# Training in nuclear science

## *The International Centre for Theoretical Physics serves as a clearinghouse for nuclear and reactor physics*

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The International Centre for Theoretical Physics (ICTP) has a long tradition in training scientists from developing countries in various fields of fundamental theoretical physics and its applications to various branches of technology. The basic philosophy underlying these activities is that technology is based upon scientific research and discovery. This assertion is amply proven by nuclear technology which is based on nuclear physics.

Fifty years ago, the physical process of nuclear fission was discovered, with the following important characteristics: heavy nuclides can be fissioned by thermal neutrons; nuclear fission is accompanied by the emission of more than one neutron; and a large amount of energy (about 200 MeV) is liberated in each nuclear fission event.

These features opened the possibility of controllable continuous chains of nuclear fission reactions which led, as early as in 1942, to the construction of the first fission reactor, thus demonstrating the feasibility of generating peaceful nuclear power. Today, more than 400 nuclear power reactors with close to 300 000 MWe and more than 300 nuclear research reactors are operating in all parts of the world, contributing significantly to the world's total electricity production as well as nuclear industrial and scientific research capacity.

While most nuclear power reactor development has taken place in advanced countries, 17 developing countries have embarked on a nuclear power programme to fill gaps in their energy resources. Twice as many developing countries have nuclear research reactors designed for training and research in basic and applied nuclear physics and for training in operation of nuclear power reactors. Close to 80 developing countries today employ nuclear techniques in various sectors of their national research and economy, using radioisotopes and nuclear radiation in agriculture, medicine, biology, geology, and environmental research.

To master all aspects of nuclear technology including the design, operation, maintenance, and safety of nuclear power and research reactors requires a thorough understanding of the type, mechanism, and size of the nuclear reaction and decay processes occurring in a reactor. Nuclear experimental and theoretical physics are the basic research tools for the qualitative understanding and quantitative determination of these nuclear reactions. The nuclear data as the end-product of this research, after several intermediate steps of evaluation and computer processing into appropriate data files, form the basic input to reactor physics calculations. Such calculations are necessary to predict the behaviour of neutrons in a reactor and to quantitatively determine the most important design, operational, and safety features of nuclear fission reactors. Nuclear data form the bond between basic nuclear physics, nuclear technology design, and applications.

Any theoretical physics-oriented training programme in nuclear science and technology must cover methods and models of basic nuclear reaction theory, tested by comparison with the results of experimental nuclear physics, and associated computer codes for the computation of nuclear data; evaluation and application of nuclear data and computer-based nuclear data libraries in nuclear technology applications; and methods of nuclear reactor physics and associated computer codes for the computation of design, operational, and safety characteristics of nuclear power and research reactors.

### An historical overview

ICTP's involvement in low-energy nuclear physics started with four courses on nuclear theory devoted to the fundamentals of nuclear theory without consideration of applications (1966, 1969, 1971, and 1973). In the 1970s, more developing countries started to embark on nuclear power technology and on the application of radiation and isotopes in various branches of nuclear sciences. Concurrently, the need for large-scale transfer of know-how in methods and techniques used in nuclear science and technology to developing countries became apparent. ICTP was, and is still today, the only place in the world for such a transfer, as far as its basic and applied theoretical physics aspects are concerned. It serves as a necessary complement to the experimental and industrial transfer of know-how in nuclear power and research reactor technology performed by the IAEA technical co-operation and assistance programme.

Recognizing this development, and following a recommendation by the International Nuclear Data Committee (INDC), the IAEA, in co-operation with the ICTP, convened a consultants' meeting at the ICTP in Trieste in 1975. It was held to review the status and use of nuclear theory, models, and computer codes in the

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evaluation of neutron nuclear data needed for fission and fusion reactor design and other nuclear applications. Another objective was to work out recommendations for future developments, with particular consideration of the requirements and possible co-operation of nuclear scientists from developing countries.

This gathering of high-level experts in basic and applied nuclear physics is considered to have been the "founder" meeting for the definition of the role of the ICTP in the field of nuclear theory and its applications in nuclear technology. Apart from formulating the needs for further intrinsic developments of basic and applied low-energy nuclear reaction theory, the meeting concluded that there was substantial potential for scientists from developing countries to make valuable contributions in the fields of nuclear theory, reactor physics, and computation and utilization of nuclear data. Due to isolation from their peers in the field, however, they needed up-to-date training and exposure to "state-of-the-art" methodology in these areas. The meeting resulted in a recommendation to organize and hold at the ICTP an extended course of several weeks duration on nuclear theory and nuclear model computer codes for applications.

