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FOREWORD

Welcome to MTA Atomki, the Institute for Nuclear Research, member of the network of the Hungarian Academy of Sciences. This booklet summarizes the broad range of activities of the Institute, from basic science to applications, and from nuclear physics to the environmental sciences.

Researchers at MTA Atomki have never believed in borders between scientific fields; in the 60 years of the history of the Institute, the interdisciplinary approach has always been strong, and proved to be successful as well. In the early years, as an example, the investigation of nuclear decay led to an indirect proof of the existence of the neutrino. Recently, this achievement was the basis for an award from the European Physical Society (EPS), which designated MTA Atomki as one of the Historic Sites in Europe.

Today, we continue our scientific research in the same direction. Our laboratories and teams – though independent – can combine to solve problems effectively. These efforts are marked by grants – from the ERC to EUROCORES – just to mention a couple.

Modern science is without borders, and so is Atomki, with its hundreds of collaborations from all over the world. Atomki researchers are among the thousands who have been hunting for the Higgs boson at CERN, and Atomki with its small-scale Accelerator Centre also hosts researchers supported by the European Transnational Access (TNA) scheme. You can find equally successful examples for both big and small science in this leaflet.

MTA Atomki laboratories are open-access, and we are always seeking collaborators to join our efforts and/or open up new directions. It is our firm belief that this leaflet serves this aim by providing interested parties with contacts for each topic.

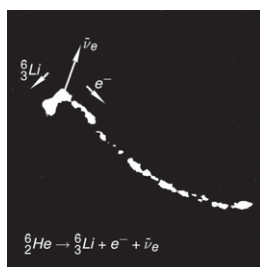
Although we have tried to cover most of the scientific fields of interest to us, science evolves rapidly. For the latest news and results from MTA Atomki, please visit www.atomki.mta.hu.

Those who are interested in our recent investigations, the Atomki Annual Report can also be downloaded from our web page.



Zsolt Fülöp D.Sc.
Director
MTA Atomki

The EPS Historic Site plaque commemorating the neutrino experiment at MTA Atomki in 1956.



EUROPEAN PHYSICAL SOCIETY – EPS HISTORIC SITE THE NEUTRINO EXPERIMENT AT MTA ATOMKI

USING A CLOUD CHAMBER LOCATED IN THIS BUILDING, IN 1956 J. CSIKAI AND A. SZÁLAY PHOTOGRAPHED BETA-DECAY EVENTS. IN SOME CASES THE ANGLE BETWEEN THE TRACKS OF THE ELECTRON AND THE RESIDUAL NUCLEUS IMPLIED THE EMERGENCE OF AN UNDETECTED THIRD PARTICLE IN THE DECAY. THIS CONFIRMING THE EXISTENCE OF THE NEUTRINO, THE DEBRECEN NEUTRINO EXPERIMENT LAID A BRICK OF THE FOUNDATION OF MODERN PHYSICS.

EUROPÁI FIZIKAI TÁRSULAT – EPS TÖRTÉNELMI EMLÉKHELY A NEUTRINÓKÍSÉRLET, MTA ATOMKI

1956-BAN CSIKAI GYÜLA ÉS SZÁLAY SÁNDOR EBBEN AZ ÉPÜLETBEN BETA-BOMLÁSI ESEMÉNYEKET FÉNYKÉPEZETT LE EGY KÓDOKAMRÁBAN. AZ ELEKTRON ÉS A MARADÓKÉNY PÁLYÁIKNAK SZÖGÉ AZT MUTATTA, HOGY A BOMLÁSBAN KELETKEZIK EGY NEM DETEKTÁLT HARMADIK RÉSZECSE IS. A NEUTRINÓ LETÉZÉSÉT IGY MEGERŐSÍTVE, A KÍSÉRLET HOZZAJÁRULT A MODERN FIZIKA MEGALAPOZÁSÁHOZ.



DEBRECEN
2013



INTRODUCTION

The Institute for Nuclear Research (MTA Atomki) is one of the member institutes in the research network of the Hungarian Academy of Sciences. MTA Atomki is situated in Debrecen, the city that is the educational and scientific centre in eastern Hungary.

SCIENCE

The primary activity of the Institute is devoted to both experimental and theoretical research in nuclear physics and related fields. This line of research was initiated by Alexander Szalay (1909-1987) after his return from Cambridge in 1936, where he was working at Cavendish Laboratory with the Nobel-laureate Ernest Rutherford. Later, in 1954, he became the founding director of Atomki.

Today, our activity focuses on both fundamental and applied research, covering a broad range of modern physics: atomic and subatomic physics, materials science, and several other areas employing the techniques of physics research, such as the environmental and biomedical sciences. This multidisciplinary nature has been gradually built on the basis of particle accelerators and the associated analytical facilities.

The activity of the research groups of the Institute is well embedded in that of leading international collaboration networks. This is characteristic of all fields of fundamental research. Our researchers work at the very frontiers of science. The research infrastructure of Atomki provides a firm basis for fundamental and applied experimental work. Some of our attractive research facilities are also popular among external users and collaborators. The Institute typically takes part in multilateral international programmes, intergovernmental and inter-academic bilateral programmes, as well as in informal and *ad hoc* cooperation agreements with research institutions worldwide.

THE MAIN RESEARCH FIELDS OF ATOMKI ARE AS FOLLOWS:

- > Fundamental research in nuclear physics
- > Fundamental research in atomic physics
- > Particle physics
- > Quantum physics
- > Applications of nuclear physics and of accelerators
- > Applications of atomic and solid state physics, surface science and analysis
- > Environmental physics

INNOVATION

The research activities and infrastructure of Atomki provide a wide range of opportunities for cooperation with industrial companies in both long-term and short-term partnerships. The Institute has close collaboration and shared facilities/properties with



Alexander Szalay
(1909-1987)
Founding director of Atomki.

Examples of successful partnerships for medical and industrial applications:



The MiniPET-3: small animal PET scanner for preclinical studies (for more details see page 43).



Vacuum leak testing of large-scale industrial facilities (fermentation tank). VTMT Ltd, spin-off company of Atomki.

some of its partners: the University of Debrecen, Isotoptech Co., Vacuum Tightness and Measurement Technique Ltd., Pharmatom Ltd. and the Prizmatech Instrument Manufacturer and Developer Cluster. Our main industrial partners are the major pharmaceutical firm Richter Gedeon Co., the NI – National Instruments Hungary Ltd., the Paks Nuclear Power Plant Ltd., and the Radioactive Waste Management Hungary Ltd. For innovation purposes, we have connections with most of the universities in Hungary.

ATOMKI HAS EXPERTISE/COMPETENCE IN THE FOLLOWING FIELDS RELATED TO INDUSTRIAL INNOVATION:

- > Complex surface analysis
- > Elemental analysis of biological, geological and archaeological samples
- > Vacuum problems and solutions
- > Isotope ratio measurements for environmental studies
- > Production and separation of medical isotopes, radiochemistry
- > Ion-beam technologies: analysis, modification, irradiation and implantation
- > Large detector arrays, imaging, electronics

EDUCATION AND OUTREACH

Ever since its foundation, Atomki has been contributing substantially to physics education at the University of Debrecen (UD). The training of junior scientists at the postgraduate level is an essential part of the activity of the Institute. Our researchers play a significant role in the Physics PhD School of UD. The PhD students get access to the high-tech laboratories and research infrastructure of Atomki. They are of course integrated into the research groups. Many of them choose subjects that allow them to obtain expertise in the use of accelerators and accelerator-based technologies.

Researchers at Atomki participate in undergraduate teaching, mainly in the Department of Environmental Physics, which is run jointly by Atomki and the University of Debrecen. However, the subjects taught in this framework transcend environmental physics. They involve the fields of atomic and subatomic physics, materials science, environmental physics and technology-oriented research. Emphasis is laid both on a broad range of interdisciplinary and on specialized topics.

Atomki researchers deliver roughly 40 undergraduate and 30 postgraduate courses per year. Moreover, they supervise approximately 20 students working for their BSc and MSc theses and 20 PhD students. From the youngest generation, typically 10 undergraduate students regularly carry out some kind of research work at the Institute. These activities are part of an integrated system, consciously formed in Atomki, for training scientists and helping their career. We have a full system of support, from undergraduate courses to the habilitation level. For students willing to work in science, we offer a research-student stipendium during their university years. Every year, a limited number of three-year “Young Scientist” positions are offered to talented students by the Hungarian Academy of Sciences, and also by Atomki from internal sources. Both PhD studies and parts of the postdoctoral research period can be covered from this source. Finally, after a successful five-year postdoctoral period, a habilitation process can be initiated by young researchers who intend to become staff members of the Institute.

The Institute is pursuing outreach activities as well, targeting secondary-school pupils, university students and the general public with colourful programmes throughout the year. The central programme is the “Physicists’ Week”, organized every year in November, from 2013 onwards, which opens up the Atomki to the public to allow them to

find out about the research work and our high-tech laboratories. The weekly programme includes lectures, exhibitions, spectacular experiments and laboratory visits. A science dissemination project was initiated in 2013 to organize visits to secondary schools in rural regions of Hungary, where it is not easy to participate in the regular outreach programmes of Atomki or of the University.

FACTS AND FIGURES

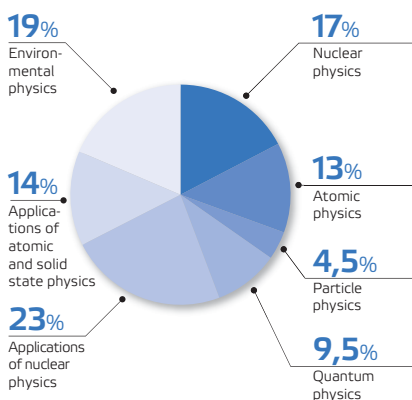
- > The number of researchers employed by Atomki has been around 100 over the past few years, while the total number of the staff has amounted to nearly 200.
- > PhD students from the University of Debrecen also contribute to research work in practically all active research fields. The average number of postgraduate students in the physics, information technology and mathematics doctoral schools has been around 12.
- > The budget of the Atomki has been between 1.5-2 billion HUF over the past few years, depending on the fluctuating sources for infrastructure investments. About two-thirds of the budget comes directly from the Hungarian Academy of Sciences, while the remaining portion is covered by various grants. The OTKA (Hungarian Scientific Research Fund) has been a major source sponsoring fundamental research. Our research groups started 37 projects funded by OTKA in the period 2003-2012, with a cumulated support of 414 million HUF.
- > The Institute has an extensive network of international collaborations. Besides 6-10 multilateral programmes, our researchers have participated in around 30 bilateral inter-academic and inter-governmental collaborations. In addition, Atomki has run more than 100 projects based on informal and *ad hoc* agreements with institutions from around 30 countries.



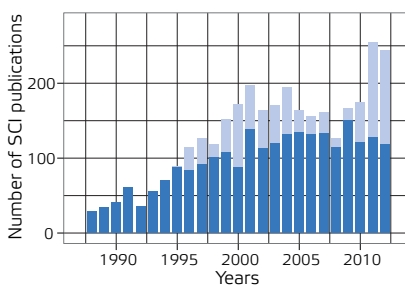
Young researchers give physics presentation and show experiments for secondary school pupils at Fehérgyarmat.



PhD students get access to high-tech laboratories and research infrastructure of Atomki (ECR laboratory).



