

CHALLENGES IN THE FRONTIERS OF PHYSICS AND ASTROPHYSICS*

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First of all I would like to thank the Indian Physical Society for inviting me to give this prestigious endowment lecture. In my talk today, I will try to highlight the interconnection between Physics and Astronomy which in a sense have moved in opposite directions, Physics in the direction of the microcosmos and Astronomy in the direction of the macrocosmos; yet of late particularly in the last few decades have come so much together that at the accelerator laboratories, you find astronomers and astrophysicists discussing the implications of the findings in elementary particle physics to the first moments of creation of the universe, and particle physicists realising that the highest energy accelerator - that could never be built by man, was in existence in these first moments and may be there are remnants of exotic particles and radiations present in the universe even now.

Physics started off as a branch of science dealing essentially with the properties of various states of matter and radiation. Mechanics, Heat and Thermodynamics, Electricity and Magnetism, Acoustics, Kinetic Theory and Optics were the sub-disciplines of physics that developed through the 17th, 18th and 19th centuries.

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A characteristic feature of physics distinctly different from other disciplines of science that were also developing, was the great emphasis on precision in measurement that led to the recognition and formulation in terms of mathematical equations, laws of physics that seemed to be part of nature. Because of these approaches namely precise observations and exact theoretical formulations the success in physics was so remarkable that towards the end of the 19th century the feeling had developed among some of the leading physicists of the day that science would reach a stage of explaining everything around us in a matter of decades. However, this was not to be. On the contrary, the discoveries made in the last decade of the 19th and the early part of this century brought about a complete change of the complexion of physics that had profound influence not only on the next phase and direction of its own development, but also on the developments in many other fields, especially of technology - which in turn influenced the developments of all sciences. The philosophy of science also underwent a remarkable transformation.

This revolution which is identified with the down fall of classical physics began with the production of radio waves by Hertz, the discovery of X-rays by Rontgen, of radio activity by Becquerel, the electron by Thomson, relativity by Einstein, quantum theory by Max Planck, the nucleus by Rutherford and Cosmic rays by Hess. These discoveries moved physics research more and more in the direction of

the ultra-small, into the realm of the microcosmos of elementary particles.

Astronomy on the other hand started off with naked eye observations of the happenings in the sky especially in the nights when the dominating influence of the Sun was not there. Naturally the first things that attracted attention of man were the day and night phenomenon, the regularity of the motion of the planets, the phases of the moon, the eclipses, the meteors, the occasional visits of the comets, the constancy of the Stellar Constellations which served as the background reference for all other motions. The introduction of the telescope by Galileo brought new dimensions to the sky making one realise the unbelievably large numbers of stars and the vastness of space that encompassed these celestial objects. With larger and larger telescopes many of the subtle features of the universe became apparent.

It was none other than Isac Newton that brought about the close connection between Physics and Astronomy. He recognised in one giant leap of scientific thought, that it was the same gravitational force that makes an apple fall from a tree as also the one that holds the moon in orbit around the earth and the planets around the Sun. In another equally major break through by analysing the Sun light, with a simple prism, Newton laid the foundation for the field of spectroscopy which played extremely important role not only in the development of physics, but also in the field of astronomy. Spectroscopy pursued vigorously in

the physics laboratories in the 19th and early part of 20th century, led to the recognition of the discrete energy states of atoms and molecules, to the Bohr's theory of the atomic nucleus, to the applications of quantum mechanics. When I speak in this lecture hall, with the photograph of Prof. Megnath Saha in front of us, I do not have to stress the importance of spectroscopy to astronomy. Megnath Saha's theory of ionisation literally brought the stars down to the laboratory to tell us all about their temperatures, pressures and chemical constitution. In the June issue of The Scientific American, there is a very enlightening article on the famous astronomer Russel of the Russel-Hertzsprung diagram fame and also of Russel-Saunders coupling - one in the area of astronomy and the other in Atomic Physics. I would like you to read this article to see what glowing compliments are paid to Megnath Saha by astronomers of the time. Incidentally there is also a nice photograph of Saha when he was young.

(A)(i) The Neutrino

As one gained better and better understanding of the Nuclear structure and the Nuclear Forces, through scattering of Alpha - particles and later through the study of interactions of particles accelerated to higher and higher energy, the possibility of Nuclear Energy through fusion and fission processes became apparent. What is most interesting is that even before Nuclear Energy became a reality in the laboratories of the earth, the possibilities of Nuclear conversion of

hydrogen to helium as source of Solar Energy was envisaged by Perrin and Eddington, as early as 1920. Bethe proposed the CNO cycle in 1939. The experimental verification of these rather exotic ideas on the source of energy in the Sun had to await further developments in the field of physics. These developments began with discovery of a large number of elementary particles in addition to the Proton and the Electron that had been recognised in the beginning of this century through the study of the discharge of electricity in gases. Many of the puzzling features of the nuclear phenomena got resolved with the discovery of the Neutron in 1932 by Chadwick. It became clear that the nucleus comprised of protons and neutrons. An important difference between the proton, electron the particles that were discovered first and the neutron was that apart from being electrically neutral, the free neutron decayed spontaneously into a proton and an electron with a life time of $\sim 10^3$ seconds. However the decay products did not have a unique energy as would be the case if the Neutron decayed into just two particles. As is well known Pauli introduced a hypothetical particle, the Neutrino, to save the principle of conservation of energy and momentum in neutron decay as well as in Radio active decay in general.

This hypothetical particle neutrino was later detected experimentally inspite of its extremely weak interaction properties. The experimental discovery of the neutrino itself was a big challenge. However this elusive particle has posed bigger challenges both in the field of physics and astronomy. The challenges relate to the

unravelling of some of the very fundamental properties of this particle - the neutrino mass, the neutrino oscillations, the neutrino magnetic moment, the number of flavours of the neutrino and the neutrino lifetime. Pauli introduced the neutrino as a particle with zero electric charge, zero or very near zero mass and spin $\frac{1}{2}$. However over a period of time, as more and more short lived particles were discovered, it was found necessary to introduce in many cases the neutrino as one of the decay products, and in this process additional properties of the neutrino came to light.

Between 1930 and 1950, a spate of particles were discovered in the analysis of the cosmic ray beam through the atmosphere. The first particle to be discovered was the positron - in fact the first anti-particle which not only satisfied the predictions of the Dirac theory of the electron, but also opened the question of anti-particles of every kind - anti protons, anti neutrons, and anti matter - which have all been subsequently discovered in the high energy accelerator laboratories. It has also raised the question of anti matter in the universe which we shall discuss later on.

The discovery of the positron was followed by the discovery of the muon which had properties very different from any of the previously known particles; turned out to be the penetrating component of cosmic radiation. However the muon is unstable and decays into an electron in a matter of 2 micro seconds in its rest frame. It became

necessary to associate 2 neutrinos with the decay of each muon in addition to the electron. The muon itself was later discovered to be the decay product of the pion; in the pion decay also the companion was again another neutrino. In the early 60's experiments at the CERN accelerator in Geneva revealed that the neutrino associated with the decay of the pion (ν_μ) is different from that in the muon decay (ν_e). It also became necessary to distinguish between neutrinos and anti-neutrinos ($\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$). In the 70's with the discovery of the τ meson, it became necessary to associate with the decay of τ yet another type of neutrino ν_τ . The ν_τ has not been experimentally discovered yet. It is yet another challenge connected with neutrino physics. It has become extremely important to establish how many flavours ($\nu_e, \nu_\mu, \nu_\tau, \dots$) are there from the point of view of the Standard Model of elementary particle physics.

(ii) Neutrinos from the Sun

Astronomically too, the neutrino has become an important entity in a variety of contexts. Let me illustrate this by discussing the Solar Neutrino Puzzle. According to the Standard Solar Model, the various reactions that give rise to neutrinos ($\nu_e, \bar{\nu}_e$) are given in the Table I and the contributions of different reactions to the Solar Neutrino Flux in Table II in units of SNU. The Solar ν_e flux at the earth $\sim 10^{11}/\text{cm}^2\text{sc}$.

