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S. FLÜGGE

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NEUTRONS AND RELATED GAMMA RAY PROBLEMS

WITH 338 FIGURES

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Contents.

The Production and Slowing Down of Neutrons.

By

EDOARDO AMALDI.

With 281 Figures.

A. Introduction.

In a note sent to Nature the 17th of February 1932 and entitled "Possible existence of a neutron", CHADWICK announced the discovery of a new fundamental particle, electrically neutral whose mass was very close to the mass of the proton.

This particle, *the neutron*, is a component of the penetrating radiations, first observed by BOTHE and BECKER and further investigated by I. CURIE and F. JOLIOT, emitted by beryllium when bombarded by polonium α-particles. Some unexpected results of the latter authors led CHADWICK to suspect the existence of the neutron. He submitted this assumption to experimental check: the neutron was discovered.

This discovery is a milestone in the history of nuclear physics and in its applications.

The experiments of CHADWICK show that the neutron is a particle of subatomic dimensions which is emitted when beryllium is bombarded with α-particles. We know today that, together with the proton, it is one of the constituents of atomic nuclei and that it is emitted in many nuclear reactions with an energy of the order of a few million electron-volts.

We know that neutrons once emitted, can collide with nuclei and undergo scattering or produce various types of reactions. The neutron's efficiency for producing these last processes, is, generally speaking, very large, as a consequence of its electrical neutrality.

As was shown by FERMI in 1934, the high initial energies of the neutrons emitted in a nuclear reaction can be reduced to energies of the order of those corresponding to thermal agitation, by means of successive elastic collisions with nuclei of hydrogen or of other light elements.

These low energy neutrons, usually known as *slow neutrons*, are much more efficient than fast neutrons in producing certain types of reactions. The investigation of their properties has provided new means of studying nuclear structure and the structure of matter in general.

Today neutron physics is a very large part of fundamental nuclear physics. It is also the starting point of applied nuclear physics, which was initiated by the discovery of HAHN and STRASSMANN in 1939, of a new type of reaction produced by neutrons, the *fission of heavy elements.*

This article, of a marked experimental character, can be considered as a general introduction to the more specialized ones dealing with particularly important branches of neutron physics.

Resonance processes of neutrons are treated by J. RAINWATER in Vol. XL, Neutron diffraction and interference by G. R. RINGO in Vol. XXXII. Fission by J. A. WHEELER in Vol. XLI and Pile technique by D. J. HUGHES in Vol. XLIV of this Encyclopedia. Other information about neutrons can be found in Vols. XXXIX, XL, XLI and XLII which refer to nuclear reactions in general and their general theory.

In spite of the fact that this chapter is devoted to a rather restricted part of fundamental neutron physics, this part is already sufficiently large and complicated to make it desirable to have an introduction in which all the basic phenomena are briefly presented. These will then be treated in detail in the succeeding parts, which have been drawn up under the assumption that the reader is familiar with the phenomena presented in the introduction. This aims at the same time to give an outline of the historical development of the part of nuclear physics which we consider. The historical approach, however, has been abandoned whenever it was necessary for reasons of clarity.

The author owes a special debt to Prof. G. C. WICK for permission to use an unpublished work on neutron physics prepared, a few years ago, in collaboration with the author, and to Prof. H. H. BARSCHALL for reading, revising and completing part B: Reactions with emission of neutrons and neutron sources. To him are due the introductory "Comparison between neutron sources" and the following sections: 37, 38, 44, 59, 60 and parts of 39, 41, 42, 53, 54.

I. The discovery of the neutron.

1. In 1930 W. BOTHE and H. BECKER[1] observed the emission of a penetrating secondary radiation by various light elements (Li, Be, B, F, Mg, Al) bombarded with polonium α-particles and interpreted it in terms of hard γ-rays. That this secondary radiation really includes a γ-ray component was proved later by the same authors[2] and by RASETTI[3] by means of experiments in which two Geiger counters in coincidence were arranged to detect fast electrons produced by Compton effect. By interposing between the two counters aluminium absorbers, BOTHE and BECKER were able to establish the presence of electrons of about 5 Mev energy.

The investigation of the penetrating radiation emitted by Be and B, the two elements in which the effect was more intense, was continued by I. CURIE and F. JOLIOT[4] who detected the secondary radiation by means of a thin-walled ionization chamber connected with an electrometer. They confirmed the results of BOTHE and BECKER about the existence of a secondary penetrating radiation and its interpretation and estimated, on the basis of absorption measurements, that the energy of the corresponding photons was still higher.

Thinking that γ-rays of such high energy could perhaps produce some kind of transmutation, they placed close to the thin wall of the ionization chamber thin layers of various substances. While no change in the ionization current was observed in all other cases studied (C, Al Cu, Ag, Pb), in the case of paraffin (or of other hydrogeneous substance, such as water or cellophane) an increase by a factor of about two was observed[5].

