# REVIEW OF THE DEPARTMENT OF THEORETICAL PHYSICS OF THE TATA INSTITUTE OF FUNDAMENTAL RESEARCH

Mumbai, September 11-13 2006

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**The Review Committee of the Department of Theoretical Physics (DTP) of the TIFR**, consisting of Profs:

– E. Brézin, ENS Paris (chair),
– M. Peskin, SLAC,
– J. Polchinski, KITP, UCSB,
– T.V. Ramakrishnan, Banaras Hindu University & IISc,
– A. Ukawa, University of Tsukuba,

convened at TIFR-Mumbai on Sept 11-13, 2006.
02/10/2006 14:50:00

The Committee was provided in advance well-prepared and extensive documents describing the activity of the Department, as well as a description of the Institute as a whole, a copy of the 1997 report of the Institute and of the 2005 report of the Review Committee of the School of Mathematics. A draft document of a new proposal by the DTP to create a Theoretical Sciences Program at TIFR was also handed to the Committee.

## I PROCEDURE OF THE REVIEW

The Committee first met with Professor S. Bhattacharya, the Director of the Institute who defined the terms of reference of the review. In particular he asked the Committee to answer the following questions :

- How are we doing?
- What are we not doing that we should? What are we doing that we should not?

He also urged the Committee to examine :

- the relationship of DTP with theoretical astrophysics and with experimental areas,
- the questions of future faculty recruitment,
- students and post-doc issues,
- new areas of research, in particular theoretical biology, and the biology/physics interface,
- the new initiative of a theoretical science program and Centre,
- other matters : structure, funding, outside collaborations, outreach ...

Prof. Bhattacharya promised the Committee that its recommendations will either be implemented by bringing them to the Management of the Council, or, if not, the Committee will be kept informed of the reasons for not doing so.

The first day was devoted to :

- a detailed presentation of the DTP by the Department Chairman, Prof. Mustansir Barma,
- a presentation of the research activities of the DTP consisting of an introduction by a group leader followed by a short presentation by every member of the faculty of his research interests :

▶ High energy physics, introduced by Prof. Gavai, plus 5 small talks

▶ Condensed matter and statistical physics, introduced by Prof. Dhar, plus 5 talks

▶ Foundations of quantum theory by Prof. S.M. Roy

▶ String theory, introduced by Prof. Wadia, plus 8 talks.

The second day was devoted to detailed meetings with various bodies. The Committee met successively with

▶ the high energy theorists

▶ the condensed matter and statistical physics theorists

▶ the string theorists

▶ the whole body of Ph.D. students

▶ the visiting fellows

▶ the junior faculty: readers and associate professors

▶ the member(s) of the Department who asked for an appointment

▶ the faculty of other Departments of TIFR

▶ the theorists of the astrophysics Department

▶ the senior Professors of the DTP.

## II. ANALYSIS OF THE DTP

There is no doubt for the Committee that the Theory Department at TIFR is the leading group in India, and in several areas, in particular in string theory, it has reached the level of one of the best groups worldwide.

We would like to make recommendations for using this strong international image even further and build up one of the top Institutes in the world of physics.

We address below a number of topics leading to some specific recommendations.

### II-1 Quality of the research groups

*A) High energy physics*

The group activity is focused around several themes.

- Lattice QCD and Quark Gluon Plasma

  Lattice QCD has been pursued worldwide both for its impact on flavour physics and for understanding hadronic matter at high temperatures and density. Technically, quenched simulations widely used in the early days have been gradually replaced by full QCD in recent years which properly includes quark pair creation annihilation effects in the vacuum. This involved both algorithmic developments and machine building. The group at DTP has been involved in lattice QCD research since the 1980's. The early work included pioneering full QCD simulations of finite-temperature QCD and its chiral phase transition, an exploration of Debye screening through numerical simulations which is relevant for possible suppression of $J/\mathrm{psi}$ production in heavy ion collisions, $Z(3)$-Potts model finite-size study which helped resolve the first-order nature of the pure $SU(3)$ gauge transition at finite temperature, and a lattice formulation of the quark action for finite-chemical potential.

  One focus by the group at the DTP is the location of the end point of the phase transition in the temperature-chemical potential plane signaling the onset of the Quark Gluon Plasma (QGP). Using Taylor expansion methods coupled with a determination of the expansion coefficients using full QCD simulations they suggested that the end point may occur at a rather small value of the chemical potential so that an experimental detection may be possible at RHIC energies. Another work concerns the strangeness content of QGP. Using the correlation function of charge and strangeness measured in lattice QCD, they found that the lattice estimate of the Wrobleski parameter giving strangeness to up-down production ratio is in agreement with phenomenology.

  Lattice QCD covers a wide area. The emphasis of the group has continuously been on finite-temperature/density QCD and quark-gluon plasma, and they were also involved in phenomenological analyses of QGP. They have worked as a group sharing research targets and computing resources since large-scale computer work often requires a joint effort of some number of researchers for carrying out coding, job execution and data analyses. Their recent effort has been substantially aided by the availability of their new supercomputer CRAY X1.

  *The Review Committee thinks that these policies have paid off. While rather small in number, the group is well-recognized worldwide as one of the important contributors of finite-temperature/density lattice QCD relevant for QGP studies.*

The group will be strengthened, and the age distribution made more balanced, by the joining of Saumen Datta in the Fall of 2006. The group should continue producing high-level research as one of the main centers of lattice QCD and related subjects in Asia at large. We feel that maintaining the size of the group at the present level (with S. Datta) will be needed for this purpose. In addition, supercomputer resources should be updated at an appropriate interval for their work to keep carrying impact worldwide. (We shall comment more on this in Sec. II-7 Infrastructure.)

