Hideki Yukawa and the meson theory

Some 50 years ago, in his first research contribution, a young Japanese theoretical physicist explained the strong, short-range force between neutrons and protons as due to an exchange of "heavy quanta."

Laurie M. Brown

A little over 50 years ago, Hideki Yukawa, a young Japanese theoretical physicist at the University of Osaka, proposed a fundamental theory of nuclear forces involving the exchange of massive charged particles between neutrons and protons. He called the exchanged particles "heavy quanta" to distinguish them from the light quanta of the electromagnetic field, but now they are known as pions, the lightest members of a large family of particles called mesons. These days, the meson theory seems to be a straightforward application of quantum field theory to the nuclear forces, but it could not have appeared so 50 years ago. Otherwise it would not have been invented by an obscure, unpublished Japanese physicist who had never even traveled abroad, but instead by one of the many Western physicists, some of them of great reputation, who were working on the theory of nuclear forces. Furthermore, Yukawa's paper was totally neglected for more than two years, although it was written in lucid English and published[1] in a respected journal of rather wide circulation. The meson theory has turned out to be an important paradigm for the theory of elementary particles, as seminal as Ernest O. Lawrence's cyclotron has been for its experimental practice. In this article I will trace the intellectual trail Yukawa followed to arrive at his theory, using unpublished documents that have recently been discovered among Yukawa's papers at Kyoto University. (These documents have been organized and cataloged in the Yukawa Hall Archival Library, and I am grateful to Rokuo Kawabe and Michiji Konuma for translations and comments.)

The problem of nuclear forces

The meson theory was the result of a powerful creative act. It incorporated a number of ideas that are common-

Hideki Yukawa, at right, with (from left) his father-in-law Genyo Yukawa, his mother-in-law Michi and his wife Sumi at their home in Osaka in 1932. (Photos illustrating this article courtesy Michiji Konuma; from reference 9, reproduced with permission of Sumi Yukawa.)

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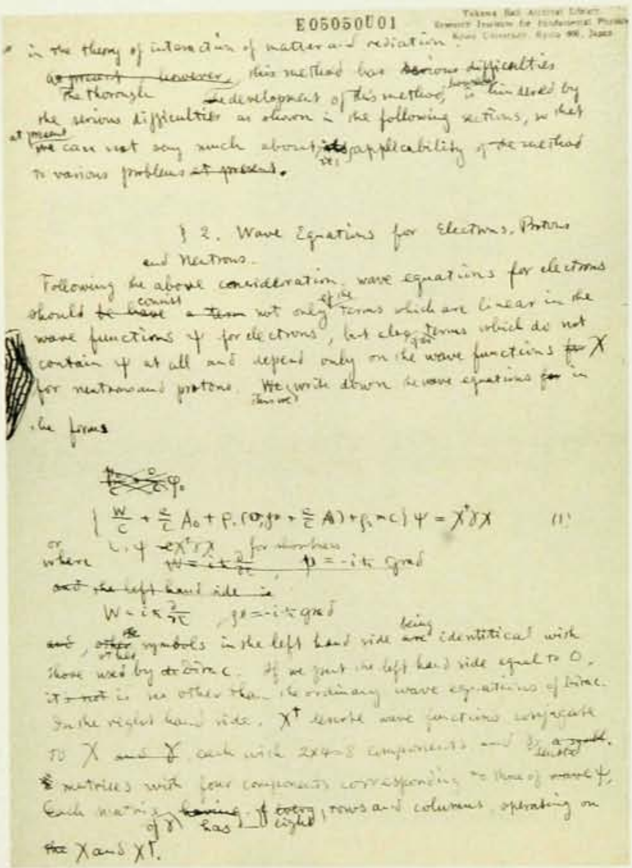

Manuscript page containing Yukawa's wave equation, based on the Dirac equation, for describing the intranuclear electron field having the nucleon-exchange current as a source. Equation 1 in the manuscript corresponds to equation 3 in the this article. (The documents illustrating this article come from the Yukawa Hall Archival Library, Kyoto University, courtesy of Ziro Maki.)

place today, but which were novel and surprising 50 years ago. These are some of the original features proposed by Yukawa:

▶ The nuclear binding force is transmitted by the exchange of massive charged particles (the heavy quanta).

▶ The range of the force is inversely proportional to the mass of the quantum.

▶ There are *two* nuclear forces, one strong and one weak, and hence two coupling constants.

▶ The weak interaction is also mediated by the exchange of the heavy quanta (charged intermediate bosons).

▶ The heavy quanta are unstable, decaying via the weak interaction.

It was a great achievement to propose such a bold solution for the nuclear-force problem, for it was difficult at that time even to grasp and to formulate the dimensions of the problem. At a symposium held in Minneapolis in 1977 on the subject of nuclear physics in the 1930s, Eugene Wigner remarked:[2]

> The disorientation in physics which existed ... [around 1932] is hard to imagine. We can remember it hardly more than we can remember the time when man's chief purpose was to hunt some animals, when he did not have chairs to sit in, did not have beds, did not have covers, did not have a jacket, did not have anything, not to mention that he did not have a radio to speak into. It is hard to remember that.