By means of a series of classical experiments these authors were able to show that the secondary penetrating radiation emitted from Be when bombarded with polonium α-particles was capable of transferring to the protons present in the hydrogeneous substances kinetic energies of about 5 Mev.

[1] W. BOTHE and H. BECKER: Z. Physik **66**, 289 (1930).

[2] H. BECKER and W. BOTHE: Congresso di Fisica Nucleare, Roma 1931, p. 153. — Naturwiss. **20**, 349 (1932). — Z. Physik **76**, 421 (1932).

[3] F. RASETTI: Naturwiss. **20**, 252 (1932).

[4] I. CURIE: C. R. Acad. Sci. Paris **193**, 1412 (1932). — F. JOLIOT: C. R. Acad. Sci. Paris **193**, 1415 (1932).

[5] I. CURIE and F. JOLIOT: C. R. Acad. Sci. Paris **194**, 273 (1932). — J. Phys. Radium **4**, 21 (1933).

In order to explain this production of recoil protons by γ-rays, CURIE and JOLIOT thought first that the observed effect was perhaps similar to the Compton effect and concluded, by applying the laws of conservation of energy and momentum, that the photons emitted from Be must have an energy of at least 50 Mev. Later, however, they realized the serious difficulties involved in such an interpretation, due to the fact that according to the Klein-Nishina formula, the cross section for Compton effect is inversely proportional to the square of the mass of the recoiling particle. In the case of protons the evaluated intensity was much too small to explain the experimental results.

They then put forward the assumption that the observed effect was due to a type of interaction between γ-rays and protons different from that of the Compton effect[1].

But in the meantime, the first results of CURIE and JOLIOT[2], presented at the Academie des Sciences of Paris, on the 11th of January 1932, had induced CHADWICK to make a series of fundamental observations.

These were performed with an ionization chamber connected to a linear amplifier, so that the ionization produced by a single ionizing particle could be measured[3].

With this apparatus CHADWICK proved that the secondary penetrating radiation emitted from Be, could produce recoil atoms not only from layers of hydrogeneous substances, but also from layers of Li, Be, B, C, N. In the case of the last element, he found that the kinetic energy of the recoiling atoms was between 1 and 1.4 Mev, that is, between two and three times the value expected according to the conservation laws, under the assumption that the incident radiation was composed of photons of 50 Mev energy. In other words the kinetic energy transferred to the atoms of hydrogen and nitrogen did not correspond to the same energy of the primary radiation if this was composed of photons. Besides this argument based on the conservation laws applied to the production of recoil atoms, CHADWICK developed a second argument, based again on the conservation laws, but applied this time to the collision process between an α-particle and a Be nucleus and the consequent emission of a photon of 50 Mev. The conclusion of both these arguments was that the interpretation of the corresponding effects in terms of photons was inacceptable. But all difficulties disappeared and the observed effects could be fitted into a satisfactory picture under the assumption that the beryllium nucleus, bombarded with α-particles, emitted a neutral particle of mass very close to that of the proton.

These experiments and arguments not only proved definitely the existence of the neutron but showed also that this new particle, indicated usually with the symbol ${}_0n^1$, could be produced in light elements through what we call (α, n) processes. In particular the production reaction in the case of beryllium—which is monoisotopic—was necessarily

$$ {}_2\mathrm{He}^4 + {}_4\mathrm{Be}^9 \rightarrow {}_6\mathrm{C}^{12} + {}_0n^1 . \tag{1.1}$$

The high energy photons originally observed by BOTHE and BECKER, are due to the fact that the residual nuclei of the (α, n) processes are frequently left in excited states.

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[1] I. CURIE and F. JOLIOT: C. R. Acad. Sci. Paris **194**, 708 (1932).

[2] See footnote 5, p. 2.

[3] J. CHADWICK: Nature, Lond. **129**, 312 (1932). — Proc. Roy. Soc. Lond., Ser. A **136**, 692 (1932).

II. The properties of the neutron as a fundamental particle and its role in nuclear structure.

2. The mass. Besides the first rough evaluation of the mass of the neutron, based on the energy of the recoiling atoms of hydrogen and nitrogen, CHADWICK[1,2] made other determinations of this fundamental quantity by applying the conservation laws to the production processes ${}_5B^{11}(\alpha, n)\,{}_7N^{14}$, ${}_3Li^7(\alpha, n)\,{}_5B^{10}$. These, as well as other determinations of the mass made, on the same principle, shortly afterwards by various authors[3], gave values very close to one unit of atomic weight, but they were all soon superseded by the determination based on the photo-effect of the deuteron.

Not long after the discovery of the neutron, CHADWICK and GOLDHABER[4] discovered this important effect, which allows a precise determination of the binding energy E_3 of the deuteron (in its triplet ground state) to be made. Once E_3 is known, one can deduce the neutron-hydrogen atom mass difference, and the mass of the neutron, making use of the obvious relation

$$\Delta = m_n - m_H = E_3 - a \tag{2.1}$$

where

$$a = H_2^+ - D^+ \tag{2.2}$$

is the separation of the mass spectroscopic doublet of the molecular ions of hydrogen and the atomic ions of deuterium [*17e*].

