Yukawa’s Prediction of the Meson

by

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1. Introduction

In October 1934, at a meeting of the Osaka Branch of the Physico-Mathematical Society of Japan, Hideki Yukawa proposed a new theory of nuclear forces involving the exchange between neutron and proton of an electrically charged “heavy quantum”. Yukawa’s theory is known today as the meson theory of nuclear forces and his “heavy quantum” is called the meson. The theory provided a fundamental explanation for the charge-exchange nuclear force that Werner Heisenberg had proposed in 1932 and had associated with the exchange of an electron between a neutron and a proton. In the same paper Yukawa suggested an alternative form of Enrico Fermi’s beta-decay theory and showed that the two forms were phenomenologically equivalent in the treatment of nuclear beta decay, although Yukawa used the meson as an intermediary in beta decay and clearly distinguished the “strong” nuclear binding force from the “weak” force responsible for radioactive beta decay.

Yukawa’s meson thus played a dual role: it carried energy, momentum, and electric charge between neutron and proton, producing a strong nuclear force, and it decayed weakly (i.e., with small probability) into electron and antineutrino, or positron and neutrino, providing a mechanism for nuclear beta decay. Yukawa showed that mesons would never be emitted in ordinary nuclear transformations (radioactive decays and low-energy nuclear reactions), but that they could materialize in nuclear processes involving sufficient energy release, such as those occurring in the interactions of cosmic rays. Produced this way, the mesons would either be absorbed by matter, or they would themselves decay by the beta-decay process.

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The meson theory, therefore, predicted the existence of a new type of elementary particle with well-defined observable properties, a particle which could be produced in a free state only in a regime of much higher energy than was available in the nuclear laboratory at that time. Yukawa's work thus went beyond the theory of nuclear forces and directed attention toward the field of high energy, or elementary particle, physics, which has ever since been on the leading edge of fundamental physics.

In treating the emission of electron and neutrino, Yukawa followed Fermi's lead and used the method of "second quantization," but his first treatment of the strong nuclear binding force was built as an analogy to the semi-classical electromagnetic theory. In this version of meson theory, protons and neutrons interact by means of "classical" but charge-carrying, meson fields. The nuclear force arises from the exchange of mesons between non-relativistic protons and neutrons in the same manner as the electrostatic Coulomb force arises from the exchange of light quanta between slowly moving charges. Soon, however, Yukawa and his collaborators formulated meson theory as a completely quantized field theory, about the same time that others, outside of Japan, took notice of Yukawa's work.

The article in which Yukawa proposed the meson is remarkable for its simplicity, effectiveness, and comprehensiveness, although it was the first original published work of a young physicist educated entirely in Japan, where up to that time little research in modern physics had been done. His was the most fundamental scientific work of modern times to be accomplished by an Oriental. Yukawa's Nobel Prize of 1949 was only the second awarded to an Asian scientist (after Raman, of India) and the first to be awarded to a Japanese.

The theory, published in February of 1935, went unnoticed for more than two years, until observational evidence for particles of intermediate mass in the cosmic rays began to be compelling. In July of 1937 Yukawa suggested that "at least a part of the penetrating component" consisted of mesons. After noting several properties of the new particles that agreed with those predicted for the meson, he concluded: "this suggestion will not be altogether meaningless as a possible explanation for the hard component of the cosmic ray, since there seems to be no alternative for the time being."

The cosmic ray particles of intermediate mass that first excited
World-wide interest in the meson theory were not, in fact, the mesons of Yukawa. They turned out to be charged particles of half-integral spin and to interact only weakly with nucleons. Resembling heavy electrons in most respects, these particles (positive and negative) are now called muons. More than a decade was to elapse before the true discovery of the meson and the identification of the muon as one of its possible decay products; meanwhile, it was generally assumed that the meson of Yukawa had been observed.12

The misidentification of the muon as the meson responsible for both nuclear forces and nuclear beta decay, as it was thought, greatly encouraged the development of meson theory.13 Many variants of the theory were proposed and investigated in the attempt to reconcile the properties of the meson needed for nuclear forces with the observed properties of the muon. In recalling this period, Oppenheimer was to say, “All of this, of course, later turned out to be nonsense. No one had ever predicted these cosmic-ray mesons. No one knew what they were; no one understands their existence today; no one has a good argument as to why they should exist, nor have the properties they have”14 and Hans Bethe wrote in 1954 that “The history of the subject of mesons and nuclear forces is an example... of both the wisdom and the folly of scientists.”15 Although it may be true that the meson theory of nuclear forces gave “no serious quantitative results for about twenty years”,16 there is little doubt that it led to important progress in the study of elementary particles, the cosmic rays, the quantum field theory, as well as providing at least a qualitative understanding of the nuclear force. The remarks of Bethe and Oppenheimer reveal the scientist’s impatience at the pace of discovery and its application, but they lack historical insight.

Even for some time after the experimental discoveries of the neutron and the positron in 1932 the term elementary particle meant something external and immutable — a primordial atom. During the 1920’s and early 1930’s every effort was made to construct theoretically all matter, including the nucleus, out of just two elements, the electron and the proton, often referred to simply as negative and positive electricity. However, when Heisenberg began to realize that his “composite” neutron behaved very much like the “elementary” proton, the groundwork was laid for a thorough revision of the concept elementary. Likewise, the ghostly hole in the “sea” of negative
energy electrons, Dirac’s positron, was found to be as substantial as its sister electron. Yukawa’s heavy quantum was never a hole, but a massive charged particle that could be created singly (like a photon); its virtual creation and subsequent annihilation was the mechanism of the nuclear force—a further significant modification of the traditional particle conception.

The present article began its life as an analysis of the nuclear force problem in the early 1930’s and of Yukawa’s theoretical proposal for its solution. As I came to realize the scope of Yukawa’s originality and was struck by the failure of his brilliant seniors and contemporaries in the West to arrive at any comparable solution, I began to ask what cultural determinants (whether social, psychological, philosophical, or esthetic) might have played a role either in Yukawa’s achievement or his counterparts’ lack of the same. This was unfamiliar ground to me, as it would be for other natural scientists or some historians of science.

This cultural puzzle (how young Yukawa could find a solution that evaded Bohr, Heisenberg, Pauli, Fermi—not to mention Bethe, Peierls, et al.) suggested another. Why did these same physicists so rapidly become true believers in the meson theory, following the discovery of the muon in 1937? And it was, after all, not even the right particle.

My treatment alternates between the physics and the persons and institutions that made it. Sections 2 and 3 are concerned with Yukawa’s family, schooling, and early cultural influences, and with his perception of the important problems of physics when he graduated from Kyoto University in 1929 and began research. Sections 4 and 5 are, respectively, studies of Heisenberg’s papers on nuclear structure and Fermi’s theory of $\beta$ decay. Section 6 follows Yukawa to his position as Lecturer at the new Science Faculty of Osaka University, his contact with nuclear experimentalists there, the beginning of elementary particle research in Japan, and the gradual emergence of the idea of the meson theory of nuclear forces.

In Sections 7 and 8 I draw out the physical and mathematical content of Yukawa’s first meson article: the meson is an intermediary, or virtual particle, in both strong and weak nuclear interactions; it is predicted to be an observable radioactive constituent of the cosmic rays. Section 9 considers “the meaning of the meson,” as an illustration of a new methodology in elementary particle physics; as a case
study about a "scientifically developing" country; as an example of social and psychological inhibition or stimulation. The rapid acceptance of the meson theory after the cosmic ray discovery of the muon is discussed briefly in Section 10. Appendix I lists some standard as well as some unusual sources; Appendix II is an English translation of Yukawa's first publication, the introduction to his Japanese translation of Heisenberg's papers on nuclear structure.

2. The traveler sets out

Hideki Yukawa was born in Tokyo on January 23, 1907. A year later he moved with his family to Kyoto when his father, Takuji Ogawa, left a staff position in Tokyo with the Bureau of Geological Survey to become Professor of Geography at Kyoto University. It was in this ancient capital and center of Japanese culture, therefore, that Yukawa grew up and received his schooling.

The autobiography of Yukawa's early years, The Traveler, conveys some of the flavor of his Kyoto childhood. The family was a large one, as there were seven children (Hideki being the fifth), the parents, and three grandparents living together. Hideki's mother, Koyuki, ran the household and spent nearly all of her time serving the family. Yukawa remembers her as hard-working and enjoying few pleasures aside from the joy she took in her children. His father, a busy professor, dressed formally and each day was brought to the University in a jinrickshaw.

A strong tradition of learning on both sides of Yukawa's family was transmitted to Hideki and his brothers. Takuji Ogawa was the second son of a Confucian scholar, Nanmei Asai, who had taught in a school for the sons of the samurai of Tanabé-han (a feudal clan). After the Meiji Restoration of 1868 and the formal abolition of the samurai class, he opened his own private school in the country. Yukawa's maternal grandfather, Komakitsu Ogawa, had himself been a samurai serving at the Tokugawa Castle in Wakayama; he later went to Tokyo and graduated from the college Keio Gijuku (now Keio University); then he became a school principal, and eventually a bank director.

Takuji Ogawa received at home from his father the traditional classical education of a samurai; he also attended the Junior High School
at Wakayama, and at seventeen he went to Tokyo to study English and to obtain a modern education. In October 1892, on a trip to Nagoya, he witnessed the immediate aftermath of a powerful earthquake and this, together with his love for the mountains and the seashore, helped fix his interest in geology. He became an important man in this field and in 1901, at the age of thirty-one, he was the youngest of the Japanese representatives who were sent to the International Exposition and Geological Conference held in Paris. He stayed in Europe for more than a year before returning to Japan. A few years later, on the eve of the Russo-Japanese War, he spent a year in China as one of six scientists making a survey of mineral resources.

Yukawa stresses the catholicity and breadth of his father's interests: "Although my father's field was geology and geography, he was a man of a great many interests, which included archeology, Chinese studies, art, swords, chess, etc. As a consequence, not only his study, but also the storage house and the living rooms of our home literally overflowed with books . . . Being in this kind of atmosphere, I naturally grew up to like books and to read omnivorously . . . probably it contributed a great deal to the fact that my life has been devoted mainly to reading, thinking, and writing."20

A many-sided cosmopolitanism characterized Yukawa's father, and even his grandfathers.21 In various essays and speeches,22 Yukawa liked to point out that it consisted of Western science and technology superposed upon a Japanese culture that was itself a complex mixture of various East Asian currents: Buddhism from India, transmitted via China and Korea, with other Chinese elements (e.g., Confucianism), as well as the indigenous Shinto tradition. By the twentieth century, the result was a heady sort of creative confusion.23

Yukawa's father was of the same sturdy generation as Hantaro Nagaoka, Japan's most famous physicist of the pre-quantum era. When Nagaoka's father returned from a trip to the West, he apologized to his eight year old son for having "misled" him up to that point by teaching him the wrong subjects.24 Nagaoka himself, whose work on atomic models attracted the attention of the Cambridge school and Ernest Rutherford, and who became an authority on spectroscopy, geophysics, and other subjects, said on one occasion that "there was no point . . . to be born a man, if I failed to enter the advanced ranks of researchers and to contribute to the development
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of some field of learning.” Nagaoka was an important role model: late in life Yukawa said that “probably the one decisive factor” to set him on the path of physics research, when he was still in high school, was that “one could find among the Japanese ahead of one such a great physicist.” In 1933, when Yukawa was appointed to his first job as Lecturer at Osaka University, Hantaro Nagaoka was its President. He exercised little direct scientific influence on Yukawa, however; while sympathetic to quantum mechanics, he was not able to master it in a technical sense.

Before deciding to be a physicist, Nagaoka had hesitated:

...wanted to know whether any Oriental had ever succeeded in research in natural science. I wanted to be sure that any Oriental could have anything to gain by doing research, or whether we were dependent upon Europeans.

Then he discovered that the Chinese had kept accurate records of eclipses, and that Chinese documents 2000 years old mention meteors and auroral phenomena:

Thus I found that in the past China was often far ahead of Europe... I finally decided on a career in physics after learning about the Oriental contributions to science.

At the age of five or six, even before he started school, Hideki began to study the Chinese classics with his grandfather. The method of instruction, called sodoku, consisted of reading the Chinese characters (kanji) aloud in Japanese pronunciation, without attending to the meaning of the text. Yukawa says: “Each kanji held a secret world of its own; many kanji made a line and several lines made a page. Then that page became a frightening wall to me as a boy; it was like an enormous mountain that one had to climb.” The beloved grandfather sat across the table and pointed to the kanji with a stick. Yukawa said, “I was even afraid of the stick in my grandfather's hand.” This training was not usual in Yukawa’s day, although it had been a part of traditional samurai upbringing. Probably all of the first generation of physicists came from samurai families and thus shared a strong background in Chinese studies; Chinese was “the Latin of East Asia”, the traditional vehicle of learned discourse.

Yukawa remembers his mother as very kind and attentive, often reading to the children. In the afternoons sweets were brought from a
neighborhood shop. However, many innocent games and entertain-
ments were forbidden as time-wasting. A tutor came to the house to
give instruction in calligraphy and this Hideki considered as tedious as
the *sodoku*. But the memorization of *kanji* turned out to have its
positive side when Yukawa began school, because he learned to read
very quickly and became an avid reader, especially of imaginative
literature.

His reading included many Japanese and Western classics, French
and German novels, as well as Turgenev, Tolstoi, and especially Dos-
toievski (in translation). Among the Japanese authors he mentions
Soseki, whose 1908 novel, *Sanshiro*, concerns a lad from the provinces
who is attending Tokyo Imperial University. At a gathering of stu-
dents, one of them makes a public speech along these lines:

> We, the youth, can no longer endure the oppression of the old Japan. Simultaneously, we
live in circumstances that compel us to announce to the world that we, the youth, can no
longer endure the new oppression from the West. In society, and in literature as well, the
new oppression from the West is just as painful to us, the young men of the new age, as is
the oppression of the old Japan.

As a boy, Yukawa says, he showed no indication of becoming a physi-
cist, but was deeply interested in literature. When he did become a
physicist, though, his attitudes were probably influenced by his early
reading, which was liberal and which encouraged originality.

Yukawa was shy, quiet and reticent, both as a child and throughout
his later life. Sometimes this took an extreme form, so that his public
lectures became almost inaudible. In *The Traveler* he contrasts his
personality with his father's in this way: "Theoretical physics, simply
stated, is a science that tries to find the things hidden at the root of the
Universe, and is actually very close to philosophy. Geology, on the
other hand, must live closely with natural phenomena. Our choice of
careers shows the difference in temperament between father and
son." On one occasion his father suggested a period of study abroad,
in which Hideki had no interest. He says, "I never felt any yearning
for foreign countries, but I never said how I felt out loud. I could not
speak in front of my father because I was afraid of him." And in
another place he remarks, "At times the silence was itself an act of
insubordination to my father. So I was not basically timid. I began to
feel antagonistic toward Confucianism." In fact his first grade teacher
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wrote of him: "has a strong ego and is firm of mind." So his quietness was more akin to rebellion than to timidity. In later years this personality was strong enough to reject the dicta of Niels Bohr and Werner Heisenberg and to find a new approach to the problem of nuclear forces.