In Table II the Solar ν_e flux for two different threshold energies one

TABLE I

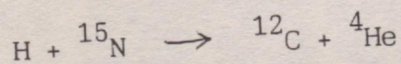
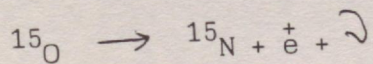
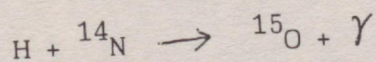
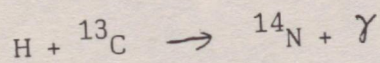
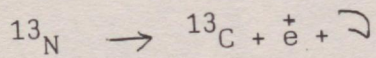
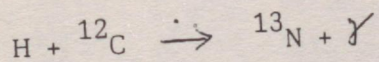
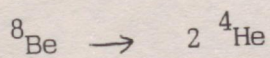
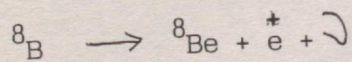
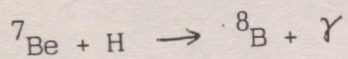
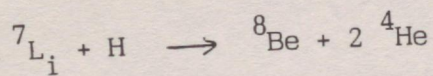
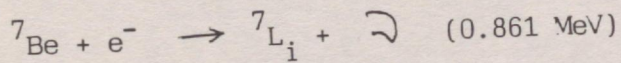
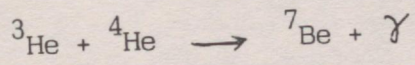
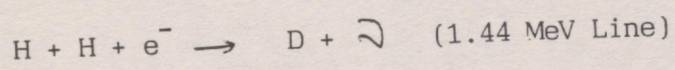
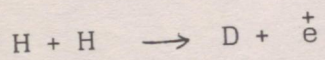


TABLE II

Reaction	Energy of ν_e (MeV)	No. of SNU in Cl (> 0.81 MeV)	No. of SNU in Gallium (> 0.236 MeV)
$P + P \rightarrow D + e^+ + \nu_e$	0 - 0.42	0	70.2
$P + P + e \rightarrow D + \nu_e$	1.44	0.2	2.5
$e + {}^7\text{Be} \rightarrow {}^7\text{Li} + \nu_e$	0.862	1.0	27.0
${}^8\text{B} \rightarrow {}^8\text{Be} + e^+ + \nu_e$	0 - 14.06	4.3	16.0
${}^{13}\text{N} \rightarrow {}^{13}\text{C} + e^+ + \nu_e$	0 - 1.2	0.1	2.6
${}^{15}\text{O} \rightarrow {}^{15}\text{Ne} + \nu_e$	0 - 1.73	0.3	3.5
		5.9 SNU	121.8 SNU

Solar Neutrino Interactions in SNU's in Chlorine and Gallium Detectors which have different energy thresholds.

corresponding to 0.81 MeV which is the threshold energy for the chlorine reaction and the other corresponding to 0.236 MeV for neutrino reaction in Gallium are given. It is seen that there is a gain by a factor of 20 if one is able to use the Gallium reaction. Gallium detectors are under construction in the Soviet Union and in Europe and are expected to go into operation in the near future.

R. Davis^[1] set up an experiment to detect the Solar Neutrinos through the reaction $\bar{\nu}_e + {}_{17}^{37}\text{Cl} \rightarrow e^- + {}_{18}^{37}\text{Ar}$ in a mine in South Dakota in 1968. Over the 15 year period 1970-85 the average $\bar{\nu}_e$ flux (>0.814 MeV) obtained by Davis was 2.1 ± 3 SNU (See Fig. 1) while the calculations of Bahcall^[2] on the Standard Solar Model gave a value of 6-8 SNU. (ISNU = 10^{-36} Captures/atom/sc. This discrepancy has come to be known as the Solar Neutrino Puzzle. In order to explain this discrepancy either one has to find something wrong with the standard solar model - (the core temperature) or with the properties of the neutrinos. The possibility has been suggested that the $\bar{\nu}_e$ may oscillate into $\bar{\nu}_\mu, \bar{\nu}_\tau$ either during its passage from the Sun to the earth or in passage through the dense medium of the earth. Since the Davis experiment can detect only $\bar{\nu}_e$, there could be a reduction of the flux by a factor of 2 if it oscillates into $\bar{\nu}_\mu$ or $\bar{\nu}_\tau$. Recently a new dimension has been added to the Solar neutrino puzzle. Davis has found that his data for the period 86-88 gives a value of 4.2 ± 0.8 SNU for the Solar $\bar{\nu}_e$ flux rather close to the expected value. This has brought up the question whether the Solar $\bar{\nu}_e$ flux changes with time.

Some have suspected for a long time a close correlation of \mathcal{J}_e emission with Solar activity. The Argon production rate observed by Davis is compared with solar activity parameters Sun spot number, and variation of solar diameter in Fig. 2. This seems to indicate an anti-correlation between production rate and Sun spot number and a positive correlation with solar diameter. What is difficult to understand if these trends are correct is the reason for correlation between a phenomenon like neutrino production that takes place in the central regions of the Sun where the temperatures are sufficiently high for the reactions of table I to take place and the 11 year solar activity which is believed to be purely a surface phenomenon. It is known that the energy transport from inside of the Sun to the surface through the normal channels of photon propagation takes millions of years. It has become therefore extremely important to follow up these trends with more efficient detectors. Several new generation detectors involving liquid scintillators, cerenkov counters, etc. are coming up to explore this problem further, in addition to the Gallium Detector. If the oscillations theory $\mathcal{J}_e(\text{sun}) \rightarrow \mathcal{J}_\mu \text{ or } \mathcal{J}_\tau$ are correct, there should also be a day and night effect in the flux detected in the underground detectors. In the night time the neutrinos have to pass through almost the entire diameter of the earth before they are detected.

The correlation with Solar activity, if genuine, may be correlated with the neutrino having a high magnetic moment according to the suggestions of Voloshin, Vysotskii and Okun^[3]. This would mean a

magnetic moment as large as $\mu(\nu_e) \approx (1/3 - 1) \times 10^{-10} \mu_{\text{Bohr}}$

The idea is that during solar activity when the magnetic field is large $10^3 - 10^4$ gauss, the spin of the neutrino may flip with the result.

\curvearrowright left handed \longrightarrow \curvearrowleft right handed

Right handed neutrino is sterile in the Chlorine-Argon reaction required in the experiment of Davis, and will result in an anti-correlation in the recorded flux with sun spot number which is a measure of the magnetic field increase. The experimental limit at accelerators for the magnetic moment of the neutrino is

$$\begin{aligned}\mu(\nu_e) &< 1.5 \times 10^{-10} \mu_{\text{Bohr}} \\ \mu(\nu_\mu) &< 9.5 \times 10^{-10} \mu_{\text{Bohr}}\end{aligned}$$

These limits cannot rule out the possibility suggested above. However the Electro-Weak Unification theory (Glashow, Weinberg, Salam) gives a value of $\mu(\nu_e) = 3.2 \times 10^{-19} \mu_B \cdot m(e)$ according to Fujikawa (Nine orders of magnitude smaller). Here again is another major experimental challenge - to determine the magnetic moment of the neutrino.

(iii) Neutrinos from Supernovae

Supernova theorists have been predicting for a long time that the explosion of a star into a Supernova would result in the production of a large burst of neutrinos and these would precede the optical flash by several hours. This remarkable prediction has been verified for the first time with the detection of a neutrino burst from the SN1987a which occurred on the 23rd Feb. 1987. The Proton decay detectors in

the U.S.^[4] and in Japan^[5] recorded neutrino bursts about 3 hours before the first optical record. Two other stations one in Mont Blanc (Italy)^[6] and the other in Baksan USSR^[7] have also reported recording of neutrino signals. The details are given in Table III. While IMB, the Kamioka and the Baksan agree reasonably well with each other in the actual time of recording of the burst, (\sim 3 hrs. earlier than optical flash) the Mont Blanc burst is 4.72 hrs. earlier than the optical flash. As can be seen from the table the energy output in neutrinos is greater than 10^{52} ergs/second. The neutrinos recorded in the Kamioka detectors are essentially $\bar{\nu}_e$ through the reaction $\bar{\nu}_e p \rightarrow e^+ n$. The absolute time sequence of the burst events recorded in the different arrays is shown in fig. 3. From the widths, time structures, and the energies of the neutrino events, attempts have been made by several authors to deduce the mass of the neutrinos. This is in the range of about $20 \text{ MeV}/c^2$ somewhat lower than what has been claimed by Lubimov et al^[8] in the laboratory experiments. It has to be pointed out however that because of lack of accuracy in the recording of time and the discrepancies of a few seconds between Kamioka and IMB in the absolute time, the results on the neutrino mass deduced from the time structure observations are not taken seriously. They clearly show the potentiality of the method for mass deduction if the requisite timing accuracies and calibrations are maintained. A lesson for the future !

TABLE III

	Mt. Blanc	I M B	Kamioka	Baxan
TONS	100	5000	2000	200
Threshold (50% η)	6 Mev	20 Mev	8 Mev	10 Mev
Number of Events	5	8	11	5
Energy Output	2×10^{54} ergs	1.8 - 2.3 $\times 10^{52}$ ergs	6 - 8 $\times 10^{52}$ ergs	2 - 2.5 $\times 10^{53}$ ergs

Neutrinos From SN 1987a

(iv) Missing Mass and the Neutrino

Astronomically, the mass of the neutrino has become an extremely important parameter in connection with what has come to be known as the missing mass paradox. It is known that some of the large clusters like the Coma cluster of galaxies do not have enough mass (as revealed through the visible and radio astronomies) to be bound gravitationally. They have only 1% of the mass required. The nature of this dark matter has become one of the challenging problems for the astronomers to unravel. The rotation curves of some of the galaxies also show that there must be a large amount of invisible matter extending far beyond the visible range of these objects. One of the strong candidates for this dark matter is the neutrino provided it does have some mass, even of the order of few eV. The neutrinos also play an extremely important role in the evolutionary history of the universe itself, as we shall presently see.

