

THE OSKAR KLEIN MEMORIAL LECTURES

Volume 3



Editors: Lars Bergström & Ulf Lindström

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Volume 3

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Volume 3

Editors

Lars Bergström & Ulf Lindström

Stockholm University
Sweden



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Preface

The Oskar Klein Memorial Lecture series has been running for thirteen consecutive years since the start in 1988. In 1994, to commemorate the 100th anniversary of Klein's birth, the lectures were extended to a symposium.

The first four lectures, delivered by C.N. Yang, S. Weinberg, A. Bethe and A. Guth have been published in Volumes I and II of "The Oskar Klein Memorial Lectures", (ed. G. Ekspong) and the symposium is published as "The Oskar Klein Centenary" (ed. U. Lindström).

The present volume is thus the fourth in a series and has some expectations to live up to. Hopefully they are well met by the contributions by T.D. Lee, N. Seiberg, A. Polyakov, P.J.E. Peebles, E. Witten and G. 't Hooft.

The typical format of the Klein Lectures is that the speaker gives one general colloquium type lecture and one specialized seminar. We have included most of the colloquia and also some of the seminars. In the first two volumes it was still possible to also include some material from Klein's own research that had not been generally available. Here we have instead included more lectures. For this reason we have had to wait a while until there was enough material to fill a volume. However, the character of the lectures is such that they remain topical, and the outstanding quality of the contributors help to make these written versions timeless. In fact, one of the instructions we usually give to the speakers is to cover general aspects of their fields as well as the latest results. An example of this more timeless aspect is provided by the contribution by A. Polyakov where he has collected ideas on the parallels between different subjects that he has clearly pondered over some years.

The lecture series has contained some very exciting moments during the time covered in the present volume. We recall, e.g., the interesting discussion of symmetry by T.D. Lee, the presentation by N. Seiberg of wonderful new types of duality in supersymmetric theories, and by E. Witten of the then new ADS/CFT correspondence and its application to the long-standing problem of quark confinement, or the lecture in 1999 by G. 't Hooft, who went on to receive the Nobel Prize later on the same year.

Theoretical high-energy physics dominates the subjects of the lectures, mirroring one of Klein's own main interest. He had other interests as well, cosmology being one of them (particularly in his later work). It is therefore very befitting that the contribution by Peebles in a nice way summarizes the phenomenal improvement in the understanding of the Universe which has taken place since Klein's days. However, we also get sobering reminders that much still remains to be understood, and that it may be dangerous to overinterpret current results - a well-placed remark by one of the founders of physical cosmology.

All in all the yearly Klein Lecture has become a very successful tradition in Swedish physics and it has inspired several similar series. We are very grateful to the Swedish Royal Academy of Sciences whose support through its Nobel Institute for Physics has made these lectures possible over the years. We also take this opportunity to express our gratitude to FYSIKUM, Stockholm University, where the lectures and the traditional dinner are held.

Stockholm, April 2001

Lars Bergström and Ulf Lindström, editors.

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THE WEAK INTERACTION: ITS HISTORY AND IMPACT ON PHYSICS

T. D. Lee

Columbia University, New York, N.Y. 10027

It is a pleasure and an honor for me to give this lecture in honor of Oscar Klein who made major contributions to field theory, quantum electrodynamics and particle physics, including weak interactions. He was the first one to observe that the μ decay and the β decay could be described by the same interaction with the same coupling constant; this led to the discovery of the Universal Fermi Interaction.

Perhaps I should begin my discussion of the history of weak interactions by separating it into three periods:

1. Classical Period, 1898-1949
2. Transition Period, 1949-1956
3. Modern Period, 1956-

1. CLASSICAL PERIOD (β DECAY)

In 1898 Lord Rutherford¹ discovered that the so-called Becquerel ray actually consisted of two distinct components: one that is readily absorbed, which he called alpha radiation, and another of a more penetrating character, which he called beta radiation. With that began the history of the weak interaction. Then, in 1900², the Curies measured the electric charge of the β particle and found it to be negative.

Sometimes when we think of physics in those old days, we have the impression that life was more leisurely and physicists worked under less pressure. Actually, from the very start the road of discovery was tortuous and the competition intense. A letter written in 1902 by Rutherford (then 32) to his mother expressed the spirit of research at that time^{3,4}:

"I have to keep going, as there are always people on my track. I have to publish my present work as rapidly as possible in order to keep in the race. The best sprinters in this road of investigation are Becquerel and the Curies... "

Most of the people in this room can appreciate these words. Rutherford's predicament is still very much shared by us to this day. Soon many fast runners came: Hahn, Meitner, Wilson, Von Baeyer, Chadwick, Ellis, Bohr, Pauli, Fermi and many others.

In preparing this lecture, I was reminded once more of how relatively recent these early developments are. We know that to reach where we are today took more than 90 years and a large cast of illustrious physicists. I recall that when Lise Meitner came to New York in the mid '60s, I had lunch with her at a restaurant near Columbia. Later K.K. Darrow joined us. Meitner said, "It's wonderful to see young people." To appreciate this comment, you must realize that Darrow was one of the earliest members of the American Physical Society and at that lunch he was over 70. But Lise Meitner was near 90.

I was quite surprised when Meitner told me that she started her first postdoc job in theory with Ludwig Boltzmann. Now, Boltzmann was a contemporary of Maxwell. That shows us how recent even the "ancient" period of our profession is.

After Boltzmann's unfortunate death in 1906, Meitner had to find another job. She said she was grateful that Planck invited her to Berlin. However, upon arrival she found that because she was a woman she could only work at Planck's institute in the basement, and only through the servant's entrance. At that time, Otto Hahn had just set up his laboratory in an old carpenter shop nearby. Lise Meitner decided to join him and to become an experimentalist. For the next thirty years, their joint work shaped the course of modern physics.

In 1906, Hahn and Meitner published a paper⁵ stating that the β ray carries a unique energy. Their evidence was that the absorption curve of a β ray shows an exponential decrease along its path when passing through matter, like the α ray.

Then W. Wilson⁶, in 1909, said "no", the β ray does not have a unique energy. By observing the absorption curve through matter of an electron of unique energy, Wilson found electrons to exhibit totally different behavior from the α particle; the absorption curve of a unique energy electron is not exponential. Consequently, Wilson deduced that the apparent exponential behavior of the absorption curve of β decay implies that the β does not have a unique energy, the same experimental observation on β but with a totally opposite conclusion.

In 1910, Von Baeyer and Hahn⁷ applied a magnetic field to the β ray; they found the β to have several discrete energies. In this way, they also reconciled the conclusion of W. Wilson. Then, in 1914, Chadwick⁸ said "no". The β energy spans a continuous spectrum, instead of discrete values. The discrete energy observed by Von Baeyer and Hahn was due to the secondary electron from a nuclear γ transition, with the γ energy absorbed by the atomic electron. In this process, the discrete energy refers to the nuclear γ emission.

Then came World War I and scientific progress was arrested. In 1922, Lise Meitner⁹ again argued that the β energy should be discrete, like α and γ . The apparent continuum manifestation is due to the subsequent electrostatic interaction between β and the nucleus. From 1922 to 1927, through a series of careful measurements, Ellis¹⁰ again said "no" to Meitner's hypothesis. The β energy is indeed continuous. Furthermore, Ellis proved that the maximum β energy equals the difference of the initial and final nuclear energy.

There would then appear a missing energy. This was incorporated by Niels Bohr¹¹, who proposed the hypothesis of non-conservation of energy.

Very soon, Pauli said "no" to Bohr's proposition. Pauli¹² suggested that in the β decay energy is conserved, but accompanying the β particle there is always emission of a neutral particle of extremely small mass and with almost no interaction with matter. Since such a weakly interacting neutral particle is not detected, there appears to be an apparent nonconservation of energy.

Fermi¹³ then followed with his celebrated theory of β decay. This in turn stimulated further investigation of the spectrum shape of the β decay, which did not agree with Fermi's theoretical prediction. This led Konopinski and Uhlenbeck¹⁴ to introduce the derivative coupling. The confusion was only cleared up completely after World War II, in 1949, by Wu and Albert¹⁵, signalling the end of one era and the beginning of a new one.