For a long time the photodisintegration of the deuteron (Sect. 46) was the only method which allowed a determination of E_3 of sufficient accuracy[5]. Later it became possible to obtain an accurate value of E_3 also by measuring the energy of the photons emitted in the radiative capture of slow neutrons by protons (Sect. 29). Table 1 shows a few recent determinations of E_3 made by various methods. The results of older measurements are collected in the review article by STEPHENS[5].

The neutron-hydrogen atom mass difference deduced by combining the value of E_3 given, for instance, by MOBLEY and LAUBENSTEIN with the value of $a = (1.442 \pm 0.002)$ Mev given by ROBERTS and NIER[6], is

$$\Delta = m_n - m_H = (784 \pm 4)\ \text{kev}.$$

This can be compared with other determinations of the same quantity obtained from various reactions assuming that the rest mass of the neutrino is zero (Table 2).

The value of the mass of the neutron adopted today is[7]

$$\left.\begin{aligned} m_n &= (1.008982 \pm 0.000003)\ \text{units of mass} = (939.505 \pm 0.010)\ \text{Mev} \\ &= (1.67470 \pm 0.00004) \times 10^{-24}\ \text{g} \end{aligned}\right\} \tag{2.3}$$

[1] J. CHADWICK: Proc. Roy. Soc. Lond., Ser. A **136**, 692 (1932).
[2] J. CHADWICK: Proc. Roy. Soc. Lond., Ser. A **142**, 1 (1933).
[3] I. CURIE and F. JOLIOT: C. R. Acad. Sci. Paris **197**, 237 (1933). — J. Phys. Radium **4**, 494 (1933). — W. D. HARKINS and D. M. GANS: Nature, Lond. **134**, 968 (1934). — G. N. LEWIS, M. S. LIVINGSTON, M. C. HENDERSON and E. O. LAWRENCE: Phys. Rev. **45**, 242, 497 (1934).
[4] J. CHADWICK and M. GOLDHABER: Nature, Lond. **134**, 237 (1934). — Proc. Roy. Soc. Lond., Ser. A **151**, 479 (1935).
[5] W. E. STEPHENS: Rev. Mod. Phys. **19**, 19 (1947).
[6] T. R. ROBERTS and A. O. NIER: Phys. Rev. **77**, 746 (1950).
[7] E. R. COHEN, J. W. M. DUMOND, T. W. LAYTON and J. R. ROLLETT: Rev. Mod. Phys. **27**, 363 (1955).

to be compared with the values of the masses of hydrogen atom, proton and electron

$$m_{\mathrm{H}} = (1.008142 \pm 0.000003) \text{ units of mass} = (938.722 \pm 0.010) \text{ Mev}, \quad (2.4)$$

$$m_p = (1.007593 \pm 0.000003) \text{ units of mass} = (938.211 \pm 0.010) \text{ Mev}, \quad (2.5)$$

$$\left.\begin{aligned} m_e &= [1836.12 \pm 0.02]^{-1} \times m_p = (0.510976 \pm 0.000007) \text{ Mev}, \\ &1 \text{ unit of mass} = (931.141 \pm 0.010) \text{ Mev}. \end{aligned}\right\} \quad (2.6)$$

3. The nuclear model based on protons and neutrons. Immediately after the discovery that neutrons are emitted in certain nuclear reactions, several authors advanced the natural hypothesis that they were among the constituents of the nucleus[1] and proposed various nuclear models in which α-particles, protons,

Table 1. *Determinations of the binding energy of the deuteron: E_3.*

Reference	$-E_3$ (Mev)	Method
(a)	2.181 ± 0.005	From the energy of photoprotons produced by γ-rays of $h\nu = 2.62$ Mev
(b)	2.229 ± 0.020	From energy of photoneutrons produced by γ-rays of $h\nu = 2.62$ Mev
(c)	2.227 ± 0.010	From the Q value of ${}^2\mathrm{D} + {}^1\mathrm{H} \to n + {}^1\mathrm{H} + {}^1\mathrm{H}$
(d)	2.230 ± 0.007	From the energy of the photons emitted in capture of slow neutrons by protons (Sect. 29)
(e)	2.226 ± 0.003	From threshold of photodisintegration of the deuteron (Sect. 46)
(f)	2.227 ± 0.003	From threshold of photodisintegration of the deuteron

(a) P. Meyer: Z. Physik **126**, 336 (1949).
(b) A. O. Hanson: Phys. Rev. **75**, 1794 (1949).
(c) R. V. Smith and D. H. Martin: Phys. Rev. **77**, 752 (1950).
(d) R. E. Bell and L. G. Elliot: Phys. Rev. **79**, 282 (1950).
(e) R. C. Mobley and R. A. Laubenstein: Phys. Rev. **80**, 309 (1950).
(f) J. C. Noyes, J. E. van Hoomissen, W. C. Miller and B. Waldman: Phys. Rev. **95**, 396 (1954).

