Particle Physics and Mathematics

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Preliminary Remarks

Now, as always, physics sees itself as the leading science for research in the natural sciences. The existence of atoms, molecules, and biological systems can be understood only on the basis of physical laws. Similarly, physical laws are needed to answer questions about the origin and evolution of the universe. Physics has many facets, which cannot easily – and never completely – be split apart.

a) Physics is a basic science

Our physical understanding of nature is based on relativity theory and quantum mechanics, which are both of crucial importance for the epistemological conception of the world. These theories required a departure from long-held "classical" ideas. We know today that mass and energy are equivalent, that space is curved and time depends on the state of motion of the system, that objects have both particle-like and wave-like properties and can be "entangled" over arbitrarily large distances, and so on. The biggest problems in the field of particle physics are the search for Higgs particles, for a better understanding of the mass of particles, and the search for supersymmetric particles, which would mean an extension of the Standard Model. The two institutes of the Academy that are active in this area (the Institute for High-Energy Physics and the Institute for Medium-Energy Physics) are concerned primarily with such problems.

b) Physics is an applied science

In hardly any other discipline are new discoveries so quickly transformed into applications and products – or in so revolutionary a way. One need only think of the whole field of telecommunications, where Maxwell's equations are applied; semiconductor technology, which is based on the laws of quantum mechanics; nuclear energy, where the binding energies of nucleons are harnessed; or new materials whose properties can to a large extent be modeled by their structure and composition. Both the Institute for Biophysics and X-Ray Structure Research and the Erich Schmidt Institute for Materials Science are doing valuable work in these areas.

Physical methods have become indispensable in medicine as well as biology, and are often applied there with no need for detailed understanding of their underlying principles. Physicists were also pioneers of the Internet, because major international collaborations and enormous data sets require fast, secure communication.

c) Physics is an international science

The major international research centers – of which CERN is an outstanding example – have strongly encouraged international cooperation. The basic fact that discoveries in physics cannot be restricted, either locally or regionally, has permitted collaboration independent of political and ideological points of view. One may regret that such collaboration makes it impossible to fairly evaluate the separate work of individual researchers, but in a time of general globalization an individual researcher's capacity for teamwork is increasing in importance. The Austrian Academy of Sciences supports cooperation not only with CERN but also with many other international research centers, such as the Paul Scherrer Institute (PSI) in Villigen, Switzerland; the Laue-Langevin Institute in Grenoble, France; the synchrotron light source ELETTRA in Trieste, Italy; and the fusion program EURATOM of the European Union. The widespread international involvements of the Space Research Institute should also be mentioned here.

As valuable as all these collaborations are, they also indicate a net flow abroad of the means and capacity for research. Hence the wish that has existed for several years, and been adopted by the Austrian federal government, for a major international research facility located in Austria. By far the most progress has been made on plans for a pulsed neutron spallation source, AUSTRON; an evaluation by the European Science Foundation resulted in a recommendation to implement the project. This could signify a fairer balance of research spending among the European nations and a readiness for increased cooperation with the nations of central and eastern Europe.

Institute for High-Energy Physics

The Institute for High-Energy Physics is at present involved in the following high-energy physics experiments at CERN:

- DELPHI experiment at the LEP collider;
- CP-violation experiment NA48 at the Super Proton Synchrotron SPS;
- preparations for the CMS experiment at the Large Hadron Collider (LHC).