2. CLASSICAL PERIOD (OTHER WEAK INTERACTIONS)

When I began my graduate study of physics at the University of Chicago, in 1946, the pion was not known. Fermi and Teller¹⁶ had just completed their theoretical analysis of the important experiment of Conversi, Pancini and Piccioni¹⁷. I attended a seminar by Fermi on this work. He cut right through the complex slowing-down process of the mesotron, the capture rate versus the decay rate, and arrived at the conclusion that the mesotron could not possibly be the carrier of strong forces hypothesized by Yukawa. Fermi's lectures were always superb, but that one to me, a young man not yet twenty and fresh from China, was absolutely electrifying. I left the lecture with the impression that, instead of Yukawa's idea, perhaps one should accept Heisenberg's suggestion¹⁸ that the origin of strong forces could be due to higher-order processes of β interaction. As was known, these were highly singular.

At that time, the β interaction was thought to be reasonably well understood. Fermi's original vector-coupling form,

$$G(\psi_n^\dagger \gamma_4 \gamma_\lambda \psi_p)(\psi_4^\dagger \gamma_4 \gamma_\lambda \gamma_5 \psi_\nu)$$

was, after all, too simple; to conform to reality, it should be extended to include a Gamow-Teller term. Fermi told me that his interaction was modelled after the electromagnetic forces between charged particles, and his coupling G was inspired by Newton's constant. His paper was, however, rejected by *Nature* for being unrealistic. It was published later in Italy, and then in *Zeitschrift für Physik*¹³. Fermi wrote his γ matrices explicitly in terms of their matrix elements. His lepton current differs from his hadron current by a γ_5 factor; of course the presence of this γ_5 factor has no physical significance. Nevertheless, it is curious why Fermi should choose this particular expression, which resembles the V-A interaction, but with parity conservation. Unfortunately, by 1956, when I noticed this, it was too late to ask Fermi.

A year later, the discovery of the pion through its decay sequence $\pi \rightarrow \mu \rightarrow e$ by Lattes, Muirhead, Occhialini and Powell¹⁹ dramatically confirmed the original idea of Yukawa. The fact that the higher-order β interaction is singular is not a good argument that it should simply become the strong force.

This was then followed by Professor Klein's important discovery that μ decay and β decay can be described by the same four-fermion interaction. An excerpt from his writing is reproduced below.

no. 4101 June 5, 1948

NATURE

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MESONS AND NUCLEONS

By PROF. O. KLEIN

Institut för Mekanik och Matematisk Fysik,
Stockholms Höskolas

Since, according to the above assumptions, the decay of the ordinary meson is, so to speak, the prototype of all β -processes, it is important that the value of the life-time, $\tau = 2 \times 10^{-8}$ sec., and the energy available in the process $\sim 100 m_e c^2$, fit in very well with the value to be expected from our knowledge of the β -decay. Let ϵ be the energy available divided by $m_e c^2$, and $F(\epsilon)$ the well-known Fermi function, which for large ϵ -values may be taken as $\epsilon^2/50$. We then obtain for the product $\tau \cdot F(\epsilon)$ —putting $\tau = 2 \times 10^{-8}$ sec. and $\epsilon = 100$ —the value 667, which is of about the expected magnitude.

..... It was then found that the interaction constant corresponding to the meson life-time is of the same order of magnitude as that to be expected from Fermi's original theory of β -disintegration, a result which is, of course, identical with that of the above calculation

At Chicago we were not aware of Professor Klein's work. In January 1949 my fellow student, Jack Steinberger, submitted a paper²¹ to *The Physical Review* in which he established that the μ meson disintegrates into three light particles, one electron and two neutrinos. This made it look very much like any other β decay, and stimulated Rosenbluth, Yang and myself to launch a systematic investigation. Are there other interactions, besides β decay, that could be described by Fermi's theory?

We found that if μ decay and μ capture were described by a four-fermion interaction similar to β decay, all their coupling constants appeared to be of the same magnitude. This was the beginning of the *Universal Fermi Interaction*. We then went on to speculate that, in analogy with electromagnetic forces, the basic weak interaction could be carried by a universal coupling through an *intermediate heavy boson*²², which I later called $W^\pm$ for weak. Naturally I went to my thesis adviser, Enrico Fermi, and told him of our discoveries. Fermi was extremely encouraging. With his usual deep insight, he immediately recognized the further implications beyond our results. He put forward the problem that if this is to be the universal interaction, then there must be reasons why some pairs of fermions should have such interactions, and some pairs should not. For example, why does

$$p \not\rightarrow e^+ + \gamma$$

and

$$p \not\rightarrow e^+ + 2\nu?$$

A few days later, he told us that he had found the answer; he then proceeded to assign various sets of numbers, +1, -1 and 0, to each of these particles. This was the first time to my knowledge that both the laws of baryon-number conservation and of lepton-number conservation were formulated together to give selection rules. However, at that time (1948), my own reaction to such a scheme was to be quite unimpressed: surely, I thought, it is not necessary to explain why $p \not\rightarrow e + \gamma$, since everyone knows that the identity of a particle is never changed through the emission and absorption of a photon; as for the weak interaction, why should one bother to introduce a long list of mysterious numbers, when all one needs is to say that only three combinations ($\bar{\pi}p$), ($\bar{\nu}e$) and ($\bar{\mu}\nu$) can have interactions with the intermediate boson. (Little did I expect that soon there would be many other pairs joining these three.)

Most discoveries in physics are made because the time is ripe. If one person does not make it, then almost inevitably another person will do it at about the same time. In looking back, what we did in establishing the Universal Fermi Interaction was a discovery of exactly this nature. This is clear, since the same universal Fermi coupling observations were made independently by at least three other groups, Klein²⁰, Puppi²³, and Tiomno and Wheeler²⁴, all at about the same time. Yet Fermi's thinking was of a more profound nature. Unfortunately for physics, his proposal was never published. The full significance

of these conservation laws was not realized until years later. While this might be the first time that I failed to recognize a great idea in physics when it was presented to me, unfortunately it did not turn out to be the last.

Thus, in 1949, there existed a simple theoretical frame based on the Fermi theory, describing the three weak interaction processes:

$$n \rightarrow p + e + \nu,$$

$$\mu + p \rightarrow n + \nu$$

and

$$\mu \rightarrow e + 2\nu.$$

So, at the end of the classical period, we moved from the observation of β decay to the discovery of the Universal Fermi Interaction.

3. TRANSITION PERIOD (1949-1956)

Beginning in 1949, extensive work was done on the shape of the electron spectrum from μ decay. From the analysis of L. Michel²⁵, it was found that this distribution is given by

$$N(x) = x^2 \left\{ \left(2 - \frac{4}{3} \rho \right) - \left(2 - \frac{16}{9} \rho \right) x \right\}$$

where

$$x = (\text{momentum of } e) / (\text{maximum } e - \text{momentum}),$$

and ρ is the well-known Michel parameter, which can be any real number between 0 and 1, and measures the height of the end point at $x = 1$, as shown in Figure 1.

It is instructive to plot the experimental value of ρ against the year when the measurement was made. As shown in Figure 2, historically it began with $\rho = 0$ in 1949, at the beginning of the transition period. Then it slowly drifted upwards; only after the end of the transition period with the theoretical prediction in 1957 did it gradually become $\rho = \frac{3}{4}$. Yet, it is remarkable that at no time did the 'new' experimental value lie outside the error bars of the preceding one.

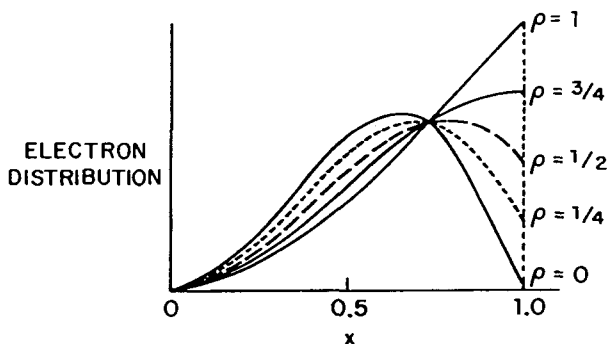


Figure 1. The ρ parameter in μ decay.

