Interaction between Theory and Experiment in the Current Century

(B.V. Sreekantan, National Institute of Advanced Studies, Bangalore).

First of all, I would like to thank the organizers of the International Conference on "70 years of Quantum Mechanics and Recent Trends in Theoretical Physics" for inviting me to ~~in~~ deliver the inaugural address and ~~to~~ Prof. Chanchal Majumdar, Director of the S.N. Bose National Centre for Basic ~~Studies~~ Sciences to make the inaugural address itself the Satyendra Nath Bose Memorial Lecture.

Having accepted, I ~~have~~ wondered what my credentials ~~would be~~ are for these two prestigious assignments. I could think of one, long, very trivial reason, namely that I was born in the same year as Quantum Mechanics!

It so happens that the variety of experimental investigations I was involved in the areas of Cosmic Rays, High Energy physics and High Energy Astronomies were ~~concerned with~~ related exactly to particles and radiations belonging to the realm of Quantum Mechanics, in fact I should say to the realm of Relativistic Quantum Mechanics. ~~Also I had the most wonderful opportunity of being active and~~ to ~~some extent involved~~

~~Also, having started my research in 1945, I had the glorious opportunity of~~ ~~witnessing and to some small extent in participating in the revolution that was taking place in the field of just born field of Elementary Particle and High Energy~~ ~~physics~~

~~of witnessing the birth of a new era of physics~~ -

2

Witnessing the ushering in ~~the eara~~ era of elementary particle physics

Also I started my research in Cosmic rays in 1948, just at the time when Cosmic ray research was ushering in ~~the eara~~ era of Elementary Particle and High Energy physics and providing the incentive and justification for the construction of higher and higher (as far experimenters advance a gating of frontier I thought) accelerators. So with this background I think the best I can do is to ~~focus~~ touch on the interaction between ~~on~~ theory and experiment ~~on the late hundred years or so, that patterning in this century, that has led to the present~~ status of quantum mechanics that guided the development of led to ~~the new physics~~ emergence of the new physics covering the micro and macro cosmos and taking us closer perhaps to a grand unified law of nature.

I will ~~start with~~ divide my talk into periods each of which had a distinct characteristic of its own. I will talk about the veterans who were responsible for bringing in all the changes in our thinking, their mutual interaction, idiosyncrasies, prejudices and forefront. My main source of information are the books that I have enjoyed reading over and over again.

NIAS

One is a Soviet [illegible] book entitled "Probability of the Quantum World" by Daniel Danin published in 1983 by MIR Publishers Moscow, originally in Russian later translated into english by Oleg Glebov and Vitaly Kisin. This book was written by Danin after ~~Spending~~ making use of the archives at the Niels Bohr Institute at Copenhagen. The archival material relating to the quantum revolution was collected in the period the 1960-64 by interviewing a large number of workers of the field, in addition to collecting letters, ~~papers~~ manuscripts, tapes etc. 133 of the 175 interviews were probed on by Thomas Kuhn. Exactly identical versions exist in the library of the University of California, Berkeley and at the Philosophical Society of America at Philadelphia.

Those interviewed include Oscar Klein, Max Born, Bohr, Pascual Jordan, Werner Heisenberg, Oppenheimer, Amaldi, Yukawa.

The Second book is that by Heinz Pagels entitled "The Cosmic Code" – Quantum Physics as the Language of Nature." published by Bantam in 1983.

The Third one is the book entitled "The Second Creation" – Makers of the Revolution in Twentieth Century Physics by Robert Crease and Charles Mann. They have published ~~written~~ ~~after interviews~~ in 1986, after interviewing a very large number of scientists all over the world. They came to Sudarshan also and interviewed him of his involvement in the Proton Decay Group at the Kolar Gold Fields.

I will divide my talk into the following periods

(1) 1888 - 1900.
(2) 1900 - 1925
(3) 1925 - 1932
(4) 1932 - 1955
(5) 1955 - 1995.

1888: In 1887, Heinrich Hertz, Professor at Karlsruhe and Bonn, succeeded in producing in the laboratory Electro-Magnetic waves, that were precisely the kind that had been predicted by Maxwell's theory in 1864. - in all respects.

1894: Albert Michelson, the most respected experimental scientist of the time said
"It seems probable that most of the grand underlying principles have been firmly established and that further advances are to be sought chiefly in the rigorous applications of these principles to all phenomena which come under our notice..
The future truths of physics are to be looked for in the sixth place of decimals"

How totally mistaken was Michelson. — as shown by the discoveries in 1895, 96 and 97 the 'hat-trick' years of physics.

1895 – discovery of X-rays by Röntgen
1896 – discovery of Radioactivity by Becquerel
1897 – discovery of electron by J.J. Thomson

* existence of bodies smaller than the atom!
* Röntgen did not recognize the electron! – not courage enough

• Changed the course of physics, philosophy and technology.

• 1900 : Max Planck's Quantum hypothesis – to explain
Dec 14th – the observed spectrum of black-body radiation – *
The world is discrete – not continuous.

• 1905 : Bombshell paper of Einstein – on photoelectric effect.
Used Planck's hypothesis to say that light itself was quantized into particles.
Experimental confirmation came only in 1915.

Millikan who had spent years in devising precise measurements of photoelectric effect said in 1915
" Despite ... the apparent complete success of of the Einstein's Equation, the physical theory of which it was designed to be the symbolic expression is found so untenable that Einstein himself, I believe no longer holds to it"
But Einstein held to it
The final confirmation came from the Compton effect (1923-24)

* "an act of hopeless despair" 'a mathematical technique' Planck did not change his mind for the end of his life; just before his death Niels Bohr said "in some sense it can be said, he used his early later 40 years of his life, not to try 50 to try to get his discovery out of the world.

• 1907 ~~Quantum Mechanics and Ca~~
The remarkable ~~successive~~ success of Planck's theory in different realms of physics silenced opposition.
Serious doubt was cast on the validity of causality in physical scale.
At the 1911, Solvay Congress, Poincaré remarked

" Newton realized (or thought he realized – today we are beginning to wonder) that the state of a mobile system, or more generally of the universe, depended only on its immediate preceding state; and that all change in Nature occurred continuously... Well, it is this fundamental belief that is being questioned to-day".

- 1907: Rutherford (36 yrs old) came to Manchester as ~~Niels Bohr (22 yrs old)~~ student of J.J. Thomson
  Structure of the Atom:

- In 1895, Rutherford came to Cambridge as student of J.J. Thomson
  " We have got a rabbit here from the Antipodes and he is burrowing mighty deep"
  In 1906, Rutherford at McGill University Canada noticed a narrow beam of α-particles passing through a mica leaf. A fraction of the particles had deviated by more than 2°. Required a field of 10,000 volts/cm.
  ∴ highly intense fields in atoms.

