Journal of Cosmology, Vol.26, No. 35, pp. 16200 – 16247

New (and Old) Light on the Vexed Question of Pion Mass

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Part One: Those Mysterious Pions (1935-1962)

Summary

Part One is of a historical nature, commencing with the prediction of the meson by Hideki Yukawa in 1935 and following the evolution of discussion and concepts over the succeeding 27 years in the physics community. An account of these early concepts, some of which were subsequently neglected, is a necessary prelude to a consideration of how there remain many unanswered questions and there may exist many surprising new things to say which echo anxieties and concerns expressed in the early period. As Yukawa himself said in 1966, there are still many things that need to be remedied in quantum physics, and we may even need a "new" one. These thoughts will inspire a much wider discussion in subsequent Parts which goes far beyond the issues which concern the strong nuclear forces.

"The origin of mass and mass spectra is one of the oldest and most elusive problems. Actually the situation has gotten worse as the fundamental particles have proliferated, their masses showing no precise regularities. Clearly mass is a dynamical quantity governed by self-energy effects. … Since divergent quantities like self-energy are a reflection of very short distance properties of dynamics, the problem of mass may be the last thing we can understand. At the same time, however, it may supply us with the keys to the short distance physics." **– Professor Yoichiro Nambu, in his closing address to the 1982 Solvay Conference on Higher Energy Physics at Austin, Texas.**

***Author's Note*: This paper is an excursion into the history of, and new developments in, short distance physics, and the startling implications of the mass of the pion for much wider issues involving the entire Universe.**

Mesons, as mediators between protons and neutrons, were first predicted in 1935 by Hideki Yukawa[1] and confirmed in 1947 after detection in cosmic rays by Lattes, Muirhead, Occhialini, and Powell[2]. Previously, "heavy electrons" had been posited by some scientists for the role of mediators between the nucleons, but Yukawa was able to demonstrate that a new particle, somewhat heavier than an electron but nevertheless *not* an electron, was required. Yukawa's paper was published in February of 1935, having been translated into English and delivered first as a lecture at Kyoto University in November of 1934. (Yukawa's former classmate and colleague Sin-Itiro Tomonaga, who later won the Nobel Prize for Physics in 1965, records that earlier: "… in 1933 Yukawa told me of his idea … by drawing a formula with a stick on the ground of the athletic playing field."[3]) The paper was published in a well-known Japanese journal which was not familiar in the West, and for two years there was no reaction or response. Even then, his idea did not meet with a good initial reception. One of the first western scientists to pronounce upon it was Robert Oppenheimer, and he rejected it out of hand.

It is worthwhile to say a few things about Yukawa as a person. He was only 27 years old at this time. He was a shy man with a quiet voice, so that it was hard to hear him giving a lecture unless one was seated up front. But despite his manner and his voice, he had a great deal of scientific ambition and immense self-confidence. He could survive any amount of opposition and criticism. But he also knew how to absorb constructive criticism, and did so without any hesitation. When putting forward his own ideas he did not hesitate to take issue with Heisenberg and other famous scientists, but stuck to his guns if he thought they were way off beam, and was not afraid to justify himself.

From the very beginning, it was recognised that the meson must have a rest mass at least 100 times that of the electron. That was Yukawa's first estimate. Later he revised that opinion and said that the meson apparently had a rest mass of approximately 200 times that of the electron. He said it had to have a mass of approximately that value in order to counteract the Coulomb Forces between the nucleons. The potential of the Coulomb force was known to be e^2/r. There was a force range of $1/k$, which he put at the familiar 10^{-13}. The kinetic energy required for the nucleon to come out of the nucleus was 10^8 eV.

After μ mesons were discovered in cosmic rays, Yukawa's mesons took on the name of "π mesons", and this was shortened to "pions", which is how they are known today. (A curious detail to note here is that the Japanese, when publishing in English, for some time shortened "π meson" to "π-on" before they abandoned the Greek letter altogether and adopted "pion".)

In June of 1939, Hans Bethe went into print in *The Physical Review* with an article entitled "The Meson Theory of Nuclear Forces".[4] In this article, Bethe did not mention Yukawa at all, and it has been suggested that he was not yet aware of him, though he does mention some other Japanese, as we shall see in a moment. Bethe says: "The meson theory of nuclear forces predicts two kinds of interactions between heavy particles (protons and neutrons). The first kind does not depend upon the spin of the heavy particles … and there will (also) be a spin-dependent force, $V = V_1 + V_2$ ... The spin-dependent interaction has been split into one part, V_1, which does not depend upon the relative position of the two particles (direction of r), and another part, V_2, whose average over all directions of r gives zero. It is usually argued that the latter part has no influence on spherically symmetrical states such as the ground state of the deuteron ..."

Bethe's main preoccupations in this article are, firstly, the simplification of nuclear forces, and secondly, the mass of the meson. Concerning the first, Bethe was pleased that V_1 meant that only a single force was operating between the nuclear particles "instead of the four different forces (Wigner, Majorana, Heisenberg, and Bartlett) used previously."

As for the question of the particle's mass, he says: "The meson mass was taken equal to 177 electron masses, in approximate agreement with the latest determination of [Yoshio] Nishina, [Tokio] Takeuchi, and Ichimiya (170±9)." This is the only mention of Japanese scientists in the article; the reference is to their article in *The Physical Review*, Volume 55, 1939, p. 1130. Bethe stresses that he likes the mass estimate of 177 best for this reason: "The value 177 is convenient for calculation because it makes $h/\mu c$ equal to one-half of the 'radius' of the deuteron." That was a very fine bit of imaginative thinking, though it turned out not to be true, because we now know that the mass is significantly different from that figure.

The best source of historical information on the origin and earliest days of pions is the book published in 1985 to celebrate the 50th anniversary of Yukawa's original paper. This book was the *Proceedings* of a conference, nicknamed MESON50, held for this purpose in Kyoto.[5] This book is extremely rare, and for instance at the time of writing there is no copy for

sale anywhere in the world, according to my internet searches. I am thus very fortunate to have a copy of this rare compendium of irreplaceable information.

Some details of these early days have recently, in 2023, been recounted by N. D. Hari Dass of the Raman Research Institute in India. His lecture notes have been printed in an anthology.[6] However, Dass seems to have been unable to obtain the correct name of the Japanese journal in which Yukawa published his discovery in 1935. In his reference Dass calls it "Prog. Theor. Phy." But "Prog" is a mistake for "Proc", referring to *Proceedings.* He refers to this same journal in other footnotes but always calls it "Prog." There is a well-known journal called *Progress in Theoretical Physics*, but that is the wrong journal in this case. Dass mistook references which had been to the *Proceedings* of a Japanese journal as seen in the endnotes here.

I have also been able to acquire the late Abraham Pais's personal file of Hideki Yukawa's offprints, which were sold by Pais's widow after his death. These offprints were given to Pais by Yukawa, who was his friend. There are 12 printed offprints and one typed one. Three of them are dated 1938 and were published in Japan (but are in English). I shall not enter all the papers from Pais's file into the endnotes for this paper, but instead I shall list them and extracts and comments in the main text now.

1. **Hideki Yukawa, Shoichi Sakata, and Mitsuo Taketani, "On the Interactions of Elementary Particles. III", *Proceedings of the Physico-Mathematical Society of Japan*, 3rd Series, Volume 20, Number 4, April, 1938, pages 319-340. (Read Sept. 25, 1937, and Jan. 22, 1938. Received March 15, 1938.) (On page 328 Pais has made extensive hand annotations and corrections to (34) in this paper.)**
2. **Hideki Yukawa, Shoichi Sakata, Minoru Kobayashi, and Taketani, "On the Interactions of Elementary Particles. IV", *Proceedings of the Physico-Mathematical Society of Japan,* 3rd Series, Volume 20, Number 9, September, 1938, pages 720-745. (Read May 28, 1938. Received August 5, 1938.) (On page 740 Paris has added a marginal note concerning (73) where he refers to page 84 of a paper by B …, a name which is unclear. There is also an annotation in the margin of page 721 mentioning the "photomeric effect" when there is a reference of a light quantum being absorbed by a neutron.)**
3. **Hideki Yukawa and Shoichi Sakata, "The Mass and the Life-Time of the Mesotron", *Proceedings of the Physico-Mathematical Society of Japan*, 3rd Series, Volume 21, Number 3, March, 1938 [1939], pages 138-140. (*This offprint has a misprint for the date on its cover; 1938 should really be 1939; Part IV above appears in its footnotes. When this***

***paper was reprinted in 1955, the date of the original was corrected to 1939. A pdf of the 1955 reprint can be downloaded from the internet.*)**

4. **Hideki Yukawa, "Models and Methods in the Meson Theory", *Reviews of Modern Physics*, Volume 21, Number 3, July, 1949, pages 474-479. (There are no works referenced in the footnotes to this paper which are earlier than 1940.)**
5. **Hideki Yukawa, "On the Radius of the Elementary Particle", *The Physical Review*, Volume 76, Number 2, July 15, 1949, pages 300-301 (page 301 is missing and was presumably blank, as the author's thanks and final footnotes are on page 300.) (Received June 2, 1949.)**
6. **Hideki Yukawa, "Remarks on Non-local Spinor Field", *The Physical Review*, Volume 76, Number 11, December 1, 1949, page 1731. (Received October 19, 1949.)**
7. ***Original typescript*: Hideki Yukawa, Letter to the Editor of the Physical Review, "S-Matrix in Non-local field Theory", submitted January 23, 1950, to *The Physical Review*.**
8. **Hideki Yukawa, "Elementary Particles and Space-Time Structure", *Annals of the Japan Association for Philosophy of Science*, Volume 1, Number 2 [1956], pages 91-100. ("This article is based on a lecture given at the sixth meeting of Nobel Prize Winners at Lindau, Germany, June 26, 1956.")**
9. **Hideki Yukawa, "Special Theory of Relativity and the Structure of Elementary Particles", *Progress of Theoretical Physics*, Volume 16, Number 6, December, 1956, pages 688-690. (Submitted October 19, 1956.)**
10. **Hideki Yukawa, "Introductory Remarks on Meson Theory", *Reviews of Modern Physics*, Volume 29, Number 2, April, 1957, pages 213-215.**
11. **Yasuhisa Katayama, Eiji Yamada, and Hideki Yukawa, "Internal Structure and Symmetry of Elementary Particles. III", *Progress of Theoretical Physics*, Volume 33, Number 3, March, 1965, pages 541-542. (*Two copies.*)**
12. **Hideki Yukawa, "Space-Time Description of Elementary Particles", *Proceedings of the International Conference on Elementary Particles*, Kyoto, 1965, pages 139-158.**
13. **Hideki Yukawa, "Atomistics and the Divisibility of Space and Time", *Progress of Theoretical Physics*, Supplement Numbers 37 & 38, 1966, pages 512-523.**

Comments on the above papers, by number:

First and Second papers: These are parts III and IV of a four-part paper sharing the same title but extending over several years. Fortunately, all four of these were reprinted in 1955 and pdfs of the reprints may be

downloaded from the internet. Part I was by Hideki Yukawa alone and was read on November 17, 1934. This was before his famous paper of 1935 predicting the pion. At this stage, he was suggesting not an intermediate particle but a spherical force field which he called the *U*-field because he had designated it by the function *U*(*x, y, z, t*). He says: "it describes the field between the neutron and the proton" and "In the presence of the heavy particles, the *U*-field interacts with them and causes the transition from the neutron state to the proton state". And he adds: "This function will satisfy an equation similar to the wave equation for the electromagnetic potential." Three years later, on September 25, 1937, Yukawa and his colleague Shoichi Sakata, read their joint paper which was Part II of the series. They continue to discuss their new field theory". They say they will make it more complete in Part III. Meanwhile they wish to simplify it by viewing the *U* potentials "as four dimensional scalars instead of time components of four vectors". They believe that when the neutron changes to the proton state there is a simultaneous emission of "a quantum of negative charge" and when the proton changes to the neutron state there is a simultaneous emission of "a quantum of positive charge". They say that "the interaction between the neutron and the proton can be described by the exchange force of a Heisenberg type." They refer to the "new particle" which Yukawa had predicted and say it seems that it has a mass "about 130 (± 25 %) times the electron mass". This brings us to Part III, published a year later by Yukawa, Soichi Sakawa, Minoru Kobayashi, and Mitsuo Taketani, in September, 1938. The paper begins: "In two previous papers, the interactions of elementary particles was discussed by introducing a new field of force. On quantizing this field, we obtained new quanta, obeying Bose statistics, each with the elementary charge either positive or negative and the mass m_u, … This field was described by two four vector functions complex conjugate to each other in I. whereas it was described by two scalar functions in II. These formulations were adopted for the sake of simplicity, but neither of them was ample enough for the derivation of complete expressions for the interaction of the heavy particles and their anomalous magnetic moments. In this paper, we begin with the construction of the linear equations for the new field, which can be considered as a generalization of Maxwell 's equations for the electromagnetic field. The field is thus described by two four vectors and two six vectors, which are complex conjugate to each other respectively." Many pages then follow of formalisms attempting to find the suitable equations for the *U*-field. A footnote mentions that the mass of the "new particle" which they identify with the heavy quantum in their theory [*later to be known as the pion*] may have a value of 120 or 130, according to recent cosmic ray work. They say more details can be expected in the next paper. Part IV is by the same four authors and was read May 28, 1938, and was

published in September, 1938. This lengthy paper contains much formalism and discussion of numerous issues too extensive to summarize. A note added in proof says a cosmic ray study by Neddermeyer and Anderson suggests a mass for what we now call a positive pion of 240 and shows the annihilation of it by emitting a positron.