At the DELPHI experiment, which has been running since 1989, data acquisition ended in November 2000. The detector is being dismantled in order to make way for the LHC. Of course, the physical analysis of the data is scheduled to continue at least until 2003. The closure of the LEP facility ends not only a significant chapter in the history of high-energy physics but also a very strong and successful participation of the Vienna Institute in the DELPHI experiment. The Institute has been working on this experiment for fifteen years, including time spent in preparation. Parts of the Vienna group will now join the CMS experiment, which in any case is in great need of collaborators for its uncompleted projects. The experiments at LHC, with about 1500 participating scientists, are the largest enterprises of high-energy physics up to now. However, it would be unsatisfactory, from more than just a scientific viewpoint, if eighty per cent of the physicists at the Institute for High-Energy Physics were to spend several years just preparing for *one* experiment, without participating in an experiment that was already under way. Because of this, it was considered that a small group should join an ongoing experiment of the greatest physical interest. But the spectrum of physics experiments at CERN through 2005 is very limited for budgetary reasons because CERN is concentrating exclusively on the construction of the LHC and on related experiments. Hence the plan is to join the BELLE experiment on the B factor at the Japanese laboratory KEK. Also contributing to this decision were the experience in B physics that had been gained at DELPHI and interest in the phenomenon of CP violation, which was already being studied in the NA48 experiment.

In 2001 the CP-violation experiment NA48 will collect data again to measure the CP-violation parameter ε'/ε. A proposal has already been made at CERN to use the detector from the NA48 experiment to measure rare K_S^0 decays with greater accuracy. This program would be scheduled for 2002–2003.

The considerations outlined above lead us to the following program of experiments for the next few years:

- intensified preparation for the CMS experiment at LHC, and its construction and installation;
- continuation of the CP-violation experiment NA48 and measurement of rare K_S^0 decays (until 2003);
- participation in the BELLE experiment at the Japanese laboratory KEK (measurement of CP violation in B decays);
- conclusion of the physical analysis of DELPHI data.

These experiments are listed according to how extensively the Institute is involved in them.

The CMS Experiment

The CMS experiment at CERN's Large Hadron Collider (LHC) is intended to help answer the most important open questions of high-energy physics. Its main goal is to explain the origin of spontaneous symmetry-breaking, which is responsible for the mass of particles (the Higgs mechanism). The hope is to find the Higgs boson that this mechanism would require. Supersymmetry theories predict a broad spectrum of additional new particles. CMS has been in the construction phase since 1998. Final startup is planned for 2005. The Institute is involved with two groups in this experiment, thus in two projects: the development and construction of the CMS trigger, and the construction of the inner tracker.

1) CMS trigger projects

The purpose of the trigger is to select the physically interesting events from the abundance of data to be obtained. Thus the trigger is of the utmost importance for the physical analysis. A discovery can depend on it.

The Institute has three main responsibilities: the construction of the whole global trigger, the global muon trigger, and the central regional muon trigger of the CMS detector. After the design and the prototypes of the two trigger components have been completed, in 2001 at the latest, the final electronic modules will be manufactured. System tests will be carried out in 2003, and the completion of all components is planned for 2004. Final testing and installation in CMS will take place in 2004–2005. Software development and preparation for the data analysis will go on continuously.

2) CMS inner tracker projects

The CMS inner tracker is based on silicon technology. The Institute's role in the construction of the silicon tracker is to manufacture the associated modules and an electronic selection system. As one of six test centers, the Institute must guarantee the uniform quality of the silicon detectors, which are delivered by industrial firms, so that they will be completely functional in the experiment.

In order to integrate these detectors into the modules, about four per cent of the total quantity of such units are to be manufactured at the Institute. In the field of electronics, the project group has accepted tasks in the production of control electronics, in particular for the front-end controller for the silicon trackers and the front-end driver in the silicon pixel system.

The CP-Violation Experiment NA48 and Measurement of Rare K_S^0 Decays

The main goal of this experiment is an extremely accurate measurement of the CP-violation parameter ε'/ε in the K^0 system. A result showing clear evidence of "direct" CP violation has already been published. Greater accuracy is still necessary to be able to infer a possible additional CP-violation mechanism, beyond that of the Standard Model. Data will therefore be collected again in 2001.

In 2002 it is planned to measure rare K_S^0 decays in a K_S^0 beam of extremely high intensity. Such measurements were approved by the CERN SPS committee in September 2000. The Research Board will make a decision on technical and economic feasibility in November 2000.