Participation by the IAEA Division of Nuclear Power and Reactors complemented the scope of the envisaged course by covering the nuclear power reactor aspects. The first winter courses on nuclear physics and reactors were held from 17 January - 10 March 1978 jointly organized in two parts by the IAEA, the ICTP, and the Centro di Calcolo, Bologna, of the Comitato Nazionale per l'Energia Nucleare of Italy.

Part I of the course was devoted to "Nuclear theory for applications" and was designed to offer nuclear physicists, nuclear data evaluators, and reactor scientists with an interest in nuclear theory and nuclear data — particularly from developing countries which had plans to embark on a nuclear power programme — a thorough review of contemporary research in low-energy nuclear reaction theory. This was combined with simultaneous training on an advanced level in the application of this theory and associated computer codes to the interpretation and computation of neutron nuclear data needed for nuclear reactor calculations. Topics covered the importance of nuclear data for nuclear technology applications, theory and interpretation of neutron resonances, advanced optical models, statistical theory of neutron nuclear reactions, theory and models of nuclear pre-equilibrium decay, and theory of neutron-induced nuclear fission. It was attended by 91 nuclear scientists from 29 developing countries, 12 scientists from six industrialized countries, and five scientists from two international research organizations.

Part II of the 1978 winter course, "Reactor theory and power reactors", was planned as a broad and thorough advanced review of nuclear reactor theory and its application to the engineering requirements for nuclear power reactor design and operation. Topics included nuclear data used for reactor calculations; advanced theoretical, calculational, and experimental reactor physics methods; reactor physics aspects of the main types of thermal nuclear power reactors; and computer codes for power reactor neutronics calculations. One hundred nuclear scientists from 27 developing countries, 16 scientists from 6 industrialized countries, and 4 from an international research organization attended.

### Current status

Several factors encouraged the ICTP and IAEA to follow up on these first courses with a series of biennial colleges and workshops. These factors included the large numbers in attendance at the winter courses on nuclear physics and reactors; the extensive interactions and contacts established between the developing country participants and the lecturers, and between the participants themselves. During and after the courses, many requests are received concerning nuclear data, scientific documents, nuclear models, reactor physics, and data processing codes. The colleges and workshops were held subsequently at the ICTP (1980, 1982, 1984, 1986, and 1988). In the 1980 and 1982 winter colleges, the same format was used as in 1978: two courses were held in sequence covering the subjects of nuclear physics and data in the first course, and nuclear reactors in the second.

Beginning in 1984, a different format was adopted, for several reasons. In the first three colleges, consisting of two parts each, both were attended by a majority of the same participants. It became clear that reactor physicists and nuclear engineers were not interested in and did not benefit from nuclear theory; nuclear theorists and nuclear data evaluators in turn were not interested in nuclear reactor theory. It was decided, therefore, to separate the courses, to continue to hold them biennially, but to alternate the subjects between nuclear theory and nuclear model calculations of nuclear data for nuclear technology applications (1984 and 1988), and reactor physics and nuclear data applications (1986 and planned for 1990).

Secondly, rapid development in the field of computer hardware resulted in the availability of cheaper and more powerful micro- and minicomputers — in particular, personal computers. This enabled developing countries to acquire more micro- and minicomputers in powerful configurations augmenting considerably their capacity to carry out sophisticated calculations with larger nuclear model and reactor physics codes. Following this development, ICTP acquired a Gould mainframe computer, connected to a rapidly growing number of personal computers.

These factors resulted in a different format for nuclear theory and reactor physics courses from 1984 onwards. The first courses had been devoted mostly to lectures, special seminars, and discussion workshops. Beginning with 1984, the courses were converted to workshops which included lectures followed by mainframe and personal computer exercises with nuclear model and reactor physics codes. The lectures were concentrated on introduction in advances in the basic theory and introduction to selected computer codes to be used in the exercises. The new format required more work-intensive preparation and performance with close co-operation between the lecturers and exercise tutors, particularly the physics and computer staff. For example, the computer codes had to be adapted to the ICTP mainframe and personal computers, and the participants needed extensive guidance by the tutors in the use of the computer equipment and performance of the exercises.

