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[2]F. H. Juergens, A. B. Ellis, G. H. Dieckmann, and R. I. Perkins, J. Chem. Ed. **64**, 851 (1987).
[3]J. N. Fox, N. W. Gaggini, and J. K. Eddy, Am. J. Phys. **54**, 723 (1986) and J. U. Trefny and J. N. Fox, Am. J. Phys. **43**, 622 (1975).
[4]X. Chen, S. Lee, J. Golben, S. Lee, R. McMichael, Y. Song, T. Noh, and J. Gaines, Rev. Sci. Instrum. **58**, 1565 (1987). See also Ref. 2.
[5]High-purity silver paint is available from SPI Supplies, PO Box 342, West Chester, PA.
[6]DMMs with an IEEE-488 output such as the Keithley 175 (10 μV resolution) or the 197 (1 μV resolution) are useful. They are available from Keithley Instruments, Inc., 28775 Aurora Rd., Cleveland, OH 44139.
[7]Model 5245L electronic counter, Hewlett–Packard, Palo Alto, CA. Circuit diagrams and software description for an IEEE-488 interface for this unit will be supplied upon request.

Nuclear structure and beta decay (1932–1933)

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Before the discoveries of the neutron and the positron in 1932, the only known fundamental material particles were the electron and the proton (referred to sometimes as "negative and positive electricity"), which were also thought to be the *only constituents of all matter*, including the atomic nucleus. Well-known nuclear phenomena, especially β decay, seemed to require that nuclei contain electrons, even though their presence violated accepted principles of microscopic physics. During 1932 and 1933, however, the picture changed considerably and the foundation was laid for a future theory of nuclear structure and β decay, with the nucleus composed of only neutrons and protons as fundamental building blocks.

I. INTRODUCTION

The year 1932 saw the discovery of the "hydrogen atom of nuclear physics," the deuteron. In the same year, the first nuclear reactions using artificially accelerated protons and deuterons were produced and a trio of new particles—neutron, positron, and neutrino—was added to the existing trinity—electron, proton, and photon.[1] In 1932, physicists thought that the nucleus consisted of protons and electrons and that the nuclear forces were essentially electric and magnetic.[2] That view prevailed, even though it was evident that standard quantum mechanics was incompatible with the presence of electrons in the nucleus.

After James Chadwick's announcement of the neutron discovery, almost everybody (including Chadwick himself) believed that the neutron was a tightly bound composite of a proton and an electron, a kind of collapsed hydrogen atom, much as Ernest Rutherford had predicted in 1920.[3] Very soon, however, Werner Heisenberg suggested that although the neutron probably had a composite structure, it might still behave as an "elementary particle" within the nucleus (Sec. II). "The idea," as Heisenberg wrote to Niels Bohr, was to "shove all the difficulties of principle into the neutron, and to apply standard quantum mechanics within the nucleus."[4]

Heisenberg's theory introduced nuclear forces of the exchange type analogous to those which enter in nuclear binding: That is, the forces between the proton and the neutron, or between two neutrons, stem from an effective exchange of one or two electrons, respectively.[5] An "incomplete" exchange of electrons, on the other hand, should represent β decay. Without going into any detailed description of the latter process, Heisenberg discussed the stability of nuclei. Thus, at the cost of blurring the distinction between "composite" and "elementary," his theory was able to treat nuclear states and transitions occurring between them.

This picture of the nucleus did not meet everyone's taste, since Heisenberg's model of the neutron structure was incompatible with quantum mechanics. His description of β decay violated accepted conservation laws, including those of energy and angular momentum. In addition, forces based upon the dominance of charge exchange did not reproduce correctly the properties of the light nuclei nor the saturation of forces seen in them and in heavier nuclei as well.[6] For those reasons, Ettore Majorana, Eugene Wigner, and others made alternative neutron–proton models of the nucleus, using potentials of different spin-dependence, adjusted to fit observed nuclear properties. These potentials were purely phenomenological in character—that is, they did not invoke any fundamental dynamical mechanism to replace Heisenberg's charge exchange—but they had the advantage that they could be incorporated into standard nonrelativistic quantum mechanics. The theories of Majorana and Wigner treated the neutron as an elementary and unproblematic particle, and *did not describe β decay at all.*

The 1933 Solvay Conference in Brussels, which dealt with the structure and properties of nuclei, had Heisenberg as one of the principal speakers (Sec. III). Others in attendance included Wolfgang Pauli and Enrico Fermi. After Heisenberg gave his report, Pauli made a discussion remark in which he suggested (for the first time "officially") the existence of the neutrino. On returning to Rome, Fermi soon afterward proposed a successful theory of β decay that incorporated the neutrino and satisfied all the standard conservation laws (see Sec. IV). In some respects, being modeled after quantum electrodynamics and Dirac's hole theory, Fermi's β-decay theory was a distinctly modern quantum field theory of particle creation and annihilation, and it had an enormous impact on elementary particle physics. Heisenberg's neutron–proton nuclear model, including modifications by Wigner, Majorana, and others, has led to the modern science of nuclear structure, while Fermi's β-decay theory has become, after some generalization, the modern electroweak gauge theory. Fundamental theories of nuclear forces were proposed later in the thirties; here, again, the starting points were the nuclear theories of Heisenberg and Fermi.[7]