(B) The Evolution of the Universe - The Big Bang Creation

A remarkable result that came out of the spectroscopic observations of the light from the distant galaxies was the realisation by Hubble of the expanding nature of the universe leading to the Big Bang theory of creation of the universe. This theory has become much more quantitative with the discovery of the universal microwave radiation by Penzias and Wilson in 1965 and the applications of our

knowledge of particle physics from accelerator experiments. The milestones in the history of the universe deduced from a lot of physics and astronomy are summarised in the Table IV. A key result of the expanding universe of Hubble was that the galaxies which are further away from each other are moving away with higher speeds with respect to each other. This means that to learn more and more about the earlier times of the universe, the observations have to be made on the most distant objects corresponding to the highest red shift values. While technologically this will pose the problem of sensitivity for observation, which perhaps can be met, there is a limit that is set by the fact that the universe was not transparent to radiation before the lapse a certain time after creation. What is most remarkable however is, using the results of nuclear and elementary particle physics it has been possible to go back to very early times - even to a few minutes, few seconds, few fractions of a second of creation of the universe. In fact as you can see from Table V we can go back to 10^{-43} s of the Big Bang!

Based on the quark theory of elementary particles, the well established Electro-Weak unification of the electromagnetic and the weak forces and the envisaged unification of the strong and electro-weak forces, the scenario of the early universe in terms of its constituents has been worked out at various epochs the first microsecond after the Big Bang. This is summarised in Table V. The size of the universe at this point of time was less than nuclear dimensions of 10^{-13} cms, the

TABLE IV

Important Milestones in the History of the Universe

Cosmic Time	Epoch notation	Red Shift	Nature of the Phenomenan
0	Singularity	Infinity	Infinite density; Zero of time
10^{-43} Sc	Planck Time	10^{32}	Particle creation begins
10^{-6} Sc	Hadron Era	10^{13}	P \bar{P} annihilation
10 Sc	Lepton Era	10^{10}	$e^+ e^-$ annihilation
2 mins.	Radiation Era	10^9	Nucleosynthesis of Helium, Deuterium
70,000 yrs	Matter Era	10^4	Matter dominates the universe
300,000 yrs	Decoupling	10^3	Universe becomes transparent to radiation
1.2×10^9 yrs		10 - 30	Galaxies form
3×10^9 yrs		5	Clustering of galaxies begins
4×10^9 yrs			Formation of Milkyway Galaxy
4.1×10^9 yrs			First Stars form
5×10^9 yrs		3	Quasars born - Pop II Stars
10×10^9 yrs		1	Pop I Stars form
15.2×10^9 yrs			Parent Interstellar Clouds that gave rise to Solar System form
15.3×10^9			Collapsed Proto-Solar Nebula
15.4×10^9			Planets form
20×10^9			Homo Sapians appear (Just 10^5 years ago)

TABLE V

Happenings in the Universe in the first Microsecond

Time From Big Bang	Temperature	Features of the Universe
10^{-6} Sc.	$> 10^{13}$ °K ($> 10^9$ ev)	Non-gravitational properties change. Weak and Electromagnetic Interactions have the same strength.
10^{-13} Sc.	$> 10^{16}$ °K ($> 10^{12}$ ev)	Spontaneous Symmetry breaking Higgs Mechanism operates to generate masses of W^\pm, Z^0
10^{-36} Sc.	$> 10^{28}$ °K ($> 10^{24}$ ev)	Unification of strong and Electro-Weak forces. Production of massive lepto-quarks X, \bar{X} , massive magnetic monopoles, exotics.
10^{-43} Sc.	$> 10^{32}$ °K ($> 10^{28}$ ev)	Quantum gravity becomes important. No good theories yet to make predictions.

temperature higher than 10^{13} °K. The present day elementary particle physics has made it possible to envisage the happenings even earlier from 10^{-6} Sc to 10^{-36} Sc when the temperature rose from 10^{13} °K to 10^{28} °K. This very early universe seems to have controlled many major features of the universe we are familiar with to-day after 20×10^9 yrs - the dominance of radiation over matter, the dominance of matter over anti-matter. To explain some of the other features of the universe like its extreme homogeneity when considered in scales of megaparsecs, and the high degree of isotropy of the microwave radiation, the euclidean flat space that we are familiar with in our normal life, it has become necessary to invoke the idea of an inflationary expansion before the presently known Hubble expansion started. The inflation involving an exponential expansion would have lasted only for 10^{-32} seconds or so. I have given some more details on these aspects in my article 'The first moments of the universe' published in the transactions of the Bose Research Institute, [9].

In this brief span of just an hour or so, I have tried to give you a flavour of the type of interconnections that have developed between physics and astronomy over the last several hundred years. This symbiosis is growing stronger with time. The particle physics aspects of the early universe have opened up many new challenges to both physicists and astronomers. The environments associated with accreting binary systems, with one of the companion being a black hole or a neutron star are proving to be yet other regions of exotic high

energy phenomena. Advances in technology are bringing with in the realm of feasibility detection of gravitational waves, neutrinos from galactic and extragalactic sources perhaps even the cold neutrino sea that is another relic of Big Bang Creation.

I must end with the note that all this is the result of lot of experimentation, observation, theory and most importantly extrapolation over enormous range of distance scales, time scales, densities, temperatures, magnetic, electric fields, etc. To what extent these bold extrapolations are valid only further experiments and observations alone can tell.

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Figure 1

The Solar Neutrino Flux recorded in Davis's experiment over the period 1970-1988.

Figure 2

Comparison of Argon production rate due to Solar neutrinos in the experiment of Davis with Solar activity over the period 1970-1988.

Figure 3

Time Sequence of Neutrino bursts recorded in the different experiments on Feb. 23, 1987 preceding the optical burst of SN1987a.