Table 2. *A few determinations of the neutron-hydrogen atom mass difference from various reactions under the assumption that the rest mass of the neutrino is zero.*

Reference	$m_n - m_{\mathrm{H}}$ (kev)	Used reactions
A. V. Tollestrup, F. A. Jankins, W. A. Fowler and C. C. Lauritsen: Phys. Rev. **75**, 1947 (1949)	786 ± 6	$\mathrm{D}+\mathrm{D} \to {}^3\mathrm{He} + n$ $\mathrm{D}+\mathrm{D} \to {}^3\mathrm{H} + n$ ${}^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \nu$
W. Franzen, J. Halpern and W. E. Stephens: Phys. Rev. **76**, 317 (1949)	783 ± 4	${}^3\mathrm{He} + n \to {}^3\mathrm{H} + p$ ${}^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \nu$ and ${}^{14}\mathrm{N} + n \to {}^{14}\mathrm{C} + p$ ${}^{14}\mathrm{C} \to {}^{14}\mathrm{N} + e^- + \nu$
R. F. Taschek, H. V. Argo, A. Hemmendinger and G. A. Jarvis: Phys. Rev. **76**, 325 (1949)	782 ± 2	${}^3\mathrm{H} + p \to {}^3\mathrm{He} + n$ ${}^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \nu$

electrons and also neutrons appeared. Iwanenko[2] was probably the first to publish the theory that neutrons and protons were the *only* fundamental constituents of the nucleus, while electrons were definitively excluded. This point was of considerable importance because many of the serious difficulties of all

[1] F. Perrin: C. R. Acad. Sci. Paris **195**, 236 (1932); see also W. Heisenberg, Rapports et discussions du 7ème Congrès de l'Institut International de Physique Solvay, p. 289, 1934.
[2] D. Iwanenko: Nature, Lond. **129**, 798 (1932).

preceding nuclear models were due to the assumption that there existed "nuclear electrons" [5], [3].

HEISENBERG[1] and MAJORANA[2] were the first to appreciate fully the importance of this new model and they attempted to explain qualitatively, and in part quantitatively, nuclear properties in terms of exchange forces between pairs of nucleons (i.e. protons and neutrons).

These attempts, as well as the recognition by WIGNER[3] that nuclear forces must have a very short range of action, constitute the first steps in the very wide chapter of nuclear physics dealing with the investigation of the nucleon-nucleon interaction [4], [5], [3], [16] and of its relations with the mesonic field[4]. These problems of paramount importance are completely outside the scope of the present chapter. The only point that has to be stressed here is that all successive developments of our knowledge on nuclear structures have confirmed the basic conclusion that protons and neutrons are the only constituents of all nuclei.

4. The spin and statistics. In this model two very important properties were attributed to the neutrons, to make them as similar as possible to protons: namely, that their spin is $\frac{1}{2}\hbar$ and that they obey Fermi-Dirac statistics.

These two assumptions are not independent of each other, at least from the point of view of the relativistic theory of wave fields, where it can be shown that particles with half integral spin must obey Fermi-Dirac statistics. But independently of this theorem, there were already many arguments in favour of these two assumptions: from the investigation of the Raman effect of the rotational spectra of homonuclear diatomic molecules[5] it had been concluded that *all nuclei with an odd mass number A obey the Fermi-Dirac statistics while nuclei with even A obey Bose-Einstein statistics*[6]. While this experimental result was in many special cases in open contradiction with the predictions of the theory in which the nucleus is built up of protons and electrons, it was completely in agreement with the new model where A represents the total number of nucleons, provided neutrons, as well as protons, obey Fermi-Dirac statistics. Moreover all empirical rules found for obtaining nuclear spins were clearly explained if the neutron had half integral spin. This argument, as well as the above mentioned theorem, requires that the neutron has half integral spin but not necessarily spin $\frac{1}{2}\hbar$, although this value is that which explains all experimental results in the simplest way.

A few other arguments also indicate that the neutron spin must be half integral and favour definitely the value $\frac{1}{2}$ rather than the value $\frac{3}{2}$. Such are for instance the energy-dependence of neutron-proton-scattering taken in connection with the properties of the deuteron (see HULTHÉN and SUGAWARA's contribution to Vol. XXXIX), the coherent scattering of neutrons by parahydrogen and by crystals containing hydrogen, and finally the total reflection of neutrons by mirrors containing hydrogen (RINGO's article in Vol. XXXII).

[1] W. HEISENBERG: Z. Physik **77**, 1 (1932); **78**, 156 (1932); **80**, 587 (1933).