II. THE NEUTRON–PROTON–ELECTRON MODEL OF THE NUCLEUS

The modern science of nuclear structure physics stems from Heisenberg's three-part article of 1932, begun just after Chadwick's discovery of the neutron, in which he introduced and elaborated on a neutron–proton model of the nucleus.[8] However, the modern reader of Heisenberg's article cannot fail to notice its profound ambiguity (a thing that seems to typify much of Heisenberg's best work). On the one hand, the constituents (*Bausteine*) of the nucleus were the neutron and proton, formally regarded as the uncharged and charged states of the particle that we now call the nucleon and obeying quantum mechanics. On the other hand, the *elementary* particles (in the usual sense) were the proton and the electron, while the neutron was treated as an electron–proton compound. Heisenberg also required, at least in heavy nuclei, additional "loose" electrons, not bound in neutrons. In that sense, his model was merely a reshaping of the electron–proton model that had preceded the neutron's discovery.[9]

The power of Heisenberg's model lay in its phenomenological aspect. With it he gave impetus to the modern study of nuclear systematics, including the stability curve (A vs Z), mass defects, and some aspects of radioactive decay. The principal defect of the model was that it required the presence of electrons in the nucleus (and *a fortiori* in the neutron), which violated some basic conservation laws (angular momentum and statistics) and incorrectly implied the failure of quantum mechanics at distances not much smaller than the nuclear radius. Heisenberg favored the presence of electrons in the nucleus on a number of empirical grounds, including β decay, as well as cosmic ray and laboratory experiments that we shall not discuss here.

In Heisenberg's theory, the structure of a given nuclear species and the extent to which it is stable are determined by forces that act between the nucleons: proton (p) and neutron (n). As a consequence of the assumption that protons are elementary, the p–p force is taken as pure Coulomb repulsion. The n–p force is an exchange force of the type found in the molecular ion H_2^+, while the n–n force is analogous to the homopolar binding force found in the H_2 molecule. Since quantum mechanics cannot account for the composite neutron, no quantitative calculation of the n–p or n–n potential is possible (and no adequate theory of β decay, either). Heisenberg thus proposed to describe the n–p force by the product of an empirical short-range potential function $J(r)$ and an operator that changes the nucleon type. The last point is to be noted as the origin of the *isospin formalism* so important in nuclear and particle physics. In the same spirit, a short-range attractive interaction potential $K(r)$ was assigned to represent the n–n force.

Having established this theoretical apparatus, Heisenberg discussed in Pt. I various aspects of nuclear systematics. One can, for example, understand the equality of the numbers of neutrons and protons in the most stable light nuclei, provided the n–p force dominates. In heavy nuclei, on the other hand, Coulomb repulsion can cause the emission of α particles if there are too many protons for stability, while if there are too many neutrons there will be β decay. The nuclei will thus approach the stability curve, i.e., the line connecting the stable species in an A vs Z plot of stable and unstable nuclei, often with the emission of γ rays as well.

Parts II and III of Heisenberg's paper each contain sections that further treat these stability problems. However, each part also contains a section on the properties of the neutron and another on the scattering of γ rays from nuclei. These last two topics, dealing explicitly with electrons in the nucleus, are generally omitted in historical discussions of Heisenberg's nuclear model, whether discussed by physicists or by historians of science.[10]

In Pt. I also, Heisenberg calls for electrons in the nucleus and stresses the compositeness of the neutron, e.g., in the following passage (see Ref. 1, Pt. I, p. 1).

> One must realize that there are other physical phenomena for which the neutron can no longer be considered a static structure (*statisches Gebilde*)....To these phenomena belong, e.g., the Meitner–Hupfeld effect, the scattering of γ-rays on the nucleus. Likewise, to this class belong all experiments in which the neutrons can be split into protons and electrons; an example of this is the slowing of cosmic ray electrons in passing through nuclei.

In Pt. II, in the section called "The properties of the neutron," the author wonders how composite neutrons "with their small mass defect (1 Million Volt)" can survive intact in nuclei where the interaction energy is much greater,[11] and gives this extraordinary answer:

> In the defense of this hypothesis, one can at once adduce that the very existence of the neutron contradicts the laws of quantum mechanics in their present form. Also the admittedly hypothetical validity of Fermi statistics for neutrons, as well as the failure of the energy theorem for β-decay, proves the inapplicability of present quantum mechanics to the structure of the neutron. However, even if one disregards these properties of the neutron, already the circumstance that the neutron is a structure of approximate extent $\Delta q \sim e^2/mc^2$ is a contradiction to quantum mechanics if the neutron is taken to be a composite of electron and proton.[12]

To paraphrase: In some sense, the neutron is more complex than the proton, but not in any way that can be described by quantum mechanics. So, when we do nuclear systematics—but not when we do, e.g., cosmic ray physics—we should treat the neutron as an elementary particle.[13]

Heisenberg's clearest statement of the advantage to be gained by putting most of the electrons in neutrons is given in the last section of Pt. III:

The discovery of the stability of the [*bound*] neutron, not describable by present theory, allows a clean separation of the realms in which quantum mechanics is applicable from those in which it is not, for this stability allows purely quantum-mechanical systems to be built up out of protons and neutrons, in which the new kind of features which enter into β-decay do not occasion any difficulty. This possibility of a sharp separation of the quantum mechanical aspects and those new features characteristic for the nucleus seems to get lost if the electrons are considered as independent nuclear constituents.[14]

Although up to now we have been dealing with the problematic side of Heisenberg's nuclear theory, we must emphasize once more that it was a major step toward understanding the nucleus as a quantum mechanical system. Applications to nuclear systematics began already in Pt. I, where Heisenberg studied the stability curve. Despite the fact that the considerations in Pt. I are qualitative, they were refined in Pt. II, where conclusions were drawn about the four radioactive decay series.