The physicist's view of matter before the discovery of the neutron was that everything, including the nucleus, consisted of protons and electrons and was held together by electric and magnetic forces.[3] In that picture, the nucleus of mass number A contained A positive protons and $A - Z$ negative electrons; the neutral atom had, of course, Z extranuclear electrons. Thus, matter was said to be made of pure electricity. Within this framework, quantum mechanics was scoring impressive successes in explaining phenomena that involved the extranuclear electrons, in fields such as spectroscopy, chemistry and magnetism, but the behavior of the intranuclear electrons was quite another matter. The mere presence of electrons in the nucleus seemed to violate important principles of physics. One problem, apparently insurmountable within the conventional framework of quantum mechanics, was that an electron, having low mass and confined within a space as small as a nucleus, would according to Werner Heisenberg's uncertainty principle have a kinetic energy so large that it would rapidly escape the nucleus. Another difficulty was that certain nuclei, those with an odd number of intranuclear electrons, should have had magnetic fields about a thousand times larger than that inferred from the hyperfine structure of atomic spectra. One such nucleus—nitrogen-14, with 14 protons and 7 electrons—should have had half-integral spin and obeyed Fermi–Dirac statistics, but was known to have integral spin and to obey Bose–Einstein statistics.

As early as 1920, Ernest Rutherford had suggested that there might exist a neutral nuclear constituent that he called the "neutron," consisting of a proton and an electron much more tightly bound than in the hydrogen atom. James Chadwick, working in the Cavendish Laboratory in Cambridge in 1932, assumed, when he discovered the neutron, that he had found Rutherford's composite neutron, which had been sought at the Cavendish for a decade. Chadwick did consider the possibility that his neutron was a new elementary particle, but said[4] that the idea had "little to recommend it."

Within a few weeks after Chadwick's announcement, Heisenberg wrote the first part of a three-part paper presenting[5] a theory of nuclear structure in which protons and neutrons were the principal constituents (*Bausteine*) of the nucleus, instead of the protons and electrons (and sometimes alpha particles) of the earlier models. (See the article by Arthur Miller, PHYSICS TODAY, November 1985, page 60.) Heisenberg did not challenge the idea that the neutron was composed of a proton and an electron, but by suppressing the electron degrees of freedom in his nuclear Hamiltonian he was able to construct the first genuinely quantum-mechanical nuclear theory. (Dmitri Iwanenko in Leningrad, at about the same time, suggested[6] treating the neutron as an elementary particle in the nucleus, but he does not seem to have developed a detailed theory of this type.) So far as nuclear systematics was concerned, Heisenberg treated the proton and the neutron as the charged and neutral states of a single entity, our present-day nucleon, and he introduced operators that changed the charge of the nucleon, turning neutrons into protons or vice versa. The force that he introduced between the proton and neutron had charge-exchange character, analogous to that in

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the hydrogen molecular ion H_2^+; the force between neutrons was analogous to the exchange force in the hydrogen molecule, but between protons, which Heisenberg regarded as elementary particles, there was only ordinary Coulomb repulsion. Thus in assigning forces Heisenberg clearly differentiated the "elementary" proton from the "composite" neutron. Nevertheless, despite its unsymmetric treatment of what we now call the nucleon doublet, Heisenberg's theory, especially as modified during the following year by Wigner and Ettore Majorana, is correctly regarded as the foundation of the modern phenomenology of nuclear structure.

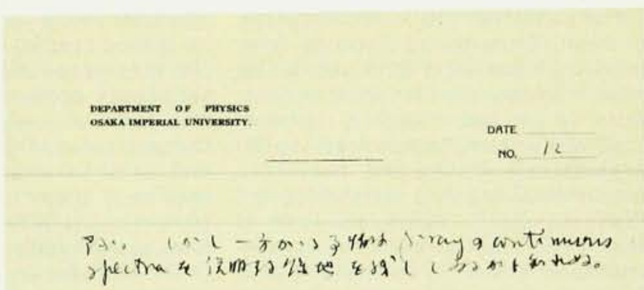
While Heisenberg had seized the opportunity presented by the discovery of the neutron to formulate a phenomenological theory of nuclear forces, he was not the sort of physicist who would sidestep the issues raised by the presence of composite neutrons (and hence, implicitly, electrons) in the nucleus. After all, to make a spin-$\frac{1}{2}$ neutron out of the proton and electron required the suppression of a half-quantum of spin. Furthermore, although Heisenberg was as sensitive as anyone could be to the further difficulties that arose from a model nucleus containing additional "loose" electrons, that is, those not bound in neutrons, his conception of beta-decay radioactivity and of the large radiative effects observed in cosmic-ray and certain laboratory gamma-ray experiments demanded[7] loose electrons in the nucleus. In this connection he said,[5] in part III of his three-part paper, that "the α particles in the nucleus must be built of protons and electrons (not protons and neutrons)" and that those electrons must add their contribution to radiative scattering to that of the "free nuclear electrons." Thus, about half of the contents of Heisenberg's three-part paper of 1932 was concerned with problems raised by the nuclear electrons and with the theory of the neutron itself as a proton–electron compound.