[2] E. MAJORANA: Z. Physik **82**, 137 (1933). — We owe it to the memory of MAJORANA, who died so prematurely, to recall how he communicated to FERMI some of his considerations about the structure of the nucleus, immediately after the first note of CHADWICK. It was only his sense of self criticism that prevented him from publishing earlier these results.

[3] E. P. WIGNER: Phys. Rev. **43**, 252 (1933).

[4] See for instance E. FERMI: Elementary particles. New Haven: Yale University Press 1951. — H. H. BETHE and F. DE HOFFMANN: Mesons and fields Row, Peterson & Co. Evanston, Ill. 1955.

[5] W. HEITLER and G. HERZBERG: Naturwiss. **17**, 673 (1929). — F. RASETTI: Z. Physik **61**, 598 (1930).

[6] For a discussion of these effects see for instance J. MATTAUCH and S. FLÜGGE: Kernphysikalische Tabellen. Berlin: Springer 1942.

5. The magnetic moment. Another fundamental property of the neutron is its intrinsic dipole magnetic moment which contributes, together with that of the proton to the magnetic moments of the various nuclei and in particular to that of the deuteron. This last one being smaller than the magnetic moment of the proton, gives an indication of the fact that the magnetic moment of the neutron must be negative. It is true that the magnetic moments of the nucleons do not simply add, as the corresponding mechanical moments do, to give the magnetic moment of the nucleus: the currents associated with the exchange of mesons among the various nucleons also give a contribution which, however, is not very large, especially in the case of the deuteron. Therefore the argument is still valid and this indication of the sign is confirmed by direct measurement of the magnetic moment of the free neutron which gives[1]

$$\mu_n = (-1.913\,148 \pm 0.000066)\,\mu_N \tag{5.1}$$

where μ_N indicates a nuclear magneton[2]

$$\mu_N = \frac{e}{2m_p c} = (0.505\,038 \pm 0.000018) \times 10^{-23}\ \mathrm{erg} \times \mathrm{gauss}^{-1}. \tag{5.2}$$

A discussion of the experimental determinations of this quantity as well as of its interpretation in terms of meson field theories, would take us too far away from the scope of the present chapter. Therefore we limit ourselves to giving the value (5.1) of μ_n and to mentioning very briefly and qualitatively the type of arguments usually presented in connection with it.

The value (5.1) is considered anomalous in the following sense. After the recognition that the behaviour of electrons was described, if not exactly at least with good accuracy, by means of the Dirac equation, it was natural to assume that all other particles, different from electrons, but with spin $\frac{1}{2}$, could also be described by the same equation. But if one applies the Dirac equation to the nucleons one finds that the proton must have a magnetic moment equal to one nuclear magneton, and the neutron a magnetic moment equal to zero. We know that these two conclusions do not correspond to the experimental results: the proton has the magnetic moment[2]

$$\mu_p = (2.79275 \pm 0.00003)\,\mu_N \tag{5.3}$$

and the neutron the magnetic moment given by (5.1).

This is expressed by saying that both nucleons have anomalous magnetic moments (with respect to the expectation based on the Dirac equation) and the following type of argument has been invoked in order to explain the experimental results.

The neutron existing in nature, indicated as physical neutron, is a mixture of states, for part of the time it is really a neutron (a bare neutron $\boldsymbol{n}$) with zero magnetic moment, but for a fraction of the time it is (virtually) dissociated into a bare proton $\boldsymbol{p}$ and a negative π-meson according to the equation

$$\boldsymbol{n} \rightleftharpoons \boldsymbol{p} + \pi^-. \tag{5.4}$$

Here $\boldsymbol{p}$ is a proton with $\mu_{\boldsymbol{p}} = \mu_N$ and π^- is a negative meson moving around $\boldsymbol{p}$ so that its orbital magnetic moment, greater and antiparallel to that of the bare proton, prevails and gives rise to the observed magnetic moment (5.1).

[1] V. W. COHEN, N. R. CORNGOLD and N. F. RAMSEY: Phys. Rev. **104**, 283 (1956).
[2] See footnote 7, p. 4.

The process (5.4) is only one of an infinite number of possible processes of dissociation, but is generally believed to be one of greatest importance.

Similarly, the physical proton p is a mixture of two states, the first that of a bare proton $\mathbf{p}$, with $\mu_{\mathbf{p}} = \mu_N$, and the second a state in which it is (virtually) dissociated into a bare neutron (with zero magnetic moment) and a positive π-meson. The presence of the π^+-meson would explain the anomalous magnetic moment (5.3).

6. The beta radioactivity. The fact that the mass of the neutron is greater than that of the hydrogen atom (Table 2) was recognized a long time ago and makes energetically possible the spontaneous disintegration of a neutron into a proton and an electron.

Such a possible instability of the neutron, first suggested by CHADWICK and GOLDHABER[1] was proved experimentally only many years later[2-4].