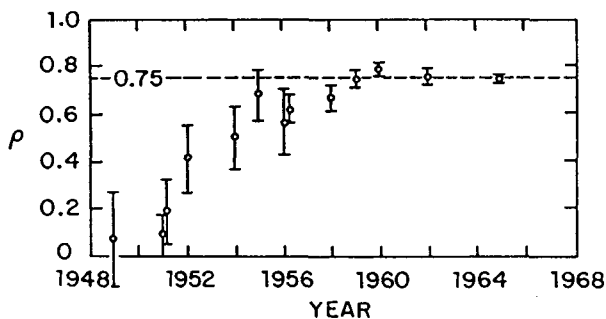


Figure 2. Variation of the ρ parameter over time.

In the same period (1949-56), a large amount of effort was also made on β decay experiments. By then, the Konopinski-Uhlenbeck interaction was definitely ruled out. The absence of the Fierz interference term²⁶ in the spectrum shows that the β interaction must be either V, A or S, T . These two possibilities were further resolved by a series of $\beta - \nu$ angular correlation experiments. In an allowed transition, the distribution for the angle θ between β and ν is given by (neglecting the Fierz term)

$$[1 + \lambda(P/E)_e \cos \theta] d \cos \theta,$$

where the subscript e refers to the momentum P and energy E of the electron. For a $\Delta J = 1$ transition,

$$\lambda = \begin{cases} +\frac{1}{3}, & \text{for } T \\ -\frac{1}{3}, & \text{for } A. \end{cases}$$

The experiment on ${}^6\text{He}$ decay by Rustad and Ruby gave²⁷

$$\lambda = +0.34 \pm 0.09,$$

which seemed to establish unquestionably that the β decay interaction should be S, T with perhaps some unknown admixture of an additional pseudoscalar interaction.

I was quite depressed at that time because, with this new result, the theoretical idea of the intermediate boson seemed to be definitely ruled out. It is bad enough to assume the possibility of two kinds of intermediate bosons of different spin-parity, one for the Fermi coupling and the other for the Gamow-Teller coupling. However, a tensor interaction with no derivative coupling simply cannot be transmitted by a spin-2 boson, since the former is described by an antisymmetric tensor and the latter by a symmetric one.

4. NEW HORIZON IN THE TRANSITION PERIOD

We now come to the $\theta - \tau$ puzzle.

During a recent physics graduate qualifying examination in a well-known American university, one of the questions was on the $\theta - \tau$ problem. Most of the students were puzzled over what θ was; of course they all knew that τ is the heavy lepton, the charged member of the third generation. So much for the history of physics.