1909: Rutherford at Manchester: (with his student Marsden)
Scattering of α-particles – 1 in 8000 bounced back.
" ... It was almost as incredible as if you had fired a 15-inch shell at a piece of tissue paper and it came back and hit you"

Rutherford suggested a non-sensical Expt. to Marsden his student. " See if you can get some effect of α-particles directly reflected from a metal surface"

NIAS

Geiger in 1911

"One day Rutherford obviously in the best of spirits came to my room and told me that he knew what the Atom looked like"

The Rutherford Atom: Electrons are revolving around the nucleus.

doomed to failure. - The electron will inevitably fall into the Nucleus.

At the first Solvay Conference in 1911 -
Einstein, Max Planck, Lorentz, Poincare, Marie Curie, Langevin, and Walther Nernst -. were present.
Rutherford was deeply hurt. Nobody said a word about the Planetary Model of the Atom. - Nobody noted even the discovery of the Nucleus.

Half a Century later, Thomas Kuhn asked Niels Bohr
"Was there no one who took Rutherford seriously"
"No One" said Bohr.
This 'anti-Thomson' atom was disregarded at the Cavendish Laboratory to such an extent that it was not even discussed, to say nothing about being criticized.

Bohr: "...I simply believed it".

The Bohr Atom: Why are the atoms stable if their structure is similar to the Solar System?

Bohr: " Early in my stay in Manchester in Spring of 1912, I became convinced that the electronic constitution of the Rutherford atom was governed throughout by the quantum of action (h)

1911-1913 – Quantum Ferment in the mind of Bohr

Bohr did not know anything about the Spectral formulae. His friend Hans Hansen who worked in Spectroscopy asked Bohr in 1913, to have a look at the formulae.

x – that was a turning point in the history of knowledge of nature

Leon Rosenfeld, who was a student of Bohr

x He told me more than once "As soon as I saw Balmer's formula, the whole thing was immediately clear to me"

Bohr discovered from Balmer's formula, the stepwise sequence of energy levels. ..

Einstein on Bohr's theory "It still seems a miracle to me. This is the highest musicality of mind"

—

Reactions to Bohr's theory:

William Bragg: Bohr's theory suggested to physicists that they use classical laws on Mondays, Wednesdays and ~~Thursdays~~ Fridays and quantum laws on Tuesdays, Thursdays and Saturdays. It was all correct mathematically, but physical picture was ambiguous.

Runge (Spectroscopist at Gottingen): This fellow is definitely mad

Rayleigh. "It is hard for me to accept all this as true picture of what really happens in nature"

Otto Stern: He would drop physics "if this non-sense proves to be true"

Rutherford himself was not convinced. but still recommended the paper for publication

1924: • S.N. Bose sends his paper on photon statistics to Einstein
• Louis ~~De~~ de Broglie submits his thesis "Studies in the theory of quanta" to University of Sorbonne.

Paul Langevin (Student of J.J. Thomson with Rutherford) told Ioffee in 1923 in Solvay Conference "His (de Broglie's) ideas, of course, are non-sensical, but he develops with such elegance and brilliance that I have accepted his thesis".
De Broglie suggested that the electron was related to some wave.
Stable orbit of the electron means that after each revolution around the nucleus everything is repeated precisely.
– integer number of wave lengths
$\lambda = h/m.v.$ λ in the X-ray range.

De Broglie (1924) "Electron waves passing through a crystal should give rise to the same diffraction picture as created by the atomic points of the crystal lattice that as that produced by X-rays."

1927: C.J. Davisson and Germer, and G.P. Thomson discover diffraction of electrons independently.
* Davisson had seen this six years earlier. did not recognise the significance.

1929: Louis de Broglie awarded the Nobel Prize.
Davisson and Thomson " in 1937.

Schrödinger

1925: Einstein publishes a paper in which he highly praised the wave concept of de Broglie.
Peter Debye and Erwin Schrödinger ~~read~~ read the paper of de Broglie together. – Conduct a joint seminar. That is how Schrödinger started on his quest.
Spends time in Alpine village of Arosa on doctor's advice.
In the quiet Arosa came the first ideas of wave mechanics – or is it the waves in the Zurich Lake?
Similarity between mechanics of the macroworld and the mechanics of waves.

[Experimental discovery of the fine structure of atomic spectra and anomalous Zeeman effect – New quantum number – Pauli – 'two-valuedness' of the electron. – abstract notion. – quantum possibilities doubled.

Kronig → rotation of the electron around its own axis.
(Semi-classical model. – unforgivable sin according to Pauli.
Kronig obtained the right formula, did not have the courage to send the result for publication.

van der Waerden: Pauli doomed Kronig.

at Leiden
Goudsmit and Uhlenbeck } Came to the rotating electron model the same year 1925.
They approached Paul Ehrenfest. He sent the paper for publication, though there was the problem of the electron rotating faster than light.
(This was later settled by Dirac)]

de Broglie had demonstrated that the electron motion in orbit (of Hydrogen Atom) is stable because the orbit length is equal to electron wave length multiplied by an integer.
Schrödinger formulated the necessary wave equation.
(Did not like that it was)

Schrödinger :. 'A moving particle is nothing but the foam on the wave radiation forming the matter of the world"

Prejudices of Schrödinger

• denounced the quantum jumps along energy ladder in the atom.

Schrödinger was unaware of Spin. – Yet another discrete feature.

"After returning from Arosa, he applied his method for the motion of electron in the hydrogen atom... The calculated results did not agree with observational data"

* He dropped it. even though he thought he had taken relativity into account

He accidentally located an error.

He saw that it was too early to introduce relativity theory.

Tried to solve the problem with lower accuracy

It worked. Result agreed with expt.

ψ still remained obscure!.

1925. Heisenberg: to the sea shore → island of Heligoland due to hay fever.

What can be measured in atomic transitions?

Observables – tangible quantities rather than intangible orbits.

States and frequencies – arrays to represent them.

Non-commutative arrays.

Max Born identified these arrays as Matrices.

$pq - qp = \hbar/i$

Heisenberg had dared to reject completely all traditions and classical descriptions for motion in the subatomic world.

Pauli to Kronig: 'Heisenberg mechanics restored to me the hope and joy of life"

Gratitude to Mathematics.

Sept. 1925. Bohr after receiving Heisenberg's paper

"It can be hoped that a new era has opened for mutual stimulation of mathematics and mechanics. Perhaps physicists will be at first sorry that in our understanding we cannot overcome limitations ~~of~~ on ~~that~~ the normal methods for describing nature. But one would like to think that this feeling will be replaced by gratitude to mathematics which provides us with an instrument for advancement in this field"

Wave-Particle Controversy.