Distribution of the research staff's cumulated full time equivalent (FTE) values among research topics



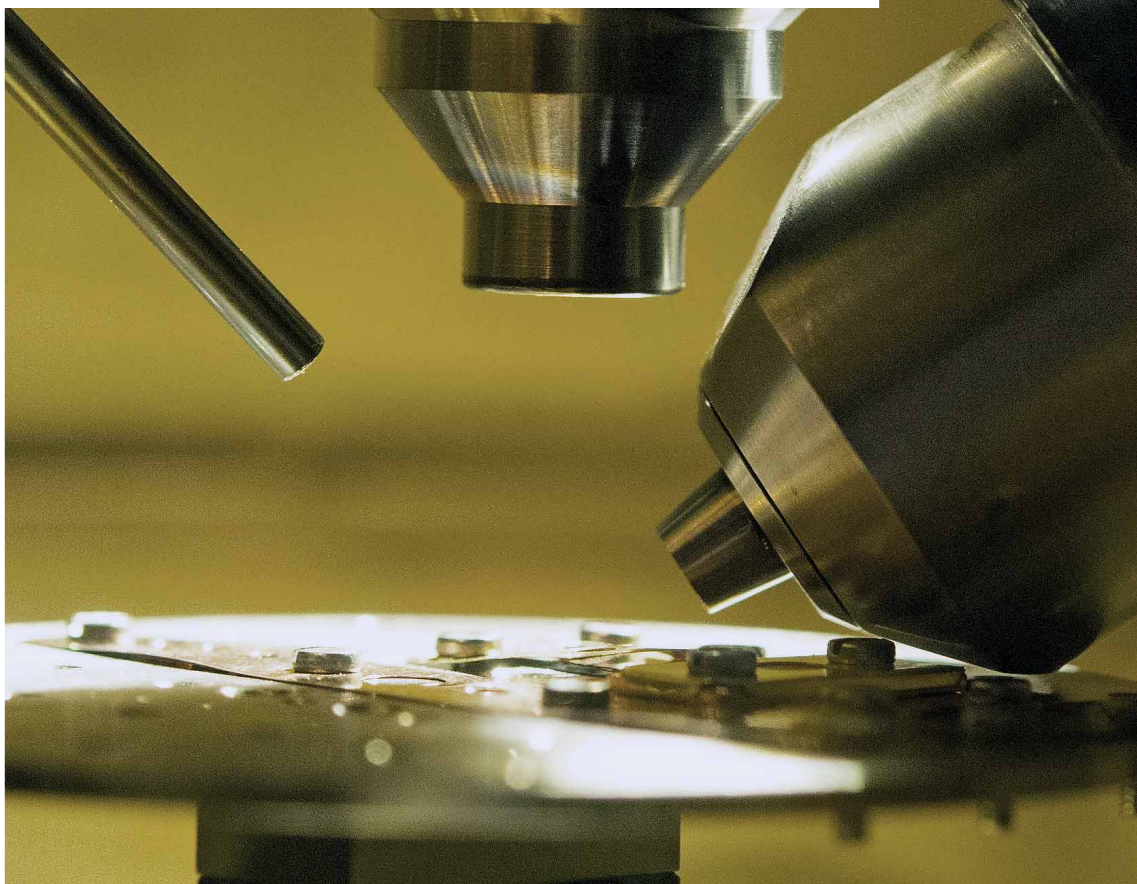
Number of SCI publications by researchers with Atomki affiliation. Light colour indicates the share of SCI publications originating from CERN collaborations. The peak in 2011/2012 is mainly due to publications related to the search for the Higgs boson.

RI

Research infrastructure

The research facilities of Atomki are run via a structured system of laboratories. Our major asset for general use is the accelerator centre. Most other laboratories also possess unique equipment in their area of interest. According to the National Research Infrastructure Register*, about 20% of the infrastructure of the country for physics research is concentrated in Atomki. This emphasizes, the importance as well as the great responsibility, of the Institute.

* regiszter.nekifut.hu/en



ACCELERATOR CENTRE

The Atomki Accelerator Centre (AAC) incorporates several low-energy charged-particle accelerators, which offer the possibility of choosing ions with various charge states, energies and beam intensities.

Currently, the AAC has six main facilities: a cyclotron ($K=20$), two Van de Graaff accelerators (1 MV, 5 MV), an ECR ion source, an electromagnetic isotope separator and a 2 MV Tandatron (under installation). The accelerators, spanning a range of beam energies from 50 eV to 27 MeV, have been designed for a broad range of research projects and applications in various fields – mainly in nuclear and atomic physics, materials science, environmental research and archaeology.

There are special laboratories serving the accelerators: a radiochemical laboratory and neutron sources for medical and industrial applications.

CYCLOTRON

The Cyclotron Laboratory has been in service since 1985, and it is still the highest-energy particle accelerator in Hungary. The MGC-20E cyclotron produces accelerated particle beams for both fundamental and applied research, as well as for medical and industrial applications. Owing to its sophisticated beam transport system equipped with an advanced beam diagnostics, the beam parameters can be flexibly adjusted to the diverse requirements of research and application projects, making it a multidisciplinary facility.

VAN DE GRAAFF ELECTROSTATIC ACCELERATORS

The Laboratory of Electrostatic Accelerators was established in 1970. Both the 1 MV and the 5 MV accelerator (VdG-1 and VdG-5, respectively) were designed and built in Atomki. These accelerators have been the basic instruments of our research infrastructure from the beginning, serving generations of researchers in a large number of research topics. The two accelerators have five beamlines, partly serving atomic physics, nuclear physics and nuclear astrophysics experiments, and partly accommodating instruments for microbeam applications used in elemental analysis and in the production of microstructured devices.

ELECTRON CYCLOTRON RESONANCE ION SOURCE

The ECR Laboratory hosts the only Hungarian electron cyclotron resonance ion source (ECRIS). The ECR ion source produces and delivers plasmas or low-energy ion beams of a wide range of elements, e.g., H, He, N, O, Ne, Ar, Kr, Xe (from gases) and Ca, Ni, Fe, Zn, C, C_{60} , Zn, Au, Pb (from solids). The highest charge achieved so far is 27. Numerous atomic and plasma-physics investigations are carried out, e.g., plasma diagnostics, X-ray spectroscopy, the study of ion-surface interactions and the production of new materials.



Cyclotron MGC-20E



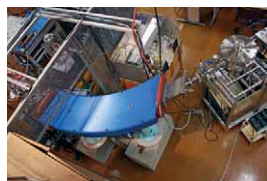
Van de Graaff electrostatic accelerator (VdG-5)



Electron Cyclotron Resonance Ion Source

The main beam parameters of the accelerators:

Accelerator	Type	Particles	Charge	Beam lines	Energy range
Cyclotron MGC-20E	cyclic	H, D, He	1, 2	9	1 – 27 MeV
VdG-1	electrostatic, multi-step	H, D, He	1	1	50 keV – 1.5 MeV
VdG-5	electrostatic, multi-step	H, D, He, C, N, O, Ne	1	4	800 keV – 3.5 MeV
ECR ion source	electrostatic, one-step	From H to Xe, molecules	1-27	2	50 eV – 800 keV
Isotope separator	electrostatic, one-step	He, Ne, Ar, N, S, Se	1,2	1	50 eV – 50 keV
Tandatron (from 2014)	electrostatic, dual multi-step	H, C, O	1	-	200 keV – 4 MeV



Electromagnetic isotope separator

ELECTROMAGNETIC ISOTOPE SEPARATOR

Ion beams with intensities up to the mA range and charge states of mostly +1 at the typical terminal voltage of 10-50 kV are mass-separated by a high-dispersion, dual-focusing sector magnet, producing high-purity isotopic beams for light and medium-heavy elements depending on the ion source. Beams for the purposes of enrichment, ion implantation, atomic deposition on surfaces can be produced for research in materials science, atomic and subatomic physics.

2 MV TANDETRON

In 2013, we started the complex process of purchasing and installing a new 2-MV Tandatron-type accelerator. This accelerator will be devoted to producing ion beams with excellent energy stability, with minimum demands for maintenance.

CONTACT

Sándor Biri, e-mail: biri.sandor@atomki.mta.hu



2 MV Tandatron

CYCLOTRON-BASED NEUTRON SOURCES

Quasi-monoenergetic and broad-spectrum neutrons are produced for basic science and application purposes. The facilities are important elements of in the portfolio of neutron sources in Hungary.

QUASI-MONOENERGETIC NEUTRON SOURCE: Quasi-monoenergetic d+D neutrons are produced in the $E_n = 3-12$ MeV neutron-energy range. The intensity-range covers three orders of magnitude. Well-characterized broad spectrum d+Be neutrons can also be produced at the same measuring site. A pneumatic rabbit system is available.

BROAD-SPECTRUM NEUTRON SOURCE: High-intensity fast neutrons are produced by bombarding a thick Be target with proton or deuteron beams from the cyclotron. Broad-spectrum p+Be neutrons can be produced in the $E_n = 0-16$ MeV energy range, while broad-spectrum d+Be neutrons are produced in the $E_n = 0-12.5$ MeV energy range. The neutron spectrum and the intensity can be controlled. The typical intensity within a cone of 10-degree half angle around the zero degree direction is $3 \times 10^{11} \text{ s}^{-1} \text{ sr}^{-1}$ for $E_p = 18$ MeV protons.

CONTACT

András Fenyvesi, e-mail: fenyvesi.andras@atomki.mta.hu



Broad-spectrum neutron source

LABORATORY FOR NUCLEAR PHYSICS AND NUCLEAR ASTROPHYSICS

In Atomki, we have strong traditions in accelerator-based nuclear physics research. Knowledge and experience have been collected in detection techniques and nuclear electronics.

SPLIT-POLE MAGNETIC SPECTROMETER

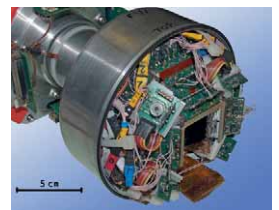
This is a high energy resolution ($\Delta E/E = 0.1\%$) spectrometer, with $K=70$, for detecting light charged particles using position-sensitive focal-plane Si-detectors. Due to the split-pole magnet, it has a very large energy bandwidth of $E_{max}/E_{min}=5$. Hyperdeformed states in ^{236}U were discovered with this spectrometer at Atomki.



Split-pole magnetic spectrometer

SCATTERING CHAMBER WITH Si DETECTOR TELESCOPES

This chamber of 78.8 cm inner diameter is equipped with two rotating wheels holding up to 10 Si detectors. To monitor the beam and target properties, two permanently mounted detectors are used. The angle and height of the target holder are controlled remotely. Its use was important in obtaining results on optical potentials and cross-sections relevant for nuclear astrophysics and ternary fission studies.



DIAMANT detector array

DIAMANT PARTICLE DETECTOR SYSTEM

This is a light-charged-particle detector system of CsI(Tl) scintillators with a photodiode readout and VXI electronics for particle identification. It was developed by an international collaboration and is used in conjunction with large gamma-ray spectrometer arrays for the efficient selection or suppression of particular reaction channels. It effectively helped in obtaining our results in studies of high-spin super- and hyperdeformation, nuclear chirality and $T=0$ n-p pairing.



ELENS detector array

ELENS – THE EUROPEAN LOW-ENERGY NEUTRON SPECTROMETER

The main features of this time-of-flight spectrometer, which is composed of plastic scintillators are: angular resolution < 1 degree, time resolution < 0.8 ns, and efficiency $\sim 25\%$ (0.5 – 4 MeV). It has been designed to study giant resonances excited in (p,n) reactions in inverse kinematics at large-scale facilities. A new method was introduced with this detector system for determining the neutron skin thickness of different exotic nuclei.



Electron-positron pair spectrometer

ELECTRON-POSITRON PAIR SPECTROMETER

This consists of five large-area plastic scintillator, $\Delta E-E$ telescopes, arranged perpendicularly to a thin wall (carbon fibre) beam-pipe (energy range: 1-20 MeV, time and energy resolution: < 1 ns and $< 10\%$, respectively). Multi-wire proportional counters between the beam-pipe and the telescopes are used for determining the angular correlations of the electrons and positrons, with an angular resolution of < 2 degree. It is mainly used to search for light neutral bosons in high-energy nuclear transitions, by observing their two-body electron-positron decay.

CONTACT

Attila Krasznahorkay, e-mail: krasznahorkay.attila@atomki.mta.hu

LABORATORY OF ION BEAM APPLICATIONS

Accelerated ion beams are applied for the analysis and modification of materials in various multidisciplinary research fields. The main activity of the IBA Lab is ion beam analysis at the microscopic and macroscopic scale, proton beam lithography and the development of analytical methods.

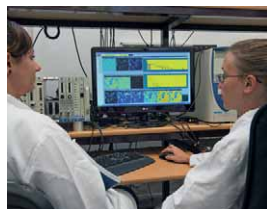


The Atomki scanning nuclear microprobe

The IBA Laboratory is operated by the Section of Ion Beam Physics of Atomki. The research activity is based on the applications of ion beams with MeV energies, which is provided by the VdG-5 accelerator. The experimental facilities are suitable for atomic and nuclear physics, materials-science applications and for analytical studies.