In the early 1950s, θ referred to the meson which decays into 2π , whereas τ referred to the one decaying into 3π :

~~~~~

$$\theta \rightarrow 2\pi$$

and

$$\tau \rightarrow 3\pi.$$

The spin-parity of  $\theta$  is clearly  $0^+, 1^-, 2^+$ , etc. As early as 1953, Dalitz<sup>28</sup> had already pointed out that the spin-parity of  $\tau$  can be analyzed through his Dalitz plot and, by 1954, the then-existing data were more consistent with the assignment  $0^-$  than  $1^-$ . Although both mesons were known to have comparable masses (within  $\sim 20$  MeV), there was, at that time, nothing too extraordinary about this situation. The masses of  $\theta$  and  $\tau$  are very near three times the pion mass, the phase space available for the  $\theta$  decay is much bigger than that for  $\tau$  decay; therefore one expects the  $\theta$  decay rate to be much faster. However, when accurate lifetime measurements were made in 1955, it turned out that  $\theta$  and  $\tau$  have the same lifetime (within a few percent, which was the experimental accuracy). This, together with a statistically much more significant Dalitz plot of  $\tau$  decay, presented a very puzzling picture indeed. The spin-parity of  $\tau$  was determined to be  $0^-$ ; therefore it appeared to be definitely a different particle from  $\theta$ . Yet, these two particles seemed to have the same lifetime, and also the same mass. This was the  $\theta - \tau$  puzzle.

My first efforts were all on the wrong track. In the summer of 1955, Jay Orear and I proposed<sup>29</sup> a scheme to explain the  $\theta - \tau$  puzzle within the bounds of conventional theory. We suggested a cascade mechanism, which turned out to be incorrect.

The idea that parity is perhaps not conserved in the decay of  $\theta - \tau$  flickered through my mind. After all, strange particles are by definition strange, so why should they respect parity? The problem was that, after you say parity is not conserved in  $\theta - \tau$  decay, then what do you do? Because if parity nonconservation exists only in  $\theta - \tau$ , *then we already have all the observable facts*, namely the same particle can decay into either  $2\pi$  or  $3\pi$  with different parity. I discussed this possibility with Yang, but we were not able to make any progress<sup>30</sup>. So we instead wrote papers on parity doublets, which was another wrong try<sup>31</sup>.

## 5. THE BREAKTHROUGH (1956)

The Rochester meeting on high energy physics was held from April 3 to 7, 1956.

At that time, Steinberger and others were conducting extensive experiments on the production and decay of the hyperons  $\Lambda^0$  and  $\Sigma^-$ :

$$\pi^- + p \rightarrow \begin{cases} \Lambda^0 + K^0 \\ \Sigma^- + K^+ \end{cases} \quad (1)$$

and

$$\left\{ \begin{matrix} \Lambda^0 \\ \Sigma^- \end{matrix} \right\} \rightarrow \pi + N. \quad (2)$$

The dihedral angle  $\phi$  between the production plane and the decay plane (which will be defined below) is of importance for the determination of the hyperon spin.

Let  $\vec{\pi}$ ,  $\vec{\Lambda}$  and  $\vec{N}$  be the momenta of  $\pi$ ,  $\Lambda$  in process (1) and  $N$  in (2), all, say, in the respective center-of-mass systems of the reactions. The normal to the production plane is parallel to  $\vec{\pi} \times \vec{\Lambda}$ , and that to the decay plane to  $\vec{\Lambda} \times \vec{N}$ . Hence the dihedral angle  $\phi$  is defined through its cosine:

$$\cos \phi \propto (\vec{\pi} \times \vec{\Lambda}) \cdot (\vec{\Lambda} \times \vec{N}). \quad (3)$$

Its distribution is

$$D(\phi) = \begin{cases} 1 & \text{if the hyperon-spin is } \frac{1}{2}, \\ 1 + \alpha \cos^2 \phi & \text{if the hyperon-spin is } \frac{3}{2}, \end{cases} \quad (4)$$

etc. By this definition,  $\phi$  varies from 0 to  $\pi$ . Furthermore,  $D(\phi)$  is identical to  $D(\pi - \phi)$ . At the Rochester Conference, Jack Steinberger gave a talk and plotted his data on  $D(\phi)$  with  $\phi$  varying from 0 to  $\pi$ . However other physicists, W.D. Walker and R.P. Shutt, plotted  $D(\phi) + D(\pi - \phi)$ ; in this way  $\phi$  can only vary from 0 to  $\frac{\pi}{2}$ . After the conference, Jack came to my office to discuss a letter which he had just received from R. Karplus. In this letter Karplus questioned why Jack did not join the others, since the total number of events was (at that time) quite limited, and a folding of  $D(\pi - \phi)$  onto  $D(\phi)$  would increase the experimental sensitivity of the spin determination. Jack wanted to know how certain was the relationship that  $D(\phi)$  is an even function of  $\cos \phi$ .

The dihedral angle, as defined by expression (3), has nothing to do with parity, since it is a scalar. In the course of explaining to Jack the  $\cos^2 \phi$  dependence of  $D(\phi)$ , I suddenly realized that if one changes the definition of  $\phi$  to be the angle of rotation around the  $\Lambda$  momentum-vector, which is the intersection of these two planes, then the range of  $\phi$  can be extended from 0 to  $2\pi$ ; that is, in place of (3), one defines  $\phi$  through the pseudoscalar

$$\sin \phi \propto (\vec{\pi}_{\perp} \times \vec{N}_{\perp}) \cdot \vec{\Lambda}, \quad (5)$$

where  $\vec{\pi}_{\perp}$  and  $\vec{N}_{\perp}$  refer to the components of  $\vec{\pi}$  and  $\vec{N}$  perpendicular to  $\vec{\Lambda}$ , as shown in Figure 3. In this case,  $\phi$  can vary from 0 to  $2\pi$ .

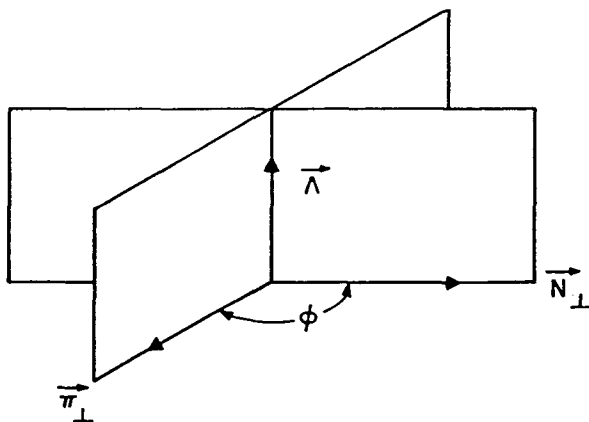


**Figure 3.** The dihedral angle  $\phi$  between the production plane and the decay plane.

If parity is not conserved in strange particle decays, there could be an asymmetry between events with  $\phi$  from 0 to  $\pi$  and those with  $\phi$  from  $\pi$  to  $2\pi$ . *This is the missing key!* I was quite excited, and urged Jack to re-analyse his data immediately and test the idea experimentally. This led to the very first experiment on parity nonconservation. Very soon, within a week, Jack and his collaborators (Budde, Chrétien, Leitner, Samios and Schwartz) had their results, and the data were published<sup>32</sup> even before the theoretical paper<sup>33</sup> on parity nonconservation. The odds turned out to be 13 to 3 in  $\Sigma^-$  decay and 7 to 15 in  $\Lambda^0$  decay (see Figure 4).

Of course, because of the limited statistics, no definitive conclusion on parity violation could be drawn. Nevertheless, had the statistics been ten times more, then with the same kind of ratio one could have made a decisive statement on parity conservation. This showed clearly that parity violation could be tested experimentally provided one measured a pseudoscalar, such as (5).

However, on the theoretical side there was still the question of parity conservation in ordinary  $\beta$  decay. In this connection, at the beginning of May, C.N. Yang came to see me and wished to join me in the examination of  $\beta$  decay. This led to our discovery that, in spite of the extensive use of parity in nuclear physics and  $\beta$  decay, there existed no evidence at all of parity conservation in any weak interaction.

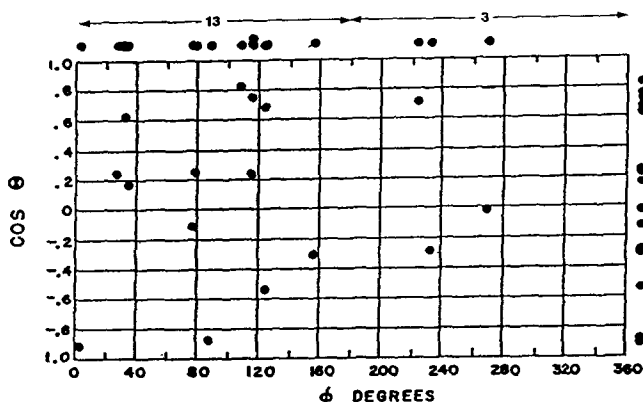


Figure 4a. Angular correlation plot of the cosine of the polar angle against the azimuthal angle  $\phi$  for the reaction  $\pi^- + p \rightarrow \Sigma^- + K^+$ ,  $\Sigma^- \rightarrow \pi^- + n$ . The point histograms on the edges of the figure represent the data after integration over the other coordinate. (Taken from Ref. 32)

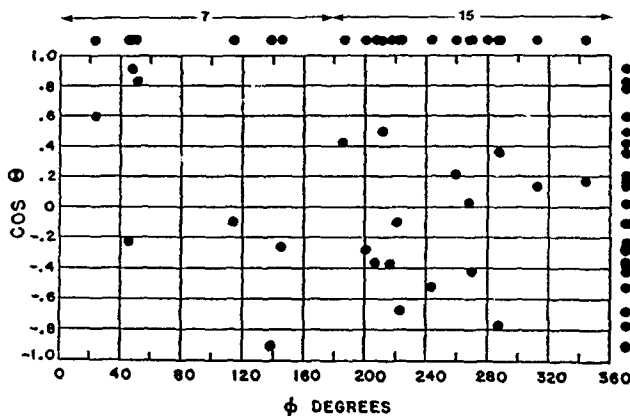


Figure 4b. Angular correlation plot for the reaction  $\pi^- + p \rightarrow \Lambda^0 + \theta^0$ ,  $\Lambda^0 \rightarrow \pi^- + p$ . (Taken from Ref. 32)