Schrödinger wave equation - enormous achievement - every aspect of physics

Max Born reading the 1st paper wrote to Schrödinger

"I want to defect. - or better return - with flying colours to the camp of continuum physics. . . .
It is hardly necessary to conceive of a quantum transition as an energy change from one vibrational mode to another. rather than to regard it as jumping of electrons"

Heisenberg told Pauli "this wave business is so much crap"

Pauli and Schrödinger both prove that the two approaches were identical.

In Summer of 1925, Heisenberg and Max Born met Hilbert, head of the Gottingen mathematical school. They asked for him to help them with matrices
Hilbert said "each time he had to deal with these square tables they appeared in his calculations as a sort of 'a bye-product' in the solution of the wave equation. So if you look for the wave equation which has these matrices you can probably do more with that.
If they had heeded they would have found wave mechanics much earlier.

(1926)

What is ψ ? Probability
de Broglie, who was delighted by the work of Schrödinger developed the theory of Pilot wave. — the ψ wave shows the way to the travelling particle
Max Born: (who had identified the square tables of Heisenberg as Matrices)
"The Schrödinger ψ waves are Probability waves"
End of 1926:
Einstein to Max Born " The quantum mechanics deserves high respect. But an inner voice tells me that it is still not what is needed." He continued
" This theory yields much, but hardly takes us closer to the mystery of God. At any rate I'am convinced that He does not play dice'

Schrödinger and Heisenberg – face to face

~~The Uncertainty Relation:~~

Late in Summer 1926 Sommerfeld held a theoretical Seminar in Münich. Schrödinger and Heisenberg met for the first time face to face

Wien was the Director of the Institute of Expt'al physics
He thought that Schrödinger was at last restoring the prequantum continuity to physics. – Nature does not make jumps.
Heisenberg talked heatedly about the unwarranted confidence of Schrödinger
Wien jumped from his seat and conscious of his position said " young man, you have yet to learn physics and it would be better if you are good enough to resume your seat".

Schrödinger at Copenhagen
" If these damned quantum jumps indeed are retained in physics I will not be able to forgive myself that I had something to do with the quantum theory"

Heisenberg much later in life
" I would always have the electron in mind as a small ball, as a sphere. Only I would say : " It may be useful sometimes to call it a wave, but only as a way of talking, not as reality".

Bohr's ~~Correspondence~~ Complementarity principle.

How can one reconcile the concepts of particles and waves?
Wilson chamber photographs of charged particles. - tracks
- the tracks trace accurately the motion of electrons -
in magnetic fields they bend like the parabolic path of stone thrown parallel to the ground.
Matrix mechanics was based on the assumption that orbits and paths of electrons were unobservable.

Heisenberg finds the answer
droplet diameter ~ 10^{-4} cms. electron diameter ~ 10^{-13} cms
('A fly in the lower sphere of a planet)

To ask about the electron path in the cloud chamber track is the same as asking the path of a fly by looking at the motion of the earth along its orbit.

Feb 1927 Heisenberg $\Delta x \cdot \Delta p \geq \hbar$

If we attempt to measure one the other becomes indefinite.

Gamma ray microscope - Gedanken Expt. - Required both the wave and corpuscular concepts →
Bohr's principle of Complementarity.

NIAS

1927:

(Nobel Prize in 1933)

- Dirac and Relativistic Wave Equation —
- Quantum Electrodynamics
- Quantization of the field – first quantum field theory.
- His oscillators did not disappear when there was no field; they went into a 'zero state' which cannot be detected.
- The spaces around and within the atoms, previously thought to be empty were now filled with a boiling soup of ghostly particles.
- Concept of virtual particles
- 4-Component equation – two associated with spin and two with energy of the particle.
- Negative Energy States — Dirac Sea – all filled up.
- 'Hole' in the Sea → Anti-particle.
- Anti-particle identified with the Proton
- Herman Weyl: "Whatever the particles may be they could not be protons"

Discovery of the Positron:

1932) Cosmic Ray Investigations with Cloud Chambers in Magnetic Field.
~~1933~~} Anderson's discovery of upward going positron in cosmic rays.
Blackett's lab had seen the tracks earlier but not trained to be "sure" that they are.

- Concept of creation and annihilation of particles takes root.
- Pair Creation – Cascade Showers – Solve the problem of the soft component of cosmic rays.

The μ-meson story. — Discovery of μ-meson and π-meson

~~Discovery of the μ meson~~

- Crisis in Quantum Electro-Dynamics —
- What is the penetrating particle in Cosmic Rays. ?
- Homi Bhabha's analysis — Cannot be electron, Cannot be proton. has to be a particle of intermediate mass. (~ 100 me)
- Cloud chamber classification of particles at Caltech
  ~~Red - normal electrons: Green~~.
  Soft electrons — red electrons penetrating - green electrons (?)
- Two years of experimentation
- August 1936 — Anderson and Neddermeyer published several photographs that might be new particles — but did not claim discovery.
- ~~This particle of~~ Yukawa recognized that the new particle fits his theory of nuclear force — Exchange of heavy mass particle. Nishina turns up with a single cosmic ray track of mass 180-360 me.

Summer 1937

→

- A few months before Anderson and Neddermeyer travel to MIT learn that Street and Stevenson have found in their cloud chamber similar new particles.
- Anderson and Neddermeyer publish their discovery paper.

- The paper of Yukawa in Proceedings of Physico-Mathematical Society Receives attention in USA.
- Complication due to wrong identification of μ with the Yukawa particle — the experiment of Conversi, Piccioni and Pancini during war time.

(1947)
- Resolved by the discovery of the pion. by Powell's group.
- Analysis of Marshak — two types of mesons.

NIAS

Strange Particles

1947. Discovery of V-particles in Cloud Chamber by Rochester and Butler. (evidence found in october 1946. published in Dec. 1947 in Nature.) Evidence for just two particles. Nothing turned up in a further year's experiment.

In June 1948 Rochester spoke to Anderson. He got interested and set up a chamber at the top of White Mountain Found.

1949 Blackett "Why do you want to waste your time building cloud chambers. Everything that can be done with cosmic cloud chambers in cosmic rays has been finished"

A few months later came reports on V-particles. discoveries at Bombay.

1950 } Blackett sends a team to Pic du Midi and another to
1955 } Jungfraujoch. Leprince-Ringuet sends teams to Pic du Midi and Aiguille du Midi — in search of V-particles.

Rossi set up a team at Echo-Lake

~~K-particles and hyperons — Emulsion Experiments.~~

Emulsion Experiments – Bristol, Bombay.

