PHYSICS

Physics research:
topics, significance and prospects

October 2002
Deutsche Physikalische Gesellschaft e.V.

PHYSICS

Physics research: topics, significance and prospects

4

04
12

PHYSICS

Physics research: topics, significance and prospects

A report
to society, policy-makers and industry

English Edition

October 2002
Deutsche Physikalische Gesellschaft e.V.

Die Deutsche Bibliothek (German Library) - CIP unit record

Physik - Themen, Bedeutung und Perspektiven physikalischer Forschung:
Denkschrift zum Jahr der Physik; ein Bericht an Gesellschaft, Politik und Industrie
[Physics - Physics research: topics, significance and prospects:
Denkschrift for the Year of Physics; a report to society, policy-makers and industry] /
Eds. Deutsche Physikalische Gesellschaft. Markus Schwoerer ... - Bad Honnef:
Dt. Physikalische Ges., 2002
ISBN 3-00-009664-7

Cover picture: Atom laser (see page 50)

October 2002

Publishing information

Publisher
Deutsche Physikalische Gesellschaft e.V. (DPG)
Hauptstrasse 5
D-53604 Bad Honnef
Tel.: +49 (2224) 9232-0
Fax: +49 (2224) 9232-50
E-mail: dpg@dpg-physik.de
Internet: www.dpg-physik.de

Editor-in-Chief
Dr. Rainer Scharf

Layout
Druck- und Werbegesellschaft m.b.H., Bonn

ISBN 3-00-009664-7

Foreword for the first (German) Edition

This *Denkschrift* is the attempt of the German Physical Society to provide a position statement at the threshold of the third millennium. More and more people have come to realise over the past decades that we are growing out of our living space on Earth and that our resources are limited. All the forces in our society need to make an effort to find the right answers to the questions arising from this realisation. With this document, the physicists of the oldest physical society in the world and the largest in Europe want to paint a picture of the present situation and the prospects, opportunities and risks of physics research. This *Denkschrift* is aimed at the general public, politicians and policy-makers, trade and industry, journalists, scientists in other disciplines and, last but not least, at physicists themselves. It is intended to illustrate the fascination of physics research today, in particular, but also to stimulate thought about the consequences of this research.

In addition, the *Denkschrift* is intended to provide an impression of the cultural benefits associated with this science and to help make people generally more aware of the extent to which many of the functions of a modern society are dependent on the knowledge and concepts of science and of physics. Future developments are of particular importance in this respect, the sensible shaping of which must be based on rational actions and decision-making processes.

Germany's Federal Minister of Education and Research, Ms. Edelgard Bulmahn, together with the German Physical Society, has declared the year 2000 as the Year of Physics in Germany as part of the "Science in Dialogue" initiative. The public events generously sponsored by the Federal Government in the Year of Physics are already revealing a high degree of receptiveness to scientific and technological problems among a broad section of the general public. For the scientists involved, this has triggered various learning processes regarding how to deal with an interested public with no specialist educational background. This initiative has also attracted international attention in the meantime, for example in the comment in the scientific journal "Nature" on 24 August 2000, stating that: "... German researchers have succeeded in enhancing the accessibility of physics. Others should benefit from their example". The German Physical Society would like to take this opportunity of thanking the Minister for her emphatic support. Special thanks must also go to Assistant Secretary Dr. Hermann-Friedrich Wagner for his initiative and constant, active support, without which this Year of Physics could not have taken place.

Finally, our sincere thanks go to Markus Schwoerer and the other members of the Committee, who pushed forward the preparation of this *Denkschrift*, and, in particular, to the many colleagues who contributed to it as authors.

Dr. Dirk Basting
President of the German Physical Society

Bad Honnef, November 2000

Prologue of the President of the Chinese Physical Society

The book entitled "*Denkschrift* of Physics" which is sponsored by the Deutsche Physikalische Gesellschaft (German Physical Society) and written by many distinguished German physicists, is an excellent and authoritative advanced popular science work. It explains the profound in simple terms, combines text nicely with figure illustrations, and is genuinely fascinating. I am sure that its publication will be very helpful for college students and physics researchers to learn the main subjects and the trends of modern physics. Here I would like to express my warm congratulations on its publication.