At the request of participants from previous courses, the ICTP workshops were extended, by short training periods of one to two weeks duration at suitable nearby laboratories, so that they could familiarize themselves with practical aspects of the course curricula. In 1986, a one-week training course in practical research reactor physics, safety, and operation was held at the research reactor of the Jozef Stefan Institute in Ljubljana, Yugoslavia. A similar one was organized after the 1988 workshop at the INFN Laboratories at Legnaro in Italy.

A high level of lectures, exercises, and discussion periods was envisaged and maintained from the beginning. Accordingly, the qualifications required of the participants were also fairly high: a post-doctoral or equivalent educational career and/or several years of study and research in one or more course topics after a first scientific degree. In the last three courses, experience in nuclear model and reactor physics computer calculations, and in the use of computers in general, were necessary pre-requisites.

For the nuclear theory workshops, participants were drawn from experimental and theoretical nuclear physicists and nuclear data evaluators, and included several nuclear reactor physicists with a broader interest. For the reactor physics workshops, nuclear reactor physicists and engineers and nuclear data evaluators were primarily selected as well as nuclear physicists which had an interest in nuclear reactor physics.

The courses were attended by 70–90 participants from developing countries. Since 1984, a constant level of between 60–70 participants is maintained which can be absorbed by the existing computer equipment of the ICTP. While the academic background of the attendees was rather heterogeneous in the first courses (tutorial lectures had to be given by more experienced participants to the less experienced ones), it became much more homogeneous during recent courses, in which the majority of the participants had a professional and educational level commensurate with the requirements of the workshops.

### Impact

The courses and workshops held at the ICTP in the last decade have had a significant impact on the development of nuclear science and technology in developing countries. The immediate impact can be judged by several statistics. In this decade, more than 350 nuclear scientists from 60 developing countries have been trained on an advanced level in the latest developments of nuclear theory and nuclear models, evaluation and application of nuclear data, nuclear reactor physics, and associated computer codes. In the same period, several participants have been granted ICTP associateships or affiliateships in applied nuclear theory and reactor physics. During the courses, about 40 special seminars were presented by course participants describing their own work to an audience of their peers which normally they would not have been able to do in their own countries. Proceedings of the courses have been published, and more than 500 copies on the average have been distributed by the ICTP and the IAEA in developing countries. *(See accompanying box.)* They are widely quoted in nuclear scientific publications and form the basic material for the development of educational curricula in nuclear and reactor physics at a number of universities in developing countries. Several previous course participants showed remarkable development,

### Proceedings from training courses at ICTP include:

- ***Nuclear theory in neutron nuclear data evaluation,*** proceedings of a consultants meeting, ICTP-Trieste, 8–11 December 1975, IAEA TECDOC, IAEA-180, Vols. I and II (1976).
- ***Nuclear theory for applications***, proceedings of part I of the winter courses on nuclear physics and reactors, ICTP Trieste, 17 January–10 February 1978, IAEA-SMR-43 (1980).
- ***Reactor theory and power reactors,*** proceedings of part II of the winter courses on nuclear physics and reactors, ICTP Trieste, 13 February–10 March 1978, IAEA-SMR-44 (1980).
- ***Nuclear theory for applications – 1980,*** proceedings of the interregional advanced training course on applications of nuclear theory to nuclear data calculations for reactor design, ICTP Trieste, 28 January–22 February 1980, IAEA-SMR-68/I (1981).
- ***Operational physics of power reactors,*** proceedings of the course on operational physics of power reactors including start-up, testing, and fuel management, ICTP Trieste, 3-28 March 1980, IAEA-SMR-68/II (1982).
- ***Nuclear theory for applications — 1982,*** proceedings of the course on advances in nuclear theory and nuclear data for reactor applications, ICTP Trieste, 25 January–19 February 1982, IAEA-SMR-13 (1984).
- ***Applications in nuclear data and reactor physics,*** proceedings of a workshop, ICTP Trieste, 17 February – 21 March 1986, ICTP Trieste, edited by D.E. Cullen, R. Muranaka, and J.J. Schmidt, published by World Scientific Publishing Co. Pte/Ltd., Singapore (1986).
- ***Applied nuclear theory and nuclear model calculations for nuclear technology applications,*** proceedings of a workshop, ICTP Trieste, 15 February – 18 March 1988, to be published by World Scientific Publishing Co. Pte/Ltd., Singapore.

growing from participants in the first courses to lecturers and exercise tutors in the last workshops.