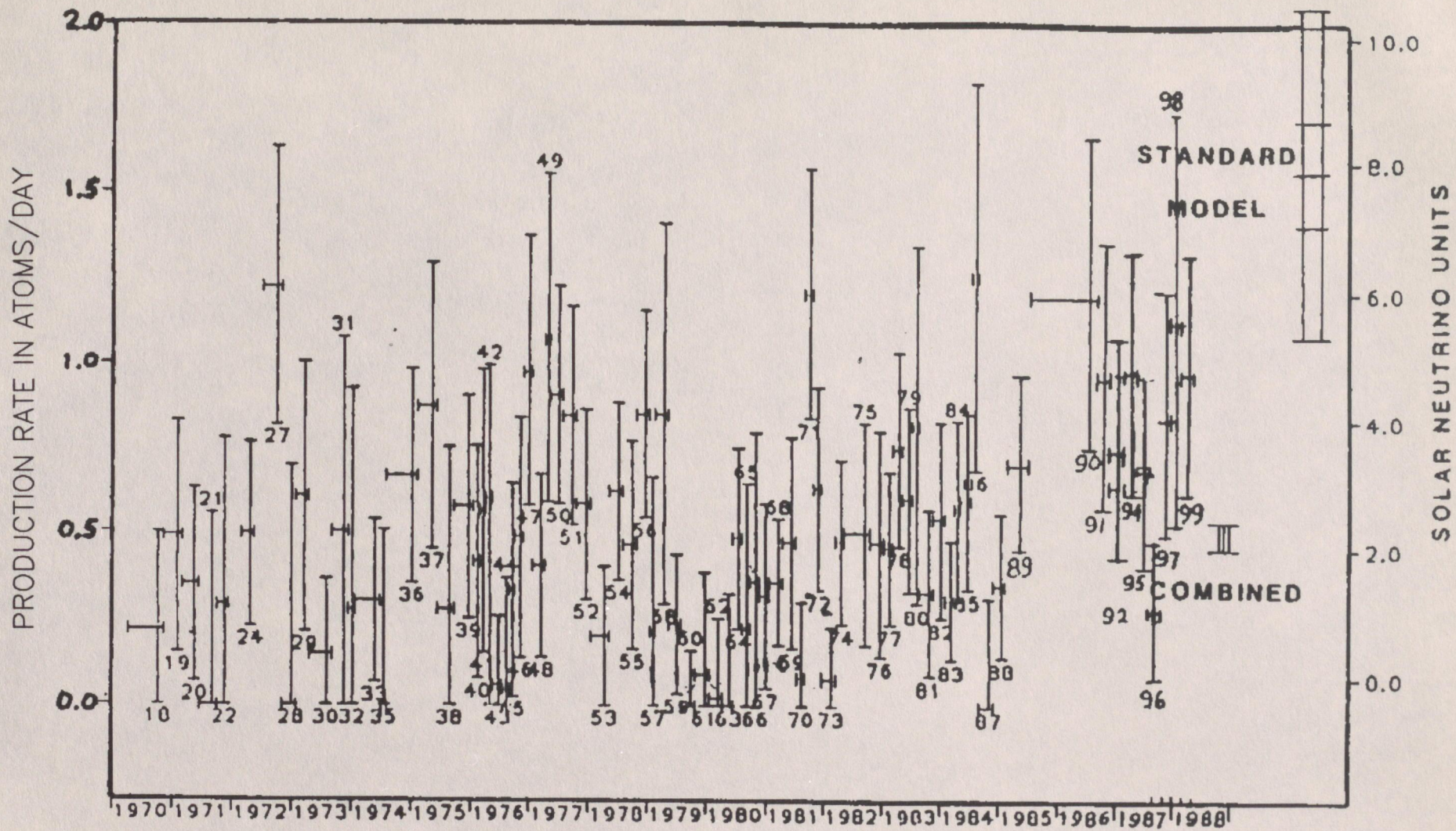
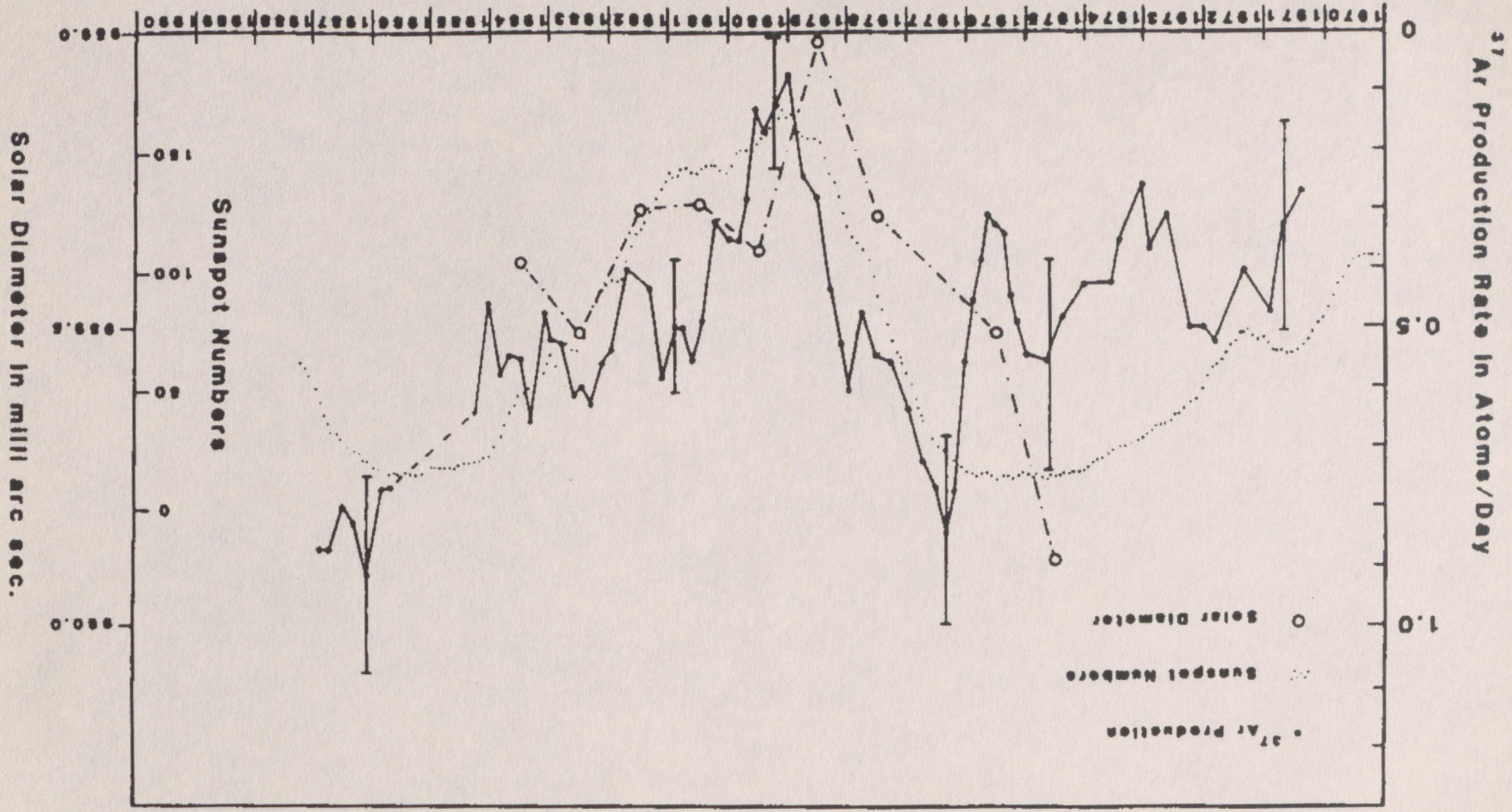
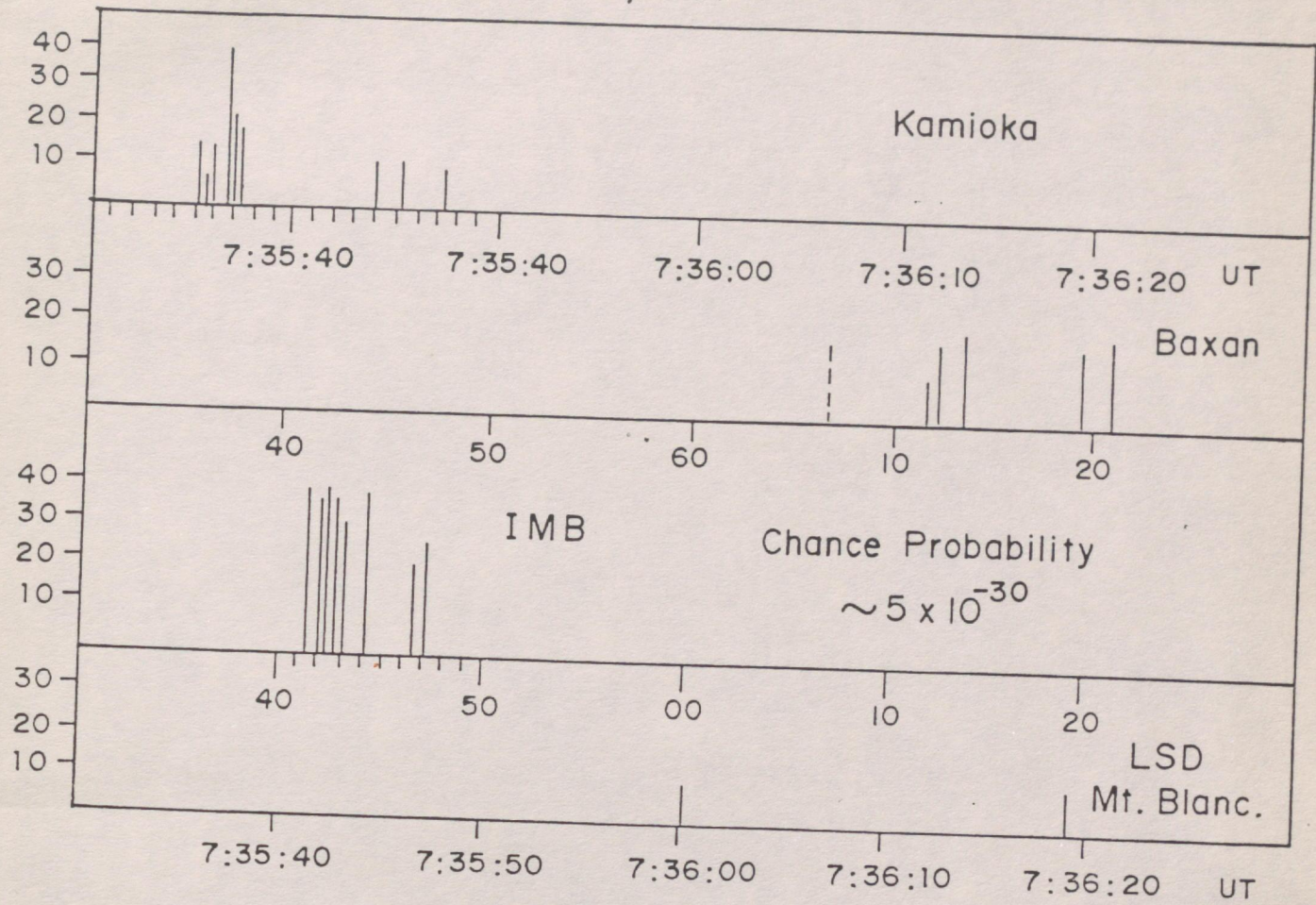