Studies of QGP via RHIC and LHC experiments require phenomenological analyses as well as the first principles approach of lattice QCD. Theorists at the DTP have been making interesting contributions in this area. Recent results include a new proposal of a Lee-Yang type method to extract the collective flow parameters of nucleus-nucleus collisions, which are basic to discuss the nature of correlations in QGP. The method is beginning to be employed in actual data analyses. We encourage the group to continue a vigorous activity in this area. We support efforts to strengthen international links and collaborations for this purpose, such as those provided by the Indo-French Center for Advanced Research.

► <u>Theoretical particle physics</u>

Theoretical elementary particle physics has traditionally been a strength of the TIFR. For many years D.P. Roy and Probir Roy have been major figures in international high-energy physics. In the past ten years, these two have continued to make important contributions to phenomenological studies for high-energy colliders and in particular to studies of experimentation on Higgs bosons and supersymmetry. Now both are retiring and there is only one senior expert left on physics beyond the Standard Model. The work concerning experimental probes of extra dimensions and other exotic models of physics at high energy colliders has received wide attention internationally.

We are pleased to see that the DTP has recently added an expert on neutrino and flavour physics. This has allowed to study the very interesting issues involving models of neutrino mass and their interaction with neutrino astrophysics and supernovae. It has also led to a collaboration with the HEP experimental group in the formulation of the proposal for the India Based Neutrino Observatory.

The broader particle physics community is now looking forward to the beginning of operation of the Large Hadron Collider (LHC) at CERN. This facility has the capability of making discoveries that will reshape our understanding of elementary particle interactions. The results will be interesting to many disciplines at the TIFR, including especially astrophysics and string theory. The High-Energy Physics Department of the TIFR is collaborating in one of the major LHC experiments.

*We feel that it is very important for the DTP to add a faculty member with expertise in the practical concerns of collider physics experiments and in the area of model-building relevant to electroweak symmetry breaking.*

Over the next five to ten years, we also expect to see progress in the understanding of large-scale cosmology, including tests of models of inflation, and, hopefully, the discovery of dark matter particles. We believe it is important for the DTP to hire a faculty member interested in the elementary particle model-building issues associated with inflation and dark matter and cosmological implications of models of new physics. This should also be someone who knows the astrophysics literature and has experience in collaborating with astrophysicists. We were very interested to learn that Subhabrata Majumdar has accepted an offer to join the astrophysics department. We hope this appointment will work synergistically with a new appointment in particle astrophysics to bring both the astrophysicists and the DTP theorists into the areas opened by new discoveries in cosmology.

*B) String theory*

Research in string theory at TIFR began in 1984 with members of the High Energy group, leading to the formation of a separate group in the early 1990's. From the beginning Tata theorists made critical contributions to the subject, including the quantization of strings in curved spacetime, the development of string/matrix models in low dimensions, including the discovery of emergent spacetime dimensions and the two-dimensional back hole, discoveries of weak-strong dualities in gauge theories and string theories, and developments of the properties of branes and their duality with black holes.

Through a series of excellent recruitments the group has grown to become one of the leading groups in the world. Its members work on central problems, and are well connected with leading string theorists world-wide. During recent years string theorists at Tata have been responsible for some of the major developments in the field. There are several notable recent research achievements, in particular:

- It has been a central problem in string theory to identify realistic and mathematically controlled vacua, which must be stable and with broken supersymmetry. In a series of papers the necessary dynamical ingredients were identified, culminating in the construction of the first such vacua and the discovery of the 'string landscape', a vast set of long-lived vacuum states; this has transformed the understanding of the phenomenology and cosmology of string theory. In addition, this has led to the first detailed models of inflationary cosmology in string theory, which have been constrained by observation of the cosmic microwave background.

- Black holes have been a central theoretical laboratory for development of quantum gravity. The recent exact counting of black hole microstates is a major advance. Other significant developments are the discovery of a phase transition in weakly coupled gauge theories which is dual to the string-black hole transition, the relation between black holes and the dual plasma-balls, and the existence of nonsupersymmetric black hole attractors.

- The duality between gauge and string theories (AdS/CFT duality) is central to the current understanding of string theory. Members of the Tata group discovered an integrable structure in this system, which has become an area of major research activity. Other developments include the study of supersymmetric states, of the plane wave limit, and the emergence of string bits in the limit of large spacetime curvature.

• Non-commutative spacetime geometry is a property of string theory, which reflects the fundamental nonlocality of the theory. Discoveries in this area include new dualities and decoupling limits, the nature of the noncommutative solitons and their decays, the map between commutative and noncommutative descriptions, and the nature of the observables in these theories.

• Many other fundamental areas including bosonization, noncritical strings, and black holes.

The current age distribution is a good mix of senior and junior theorists. We understand that unfortunately Atish Dabholkar will soon leave the group.

The string group has been rather focused on fundamental questions of the formulation of string theory. In recent years, and in part due to the discoveries made by the group, string theory has begun to connect to cosmology, particle phenomenology, quantum field theory, and QCD (through AdS/CFT duality). Many excellent young theorists work in these areas.

*We recommend that the string group should maintain its strength through identification of outstanding candidates when these emerge.*
*We recommend that the Department should build on its strength in string theory by hiring in related areas such as the areas of high-energy particle physics and particle astrophysics already noted above.*

C) *Statistical physics and condensed matter physics*

At the moment the activity in statistical and condensed matter physics is in the hands of two senior professors who enjoy a strong international reputation, with the recent addition of two new and excellent members of the young faculty.

