The Negative Proton

By DR. G. GAMOW

Alice laughed. "There's no use trying," she said: "one *can't* believe impossible things." "I daresay you haven't had much practice," said the Queen. "When I was your age I always did it for half-an-hour a day. Why, sometimes I've believed as many as six impossible things before breakfast".

"*Through the Looking-Glass*".
LEWIS CARROLL.

DURING the last few years, physical knowledge has been considerably enriched by the discovery of several new kinds of particles. Besides the old-fashioned protons and electrons, *neutrons*, *positive electrons* and hypothetical *neutrinos* came on to the stage of the physical world. However, the discovery of new particles did not make our picture of the physical world more complicated, but on the contrary led to simplification and added to the symmetry of this picture; in fact, the existence of such particles was expected from general theoretical considerations long before their discovery. We must notice particularly that the discovery of positive electrons removed the principal problem of the dissymmetry of electric charge, and at the present time the predomination of negative electrons in our observations is just a matter of the part of the universe in which we are living. However, this question is still outstanding in connexion with heavier particles, and the only way to remove completely the existing asymmetry in the electric charge would be to introduce the notion of *negative protons* and to prove their existence.

It might seem at first sight that the negative protons could be introduced in the same way as positive electrons in Dirac's theory, that is, by considering them as holes in the continuous distribution of protons corresponding to negative energy-levels. However, this extension of Dirac's hole theory for protons can be justified only if the Dirac relativistic wave-equations are applicable to these particles, which does not seem to be true. In fact, the analysis of the foundations of Dirac's theory given by Bohr has shown that this theory may be applied to a particle only under the condition that *the radius of the particle is small compared with the critical length*: $l = h/mc$ (where m is the mass of the particle in question).

For an electron, we have:

$$l_e = \frac{6 \cdot 5 \times 10^{-27}}{0 \cdot 9 \times 10^{-27} \times 3 \times 10^{+10}} = 2 \cdot 4 \times 10^{-10} \text{ cm.}$$

which is much larger than the radius of the electron estimated from its mass according to the classical relation $r_e = e^2/mc^2$ ($= 3 \times 10^{-13}$ cm.). Even if we do not believe in this formula, based on the hypothesis of pure electromagnetic mass for the electron, we can be quite sure that the electron is not so large as 2×10^{-10} cm., because otherwise the finite radius of the electron would be noticeable for the electronic orbits of heavier atoms which have radii of the same order of magnitude. Thus for electrons, the conditions for validity of Dirac's theory are fulfilled and it can be successfully applied with all its consequences.

The situation is rather different for a proton, as here the critical length becomes:

$$l_p = \frac{6 \cdot 5 \times 10^{-27}}{1 \cdot 7 \times 10^{-24} \times 3 \times 10^{+10}} = 1 \cdot 4 \times 10^{-13} \text{ cm.}$$

Although the direct observations of anomalous scattering of fast protons in hydrogen which would give us the value for the radius of proton have not yet been made*, we have still much evidence that the real radius of the proton is not much smaller than l_p and most probably of the same order of magnitude. General considerations concerning the nuclear model constructed from protons and neutrons show that the stability of such a model can only be secured if we accept the strong repulsion between constituent particles at small distances, which is equivalent to the introduction of 'rigid radii' of the order of magnitude $1 \cdot 3 \times 10^{-13}$ cm. The same value can be obtained from the experiments on scattering of neutrons in hydrogen. One can say, of course, that applying to a proton the same classical mass-radius relation as for an electron, we shall have a much smaller value for the radius ($= 2 \times 10^{-16}$ cm.), but the applicability of this relation is based on the hypothesis of pure electromagnetic mass of a proton, which does not seem to be correct for heavy particles; applying the same relation to a neutron, we should have for it the radius zero, which is definitely wrong. *Thus it is not to be expected that a proton can be described by Dirac's equations*, and there are no reasons to expect that the consequences of these equations also should hold for a proton. First of all, as indicated by Bohr, the magnetic moment of the proton need not necessarily be given by Dirac's relation $\mu = eh/4\pi cm$, and in fact it was shown by the experiments of Stern and Frisch that this moment *is about two and a half times larger*. There is also no justification for speaking of the negative proton level-distribution, of the holes in

* Experiments on the scattering of fast protons in hydrogen have been carried out by Wills (Johns Hopkins dissertation, 1934), but the number of observed collisions was not enough to support any conclusions about deviations from Rutherford's scattering formula.

such a distribution, or of the existence and annihilation of negative protons in the sense of Dirac's theory.