To summarize: In working out the systematics of nuclear structure, Heisenberg regarded the proton and the neutron as sisters, so similar that the exchange currents in terms of which he expressed his charge-exchange forces were formulated in terms of raising and lowering operators adapted from the Pauli spin matrices. Those are precisely the modern isospin operators, although Heisenberg employed them without the accompanying idea of the charge independence of nuclear forces. Nevertheless, he insisted that electrons of both the bound and loose varieties were present in the nucleus. This view so characterized Heisenberg's nuclear model that in 1933 Wigner, listing[8] "three different assumptions possible concerning the elementary particles" in the nucleus, began his list: "(a) The only elementary particles are the proton and the electron. This point of view has been emphasized by Heisenberg and treated by him in a series of papers."

Yukawa's first research

Yukawa graduated from Kyoto Imperial University in 1929, the first year of the Great Depression and a difficult time in which to find a job. He therefore continued to live with his family in Kyoto, where his father, Takuji Ogawa, was a professor of geography at the university. For three years, together with Sinitiro Tomonaga—his classmate, the son of a Kyoto philosophy professor, and a future fellow Nobel laureate—Yukawa worked as an unpaid assistant in the theoretical-physics research room of Professor Kajuro Tamaki. Intensely ambitious, he was afraid that he had arrived upon the physics scene too late to make a fundamental contribution to quantum theory. Much later, Yukawa wrote[9] in his autobiography, "As I was desperately trying to reach the front line, the new quantum physics kept moving forward at a great pace."

After his graduation Yukawa reflected that there were two outstanding problems facing physics. One was the structure of the nucleus. The other consisted of the questions of principle raised by Paul A. M. Dirac's relativistic electron theory, especially the puzzle



Yukawa's Green's function solution of the wave equation (equation 3 in the text) for the hypothetical Bose electron of mass m within the nucleus. (From document F01 010 U01.)

that the theory required negative-energy states, for which there appeared to be no meaning in the theory of relativity. With these problems in mind, Yukawa began to look into hyperfine structure, a small but observable splitting of atomic spectral lines. The effect was believed to be due to the action of the nuclear magnetic field on the extranuclear atomic electrons, the main influence being on those electrons that penetrate nearest to the nucleus and thus feel the strongest magnetic field. At the same time, because of the strong attractive electric field near the nucleus, those electrons would attain velocities near that of light. Thus the problems associated with electrons in or near the nucleus and the problems of Dirac's electron theory would be present at the same time, and Yukawa hoped they would shed light upon each other.

As it happened, Enrico Fermi in Rome was thinking along the same lines. He was an experienced and established theorist and, moreover, did not have to deal with Tamaki. When Yukawa handed his manuscript to Tamaki, the professor stored it in a safe place and said that he would study it when he had the time. Meanwhile, Fermi published[10] his treatment of the problem, discouraging Yukawa from pursuing it further or from considering what it might mean for nuclear structure, as he had originally planned. Instead, his attention was drawn to the appearance[11] of the first part of a monumental paper by Heisenberg and Wolfgang Pauli, which set forth a relativistic quantum theory of the electromagnetic field in interaction with Dirac electrons. That paper Yukawa later repeatedly called a partial "settling of accounts" and "in certain respects the final balance sheet of the quantum theory originated by Planck."

The account that needed settling was wave–particle duality. The quantum of action (Planck's constant) was introduced into physics by Max Planck in 1900 in his treatment of the spectrum of blackbody radiation. In 1905 Einstein showed that Planck's theory implied that electromagnetic radiation, whose behavior had been seen as fundamentally wavelike, must at times behave in ways that are particlelike. But waves and particles are conceptually incompatible, so Einstein's quantum theory gave rise to what was called the wave–particle paradox. After Niels Bohr's successful treatment of the hydrogen spectrum in 1913, Planck's quantum of action became recognized as setting the scale of quantum effects in matter as well as radiation. The mystery was only deepened by Louis de Broglie's conjecture that electrons have a wavelike nature in addition to their particulate properties, which was soon experimentally confirmed. By 1929, after the new quantum mechanics of Heisenberg and Erwin Schrödinger had resulted in a broad understanding of atomic phenomena, Yukawa felt that the time had come to make a fresh attack on resolving the wave–particle paradox.

Dirac had already in 1927 introduced methods that took into account the quantum nature of the electromagnetic field when calculating, for example, the spontaneous decay rates of atomic states (determining the intensity of the lines in atomic spectra), but Heisenberg and Pauli's 1929 paper was the first fully relativistic quantum theory of the electromagnetic field. Dirac had quantized only the transverse degrees of freedom of the field, those corresponding to free radiation, and he had left the static Coulomb potential in its classical form. Heisenberg and Pauli found a way to quantize both transverse and longitudinal components of the electromagnetic vector potential, as required in a fundamental relativistic theory. But they were discouraged to find that the theory predicted an infinite electron mass, as well as other infinities that contradicted observation. Finding and curing the source of those infinities became a major task of theoretical physics in the 1930s, a task that was at least provisionally accomplished only in the 1940s by the so-called renormalization program, in which Tomonaga played a leading role.