Results on K-particles and hyperons

(·) Associated Production }
(·) Life time longer than 10^{-12} seconds }
· τ-θ ($K_{\pi 2}$ and $K_{\pi 3}$) puzzle.
  Ξ $K_{\mu 3}$

Gell-Mann – Nishijima – · Strangeness quantum number. Isotopic Spin Number Conservation in · Strong interactions and breakdown in weak interactions

(Quantum Numbers given to fix spin, parity, charge, baryon number strangeness, isotopic spin)

Lee and Yang – to solve τ-θ — Parity Non-Conservation. Madam Wu's Expt'al Confirmation.

Emmy Noether Each Conservation Law is connected with a symmetry.

NIAS

Gell-Mann's Eightfold Way
Similar Model by Yuval Ne'eman.

(1962) ~~Prediction of Ω^- - Strangeness (-3) by Gell-Mann.~~
Yamaguchi refused to let Ne'eman talk on his model at the 1962 Rochester Conference held at CERN.
At the same conference Gell-Mann predicts Ω^- with strangeness (-3) and mass 1685 MeV.

1964 Jan: Maurice Goldhaber tells Gell-Mann, Ne'eman at the Coral Gables Conference — nothing interesting found in 50,000 bubble chamber exposures
Eightfold Way in trouble (?)

1965: Samios's team discovers Ω^-
Clinched the case for SU(3) scheme of Gell-Mann.

Quarks, Partons

Feb. 1964: A Schematic Model of Baryons and Mesons
first paper introducing 'quarks' by Gell-Mann. - 3 quarks (u, d, s)

1965 Experimental searches - negative. in cosmic rays.

George Zweig at CERN had a different theory identical to quarks, - he called them 'aces'
Editor of Physical Letters refused to publish.
Gell-Mann got his letter paper published in Physics Letters since he thought he would be hassled by Physical Review Letters
(Status of Gell-Mann was different?)

CHARM

Discovery of Charm

~~In~~ 1950: Role of Intermediate Vector Bosons in Weak Interactions invoked. (W+, W-

Gary Feinberg on μ-decay - ~~If μ turns~~

If μ → W- + ν, W- releases a photon and W and ν recombine into electron. This decay rate would be 5 times the experimental limit.

∴ possibility νμ is different from νe. (?)

1962. Schwartz, Leon Lederman and Steinberger

1959 ~~1960: T.D. Lee~~ establish νμ is different from νC with

~~1960~~: AGS at Brookhaven.

1964: ~~Glass~~ Glashow and Bjorken suggest that there might be a fourth quark to balance the four leptons (electron, muon and νμ, νe). They call the fourth quark Charm.

1974 J/ψ discovered as Resonance around 3.1 GeV. by Ting's team at MIT and Richter's team at SLAC.

(November Revolution)

Glashow: J/ψ was a meson formed of a Charmed quark and Charmed anti-quark. dubbed Charmonium.

Goldhaber finds the Charm mesons in the SLAC data.

~~1976~~ 1975

Discovery of τ Lepton Experimental Surprise. No Theoretical prediction ~~1.78~~ GeV

At the electron positron Collider (SPEAR) by Martin Perl. ~~3.1 GeV~~ 1.78 GeV. Mass lepton.

$\tau_\tau = 2.956 \times 10^{-13}$ s.

The Intermediate Vector Bosons - ~~Weak Gluons~~
$W^{\pm}, Z^0$

- Weak Gluons change the flavour of quarks in the hadrons and make them decay. They let Strangeness and Charm leak away.
- Weak Gluons interact with Leptons and make them decay.

The Neutrino ν, (ν_e, ν_μ), Anti-Neutrinos, ν_τ.

Nobel ~~Ment~~ Leptons (K.V.L. Sharma. Current Sci. 69, 25th Dec 1995)

1930: Dec 4. (1930) . Pauli's Letter
"desperate remedy" to save principle of Conservation of energy in β-decay. - new neutral particle was introduced.

1931. The name 'neutrino' given by Fermi

1933. Official announcement at Solvay Conference Octobr 1933.

1934 β-decay theory developed by Fermi
Penetrating power of neutrinos pointed out by Bethe and Pontecorvo. (~~260 l.y.~~ λ = 260 l.y. in water)

1956 Experimental discovery of electron neutrino by Cowan and Reines. (Nobel Prize in 1995).

1962. • ν_μ discovered Danby et al. (Nobel Prize (1988) Schwartz Lederman Steinberger.

ν_τ assumed. Not discovered yet.

COMMUNICATIONS IN MATHEMATICAL
AND THEORETICAL PHYSICS
VOL. 1, 1998

INTERACTION BETWEEN THEORY AND EXPERIMENT IN THE CURRENT CENTURY

B. V. Sreekantan
National Institute of Advanced Studies, IISc. Campus, Bangalore

First of all I would like to thank the organizers of the International Conference on "70 Years of Quantum Mechanics and Recent Trends in Theoretical Physics" for inviting me to deliver the inaugural address of this conference. Further, I would like to thank Professor Chanchal Majumbar, Director of the S N Bose National Centre for Basic Sciences for suggesting to make this address itself the S N Bose Memorial Lecture of the Year.

Having accepted, I have wondered what my credentials are for undertaking these two prestigious assignments. Of course, there was one trivial reason namely that I was born in the same year as quantum mechanics. As I pondered, I realized that all the experimental investigations that I have been involved since 1948, in the fields of cosmic rays, elementary particles, high energy physics and high energy astronomies belonged entirely to the domain of quantum mechanics. Also I had the glorious and wonderful opportunity of being right in the midst of all this excitement as an active experimentalist when cosmic ray studies were ushering in the era of elementary particle and high energy physics-a period when there was symbiosis between theory and experiment, theory and mathematics, experiment and technology. So I thought it would be appropriate to share the excitement of the period with you all on this occasion-especially since the conference has a historical intonation.

My plan is to begin with a brief account of the pre-quantum mechanics days, which in a sense laid out the menu for this century and then talk about the days of quantum mechanics development, then come to the era of particle and high energy physics. I will be not talking about the details of experiments. I will try to give you a flavour of the unique personalities of the founders, their interactions with each other that was really responsible for all the developments-some interesting episodes that reveal the stubborness characteristic of these great men wedded to their pet ideas.

