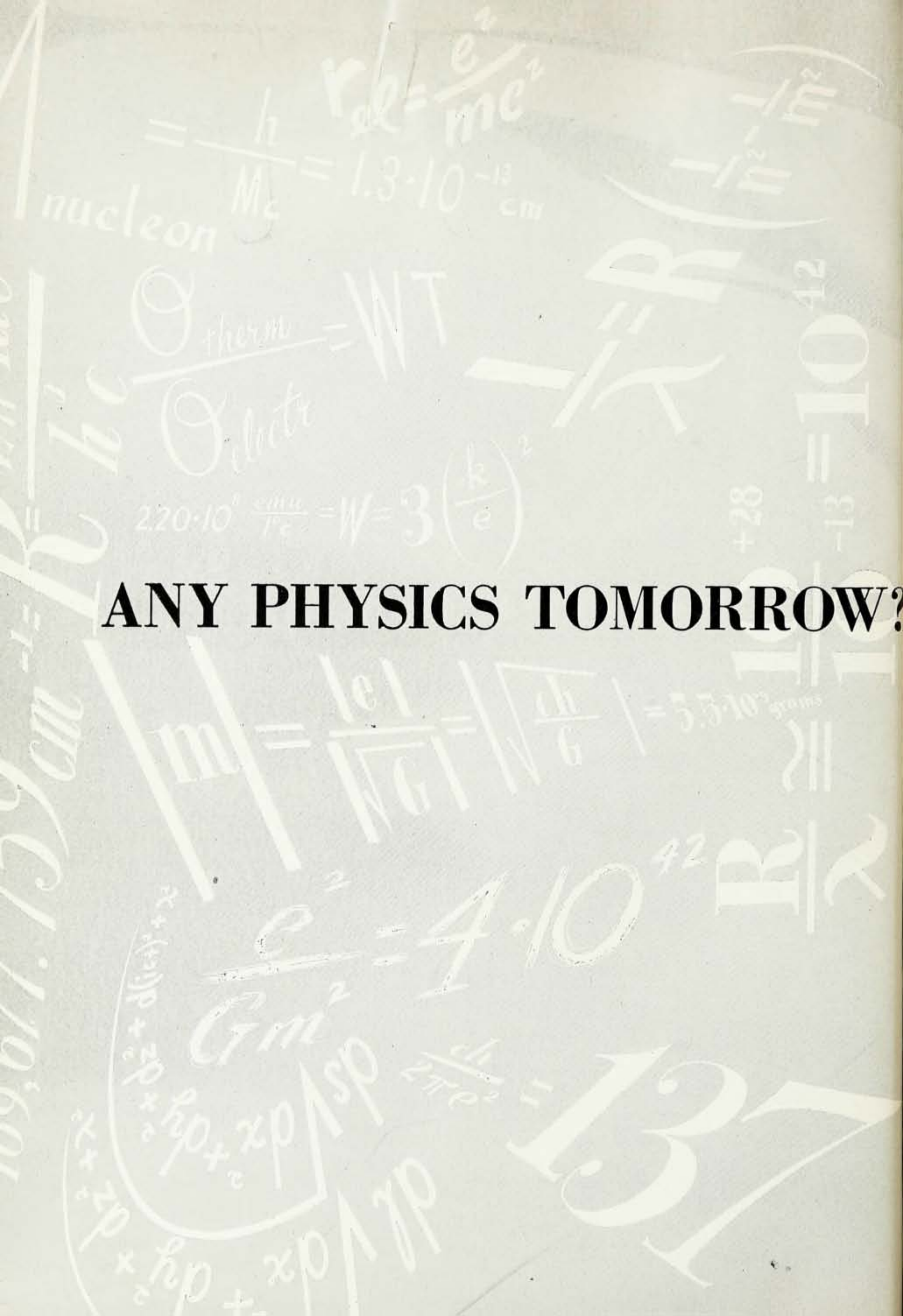

ANY PHYSICS TOMORROW?

n physics come to an end with nothing left to do but the lium of cleaning up details? There is a kind of game going on tween the experimentalist and the theoretician. The former eps bringing in new empirical constants and the latter keeps ring to reduce their number by expressing them through each ner. The author speculates on what the chances are of this me's coming to an end. Then all new constants brought in by e experimentalists would be expressible in terms of only four sic constants.

by George Gamow

Will the development of physics in the years to come always present us with ever broadening horizons offering limitless possibilities for further explorations, or is our science converging towards a complete and self-consistent system of fundamental physical knowledge with all the ground thoroughly explored and with no new striking discoveries to be expected?

Being of purely philosophical nature, i.e., not presupposing the existence of any definite answer, this question serves as the source of many heated discussions between the proponents of the two opposing points of view. But even without hoping to answer this essentially "wait-and-see" question, it may be interesting to give it a somewhat more definite formulation, and to find the possible criteria which may give us a hint concerning the plausible answer.