Partly out of disappointment over losing his unwitting race with Fermi on the hyperfine-structure problem, Yukawa applied his energy to quantum field theory, hoping that he could complete the "settling of accounts" that Heisenberg and Pauli had begun. In *Tabibito* he vividly describes[9] the frustration of his attack on the infinities of quantum electrodynamics:

> Each day I would destroy the ideas that I had created that day. By the time I crossed the Kamo River on my way home in the evening, I was in a state of desperation. Even the mountains of Kyoto, which usually consoled me, were melancholy in the evening sun. . . . Finally, I gave up that demon hunting and began to think that I should search for an easier problem.

The demons, in fact, continued to haunt him throughout the rest of his career. Even after the provisional solution of renormalization in the 1940s, he continued to regard the forging of a finite quantum field theory as the prime objective of theoretical physics, and he continued to investigate fundamental theories (for example, nonlocal field theory) that were alternatives to the accepted renormalized theories.

The meson theory

For the time being, however, Yukawa resolved to think of other matters. He saw Chadwick's announcement of the neutron and soon afterward read part I of Heisenberg's paper on the stucture of atomic nuclei. This rekindled his interest in the nuclear-force problem, although he was not prepared to accept a purely phenomenological theory such as Heisenberg's. An unpublished document of early 1933 by Yukawa is entitled[12] "On the problem of nuclear electrons. I." It is in English, and begins, "The problems of the atomic nucleus, especially the problems of nuclear electrons, are so intimately related with the problems of the relativistic formulation of quantum mechanics that when they are solved, if they ever be solved at all, they will be solved together." Nevertheless, recognizing the importance of Heisenberg's contribution, he prepared a summary in Japanese of the two parts of Heisenberg's paper that had appeared; it became his first publication, although his first published *research* was his later meson paper.

In introducing his summary, Yukawa discussed the strengths and weaknesses of Heisenberg's model, placing particular stress on issues of principle. He wrote:[13]

> 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 makeup 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 pres-

The Ogawa family. In front are Takuji, a professor of geography at Kyoto University, and his wife Koyuki; standing are (from left) Tamaki, Shigeki, Hideki and Masuki. Hideki adopted his wife's family name when he married Sumi Yukawa in 1932.

ent a definite view on whether neutrons should be seen as separate entities or as a combination of a proton and an electron, this problem, like the beta-decay problem ... 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.

During 1933, Yukawa argued in several unpublished documents that Heisenberg's program could be carried one step further toward a fundamental theory of nuclear forces and beta decay. However, that step made it necessary to treat the neutron as a truly elementary particle because, he said,[14] any treatment of its structure would lie "outside the applicability of present quantum mechanics." He attempted to formulate the Heisenberg charge-exchange force by analogy to quantum electrodynamics, taking the exchange of an electron between a neutron and a proton in the theory of the nuclear force as analogous to photon exchange between charged particles in QED.

In classical electrodynamics, the electric and magnetic fields are derived from a relativistic vector potential A_μ that obeys the wave equation

$$\Box A_\mu = j_\mu \qquad (1)$$

Here, $\Box$ is the d'Alembertian operator $\nabla^2 - \partial^2/c^2\partial t^2$. The four-vector charge–current density j_μ is regarded as the "source" of A_μ. In a region free of charges and currents j_μ vanishes, and equation 1 describes the free electromagnetic field. The equation holds also in quantum electrodynamics, with A_μ as the quantized electromagnetic field and j_μ the appropriate quantized charge–current density, for example, that of the Dirac electron–positron field.

What Yukawa did was to start from the Dirac relativistic electron equation, regarded as the free-field equation of the classical electron field,

$$D\psi = 0 \qquad (2)$$

where D is the 4×4 matrix Dirac differential operator (including the electromagnetic potentials) and ψ is the four-component Dirac relativistic spinor wavefunction of the electron. He then modified this equation by introducing on its right-hand side a source term J depending on the neutron and proton (regarded as the neutral and charged states, respectively, of the nucleon):

$$D\psi = J \qquad (3)$$

While the source term J has a form somewhat similar to the electromagnetic current j_μ, it is significantly more complicated: It is constructed out of an eight-component nucleon spinor and its adjoint, and it contains Dirac matrices that act upon the spinor as well as matrices that change a neutron into a proton or vice versa. While j_μ (like A_μ) transforms as a relativistic four-vector, J (like ψ) must transform as a relativistic spinor. That was an essentially new and problematic aspect, as Yukawa realized. In QED the same j_μ that is responsible for the exchange of photons between charges, accounting for forces, is also the source of free photons. But if J were to account for beta decay as well as nuclear forces, then beta decay would necessarily be nonconserving of energy and angular momentum, as in any theory where the electron emerges unaccompanied from the nucleus. Of course, that was the case in Heisenberg's theory as well; Yukawa was trying to construct a theory that would justify Heisenberg's phenomenology, and not necessarily one with different practical consequences.

