seemed to possess.   But this is not all; we must further concede that even the mass of the atom— or the ensemble of masses of the atoms—of an element is not by any means so distinctive and important a quality of the element as one would expect.   Not only may one element have atoms of several different masses, but two distinct elements may have atoms of, so far as we can distinguish, the same mass; argon and calcium, selenium and krypton, tin and xenon.   Now if an atom of the gaseous and inert argon may have the same mass as an atom of the metallic and active calcium, we cannot evade the conclusion that the mass of an atom is, in the terms of logic, an *accidental* property of the atom rather than an essential one.   There must be some fundamental and essential feature or quality of the atom, which determines its ensemble of physical and chemical properties, and which is not the atomic mass; perhaps this quality determines the atomic mass as well, but cer- tainly not in so rigorous a manner that one value of atomic mass cor- responds invariably to one set of chemical and physical properties, and vice versa.   This fundamental feature of the atom we recognize as the charge upon its nucleus, which, expressed as a multiple of the electron-charge e (of which it must be an integer multiple [15]) is also the number of electrons accompanying the nucleus, and the *atomic number* of the element.

This nuclear charge, or (cardinal) electron-number, or (ordinal) atomic number, is the same for all the atoms of a single element, and never the same for two atoms of different elements.   It is 50 for all of the eight kinds of atoms of tin, and 54 for all of the nine kinds of atoms of xenon.   It is 18 for all atoms of argon and 20 for all atoms of calcium, though some atoms of the one have the same weight (within one part in a thousand, Aston says) as some atoms of the other.   It is 26 for all atoms of cobalt and 27 for all atoms of nickel, though most of the atoms of nickel are lighter and a few heavier than the atoms of cobalt.   It is the true basis for the ordering of the elements, of which the ordering of the atomic masses is but an im- perfect and distorted (though not a badly distorted) imitation.

Five observations or assemblages of observations, made in fields of physics separated almost as widely as any five fields could be, sustain this principle; and, combined with its philosophical   attractiveness for the idea of arranging the elements in a single procession and attaching consecutive integer numbers to their fundamental qualities is as irresistibly attractive as a scientific idea can be—make it about

[15] Otherwise the nuclear charge could not be exactly balanced by the charges of the environing electrons.

as certain as any principle not dealing with things which can be seen and handled.   I shall mention them briefly, in a nearly chronological order.

The direct measurement of the charge of the helium nucleus.   Rutherford and Regener independently measured the charge on the alpha-particle in the simplest, most direct and most incontrovertible way; they counted the alpha-particles emitted from a sample of a radioactive element in a given time, and measured the total charge they carried away from it, and divided the one datum by the other. Rutherford obtained twice $4.65 \cdot 10^{-10}$ (electrostatic units) for the charge of the individual particles; Regener obtained twice $4.79 \cdot 10^{-10}$.   The agreement of the latter value with twice Millikan's standard value of the electron-charge ($4.774 \cdot 10^{-10}$) is magical; the agreement of the former value is also good.   Though this is an average value for a great number of particles, the fact that a beam of alpha-particles is not spread or split by a magnetic field proves that each has the same charge (at least, to be perfectly precise, the same charge-to-mass ratio).   It is established that the alpha-particle is the bare helium nucleus.[16]

The determination of nuclear charges by the scattering of alpha-particles.   When a beam of alpha-particles is played against a sheet of metal foil, the nuclei of the metal atoms deflect the alpha-particles passing very close to them, by virtue of the electrostatic repulsion between the charge $+2e$ on the alpha-particle and the charge $+Ne$ on the nucleus of the metal atom.   The distribution-in-angle of the scattered alpha-particles can be calculated, assuming that the action of the metal nuclei is not complicated by any forces due to the electrons surrounding them.   The distribution-in-angle actually observed agrees in form with the calculated one; this proves not that there are no electrons surrounding the metal nuclei, but that there is a vacant space around each nucleus, wide enough so that the major part of the deflection of an alpha-particle takes place within it.   All this was discussed in the second article of this series.   The form of the distribution-in-angle and its variation with the speed of the alpha-particles prove the existence of the atom-nuclei, of their positive

[16] For helium gas, evinced by its spectrum, appears in a tube into which alpha-particles are fired through the wall, and is exuded from a piece of metal which is melted after alpha-particles have been shot into it (Rutherford's experiments); furthermore impacts between alpha-particles and atoms of helium gas show them to be of the same mass (Blackett's experiments), and the value of the e/m ratio is correct for doubly-ionized helium atoms but not for any other admissible variety of atom.   And the radius of the alpha-particles, calculated from the experiments on scattering, is smaller by several orders of magnitude, than the effective radius of any known atom having electrons in addition to its nucleus.

charges, of the vacant space around them; and if the percentage of scattered particles is measured absolutely, the absolute value of the charge of the nucleus can be calculated. These values have actually been obtained: [17]

> Platinum: nuclear charge $(77.4 \pm 1)e$ (Chadwick)
> Silver: $(46.3 \pm 0.7)e$ (Chadwick)
> Copper: $(29.3 \pm 0.5)e$ (Chadwick)
> Argon: $19e$ (Auger and Perrin)
> "Air" $6.5e$ (C. T. R. Wilson)

Bohr's interpretation of the spectra of hydrogen and ionized helium. There is a complete and perfect agreement between the observed frequencies in the spectra of hydrogen and ionized helium, and the frequencies predicted by Bohr. An essential feature of Bohr's theory is that the charge on the nucleus of the hydrogen atom is assumed to be e, and the charge on the nucleus of the helium atom to be $2e$. As there is no other element of which the spectrum has been perfectly and completely explained by Bohr's theory (or any other) this affirmation cannot be extended beyond hydrogen and helium.