Fig. 1

Fig. 2



Feb 23, 1987



Feb 23, 1987

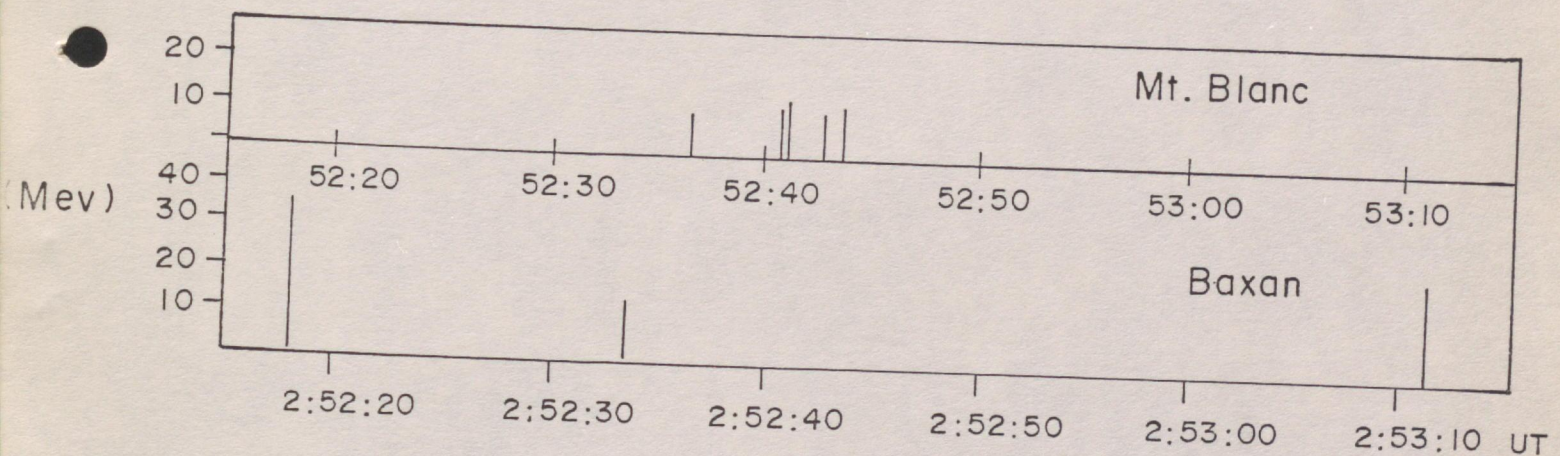


Fig. 3

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Shyamadas Chatterjee Endowment Lecture (1989)

89

(Indian Physical Society)

Challenges in the Frontiers of Physics and Astrophysics

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1. Introduction

First of all I would like to thank the Indian Physical Society for inviting me to give this prestigious endowment lecture. In my talk today, I will try to highlight the interconnection between Physics and Astronomy which in a sense have moved in opposite directions, Physics in the direction of the microcosmos and Astronomy in the direction of the macrocosmos; yet of late, particularly in the last few decades have come so much together that at the accelerator laboratories, you find astronomers and astrophysicists discussing the implications of the findings in elementary particle physics to the first moments of creation of the universe, and particle physicists realising that the highest energy accelerator—that could never be built by man, was in existence in these first moments and may be there are remnants of exotic particles and radiations present in the universe even now.

Physics started off as a branch of science dealing essentially with the properties of various states of matter and radiation. Mechanics, Heat and Thermodynamics, Electricity and Magnetism, Acoustics, Kinetic Theory and Optics were the sub-disciplines of physics that developed through the 17th, 18th and 19th centuries. A characteristic feature of physics distinctly different from other disciplines of science that were also developing, was the great emphasis on precision in measurement that led to the recognition and formulation in terms of mathematical equations, laws of physics that seemed to be part of nature. Because of these approaches namely precise observations and exact

theoretical formulations the success in physics was so remarkable that towards the end of the 19th century the feeling had developed among some of the leading physicists of the day that science would reach a stage of explaining everything around us in a matter of decades. However, this was not to be. On the contrary, the discoveries made in the last decade of the 19th and the early part of this century brought about a complete change of the complexion of physics that had profound influence not only on the next phase and direction of its own development, but also on the developments in many other fields, especially of technology—which in turn influenced the developments of all sciences. The philosophy of science also underwent a remarkable transformation.

This revolution which is identified with the down fall of classical physics began with the production of radio waves by Hertz, the discovery of X-rays by Rontgen, of radio activity by Becquerel, the electron by Thomson, relativity by Einstein, quantum theory by Max Planck, the nucleus by Rutherford and Cosmic Rays by Hess. These discoveries moved physics research more and more in the direction of the ultra-small, into the realm of the microcosmos of elementary particles.

Astronomy on the other hand started off with naked eye observations of the happenings in the sky especially in the nights when the dominating influence of the Sun was not there. Naturally the first things that attracted attention of man were the day and night phenomenon, the regularity of the motion of the planets, the phases of the moon, the eclipses, the meteors, the occasional visits of the comets,

* Delivered on 13th September 1989, at Saha Institute, Calcutta.

the constancy of the Stellar Constellations which served as the background reference for all other motions. The introduction of the telescope by Galileo brought new dimensions to the sky making one realise the unbelievably large numbers of stars and the vastness of space that encompassed these celestial objects. With larger and larger telescopes many of the subtle features of the universe became apparent.

It was none other than Isaac Newton who brought about the close connection between Physics and Astronomy. He recognised in one giant leap of scientific thought that it was the same gravitational force that makes an apple fall from a tree as also the one that holds the moon in orbit around the earth and the planets around the Sun. In another equally major breakthrough by analysing the Sun light, with a simple prism, Newton laid the foundation for the field of spectroscopy which played extremely important role not only in the development of physics, but also in the field of astronomy. Spectroscopy pursued vigorously in the physics laboratories in the 19th and early part of 20th century, led to the recognition of the discrete energy states of atoms and molecules, to the Bohr's theory of the atomic nucleus, to the applications of quantum mechanics. When I speak in this lecture hall, with the photograph of Prof. Meghnad Saha in front of us, I do not have to stress the importance of spectroscopy to astronomy. Meghnad Saha's theory of ionisation literally brought the stars down to the laboratory to tell us all about their temperatures, pressures and chemical constitution. In the June issue of *The Scientific American*, there is a very enlightening article on the famous astronomer Russel of the Russel-Hertzsprung diagram fame and also of Russel-Saunders coupling—one in the area of astronomy and the other in Atomic Physics. I would like you to read this article to see what glowing compliments are paid to Meghnad Saha by astronomers of the time. Incidentally there is also a nice photograph of Saha when he was young.

2. (i) The Neutrino

As one gained better and better understanding of the nuclear structure and the nuclear Forces, through scattering of alpha—particles and later through

the study of interactions of particles accelerated to higher and higher energy, the possibility of nuclear energy through fusion and fission processes became apparent. What is most interesting is that even before nuclear energy became a reality in the laboratories of the earth, the possibilities of nuclear conversion of hydrogen to helium as source of Solar Energy was envisaged by Perrin and Eddington, as early as 1920. Bethe proposed the CNO cycle in 1939. The experimental verification of these rather exotic ideas on the source of energy in the Sun had to await further developments in the field of physics. These developments began with discovery of a large number of elementary particles in addition to the proton and the electron that had been recognised in the beginning of this century through the study of the discharge of electricity in gases. Many of the puzzling features of the nuclear phenomena got resolved with the discovery of the neutron in 1932 by Chadwick. It became clear that the nucleus comprised of protons and neutrons. An important difference between the proton, the electron, the particles that were discovered first, and the neutron was that apart from being electrically neutral, the free neutron decayed spontaneously into a proton and an electron with a life time of $\sim 10^8$ seconds. However the decay products did not have a unique energy as would be the case if the neutron decayed into just two particles. As is well known Pauli introduced a hypothetical particle, the neutrino, to save the principle of conservation of energy and momentum in neutron decay as well as in radio active decay in general.

This hypothetical particle neutrino was later detected experimentally inspite of its extremely weak interaction properties. The experimental discovery of the neutrino itself was a big challenge. However this elusive particle has posed bigger challenges both in the field of physics and astronomy. The challenges relate to the unravelling of some of the very fundamental properties of this particle—the neutrino mass, the neutrino oscillations, the neutrino magnetic moment, the number of flavours of the neutrino and the neutrino life-time. Pauli introduced the neutrino as a particle with zero electric charge, zero or very near zero mass and spin $\frac{1}{2}$. However over a period of time, as more and more short lived particles were discovered, it was found necessary to introduce in many cases the neutrino as one of the decay products,

and in this process additional properties of the neutrino came to light.