In addition to carrying out the physical analysis, the Vienna group will have the task of restarting the systems developed and constructed in Vienna, namely the trigger for neutral particles, the tagger, and the clock. As of 2003, the tagging system will no longer be needed; the selection system developed in Vienna will be used with other detectors.

Participation in the BELLE Experiment at KEK (Japan)

The scientific goal at BELLE is the complete measurement of CP violation in a $B\bar{B}$ system. This project thus represents an ideal continuation or combination of two current research areas: DELPHI (physics at the Z^0, with the production of 20% *b* quarks) and the CP-violation experiment NA48. The KEK-B asymmetric accelerator (e^- with 8.0 GeV/c and e^+ with 3.5 GeV/c) acts as a "factory" for B mesons with center-of-mass energy [$Y(4S) \rightarrow B^0\bar{B}^0$]; that is, around 10.6 GeV center-of-mass energy, with a design luminosity of 10^{34} $cm^{-2}sec^{-1}$, which reaches the limits of accelerator development. In one year, at the lower luminosity (~ 20%) achieved up to now, around 6 million $B\bar{B}$ events were produced. This number alone shows that the quantity of available events lies far beyond that achieved at the Z^0 pole at LEP (~ 0.6 million $B\bar{B}$ events).

The BELLE experiment thus makes possible an extremely accurate measurement of CP violation, and in particular (through a combination of a large number of decays of the $B\bar{B}$ system) a test of CP violation in the Standard Model. Via the CKM matrix, this model links the flavor and mass eigenstates of quarks. Of course, discovering a deviation from the Standard Model would be especially interesting because this would suggest "new physics." KEK is very interested in internationalization and bringing in international expertise. For this reason, collaborators are not required to contribute to the cost of running the experiment or the accelerator – in complete contrast to the common practice at other accelerators (CERN, DESY, SLAC).

The period of the BELLE experiment fits exactly into the time between the end of LEP and the beginning of LHC, and thus makes it possible to test the Standard Model with great accuracy or to indicate the limits that would suggest new phenomena.

Concurrent and Complementary Research Activities

In accordance with the structure of the Institute, these collaborations in high-energy physics experiments will be accompanied by concentrated activity in the following research areas:

- theoretical and phenomenological studies, especially in the area of Higgs particles and supersymmetry;
- development in the field of solid-state detectors for CMS, later with a view to an e^+e^- linear collider;
- development in the field of electronics (global muon trigger and global trigger, front-end driver for the pixel detector, and selector chip for the silicon tracker) for the CMS experiment, and possibly selector modules for the BELLE experiment;
- development of algorithms for track reconstruction for the CMS experiment, and later also for an e^+e^- linear collider.

Institute for Medium-Energy Physics

In the field of subatomic physics, the core of the Institute's work is represented by selected topics in fundamental symmetries and interactions, primarily quantum chromodynamics (QCD) and the electroweak interaction in the low-energy and high-energy realms of hadrons and leptons. This general course has been followed for years and will be maintained in the proposed 2001–2005 Medium-Term Research Program. Shifts of emphasis, but no major course changes, will naturally occur for various reasons. The general course is marked out as laboratories for special problems, by way of hadronic few-particle systems and "exotic atoms" (atoms in which standard orbital particles or nuclear particles are replaced by "exotic" elementary particles – electrons by muons, pions, or kaons, for instance, or the proton in the hydrogen atom by an antiproton).

Important reasons for shifts of emphasis are

1) New accelerators, which offer new possibilities:
For instance, CERN's Antiproton Decelerator (AD), at which the ATRAP antihydrogen experiment is being carried out (see below); the meson factory DAFNE for K-meson production (LN Frascati of the INFN).