We can ask, of course, what equations must be applied to describe the relativistic quantum motion of a proton. So far, Dirac's equations have been shown to be the only wave-equations mathematically possible which are consistent with the theory of relativity. The most plausible way out from this paradoxical situation would be perhaps to say that we do not need any relativistic quantum equations for a heavy particle in such a case. In fact, we shall need such equations for a proton only in extremely strong fields (not existing even inside nuclei) and it is very probable that under such violent external forces the transformations of a proton into a neutron and vice versa, with the creation of positive and negative electrons ($p \rightarrow n + \overset{+}{\beta}$; $n \rightarrow p + \overset{-}{\beta}$), will happen so often that there will be no longer any physical meaning in speaking about *one particle*. However, even for strong intranuclear fields, the velocities of protons and neutrons are still small compared with the velocity of light, and in these cases the ordinary Schrödinger equations can be applied. It may be that just the fact that the ratio (velocity of nuclear particle/velocity of light) is not exactly zero is responsible for the neutron-proton transformations in the nuclei, for the description of which we must have an as yet unknown theory for the *behaviour* (*motion and transformations*) of heavy particles.

The considerations given above show us that, in introducing negative protons for the sake of considerations of general symmetry, we must not be guided at all by the analogy with the theory of positive electrons. We must choose the properties of this new particle in the way most consistent with the observed symmetry of the physical world. It seems, therefore, most natural to consider the negative proton as symmetrical with the positive proton in respect to a neutron. From this point of view, the mass and the absolute value of charge for a negative proton must be exactly equal to those for a positive one. As already mentioned above, no such process as annihilation must be expected for two kinds of protons, but for the sake of symmetry we have to accept for the negative proton the possibility of transformation into a neutron and vice versa, with the emission of an electron. Thus we obtain the following general scheme of transformations for heavy particles :

$$\overset{-}{P} \underset{\overset{+}{\beta}}{\overset{\overset{-}{\beta}}{\rightleftarrows}} n \underset{\overset{+}{\beta}}{\overset{\overset{-}{\beta}}{\rightleftarrows}} \overset{+}{P}.$$

We see that for nuclei containing also negative protons the processes of negative- or positive-electron emission can both happen in two different ways ; this can be of great use for the explanation of the two different types of β-decay of the same nucleus which are observed, for example, for uranium-X_1 (see later).

The forces between negative protons and other particles can also be obtained to a large extent from symmetry considerations : the interaction between a negative proton and a neutron must be identical with the interaction between a positive proton and neutron as suggested by Heisenberg (a strong attraction, rapidly decreasing with distance, changing to a strong repulsion at very small distances) and the interaction between two negative protons must be mainly due to Coulomb forces. Symmetry considerations cannot, however, give us any idea of the forces between a negative and a positive proton ; in order to estimate these, we must consider the general stability conditions of an atomic nucleus. One can show that in order to explain the existence of positively charged stable nuclei, it is necessary to introduce *a rather strong repulsion between two kinds of protons*. In fact, if there were no such repulsion, the most stable state of the nucleus of a given total number of particles of atomic weight A (the state with maximum binding energy) should correspond to $A/2$ neutrons, $A/4$ positive protons and $A/4$ negative protons, because in this case we have the maximum number of neutron-proton-bindings and minimum of repulsive Coulomb forces. Since for real nuclei the most stable state does not correspond to zero charge, we must introduce forces preventing the formation of equal number of positive and negative protons in the nucleus, which can only be done if we accept a very strong repulsion between the two kinds of protons at nuclear distances. Such forces will reduce considerably the number of protons of one kind in any given nucleus, and will permit none or perhaps just one negative proton in the light nuclei and more in heavier ones. Of course, from this point of view, we should expect the existence of negative nuclei with positive electrons circulating around them in some part of our universe.

We come now to an interesting question about the magnetic moments of heavy particles. The symmetry considerations force us to ascribe to a negative proton the magnetic moment of the same absolute value but of opposite sign to that of a positive proton. We must also expect that *the magnetic moment of a neutron is exactly zero*. This seems, however, to cause serious difficulties in understanding the small value of the magnetic moment of a deuton, which according to Stern and Esterman is only about 0·7 nuclear magnetons. In his attempt to explain the observed momenta of atomic nuclei, Schüler argues in the following way. Accepting the spins of neutron and proton as each equal to $\frac{1}{2}$, and supposing that those two particles move in the deuton on the fundamental S-level with the orbital momentum $j = 0$, we must conclude that both spins are parallel in order to explain the observed spin of the deuton, which is equal to 1. Since the magnetic moment of a proton is about 2·5 nuclear magnetons (Stern and Frisch) and the magnetic moment of the deuton only about 0·7 (Stern and Esterman)*, we must conclude that the magnetic moment of the neutron is equal to $0{\cdot}7 - 2{\cdot}5 = -1{\cdot}8$ nuclear magnetons and is directed oppositely to the spin.