In studying the progress of physical science we may distinguish between experimental and theoretical advances. The development of experimental physics leads to the discovery of new phenomena, and to the formulation of observed relations between various measured quantities in the form of empirical laws. Such laws usually contain numerical coefficients, or constants, the values of which are determined from the observed data.

The role of physical theory, on the other hand, consists in finding out the hidden relations between various observed phenomena, and in reducing numerous empirical laws to the smallest possible number of fundamental laws which can serve as basic postulates for the logical development of the entire system. In doing so, the theory strives to establish purely mathematical relations between the observed empirical constants, and to reduce them to the smallest possible number of mutually independent basic constants. As an example of such a reduction process we mention the case of the Rydberg constant, R, which appears in the experimentally established Balmer formula for the line spectra of the hydrogen atom.

The quantum theory of atomic structure permits us to express this empirical constant through the other more fundamental constants by the mathematical relation involving only the mass m and charge e of an electron, and h, Planck's constant. Another example is supplied by the Wiedemann and Franz law expressing the relation between the thermal and electric conductivities of metals and their absolute temperature through the value of a constant W. By means of the electron theory of metals this originally empirical constant can be expressed through a simple relation between the electron charge e and Boltzmann's constant k.

Basic Constants

Since all our physical measurements are based on four independent units of measure, the centimeter, second, gram, and degree centigrade, one may expect, on the basis of the theory of physical dimensions, that all the multitude of empirical constants is reducible to only four mutually independent basic constants whose numerical values depend only on

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$$09{,}677.759\,\mathrm{cm}^{-1} = R = \frac{2\pi^2 me}{h^3 c}$$

the choice of basic units of measure. We say "may expect" because there is actually no reason to insist that it is always possible to construct a theory which would give a purely mathematical interpretation of any pure number which could appear in a new empirical formula. There is, however, a deep-seated wishful thinking among theoretical physicists to the effect that in nature there are no incidental numerical constants, i.e. pure numbers which cannot be derived by purely mathematical reasoning. Thus, for example, the famous dimensionless number 137, representing the relation between the elementary electric charge and the two basic constants c (the velocity of light) and h (Planck's constant) was interpreted by Eddington as "the number of independent elements of a symmetrical tensor in the space of sixteen dimensions" (and please add one unit to make it fit!).

Although nobody except Eddington himself was able to understand that particular theory, we still continue to hope that 137 is not just a number but that it can be interpreted in some rational way, like the coefficient $2\pi^2$ in the expression of the Rydberg constant, or the number 3 in the Wiedemann-Franz law. But the only way to prove that this and other similar expectations are justified would be to develop a complete theory of physical phenomena containing only the mathematically derived coefficients.

If and when all the laws governing physical phenomena are finally discovered, and all the empirical constants occurring in these laws are finally expressed through the four independent basic constants, we will be able to say that physical science has reached its end, that no excitement is left in further explorations, and that all that remains to a physicist is either tedious work on minor details or the self-educational study and adoration of the magnificence of the completed system. At that stage physical science will enter from the epoch of Columbus and Magellan into the epoch of the National Geographic Magazine!

The Quadrumvirate

From this point of view we can consider the progress of physics as some kind of game between the experimentalists who are bringing in new empirical constants (for example, several different meson masses which were recently thrown into the game), and the theoreticians who are trying to reduce the number of these constants by expressing some of them through the others. In this sense the history of physics can be represented by a curve showing the number of different independent constants during various epochs as a function of time. At the present stage of the game, we still (or rather again!) have more than a dozen constants, some of which are well established while the others, shown in square brackets in the table below, are more or less questionable. Here is what can be considered as a reasonably complete list at the present time:

- c—velocity of light
- h—quantum constant
- G—the constant of gravity
- k—Boltzmann's constant
- e—elementary electric charge
- m—mass of the electron
- M—mass of the nucleon (two close-lying values)
- $\mathfrak{m}_\mu$—mass of the light meson
- $\mathfrak{m}_\pi$—mass of the heavy meson
- $[\mathfrak{m}_0]$—mass(es) of neutral meson(s)
- $[\mu]$—mass of the neutrino
- $[\tau_\mu, \tau_\pi \ldots]$—lifetimes of mesons
- g—Fermi constant
- $[f \ldots]$—meson-interaction constants

$$\mathfrak{m} = \frac{e}{\sqrt{G}} = \sqrt{\frac{ch}{G}} = 5.5\cdot 10^{-5}\ \text{grams}$$

$$ds = \sqrt{dx^2 + dy^2 + dz^2 + \lambda^2}$$

$$ds = \sqrt{dx^2 + dy^2 + dz^2 + d(ic\ldots}$$

$$\frac{\vartheta_{therm}}{\vartheta_{electr}} = WT$$

$$2.20\cdot 10^{8}\ \frac{emu}{1^{\circ}c} = W = 3\left(\frac{k}{e}\right)$$

Thus we are still far from the end of the game which will come when this table (including the future possible additions) is reduced to only four lines.