In recent years there are several books on the historical aspects of development of physics in the current century. The books "Niels Bohr's Times" and 'the Inward Bound' by Abraham Pais and 'the Quark and Jaguar' by Gell Mann make very Valuable reading. In this talk, I have drawn the material mostly from :

---

* S. N. Bose Memorial Lecture, delivered on 29.01.96 at the Indian Statistical Institute, Calcutta

1. The book entitled "Probabilities of Quantum World" by Daniel Danin It is a small red book published by MIR Publication, Moscow. The narration in this book is based on the archival material that is available at the Niels Bohr Institute at Copenhagen and also at Berkeley and Philadelphia. The material was collected during 1960-64-133 interviews by Thomas Kuhn-with Oscar Klein, Max Born, Bohr, Pascal Jordan, Heisenberg, Oppenheimer, Amaldi, Yukawa and others.

2. The second book is "The Second Creation" by Robert Crease and Charles Mann. They went round the world and interviewed many many active scientists. They came to India also in the 1980's.

The theme of my lecture is inspired by the following remarks of Robert Millikan made while receiving the Nobel Prize.

"Science walks forward on two feet, namely, theory and experiment sometimes it is one foot which is put forward first, sometimes the other, but continuous progress is made by the use of both-by theorizing and then testing or by finding new relations in the process of experimenting and then bringing the theoretical foot up and pushing it on beyond and so on in unending alterations"

I will divide my talk to highlight the developments in the following five periods :

1. 1887-1900
2. 1900-1925
3. 1925-1932
4. 1932-1955
5. 1955-1995

Why do I begin with the year 1887 ? This is the year in which Heinrich Hertz, succeeded in producing in the laboratory Electro-Magnetic waves, the kind that had been predicted by Maxell in 1864, and which is recognised as the first unification in physics of what till then had been regarded as two distinct phenomena–Electricity and Magnetism. Maxwell had envisaged light as electromagnetic radiation as well.

As a consequence of this major development, Albert Michelson, the most respected experimental scientist of the time said in 1894.

"It seems probable that most of the grand underlying principles have been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all phenomena which come to our notice....... The future truths of physics are to be looked for in the sixth place of decimals."

How totally mistaken was Michelson ! The next three years 1895, 1896 and 1897 turned out to be the hat-trick years of modern physics.

1895 : Discovery of X-rays by Rontgen

1896 : Discovery of Radioactivity by Becquerel

1897 : Discovery of Electron by J. J. Thomson

The most starting aspect of these discoveries was that bodies existed smaller than the "Atom." It is said that Rontgen did not believe for a long time (till 1911) in the existence of the electrons. He had no faith in J. J.'s experiments! It is important to mention that none of these three discoveries* changed the course of physics both experimental and theoretical and ushered in many new technologies.

As if to match these experimental discoveries entriely new streams of theoretical ideas began with the year 1900. On December 14th 1900 Max Planck put forward the Quantum Hypothesis to explain the difficult features of the spectrum of black body radiation-to overcome the ultra-violet catastrophy. According to Planck himself he was putting forward this idea "most reluctantly," as "an act of despair" and "as a mathematical trick." Planck did not change his views on this unsatisfactory aspect of quantum hypothesis till the end of his life. On this attitude of Planck, Niels Bohr has remarked "In some sense it can be said he used his forty last years of his life, not to say fifty, to try to get his discovery out of the world."

The quantum hypothesis, among many other problems cast serious doubt on the validity of casualty in physical science. In 1911, Poincare remarked at the Solvay Congress :

"Newton realized (or thought he realized ... today we are beginning to wonder) that the state of a mobile system or generally of the universe depends only on its immediate preceeding state, and that all change in nature occurred continuously ... well it is this fundamental belief that is being questioned to-day."

On the basis of Planck's quantum hypothesis, Einstein wrote in 1905 what has been characterized by some as a bomb shell paper emphasizing that light itself is in the form of quantized particles and it is this particle aspect that is the key to explaining photoelectric effect. Einstein emphasised the particle aspect of light even when the experimental results on photoelectric effect were not reliable. Even in 1915, Millikan who had spent years devising suitable approaches to a measurement of photoelectric effect said :

"Despite the apparent complete success of Einstein's equations, the physical theory of which it was disigned to be the symbolic expression, is found to be untenable that I believe that Einstein no longer holds to it."

But Einstein held on to it. The confirmation came in 1923-24 with the discovery of "Compton Effect."

In 1895, Rutherford came to Cambridge all the way from Audstralis as a student of J. J. Thomson. The latter remarked very soon afterwards "we have got a rabit here from the antipodes and he is burrowing mighty deep". In 1906 when Rutherford had moved to Mc-Gill University in Canada and was conducting experiments with α particles noticed that a narrow beam of them while passing through a mica leaf rusulted in a fraction of them deviating by more than 2° . Such a large deviation of the massive α-particles required

* had been predicted by theories of the time. These discoveries

intense electric fields inside the atoms, as high as 10,000 volts/cm. Back in Manchester in England in 1909, Rutherford suggested to his student Marsden, what in the first instance, appeared to be a non-sensical experiement. He wanted Marsden to see whether any α-particles got directly reflected back when incident on a metal surface. (Rutherford did not suggest this to Geiger who was more senior!) Geiger and Marsden tried out and found to their surprise that 1 in 8000 α-particles bounced back!

Describing this result, Rutherford remarked "It was almost as incredible as if you had fired a 15 inch shell on a piece of tissue paper and it came back and hit you."

Rutherford was pondering on the meaning of this scattering experiment on the constitution of the atom for almost two years. Geiger says in 1911 : "one day Rutherford obviously in the best of spirits came to my room and told me that he knew what the atom looked like"-All the matter of the atom was in the central positively charged nucleus. The electrons orbit around.

This Rutherford Atom was clearly doomed to failure at that point of time, since the electrons would just ultimately fall into the nucleus. At the Solvay Conference in 1911, attended by Einstein, Max Planck, Marie Curie, Langevin, Nernst, ... no body said a word about the planetary model of the atom—no-body noted the discovery of the nucleus ! Rutherford was deeply hurt. Even in the Cavendish Laboratory this Anti Thomson atom was not even discussed - to say nothing about being criticised. Only one scientist took note of it. That was Niels Bohr. What bothered Niels Bohr was the question why atoms are stable if their structure is similar to the planetary model of Rutherford. Bohr says : "Early in my stay in Manchester in the spring of 1912, I became convinced that the electronic constitution of the atom was governed by the "Quantum of Action $\hbar$."

Bohr was not aware of Balmer's formula on the spectrum of hydrogen. Hans Hansen a spectroscopist suggested to Bohr to have a look at Balmer's formula. Well the rest is history. Leon Rosenfeld, a student of Bohr says : "He (Bohr) told me more than once "as soon as I saw Balmer's formula, the whole thing was immediately clear to me."

