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WHAT IS THE MEAN SQUARE CHARGE RADIUS OF THE NEUTRON ACTUALLY EQUAL TO?

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INTRODUCTION

Recently, the issue concerning the actual value of the mean square charge radius, related to the internal structure of the neutron, ($\langle r^2_{1n}\rangle_N$) has been under discussion. What is the history of the problem, and, ultimately, what is $\langle r^2_{1n}\rangle_N$ equal to?

More than 40 years ago Feshbach demonstrated [1] that the scattering of electrons at energies of the order of magnitude of several tens of MeV ($qR \ll 1$, where $q = 2k\cdot\sin\frac{\Theta}{2}$ is the recoil wave number) only makes possible the measurement of a sole parameter providing information on the size of the nucleus, namely of the mean square charge radius determined by the expression

$$\langle r^2_{1n}\rangle = \int\rho(\vec{r})r^2 d^3\vec{r}. \tag{1}$$

At about the same time Foldy found the relation between $\langle r^2_{1n}\rangle_N$ and a_{ne}, the measurable scattering length of a slow neutron on an electron (see review of ref. [2]):

$$\langle r^2_{1n}\rangle_N = 6(dF_1/dq^2)_{q^2=0} = \frac{3\hbar^2}{Me^2}(a_{ne} - a_F), \tag{2}$$

where $a_F = \mu_n\cdot\frac{e^2}{2Mc^2} = -1.468\cdot10^{-3}$ fm is the Foldy scattering length related to a free neutron satisfying the Dirac equation and exhibiting an anomalous magnetic moment, while F_1 is the Dirac form factor describing the spatial distribution of the nucleon charge. The Foldy effect depends on a combination of known constants, and for the determination of $\langle r^2_{1n}\rangle_N$ it must be subtracted from the quantity a_{ne}.

Besides the Foldy effect, however, there may exist a more interesting kind of interaction between the neutron and the electron. This interaction is a consequence of the meson theory of nuclear forces. The neutron is surrounded by a "meson cloud" ("fir coat") which has a size of the order of magnitude of $\hbar/(m_\pi c)$, so in the immediate vicinity of the neutron the presence of an electric field may be expected. If a neutron and an electron come sufficiently close to each other, electrostatic interaction forces must arise between them, and these forces should be short-ranged. Such an interaction will influence the quantities a_{ne} and, consequently, $\langle r^2_{1n}\rangle_N$. Since a_{ne} and a_F are both of the same order of magnitude, the determination of $\langle r^2_{1n}\rangle_N$ will require very precise measurements. Such measurements can be performed within the framework of studies of the interaction of low-energy neutrons with heavy atoms. The mean square radius of the charge distribution is a fundamental characteristic of the neutron, and its measurements permit verification of modern theoretical ideas concerning nucleons (for instance, of the quark-bag model and others).

WHAT IS THE $\langle r^2_{1n}\rangle_N$ ACTUALLY EQUAL TO?

Knowledge of the signs and values of the anomalous magnetic moments of the neutron and proton permits establishing a qualitative picture of the distribution $\rho(r)$ in the nucleon. This point is illustrated by Fig. 1 [3]. Note that the sign of $\langle r^2_{1n}\rangle_N$ in the case of an object, that, as a whole, is neutral, may be either positive, or negative. This depends mainly on which charge is to be found at the periphery. Thus, for instance, the charge distribution in a neutron, depicted in Fig. 1, should provide for the sign of $\langle r^2_{1n}\rangle_N$ being negative.

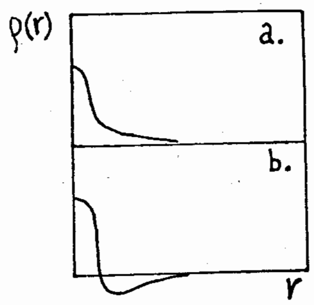

Fig.1. Expected electric charge distribution for a nucleon: (a) proton, (b) neutron.

The first attempts to reveal some interaction between the neutron and the electron were undertaken quite a time ago, in 1932; however, more accurate measurements were performed by the middle of the forties and also in later years. These attempts were either based on asymmetry observations in the scattering of thermal neutrons, or on studies of the energy dependence of the total cross section in the electronvolt region. The results of these measurements are presented in the Table. From the Table it follows that the most accurate experiments can be divided into two groups: the measurements of refs. [6, 7] lead, in accordance with formula (2), to $\langle r^2_{1n}\rangle_N > 0$, which contradicts qualitative conclusions based on Fig. 1, and the measurements of refs. [5, 8, 9] ($\langle r^2_{1n}\rangle_N < 0$) in agreement with Fig.1. Now, some words are about the experimental approaches. The principal disadvantage of the methods described in refs. [6, 7] is the extremely small value of the measured effect as compared to the strong neutron-nucleus interaction. The danger always exists, therefore, of some unaccounted for effect (for instance, the influence of p-resonances, of admixtures of light gases,etc.) giving rise to false asymmetry. In this connection it seems attractive to find a method resulting in measurements being significantly more effective. In Dubna it was suggested that