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Table 1.

Several months later followed the decisive experiments by Wu, Ambler, Hayward, Hoppes and Hudson, at the end of 1956, on  $\beta$  decay<sup>34</sup>, and by Garwin, Lederman and Weinrich<sup>35</sup> and by Friedman and Telegdi<sup>36</sup> on  $\pi - \mu$  decay. Table 1 lists the important papers on symmetry violation in weak interactions.

## 6. SYMMETRY VIOLATIONS

Wu *et al.* investigated the decay of polarized cobalt nuclei,  $\text{Co}^{60}$ , into electrons. Because these nuclei are polarized they rotate parallel to each other. The experiment consisted of two setups, identical except that the directions of rotation of the initial nuclei were opposite; that is, each was a looking-glass image of the other. The experimenters found, however, that the patterns of the final electron distributions in these two setups are not mirror images of each other. In short, the initial states are mirror images, but the final configurations are not (see Figure 5). This established parity nonconservation, i.e., right-left asymmetry.

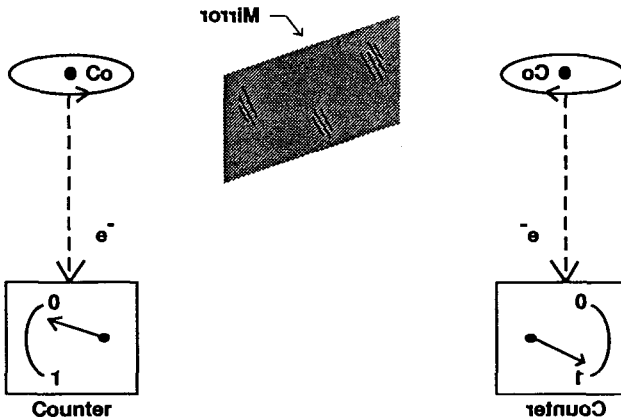


Figure 5. The initial setups of these two experiments on  $\text{Co}^{60}$  decay are exact mirror images, but the final electron distributions are not, as indicated by the different readings on the counters.

The  $\beta$  decay experiment by Wu *et al.* and the  $\pi - \mu$  decay experiment by Garwin, Lederman and Weinrich and by Friedman and Telegdi proved not only parity  $P$  violation, but also asymmetry under particle-antiparticle conjugation  $C$ . This is illustrated in Figure 6. Both the neutrino and the antineutrino possess a spin (angular momentum). For a neutrino, if one aligns one's left thumb parallel to its momentum, then the curling of one's four fingers would always be in the direction of its spin, indicating  $P$  violation. Therefore, the spin and momentum direction of a neutrino defines a perfect left-hand screw, whereas the spin and momentum direction of an antineutrino defines a perfect right-hand screw, showing  $C$  violation in addition to  $P$  violation. This property holds for neutrinos and antineutrinos everywhere, independently of how they are produced.

In 1964, the experiment by Christenson *et al.*<sup>37</sup> established  $CP$  violation. An example of how such a violation can be established experimentally is to examine the decay<sup>38</sup> of  $K_L^0$  into  $e^+ \pi^- \nu$  and  $e^- \pi^+ \bar{\nu}$ . The long-lived neutral kaon  $K_L^0$  is a spherically symmetric particle with zero spin; it carries no electric charge and no electromagnetic form factor of any kind. Yet these two decay modes have different rates:

$$\frac{\text{rate}(K_L^0 \rightarrow e^+ + \pi^- + \nu)}{\text{rate}(K_L^0 \rightarrow e^- + \pi^+ + \bar{\nu})} = 1.00648 \pm 0.00035.$$

Consequently, by using a time-clocking device it is possible to differentiate the positive sign of electricity vs. the negative sign of electricity, showing  $C$  violation. Because this rate difference remains true under mirror reflection,  $CP$  is also violated. The present status of these discrete symmetries and asymmetries is given in Table 2.

At present, only the combined symmetries  $CPT$  remain valid. In other words, only when we interchange

particle  $\leftrightarrow$  antiparticle,

right  $\leftrightarrow$  left,

past  $\leftrightarrow$  future,

do all physical laws appear to be invariant. From  $CPT$  symmetry, it follows that  $CP$  violation also implies time reversal  $T$  asymmetry.

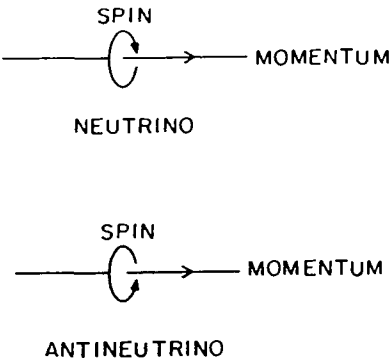


**Figure 6.** The spin momentum of a neutrino defines a left-hand screw; that of an antineutrino defines a right-hand screw.

| <i><b>Present Status</b></i> |                          |
|------------------------------|--------------------------|
| CPT                          | Good                     |
| P                            | X                        |
| C                            | X                        |
| CP                           | X                        |
| T                            | X ← without assuming CPT |
| CT                           | X                        |
| PT                           | X                        |

**Table 2.**

## 7. TIME REVERSAL

Time reversal symmetry  $T$  means that the time-reversed sequence of any motion is also a possible motion. Some of you may think this absurd, since we are all getting older, never younger. So why should we even contemplate that the laws of nature should be time-reversal symmetrical?

In this sense we must distinguish between the evolution of a small system and a large system. Let me give an example. In Figure 7a each circle represents an airport, and a line indicates an air corridor. We assume that between any two of these airports the number of flights going both ways along any route is the same (this property will be referred to as microscopic reversibility). Thus a person in "X" can travel to Stockholm (for this discussion we assume the only air connection from "X" is to Stockholm), then through Stockholm to Paris or New York. At any point in his travel, he can return to "X" with the same ease. But suppose that in every airport we were to remove all the signs and flight information, while maintaining exactly the same number of flights, as shown in Figure 7b. A person starting from "X" would still arrive in Stockholm, since that is the only airport connected to "X". However, without the signs to guide him, it would be very difficult for him to pick out the return flight to "X" from the many gates in the Stockholm airport. The plane he gets on may be headed for New York. If, in New York, he then tries another plane again without any guidance, he could perhaps arrive in Tokyo. If he keeps on going this way, his chance of getting back to "X" is very slim indeed. In this example, we see that microscopic reversibility is strictly maintained. When all the airport destination signs and other flight information are given clearly, then macroscopically we also have reversibility. On the other hand, if all such information is withheld, then the whole macroscopic process appears irreversible. Thus, macroscopic irreversibility is not in conflict with microscopic reversibility.

Time reversal symmetry in physics refers to *microscopic reversibility* between all molecular, atomic, nuclear and subnuclear reactions. Since none of these molecules, atoms, nuclei or subnuclear particles can be easily marked, any microscopic system in nature would exhibit irreversibility. This result is independent of microscopic reversibility. In any macroscopic process, we have to average over an immense number of unmarked microscopic units of atoms, molecules, and so forth (as in the example of unmarked airports and air routes), and that gives rise to *macroscopic irreversibility*. It is in this statistical sense of ever increasing disorder (entropy) that we define the direction of our macroscopic time flow. We may recall the words from *H.M.S. Pinafore*, by Gilbert and Sullivan,

What never? No, never!

What never? Well, hardly ever!

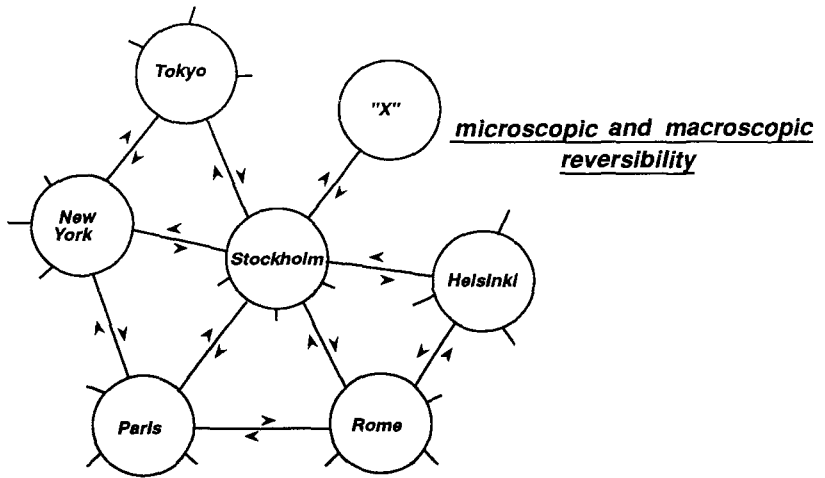


Figure 7a. In this example, microscopic reversibility means an equal number of flights in either direction on every air route. When the names of the airports, the numbers of the gates, and all flight information are known, there is also macroscopic reversibility.

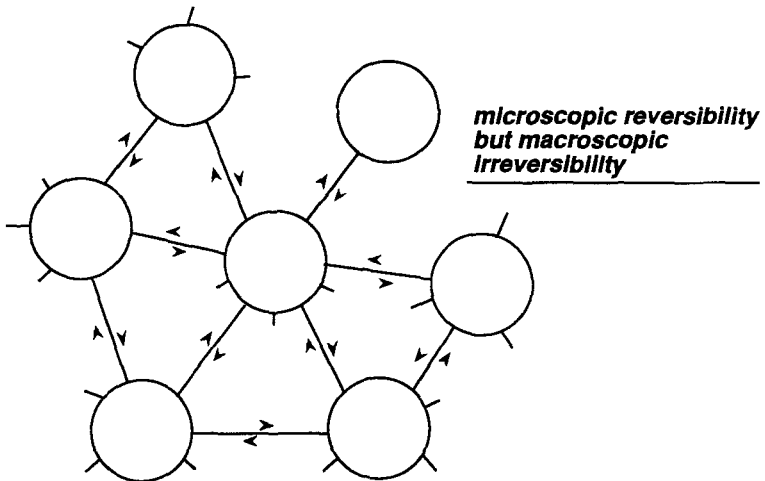


Figure 7b. If we maintain the same number of flights in each direction on any route (i.e., microscopic reversibility), but remove destination signs, gate numbers, and all other information, then it is nearly impossible to find our way back (i.e., macroscopic irreversibility).