Yukawa used the known properties of the Green's function for the Dirac equation (with the electromagnetic four-potential set to zero) and wrote a solution to equation 3 in the following form: A Dirac operator acts upon an integral that for vanishing electron mass is entirely analogous to the retarded potential due to the source J. Explicitly, for zero electron mass, the integral is

$$\int d^3r' \, \frac{J(\mathbf{r}, t - |\mathbf{r}' - \mathbf{r}|/c)}{|\mathbf{r}' - \mathbf{r}|}$$

Here $\mathbf{r}'$ is the source point, $\mathbf{r}$ is the field point, t is the time and c is the velocity of light. However, for an electron of mass m there is an additional exponential factor, with oscillating character, in the integral. In his manuscript, Yukawa says:[14]

> Substituting this solution into [the Hamiltonian] H, we find the interaction energy that corresponds to Heisenberg's "*Platzwechsel*" interaction. Its exact form and the retardation effect can be seen, and a factor
>
> $$\exp(i\rho_3 mc|\mathbf{r}' - \mathbf{r}|/\hbar)$$
>
> [ρ_3 is a Dirac matrix] appears as a kind of phase factor, so that the term corresponding to Heisenberg's [*Platzwechselintegral*] $J(r)$ has a form like the Coulomb field and does not decrease sufficiently with distance.

He is referring here to the most striking difference between the nuclear force and electromagnetism or gravitation: its short range of influence. In the expression Yukawa derived from the Green's function, the small length $\hbar/mc$ does appear in the exponent and sets the scale of oscillation of the "phase factor," but it does not limit the range of the force.

However, for a time in preparing the quantized-field version of the theory based on equation 4, Yukawa thought he had the kind of solution he was seeking. On 3 April 1933, he gave his first talk to a meeting of the Physico-Mathematical Society of Japan; in the published abstract of that talk, he claims[15] to have obtained the nuclear charge-exchange force of range $\hbar/mc$, where the mass m is that of the electron. This gives a range that would still have been about 200 times too large. Nevertheless, had the result been mathematically correct, it would have been highly suggestive, for a heavier "electron" would have given a shorter range. Yukawa later recalled that when he gave the talk at Sendai, Yoshio Nishina (of Klein–Nishina fame) actually proposed to him that he introduce a "Bose electron." But in the manuscript that he read at Sendai, he withdrew the promising result, saying,

> The practical calculation does not yield the looked-for result that the interaction term decreases rapidly as the distance becomes larger than $\hbar/mc$, unlike what I wrote in the abstract of this talk.

On the blank reverse side of the previous page is written, "mistaken conjecture."

Yukawa was trying to derive Heisenberg's nuclear theory from deeper principles. However, that theory contained the questionable feature that the emission of an electron by a neutron violated the conservation of angular momentum, whether the neutron was treated variously as fundamental or composite. Pauli had proposed as early as 1930 that the electron emitted in beta decay might be accompanied by a light, neutral particle of spin ½ (the neutrino), thus permitting the conservation of both linear and angular momentum, as well as energy. At the Solvay Conference of 1933, held in Brussels, he gave[16] his first public notice of the neutrino that he allowed to be published. Fermi also attended the conference, and upon returning to Rome made[17] a new, strikingly successful quantum field theory of beta decay that incorporated the neutrino.

At first Yukawa thought that Fermi had once again beaten him to the punch (as he had in the case of the hyperfine structure of spectral lines), for Yukawa had assumed with Heisenberg that the beta-decay interaction was the same as that responsible for nuclear forces. The success of Fermi's beta-decay theory suggested that the charge-exchange force might be implementable by the exchange of a *pair* of particles, namely an electron and a neutrino, rather than just a single electron. That would preserve all conservation laws. Yukawa began calculations along this line, as did Heisenberg and others. The first results using this approach were published[18] in independent letters to *Nature* by two Soviet physicists, Iwanenko and Igor Tamm. They both concluded that the Fermi field, as electron–neutrino exchange was called, could explain either the short range or the great strength of the nuclear binding force, but that the theory as formulated could not explain both simultaneously.

When Yukawa read the results of Tamm and Iwanenko in the fall of 1934, his explicit reasoning and subconscious intuition began to come together. As he recalled[9] in his autobiography:

> I was heartened by the negative result [of the Soviet scientists], and it opened my eyes, so that I thought: Let me not look for the particle that belongs to the field of nuclear force among the known particles, including the new neutrino. . . . When I began to think in this manner, I had almost reached my goal. . . . The crucial point came to me one night in October. . . . My new insight was that [the range of the force] and the mass of the new particle that I was seeking are inversely related to each other. Why had I not noticed that before? The next morning I tackled the problem of the mass of the new particle and found it to be about two hundred times that of the electron.

Within weeks, Yukawa completed the formulation of his theory and reported on it at a branch meeting of PMSJ in Osaka. On 17 November 1934, he spoke on it at the annual PMSJ meeting in Tokyo. Meanwhile, he prepared[1] a paper in English on his theory—his first original research paper—and submitted it to the *Proceedings of the Physico-Mathematical Society of Japan*.