Essentially Bohr discovered the stepwise sequencing of energy levels from Balmer's formula. Einstein's reaction of Bohr Theory : "It still seems a miracle to me. This is the highest musicality of mind." Some scientists reacted violently to Bohr's ideas.

William Bragg : "Bohr's theory suggested to physicists that they use classical laws on Mondays, Wednesdays and Fridays and quantum laws on Tuesdays, Thursdays and Saturdays. It was all correct mathematically but the physics picture was ambiguous."

Runge : "This Fellow is definitely mad"

Otto Stern : "I would drop physics if this non-sense proves to be true"

Lord Rayleigh : "It is hard for me to accept all this as true picture of what really happens in nature"

Rutherford himself was not fully convinced. Still he recommended the paper for publication

By 1924, when Quantum Mechanics had still not been born, S. N. Bose sent his paper on photon statistics to Einstein, who translated it into German and got it published. In his letter to Ehrenfest in July 1924, Einstein says "Bose' derivation is elegant, but the essence remains obscure."

In 1924, Louis de Broglie submits his thesis "Studies in the theory of quanta" to the University of Sorbonne.

Paul Langevin who was a student of J. J. Thomson along with Rutherford, told Ioffe in 1923 itself at the Solvay Conference "His (de Broglie's) ideas are of course non-sensical, but he develops with such elegance and brilliance that I have accepted his thesis."

A consequence of de Broglie's theory of matter waves was that "electrons passing through crystals should give rise to the same diffraction pattern as created by atomic joints of a crystal lattice, as that produced by x-rays."

In 1927, Davisson and G.P. Thomson discovered diffraction of electrons independently. It is said that Davisson had these diffraction patterns six years earlier-even before de Broglie's Theory-but he had not recognised the significance.

In 1925, Einstein published a paper in which he highly praised the wave concept propounded by de Broglie. Peter Debye and Erwin Schrodinger read the paper of de Broglie together at a seminar. This started Schrodinger on his quest and being ill on doctor's advice went to the village Arosa. In the quiet Arosa, the first ideas of quantum mechanics were born. On his return from Arosa, he wrote down "the Schrodinger equation" for the motion of the electron in the hydrogen atom. Eventhough he thought he had taken into account the relativistic aspect, the calculated results did not agree with the experiment. He reformulated the problem less accurately and got better agreement.

Schrodinger had no idea what the ψ in his wave equation was !

In the same year 1925, Heisenberg who was also working on the same problem and who was also not well went to the sea-shore Island of Helgioland. He turned his attention to the tangible observable quantities in measurements involving atomic transitions. He did not bother about orbits and frequencies. He came up with the idea that the observables can be represented by non-commutative arrays of numbers! Max Born later identified these arrays as matrices familiar to mathematicians.

On Heisenberg's mechanics, Pauli exclaimed to Kronig "Heisenberg's mechanics restored to me the hope and joy of life."

Bohr remarked :

"It can be hoped that a new era has opened for mutual stimulation of mathematics and mechanics. Perhaps physicists will at first be sorry that in our understanding we cannot overcome limitations on the normal methods of describing nuture. But one would like to think that this feeling will be replaced by gratitude to mathematics which provides us with an instrument of advancement in this field."

Max Born, who had helped Heisenberg in identifying his arrays as matrices, wrote to Schrodinger after receiving his first paper.

"I want to defect or better return with flying colours to the camp of continuous physics. It is comforting to conceive of a quantum transition as an energy exchange from one vibration mode to another rather than regard it as jumping electrons"

Heisenberg wrote to Pauli

"This wave business is so much crap...."

In the summer of 1925, Heisenberg and Born met Hilbert, head of the Gottingen mathematics school. They asked him to help them with matrices. Hilbert said "Each time he had to deal with those square tables, they appeared in his calculations as a sort of a 'bye-product' in the solution of a wave equation. So if you look for the wave equation which has those matrices you can probably do more than that.

Well if only Heisenberg and Born had heeded his advice they probably would have discovered wave mechanics much earlier!

What is waving in the Schrodinger Wave Equation? What is ψ in the Schrodinger equation? De Broglie who was delighted by the Schrodinger equation developed the theory of Pilot Wave—the ψ wave shows the way to the travelling particle.

Max Born said " The Schrodinger waves are probability waves"

In 1926, Einstein wrote to Max Born

"The quantum mechanics deserves the highest respect. But an inner voice tells me that it is still not what is needed"

"This theory yields much, but hardly takes us to the mystery of God. At any rate I am convinced that "HE DOES NOT PLAY DICE"

In 1926, Wien was the Director of the Institute for Experimental Physics at Munich. He thought that Schrodinger was atleast restoring the prequantum continuity to physics. He believed that Nature does not make jumps. At a meeting in Munich, Heisenberg talked heatedly about the unwanted confidence of Schrodinger. Wien jumped from his seat and conscious of his position said "young man, you have yet to learn physics and it would be better if you could resume your seat."

Schrodinger said when he was at Copenhagen :

"If these damned quantum jumps indeed are retained in physics, I will not be able to forgive myself that I had something to do with quantum theory.

Heisenberg reflected much later in his life

"I would always have electron in mind as a small ball, as a sphere. Only I would say "It may be useful sometimes to call it a wave, but only as a way of talking not as reality."

This wave particle duality, which led to the Bohr's complementarity principle posed and continues to pose serious problems.

In the Wilson cloud chambers in magnetic fields the curved tracks of the electrons were clearly seen. On the other hand, Matrix mechanics was based on the assumption that the orbits and paths of electrons were unobservable. Heisenberg found an answer to this puzzle. The water droplets in the cloud chamber tracks have typically a size of ~ 1 mm in diameter. The radius of the electron in contrast was 10^{-13} cms. Therefore, the position of the electron in the track is not that accurately specified. In fact, the comparison would be of locating a fly(~1 cm in size) in the Solar Planetary System.

In February 1927, Heisenberg wrote down the famous uncertainty relation $\Delta P. \Delta X \geq .\hbar$ in the so called Gedanken Gamma ray microscope experiment, Heisenberg talked of the interference of the observer. Bohr had to gently remind Heisenberg who was so much opposed to the wave concept, that the position determination in his experiment depended on the parameter χ which was a wave concept!

"Quantum Mechanics had a difficult delivery that required dozens of modwives ... unlike Relativity".

In 1927, another outstanding scientist entered the field-Paul Maurice Dirac. He framed the Relativistic Wave Equation of the electron-the solution of which had 4 components-two turned out to be associated with spin and the other two with the energy of the particle.

In this connection, Dirac introduced the concept of negative energy states all filled to form the Dirac Sea-the 'Hole' in the Sea corresponded to the Antiparticle of the electron. In the first instance, Dirac thought that the anti-particle could be the Proton. However, Herman Weyl showed that whatever be the antiparticle, it cannot be the proton.