Third paper: This brief paper is by Yukawa and Sakata. The concentration here is not on the *U*-field but on what they now call the mesotron. They assume its mass to be 200, but again say it could be between 100 and 200. And they are specially concerned with the lifetime of the mesotron.

(All of the above papers published in Japan were later ignored, as if they had never appeared.)

Fourth paper: Eleven years after the last paper above, Yukawa published this paper concerning what he now called meson theory. Yukawa admits that the meson now takes the place of the *U*-field (although at the end of the paper he makes it clear he still believes there is a pion field). He now knows from cosmic ray work by others that there are two kinds of meson, and that the π- meson, being the heavier, has a mass of about 300. These can "interact strongly with nucleons and can decay spontaneously into μ-mesons with a lifetime of the order of 10^{-8} sec." He then goes into a discussion of the spins of the two main types of mesons. He says the pions must have an integral spin and when captured by a nucleon most of their rest energy of about 130 Mev is transferred as kinetic energy to nuclear particles "accompanying the disruption of the whole nucleus". But as for the μ- mesons, they can have a spin of ½. He bemoans the present state of ignorance: "Thus, the situation of the meson theory on the whole is not so bad as it was a few years ago. However we are still at a stage of accepting different kinds of mesons, which have been discovered one after another, only as such. We know nothing about the fundamental law determining the masses of various kinds of elementary particles, which seem to us to be so irregularly distributed. We know also very little about the law, which guarantees the stability of the whole system of elementary particles interacting with each other and changing from one to another."

Fifth paper: This brief paper by Yukawa records the friendly connection between him and Abraham Pais, in particular thanking Pais for allowing Yukawa to see some unpublished results. Yukawa records that according to Pais, the theory of non-localizable field with non-zero mass could be formulated in the usual four-dimension space. Yukawa is still talking about his *U*-field and its scalar *U* operator. In fact he says: "… the whole field *U* can be regarded as a field theoretical representation of an assembly of elementary particles with the same mass *m* and the radius λ, which move without any change in their form except the Lorentz contraction associated with the change of the proper time axis. …Whether a consistent field theory can be constructed from the above model is, of course, an open

question." Yukawa thanks Robert Oppenheimer, George Uhlenbeck, and Pais for discussions and promises more material in further papers.
Sixth paper: This is a very short note by Yukawa. Yukawa writes affirming his belief that "quantized non-local fields could be so constructed as to represent assemblies of particles with definite mass and radius". And he says he will be publishing more details. But here he wishes only to address the case of a non-local spinor field. He then briefly records his latest thinking about this and gives the math.
Seventh paper: This is in typescript form and was clearly handed to Pais by Yukawa personally. It begins: "Recently, the present author discussed certain types of quantized non-local fields, which were supposed to correspond to assemblies of elementary particles with finite radii. In order to deal with the system consisting of two non-local fields, or a local field and a non-local field, which interact with each other, one must first find the substitute for the Schrödinger equation for the total system. However, it is naturally anticipated that the S-matrix in local field theory, which was obtained as the result of integration of the Schrödinger equation by successive approximations, may well find a counterpart in non-local field theory … In fact, the S-matrix in non-local field theory can be obtained by a straightforward extension of the usual formalism. … Detailed accounts will be given in the later issue of this journal."
Eighth paper: We jump forward here by six years to 1956. This paper was delivered on June 26, 1956, to the sixth meeting of Nobel Prize Winners in Lindau, Germany. [Yukawa himself won the Nobel Prize in 1949.] The paper is profoundly philosophical and raises many issues of importance. He is very concerned about the possible over-proliferation of particles and discusses which are elementary and which may be composite and therefore not elementary. He discusses the recent addition to quantum numbers of the "strangeness" numbers, which seems to have caused him some anxious moments. He gives considerable attention to non-linearity. He discusses the internal motions of particles being separate from the motions of their center of mass, meaning that they have double motion, and says we could possibly consider "the internal motion as something attached rigidly to the motion of the center of mass provided that the mass was different from zero." He discusses non-locality and causality and says: "… one must ask himself at the outset: To what phenomena are the causal laws to be applied? Such a question has become more significant since the development of field theory in recent years by which the procedure of renormalisation turned out to be indispensable …" He wonders whether a unified theory of particles could be achieved in a new way: "Hitherto, theories of elementary particles started from certain types of classical fields which were subject to quantisation afterwards. In other words, we took up the wave aspect of the elementary particle first and the particle aspect

subsequently. Now, one may ask the question: Is it at all possible to reverse the order?" He elaborates on this in a fascinating manner, and suggests his new idea of an approach "would be of some help for further progress."
<u>Ninth paper</u>: This is a short two page paper dated October 12, 1956. Yukawa here challenges whether the theory of special relativity should apply at all times in quantum mechanics. He says bluntly: " … we are beginning to doubt that the rigid framework of the special theory of relativity and quantum mechanics will remain without modification in the future theory of elementary particles. For this reason, it is all the more important at the present time to investigate whether the space-time framework of the special theory of relativity is appropriate for discussions of the possible internal structure of elementary particles." He elaborates strong reasons to support his doubts about special relativity and gives thanks to Ernst Lawrence, Ziro Koba, and Donald Robert Yennie for instructive comments, all of whom appear to have supported his views. This is certainly a most important paper and deserves to be much better known, as the points Yukawa makes are strong ones. The question as to whether special relativity has any place in short distance physics is crucially important.
<u>Tenth paper</u>: Yukawa turns his attention strongly to mesons in this prominent paper published in April, 1957. He stresses the doubts and uncertainties in no uncertain terms: "It is really very hard to say something definite and precise about meson theories. This is partly because of the strong interaction between mesons and nucleons, as well as between two nucleons. But more than that, it is because any simple-minded meson theory cannot be a complete and closed theory. Obviously it is much more an open theory than quantum electrodynamics. There are two reasons for this: First, the existence of strange new particles compels us to enlarge the scope of the theory so as to include these particles; second, we believe some real fundamental change is necessary in quantum field theory. We do not know when and how it will come, but the future modification in field theory will affect meson theory substantially … In the early days we had only limited knowledge about the nucleon-nucleon interaction. We actually knew nothing about mesons themselves. They were just introduced in order to account for nuclear forces. … The assumption of a strong meson-nucleon interaction was generalized in recent years, so as to include strong interactions between other types of particles. A compact scheme which was originated by Pais and later refined by Gell-Mann and independently by Nishijima for strongly interacting particles was reached on these lines. Here one of the important concepts in meson theory is taken over. That is the concept of charge independence, which is reflected in meson theory as the so-called symmetrical coupling. If you expand this concept in such a way that you can include strange new particles, then you arrive at the concept

of isospin space which was introduced by Pais, and this concept of isospin space works quite well, if you consider only strongly interacting particles. … The intervention of the mu meson completely destroyed what I had had in mind. Today, I still do not understand mu mesons at all. Where does the big difference between the masses of the electron and the mu meson come from, if we suppose that the mu mesons interact with other particles only weakly? Maybe the spin of mu mesons is higher than one half, but in such a case you have to worry about why the radiative cross sections are not large, actually. Perhaps you would have to take into account certain internal structure of the mu meson. Whatever you may think, the problem of the mu meson is very challenging. … [Here he proposes a scheme.] … Perhaps the most disappointing feature of our scheme is that we still cannot easily get rid of the well-known dilemma of theta and tau modes of decay of *K* mesons. I do not know whether a more complicated scheme involving higher spins could serve for the final solution of this crucial problem. We cannot yet tell whether we are already facing the problem which concerns the validity of the rigid framework of special relativity." (Here he hints at his earlier suggestion that special relativity may not apply to the strong forces.) This summary is incomplete, and the full paper is therefore highly recommended, as discussions of strangeness and other matters have been omitted from the summary here. Yukawa also once again refers to the mass of the pion being approximately 200 (i.e, 200 Mev).

At this point in the Pais file we jump forward by seven years and pass the chronological boundary intended for this paper, which is 1962. However, we shall summarize the three remaining papers, which take us to 1966, at which point the Pais file on Yukawa ends.

<u>Eleventh paper</u>: This brief paper was jointly written by Yukawa with Yasuhisa Katayama and Eiji Yamada. It was submitted December 23, 1964, and published in March of 1965. This is Part III of a series dealing with the possible internal structures and symmetries of elementary particles. (Parts I and II are not in the file. It seems that they both appeared during 1964.) The authors say (I have slightly improved the grammar): "In previous notes, models of elementary particles with internal structure based on nonlocal fields were proposed. The introduction of nonlocality of fields made it possible to consider the internal freedom of elementary particles, not only that of rotation discussed in many papers, but also of vibration. The original bilocal field, however, could not cover the whole class of deformations allowed in spatially extended objects. Although quite a complicated formalism is needed to treat all possible deformations, four representative points will be necessary and sufficient to describe characteristic deformations such as dilatation. The purpose of this note is the generalization of the previous model to include a quadrilocal field. A similar model was proposed by Takabayasi [also in 1964]. In our model the

field quantity is determined by four sets of space-time coordinates." They then lay out the details and the formalism and suggest two possible models.
Twelfth paper: This lengthy paper by Yukawa was presented at an International Conference on Elementary Particles held at Kyoto in 1965 and was published in the *Proceedings*, but is here present as an offprint. The paper itself is followed by seven pages of Discussion, including comments made by David Bohm, Robert Marshak, and Chen Ning Yang. (Bohm says he supports the idea that "relativity should be limited" and says he will discuss that further with Yukawa privately. Both Marshak and Yang are sympathetic to Yukawa.) The paper is far too wide-ranging for a summary to be adequate, but here are Yukawa's closing comments: "I am well aware that we are still very far from something which can be called an accomplished theory. Apart from the great difficulty in dealing with the all important problem of interaction, there are many other points which were not clarified so far. Among them, one can count the concept of antiparticle and the origin of half integer spin. Finally, I must confess that our way of approach is so different from the way of approach which lead to meson theory that I can have for the moment, only a vague idea about how those two approaches can be compatible with each other." This paper needs a full study and consideration.
Thirteenth paper: The following year, Yukawa wrote this extensive paper for the journal *Progress of Theoretical Physics*, it was received on August 20, 1966, and published as a Supplement to the journal in 1966. This paper expresses profound unhappiness with some of the present theories, and he presents some ideas. He says it is necessary to allow for "more degrees of freedom of internal motion". He believes quantum theory needs to be reformulated in a "new version". It would be inadequate to attempt to summarize here such sensitive points, and this full paper definitely requires a careful consideration.
This is the final paper included in Abraham Pais's Yukawa file.

Hideki Yukawa died September 8, 1981. Abraham Pais died August 2, 2000.

Returning now to our survey of meson discussions between 1935 and 1962, we continue where we earlier left off so that we could survey Abraham Pais's Yukawa file:

In 1939, Lothar Nordheim and Malcolm Hebb (who had only received his Ph.D. from Harvard three years before) published a paper questioning whether any simple theory of meson production were possible because all the suggestions advanced so far were contradicted by cosmic ray evidence.[7]

The Second World War prevented extensive discussion of mesons between 1939 and 1945, and little progress was made, as both the Germans and the Americans were engaged in a race to make atomic bombs, a quest which absorbed the full attention of most Western atomic physicists.