SCANNING NUCLEAR MICROPROBE

This focuses the ion beam down to the micrometre scale and scans it across the surface of a sample, thus allowing the measurement or modification of materials at the microscopic level. It is used for nuclear microscopy and proton beam writing. Available techniques: micro-PIXE, micro-RBS, micro-ERDA, STIM, micro-PIGE. Capabilities: quantitative elemental concentrations and mapping for all elements (~1 μm resolution), depth profile with ~10 nm resolution, structural imaging with ~700 nm resolution.



Data acquisition

EXTERNAL NUCLEAR MICROBEAM

The focused ion beam is extracted through a thin silicon nitride window into the air (measurements are made in air or in a helium atmosphere). It is used for the characterization of objects that cannot be placed into the vacuum chamber due to their size, value, fragility or other reasons. Available techniques: PIXE, RBS, PIGE. Capability: elemental characterization of samples for $Z \geq 12$.

MACROPIXE CHAMBER

This is used for the bulk characterization of atmospheric aerosols, environmental and geological samples and for target irradiation. Capability: determination of elemental concentration for $Z \geq 13$.

NUCLEAR REACTION BEAMLIN

This is used for cross-section measurements for reactions relevant to analysis, and the bulk characterization of archaeological, environmental samples. Techniques: PIGE, DIGE. Capability: concentration of Li, Be, B, C, N, O, F, Na, Mg, Al, Si + isotopes.



Operating the microprobe

CONTACT

István Rajta, e-mail: rajta.istvan@atomki.mta.hu

Typical beam parameters:

accelerated ions: H^+ , He^+ , D^+
 beam energy: 1-3.8 MeV
 beam intensity: 1 pA – 500 nA

HERTELENDI LABORATORY OF ENVIRONMENTAL STUDIES

The Hertelendi Laboratory of Environmental Studies (HEKAL) is a multidisciplinary laboratory dedicated to environmental research, the development of nuclear analytical methods and systems technology. HEKAL was founded and jointly operated with ISOTOPTÉCH Zrt.

The main task of the of the laboratory is environmental and climate research. The information obtained by the different analytical equipment alone is important, but we attain a more complex picture of the problems by combining various methods. The isotope analytical arsenal of the laboratory is unique in Hungary, and probably also in Europe.

K–Ar LABORATORY

It serves for the applications of the K–Ar method for dating different geochronological events (volcanism, metamorphism, mineralization, etc.) and for work on developing the method.

NOBLE GAS AND STABLE ISOTOPE MASS SPECTROMETRY

The main equipment of the laboratory includes: a static vacuum noble-gas mass spectrometer, a stable-isotope mass spectrometer (IRMS) and ICPMS used for groundwater and climate research.

GAS PROPORTIONAL COUNTING LABORATORY

A counter system for high-precision ^{14}C dating with pre-treatment unit (GPC Lab). Counters are also used for ^{85}Kr analyses.

BETA- AND GAMMA SPECTROMETRY

A low-background laboratory for detection and quantification of different beta- and gamma-emitting isotopes in the environment and in nuclear facilities.

GAS ANALYSIS

Quadrupole mass spectrometers (QMS) for gas-component analyses. A mobile, high-precision atmospheric CO_2 monitoring station (FOCAM) used for detecting and quantifying the fossil carbon load in the air (Atomki development).

AMS ^{14}C FACILITY

The AMS Laboratory is designed for high-sensitivity radiocarbon studies. It was developed in close cooperation with ETHZ (Zürich, Switzerland) and the NSF AMS Laboratory of Arizona University (Tucson, Arizona, USA). Several national and international research organizations, museums, and industrial partners are using the fast and effective ^{14}C analysis method at Atomki.

CONTACT

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Static vacuum noble-gas mass spectrometer Fisons VG-5400.



Thermo Finnigan Delta plus XP type stable-isotope mass spectrometer.



Gas proportional counter system for high-precision ^{14}C dating + pre treatment unit (Atomki).



MICADAS type ^{14}C AMS for radiocarbon research (ETHZ).

LABORATORY FOR MATERIALS SCIENCE AND SURFACE PHYSICS

The aim of the laboratory is to study the quantitative composition and structure of different samples. We are able to analyze conducting and insulating materials, and carry out depth profiling of scientific and industrial samples.

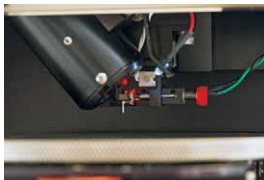
Laboratory for Materials Science and Surface Physics is a joint laboratory of the Department of Solid State Physics (University of Debrecen) and MTA Atomki.



Krypton plasma in SNMS.



SNMS/SIMS-XPS laboratory.



Ambios XP-1 profilometer for measuring sputtered crater depth and shape, as well as the surface roughness on the nm scale.

SNMS/SIMS-XPS

The SNMS/SIMS-XPS assembly contains a secondary neutral mass spectrometer, a secondary ion mass spectrometer and an X-ray photoelectron spectrometer (XPS) with a common vacuum system. This arrangement enables the analysis of samples in ultra-high vacuum to be carried out without opening the vacuum chamber during the sample transfer. While mass spectrometry measurements can be performed in the SNMS/SIMS part of the system, the chemical state of elements can be determined in the XPS part. A complete quantitative surface analysis can be performed with high depth resolution (~1 nm) or high lateral distribution.

ALD

A plasma enhanced atomic layer deposition (ALD) system allows us to deposit thin films precisely, using a layer-by-layer technique. In ALD process chemical vapours or gaseous precursors react sequentially at the surface of the substrate, producing a solid thin film, which may be only one atomic layer. It is possible to coat planar objects, particles, porous bulk materials, and complex 3D structures.

MAGNETRON SPUTTERING

Magnetron sputtering is a convenient method for depositing thin films with a thickness of few nm. The sputtering methods applied in our system are direct-current (DC), radio-frequency (RF) and reactive sputtering. We are able to produce metallic, semi-conducting and insulating thin films or multilayers, with 2-3 nm individual layer thicknesses. It is also possible to produce thin layers at a controlled substrate temperature up to 600 °C.

OTHER EQUIPMENT

This includes a profilometer, scanning and transmission electron microscopes (SEM, TEM) equipped with an energy-dispersive X-ray analyser (EDX), X-ray diffractometer (XRD), atomic force microscope (AFM), X-ray excited Auger electron spectroscopy (XAES), reflected electron energy-loss spectroscopy (REELS), and low-energy ion scattering (LEIS).

CONTACT

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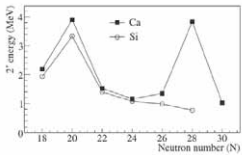
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Fundamental research in nuclear physics

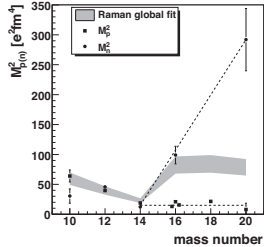
The Debrecen traditions and knowledge are strong in planning and performing experiments with accelerators, in the nuclear electronics of constructing detector systems and in the theoretical interpretation of data. We carry out such experiments and cooperate on their theoretical interpretation in Debrecen and in other internationally recognized laboratories.

GAMMA-RAY SPECTROSCOPY WITH RADIOACTIVE BEAMS

Production of radioactive nuclear beams at leading nuclear physics laboratories has made it possible to study nuclear structure up to the drip lines. Our group is involved in collaborative studies of the evolution of shell closure and in searching for drip-line effects in nuclear correlations.



Evidence for the collapse of the N=28 shell closure at Z=14.



Enhancement of the role of neutron contribution to the quadrupole excitation of carbon nuclei approaching the drip line.

At Atomki, the study of the low-excitation-energy states of nuclei far from the stability region started in the 1960s. A new era in this subject began in the 1980s when it became possible to accelerate and study such nuclei as secondary beams. In the past few years, such experiments were performed in GANIL, RIKEN and GSI. The shift of the shell closure, and the coupling between the valence neutrons and the core, have been investigated for nuclei with a large neutron excess ($N/Z \sim 2$). The Atomki group has made an appreciable contribution to the exploration of the following phenomena: (1) the substantial reduction of the N=20 shell gap with decreasing proton number, (2) the gradual

disappearance of symptoms of the N=28 shell closure with decreasing proton number, (3) the understanding of the formation of a closed shell around N=14, 16; (4) the incompleteness of the shell closure at N=40, and, finally, (5) the decoupling of the valence neutrons in the halo isotopes of carbon and boron and a spectacular reduction of their effective charge. The construction of the next generation radioactive-beam facilities around all over the world opens up new possibilities in the field. The experimental physics programme at the RIKEN radioactive-beam facility has already been started. We are involved in the experiments exploring the ^{100}Sn and ^{132}Sn , as well as the ^{78}Ni region.

COOPERATION

- > RIKEN Sunflower and EURICA collaborations
- > GANIL SPIRAL2 consortium
- > GSI RISING collaboration

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- > Z. Elekes, et al.: *Spectroscopic study of neutron shell closures via nucleon transfer in the near-drip-line nucleus ^{23}O* . Physical Review Letters 98 (2007)102502
- > F. Rotaru, et al.: *Unveiling the intruder deformed 0+2 state in ^{34}Si* . Physical Review Letters 109 (2012)92503
- > G. Guastalla, et al.: *Coulomb excitation of ^{104}Sn and the strength of the ^{100}Sn shell closure*. Physical Review Letters 110 (2013)172501

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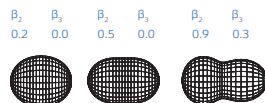
Zsolt Dombrádi, e-mail: dombradi.zsolt@atomki.mta.hu

COLLECTIVE EXCITATIONS IN NUCLEI

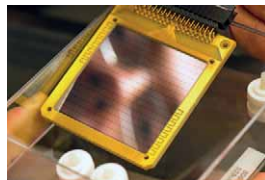
We investigate two types of large-scale collective motions in atomic nuclei: giant resonances and nuclear fission.

Giant resonances are small-amplitude high-frequency and highly collective vibrational modes of atomic nuclei, in which most of the nucleons (>50%) are involved. We are interested in searching for new exotic giant resonances like the isoscalar giant dipole resonance, in measuring their decay modes (neutron, proton, gamma, fission) and in using them as tools to constrain some parameters of the nuclear equation-of-state (EoS), such as compressibility, symmetry energy and their density dependence. Such quantities are important for describing the properties of nuclei far from the stability line, which play a significant role in the creation of the elements in stars, and also for understanding the properties of neutron stars and other exotic objects relevant to astrophysics. Nuclear fission is a really large-scale nuclear dynamical event, in which all the nucleons are

involved. We investigate the fission modes, in which nuclei go through highly deformed nuclear states (super- and hyperdeformed states with axis ratios of 2:1 and 3:1, respectively). Below the fission barrier, we map such states as transmission resonances as a function of the excitation energy. By measuring the fission probability as a function of the excitation energy, we could constrain the fission potential, which is important not only for understanding the fission process itself, but also for calculating cross-sections relevant to next-generation nuclear power stations. Very recently, our group initiated a research campaign on studies of extremely deformed actinides via photofission at new gamma-beam factories, which provide highly-brilliant gamma beams, with properties so far unprecedented, via Compton backscattering of laser photons from a relativistic electron beam.



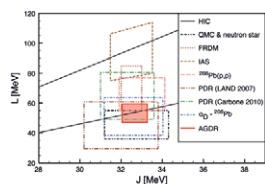
Normal, super-, and hyperdeformed states of an atomic nucleus



DSSSD – double-sided silicon strip detector.



Assembling the focal plane detector of the split-pole magnetic spectrometer.



Constraints on the parameters of the nuclear equation of state (L , J) in terms of the symmetry energy at saturation density from different experiments (Phys. Rev. C 86, 015803 (2012)) compared to our present result on anti-analogue giant dipole resonance (AGDR).