In Pt. III, the molecular analogy was extended, the n–p exchange force being supplemented with an "electrostatic" (nonexchange) force as occurs in the molecular ion H_2^+, and the well-known Thomas–Fermi method is employed. Heisenberg carried out a minimization of the energy using an approximate many nucleon Hamiltonian, with the restriction that the magnitude of the total ρ-spin (the present-day isospin!) was fixed. This yielded an effective potential in which the neutrons and protons behaved as gases of free particles obeying Fermi–Dirac statistics. The results were seen to justify the conclusions made regarding the stability curve in Pts. I and II, in which the same assumptions have been made concerning the forces.

By October 1933, at the seventh Solvay Conference,[15] Heisenberg had rejected his purely charge-exchange force in favor of a modification proposed by Majorana.[16] He also took account of a work by Wigner on the lightest nuclei.[17]

III. THE 1933 SOLVAY CONFERENCE

The Solvay Conference on Physics in 1933 had as its theme *The Structure and Properties of Atomic Nuclei*. Coming, as it did, after the brilliant discoveries of 1932, it actually considered a broader range of topics, including the positron and the neutron. Pauli gave his first official presentation of the neutrino idea, and for the first time permitted it to be published.[18] We confine our discussions here to papers bearing directly on the nuclear forces.

To put this in a general framework, we note that at this time there was nothing that could be called a fundamental nuclear theory, as the Heisenberg, Majorana, and Wigner theories all used potentials whose functional form was to be taken from experiment; hence, they were phenomenological. Indeed, it was not all certain that there was a specifically *nuclear force*, as opposed to some form of electromagnetic interaction. In particular, it was nowhere proposed that there were *two* nuclear forces, one strong and one weak, until Yukawa published his meson theory in 1935.[19]

Although there are logical alternatives, practically speaking, a fundamental theory for short-range forces must be a quantum field theory.[20] Before such a theory is formulated, the following two questions must be addressed[21]:

(a) What are the *characteristics* of the forces that one expects to derive from the fundamental theory, and how can they be inferred from the phenomena?

(b) What are the *constituent objects*, i.e., particles involved in the fundamental interactions?

We have not used "elementary" in connection with either the particles or the interactions, as that word often connotes the notion of irreducibility. The interaction between two electrons, e.g., can be regarded as fundamental, but it is not elementary, since it involves the exchange of photons. Already in the early 1930s, the classification of a particle as elementary was breaking down because of such processes as pair production.

General properties of the nuclear forces were known before 1932, namely, the necessity for an attractive force of short range ($\sim 10^{-13}$cm) that was strong enough to overcome the powerful repulsive Coulomb force. It manifested itself, for example, in the anomalous large-angle scattering of α particles on light nuclei. It was also known from the curve of binding energy versus atomic mass number (BE vs A), or the equivalent mass-defect curve, that for the stable nuclear species:

(a) BE grows nearly linearly with A;

(b) nuclear charge $Z \approx A/2$ for light nuclei, and $Z < A/2$ for heavier nuclei.

Property (a), sometimes called saturation, is connected with the linear growth of nuclear volume with A. It was also known that the α particle was an especially stable structure.

The discoveries of 1932 that helped to complete this general phenomenology were those of the neutron and the deuteron. The loosely bound deuteron, besides being a simple system on which to test hypotheses concerning the two-nucleon interaction, provided a means of accelerating the neutron it contained, so that it greatly extended the range of possible artificially produced nuclear reactions. Results from accelerated deuterons were presented at the Solvay Conference by John D. Cockroft, Ernest Rutherford, and Ernest Lawrence. However, those early experiments were not reliable enough to infer firm conclusions about nuclear forces.

At the conference George Gamow discussed the origin of γ rays and nuclear energy levels.[22] In his introduction, he presented an especially clear discussion of what one might learn about nuclear constituents from nuclear BEs. To *paraphrase* Gamow: One generally supposes that two kinds of particles, protons and electrons, are in the nucleus, but that the nucleus also contains stable complexes of these, such as the α particle. Thus the total BE has two parts: the internal BE of the stable structures and the BE of protons, electrons, and stable structures with each other. The second part appears to vary in a continuous manner as elements are added to the nucleus, which rules out certain assumptions. For example, it was once assumed that as many α particles as possible are formed out of the protons and electrons; then certain discontinuities in the BE curve should be found, but they are not. So one must assume instead that often α particles do not form in the nucleus, even when a suitable number of protons and electrons are present. In fact, the behavior of the BE with A suggests that instead one first forms from the protons and electrons the maximum number of neutrons, and then the maximum number of α particles.[23] The results regarding the nuclear spin are also in accord with the idea that it is necessary to include *neutrons* among the nuclear constituents. The saturation property resembles the situation in a liquid drop or in molecules, where short-range repulsion prevents collapse.

Another part of Gamow's talk concerned the anomalous scattering of high-energy γ rays on matter of high Z, which appeared to give secondary radiation with components of 0.5 and 1.0 MeV quantum energy.[24] Gamow called this effect *nuclear fluorescence*, and explained it as follows:

> The γ-quantum of the incident radiation acts on the electron of a nuclear neutron and expels it from the nucleus, producing an artificial β-disintegration. If one finds that the dissociated neutron belongs to a high-lying energy level, the proton that remains, exactly as in the case of a spontaneous β-disintegration, is in an excited state and falls to a lower level, emitting a γ-ray.[25]

Gamow mentions then an alternative explanation proposed by P.M.S. Blackett—namely, that the γ-ray produces an electron–positron pair in the field of the nucleus and the positron subsequently annihilates with another electron. (Blackett's explanation proved later to be correct!)