Between 1930 and 1950, a spate of particles were discovered in the analysis of the cosmic ray beam through the atmosphere. The first particle to be discovered was the positron—in fact the first anti-particle which not only satisfied the predictions of the Dirac theory of the electron, but also opened the question of anti-particles of every kind—anti protons, anti neutrons, and anti matter—which have all been subsequently discovered in the high energy accelerator laboratories. It has also raised the question of anti matter in the universe which we shall discuss later on.

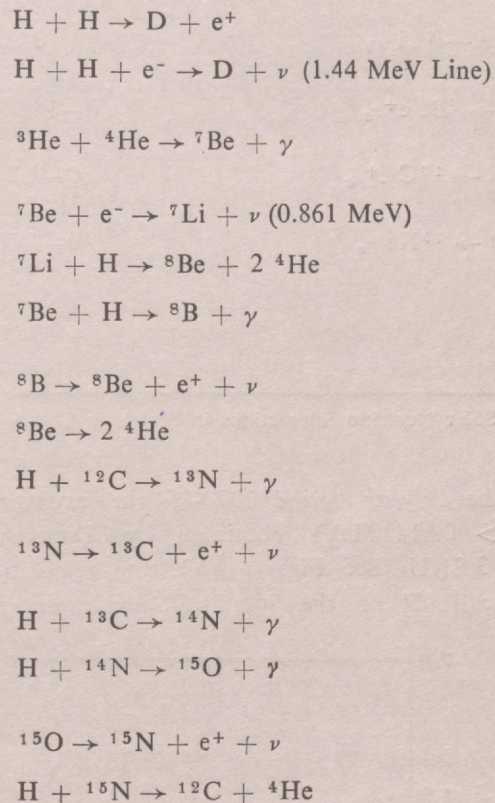
The discovery of the positron was followed by the discovery of the muon which had properties very different from any of the previously known particles ; it turned out to be the penetrating component of cosmic radiation. However the muon is unstable and decays into an electron in a matter of 2 micro seconds in its rest frame. It became necessary to associate 2 neutrinos with the decay of each muon in addition to the electron. The muon itself was later discovered to be the decay product of the pion ; in the pion decay also the companion was again another neutrino. In the early 60's experiments at the CERN accelerator in Geneva revealed that the neutrino associated with the decay of the pion (ν_μ) is different from that in the muon decay (ν_μ). It also became necessary to distinguish between neutrinos and ant-neutrinos ($\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$). In the 70's with the discovery of the τ meson, it became necessary to associate with the decay of the τ yet another type of neutrino ν_τ . The ν_τ has not been experimentally discovered yet. It is yet another challenge connected with neutrino physics. It has become extremely important to establish how many flavours (ν_e, ν_μ, ν_τ ?) are there from the point of view of the Standard Model of elementary particle physics.

2. (ii) Neutrinos from the Sun

Astronomically too, the neutrino has become an important entity in a variety of contexts. Let me illustrate this by discussing the Solar Neutrino

Puzzle. According to the Standard Solar Model, the various reactions that give rise to neutrinos ($\nu_e, \bar{\nu}_e$) are given in the Table I and the contributions of different reactions to the Solar Neutrino Flux in Table II in units of SNU. The Solar ν_e flux at the earth $\sim 10^{11}/\text{cm}^2\text{sc}$.

Table I



In Table II the Solar ν_e flux for two different threshold energies, one corresponding to 0.81 MeV which is the threshold energy for the chlorine reaction and the other corresponding to 0.236 MeV for neutrino reaction in Gallium are given. It is seen that there is a gain by a factor of 20 if one is able to use the Gallium reaction. Gallium detectors are under construction in the Soviet Union and in Europe and are expected to go into operation in the near future.

R. Davis [1] set up an experiment to detect the solar neutrinos through the reaction $\nu_e + {}^{37}_{17}\text{Cl} \rightarrow \text{e} + {}^{37}_{18}\text{Ar}$ in a mine in South Dakota in 1968.

Table II

Reaction	Energy of ν_e (MeV)	No. of SNU in Cl (> 0.81 MeV)	No. of SNU in Gallium (> 0.236 MeV)
$PP \rightarrow De^+ \nu_e$	0-0.42	0	70.2
$Ppe \rightarrow D \nu_e$	1.44	0.2	2.5
$e^7Be \rightarrow ^7Li \nu_e$	0.862	1.0	27.0
$^8B \rightarrow ^8Be e^+ \nu_e$	0-14.06	4.3	16.0
$^{13}N \rightarrow ^{13}C e^+ \nu_e$	0-1.2	0.1	2.6
$^{16}O \rightarrow ^{16}Ne \nu_e$	0-1.73	0.3	3.5
		5.9 SNU	121.8 SNU

Solar Neutrino Interactions in SNU's in Chlorine and Gallium Detectors which have different energy thresholds.

Over the 15 year period 1970-85 the average ν_e flux (> 0.814 MeV) obtained by Davis was 2.1 ± 3 SNU (See Fig. 1) while the calculations of Bahcall [2] on the Standard Solar Model gave

a value of 6-8 SNU. ($ISNU = 10^{-36}$ Captures/atom/sc.) This discrepancy has come to be known as the Solar Neutrino Puzzle. In order to explain this discrepancy either one has to find something

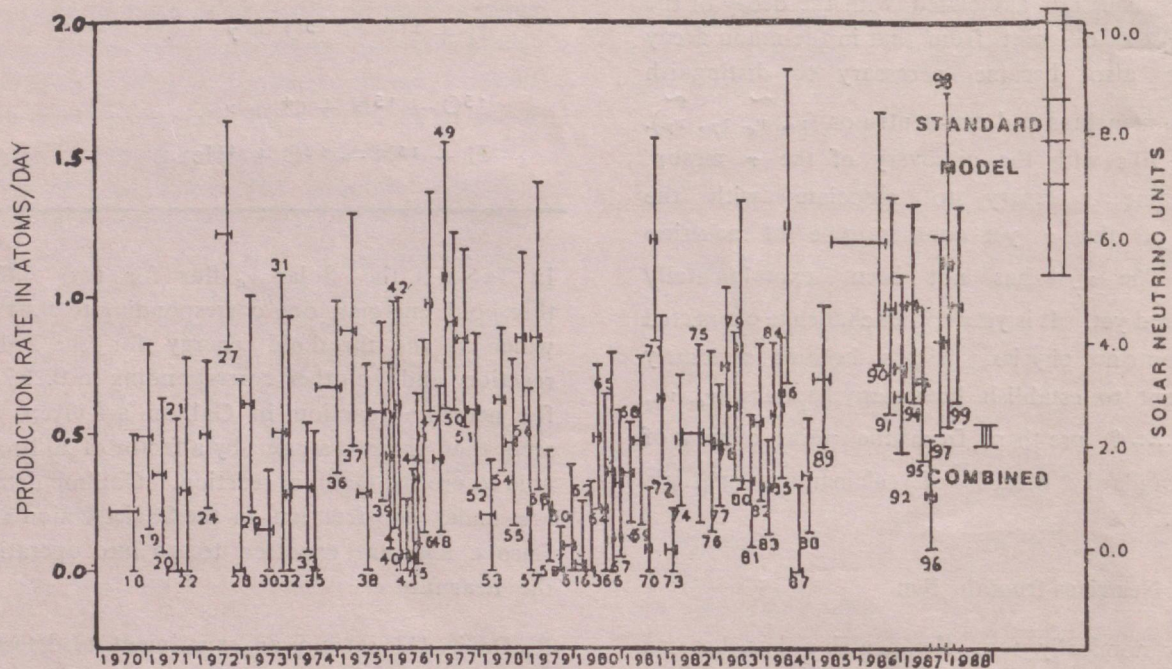


Fig. 1. The Solar Neutrino Flux recorded in Davis's experiment over the period 1970-1988.

wrong with the standard solar model—the (the core temperature) or with the properties of the neutrinos. The possibility has been suggested that the ν_e may oscillate into ν_μ , ν_τ either during its passage from the Sun to the earth or in passage through the dense medium of the earth. Since the Davis experiment can detect only ν_e , there could be a reduction of the flux by a factor of 2 if it oscillates into ν_μ or ν_τ . Recently a new dimension has been added to the solar neutrino puzzle. Davis has found that his data for the period 86-88 gives a value of 4.2 ± 0.8 SNU for the Solar ν_e flux rather close to the expected value, This has brought up the question whether the Solar ν_e flux changes with time. Some have suspected for a long time a close correlation of ν_e emission with solar activity. The Argon production rate observed by Davis is compared with solar activity parameters Sun spot number and variation of solar diameter in Fig. 2. This seems to indicate an anti correlation between production rate and Sun spot number and a positive correlation with solar diameter. What is difficult to understand if these trends are correct is the reason for correlation between a phenomenon like neutrino production that takes place in the central regions of the Sun where the temperatures are sufficiently high for the reactions of Table I to take place and the 11 year

solar activity which is believed to be purely a surface phenomenon. It is known that the energy transport from inside of the Sun to the surface through the normal channels of photon propagation takes millions of years. It has become therefore extremely important to follow up these trends with more efficient detectors. Several new generation detectors involving liquid scintillators, Cerenkov counters, etc. are coming up to explore this problem further, in addition to the Gallium Detector. If the oscillations theory $\nu_e(\text{Sun}) \rightarrow \nu_\mu$ or ν_τ is correct, there should also be a day and night effect in the flux detected in the underground detectors. In the night time the neutrinos have to pass through almost the entire diameter of the earth before they are detected.