In adolescent search for life's meaning, Yukawa discovered the writings of the Taoist sages Laozi, Chuangzi, and later Mote. These authors, unlike Confucius, placed nature, not man, at the center of the universe. "Their is a type of fatalistic naturalism very much like that to which the scientific view of nature may ultimately lead."29 Yukawa, partly in rebellion, was thus attracted to a style of thinking that was materialist and dialectical, but that was still very different from the dialectical materialism of Karl Marx and Friederich Engels that strongly influenced his first students and collaborators.30 When asked about Yukawa's philosophy recently, Mituo Taketani responded "Well Yukawa is a genius-type, and so he has his own philosophy." Although philosophically inclined, and although interested in hearing about Marxist philosophy and Taketani's own methodology of science, Yukawa says little about the latter subjects in his essays, public talks, and dialogues.

In 1923 Yukawa entered the Third High School of Kyoto, an institution more like a German Gymnasium or French lycée than an American high school. Only eight high schools then existed in all Japan; to obtain admission as a student was difficult. His outside reading at this time was directed toward philosophy, especially the philosophy of science, and he read books by popularizers of science, especially Jun Ishiwhara.31 Einstein's visit to Japan in 1922 (during which he learned that he had won the Nobel Prize in Physics for 1921) further stimulated Yukawa's interest in physics. The visit, treated as a great public event, impressed many of Yukawa's generation.

As Yukawa searched through bookstores for practice material for his second foreign language, German (his first was English), he discovered the first volume of Max Planck's Introduction to Theoretical Physics. Delighted to find that he could understand both the German and the physics, this experience helped to resolve his future career. He took and passed the entrance examination of the Department of Physics of Kyoto University and began his studies there in 1926.

One of his classmates at the Third High School, who also went to
Kyoto University to study physics, was Sin-itiro Tomonaga, the son of a philosophy professor at the University. In their third and final year as undergraduates, Tomonaga and Yukawa helped each other to learn quantum mechanics; after graduation they stayed on together for several years as unpaid “assistants” at the Physics Department. (Yukawa says, “The Depression had made scholars.”) In 1932 Tomonaga moved to Tokyo to join the group of Yoshio Nishina at the Institute for Physical and Chemical Research, a private research foundation, while Yukawa remained at Kyoto University as Lecturer of Physics. Tomonaga shared the Nobel Prize for Physics in 1965 with Julian Schwinger and Richard P. Feynman “for their fundamental work in quantum electrodynamics.” In *Tabi-bitō* Yukawa contrasts himself as a stubborn person who tends “to go too far” without enough thinking, with Tomonaga, who was more controlled: “a person aware of the limits, who yet comes up with clever ideas.”

None of the professors at Kyoto understood quantum mechanics well enough to lecture on it (with the possible exception of the astronomer Toshima Araki), but Masaji Kimura invited a young German, Otto Laporte. Then Arnold Sommerfeld, Laporte’s teacher, came to Kyoto to lecture, followed by Paul A. M. Dirac and Werner Heisenberg; and then there were lectures by the Japanese physicists Bunsaku Arakatsu, Yoshikatsu Sugiura, and Yoshio Nishina, all of whom had studied abroad. Yukawa said, “I felt as if I had been entrusted with the task of nurturing the bud of new physics which they had planted in me.”

During his second year at the University (1927–28), he spent all of his spare time in the physics library ignoring, he said, all the old books on the shelves, but reading eagerly the recent issues of the foreign journals, especially those in German. After “nibbling” at a variety of papers on quantum mechanics, he began the systematic study of Erwin Schrödinger’s papers. He realized that these papers emphasize the continuity of nature (in the form of the wave function), in contrast to Max Born’s *Mechanics of the Atom*, read the previous year, which stressed the discontinuity of the quantum jumps. The young scholar saw the need for unifying these two views, a task that was soon to be accomplished by Schrödinger and by Dirac.

In the third year Yukawa did experimental work in spectroscopy in the laboratory of Professor Kimura, but although he found the work
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fascinating he elected to do a theoretical undergraduate thesis. "Desperately trying to reach the front line of physics," he became afraid that he might be too late to make a significant contribution. Still, he noted that there remained the problem of relativistic quantum mechanics.

A great step toward a consistent theory combining quantum mechanics with the restricted theory of relativity, although not the complete solution, was made by Dirac in 1928. His theory had as one consequence the existence of states of negative energy (negative mass), which appeared to be meaningless. Nevertheless, the theory was highly respected for its originality. It was on the Dirac equation that Yukawa did his undergraduate thesis, and although he contributed nothing original to the subject in his work, it is significant that he chose that difficult and controversial problem to study. After this he remained at Kyoto, working in the research group of Professor Kajuro Tamaki, as did his colleague Tomonaga. Tamaki's special fields of interest were classical mechanics, relativity, and musical acoustics.

3. Beware of nuclear electrons!

In 1974 Yukawa gave a lecture in which he discussed the natural philosophy that prevailed when he graduated from Kyoto University:

At this period the atomic nucleus was inconsistency itself, quite inexplicable. And why? -- because our concept of elementary particle was too narrow. There was no such word in Japanese and we used the English word -- it meant proton and electron. From somewhere had come a divine message forbidding us to think about any other particle. To think outside of these limits (except for the photon) was to be arrogant, not to fear the wrath of the gods. It was because the concept that matter continues forever had been a tradition since the times of Democritus and Epicurus. To think about creation of particles other than photons was suspect, and there was a strong inhibition of such thoughts that was almost unconscious.

In the same lecture he stressed the inadequacy of the proton-electron nuclear model, evidenced by the notorious violation of the spin and statistics theorem of quantum mechanics. For example, in the proton-electron model, the nitrogen-14 nucleus would contain 14 protons and 7 electrons, or 21 fermions; yet the molecular spectrum of nit-
rogen gas showed that it behaved as though it contained an even number of fermions. Before a satisfactory quantum mechanical model of the nucleus could be formulated, it was essential to remove the electrons from the nucleus. In retrospect, all nuclear theorists agree, and Hans Bethe adds: "Regardless of the particular difficulties with spin and statistics, it would have been impossible for anybody to do a quantum mechanics of a nucleus composed of protons and electrons." 36

Aside from the problem of understanding the nucleus, the other major challenge to theoretical physics, as seen by young Yukawa, was to make a theory of photons interacting with electrons in a relativistically self-consistent way. Heisenberg and Pauli had already attempted to make such a quantum electrodynamics, 37 but they discovered that the value predicted by the theory for the electromagnetic mass of the electron was infinite! The theory, therefore, was either not complete or not correct, and its other predictions were accordingly put in doubt. Yukawa likes to refer to the problem of relativistic quantum field theory as a "settling of accounts". By this he means that after reaping the great rewards of quantum theory in treating non-relativistic mechanical systems (atoms, molecules, and crystals), theoretical physics was morally obliged to try to solve that old puzzle of the quantum theory: the wave-particle duality of the photon.

The leading theorists of the day were prepared to accept quite radical hypotheses in order to solve the nuclear problem. Indeed, it seemed that at the nuclear scale of distance (the same as that at which H. A. Lorentz had, early in the century, predicted a breakdown in electromagnetic theory), the triumphant revolution of quantum mechanics was about to be repeated, and that a new fundamental generalization of dynamics might be realized. Bohr attributed the peculiarities of beta decay to a failure of energy conservation; Heisenberg sought to introduce a new fundamental constant, a quantum of length to characterize the nuclear region. 38

Yukawa chose a problem in spectroscopy, the inexhaustible testing ground for quantum theory, for his first theoretical research after graduation. He had written on Dirac's electron theory for his senior thesis and knew that the theory gave correctly the fine structure of the spectral lines of hydrogen, an effect that Sommerfeld had earlier been able to account for as a relativistic "correction" to the Bohr
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Yukawa's idea was to calculate an additional very small splitting of the atomic spectral lines, called hyperfine structure, that corresponds to the energy difference of an electron taking one or the other of its two allowed orientations in the magnetic field of the nucleus.

This splitting is largest for electrons that approach the nucleus most closely, the so-called s-electrons, and these are also the "most relativistic" ones. Thus hyperfine structure tests quantum theory for electrons near the nucleus and for large electron velocities; while it can be handled by the methods of atomic physics, it probes at the same time the nucleus and the relativistic unknown. Yukawa presented the finished manuscript of his work to Professor Tamaki, who locked it in his office safe, saying he would examine it "when he had time".

A few months later, an article on the same subject by Enrico Fermi appeared in Zeitschrift für Physik. It covered the same ground and was much better done, as Yukawa later ruefully admitted.

In the spring of 1931, Yoshio Nishina (1890–1951) of the Institute of Physical and Chemical Research (IPCR) of Tokyo lectured on quantum mechanics at the University of Kyoto. The lectures were intended for the professional staff rather than students, and they consisted of an introduction to Heisenberg's Die physikalischen Prinzipien der Quantenmechanik (1930). In the discussion period, Yukawa and Tomonaga raised most of the questions.

Nishina is generally regarded as the father of nuclear and cosmic ray physics in Japan. A graduate in Electrical Engineering of Tokyo University, he joined IPCR one year after it was founded in 1917, with H. I. H. Prince Fushimi at the head of its distinguished Board of Trustees. After several years he was sent abroad for further study and research: one year at the Cavendish Laboratory in Cambridge, England, one year at Gottingen, and six years at Copenhagen with Niels Bohr, where he wrote a famous theoretical paper with the Swedish physicist Oskar Klein on the rate and angular distribution of Compton scattering, using Dirac's theories of the electron and of quantum electrodynamics. Returning to Japan in 1928, he began to build the Nishina Group at IPCR in Tokyo, primarily to do research in nuclear physics.

The lectures at Kyoto and, perhaps to a greater extent, the social
contact with Nishina, transformed Yukawa. Sakata, who was a relative of Nishina by marriage, often visited him and was introduced on one occasion to both Yukawa and Tomonaga when the two were having intense discussions with Nishina on nuclear physics. "Professor Nishina's lectures were not just explanations of quantum physics", Yukawa said, "for he carried with him the spirit of Copenhagen, the spirit of that leading group of theoretical physicists with Niels Bohr as its center." Furthermore, Nishina's personality put Yukawa at ease; usually silent and withdrawn, he found that he could talk easily with the older man. "My solitary mind, my closed mind, began to open in the hands of Doctor Nishina".

The year 1932 was a turbulent one for Hideki Ogawa. In that year he married Sumi Yukawa, took her family name, and went to live in her family's home in the brash, crowded, busy city of Osaka, a commercial seaport very different from his own restrained and traditional Kyoto. He was appointed an instructor in the University of Kyoto and asked to lecture on quantum mechanics. To the shy young man, who still wore the short-cropped hair and the school uniform of a student, so many changes were bound to be upsetting. Among those attending his first lectures were Shoichi Sakata and Minoru Kobayasi, followed the next year by Mituo Taketani. These three later became collaborators of Yukawa in the work on the meson theory that followed the discovery of the cosmic ray meson (the muon) in 1937.

As Yukawa points out in his autobiography, 1932 was even more turbulent for nuclear physics than it was for his personal life. That year saw the discoveries of the neutron and the positron, as well as the disintegration of nuclei by artificially accelerated protons (and even by deuterons, discovered that very year). Yukawa became aware of the opportunity to make a truly significant contribution to physics. For this reason, the next two years were the most difficult, and at the same time, the most satisfying of his life.

Before the discovery of the neutron brought about the possibility of making a nuclear model without electrons, Yukawa was having the same difficulty as other more mature physicists in understanding the nucleus. He studied "what was probably the only organized book on the theory of the nucleus at that time", George Gamow's *Constitution of Atomic Nuclei and Radioactivity* (1931). In Gamow's book many discussions dealt with properties of "nuclear electrons", and
these passages were always set off between special signs (intended to be skull and crossbones originally) to remind the reader that the content was speculative, and possibly incorrect.

One such passage deals with the nuclear beta decay process, in which electrons appear to emerge directly from the nucleus. (Could there be a better proof that the nucleus contained electrons?) However, Gamow says,

These results lead us to a very strange conclusion. Since there is no process compensating for the difference of energy lost by different nuclei of the same element in the ejection of a $\beta$-particle, we must deduce, according to the principle of conservation of energy, that the internal energy of a given nucleus can take any value within a certain continuous range. This . . . however, has not the slightest effect before or after the $\beta$-emission . . . there is no trace of a continuous distribution of energy in the emission of $\alpha$-particles or $\gamma$-rays. In these processes all the nuclei seem to be again identical.

Perhaps, Gamow concludes, “as was pointed out by N. Bohr, we must reckon with the possibility that the continuous distribution of energy among the nuclei is fundamentally not observable, or, in other words, has no meaning in the description of the physical processes . . . This would mean that the idea of energy and its conservation fails in dealing with processes involving the emission or capture of nuclear electrons.”

It is important to realize that although Pauli had begun to suggest the possible existence of a neutrino (he called it “neutron”) by the end of 1930, he did so very cautiously and without publishing it. In his “Ancient History of Beta Decay”, Yukawa says that he was unaware of Pauli’s thinking on beta decay, but knew Bohr’s ideas. “Hastily gathering the papers from the 1931 International Conference on Nuclear Physics, held in Rome, I noted quite a few papers in Italian, but fortunately Bohr’s papers were in English: it was strange to put electrons in something as small as the nucleus, even with quantum mechanics, but an electron must be there. However, it may behave in a completely different manner; even the law of conservation of energy does not survive . . .”
4. Heisenberg’s papers on nuclear structure

Although few theorists doubted by the end of 1934 that electrons should be strictly excluded from the nucleus,46 this was far from clear to Heisenberg when he wrote his nuclear structure papers in 1932; on the contrary, it became the common view of physicists only after Fermi’s publication of his theory of nuclear beta decay, according to which electrons or positrons that come out of the nucleus are created, together with neutrinos, as they emerge.

Iwanenko had proposed a neutron-proton nuclear model even before Heisenberg, and was also probably the first to suggest (at least in print) that beta-decay electrons are born at their moment of emission.47 “Heisenberg”, says Peierls, “took a very complicated view”, and offers these direct quotations: “The disintegration experiments permit us to regard . . . the neutron as an immutable elementary particle”, but “the heavy nuclei . . . include β-emitters and, on the assumption of immutable neutrons, would also have to contain electrons.” Heisenberg’s complicated views are also attested to by Bromberg, who discussed them personally with Heisenberg in 1970. She concluded that Heisenberg had believed “the neutron seemed to be elementary as well as complex.” Heisenberg himself recalled

...we had an unclear feeling that the neutron somehow can be considered as consisting of proton and electron, but also somehow not.48

The confusion that still surrounds Heisenberg’s papers comes from his attempt to combine two immiscible theories. One was an essentially correct theory (though requiring substantial modification) of nuclear structure; the other was an essentially incorrect theory of neutron structure. The former, in its purely phenomenological aspect, treated the neutron as an elementary particle of spin one-half, of small magnetic moment, obeying Fermi-Dirac statistics, etc.; the latter, a fundamental theory of the neutron, treated it incorrectly as a proton-electron compound.