We know today that free neutrons undergo a spontaneous beta decay process with emission of an electron and a neutrino

$$ {}_0n^1 \rightarrow {}_1p^1 + e^- + \nu . \tag{6.1}$$

Beside this process of transformation of a neutron into a proton, one has to consider a process of transformation of a proton into a neutron with emission of a positive electron and a neutrino. This is energetically impossible in the case of a free proton, but can take place in the presence of other nucleons, whenever it is allowed by the various conservation laws. These two processes of transformation of one nucleon into another with emission of negative or positive electrons not only are the basis of FERMI's theory of beta decay [*5*], [*9*], [*3*], but also represent important examples of the so-called Fermi universal interaction in which four particles, obeying the Pauli principle, are involved[5].

This fundamental property of the neutron has no part in the various phenomena treated in this chapter, and so we refer for details of process (5.4) and of the experimental determinations of the corresponding β-ray spectrum and half-life, to Vol. XLI; here we limit ourselves to giving in Table 3 the experimental values of the half-life and of the maximum energy of the β-ray spectrum as they result from direct measurements[3,4].

Table 3. *Properties of the neutron.*

Charge	$< 10^{-18}\, e = 4.8 \times 10^{-28}$ e.s.u.
Mass	(1.008982 ± 0.000003) units of mass $\left(\frac{1}{16}\, O^{16}\right)$ $= (939.505 \pm 0.010)$ Mev $= (1.67470 \pm 0.00004) \times 10^{-24}$ g
Spin	$\frac{1}{2}\hbar$
Statistics	Fermi-Dirac
Magnetic moment	(-1.913148 ± 0.000066) nuclear magnetons
Half life	(12.2 ± 1.3) minutes
Maximum energy of β-ray spectrum	$E_{\max}^{(-)} = (782 \pm 1)$ kev

[1] See footnote 4, p. 4.
[2] A. H. SNELL and L. C. MILLER: Phys. Rev. **74**, 1217 A (1948). — A. H. SNELL, F. PLEASANTON and R. V. MCCORD: Phys. Rev. **78**, 310 (1950).
[3] J. M. ROBSON: Phys. Rev. **78**, 311 (1950); **83**, 349 (1951).
[4] P. E. SPIVAK, A. N. SOSNOVSKY, A. Y. PROKOFIEV and V. S. SOKOLOV, p. 33 of Ref. [*15a*]
[5] See for instance L. MICHELL: Progress in cosmic ray Physics. Windfork 1952.

III. General remarks on the interaction of neutrons with matter. The first neutron reactions.

7. The neutron-electron interaction. When neutrons move through matter, they produce ions indirectly, by the action of the recoil atoms. This is just the effect that made the discovery of the neutron possible, and it obviously gives a clear proof of its interaction with nuclei.

One can, however, ask, and the answer is of a considerable interest, whether some kind of *direct* interaction exists between neutrons and electrons which might be responsible for some observable effect, in particular for the direct production of ions by neutrons.

This problem was originally investigated by CHADWICK[1] and by DEE[2]. Both these authors gave an upper limit for the number of pairs of ions produced by a neutron per unit length of path. The value given by DEE is not more than one pair of ions per 3 meters of path in air. By comparing this upper limit for the energy loss through ionization, with that of protons, FLÜGGE established an upper limit for the possible electric charge of the neutron at about $^1/_{700}$ of the electronic charge [*18b*].

Much lower limits for the value of the possible charge of the neutron ($\lesssim 10^{-12} e$) can be established through various indirect arguments given by FELD [*17b*] which are based on the neutrality of atoms, or on the neutron decay process (6.1), or finally on the observed small deviation ($\sim 1\%$) from spherical symmetry observed by FERMI and MARSHALL[3] in the scattering of slow neutrons by xenon atoms ($\lesssim 10^{-18} e$).

This experiment was the first one of a series devoted to establishing the existence of a neutron-electron interaction which have been described in detail by G. R. RINGO in Vol. XXXII because they necessarily make use of the methods of neutron optics. These experiments are also discussed by HOFSTADTER and FUBINI in Vol. XLIII. Here we limit ourself to mentioning the main considerations and conclusions which are of general interest from the point of view of the interaction of neutrons with matter.

When in this connection we speak of the interaction between neutrons and electrons we do *not* refer to the interaction between the magnetic moment of the neutron (5.1) and the magnetic field produced by the atom as a whole. This interaction, usually called the magnetic interaction, depends on the orientation of the spin of the neutron with respect to the atomic magnetic field and is used, for instance, to produce polarized beams of slow neutrons by scattering them in magnetized ferromagnetics (see RINGO's article in Vol. XXXII). The magnetic interaction should not exist for diamagnetic atoms such as those of the noble gases in which the electrons are bound in closed shells.

Beside the magnetic interaction one might expect also the existence of a potential energy between neutron and electron which gives rise, even in the case of diamagnetic atoms, to a very weak scattering of the incident neutrons superimposed on the uncomparably bigger scattering due to the nuclei.