In 1932, Carl Anderson of CIT discovered in the Cosmic Radiation the positron positively charged particle with the same mass as the electron. Anderson published the discovery of the positron without being aware of Dirac's work. The experimental discovery of the positron solved many problems. It was immediately identified as the anti particle of the electron that Dirac's equation had led to. The annihilation of positrons and electrons producing γ-rays and the production of electron pairs by γ-ray solved the problem of the soft component of cosmic rays. Bethe and Heitler worked out the cross section for bremstrahlung and pair production. Based on these cross sections Bhabha and Heitler and Carlson and Oppenheimer developed the cascade theory.

Dirac on Mathematics :

"One should allow oneself to be led in the direction which mathematics suggests ... one must follow up a mathematical idea and see what its consequences are, eventhough one gets led to a domain which is completely foreign to what one started with ... Mathematics can lead us in a direction we would not take if we only follow up physical ideas by themselves."

In the early 30's, investigations in the field of Cosmic Rays had led to the recongnition of two distinct components - ~~components~~ -the soft (absorbed in a few mms of lead) and the hard (penetrating more than a meter of lead). With the development of the Cascade theory, the soft component was identified as resulting from the cascade development of electrons and γ-rays. However, the question remained-what is the penetrating component?

In 1935-36, Anderson and Neddermeyer were analysing the particles in the Cosmic ray beam with their magnetic cloud chamber. So also the group of Blackett at Manchester. Some cases of penetrating tracks (penetrating a few cms of lead) were recorded by both the groups. In August 1936, Anderson and Neddermeyer published the photographs of some tracks. However, they did not claim the discovery of any new particle since Oppenheimer was of the strong opinion that they were just fast electron tracks.

In 1937, Yukawa who was working on the theory of nuclear forces had come up with the idea of exchange forces. His idea was that the nuclear force was due to the exchange of a particle that had to have a heavy mass to account for the short range of the nuclear force. Anderson's paper encouraged Yukawa to pursue his ideas. In fact, he pursuaded Nishina to look for experimental evidence for these heavy mass particles. In spite of war, Nishina set up a cloud chamber experiment and recorded one clear case of a charged particle of mass 180-360 m_e. Around the same time 1936-37, Homi Bhabha who was in Cambridge, England, analysed the experimental results on the soft and penetrating components of cosmic rays and came to the conclusion that

(i) either Quantum-Electro Dynamics breaks down at high energies or

(ii) there is a particle in cosmic radiation which has a mass between the electron and proton possibly ~100 m_e.

Anderson during a visit to Harvard came to know that Street and Stevenson had also gathered evidence from their cloud chamber experiment for the presence of penetrating particles which could not be electrons.

Anderson and Neddermeyer immediately published their findings claiming the discovery of a new particle in cosmic radiation. The name Mesotron was given to this particle by Anderson, which was changed to Meson by Millikan.

In 1937, Yukawa published his paper on meson theory of nuclear forces in the Japanese journal-Proceedings of physico-mathematical sciences. He called the particle responsible for the nuclear force u-particle (also Yukon). He (wrongly) identified the u-particle with the meson discovered in cosmic rays.

This hasty identification led to many complications. The italian scientists Conversi, Piccioni and Pancini showed that the meson is not a strongly interacting particle as required by Yukawa for his nuclear theory. Negative mesons did not get captured in a nucleus like carbon when brought to rest, but decayed like positive mesons. They however did not decay when stopped in a heavier nucleus like lead. Fermi. Teller and Weiskopf showed that the meson interaction was 10-12 orders of magnitude weaker than that of the u-particles. Sakata and later Marshak postulated the existence of two mesons one heavier than the other and the heavier one decaying into the lighter one.

Powell in collaboration with llford photographic company developed electron sensitive nuclear emulsions for detection of fast particles (minimum ionizing). In an exposure made to cosmic rays at jungfraujoch Lattes, Powell and Occhialini recorded the first examples of one type of meson decaying into another type

$\pi \rightarrow \mu + \nu$, $\mu \rightarrow e + \nu + \nu$

The discovery of the pion resolved the problem connected with the Yukon, since the pion was the yukon, the strongly interacting particle involved in the binding of nuclei. The pion decaying with a lifetime of 10^{-8} seconds resolved the discrepancy regarding the lifetime of the yukon which with the earlier identification with the muon had to have a lifetime of microseconds. It soon became clear that the penetrating particles in the cosmic ray were the muons. resulting from the decay of charged π and the soft component arise from the decay of the neutral poins into γ-rays. The unstable particles the poins and mouns were able to traverse long distances in the atmosphere before decaying because of the relativistic elongation of time, a relativistic effect pointed out by Homi Bhabha immediately after the discovery of the muon, which had also been arrived at by Rossi on the basis of the experimentally observed differences in the absorption characteristic of the penetrating component in air and in a condensed medium like water.

In 1946, immediately after the resumption of the operation of the magnetic cloud chamber at Manchester which had been stopped because of war, Rochester and Butler observed two cases of V-particles suspected to be decays of heavy mass particles. No further cases were seen in another year of operation. Anderson set up a cloud chamber in the high altitude station at White Mountains, and recorded 30 cases of V-particles confirming the observations of Rochester and Butler.

During 1949-1955 cloud chamber installations came up at Pic du Midi, Aiguille du Midi, Echo Lake, Jungfraujoch, Ooty specifically to study the V-particles. Nuclear Emulsion Stacks were flown to balloon altitudes by groups from Bristol, Bombay, Rochester. Chicago NRL etc.

These resulted in the discovery of K-mesons and Hyperons $K^{\pm}$, τ, θ, Λ_0, $\Sigma^{\pm}$, Σ_0, Ξ^-

The K-mesons had a mass between pions and nucleons and the hyperons had a mass heavier than that of the nucleon. All these particles decayed with a lifetime in the range 10^{-10}-10^{-13} Seconds.

None of these had been predicted by any theory at that time. Detailed studies of the properties of these particles revealed the following spacial features which any theory had to account for

(i) Produced in strong interactions

(ii) Abundance at production ~ 1% of pions

(iii) Associated production K's with other K's and Λ^s

(iv) Life time for decay 10^{-10} - 10^{-13} seconds- considerably larger than nuclear life time (10^{-23} seconds)

A very surprising feature that was noticed in the very early days of the discovery of these new particles was that the some K-meson decayed in different contradictory modes- sometimes into two pions and sometimes into thrree pions. To separate the two modes, the first one was called the θ-meson and the second the τ-meson and the puzzling feature came as τ-θ puzzle.

