CHEN NING YANG

BING-AN LI AND YUEFAN DENG

ABSTRACT. Chen Ning Yang (Franklin or Frank), was born in Hefei, Anhui Province, China, on October 1, 1922. [His birth date was erroneously recorded as September 22, 1922 in his 1945 passport. He has used this incorrect date on all subsequent official documents.] His fields of expertise are theoretical particle physics, statistical mechanics, and condensed matter physics.

Yang's family was originally from Feng Yang County of Anhui Province. Chen Ning Yang's great grandfather, Jia Ju Yang (Yue Qian), was once an official of Tai Hu County in Anhui Province. On his way back home to Feng Yang after finishing his term at Tai Hu, he was asked by friends to settle in Hefei and he did. The Yang family has lived there since. Ko Chuen Yang (Wu Zhi), Chen Ning Yang's father, was the eldest son of his grandfather, Bang Sheng Yang (Mu Tang). K. C. Yang obtained a Ph.D in mathematics from the University of Chicago. Upon completion of his studies, he returned to China and became a Professor and later Chairman of the Mathematics Department at Tsing Hua University and later at the Southwest Associated University for many years.

C. N. Yang was born in their house on Si Gu Lane, West Street, in Hefei. He attended the Chung Te Middle School in Peking, 1933–1937. In the Autumn of 1937 he enrolled in the Sixth Provincial Middle School in Hefei. In early 1938, the family moved to Kunming where Yang joined grade 11 of the Kun Hua Middle School. During 1938-1942 he was a student at the Southwest Associated University.

The faculty at the Southwest Associated University was extremely strong. Zhu Zi-Qing, Wen Yi-Duo, Luo Chang-Pei, Wang Li and others taught Yang freshman Chinese. C. Y. Chao taught him freshmen physics; Y. H. Woo sophomore electromagnetism; and P. Y. Chou mechanics. T. Y. Wu was Yang's Bachelor's thesis advisor. Professor Wu gave him a copy of a 1936 review article on group theory and molecular spectroscopy written by T. E. Rosenthal and G. M. Murphy. Upon learning of this, Yang's father gave him a copy of "Modern Algebraic Theories" by L. E. Dickson, a famous algebraist, to read about group theory. Dickson was Yang's father's Ph.D. thesis advisor. Yang found the book very much to his taste: representation theory of groups was made clear in just 20 pages! As a matter of fact, it was in high school that he had first learned simple group theory from his father. He had also been attracted to the many beautiful pictures in "Die Theorie der Gruppen von Endlicher Ordnung" by A. Speiser (1923) which was on his father's bookshelf. These early family influences and the experience in completing his Bachelor's thesis resulted in his lifelong appreciation of the importance of group theory and of symmetry in physics.

Yang graduated from the Southwest Associated University in 1942 and enrolled as a graduate student at Tsing Hua University for the next two years. Professor J. S. Wang was his Master's thesis advisor. Before entering Tsing Hua, Yang had listened to some of Wang's lectures about phase transitions and had realized the importance of this area of physics. Under the guidance of Wang, Yang finished a paper, "A generalization of the quasi-chemical method in the statistical theory of superlattices". Combining this paper with other works, Yang wrote his Master's thesis. During this period, he also learned a lot of field theory from S. T. Ma.

Yang has always emphasized that the two directions of research shown him by T. Y. Wu and J. S. Wang, symmetry and statistical mechanics, have been the main research directions throughout his career.

In the summer of 1944 Yang passed an examination for a fellowship to study in the United States. While waiting for his papers, he taught mathematics at the Middle School attached to the Southwest Associated University for two semesters, from the fall of 1944 to the summer of 1945. While teaching, he researched field theory and thoroughly absorbed the review article on field theory by W. Pauli.

The seven years spent in Kunming were very fruitful and essentially determined Yang's future research directions. He learned enough physics to form his own taste. Already at that time, he wrote later in 1983, A. Einstein, P. A. M. Dirac, and E. Fermi were his most admired physicists. Late in November 1945 he arrived in America and hoped to study under Fermi but was very disappointed when he learned that Fermi had left Columbia University and was nowhere to be found. After an exhausting search, he finally learned from Professor W. Y. Chang that Fermi would be at the University of Chicago.

Early in 1946 Yang registered at the University of Chicago as a graduate student. He proposed to Fermi that he write a thesis in experimental physics under his supervision. But, as a foreign student, Yang was not able to do this because Fermi was then working at the Argonne National Laboratory which did not allow participation by foreign nationals. Later, Fermi recommended Yang to work in S. K. Allison's laboratory, which was building a 400 KeV Cockcroft-Walton accelerator. After spending 20 months on the project, Yang and a half dozen fellow students finished building the accelerator. Unfortunately, his experiment on this accelerator was unsuccessful. Advised by E. Teller, Yang gave up experiments and finished up a nearly completed theoretical paper. This paper was used as Yang's Ph.D. dissertation.

Yang had learned much from Teller, who had deep intuition of the application of group theory in physics. Yang's Ph.D. dissertation, "On the Angular Distribution in Nuclear Reactions and Coincidence Measurements", was a combination of physical intuition and group theory.