The existence of the macroscopic time direction then leaves open the important question whether time-reversal symmetry, or microscopic reversibility, is true or not. Since 1964, after the discovery of  $CP$  violation by Christenson *et al.*, through a series of remarkable experiments involving the kaons, it was found that the microscopic reversibility is indeed violated. Nature does not seem to respect time-reversal symmetry!

## 8. PRESENT STATUS

In 1967, the paper of S. Weinberg<sup>39</sup> unified the weak interaction with the electromagnetic force, called the electroweak interaction, which is mediated by the photon  $\gamma$ , the charged intermediate bosons  $W^\pm$  and their neutral partner  $Z^0$  (these particles were discovered at CERN in 1983<sup>40</sup>).

At present, our theoretical structure of electroweak, strong and gravitational forces can be summarized as follows:

**QCD** (strong interaction)

**$SU(2) \times U(1)$  Theory** (electro-weak)

**General Relativity** (gravitation).

However, in order to apply these theories to the real world, we need a set of about 17 parameters, all of unknown origins. Thus, this theoretical edifice cannot be considered complete.

The two outstanding puzzles that confront us today are:

i) **Missing symmetries** - All present theories are based on symmetry, but most symmetry quantum numbers are *not* conserved.

ii) **Unseen quarks** - All hadrons are made of quarks; yet, no individual quark can be seen.

As we shall see, the resolutions of these two puzzles probably are tied to the structure of our physical vacuum.

The puzzle of missing symmetries implies the existence of an entirely new class of fundamental forces, the one that is responsible for symmetry breaking. Of this new force, we know only of its existence, and very little else. Since the masses of all known particles break these symmetries, an understanding of the symmetry-breaking forces will lead to a comprehension of the origin of the masses of all known particles. One of the promising directions is the spontaneous symmetry-breaking mechanism in which one assumes that the physical laws remain symmetric, but the physical vacuum is not. If so, then the solution of this puzzle is closely connected to the structure of the physical vacuum; the excitations of the physical vacuum may lead to the discovery of Higgs-type mesons.

In some textbooks, the second puzzle is often "explained" by using the analogy of

the magnet. A magnet has two poles, north and south. Yet, if one breaks a bar magnet in two, each half becomes a complete magnet with two poles. By splitting a magnet open one will never find a single pole (magnetic monopole). However, in our usual description, a magnetic monopole can be considered as either a fictitious object (and therefore unseeable) or a real object but with exceedingly heavy mass beyond our present energy range (and therefore not yet seen). In the case of quarks, we believe them to be real physical objects and of relatively low masses (except the top quark); furthermore, their interaction becomes extremely weak at high energy. If so, why don't we ever see free quarks? This is, then, the real puzzle.

The fact that quarks and gluons cannot be seen individually suggests an entirely new direction in our understanding of particles. Traditionally, any particle is either stable or unstable; the former is represented by a pole on the physical sheet and the latter by a pole on the "second" sheet. But now, we have a new third class: particles that cannot be seen individually. This is illustrated in Table 3, and its solution in Table 4. Following the KLN Theorem,<sup>41</sup> gluons and quarks are indeed discovered by observing high energy jets. The second method, of using entropy change, will be discussed shortly. Before doing that, we may recall what has happened in the past.

At the end of the last century, there were also two physics puzzles:

1. No absolute inertial frame (Michelson-Morley Experiment 1887),
2. Wave-particle duality (Planck's formula 1900).

These two seemingly esoteric problems struck classical physics at its very foundation. The first became the basis for Einstein's theory of relativity and the second laid the foundation for us to construct quantum mechanics. In this century, all the modern scientific and technological developments—*nuclear energy, atomic physics, molecular structure, lasers, x-ray technology, semiconductors, superconductors, supercomputers*—only exist because we have relativity and quantum mechanics. To humanity and to our understanding of nature, these are all-encompassing.

Now, near the end of the twentieth century, we must ask what will be the legacy we give to the next generation in the next century? At present, like the physicists at the end of the 1890's, we are also faced with two profound puzzles. It seems likely that the present two puzzles may bring us as important a change in the development of science and technology in the twenty-first century.

| <i>STABLE PARTICLES<br/>POLES ON THE<br/>"PHYSICAL" SHEET</i>                                                           | <i>UNSTABLE PARTICLES<br/>POLES ON THE<br/>"SECOND" SHEET</i>                                                                                                                                                              | <i>PARTICLES THAT<br/>CANNOT BE SEEN<br/>INDIVIDUALLY</i> |
|-------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------|
| <p>GRAVITON</p> <p><math>\gamma</math></p> <p><math>\nu</math></p> <p><math>e</math></p> <p><math>p</math></p> <p>:</p> | <p><math>\mu</math></p> <p><math>\pi</math></p> <p><math>K</math></p> <p>:</p> <p><math>n</math></p> <p><math>J/\psi</math></p> <p><math>\Upsilon</math></p> <p>:</p> <p><math>W</math></p> <p><math>Z</math></p> <p>:</p> | <p>GLUONS</p> <p>QUARKS</p> <p>:</p>                      |

Table 3.

|                                                                                          |
|------------------------------------------------------------------------------------------|
| <p><i>HOW TO DETECT PARTICLES THAT<br/>CANNOT BE SEEN INDIVIDUALLY?</i></p> <hr/>        |
| <p>1. JETS      (KLN THEOREM ON<br/>MASS SINGULARITIES (1964))</p>                       |
| <p>2. ENTROPY DENSITY CHANGE<br/>(VACUUM EXCITATIONS<br/>T.D.L. AND G.C.WICK (1974))</p> |

Table 4.

9. PHYSICAL VACUUM

The current explanation of the quark confinement puzzle is again to invoke the vacuum. We assume the QCD vacuum to be a condensate of gluon pairs and quark-antiquark pairs so that it is a perfect color dia-electric<sup>42</sup> (i.e., color dielectric constant  $\kappa = 0$ ). This is in analogy to the description of a superconductor as a condensate of electron pairs in BCS theory, which results in making the superconductor a perfect dia-magnet (with magnetic susceptibility  $\mu = 0$ ). When we switch from QED to QCD we replace the magnetic field  $\vec{H}$  by the color electric field  $\vec{E}_{color}$ , the superconductor by the QCD vacuum, and the QED vacuum by the interior of the hadron. Just as the magnetic field is expelled outward from the superconductor, the color electric field is pushed into the hadron by the QCD vacuum, and that leads to color confinement, or the formation of bags.<sup>43</sup> This situation is summarized below.

| QED superconductivity<br>as a perfect dia-magnet |                       | QCD vacuum<br>as a perfect color dia-electric |
|--------------------------------------------------|-----------------------|-----------------------------------------------|
| $\vec{H}$                                        | $\longleftrightarrow$ | $\vec{E}_{color}$                             |