One can, however, show that these conclusions are not necessarily unique, and that it is possible to explain the observed values for the deuton while still accepting a magnetic moment of the neutron equal to zero and compensating the magnetic moment of a proton by its orbital magnetic moment. In fact, accepting the fundamental level of two particles in the deuton as a D-level with orbital angular momentum $j = 2$, we can explain the observed spin of this nucleus by supposing that the spins of proton and neutron are both parallel and opposite to the orbital momentum $(2 - \frac{1}{2} - \frac{1}{2} = 1)$. Of course, one can argue against the D-level hypothesis by saying that there is a theorem of wave-mechanics according to which the fundamental state of a system of two particles interacting with central forces is always an S-state. However, it is very doubtful whether this theorem can be applied to our case for, as we have seen, the radii of the two particles in question are of the same order of magnitude as the distance between them in the deuton nucleus. Putting the matter pictorially, one may say that the radius of the S-orbit for a neutron and a proton may be smaller than the sum of the radii of two particles, so that this orbit is excluded by geometrical considerations. In more technical terms, that would mean that *the laws of ordinary wave-mechanics are no longer applicable in detail when the heavy particles more or less penetrate into each other's structure*, which seems to be quite rational if we remember what was said before in this connexion.

It may seem at first that the introduction of a D-orbit would immediately give us two units of magnetic moment to compensate the large moment of the proton. This is not so, however, for since one of the particles is neutral, the total orbital momentum $j = 2$ will give rise only to one unit of magnetic moment. Here again the finite size of the proton comes in to help us. We have seen that for the rotation of a proton around its axis, the *gyromagnetic ratio* is about five times larger than for the rotation of a proton around a distant axis: in the first case we have:

$$\frac{\text{magnetic moment}}{\text{mechanical momentum}} = \frac{2{\cdot}5}{\frac{1}{2}} = 5\,;$$

and in the second:

$$\frac{\text{magnetic moment}}{\text{mechanical momentum}} = \frac{1}{1} = 1.$$

The fact that this ratio for the proper rotations of a proton is equal to 5 and not to 2, as required by Dirac's theory, was accounted for by the finite size of a proton, and will be explained only when we know the distribution of charge and mass in this particle. *In any event, we must expect that if the proton is rotating around an axis at a distance comparable with its own radius (which is usually the case in the nuclei) the gyromagnetic ratio for orbital motion must not be expected to be unity but may be considerably larger:* this effect can increase the orbital magnetic moment of a proton in the deuton nucleus to a large extent and make the total magnetic moment of the deuton sufficiently small. It should be noticed, of course, that the above considerations do not pretend to give any explanation of the observed magnetic moments of nuclei, but just show that one must be very careful when drawing definite conclusions in this region before the theory of heavy particles is really constructed.

One of the most interesting applications of negative protons to the theory of nuclear structure is the possibility of the existence of nuclei with equal atomic numbers and equal atomic weight but still possessing different structure and different properties. Such *isomeric nuclei* can be obtained if we replace a pair of nuclear neutrons by one positive and one negative proton. Two such nuclei evidently possess the same mass and charge, but may have different spins and different binding-energies (mass-defects). One of such isomeric nuclei possessing larger energy will usually be unstable and subject to transformation into the other isomer by the simultaneous internal transformation of two particles

$$\begin{matrix} \overset{+}{p} \to n \\ \overset{-}{p} \to n \end{matrix} \quad \text{or} \quad \begin{matrix} n \to \overset{+}{p} \\ n \to \overset{-}{p} \end{matrix}\;;$$

however, the probability of such double transformations (just as in the case of double α- or β-emission) is extremely small and we should expect such isomeric nuclei to be metastable. Thus the isomeric nucleus will differ widely from an ordinary excited state of a nucleus, for which the emission of surplus energy in the form of a γ-quantum usually takes place in a very small fraction of a second ($\sim 10^{-16}$ sec.).

* Both values with considerable probable error.