Following Gamow's talk, Bohr called attention to the β-ray theory of Guido Beck, saying that "even if it does not resolve the fundamental difficulties, it nevertheless deserves our full attention."[26] The theory involved the virtual creation just outside the nucleus of an e^+e^- pair, with subsequent capture of the positron by the nucleus and emission of the electron.[27] Among the fundamental difficulties *not* solved by this theory were the apparent nonconservation of energy and angular momentum. Beck's attitude was expressed as follows:

> It has been suggested that the [lost mechanical] quantities be ascribed to an unknown particle which it is proposed to call a "neutrino." There is, however, at present no need to assume the real existence of a neutrino, and the assumption of its existence would even be an unnecessary complication of the description of the β-decay process.[28]

Chadwick's Solvay report dealt with anomalous scattering of α rays, with nuclear reactions induced by α rays, and with the properties of the neutron.[29] We mention only a few points about the last item. By analyzing the reaction (using polonium α particles)

$$\alpha + {}^{7}\text{Li} \rightarrow {}^{10}\text{B} + n,$$

which results in neutrons of very low kinetic energy, Chadwick deduced an upper limit for the neutron mass and concluded that "... there seems no doubt that the mass of the neutron should be less than that of the hydrogen atom. That is what we would expect if the neutron results from the intimate union of a proton with an electron."[30]

This sounds like another endorsement of the idea of a composite neutron. However, Chadwick then presents some arguments that favor a simple neutron: If composed of a proton and electron, why would not a hydrogen atom collapse to the "neutron state," and how account for its spin and statistics? He stated:

> It seems that the assembled facts suggest that the neutron and proton are both elementary particles. However, I shall show later that one can deduce from results concerning the collisions between neutrons and protons some arguments favoring the complexity of the neutron and the proton.[31]

Heisenberg's Solvay report, entitled "General Theoretical Considerations on the Structure of the Nucleus," had three sections that dealt with principles, hypotheses, and applications.[32] Between June and October 1933, Heisenberg exchanged about a dozen letters with Pauli, much of the contents dealing with Heisenberg's Solvay report, which he sent to Pauli in July.[33] Topics discussed were the properties of the nuclear particles, the possible existence of a neutrino, and the exchange character of the nuclear force. The manuscript of the report contained the sentence: "At the moment it is not clear whether the statement 'energy conservation is violated in β-decay' represents a valid application of the energy concept."[34] However, the sentence is struck out and replaced by a statement that shows the beginning of a shift in attitude on Heisenberg's part. It is not unlikely that the replacement was made when he received Pauli's letter of 2 June 1933, which contained the following paragraph:

> Concerning nuclear physics I again believe very much in the validity of the energy theorem in β-decay, since other very penetrating light particles will be emitted. I also believe that the symmetry character of the total system as well as the momentum will always be preserved in all nuclear processes.[35]

In any event, whether or not due to Pauli's letter, Heisenberg replaced the expunged sentence by:

> Pauli has discussed the hypothesis that, simultaneously with the β-rays, another very penetrating radiation always leaves the nucleus—perhaps consisting of "neutrinos" having the electron mass—which takes care of energy and angular momentum conservation in the nucleus. On the other hand, Bohr considers it more probable that there is a failure of the energy concept, and hence also of the conservation laws in nuclear reactions.[36]

The "principles" section of the Solvay report begins by stating that one of the first tasks of theory in the nuclear domain is to determine "as precisely as possible a limit to the possibility of applying quantum mechanics."[37] There was evidence from α decay, it is said, that quantum mechanics applied to the heavy constituents, and Bohr had recently concluded that nuclear mass defects were consistent with the uncertainty principle of quantum mechanics. Bohr, however, had been working with a nuclear model that included electrons, and to this Heisenberg made two objections: First, it was not justified to ignore, as Bohr had done, the substantial contributions to the energy that would be made by the electrons; second, unlike the atomic case, in the nucleus, "we have no theoretical means to study the forces that act between the various heavy constituents."[38]

Other difficulties in principle arise if electrons are present in nuclei, and Heisenberg reviews them. There is no question of applying quantum mechanics to the electrons in nuclei, nor even the electron theory of Lorentz, nor even the correspondence principle, but: "The statement that electrons act as nuclear constituents possesses no well-defined meaning other than the fact... that some nuclei emit β-rays."[39]

In the section on "hypotheses" in his Solvay report, Heisenberg first discusses Gamow's "liquid-drop model," which emphasizes the α-particle structure of the nucleus, then discusses neutrons as nuclear constituents, and then passes on to consider the laws of interaction between neutrons and protons. In the first place, he assumes that the approximate equality of neutron and proton numbers in the light nuclei is accounted for (given the repulsive Coulomb attraction between protons and the possibly attractive force between neutrons) by assuming that the like-particle forces are negligible. As for the dominant n–p force, he points out that it could be an exchange force of molecular type, or an "ordinary" (i.e., nonexchange) type. If an exchange force, it could either be of pure charge-exchange type or, as proposed by Majorana, of a type that exchanges both the charge *and* the spin direction of neutron and proton.[40] Majorana had pointed out, Heisenberg remarked, that if one wanted to meet the saturation requirement (that is, the linear increase of nuclear volume with the mass number), without introducing arbitrarily a short-range repulsion between neutron and proton (a thing "rather difficult to accept"), it was necessary to have an exchange force.[41] And furthermore, according to Heisenberg, "Majorana legitimately drew the conclusion," that a space-exchange, rather than a charge-exchange, force fits the nuclear systematics best—for with Heisenberg's force, the deuteron was already a "closed" system, instead of the α particle.[42]

Heisenberg concluded his report with a recapitulation of nuclear systematics, e.g., stability curves, on the basis of his own work and that of Majorana using statistical models. With that, the subject of nuclear structure physics was fairly launched. It remained to really deal with, i.e., to *solve* the problem of β decay, and this was to come very soon after the Solvay Conference.