Thus we have excellent evidence from three distinct sources that the nuclear charge of helium, the second element of the periodic table, is $2e$; excellent evidence from two sources that the nuclear charge of the first element, hydrogen, is e; and good evidence by the alpha-ray method that the nuclear charges of the 18th, 29th, 46th and 78th element are as close to $18e$, $29e$, $46e$, and $78e$ as to any other integer multiple of e. In addition, there is evidence from two more sources that, in passing from one element to the next along the procession of elements, one finds the nuclear charge augmented by the amount e at each step; thus completing the itemized evidences foregoing by a process somewhat like what is called "mathematical induction."

The displacement-law of Fajans and Soddy. When an atom-nucleus of a radioactive element disintegrates by shooting off an electron bearing a charge $-e$, the residuum is found to be a nucleus of an element one step farther up in the procession of elements. When an atom-nucleus disintegrates by shooting off an alpha-particle bearing a

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[17] The earliest experiments (discussed by Rutherford in 1911) demonstrated that for several metals the nuclear charge (measured in terms of e) was about one-half the atomic weight; and those of Geiger and Marsden (1913) were arranged primarily to demonstrate the validity of the concept of the nuclear atom, but confirmed that statement for gold. Chadwick repeated these experiments upon *Pt*, *Ag* and *Cu* with the object of determining the nuclear charge as accurately as possible. The values for argon and "air" were determined by what is in principle the same method though in a very different form; the former with alpha-particles, the latter with fast electrons.

charge $+2e$, the residuum is found to be a nucleus of an element two steps farther down in the procession of elements. Thus in passing from one element to the next above it, the nuclear charge is found to be augmented by e. This law is deduced from numerous observations on the elements beyond the eighty-first.

Moseley's law. The square root of the frequency of the $K\alpha$-ray (a prominent and easily-identified member of the X-ray spectrum) increases by a constant amount in passing from one element to the next above it. This law is valid from the twelfth to the ninety-second element in the periodic table. The same law governs, though not with such entire accuracy, the other identifiable members of the X-ray spectrum.

Apart from all interpretation, Moseley's law means that there is a certain important measurable quantity which is very characteristic of the elements and increases uniformly and steadily from one to the next, over almost the entire procession. The mere existence of such a quantity inspires confidence that there is a true physical seriation of the elements, but by interpretation a great deal more can be added. Bohr's theory of the atoms of hydrogen and ionized helium lead to this result: when a single electron forms an atomic system with a nucleus of charge Ne, one of the frequencies which this system can radiate—and the frequency which, on the whole, it would oftenest and most intensely radiate—is equal to

$$v = \frac{3}{4} RN^2, \qquad R = 2\pi^2 m \, e^4/h^3. \tag{1}$$

This is verified for hydrogen and ionized helium, each of these atoms consisting of a nucleus and a single electron. No other such atom has yet been isolated and made to radiate. But we might imagine that in a massive atom containing many electrons, one lies deep down beneath the others, and revolves by itself in the field of the nucleus, undisturbed by the rest. In this case there would be an X-ray frequency emitted by the atom, given by (1). The difference between the values of the square root of this frequency for consecutive elements would be constant and equal to

$$\Delta = \sqrt{\frac{3}{4} R}. \tag{2}$$

Now the observed constant difference between the values of the square root of the $K\alpha$ frequency for consecutive elements does conform to (2). But the actual value of the frequency does not conform to (1)

unless we get the quantity N equal, not to the order-number of the element in the procession, but to the order-number minus one.

Does this mean that the nuclear charge of the nth element in the periodic table is $(n-1)e$ for all the values of n exceeding 11 (the values for which Moseley's law holds)? I fear this could not be contradicted from the direct experimental evidence, for Chadwick's values of the nuclear charges for the elements $n-78$, 47, 29 fall just short of being exact enough to prove that they are $78e$, $47e$, $29e$ instead of $77e$, $46e$, $28e$, respectively. However, we should do too much violence to the beauty of the principle if we admitted that there are only eight values between $2e$ and $11e$ to be distributed among the nuclear charges of the nine elements between helium and magnesium, and happily it is not necessary, for the apparent discordance can plausibly be blamed upon too simpe a view of the internal economy of the atom which we took in deriving equation (1). Instead of assuming that the deepest-lying electron of the atom revolves in an otherwise vacant space surrounding the nucleus, wide enough to contain the first two of its permissible orbits, we should do better to assume that there are several deep-lying electrons similarly placed and interacting with one another, or at least that there is no single deepest-lying electron too far inward to be affected by the others. The effect of thus changing the assumption is to change the calculated value of the $K\alpha$-frequency, for an atom of nuclear change Ne, from the value (1) to a value $\frac{3}{4}R\,(N-k)^2$; in which k depends on the particular configuration assumed for the internal electrons. It is clear, therefore, that we are in no wise compelled by Moseley's law to conclude that the nuclear change of the atom of the nth element is $(n-1)e$ when $n>11$, and may continue to accept the much more satisfying principle that the nuclear change of the nth element is ne.[18]