The Abelian sandpile model for self organized criticality, developed at TIFR, is one of the theoretical cornerstones in the field. Exploring the statics and dynamics of such models, their relationship with other statistical models and their pattern of universal behaviour has been very fruitful. Other areas of nonequilibrium statistical physics to which the group has contributed notably include glasses, linear and branched polymers and growing surfaces. The recent work on strong clustering effects in models of passive sliders on fluctuating surfaces is well known. This is part of a concerted effort, well recognized, on diffusion in driven systems in the presence of disorder. The emphasis on questions in the emerging field of nonequilibrium statistical mechanics is one of the common themes of the activity of the group, involving the senior members, S.N. Majumdar – a brilliant theorist who was a member of the group, as well as many graduate students, past and present.

In the last several years, several areas in the physics of strongly correlated as well as disordered quantum systems have been pursued vigorously in the DTP, leading to many important contributions, international recognition for the group as a leading centre, and training of very good PhD students and postdocs. The work of Mohit Randeria (member of the group till 2004) on the development of high resolution ARPES (Angle Resolved PhotoEmiSsion) to describe the nature of low energy electronic excitations in high temperature superconductors, done in close collaboration with experimentalists, has helped define this field. Mohit Randeria and Nandini Trivedi (also a member of the theory group till 2004) along with their then PhD student Arun Paramekanti developed about five years ago, the consequences of a strongly correlated ground state wave function for a high $T_c$ superconductor. This has been highly influential. The group also studied using a mixture of numerical and analytical methods the consequences of strong disorder for superconductivity and for the metal insulator transition in low dimensional interacting electronic systems.

Kedar Damle, who joined the group about two years ago, has focused notably on the effect of exponentially rare localized configurations in quantum spin systems, on models exhibiting emergent critical behaviour near quantum critical points and those with a supersolid phase. Vikram Tripathi, a very recent addition, has proposed a novel quantum mechanism for energy transport in granular metals.

The recent addition of two strong young theorists in condensed matter physics, with broad interests, will certainly have a beneficial influence on the whole group. This is already clear if one looks at the number of students with this group which is comparatively large.

However the departure of S. Majumdar, M. Randeria and N. Trivedi has deprived the group of brilliant young theorists and the present gap in the age distribution of the group should be filled by hiring at least one new young theorist. Given the importance of the area of condensed matter physics, and the huge variety of fields that it encompasses, the group is much too small. It should then grow and serious efforts for hiring new people should be made in several directions: in particular theoretical biology and soft condensed matter physics are areas of great importance nowadays which ought to be added to the DTP.

The project of a future "Interdisciplinary Life Sciences" (ILS) Department should concern the DTP, and in particular this group in a major way. We understand that some of the people being considered for this new Department, such as Anirvan Sengupta, who have made in the past strong contributions to theoretical physics, could play a major role to build up the interactions of DTP with this new field.

A joint appointment of such a person with both Departments would be extremely advisable.

*We recommend to increase the size of the condensed matter-statistical physics group.*

*We recommend to identify and hire new young faculty in the areas of theoretical biology and soft condensed matter.*

*We recommend to make a joint appointment between the future ILS and the DTP.*

## II-2 A strategy for the DTP: perform recruitments based on its international recognition

It is a special moment now for physics in India and for the TIFR in particular. A number of developments in Indian science and in society make it possible for India to have a direct impact on the world scientific community. These include :

1. The growth of the computer and informatics industry in India, bringing prosperity to the country and especially to the social class that includes engineers and scientists.
2. The broad availability of inexpensive computing and electronic communication, which offers any scientist significant computational resources and – more significantly – connects Indian science instantaneously to the rest of the world.
3. The nucleation, at multiple institutions including TIFR, IISc, and HRI, of research groups that have achieved recognition as world leaders in physics.

Theoretical physicists, who typically do not require expensive equipment or infrastructure, and, indeed, whose main requirement for successful work is communication and exchange of ideas, are especially well positioned to take advantage of these trends and to build up research groups at the highest world level.

We are already seeing the results in the recent additions to the faculty of the TIFR Department of Theoretical Physics. All four of the most recent hires – Damle, Dighe, Minwalla, and Tripathi – would be strong candidates for top academic positions anywhere in the world. Two of them in fact resigned from such positions in the United States to return to India.

It remains true that life in India has many challenges that are not found in the West. But, for those who chose to live in India, there are no longer obstacles to making a scientific career with direct impact on the world community. This has important implications for all aspects of the management of the TIFR, but especially for recruiting of new young faculty. From here on, we will talk specifically about the implications for the DTP, but many of the conclusions apply as well to the other departments of TIFR. In the remainder of this section, we will speak specifically about faculty recruiting, but this general idea of the high and growing stature of Indian physics will also colour many of the recommendations that we make in later sections of the report.

At the highest level, faculty recruiting at TIFR should change its overall emphasis from response to applications to a direct search among young scientists working at the highest level. The group has needs to fill in various fields, and we will discuss this later in the report. However, the main effort in recruiting should be directed at the identifying the top young scientists in the world theoretical physics community who might become available, and to pursue those people as targets of opportunity for new faculty appointments.