Mesons and 'mesotrons'

Yukawa's article, which appeared in February 1935, aimed at nothing less than a quantum field theory that would unify the nuclear binding force and the nuclear beta-decay interaction. That is, he set out, in the light of the insight gained by the analyses of Tamm and Iwanenko, to modify the theories of Heisenberg and Fermi in such a way that they could be combined. The model for such a theory was QED; following that model closely had important heuristic and pedagogical advantages. His paper appears transparent and appealing to us now, and it remains something of a puzzle why it was entirely ignored for two years in both Japan and the West. Yukawa's work began to be noticed only in 1937, when a particle whose mass closely fit the requirements of meson theory was detected in cosmic rays.

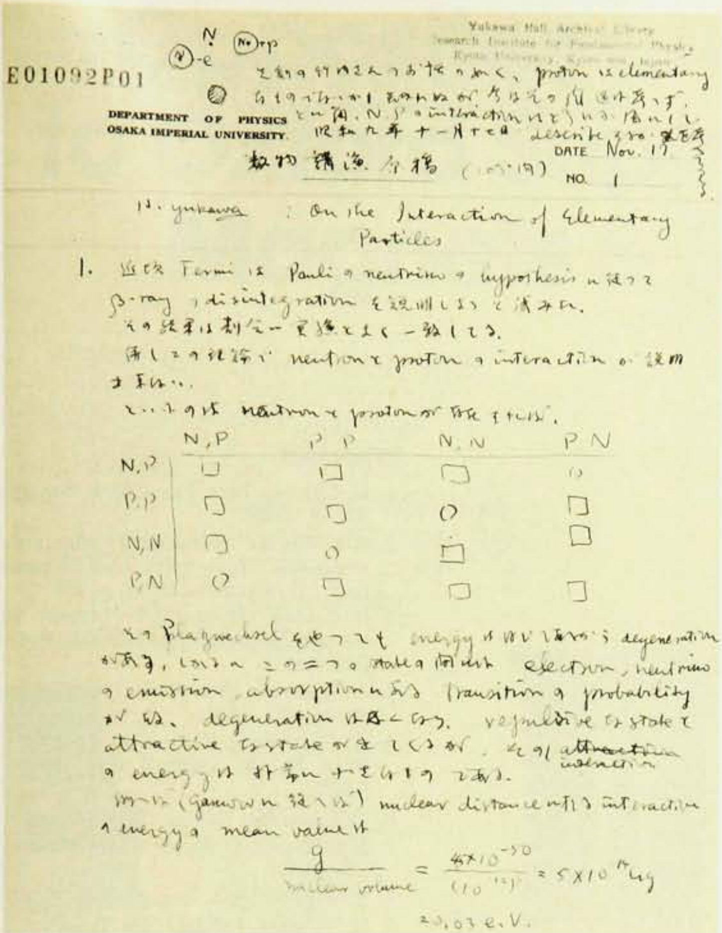
In his meson paper, Yukawa exploited the electromagnetic analogy from the outset, beginning with the "classical" theory. Generalizing d'Alembert's equation for the scalar potential of electromagnetism, which has the well-known static solution $1/r$ for a point source, Yukawa pointed out that a potential having a finite range, namely

$$U(r) = \pm g^2 \frac{e^{-\lambda r}}{r}$$

is a spherically symmetric static solution of the generalized wave equation

$$(\Box - \lambda^2)U = 0$$

He then introduced a source term J' on the right-hand side of this equation,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DEPARTMENT OF PHYSICS
OSAKA IMPERIAL UNIVERSITY

DATE Nov. 17

NO. 1

H. Yukawa : On the Interaction of Elementary Particles

Notes for Yukawa's talk on meson theory at a meeting of the Physico-Mathematical Society of Japan on 17 November 1934. This talk introduced the meson theory of nuclear forces. (Document E01 092 P01.)

something like the source term J of equation 3. However, in this case the particle to be created has the transformation character of U—that is, it transforms like the electromagnetic scalar potential rather than a spinor. (I shall refer to Yukawa's U particle, which has no spin, as a "scalar" particle even though it does not transform as a Lorentz scalar.)

The new source term J' is constructed of nucleon spinors (as J had been) in such a way that the emission of a negatively charged particle corresponds to the transition neutron to proton, while the emission of a positively charged particle corresponds to the transition proton to neutron. Yukawa sought a solution analogous to that given in equation 4, and he obtained nearly the same result, but with an important difference: The exponential factor that appears when the mass m of the U particle is not zero here has the form

$$e^{-\mu|\mathbf{r}'-\mathbf{r}|}$$

The factor μ is determined from the change in energy $W_N - W_P$ in the transition of the heavy particle (what we now call a "nucleon") from neutron to proton by emission of a positive U particle (a meson):