In 1946, Wolfgang Pauli, who in that year was at Princeton, issued a 69-page booklet in English entitled *Meson Theory of Nuclear Forces*.[8] On the first page of the book Pauli records that the quadrupole moment of the deuteron, Q, is equal to 2.73 x 10^{-27} cm^2. This number, which is correct, will be re-examined later in more advanced contexts, when it will be seen to be of perhaps even greater importance than has been recognised until now. Thirty-seven people delivered papers at this conference, a mixture of Japanese and Westerners. And 260 participants came to the symposium from 19 countries, including four Nobel laureates. Also in an Appendix to the volume are two previously unpublished articles by Yukawa on meson theory. They both date from 1937. The Japanese rightly wished to honour the memory of their great scientist. As Toshio Sawada said in his opening address:

"Yukawa's theory not only predicted the existence of the mesons responsible for nuclear forces, which were experimentally found later, but also established the fundamental idea that forces are created by exchange of particles …"

This aspect of Yukawa's idea of *exchange* is an idea which has still not been as fully developed as it should, and as this paper proceeds, we shall see that there are additional aspects to the concept which until now have not been fully realised. This is despite the truly vast and overwhelming amount of publications dealing with mesons over many decades.

In November of 1946, William B. Fretter published a paper in *The Physical Review* entitled "The Mass of Cosmic-Ray Mesotrons".[9] He points out that based upon what is known so far, the mass determination values of mesons varies between 142 and 264 electron masses. He studied the errors and decided that the correct value of the meson mass was 202 times the mass of the electron. The paper contains drawings and two cloud chamber photos. In terms of estimate of pion mass, Fretter had gone backwards from Pauli.

In June of 1947, freed from his full-time atomic bomb duties, Robert Oppenheimer delivered a paper to the American Physical Association discussing difficulties concerning mesons. He pointed out that calculations made on the basis of the strong coupling theory become invalid at high energies of about one Bev.[10]

Mesons received a very great deal of attention in *The Physical Review*, Volume 72, for the second half of 1947. (This volume is famous for containing the first report of the Lamb Shift by Willis Lamb.) On the very first page of the volume appeared a paper about mesons, which they still called by the earlier (and soon to be obsolete) name of 'mesotrons', by Willam G. McMillan and Edward Teller.[11] Although the paper was discussing the production of mesons by nuclear bombardment, they admitted that they had not attempted this, and the paper is thus entirely theoretical. In their theory, taking the target nucleons to be at rest, and based upon Fermi's degenerate gas model, they estimate that the threshold incident energy would be about 95 Mev, rather than the 210 Mev predicted by others. That is their estimate for positive mesons, and they say that the threshold would be higher for negative mesons. They say that the small difference between the energies for the two different kinds of mesons arises from the necessity of giving the negative mesons a non-zero initial kinetic energy. They call their calculations "more refined" than previous ones, but in fact they were wrong, and their calculations are now known to be less accurate rather than more accurate.

The next paper about mesons in Volume 72 is by Bruno Rossi, Matthew Sands, and Robert F. Sard, all of MIT.[12] It reports an extremely interesting study of the variations in meson intensities at different altitudes. They took a horizontal aluminium plate 2 inches thick and measured the number of mesons stopped by it at numerous different altitudes ranging between 35,000 feet and sea level. They say: The mesons were detected by recording the delayed emission from the absorber of the electrons produced by the decay of the absorbed mesons. An increase by a factor of about 37 between sea level and 35,000 feet was observed." The subject of meson mass is stressed by their saying: "The methods for the detection of slow mesons mentioned above are based upon properties of mesons which depend on their mass." And regarding that, they say: "Mesons have a mass of 10^8 ev/c^2 and a lifetime of 2.15 microseconds."

The next meson paper in this volume is entitled "On the Meson Theory of Nuclear Forces", by Leslie L. Foldy.[13] At the end of the paper, the author thanks David Bohm and Robert Oppenheimer (who was Bohm's Ph.D. supervisor) "for many illuminating discussions". Foldy is concerned with creating better ways of making calculations, especially because, as is well known, "the square of the coupling constant increases indefinitely inversely as the difference in [meson] masses." For his calculation, Foldy opts for a "meson mass of the order of 300 meson electron masses". This was possibly higher than anyone had gone before, and indeed, as we know now, too high.

The Proceedings of the American Physical Society for a meeting in Washington May 1-3, 1947, are recorded, and reveal that at that meeting, Banesh Hoffmann delivered a paper entitled "The Vector Meson in Projective Relativity".[14] This paper is not printed and is described in a single paragraph precis. It states that the paper had contained a calculation of the vector meson field and "additively, the usual gravitational and vector meson stress energy tensors". (The Projective Relativity Theory was an early attempt by Hoffmann and Oswald Veblen to unify gravitation and electromagnetism as a four-dimensional unitary theory, originally published by them in *The Physical Review*, Volume 36, 1930, page 810. I must confess not to have studied this theory. I might point out that Banesh Hoffmann was the main supporter within the physics community of the work and theories of the electrical engineering genius Gabriel Kron, which I have analysed and explained at great length in a forthcoming book entitled *The Many Faces of Unity in Science, Nature, and Mathematics*. In his work on electrical networks for the General Electric Corporation Kron made an epochal discovery which I have apparently been the first person to notice, explain and make public properly, as Kron died prematurely before he could do so himself. It is hoped that the book will appear in 2027.)

Four other meson papers are reported in one-paragraph summaries from that same conference:[15]

McMillan and Teller have another paper entitled "Theoretical Mesotron Production by Nuclear Bombardment" which seems just to be another version of their previously mentioned paper.[16]

Victor F. Weisskopf of MIT presented a paper entitled "On the Interactions of Mesons with Nuclei".[17] The subject is somewhat convoluted: "According to current theories, a negative meson which finds itself in a bound orbit around a nucleus should be absorbed even by the lightest nuclei in a time much shorter than its natural lifetime. Recent experiments have shown, however, that they are absorbed in Fe, but not in C, although they find their way into a bound orbit in a negligibly small time. A possible explanation could perhaps be attempted with the assumption that mesons interact only as pairs with the nucleus. A negative meson would be absorbed only if, say, a neutral meson were emitted simultaneously. This type of interaction is found in theories using mesons of spin one-half … The mass difference between the negative and the neutral meson may be such that the absorption process can take place in Fe but not in C."

Wendell H. Furley of Harvard's paper "Discussion of a Possible Method for Measuring Masses of Cosmic-Ray Mesotrons" suggests measuring a meson's mass by "measurement of its momentum by magnetic deflection, and a measurement of its velocity or range. Measurement of range offers a method which, if applied to high energy, long range particles, may be capable of giving very good results … Measurements on slow mesotrons are inherently unsatisfactory, as Bethe has shown, and the determination of velocity from ionization is possible at all only for slow mesotrons."

Malcolm Correll's paper dealt with "Positive Excess of Slow Mesotrons at an Altitude of 11,500 Feet". He discovered that there were equal numbers of positive and negative mesotrons.

The next paper about mesons in Volume 72 is by James Bartlett, and is entitled "The Vector Meson".[18] This paper, which is almost entirely concerned with elaborate formalisms, brings in information about work on mesons by Henry C. Corben, Julian Schwinger, and Igor Yevgenyevich Tamm dating from 1940 and the Romanian physicist Alexandru Proca dating from 1938. Bartlett uses a Proca wave equation for a vector meson in an external field, and discusses the work of Corben, Schwinger and Tamm concerning the stationary states of a vector meson in a coulomb field. Bartlett says that Tamm has found the general nature of the solution and that he wishes to give further details of that solution. He then does so in five pages of equations.

The above paper is immediately followed by another meson paper by Edgar Zilsel, John S. Blair, and John L. Powell entitled "Effect of Pais' '*f*-Field' on the Symmetry of the Meson Field Part of the Nuclear Hamiltonian"[19]. This paper is concerned with reconciling suggestions by Abraham Pais with the Hamiltonian for two protons. If Pais's idea of an '*f*-field" is introduced into the Hamiltonian, it would effect calculations about low-energy proton-proton interactions to the extent that symmetries would be threatened. They point out that "… the phase shift contribution caused by the '*f*-field' increases much more slowly with energy than the observed proton-proton phase shifts at low energies". And they conclude that "… the symmetry between the specific nuclear proton-proton and proton-neutron ^1S potentials would have to be abandoned if an '*f*-interaction' were introduced into the proton-proton potential."

A Letter to the Editor by Bruno Pontecorvo dated June 21, 1947, is entitled "Nuclear Capture of Mesons and the Meson Decay".[20] He says that the probability of capture of a meson by nuclei is much smaller than what one would expect from Yukawa Theory. He says there is no need to assume that

charged mesons have integral spin. It is not necessary to postulate the existence of neutral mesons. He supports Marshak's heavy electron pair theory of nuclear forces.

There is another Letter to the Editor from Harold K. Ticho and Marcel Schein, entitled "On the Change of the Mean Life of Negative Mesotrons".[21] This paper deals with the issue of disintegration versus capture of negative mesons. The authors believe that more are disintegrating than current theory had suggested, and that the increase of very short decay times must be more intensively studied. Meanwhile the change of the decay curve must be changed by about 11%.

W. Horning and M. Weinstein of the Department of Physics at the University of California Berkeley published another Letter to the Editor entitled "Meson Production".[22] Efforts to find out more about these two men have failed, except that they were working on the Berkeley cyclotron in 1947. Even the author index of Volume 72 knows them only as W. Horning and M. Weinstein. At the end of their paper they thank Robert Oppenheimer "for his guidance in this problem". No evidence has been found elsewhere of who Weinstein was or what happened to him, but it seems certain that W. Horning was the same man as W. A. Horning who was working with Herbert C. Corben in 1957 and 1958, when they wrote a report together for the US Atomic Energy Commission about the SPERT 1 reactor. Horning became involved in secret work for the US Government on plutonium, and we learn something of him from a declassified 52-page Report known as HW-26916 and marked "Secret", of the Physics Section of the Applied Research Section of an unnamed agency (its name being redacted). Dated January 14, 1953, it lists Horning as one of the important persons for distribution of the report and it states of the recoil-range neutron spectrometer which is the subject of the report: "This spectrometer was proposed by Dr. W. A. Horning …". The Report was signed by James E. Drummond (later author of the book *Plasma* Physics, 1961) and T. A. Jayne (of whom nothing more seems to be known). Horning therefore seems to have been swallowed up by the world of secret government research, which is why he vanished from view and "nothing is known about him", and Jayne was apparently the same. In their Letter, Horning and Weinstein comment upon the paper by McMillan and Teller which has already been described (which was the first paper in Volume 72, on page 1), and which they strongly criticise. They stress the importance of "the finiteness of the ratio of the meson mass to the mass of the heavy particle". They stress that "The heavy particles transfer momentum by exchanging a meson; the final meson is emitted before, during, or after the exchange." They insist that "the mechanism for heavy particle momentum transfer

(cannot be) a potential interaction … using a potential interaction, the contribution from terms in which scattering precedes meson emission is, at threshold, equal and opposite in sign to that in which scattering follows meson emission. This equality is destroyed if exchange of positive, negative, and neutral mesons scatters the heavy particles. These properties of the meson field distinguish it from the more familiar case of the electromagnetic field, for which a potential description of the interaction is valid." And they conclude by emphasizing that there is a "large uncertainty in all present meson theories." This paper seems to me to have considerable importance, but it does not appear to have had any impact at the time, and it is also not remembered. The central point of the transfer of momentum taking place without any potential being involved is possibly crucial.

Another Letter was from Harold E. Ticho at Chicago, entitled "The Mean Life of Mesotrons at an Altitude of 11,5000 Ft."[23] This paper relates to cosmic ray mesons, and reports a ground-based study of mesons in Colorado at the Harvard Climax Observatory which is at an altitude of 11,500 feet. The author reports a slight difference between the mean life of a meson at that altitude and the mean life which had been previously been calculated for a meson at sea level. But he says that the result "… however, may be due to a contribution by negative mesotrons decaying in the absorber."

That is the end of the Letters to the Editor.

A paper then appears by Walter Heitler and Sheila Christina Power (later Sheila Tinney), both working at the Dublin Institute for Advanced Studies, entitled "On the Origin of the Soft Component of Cosmic Radiation".[24] They suggest that the soft component of the upper atmosphere "is produced by a short-lived meson which, along with ordinary mesons, is produced by primary protons. … This 'mixed meson theory' was chosen as the one which leads to the best understanding of the nuclear forces. … We shall be concerned in this paper only with the bulk of the soft component in the high part of the atmosphere, which will be seen to consist mainly of comparatively slow electrons." The discussion is very lengthy and they stress "… it is clear that we have also taken account of any secondary nucleons which further contribute to meson production." An attempt to summarise this paper would take too long, and atmospheric scientists who may be interested in it really do need to consult the original paper. A few words need to be said here about Sheila Power, who later married and became Sheila Tinney (1918-2010). This remarkable Irish woman is the only female scientist to appear in this entire survey of discussions of mesons. She deserves special praise for overcoming the male domination of

science in those days and rising to scientific prominence. Well done, Sheila! She was a student of Max Born and is believed to be the first Irish-born woman to receive a doctorate in the mathematical sciences. She unequivocally qualifies as a heroine.