We can give an example in which the notion of isomeric nuclei may be of great use. In the region of the heavy elements there exist the stable isotope of lead $_{82}Pb^{210}$ found by Aston* which is isomeric with β-decaying RaD, and the isomeric nuclei UX_2 and UZ resulting by β-forking from UX_1 and both giving after the emission of a second β-particle the nucleus of U_{II}. In the last case, two different β-branches leading from UX_1 to U_{II} : $UX_1 \xrightarrow{\bar{\beta}} UX_2 \xrightarrow{\bar{\beta}} U_{II}$ and $UX_1 \xrightarrow{\bar{\beta}} UZ \xrightarrow{\bar{\beta}} U_{II}$ may be considered as due to the above mentioned two possibilities for $\bar{\beta}$-emission: $n\bar{p} \xrightarrow{\bar{\beta}+} pp \xrightarrow{-\bar{\beta}+} pn$ and $np \xrightarrow{\bar{\beta}} nn \xrightarrow{\bar{\beta}+} pn$ giving rise to isomeric nuclei at the half-way stage.

* The existence of this isotope is unfortunately not quite definitely proved.

It is interesting to notice here that the negative protons are the only particles, apart from neutrons, for which there are no potential barriers around the nuclei, and therefore one would expect that substitutional reactions of the type

$$_{n}X^{m} + {}_{0}n^{1} \rightarrow {}_{n+1}Y^{m} + {}_{-1}p^{1}$$

would be probable even for the heaviest elements. It is not impossible that some of the Fermi reactions for heavy elements may be explained on this basis.

In conclusion, we may say that there are so many indications of the existence of negative protons that the hope is justified that these as yet hypothetical particles, completing the symmetry of the physical world, will be found sooner or later.

Progress in Medical Research*

THE report of the Medical Research Council for 1933–34 reveals the wide boundaries within which investigations relating to health and disease are being initiated and supported throughout Great Britain, and reflects the rapid development of medical science as well as the need for scientific knowledge as a guide in practical affairs. Parliament provided a grant-in-aid of £139,000 for the Council's expenditure during the present financial year, the provisional allocation of which is, for administration £9,000, for the expenses of the National Institute for Medical Research including the farm laboratories £54,000 and for research grants to scientific workers and for the investigations of the Industrial Health Research Board £76,000. The funds available have, as usual, been augmented from other sources for the promotion of particular schemes of research.

Lord D'Abernon resigned his membership of the Council; the vacancy was filled by the appointment of the Marquess of Linlithgow, who was also elected chairman of the Council in succession to Lord D'Abernon. Prof. E. Mellanby also resigned his membership on being appointed secretary of the Council; Prof. H. S. Raper was appointed to succeed him. Sir Charles Sherrington and Dr. J. A. Arkwright retired and Prof. A. J. Clark and Prof. J. C. G. Ledingham were appointed members. It was decided that the tribute to the late Sir Walter Morley Fletcher, for which funds had been collected during the year, should consist in the first place of a personal memorial, in the form of a portrait bust to be placed in a suitable setting in the National Institute for Medical Research, and secondly of the inception of some scheme for the advancement of knowledge for the relief of human suffering, which, it is proposed, should be the foundation of a Walter Fletcher Laboratory at Mill Hill, to be devoted particularly to nutritional studies.

The Department of Biological Standards at the National Institute now holds twenty-three different standards. Thirty-three different countries, including British Dominions, have been supplied with samples of some of them during the year. The standards for gas gangrene antitoxin, staphylococcus antitoxin and two anti-pneumococcus sera, prepared at the Institute, have now been adopted by the Permanent Commission on Biological Standardisation of the League of Nations, and units defined in terms of them. They will be preserved at the State Serum Institute, Copenhagen, for international distribution. The work carried out on vitamin standards by and for the Accessory Food Factors Committee was reported to the second International Conference on Vitamin Standards held in London last June: the National Institute continues to hold the four standards for vitamins A, B_1, C and D and is responsible for their international distribution.

In the field of clinical research the Council has applied the funds released by the permanent endowment by the Rockefeller Foundation of the post held by Sir Thomas Lewis at University College Hospital, to the establishment of a new Clinical Research Unit at Guy's Hospital; Dr. R. T. Grant has been appointed director. The opportunities for clinical research are steadily widening. The report refers to the departments established during the past few years, including

* Committee of the Privy Council for Medical Research: Report of the Medical Research Council for the Year 1933–34. (Cmd. 4796.) Pp. 172. (London: H.M. Stationery Office, 1935.) 3s. net.