3 M. Gell–Mann and A.Pais, Proc. Int. Conf. Glasgow, Pergamon Press, 1955.
4 S. Filippov, J. Exptl. Theoret. Phys. (U.S.S.R.) **29**, 707 (1955). Soviet Phys. JETP **2**, 572 (1956).
5 V. Karpman, J.Exptl. Theoret. Phys. (U.S.S.R.) **30**, 781 (1956). Soviet Phys. JETP **3**, 754 (1956).
6 T. Lee and C.Yang , Phys. Rev. **102**, 290 (1956).
7 B. d'Espagnat and I. Prentki, Nucl. Phys. **1**, 33 (1956).
8 S. Oneda and A. Wakasa, Nucl. Phys. **1**, 445 (1956)

Translated by W. H. Furry
28

## On the Structure of Nucleons

I. E. TAMM
*P. N. Lebedev Physical Institute,*
*Academy of Sciences, USSR*

(Submitted to JETP editor October 26,1956)
J. Exptl. Theoret. Phys. (U.S.S.R.) 32, 178–180 (January,1957)

COMPARISON of the results of the measurements of the scattering of fast electrons (with energy up to 550 mev ) by protons, carried out by Chambers and Hofstadter.[1] with measurements of the interaction of electrons with neutrons[2,3] has led a number of physicists to the conclusion that these data as a whole are in contradiction either with the charge independence of the interaction of $\pi$–mesons with nucleons, or else with the foundations of quantum electrodynamics. The purpose of this note is to present arguments against the legitimacy of this sort of conclusions.

The most direct argument in favor of the conclusion mentioned has been formulated by Yennie, Lévy and Revenhall[4]; it reduces to the following. Chambers and Hofstadter have shown that the root–mean-square radius of the electric charge distribution of the proton is close to the value

$$r_p = 0.77\cdot 10^{-13}\text{cm} = 0{,}55\, h/\mu c. \qquad (1)$$

On the other hand, if the interaction of $\pi$–mesos with nucleons is charge invariant, then the meson clouds of proton and neutron must be mirror–symmetric (identical charge distributions, but with opposite signs). Therefore if, following Saks, one superposes the charge densities of proton and neutron, their meson charges cancel mutually and we obtain the charge density of the so–called "core" of the nucleus , i.e., the charge density due to the distribution of just the single nucleons and of nucleon pairs:

$$\rho_c(r) = \rho_p(r) + \rho_n(r).$$

Using the above–mentioned experimental data, Yennie et al, found that the root mean square radius of the charge of the core is practically equal to $r_p$ :

$$r_c \sim r_p \sim 0.77\cdot 10^{-13}\text{cm} \sim 3.7\, h/Mc. \qquad (2)$$

It is just this result that is regarded as paradoxical, and for the following reason. If we confine ourselves to the consideration of mesons with energies less than $\mu c^2$, then the recoil in the emission of a meson by a "bare" nucleon can be neglected, so that the nucleon must be in the center of the physical nucleon ($r_c \sim 0$), while the radius of the distribution of mesons must be of the order $h/\mu c$, which does not contradict Eq. (1), but does contradict Eq. (2). But in the case of emission of mesons with energies of the order of $\mu c^2$, it is necessary to take into account the recoil experienced by the nucleons, and owing to the recoil, the nucleons will be displaced by about the same distance as the mesons; but this distance must be of the order of $h/Mc$. According to Eq. (2), however, $r_c$ is considerably greater than this value.

In my opinion, the argument that has been presented is based, though not obviously, on the idea of weak interaction of mesons with nucleons.

Since in reality this interaction is strong, each meson must be dissociated for an appreciable fraction of the time into a $\vartheta$ nucleon–antinucleon pair. Therefore, the distribution of these pairs (which by definition forms part of the core of the nucleon) must be just about the same as the meson distribution itself

$$(r \sim h/\mu c),$$

in accordance with Eq. (2).

It is true that if we confine ourselves to consideration of processes of the type $\pi \to N + \tilde{N} \to \pi$ (where $\tilde{N}$ denotes an antinucleon ), then the charge of the nucleon pairs will be distributed in just the same way as the charge of the mesons, and consequently cancels out in the calculation of the quantities $p_c$ and $r_c$ . But measurements by Segre′ and others have shown that the cross–section for annihilation of antiprotons on nucleons is very large* (which is quite understandable from the point of view of meson theory). Therefore the antinucleons produced at the mesonic periphery of the physical nucleon will have a large probability of being annihilated with the nucleon located at its center, being created again, and so on. The result is that thc charges of all the nucleons and antinucleons (i.e., the charge of the core) is distributed more or less uniformly over the whole volume of the meson cloud, in agreement with Eqs. (1) and (2).