2) Advances in laser technology:
2-photon excitation of ($1s \rightarrow 2s$) transitions, e.g. in hydrogen (1-photon transitions forbidden); new technical developments (e.g. CCD detectors for evidence of X-ray radiation, solid-state position-resolving particle detectors, miniaturization of electronic and computing components, and so on).

3) New discoveries:
The successful use of pulsed electric fields for the production of atoms in particle traps demonstrates an efficient way to create an atomic state consisting of an antiproton (antiparticle of the proton) and a positron (antiparticle of the electron), the simplest atomic system for the study of antimatter.

Three themes will initially dominate the work of the institute:

- antihydrogen at CERN (ATRAP);
- pionic hydrogen at PSI (R-98-01.1);
- kaonic hydrogen at DAΦNE.

The ATRAP experiment at CERN's Antiproton Decelerator (AD), for the first preparation of antihydrogen atoms in large quantities, is attempting the first precision spectroscopy of this atom so that ultimately, by comparison with the spectroscopy of normal hydrogen, CPT can be tested for the first time at the atomic level. (CPT = charge conjugation C, parity P, and time reversal T.) ATRAP's high international ranking and CERN's construction of the dedicated antiproton facility AD derive from the fundamental interest in CPT symmetry. This experiment, which is challenging both intellectually and because of the experimental technology involved, has the highest priority in the work of the Institute. Of course, like all the Institute's experiments, it is being run with international collaboration. Like all the Institute's previous collaborations, this one demonstrates both the Institute's capacity and need for international collaboration. The Institute will produce some of the necessary experimental technology itself, and some will be furnished by partners. ATRAP is a good example of the diversity of disciplines and capabilities:

Accelerator (CERN): the best facility in the world for low-energy antiprotons.

Atomic physics: Harvard University, responsible for storage mechanisms for slow antiprotons and positrons in the production of antihydrogen.

Quantum optics: Max Planck Institute for Quantum Optics (Munich), responsible for comparative spectroscopy of antihydrogen and hydrogen.

Subatomic physics (medium-energy physics, particle physics): Institute for Medium-Energy Physics of the Austrian Academy of Sciences, Jülich Research Center

Particle detectors, as well as associated electronics and data selection: Jülich Research Center.

The Institute's collaborations have always been distinctively international, extending across Europe, America, and Asia. This is also true of the Institute's other projects, which deal with special topics in low-energy QCD, namely chiral symmetry-breaking in pion-nucleon and kaon-nucleon interactions. The high international ranking of these experiments is evident:

- pionic hydrogen: particularly large investments by PSI and the Jülich Research Center.
- kaonic hydrogen: In Frascati, the Italian INFN is building an accelerator devoted to kaon production (DAΦNE).

Because of their scientific potential, these experiments are receiving high priority in the Institute's program.

In the framework of the medium-term Joint Research Program of research in QCD in the low-energy realm, the pion-nucleon (strong) interaction in pionic hydrogen is being studied at PSI. The goal of this important experiment is to determine the pion-nucleon sigma term as a test of chiral symmetry-breaking in the realm of up and down quarks. The accurate measurement of the strong-interaction shift and width of the ground state of pionic hydrogen (measurement of the K_α X-ray line) furthers this goal. The experiment is being conducted with international collaboration:

Accelerator (PSI): Intense pion and muon beams of high phase-space quality (focus, impulse sharpness).

Target system: Institute for Medium-Energy Physics, responsible for the cryogenic hydrogen target system.

Cyclotron trap for pions: PSI, responsible for the cyclotron trap.

Crystal spectrometer: Jülich Research Center, responsible for the high-resolution X-ray spectroscopy.

CCD X-ray detector system: Leicester University, Institute for Medium-Energy Physics.

The DEAR experiment (DAΦNE Exotic Atomic Research) on the kaon-nucleon interaction, in Frascati, Italy, belongs to the same general theme of QCD in the low-energy realm (chiral symmetry-breaking). For a long time, the Particle Data Group has been requesting the precise measurement of the strong-interaction shift and width of the K_α line of kaonic hydrogen and deuterium as an especially important experiment in kaon physics.