$$\mu = \sqrt{\lambda^2 - (W_N - W_P)^2/\hbar^2c^2}$$

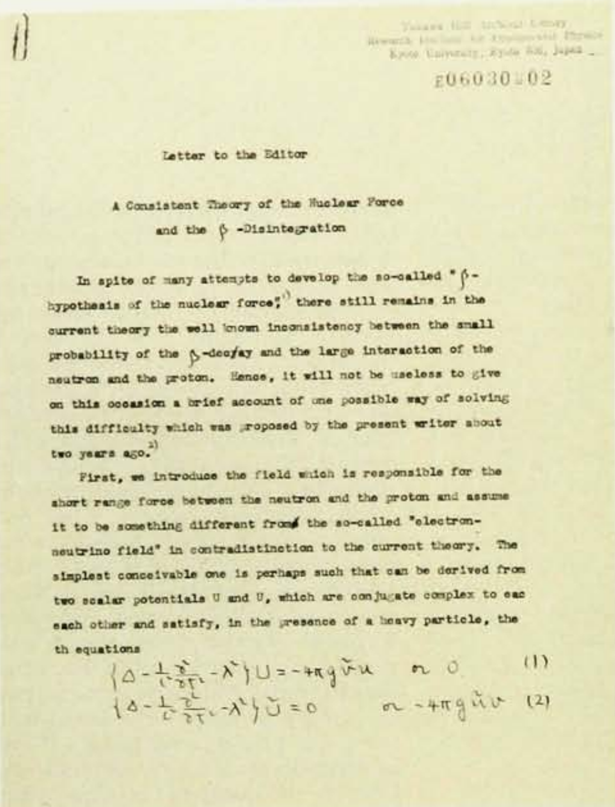
Thus, providing the energy difference is less than $\lambda c\hbar$, the exponential is a decreasing function of $|\mathbf{r}' - \mathbf{r}|$, and not the oscillating one found earlier in connection with the electron-emission theory. Upon quantizing the U field, Yukawa showed immediately that the quantity λ is $mc/\hbar$, so that the range of the force is inversely proportional to the mass of the U quantum. (That was the insight that crystallized the meson theory in Yukawa's mind that sleepless October night in 1934. While the range–mass relation is today so commonplace as to seem self-evident to most physicists, that was not the case in the 1930s. As late as 1938, the well-known Italian physicist Gian Carlo Wick took the trouble to present[19] an *anschaulich* explanation of Yukawa's result.)

Yukawa also assumed that the U field (or equivalently, the U quantum) was coupled to an additional charge-changing current constructed analogously to J' but with the electron and neutrino replacing the proton and neutron. Thus he made the meson an "intermediate boson," carrying the weak as well as the strong interaction. The very notions of strong and weak nuclear interaction were not part of the general thinking before Yukawa made his meson theory. On the contrary, as we have seen, Heisenberg tried to make the beta decay and the nuclear charge-exchange forces the same; that is, he characterized them by a single coupling strength. After Fermi's beta-decay paper appeared, the same single-coupling idea was carried over into the so-called Fermi-field approach to nuclear forces. However, Yukawa introduced one large constant, g, and another small one, g', so that the decay amplitude of a neutron, say, into a proton, electron and neutrino was proportional to gg'. If one substituted for Fermi's coupling constant g_F the quantity $(4\pi/\lambda^2)gg'$, then, Yukawa pointed out, his theory of nuclear beta decay was effectively equivalent to Fermi's.

There was, however, an important additional consequence of Yukawa's assumption that the meson had a beta-decay interaction. It implied that the meson itself would decay radioactively if it were produced in a free state (that is, not bound in the nucleus). Curiously, Yukawa and his associates ignored this fact until 1938, when the Indian physicist Homi J. Bhabha pointed out[20] that important prediction of the theory. The short mean lifetime of the meson is the main reason why such particles are not found in abundance on the Earth.

The question of why mesons were not commonly observed was raised at Yukawa's first presentation of the theory, at one of the informal luncheon meetings of the nuclear-physics group at Osaka Imperial University, which Yukawa regularly attended. Yukawa responded that an energy sufficient to create a meson was required, that is, at least its rest energy of about 100 Mev, and such energies were in those days not available in the nuclear-physics laboratory. The only terrestrial anvil on which such a particle could be forged was the atmosphere, the hammer being the cosmic rays; Yukawa suggested to his experimenter colleagues at Osaka that they should look for U quanta in cosmic-ray cloud-chamber photographs.

In the *Physical Review* of 15 August 1936, Carl Anderson and Seth Neddermeyer published photographs of parti-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Letter to the Editor

A Consistent Theory of the Nuclear Force
and the β -Disintegration

In spite of many attempts to develop the so-called "β-hypothesis of the nuclear force",[1] there still remains in the current theory the well known inconsistency between the small probability of the β-decay and the large interaction of the neutron and the proton. Hence, it will not be useless to give on this occasion a brief account of one possible way of solving this difficulty which was proposed by the present writer about two years ago.[2]

First, we introduce the field which is responsible for the short range force between the neutron and the proton and assume it to be something different from the so-called "electron-neutrino field" in contradistinction to the current theory. The simplest conceivable one is perhaps such that can be derived from two scalar potentials U and Ũ, which are conjugate complex to eac each other and satisfy, in the presence of a heavy particle, the th equations

$$\left\{\Delta - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \lambda^2\right\} U = -4\pi g \tilde{\psi} u \quad \text{or } 0 \qquad (1)$$

$$\left\{\Delta - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \lambda^2\right\} \tilde{U} = 0 \quad \text{or } -4\pi g \tilde{u} v \qquad (2)$$

First page of Yukawa's rejected letter to *Nature* suggesting that particles observed in cosmic rays might be the mesons of his theory. The letter was sent on 18 January 1937. (From document E06 030 U02, Yukawa Hall Archival Library.)

cle tracks obtained in a cloud chamber operated in the field of a strong magnet atop Pike's Peak in Colorado. In some cases they could not positively identify the tracks as belonging to either electrons or protons. Yukawa wrote a letter to *Nature* pointing out that it was "not altogether impossible" that the ambiguous particles were his heavy quanta. That letter was rejected by the editor, but Yukawa succeeded in publishing[21] a "Short note" having the same contents in the *Proceedings of the Physico-Mathematical Society of Japan* in July 1937. By then, several experimental groups had reported[22] the observation of particles of both signs of electric charge and of mass between that of the electron and the proton, at roughly one-tenth of the proton mass.