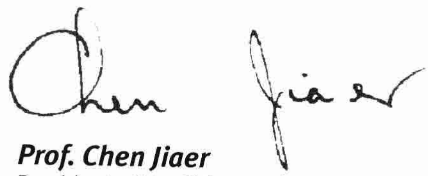
Physics is a discipline of science which studies the structures and basic laws governing the motion of matter at all levels in nature. During the 20th century, tremendous progress has been achieved in physics. The revolutionary development represented by quantum mechanics and relativity has not only greatly deepened human understanding of the laws of Nature and strongly promoted the advancement of natural science as a whole, leading to major changes of people's view of the Universe, but has also brought about leaps in technology, promoted the rapid development in semiconductor technology, computer technology, laser technology, communication technology, nuclear technology, new materials and new energy resources, and given rise to enormous changes to the productivity and lifestyle of human beings, exerting an extremely important influence on modern society and human civilization. It has been realized that quantum mechanics and relativity are not only the basis of modern physics, but also the basis for many other disciplines of science, such as biology, information science, chemistry and materials science.

Being the foundation of natural science, modern physics has developed into a very rich and diversified discipline of science. It includes many relatively independent subdisciplines, such as particle physics, nuclear physics, atomic and molecular physics, plasma physics, condensed matter physics, astrophysics, electromagnetism, optics, acoustics, theoretical physics and computational physics. It is pushing human understanding of Nature to an unprecedented depth and extent from the perspectives of microscopic, macroscopic and complex systems and is revealing the secrets of Nature from a deeper level and a broader scope. During this process, many new ideas, theories, methods and technologies in physics are springing up and are adding new contents to the human treasure house of knowledge.

The mutual penetration and interaction between various subdisciplines of physics and that between physics and chemistry, biology, materials science and information science will inevitably produce new borderline disciplines, which not only expand and enrich the research areas of natural science, but also themselves are usually the most promising frontiers.

Undoubtedly, physics will remain the foundation of natural science in the 21st century and will play its fundamental role in its integration with other disciplines. New methods and technologies originated from the development of physics will continue to be the sources and growing points for new technological revolution.

It is rather difficult for us to predict at the beginning of the 21st century the development of physics to be achieved in the whole 21st century or even in the mid-21st century, just as half a century ago people could hardly imagine that physics could have reached such an intensive and extensive level at present. In any case, physicists will continue their exploration of the structures and basic laws governing the motion of matter at all levels in Nature in their persistent pursuit of science by making use of the modern precision scientific instruments and applying strict mathematical methodologies – with the strongest thirst for knowledge and in the most rigorous way – and will continue to make great contributions.



Prof. Chen Jiaer
President of the Chinese Physical Society

Greeting from the President of the German Physical Society

From its beginnings in the late middle ages, modern science has been an international endeavor. While physics was initially mostly concentrated in Europe, the 20$^{\text{th}}$ century brought a world-wide dissemination of the physical sciences. Today physics has become part of a world civilization with contributions from many countries. In fact, without physics and the technologies that grew out of it the basis for a truly international society which relies on mobility and information would not exist. The present Memorandum or *Denkschrift* reviewing physics at the beginning of the 21$^{\text{st}}$ century was initially written from a German perspective. In its entirety, however, it may also represent a summary of physics which is shared by the international community of physicists.

The *Denkschrift* gives an overview over all aspects of modern physics. It is written in a style that should be accessible not only to physicists and other scientists, but also to interested non-specialists. An important reason for writing this *Denkschrift* was – in addition to exhibiting the status of modern physics in Germany – to show the relations between physics, society, and culture.

The German Physical Society is grateful to the German Ministry for Education and Research for its continuing support in publicizing physics through the initiative "Highlights in Physics" which started with the first edition of the *Denkschrift* "Physics – topics, significance and prospects of physics research" in the year 2000.

It is a great pleasure for the German Physical Society to present the third edition of this *Denkschrift* to the Chinese physicists. The German Physical Society recognizes the rich history of Chinese physics and the important contributions of Chinese physicists to our science. For the future we hope that this exchange of scientific ideas might stimulate an ever closer collaboration between Chinese and German physicists. This collaboration may in turn initiate new ideas and lead to novel and important results in our science for the benefit of both of our countries.