An important paper by Enrico Fermi and Edward Teller is entitled "The Capture of Negative Mesotrons in Matter".[25] They commence by saying this: "Recently, the significance of experimental results [*in the preceding year*] on the capture of negative mesotrons in matter has been discussed from the point of view of the information it gives concerning the interaction between mesotrons and nucleons. The interaction between slow negative mesotrons with matter has been described [*by the authors and Victor Weisskopf*] as consisting of two steps; first, one in which the mesotron is captured in the Bohr orbit with a radius of the order of 10^{-12} cm near the nucleus; second, a step in which more typically nuclear interactions play a role during which the mesotron is destroyed by its collisions with the nearby nucleons. The present paper will be primarily concerned with the detailed description of the first step." And here are their conclusions at the end of their paper: "The over-all conclusions can be summarized as follows. In condensed substances, both conductors and insulators, a negative mesotron is captured in its orbit nearest to the nucleus in about 10^{-13} second. In a gas the corresponding time is a little longer than is indicated by the ratio of densities. In particular, in normal air, it is of the order of 10^{-9} second. In both cases this time is very short compared with the mesotron natural lifetime of 2×10^{-6} second, so that the mode of disappearance of the negative mesotron is governed by the balance between natural decay and typically nuclear phenomena leading to mesotron disappearance."

An important paper by Robert Jay Finkelstein entitled "The γ-Instability of Mesons"[26] deals with meson clouds and challenges the competence of existing formalisms to deal with discussions of mesons adequately. The paper begins like this: "According to current meson theory both the nucleon and the electron-neutrino carry a virtual meson cloud; conversely, a free meson carries a nucleon cloud and can emit an electron-neutrino pair. The possibility of emitting an electron-neutrino pair permits the β-decay of the free meson, and the nucleon cloud, coupling even a neutral meson to the electromagnetic field, permits β-decay. Unfortunately, the whole status of meson theory is at present quite uncertain, and our numerical results probably have at most an order of magnitude significance, not only because of uncertainties about the form and numerical constants of the theory, but also of the dangers of working with a divergent formalism at the limits of validity." Finkelstein says he believes the mass of the neutral meson to be 177 electron masses. He thanks Robert

Oppenheimer for raising the issues with him and discussing them. One should remember Finkelstein's memorable phrase: *a divergent formalism at the limits of validity.* Many are those who have been tempted to have such thoughts.

Banesh Hoffmann, joint author of a Letter cited earlier, published a paper entitled "The Vector Meson Field and Projective Relativity".[27] Hoffmann attempts to unify the gravitational and vector meson fields by means of the general metric $G_{\alpha\beta}$. He says: "It is shown that a natural four-dimensional gauge invariant variational principle, involving the curvature scalar $G_{\alpha\beta}$, yields field equations unifying the gravitational and vector meson fields, the range of the meson force being determined by the inverse length *N*. Reasons are given for supposing that an extension to conformal geometry could prove of interest." He relies upon the Kaluza-Klein Theory and uses the projective formalism of Oswald Veblen, with whom Hoffmann had collaborated in 1930.

Robert E. Marshak and Hans Bethe contributed a paper entitled "On the Two-Meson Hypothesis". It commences like this: "Weisskopf has underlined the difficulty of reconciling the high rate of production of mesons with their subsequent weak interaction with matter. He has also suggested one possible way of overcoming the apparent lack of reversibility, namely, by postulating that the primary cosmic-ray proton converts a normal nucleon in an 'air' nucleus into an 'excited' nucleon, capable of emitting mesons. The lifetime of the "meson-pregnant' state can be chosen sufficiently long to account for the weak interaction between mesons and nucleons. An alternative solution of the difficulty was suggested by one of the present authors (R.E.M.) at the Shelter Island Conference. The hypothesis was that two kinds of mesons exist in nature, possessing different masses: the heavy meson was supposed to be produced with large cross section in the upper atmosphere, and to be responsible for nuclear forces, whereas the light meson was regarded as a decay product of the heavy meson, and as the normal meson was observed at sea level to interact weakly with matter. In this note we examine briefly some of the consequences of the two-meson hypothesis." The authors estimate the mass of the heavy meson at about 125 Mev and that of the light meson at 100 Mev. They also estimate that both the heavy and the light mesons have a spin of zero. They say they do not agree with Julian Schwinger's mixed-meson theory.

A Letter to the Editor follows this paper, from Victor F. Weisskopf, entitled "On the Production Process of Mesons".[28] The author states: "According to present cosmic-ray evidence, it seems that mesons are produced in the

upper atmosphere by the primary cosmic radiation, which consists primarily of protons. … After being produced in the first 100 g/cm^2 of the atmosphere, a considerable fraction of the mesons are able to penetrate through the total atmosphere and even deep underground. The only interaction with matter seems to be the one which is caused by its charge. Scattering by interactions other than electric is small and perhaps non-existent. Recent experiments have shown that even the absorption of slow mesons by nuclei takes place with a probability far below the expected one." They continue: "Nordheim and Hebb have shown [*in 1939, see above*] that these facts are in contradiction with any simple theoretical description of meson production." Weisskopf then speculates on various possibilities of meson production by a succession of various processes and not by any single process. He says that his ideas arose out of conversations he had at the Shelter Island Conference. [Shelter Island is on Long Island in New York.]

Carl D. Anderson, Raymond D. Adams, Paul E. Lloyd, and Ronald Rau, all of Caltech, published the important paper "On the Mass and the Disintegration Products of the Mesotron", accompanied by two cloud chamber photographs.[29] They report "a recent series of cloud-chamber observations made at an elevation of 9200 meters in a B-29 airplane" and reproduce the photos. These show a meson coming to rest in the gas of the cloud chamber, and when it stopped it emitted a lightly-ionizing particle of positive charge i.e., a positron. They comment: "… the assumption that two known particles, *viz.*, an electron and a neutrino (or photon) are produced in the disintegration requires that the mass of the mesotron lie between the limits of 90 and 110 electron masses." However, they cite other data that suggests "a value for the mass of the mesotron of about 200 electron masses. The first and most accurate such determination … gave a value for the mass of 220 electron masses with a possible error conservatively estimated as ± 35 electron masses. … Additional determinations [*in 1946 and 1947*] … are also consistent with a mass equal to about 200 electron masses." But they add that: "an accurate, direct determination of the mass of the mesotron in the present case cannot be made. Although the radius of curvature and the range of the particle would seem to indicate a mass of about 100 electron masses, the probable effects of multiple scattering on the observed curvature are such that a mass as large as 200 electron masses cannot be excluded." However, further on in the paper, the authors say that "on the basis of the conservation of momentum and energy" the mesotron "must have a value of about 140 electron masses, and its kinetic energy must be about 4 Mev."

Marcel Schein and "Jack" Steinberger (technically Hans Jakob Steinberger) published a Letter to the Editor entitled "On the Production of Cosmic-Ray Mesotrons by Primary Protons". The authors are convinced that the primary particles producing mesons are protons. The paper is concerned exclusively with the upper atmosphere.

The Proceedings of a conference of the American Physical Society held at Stanford University July 11-12, 1947, are recorded with the usual brief précis of papers delivered. A one-paragraph paper by Robert Jay Finkelstein is published with the title "The γ-Instability of Mesons".[30] This was presumably the same paper which would be published in *The Physical Review* seven weeks later (on September 1), and which has been described above.

George E. Valley, Junior, published a paper entitled "The Radioactive Decay of Slow Positive and Negative Mesons".[31] This extensive paper is illustrated with four Figures and two cloud chamber photographs. In Footnote 12 he refers to Victor Weisskopf's Letter mentioned above. Most of the paper is dedicated to detailed explanations of cloud chamber, photographic, and other equipment and apparatus, procedures, and observational techniques. Figure 6 reproduces two cloud chamber photos described as follows: "A positive and a negative meson track photographed on adjacent frames of the same film strip". The equipment was operated over a period of several weeks. The work was funded by the Office of Naval Research.

Malcolm Correll published a paper entitled "Positive Excess of Slow Mesotrons at an Altitude of 3.5 km".[32] This paper is illustrated with three Figures and two cloud chamber photos. This expedition examined 320 meson tracks of which 47.2 percent carried positive charges while 52.8 percent carried negative charges. The author states: "Hence, within the ±5.6 percent precision of this experiment, positive and negative mesotrons having energies between 0.6 x 10^8 ev and 1.7 x 10^8 ev occur in equal numbers at an elevation of 3.5 km."

That is the last meson paper in Volume 72 of *The Physical Review.* The subject of mesons tended to fade away towards the end of the volume because most people had had their say by then, and there was little more to add until more experiments could be carried out, and the many brilliant scientists could compare notes and have a good think. This task of listing and describing all the meson papers in Volume 72 was facilitated by the fact that I own my own copy of the volume (purchased because of Willis

Lamb's announcement of the Lamb Shift), as to do this survey from a copy in an institutional library would probably have been impossible.

In March of 1950, Homi Jehangir Bhabha of the Tata Institute in Bombay, published a challenging paper in *The Physical Review*, entitled "On a New Theory of Nuclear Forces".[33] He rejected Yukawa's theories. This was an important and drastic variation in the standard views which were then in process of formation. He believed that the static potential between two nucleons is "a sum of the interaction between two point charges and the dipole-dipole interaction multiplied by numerical coefficients and isotopic spin factors. This interaction, unlike the usual one based on the Yukawa theory, allows an exact solution of the deuteron problem." He maintains that other theories than his own lead to a situation where "no rigorous solution to the deuteron problem exists." He appears to abandon the notion of a meson field. This paper still requires and justifies close study even today, as its implications not only historically but possibly also for current thinking, may offer important ideas, especially as they concern the "meson field" (and, for that matter the "nucleon field").

In this same issue of *The Physical Review* appear two Letters to the Editor dealing with mesons. The first is from Alex E. S. Green and is entitled "Multiple Meson Processes and Nucleon Recoil".[34] He criticises both Tomonaga and Julian Schwinger by saying: "… the Tomonaga-Schwinger invariant methodology which, in meson theory, suffers from significant ambiguities and the use of the unreliable power series method. Green prefers the functional formalism of Vladimir Aleksandrovich Fock. He believes that "The exact interaction is quadratic in the coupling constant" and "The results of any development employing power series in the coupling constant must be regarded with very great suspicion. The fact that in electrodynamics such a perturbation method when augmented by cut-off devices may be used to predict unambiguously a wide range of physical phenomena, is due to a combination of circumstances which is not duplicated in meson theory." These ideas require deeper thought.

The second Letter to the Editor is from H. H. Forster and is entitled "Evidence for a Charged Heavy Meson".[35] Forster reports in very great detail a finding made at 30,000 feet of a cloud chamber track of a μ-meson (muon) which was estimated as having a mass of between 210 and 280 times the mass of an electron. This was in the context of a deuteron-proton collision. In a footnote he records a similar observation made the previous year (1949) by Louis Leprince-Ringuet and reported in *The Review of Modern Physics*, Volume 21, 1949, page 42.

In his book *Elementary Particles* published in 1951,[36] Enrico Fermi stated firmly: "The Yukawa interaction is responsible for the nuclear forces …" (p. 37) but then went on to stress how little of detail was yet known. He represented "the interaction constant" by e_2. He then said that "the constant e_2 "must be taken about twenty times larger than the elementary charge [the electron]. … It should be stressed that this value is merely an order of magnitude. The quantitative agreement between the Yukawa Theory of nuclear forces and experiment is so indefinite that it has not been possible to determine the precise form of the interaction energy and therefore the value of the constant must also be left uncertain. In particular, the value of the spin of the pion is not known. It could be 0 or 1, or perhaps have an even higher value. In our simplified discussion a spin zero has always been assumed."

Later Fermi goes on to say the following: "The Yukawa theory of nuclear forces is based on the assumption that the force acting between two nucleons are transmitted by the pion field that surrounds them. The phenomenon is usually described by stating that when two nucleons approach each other one of them may emit a pion which is absorbed by the other. Assuming for example that the two nucleons are a proton and a neutron, it may happen first that the proton emits a positive pion so that an Intermediate State with two neutrons and a positive pion will be formed. The positive pion is subsequently absorbed by the original neutron and converted into a proton…The overall result … is the scattering of the two nucleons which change their momentum direction. This scattering is interpreted as if it were due to a force acting between the two nucleons. …We will assume therefore that between proton and neutron there exists a mutual energy represented by $V = U(r)P_{ex}$ where P_{ex} is the neutron-proton exchange operator. … The force field of a nucleon extends as far as the pions which it continually emits and reabsorbs are able to reach. When a pion is emitted the system 'borrows' an energy of the order of μc^2.This loan, according to the time-energy complementarity, cannot last a longer time than about $h/\mu c$. This is, therefore, the magnitude of the range."