COOPERATION

- > GSI, Darmstadt (Germany)
- > LMU, Garching (Germany)
- > RIKEN, Tokyo (Japan)
- > RCNP, Osaka (Japan)

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STRUCTURE OF NUCLEI AT THE EXTREMES OF SPIN, ISOSPIN AND SHAPE

The main interest of our group is the study of nuclei at the extremes of their spin, isospin and shape, studies of shape changes, the structure of chiral nuclei and very neutron-rich nuclei, with the use of large gamma-spectrometer arrays, often equipped with selective ancillary devices, e.g., the DIAMANT.



The DIAMANT array inside the EXOGAM spectrometer.

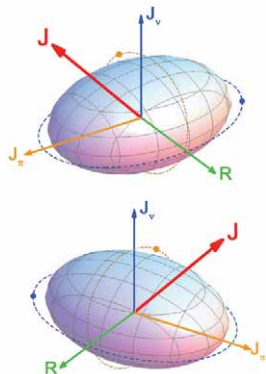
In nuclei close to the $N=Z$ line, the valence protons and neutrons occupy identical orbitals, which allows the formation of a new n-p type of pairing phase. Such an n-p pair, in contrast to the widely known n-n and p-p pairing with zero spin and $T=1$ isospin, have non-zero total angular momentum and $T=0$ isospin. We study the properties of such $T=0$ pairing in ^{92}Pd and nearby $N=Z$ nuclei, for which the neutron and proton can have their angular momenta even fully aligned.

Chirality is a recently discovered type of spontaneous symmetry-breaking in nuclei, which is related to time-reversal symmetry. It is expected in triaxial nuclei, in which the three angular momentum vectors of the unpaired proton(s), neutron(s) and that of the core rotation are mutually perpendicular. We search for new features of nuclear chirality, e.g., composite chirality and multiple chiral

doublet bands, and new regions of chiral nuclei in the chart of nuclides.

The shape of nuclei changes with the increase of spin. We study the properties of terminating rotational bands, which result from a prolate-to-oblate shape change, and the excited states above termination. Some nuclei possess a superdeformed shape (axis ratio 2:1) at very high spins, others may even develop a hyperdeformed (axis ratio 3:1) shape at the highest sustainable spins. We study rotational bands corresponding to such shapes and investigate their formation, decay-out and other properties.

We also study the collectivity in some very neutron-rich nuclei produced in cold-neutron-induced fission of ^{235}U and ^{241}Pu at the Institut Laue-Langevin, Grenoble.



Schematic picture on the chiral arrangement of angular momentum vectors in an atomic nucleus.

COOPERATION

- > EXOGAM, AGATA: European gamma-ray spectrometer collaboration
- > EGAN: European Gamma and Ancillary Detectors Network
- > ILL (France), Univ. Liverpool (UK), iThemba LABS (South Africa), ANL (USA), etc.

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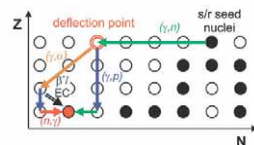
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NUCLEAR ASTROPHYSICS

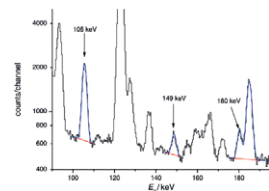
The aim of the nuclear astrophysics group of Atomki is the experimental study of the nuclear reactions that are relevant to the energy production and evolution of stars or to the synthesis of chemical elements.

Nuclear astrophysics is an interdisciplinary science, which connects nuclear physics and astrophysics. The aim of nuclear astrophysics research is to study those nuclear reactions that take place in stars and contribute to the energy generation and evolution of stars and to the synthesis of chemical elements building up our Universe. Our group carries out research in various sub-fields of nuclear astrophysics. One of our main research fields is the study of the astrophysical p-process, which is the production mechanism of the heavy, proton-rich isotopes. Using Atomki's accelerators, we study proton- and α -induced reactions relevant

to the p-process in order to provide data for this poorly known nucleosynthetic process. We are also involved in the international LUNA collaboration, which operates the world's only deep underground accelerator to study extremely low-cross-section reactions of astrophysical relevance. We are also interested in some other activities, such as the measurement of the half-lives of various radioactive isotopes (and the dependence of the half-life on different parameters), the application of the Trojan Horse indirect method for cross-section measurement and radioactive ion beam experiments relevant to astrophysics.



Typical p-process reaction flow, which results in the synthesis of the heavy, proton-rich isotopes.



Activation γ spectrum measured in the $^{130}\text{Ba}(\alpha, \gamma)^{134}\text{Ce}$ reaction.

COOPERATION

- > The LUNA collaboration (<http://luna.lngs.infn.it/>)
- > Helmholtz-Zentrum Dresden-Rossendorf (Germany)
- > LNS, Catania (Italy)
- > Department of Physics, University of Basel (Switzerland)
- > Department of Physics, Kocaeli University (Turkey)
- > Dipartimento di Matematica e Fisica, University of Naples (Italy)
- > Institut für Kernphysik, University of Cologne (Germany)

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European Research Council

Established by the European Commission



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NUCLEAR-STRUCTURE AND DECAY DATA EVALUATION

We evaluate nuclear-structure and decay data for isotopes belonging to the $A=101-105$ mass chains, and publish recommended values in the ENSDF online database and in Nuclear Data Sheets.



Partial evaluated, adopted level scheme of a nucleus

Knowledge of the up-to-date values of the nuclear structure and decay data is very important for all fields of nuclear applications, as well as for the fundamental nuclear physics research. The International Network of Nuclear Structure and Decay Data (NSDD) has been set up to satisfy this need. NSDD is an international team of experts who provide recommended nuclear structure and decay data to be used in basic and applied research. The evaluated nuclear quantities include the following: disintegration energies, radiation and transition probabilities, nuclear-level schemes, excitation energies, half-lives, decay modes, spin-parity values, magnetic and electric

multipole moments, and nuclear band structure. Network scientists evaluate nuclear structure and decay data for all isotopes on an agreed basis. Atomki is one of the evaluation centres of the NSDD. Since 2012, the team in Atomki has been responsible for the evaluation of the isotopes belonging to the $A = 101 - 105$ mass chains. NSDD databases contain these data in computerised format and are available both online (ENSDF, NuDat) and offline (Nuclear Wallet Cards). These evaluations are also published in the journals, *Nuclear Physics A* and *Nuclear Data Sheets*. The evaluators also compile the most recent experimental results in the Unevaluated Nuclear Data Library (XUNDL).

COOPERATION

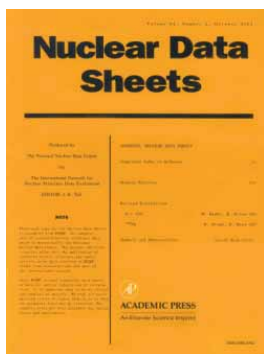
- > Nuclear Data Section, IAEA, Vienna (Austria)
- > McMaster University, Hamilton (Canada)
- > National Nuclear Data Center, Brookhaven National Laboratory, Upton, NY (USA)

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Cover page of Nuclear Data Sheets



B

Fundamental research in atomic physics

Our research activity focuses on how atomic and molecular systems respond to the perturbations due to external fields or colliding charged particles. The processes are investigated by detecting the emerging charged fragments with electron and ion spectrometers constructed by our group.

ION-MOLECULE INTERACTIONS

The experimental investigation of molecule fragmentation and theoretical analysis of the direct core-core interaction, ionization and charge-transfer mechanism in ion-molecule collisions are studied from the point of view of fundamental research.



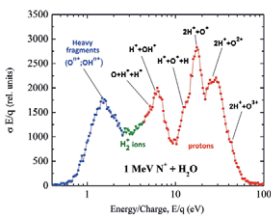
Experimental setup with the electrostatic spectrometer for molecule fragmentation experiments.

Ion-molecule collisions are of major interest, not only in fundamental research, but also in several applied fields, such as radiotherapy and atmospheric chemistry. In tumour treatments, the extremely complex sequence of events, which finally leads to cell death, begins with processes that are purely physical: excitation, ionization and molecular dissociation. In the past few years at Atomki, a special experimental arrangement has been designed and constructed for investigating ion-induced molecule fragmentation processes. The ion beams, provided by the 5-MV Van de Graaff accelerator in Atomki, are ideal for these experiments.

The fragmentation of small molecules such as water and methane are studied in detail. Water is a dominant constituent of living tissues, and methane is a regularly used tissue-equivalent material. The angle, energy and charge states of the fragments emerging from the reactions are selected by spectrometers, which are

designed specifically for these collision experiments. The spectra of the ejected electrons and negative ionic fragments are also measured.

Our experimental studies are supported by theoretical investigations. The charge-transfer mechanism in ion-molecule collisions is studied theoretically in relation to the non-adiabatic interactions between the electronic states of the projectile-target quasi-molecule, with special regard to anisotropy and vibrational effects. The potential energy curves and the nonadiabatic coupling matrix elements are calculated by means of *ab initio* quantum chemistry methods, followed by a semi-classical dynamical treatment in the low- and medium-impact energy range. Beyond the charge-transfer reaction, the formation of the different molecular dissociation channels (starting with direct ionization, collisions of atomic cores, etc.) is also the subject of our theoretical interest.



Energy spectrum of fragment ions from water molecule dissociation induced by ion impact.

COOPERATION

- > Helmholtzzentrum Berlin für Materialien und Energie, Berlin (Germany)
- > CIMAP-GANIL, Caen (France)
- > Quantum Theory Project - University of Florida (USA)

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FUNDAMENTAL ATOMIC COLLISION PROCESSES

This subject involves the experimental and theoretical investigation of fundamental atomic collision processes.

The investigation of atomic collision processes forms a considerable part of our research activity. The applied experimental technique is partly based on the use of particle accelerators, and so this research field is often known as “accelerator-based atomic physics”. The basic collision processes are as follows: excitation, ionization, charge-exchange and relaxation. The primary aim of investigations is to understand better the dynamics of fast atomic collisions by studying, first of all, those involving a few particles. The most direct information on the dynamics can be obtained by observing the ejected primary electrons of continuous energy distribution.

The most important experimental method applied in this research field is, therefore, electron spectroscopy. Currently, the experimental investigations are pursued along two lines with the use of: (1) high-energy ions obtained from the Atomki accelerators; and (2) low-energy positrons. The latter experiments are carried out in London, in collaboration with researchers at University College, London.

The basic collision processes are also studied theoretically. Calculations are performed in order to interpret the experimental results obtained by Atomki researchers, and also for other problems of current interest in this field.

COOPERATION

- > Department of Physics and Astronomy, University College London, London (UK)
- > Department of Physics and Astronomy, York University, Toronto (Canada)
- > Department of Applied Physics, Faculty of Engineering, University of Miyazaki (Japan)
- > Bhabha Atomic Research Centre, Trombay, Mumbai (India)
- > Centro Atómico Bariloche, S. C. de Bariloche (Argentina)

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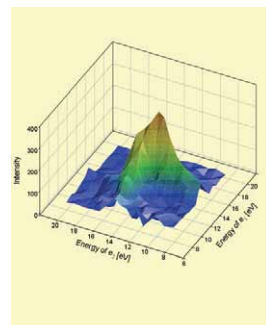
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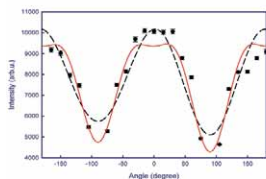
Time-of-flight electron spectrometer for studies of ion-atom collisions.



Experimentally observed correlation between the energy of two electrons simultaneously ejected from atomic collisions.

THE LIGHT-MATTER INTERACTION

The Universe is filled with photons (their wavelength range is between 10^8 – 10^{-16} m), and their interaction with matter is a common and fundamental process. For example, life is unimaginable without the light–matter interaction.



The figure shows a measured angular distribution of Kr 4p photoelectrons relative to the polarization vector at $h\nu=93.1$ eV (circles). The dashed solid lines are the results of the fit without and with higher order corrections.