Prof. Roland Sauerbrey
President of the German Physical Society

Bad Honnef, October 2002

Table of Contents

TABLE OF CONTENTS

1 PREFACE

What is physics and what is the purpose of studying it?

Friedrich Schiller, *Professor of History at Jena*, asked and discussed the same question in his *academic inaugural address at the commencement of his lectures* on 26 May 1789, although he was referring to world history. On reading his lecture today, fascinating analogies can be seen between the fundamental problems of these two, so very different sciences. Physics is fundamental, fruitful and all-embracing. The laws of Nature are explored in physics with the greatest possible methodological rigour. To do so, the physicist makes use of experiments and mathematics, both of which are timeless and universally applicable, like the laws of physics themselves. The urge of humankind to discover these laws is as old as civilisation itself. To paraphrase a dictum of Schiller, *without knowing it or achieving it, every previous era has striven to bring about the twentieth century* – the century of physics. The achievement of pure physics research in the twentieth century is to have gained an understanding of the fundamental laws of Nature, neither the depth nor breadth of which could have been imagined even fifty years ago.

The desire to apply the laws of Nature is just as old as the urge to understand them. *Very different is the plan of study of the scholar who looks towards future earnings from that of the philosophically inclined* (F. S.). Pure research and its applications are inseparable in physics. Without pure research, there will be no new knowledge, and without new knowledge, culture and civilisation will wither. The people of this country can control whether new knowledge will be a blessing or a curse if, and only if, they have been given a broad education. In the future, this education will increasingly have to include a broad base of mathematical and scientific education.

The title of this *Denkschrift* is an updated formulation of Schiller's question:

Physics research: topics, significance and prospects.

By publishing the first edition in the year 2000, which was the Year of Physics in Germany, the German Physical Society made a contribution to fulfilling its obligation to the general public – society, policy-makers and industry. The first two editions were already sold out shortly after publication. The third, expanded German edition and this English edition of the *Denkschrift* now contain three introductory theses in Chapter 2, the third of which, on the ethical principles and responsibilities of physicists, is new.

The two, long Chapters 3 and 4 describe current topics in physics. The structure of Chapter 3 follows the principles for classification of the subfields of physics, as accepted all over the world. However, this breakdown must not be allowed to disguise the fact that physics is a single entity. Only from this entity can new, fundamental areas of research continue to develop. To this end, each generation must study anew at least the elementary principles of the major subdivisions of physics as a whole. One example of a subfield that is developing successfully at present is physics in biology (Chapter 3.5). In terms of content, it has very little in common with the biophysics of fifty years ago. Nor, in many cases, can the research content or topicality of the other subfields be deduced from their names.

The contents of Chapters 3 and 4 can only be seen as examples. The *Denkschrift* makes no claim to be encyclopaedic – it is far too short for that. Rather, one of its objectives is to give the reader an idea of the fascination that emanates from physics research. The examples are also intended to provide orientation regarding those areas of physics research that are likely to be of particular importance over the next few years. In Chapter 4, in particular, the number of examples had to be reduced to such an extend, that it appears minimal in relation to the role that physics plays in our modern technology, in spite of the addition of a section on microelectronics in the third and this English edition. The reader will also notice that the breakdown of the topics into Chapters 3 and 4 is arbitrary in many places. The reason for this unavoidable arbitrariness has already been mentioned: the close ties between pure research and application.

Chapter 5 discusses historical, cultural and philosophical aspects of physics. It has its origins in philosophy, after all.

Chapter 6 of the first edition has been restructured, greatly expanded and split into the two Chapters 6 and 7 in this edition. Both chapters cover issues of science policy, the content of which is considered to be of particular importance for securing the existence of our society in the long term. In Chapter 6, these subjects are "Physics in School" and "Physics Education at German Universities". These topics are a primary concern of the German Physical Society: our society must make a major effort to improve general education in mathematics and the natural sciences in the near future, and teaching and research at German universities must be designed so that the physicists trained there can continue to hold a leading position in the international competition in research and industry in the future. In addition, the working conditions for women in physics must be specifically improved. Chapter 7 describes the professional sphere of the physicist, the well-organised structure and financing of research centres and the large-scale facilities required for physical research and the continuous promotion of internationality.