At Chicago, Yang worked on particle physics, and at the same time pursued his interests in statistical mechanics. He attempted to read L. Onsager's 1944 paper on the two-dimensional Ising model without much success. In order to understand the mechanism of ferromagnetism, he studied F. Bloch's paper on spin waves, also H. A. Bethe's 1931, and L. Hulthen's 1938 articles. These efforts, despite lack of immediate success, did lay a solid foundation for future works.

Yang has said the research styles of Fermi and Teller, particularly of Fermi, have the characteristics of starting from physical phenomena, rather than from principles. Yang called this the inductive method, which had greatly influenced him. While in

China, Yang's education was focused on the deductive method. Combining these two methods, one learned at Chicago and another in China, Yang had the best of both worlds, he said.

Chicago's research atmosphere was very active and Yang came into contact with several promising research topics. That was when particle physics was in its infancy. He and his colleagues thus grew with this field. In an article,[1] "Forty Years as Student and Teacher", written on his 60th birthday, he wrote: "[We] were very lucky".

In the Spring of 1949 Yang applied for a postdoctoral position at the Institute for Advanced Study in Princeton which had many excellent young theoretical physicists working on renormalization. Pauli and S. Tomonaga were also going to be there. After J. R. Oppenheimer, the Director of the Institute, accepted Yang's application, Fermi advised him not to remain at the Institute for too long because the physics there was too abstract. In fact, Fermi, Allison, and Teller had already arranged with the University of Chicago to invite Yang back in 1950.

In the spring of 1950, Oppenheimer offered Yang another five years to continue his work at the Institute. This added to the list of options available to him, the most important being to return to Chicago. He did not forget Fermi's advice, but his girl friend, Miss Chih-Li Tu, was then studying in New York which is only a one-hour train ride from Princeton. That settled it, he would stay in Princeton. Tu is the daughter of General Yu-Ming Tu (Du Yu-Ming). She was one of Yang's students in the Middle School attached to the Southwest Associated University in Kunming while Yang was a teacher there. They were married on August 26, 1950. They have two sons and one daughter. The elder son, Franklin Yang, was born in 1951, the second son, Gilbert Yang, in 1958, and the daughter, Eulee Yang, in 1961.

In mid-December 1952, Yang received a letter from G. B. Collins, the Chairman of the Cosmotron Department of the Brookhaven National Laboratory, inviting him to spend one year at the Laboratory. The Cosmotron was then the world's largest proton accelerator (3 GeV), capable of producing π mesons and strange particles. It had attracted many groups of experimentalists and was producing a lot of interesting results. Yang accepted the offer and worked at Brookhaven from 1953 to 1954. He returned to Princeton in 1954 and was promoted to full professor in 1955.

Yang stayed at Princeton for 17 years, 1949 through 1966. Yang says that these 17 years were the most productive for scientific research in his life. In the spring of 1965, Oppenheimer told Yang that he was preparing to retire from his post as the Director of the Institute and would recommend Yang to the Board to be his successor. Yang replied he would not like to be the Director of the Institute. Oppenheimer asked Yang to think it over and then decide. Yang did and in a letter to Oppenheimer, he said: "It is quite uncertain that I shall make a good Director, while it is quite certain that I shall not enjoy the life of a Director." Later, in 1983, writing about this period of his life, Yang said: "But destiny seemed to be arranging things to change my career anyway." In 1964 and 1965, the State of New York created five Einstein Professorships for the universities in the State of New York. President J. S. Toll and the Physics Department Chairman, T. A. Pond, of the State University of New York at Stony Brook contacted Yang, hoping to attracted him to an Einstein Professorship at Stony Brook. They also hoped to create an Institute for Theoretical Physics at Stony Brook and asked Yang to be its Director. This Institute would be small and easy to manage. After due consideration, Yang accepted the offer and arrived at

Stony Brook in 1966.

In a February 22nd 1991 letter, Toll, replying to our inquiry, said: "In my judgment, the single most important development that established the State University of New York at Stony Brook was the decision of Professor C. N. Yang to accept the Einstein Professorship of Physics at SUNY at Stony Brook and to serve as Director of the Institute for Theoretical Physics there." He also said: "After more than 25 years at Stony Brook, Professor Yang has continued to be, by far, the most valuable member of the university community. He symbolizes the University's respect for scholars and for the best scholarship. His impeccable manners and dedication to research have set a model for all other members of the academic community. In brief, by coming to campus in the third year of its operation, he has through a quarter century transformed a fledgling institution into a great university." Stony Brook's present President, J. H. Marburger, on April 1st 1991, replied to a letter from the authors, saying: "Professor Yang's coming to Stony Brook represented a breakthrough for Stony Brook in its drive for excellence in research and scholarship that started Stony Brook's fast ascendancy as a center of academic excellence in the United States."

In the summer of 1971 Yang visited China. He was the first well-known Chinese-ethnic scholar to do so. That visit played an important role in increasing Sino-America cultural exchanges and improving the mutual understanding between the two peoples. Chairman Mao Zedong and Premier Zhou Enlai had both praised his contributions in these directions.

In 1983 Yang recalled[1] his 1971 visit to China: "[at that time], I thought, I knew both China and the United States and loved both countries. At a time when the two great countries were approaching each other, I realized I had the responsibility to help build a bridge of friendship and understanding between the two countries."