IV. FERMI'S THEORY OF BETA DECAY

Among the radioactive phenomena, β decay was the first whose details seemed to be understood physically: The nuclear transitions simply occurred with the emission of a β particle, i.e., an electron. However, the continuous energy range of the β electrons ranging from zero to some maximum value, posed for a fixed change of nuclear energy a riddle that—unlike the problem of α decay—could not be solved even after the advent of quantum mechanics. In particular, one had to question whether energy conservation held in β decay, i.e., whether the known laws of physics still applied to this radioactive transition process, or whether the latter involved a hitherto undetected source or sink of energy. Then, in the early 1930s, the crucial ingredients of a successful approach to β radioactivity emerged: first, the idea of the neutrino; and second, the conviction that the atomic nucleus contained no electrons, but that they were produced only at the moment of transition.[43] The proposal that β decay involved the emission of new neutral objects, later called neutrinos, goes back to Pauli's suggestion of December 1930.[44]

On the other hand, the first clear statement concerning the creation of the electron in β decay can be found in a note of Dimitri Iwanenko of August 1932.[45] The question, therefore, must be asked: Why didn't Pauli go further and formulate the theory of β decay himself? The principal answer must be found in the conviction he shared with other leading physicists, e.g., Bohr and Heisenberg: The known physical theory, including quantum mechanics and relativistic quantum field theory did not suffice to describe nuclear phenomena. Thus the solution of the problem was made by his less hesitant Italian friend, Fermi.

Since the late twenties, "it had been felt by Fermi that physicists would be ready in the near future to attack problems of nuclear structure."[46] He began in 1929 by considering the magnetic moments of nuclei derived from hyperfine structure.[47] A little later he tried to enter the field of cosmic ray and nuclear physics experimentally.[48] During this period, Fermi acquainted himself thoroughly with quantum electrodynamics: He reformulated the theory in a Hamiltonian scheme, applied it to selected problems, and presented lecture courses about it.[49]

Fermi learned quite early about Pauli's neutrino hypothesis, namely, at the Rome meetings, *Convegno di fisica nucleare* held 11–18 October 1931. Pauli, who had in June 1931 presented a talk in Pasadena on what he then called "neutrons," attended the meeting, as did Samuel Goudsmit, who was requested by Fermi to give a summary of Pauli's Pasadena talk.[50] As Pauli recalled, Fermi "immediately showed a lively interest for my idea [of β decay] and a very positive attitude to my new, neutral particle."[51] This idea implied energy conservation in β decay, which from now on Fermi advocated as well.[52] After the acceptance of Chadwick's (heavy) neutron in 1932, Fermi invented the presently accepted name for Pauli's neutral particle, "neutrino."[53] At the Seventh Solvay Conference of October 1933, to which Fermi was invited, the last act was presented in the preparation for a theoretical description of β decay. Heisenberg, in his report, and Pauli, in the public discussion, outlined the "new view" of the process, including the additional neutral decay product, the neutrino, which ensured the validity of energy and momentum conservation. The task remained to assemble the two elements in a quantum theory of β decay.

On returning home from Brussels, Fermi sat down and performed the job in November 1933. In his solution, several aspects play a decisive role:

(i) The problem of β decay is considered as a problem of second quantization, i.e., a quantum field theoretical description involving the creation of an electron–neutrino pair must be applied.[54]

(ii) The electron–neutrino pair acts like a field coupled to the charge-changing proton–neutron current, in analogy to the situation in quantum electrodynamics (coupling of the electron current to the radiation field).

(iii) Energy and momentum conservation is strictly enforced by writing down a Hamiltonian scheme.

(iv) A special coupling constant g, accounting for the small β-decay rates, is introduced; no attempt is made to relate g to other interactions (e.g., electric or magnetic couplings).

The timetable of completion of the first β-decay theory was quite condensed: The entire solution was worked out in November and December 1933. As his collaborator at that time, Rasetti recalled:

> Fermi intended to announce the results of his β-decay theory in a letter to "Nature," but the manuscript was rejected by the Editor of that journal as containing abstract speculations too remote from physical reality to be of interest to the readers. He then sent a somewhat larger paper to "Ricerca Scientifica" where it was promptly published. The article includes all essential results, showing that the calculations (including the numerical ft-value) had been completed. The larger papers in "Nuovo Cimento" and "Zeitschrift für Physik" were sent to the respective journals very early in 1934.[55]

The main results, apart from theoretical details, may be found already in the unpublished letter to *Nature* (submitted in November 1933) and especially in the subsequent extended note to *Ricerca Scientifica*, with the title (in English translation), "Attempt at a theory of the emission of beta rays" (published still before the end of the year).[56] The theory tried to provide a quantitative description of β decay on the basis of the known principles of relativistic quantum theory, starting from the assumption that "the total number of electrons and neutrinos in the nucleus is not necessarily constant" and employing Heisenberg's idea to consider "the heavy particles, neutron and proton, as two quantum states connected with the two possible values of an internal coordinate ρ."[57] The crucial step of the theory, then, was the particular choice of the interaction energy, which had to satisfy the requirement that in the transition of a neutron into a proton (described by the ρ-spin operator Q) there is always created an electron (ψ)–neutrino (φ) pair.