Fermi extends his discussion of pions by many further pages, which I shall not discuss here, and which may be found in his book. He especially calls attention to publications by Bethe, Pauli, Schwinger, Wheeler and others as important sources for further information. We know from the memoirs of Eugene Wigner that Fermi, one of his best friends, was a very open and generous person who always had consideration for colleagues. (He especially had an excellent sense of humour, and humour was also an essential trait of John Wheeler, as I know from my several meetings with him in the 1970s. Wheeler always included jokes of some kind in his

lectures, and he did so in a subtle deadpan manner. Fermi, on the other hand, was more inclined to loud and open laughter, according to Wigner. But then, Fermi was an Italian, and Italians tend to be highly demonstrative whether they are laughing, arguing, or crying.)

In 1952, Robert E. Marshak published his 378-page book *Meson Physics*[37], issued as a Dover trade paperback, which meant that it was widely circulated in university bookshops all over the USA, and the author specifically states in his Preface: "It is hoped that this book will be useful to research workers in meson physics. … It is conceivable that this book may also serve as a primary or secondary text in a course on meson or high-energy physics." Most of the material in the book actually originated in two series of lectures which Marshak gave in 1950 at the University of Rochester and at Columbia University, which preceded the appearance of Fermi's 1951 book discussed above. Marshak freely admits that so little is yet known of pions interacting with nucleons that his book will be largely concerned with what has been discovered about pions from work on cosmic rays. He admits in his Preface that "… no genuine meson theory exists but only plausible conjectures which occasionally illumine the complexities of the experimental material." One thing he is emphatic about is that the μ-mesons (now called muons) discovered in the cosmic rays are produced by disintegration of the π-mesons, and not the other way around as some physicists had maintained. In other words, pions are the primary mesons. He makes this important point in Chapter One. But because more was known about them from the cosmic ray studies, the majority of the material in the book concerns the μ-mesons. He stresses that in the book when he mentions pions, he shall be referring to plus, minus, and neutral pions. (He uses the Greek letter throughout, which I am not doing in this summary.) The first 129 pages of his book are concerned with the creation of pions. In his Preface, Marshak warns his readers: "… no genuine meson theory exists but only plausible conjectures which occasionally illumine the complexities of the experimental material." Chapter 4 is entitled "Properties of π Mesons", and this is the most interesting part of the book. He says that pions have a mass "in the vicinity of" 300 electron masses. He says that charged mesons can be described as pseudoscalars, and can either have a spin zero with an odd parity field, or they can have spin one and an even parity field. He says that neutral mesons seem to have an odd parity field and a spin either of 0 or greater than one. Returning to the question of pion mass, he points out that the Berkeley researchers seem to have established that a plus pion has a mass of 277.4 electron masses. But he says the momentum-range method of Barkas and his colleagues has established a plus pion mass of 276.1 electron masses, whereas Cartwright deduced a plus pion mass of 275.1 electron masses. He says the neutral pion mass is

more difficult to determine but that Carlson at 70,000 feet determined it to have a mass of 295 electron masses. But he says that none of the estimates of neutral pion masses so far is accurate. Marshak's book is a major achievement and must have been the product of immense labour, although it would be superseded within only three years by Bethe and de Hoffmann.

Some interesting papers about mesons appeared in 1952, in Volume 85 of *The Physical Review*. The first was a Letter to the Editor from Malvin Avram Ruderman entitled "Decay of the π- Meson".[38] His work at Caltech was funded by the Atomic Energy Authority and he was advised by Richard Feynman. He said: "The decay of the charged π- meson through virtual nucleon pairs and the annihilation of a pair with the creation of a neutrino and an electron or μ- meson is permitted by the accepted coupling of these particles [which he had reported in Volume 76 in 1949]. Conservation of angular momentum and parity together with [Wendell Hinkle] Furry's theorem [of 1937] forbid the decay for most choices of the meson field and the β- decay coupling. The forbiddenness is independent of perturbation theory."
The next paper was by Cooper Richman, Mitchel Weissbluth, and Howard A. Wilcox, and entitled "Production Cross Sections for π^+ - and π^- - Mesons by 340-Mev Protons on Carbon and Lead at 90º to the Beam". They begin by stating: "The artificial production of mesons was first achieved by E. Gardner and C. M. G. Lattes in 1948. In their experiments they used the 380-Mev internal α-particle beam produced by the Berkeley 184-inch synchro-cyclotron. The experiment was carried out by bombarding a target on a probe inside the cyclotron. The charged mesons produced by the beam were bent away from the beam by the cyclotron magnet and were detected in suitably placed nuclear emulsions. When the 184-inch cyclotron was converted so that protons could be accelerated to 340 Mev, and when subsequently these protons were deflected out of the cyclotron tank, the experimental possibilities for studying production of mesons were greatly improved. … The problem of the production of charged π- mesons from a light and a heavy nucleus by protons was undertaken." The paper describes the experimental method. This led to an improved classification of types of mesons. There is a great deal of detail, some of which is somewhat bizarre, concerning such things as how many prongs show in the emulsion.
The next meson paper in this volume is "π-meson Production by Protons on Nuclei" by Ernest M. Henley.[39] This lengthy paper of 11 pages is mostly concerned with the production, detection and scattering of mesons, with much description of techniques and calculations, but with little by way of conclusion other than: "We have seen that it is possible to analyze the

meson production process in nuclei in terms of the free nucleon-nucleon production cross sections. We have shown, furthermore that the exclusion effect is not expected to play a very large role in determining the meson spectrum, at the experimental incident proton energies considered (341 Mev), except possibly for mesons emitted in the direction of the beam". It is essentially a procedural paper. (A further paper by Henley appears later.) The next meson paper is by Frank L. Adelman and is entitled "Fast Protons from the Capture of π^- Mesons in Photographic Emulsions". This paper is all about negative pion capture at different energies, and the counting of prongs in the emulsion.
A Letter to the Editor entitled "Charged π- Meson Production from Deuterium" by Sidney Passman [who received his Ph.D. at Columbia this same year], Martin Moses Block, and William Westerfield Havens, Junior [who had worked on the Manhattan Project][40], reported experimental results of positive pion production from deuterium. A 381 Mev proton beam was used for the proton bombardment in "the Nevis Cyclotron". A useful drawing of the cyclotron, the beam, and the target accompanies the letter, along with a graph showing the theoretical curves for the positive pions produced by bombarding the deuterium. They confess that they are puzzled by the large ratio of positive pion production of deuterium to hydrogen.
Another Letter to the Editor was "The Yield of Neutral Mesons from Proton Bombardment of Light Nuclei" by Richard Wayne Hales, Roger Henry Hildebrand, Norman Knable, and Burton Jones Moyer.[41] They report an experiment to try to study the production of neutral pions by a 340 Mev proton beam. They say they need to do further experiments.
Another Letter to the Editor was written by Richard L. Martin, Herbert Lawrence Anderson, and Gaurang Bhaskar Yodh, entitled "Nuclear Cross Sections for Negative Pions of Energy 109 and 133 MEV".[42] A useful diagram of the cyclotron, the magnet, the meson beams, etc. is provided. The pions were produced by the bombardment of a beryllium target with the 430 Mev proton beam of the Chicago synchro-cyclotron.
Another Letter to the Editor was "Photoproduction of Neutral Mesons from Deuterium", by Warren Heckrotte, L. R. Henrich, and Joseph V. Lepore.[43] They report an experiment of the photoproduction of neutral mesons from deuterium. They say: "This experiment could have interesting implications regarding the charge independence of nuclear forces …"
Another Letter to the Editor is by Norman Charles Francis and Robert Eugene Marshak, entitled "Elastic Photoproduction of π^0 – Mesons in Deuterium".[44] Their approach is to assume that the anomalous magnetic moment interacts directly with the electromagnetic field and is responsible for neutral pion production in hydrogen so that "the anomalous magnetic

moment of the neutron should contribute an almost equal amount in a nucleus like deuterium". However, they did not make much progress.
The next meson paper is entitled "Mesonic Proper-Field" and is from Hiroomi Umezawa, Yashushi Takahashi, and Susumu Kamefuchi at Nagoya University in Japan.[45] This is an eleven-page paper. It presents a method of treating the meson cloud around the nucleon. It deals with the problems of the multiple production of mesons and of the magnetic moment of the meson-nucleon system. The authors use their own formalism, though leaning on Heisenberg. The paper challenges the two-meson theory. They stress that when dealing with the meson field there are problems which cannot be solved by renormalisation. They say that the meson cloud "has a greater singularity in the vicinity of a nucleon". That is certainly a way of stating things which provokes much thought. They admit that the nature of the meson cloud is unknown. They speak of Fermi's recent "new theory [of 1950] of the multiple production of mesons based on statistical considerations. His method consists in assuming that the meson cloud is so rigidly attached to the nucleon that an external disturbance is rapidly transferred to the whole cloud. As a result of this assumption, the probabilities for multiple production of mesons are determined only by the statistical weight, i.e. the magnitude of volume in phase space. Fermi's idea is, essentially different from our theory in which probabilities are determined essentially by the cloud spectrum itself." And the authors also say: "The magnetic moment of the nucleon may also be interpreted as a phenomenon which expresses the effect of the meson cloud around it. … The external magnetic field exerts on the meson cloud the following effects: (1) the scattering of mesons, and (2) the pair creation and annihilation of mesons, by which the current due to the meson cloud is disturbed and then returns to its stationary state. … the positively and negatively charged parts of the meson cloud have their respective angular momenta." These thoughts are still stimulating today. It might be a good idea for people to read this paper.
A paper by Donald L. Clark, Arthur Roberts, and Richard Wilson appears next, entitled "Disintegration of the Deuteron by π^+ Mesons and the Spin of the π^+ Meson".[46] From their studies they believe they have proved that positive pions have spin zero. They insist they have determined this "unambiguously". There are four helpful drawings and diagrams. They created meson streams coming out of aluminium in the Rochester synchrocyclotron. They had to be careful to guard against the contamination of the meson beams. The section of the paper dealing with that is quaintly called "Meson Purity". There is a great deal of discussion about their techniques. They worry however about the possibility that the spin zero is "being counterfeited" and from their experiments of the absorption of negative pions in deuterium they worry that negative pions

have odd parity if they have spin zero. However, if one assumes that the positive and negative mesons both have spin zero and the same parity the conclusion is inescapable that both types of pions are pseudoscalar. And: "It ought to be pointed out that it is normally assumed that both the proton and the neutron have even intrinsic parity, although there is, as far as we are aware, no evidence for such a belief. The intrinsic parities of the proton and the neutron enter into consideration only in reactions in which a proton is transformed into a neutron or vice versa; thus they are not important in ordinary nuclear combinations, becoming only a sign convention in nuclear models and ordinary nuclear reactions. However, in beta-decay or meson reactions, the intrinsic parities do indeed enter. Thus, in concluding that π- mesons are pseudoscalar, we assume that protons and neutrons have the same parity, if their parity type is real; or opposite parities if it is imaginary."

The next meson paper is: "Meson Tail Effect and Treatment of Proton-Proton Scattering Data" by Marshall Clinton Yovits, R. L. Smith, M. H. Hull, Junior, J. Bengston, and Gregory Breit.[47] This group at Yale, supervised by Professor Gregory Breit, are favourable to "agreement with the long-failed Yukawa and exponential well potentials". So Yukawa is back! But they are inclined to believe that the pion has a mass of 333. They paid particular attention to the effect of the tail of the Yukawa potential on scattering and its influence on the nearly linear functions of energy used in the analysis of experiment". The paper is 14 pages long, with charts and graphs.

Geofrey F. Chew and Gian Carlo Wick published a paper entitled "The Impulse Approximation"[48] which has an important short section on mesons. Their introductory remarks are: "An analysis is made of the assumption that the scattering of an elementary particle by a complex nucleus is well approximated by the superposition of outgoing waves generated by the individual nucleons acting independently. The special case of nucleon-nucleon scattering is discussed in detail and an estimate given of the order of magnitude of the error in the approximation. Application of the method to meson problems is also discussed." At the end of the paper they have a section entitled "The scattering of mesons by complex nuclei" in which they say: "The scattering of mesons by nucleons is even less understood theoretically, if that is possible, than the scattering of nucleons by nucleons. Nevertheless, the validity of the impulse approximation is highly probable. In the hundred-million volt region, the meson-nucleon cross section is of about the same size as the nucleon-nucleon cross section [published in 1951]. … The meson cross section decreases sharply with decreasing meson momentum, however … An application has also been made to the production of mesons in nucleonic collisions. The criterion of

validity is here obscured by the great loss of energy suffered by the incident nucleon in creating the nucleon."