Indeed, since 1971, Yang has done a lot in this respect. He became the first President of the National Association of Chinese-Americans, and worked hard for the 1979 establishment of Sino-American diplomatic relationship. Raising funds from Hong Kong and the United States, he created the CEEC fellowship at Stony Brook in 1981. With this fellowship, he has been able to invite visiting scholars to Stony Brook from Chinese universities and research institutions. Up to 1991, more than 80 scholars have been supported by this program and the majority of them have returned to their original institutions in China.

In 1983 Yang established the Foundation for the Center for Advanced Research at Zhongshan University and became its Chairman. In the eight years since its establishment, the Foundation has raised more than 10 million Hong Kong dollars to support nearly 100 research projects at the Center and to built a Research Building for the Center.

Since 1986, with an invitation from Professor Shiing-Shen Chern, Yang organized a theoretical physics division at the Nankai Institute of Mathematics, which has received international attention in recent years.

In 1957 Yang was awarded the Nobel Prize. In 1980 he received the Rumford Prize. In 1986 he was awarded the National Medal of Science of the USA. He holds numerous honorary degrees and is honorary professor of many universities in China.

THREE MOST IMPORTANT RESEARCH WORKS

Yang's contributions to theoretical physics cover a wide range, from particle physics to statistical mechanics to condensed matter physics. He made great impact both on abstract theory and on phenomenological analysis. Of his works, the Yang-Mills theory, parity nonconservation in weak interactions, and the Yang-Baxter equation are lasting contributions to physics and to mathematics.

(A) Yang-Mills theory. In 1953 while visiting the Brookhaven National Laboratory, Yang formulated with R. L. Mills the non-Abelian gauge field theory, later called Yang-Mills theory.[2,3]

The Yang-Mills field is different from Abelian gauge field (electromagnetic field). It is based on the non-Abelian gauge principle. It naturally contains non-linear interactions. The field strength is

$$F^a_{\mu\nu} = \partial B^a_\mu/\partial x_\nu - \partial B^a_\nu/\partial x_\mu + gC_{abc}B^b_\mu B^c_\nu. \tag{1}$$

The Lagrangian is

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^a_{\mu\nu}. \tag{2}$$

The interaction of this field with other fields is governed by the gauge principle. When Yang was a graduate student at Chicago, he was already intrigued by the relationship between charge conservation and invariance under phase transformations. At that time, many particles had been discovered, and their interactions had seemed very complex. Yang thought that one must find a principle to determine such interactions. He tried to generalize the phase transformation principle to apply to isospin conservation, but did not succeed after many attempts due to failure to include the last term in equation (1). He returned to the idea when visiting Brookhaven during 1953-1954. Mills, a Columbia doctoral student working with Professor N. Kroll, was also visiting Brookhaven and shared an office with Yang. Mills was close to finishing his Ph.D. dissertation. Yang invited him to collaborate on the problem. By February 1954 they had basically finished the project. Their paper was completed in June and was published in the Physical Review in early October.

This paper introduced the concept of non-Abelian gauge invariance and the related gauge field theory. It was an epoch-making contribution, laying the foundation, and supplying the fundamental principles and fundamental equations, for the whole of particle physics. There exist four types of interactions in nature: strong, electromagnetic, weak, and gravitational. It is now known that the fields transmitting these interactions are all Yang-Mills fields.

Reviewing the development of physics in the past 300 years, we could properly understand the historical position of Yang-Mills theory. Starting with Galileo and Newton, the spirit of physics has been to extract principles from countless physical phenomena and to reduce these principles to a few fundamental equations. These equations are the essence of the essence of physics. B. A. Li in an article[25] has summarized nine sets of such equations discovered over the past 300 years: (1) Newton's laws of motion and of gravity; (2) the first and second laws of thermodynamics; (3) Maxwell equations; (4) the fundamental equations in statistical mechanics; (5)

the equation of special relativity; (6) the equation of general relativity; (7) quantum mechanical equations; (8) Dirac equation; (9) Yang-Mills equations.

Yang-Mills theory also created great impact in mathematics. Mathematicians have used Yang-Mills theory as a tool to explore properties of differential manifolds. In 4 dimensions, Yang-Mills equations have a special kind of solution called Instanton solutions. These Instanton solutions form a parameter space. Recently, S. Donaldson extended the earlier basic work done by M. F. Atiyah, C. H. Taubes, and K. Uhlenbeck to obtain the Donaldson theorem by studying the topological structure of a 4-dimensional differential manifold related to this parameter space. Combining this theorem with the Freedman theorem, he was led to the brilliant discovery that there exist strange differential structures on 4-dimensional Euclidean space. For this, Donaldson was awarded a 1986 Fields Medal.

(B) Parity nonconservation in weak interactions. In the mid-50s, particle physics was a hot field. Major research efforts were devoted to understanding the properties of newly discovered particles: their charge, spin, mass, and decay etc. Out of such research, there emerged the so-called $\theta - \tau$ puzzle: $\theta \to \pi\pi$ and $\tau \to \pi\pi\pi$ were believed at the beginning to be two different particles, because according to the simplest ideas they were given different parities. This idea later appeared to be consistent with much experimental data, and it was concluded that θ and τ were indeed two different particles. On the other hand, many other experiments indicated that they ought to be the same particle. This led to the $\theta - \tau$ puzzle. During 1953–1956 this problem was gradually recognized as a key problem in particle physics.