As we shall discuss later, this interaction is expected to exist as a consequence of two effects: the anomalous magnetic moment (5.1), and other structure terms of the neutron arising from the mechanism of Eq. (5.4) which were in fact, introduced in order to explain its anomalous magnetic moment.

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[1] J. CHADWICK: Proc. Roy. Soc. Lond., Ser. A **136**, 692 (1932).
[2] P. I. DEE: Proc. Roy. Soc. Lond. **136**, 727 (1932).
[3] E. FERMI and L. MARSHALL: Phys. Rev. 72, 1139 (1947).

Such an interaction is certainly very weak and has a short range of action; therefore, its effect on the neutron can be calculated by means of the Born approximation. The corresponding cross section increases with increasing wavelength λ of the neutron, and for neutrons of very low energy ($\lambda \to \infty$) it does not depend on λ nor on the shape of the potential well but only on the volume integral of the interaction potential. The situation is similar to that considered later in Sects. 18 and 21.

This remark justifies the use of the rather arbitrary convention of representing the neutron-electron interaction in terms of the depth V_0 of a fictitious spherical potential well of radius equal to the classical electron radius

$$r_e = \frac{e^2}{m_e c^2} = 2.82 \times 10^{-13}\,\text{cm}. \tag{7.1}$$

As already mentioned above the effect is so small that in all the experiments made to reveal its existence it was necessary to take advantage of the coherent scattering of slow neutrons by the peripheral electrons surrounding heavy nuclei in order to obtain an enhanced effect.

The method of FERMI and MARSHALL is based on the experimental determination of the deviation from spherical symmetry of the slow neutrons scattered by xenon. For neutrons of wavelength comparable with atomic dimensions and therefore much larger than nuclear dimensions, the scattering by the nucleus is spherically symmetrical (see Sect. 21) while the scattering by the electrons shows an asymmetry with respect to the equatorial plane, due to the form factor $\mathcal{F}(\vartheta)$ of the electron distribution which is known from X-ray experiments or from the corresponding well-known calculations.

The differential scattering cross section of a neutral atom of atomic number Z and nuclear cross section σ_s, may be written as follows

$$\left(\frac{d\sigma}{d\omega}\right)_{\text{atom}} = \frac{\sigma_s}{4\pi}\{1 + cZ\,\mathcal{F}(\vartheta)\}^2 \tag{7.2}$$

where c represents the relative contribution of a single electron

$$c = \frac{\frac{4\pi}{3} r_e^3 V_0}{\left[\frac{\pi \hbar^4}{m^2}\sigma_s\right]^{\frac{1}{2}}} = 1.28 \times 10^{-7} \frac{V_0\,(\text{ev})}{\sqrt{\sigma_s\,(\text{barns})}}. \tag{7.3}$$

Its value is so small that only the interference term between the nuclear and the electronic scattering is appreciable. The sign of this term can be used in order to establish the sign of the neutron-electron interaction, that is its repulsive or attractive nature. The method of HAVENS, RAINWATER and RABI[1] is based on the measurement of the variation with the wavelength λ of the incident neutrons of the total cross section of liquid bismuth. In these experiments advantage is taken of the fact that while the nuclear scattering is constant in the interval of variation of λ considered, the form factor of the electron distribution is a known function of the wavelength.

Finally, the method of HUGHES, HARVEY, GOLDBERG and STAFNE[2] makes use of the so-called balanced mirror technique, in which the total reflection of a beam of slow neutrons by the surface of separation between liquid oxygen and bismuth is studied [*12*], [*13*].

[1] W. W. HAVENS, L. J. RAINWATER and I. I. RABI: Phys. Rev. **82**, 345 (1951).

[2] D. J. HUGHES, J. A. HARVEY, M. D. GOLDBERG and M. J. STAFNE: Phys. Rev. **90**, 497 (1953).

These substances are chosen because their corresponding nuclear scatterings are almost equal while the electron scattering is much higher in bismuth than in oxygen because of the higher Z.

Table 4 contains the results of these authors expressed by giving the corresponding values of V_0. The negative sign means that this short range interaction between neutron and electron is attractive.

Table 4. *Neutron-electron interaction.*

Depth of a potential well of radius $r_e = \frac{e^2}{m_e c^2}$.

	Used material	Method	Result V_0 in ev
FERMI and MARSHALL: Phys. Rev. **72**, 1139 (1947)	Xe, gas	angular asymmetry	-300 ± 5000
HAVENS, RAINWATER and RABI: Phys. Rev. **82**, 345 (1951)	Bi, liquid	total cross section for λ varing between 0.3—3 Å	-5300 ± 1000
HAMMERMESH, RINGO and WATTENBERG: Phys. Rev. **85**, 483 (1952)	Xe and Kr gases	angular asymmetry	-4100 ± 1000
HUGHES, HARVEY, GOLDBERG and STAFNE: Phys. Rev. **90**, 497 (1953)	O_2—Bi	balanced mirror	-3900 ± 400

FOLDY[1] has investigated the electromagnetic properties of a particle obeying the Dirac equation with the additional term introduced by PAULI in order to take into account the possible existence of an anomalous magnetic moment, and has shown that the neutron-electron interaction can be divided into two parts. The first part is due to the anomalous magnetic moment of the neutron and corresponds to an attraction between neutron and electron which, referred again to the conventional potential well of radius r_e, gives $V_0 = -4080$ ev[2].