A Letter to the Editor entitled "Photomeson Production from Deuterium" was printed from Irwin Leon Lebow, Bernard Taub Feld, David Henry Frisch, and Louis Shreve Osborne,[49] who point out that "The photoproduction of a charged meson from a deuteron results in a pair of identical nucleons, whose possible quantum states are limited by the Pauli Exclusion Principle. Since the initial deuteron state is primarily $^3S_1$, the possibility of leaving the final two-nucleon system in an *S*-state depends on the occurrence of 'spin flip' in the charged photomeson production reaction." (This point will be returned to in discussion in a later section of this paper.)

Immediately following the above there is another Letter to the Editor entitled "Is There a Neutral μ-Meson?" from George Eugene Uhlenbeck and C. S. Wang Chang.[50] After discussing this and raising numerous points, they realize they don't know.

Bertram Julian Malenka contributed a Letter to the Editor entitled "Nonlinearities Resulting from Vacuum Polarization in Meson-Nucleon Interactions"[51]He was advised by Julian Schwinger. He ends by saying: "Although one would also want to examine real particle interactions in some detail, the form of Eq. (11) does suggest a starting point for a phenomenological investigation involving nonlinear meson theory. Such investigations are under consideration. And here he gives a footnote to his own 1951 Harvard Ph.D. thesis (but does not give its title).

At this point in the Volume, the Proceedings of a Chicago meeting of the American Physical Society are reported in precis of the papers given there. One of them is "Regular Meson Type Potentials in Proton-Proton Scattering" by Robert Douglas Hatcher and H. E. Hart[52] (the latter described as on leave of absence from the Board of Education of New York City). Their research at New York University has resulted in a calculation of a mass for the pion of 316 times the mass of the electron.

Pages 718-720 of the volume contain a series of précis of meson papers delivered at a session of the Chicago meeting presided over by Enrico Fermi. None of these is particularly interesting, so I do not list them. But there is an extremely interesting meson paper which was delivered in the "General Physics – Theoretical" section of the meeting by Peter Havas of Lehigh University, entitled "Classical Meson Theory and Action at a Distance".[53] (Havas would later become well known as editor of Einstein's papers.) The brief summary of this paper says: "A theory of action at a distance was developed recently for particles interacting through neutral meson fields. [He refers to a yet unpublished paper of his own destined for *The Physical Review* and papers by H. Kanazawa of 1950 and a paper by Helmut Steinwedel and S.-B. Heidelberger of 1951.] This work has now

been extended to charged fields in the classical counterpart of the charge symmetrical theory of [Nicholas] Kemmer. The field theoretical equations of motion, found recently for retarded interaction through vector meson fields [He is referring to a 1949 paper by Kenneth James Le Couteur.] contain integrals over the past and entire motion of the retarded and half-retarded, half-advanced interaction, respectively. As in the neutral theory we omit them from the postulated equations of motion of action at a distance. A variational principle is developed for these new equations with symmetric interaction; the equations of motion, of the variation of charge and the fields of the "adjunct" field theory are derivable from it. An energy-momentum tensor and a charge-current vector guaranteeing detailed conservation laws are defined. The application of the Wheeler-Feynman method to the equations of both theories is discussed. Analogous results are obtained for scalar mesons." Well, with all these tantalising remarks my tongue is hanging out, but alas we do not have the actual paper.

The précis of a paper by Robert Stephen White (not to be confused with the later Stephen R. White), Mark John Jakobson and Alvin George Schulz was published, entitled "Photomesons from Deuterium". They used the Berkeley synchrotron to bombard hydrogen and deuterium gases by photons and produced charged pions, which they studied. "The statistics of the data are not sufficient to compute the proton spin-flip probability from the theory of [Geoffrey] Chew and Lewis."

D. F. Sherman, Harry H. Heckman, and `Walter H. Barkas presented a paper entitled "The Capture of μ-Mesons in Nuclear Emulsions". Talk of the stars and blobs in the emulsion, and how many prongs.

Harry H. Heckman and Walter H. Barkas then presented a further paper entitled "Scattering of Negative π-Mesons in Aluminum, Copper, and Lead". "The analysis does not differentiate between elastic and inelastic scattering."

R. E. LeLevier presented a paper entitled "Photo Production of Negative Pions from Deuterium". Trying to find a measure of the spin-flip process.

Francis M. Smith, W. Birnbaum, and Walter H. Barkas presented a paper entitled "Range Struggle of μ^+ - Mesons". A study of positive muons arising from decay of positive pions stopping in photographic emulsion. Some results "presumably must be attributed to another process."

W. E. Crandall, Kenneth M. Crowe, Burton J. Moyer, Wolfgang Kurt, Hermann "Pief" Panofsky, R. Phillips, and D. Walker presented a paper entitled "Analysis of Neutral Meson Gamma-Ray Spectra from Carbon". Trying to deduce the excitation function for neutral pion production".

Richard Madey, Kenneth C. Bandtel, and Wilson J. Frank presented a paper entitled "The Photoproduction of Negative Mesons from Deuterium". They used photons from the Berkeley synchrotron.

Marian Whitehead and Chaim Richman presented a paper entitled "Angular Distribution of π^+ - Mesons Produced in *P - P* Collisions". They report that this enabled them to "fix the constants with greater precision."
Mark J. Jacobson, Alvin G. Schulz, and Robert Stephen White presented another paper entitled "The Production of Photo-mesons from Helium". Results are said to be presented in Table 1, but Table 1 is not shown in this précis.
Ernest Mark Henley of Stanford University presented a paper entitled "Nonlinear Pseudoscalar Meson Theory". This is a particularly interesting paper shown only in précis. Henley had an exceptional intellect, and this paper suggests a great deal of fresh-thinking. He has introduced a non-linear term into the usual meson wave equation. He says that experimental evidence suggests a pseudoscalar meson and pseudoscalar coupling rather than scalar ones. So he undertook an experiment to determine the effect of a non-linearity corresponding to a point-contact repulsion on the neutral meson field, making use of classical field theory. He got some interesting results. "It is hoped to carry this analysis further." Henley was exceptional. Ideas such as this should be kept in the "may be useful" file.
Another paper was presented by I. D. Fox and James Ricker Wilson entitled "Classical Meson Fields". This paper is interesting and raises issues concerning point charges and also of isotopic spin. The authors begin by mentioning that Paul Dirac in 1938 had derived an equation of motion for a point electron. They then point out that Homi Jehangir Bhabha in 1939 had dealt with the problem of the point nucleon in a classical neutral vector meson field and that Tsung-Dao Lee had dealt similarly with the case of the neutral scalar field. [Lee would win the Nobel Prize only five years later at the age of 30.] Fox and Wilson say: "The method has been extended by the present authors to the treatment of the symmetric and charged scalar fields." And: "conservation of charge was used to derive the equation of motion of the isotopic spin." This was clearly a significant paper, and one wishes for the full text. (It is interesting that the information about Lee's work is footnoted as being the result of "private communication" from him.) This paper should be flagged as important.
Carl E. Miller, Joseph E. Henderson, Gerald Garrison, and Wayne Sandstrom presented a paper entitled "Zenith Angle Effects for Cosmic-Ray Protons and Mesons". They used a magnetic cloud chamber to study the distribution in momentum of those charged particles stopping in 15 cm of lead absorber, at an altitude of 3.3 km. They were interested in the angles of the rays, upon which they give their comments.
Robert Hofstadter and Alvin M. Hudson presented a paper entitled "Energy Loss of Cosmic-Ray μ-Mesons". They say: "A triple-coincidence telescope, consisting of three NaI(Tl) crystals, has been used to measure the energy loss of μ-mesons in the cosmic rays at sea level." There were six

inches of lead above the telescope, etc. This elaborate plan seems to have led to no conclusions, and the authors say: "The possible significance of these results will be discussed."
Arthur Z. Rosen presented a paper entitled "Protons and Mesons at 9000 Feet". He used three cloud chambers at once, at 9000 feet, and promises to compare the results with those to be obtained at sea level using the same apparatus sometime in the future.
That is the end of the survey of conference papers.[54]

P. J. Isaacs, Allan Maxwell Sachs, and Jack Hans Steinberger published a paper entitled "Total Cross Sections of 60-Mev Mesons in Hydrogen and Deuterium"[55]. They say: "The total cross sections of positive and negative mesons of average energy 58 Mev have been measured in hydrogen and deuterium."

Daniel Leenov published a paper entitled "Electromagnetic Properties of Spin-One Particles"[56]. Although this does not appear to be about mesons, it does actually have a section about pions, and the article has numerous important things to say. In his study of spin-one charged particles, Leenov attempts to pursue two successive theories. The second he describes like this: "The μ-pair theory has been used by [Gregor] Wentzel [published in 1949] as a description of the π-meson in order to predict certain of its properties. In Part II this theory has been generalized to the case of a vector particle made up of a spinor pair, and descriptions are given of the computation of the magnetic dipole moment and the electric quadrupole moment, as well as the cross sections for scattering and for dissociation because of interactions with a Coulomb field, here including the case of a pseudoscalar π-meson. These results, it must be noted, cannot be considered quantitative, owing to the cut-off method used; however, they may give useful qualitative information. … The Coulomb scattering of a pion moving with a sufficiently high velocity may lead to dissociation into two muons, according to the pair theory. This problem is conveniently treated by considering the pion at rest, acted on by a moving Coulomb field." He believes that with scattering, the internal structure (spins) of the pion can change. The equations and exposition are too lengthy and complex to summarise here. (The author appears to be a Ph.D student of Wentzel, whom he thanks for suggesting these problems.)

Kenneth Marshall Watson has contributed an important paper entitled "The Hypothesis of Charge Independence for Nuclear Phenomena"[57]. He describes the idea of Charge Independence as follows: "The equivalence of the nuclear forces between two protons, two neutrons or a proton and neutron as suggested by low energy scattering experiments and the binding

energies of light nuclei raises the question whether this may reflect some general symmetry principle in nature. [Here he refers to a paper by Gregory Breit and Eugene Feenberg of 1936.] Such a principle should presumably be extended to include not only the phenomena involving just nucleons, but also to those involving other particles whose existence is related to nuclear forces (supposedly π- mesons, for instance). This hypothetical symmetry principle has been called the hypothesis of charge independence. … The physical content of this hypothesis is that neutrons and protons represent different states of the same particle and have identical properties … It seems highly probable that π-mesons contribute to the nuclear forces, so it is quite natural to attempt to extend this hypothesis to phenomena involving π-mesons. The physical content here is that the three charge states of π-mesons, i.e., positive, negative, and neutral, have identical physical properties … a particle which is a proton after (its) transformation was a mixture of proton and neutron states before the transformation, and the mesons which it can emit will be a linear combination of the mesons which were emitted by the proton and neutron states before the transformation. This transformation is a three-dimensional representation of the three dimensional rotation group, since there are three types of mesons. It is further irreducible; it cannot consist of three one-dimensional representations, since the mixing of states actually does occur; it cannot consist of a two-dimensional and a one-dimensional representation, since then it would not be possible to describe the emission of a meson by a single nucleon in an invariant manner. Therefore, the representation is irreducible." This is profound thinking, and the full paper needs to be consulted even after all these years. (It is perhaps worth mentioning that Ernest Henley, mentioned earlier, was Kenneth Watson's doctoral student.)

Donald Robert Yennie published a paper entitled "Angular Momentum in Nonlocal Field Theory"[58] which has important implications for mesons even though mesons are not specifically mentioned at all. The paper deserves a very close and extended study, but here we shall have some brief indications. Yennie says: "In field theory, the concept of an elementary particle is intimately associated with the notion of irreducible types of fields. In this paper we shall be concerned primarily with the decomposition of arbitrary nonlocal fields into irreducible parts and the association of these irreducible parts with particles of a given mass and spin. The decomposition of scalar and spinor nonlocal fields has already been discussed by Yukawa [*Physical Review*, Volume 80, 1950, page 1047; and Yennie thanks Yukawa for discussing the subject with him personally]. He found that the scalar nonlocal field could be decomposed into irreducible parts characterised by four invariant quantities which could be

interpreted as the mass, spin, internal radius, and the time component of the internal extension of a resting particle. … In this paper we shall restrict ourselves to particles of nonvanishing mass so that a rest frame will always exist. … In conclusion, it should be emphasized again that the preceding consideration apply only to free fields. It has been shown that an arbitrary nonlocal field can be decomposed into irreducible parts whose transformation properties are determined by the irreducible representations of the inhomogeneous Lorentz group. As far as transformation properties are concerned, an irreducible part of a nonlocal field is therefore equivalent to some type of local field, as asserted by [Markus] Fierz [in 1950]. This equivalence can be removed only by introducing an interaction between fields in a way which depends on the nonlocal character of the fields involved. Although it is unsatisfactory in certain respects, such as interaction scheme has been introduced by Yukawa [in 1950, see reference given above]; in his formalism, the nonlocal character of the field is manifested in the occurrence of convergence factors, demonstrating that *r* is more than a spin variable." To be clear, Yennie says of his paper: "It is shown that the spin of a nonlocal particle is made up of two parts arising, respectively, from the transformation properties and from the nonlocal nature of the field; the two parts combine vectorially, to give the total spin." This seems to me to be a promising insight, the implications of which have by no means yet been exhausted, and in particular if it were applied to pions in ways perhaps not yet attempted.