Experimental setup of ESA-22 electronspectrometer

The photon–matter interaction may be viewed as an interaction of atoms with light as described by classical electrodynamics. The atomic electron, when treated quantum mechanically, interacts with a periodic electromagnetic field, which is represented by its polarization and wave vector. The initial and final states of the system are those of the atomic electrons, without the wave functions of photons. We experimentally investigate the limits of this quantum mechanical description using high-resolution electron spectroscopy. The angular distribution of electrons ejected in photoionization is sensitive to the dynamics of the multielectron correlation, and to the interaction between the direct and indirect ionization channels of single- and multi-photon single ionization. In some cases, our experimental observations show that the contribution of the non-dipole and channel interactions is stronger than that predicted theoretically. Our experimental study is based on an electron spectrometer (ESA-22, developed in Atomki), which is capable of

measuring the energy and total angular range of emitted electrons simultaneously (at 22 polar angles between $\theta = 15^\circ - 165^\circ$). This unique instrument is able to determine the higher-order multipole components of the angular distribution of a photoelectron with high precision, and investigate the dynamics of multi-correlation effects in atomic and molecular systems. We plan to extend our investigation to the multi-photon ionization of valence and inner shells in the photon energy range of ultrashort laser light to XUV. Furthermore, we want to determine the anisotropy and asymmetry parameters in this photon energy range. We note that the non-zero asymmetry parameters show the limit of the above-mentioned quantum mechanical model in its short wavelength limit. The Attosecond Beamline at the University of Szeged, and later at the ELI (Extreme Light Infrastructure, Szeged), will produce pulses of a few attoseconds. Further investigation will be carried out at the newly built PETRA III synchrotron, HASYLAB, Hamburg.

COOPERATION

- > Institute for Atomic and Molecular Physics of Justus Liebig University, Giessen (Germany)
- > DESY, Hamburg (Germany)

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DYNAMICS OF IONS IN MICROSCOPIC STRUCTURES

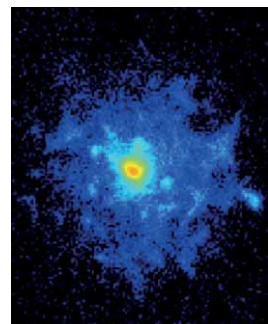
The guided transmission of slow ions by a self-organizing charging-up mechanism in insulating nano- and micro-capillaries is studied.

Slow ions of a few keV energy can pass through narrow capillaries in thin insulating foils without changing their charge state even when the capillaries are tilted. In the long channels (the length of the capillaries is about 100 times larger than their diameter), the ions are deflected and guided by the charges previously deposited on the capillary walls by the incident ion beam. Understanding the self-organizing process that enables the ion beam to be transmitted and guided along the capillaries, is important from a fundamental point of view. Furthermore, insulating capillaries can be used for directing and focusing ion beams on the micrometre scale.

This phenomenon is investigated experimentally for capillary samples of polyethylene terephthalate, polycarbonate, aluminium oxide and glass at the Atomki ECR ion source. Two-dimensional imaging of the angular distribution of the transmitted ions and neutral species is performed. The different charge states are separated by an electric field and are studied simultaneously. The time development of angular distributions, the charge-up dynamics, the successive development of charge patches inside the capillaries, the formation of neutrals and charge migration in the capillaries after irradiation are also studied. This has led to further insights and a better understanding of the process.



Microscopic image of a glass microcapillary array



Angular distribution of ions and neutrals transmitted through a glass microcapillary array

COOPERATION

- > Department of Experimental Physics, University of Debrecen (Hungary)
- > ITS LEIF – European Integrated Infrastructure Initiative (FP6 - I3)
- > KVI Groningen (Holland)
- > Université Catholique de Louvain (Belgium)
- > Helmholtzzentrum Berlin für Materialien und Energie, Berlin (Germany)

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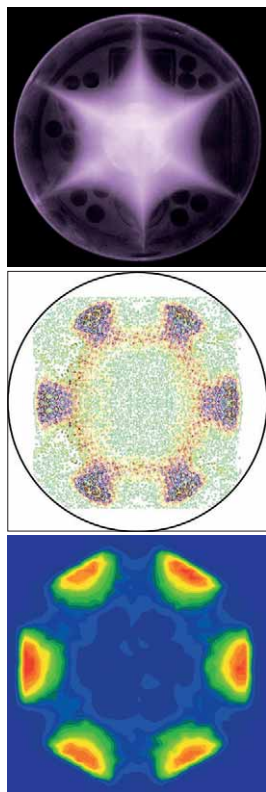
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PLASMA PHYSICS

The electron cyclotron resonance (ECR) ion source of Atomki is devoted to the production and delivery of highly charged plasmas and low-energy ion beams of a wide range of elements.



Different visualizations of plasma produced in the ECR ion source: digital photograph (top); energy-filtered X-ray image (middle); computer simulation (bottom).

The ECR ion source is a facility used worldwide as a beam injector for large accelerators. At Atomki, however, it is a stand-alone device for producing highly charged plasmas and low-energy ion beams for atomic physics and plasma-physics research and for applications. The ion charge in the plasma and in the beam can be varied from 1 up to almost 30 (depending on the element). The beam energy is variable between 50 eV and 800 keV. In the laboratory, numerous atomic and plasma physics investigations are carried out, e.g., plasma diagnostics, X-ray spectroscopy, the study of ion-surface interactions, the production of new materials. For plasma physics, it is important to know where, why and

how the highly charged ions are produced and trapped. The answer to these questions, has been sought by different means. Small-size electrostatic electrodes (Langmuir probes) are used to obtain local information on certain plasma parameters. The plasma emits radiation in the infrared, visible light, ultraviolet and X-ray regions of the electromagnetic spectrum, and numerous such photographs and spectra have been recorded and analysed in the laboratory. These methods are combined and complemented with computer modelling and simulation. The results obtained so far have shown that these techniques give important new insight into the structure and properties of the highly charged plasmas.

COOPERATION

The design of the original ion source and many of the developments and plasma research experiments have been carried out in domestic and international collaborations. Here are the names of those institutions with whom joint publications were written on ECRIS developments and research in the past 20 years: University of Debrecen (Hungary), Budapest T&E University (Hungary), Universität Frankfurt a.M. (Germany), UCL (Belgium), NIRS (Japan), RIKEN (Japan), University of Jyväskylä (Finland), PSI (Switzerland), CEA Grenoble (France), NIST (USA), Babeş-Bolyai University (Romania), GANIL (France), Toyo University (Japan).

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THE INTERACTION OF CHARGED PARTICLES WITH PLANAR AND CYLINDRICAL SURFACES

We focus on the study of fundamental scattering processes in atomic and surface physics based on nano-structured materials and capillaries from nano- to the micrometre scale.

Over the past few years, research activities in the field of charged-particle physics have turned to the investigation of charged-particle interactions with flat and cylindrical surfaces and interfaces based on nano-structured materials and capillaries, from the nano- to micrometre scale. Work in this field is strongly motivated because the new knowledge holds the possibility for many technical applications. One potential technical application of recent investigations aims at the nano-fabrication and nano-structuring of surfaces. Our research also has impact for biological applications such as the investigation of radiation effects in biological tissue. In our investigations, we combine our experimental findings with theoretical work.

THE MAIN GOALS ARE AS FOLLOWS:

- > The investigation of electron and ion transport through a single macro-capillary for a possible future medical application.
- > The investigation of charged-particle transmission between flat plates. The completely new feature of these investigations may lead us to the development of a special ion-optical tool.
- > The investigation of surfaces and interfaces in simple and multi-layered samples using electron Rutherford back-scattering spectroscopy, and reflected energy loss spectroscopy.
- > The investigation of the effect of multiple electron scattering in electron–solid collisions, from low to relativistic electron energies.

COOPERATION

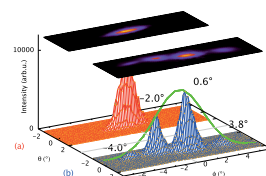
- > Vienna University of Technology, Vienna (Austria)
- > Missouri University of Science and Technology, Rolla (USA)
- > Western Michigan University, Kalamazoo, Michigan (USA)
- > Tokyo University of Science, Tokyo (Japan)
- > RIKEN, Tokyo (Japan)
- > University of Science and Technology of China, Hefei (P.R. China)
- > Babes-Bolyai University, Cluj-Napoca (Romania)

REFERENCES

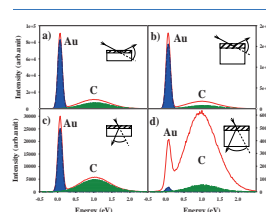
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Angular distributions of the direct beam, collimated by a 0.5 mm aperture (a) in comparison with the guided distributions (b) for four different tilt angles as indicated. The z-axis shows the number of ion impacts per unit area. The green curve is a gaussian fit of the maxima of the distributions. ϕ is the lateral deflection angle in the horizontal plane, the elevation angle is θ .



Energy distributions of electrons scattered elastically from Au-C double layer at 40 keV primary energy for two different thicknesses in transmission and reflection geometry. Panel a) – reflection mode, $d(\text{Au})=1 \text{ \AA}$, $d(\text{C})=90 \text{ \AA}$; panel b) – reflection mode, $d(\text{Au})=2 \text{ \AA}$, $d(\text{C})=1400 \text{ \AA}$; panel c) – transmission mode, $d(\text{Au})=1 \text{ \AA}$, $d(\text{C})=90 \text{ \AA}$; panel d) – transmission mode, $d(\text{Au})=2 \text{ \AA}$, $d(\text{C})=1400 \text{ \AA}$. Red solid line: total spectrum, blue area: the single scattering contribution from Au atoms, green area: the single scattering contribution from C atoms.

The background of the slide is an abstract composition. It features several overlapping, wavy, semi-transparent shapes in shades of red, orange, and green. Overlaid on these shapes is a dense field of small, multi-colored arrows (red, orange, yellow, green, blue) pointing in various directions, creating a sense of dynamic movement or a vector field. The overall aesthetic is modern and scientific.

C

Particle physics

Both experiment and theory are represented in our particle physics programme. The experimental group takes part in the CMS experiment, which is one of the main experiments at the LHC in CERN. The main focus of our theory group is lattice QCD and applications of the functional renormalisation group.

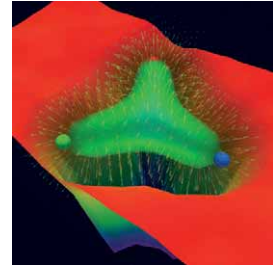
LATTICE QUANTUM CHROMODYNAMICS

We study strongly interacting systems under the extreme conditions of high temperature.

Quantum chromodynamics (QCD) is the fundamental theory of strong interactions that confine quarks into hadrons, such as the proton and the neutron. Ninety-nine percent of the mass of matter has its origin in the strong interaction of quarks. Thus strongly interacting systems are very different from the sum of their constituents and this makes their study a real challenge. The only possible way to treat strongly interacting systems starting from first principles is to discretize QCD on a four-dimensional space-time lattice. This enables us to perform “computer experiments” to gain better understanding of the properties of these systems. Currently, we are

studying the high-temperature, so-called quark–gluon plasma state of QCD, where we have found that quarks undergo a transition analogous to that of electrons at the Anderson metal–insulator transition in conductors. The transition that we discovered has the same universal critical behaviour as Anderson transitions previously found in systems characterized by energy- and length-scales vastly different from those of QCD. Most of our computations are performed on a locally available computer cluster utilizing Nvidia GPU-s.

Our group is supported by a “Lendület” grant of the Hungarian Academy of Sciences.



Three quarks forming a baryon, such as a proton or a neutron. The quarks are connected by flux tubes of gluons, the mediators of the strong interaction. This visualization is based on lattice computer simulations.

COOPERATION

- > Department of Physics, Universität Regensburg (Germany)
- > Department of Physics, Shimane University (Japan)
- > Department of Theoretical Physics, Eötvös Loránd University, Budapest (Hungary)

REFERENCES

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CONTACT

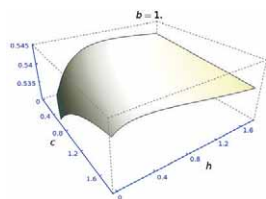
Tamás Kovács, e-mail: kovacs.tamas.gyorgy@atomki.mta.hu



The lattice-QCD computer cluster is housed together with the CERN Tier3 Grid Center belonging to the particle physics group of Atomki.

QUANTUM FIELD THEORY

The natural theoretical framework for particle physics is quantum field theory, in which the so-called renormalization procedure is required in order to calculate measurable quantities. We investigate various aspects of non-perturbative renormalization.