This term appears almost sufficient to account for the observed interaction (see Table 4), and therefore leaves little place for the second effect expected according to Eq. (5.4). If the view expressed by this equation is correct, in the immediate vicinity of a neutron one would expect an electric field due to the charge of the bare proton to exist there, for a fraction of the time. This field, of course, would extend only to a very small distance, because it would be screened by the negative charge of the π-meson. Various calculations of this effect indicate a value of the corresponding potential V_0 larger than the difference between the experimental results and the value given above for the contribution arising from the anomalous magnetic moment. According to FRIED[2] the second part of the neutron-electron interaction corresponds to $V_0 = -1300$ ev. However, the uncertainties involved in calculations based on meson theory are so large that the apparent conflict between the experimental results and current ideas about the cloud of virtual mesons surrounding the neutron must be treated with some reservation.

This discussion takes us too far away from the province of the present chapter. Therefore we refer to [*18b*][3] and to Vol. XLIII for more details and we conclude that whatever may be the theoretical interpretation, the above mentioned experiments prove the existence of a short range interaction between electrons and neutrons corresponding to an attractive potential well characterized by the

[1] L. L. FOLDY: Phys. Rev. **87**, 688, 693 (1952).
[2] B. D. FRIED: Phys. Rev. **88**, 1142 (1952).
[3] L. L. FOLDY: Rev. Mod. Phys. **30**, 471 (1958).

following value of the potential well of radius (7.1)

$$V_0 = -(3900 \pm 400)\,\text{ev}. \tag{7.4}$$

In order to appreciate the physical meaning of this figure we can introduce it in (7.3) and compute the electron contribution to scattering in various elements. The results of such a computation are shown in Table 5. Considering the data given in the fourth column of Table 5 and that the form factor $\mathscr{F}(\vartheta)$ is strongly peaked in the forward direction, we feel justified in the following to neglect the neutron-electron interaction and to consider it as a small correction only in experiments in neutron optics.

Table 5. *Relative contribution of electrons to the scattering cross section of various neutral atoms for slow neutrons* ($V_0 = -3900$ ev).

Element	Z	σ_s (barns)	c	cZ
C	6	4.8	-2.3×10^{-3}	-1.4×10^{-2}
Xe	54	4.3	-2.4×10^{-3}	-13×10^{-2}
Bi	83	9	-1.67×10^{-3}	-15×10^{-2}

8. The interaction of neutrons with nuclei. The elastic scattering and the (n, α) processes. In conclusion, in speaking of the interaction of neutrons with matter it is generally the interaction of neutrons with nuclei that is meant. However the field is so wide and complex that only very few historical and general remarks can be given in this section.

Even from the first transmission experiments of CHADWICK it was possible to conclude that the absorption cross section of lead for the neutrons emitted in process (1.1), was of the order of the geometric cross section. This result, although very important, had only a qualitative character because the neutron cross section is a function of the energy, different for every nucleus, and the energy spectrum of the neutrons used in these experiments was complex and extended over a very wide energy interval.

Later it was shown that for neutrons with an energy between 7 and 20 Mev the absorption coefficient varies regularly with the mass number of the nucleus according to the law deduced assuming a nuclear cross section equal to the geometric one (see Sect. 19).

At higher energies "transparency phenomena" begin to reduce the absorption by matter, while at lower energies the individual properties of the various nuclei become evident through a rather complicated and characteristic variation with neutron energy of the corresponding absorption cross sections.

Absorption measurements give only very partial and incomplete information about the nuclear processes produced by neutrons.

The scattering of neutron, the process that had first revealed the existence of this new particle, was further investigated by observing the recoiling atoms[1,2] or the scattered neutrons[3]. But it was also shown, by FEATHER[1] that neutrons can produce nuclear disintegrations, which appear in a cloud chamber as "forks",

[1] N. FEATHER: Proc. Roy. Soc. Lond., Ser. A **136**, 709 (1932).

[2] J. CHADWICK: See footnote 1, p. 9. — M. DE BROGLIE and L. LEPRINCE-RINGUET: C. R. Acad. Sci. Paris **194**, 1616 (1932). — P. AUGER: C. R. Acad. Sci. Paris **194**, 877 (1932); **195**, 234 (1932).

[3] J. R. DUNNING and G. B. PEGRAM: Phys. Rev. **43**, 497 (1933). — J. R. DUNNING: Phys. Rev. **45**, 586 (1934).