In discussing the possible "final" form of physical theory, one must remember that, although in principle it does not matter which four constants should be used as basic ones, the historical development suggests for this role the most general constants that characterize the broad avenues of theoretical thought. We would hardly expect the Rydberg spectral constant or the constants of the electron theory of metals to become one of these four fundamental constants. On the other hand, the velocity of light, c, dominating the entire field of electrodynamics, and the quantum constant, h, are certain to occupy two honor seats in the quadrumvirate of complete physical theory. The Boltzmann constant k will, of course, also be there, sitting in comparative isolation, due to its statistical nature. But which is the fourth candidate?

Looking through the dimensional relations between the constants listed in our table, we can easily notice that the triumvirate c, h, k cannot help us to describe the masses of elementary particles. In fact, although the elementary electric charge can be easily constructed from c and h alone by the relation mentioned before, involving the pure number 137, it is impossible by using these two constants alone (or even with k) to build a quantity of the dimension of a gram.

It would seem, at first sight, that the fourth seat of the quadrumvirate should be offered to Newton's constant of gravity G, which certainly represents one of the most time-honored and universal members of the constants' society. We can indeed easily construct the dimensionally correct expression for mass from c, h, and G.

Putting in numerical values for c, h, and G we find that our dimensional formula leads to a value thirty million million million times larger than the mass of nucleon, and two thousand million million million times larger than the mass of the electron! Of course, being only a dimensional formula, the expression is not expected to produce the exact value we are looking for, and there could be a numerical coefficient which puts the thing right. But it is extremely unlikely that such tremendously large coefficients as are needed in this case could emerge as a bona fide mathematical constant. Besides, we must remember that the phenomenon of gravity, important as it is in cosmological problems, does not play any role in the atomic and nuclear phenomena involving elementary particles. Thus, it would be really very surprising if G should win the fourth seat.

Elementary Length

Under the existing circumstances it seems reasonable to expect that some new universal constant pertaining directly to the properties of elementary particles will be brought to light and acclaimed for the fourth seat in the quadrumvirate. In recent years such a dark horse candidate was suggested by Heisenberg and other physicists. It seems, in fact, that a length of the order of magnitude 10^{-13} centimeter plays a fundamental role in the problem of elementary particles, popping out whenever we try to estimate their physical dimensions. It describes the so-called classical radius of an electron, comes out as the cutting-off distance in the problems of quantumelectrodynamics, and emerges quite independently as the empirical range of nuclear forces. It seems also that all kinds of physical considerations become senseless if we try to apply them to distances smaller than 10^{-13} centimeter.

If a new universal constant of elementary length,

$$\frac{1}{\lambda} = R\left(\frac{1}{n^2} - \frac{1}{m^2}\right)$$

$$\frac{ch}{2\pi e^2} = 137$$

$$\frac{e^2}{Gm^2} = 4\cdot 10^{42}$$

λ (approximately equal to 10^{-13} centimeter) is to be introduced in the basic physical theory, it will have to be interpreted as the smallest numerical value of the distance that can be used in any physical sense to characterize the space separation of two elementary particles. Thus it would play a role similar to h, Planck's constant, which gives the smallest possible value of mechanical action, and to c, the velocity of light, representing the highest possible value of any physical velocity.

How this new constant of elementary length can be introduced into the existing formalism of physical theory is, of course, anybody's guess. Attempts have been made to consider discontinuous physical space formed by a point lattice with the distance of the elementary length between each two neighbouring points. It seems to me that more rational ways of achieving the same end lie in considering a continuous space introducing, however, a finite length into the elementary expression for the physical distance between two points. Thus, for example, we could write formulas for the element of distance as a unit of length in a three-dimensional system or in more general relativistic form, as a unit of space in a four-dimensional system, involving the fourth Einsteinian coordinate. The differential equations of theoretical physics would have to be written in appropriate physical coordinates and will contain the new constant when referred to the mathematical coordinates.

The main reason for introducing such elementary length lies, of course, in the fact that, being combined with c and h, it gives the mass value comparable to those of elementary particles. In fact the familiar relations for the classical radius of the electron and the Compton wavelength of a nucleon which can give simple expressions for these two masses in terms of c, h, and λ, the constant of elementary length. How this is to be done, and how the intermediate meson masses will fit into the picture, is, of course, as yet a mystery. But, following that plan, we are certain to avoid the difficulty presented by *very large pure numbers* connected with the gravitational point of view.