Herman Yagoda published a paper entitled "The Emission of Slow Positive and Negative Mesons from Nuclear Disruptions Produced by Cosmic Radiation".[59] This is a ten page paper filled with numerous illustrations and charts, dealing with proportions of plus pions to negative pions, and all such cosmic ray studies concerns.

Morton Fischel Kaplon, Bernard Peters, and David Mark Ritson published a paper entitled "Emulsion Cloud-Chamber Study of a High-Energy interaction in the Cosmic Radiation"[60]. This well-illustrated paper is largely devoted to cosmic rays, but the interpretation of the findings makes clear that the true importance of the authors' work relates to neutral mesons. The authors promised to give further information and discussion in a future paper. An advisor to their work was Robert Marshak.

A Letter to the editor by Giorgio Salvini and V. Kim is entitled "Production Cross Section and Energy Spectrum of the Neutral Mesons in Cosmic Rays".[61] This concerns the energy distributions and numbers observed.

A Letter to the Editor by Herbert Lawrence Anderson, Enrico Fermi, E. A. Long [not to be confused with the Elena Amanda Long of the present day], R. Martin, and Darragh Edmund Nagle was entitled "Total Cross Sections of Negative Pions in Hydrogen"[62]. (Anderson and Nagle were long term collaborators with Fermi at Chicago.) They say: "The interaction between negative pions and protons has been investigated by Steinberger and co-workers …" They have carried this work further. They did not reach a definitive result.
A further Letter to the Editor immediately follows from Enrico Fermi, Herbert Lawrence Anderson, Arvid Lundey, Darragh Edmund Nagle, and Gaurang Bhaskar Yodh entitled "Ordinary and Exchange Scattering of Negative Pions by Hydrogen"[63]. This is a companion Letter to the preceding, giving further details.
Yet another Letter to the Editor immediately follows this from Anderson, Fermi, Long, and Nagle entitled "Total Cross Sections of Positive Pions in Hydrogen"[64]. This is another companion Letter. Here they report that they have discovered, using their cyclotron, that positive pions are emitted in the backward direction from the proton beam whereas negative pions are emitted in the forward direction. At last they got somewhere! This really was a major discovery, with potentially unexplored implications today, as will be discussed later on, in another Part of this paper.
Tetsuo Eguchi wrote a Letter to the Editor entitled "Radiative π- μ Decay"[65] concerning the decay of pions into muons. He discovered some anomalous decay processes which troubled him and he put a huge amount of effort into calculations and analysis but still did not solve the anomalies. He says he hopes to continue studying this problem by studying decay processes of pions which interact only with nucleons, which "might be of special interest, and is under consideration."

Warren B. Cheston published a paper entitled "The Interaction of a Charged Pi Meson with the Deuteron"[66]. Cheston's investigation is of *positive* charged pions interacting with deuterons. He favours the *PS* Theory rather than the *PV* Theory. He has had an encouraging result. He examined the nonradiative absorption of a positive pion by a deuteron, "and the inverse reaction has made possible the determination of the spin of the π^+ meson." The discussion and results of this lengthy paper raise numerous issues, such as radiative versus nonradiative interactions, too extensive to summarise. The author was advised by Robert Marshak.

Carl Monroe York, Junior, published a paper entitled "The Differential Range Spectrum of Cosmic-Ray Mesons at Sea Level"[67]. York carried out his observations by using a counter controlled cloud chamber in an experiment which "employs a geometrical arrangement of the apparatus

which minimizes the corrections to be applied to the data to allow for loss of mesons from the apparatus due to scattering." He got 20% more results as a consequence.

A Letter to the Editor from Morton Fischel Kaplon was entitled "Electromagnetic Interference Effects in Charged Meson-Proton Scattering"[68]. Kaplon wishes to study the sign of the scattering amplitude for meson-nucleon scattering, but Bethe and Wilson [1951] say that it "depends on the charge of the meson and the specific meson theory employed." He says that evidence to date supports the pseudo-scalar theory, and so he adopts that. He hopes that "one should be able to obtain useful information concerning the meson-nucleon scattering amplitude by observations on the interference effects with the electromagnetic scattering". Kaplon was advised by Robert Marshak and presumably continued this work later.

This is the end of the survey of Volume 85, of which I had my own copy because it contains the two fundamental 1952 papers of my good friend David Bohm on the hidden variables interpretation of quantum mechanics, which had the effect of stimulating Louis de Broglie to revive his old pilot wave theory and re-issue it in its new form as his Theory of the Double Solution.

In 1955, Hans Bethe, Silvan Schweber, and Frederic de Hoffmann published their two volume work *Mesons and Fields.*[69] In Volume I, which deals with fields, they have this to say about Yukawa:

"In 1935, Yukawa (1935) [*in the reference they use "Proc" instead of "Prog", fortunately avoiding the mistake made by some*] studied the equation (25) with $\Gamma = 1$, assuming that the nucleon mass is very large compared to that of the meson. This then allows us to localize (even quantum mechanically) in a small region of space – for example, at the origin. The right-hand side of (25), which may be considered as proportional to the density of nuclear matter, then reduces to a delta function in space. Since the source term does not depend on time, there exist solutions of (25) which are independent of time, … (Of course, to these solutions we may add solutions of the homogeneous equation. The latter, just as in electromagnetic theory, correspond to meson waves travelling freely through space; we are not concerned with these.)"[70]

The authors then go on to refer to the "Yukawa potential". They say they will discuss this in much greater detail in Volume II, which deals specifically with mesons.

For this paper, however, the meson wave travelling freely through space which these authors say they are not concerned with is a major subject in the discussion which is to come.

Volume II was published without any date and the strange statement that the book was 'not copyrighted in the United States of America". I don't know what any of that means, but I thought I ought to mention it. The volume is a huge treasure trove of meson info, as this second volume extends to 446 pages. By page 4 the authors already discuss pion mass. They say that positive and negative mesons have the same mass within statistical error, and that it is 273.3 electron masses (plus or minus 0.2). They give considerable attention to spin: "The spin of the π meson is perhaps the most important property from the theoretical point of view. … One assumes, of course, that the π^- and π^+ mesons have the same spin. … The spin of the π^o cannot be determined directly. … In any case it is plausible that the neutral and charged π mesons should have the same spin, just as neutron and proton have the same spin." They assume therefore that the spin of all three types of pion is 0. And they add: "The wave function of any particle of spin 0 is a scalar and thus remains unchanged under any rotation …" As the authors move on to a discussion of parity, they make the statement (page 15, though this is unindexed) that the rest mass of the negative (minus) pion is 273 mc^2. They say this in the context of saying they wish they could find a gamma ray of 273 mc^2. But they have been unsuccessful. Later on, they turn to the subject of the isotopic spin of the meson. They say they approve of the concept that the isotopic spin of a system should be to one "containing mesons as well as a nucleon". They wish to adopt a phenomenological approach "to generalize the definition of the projection of the isotopic spin on the ζ direction, m_τ, because this quantity will be connected with the charge. For simplicity, consider again the case of a single nucleon. We know that a proton, for which $m_\tau = ½$ can transform into a neutron ($m_\tau = - ½$ by emission of a positive meson). Therefore, if we wish the entire M_T to be conserved in the emission process we must assign to the positive meson the value $m_\tau = 1$." They go on to say that the isotopic spin of the meson is $T = 1$. (pages 55-6) On page 103 they commence a discussion of mesic atoms. They explain the well-known fact that the meson orbits are within the electron orbits and that thus the electrons of the atom "have a negligible influence on the energy levels of the meson". They continue: "A mesic atom is formed by the capture of the meson in an outer orbit, followed by energy loss either through radiation or through Auger effect (ejection of an electron from the atom). These processes have been studied in detail by [Arthur Strong] Wightman (1949,

1950), who also gives references to the earlier literature. This theory leads to the conclusion that a meson which arrives in a state of given (small) principal quantum number *n*, will usually have the highest possible orbital momentum, $l = n - 1$. … If the π meson is in an *S* state, especially in the 1*S* state, two effects will occur. The first is the absorption of the π^- by the nucleus. This process will change a proton in the nucleus into a neutron, and the mass of the pion will normally be converted into kinetic energy of nucleons." They say that the nucleus then causes a shift in the energy of the meson, which would ordinarily mean that "we can define a 'potential' between meson and nucleon". But they prefer to adopt a theory of [Stanley] Deser and colleagues of 1954 which makes the idea of a potential unnecessary. If a potential is to be retained as a concept then it will be designated as *V* as being the potential between the meson and a nucleus of charge *Z* and mass number *A*." And they add: "We assume that *V* extends over a distance which is small compared to the meson wave length …" The book continues for another 300 pages, which includes extremely lengthy discussions of scattering, experiments, normalisation, production and destruction of mesons, and so forth. There are 26 pages of references at the back of the volume. The book massively superseded that by Robert Marshak (to which they refer respectfully upon occasion), and remains a classic collection of data and discussion as things appeared to them in 1955.

In 1957, Francis E. Low of MIT (who had worked on the Manhattan Project) published a paper entitled "Pi Mesodynamics" in *Reviews of Modern Physics*[71] which begins with this statement: "I would like to discuss in a qualitative way how far we can come in understanding the behavior of low-energy pi mesons." Low is especially concerned with the pion mass, which he accepts as 273. It is worthwhile giving extended extracts: " … we are faced with the unfortunate situation of not knowing the correct theory that we have to use to try to explain the phenomena. Two theories have become fair game for theoretical physicists. The first of these is the relativistic, symmetric pseudoscalar meson theory, the γ_5 theory; the second is the [Geoffrey] Chew Theory. Neither is a correct theory in the sense that quantum electrodynamics is a correct theory. Let me emphasize the two reasons that quantum electrodynamics is what we call a correct theory. In the first place the fine structure constant is small, 1/137, so we can calculate in a power series, or a quasi-power series, and get accurate answers. The second reason is that the mass ratio of the particles that are involved in quantum electrodynamics to the particle that we like to keep out of quantum electrodynamics (such as the pi meson) is small, about 1/273. For this reason the contribution of pi mesons to the vacuum polarization part of the Lamb Shift is $(1/273)^2$ compared to the contribution of the electrons. … Neither of these two conditions holds in a meson theory.

… The mass ratio of the electron to the pi meson, the relevant mass ratio of quantum electrodynamics, is 1/273.The mass theory in the pion theory case is effectively about 1/5; therefore, pi meson phenomena probably may not be isolated from the effects of other particles." He prefers the Chew Theory and explains why at some considerable length.

Also in 1957, in Part 4 of *The Physical Review*, Volume 108, a paper appeared by Asoke Nath Mitra and Renuka P. Saxema, entitled "Meson-Meson Interaction in the [Hans] Bethe- [Edwin Ernest] Salpeter Approximation".[72] They write: "The concept of meson-meson interaction (which can be pictured as taking place through virtual nucleon pairs) is almost as old as that of the more fundamental meson-nucleon interaction. However, unlike the latter which can be realized directly by means of a meson-nucleon scattering experiment, the former finds only indirect verification by the effect it produces on a system consisting of two or more mesons, since it is not possible to conduct a direct experiment for scattering a meson beam by another. One of the most important processes in which π-π interaction plays an indirect role is one involving scattering of mesons by nucleons, if it is remembered that a nucleon is always 'dressed' with its own meson field which the incident meson beam has to encounter." Most of the rest of the paper is expressed in formalism designed to study these interactions. The authors do not explain or define the meson field or how it 'dresses' the nucleon. The authors were advised by Freeman Dyson on the mathematical formulation.
A Letter to the Editor entitled "Photoproduction of Pion Pairs in Hydrogen" also appears in this same issue, and is by Michel Bloch and Matthew Sands.[73] It begins: "Negative pions from the interaction of γ rays with protons are presumed to arise from events in which two or more pions are produced." They describe detections made at the Caltech Synchrotron where they work. The work was supported by the U.S. Atomic Energy Authority.