The ideas that have been explained here also agree entirely with the fact[1] that there are no experimental indications of any concentration of the charge of the proton near its center.

If the total charge of the nucleon is indeed distributed over its whole volume then there cannot be mirror symmetry of the charge distributions even in the peripheral regions of proton and neutron. This, however, does not necessarily have to be in contradiction with the mirror symmetry of their anomalous magnetic moments, since, in view of the difference of the masses of meson and nucleon, these moments are probably mainly due to meson (and not to nucleon) currents, and the meson currents have mirror symmetry owing to the charge invariance.

We take note of one further misunderstanding in connection with the structure of nucleons. In nonrelativistic approximation, the interaction between the electromagnetic field and an (on the whole) neutral particle with spherically symmetric charge distribution (a neutron ) is characterized by a potential energy

$$V = -a\,\mathrm{div}\,\mathbf{E}. \qquad (3)$$

Foldy[5] pointed out that the experimental value of the constant $a$ for the neutron is very close to the value

$$a_m = (h/2Mc)\,\mu_n$$

(where $\mu_n$ is the magnetic moment of the neutron) which corresponds in nonrelativistic approximation to a Dirac particle having a relativistic interaction with the electromagnetic field given by the Pauli term

$$(i/2)\,\mu_n\gamma^\alpha\gamma^\beta F_{\alpha\beta}.$$

According to the latest experimental data[2,3], the difference between $a$ and $a_m$ amounts to only $2 \pm 7$ percent. Thus there is practically nothing left of the interaction of the neutron with the electric field to correspond to the electric charge in it.

On the other hand, if we estimate this latter part of the interaction, starting from the usual model of the neutron (a small positive core, surrounded by a negative meson cloud of radius of the order $h/\mu c$) this contribution to the quantity $a$ must be several times as large as the whole experimental value of $a$.

This contradiction is removed if we adopt the model of nucleons described in this note: they contain inside them nucleons and antinucleons distributed according to approximately the same law as the $\pi$ mesons, an since the total charge of the neutron is equal to zero, the charge density in it is close to zero and the contribution it makes to the value of $a$ must be small.

It is necessary, however, to register the objection that both attempts to estimate the value of the difference $a-a_m$ from a definite model of the neutron are unreliable. In the phenomenological theory

$$a = a_m + a',$$

where the value of the constant $a'$ is entirely arbitrary ( in the relativistic theory $a'$ appears in an interaction term

$$a'\gamma_\alpha \partial F^{\alpha\beta}/\partial x^\beta).$$

A direct calculation, starting from a definite (relativistic ) model of nucleons, can determine the dependence of the quantity $a'$ on the distribution of charges in the particle. It is hard to foresee the result of these calculations. Thus, for example, from calculations conducted according to meson theory by perturbation method and including the second order in $g$, it is found [6] that $a' = 0.32\,a_m$. But in any case there is at present no reason to suppose that the so–called zero value of the electrical radius of the neutron (i.e., the equation $a - a_m \approx 0$) is not consistent with charge invariance.

From the point of view of the ideas that have been presented here, theories that do not take into account the production of nucleon pairs by mesons (for example, the theory of Chew and Low) cannot be expected to give a successful explanation of the structure of nucleons. An exact theory of nucleons must also take account of the peculiar properties of the cloud of virtual $K$–mesons occurring around a nucleon.[7]

*According to data presented at the Conference on Theoretical Physics in Seattle in September 1956, this cross–section is equal to 120 to 100 mb at antiproton energies 200 to 500 mev.

1 E. E. Chambers and R.Hofstadter, CERN Symposium, 1956.

2 Hughes, Harvey, Goldberg and Stafne, Phys. Rev. 90, 497 (1953).

3 Melkonian, Rustad, and Havens, Jr. Bull. Am. Phys. Soc. 1, 62 (1956).

4 M. Levy, Report at the Moscow Conference on High–Energy Physics, May, 1956.

5 L. L. Foldy, Phys. Rev. **87**, 693 (1952).

6 B. D. Fried, Phys. Rev. **88**, 1142 (1952).

7 G. Sandri, Phys. Rev. **101**, 1616 (1956).

Translated by W. H. Furry

42