Aside from the natural wish to account for the existence of the neutron and the apparent need, at some level, to include electrons in the nucleus to allow for beta decay, there were two physical effects that seemed to require a composite neutron. One was the “anomalous absorption” of hard gamma rays, while the other had to do with
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cosmic ray electrons. The processes are mentioned by Heisenberg at the end of his first paper on nuclear structure, where he says that his theory does not hold for them:

Such phenomena are the Meitner-Hupfeld effect, the scattering of γ-rays on nuclei; further all experiments which split neutrons into protons and electrons (an example is the stopping of cosmic ray electrons on their passage through nuclei). For the discussion of such experiments we have to investigate more precisely all the fundamental difficulties that appear in the continuous β-ray spectra.49

These effects are discussed in Parts II and III in terms of a composite neutron, and one even finds the statement in Part III that alpha particles must be made, not of protons and neutrons, but of protons and electrons, in order that they have the large polarizability required to explain the gamma ray phenomena.50 In fact, the high energy processes mentioned turned out to involve electromagnetic shower or cascade processes: photons converting into electron-positron pairs, subsequent annihilation of the positrons producing photons, and electron and positron deflection, likewise producing photons (Bremsstrahlung). These are all electromagnetic processes and in no way related to the continuous β-ray spectrum. We turn, therefore to the part of Heisenberg's work that concerns nuclear structure, the part generally conceded to have had lasting value.

Heisenberg sets out an admirable program: "to discuss the consequences of the assumption that atomic nuclei are built out of protons and neutrons without the collaboration of electrons",51 i.e., "loose" electrons, not bound in neutrons. This reduces the β-decay problem to the question of how the neutron in the nucleus decays into proton and electron; the nitrogen statistics problem becomes that of the statistics of the neutron; and most important of all, the structure of the nucleus itself is described by quantum mechanics in terms of the interaction forces between heavy (thus non-relativistic) nuclear particles.

Heisenberg inferred from experiment that the neutron has spin $\frac{1}{2}$ and that it obeys Fermi-Dirac statistics. These are properties of the proton as well, so that: "To interpret the neutron as composed of a proton and electron, one would have to ascribe to the electron Bose statistics and spin zero. However, it does not seem useful (zweckmässig) to consider this picture more closely." Rather, "the neutron
should be considered an independent fundamental particle that can, under appropriate circumstances, split into a proton and electron, whereby presumably the conservation laws of energy and momentum are no longer applicable.” The violation of these last conservation laws does not follow from Heisenberg’s picture, but is assumed in order to fit the β-decay observations, while angular momentum conservation and the spin-statistics theorem necessarily fail.

To build a quantum mechanical model of the nucleus, analogous to those for the atom, the molecule, and the crystal, Heisenberg constructs the Hamiltonian function of the nucleus, formulated as the sum of kinetic energy terms for each proton and neutron and interaction energies for each nucleon pair, but without electron coordinates appearing explicitly.

At this point, as a pure hypothesis, Heisenberg introduces a series of analogies drawn from molecular physics that result in his famous charge-exchange force. The strongest interaction, by analogy with the \( H_2^+ \)-ion, is supposed to be that between proton and neutron. In one picture of the \( H_2^+ \)-ion (which consists of two protons and an electron), the electron was associated in a quasi-atomic state, with one or the other proton alternately. In Heisenberg’s nuclear model, the analogue of that quasi-atomic state is the neutron, viewed as a closely bound state of a spinless electron obeying Bose statistics. However, he uses the resulting phenomenological form of the exchange force “without reducing it to electronic motions.”

The composite picture of the neutron leads to the introduction of an additional neutron-neutron force in analogy to the force in the neutral hydrogen molecule, where two protons share a pair of electrons. As in the molecular analogy, the neutron-neutron force is weaker than that between proton and neutron. Both of these nuclear exchange forces are expected to vanish beyond some distance like \( 10^{-12} \) cm. Since Heisenberg considers the proton fundamentally simple, he assumes only the basic Coulomb repulsion to act between protons. Finally, in order to complete the energy balance he adds a term to the Hamiltonian function to account for the mass difference between neutron and proton.

The Hamiltonian finally written by Heisenberg depends only upon the coordinates of the protons and neutrons, consisting of the usual space and spin coordinates and a new fifth one, \( \varphi \), to distinguish the
character “neutron” (with $\varrho = +1$) from “proton” (with $\varrho = -1$). Formally introducing a new space (later called “charge space”) and a $2 \times 2$ formalism analogous to Pauli’s spin matrices, Heisenberg’s $\varrho$-coordinate is the forerunner of the isospin formalism, prominent in modern nuclear and elementary particle physics. In Heisenberg’s nuclear structure papers, the new labels for proton and neutron are convenient for writing interaction terms that transform one of the nucleons into the other, but their use does not provide any new dynamical insight and is not necessary; Majorana, for example preferred to ignore these labels when he extended Heisenberg’s work.

Having written down a Hamiltonian function with five sets of terms (kinetic energies, proton-neutron exchange $J$, neutron-neutron exchange $K$, proton-proton Coulomb energy, and mass difference term), Heisenberg claims that the problem of nuclear structure has been reduced to a purely mathematical one, that of drawing out the content of the Hamiltonian function.

Even without detailed calculation, a rough qualitative picture of nuclear systematics emerges. The largest terms of the Hamiltonian, the kinetic energy and the charge-exchange $J$, are symmetric in neutrons and protons. Considering these terms alone, one would conclude that having equal numbers of neutrons and protons would be energetically favored, and would thus lead to greatest stability. On the other hand, the long-range repulsive Coulomb force between protons and the short-range weak attraction between neutrons both favor increasing numbers of neutrons for the stability of heavier nuclei, in accord with observation.

Heisenberg applied his Hamiltonian function to write a Schrödinger equation to describe the nucleus of recently discovered deuterium, the deuteron. This contains one proton and one neutron and so resembles, in essentials, the two-electron problem of atomic physics, typified by the helium atom. The normal state of the deuteron, that of lowest energy, has neutron and proton in the same orbital state, i.e., it is symmetric in the exchange of positions of the two nucleons. The spin function of the two nucleons can be either symmetric (spin one) or antisymmetric (spin zero), while the wave function, similarly, can be either symmetric or antisymmetric in the exchange of neutron-proton character ($\varrho$-coordinate). If the interaction potential $J$ is chosen to have the same sign as it has in the hydrogen-molecular ion, then the
deuteron spin must be zero, by extension of Pauli's exclusion principle to the nucleus. This prediction is false (though Heisenberg did not know it at the time), necessitating a choice of the opposite sign for $J$.\textsuperscript{55}

Heisenberg continues in Part I to show that the helium nucleus has “closed shells” of both protons and neutrons, and should thus be particularly stable. Structures containing only neutrons would be bound (by the attractive neutron-neutron force $K$), but not so strongly as structures having the same number of nucleons (i.e., isobars), some of them being protons. Thus the beta-decay process occurs in nuclei that are too “neutron-rich”, a neutron becoming a proton plus an electron. (Heisenberg does not accept Pauli’s neutrino at this stage.) As the positron had not been discovered at the time of Part I, he does not discuss the possibility of positron decay of “proton-rich” isotopes. Indeed, Heisenberg’s theory, in which the proton is not composite, provides no mechanism for it.

Part II of Heisenberg’s paper was sent from Ann Arbor, Michigan, in July of 1932, still before the positron discovery was announced in August. Again, his purpose is to determine “to what extent the fundamental difficulties in the theory of the nucleus can be reduced to the questions concerning the existence and properties of the neutron.” He points out that the stability of the neutron in scattering, together with its size, implies a very large binding energy of electron to proton, “of the order of $137 \text{mc}^2$ \text{[m is the electron mass]}, while the observed mass defect is about one hundred times smaller.”\textsuperscript{56} He concludes that the very existence of the neutron (as an electron-proton compound) contradicts quantum mechanics and so, making a virtue of necessity, argues that there is nothing wrong with considering it as a “fixed elementary particle in the nucleus.”

Part III reveals a new problem: Heisenberg’s charge-exchange force and/or an ordinary (non-exchange) neutron-proton force do not produce saturation. In other words, the model nucleus collapses with increase in particle number, and the binding energy increases proportional to the square of the number of nucleons, rather than linearly, as observed. Heisenberg reaches this conclusion from a statistical treatment of the nucleus (Fermi-Thomas model). His remedy is to introduce a repulsive core at short distances to the two-nucleon interaction potential.

Ordinary (i.e., non-exchange) forces between neutron and proton
were considered about the same time by Eugene Wigner, who also neglected the forces between like particles in the very light nuclei.\textsuperscript{57} Wigner explained that the very large binding energy per particle of the helium nucleus could be reconciled with the much smaller binding energy of the deuteron providing the nuclear potential well is taken to be deep, but narrow. The deuteron is weakly bound because its wave function spreads mostly outside of the well, while the wave function of the helium nucleus is “pulled in” by the larger number of attractive bonds, so that its nucleons spend a longer time, on the average, in the deep attractive well; this increases the binding energy per nucleon pair.

Majorana's modification of Heisenberg's Hamiltonian also deserves mention. Abandoning the latter's atomic physics analogies, Majorana considers a specific nuclear strong interaction force between elementary neutron and elementary proton, ignoring like-particle forces for the light nuclei. This force is chosen to produce a constant nuclear density, i.e., saturation, ruling out both ordinary and charge-exchange forces if only one kind of nuclear force is assumed. Majorana proposes a force of space-exchange character, but spin-independent, so that in the strongly bound helium nucleus both neutrons are attracted equally by each proton. (Heisenberg's charge exchange force is equivalent to a combined space and spin exchange.) Majorana's exchange force produces saturation without the need for introducing a repulsive interaction core.\textsuperscript{53} Eventually, however, both the spin-independence and the dominance of neutron-proton force had to be dropped.

5. Fermi's theory of beta decay

Heisenberg initiated the study of a nuclear model having protons and neutrons interacting in pairs according to non-relativistic quantum mechanics. He assumed the validity of the usual conservation laws in determining nuclear structure, but nevertheless denied their applicability to the structure of the neutron itself, or to processes, like beta decay, that seemed to be related to the neutron's structure. Thus in spite of the supposed analogy with molecular exchange forces, the strong nuclear forces introduced by Heisenberg (and Wigner, and Majorana) must be considered only phenomenological.

On the basis of strong forces of short range, and perhaps a repulsive
core interaction to achieve saturation, a reasonable picture of the nucleus emerged, yielding at least qualitative understanding of the tendency for nucleons to cluster into alpha particles within the nucleus, the nuclear energy level spectrum, and elastic and inelastic scattering by the nucleus of projectiles such as protons, neutrons, and alphas. No important conceptual problems remained with alpha and gamma radioactivity, but without introducing the neutrino (or its equivalent), it was impossible to construct a consistent theory of beta decay on the basis of any known form of quantum mechanics, relativistic or not. As long as beta decay was regarded as a process in which a single electron or positron emerged from the nucleus with a variable amount of energy, while the nucleus made a transition between definite quantum states, it was impossible to maintain the conservation of energy and momentum.

Nevertheless Heisenberg, like Bohr and others, rejected the neutrino; he failed even to mention it! Before admitting the possible existence of a new substance, a new elementary particle, he was willing to abandon even the hard-won conservation laws, considered by most physicists to be the very pillars of physical science. Bohr and Heisenberg, indeed, seemed to welcome the apparent failure of quantum mechanics, relativity, electrodynamics (and what else?) at nuclear dimensions, and hoped that it might lead to new conceptions of space, time, and causality — possibly to a new unification of natural philosophy.

While some who had made the modern quantum theory were plotting a second revolution, Enrico Fermi made a “tentative theory of beta rays” that conserved all the important dynamical quantities through the simultaneous creation and emission of a neutrino together with the beta decay electron. His theory complemented Heisenberg’s nuclear model; using both, the nucleus could be regarded as an entirely quantum mechanical system. Fermi assumed the existence of Pauli’s neutrino and allowed only protons and neutrons in the nucleus. Consequently electrons and neutrinos must be created when emitted; in this respect they resemble the photons emitted by an excited atom or nucleus.

A typical beta process involves the decay of a neutron into a proton plus electron plus neutrino. Fermi does not treat the decay of a free neutron, but of one bound in a nucleus. In order for a free neutron to
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decay, it must be more massive than a proton plus an electron, but at
the time that Fermi wrote his paper it was not even known that the
neutron was heavier than the proton alone.\(^5\) On the other hand, for a
neutron bound in a nucleus, and therefore interacting with the other
nucleons, the source of the decay energy is the difference of mass
between the parent and the daughter nucleus, of which the neutron-
proton mass difference is only a part. (For the same reason, *mutatis
mutandis*, the proton in a proton-rich nucleus can decay into a neutron
plus a positron plus a neutrino, even though the free proton is lighter
than the free neutron.)

The fundamental process of beta decay is thus described by Fermi
as one in which a neutron in the nucleus transforms into a proton, with
the simultaneous emission of an electron and a neutrino. In the re-
verse process, a proton transforms into a neutron upon the absorption
of an electron and a neutrino.\(^6\) The heavy particles, proton and
neutron, are characterized by Heisenberg's \(\rho\)–coordinate and treated
as different charge states of a single nucleon. As in Heisenberg's nu-
clear model, the heavy particles are constant in number and are de-
scribed by non-relativistic wave functions.

On the other hand, to deal with the variable number of light parti-
cles, it is necessary to use the method of quantum field theory which,
especially when it is used to describe spin \(1/2\) particles like electrons
and neutrinos, is often called "second quantization".\(^6\) This procedure
is analogous to the quantization of the classical Maxwell elec-
tromagnetic field that allows it to be represented by a collection of
identical elementary particles, the photons. However, in the case of
electrons, say, the "field" that is to be quantized is not really a classi-
cal field, but is the Dirac wave function that represents the first quan-
tization. (Hence the name "second quantization".) For the \(\beta\)-decay
electrons and the neutrinos, both the wave function theory and its
second quantized version must be relativistic. The field theory must
lead to the Pauli exclusion principle for the Dirac particles—not to the
symmetric (Bose-Einstein) statistics that light quanta obey.