The Institute's research projects are supported in the framework of the program *transnational access to research infrastructure* in the Fifth Framework Program of the EU. The international participation in DEAR combines complementary expertise of the collaborating institutions:

Accelerators (DAΦNE, LNF): Production of practically mono-energetic kaons from the decay of phi mesons.

Experimental technology: Institute for Medium-Energy Physics, responsible for the cryogenic hydrogen target, among other things.

CCD X-ray detector system, kaon monitor, data acquisition and analysis: Institute for Medium-Energy Physics, jointly with LNF, University of Neuchâtel, Tokyo Institute of Technology.

Theory: Institute for Medium-Energy Physics; California State University at Northridge.

The experimental program of DEAR is starting with research on kaonic nitrogen. These measurements are intended both to investigate the X-ray transitions of kaonic nitrogen, which are interesting per se, and to clarify important parameters for the experiment on kaonic hydrogen.

A new idea for directly measuring the sticking probability of the muon in the fusion product helium (the sticking factor) is being tested. The goals are to determine the sticking at high density and to investigate stripping reactions directly. Collaborations with TRIUMF, in Canada, and RIKEN, in Japan, are being considered. Determining the loss term in the reaction cycle of muon-catalyzed fusion is of great importance in the long run for information about efficiency and hence about possible applications of muon-catalyzed fusion to energy technology.

Other attractive ideas are in the stage of preliminary studies. These are related to the general theme of muon physics, and range from muon-catalyzed fusion in triple mixtures of hydrogen, deuterium, and tritium and muon-catalyzed fusion at high temperatures to a high-flux neutron source based on muon-catalyzed fusion.

Institute for Discrete Mathematics

The following themes are to be treated in the next few years:

1) Quasi–Monte Carlo Methods, Pseudorandom Numbers

At the Institute for Discrete Mathematics, the subproject *quasirandom points and pseudorandom numbers* is being worked on within the FWF (Austrian Science Fund) Joint Research Program *number-theoretic algorithms and their applications*. Research groups at universities in Graz, Leoben, Linz, Salzburg, and Vienna are also participating in this Joint Research Program. This is the point of view from which the research plans presented in this section should be considered.

(t,s) sequences and (t,m,s) nets: In the theory of low-discrepancy point sets, attention will continue to be focused on *(t,s)* sequences and *(t,m,s)* nets. Research will particularly emphasize the so-called propagation rules and the use of interconnections in coding theory.

Software development: Software implementation for Niederreiter-Xing sequences will continue to be accelerated and optimized (duration of the project: until 2002); the "Salzburg Tables" will be brought up to date.

Pseudorandom numbers: The productive research on nonlinear generators – in particular, the search for lattice tests and studies of the distribution behavior in parts of the period – will be continued. New generators will be implemented and empirically evaluated.

2) Coding Theory and Cryptography

XNL codes: In the field of asymptotics, the construction of codes by way of algebraic curves, introduced by Goppa, made possible an improvement of the Gilbert-Varshamov bound. But this does not yet include the case of binary codes, which is particularly important for applications. Generalizations to this case are already known; among them, the codes developed recently by Xing, Niederreiter, and Lam (XNL codes) lead to the explicit construction of binary codes with improved asymptotic properties.

Hyperelliptic curves: For cryptographic purposes, it is of interest to construct groups whose order is divisible by a large prime number. The Jacobians of hyperelliptic curves seem to be particularly well suited to this. "Good" hyperelliptic curves will be sought by means of explicit, rapidly computable character sums. Collaborating institutions: University of Illinois at Urbana-Champaign, University of Essen.

Linear complexity: Known results on linear complexity (with tolerance k) of periodic sequences and of finite sequences over finite fields are to be generalized or refined. Other questions about the complexity of random sequences will also be considered.