To resolve this puzzle, Lee and Yang proposed the hypothesis of parity breakdown in week interactions. This was confirmed by famous experiment of Madam Wu of Columbia University.

To explain the associated production, Gell-Mann and Nishijima proposed independently the conservation of a new quantum number- "strangeness" in strong interactions. This was followed by the eightfold way and the prediction of the Ω^- with strangeness (-3) by Gell Mann. In 1964, Maurice Goldhaber told Gell-mann and Neeman at the Coral Gables Conference "nothing interesting was found in 50,000 bubble chamber exposures and the eight fold way was in trouble."

However, in 1965, Dame Luck smiled and Samios apprised Gell-Mann of the first Ω event. In 1962 at the Rochester conference held at CERN Yamaguchi had refused Neeman to present his paper on SU(3) .. in which he had also envisaged a particle of strangeness-3.

In 1964, the Quark model of Baryons and Mesons with three quarks u, d, s, was put forward by Gell Mann. Experimental searches for fractionally charged quarks in the cosmic ray beam proved negative.

Interestingly, a similar theory proposed by George Zweig of CERN had been refused publication by the editor of Physics Letters. However, Gell-Man's paper was published in Physics Letters since Gell-Mann did not submit it to Physical Review Letters fearing that it may not be published. It was soon recognised that the Partons that Feynman had proposed and the quarks are the same.

In 1954, Yang and Mills published the paper "Gauge Invariance and Isotopic spin" in the Physical Review. The idea of Intermediate Vector Bosons was intorduced in this paper. The work of Sudarshan and Marshak and Gell-Mann and Feynman led to the establishment of the V-A form of Weak Interactions by 1956. Schwinger published in November 1957 his paper. "A theory of Fundamental Interactions" in Annals of Physics. He introduced the idea that the photon and two intermediate vector bosons were responsible for all Weak Interactions. He urged his student Sheldon Glashow to look into the possibility of the connection between Weak and Electro Magnetic interactions. "Think about the Intermediate

Vector Bosons as the agents of Weak Interactions." In 1958, Glashow published the paper "The Renormalizability of Vector Meson Interactions" which was proved wrong by Salam. In 1961, he published his nobel prize winning paper "Partial Symmetries of Weak Interactions" in which he spelled out the similarity of electro-magnetic and weak interactions and pointed out that there has to be a neutral vector boson in addition to the charged vector bosons, so that the photon need not be the carrier of weak interaction as envisaged earlier.

Salam had also been working with Gauge Theories right from 1957. He was the first to introduce the idea of "Broken" or "hidden symmetry" -the manner in which a real asymmetrical world can be described by a perfectly symmetrical theory. You may start with massless particles and end up with massive ones.

Glashow, Weinberg and Salam tied the weak and electromagnetic interactions requiring the photon, two W particles and a Z^0 to form a 'family.' The huge masses of W's and Z^0 were explained in term of Higgs Mechanism. What was required was experimental confirmation of these particles and their masses.

In 1973, the existence of neutral currents were discovered with the help of 'Gargamelle' the largest bubble chamber by Masset (along with Lagarrigue and Rousett). Caltech confirmed the same in April 1974. (Unfortunately both Lagarrigue and Masset died soon after) Eventhough, the $W^{\pm}$ and Z^0 had not been discovered yet, Salam, Weinberg and Glashow were awarded the Nobel Prize in 1979.

In 1983 $W^{\pm}$ and Z^0 were discoveredd by Carlo Rubbia and Collaborators at CERN. In 1984, Rubbia and Van der Meer got the Nobel prize. Now, let me narrate briefly the neutrino story.

On December 14th 1930, Pauli wrote a letter to the participants of a conference "Dear Radioactive Ladies and Gentlemen, ... to save the principle of conservation of energy, ... I propose a desperate remedy ... a new neutral particle" In 1931, the name 'neutrino' was given to this particle by Fermi who developed the β-decay theory. In 1934, the penetrating power of the neutrino was calculated by Bethe and Pontecarvo to be 260 light years of water.

In 1956, Reines and Cowan experimentally established the existency of the neutrino. In 1958, Marurice Goldhaber and his collaborators demonstrated that the neutrino was left-handed and the antineutrino was right-handed. In 1962, the muon neutrino ν_μ as different from the electron neutino (ν_e) was established by Schwatz, Lederman and Steinberger.

While the τ particle as another heavy lepton was discovered in 1975 by Martin Perl, the neutrino counterpart ν_τ has not been discovered yet experimentally though it has become very much a part of the standard model. Between 1970 and 1995 the neutrino had come to the central stage of many experimental efforts because of its importance in stellar processes. It all started with the experimental observation of Davies that the recorded flux of neutinos from the sun was deficient by almost a factor of 3. To explain this anomaly the possibility of neutrino oscillators has been suggested and experimental effort is now on to hunt for these oscillations. Another remarkable development was the observation of neutrinos from the explosion of the Super Nova SN 1987. With the hypotheseis of giant blackholes of millions of solar masses in the centres of active galactic nuclei, the exciting scenario of ultra high energy neutrino emission from these objects has opened up with feasibility of ultra high energy neutrino astronomy in the coming decades.

Another important development was the search for Proton decay. The Electro Weak Unification had given a boost to the possibility of unification of atleast the Strong, Weak and Electro-Magnetic forces if not the unification of Gravitation as well. Experimentally the observation of the varation of coupling strengths of the three forces with energy had indicated the possibility that the three may unify at an energy scale of 10^{14} Gev (the mass of X particles). While there is no possibility of producing these X particles at accelerators even in the remote future, the early universe as spelled out in the Big Bang theory of Creation has the potential of having created such particles. One consequence of the unification of three forces that was predicted by theorists was the spontaneous decay of the proton through the interactions of the quarks inside the proton exchanging X-particles. The expected lifetime was anything greater than 10^{30} years (the lower limit that had been set by the existing experiments). This suggestion triggered offf a major experimental effort by several groups in the world to look for proton decay (KGF, Mont Blanc, Kamiokande, Sudan, IMB,) The results so far have been negative. The lower limit to the lifetime of the proton has been set at 10^{32} years.

While many detailed features of the high energy cosmic rays have been established, the origin and acceleration mechanisms still remain a very open question. Three examples of cosmic ray particles of energy beyond 10^{20} ev have been recorded. The question has arisen whether these are just the decays of topological defects produced in the very early universe in which case no accelerating mechanism is necessary.

Clearly the 20th century has been one in which experiment and theory have propelled each other and the major discoveries have led to new technologies and the new technologies have helped to push the frontiers of science. Prehaps this will happen to a greater extent in the coming centuries.