| $\mu_{inside} = 0$                               | $\longleftrightarrow$ | $\kappa_{vacuum} = 0$                         |
| $\mu_{vacuum} = 1$                               | $\longleftrightarrow$ | $\kappa_{inside} = 1$                         |
| inside                                           | $\longleftrightarrow$ | outside                                       |
| outside                                          | $\longleftrightarrow$ | inside                                        |

In the resolution of both puzzles, missing symmetry and quark confinement, the system of elementary particles no longer forms a self-contained unit. The microscopic particle physics depends on the coherent properties of the macroscopic world, represented by the appropriate operator averages in the physical vacuum state.

If we pause and think about it, this represents a rather startling conclusion, contrary to the traditional view of particle physics which holds that the microscopic world can be regarded as an isolated system. To a very good approximation it is separate and uninfluenced by the macroscopic world at large. Now, however, we need these vacuum averages; they are due to some long-range ordering in the state vector. At present our theoretical technique for handling such coherent effects is far from being developed. Each

of these vacuum averages appears as an independent parameter, and that accounts for the large number of constants needed in the present theoretical formulation.

On the experimental side, there has hardly been any direct investigation of these coherent phenomena. This is because hitherto in most high-energy experiments, the higher the energy the smaller has been the spatial region we are able to examine. In order to explore physics in this fundamental area, relativistic heavy ion collisions offer an important new direction.<sup>44</sup> The basic idea is to collide heavy ions, say gold on gold, at an ultra-relativistic region. Before the collision, the vacuum between the ions is the usual physical vacuum; at a sufficiently high energy, after the collision almost all of the baryon numbers are in the forward and backward regions (in the center-of-mass system). The central region is essentially free of baryons and, for a short duration, it is of a much higher energy density than the physical vacuum. Therefore, the central region represents the excited vacuum (Figure 8).

As we shall see, we need RHIC, the  $100 \text{ GeV} \times 100 \text{ GeV}$  (per nucleon) relativistic heavy ion collider at the Brookhaven National Laboratory, to explore the QCD vacuum.

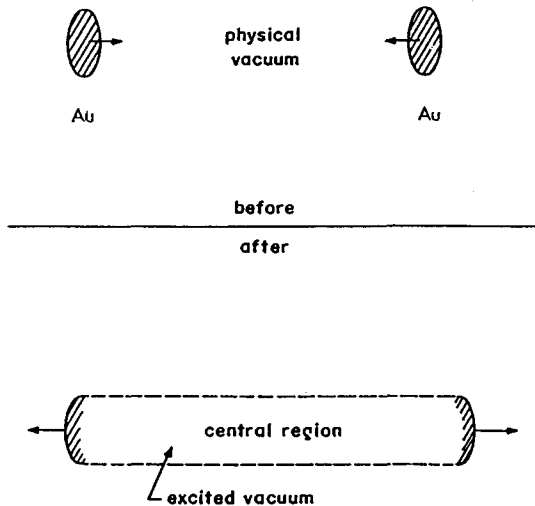


**Figure 8.** Vacuum excitation through relativistic heavy ion collisions.

## 10. PHASE DIAGRAM OF THE QCD VACUUM

A normal nucleus of baryon number  $A$  has an average radius  $r_A \approx 1.2A^{\frac{1}{3}} fm$  and an average energy density

$$\mathcal{E}_A \approx \frac{m_A}{(4\pi/3)r_A^3} \approx 130 MeV/fm^3.$$

Each of the  $A$  nucleons inside the nucleus can be viewed as a smaller bag which contains three relativistic quarks inside; the nucleon radius is  $r_N \approx 0.8 fm$  and its average energy density is

$$\mathcal{E}_N \approx \frac{m_N}{(4\pi/3)r_N^3} \approx 440 MeV/fm^3.$$

Consequently, even without any sophisticated theoretical analysis we expect the QCD phase diagram to be of the form given by Figure 9.

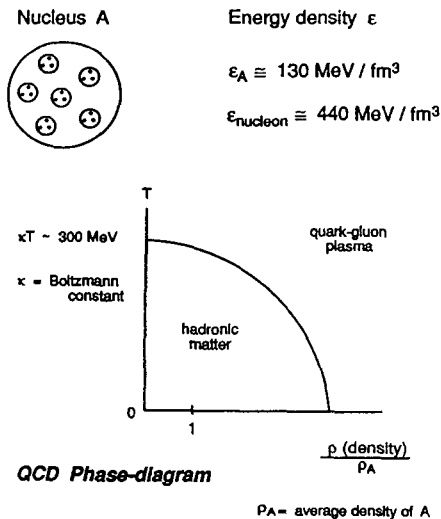


Figure 9.

In Figure 9, the ordinate is  $\kappa T$  ( $\kappa$  = Boltzmann constant,  $T$  = temperature), the abscissa is  $\rho/\rho_A$  ( $\rho$  = nucleon density,  $\rho_A$  = average nucleon density in a normal nucleus  $A$ ). A typical nucleus  $A$  is when  $\rho = \rho_A$ . The scale can be estimated by noting that the critical  $\kappa T \sim 300$  MeV is about the difference of  $1\text{fm}^3$  times  $\mathcal{E}_N - \mathcal{E}_A$  and the critical  $\rho/\rho_A \sim 4$  is just the nearest integer larger than  $(1.2/0.8)^3$ .

Accurate theoretical calculation exists only for pure lattice QCD (i.e., without dynamical quarks). The result is shown in Figure 10.

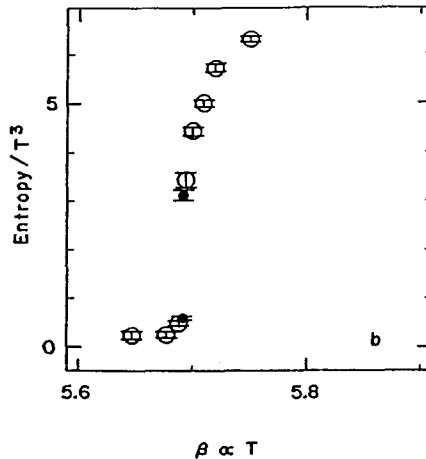


Figure 10. Phase transition<sup>45</sup> (pure QCD)

If one assumes scaling, then the phase transition in pure QCD (zero baryon number,  $\rho = 0$ ) occurs at  $\kappa T \sim 340$  MeV with the energy density of the gluon plasma

$$\mathcal{E}_P \sim 3\text{GeV}/\text{fm}^3.$$

To explore this phase transition in a relativistic heavy ion collision, we must examine the central region. Since only a small fraction of the total energy is retained in the central region, it is necessary to have a beam energy (per nucleon) at least an order of magnitude larger than  $\mathcal{E}_N \times (1.2\text{fm})^3 \sim 5$  GeV; this makes it necessary to have an ion collider of  $100\text{ GeV} \times 100\text{ GeV}$  (per nucleon) for the study of the QCD vacuum.

Another reason is that at  $100 \text{ GeV} \times 100 \text{ GeV}$  the heavy nuclei are almost transparent, leaving the central region (in Figure 10) to be one almost without any baryon number. As remarked before, this makes it an ideal situation for the study of the excited vacuum. Suppose that the central region does become a quark-gluon plasma. How can we detect it? This will be discussed in the following.

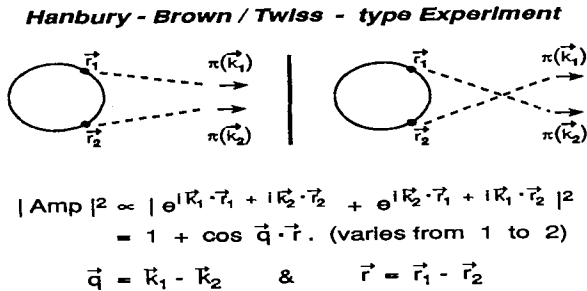
## 11. $\pi\pi$ -INTERFEROMETRY

As shown in Figure 11, the emission amplitude of two pions of the same charge with momenta  $\vec{k}_1$  and  $\vec{k}_2$  from points  $\vec{r}_1$  and  $\vec{r}_2$  is proportional to

$$A \equiv e^{i\vec{k}_1 \cdot \vec{r}_1 + i\vec{k}_2 \cdot \vec{r}_2} + e^{i\vec{k}_2 \cdot \vec{r}_1 + i\vec{k}_1 \cdot \vec{r}_2},$$

because of Bose statistics. Let

$$\vec{q} \equiv \vec{k}_1 - \vec{k}_2 \quad \text{and} \quad \vec{r} \equiv \vec{r}_1 - \vec{r}_2.$$



*If the central rapidity region is a plasma of entropy density  $S_{\text{plasma}}$ , which later hadronizes (of entropy density  $S_{\text{Had}}$ ),*

$$(\text{vol} \cdot S)_{\text{plasma}} \leq (\text{vol} \cdot S)_{\text{Had}}$$

$$S_{\text{Had}} \ll S_{\text{plasma}} \quad \therefore \quad (\text{vol})_{\text{Had}} \gg (\text{vol})_{\text{plasma}}$$

Figure 11

Since

$$|A|^2 \equiv 1 + \cos \vec{q} \cdot \vec{r}$$

changes from  $|A|^2 = 2$  as  $\vec{q} \rightarrow 0$ , to  $|A|^2 = 1$  as  $\vec{q} = \infty$ , a measurement of the  $\pi\pi$  correlation gives a determination of the geometrical size  $R$  of the region that emits these pions, like the Hanbury-Brown/Twiss determination of the stellar radius.

Now, if the central region is a plasma of entropy density  $S_P$  occupying a volume  $V_P$ , which later hadronizes to ordinary hadronic matter (of entropy density  $S_H$  and volume  $V_H$ ), the total final entropy  $S_H V_H$  must be larger than the total initial entropy  $S_P V_P$ . Since  $S_P > S_H$ , we have

$$V_H > V_P.$$

The experimental configurations and results<sup>46</sup> are given in Figure 12 and Table 5. One sees that the hadronization radius in the central region is indeed much larger than that in the fragmentation region. This is, at best, only indicative of the quark-gluon plasma. Much work and higher energy are needed for a more definitive proof. Nevertheless, it does show that relativistic heavy ion can be an effective means of exploring the structure of the vacuum.

## 12. CONCLUDING REMARKS

To conclude we emphasize, once again, that the most challenging problems in physics are

- (1) the symmetry-breaking force, and
- (2) the structure of the vacuum.