Yang and T. D. Lee devoted tremendous amounts of energy to this problem. Starting from late 1955 to early 1956, they explored several avenues to solve it. No luck! One of these was to propose parity nonconservation. At a Rochester particle physics conference April 3 to 6 in 1956, Yang, in answering a question about possible parity nonconservation by R. P. Feynman, said he and Lee had tried this avenue, but had failed to get any concrete results.

It is clear now that the main reason for failing to get concrete results was that the key idea was missing: *parity nonconservation in weak interactions only.* Not only did physicists not entertain this idea, but they also had further gross misconceptions. They thought the many successful selection rules in β-decay had proved that parity *is* conserved. This misconception resulted in the failure to resolve the $\theta - \tau$ puzzle.

One day in late April or early May in 1956, this key idea suddenly occurred to Yang and Lee at their lunch in a Chinese restaurant in New York City. Two to three weeks after that lunch, through many calculations, they proved that *all previous β-decay experiments were in fact too simple to test parity conservation in β-decay.* Thus parity conservation in weak interactions was an open question and they proposed several experiments to test it.

Their preprint was finished in June 1956 and was later published[4] in the Physical Review. It was not well-received. In a famous letter to V. Weisskopf, Pauli wrote: "I do not believe that the Lord is a weak left-hander..." Experimental physicists generally did not want to try the proposed experiments because none of them appeared to be simple. Furthermore, they were skeptical that Yang and Lee's proposal would resolve the $\theta - \tau$ puzzle.

Chien-Shiung Wu of Columbia University was a great authority on β-decay experiments. She was one of the few experimentalists who realized the importance of the proposed experiments. She decided to collaborate with four low-temperature physicists from the National Bureau of Standards to do one of the experiments Yang and Lee had proposed. Half a year later, in early 1957, Wu made public their results. Parity is *indeed* not conserved in β-decay. This striking discovery was a shock to the whole physical community. Since β-decay is only one type of weak interaction, one should test parity conservation in all other types of weak interactions as Yang and Lee had suggested. Many laboratories rushed into this and verified within a couple of years that indeed parity is not conserved in all weak interactions.

For their achievement, Yang and Lee were awarded the 1957 Nobel Prize in Physics. Their work also directly or indirectly focused particle physicists' attention in the next decade on various aspects of symmetry.

(C) Yang-Baxter equation. In November and December, 1967, Yang published two papers[5,6] on the following extremely simple one-dimensional quantum many-body problem:

$$H = \sum_i p_i^2 + 2c \sum_{i>j} \delta(x_i - x_j). \tag{3}$$

He found that this problem is completely solvable. A key point is the following important equation

$$A(u)B(u+v)A(v) = B(v)A(u+v)B(u) \tag{4}$$

where $A(u)$ and $B(v)$ are square matrices and u and v are variables. From equation (3), he obtained two matrices $A(u)$ and $B(v)$ which do satisfy equation (4). Using equation (4) he then proved that the original many-body problem (3) is completely solvable. In 1972 R. J. Baxter, while studying some classical statistical mechanical problems in two dimensions, also noticed the importance of equation (4), which was named in 1981 the Yang-Baxter equation. In the last half dozen years, people have discovered further and deeper significance of this equation in mathematics and in physics. It is one generalization of the permutation group.

Up to the present, scientists have found strong relevance of the Yang-Baxter equation in the following areas of mathematics and physics:

Physics:

- One-dimensional quantum mechanics problems,
- Two-dimensional classical statistical mechanical problems,
- Conformal field theory.

Mathematics:

- Knot and braid theory,
- Operator theory,
- Hopf algebra,
- Quantum group,
- Topology of three-dimensional manifolds.

At the Kyoto International Mathematics Congress in August 1990, three of the four Fields Medalists were awarded prizes for their work related to the Yang-Baxter equation. It is generally believed that the Yang-Baxter equation is a *fundamental mathematical structure* which will have even more relevance in future developments.

OTHER RESEARCH WORKS

Yang has worked in many areas of physics, having published more than 200 papers. In addition to the three most important research works discussed above, he has published many other important papers, some of which are discussed below. These papers are chosen with the following considerations in mind: (a) long-range significance, (b) importance at the time when the work was done, (c) beautiful concept or method and Yang's personal partiality, and (d) those that especially demonstrate Yang's research style.

(A) Particle physics.

1) Strength of weak interactions. In 1949 Yang, Lee, and M. Rosenbluth wrote an article about the strength of various weak interactions.[7] This article, along with those by several others, laid the foundation for the classification of the four types of interactions, which is still in use today.

2) Fermi-Yang model. In 1947 π mesons and μ mesons were discovered and were believed by most researchers to be elementary particles. Fermi and Yang wrote an article[8] entitled "Are mesons elementary particles?" in which they suggested that a π meson might be the bound state of a nucleon and an anti-nucleon. Later called the Fermi-Yang model, this paper pioneered the field of constituent structure of hadrons.

3) G parity. In the Autumn of 1955 the anti-proton was discovered at Berkeley. This prompted Yang and Lee to combine[9] the concept of charge conjugation symmetry and that of isospin symmetry to form a new concept: G parity. They identified the G parity for π meson to be -1. With this, they found a number of simple selection rules in strong interactions. G parity is now one of the fundamental quantum numbers in particle physics.