The figure demonstrates the regulator-dependence of a measurable physical quantity, the so-called critical exponent obtained by the functional RG study of the three-dimensional Ising model. Higher exponents indicate better regulators.

One cannot obtain physical results in quantum field theory (QFT) without renormalization, and the formalism needs to be extended to the renormalization group (RG) in order to understand the physics of quantum field theories on different length or momentum scales. The RG analysis is thus of importance in other applications, in the main application of QFT, which was originally centred in particle physics. Renormalization can be performed by the functional RG method, which is a non-perturbative

technique. On the one hand, we use the functional RG approach to perform the renormalization of sine-Gordon-type scalar theories, which find important applications, not only in particle physics, but also in condensed matter systems such as high-temperature superconductors. On the other hand, we study the technique itself – more precisely, we improve the predictive power of functional RG by optimising the one of its most important unsolved problems – the regulator-dependence.

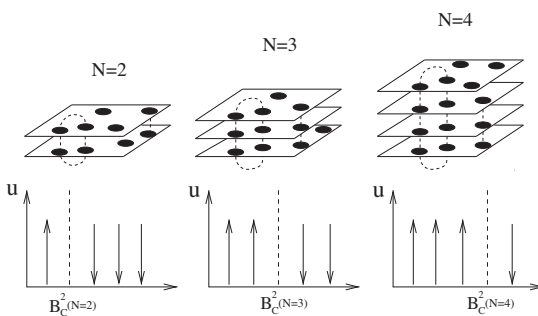


Illustration of the schematic RG trajectories of the multi-layer sine-Gordon model with $N = 2, 3, 4$ layers. Each layer corresponds to a sine-Gordon model, which is coupled to the other. The solid discs represent topological excitations of the layered system.

COOPERATION

- > Missouri S&T University (USA)
- > SISSA, Trieste (Italy)
- > University of Debrecen, Debrecen (Hungary)

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EXPERIMENTAL PARTICLE PHYSICS

An Atomki group has been playing an important role in various CERN experiments and development work. Formerly, these were related to the NA49 experiment and the DELPHI detector system at LEP. Today, our contributions are to the CMS (Compact Muon Solenoid) experiment.

The performance of the CMS detector is affected by the position and orientation of the individual detectors. Therefore, the CMS detector has an alignment system that consists of the internal alignment of the inner tracker, the link system (which transfers the position of the tracker to linking points located between the barrel and the end-cap muon regions), and the barrel and end-cap internal alignments (which measure the positions of the muon detectors with respect to the linking points) The group has been responsible for the designing, manufacturing and maintaining of the muon barrel alignment system. The positions of the 250 barrel muon chambers have to be measured

with 150-350 μm accuracy in order to be able to determine the muon momentum with 5-20% accuracy depending on the muon energy. The measurements of the positions of the muon chambers are performed by means of around 10,000 LEDs mounted on the chambers and observed by an opto-mechanical network composed of 36 rigid structures called MABs (Module for Alignment of the Barrel) holding 600 CMOS video cameras. The operation, synchronization, data-taking and preliminary evaluation of the collected data are executed by 36 personal computer modules mounted on the detector and connected to each other, as well as to the main control computer via an ethernet network.

COOPERATION

- > CERN, Geneva (Switzerland)

REFERENCES

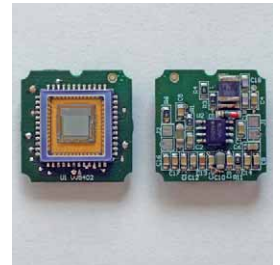
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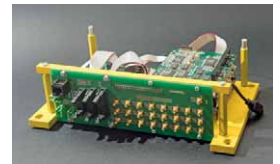
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Fork with LED light sources



VLSI camera based on active pixel sensor



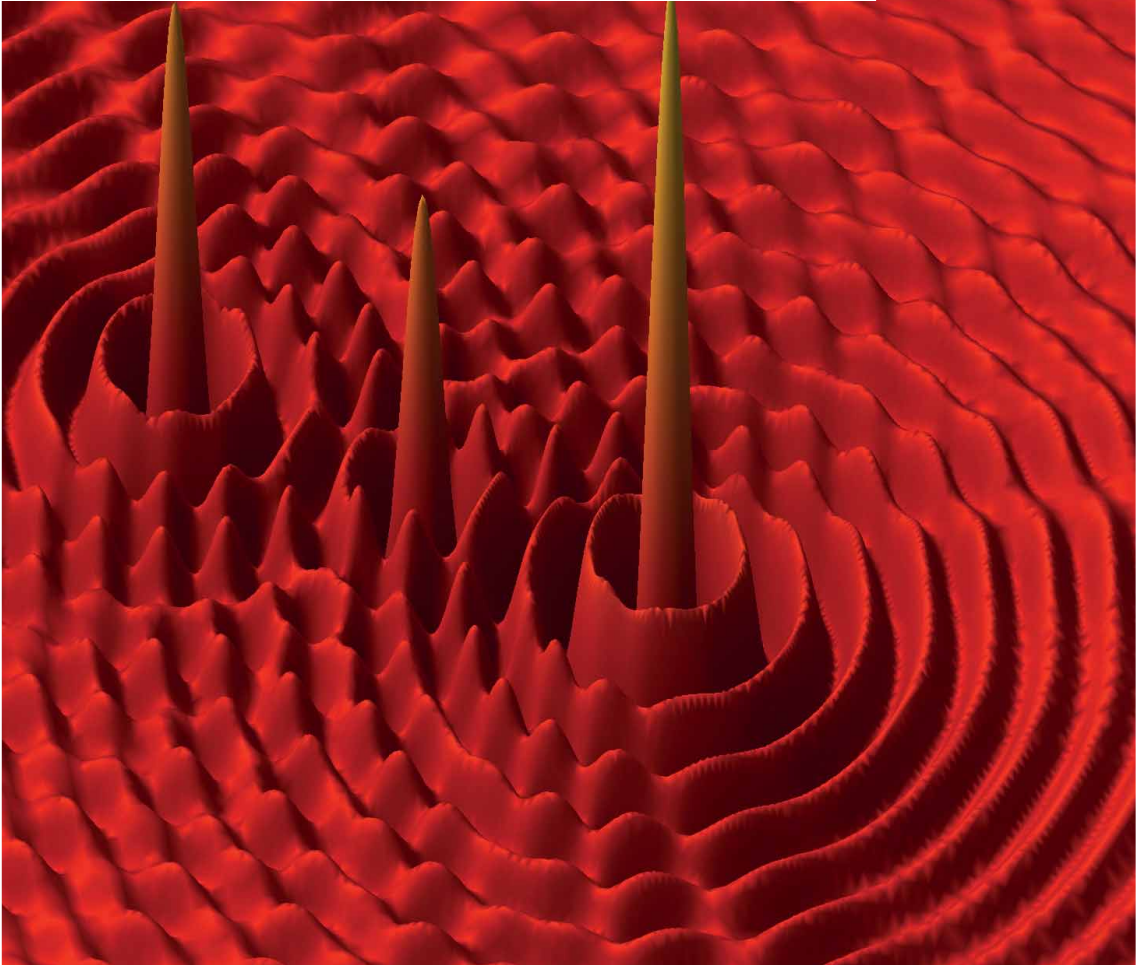
Board Computer processing camera signals

The background of the entire page is a vibrant red color with a complex, wavy, and textured pattern that resembles ripples in water or a topographical map. The waves are concentric and flow from the top right towards the bottom left, creating a sense of depth and movement. The lighting is dramatic, with highlights and shadows that emphasize the three-dimensional quality of the ripples.

D

Quantum physics

The main subject within this category is nuclear theory. Models of light exotic nuclei, states of specific symmetries and clustered states are being investigated. Bound and scattering aspects of quantum systems are studied both numerically and analytically. The nonlocal nature of quantum physics, quantum correlations and their possible applications to quantum informatics are new research areas.

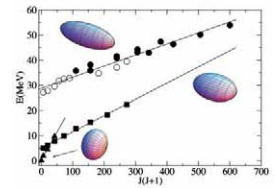
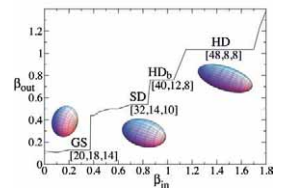


NUCLEAR STRUCTURE AND SYMMETRIES

We study the structure of atomic nuclei with special emphasis on symmetry aspects and methods.

The nucleus of the atom is a very tiny object, nevertheless it consists of many (up to a few hundred) constituents, called nucleons. Therefore, its theoretical description can be carried out only in terms of simplifying models. The fundamental models of nuclear structure are based on different physical pictures: the shell model treats the nucleus as a miniature solar system; the collective model says it is a microscopic liquid drop; while the cluster model considers it as a small molecule. The interrelations of these models are essential for our understanding, and can be established in terms of symmetries. These help us also to find some simple solutions to this difficult many-body problem. In nuclei, a large variety of symmetries show up.

The simplest and most familiar ones are the symmetries of the shape of the spherical or cylindrical nuclei. The symmetries of the interactions acting between the nucleons are also very important. Finally, one finds fairly abstract symmetries of the basic equations, describing a situation where neither the interaction, nor the state is symmetric, yet the symmetry is present and has important physical consequences. One of the phenomena we search for is the exotic nuclear deformation. For example, superdeformation and hyperdeformation correspond to the ratios of the main axes of 2:1:1, and 3:1:1, respectively. In case of ^{36}Ar experiments resulted in good candidates for these shapes, following the theoretical prediction.



The ground (GS), superdeformed (SD) and hyperdeformed (HD) states of the ^{36}Ar nucleus from the symmetry-based model calculation (a) and from the experimental observation (b).

COOPERATION

- > Yukawa Institute, Kyoto (Japan)
- > Hokkaido University, Sapporo (Japan)
- > Joint Institute, Dubna (Russia)
- > University of São Paulo (Brasil)
- > UNAM Mexico (Mexico)

REFERENCES

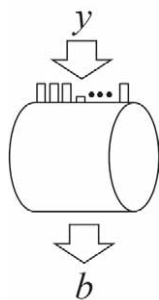
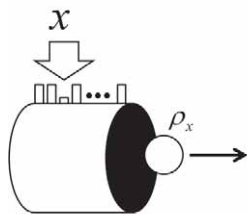
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QUANTUM CORRELATIONS

Device-independent quantum Information: how to access information from non-local quantum correlations?



Quantum nonlocality is one of the central aspects of quantum mechanics. It is the strange ability of quantum objects to synchronize actions over large distances in a powerful way, which could not occur through any classical mechanism.

In addition to its fundamental interest, quantum nonlocality is instrumental in the emergent field of device-independent quantum information processing. In this new paradigm, local systems are regarded as black boxes, between which all the accessible information is given by a collection of measurement results, the only assumptions invoked being that individual devices are properly separated from each other and that inputs are chosen freely. Several quantum information tasks, such as quantum cryptography

or randomness amplification can be accomplished in a device-independent manner. This new concept, for instance, allows novel key-distribution protocols, whose security is independent of the quantum states and measurements used to establish the key.

In Atomki, we are working in this device-independent framework, developing novel applications for assessing quantum information, for instance, we are able to witness dimension of quantum resources or certify genuine multipartite entanglement – a form of nonlocal correlations. A challenge in this field is to devise even more powerful protocols in the multipartite setting by exploiting the rich structure of multipartite nonlocality.

Testing the dimension of an unknown system in a prepare-and-measure scenario.

COOPERATION

- > The Institute of Photonic Sciences (ICFO), Barcelona (Spain)
- > Group of Applied Physics, University of Geneva, Geneva (Switzerland)
- > Centre for Quantum Technologies, Singapore (Singapore)

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EXACTLY SOLVABLE PROBLEMS IN QUANTUM MECHANICS

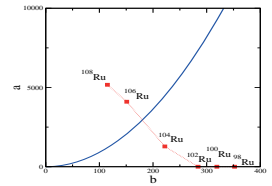
We search for new potentials, for which the Schrödinger equation can be solved exactly, discuss their properties, including their symmetries, and look for concrete physical systems that could be described by these potentials.