As an example of a formal mechanism that might reflect this goal, we make the following specific proposal:

*We recommend that the DTP set up a standing departmental search committee with representatives from all of the groups within the department, and with some representation from the experimental physics and astrophysics groups at TIFR. The committee should be made up primarily of younger members of the Institute with broad international contacts.*

The committee should have the power to identify targets of opportunity for appointment to the DTP, and to solicit, on a short time scale, letters of evaluation that would be suitable for bringing the hiring decision to the full TIFR faculty. According to the governing rules of the TIFR faculty, the junior members of the faculty do not have the right to vote on new appoinements at the same or higher level.

*However, it is important that, as a matter of procedure, they be invited to the faculty discussion of these appointments. The full faculty should be able to hear the evaluations and analysis from the search committee directly.*

Once the faculty has been persuaded and has approved the appointment of a candidate, the Director of the TIFR should have the power to move quickly and flexibly toward a formal offer. This should include, in particular, guarantees of travel support (say, for a period of 3 years) and an appropriate quality of housing. (The general importance of travel support for theoretical physicists is discussed in detail in a later section of this report.) It might be necessary to increase the fraction of the TIFR housing in the "Director's Reserve" in order to make attractive offers possible. Once a top candidate is identified who is eager to return to India and set up a leading group at the TIFR, there should be no obstacles put in the way of actually bringing that person into the Institute.

Furthermore the review committee would also like to emphasize that the postdoctoral programme of the DTP and of the TIFR should be strengthened both in terms of numbers and in terms of the realization that it is an important phase in one's professional growth and career. Ph.D.'s from other institutions in India and from other countries are the natural prospects here. Indeed, the committee was happy to note that there are international postdocs in the DTP for professional reasons despite the salary differential.

## II-3 Students and Teaching

We consider the education of young scientists one of the top goals for TIFR as a whole. We were delighted to meet the graduate students of the DTP, whom we found to be bright and articulate and genuinely enthusiastic about the pursuit of science. We were impressed by their level of engagement in the research projects of the Institute. We were pleased to learn that TIFR has recently become a "deemed University" empowered to organize a formal graduate program. We strongly encourage the Institute and the DTP to continue toward the goal of becoming a leading department for student training in physics.

In this section, we will comment on some of the strengths and weaknesses of the graduate program and suggest some means of improvement.

Our most important observation is that the TIFR has many fewer graduate students than it could support intellectually. In the DTP, the student-to-faculty ratio is about 1:1, a minimal level. We understand that the ratio is similarly low in the experimental groups, where students are needed to play a day-to-day role in the operation of the laboratories. We find both that there is an opportunity to bring many more students to be educated at TIFR and also that the overall low number of students is a source of tension between groups in the Institute.

*We strongly recommend that the number of students admitted annually to the graduate program of the TIFR be doubled, and that this be done as soon as possible.*

At the moment, the TIFR offers a minimal set of courses appropriate to basic graduate training in physics. We see no reason why this program should not amplified and made better organized. As a basis for planning and recommendations, we applaud the decision of the TIFR to admit students, as a rule, after the B.Sc. rather than after the Master's degree. The program of courses at the TIFR can then be structured as a ground-up foundational training in Physics. The current course offerings attempt this, but the set of courses needs to be systematized and also broadened to a menu typical of a major research university. Specific proposals are contained in the Annex A to this report. The system of first-year courses should be structured so that the elements of all basic subjects, including classical mechanics and electrodynamics, quantum mechanics, mathematical (including numerical) methods, and statistical and thermal physics, are presented. For the second year of study, we recommend that introductory survey courses be given annually in the various subfields of physics represented at the TIFR – astrophysics, atomic physics, condensed matter and solid state physics, and particle physics. We also recommend that the basic higher-level courses needed by theorists to enter the research literature – quantum field theory, statistical and many-body physics, and gravitation – be given every year. We emphasize that this is a menu of basic courses that are meant to provide a foundation for further study. Advanced topical courses should be offered as additions to, rather than replacements for, the courses on this list.

At a university in the US, it is typical that the theorists teach most or all of the foundational graduate courses, while experimenters do the bulk of the introductory teaching of undergraduates. At the TIFR, there are no undergraduates, and so the burden of teaching falls mainly on the theorists. We recognize this, but it is necessary that the members of DTP accept their responsibility to provide the basic education of all students at the Institute. We note however that at its current strength the DTP is not able to cover these courses completely.

*We expect that, with the participation of faculty members from other departments, the core courses could be staffed by having each faculty members in the DTP teaching one semester of the core program every two years. We consider this a reasonable teaching load to require of members of the DTP.*

At the same time, we encourage members of other departments to contribute to the basic teaching program where appropriate. At present, the theoretical astrophysicists and members of the High-Energy Physics group are sharing in the teaching of the first-year courses. We recommend that the introductory surveys of subfields that we have recommended above always be taught by experimenters. Aside from the obvious advantage that this will make the coverage of basics more accessible to the general student body, it will have two more advantages – first, providing theory students with a view of the subject that is rooted in the data and in observational facts and issues; and second, providing experimental faculty with a forum to display the fascination of their subjects and, through this, to recruit students into their labs.

As part of our belief that education of students is one of the natural activities of the DTP, we would like to suggest a few further steps which may help strengthen it:

*We strongly recommend that student evaluations of teaching be solicited systematically for every course.*

*We recommend that the classroom teaching record of faculty should be considered at each promotion, and that positive incentives, in the promotion process or in other Institute resources, should be given to faculty whose teaching is of high quality.*

An issue in recruiting students to the TIFR is providing for them an adequate environment for living and study. We understand that the general problems of space on the TIFR site present difficulties. (We will discuss student office space specifically in Section II-7.1). However, we also heard complaints from the students about the cleanliness of their facilities and canteens; these issues ought to be remedied immediately.