The correlation with Solar activity, if genuine, may be correlated with the neutrino having a high magnetic moment according to the suggestions of Voloshin, Vysotskii and Okun [3]. This would mean a magnetic moment as large as $\mu(\nu_e) \approx (\frac{1}{3} \sim 1) \times 10^{-10} \mu_{Bohr}$. The idea is that during solar activity when the magnetic field is large, 10^3 - 10^4 gauss, the spin of the neutrino may flip with the result.

ν left handed $\rightarrow \nu$ right handed

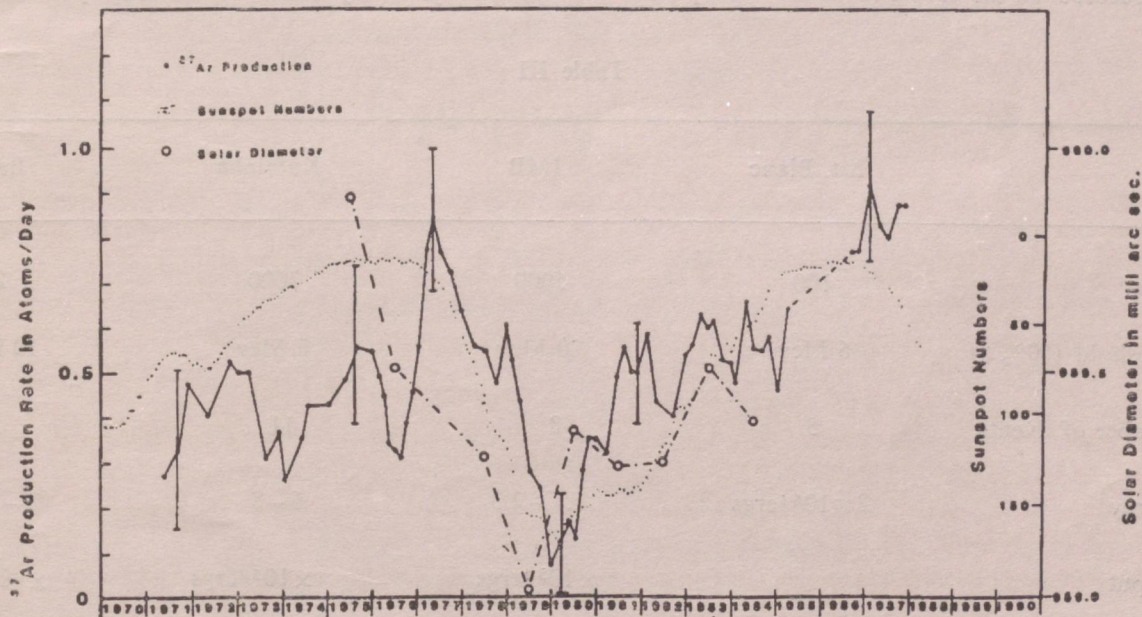


Fig. 2. Comparison of Argon production rate due to Solar neutrinos in the experiment of Davis with Solar activity over the period 1970-1988,

Right handed neutrino is sterile in the Chlorine-Argon reaction required in the experiment of Davis, and will result in an anti-correlation in the recorded flux with sun spot number which is a measure of the magnetic field increase. The experimental limit at accelerators for the magnetic moment of the neutrino is

$$\mu(\nu_e) \leq 1.5 \times 10^{-10} \mu_{Bohr}$$

$$\mu(\nu_\mu) \leq 9.5 \times 10^{-10} \mu_{Bohr}$$

These limits cannot rule out the possibility suggested above. However the Electro-Weak Unification theory (Glashow, Weinberg, Salam) gives a value of $\mu(\nu_e) = 3.2 \times 10^{-19} \mu_B$. m(e) according to Fujikawa (Nine orders of magnitude smaller). Here again is another major experimental challenge—to determine the magnetic moment of the neutrino.

2. (iii) Neutrinos from Supernovae

Supernova theorists have been predicting for a long time that the explosion of a star into a Supernova would result in the production of a large burst of neutrinos and these would precede the optical flash by several hours. This remarkable prediction has been verified for the first time with the detection of a neutrino burst from the SN1987a which occurred on the 23rd Feb. 1987. The proton

decay detectors in the U.S. [4] and in Japan [5] recorded neutrino bursts about 3 hours before the first optical record. Two other stations, one in Mont Blanc (Italy) [6] and the other in Baksan USSR [7] have also reported recording of neutrino signals. The details are given in Table III. While IMB, the Kamioka and the Baksan agree reasonably well with each other in the actual time of recording of the burst, (~ 3 hrs. earlier than the optical flash) the Mont Blanc burst is 4.72 hrs. earlier than the optical flash. As can be seen from the table the energy output in neutrinos is greater than 10^{52} ergs/second. The neutrinos recorded in the Kamioka detectors are essentially ν_e through the reaction $\nu_e p \rightarrow e^+n$. The absolute time sequence of the burst events recorded in the different arrays is shown in Fig. 3. From the widths, time structures and the energies of the neutrino events, attempts have been made by several authors to deduce the mass of the neutrinos. This is in the range of about 20 MeV/C² somewhat lower than what has been claimed by Lubimov et al [8] in the laboratory experiments. It has to be pointed out however that because of lack of accuracy in the recording of time and the discrepancies of a few seconds between Kamioka and IMB in the absolute time, the results on the neutrino mass deduced from the time structure observations are not taken seriously. They clearly show the potentiality of

Table III

	Mt. Blanc	IMB	Kamioka	Baxan
Tons	100	5000	2000	200
Threshold (50% η)	6 Mev	20 Mev	8 Mev	10 Mev
Number of Events	5	8	11	5
Energy	2×10^{54} ergs	1.8–2.3	6–8	2–2.5
Output		$\times 10^{52}$ ergs	$\times 10^{52}$ ergs	$\times 10^{53}$ ergs

Neutrinos From SN 1987a

the method for mass deduction if the requisite timing accuracies and calibrations are maintained. A lesson for the future !

3. Missing Mass and the Neutrino

Astronomically, the mass of the neutrino has become an extremely important parameter in connection with what has come to be known as the missing mass paradox. It is known that some of the large clusters like the Coma cluster of galaxies do not have enough mass (as revealed through the visible and radio astronomies) to be bound gravitationally. They have only 1% of the mass required. The nature of this dark matter has become one of the challenging problems for the astronomers to unravel. The rotation curves of some of the galaxies also show that there must be a large amount of invisible matter extending far beyond the visible range of these objects. One of the strong candidates for this dark matter is the neutrino provided it does have some mass, even of the order of few eV. The neutrinos also play an extremely important role in the evolutionary history of the universe itself, as we shall presently see.

4. The Evolution of the Universe—The Big Bang Creation.

A remarkable result that came out of the spectroscopic observations of the light from the distant galaxies was the realisation by Hubble of the expanding nature of the universe leading to the Big Bang theory of creation of the universe. This theory has become much more quantitative with the discovery of the universal microwave radiation by Penzias and Wilson in 1965 and the applications of our knowledge of particle physics from accelerator experiments. The milestones in the history of the universe deduced from a lot of physics and astronomy are summarised in the Table IV. A key result of the expanding universe of Hubble was that the galaxies which are further away from each other are moving away with higher speeds with respect to each other. This means that to learn more and more about the earlier times of the universe, the observations have to be made on the most distant objects corresponding to the highest red shift values. While technologically this will pose the problem of sensitivity of observation, which perhaps can be met, there is a limit that is set by the fact that the universe was not transparent to radiation before the lapse a certain time after

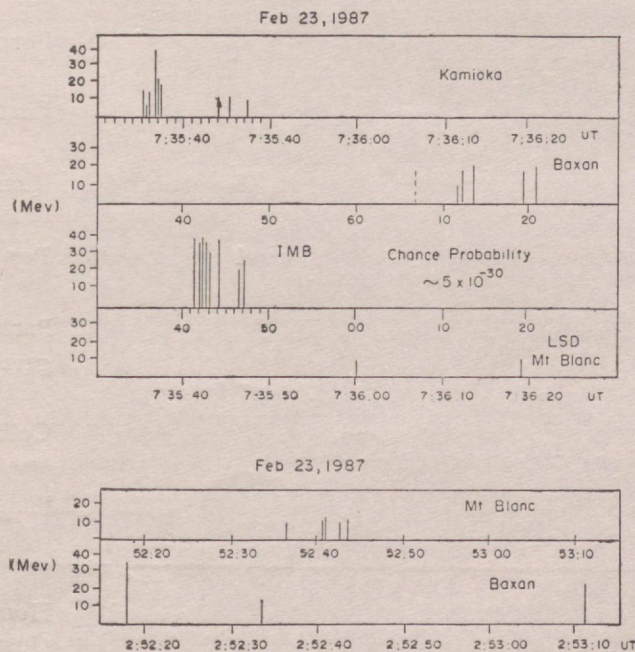


Fig. 3. Time Sequence of Neutrino bursts recorded in the different experiments on Feb. 23, 1987 preceding the optical burst of SN1987a.