It is quite likely that the answer to these two problems lies in the same direction. They can only be solved when we learn how to excite the vacuum. In the traditional way of thinking, our world is the world of particles. Larger units are made of small ones, which in turn are made of even smaller elements. The search for the smallest building block that everything is made of drives us to explore physical phenomena within smaller and smaller distances; that necessitates energies higher and higher in inverse proportion to the distance in question. On the other hand, the puzzles of missing symmetry and quark confinement have forced us to face the profound possibility that the vacuum could be a physical medium.

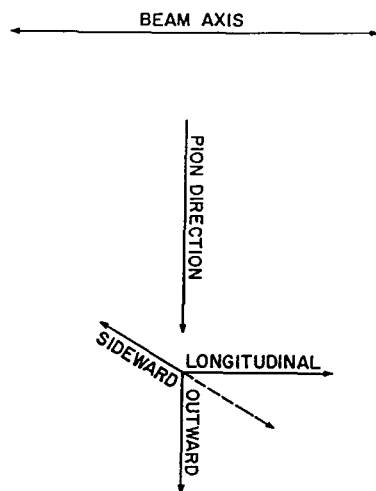


Figure 12

| Rapidity Interval | Gaussian                                     |                     |                        |
|-------------------|----------------------------------------------|---------------------|------------------------|
|                   | $R_T(\text{fm})$                             | $R_L(\text{fm})$    | $\Lambda$              |
| $1 < y < 2$       | $4.3 \pm 0.6$                                | $2.6 \pm 0.6$       | $0.34^{+0.09}_{-0.06}$ |
|                   | $R_T^{\text{side}} = 4.0 \pm 1.0 \text{ fm}$ | $2.6 \pm 0.6$       | $0.34^{+0.09}_{-0.06}$ |
|                   | $R_T^{\text{out}} = 4.4 \pm 1.0 \text{ fm}$  | $2.6 \pm 0.6$       | $0.34^{+0.09}_{-0.06}$ |
| $2 < y < 3$       | $8.1 \pm 1.6$                                | $5.6^{+1.2}_{-0.8}$ | $0.77 \pm 0.19$        |
|                   | $R_T^{\text{side}} = 6.6 \pm 1.8 \text{ fm}$ | $5.6^{+1.2}_{-0.8}$ | $0.77 \pm 0.19$        |
|                   | $R_T^{\text{out}} = 11.2 \pm 2.3 \text{ fm}$ | $5.6^{+1.2}_{-0.8}$ | $0.77 \pm 0.19$        |

$R(\text{Oxygen}) \cong 3 \text{ fm}$

Table 5.  $\pi\pi$ -interference result<sup>46</sup> from the collision of an O beam (200 GeV/nucleon) on a stationary Au target

As we look into the future, the completion of RHIC in 1997 offers an unprecedented opportunity for physicists to explore the possibility of exciting the vacuum and to examine whether it is indeed a physical medium.

If the vacuum is the underlying cause for the strange phenomena in the microscopic world of particle physics, it must also have been actively responsive to the macroscopic distribution of matter and energy in the universe. Because the vacuum is everywhere and forever, these two, the micro- and the macro-, have to be linked together; neither can be considered a separate entity. Future history books will record that ours was a time when humankind was able to forge this bond on a scientific basis.

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# ELECTRON ORBITS AND SUPERCONDUCTIVITY OF CARBON 60

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## 1. Introduction

The discovery of  $C_{60}$  and the superconductivity of its alloy compounds<sup>1-4</sup> provides a rich field for new theoretical and experimental investigations.<sup>5-8</sup> In this paper, we show that the near degeneracy of the low-lying vector ( $T_{1u}$ ) and axial-vector ( $T_{1g}$ ) levels of an isolated  $C_{60}$  may provide a simple pairing mechanism in  $C_{60}^{--}$ ,  $C_{60}^{---}$  and the  $K_n C_{60}$  crystal.

We will begin with a review of the single-electron energy levels of a  $C_{60}$  molecule. Above the 60-closed shell lie two triplets possessing the same icosahedral symmetry label  $T_1$  but of opposite parity. We shall derive their wave functions in the tight-binding limit of the molecular orbit approximation, and exhibit these functions in a simple and useful form which prompts us to refer to them as "vector" and "axial vector". Our analysis is then extended to  $C_{60}^{--}$ . By taking into account the strong Coulomb energy between electrons, we find that the spectrum of  $C_{60}^{--}$  contains two low-lying states invariant under the proper icosahedral symmetry transformations, but again of opposite parity and hence naturally called "scalar" and "pseudoscalar", with an energy degeneracy within 1% of their excitation energy (in our approximate calculation), even closer than the vector axial-vector doublets in  $C_{60}$ .

Since parity doublets, two states of opposite parity with nearly the same energy, are not a common occurrence in physics, it is worthwhile to examine the mechanism that gives rise to them in  $C_{60}$ . For a microscopic system, such as mesons and baryons, composite particles of opposite parities usually have quite different internal structures which make them unlikely to be degenerate. In most macroscopic systems, as in the case of left-handed or right-handed sugar molecules, it is conceptually simple to construct coherent mixtures of opposite parities that are nearly degenerate; the difficulty lies in the practical realization of such coherent mixtures.

## 2. Icosahedral Group

In order to have the necessary tools for our subsequent analysis, we give a brief discussion of the molecular orbits of  $C_{60}$ . As will be shown below, these can be expressed in terms of the regular representation of the proper

$$\text{icosahedral group } \mathcal{G} = \{g\} \quad (1)$$

where  $g$  denotes its sixty group elements. Corresponding to the identity element  $e$ , we may take any point  $\hat{e}$  on a unit sphere with center 0. The application of the finite rotation that associates with  $g$  transforms  $\hat{e}$  to  $\hat{g}$ . For  $\hat{e}$  not lying on any of the symmetry axes, the resulting sixty  $\hat{g}$  are all different. (A convenient notation is to use the same  $\hat{e}$  and  $\hat{g}$  to denote the corresponding unit radial vectors of the sphere, as well as their end points on the sphere.) For definiteness, let the unit sphere be the *circumsphere* of a regular icosahedron of vertices  $N, A_1, \dots, A_5, S$ . As in Figure 1, choose the point  $e$  (corresponding to the identity element  $e$  in  $\mathcal{G}$ ) on the edge  $\overline{A_1 N}$ , with  $\overline{eN} = \frac{1}{3} \overline{A_1 N}$  and  $\overrightarrow{0e} \parallel \hat{e}$ . Each unit radial vector  $\hat{g}$  intersects a point  $g$  on one of the edges of the icosahedron. The location of each point  $g$ , thus generated, gives the position of a carbon nucleus in  $C_{60}$ , provided the unit scale of the radius is  $R \cong 4.03\text{\AA}$ , so that the circumspherical radius of  $C_{60}$  is its actual value  $R_0 \cong 3.5\text{\AA}$ , with the ratio

$$\frac{R}{R_0} = 3 \left( 5 + \frac{4}{\sqrt{5}} \right)^{-\frac{1}{2}} \cong 1.15. \quad (2)$$

(The same notation  $g$  denotes both the group element as well as the position of the carbon nucleus.) Any function  $f(g)$  of these sixty positions  $g$  can be expressed in terms of the irreducible representations of the icosahedral group  $\mathcal{G}$ , which consist of a singlet 1, two triplets  $\mathbf{3}$  and  $\tilde{\mathbf{3}}$ , a quartet 4 and a quintet 5. This gives

$$60 = 1^2 + 3^2 + 3^2 + 4^2 + 5^2. \quad (3)$$

In the literature<sup>9,10</sup>, these representations are often referred to as  $A, T_1, T_2, G$  and  $H$  respectively. Our notations follow those used in particle physics, with the dimensionality of the irreducible representation shown explicitly.

The irreducible representations 1, 3 and 5 can be readily identified with the usual  $\ell = 0$  ( $s$ -wave),  $\ell = 1$  ( $p$ -wave) and  $\ell = 2$  ( $d$ -wave) of the spherical harmonics  $Y_{\ell,m}(\theta, \phi)$ , where  $m = -\ell, -\ell+1, \dots, \ell$ , and  $\theta, \phi$  are the polar and azimuthal angles. To derive the remaining two irreducible representations  $\tilde{\mathbf{3}}$  and 4, we designate one of the icosahedral vertices as the north pole  $N$  ( $\theta = 0$ ), as in Figure 1. Express any function  $F$  of  $\theta, \phi$  defined on the twelve vertices of the icosahedron in terms of the sixteen spherical