## II-4 Travel Funds

The need for travel funds, in particular for foreign travel, was raised repeatedly by members of the Department at all levels. Our understanding is that the limitations on travel funding come not from the availability of money but rather from administrative restrictions on the use of available funds. These restrictions are seriously harmful to the theoretical research effort of the TIFR, and we strongly recommend that they be lifted.

Travel is vital to the activity of theoretical physics. The central issues in theoretical physics are involved with finding the correct set of ideas that clarify phenomena in Nature. In a worldwide discussion, theorists present new ideas and recombine and evaluate them. Finished ideas are presented in the literature – and the internet and electronic archives now give unprecedented worldwide access to the finished work. But it is important also for active scientists to be a part of the ongoing conversation on the implications of these ideas, and on new perspectives that might be built on them. For this, there is still no preplacement for direct personal discussions with colleagues. Given the small size of the Indian theoretical community, it is important that theorists in India travel on a regular basis to other parts of the world for such informal discussions. Such trips can be structured around presentations at major international physics meetings. But, also, travel to Europe or the US also allows the opportunity for less formal interaction.

Conference presentations and face-to-face discussions with colleagues are also important to the careers of young scientists. In theoretical physics, one's stature depends on the quality of ones ideas and on one's ability to present them clearly. It is of immense value to students or postdoctoral fellows to have the opportunity to explain their ideas face-to-face to experts in other parts on the world grappling with the same issues. The importance is magnified in the situation in which the young physicists would like to find positions in one of the world centers, to gain broad experience before returning to faculty positions in India. It is much easier to find such a position if they are known in the world community, if senior physicists have met them and had an opportunity to discuss their ideas.

We were especially disappointed to learn that it is difficult for postdoctoral fellows and students to travel even within India. Since their salaries are so low, they rely on the Institute for travel funds. But, even for travel within India, these funds are controlled by a rigid system that allows only a few trips and requires that those are approved mohths in advance. For an activity whose essence is the free exchange of ideas, these restrictions are stifling.

*We recommend that the TIFR provides travel funds for every student to travel abroad once in the period of their studies, and for postdoctoral fellows to travel abroad once every year, to attend an international scientific conference. We further recommend that* *funds be set aside to be used at short notice for travel to topical scientific meetings in India.*

The DTP can attract visitors from abroad to come to the TIFR for short-term stays of one to a few months. This provides an opportunity for many scientists in India and especially young people to connect with new ideas that are being developed in other parts of the world. *We recommend that money also be set aside for support of such visitors.*

## II-5 Interactions with other Departments of TIFR

It is clear that the scientific interactions of the DTP with the other Departments of TIFR are not very developed. The experimental groups often complain that the theorists that they would need are not available. This is everywhere a difficult question which often leads to similar complaints. A delicate balance though is needed here: the theory has questions of internal logic to explore which may not have immediate experimental counterparts: for instance the Weinberg-Salam model was developed, not because Fermi's theory of weak interactions was failing experimentally, but because of its lack of quantum consistency.

The complaints are particularly vocal in condensed matter physics, although one should hope that the recent addition of K. Damle and V. Tripathi may significantly modify this negative impression. However it would make sense if the Departments of Condensed Matter Physics and the DTP jointly identified theorists who could strengthen their interactions as a part of the search process already described.

We make here a suggestion, which has led to significant improvements in other institutions:

*Short term visits to the Theory Group of one-two months by theorists who have specific interests in experiments being carried out in one of the experimental Departments of TIFR, could lead to real improvements. The visiting scientists would be hosted by the DTP and would naturally also spend time discussing with the experimentalists involved in his field.*

Let us add a remark concerning the Department of Mathematics. The interactions with the DTP leave room for improvement; the gap is probably the combined effect of the difference of style, of level of rigor, of interests of the two communities. This is true in many places in the world, and clearly it is not our intention to criticize here anybody for this state of affiairs.
However over the centuries and even more in the modern era, physics has been a rich source of inspiration for mathematicians, as reflected by the research topics of numerous Fields medialists over more than a decade. In a number of institutions the mathematics students are either required, or often choose, to take some courses in

physics in topics such as quantum mechanics, statistical mechanics or quantum field theory. This is not meant to turn mathematicians into physicists but to make them aware of the basic structure of physics.
This leads us to the following recommendation

*We recommend to encourage mathematics students to take some physics courses and vice versa.*

## II-6 The relationship between the DTP and the theorists in the Astronomy and Astrophysics Department

The Astronomy and Astrophysics Department (AAD) at TIFR has a strong activity in theoretical astrophysics, particularly in the area of compact objects and black holes and X-ray and radio probes of these systems. In this field, the division between theorists and experimenters is not so sharp. Theorists regularly analyze data and make proposals for observations. Thus, the situation of those theorists in the AAD rather that in the DTP seems justified.

However, in the past ten years, there has been a shift of the astrophysical community toward interest in cosmology and in the role of dark matter and dark energy in the formation of structure in the universe. Candidates for dark matter are naturally constructed in models of physics beyond the Standard Model. Models of inflationary cosmology often invoke further new quantum fields at very short distances. Thus, these subjects connect to areas of interest of the DTP.

It would be ideal to have the intellectual resources at the TIFR to allow a dialogue between astrophysicists on the one hand and particle and string theorists on the other. Unfortunately, the gulf between these fields is very broad, broader than that could be bridged by a single new faculty appointment.