3) Algebra and Number Theory

Theory of finite fields: To break current cryptographic systems, it is of interest to represent the discrete logarithm in a finite field by a simple function. The intention is to show that this is impossible for certain classes of functions. The tools are exponential sums. Other problems in the theory of finite fields will also be considered.

Global fields: The research in coding theory described above leads to problems in pure algebraic number theory, such as the study of the behavior of places (especially those of higher degree) in towers of function fields. The determination of Riemann-Roch bases, which is important for coding theory and quasi–Monte Carlo methods, will be continued.

Diophantine approximation: The classical $n\alpha$ sequences and their higher-dimensional generalization, Kronecker sequences, will continue to be a topic of research at the Institute. In the one-dimensional case, results are emerging that lead in the direction of Baire categories. In the higher-dimensional case, one is first looking for analogies to the continued-fraction expansion. The most recent results suggest that, at least for a qualitative theory, there are connections with certain filters on the set of integers. Collaborating institutions: Graz University of Technology, Vienna University of Technology, Free University of Berlin; planned: University of Marseille-Luminy.

Commutativity: Existing results on permutations, polynomial functions over finite fields, and certain real-valued functions over the reals will, as far as possible, be unified into a coherent point of view and generalized. The commutativity of mappings is of particular interest for encoding data.

Lattice theory: Research on orthomodular lattices and generalized MV algebras will be continued. Collaborating institutions: Vienna University of Technology, Olomouc University (Olmütz).

4) Measure-Theoretic and Topological Methods

Group compactifications: The filters mentioned above provide connections between classical number theory and topological groups. This builds a bridge to the almost-periodic functions.

Dynamical systems: Many of the number-theoretic research projects outlined above can also be considered from the point of view of dynamical systems, in particular that of symbolic dynamics. Collaborating institutions: Free University of Berlin, Berlin University of Technology, University of Marseille-Luminy.

5) Graph Theory, Complexity, and Logic

Basic research in graph theory: When the last volume of the monograph *Eulerian Graphs and Related Topics* is written, its central themes will include previous Joint Research Programs such as the *cycle double cover conjecture* and the *compatibility conjecture* (in which the Institute has been involved in long-standing collaborations). A textbook on graph theory is to be written afterwards. Collaborating institutions: universities in Pilsen and Montreal; Belorussian Academy of Sciences (INTAS project; duration until 2001).

Algorithmic complexity: The applications of graph-theoretic methods to the satisfiability problem that have been worked out in the framework of the FWF project *graph-theoretic investigation of proof graphs* will continue to be developed. So will the research on autarky systems and on attainability in formula graphs. Collaborating institution: University of Toronto.

Logic: The latest results in order theory appear to have applications to the theory of multivalued logics, but the future significance of this research area cannot yet be measured.

Concluding Remark

In the near future, the conversion of one of the rooms at the Institute into a seminar room is being considered, not only to facilitate the internal networking of the Institute but also to improve collaboration with visitors to the Institute. The resources needed for this are relatively modest. The following Joint Research Programs were listed in the medium-term research program of the Institute: *quasi–Monte Carlo methods and pseudorandom numbers; coding theory and cryptography; algebra and number theory; measure-theoretic and topological methods; graph theory; complexity and logic.* Strengthening these research areas and developing new ones are critically dependent on funding, and thus on the possibility of increasing the staff of the Institute. As a first step in this direction, the expansion of the research area *discrete algorithms and algorithmic complexity* is being considered. This is intended to take into account the field's explosive development in the last decade from an applied viewpoint as well. It also influences the basic research of the Institute. (Keywords: algebraic properties of discrete structures or estimates of such structures.) Enhancing existing research in the area of symbolic dynamics is also desirable. Finally, in the further development of the Institute, one worthwhile goal in basic research would be to pursue new research areas in discrete mathematics. More detailed ideas are to be presented in written form in the near future.