Quantum mechanics describes the structure and dynamics of the subatomic world. The mathematical description of quantum systems is usually done in terms of differential equations, e.g., the Schrödinger equation, which contain some potential describing the interactions that govern the system. The solutions of these differential equations – the wave functions – contain all information on the problem. These solutions are usually obtained by numerical techniques, but sometimes they can be written in exact mathematical form.

The practical importance of these exactly solvable problems lies in the fact that they can be used to develop and test numerical techniques.

Furthermore, they give insight into the fundamental aspects of quantum mechanics. For example, they are essential in interpreting various symmetries characterizing quantum systems. Our activity in this field includes extending the range of exactly solvable Schrödinger equations, exploring their symmetries, and finding physical problems where these results can be applied.

In quantum mechanics, we study systems with special arrangements of complex potentials giving rise to PT symmetry and its spontaneous breakdown. In nuclear physics, we apply potentials to discuss different equilibrium shapes of nuclei, as well as phase transitions between them.



Transition of Ru isotopes from the spherical to the deformed shape phase in the parameter space of the quasi-exactly solvable sextic oscillator. The two parameters (a and b) were determined by fitting the model spectrum to the experimental energy eigenvalues. The spherical and deformed domains are located below and above the parabola, respectively. The harmonic oscillator corresponds to $a=0$.

COOPERATION

- > Nuclear Physics Institute of the Academy of Sciences of the Czech Republic, Řež (Czech Republic)
- > Indian Statistical Institute, Kolkata (India)
- > University of Sevilla, Sevilla (Spain)

REFERENCES

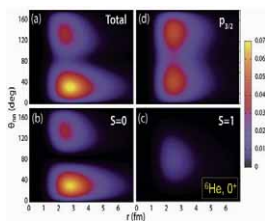
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CONTACT

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SCATTERING THEORY AND RESONANCES

Scattering and resonance states of few-body quantum systems are studied.



Two-neutron correlation in the ground state of ${}^6\text{He}$ described by a three-body model ($\alpha+n+n$). The density in the plane spanned by the three particles is shown, coded in colour, in an arrangement in which the two neutrons are equally displaced to distance r from the alpha particle. The abscissa is r , while the ordinate is the angle between the two neutrons with respect to the point-like α particle.

Top left: total density; top right: the $p_{3/2}$ contribution; bottom: $S=0$ and $S=1$ contributions.

The description of the decay processes of unstable systems is of great physical importance. In fact, almost all known elementary particles are unstable. The advent of radioactive ion beam facilities has opened up the way to probing unstable nuclei and reaching new regions of the nuclear chart with extreme neutron-to-proton ratios. Many of these nuclei and their reactions play key roles in the processes of nucleosynthesis and of energy production in stars. One of the most relevant questions in nuclear physics is exploring the limits of nucleon numbers within which nuclei can exist. Nowadays, the focus of nuclear theory is moving from studies of nuclei close to

the valley of stability towards a description of short-lived and exotic nuclei. Nuclei are typical mesoscopic open quantum systems and splendid laboratories of many-body physics. Describing such systems requires techniques rather different from those developed for stable systems that possess well-understood bound states. These structural models either cannot be applied to unbound systems, or have to be modified considerably. The aim of our investigations is to obtain a better understanding of unbound quantum systems, to develop new methods, and to solve the Schrödinger equation with high-precision numerical methods.

COOPERATION

- > Oak Ridge National Laboratory, Oak Ridge (USA)
- > Hokkaido University, Sapporo (Japan)
- > Physics Institute of Rosario (Argentina)
- > Royal Institute of Technology, Stockholm (Sweden)

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E

Application of nuclear physics and of accelerators

This area of scientific activity covers the application of nuclear physics, mainly in connection with the application of low-energy particle accelerators (cyclotron, VdG). It also includes the production and application of radioactive isotopes in research, industry, agriculture and medicine.

RADIATION HARDNESS TESTS

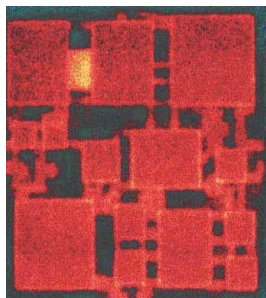
Atomki has a long tradition, high-level expertise and facilities for irradiation tests of different semiconductor-based electronic and photonic devices used in a harsh radiation environment, high-energy physics, space research and other applications.



Image of the SMART-1 satellite
(Copyright ESA-J. Huart)



This multilayer plate was developed for thermal protection of Smart-1, but the surface cracked during the radiation hardness tests performed in Atomki



Gamma autoradiogram of an irradiated multi-chip IC

The radiation environment is one of the major problems for electronics in orbiting satellites or detectors at high-energy physics facilities like the Large Hadron Collider at CERN. “Single-event upsets” are created when ionizing radiation hits a working electronic circuit and the charge created alters its state. The use of submicron technology for the fabrication of ICs, in combination with lower operational voltages, lowers the critical charge for temporary upsets, resulting in heightened sensitivity to radiation. The Electronics Section at Atomki has contributed to several international science collaboration projects (e.g., Royal Institute

of Technologies, CERN, ITER, SSC, ESA), and its nuclear electronics designs have been recognized internationally. Several systems developed and tested using gamma-ray, proton, heavy ion and neutron irradiation at Atomki have been in operation at international research centres, or are still functioning onboard satellites. The SMART-1 satellite – the first member of ESA’s Small Mission for Advanced Research in Technology programme – was developed to test various new techniques in the real space environment. The radiation-hardness tests on the satellite’s electronic components were carried out by Atomki.

COOPERATION

- > Royal Institute of Technology (Sweden)
- > National Instruments Hungary Kft. (Hungary)
- > CERN (Switzerland)
- > BME Institute of Nuclear Techniques (Hungary)

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CONTACT

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RADIOCHEMISTRY AND ISOTOPE SEPARATION

The synthesis of pharmaceuticals can be studied by labelling them with radioisotopes produced on-site and then carrying out single-photon (SPECT) and positron emission (PET) tomography.

Radioactive isotopes produced in the Atomki cyclotron are chemically separated from the irradiated targets in the radiochemical laboratory using wet chemistry or a dry distillation procedure. From these radioisotopes, radiopharmaceuticals are synthesized for diagnostic (PET: ^{11}C , ^{61}Cu , ^{64}Cu , ^{76}Br , ^{124}I ; SPECT: ^{123}I , ^{111}In , ^{67}Ga) and therapeutic (^{103}Pd , ^{131}Cs , ^{165}Er , ^{169}Yb , ^{186}Re , $^{209,210}\text{At}$) applications. The main fields of routine radiopharmaceutical productions are ^{11}C -labelled

methionine and ^{18}F -labelled fluorodeoxy-D-glucose as well as ^{67}Ga -citrate and different ^{123}I -labelled products. Some of these labelled compounds can also be used for agricultural investigations and animal diagnostics. In the laboratory, we also carry out PET imaging of the catalytic process of ^{11}C -methanol on zeolite, and analyse radioactive water and ion-exchange resin samples of nuclear plants.



Vertical beam line for irradiation of solid and gas targets.

COOPERATION

- > National Institute for Radiological Research, Chiba (Japan)
- > iThemba Laboratory for Accelerator Based Sciences, Somerset West (South-Africa)
- > Saha Institute of Nuclear Physics, Kolkata (India)
- > Nuclear Energy Corporation, Pretoria (South-Africa)
- > Institute of Organic Chemistry of Bulgarian Academy of Sciences, Sofia (Bulgaria)

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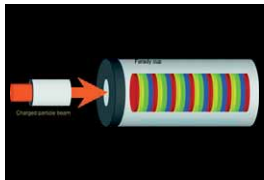
Zoltán Kovács, e-mail: kovacs.zoltan@atomki.mta.hu



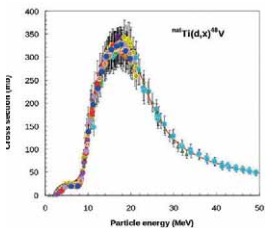
Valve system of the equipment for radiopharmaceutical production.

THE MEASUREMENT OF NUCLEAR DATA

The measurement and compilation of cross-section and yield data for charged-particle-induced nuclear reactions is carried out, as well as building databases and testing nuclear reaction model codes.



Nuclear data measurement with stacked foil technique



Typical example for compilation of a monitor reaction

Modern fundamental research and applications require accurate nuclear data to be available to the scientific community. The group carries out systematic experimental studies and compilations of charged-particle-induced nuclear-reaction data. The programme includes the measurement of new experimental data, comparison of experimental results and predictions, and the development of recommended nuclear reaction cross-section libraries and new methodologies relevant to different applications. Real application of the gathered information in everyday practice is part of the activity. The research group is a member of the international network of Nuclear Reaction Data Centres (NRDC) since 1992, and participates in the compilation of experimental data in the data library EXFOR, which

is maintained by IAEA. It is the most extensively used data library. The members of the group, as experts, also contribute to the international team work of different Coordinated Research Projects (CRP) organized by IAEA. (CRPs: F22062, F22041, F22033, F22019, F41029, F41021, F41014).

The applications are related to the following fields:

- > The production of diagnostic and therapeutic medical radioisotopes;
- > Nuclear accelerator and target technology;
- > Thin-Layer activation for wear, erosion and corrosion studies;
- > Nuclear analytical technology;
- > Nuclear astrophysics.

COOPERATION

- > International Atomic Energy Agency, Nuclear Data Services, Vienna (Austria)
- > International Atomic Energy Agency, Radioisotope Products and Radiation Technology Section, Vienna (Austria)
- > Free University of Brussels, Cyclotron Laboratory, Brussels (Belgium)
- > Tohoku University, Cyclotron and Radioisotope Center, Sendai (Japan)
- > Institute for Physics and Power Engineering, Obninsk (Russia)

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NEUTRON PHYSICS

The excitation function of neutron-induced nuclear reactions, neutron transport in bulk media, and methods for detection and identification of illicit materials hidden in bulk media, are studied and developed.

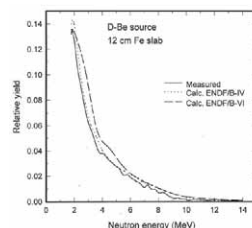
The main topics are:

- > The measurement of excitation functions of neutron induced nuclear reactions;
- > Testing libraries of evaluated neutron-cross-section data;
- > The study of the neutron transport and leakage in extended media;
- > The development of methods for detection of illicit materials hidden in bulk media.

Experimental data and the results of Monte Carlo simulations are compared. The medium to be studied can be exposed to broad-spectrum d+Be neutrons or quasi-monoenergetic d+D neutrons produced at the MGC-20E cyclotron. The multi-foil activation technique and the pulse height response spectrometry (PHRS) method, using NE-213 or EJ-301

liquid scintillators, are used for fast-neutron spectrometry. ^3He and BF_3 counters and foils (Dy, In, Au), with and without thermal neutron shielding, are used for detecting thermal and epithermal neutrons. One of the group's research fields relates to the development of diagnostics methods for thermonuclear fusion reactors.

An epithermal neutron analyser (ETNA), developed at the Department of Experimental Physics of University of Debrecen, is used for bulk hydrogen analysis. The results obtained with ETNA are useful in developing instruments for detection and identification of illicit materials (plastic anti-personnel landmines, explosives, etc.) hidden in airline baggage and cargo containers.



Measured and simulated leakage spectra of d+Be neutrons behind an iron slab.

COOPERATION

- > Department of Experimental Physics, University of Debrecen (Hungary)
- > International Atomic Energy Agency, Vienna (Austria)

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INDUSTRIAL AND MEDICAL APPLICATIONS

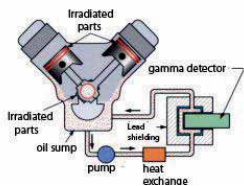
Radioactive tracing of industrial and biological processes, wear measurement, the development of radioisotope production for medicine are carried out.