Before stating the conclusion let me restate the evidence in a briefer form and an altered order. Originally the elements were arranged in the order of their combining weights. It was seen that when they are arranged in this way, there is a periodic variation of the ensemble of chemical and physical properties from element to element. But to make the periodic variation quite smooth and unbroken, it was found necessary to violate the order of the combining weights at several places in the series; three pairs of con-

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[18] The agreement with experiment indeed becomes very good, at least over a certain range of elements, if we assume that there are normally 3 electrons in the innermost or one-quantum ring and nine in the second or two-quantum ring orbit (J. Kroo). But nobody wants to accept this particular repartition of electrons, and it is customary to assume that the inner orbits are mostly elliptical. But it would be gratifying to attain a quantitatively successful theory.

secutive elements had to be reversed, and at several points it was necessary to leave vacant spaces between apparently-adjacent elements, imagining undiscovered ones to separate them. Thus it became clear that the true arrangement of the elements was controlled by something deeper and more fundamental than the combining weights; yet there was no adequate reason for preferring one of the measurable physical or chemical properties above all the others as the fundamental one. Moseley then discovered that the square root of the most conspicuous X-ray frequency increased at a steady and even pace from one element to the next, throughout almost the entire list of elements. Where the order of combining weights disagreed with the order of physical and chemical properties, the order of X-ray frequencies agreed with the latter and not with the former; where the succession of chemical and physical properties suggested that an element was missing from the list, the excessive leap of the root of the X-ray frequency in passing from the element below to the element above the suspected gap gave a striking confirmation. This important quality of the elements, advancing by equal steps from one to the next, testified far more impressively than the periodic variations of the various chemical and physical qualities to the close affiliation among them.

Measurements of the deflections of alpha-particles by atoms had shown that the atom has a massive nucleus bearing a positive charge; as there are also electrons surrounding the nucleus, and as no one has proved the existence of negative electricity otherwise than in electrons, it was inevitable to believe that the positive nuclear charge is balanced by and balances the charges of the surrounding electrons, and so is an integer multiple of the electron-charge e. Moseley's law could be interpreted to mean that the nuclear charge increases by e in passing from one element to the next. Fajans and Soddy had already found that when one of the radioactive elements is transformed into another, the transformation is always such that an increase of e in nuclear charge goes with an advance of one step along the series of elements. Therefore, it would be possible to assign the nuclear charges of all the elements if the nuclear charge of one, or preferably of several, could be absolutely determined. The experiments upon scattered alpha-particles did show for several elements that the nuclear charge of the nth element is at least as close to ne as to any other integer multiple of e; direct measurement of the nuclear charge of the second element showed that it is quite accurately $2e$; and Bohr's theory, of which the interpretation of Moseley's law was an offshoot, derived its own successes partly from the essential as-

sumption that the nuclear charges of the first and second element are e and $2e$, respectively.

Meanwhile the combining weights, without losing their practical utility, were slipping out of the prominence into which they had been forced. It was discovered that they were not always to be identified with the atomic weights; that an element might have several kinds of atoms; that even the masses of these atoms were not absolute characteristics of the elements, as two very different elements might have atoms of apparently identical mass. In Remy de Gourmont's phrase, there occurred a *dissociation of ideas*; the idea of atomic weight was dis-associated from the idea of element, and the idea of atomic number supplanted it. The eighty-seven (now the eighty-eight) known elements formed themselves into a procession, which is a procession of atoms bearing eighty-eight of the ninety-two admissible nuclear charges between e and $92e$, and possessing consecutively all except four of the possible electron-families ranging in number from one to ninety-two. That at least eighty-eight out of these ninety-two conceivable atoms should actually exist and have been discovered, may seem strange; one might perhaps have expected that a stable nucleus with a net charge of ne could be built only for an occasional value of n; but among the first eighty-two integers there are certainly not more than two, perhaps none, which are not represented by durable nuclei; and among the next ten at least eight are represented by not-too-transient nuclei. We have also seen that nuclei with certain values of charge, $54e$ or $90e$ for example, can be constructed in several different ways. These problems of nuclear structure are, however, problems for the future. What does seem established at the present moment is, that if we could determine the properties of the system formed by n electrons and a nucleus of charge ne, we should know all the properties of the elements except a very few having to do with intra-nuclear events. As the only case thus far successfully dealt with is the case $n = 1$, and we cannot even explain what happens when two such atoms combine, this is not meant as an augury of an early complete liquidation of the mysteries of physics. Nevertheless, we have good reason to believe that, though ours is doubtless not the generation which will complete the solution of the problem of the atom, it is the first to which the nature of the problem has been revealed.

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