It is curious that Fermi insists that his theory has no analogy to the
creation or disappearance of an electron-positron pair in Dirac's hole
theory, since (he argues) the latter processes can be interpreted "sim-
ply as a quantum jump of an electron between a state with negative
energy and a state with positive energy with conservation of the total
(infinitely large) number of electrons.” It is possible that Fermi was trying to draw a sharp distinction between his theory and that of Beck and Sitte\textsuperscript{62}, which \textit{did} make use of Dirac’s hole theory but implied a violation of energy conservation, since it assumed no neutrino. But the explanation may be simply that Fermi was not willing to regard electron and neutrino (unlike the case of proton and neutron) as different charge states of a single particle. He could have regarded electron-neutrino creation as the promotion of a negative energy neutral neutrino to a positive energy negatively charged electron, leaving behind a neutral antineutrino (hole in the neutrino “sea”). He does not mention the antineutrino (although it is implicit in his theory) or neutrino holes, which Gian Carlo Wick introduced in applying Fermi’s theory to positron emission\textsuperscript{63}.

The mathematics of Fermi’s theory rests on a Hamiltonian consisting of the sum of kinetic energy terms for the heavy and light particles and terms describing their mutual interaction. The latter contain the operator $Q$, which transforms a proton into a neutron (raising operator) and $Q^*$, its hermitian conjugate, which transforms a neutron into a proton (lowering operator). They also contain the field operators which either create an electron at the position $x$, namely $\psi^*(x)$, or a neutrino at the same position, $\varphi^*(x)$, or destroy, respectively, electron and neutrino, namely $\psi(x)$ and $\varphi(x)$. The interaction part of the Hamiltonian reads,

$$H = g \{Q\psi(x)\varphi(x) + Q^*\psi^*(x)\varphi^*(x)\},$$

where the Fermi constant $g$ is analogous to the electric charge which determines the strength of the photon interaction, or in other words, the probability of photon emission.

The operators $\psi(x)$ and $\varphi(x)$, and also $\psi^*(x)$ and $\varphi^*(x)$, each have four components with the same relativistic transformation properties as a Dirac wave function, although they are \textit{not} wave functions but field operators, responsible for creating and annihilating particles. They are analogous to the field operators in quantum electrodynamics that give the emission and the absorption of photons. Fermi recognized that his Hamiltonian function was not unique, and that various combinations of the field components of electron and neutrino would allow the interaction Hamiltonian $H$ to be Lorentz invariant. Subject
to possible later modification, Fermi chose those particular bilinear combinations of the components of $\psi(x)$ and $\varphi(x)$ which transform as Lorentz four-vector, like the electromagnetic four-potential. By putting these bilinears into the heavy particle Hamiltonian, where normally the electromagnetic four-potential would appear instead, he obtained a familiar looking Lorentz-covariant interaction.

Since beta-decay half-lives are very long on the atomic scale, Fermi knew that the constant $g$ is small, and applied the perturbation theory to calculate the half-lives and the decay-electron spectra of radioactive elements. He showed how the shapes of the latter depend, at their high energy endpoints, upon the mass of the neutrino, and deduced that the value of that mass was most likely zero.

6. From neutron to meson; Japanese physics in the early 1930’s

Let us return to Yukawa in 1932 – recently married, an Instructor at Kyoto University, and full of doubts, both personal and scientific. Only a few days after his marriage in April, he was scheduled to begin lecturing on quantum mechanics; there was not enough time for a honeymoon, and the bridal pair settled for a day trip to the seashore.

Some of the students that heard his Kyoto lectures were to become his scientific collaborators a few years later, but the lectures that caused so much anxiety to Yukawa did not make any great impression on them. In Tabi-bito, Taketani is quoted:

There were no particular characteristics to Mr. Yukawa’s lectures, which followed Dirac’s textbook for the most part. His voice was gentle as a lullaby and he spoke with little emphasis – it was ideal as an invitation to sleep.

Kobayasi added that the lectures were delivered with his back to the audience, as he addressed the blackboard.

Yukawa lived with his wife’s family in Osaka and commuted by train. In the new environment of the Osaka house (and out of his father’s shadow), some changes began to take place in Yukawa’s personality, although he still found it difficult to break his “life-long habit of silence”. He admits, “I never spoke with my adopted parents unless absolutely necessary.” His father-in-law, a retired physician, was an
Orientalist who collected art objects and required his family to study Japanese dance, tea ceremony, and other arts. The atmosphere was old-fashioned, and for Yukawa "easy to accept... It gave relief to the tired and strained mind."18 His marriage, his new job, and his new home in busy Osaka, all conspired to his awakening — but equally so the new physics of 1932.

After the neutron discovery, when Heisenberg’s papers on nuclear structure arrived in Japan, Yukawa’s interest in nuclear physics quickened. Shoichi Sakata, then a third year student at Kyoto, recalls that Yukawa advised him to write his bachelor’s thesis on that subject.41 Yukawa translated Heisenberg’s papers and wrote a perceptive introductory essay, his first publication.65 It shows his recognition of the phenomenological nature of Heisenberg’s theory and the need for a better fundamental mechanism. Very soon after this, Yukawa presented his first paper at a meeting of the Physico-Mathematical Society of Japan, held at Sendai in April of 1933, on the “Theory of Nuclear Electrons.”66

Tomonaga, during a symposium held in 1961, recalled Yukawa at the Sendai Meeting, sitting on the ground and writing equations in the dirt of the exercise field of Tohoku University, trying to relate the nuclear force to the β-decay process. Tomonaga: “He was saying that the nuclear force is all right [in Heisenberg’s theory] but in β decay a strange particle emerges.”67 Yukawa was trying to understand β decay and nuclear forces on the basis of Heisenberg’s electron exchange. In a later interview, Yukawa discussed his unsuccessful attempt to make an “electron field” theory of nuclear forces, saying that Nishina had suggested an electron with Bose statistics but, of course, no such electron had ever been detected.68

“By taking up these difficult problems,” Yukawa says in Tabi-biyo, “I had to expect long days of suffering.” He was troubled with insomnia. When his father suggested that he might go abroad for study, he rejected the proposal: “I did not want to go to foreign countries until I had finished a work I could call my own. I would find my own theme and pursue it as far as I could, not caring how many times I might fail. If I succeeded, then I would talk with foreign scientists.”18

During the 1933 Sendai meeting, Yukawa’s brother introduced him to a colleague at Tohoku University, a well-known Professor of Electrical Engineering, Hidetsugu Yagi, who had just become Head of the
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physics department in the new Science Faculty of Osaka University. Offered a lectureship, Yukawa accepted and during the next year divided his time between Kyoto and Osaka Universities. In April, 1934 he moved into the new physics building in downtown Osaka as full-time Lecturer and head of the "Yukawa Group". In the same month Seishi Kikuchi came from Tokyo Riken as Professor, and Sakata, who had been working in Tokyo with Tomonaga, came and shared an office with Yukawa. His impression was favorable:

Dr. Yukawa looked much more lively and active than the year before when I was taking his course in Kyoto. Apparently he was influenced by the fresh atmosphere in the University, generated by the presence of a number of young and active research colleagues. But it must also have been due to the environment of busy Osaka; all day we felt the office vibrate because of the passing trucks. Yukawa used to say that he always felt the urge to do something there.

According to Professor Koji Husimi, who joined Kikuchi's research group in 1934 after graduating from Tokyo University, it was customary for the Kikuchi and the Yukawa groups to have lunch together every day. When Husimi came to Osaka he brought with him issues of the Italian journal "La Ricerca Scientifica", not available in Osaka or Kyoto, containing Majorana's paper on nuclear forces (also published in German), and most importantly, Fermi's paper on beta decay. These were discussed at lunch (as were all sorts of questions, including politics).

Yukawa himself said that he first came upon Fermi's paper in the Zeitschrift für Physik version, later in 1934. And in Tabi-bito he says, "I must have paled as I read it. Had I been beaten by Fermi for a second time?" For the grasped immediately that the electron-neutrino pair could provide a nuclear force that would be free of the contradictory aspect of mere electron exchange, and could preserve the conservation laws even in nuclear beta decay. Very shortly afterwards, when it was shown that the force of electron and neutrino exchange was far too weak, Yukawa recalled another idea that had earlier kept coming briefly into his consciousness, only to be suppressed. Now, with eyes fully open, he said, "Let me not look for the quantum of the nuclear force field among the known particles - including the new neutrino. If I pursue the characteristics of the nuclear force field, then the nature of the quantum of that field must also become apparent. Thinking in this manner, I was almost there."
One night in October 1934, shortly after his wife had given birth to their second child, unable to sleep, Yukawa suddenly saw that the range of the nuclear force must be inversely proportional to the mass of its field quantum, and that there must be a new particle. In the morning he found the mass to be about 200 electron masses, and concluded that it should appear both positively and negatively charged. At the lunch with the Kikuchi group, he reported his results. (This is recalled also by Husimi.) Kikuchi remarked that this particle should be visible in the Wilson cloud chamber; Yukawa agreed—and argued that it should be found in cosmic rays. Not long afterwards the theory was given at the Osaka branch meeting of the Physico-Mathematical Society of Japan, and presented a month later at the Tokyo Imperial University.

Before analyzing Yukawa’s theory of the nuclear force I want to place him more accurately in the Japanese physics milieu. I shall not try to be complete, in part because Japanese historians have already covered some of the ground, but also because, except for some letters and unpublished reminiscences referred to below, my access to institutional sources has been limited.

As regards the beginnings of soryushiron (i.e., nuclear and elementary particle physics) the most important institutions have been mentioned, namely, the Imperial Universities of Tokyo, Kyoto, Tohoku, and Osaka, and the Institute of Physical and Chemical Research in Tokyo, the Riken. In fact practically all prewar nuclear and cosmic ray research was done at the “new” University of Osaka, at Kyoto, and at Riken. In Sakata’s opinion, the reason was this:

An unfortunate circumstance in Japanese science was... that the centers of research were concentrated in the Imperial Universities, so that the abuse of bureaucracy hindered the free development of science in various ways. Nuclear physics, however, being a newly born scientific field was fortunate in having begun its life (in Japan) at the only large non-governmental research institute in the country, the Institute of Physical and Chemical Research, and to having always advanced with this Institute at its core.

Recall that it was Riken that sent Yoshio Nishina abroad for what turned out to be eight years of study and research, and that it was Riken to which he returned in December 1928. Everyone agrees that Nishina became the father of both nuclear and cosmic ray research in Japan. After a period of cultural readaptation, marriage, etc., Nishina
established his laboratory at Riken in July 1931, and began work immediately on nuclear instrumentation. 72 Ryokichi Sagane, the son of Nagaoka, had just joined the group and was designing Geiger-M"uller counters. Masa Takeuchi, hired originally to help Nishina with x-ray analysis (an old Copenhagen interest), was told to assist Sagane with cosmic ray research. A large cloud chamber was built and operated in a vertical plane with a strong uniform horizontal magnetic field, so that the curved tracks of cosmic ray particles could be photographed and identified. Through 1932 Sagane tried to use coincident signals from charged cosmic rays passing through electronic counters (G.-M. tubes) placed above and below the cloud chamber, to actuate the chamber's expansion. 73 This did not succeed, but in March 1933, P. M. S. Blackett and G. P. S. Occhialini in England reported observing cosmic ray shower phenomenon in their counter-controlled cloud chamber.

A second cosmic ray group used counters to measure total ionization. They made comparative measurements at sea level, at mountain altitudes, and in a deep railroad tunnel (the Shimizu Tunnel, at 800 meters of water equivalent depth), continuing this type of observation well into the War. In 1935 Nishina wrote to Robert A. Millikan requesting aid in either the construction or the purchase of a "vibration-free, self-recording electrometer" of Millikan-Neher type (H. Victor Neher), in order "to carry out the survey of cosmic-ray intensities in Japan." The instrument was built in Pasadena, and arrived in Tokyo in June of 1936.

Several small groups did nuclear physics research at Riken, using natural radioactive sources. The Nishikawa Group studied proton and deuteron induced nuclear reactions, using a high voltage source (Cockroft-Walton machine) in 1934; the Nishina Group began the construction of a small, and then a large (60 inch) cyclotron; slow neutron work, inspired by the success of the Rome group of Fermi, began in 1937. 74, 75

Sin-itiro Tomonaga left Kyoto in 1932 to work at the theoretical group of the Nishina Laboratory, and was joined later by Kobayasi, Sakata, and H. Tamaki. 76 The first five papers of Tomonaga use Dirac's positron theory and deal with the creation and annihilation of electron pairs. All include the name of Nishina, as well as other collaborators, and are written in English. The sixth paper (1936) is on the
interaction of neutron and proton. From 1937 to 1939 Tomonaga was in Leipzig with Heisenberg; he continued his work on nuclear forces, and published in German at that time.77

Osaka University founded its Science Faculty and began its lectures in physics in 1933. Yagi was appointed by President Nagaoka as Head of the Physics Department and hired new professors, S. Tomochika from Tokyo Imperial University, and J. Asada and T. Okaya from the Shiomi Institute for Physical and Chemical Research in Osaka.78 A fifth position went to Seishi Kikuchi, who came from the Tokyo Riken in April 1934 and began the construction of a Cockroft-Walton accelerator and other equipment for nuclear physics research. Born in 1902, the son of a noted mathematician and seismologist, Seishi Kikuchi did pioneering work in electron diffraction in the late 1920’s, for which he was awarded the Academic Prize in 1931. His nuclear physics group at Osaka was second only to Nishina’s in Tokyo, and it was with this group that Yukawa and his students worked, although officially they “belonged” to Professor Okaya. The theory group worked on problems of interest to the experimentalists and used the latter as a sounding board. Thus it was that the first presentation of the meson theory was made to the Kikuchi group. Sakata says that “Kikuchi brought the free atmosphere of Riken to Osaka University,” and the generally active and youthful spirit of the group encouraged Yukawa’s speculative mood.79

Comparison may be in order with Italy where revitalization of a tradition in decline was brought about through the theoretical work of Fermi and Majorana in Rome, by the work of Fermi’s nuclear group in Rome, and by the cosmic ray group of Bruno Rossi in Florence. It is tempting to imagine that Nagaoka in Tokyo and Orso Mario Corbini in Rome played analogous roles as politicians and elder statesmen.80

7. Yukawa predicts the meson

As we have seen, Yukawa’s thoughts had been filled for several years with the problem of the nature of the nuclear force field; it was a continuous preoccupation, and it appeared to him later that he had glimpsed the solution repeatedly without arriving at a definite formulation of it. When he did grasp the essential relation between the
quantum mass and force range and sat down in October 1934 to do
the necessary mathematics and to write his article, it took barely a
month for him to complete the work. It contains several new and
valuable ideas, and its physical logic proceeds inexorably.

Later physicists (until again quite recently) found little reason to
assume any unifying relation between the strong and the weak nuclear
interactions, but it was a temptation for physicists of the 1930's. Only
for a year or two had they even considered a specific nuclear force,
unrelated to electricity and magnetism; naturally, one new force was
preferable to two. Furthermore, Heisenberg had proposed a nuclear
charge-exchange force, arising from the transfer of a spinless electron
obeying Bose-Einstein statistics. That is not the description of a real
electron, but it is a possible metaphor for an electron-neutrino pair.

