certainly shown us a path to overcome the limitations of the present accelerator technology and move towards multi-TeV energies. This should serve as an encouragement to dream of higher goals.

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High Energy Physics in the 21st century – A summary

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NOT too long ago there was a startling suggestion by Stéphen Hawking asking whether the end of Theoretical Physics was in sight. This was soon after the euphoria that accompanied the emergence of the string theory as a possible Theory of Everything and a feeling that there was now a satisfactory explanation for at least all of basic issues. After about ten years, we now perceive that unless new ideas for particle acceleration emerge, experimental high energy physics may be at an end. And that indeed can have a deleterious effect on theoretical High Energy Physics as well.

Particle Physics is, indeed, on important cross-roads at the moment. As described by D. P. Roy, we now have a standard model, with almost all experimental data in the energy range up to about TeV (10^{12} eV) accounted for, by means of about 20 parameters in a quantum field theory with adequate local symmetry. There are many hints as to what lies beyond the standard model and it is only to be expected that the situation will become clear once the experiments, currently being pursued, provide the necessary data.

As a check list, it is worth drawing up a collection of an immediate set of problems for the early 21st century as was done by Gross, Witten and Kane as a part of their assessment of outstanding questions.

(i) What determines the gauge symmetry at ordinary (?) energies (1 TeV) to be $SU(3)_c \otimes SU(2) \otimes U(1)$; $SU(3)$ signifying quantum chromodynamics and $SU(2) \times U(1)$, the unified electroweak theory of Salam and Weinberg?

(ii) How will gravity enter this picture? Through superstrings?

(iii) What is the nature of unification of the familiar forces? Is there a grand unified gauge symmetry group relevant at higher energies? Is such a unification a forerunner to incorporating gravity?

(iv) What constrains the quantum numbers of quarks and leptons? Why are the left-handed and right-handed fermions different? Is there a fundamental reason for us to have 'chiral' fermions?

(v) Why do we have different families or generations of fermions? How many? (The old version of the same question was asked by Rabi: Who ordered muon?)

(vi) What is the physics of Yukawa coupling? (What determines the masses and mixing angles of the quarks and leptons?)

(vii) Most abundant constituents of all matter are (u, d) quarks and electrons. Why are they so light in comparison with $W^{\pm}$, Z, top quark, Higgs (?) which appear to be in the 100 GeV range, presumably the natural scale of the theory.

(viii) Why is the vacuum energy (cosmological constant Λ) vanishing? How can we ensure this when the supersymmetry (boson $\leftrightarrow$ fermion symmetry) is broken, as it indeed must.

We can be sure that as we provide answers to these issues, new queries will arise.

We observe that the main theoretical tools, that we now use, to answer the many puzzles, appear to be taking a somewhat universal shape; seem to be endowed with abilities to answer many varieties of phenomena in diverse fields. And this is a welcome trend. There has been considerable sharpening of the ideas in relativistic quantum field theory and symmetry principles. Kaul has described how supersymmetry is helpful in explaining certain notions of 'naturalness' and how different energy scales coexist in our theoretical framework. Supersymmetry, appears to have special virtues. It helps tame infinities in theories with scalar fields, which in turn are necessary for spontaneous symmetry breaking by Higgs phenomenon since fermion and boson loop divergences are negative of each other and protect the hierarchy of energy scales. Further, it provides a natural explanation for the vanishing of the cosmological constant (since there is a neat cancellation of all zero point energy in a supersymmetric quantum world). Perhaps direct evidence for supersymmetry is just around the corner.

One of the exciting developments in the closing stages of the twentieth century is the emergence of the string theory. This has turned out to be an incredibly rich framework and the string experts feel that it will have applications not only in understanding basic aspects of High Energy Physics, but will be of value in many other disciplines as well. Among its properties are many new hidden symmetries. It comes endowed with many kinds of dualities – for instance, indicating a relationship between one string theory with a coupling parameter g with another with a coupling parameter $1/g$. This opens up a possibility of understanding the strong coupling regime of one theory by looking at the weak coupling (and hence well understood) aspects of another related string theory. What is more, string theories have greater control over singularities by virtue of the presence of a natural length scale in it. Further, superstring theory, which incorporates supersymmetry as well, has ingredients of a renormalizable field theory of all interactions that encompasses all known forces of interaction and species of matter. The versatility of the theory is such that it has resulted in hitherto unknown proofs in the geometry of manifolds and this has made an impressive impact in some areas of pure mathematics.