However, as we have already noted in the evaluation of the Theoretical Particle Physics Group, the AAD expects to add an expert in galaxy clusters and large-scale structure, S. Majumdar. We are hopeful that this appointment together with the appointment of the expert in particle astrophysics that we have recommended in that section can provides enough of a connection to allow the theory community of the TIFR to react to the new experimental discoveries related to inflation and dark matter that we expect to occur in the next few years.

## II-7 Infrastructure

Matter related to the infrastructure of DTP were discussed in a variety of contexts while meeting with the DTP members. The problem with space was often mentioned both by the faculty and students. Requests were made concerning the general computing and networking environments by the faculty. Facilities for high performance computing requires a separate comment since lattice QCD occupies one of the main activities of the High Energy Physics sub-area. Finally, the issue of housing repeatedly came up.

A) **Space**
The Review Committee learned that DTP now possesses 26 office rooms and 1 room for students. Since DTP currently has 20 faculty members, 7 postdoctoral fellows and 24 students, the space capacity is clearly saturated. Concerns were expressed by the DTP members that lack of office rooms will make it difficult to allocate an independent office to new faculty members; visitor programs will have difficulty functioning if offices cannot be given to visitors. The Review Committee visited the student room where we saw a dozen students sharing a single room of medium size, literally sitting elbow to elbow in rows of small desks.
Since DTP expects new faculty appointments replacing the recent retirements and expanding the department in new directions, and since there is strong desire, both within and outside DTP, to increase the number of students, securing enough space is one of the crucial issues for expanding the vigorous activity of DTP.
The Review Committee understands that TIFR has been considering a possibility of an additional campus to resolve the space issue. Since this issue cannot be solved by the effort of DTP alone, we strongly suggest that TIFR formulates a long term strategy for its campus plan. *In the short term, the request made by DTP for at least 6 more offices is quite understandable, and we recommend that TIFR makes effort to meet the request. In addition the Review Committee recommends that TIFR seek to expand the space for students by at least a factor of two per student, either by reallocation of rooms or by converting open spaces to office rooms.*

B) **General computing and networking environments**
General computing services at the DTP are provided by 5 servers with Itanium2 CPU. While these are adequate for day-to-day operations of a theory department (e.g., e-mail services, internet access for archives and e-journals, document processing, small-scale computations, etc.), we recommend a periodic update of the system for enhancing an effective and comfortable work environment and cost/performance reasons.

The internal network of DTP is currently 100 Mbps Ethernet LAN and 55 Mbps wireless LAN. While these are standard network environments for internal LAN today, the Review Committee was told that the internet connection off-campus has a bandwidth of only 16 Mbs. This is clearly inadequate except for minimum general services, and should be enhanced at least to 64 Mbps, as requested by DTP, as soon as possible. This goal does not seem ambitious enough to the Committee. It is not clear to the Committee that the expected availability of a 622 Mbps connection to CERN, a priori dedicated to the LHC grid, will be available for the DTP users.

This is important also for lattice gauge theory activities of DTP which requires much more data traffic in volume and frequency than the general services. Indeed, demands for fast network connection will only grow, both from DTP and much likely more from other experimental departments which deals with large amount of data. The Review Committee notes that national research networks in countries such as USA, Europe and Japan have reached 10 Gbps level for some time by now. Therefore,

*we recommend that the Institute work to secure internet bandwidth that supports on-demand (i.e. non-dedicated) usage up to several hundred Mbps to the DTP users.*

Since building high bandwidth network is a national matter, we suggest that TIFR seeks to work in consultation with the overall Indian planning to improve their internet environment.

C) **High performance computing**

Modern theoretical physics often requires extensive numerical calculations. Lattice QCD which has been vigorously pursued by the High Energy Physics sub-area is a representative example. DTP currently operates a CRAY X1 (1Tflops peak performance) supercomputer purchased under the Indian Lattice Gauge Theory Initiative. The Review Committee appreciates the importance of this purchase since CRAY X1 provided the computing power which produced the studies of QCD thermodynamics carried out at DTP and quoted widely.

Worldwide, supercomputers dedicated to lattice QCD have reached 10 Tflops scale since 2005; 3 QCDOC's (peak 10Tflops), 1 in Edinburg and 2 at Brokhaven, PACS-CS (14 Tflops) in Tsukuba, apeNEXT (6-7Tflops) in Rome, Berlin and Bielefeld, and a number of Blue-Gene/L systems (57Tflops system at KEK, 40 Tflops system at Julich, several smaller systems at various institutions).

The Review Committee understands the need expressed by DTP that updating their supercomputer resources at regular intervals is needed to make continued impact in researches in lattice QCD and quark-gluon plasma physics. The peak performance of high-end systems generally available will surpass 100 Tflops mark within a few years, and the cost performance will correspondingly improve.

*The Review Committee strongly supports the updating of the current supercomputer system to 10 Tflops range by 2009.*

Supercomputing is not the only need of DTP but also required by other departments such as the Department of Astrophysics. The Review Committee recommends that (i) DTP makes continued effort toward a joint planning and proposal for the supercomputer facilitywith other departments which has interests, and (ii) TIFR views the matter of high performance computing as one of the important areas for support and make a long-range plan for its funding and maintenance.