Thus Fermi wrote down the most general *ansatz* for the interaction Hamiltonian H,

$$H = QL(\psi\varphi) + Q^*L^*(\psi^*\varphi^*), \tag{1}$$

with L representing a bilinear expression of the wavefunction ψ and φ (and the starred operators denoting the Hermitian conjugate ones). He then restricted the form of L by assuming it to transform under coordinate transformations like the time component of a polar four-vector, i.e.,

$$L(\psi\varphi) = g(\psi_2\varphi_1 - \psi_1\varphi_2 + \psi_3\varphi_4 - \psi_4\varphi_3), \tag{2}$$

with g a constant expressing the strength of the β-decay interaction.

Inserting the above interaction, Fermi obtained for the decay time τ the equation

$$1/\tau = \text{const } g^2 qF(\eta_0), \tag{3}$$

where q is the space integral over the eigenfunctions of neutron and proton and $F(\eta_0)$ is a complicated function of the maximum momentum of the electron (η_0). The product $\tau F(\eta_0)$ assumed in the observed β-decay reactions is roughly valued between 1 and 10^2. In case of a zero neutron–proton integral q, the transition corresponds to a forbidden one in atomic spectroscopy. The coupling constant q finally can be calculated as

$$g = 5\times 10^{-5}\text{cm}^5\text{ g s}^{-2}. \tag{4}$$

With these results, which Fermi refined in the papers for the *Rendiconti dell' Accademia Lincei* and the *Zeitschrift für Physik*,[58] the foundation of the future theory of β decay was established. The next years (and decades) would alter the details of the interaction expression, i.e., the form of the bilinear expression L, but not the principle of Fermi's description of the "weak" β-decay. Fermi intended his theory to apply only to β decay (and its inverse processes, namely, neutrino capture with electron emission and electron capture with neutrino emission), but Heisenberg and other physicists tried to use the Hamiltonian (1) as the basis of a unified field theory of both weak and strong nuclear forces. That is, the field of electron–neutrino pairs, the so-called Fermi field, was to be used as a medium for the transmission of the strong force responsible for nuclear binding, scattering, and reactions. Although subsequently supplanted by Yukawa's meson theory, the Fermi field theory occupied many nuclear experts in the later 1930s and it was the first modern field theory of nuclear forces.

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[1]See, e.g., C. Weiner, Phys. Today **25** (5), 40 (1972). The neutrino was not directly observed until the mid-1950s. It was informally suggested by Pauli in 1930, but his proposal reached published form only in the report of the 1933 Solvay Conference (see below). For more on the neutrino: K. von Meyenn, Naturwissenschaften **69**, 564 (1982); L. M. Brown, Phys. Today **31** (9), 23 (1978).

[2]Roger Stuewer, in *Otto Hahn and the Rise of Nuclear Physics* (Reidel, Dordrecht, The Netherlands, 1983), pp. 19–67. G. Gamow's *Constitution of Atomic Nuclei and Radioactivity* (Oxford U.P., London, 1931) is the most complete account of nuclear theory before the neutron. It accepts the presence of electrons in the nucleus, while emphasizing the difficulties to which they gave rise.

[3]E. Rutherford, Proc. R. Soc. London Ser. A **97**, 374 (1920). The first person to insist on the elementary neutron was D. Iwanenko, C. R. (Paris) **195**, 236 (1932).

[4]Heisenberg to Bohr, 20 June 1932: "Die Grundidee ist: alle prinzipiellen Schwierigkeiten auf das Neutron abzuschieben und im Kern Quantenmechanik zu treiben." (Bohr Archives, Copenhagen and Archive for the History of Quantum Physics, AHQP).

[5]The looseness of this description is emphasized in many textbooks of quantum mechanics and may be judged from the following excerpt from V. F. Weisskopf, Am. J. Phys. **53**, 399 (1985): "The chemical bond is often described as an 'exchange effect.' I believe that such a formulation is misleading. It refers to mathematical terms appearing in the detailed calculation, in which two terms are a consequence of the Pauli principle requiring antisymmetric wavefunctions. They have no direct physical significance. Electrons are 'exchanged' only in the sense that in the merged molecular quantum state it is no longer possible to assign an electron to one or the other nucleus."

[6]"Saturation" in this case implies a nuclear volume that increases linearly with mass number, i.e., constant volume per nucleon.

[7]We shall discuss the fundamental theories of nuclear forces of the thirties at another place.

[8]W. Heisenberg, Z. Phys. **77**, 1 (1932); **78**, 156 (1932); **80**, 587 (1933).

[9]For this reason, as well as others, we cannot agree with the claims in A. I. Miller, *Imagery in Scientific Thought* (Birkhauser, Boston, 1984), that "Modern nuclear physics and particle physics began" with Heisenberg's introduction of an exchange force (*Platzwechsel*) that was an analog of the molecular binding force in the H_2^+ ions (see Ref. 5). Heisenberg's force was not realizable, and hence not visualizable, within quantum mechanics by the "migration" of an electron, unless it were a spinless electron obeying Bose statistics. [*Platzwechsel* is translated (in our opinion mistranslated) by Miller as "migration."] The first quantum field theory of nuclear forces was that of the Fermi field theory; the second was that of Yukawa.