1. Physics is a fundamental natural science, a part of our culture and the basis of technology.

Physics strives to understand events in Nature and technology, to link the course of these events to generally valid laws – the laws of Nature – and to identify the effect of chance, which has its own laws, on the course of these events. It is said that interest in physics stems from the need to allay the superstition that evil spirits can trigger an unfavourable chain of events at any time. The laws of Nature teach us that the world has an inherent order. As far as we know at present, this order is universally valid; nothing can escape it. While all matter in our world is subject to constant change, the order based on the laws of Nature is, to the best of our knowledge, timeless and beyond the realm of temporal change. It is this order that represents constancy in our world. It is entirely beyond the reach of human intervention. It is inviolable. There do not appear to be any violations of this order, no matter how wildly material processes rage in the cosmos or war and terror ravage our earthly realm. We can put all our trust in this natural order, at any given place and time. We must build on this order in everything we do and plan. That is the message.

Physics has its roots in antiquity. "At the beginning of Western culture, we find the close link between questions in principle and action in practice, as introduced by the Greeks. The whole strength of our culture still remains based on this link today" (Werner Heisenberg). In the 17th century, Johannes Kepler, Galileo Galilei and Isaac Newton established the methodology of modern physics by extracting individual processes in Nature from their context and investigating them quantitatively using experiments. This ultimately enabled them to formulate basic laws of physics in mathematical terms, as a result of which they could "understand" processes as varied as free fall, the motion of the planets and the swing of a pendulum.

At the end of the 19th century, scientists started to clarify the electronic structure of matter. This made it possible for the first time to understand the essence of X-rays and the natural radioactivity discovered by Henri Becquerel, Marie Curie and Pierre Curie. Joseph Thomson discovered the electron, the first indivisible particle, in 1897. At the start of the 20th century, Albert Einstein through his theory of relativity revolutionised our concept of space and time. He and Max Planck discovered the photon, the elementary particle of light. By developing quantum theory, Werner Heisenberg, Erwin Schrödinger, Paul Dirac and Wolfgang Pauli resolved the problem of wave-particle duality not only for light, but for all particles. From quantum theory, we have learned that our traditional notions of causality and determinism become "blurred" in the microscopic world, and how this happens.

These discoveries constituted the start of modern physics of the 20th century. Since then, physicists have constantly been discovering new, exciting phenomena and laws of Nature. Causality and determinism are blurred in the macroscopic world as well. We learn this from nonlinear dynamics. The realisation that, despite strict laws of Nature, much that is important in the world cannot be predicted, is one of the major recent discoveries of physics. The evident failure of the mechanistic way of thinking, which prevailed for centuries in physics, is one of the reasons for the fear of physics and technology that can be perceived among the general public.

The primary aim of physicists is to explore the laws of Nature. The discoveries they make, the insights they gain, and the applications based on these, have shaped our picture of the world to an extent that we can survey in its entirety only by moving our outlook back to a past age. We do not need to go back hundreds of years to do this, to the time of Nicolaus Copernicus, for example. A single century will suffice. Just a hundred years ago, not even the existence of atoms was considered certain. Since then, physics has provided us with an image of the structure and dynamics of our world that is often beyond human powers of imagination but that, at the same time, has been proved experimentally and is constantly better understood. It ranges from the smallest to the largest, the lightest to the heaviest, the slowest to the fastest, the coldest to the hottest, the brightest to the darkest, the most tenuous to the most dense matter and from the beginnings of the Universe to today. Twenty or more orders of magnitude lie between these extremes in whatever dimension is being considered. Much of this grandiose picture is based on extrapolations from the known into the unexplored, some is based on bold hypotheses. This is the lifeblood of all science. Columbus believed the hypothesis that the world was round and that he could therefore reach India by sea. This belief gave him his impetus. Admittedly, he did not reach India, but he did discover America. The research objects of physics are often initially way beyond what we can experience directly. But sooner or later, fundamental scientific discoveries will affect us just as directly as the discovery of America. Physics is the most elementary of all the natural sciences. It is a formative part of our culture.