The observations of the new cosmic-ray particles, which came to be called mesotrons, aroused[23] interest in Yukawa's theory. Yukawa and his students at Osaka had not been idle during the more than two years during which no one had paid attention to the heavy quantum. With Shoichi Sakata, Yukawa used the meson theory in a calculation of the K-capture process. That weak-interaction process had not been observed, but its existence had been suggested by the Austrian physicist Guido Beck, who visited Japan in 1935. By mid-1936, Yukawa had already begun to reformulate[24] the meson theory using the Pauli–Weisskopf relativistic theory of scalar particles. (Pauli liked to call his theory "anti-Dirac" because it flouted some of the basic assumptions Dirac made in deriving his relativistic electron theory. Dirac's work had been interpreted to imply that fundamental particles had to have spin ½.)

After the mesotron discovery, Yukawa and his students redoubled their efforts and soon became engaged in the development of the theory and its consequences, a process that so closely paralleled similar efforts in the West that one of the chief Western meson theorists, Nicholas Kemmer, later referred[25] to the Japanese and the Western efforts as a "joint enterprise." The mesotron turned out to be the second-generation heavy electron that we now call the muon, and the true meson of Yukawa, the pion, was found in cosmic rays only in 1947. That is another story, of course, one well worth the telling.

Fifty years later, the meson theory is still alive and well. In spite of its grandeur, today's standard model has not been able to calculate "low-energy" processes, such as meson–nucleon scattering, or the nuclear forces. But even when that becomes possible, Yukawa's meson will still be a shining star.

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References

1. H. Yukawa, Proc. Phys.-Math. Soc. Jpn. **17**, 48 (1935).
2. E. P. Wigner, in *Nuclear Physics in Retrospect*, R. Stuewer, ed., U. of Minnesota P., Minneapolis (1979), p. 160.
3. G. Gamow, *Constitution of Atomic Nuclei and Radioactivity*, Oxford U. P., Oxford (1931).
4. J. Chadwick, Proc. R. Soc. London, Ser. A **136**, 692 (1932).
5. W. Heisenberg, Z. Phys. **77**, 1 (1932); Z. Phys. **78**, 156 (1932); Z. Phys. **80**, 587 (1933).
6. D. Iwanenko, Nature **129**, 1312 (1932).
7. L. M. Brown, D. Moyer, Am. J. Phys. **52**, 130 (1984).
8. E. Wigner, Phys. Rev. **43**, 252 (1933).
9. H. Yukawa, *Tabibito* (The Traveler), L. M. Brown, R. Yoshida, trans., World Scientific, Singapore (1982).
10. E. Fermi, Nature **125**, 16 (1930); Z. Phys. **60**, 320 (1930).
11. W. Heisenberg, W. Pauli, Z. Phys. **47**, 1 (1929).
12. Document E05 030 U01, Yukawa Hall Archival Library, Kyoto University.
13. H. Yukawa, J. Phys.-Math. Soc. Jpn. **7**, 195 (1933).
14. Document E05 060 U01, Yukawa Hall Archival Library, Kyoto University.
15. H. Yukawa, Bull. Phys.-Math. Soc. Jpn. **7**, 131A (1933).
16. See, for example, L. M. Brown, PHYSICS TODAY, September 1978, p. 23.
17. E. Fermi, Ric. Sci. **4**(2), 491 (1933); Nuovo Cimento **2**, 1 (1934); Z. Phys. **88**, 161 (1933).
18. I. Tamm, Nature **133**, 981 (1934). D. Iwanenko, Nature **133**, 981.
19. G. C. Wick, Nature **142**, 994 (1938).
20. H. J. Bhabha, Nature **141**, 117 (1938).
21. H. Yukawa, Proc. Phys.-Math. Soc. Jpn. **19**, 712 (1937).
22. S. H. Neddermeyer, C. D. Anderson, Phys. Rev. **51**, 884 (1937). J. C. Street, E. C. Stevenson, Phys. Rev. **51**, 1005 (1937). Y. Nishina, M. Takeuchi, T. Ichimiya, Phys. Rev. **52**, 1198 (1937).
23. J. R. Oppenheimer, R. Serber, Phys. Rev. **51**, 1113 (1937). E. C. G. Stueckelberg, Phys. Rev. **52**, 41 (1937).
24. Document E02 130 P12, Yukawa Hall Archival Library, Kyoto University.
25. See N. Kemmer, Biog. Mem. Fellows R. Soc. **29**, 661 (1938). □