[10]Exceptions to this are: J. Bromberg, Hist. Stud. Phys. Sci. **3**, 307 (1971); L. M. Brown and D. F. Moyer, Am. J. Phys. **52**, 130 (1984). Bromberg's article is an interesting pioneering work, based on her study of the Bohr Scientific Correspondence, unpublished manuscripts of Bohr in Copenhagen, and her interview with Heisenberg of 16 June 1970 (on deposit in the Center for History of Physics of the American Institute of Physics in New York City). In her article, Bromberg gives a good account of the concerns of the two physicists before the neutron discovery. They treated the puzzles of nuclear physics (together with those of QED and cosmic rays) as indications of the dawning of a new dynamical era in physics. Her views on Heisenberg's n–p model do not differ substantially from ours, except that we feel she overstated Heisenberg's willingness to accept the simultaneous compatibility of a state and its contrary. Our reading of Heisenberg's letters, papers, and interviews, does not support that view. Thus such statements as "the neutron seemed to be elementary as well as complex" belong to Bromberg, and not to Heisenberg, whose view was rather that of deciding to which nuclear phenomena quantum mechanics applied, and to which it did not:

[11]The neutron's mass defect is actually negative; i.e., the free neutron is unstable, a fact not known at that time.

[12]Reference 8, Pt. II, p. 163.

[13]Miller (Ref. 9, p. 151) says of the elementary versus composite neutron points of view: "Actually, Heisenberg considered both cases seriously!"

However, Heisenberg did not consider them as two separate cases, but tried (as we have said) to blur the distinction between the two.

[14]Reference 8, Pt. III, p. 595. An exception is still claimed for heavy β-active nuclei, where some electrons are admitted as constituents.

[15]The papers and their discussions were published as W. Heisenberg, *Structure et Proprietes de Noyaux Atomiques: Rapports et Discussions du Septième Conseil de Physique* (Gauthier-Villars, Paris, 1934). A good summary of the conference is given in J. Mehra, *The Solvay Conferences on Physics* (Reidel, Dordrecht, The Netherlands, 1975), pp. 207–226.

[16]E. Majorana, Z. Phys. **82**, 137 (1933).

[17]E. Wigner, Phys. Rev. **43**, 252 (1933).

[18]See Ref. 15, pp. 324–325, as well as Ref. 50.

[19]H. Yukawa, Proc. Phys. Math. Soc. Jpn. **17**, 48 (1935). Yukawa introduced separate strong and weak "coupling constants," analogous to the electric charge.

[20]By "quantum field theory" we mean to include not only linear theories, but also gauge theories of the Yang–Mills type, as well as others that are nonlinear, supersymmetric, nonlocal, etc., provided that they imply the conservation of the energy momentum and angular momentum tensors and of electric charge.

[21]"Before" is here used in the historical, not the logical, sense. The pattern is that given by Mituo Taketani in his "methodology of three stages," which is a general historical analysis applied to physics. The search for the characteristics of the phenomena, the constituents of the system, and finally the fundamental theory of interaction within the system, correspond, respectively, to Taketani's three stages: phenomenological, substantialistic, and essentialistic. See, e.g., M. Taketani, in *Science and Society in Modern Japan*, edited by S. Nakayama, D. L. Swain, and E. Yagi (MIT, Cambridge, 1974).

[22]G. Gamow, Ref. 15, pp. 231–288.

[23]For the lightest elements, the two methods do not differ very much. For example, for $^{9}_{4}$Be, one would get by the first method $2\alpha + 1p + 1e^-$ and by the second method $5p + 4n \rightarrow 2\alpha + 1n$. On the other hand, for $^{208}_{82}$Pb, the first method gives $52\alpha + 22e^-$, the second gives $82p + 126n \rightarrow 41\alpha + 44n$. These examples were given by Heisenberg in his Solvay report, Ref. 15, p. 298.

[24]This is the Meitner–Hupfeld effect, discussed by Brown and Moyer, Ref. 10.

[25]Reference 15, p. 259.

[26]Reference 15, p. 287.

[27]G. Beck, Z. Phys. **84**, 811 (1933); G. Beck and K. Sitte, Nature **133**, 722 (1934); G. Beck and K. Sitte, Z. Phys. **89**, 259 (1934); G. Beck, in *International Conference on Physics, London 1934* (Cambridge U.P., Cambridge, 1935), Vol. I, pp. 31–42.

[28]G. Beck, Nature **132**, 967 (1933).

[29]Reference 15, pp. 81–120.

[30]Reference 15, p. 102.

[31]Reference 15, p. 103.

[32]Reference 15, pp. 289–344.

[33]Pauli to Heisenberg, 14 July 1933, in *W. Pauli: Scientific Correspondence, Vol. II:1930-1939*, edited by K. von Meyenn with the cooperation of A. Hermann and V. F. Weisskopf (Springer-Verlag, Berlin, 1985). Letter [314], pp. 184–187; facsimile given on pp. 174–183.

[34]W. Heisenberg "*Allgemeine theoretische Uberlegungen über den Bau der Atomkerne*" (original German manuscript of the 1933 Solvay report, contained in the Werner Heisenberg Archive, Max Planck Institut für Physik und Astrophysik, Munich), p. 27: "*Es scheint also einstweilen nicht klar, ob die Audrucksweise 'beim β-Zerfall ist der Erhaltungssatz der Energie verletzt' eine berechtigte Anwendung des Begriffes Energie darstellt.*"

[35]Reference 33, Letter [311], p. 166.