It may have been Heisenberg who first suggested a connection be-
tween exchange forces and what became known as the “Fermi field”,
the latter an analogue of the electromagnetic field, with the elec-
tron-neutrino pair substituting for the electron.51 In letters to Nature
shortly after the appearance of Fermi’s β-decay theory, Tamm and
Iwanenko estimated the effective potential arising from the exchange
of a pair of light particles. They found dependence upon the distance
as the inverse fifth power, when the distance is small. However, the
resulting force was too weak to provide the neutron-proton binding
force, falling short by a factor of at least $10^{10}$.82

In view of this result Yukawa said, “it seems natural to modify the
theory of Heisenberg and Fermi . . . ”, and he suggested:

The transition of a heavy particle from neutron state to proton state is not always
accompanied by the emission of light particles, i.e., a neutrino and an electron, but the
energy liberated by the transition is taken up sometimes by another heavy particle, which
in turn will be transformed from proton state into neutron state. If the probability
of occurrence of the latter process is much larger than that of the former, the interaction
between the neutron and the proton will be much larger than in the case of Fermi,
whereas the probability of emission of light particles is not affected essentially.83

Yukawa states here that the interactions of Fermi and Heisenberg are
different, that they give alternative ways for a neutron to become a
proton (or the reverse): either an electron-neutrino pair is emitted
(Fermi process), or the energy and negative electric charge are taken
up directly by another proton in the nucleus, which thereby becomes a
neutron (Heisenberg process). The first occurs with small probability (i.e., it is a weak interaction); the second has a probability large enough to provide the binding of nucleons in the nucleus (i.e., it is a strong interaction).

Up to this point, little has been accomplished but a modest step backward, disassociating $\beta$ decay from nuclear binding forces, but forward progress follows immediately:

Now such interaction between the elementary particles can be described by means of a field of force, just as the interaction between the charged particles is described by the electromagnetic field. The above considerations show that the interaction of heavy particles with this field is much larger than that of light particles with it.

Attention has been focused upon a new field of force, which like gravitation and electromagnetism is universal, interacting with both heavy and light particles, but with very different strengths. The final step in the reasoning leading to the meson theory is contained in the next paragraph:

In the quantum theory this field should be accompanied by a new sort of quantum, just as the electromagnetic field is accompanied by the photon.

The parallel with electromagnetism is now exploited, the force between neutron and proton being expressed first in terms of a static potential, "in analogy with the scalar potential of the electromagnetic field" that gives rise to the Coulomb force. "The potential of force between the neutron and the proton should, however, not be of Coulomb type, but decrease more rapidly with distance. It can be expressed, for example, by

$$\pm g^2 \exp (-\lambda r)/r$$

where $g$ is a constant with the dimension of electric charge . . .". The second constant that appears in this generalization of the Coulomb potential is $\lambda$, having the dimensions of an inverse length, whose value determines how the potential falls off with the distance $r$. The reciprocal of $\lambda$ is identified with the range of the potential, for the potential falls off very rapidly at distances greater than $1/\lambda$. By choosing $\lambda$ to be about $10^{13}$cm$^{-1}$, one obtains the nuclear force range of about $10^{-13}$
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On the other hand, if $\lambda$ is allowed to become very small, the range of Yukawa’s potential becomes infinite, the exponential becomes unity, and the potential becomes $\pm g^2/r$, the familiar Coulomb potential.

Yukawa pursues the electromagnetic parallel. The potential above is a static one; in general, it can be time-dependent. Furthermore, the usual electric and magnetic fields are not derived from a scalar potential alone; there is a vector potential as well, which forms a relativistic four-vector together with the scalar potential. The source of the electromagnetic four-potential (which usually appears on the right-hand side of the wave equation) is the charge-current density four-vector; Yukawa needs to write the analogue of this source. Finally, up to this point the theory has been classical; when it is quantized, one gets the quanta of the nuclear field, the analogue of photons, the mesons.

I consider these steps of generalization, beginning with the wave equation for the scalar potential. If $V(x, y, z, t)$ is the electromagnetic scalar potential, it satisfies, in the absence of sources, the wave equation

$$
\left( \Delta^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) V(x, y, z, t) = 0.
$$

In addition to time-dependent solutions, the equation possesses the static centrally symmetric solution: $V = \text{constant times } 1/r$. The generalized wave equation for Yukawa’s $U$-field (his “scalar potential”), is

$$
\left( \Delta^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \lambda^2 \right) U(x, y, z, t) = 0;
$$

it possesses as solution the static Yukawa potential given above, in addition to time-dependent solutions; for $\lambda = 0$, the equation for $U$ becomes that for $V$.

With regard to the analogue of the vector potential of the electromagnetic field, Yukawa says “we disregard it for the moment, as there is no correct relativistic theory for the heavy particles”. (The Dirac theory, e.g., would not be considered appropriate, as the neut-
ron and proton have anomalous magnetic moments.86 Within nuclei, nucleons move with an average speed about one-tenth that of light, so that relativistic effects are not entirely negligible; but the description used by Yukawa, representing the nucleons by simple non-relativistic Schrödinger wave functions, is a very reasonable first approximation. In the same spirit, the vector part of the nuclear interaction, which has both a velocity-dependent source term and gives a velocity-dependent interaction, is ignored.

Aside from the way that it depends upon distance, Yukawa's new field also differs from electromagnetism in that its "source" is the transition from neutron to proton (or vice versa); thus the field itself must carry electric charge (while the electromagnetic field, of course, is neutral). From the canonical theory of fields, it follows that a field carrying electrical charge must be complex.87

To build the charge-exchange character into the source of the $U$-field, Yukawa uses Heisenberg's $\varrho$-coordinate (see Sec. 4) and the $2 \times 2$ matrices which act upon that coordinate.88 As the analogue of Pauli operators which flip the spin, Heisenberg has the operator $\tau_+^v$ to transform a proton state to a neutron state and $\tau_-^v$ to perform the inverse process. The source of Yukawa's $U$-field (carrying negative electric charge) is the neutron-to-proton transition, given by $g \psi \tau_-^v \psi$, where $\psi$, the wave function of the heavy particles (proton or neutron) is a function of space, time, and spin, as well as of $\tau_3$ (Yukawa's name for Heisenberg's $\varrho$-paraméter).89 Similarly, the source of the field $\bar{U}$ (the complex conjugate of $U$), carrying positive charge, is $g \psi \tau_+^v \psi$. These source terms appear in the wave equations for $U$ and $\bar{U}$, analogous to the electric charge density in the wave equation for the electromagnetic scalar potential.

Next he writes a one-particle Schrödinger equation for the nucleon, neglecting spin. The potential function is $g(U \tau_+^v + \bar{U} \tau_-^v)$; the first term corresponds to a proton absorbing the $U$-field and becoming a neutron; the second corresponds to the transition of a neutron to a proton. If $U$ and $\bar{U}$ are the static central potentials that have as their sources other protons and neutrons, moving relatively slowly, then $U$ and $\bar{U}$ are given, respectively, by $(g/r) \tau_+^v \exp(-\lambda r)$, where $r$ is the distance to the source, and $\tau_+^v$ and $\tau_-^v$ are the "raising" and "lowering" operators that act upon the source nucleon.

Inserting these static solutions, Yukawa obtains the symmetric
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Hamiltonian function for a pair of interacting non-relativistic nucleons:

\[
H = \frac{p_1^2}{2M} + \frac{p_2^2}{2M} + \frac{g^2}{4r_{12}} (\tau_+ \tau_- + \tau_- \tau_+) \exp (-\lambda r_{12}) + (\tau_3 + \tau_3') D.
\]

Here \( p_1 \) and \( p_2 \) are the momenta of the particles and \( D \) is the mass difference of neutron and proton (in energy units). “This Hamiltonian”, says Yukawa, “is equivalent to Heisenberg's Hamiltonian if we take for 'Platzwechselintegral' \( J(r) = -(g^2/r) \exp (-\lambda r) \ldots' ”, except for neglect of forces between like particles (n-n or p-p).

The sign that Heisenberg assumed for \( J(r) \) led to the deuteron having zero spin, but the true spin is one. Yukawa assumed that he could correct this by choosing appropriately the sign of his charge exchange interaction, but he was wrong. To the extent that Heisenberg regarded the exchange interaction as phenomenological, he could choose its sign to be either that of the exchange force in atoms (and get the wrong spin dependence of the forces), or the opposite (and get it right). However, Yukawa’s theory contains a definite mechanism for producing the exchange interaction, and it is a fundamental theory that makes a definite (incorrect) prediction. He realized later that other versions of the meson theory (e.g., other spin choices) would need to be explored, to fit the observed nuclear forces. Regarding the size of the “charge” \( g \) and the range of the force, given by \( 1/\lambda \), he says:

Rough estimation shows that the calculated values agree with the experimental results, if we take for \( \lambda \) the value between \( 10^{12} \text{cm}^{-1} \) and \( 10^{13} \text{cm}^{-1} \) and for \( g \) a few times of the elementary charge \( e \), although no direct relation between \( g \) and \( e \) was suggested in the above considerations.

The theory presented to this point is classical or semiclassical, from the viewpoint of field theory; i.e., it is a quantum mechanical description of nucleons interacting through a classical \( U \)-field. The description of this field in vacuum parallels Maxwell’s treatment of the electromagnetic potential. However, there is another interpretation for the wave equation for \( U \): it can be regarded as the relativistic Schrödinger equation (also called the Klein-Gordon equation) for a
free particle, so that $U$ is the particle's wave function. The range parameter $\lambda$ is then the inverse Compton wave length of the particle, $mc/\hbar$.

This interpretation calls for the second quantization of the $U$- and $\bar{U}$-fields, and it shows immediately that the quanta have the mass $m = h\lambda/c$. In the second quantized field theory, $U(x, t)$ is an operator that either destroys a positively charged quantum at $x$ or creates a negatively charged quantum; $\bar{U}(x, t)$ does the reverse.

Assuming $\lambda = 5 \times 10^{12}\text{cm}^{-1}$, corresponding to a nuclear force range of $2 \times 10^{-13}\text{cm}$, Yukawa predicts that the mass of the $U$-quantum (of either charge) should be about 200 electron masses. He notes,

As such a quantum with large mass and positive or negative charge has never been found by the experiment, the above theory seems to be on a wrong line. We can show, however, that, in the ordinary nuclear transformation, such a quantum can not be emitted into outer space.

In a sense, this is obvious, since such an emission would violate the energy principle; the energy available in nuclear transformation of the ordinary sort is not larger than about 10 MeV, while a mass equivalent to 200 electrons requires more than 100 MeV. Yukawa makes a less obvious argument, though, which shows the relationship between the mass of the quantum and the range of the force; at the same time, it relates the concepts force field and particle creation.

He does this by solving the wave equation for the $U$-field by the Green's function method, and showing that in cases where the energy of the neutron-to-proton transition (for example) is less than $mc^2$, the $U$-field is exponentially damped, falling off rapidly beyond the distance $1/\lambda$. On the other hand, if the transition energy exceeds $mc^2$, then $U$ is an undamped propagating wave and the $U$-quantum emerges from the nucleus, or to use Yukawa's phrase, "can be emitted in outer space."

Yukawa thus explicitly predicts that $U$-quanta should be observable when sufficient energy is available, and he concludes:

The reason why such massive quanta, if they ever exist, are not yet discovered may be ascribed to the fact that the mass $m_U$ is so large that condition $|W_N - W_P| > mc^2$ is not fulfilled in ordinary nuclear transformation.
These are the possibilities that arise from the strong interaction of the \( U \)-quantum with the nucleons:

(a) A neutron becomes a proton, emitting a negatively charged quantum; this quantum is absorbed by a proton in the same nucleus, the proton becoming a neutron.

(b) A proton becomes a neutron, emitting a positively charged quantum; this quantum is absorbed by a neutron in the same nucleus, the neutron becoming a proton.

(c) The same processes described by (a) and (b), but with the second interaction occurring in another nucleus. This provides a force acting between nuclei, responsible for nuclear scattering and nuclear reactions.

(d) The same production processes as in (a) and (b), with the \( U \)-quantum emitted and moving as a free particle.

In case (d), one can ask for the ultimate fate of the \( U \)-quantum. Evidently, it may have a strong reaction at a nucleus far removed from its birthplace, or it may undergo some other transformation as a free particle in free space. (See Figures 1, 2, 3.)

8. The radioactive meson

Yukawa assumes that the \( U \)-quantum (or meson) interacts not only with the “heavy particles”, proton and neutron, but also with the “light particles”, electron and neutrino (actually antineutrino) and their antiparticles. As with the nucleons, the light particles interact as a pair, having one charged and one neutral member.94 A negative meson can be absorbed by the “vacuum”, and raise a negative energy neutrino to a positive energy electron state, leaving a hole in the Dirac “negative energy sea” of neutrinos; this hole is an antineutrino. The process occurs with a much smaller probability than the interaction of the meson with nucleons; it can be regarded as the radioactive \( \beta \) decay of the \( U \)-quantum, when the latter is a free particle. (Fig. 3). On the other hand, if the process takes place in the same nucleus in which the \( U \)-quantum is produced, it is regarded as the \( \beta \) decay of the nucleus (Fig. 2), the process described by Fermi and, “as in the theory of
Figure 1. Models of the strong nuclear charge-exchange force. \( p, p' \), protons; \( n, n' \), neutrons; \( e^- \), electron; \( \nu \), neutrino; \( U^- \), heavy quantum.

Figure 2. Models of the (weak) \( \beta \) decay interactions. (Notation as in Figure 1.)

Figure 3. Other processes predicted by Yukawa's theory. (Notation as in Figure 1.)
internal conversion of $\gamma$-rays, the intervention of the photon does not affect the final result. Our theory, therefore, does not differ essentially from Fermi's theory.\textsuperscript{95}

While Fermi specifically disclaimed any analogy between his $\beta$-decay theory and Dirac's hole theory of electromagnetic pair production, Wick \textit{did} invoke the analogy in his treatment of positron $\beta$ decay. Yukawa, independently of Wick, also demonstrated that the creation of an electron and an antineutrino, both with positive energy, is equivalent to the creation of an electron together with the destruction of a negative energy neutrino (i.e., to raising a negative energy neutrino to a positive energy electron state, leaving behind a hole). Since the process we have described is essentially analogous to the proton-neutron transition (destruction of proton and creation of neutron), Yukawa adds a new \textit{light particle source}, $-4\pi g' \bar{\psi}_k \varphi_k$ (summed over the Dirac index $k=1 \ldots 4$), to the \textit{heavy particle source}.\textsuperscript{96} The new constant $g'$, of the same dimensions as $g$, is assumed to be \textit{much smaller} than $g$.