Thus, for example, radio and X-ray astronomy, and the knowledge and application of the basic laws of relativistic mechanics and electromagnetic radiation, are essential for our current knowledge of the structure and development of the Universe. The interest of humankind in exploring the tiniest or most short-lived building blocks of matter, the elementary particles, and their interactions, is just as great as the ancient interest in cosmological questions. This research is vitally dependent on the high energies to which electrons and other charged particles are accelerated in large-scale research facilities, e.g. in the German Electron Synchrotron (DESY), at the Organisation (formerly Conseil) Européenne pour la Recherche Nucléaire (CERN – European Organisation for Nuclear Research) or the Gesellschaft für Schwerionenforschung (GSI – Society for Heavy-Ion Research). Nuclear physics, high-energy physics and cosmology are inseparably linked to one another and part of the foundations of physics. Thus, physics covers a broad spectrum, from the dimensions of the cosmos to those of elementary particles. Exploration of the smallest building blocks of matter is decisive if we are to understand the Big Bang and the development of the cosmos.

The direct and day-to-day interest of humankind is in the macroscopic matter surrounding us: the solids, liquids, gases and plasmas. Their atomic structure and molecular dynamics were first brought to light by quantum theory and the experimental methods of spectroscopy and microscopy with photons, electrons, neutrons and other particles. This applies to both animate and inanimate matter. For instance, the discovery of the double helix structure of deoxyribonucleic acid (DNA) by Francis Crick, Rosalind Franklin, James Watson and Maurice Wilkins was fundamentally characterised by the methods of physics, as is the clarification of the human genome sequences which is evidently close to completion today.

Physics has a broad and sometimes decisive influence on other disciplines: the development of apparatus, together with the experimental and theoretical methods of physics, form the basis for many other sciences and their continued successes. The "mathematisation" of science is also derived from the example of physics. Physics research thus forms an indispensable component of the natural and engineering science disciplines, in particular. It has been, and still is, the basis of an economy based on modern technology.

The laser, invented only 40 years ago, is the basis of compact disc (CD) technology, laser welding technology, laser ophthalmology and, of course, of all the technologies of laser optics. – The transistor, invented 50 years ago, has left a decisive mark on all our electronic equipment. Without it and other semiconductor components and their miniaturisation in large-scale integrated circuits, neither computer technology, nor the technology for controlling electronic equipment, nor modern telecommunications could exist. – Without the nuclear spin postulated for the first time by Wolfgang Pauli in 1924, and directly demonstrated shortly afterwards, we would have neither the medical technique of NMR imaging for generating sectional images of the inside of the body, nor the atomic clock as an essential component for controlling high-speed telecommunication and satellite-aided navigation (GPS). The list of examples could go on almost indefinitely: our cars are also loaded with physics-based components. The applications of pure physics research are thus obviously of major economic importance.

Decisive technological breakthroughs are, however, often based on the results of physics research whose original goal was not an application at all. The revolutionary technological developments of the twentieth century have always evolved from the close link between pure research and the development of new experimental and theoretical methods. Most of them were based on physics. One-sided gearing of all research in the natural sciences, and particularly in physics, to technical application, market orientation and interdisciplinarity would, therefore, ultimately result in irreparable damage. This is why high priority must be given to free development in pure research, and to estimating and preventing major risks.