The long-term effects of these nuclear scientific activities at the ICTP demonstrate their impact on a wider level than represented by the actual participants. For example, since 1980, the IAEA experienced a drastic increase in requests from scientists from developing countries for numerical nuclear data, data processing codes, and scientific documentations and reports from an annual average of 2–300 in the 1970s to 7–800 in the 1980s. Through concurrent automatization of the data collection, testing, and transfer procedures, it was possible to satisfy these increasing requirements.

The courses enhanced considerably the interaction of nuclear scientists in developing countries with the IAEA, which increasingly serves as a guide and adviser in the generation, processing, and utilization of nuclear data for practical reactor physics and other calculations. Participation in the courses also led to the development and/or consolidation of specific nuclear data groups and centres in several developing countries, including Argentina, Brazil, China, India, and Yugoslavia. Some of these centres, such as that in São José dos Campos in Brazil and the Chinese Nuclear Data Center at the Institute of Atomic Energy in Beijing, China, serve as focal points for the generation, collection, processing, and dissemination of nuclear data in their countries.

The transfer of nuclear model and reactor physics computer codes to developing countries has increased as well. For example, the recent 1988 workshop involved operational training in 11 advanced computer codes dealing with nuclear reaction model calculations of nuclear cross-sections. At the end of the workshop, 58 requests were received from participants from eight developing countries for transfer of some of these codes, which are transmitted to the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (NEA/OECD) data bank. A significant fraction of its code services are transferred to developing countries, mostly in the aforementioned fields. In the past several years, the NEA Data Bank also organized intercomparison exercises between different laboratories for computer codes covering various aspects of low-energy nuclear reaction theory, such as the statistical model, the optical model, and pre-equilibrium decay.

ICTP has proven to be an ideal meeting place for nuclear scientists from developing and developed countries. A number of scientific co-operative efforts between individual scientists was initiated as well as new multi-year projects developed by the course participants.

A major outcome of the 1980 course was an IAEA interregional technical co-operation (TC) project on nuclear data techniques and instrumentation, the objectives and scope of which were developed by 40 participants in the course. This was the Agency's first interregional TC project designed to enhance the capability of developing countries in accurate nuclear measurements, using the techniques which had been developed since the beginning of the nuclear era in the nuclear data field. With additional support by national technical co-operation projects, this interregional project brought several laboratories in developing countries such as Morocco, Pakistan, and Thailand, to the level of self-supporting nuclear analytical laboratories. These and other laboratories participated in high-level IAEA co-ordinated research programmes designed to improve the status of neutron cross-section data for fission and fusion reactor applications through measurement, computation, and analysis of such data.

This interregional project, in which 28 laboratories from 25 developing countries and 14 tutoring laboratories from 11 other countries participated, was conducted from 1982-86. After a thorough evaluation by IAEA experts of the results and impact, a second interregional technical co-operation project on training in nuclear measurement techniques was started with a widened scope encompassing the main nuclear measurement and analysis techniques initiated and supported by IAEA through such projects in developing countries. Its aim was to enhance the capabilities of the participating laboratories in accurate and reliable applied nuclear physics measurements. More than 40 laboratories have indicated an interest and have started active participation in this project, which is designed to last for the 5-year period 1987-91.

These courses also have led to a stronger interaction between IAEA and ICTP. Scientist staff members of IAEA presented lectures at the courses on various aspects of the IAEA programme, such as activities of the Seibersdorf Laboratories, the Agency's nuclear power programme, the aftermath of the Chernobyl accident, radioprotection of nuclear facilities, and the technical co-operation and assistance programme. This led to an improved understanding of scientists from developing countries of the aims, objectives, and procedures of the IAEA and has helped to increase the efficiency of co-operation between the Agency, especially its technical co-operation and assistance programme, and the nuclear organizations and institutes in developing countries.

During the courses in nuclear and reactor physics, experience has been gained and collected by the course organizers. Each course presented new problems and many participants were helpful, through regular feedback sessions, in making suggestions for improvement of the efficiency and impact of the courses. On the basis of such experience and advice, the organization of the courses are steadily improved to make them an efficient tool for the transfer of nuclear physics know-how to developing countries. The courses have thus become a consolidated part of ICTP scientific activities and are an important channel for the transfer of up-to-date nuclear and reactor physics know-how to a growing number of nuclear scientists in developing countries.