In Yukawa's view the beta decay of a nucleus is, accordingly, a double process: a neutron changes to a proton emitting a virtual negative meson that subsequently (in a time too short to be observable, even in principle) decays into an electron and an antineutrino. Positron $\beta$-decay occurs analogously, with a proton turning into a neutron. Taking into account the short range of the potential $(1/r)\exp(-\lambda r)$, Yukawa demonstrates that the Fermi constant (that appearing in Fermi's theory described in Sect. VI) is equal to $4\pi gg'/\lambda^2$. Fermi's constant is related empirically to the rate of $\beta$ decay (by Fermi's theory), while $g$ and $\lambda$ are determined by the properties of the strong interaction. In principle, then, Yukawa's weak interaction constant $g'$ can be determined, and would lead to a prediction of the radioactive half-life of the meson. Estimates of the half-life were, however, \textit{not} made on this basis before 1938.\textsuperscript{97}

I emphasize that Yukawa introduced two new coupling constants or "charges", having the same physical dimensionality as that of electric charge, but of very different strengths. The larger one measures the strength of coupling of the meson to the heavy particles; it accounts for the exchange of mesons that gives rise to the binding of nucleons to form nuclei, for the scattering of nucleons on each other, and for the production of free mesons when sufficient energy is available. The
other charge is much weaker (about $10^{-8}$ times smaller than the strong coupling constant). It measures the coupling strength of the meson to the light particles, electron and neutrino, and accounts for the weak interactions: nuclear beta decay, free neutron beta decay, and meson decay. While Heisenberg's and Fermi's theories each involve only one coupling constant, Yukawa's theory is in much better accord with nature.

In his concluding summary, Yukawa does not refer to a finite life-time for the free meson, but assumes that mesons may be present in the cosmic ray beam and may be absorbed by the earth. Should negative quanta be in excess, the earth could be charged to a negative electrical potential. Some cosmic ray workers had suggested that the latter could be responsible for the acceleration of cosmic rays. These remarks are not well-founded, but another one is prophetic: "The massive quanta may also have some bearing on the shower produced by cosmic rays." Indeed, the main origin of the electromagnetic cascade or shower in cosmic rays is the neutral pion, which became an essential requirement of the theory when the nuclear forces were seen as charge-independent, about two years later.

9. The meaning of the meson

One of Yukawa's first students wrote recently that the meson theory opened up a new fundamental view of nature. This event might be regarded as a miracle in the history of Japanese physics. Through all of his works and thoughts, we are impressed by the simplicity of approach, the unfailing intuition and the creativity of a great master, which are deep-rooted in Yukawa's culture.

Here the meson theory is said to enlarge the class of elementary particles, providing a new view of nature; it is called a miracle for Japanese physics, in which native cultural traits may have played a significant role. There may be other "meanings" for the meson, but I shall deal with the subject mainly under these rubrics.

At the beginning of Section 3 we quoted Yukawa on the usage of the term "elementary particle" at the beginning of the 1930's; it meant simply electron or proton, and there was a prohibition of new elementary objects that was sometimes unspoken, at other times
explicit.\textsuperscript{100} When Pauli proposed a new type of particle, the neutrino, he waited three years to publish his idea — and then did so only in the form of a discussion remark.\textsuperscript{101} When Dirac was “led to a new kind of particle caused by a hole in the distribution of negative-energy states,” and the symmetry properties of the theory suggested that the particles have positive charge and electronic mass, Dirac still called it a proton:

I just didn’t dare to postulate a new particle at that stage, because the whole climate of opinion at that time was against new particles. So I thought that this hole would have to be a proton. I was very well aware that there was an enormous mass difference between the proton and the electron, but I thought that in some way the Coulomb force between the electrons in the sea might lead to the appearance of a different rest mass for the proton. So I published my paper on this subject as a theory of electrons and protons.\textsuperscript{102}

Reluctance to admit new elementary particles to help explain the puzzling phenomena of nuclear physics went beyond abhorrence of the \textit{ad hoc}, and beyond aesthetic judgement. It seemed natural to expect the quantum generalization of classical mechanics to fail in that much smaller region of space, the atomic nucleus. Moreover, the nuclear size is about the same as the “classical electron radius” (about $10^{-13}$ cm), where H. A. Lorentz had predicted that classical electrodynamics would break down. Physicists were predisposed to look for an explanation of the crisis of nuclear physics in the breakdown of dynamics, rather than to postulate new particles or new forces.\textsuperscript{103}

Bohr’s insistence upon the failure of energy conservation in the nucleus is well-known. Heisenberg’s interest in a microscopic universal length persisted even after the muon was discovered in cosmic rays and Yukawa’s theory of nuclear forces became generally accepted. He wrote to Pauli in 1938 that he had learned from H. J. Bhabha and W. Heitler why “explosions” (also called “bursts” or “stars”) should occur in the cosmic rays, according to Yukawa’s theory, and continues:

\begin{quote}
It was interesting to me, however, that Bhabha as well as Heitler also obtain [in the expression for the force between neutron and proton a term of the form $\delta(|r_1 - r_2|)$ … [i.e., an infinite contact force] This result is very agreeable \textit{[sehr sympatisch]} to me, because it shows again that one cannot make further progress without the universal length.\textsuperscript{104}
\end{quote}

These are some of the reasons why Western physicists did not anticipate Yukawa’s nuclear force model. When the “heavy electron” or
“mesoton” (as the muon was then called) was found, Léon Brillouin identified it as Yukawa’s $U$-quantum. Referring to Heisenberg’s suggestion to use the Fermi $\beta$-decay mechanism as a realization of the charge-exchange nuclear force, Brillouin said:

A Japanese, Yukawa, found in 1935 a very simple way of improving the theory. “Fermi’s Field” surrounding a heavy particle corresponds to the exchange of an electron with a neutrino. Yukawa had the idea of admitting that this field should actually correspond to the exchange of one new particle differing both from an electron and a neutrino.\(^{105,106}\) (original emphasis)

On occasion the scientific process is described by political analogies\(^{107}\); sometimes the analogy is mechanical or thermodynamic.\(^{108}\) Such analyses seem inappropriate to apply to Yukawa’s achievement, for they emphasize a shift, perhaps profound, in the understanding of a given system. But Yukawa’s prophetically entitled “On the Interaction of Elementary Particles. I.” is a door opening on a world of high energy processes, involving the creation and annihilation of new ephemeral substances (the mesons, unstable leptons, strange and charmed particles, etc.) of astonishing novelty. One is justified in regarding this as a lesser revolution than, say, quantum theory or relativity, only by placing an exaggerated value on modes of thought, as opposed to understanding the content of nature.

From a certain standpoint, we may regard atomic and nuclear forces as having paramount scientific interest, but if the physicist’s task is to discover new phenomena, as well as deeper ways of understanding the old phenomena, then the prediction of the meson and its relation to nuclear forces is a towering achievement. Indeed, in most episodes of the history of physics, a necessary preliminary to the dynamical treatment of a system, is the discovery of its constituents. The importance of this point has been stressed especially by Taketani.

Although Yukawa has his own, probably unique, philosophical orientation, it would be as inappropriate to discuss Yukawa’s thought without reference to the philosophical ideas of Sakata and Taketani as it would be to discuss Einstein’s thought without reference to Ernst Mach. To compare the two cases may appear to be absurd; after all, Sakata and Taketani were students of Yukawa, while Mach was almost forty years older than Einstein and influenced the latter by his writings. Nevertheless, the relationship between Yukawa and his brilliant
students was a complex and reciprocal one, and was especially important in the social and political circumstances of Japanese physics in the 1930's.

Sakata spent the year after graduation on a fellowship at the Riken in Tokyo, under the guidance of Tomonaga who, together with Nishina, was working on several processes involving the positron. Sakata helped Tomonaga to calculate the creation of a positron-electron pair by a $\gamma$ ray incident upon a nucleus, but they were beaten to publication by W. Heitler and F. Sauter. After Sakata moved to Osaka, he and Yukawa calculated the probability for creation of an electron-positron pair by a nuclear transition in which no $\gamma$ ray is emitted, a process rather similar to internal conversion. Then stimulated by a suggestion of Guido Beck, who visited Japan at this time, they considered the process in which a nucleus captures an electron from the innermost atomic orbit (K-shell), at the same time emitting a neutrino.

The paper of Yukawa and Sakata on the K-capture process was important for two reasons. It was the first treatment of this fundamental process, and it uses Yukawa's meson theory. Between the first meson paper and Yukawa's "short note" identifying the cosmic ray "heavy electron" with his $U$-quantum, Yukawa published seven papers, all in the Proceedings of the Physico-Mathematical Society of Japan, five of them jointly with Sakata.

Sakata wrote that Taketani used to visit the Osaka group about once a month, after his graduation from Kyoto University in 1934. "He always had ideas about the theory of the nucleus and we used to discuss it until late at night. Sometimes he talked about Hegel's logic and Yukawa would listen with great interest." Taketani's graduation thesis at Kyoto had been a study of the logical structure of quantum mechanics, which served as the starting point for his "three-stage methodology" of physics. This adds a third "substantialist" stage between the "phenomenological" and "fundamental" stages that are often viewed as part of the development of a particular theory. (Taketani uses the term "essentialistic" for the third stage.) In the substantialistic stage one recognizes the substances in the model; for example, electrons and the nucleus are identified as the constituents of the Bohr-Rutherford atom. Taketani's methodology is materialist, emphasizing concrete objects, and it is dialectical, since the final stage
of one theoretical development can become the beginning stage of the next.\footnote{114}

Although Sakata was the more orthodox Marxist, Taketani was more active politically and wrote for a radical journal called \textit{World Culture (Sekai bunka)} that served as an intellectual spearhead of the movement against fascism. In 1938 there was a crackdown, and Taketani left Kyoto to “seek refuge” with a friend in Kobe. Then:

Three days after I had once again changed my Kobe lodging, some plainclothesmen forced themselves into my apartment while I was asleep and arrested me. . . After a month I was taken to the Kawabata police station, which was responsible for investigations related to Kyoto University. . . The unlawful acts for which I was held were: my analyses of quantum mechanics, my analyses of the development of nuclear physics, and my methodological approach to the meson theory— in short, my research activities on natural dialectics. I was forced to state that I had participated, through my research, in the cultural movement of the popular front under instructions of the Comintern, thus helping to promote the Communist Party in Japan.\footnote{115}

Sakata and Taketani do not claim to have influenced Yukawa’s meson prediction, except most indirectly. Sakata wrote, “Yukawa is really not a dialectical materialist.”\footnote{116} Tetsuo Tsuji recently interviewed Taketani, and asked about his contacts with Yukawa in Osaka, with the reply:

\begin{quote}
He is such a genius-type, you know; he listened to me, saying only “yes, yes, . . .”

Detailed discussions on my methodology were mainly with Sakata.\footnote{117}
\end{quote}

Yukawa’s attitude shows up in his preface to a recent intellectual biography. Asked by his poet-biographer if a dog-motif appearing in Yukawa’s published poems represents “fear”, and whether Yukawa was fearful or confident in proposing the meson, his reply was that he had perfect confidence.\footnote{118} Poincaré argued that physics should be based upon hypothesis, but like Descartes, Yukawa viewed his theory as self-evident truth. He felt that this kind of revelation is a most valuable approach to fundamental physics. After the discovery of the cosmic ray meson, however, he began to have doubts and worried about its reluctance to conform to his predictions— but his confidence was then restored by the two-meson hypothesis.\footnote{119}

In the same preface he says that he regarded the divergence problems of quantum field theory as more fundamental than the theory of
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the nuclear force. Using the language of Taketani, he asserts that his main intellectual interest lies in the "essentialistic" stage of the theory, while the meson theory was a contribution to the "substantialistic" stage. He took these up again in 1942, and this led eventually to an interest in non-local field theory, which he introduced in 1950 to try to deal with the problem of divergences (infinities) and newly discovered particles.

While expressing his appreciation of Taketani's methodology, he says that in the future there must be a fusing together of the last two stages, the substantialistic and the essentialistic. Quoting the Chinese poet Li Po ("The universe is an inn that accommodates all things; time is a traveler of one hundred generations."), he says that one day in 1966, he conceived of the idea of the "elementary domain", a modification of the ideas of space-time and causality — requiring the use of difference equations, rather than differential equations.  

Although Yukawa does not identify himself with the Sakata-Taketani methodology or with their political philosophy, his close association with them in the 1930's helped to relieve his sense of scientific isolation, while strengthening his independence of the various "authorities" — among them the state and its institutions, the family and its traditions, and intellectual authorities, both at home and abroad.

10. Acceptance of the meson theory

The story of the discovery of the "heavy electron", the particle now known as the muon, in the cosmic rays does not belong to the "prediction" theme, but rather to that of "discovery". Neither process is ever simple, and the sorting out of "soft" and "hard" components of the cosmic rays, the observation of cloud chamber tracks that had too little radiation interaction to be electrons (yet could not be protons, as they were almost as often negative as positive), and the other observations and shifts of sentiment that eventually convinced the experimentalists that they were viewing new particles of intermediate mass will be taken up in another place. What is important here is that by July 1937, the experimental announcements had been made, and very soon afterwards Yukawa wrote a "short note" to point out that his theory had predicted just such particles.

One of the first European theorists to apply and generalize
Yukawa's theory was Nicholas Kemmer, who summarizes the situation in the passage that follows. After remarking that the origin of nuclear forces in the first half of the 1930's was "definitely overshadowed as a topic for theoretical speculation by the everpresent problem of 137, of the strength of electromagnetic interactions," he continues:

This then was the mood which made it possible for Hideki Yukawa's paper to appear in the Proceedings of the Physico-Mathematical Society of Japan in 1935 and to remain virtually unnoticed and certainly entirely unappreciated. Though Yukawa's idea was basically so simple and also so clearly stated, it attracted no attention. Perhaps part of the explanation was that the journal in which it was published was not widely read. But this cannot be the whole story for in those days the volume of work published in this field was so small compared with today that any serious minded student would find no difficulty whatever in taking note of the contents of all relevant papers in whatever journal they were published. More important perhaps was the fact that among the leaders of theoretical physics in Western Europe all important results were instantly communicated at private meetings or by correspondence, while Yukawa's ideas never even started being spread by this "grapevine" method. But having said all this, it is quite clear that Hideki Yukawa in 1935 was ahead of his time and found the key to the problem of nuclear forces when no other theoretical physicist in the world was ready to accept it.

All this was changed in 1937 after Anderson announced his discovery in cosmic radiation of a particle of approximately the mass required by Yukawa's theory. Within weeks we were studying and attempting to extend Yukawa's ideas. And within a few months, if not weeks, workers in Japan and in Europe discovered that they were thinking on practically identical lines and Yukawa's ideas had been completely assimilated. What can only be called a joint enterprise from that moment onwards was of course abruptly terminated by the outbreak of war.\(^{123}\)

The "joint enterprise" to which Kemmer refers, and in which Kemmer himself played a leading role, consisted of applying the meson theory to new problems (e.g., the magnetic moments of the neutron and proton) and in generalizing it (e.g., with inclusion of a neutral meson). There was also the effort to match the properties of the cosmic ray "heavy electron" to those expected for the nuclear force meson. Since the muon has no strong interaction, this could not really be done, but various types of quantum field, various spins and "mixtures" were tried.