Table IV
Important Milestones in the History of the Universe

Cosmic Time	Epoch notation	Red Shift	Nature of the Phenomenon
0	Singularity	Infinity	Infinite density ; Zero of time
10^{-43} Sc	Planck Time	10^{32}	Particle creation begins
10^{-6} Sc	Hadron Era	10^{13}	$P \bar{P}$ annihilation
10 Sc	Lepton Era	10^{10}	$e^+ e^-$ annihilation
2 mins.	Radiation Era	10^9	Nucleosynthesis of Helium, Deuterium
70,000 yrs	Matter Era	10^4	Matter dominates the universe
300,000 yrs	Decoupling	10^3	Universe becomes transparent to radiation
1.2×10^9 yrs		10–30	Galaxies form
3×10^9 yrs		5	Clustering of galaxies begins
4×10^9 yrs			Formation of Milkyway Galaxy
4.1×10^9 yrs			First Stars form
5×10^9 yrs		3	Quasars born—Pop II Stars
10×10^9 yrs		1	Pop I Stars form
15.2×10^9 yrs.			Parent Interstellar Clouds that gave rise to Solar System form
15.3×10^9			Collapsed Proto-Solar Nebula
15.4×10^9			Planets form
20×10^9			Homo Sapiens appear (Just 10^5 years ago)

Table V
Happenings in the Universe in the first Microsecond

Time From Big Bang	Temperature	Features of the Universe
10^{-6} Sc.	$> 10^{13}$ °K ($> 10^9$ ev)	Non-gravitational properties change. Weak and Electromagnetic Interactions have the same strength.
10^{-13} Sc.	$> 10^{16}$ °K ($> 10^{12}$ ev)	Spontaneous Symmetry breaking Higgs Mechanism operates to generate masses of $W \pm Z^0$
10^{-36} Sc.	$> 10^{28}$ °K ($> 10^{24}$ ev)	Unification of strong and Electro-Weak forces. Production of massive leptons, quarks X, \bar{X} , massive magnetic monopoles, exotics.
10^{-43} Sc.	$> 10^{32}$ °K ($> 10^{28}$ ev)	Quantum gravity becomes important. No good theories yet to make predictions.

creation. What is most remarkable however is, using the results of nuclear and elementary particle physics it has been possible to go back to very early times—even to a few minutes, few seconds, few fractions of a second of creation of the universe. In fact as you can see from Table V we can go back to 10^{-43} s of the Big Bang !

Based on the quark theory of elementary particles, the well established Electro-Weak unification of the electromagnetic and the weak forces and the envisaged unification of the strong and electro-weak forces the scenario of the early universe in terms of its constituents has been worked out at various epochs the first microsecond after the Big Bang. This is summarised in Table V. The size of the universe at this point of time was less than nuclear dimensions of 10^{-13} cms, the temperature higher than 10^{13} °K. The present day elementary particle physics has made it possible to envisage the happenings even earlier from 10^{-36} sc when the temperature rose from 10^{13} °K to 10^{28} °K. This very early universe seems to have controlled many major features of the

universe we are familiar with to-day after 20×10^9 yrs—the dominance of radiation over matter, the dominance of matter over anti-matter. To explain some of the other features of the universe like its extreme homogeneity when considered in scales of megaparsecs, and the high degree of isotropy of the microwave radiation, the euclidean flat space that we are familiar with in our normal life, it has become necessary to invoke the idea of an inflationary expansion before the presently known Hubble expansion started. The inflation involving an exponential expansion would have lasted only for 10^{-32} seconds or so. I have given some more details on these aspects in my article 'The first moments of the universe' published in the transactions of the Bose Research Institute [9].

In this brief span of just an hour or so, I have tried to give you a flavour of the type of inter-connections that have developed between physics and astronomy over the last several hundred years. This symbiosis is growing stronger with time. The particle physics aspects of the early universe have

opened up many new challenges to both physicists and astronomers. The environments associated with accreting binary systems, with one of the companion being a black hole or a neutron star are proving to be yet other regions of exotic high energy phenomena. Advances in technology are bringing within the realm of feasibility detection of gravitational waves, neutrinos from galactic and extragalactic sources perhaps even the cold neutrino sea that is another relic of Big Bang Creation.

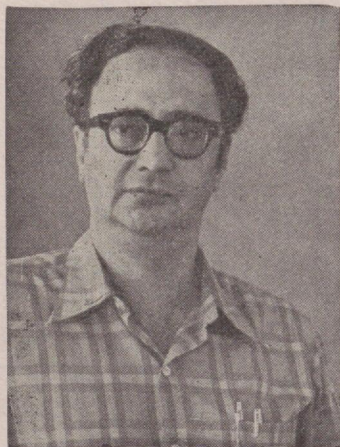
I must end with the note that all this is the result of lot of experimentation, observation, theory and most importantly extrapolation over enormous range of distance scales, time scales, densities, temperatures, magnetic, electric fields, etc. To what extent these bold extrapolations are valid only further experiments and observations alone can tell.

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The *Shyamadas Chatterjee Endowment Lecture* (formerly the IPS Endowment Lecture) is an important annual event in the activities of the Indian Physical Society. This event has been made possible due to the generosity of *Prof. Shyamadas Chatterjee*, one of the earliest members of the Society and one of its past Presidents.

Prof. B. V. Sreekantan, a distinguished high energy physicist, was born on June 30, 1925 at Nanjangurd in Mysore. He took his B.Sc. (Hons) in Physics from the University of Mysore in 1946 and his M.Sc. in 1947. He obtained his Ph.D. from Bombay University in 1954.



He joined the Tata Institute of Fundamental Research as a research student in 1948 and has been associated with that Institute ever since. He was the Director of that Institute from 1975 to 1987. He was also a Visiting

Scientist at the Laboratory of Nuclear Science at M. I. T., U. S. A. in 1954 and again a Visiting Scientist at the Centre for Space Research of the same institute from 1965 to 1967. He was a UGC National Lecturer in 1981-82. He was the Indian National Science Academy Srinivasa Ramanujan Professor in 1987.

Prof. Sreekantan is a Fellow of both the Indian Academy of Sciences and the Indian National Science Academy. He was the President of the Indian Physics Association from 1976 to 1978 and the President of the Physics Section of the Indian Science Congress in 1981. He was a member of the Cosmic Ray Commission of IUPAP in 1982 and its Vice Chairman in 1987. He was also a member of the Atomic Energy Commission in 1986-87. He was awarded the C. V. Raman Award for Physical Sciences, 1977 by the UGC and the Homi Bhabha Medal for Physical Sciences, 1978 by the Indian National Science Academy. He also received the R. D. Birla Memorial Award, 1982 of the Indian Physics Association. He became a Padma Bhushan in 1988.

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- Date and time : January 21, 1990 (Sunday) 10.00 a.m. to 12.30 a.m.
Eligibility : Students of XII or PUC or equivalent or lower classes
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Contact : Prof V Srinivasan, Head, Physics Deptt (PG), American College, Madurai 625002.

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Question Paper: *Part A*, 60% weightage of 90 minutes, multiple choice questions.
Part B, 40% weightage of 60 minutes with short description/explanation, problem, etc
Question papers to be taken home by the candidates.
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*Top 1% at national level get certificates of merit plus book prizes.
*Top 1% from each State get certificates of merit.
*Top 10% at each Centre get a certificate (for Part A only)
Centres : Any institution offering 20 (for NSEP)/ 10 (for MGPE) or more candidates is made a centre on applying to the contact person.
Deadlines : Last date for enrolment of candidates is *November 23, 1989* without late fee, and *December 7, 1989* with late fee of Rs. 5 per candidate.

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