4) Nonconservation of charge conjugation and time reversal. After reading Yang and Lee's preprint on parity nonconservation in weak interactions, R. Oehme of the University of Chicago wrote a letter to Yang in August 1956. This led to a new paper[10] in late 1956, which extended the possibility of parity nonconservation to the nonconservation of charge conjugation and time reversal. This paper laid the foundation for the discussion of the three kinds of nonconservative phenomenon in β-decay. It was also deeply related to the later CP nonconservation analysis in 1964 (See *8)* below).

5) Two-component theory of the neutrino. Parity nonconservation led to the reintroduction[11] of H. Weyl's two-component theory for describing the neutrino by Yang and Lee. Almost at the same time, A. Salam and L. Landau also made similar proposals separately. We shall in a later section compare these three papers to learn of their difference in styles.

6) Analysis of high-energy neutrino experiments. In the Autumn of 1959 Lee and Yang got very interested in how to obtain more information about weak interactions. Under Lee's influence, M. Schwartz of Columbia University made an important proposal for a neutrino beam experiment, which led to many later developments. In 1960 Lee and Yang wrote the first article[12] in the theoretical analysis of such neutrino experiments.

7) Research on intermediate bosons. In the early 1930's Yukawa had discussed the possibility of transmitting through an intermediate boson the interaction for β-decay. The work by Yang, Lee, and Rosenbluth in 1949 had also discussed such a possibility. (As we know today, intermediate bosons, W and Z, are indeed the media for weak interactions. They are gauge fields.) In the summer of 1957 research on β-decay became a hot topic due to the discovery of parity nonconservation. After a presentation by J. Tiomno at the April 15–19, 1957 Rochester conference, Yang said: "if the β-decay interaction turns out to be a vector interaction and not a scalar interaction, one might ask the question if this has anything to do with the vector fields that seem always to arise out of these localized conservation law concepts." The localized conservation law mentioned here by Yang is the gauge field concept he and Mills had introduced in 1954. That was the first time that gauge fields were mentioned in the literature as the transmitters for weak interactions.

In the theoretical paper on high energy neutrino experiments mentioned in the previous section, Yang and Lee also discussed the intermediate boson, which they named the W particle. In the subsequent two years, they studied extensively properties of the intermediate boson from both the phenomenological and the theoretical viewpoints.

8) Phenomenological analysis of CP nonconservation. After the experimental discovery of CP nonconservation in 1964, numerous papers were published speculating about the origin of CP nonconservation. Yang and T. T. Wu spurned these speculations and chose to make a phenomenological analysis. Starting from the article mentioned in Section 4 above and using the fact that CP nonconservation is a minute effect, they clarified[13] the measurable parameters (quantitatively of different orders of magnitude) in $K - \bar{K}$ decay and the relationship between these parameters. The concepts and parameters (*e.g.*, $K_L, K_S, \eta_\pm, \eta_{00}, A_2/A_0$ *etc.*) introduced by this work have been used by experimental and theoretical researchers in this area ever since.

9) Fiber bundles and integral formalism for gauge fields. A 1974 paper[14] by Yang and a 1975 paper[15] by Yang and Wu clarified the fundamental meaning of electromagnetic fields in quantum mechanics. Furthermore, the topological meaning of the Aharonov-Bohm experiment was made clear, thereby establishing the relationship between gauge fields and fiber bundles in differential geometry. Yang and Wu constructed a "dictionary" comparing the terms used by physicists and those used by mathematicians, which led many mathematicians to the study of gauge fields. The Instantons and Donaldson's work mentioned above were related to these developments.

The concept of fiber bundles is deeply rooted in topology. Thus topological concepts have entered field theory in important ways in recent years.

10) Geometric model. Since 1967, Yang, with T. T. Chou and Ed Yen, developed a geometric model for high energy scattering. This model, being phenomenological, grew out of concepts related to angular momentum conservation. During the past two decades, it has led to many widely used concepts: fragmentation, limiting fragmentation, explanation of KNO scaling, and analysis of elastic scattering, *etc.*

(B) Statistical mechanics.

1) Spontaneous magnetization and critical exponent. In early November of 1949, Yang learned in a discussion that B. Kaufman had simplified Onsager's analytical solution of the two-dimensional Ising model. Being quite familiar with the mathematics used, Yang quickly understood the newly simplified solution. In January 1951, Yang realized that Kaufman's method may be used to compute the spontaneous magnetization. It turned out to be rather involved. After six months of hard calculation, the longest[21] in his life according to Yang himself, he obtained a very simple expression, which was later published[16] in the Physical Review. In 1952, while visiting the University of Washington in Seattle, Yang suggested that C. H. Chang extend the work to a rectangular Ising model. Chang then discovered that the critical exponents for both the rectangular and the square model are the same: 1/8. This led to Chang's suggestion in his paper[28] that critical exponents are universal, which was the earliest published suggestion of this important concept.

At that time, this critical exponent could not be measured. With the advancement of technology, the situation changed and in 1984, M. H. W. Chan did a beautiful experiment[29] which proved that this critical exponent was indeed 1/8, which is consistent with theory.