[36]Reference 34, p. 27.

[37]Reference 15, p. 289.

[38]Reference 15, p. 292.

[39]Reference 15, p. 292.

[40]In his Solvay report, pp. 301–302, Heisenberg shows that charge exchange is equivalent to space and spin exchange, hence Majorana's exchange force is equivalent to space exchange alone. Majorana's paper is Ref. 16. Also E. Majorana, Ric. Sci. **4**, 559 (1933). Majorana's ideas on nuclear physics appear to have been well formed before he went to Leipzig to work with Heisenberg on a fellowship in January 1933, but he was reluctant to publish them until Heisenberg encouraged him to do so. More details will be found in E. Amaldi, in *Strong and Weak Interactions: Present Problems*, edited by A. Zichichi (Academic, New York, 1966), pp. 10–77.

[41]That is, since the deuteron has spin-1, a third nucleon of either charge could not be in the same space wavefunction and exchange its charge with the original constituents, as that would violate the Pauli exclusion principle. With Majorana's force, this closure occurs for ^{4}He, but not for ^{2}H.

[42]See Ref. 15, pp. 303–304. At present, nuclear saturation is believed to come about mainly due to short-range repulsive forces between nucleons.

[43]Accounts of the historical development of Fermi's theory of β decay have been given by W. Pauli, in *Aufsätze und Vorträge uber Physik und Erkenntnistheorie*, edited by V. F. Weisskopf (Ft. Vieweg, Braunschweig, 1961), pp. 156–180; F. Rasetti, in *Enrico Fermi: Collected Papers, Vol. I*, edited by E. Segrè *et al.* (University of Chicago Press and Accademia Nazionale dei Lincei, Chicago and Rome, 1962), pp. 538–540. See also, E. Segrè, in *Nuclear Physics in Retrospect*, edited by R. H. Stuewer (University of Minnesota Press, Minneapolis, 1979), pp. 33–62.

[44]Reference 33, Letter [259], pp. 39–40.

[45]The translation of the quote is: "The electrons in nuclei are really quite analogous to the absorbed photons, the emission of a β electron being parallel to the birth of a new particle, which in the state of absorption has no individuality." C. R. (Paris) **195**, 439 1932.

[46]E. Segrè, in *Enrico Fermi: Collected Papers I*, quoted in Ref. 43, p. 328. See also E. Segrè, *Enrico Fermi, Physicist* (University of Chicago Press, Chicago 1970).

[47]See E. Fermi, *Nature* **125**, 16 (1930). He continued to publish papers on this subject until 1933.

[48]In the winter of 1930 to 1931, Fermi started "as a first task the construction and operation of a cloud chamber, with the help of E. Amaldi" (F. Rasetti, Ref. 43, p. 548). Due to inadequate workshops in the Rome institute, the project failed. Rasetti, another of Fermi's associates, was sent in the fall of 1931 to Lise Meitner at Berlin to learn nuclear physics techniques (such as cloud chamber and counter methods that could eventually be used to detect neutrons). After his return, the Rome physicists constructed a well-working cloud chamber and a gamma-ray crystal spectrometer (Fall 1932).

[49]Actually Fermi began to study the topic in the winter 1928–1929 by reading Dirac's fundamental papers of 1927 on the theory of radiation. He submitted the first paper in March 1929 [E. Fermi, Rend. Accad. Lincei **5**, 881 (1929)], delivered the first lecture course in April 1929 at the Institut Henri Poincaré in Paris, and, in a more complete form, during the summer of 1930 at the Summer School of Theoretical Physics at Ann Arbor, Michigan. Out of these lectures grew his well-known review article, E. Fermi, Rev. Mod. Phys. **4**, 87 (1932).

[50]For the story of Pauli's Pasadena talk and Goudsmit's Rome report on it, see L. M. Brown, Ref. 1, pp. 24–25.

[51]Pauli, quoted in Ref. 43, p. 161.

[52]See. E. Fermi, Ric. Sci. Parte 2 **3**, 101 (1932), and his similar report read on 7 July 1932 at the *V^e Congrès International d' Electricité* in Paris.

[53]Pauli's neutral particle was still called *neutron* ("neutrone") by Fermi at the time of the Paris Conference, although he remarked then that it differed from the neutron of Chadwick (see F. Rasetti, quoted in Ref. 43, p. 488). However, Fermi renamed Pauli's particle "neutrino" in his Rome seminars, in order to distinguish it from the heavy neutron. (See Pauli, Ref. 43, p. 162).

[54]Although Fermi had successfully handled problems of quantum electrodynamics, he avoided the methods proposed about 6 years earlier by P. Jordan and O. Klein. His friends even claimed later: "Apparently he had some difficulty with the Dirac–Jordan–Klein method of the second quantization of fields, but eventually also mastered that technique and considered a beta-decay theory as a good exercise on the use of creation and destruction operators." (F. Rasetti, Ref. 43, p. 539.)

[55]F. Rasetti, Ref. 43, p. 540.

[56]E. Fermi, Ric. Sci. Parte 2 **4**, 491–495 (1933).

[57]E. Fermi, Ref. 56, p. 492.

[58]E. Fermi, Nuovo Cimento **11**, 1 (1934); Z. Phys. **88**, 161 (1934).