It should be mentioned here that we may not be able to chase G altogether out of the field of elementary particles. In fact, it is known that the probabilities of nuclear processes involving the emission or absorption of neutrinos lie about halfway between the probabilities of ordinary electromagnetic phenomena fitting nicely into the c, h, λ scheme and the emission probabilities of gravitational waves in Einstein's general theory of relativity. It may indicate that neutrinos represent some kind of connecting link between the particle phenomena, governed presumably by the elementary length λ, and the gravitational phenomena, governed by Newton's constant G.

If the elementary length, λ, is to be chosen as the fourth member of quadrumvirate the constant of gravity G will have to be considered as a secondary constant, and we will ask ourselves if it is expressible in terms of c, h, k, and λ. (We include k only for the sake of generality, since it is rather clear that, because of its isolated position, it can hardly play a role in this particular problem.) Here, of course, the "big pure number" will again make its appearance with the difference, however, that it will now underline the contrast between the microcosmos of atoms and macrocosmos of stars.

The situation can be expressed in the best way by writing the (dimensionless) ratio of the electric and gravitational forces between two electrons which gives the number: $4\cdot 10^{42}$. As we have said before, it is very hard to believe that such a big number will turn out to be a definite mathematical quantity like $3/5$ or $2\pi^2$. But it is also not so important (from the point of view of our wishful think-

$$\frac{R}{\lambda} \cong \frac{10^{+28}}{10^{-13}} = 10^{42}$$

$$r_{el} = \frac{e^2}{mc^2}$$

$$2.20\cdot10^{8}\ \frac{emu}{1^{\circ}c} = W = 3\left(\frac{k}{e}\right)^{2}$$

ing), since the cosmological nature of the problem can easily bring in some large pure numbers of purely astronomical meaning.

Thus, it was suggested by Eddington that 10^{42} represents a square root of the total number of particles in the closed Einsteinian universe. This possibility does not seem very likely, however, since according to our best information based on astronomical data, our universe is infinite and so is the number of particles in it. Another possibility would be to relate this constant with the ratio of the curvature radius of infinite space to the elementary length λ. In fact, astronomical data suggest that the numerical value of the (imaginary) curvature radius of the universe is about three thousand million light years or thirty thousand million million million million centimeters, so that this ratio can be shown as approximately equal to our new large constant. In this case the curvature of the universe would be one of these "incidental" constants discussed in the beginning of the present article.

Finally, one can follow the suggestion of P. A. M. Dirac, who is inclined to believe that this 10^{42} value represents the ratio of the age of the universe ($3\cdot10^{9}$ years $\cong 10^{18}$ seconds) to the elementary time ($\sim 10^{-23}$ second) during which the light signal covers the distance of one elementary length. Philosophically, such an explanation would be the most satisfying one, since it considers the large number 10^{42} simply as a parameter characterizing the present stage of the universe. However, it would force us to assume that Newton's constant G is not actually a constant but is decreasing with the age of the universe. Such a conclusion seems to stand, however, in contradiction to the facts of geology. In fact, it was recently shown by E. Teller that, assuming such variability of G, we would find that during the past geological epochs the sun was considerably brighter and the Earth was much closer to the sun. One can easily calculate that in this case the surface temperature of our planet would have been above the boiling point of water, which would make life there quite impossible.

We come to the end of our discourse, which is, of course, only informal talk. What does it contribute to our original question concerning the end of physical science in the foreseeable or unforeseeable future? It seems to me that our science definitely shows signs of convergence, although this statement can also be easily classified as wishful thinking. We see, nevertheless, from our analysis, that in the field of microphenomena there is only one big region remaining to be explored: the theory of elementary length in its relation to the problem of elementary particles. Ad hoc, this λ-theory should not be expected to be specifically more difficult than the c-theory of relativity, or the h-theory of quanta. And since each of these latter fields took not more than half a century to be brought in order (Maxwell to Einstein, and Planck to Schrödinger), there are good reasons to believe that before the close of the present century (if not much sooner), we may have a good theory explaining all different elementary particles as some kind of mathematical singularities in the λ-space-time geometry.

It may be argued, of course, that future experimental studies will show that the electrons and other elementary particles of today's physics, are not at all elementary, but as complex as the "indivisible atoms" of the old physics. Or the construction of an n-hundred-inch telescope will show us sights that will cause a complete turnover of present ideas concerning the universe.

Not having a crystal sphere, I am, of course, unable to disprove the possibility of such future events, just as I am unable to offer definite proof that there are no more mystery islands and hidden lakes, unlisted in geography texts.

$$\lambda_{nucleon} = \frac{h}{Mc} = 1.3\cdot10^{-13}\ \text{cm}$$