Table

Authors, year	Method	Magnitude of effect, ne/tot	$-a_{ne}(10^{-3})$fm	Ref.
P.Dee, 1932	Recoil electrons in cloud chamber	–	< 1000	–
E.Fermi, L.Marschall, 1947	Neutron scattering on noble gases	$\Delta\sigma/\sigma \cong 0.5\%$	100±1800	–
W.Havens et al., 1947 - 51	Total neutron cross section on lead and bismuth	$\Delta\sigma/\sigma \cong 1.5\%$	1.91±0.36	–
D.Hughes et al., 1952 - 53	Neutron total reflection from O_2-Bi mirror	$\Delta\Theta/\Theta \cong 50\%$	1.39±0.13	[4]
M.Hamermesh et al.,1952	Neutron scattering on noble gases	$\Delta\sigma/\sigma \cong 0.5\%$	1.5±0.4	–
M.Crouch et al.,1956	Neutron scattering on noble gases	$\Delta\sigma/\sigma \cong 0.5\%$	1.43±0.30	–
E.Melkonian et al.,1959	Total neutron cross section on bismuth	$\Delta\sigma/\sigma \cong 1.5\%$	1.56±0.05[1]	[5]
V.Krohn, G.Ringo, 1966-73	Neutron scattering on noble gases	$\Delta\sigma/\sigma \cong 0.5\%$	1.30±0.03	[6]
L.Koester et al., 1970-1988	Total neutron cross section and atomic scattering length on bismuth and lead	$\Delta\sigma/\sigma \cong 1.2\%$	1.32±0.04	[7]
Yu.Alexandrov et al., 1974 - 85	Neutron diffraction on a tungsten-186 single crystal	$\Delta\sigma/\sigma \cong 20\%$	1.60±0.05	[8]
Yu.Alexandrov et al., 1985	Total neutron cross section on bismuth	$\Delta\sigma/\sigma \cong 1.2\%$	1.55±0.11	[9]

[1]Without corrections for Schwinger scattering and resonance scattering

tungsten-186 was used for studying neutron-electron interaction by measuring the diffraction of thermal neutrons from a single crystal made of this isotope. The neutron scattering length for tungsten-186 is by an order of magnitude smaller, than the corresponding value for a natural mixture of isotopes, so the measured neutron-electron effect must be enhanced up to several dozen per cent[8].

The value reported[9] by a Dubna group (at the pulsed IBR-30 reactor) seems to be realistic, also. This value was obtained by measurement of the total cross section for bismuth in the neutron energy range from 1 up to 90 eV and applying a processing procedure differing from the one presented in ref.[7]. Thus, the value $<r^2_{in}>_N < 0$ which follows from refs. [5, 8, 9] seems to be the most plausible one.

THE NEUTRON MODEL AND CONCLUSION

The result obtained for $<r^2_{in}>_N$ represents an important confirmation of the modern models of the nucleon, for example, of the quark bag models. One of such models is the CBM (Cloudy Bag Model)[10]. According to this model the neutron is composed of three quarks confined inside a certain volume of radius R and interacting with the pion field at the surface of the bag. The surface of the bag serves as the source of a negative pion field extending over a distance of the order of $\frac{\hbar}{m_\pi c} > R$. Hence it follows that $<r^2_{in}>_N$ should be negative in the CBM. The experimental results presented in refs. [6, 7] contradict the CBM, even with respect to the sign, as well as the conclusion drawn from Fig. 1. No interpretation of the experimental results of refs. [6, 7] can be achieved within the framework of known models of the nucleon. If, nevertheless, the values of a_{ne} presented in refs. [6, 7] are correct, then a serious fault occurs in our understanding of the neutron structure, otherwise the results of [6, 7] are erroneous.

To conclude we shall point out that sometimes the question arises as to with what quantities the theoretically calculated charge radii (for instance, obtained in the CBM model) should be compared: with $\langle r^2_{in}\rangle_N$ or with $\langle r^2_{in}\rangle_N + \frac{3\hbar^2}{Me^2}\cdot a_F$. This point was already discussed at the end of the fifties and the beginning of the sixties within the framework of the Chew-and-Low model. Since all calculations of nucleon radii are performed in the approximation of a motionless (recoilless) heavy nucleon ($M \longrightarrow \infty$), it seems correct to compare the results of calculations with $\langle r^2_{in}\rangle_N$, i.e. subtracting from the measured value of a_{ne} the Foldy scattering length (in accordance with formula (2))[11].

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