D) **Housing**

Given the extremely high price of housing in the vicinity of the TIFR campus in Mumbai, *good on-campus housing is an absolutely necessary condition to ensure a high-level academic program as a whiole.*

The Review Committee understands that the situation with housing is extremely severe at TIFR, since the TIFR campus is not easily expanded into neighboring areas, and housing and land surrounding the TIFR campus are very expensive. The Review Committee noted a number of issues connected to housing:

- If it remains difficult to offer reasonable housing to newly recruited faculty members, TIFR will lose competitiveness;
- Junior faculty members are initially allocated inadequate housing, following a certain formula which seems to put more weight on the length of association with TIFR rather than the hiring position;
- It generally takes a long time for junior members to be able to move into a more reasonable housing;
- Limited housing constrains hiring postdoctoral fellows;
- Students have to share rooms, sometimes even five or so to a suite of rooms.

The Review Committee understands that a new hostel will be built for students, and this will ease the pressure somewhat. In the long run, however, the ultimate resolution will require more space. *The Review Committee feels that TIFR seeks to solve the housing and space issues via a long-range planning of a new campus, perhaps including the possibility of moving out as a whole from the present one.*

## II-8 Careers of the TIFR faculty

In addition to the measures recommended above concerning a better involvment of the junior faculty in shaping the future of the Department, it seems also important to acknowledge the achievements of the confirmed scientists. The DTP for example has outstanding faculty at the senior level, whose contributions and commitment have been and are essential. The TIFR has always recognized and rewarded academic excellence.

*For those who excel in their research, as well as by their involvment in training students and in building up the Department, we believe that TIFR should consider awarding the Distinguished Professors (level J), which is empty at present.*

The DTP should also open the possibility of continued professional association of faculty still active but formally retiring.

### II-9 A Theoretical Sciences Program

The proposed plan of a Theoretical Sciences Program is based on a variety of highly successful models in other countries (KITP in Santa Barbara, Isaac Newton Institute in Cambridge, etc.). The existing proposal describes an initial phase in which the program moves among host institutions, followed by the establishment of a permanent site.

Such a program requires a substantial infrastructure: a well-designed building with ample and flexible office space, sufficient quality housing for visitors, proximity to excellent research institutions whose faculty can assist in the operations of the program (and the existence of such a program will also enhance these institutions), and a location which is attractive to long term visitors. The education of postdoctoral fellows is a key part of such a program. A small but excellent scientific staff is necessary to mentor the postdocs and to establish a local scientific culture. A strong IT group is necessary. Education of students and outreach to the public are important components of the program, as is the propagation of the program's activities to researchers around the country and the world via the web. Successful operation of such requires the identification of a visionary Director, and a strongly involved program advisory committee consisting of a wide spectrum of leading scientists. A further essential ingredient of the success of such programs is the ability to bring together a critical mass of scientists with diverse expertise; in general this requires international participation.

*The Committee endorses the proposed Theoretical Sciences Program as a means of establishing long-term research collaborations among theorists at diverse institutions, finding and developing new connections between scientific disciplines, and helping to develop the next generation of Indian scientists.*

## III SUMMARY OF THE MAIN RECOMMENDATIONS

The main recommendations may be organized under several headings:

### III-1 New appointments

1. *We recommend to the DTP to increase the size of the condensed matter-statistical physics group;*
2. *We recommend to the DTP to identify and hire new young faculty in the areas of theoretical biology and soft condensed matter;*
3. *We recommend that the DTP add a faculty member with expertise in the practical concerns of collider physics experiments and in the area of model-building for physics relevant to electroweak symmetry breaking;*

4. *We recommend that the DTP add a faculty member in the field of particle astrophysics;*
5. *We recommend that the DTP should maintain is strength in string theory through identification of outstanding candidates when these emerge. We note also that the department's strength in string theory should make it more attractive to outstanding candidates in the area we have highlighted in recommendations #3 and #4;*
6. *We recommend to the DTP to build on its strength in string theory by hiring in related areas;*
7. *We recommend to the DTP to make a joint appointment between the future Interdisciplinary Life Sciences centre and the DTP;*
8. *We recommend that the DTP appoint an expert in particle astrophysics to allow the theory community of the TIFR to react to the new experimental discoveries related to inflation and dark matter that are expected to occur in the next few years.*

### III-2 Organisational matters

9. *We recommend that the DTP set up a standing departmental search committee with representatives from all of the groups within the department, and with some representation from the experimental physics and astrophysics groups at TIFR. The committee should be made up primarily of younger members of the Institute with broad international contacts;*
10. *We recommend to invite the junior faculty to the discussions concerning the new appointments. The full faculty should be able to hear the evaluations and analysis from the search committee directly.*

### III-3 Students and teaching

11. *We strongly recommend that the number of students admitted annually to the graduate program of the TIFR be doubled, and that this be done as soon as possible;*
12. *We strongly recommend that student evaluations of teaching be solicited systematically for every course;*
13. *We recommend that the classroom teaching record of faculty should be considered at each promotion, and that positive incentives, in the promotion process or in other Institute resources, should be given to faculty whose teaching is of high quality;*

14. *We recommend to TIFR that the set of courses offered at TIFR ought to be systematized and also broadened to a menu typical of a major research university;*
15. *We recommend to the DTP that, with the participation of faculty members from other departments, the core courses could be staffed by having each faculty members in the DTP teaching one semester of the core program every two years.*