2) Liquid-gas phase transition and unit circle theorem. After his work on the Ising model, Yang used it to study the phase transition of a "lattice gas." During 1951–1952, he and Lee wrote two papers on phase transitions,[17] which clarified the mechanism of liquid-gas phase transitions. These papers convinced many physicists who had believed that liquid-gas transitions were related to the convergence of the virial series to give up their original misconception.

These two papers introduced the concept of complex fugacity and proved an elegant theorem now called the "unit circle theorem". These developments greatly influenced later work both in statistical mechanics and in field theory.

3) Development of Bethe's hypothesis. In order to study the quantum effect on a "lattice gas" and to study off-diagonal long-range order, Yang returned in the 1960's to the study of Bethe's 1931 hypothesis on which he had spent considerable amount of time before. This time, with C. P. Yang, he re-visited[18] Bethe's method. The equations in Bethe's and several others' later papers were too complex to exhibit the properties of their solutions. The Yangs found that if Bethe's function $cot^{-1}\alpha$ is replaced by $tan^{-1}\alpha$ through the relationship $cot^{-1}\alpha = \pi/2 - tan^{-1}\alpha$, one could use continuity arguments to study the solutions of the equations. This simple method led to a breakthrough in Bethe's hypothesis.

From 1966 to the 1970's, C. N. Yang, C. P. Yang and C. N. Yang's doctoral student, B. Sutherland, wrote about a dozen papers on statistical mechanical models. One of these was the famous paper introducing the Yang-Baxter equation. Several others also introduced new ideas and became classics in this field of research.

(C) Condensed matter physics.

1) The quantization of magnetic flux. In the Spring of 1961, Yang visited Stanford University for several months. At that time, W. M. Fairbank and B. S. Deaver were doing experiments on the quantization of magnetic flux in superconductors. F. London and Onsager had each considered this problem theoretically before, in 1948 and 1953 respectively. Yang and N. Byers found that London and Onsager's intuition was excellent but their reasoning was wrong. Yang and Byers pointed out that a correct treatment involves the single-value property of wave functions and the BCS theory of superconductivity. The importance of their paper[19] has been commented upon by Bloch in reference.[24]

2) The concept of off-diagonal long-range order (ODLRO). Yang realized the importance of the concept of Bose-Einstein condensation in the 1950's when he studied the superfluidity of helium. He also appreciated the importance of the BCS theory in superconductors when he studied the quantization of magnetic flux in superconductors. But he felt the concept of Bose-Einstein condensation of fermions had never been satisfactorily defined and analyzed. He made an in-depth research in this problem during 1961-1962 and wrote an article introducing the concept of ODLRO.[20] He was very proud of this paper.

3) Suggestion about the Aharonov-Bohm experiment. His interest in the Aharonov-Bohm experiment and his own work on magnetic flux quantization prompted Yang to propose[22] to A. Tonomura at the International Symposium on the Foundation of Quantum Mechanics in 1983 to do the Aharonov-Bohm experiment with superconducting shielding. This led to a most beautiful experiment[30] in 1986. To date, this experiment is the most accurate Aharonov-Bohm experiment.

(D) History of physics. Yang has written several articles about the historical development of modern physics and about physicists like Einstein, Schrodinger, and Weyl. He also felt that earlier analyses of the contributions of modern Chinese physicists were not good. Some were amateurish, others immature. Yang has thus devoted some efforts to correct the situation. In collaboration with B. A. Li, he has written two articles on the contributions of C. Y. Chao[31] and of K. C. Wang.[32] He believes more work should be done.

CHARACTERISTICS AND PERSONALITY

The most striking thing about Yang's research was his ability to choose problems which became important ten or twenty years later. The work on gauge theory was only recognized for its fundamental value twenty years after publication. The Yang-Baxter equation of 1967 did not receive much attention until the late 1980's. Furthermore, these two works will continue to influence future developments in physics for the next decades. What is the secret, we asked. Yang answered that first, one should not always follow fashion. One should have one's own focus. Second, one should work on both small and big problems. If one works only on big problems, one is unlikely to succeed and may even end up psychotic. Although the gauge theory problem was big, the Yang-Baxter equation was small. But how did a small problem become big? This leads to the third point: one must look for topics that have *direct connections* with physical phenomenon or with the basic structure of physics. The Yang-Baxter equation resulted from studying (3), which is the most basic and simple problem in quantum many-body problem. Working on such problems, one is more likely to arrive at results of more basic values.

When asked whether there were failures in his work, Yang said, "Of course." The most important failure was not having recognized the importance of symmetry breaking in the 1960's. "I did not at that time like symmetry breaking. I had a set of reasons which were wrong in retrospect. There are discussions on this on Page 67 of my Selected Papers."[21]

Yang enjoys exploring new territories and likes pioneering new ideas. Is this always good? Yang said, "Of course not, but it comes to me naturally and cannot easily be changed."

On June 4 1986 Yang talked to a group of graduate students in Beijing.[23] He said that he believes there are three P's in research. These are Perception, Persistence, and Power. All three factors are necessary, but perception and power are the more important. Persistence will come naturally with perception and power. Using this terminology, we found Yang himself to indeed possess all three. His perception is remarkably penetrating. His persistence can be seen from the history of his research on gauge fields, and on the calculation of the spontaneous magnetization in 1951. As to his power, one can sense that from many of his works. His 1956 work on parity nonconservation revealed his analytical power in physics and his 1962 paper on ODLRO demonstrated his power both in physics and mathematics.