On the experimental side, Particle Physics has always depended on large projects involving many institutions and a very large number of physicists. We seem to need gigantic accelerators (and hope to reach 200 GeV in e^+e^- collisions by the turn of the century and make a jump from 2 TeV for $\bar{p}p$ at Fermilab tevatron to 14 TeV at the CERN Large Hadron Collider in the first decade of the next century) and complex detector systems that go with them. The accelerator-based HEP is supplemented by the 'underground' labs to do precision measurements making use of solar and atmospheric neutrinos and other exotics and further look for signals from astroparticle physics-related observations. In the 21st century, the need will be to push to higher energies as well as to higher precision. Both require innovative efforts as pointed out by Cowsik and Sen.

There is much concern that the projects in High Energy Physics are getting bigger and more expensive. SSC (Superconducting Super Collider) at Texas had to be abandoned as unaffordable. There is a perception of growing fatigue in the support of science for science-sake. It is suggested that there are more deserving claimants for the public support and there is a perennial debate between 'big' science and other sciences. It is unfortunately forgotten that the quest for new acceleration techniques and new principles of particle detection, identification and computing, etc, will have a direct impact not only in High Energy Physics, but in a whole variety of disciplines. It is inescapable that there will be direct consequences for: Condensed Matter Physics, basic as well as applied areas; advances in informations technologies / computing / data handling (WWW – the world wide web of distributed information network had originated from CERN); and many aspects of Material Science. Indeed, Experimental Particle Physics may be the most efficient way to develop high-tech applied sciences.

It is with this background that we should review the programme of Experimental High Energy Physics in India. In the past, our efforts had banked on (i) cosmic ray experiments (ii) analysis of emulsion stacks and bubble chamber data from High Energy Physics experiments elsewhere (iii) KGF underground laboratory for proton decay and ν interactions and (iv) experiments at CERN and Fermilab. At present, we play important roles in both CERN LEP experiments (L3 collaboration) and Fermilab efforts (D ∅ collaboration). In the future there are plans for active participation in the Large Hadron Collider project at CERN ($p\bar{p}$ collider at centre of mass energy of about 14 TeV in the LEP tunnel) both at the stage of construction of the accelerator and later on in doing physics experiments with it.

We should, I believe, think in terms of supplementing these efforts by activities based in India. It will be useful to initiate thinking about various options we may pursue. For instance, let me start with a short list for active consideration:

(i) A new innovative 'underground' laboratory, with international funding and participation.

(ii) A new task force (think tank?) as suggested by Rajasekaran for new principles of particle acceleration (Planckian?).

(iii) A time-bound programme for building a high energy accelerator in India, say in the range 10 GeV–20 GeV, targeting a specific niche. The aim should be for a unique device, say, for example, to study high precision polarization (beam/target) phenomena. We may thus look forward to having a component of High Energy Physics activity based in India in the not-toodistant future, so that our national efforts complement our commitment to the collaborations elsewhere.

To conclude, what, may we expect, the shape of 21st century High Energy Physics to be? It is worth recalling that in the early sixties, particle physicists *expected* (i) to reach the region of asymptotic flat cross-sections, signifying the diffraction scattering of strongly interacting particles as being due to dominant Pomeron exchange at 60 GeV (at that time, next high energy (ISR: intersecting storage ring) machine), and the culmination of Regge Theory; and (ii) made bold predictions that the intermediate vector bosons that mediate weak interaction could be as heavy as 2 GeV! However we now find that (i) $W^{\pm}$, Z have masses 40 to 46 times heavier! and (ii) there is no hint of asymptopia, but we have something much better. A gauge theory of strong interaction described by QCD!! Regarding the future, therefore, it would be hazardous to make any guess; maybe the space–time will be granular. and new paradigms will begin to take shape. Perhaps any guess that we now make may not be wild enough.

I would like to, nevertheless, believe that 'particle physicists are grappling with wonderful questions and marvelous and mysterious ideas'. No marks for guessing who said this.