## III-4 Infrastructure

16. *We recommend that the TIFR provides travel funds for every student to travel abroad once in the period of their studies, and for postdoctoral fellows to travel abroad once every year, to attend an international scientific conference. We further recommend that funds be set aside to be used on short notice for travel to topical scientific meetings in India.*
17. *We recommend to the DTP that money be set aside for attracting short-term visits from abroad of one to a few months.*
18. *We recommend that TIFR seeks to solve the housing and space issues via a long-range planning of a new campus, perhaps including the possibility of moving out as a whole from the present one.*
19. *In the short term we recommend that TIFR makes effort to meet the request for at least 6 more offices.*
20. *The Review Committee recommends that TIFR seeks to expand space for students to at least twice per student, either by reallocation of rooms or by funding conversions of open spaces to office rooms.*
21. *We recommend that the Institute work to secure internet bandwidth that supports on-demand (ie non-dedicated) usage up to several hundred Mbps to the DTP users.*
22. *The Review Committee supports strongly the updating of the current supercomputer system to 10 Tflops range by 2009.*

## III-5 Interdepartmental activities

23. *We recommend to the DTP to organize short term visits to the Theory Group of one-two months, by theorists who have specific interests in experiments being carried out in one of the experimental Departments of TIFR. These visits could lead to real improvements in the interactions between theory and experiment;*

24. *We recommend to TIFR to encourage mathematics students to take some physics courses and vice versa.*

## III-6 Theoretical Sciences Program

25. *The Committee endorses the proposed Theoretical Sciences Program as a means of establishing long-term research collaborations among theorists at diverse institutions, finding and developing new connections between scientific disciplines, and helping to develop the next generation of Indian scientists.*

## Annex A: Program of graduate course

The graduate curriculum has grown up organically without an attempt to write a set of basic requirements or to provide a complete set of courses such as one would find at a major university. This ought to be done.

The B.Sc. curriculum in India is a three-year program which generally does not provide adequate preparation for beginning physics research. Thus, the TIFR graduate program must begin with a set of "core" courses that provide a basic foundation in physics. This would include:

**1st year:**

> 6 semesters of foundational courses: Classical Mech, Electrodynamics, Math Methods, Statistical and Thermal, Quantum Mech(2).
>
> All students entering with a B.Sc. should take these courses in their 1st year. In addition, a lab project and an "Introduction to Experimental Methods", plus seminars in research activities in the department, would make a full 1st-year program.

**2nd year:**

> 4 semesters of area survey courses: Atomic, Cond Matter and Solid State, Particle Physics, Astrophysics. These are not be confused with special topics courses; these courses should cover, e.g., what are bands and how do you measure them, what is a pion, what is a gluon etc.
> We recommended that these courses should be taught by the experimenters.
>
> 6 semesters of foundational theory courses : Quantum Field theory (2), Gravitation, Cosmology and Black Holes, Many-Body Physics, Advanced Statistical Mechanics. These courses also should not be confused with special-topics courses.
>
> A typical 2nd year experimenter would take 1 area course and 1 theory course, while beginning research. A typical theory student would take 1 area course and 4 theory courses. Students might wish to take additional courses from this menu later in their studies.
>
> Special topics courses (including "Introduction to String Theory") would be on top of this menu of basic courses.

**Teaching load**. There are 6 semesters of first-year core courses and 6 semesters of foundational theory courses that need to be covered every year. At the moment, two faculty members outside of the DTP (one from experimental HEP, one from astrophysics) are teaching first-year core courses. This leaves 10 semesters of core courses to be covered by 16 DTP faculty. This is not an excessive load. However, the contribution of one or two more semesters from the experimental faculty, and the addition of new DTP faculty, could easily bring the ratio of these numbers to the more preferable 1:2 ratio that we have called for at the end of Section II-3.

## Annex B: Career paths of graduate students

The faculty of TIFR needs to give serious thought to finding the best career paths for its students. This needs to be considered both for students who will pursue careers in academic science and for students who will seek careers in industry.

First, we will discuss students who are pursuing academic careers in science. For the forseeable future, it will remain a necessary part of any young scientist's education to spend several years abroad. The Indian physics community is still small, and it is important for developing young scientists to swim in the much larger world community, to absorb its wealth of ideas and insights.

We suggest that the TIFR consider a model in which it is expected that its Ph.D. graduates seek postdoctoral positions in the best international institutes, trying to instill at the same time the expectation that they will return to India for faculty positions. The physics community of Israel, for example, has been successful with a model of this type. There, theoretical research is done primarily by professors and graduate students. Young scientists go often to the US for postdoctoral training, and those that gain recognition are hired back to Israel as faculty members.

The model implies that, where decisions about placement of resources are necessary, priority should be given to graduates students over postdoctoral fellows. It is the students who would be more likely to become the future leaders of the Indian community. It implies also that TIFR should spend resources to keep contact with promising students after they graduate, offering these people visits of one to several months. The TIFR summer program for undergraduates also has a role to play in this model, in identifying very promising students who might go to the West for graduate study, to give them a connection to the TIFR to begin reinforcing their ties to India.

While TIFR is sending its own graduate students abroad, it might look to attract postdoctoral fellows from other countries. Recently, several of the best young US and European postdoctoral fellows in string theory have chosen to spend six months to a year at TIFR. The various groups in the DTP should encourage further such visits, which add to the scientific life of TIFR and also increase its international connections.

It is also important to think about the career options for students who choose to look for careers in industry. In the US, the majority of graduate students in Physics eventually make careers outside of academia. This includes theorists and even string theorists, who are sought out, for example, by the financial industry as statistical analysts. This pathway into industry seems hardly to exist in India. This is a shame, both because it limits the career options of TIFR graduate and because it deprives companies in India of an important source of talented technical experts. The faculty and Director of

TIFR ought to try to build contacts with Indian companies in the high-technology and financial industries that might provide fulfilling careers for the students who graduate from TIFR.