One of the last international conferences that was held before World War II, took place in Warsaw, May 30 to June 3, 1938. Entitled "New Theories in Physics", it was organized by the International Institute of Intellectual Co-operation, in collaboration with the
International Union of Physics and the Polish Intellectual Co-operation Committee. Participants ranged from Niels Bohr to Eugene P. Wigner, by way of de Broglie, Eddington, von Neumann, etc. Of eight speakers, three (L. Brillouin, O. Klein, H. A. Kramers) dealt with Yukawa's meson theory, citing him by name twelve times. A year earlier no one who had not visited Japan would have known his name.

11. Summary and Conclusion

At the time when Hideki Yukawa graduated from Kyoto University in 1929 as a highly motivated and partly self-taught theoretical physicist and began his research on nuclear theory, the empirical knowledge of nuclear physics accumulated since the start of the century had led to a crisis. It was believed that electrons and protons must be the constituents of the nucleus, for they could be observed, in special circumstances, leaving the nucleus, and because they were the only known elementary material particles.

The solution to the nuclear problem was therefore thought to lie in a new dynamics, or possibly in a modified microscopic structure of space and time. This turned out not to be the case; instead, the major paradoxes were resolved by the experimental discovery of new elementary particles, the neutron and the positron, and by Pauli's theoretical invention of the hard-to-observe neutrino. Using these new particles, Heisenberg and Fermi made theories which provided, with some later modification, the phenomenological basis for our present understanding of the strong and the weak nuclear interactions.

There remained the problem of providing a fundamental theoretical foundation for these phenomenological theories (or, at least, a deeper-lying level of phenomenology), and this was given by the meson theory of Yukawa. I have studied in detail its conceptual development through the first meson article.

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Appendix I. Historiographic notes

1. General works in English.

(a) Related to Japanese physics:

(b) Early reviews on the meson and on nuclear forces:
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(c) Useful collections:
Shoichi Sakata, Scientific Works (Publication Committee of Scientific Papers of Prof. Shoichi Sakata, 1978). This includes philosophical papers, translated into English by his students.

2. Unpublished works in English.
Letters in the Archive for History of Quantum Physics: Nagaoka to Goudsmit (1930); Nishina to Goudsmit (1926–30); Nishina – Bohr correspondence (1923–40).
Letters in the Nagaoka Collection, National Science Museum, Ueno Park, Tokyo.
Letters between Nishina and Dirac, Nishina Memorial Foundation, Bunkyo-ku, Tokyo.

3. Books and articles, previously available only in Japanese and translated for this project.
Hideki Yukawa (assisted by Hisao Sawano), Tabi-bitō (the traveler), (Asahi Press, Tokyo, 1959); translation by Rikutaro Yoshida, about 200 pages.


Sin-itiro Tomonaga, “German Diary – 1938,” from My Teachers and My Friends (Kodansha, 1976); translated by Fumiko Tanihara, 9 pages.


S. Tomonaga, H. Yukawa, S. Taketani, Y. Fujimoto, “Thirty Years of Particle Physics (a symposium)” in S. Sakata, The
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Appendix II

Introduction to W. Heisenberg, Über den Bau der Atomkerne,1 by Hideki Yukawa. [From Journal of the Physico-Mathematical Society of Japan 7, (1933), 195–205; translated from the Japanese by Rikutarō Yoshida; the footnotes are Yukawa's].

Since Chadwick suggested the neutron as the theoretical explanation of the experiments of Curie, Joliot, etc., attempts to explain the systematics of atoms assuming that the nucleus consists of protons and neutrons began to possess considerable meaning. If, under the assumption that protons and neutrons make up shells obeying Pauli's exclusion principle, protons and neutrons are added one by one successively, we are able to list the nuclei from $H^1$ to $A^{36}$ (although $H^3$ and $He^5$ are not known experimentally); not only that, but the chief difficulty of the hypothesis that nuclei consist of protons and electrons, namely the fact that the nucleus of $N^{14}$ obeys Bose statistics, is explained by the hypothesis that $N^{14}$ consists of 7 neutrons and 7 protons, both obeying Fermi statistics. However, it is difficult to explain the nuclei heavier than $Cl^{37}$ as consisting only of protons and neutrons (of course, there is no problem in admitting $\alpha$ particles as secondary elements), and perhaps the presence of electrons within the nucleus must be admitted.2 This point has not been resolved either

1. Zeit. f. Phys. 77 (1932); 78 (1932), 156; after the present work, a third paper [Zeit. f. Phys. 80 (1933), 587] was published.

way, but basically the behavior of electrons in nuclei is difficult to understand with present day quantum mechanics, and the fact that $\beta$ rays come out of certain radioactive atoms with continuous energy values that do not seem to be due to influences received outside the atom, and that the decay constant does not vary with the speed of the $\beta$ ray, make one doubt the validity of the law of energy conservation and to further imagine that the electrons lose their individuality inside the nucleus.\(^3\)

In this paper Heisenberg ignored the difficult problems of electrons within the nucleus, and under the assumption that all nuclei consist of protons and neutrons only, considered what conclusions can be drawn from the present quantum mechanics. This essentially means that he transferred the problem of the electrons in the nucleus to the problem of the make-up of the neutron itself, but it is also true that the limit to which the present quantum mechanics can be applied to the atomic nucleus is widened by this approach. Though Heisenberg does not present a definite view on whether neutrons should be seen as separate entities or as combinations of a proton and an electron, this problem, like the $\beta$ decay problem stated above, cannot be resolved with today's theory. And unless these problems are resolved, one cannot say whether the view that electrons have no independent existence in the nucleus is correct.

REFERENCES


2. Yukawa called his particles “heavy quanta” or “$U$-quanta”. The name meson refers to the particle’s mass, intermediate between that of the electron and the nucleon. (The last term is the generic name for the nuclear particles, proton and neutron, nearly equal mass.) Before about 1948, when it became known as the pi-meson or pion, it was referred to by other names as well, such as heavy electron, barytron, mesotron, etc. The designation meson is perhaps due to H. J. Bhabha (Nature 143 (1939), 276). For a discussion of this point, see V. Mukherji, “A History of the Meson Theory of Nuclear Forces from 1935 to 1952”, Archive for History of Exact Sciences 13 (1974), 27–102, p. 38.


5. Fermi’s papers on beta decay did not discuss the strong forces responsible for nuclear binding, but as discussed below, there were a number of attempts by others to make a unified theory of strong and weak forces based solely on Fermi’s beta-decay interaction or some modification thereof.

6. P. Jordan and O. Klein, Zeit. f. Phys. 45 (1927), 751–765. (See Sect. 5 below for the meaning of this term.)


8. The earliest reference to Yukawa appears to be J. R. Oppenheimer and R. Serber, Phys. Rev. 51 (1937), 1113 (sent June 1, 1937). For a discussion of the “unfavourable remarks” of Oppenheimer and Serber and the coolness of reception of the theory, see Mukherji, loc. cit., pp. 35–37 and 96–97.


12. See, e.g., L. Jánossy, Cosmic Rays (Clarendon Press, Oxford, 1948). Throughout this monograph the “cosmic ray meson”, i.e., the muon, is identified as Yukawa’s particle and only distinguished from it in an appendix.


17. The family name Yukawa was assumed by Hideki in 1932 when he married Sumi Yukawa and was adopted by her father Genyo, an Osaka physician. The practice of adopting the younger son of one family into a family without a son is quite common in Japan; Hideki Yukawa’s father Takui had also been adopted in this way.

18. H. Yukawa, Tabi-biso, unpublished translation by Rikutaro Yoshida. The period described by this book is from childhood to 1935, the year of publication of Yukawa’s first article on the meson. Other autobiographical material by Yukawa in Japanese: Butsurigaku ni
kokorozashite (Aspiring for Physics; Kyoto, 1944); Meni mienai mono (Of things that cannot be seen; Kobunsha, 1942); Shinri no be ni tachite (In the course of our study), with S. Sakata and M. Taketani (Mainichi Shimbun, Tokyo, 1951).

19. Yukawa's youngest brother Masuki Ogawa died in the Second World War; the other three became university professors. For further details of Yukawa's family see Yasutaka Tanikawa, "Introduction and Biographical Sketch" in H. Yukawa, Scientific Works, edited by Y. Tanikawa (Iwanami; Tokyo, 1979). I am indebted to Professor Tanikawa for a copy in advance of publication.


21. After the Meiji Restoration, the samurai Komakitsu Ogawa studied European culture and read the English language Times "every day until his death", according to *Tabi-bito* (ref. 18).

22. For example, in *Creativity and Intuition*, a collection of Yukawa's essays in English, translation by John Bester (Kodansha International, Tokyo, 1973). See especially the 1968 essay, "On learning and life".


27. The Chinese character for "Elementary", drawn by Yukawa, was chosen as the logo for the 19th International Conference on High Energy Physics, held in Tokyo in August 1978. It appears on the cover of the September, 1978 issue of the *CERN Courier*.


29. This quotation is from a 1948 essay "The Oriental Approach" in *Creativity and Intuition* (ref. 22). There are separate essays also on the Taoist writers in this book. See also H. Yukawa, "Modern Trend of Western Civilization and Cultural Peculiarities in Japan", in *The Japanese Mind*, ed. Charles A. Moore (East-West Center Press, Honolulu, 1967).

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31. Ishiawara was an important theoretical physicist who studied with Einstein and Sommerfeld in Germany and returned to Japan in 1915. He worked on both relativity and quantum theory and is credited with generalizing Bohr's quantum condition. After losing his position at Tohoku University because of a love affair, he began to write popular scientific books. Two of these that were read by Yukawa were: Theory of Relativity and Fundamental Problems in Physics.

32. According to Minoru Kobayasi (private communication) Araki lectured in 1926 or 1927. The connection was with the Hamilton-Jacobi formalism used in celestial mechanics, as applied to atomic physics. "His lectures were very beautiful, like a classical theatre performance."


34. Carl F. von Weizsäcker recalls being told by Heisenberg that the problem of relativity and quantum theory and the electron had been solved by a young Englishman by the name of Dirac, who was so clever that it did not pay to compete with him. (AHQP interview of 1963).


37. W. Heisenberg and W. Pauli, Zeit. f. Phys. 47 (1929), 1-61. Earlier treatments involved the quantization of only the radiation part of the electromagnetic field, while the static Coulomb potential, for example, was treated classically.


40. The Japanese name is Rikagaku Kenkyusho, or Riken for short. The overriding importance of this private research foundation to Japanese physics between the two great wars of this century is emphasized in several articles in Science and Society in Modern Japan (ref. 30).

41. S. Sakata, "Reminiscences of Research on Meson Theory" in H. Yukawa, S. Sakata, M. Taketani, Quest for Elementary Particles (Keiso Shobo, 1965); originally published in In the Course of Our Study (1951); see ref. 18. Unpublished translations by Noriko Eguchi and by R. Kawabe.

42. See, e.g., Charles Weiner, "1932 – Moving into the new physics", Physics Today, May 1972, 40-49; Ch. Weiner, "Institutional Settings for Scientific Change: Episodes from the

43. Gamow, pp. 55 and 56; emphasis supplied by Gamow.


46. E. N. da C. Andrade, *Reports on Progress in Physics I* (1934), 269–320. However, George Gamow's *Structure of Atomic Nuclei and Nuclear Transformations* (Oxford, 1937) argues that since "the classical electron radius is the same as the distance between nuclear particles", a yet unknown theory is needed to describe electron behavior within nuclei. See also Rudolf Peierls, "The Development of Our Ideas on the Nuclear Forces", *Nuclear Physics in Retrospect*, etc. (ref. 36), 183–211.

47. D. Iwanenko, *Comptes rendus* 195 (Aug., 1932), 439–441. Iwanenko wrote: "les électrons intranucléaires sont réellement très analogues aux photons absorbés, l'expulsion d'un électron β étant pareille à la naissance d'une particule nouvelle qui, en état d'absorption, ne possédait pas d'individualité."

48. See Bromberg, ref. 38, p. 333. Cf. Brink, ref. 3, pp. 14–16; note that Brink omits those parts of Heisenberg's papers which most strongly point up their contradictory assumptions.


54. Because of Heisenberg's picture of the neutron as a proton-electron compound, the mass of the free neutron was required to be less than the mass of proton plus electron; i.e., the free neutron was stable. This did not contradict what was known of the neutron at that time. The "mass defect" of the neutron (whatever its sign) is, in any case, small and did not play a decisive role in nuclear systematics.

55. By the time of the 1933 Solvay Conference, Heisenberg agreed with Majorana that the sign of the exchange term should be the opposite of that which he had assumed. *Rapport du septième conseil de physique Solvay, 1933* (Paris, 1934), p. 303.

56. Heisenberg, Part II, p. 164. The "mass defect" is, in fact, negative, since the neutron is heavier than the proton.

57. E. Wigner, *Phys. Rev.* 43 (1933), 252–257. Wigner says that he expects his work to be applicable, whichever of the nuclear structure hypotheses are adopted. He mentions the ideas of several physicists, including Heisenberg, whose model he understands to employ elementary protons and electrons, but not neutrons.

58. In Enrico Fermi, *Collected Papers*, Vol. I (Univ. of Chicago Press, 1962), E. Segre, Ed. in Chief, the articles of ref. 4 are reprinted as items 76, 80a, and 80b, with an introduction by F. Rasetti, one of Fermi's earliest coworkers. The two articles published in 1934, one Italian
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and the other German, appear to be exact translations of each other, while the 1933 article is referred to as a “preliminary note”.

59. That the neutron was definitely heavier than a hydrogen atom (a proton plus an electron) was first shown by an experiment on the disintegration of the deuteron by γ rays: J. Chadwick and M. Goldhaber, Nature 134 (1934), 237–238; Proc. Roy. Soc. (London) A151 (1935), 479–493. This same experiment, the first photonuclear disintegration, also showed that the deuteron was “made of” a proton and a neutron. Recalling this experiment, Goldhaber said, “I remember being quite shocked when it dawned on me that the neutron, an elementary particle, as I had by the time already learned to speak of it, might decay by β emission with a half-life that I could roughly estimate . . . to be about half an hour or shorter . . .” “The Nuclear Photoelectric Effect, etc.” in Proceeding of a Symposium, etc., pp. 83–110 (ref. 36).