Yang always emphasized to his students the importance of intuition and that intuition can be sharpened. He said that whether one is a college student, a graduate student, or a professor, it is important to nurture one's intuition, and believe in it. When one finds one's intuition to contradict new phenomena, new principles, or new knowledge, that is when one has an opportunity to sharpen or improve one's intuition. Understanding the origin of the contradiction would allow one greater penetration. This is a matter to be taken seriously. The attitude of easily surrendering one's own judgment and believing others' words is to be avoided.

The Chinese saying, "the article resembles the man," fits Yang admirably. Those who know Yang know that he values sincerity, honesty and integrity. He never tricks or intimidates people. He never plays to the gallery. Reading his papers one gets the same impression: he does not insinuate, does not play on words. He always confronts head-on the problems he chooses to attack. Some of his papers are very easy to understand. The one on parity nonconservation is one example. Others are too dry and too condensed, particularly those with lots of mathematics. The ODLRO paper is one example. It is clear that in these papers he puts the logic of mathematics before understandability.

Yang loves the dictum by an ancient Chinese poet "better slow and steady, not flighty and tricky; better plain and honest, not flowery and showy." He said this is also his attitude towards research.

Although some of Yang's papers appear to be too condensed, they do not give the impression that they were hastily written. The best example to illustrate this is the paper on the two-component neutrino. At that time, there were three papers on the subject, by Salam, by Landau, and by Yang and Lee. All three papers contained largely the same results. But Yang's and Lee's paper analyzed other related phenomenon, especially the question of detailed balance. They thus pointed out a mistake in the measured neutrino absorption cross section, which was not analyzed in the other two papers. Yang's papers are carefully written. That may be the reason why he quoted in the Preface of his Selected Papers the following lines by Tu Fu (Du Fu): 文章千古事, 得失寸心知

> A piece of literature
> Is meant for the millennium.
> But its ups and downs are known
> Already in the author's heart.

Yang loves helping others. When he was a graduate student at the University of Chicago during 1946–1948, he was already known to other students as a student-teacher. A classmate, J. Steinberger, wrote[26] in 1985, "The most impressive student-teacher is Yang, who came from China after the war and at the age of twenty-four, despite the limited wartime possibilities in China, knew all of modern physics fluently by the time he entered the graduate school at Chicago." In recalling the discovery of Yang-Mills theory, Mills wrote[27]: "Yang, who has demonstrated on a number of occasions his generosity to young physicists beginning their careers, told me about his idea of generalizing gauge invariance and we discussed it at some length. Having some background in quantum electrodynamics, I was able to contribute something to the discussions, especially with regard to the quantization procedures, and to a small degree in working out the formalism; however, the key ideas were Yang's."

Yang does not have many graduate students. He had none when he was in Princeton. There was speculation that he would take many graduate students in Stony Brook. He did not. He said, "I am not an Empire Builder." He maintained he "did not have many good topics for students to work on." Up to now, there have been fewer than 10 students who have worked for Ph. D. degrees under his supervision. The most famous one is Alexander W. Chao. Yang is proud of the fact that around the time that Chao was about to get his Ph.D. in 1974, Yang forced, or almost forced, Chao to switch to accelerator theory. Yang recalls: "Chao is very talented. But I said there were too few significant problems for too many physicists in particle theory. The output per person per year was small. In accelerator theory, the situation was the other way around, but young people did not know this." Chao took his advice and soon became famous.

ACKNOWLEDGMENTS

We thank Professor C. N. Yang for his help in the writing of this article. Many other people helped us. J. Toll, J. Murbuger, M. L. Ge, M. L. Yan, and Y. L. Xin deserve special acknowledgments.

REFERENCES

1. C.N. Yang, *Forty Years as Student and Teacher*, Joint Publishing Co., Hong Kong (1985).
2. C.N. Yang and R. Mills, *Isotopic spin conservation and a generalized gauge invariance*, *Phys. Rev.* **95** (1954), 2, 631.
3. C.N. Yang and R. Mills, *Conservation of isotopic spin and isotopic gauge invariance*, *Phys. Rev.* **96** (1954), 1, 191–195.
4. T.D. Lee and C.N. Yang, *Question of parity conservation in weak interaction*, *Phys. Rev.* 104 (1956), 1, 254–258.