At the start of the 21st century, too, physicists are looking into fundamental problems of physics, chemistry, engineering and, to an increasing extent, of biology, as well. The wide-open field of exciting physics research in the future is enormous. This *Denkschrift* contains a wealth of interesting examples of this, of which only a few will be mentioned here, selected more or less at random. Physicists today are capable of generating macroscopically coherent matter waves consisting of a very large number of atoms, but possessing wave characteristics corresponding to those of laser light. The exploration of these coherent matter waves and their interactions with other matter and with light promises to be very exciting. – Up to a few years ago, it would have been considered impossible to produce and explore minute structures consisting of only a few atoms or molecules. But, in the meantime, new experimental techniques are making it possible to analyse and manipulate even single atoms or molecules. This area of physics, investigating particles with a diameter of a few nanometres (millionths of a millimetre) or less, is expected to yield numerous technological applications in the field of "nanotechnology". – The methods of mathematical physics will remain indispensable for the analysis of complex dynamic processes and processes of structure formation. – High-temperature superconductivity is continuing to be studied with the aim, among other things, of reducing losses in the supply of electrical power and in transport engineering. – Controlled nuclear fusion is one of the most ambitious international projects of the future. It is intended to reduce the peremptory problems with which we are encumbering future generations by largely using up the limited supplies of fossil fuels. – Scanning the cosmos using X-ray telescopes on unmanned satellites, for example, will increase our knowledge of the origin, structure and dynamics of the Universe, as will the analysis of "invisible" neutrino fluxes using complex and costly subterranean detectors. – Experiments and theoretical developments will lead to a new understanding of the elementary building blocks of the Universe and to a uniform description of the fundamental forces of Nature. – The investigation of the biophysical elementary processes of photosynthesis, which are a precondition for life on the Earth, is making astonishing progress at present. Photosynthesis is just one example of the fact that physicists are exploring intensively and with great success essential questions of a physical nature in other natural sciences. In the field of chemistry, this interdisciplinary cooperation has long had major economic effects.

Physics is alive and well. It will therefore continue in future to be the fundamental natural science, a part of our culture and the basis of our technology.

2. Physics is indispensable and must be an essential part of our general education.

The laws of Nature govern what happens around us, what happens inside us and also the possibilities and ways we, as living beings, interact with our natural and technical environment. In short, knowledge and study of the laws of Nature give us insight into the workings of the world around us and inside us. Furthermore, they show us ways to find answers to pressing questions regarding our existence and our role as living creatures in this world: Where do we come from? Where are we going? What should we do? What can we do? What may we do? These are questions which certainly cannot be answered from the standpoint of the natural sciences alone, which challenge the very essence of our human nature, and which likewise cannot, and should not, be answered without Humankind being familiar with Nature and in touch with the natural sciences.

Science and technology are highly regarded in Germany. Only if Germany continues to be active at the forefront of the sciences and their applications in the future will it survive in the face of global competition. The innovation cycles for new technologies are very short – far shorter than one person's working life. Although most people do not work at the forefront of the natural sciences and their applications, they are constantly using these applications. More than that: they are dependent on them for their very existence.

A sound basic knowledge of physics is essential for many non-physics disciplines (e.g. mathematics, chemistry, biology, medicine, engineering sciences). A knowledge of the methods of working and the concepts in physics is of fundamental importance, even for areas such as philosophy, epistemology and the theory of science, economic and financial studies.

We therefore believe it essential to offer and impart a basic knowledge of Nature and processes in Nature to broad segments of the population in a suitable form. This is primarily the responsibility of schools, technical colleges and universities. In a broader sense, however, it is also the responsibility of all institutions entrusted with educational tasks, religious communities of all denominations, all media and all institutions called upon to help shape our lives.

Only schools providing general education can impart a basic knowledge of physics on a broad scale. For many young people, this is the only place where they can grapple with the problems of physics. Physics instruction must start as early as possible, but not later than the 6th or 7th year of school in a form that the pupils can understand and must be offered in every subsequent year at schools offering general education.

A school offering general education must give the population the knowledge that the revolutionary technological developments of the 20th century always developed from the close link between pure research and new experimental and theoretical methods. Building on physics and technology classes in the first stage of secondary education, every pupil in the second stage of secondary education can and must learn that all our knowledge is the result of research and that it is only with this knowledge that people are in a position to play an active role in shaping their own future.

The prerequisite for political decisions regarding the scale and priorities of research funding and the promotion and assessment of large-scale technical projects is a sound school education in physics, the science of fundamental importance for technology. These decisions must be communicated to the entire population, which must understand them and support them. But an appropriate school education in physics is again required for this to be possible. This is why the insights of the natural sciences, as a part of our culture, must be a part of general education in this country as a matter of course, just as are the great works of the poets, philosophers and artists.