60. According to this, a neutrino and an electron must be present “at the proton” for the reverse of beta decay to occur. This process is evidently very rare. Fermi does not consider explicitly the possibility of positron beta decay, which was reported by the Joliot-Curies early in 1934, but presumably after Fermi had submitted his beta decay paper. Fermi’s theory, however, already implied a description of this process (as well as others, such as neutrino capture with positron emission, capture of an electron from an atomic K-shell, etc.); the application to the new type of radioactivity of the Joliot-Curies was made by G. C. Wick, Rend. Accademia dei Lincei (6) 19 (1934), 319–324.


62. G. Beck and K. Sitte, Zeit. f. Phys. 86 (1933), 105–119; ibid. 89 (1934), 259–260. Their theory assumed that the β-decay process begins with the virtual production of an electron-positron pair; one particle is then absorbed, while the other is emitted. This theory was for a time a strong competitor to Fermi’s. Recently Guido Beck wrote to me from Rio de Janeiro, agreeing that Fermi’s paper of 1934 brought about “one considerable improvement to our model, because it attributed to the lost particle, the neutrino, the rest mass zero . . . But, basically there is hardly a fundamental difference between saying that a particle (neutrino) exists but cannot be detected by experiments, or to say this particle is lost.” I am indebted to Professor V. L. Telegdi for the suggestion that Fermi might have disclaimed the use of the Dirac hole theory to emphasize his differences with Beck and Sitte.

63. See G. C. Wick, ref. 60. In ref. 1 Yukawa uses the term “anti-neutrino”.

64. Fermi was already an expert at this type of calculation, having lectured on it at the Symposium for Theoretical Physics of the 1930 Summer Session of the University of Michigan at Ann Arbor. Rev. Mod. Phys. 4 (1932), 87–132 (i.e. for the electromagnetic field).

65. The reference and a translation of the introduction are given in Appendix II.

66. See ref. 20, p. 155.


69. Now President of the Science Council of Japan and Director Emeritus of the Institute of Plasma Physics at the University of Nagoya. I am greatly indebted to Prof. Husimi for discussions in Tokyo in October, 1978.
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70. See ref. 30. Another excellent discussion of the period to about 1930 is Shigeru Nakayama, *Characteristics of Scientific Development in Japan* (four lectures given at and published by The Centre for the Study of Science, Technology and Development, CSIR, New Delhi, India, 1977).

71. See ref. 41. Sakata adds that at Osaka, a new Imperial University, "bureaucratism was not too marked". His remarks apply to both theoretical and experimental research. Another student of Yukawa, Minoru Kobayasi, agreed with the general thesis but said:

"Kyoto was known as a conservative university, but it was very open to new ideas and allowed young people to study them. Tamaki [the mentor of Yukawa and Tomonaga after their graduation] worked on relativity and hydromechanics and showed no interest in quantum theory, but he was generous to young people who worked on quantum theory."

72. Three months after his arrival, on 6 April 1929, Nishina wrote to Samuel A. Goudsmit, an old friend from Copenhagen days, whom he visited at Ann Arbor, Michigan, on his way home. He wrote that because of the 1923 earthquake, Tokyo was unrecognizable to him, and "At first it was interesting to see Japanese customs, houses and cloths [sic], but now they do not interest me any more." Nishina asks the news from Europe, "from which a great distance isolates me totally."


74. The late Tetu Hirose in "Social Conditions for Prewar Japanese Research in Nuclear Physics" (see ref. 30) stresses the support given to nuclear and cosmic ray research by the Japan Society for the Promotion of Scientific Research (Nihon Gakujutsu Shinkokai), established in December 1932. In particular their Subcommittee No. 10 (for cosmic rays) had funds to distribute to university chairs and to Riken which "were extraordinarily large for those days." With their support the number of papers related to nuclear physics that were presented at the Annual Meetings of the Physico-Mathematical Society of Japan grew from two in 1933 (one by Yukawa and one by Nishina and Tomonaga) to forty-two in 1942, the latter amounting to 25% of all papers presented at that meeting.

75. The importance of Riken was emphasized in discussions and workshops conducted in Japan during Sept.-Oct., 1978 and May, 1979 by a group of Japanese and American physicists and historians, including myself. The former Riken workers participating in these discussions included: M. Kobayasi, S. Tomonaga, M. Takeuchi, H. Tamaki, C. Ishii, O. Minakawa. The former Osaka University members participating included: Y. Tanikawa, M. Taketani, K. Husimi. Others involved were: Y. Nambu, Z. Maki, S. Hayakawa, R. Kawabe, M. Konuma, S. Nakamura, T. Takabayashi, Y. Fujimoto, and T. Tsuji. I wish to thank all of these collaborators and the National Science Foundation, USA, and the Japan Society for the Promotion of Science for grants supporting this work, and to thank the Research Institute for Fundamental Physics at Kyoto University and its Director Humitaka Sato for extending warm hospitality to me.

76. This was Hidehiko Tamaki, not Kajuro Tamaki, the Kyoto University professor who died in 1939 and was succeeded by Yukawa.

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78. This was a smaller private research foundation, begun in 1961 by Seiji Shiomi. See Itakura and Yagi, "The Japanese Research System", ref. 30.

79. See ref. 41.


82. Ig. Tamm, Nature 133, 981 (1934); D. Iwanenko, ibid., 981. The negative result of Tamm and Iwanenko did not chill the temptation. At the London Conference, 1934 [Papers and Discussions, International Conference on Physics, London, 1934 (Cambridge, 1935)], Bethe proposed a modification of Fermi's beta decay Hamiltonian, in part to obtain a stronger Heisenberg exchange force. In 1936, Bethe and Bacher (ref. 81) use a modified Fermi theory, containing derivatives of the fields (Konopinski-Uhlenbeck form); but they still obtain binding forces that are too weak. In spite of the gross disagreement, they maintain that "the general idea of a connection between $\beta$-emission and nuclear forces is so attractive that one would be very reluctant to give it up." (See also Mukherji, ref. 2, p. 34 for a discussion of this point). A. Nordsieck [Phys. Rev. 46 (1934), 234–5] calculates the scattering of neutrons by protons, assuming that the force is given by electron-neutrino exchange, and finds absurdly small cross-sections. Wick tries the same approach, intending to "shed a bit of light" on the proton's magnetic moment. [G. C. Wick, Rend. Accademia dei Lincei (6) 21 (1935), 170–173.] Assuming that the proton spends a certain fraction of its time virtually dissociated into neutron, positron, and antineutrino, it should have the large Bohr magneton, $e\hbar/2mc$ (rather than the nuclear magneton) during this time. By modifying Fermi's interaction, Wick claims to obtain reasonable values. His motivation is clear: "It would evidently be notable progress to be able to treat the exchange interaction and the theory of $\beta$ rays from a unified point of view." In some cases, ideas similar to those of Nordsieck and Wick were later applied in meson theory, with the meson replacing the electron-neutrino pair.

83. Unless otherwise indicated, quotations in this section and the following are from ref. 1.

84. The word scalar is used in the three-dimensional sense. Yukawa's nuclear potential transforms under Lorentz transformations as the fourth component of a four-vector, and not as a relativistic (i.e., four-dimensional) scalar. The $U$-quanta (or mesons) have spin zero, but are not what were later called scalar mesons.

85. More exactly, the said solutions (both the electromagnetic and nuclear ones) are valid except in the infinitesimal neighborhood of the origin. The physical interpretation (in either case) is that there is a point "charge" located at the origin.

86. In modern meson theory the nucleons are described (at least in principle) by the Dirac field, and the anomalous magnetic moments are considered to be a consequence of the interaction of the nucleons with the meson field.

87. More precisely, the field must have more than one real component. (Being complex is equivalent to having two real components.)
88. Yukawa calls these matrices $\tau_1, \tau_2, \tau_3$ (as they are usually designated today). Heisenberg's $\rho$-value corresponds to $\tau_3$, which has the value $+1$ for neutron, $-1$ for proton.

89. The spin plays no dynamical role in this, the first of the meson papers. Yukawa says he will ignore it for the heavy particles. It does enter in symmetry considerations.

90. The interaction energy $J(\gamma)$ is proportional to $g^2$, and the same sign of the "charge" $g$ (either positive or negative) must be used both for absorption and emission of the $U$-field, since $g$ is not associated with either proton or neutron state, but with their product.

91. The estimates are made by comparing certain predictions of the theory with experiment (e.g., the deuteron binding energy and the $n$-$p$ scattering cross-section). Yukawa acknowledges assistance from Tomonaga in making these comparisons.

92. See Heisenberg and Pauli, ref. 37; also ref. 61 and the text thereto. The second quantization of the $U$-field, which parallels the quantization of the electromagnetic field, leads to Bose-Einstein statistics for the $U$-quanta.

93. The connection between force range and the mass of its quanta is taken for granted today, but it was not obvious before Yukawa's work. Several years later, G. C. Wick gave an elementary discussion of this relation, based upon the uncertainty principle: Nature 142 (1938), 994.

94. Some readers may find it puzzling to consider the neutron and proton as a "pair", since they appear successively, rather than simultaneously. From the standpoint of quantum field theory, however, the important point is that a three fold product of field operators appears in the strong interaction, as it does in the weak. In the strong case, it is neutron-proton-$U$-quantum; in the weak case, it is electron-antineutrino-$U$-quantum. Three-particle interactions that involve the emission or absorption of a massive boson are generally called "Yukawa interactions".

95. In the internal conversion process an excited nucleus gives up its excitation energy to an atomic electron, the latter being ejected from the atom. A $\gamma$ ray is supposed to carry the energy and momentum from the nucleus to the atomic electron, but it is not observable. (We have corrected some obvious misprints in the text quoted from Yukawa).

96. $\psi_k$ and $\phi_k$ are relativistic field operators of spin $\frac{1}{2}$ neutrino and electron.

97. Yukawa and S. Sakata calculated the spontaneous half-life of the meson after seeing a letter in Nature, where this consequence of the theory was noted by Bhabha. (This is stated by Yukawa in the Wheeler interview, ref. 68. The letter in question is probably: H. J. Bhabha, Nature 141 (1938), 117–118).

98. G. H. Huxley, Nature 134 (1934), 418–419 and 471–472; T. H. Johnson, Phys. Rev. 45 (1934), 569–585. Johnson concluded from his observations that the primary cosmic radiation was "largely and probably exclusively positive".

99. Tanikawa, ref. 19.

100. See ref. 38 and the text thereto. See ref. 16, pp. 170–172 for another discussion of this point.

101. See L. M. Brown, ref. 44.

102. P. A. M. Dirac, "The Prediction of Antimatter", The 1st H. R. Crane Lecture, April 17, 1978 at University of Michigan, Ann Arbor.

103. There is an interesting analogy between the idea that different laws of physics apply at different space-time scales and the idea that science itself is culture-bound (or put otherwise, that "all science is ethnoscience").
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104. Heisenberg, to Pauli, April 5, 1938 (Pauli Letter Collection). Late in life he argued that we must learn to do without pictures, for “the antimony of the smallest dimensions is solved in particle physics in a very subtle manner, of which neither Kant nor the ancient philosophers could have thought: The word ‘dividing’ loses its meaning.” Werner Heisenberg, “The Nature of elementary particles”, Physics Today March 1976, pp. 32–39.


106. Brillouin afterwards remarks parenthetically that Yukawa’s hypothesis was “also arrived at independently” by E. C. G. Stueckelberg. This is claimed by Stueckelberg, in the second reference to Yukawa’s work, outside of Japan (ref. 9). After noting the cosmic ray evidence (ref. 10) for a “heavy electron”, the letter says: “The writer wishes to call attention to an explanation of the nuclear forces, given as early as 1934, by Yukawa, which predicts particles of this sort. Independently of Yukawa the writer arrived at the same conclusion…” This may be true, but it is not supported by an examination of Stueckelberg’s published works that precedes his letter to the Editor of the Physical Review. [These are as follows: Nature 137, (1936), 1032; Helv. Phys. Acta. 9, (1936), 389–404; ibid., 533–554; C.R. de la Soc. phys. et sc. nat. Genève 53 (1936), 64. (The last I have not seen.)] On the basis of the published record, Stueckelberg’s claim seems to be the following: A “unitary field theory” was proposed (quotations here are from the Nature letter) under the hypothesis “that positive electron, neutrino, positive proton and neutron are four different quantum states of one elementary particle.” Also: “Such an assumption would be trivial unless transitions between the different states occur.” The unitary field is then described by a 16 component Dirac spinor. Electromagnetic effects can be included “as soon as the neutrino theory of light can be formulated in a satisfactory way.” The nuclear exchange force, related to the neutron-proton transition is to be that of Majorana (ref. 53). The only reference to a new light charged particle appears in the second Helvetica article, on p. 534: “Man kann daher die Fermi’she Theorie formal analog der Wechselwirkung zwischen electromagnetischem Feld und Dirac-eletron behandeln.” (my emphasis). The particle is thus seen as a formal analogue of the photon, allowing the application to the Fermi theory of a previously developed form of perturbation theory. Stueckelberg’s theory of the nuclear force is thus a version of the “Fermi field” theory of nuclear forces. As befits a “unitary theory”, Stueckelberg has only one coupling constant, that of Fermi, and his theory lacks the strong coupling constant of Yukawa.


109. Shoichi Sakata was the son of Mikita Sakata, who was the secretary of Taro Katsura, Premier of Japan during the Russo-Japanese War.

110. See ref. 41. Also: W. Heitler and F. Sauter, Nature 132, (1933), 892.


113. See ref. 41.


115. Taketani, ref. 30.


119. This is the idea that the cosmic ray meson (muon) is a weakly interacting decay product of the Yukawa meson (pion). A complete documentation of this idea is lacking, and is being investigated. Since it is a complex question requiring a full study, I will merely remark here that it was first proposed in early 1942 by Yasutaka Tanikawa and discussed (in at least two versions) by him and others at the 41st Meeting of Riken on June 12, 1942. The history of the two-meson (and two-neutrino) theory is discussed by M. Konuma, *Soryushiron kenkyu (Particle Research)* 38 (1968), p. 482.

120. This idea is similar to Heisenberg's; see ref. 104.

121. See ref. 10 for the first announcements. For background and brief history see, e.g., Satio Hayakawa, *Cosmic Ray Physics* (Wiley Interscience, 1969), Chapter I. For additional material on this section see Mukherji, ref. 2.

122. Ref. 11. None of the first experimental papers mentioned Yukawa (not even the Japanese one). Yukawa's note pointed out: "The most important and at the same time inevitable consequence of the theory was that the field was to be accompanied by new sorts of quanta obeying Bose statistics and each having the elementary charge $+e$ or $-e$ and the proper mass $m_{\mu}$ about 200 times as large as the electron mass." Although there is no doubt that most (if not all) theoreticians assumed the muon to be Yukawa's meson, this played no role in its discovery. Thus S. H. Neddermeyer says "the muon, like the positron, was a purely experimental discovery in the sense that it was made entirely independently of any theoretical considerations of what particles should or should not exist." F. F. Deery and S. H. Neddermeyer, *Phys. Rev.* 121 (1961), 1803-1814, Note 1.


124. See ref. 105.