In 1959, four interesting articles appeared in *The Physical Review*, which can be cited next. One is by Gerald Feinberg and Ralph Eugene Behrends, entitled "Some Consequences of Symmetries of the Strong Interactions".[74] As the study of mesons progresses, the question of symmetries has been seen to be important to the subject. This paper is primarily concerned with the *K* mesons (kaons), and pions are mentioned only incidentally.
Another paper in the same issue of *The Physical Review* is by Sigenobu Sunakawa and Katsumi Tanaka, and is entitled "Proton-Neutron Mass Differences".[75] This paper is largely concerned with what its title says, but in the context of exploring that subject, the authors particularly remark; "One must distinguish here between nucleon pairs which are due to

electromagnetic interaction (which brings in a factor e^2) and those which are due to mesonic interaction (which brings in the factor g^2). Not more than one nucleon pair can result from electromagnetic interaction since the self-mass is considered to order e^2." They go on to discuss how two nucleon form factors in one of their equations "are due to the virtual meson cloud surrounding the nucleon. The most reliable way of taking account of the effects of the meson cloud appears to be the procedure of using directly the data on the form factors obtained at Stanford. … The electronic proton-neutron mass difference has been obtained in two ways, taking into account the mesonic effects by using the experimental form factors obtained at Stanford." (Regrettably, I shall not here include description of the work at Stanford.)

Another relevant paper in the same issue of *The Physical Review* is "Significance of Electromagnetic Potentials in the Quantum Theory" by David Bohm and Yakir Aharonov.[76] The authors begin by stressing that quantum potentials can exist where there is no field. They insist that "a further interpretation of the potentials is needed in quantum mechanics." And: "… in quantum theory, an electron (for example) can be influenced by the potentials even if all the field regions are excluded from it. In other words, in a field-free multiply-connected region of space, the physical properties of the system still depend on the potentials. … some further development of this theory is needed. … we need to be able to define the physical difference between two quantum states which differ only by gauge transformation. … in a system containing an undefined number of charged particles (i.e., a superposition of states of different total charge), a new Hermitian operator, essentially an angle variable, can be introduced which is conjugate to the charge density and which may give a meaning to the gauge. Such states have been used in connection with recent theories of superconductivity and superfluidity and we will show their relation to this problem in more detail." Although the authors do not mention pions in this paper, these opinions are relevant to Yukawa's original concept of "the exchange potential" of pions. I first met David Bohm in 1981, and he and his wife Saral became friends of me and my wife Olivia. I taped numerous conversations with him about physics (which have never been transcribed) and he never ceased to insist upon the importance of potentials. His ideas evolved into the concept of "the quantum potential". But as he went on to say to me in the eighties: "But we don't know what the quantum potential actually is. All we know is that there is one."

The fourth relevant paper in this issue is "Heavy Nuclei and α Particles between 7 and 100 Bev/ Nucleon. II. Fragmentations and Meson Production" by Piyare Lal Jain, Erich Lohrmann, and Martin W. Teucher. (This is a sequel to Part I which immediately precedes it in the same issue.)[77] This is a very long paper. It is concerned with meson production in

shower particles, and their angular distribution. 175 examples were studied.

In 1959, Chen Ning Yang delivered his Vanuxem Lectures at Princeton University which he edited in 1961 and published in 1962 as his slim volume *Elementary Particles: A Short History of Some Discoveries in Atomic Physics.*[78] (The lectures and volume were an expansion of a five-page paper which he had published in 1957 in *Reviews of Modern Physics.*[79]) On page 19 of his book he introduces the pions into his general discussion and writes: "The story of the next elementary particle is long and involved. It started in 1935 with a suggestion of H. Yukawa that the protons and neutrons in a nucleus are bound together through a mediating field in much the same way that the nucleus and the electron are bound in an atom through the intermediary of the electromagnetic field. Yukawa pointed out that the small size of the nucleus implies the shortness of the range of nuclear forces, which in turn, as we discussed in the previous lecture, is related to a large momentum carried by the field. Now by the principles of special relativity, the average momentum carried by the field is of the order of the velocity of light multiplied by the mass of the quantum that is associated with the field. From the size of nuclei, Yukawa thus estimated this mass to be approximately 200 times the electron mass." Yang briefly gives the history of the cosmic ray studies which confirmed Yukawa's predictions: "These particles had a mass between the masses of the electron and the proton, and it was natural to conclude that they were the particles predicted to exist by Yukawa, which serve to transmit the nuclear forces. They were at first called mesotrons but later mesons. This discovery caused quite a stir among the physicists …" He then quotes a letter sent in 1938 by Niels Bohr which says "The story of the discovery of these particles is certainly a most wonderful one …" He then recites the convoluted difficulties encountered by the cosmic ray observations and explains that certain discrepancies were finally explained by realizing that there were two types of mesons, the pions of mass 273 and the muons of mass 207. This was a happy resolution, as he says: "The discovery of the existence of two kinds of mesons eliminated the discrepancy mentioned earlier. The π meson is identified with Yukawa's meson, and serves as the intermediary for nuclear forces, while its daughter, the μ meson is the cosmic ray meson observed by Conversi, Pancini, and Piccini which does not interact strongly with atomic nuclei." Yang's book continues with fascinating discussions of symmetries in general.

Towards the end of 1958 what we might consider the first really major paper appeared which heralded an overwhelmingly dramatic revolution in particle physics. The paper was by Stanley Mandelstam.[80] In that paper he

introduced what are now named after him and called the Mandelstam Variables, which are numerical quantities which encode the energy, momentum, and angles of particles in a scattering process in a Lorentz-invariant fashion, which by accommodating special relativity, asserts that the laws of physics stay the same for all observers that are moving with respect to each other within an inertial frame of reference. This may have seemed of minor importance at the time, but it was to be followed by a tidal wave of related papers by Mandelstam and his colleagues over the next four years which would shake the entire edifice of particle physics, under the guidance and leadership of that controversial figure, Geoffrey Chew.

The history of this movement during the years 1959-1961 has been discussed in a paper published as recently as December, 2025, by two German scientists, Alexander S. Blum and Jens Salomon.[81] It is therefore not necessary for me to give a detailed survey here of that material. Their footnotes contain the references to the important papers. Their main text is preoccupied with discussing the theories and ideas themselves.

In 1960, Geoffrey Foucar Chew gave a series of lectures at summer schools at Les Houches and Edinburgh, one of which was "The Pion-Nucleon Interaction". Those lectures were published in the relevant *Proceedings*, but Chew extensively revised and extended those lectures in the summer of 1961, and in their new form, they were published in 1962 in his book *S-Matrix Theory of Strong Interactions*.[82] Several of the other lectures dealt with pions also. In citing Chew's views and remarks I shall simply give the page numbers to the volume, for the sake of simplicity of reference.

The appearance of Chew's book is something which I liken to throwing a stink bomb into a room full of physicists and watching them flee. It was uncompromising, arrogant, denunciatory, and in my personal view fanatical. Chew did not have a gentle approach, and persuasion was apparently not in his toolkit. He wished to overthrow the entire Standard Model of particle physics and said so in a shouty manner. He had several followers and colleagues, amongst whom were Stanley Mandelstam, Steven C. Frautschi, Francis Eugene Low, and Richard Edwin Cutkosky. The physicist-turned science populariser Fritjof Capra became a close friend and promoter of Chew and his work, as may be seen from the fascinating book *A Passion for Physics*, which is about Chew, published in 1985.[83] Anyone who really wants to know about Chew needs to read that book. The man and his work are well portrayed by a wide variety of friends who knew and worked with him. They were all very devoted to him and agree that he was charming and delightful.

At first Chew referred to his new theory as "the S-matrix theory of strong interactions". Later it became known colloquially as The Bootstrap Theory. It had its earliest origins in work by Werner Heisenberg, as Chew relates: "A sustained series of field-theoretical developments over the past decade has brought the concept of an S-matrix theory of strong interactions close to realization. Although he has long since renounced the S-matrix approach, the original work was done by Heisenberg in 1943. [*Zeitschrift für Physik*, Volume 120, 513, 673 (1943).] Heisenberg lost interest, probably because in the forties he lacked the full analytic continuation that is required to give the S matrix dynamical content. He also, as is well known, … subsequently abandoned conventional many-field theory, and has thrown all his efforts behind the idea of a single underlying field [in 1958]. It should be realized that the S-matrix theory of strong interactions, at least as I shall describe it in these lectures, has the same goal as the single-field approach: that is, given certain symmetries, to predict all the observed particles, together with masses and mutual interactions, in terms of a single constant with the dimensions of length. There should be no arbitrary dimensionless constants. … So that there can be no misunderstanding of the point of view of these lectures, let me say at once that I believe the conventional association of fields with strongly interacting particles to be empty. … no aspect of the strong interactions has been clarified by the field concept. … It is my impression now … that future development of an understanding of strong interactions will be expedited if we eliminate from our thinking such field-theoretical notions as Lagrangians, 'bare' masses, 'bare' coupling constants, and even the notion of 'elementary particles'. I believe, in other words, that in the future we should work entirely within the framework of the analytically continued S matrix."[84]

It would become clear that Chew also wished to replace the notions of space and time with abstract mathematical properties of the S-matrix. So there would be no space and time, no mass, no constants, no fields, and no particles. One might well ask: what then is left?

Well, there was Geoffrey Chew.

Rather than give a description of Chew's theories myself, it makes more sense for me to quote such a description of them from a book by his devoted follower Fritjof Capra, published in 1982[85]:
"The philosophical foundation of *S*-matrix theory is known as the bootstrap approach. Geoffry Chew proposed it in the early 1960s, and he and other physicists have used it to develop a comprehensive theory of strongly interacting particles. Together with a more general philosophy of nature. According to this bootstrap philosophy, nature cannot be reduced

to fundamental entities, like fundamental building blocks of matter, but has to be understood entirely through self-consistency. All of physics has to follow uniquely from the requirement that its components be consistent with one another and with themselves. This idea constitutes a radical departure from the traditional sprit of basic research in physics which had always been bent on finding the fundamental constituents of matter. At the same time it is the elimination of the material world as an interconnected web of relations that emerged from quantum theory. The bootstrap philosophy not only abandons the idea of fundamental building blocks of matter, but accepts no fundamental entities whatsoever – no fundamental constants, laws, or equations. The universe is seen as a dynamic web of interrelated events. None of the properties of any part of this web is fundamental; they all follow from the properties of the other parts, and the overall consistency of their interrelations determines the structure of the entire web.
"The fact that the bootstrap approach does not accept any fundamental entities makes it, in my opinion, one of the most profound systems of Western thought, raising it to the level of Buddhist or Taoist philosophy. At the same time it is a very difficult approach to physics, one that has been pursued by only a small minority of physicists. The bootstrap philosophy is too foreign to be appreciated yet, and this lack of appreciation extends also to *S*-matrix theory. … In the framework of *S*-matrix theory, the bootstrap approach attempts to derive all properties of particles and their interactions uniquely from the requirement of self-consistency. The only 'fundamental' laws accepted are a few very general principles that are required by the methods of observation and are essential parts of the scientific framework. All other aspects of particle physics are expected to emerge as a necessary consequence of self-consistency. If this approach can be carried out successfully, the philosophical implications will be very profound. … The picture of subatomic particles that emerges from the bootstrap theory can be summed up in the provocative phrase 'Every particle consists of all other particles."… Subatomic particles are not separate entities but interrelated energy patterns in an ongoing dynamic process. These patterns do not 'contain' one another but rather 'involve' one another in a way that can be given a precise mathematical meaning but cannot easily be expressed in words."

And so there you are.

In July of 1962, Chew followed with a paper in *Reviews of Modern Physics* entitled "S-Matrix Theory of Strong Interactions without Elementary Particles"[86] The paper begins with these extraordinary remarks, written in the manner of a lovesick student to the object of his grand passion:

"In this paper I present an indecently optimistic view of strong interaction theory. My belief is that a major breakthrough has occurred and that within a relatively short period we are going to achieve a depth of understanding of strong interactions that a few years ago I, at least, did not expect to see within my lifetime. I know that few of you will be convinced by the arguments given here, but I would be masking my feelings if I were to employ a conventionally cautious attitude in this talk. I am bursting with excitement … My oldest and dearest friends tell me that this is a fetish, that field theory is an equally suitable language, but to me the basic strong-interaction concepts, simple and beautiful in a pure S-matrix approach, are weird, if not impossible, for field theory."

This exercise in the early history of one aspect of particle physics, namely the mesons, has been far from complete. But I hope it is a useful contribution, however inadequate, to our understanding of what preceded the more modern approaches of today. This portrait of an innocent world before the invasion of the quarks and the gluons reminds us of what things were like in the garden before the forbidden fruit of further knowledge was tasted.

This is the end of Part One of this paper. The rest of the paper will be completely different, and will contain some surprises. Some of the most recent developments have some unexpected affinities with these beginnings.

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