5. C.N. Yang, *Some exact results for the many-body problem in one dimension with repulsive delta-function interaction*, *Phys. Rev. Lett.* **19** (1967), 23, 1312–1315.
6. C.N. Yang, *S matrix for the one-dimensional N-body problem with repulsive or attractive delta function interaction*, *Phys. Rev.* **168** (1968), 5, 1920–1923.
7. T.D. Lee, M. Rosenbluth, and C.N. Yang, *Interaction of mesons with nucleons and light particle*, *Phys. Rev.* **75** (1949), 5, 905.
8. E. Fermi and C.N. Yang, *Are mesons elementary particles? Phys. Rev.* **76** (1949), 12, 1739–1743.
9. T.D. Lee and C.N. Yang, *Charge conjugation, a new quantum number G and selection rules concerning a nucleon-antinucleon system*, *Il Nuovo Cimento* **10** (1956), 749–753.
10. T.D. Lee, R. Oehme, and C.N. Yang, *Remarks on possible non-invariance under time reversal and charge conjugation*, *Phys. Rev.* **106** (1957), 2, 340–345.
11. T.D. Lee and C.N. Yang, *Parity nonconservation and a two-component theory of the neutrino*, *Phys. Rev.* **105** (1957), 5, 1671–1675.
12. T.D. Lee and C.N. Yang, *Theoretical Discussion on possible high-energy neutrino experiments*, *Phys. Rev. Lett.* **4** (1960), 6, 307–331.
13. T.T. Wu and C.N. Yang, *Phenomenological analysis of violation of CP invariance in decay of* K^0 *and* $\bar{K}^0$, *Phys. Rev. Lett.* **13** (1964), 12, 380–385.
14. C.N. Yang, *Integral formalism for gauge fields*, *Phys. Rev. Lett.* **33** (1974), 7, 445–447.
15. T.T. Wu and C.N. Yang, *Concept of nonintegrable phase factors and global formulation of gauge fields*, *Phys. Rev.* **D12** (1975), 12, 3845–3857.
16. C.N. Yang, *The spontaneous magnetization of a two-dimensional Ising model*, *Phys. Rev.* **85** (1952), 5, 808–816.
17. C.N. Yang and T.D. Lee, *Statistical theory of equations of state and phase transition, I. Theory of condensation*, *Phys. Rev.* **87** (1952), 3, 404–409; T.D. Lee and C.N. Yang, *II. Lattice gas and Ising model*, *Phys. Rev.* **87** (1952), 3, 410–419.
18. C.N. Yang and C.P. Yang, *One-dimensional chain of anisotropic spin-spin interactions, I. Proof and Bethe's hypothesis for ground state in a finite system*, *Phys. Rev.* **150** (1966), 1, 321-327; *II. Properties of the ground state energy per lattice site for an infinite system*, *Phys. Rev.* **150** (1966), 1, 327–339; *III. Application*, *Phys. Rev.* **151** (1966), 1, 258–264.
19. N. Byers and C.N. Yang, *Theoretical considerations concerning quantized magnetic flux in superconducting cylinders*, *Phys. Rev. Lett.* **7** (1961), 2, 46–49.
20. C.N. Yang, *Concept of off-diagonal long-range order and the quantum phases of liquid He and of superconductors*, *Rev. Mod. Phys.* **34** (1962), 4, 694–704.
21. C.N. Yang *Selected Papers 1945–1980 with Commentary*, W. H. Freeman and Company (1983).
22. C.N. Yang, *Gauge fields, electromagnetism and the Bohm-Aharonov effect* in: International symposium on foundation of quantum mechanics, 1983, Physical Society of Japan (1984), 5–9.
23. C.N. Yang, *The stories about several scientists (in Chinese)* in The Collected Works of C.N. Yang, Eds. P.Z. Ning, X.M. Tang, and Q.H. Zhang (1989), 470-498, Nankai University Press, Tianjin, China.
24. F. Bloch, *Off-diagonal long-range order and persistent currents in a hollow cylinder*, *Phys. Rev.* **A137** (1965), 3, 787–795; *Simple interpretation of the Josephson effect*, *Phys. Rev. Lett.* **21** (1968), 17, 1241–1243; *Josephson effect in a superconducting ring*, *Phys. Rev.* **B2** (1970), 1, 109–121.
25. B.A. Li, *The essence of Physics—Nine sets of equations (in Chinese)*, *Nature Magazine* **13** (1990), 666.
26. J. Steinberger, *Pions to quarks*, ed. by L. Brown, M. Dresden, and L. Hoddeson, Cambridge (1989), 307.
27. R. Mills, *Gauge field*, *Am. J. Phys.* **56** (1989), 6, 493–507; *Gauge Field (Chinese Translation)*, *Nature Magazine* **10** (1987), 8, 563–577.
28. C.H. Chang, *The spontaneous magnetization of a two-dimensional rectangular Ising model*. *Phys. Rev.* **88** (1952), 6, 1422.
29. H.K. Kim, and M.H.W. Chan, *Experimental determination of a two-dimensional liquid-vapor critical-point exponent*, *Phys. Rev. Lett.* **53** (1984), 2, 170-173.
30. A. Tonomura, *Evidence for Aharonov-Bohm effect with magnetic field completely shielded from wave*, *Phys. Rev. Lett.* **56** (1986), 8, 792-795.
31. B.A. Li and C.N. Yang, *C. Y. Chao, Pair Creation and Pair Annihilation*, *International J. of*

Math. Phys. **A4** (1989), 4325.

32. B.A. Li and C.N. Yang, *K.C. Wang and the Neutrino (in Chinese), J. Dialects of Nature* 5 (1986), 34.

This article is translated by the authors with minor revisions from an article in Chinese in "Biographies of Contemporary Chinese Scientists", Volume 3 (1992, Science Publisher, Beijing).

DEPARTMENT OF PHYSICS AND ASTRONOMY, UNIVERSITY OF KENTUCKY, LEXINGTON, KENTUCKY 40506

DEPARTMENT OF APPLIED MATHEMATICS, STATE UNIVERSITY OF NEW YORK AT STONY BROOK, STONY BROOK, NEW YORK 11794