Automobile camshaft irradiation for wear measurement by using TLA (Thin Layer Activation)

The production of radioisotopes with appropriate decay and radiation parameters for tracing industrial and biological processes has been developed. The type of the radioisotopes depends on the requested study duration (half-life), the distance and shielding during the measurement (energy and intensity), as well as the type of radiation. In the most recent improvements in the tracing method, the radioisotope production parameters were chosen in such a way that the activity produced is under the so-called “free handling limit”, so that it is possible to use them at sites without a special license. These isotopes are produced in the surface layers of the sample

being investigated, by irradiating them with a charged particle beam of appropriate energy, intensity and irradiation time. The activated samples are installed in their normal work environment and subjected to typical wear. The change in surface activity is then measured. The amount of wear (or corrosion or erosion) can be calculated from the change. The production of radioisotopes for potential applications in biology and medicine is also investigated. These isotopes can be used for human diagnostics or treatment, or for tracing biological processes by using them to label appropriately selected compounds.



Schematic diagram of wear measurement of activated machine parts

COOPERATION

- > AC2T (Austrian Competence Center for Tribology), Wiener Neustadt (Austria)
- > IAVF (Institute for Applied Wear Studies) Karlsruhe (Germany)
- > IAEA (International Atomic Energy Agency) Vienna (Austria)

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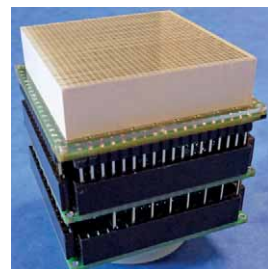
DETECTOR DEVELOPMENT

The PET technique is widely used in human clinical studies and the recent developments of image resolution have made it suitable for small-animal research. The Electronics Section has more than 10 years' experience in small-animal PET development.

Acquiring high-resolution anatomical data and also quantitative functional information *in vivo* is becoming an important factor in the diagnosis of disease. PET provides high sensitivity and high specificity functional information – while MRI supplies good anatomical detail.

The small-animal PET scanner, MiniPET-3, was developed within the framework of the EU project – ENIAC CSI (Central Nervous System Imaging) – by the Electronics Section at Atomki, in close collaboration with the Institute of Nuclear Medicine (University of Debrecen). The new scanner is based on technologies developed for MiniPET-2, e.g., DSP technology, scalable individual detector modules, and

a network-based data-acquisition system. The design of the detector modules is similar to that of MiniPET-2. However, the bulky H9500 PSPMTs (position-sensitive photomultipliers) were replaced with SiPMs (silicon photomultipliers). The SiPMs are unaffected by strong magnetic fields, so are suitable for a PET-MRI insert or scanner. The results of optical and nuclear characterization proved that SiPM tiles using 1-mm light-guides provide a feasible solution for small-animal PET imaging. Performance tests, carried out according to the NEMA-NU4 standard, show that the parameters of the SiPM-based scanners are comparable to, or better than, conventional PSPMT-based systems.



Detector module of MiniPET-3: LYSO crystal matrix (on the top), SiPM tile and front-end electronics before final assembly.



MiniPET-3 small animal PET camera

COOPERATION

- > ST Microelectronics (Italy)
- > Philips Ltd. (The Netherlands)
- > Institute of Nuclear Medicine, University of Debrecen, Debrecen (Hungary)

REFERENCES

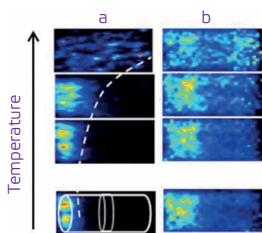
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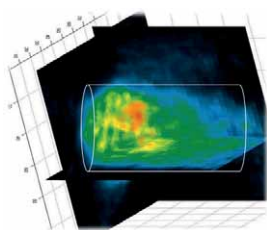
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IMAGING OF SURFACE CHEMICAL PROCESSES

Three-dimensional imaging of surface chemical processes in catalysis can be carried out using high-resolution positron emission tomography.



^{11}C -radiolabelled methanol distribution on fresh (a) and used (b) zeolite catalysts.



3D imaging of catalysis

The positron emission tomography (PET) technique is a well-known method in diagnostic nuclear medicine for the molecular imaging of biochemical functions in the human body. However, it can also be applied to the molecular imaging of chemical processes on the surfaces of heterogeneous catalysts. Dynamic studies of adsorption, desorption, and realignment of ^{11}C positron-emitter labelled compounds can be performed. Surface imaging techniques help one to look inside a catalyst bed, and understand the kinetics and surface dynamics of catalysis and the reaction mechanisms on surface sites under different experimental conditions.

A small PET scanner (MiniPET-2) had been developed in Atomki in collaboration with the University of Debrecen, for small-

animal preclinical imaging (with parameters similar to those of a commercial 'small-animal PET apparatus). The camera has 12 detector modules in a full ring configuration. The 3D image is formed from 35 cross-sectional slices.

Such PET scanners have great potential for both academic and industrial research in imaging catalyst surfaces, whether they are well- or poorly-functioning, or partially covered. The imaging system is powerful because the sample is scanned both radially and axially, so that the distribution of radioactive compounds is analyzed in the total catalyst volume. This PET camera was used to map the location and quantitative distribution of a ^{11}C -methanol compound in a zeolite catalyst bed (4 cm long and 1.6 cm across) in three dimensions.

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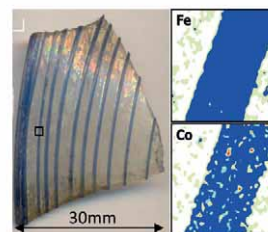
APPLICATION OF FOCUSED ION BEAMS: ION BEAM ANALYSIS (IBA) AND PROTON BEAM WRITING (PBW)

Sensitive IBA methods can be used to characterize objects quantitatively at the macroscopic and microscopic scale, while PBW employs a focused MeV-energy ion beam to scan a resist material, which is then chemically developed to create different microstructures.

Ion beam analysis is a comprehensive term referring to a group of modern analytical techniques that employ MeV ion beam interactions with a target sample in order to characterize them in a nondestructive way. The simultaneous application of IBA techniques (PIXE, PIGE, RBS, STIM, NRA, ERDA), combined with a focused ion beam, enables the quantitative mapping of all elements in the Periodic Table down to the parts-per-million level with high accuracy, as well as simultaneously carrying out structural imaging and depth profiling. Ion beam analysis and ion microscopy have a wide range of applications in archaeometry, environmental research, atmospheric science, biology, medical science, geology and materials science.

Proton beam writing uses a focused beam of MeV-energy protons to pattern

resist-materials at microscopic or nanoscopic scales. The process, although similar in many ways to direct writing with electrons, nevertheless offers some interesting and unique advantages. Protons have a deeper penetration in materials and travel in an almost straight path. This feature allows the fabrication of three-dimensional structures of high-aspect ratios, with vertical, smooth side-walls and low line-edge roughness. The primary mechanisms for producing structures in resist-materials is, in general, bond-breaking in positive resists such as PMMA, or crosslinking in negative resists such as SU-8. In positive resists, the regions damaged by protons are removed by chemical development to produce structures, whereas in negative resists, the development procedures remove the undamaged resist, leaving the cross-linked structures behind.



Elemental maps of the cobalt blue pigment in an archaeological glass sample.



Microturbine made by PBW and subsequent selective porous Si etching in collaboration between MTA Atomki and MTA TTK MFA.

COOPERATION

- > National University of Singapore, Centre for Ion Beam Applications (Singapore)
- > Institute of Microelectronics, NCSR Demokritos, Athens, Greece (Greece)
- > Laboratory of Nuclear Analytical Methods, Nuclear Physics Institute AV CR, Rez (Czech Republic)
- > The CHARISMA FP7 project partners / The NANODERM FP5 project partners
- > MTA Research Center for the Humanities, Institute of Archaeology (HU)
- > Déri Museum, Debrecen (Hungary)
- > Josef Stefan Institute, Microanalytical Center, Ljubljana (Slovenia)

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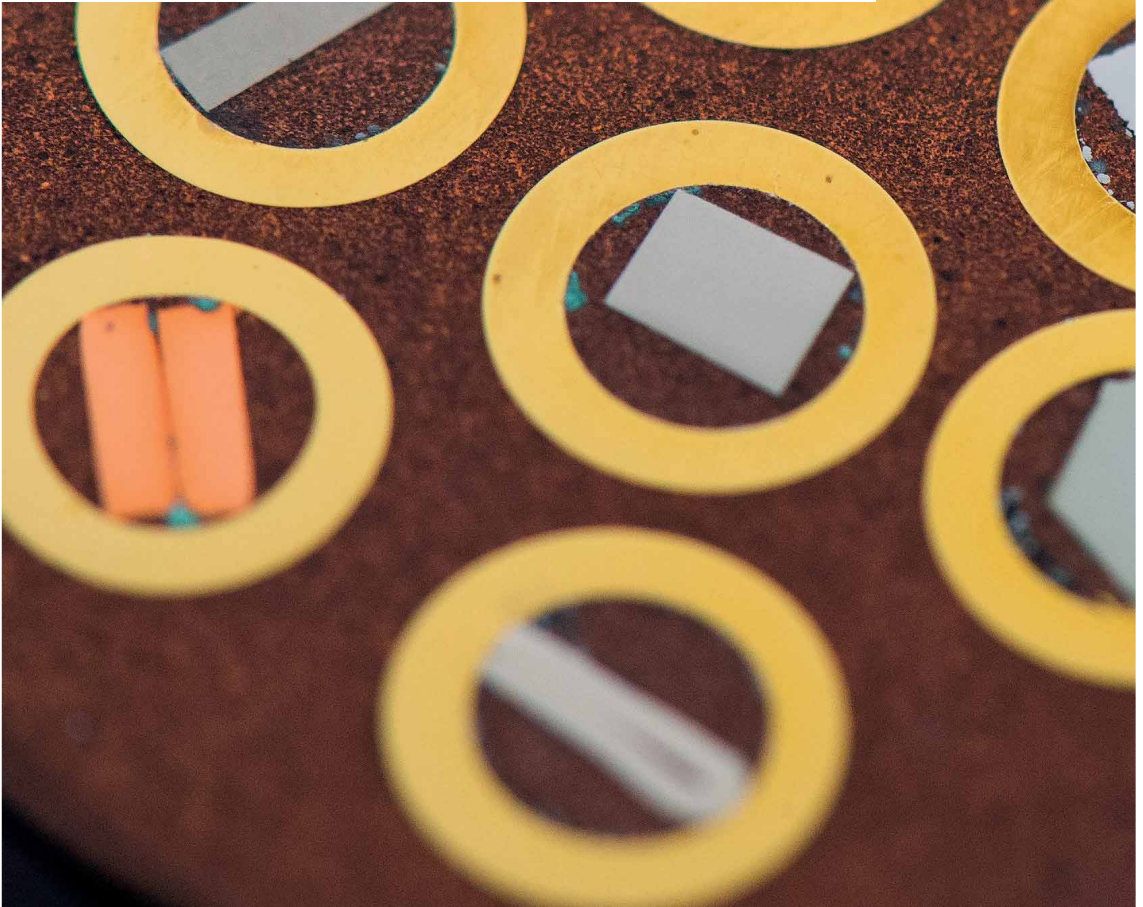
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F

Applications of atomic and solid state physics, surface science and analysis

This area of scientific activity includes studies of the interaction of photons and charged particles with solid surfaces, physical phenomena in solids at low temperatures, preparation of thin-film structures and a wide range of applications of electron and mass spectroscopy, X-ray diffraction methods for elemental, chemical and structural analysis of surface and interface layers of solids.



ELECTRON SPECTROSCOPY FOR CHEMICAL ANALYSIS – DEVELOPMENT OF METHODS

Various methods of electron spectroscopy are available for studies of chemical and electronic structures of surface and interface layers of solids. Novel methods and instruments are also developed.

To analyse the electronic structure and chemical state of the components of surface and interface layers of solids, a number of different methods are available in the Electron Spectroscopy Laboratory of Atomki:

- XPS** = X-ray photoelectron spectroscopy
X-AES = X-ray induced Auger-electron spectroscopy
ARXPS = angle resolved XPS
HAXPES = hard X-ray photoelectron spectroscopy

High-energy-resolution XPS measurements with monochromated X-rays for excitation and XPS measurements with lateral resolution are also possible. The application of the ARXPS method provides a non-destructive tool for determining the concentration depth profile of components in surface and interface

layers to a depth of several nm, while the HAXPES method can give information on the chemical and electronic structure at deeply (several tens of nm) buried interfaces.

The range of research and applications covers the surface studies of functionalized and nanoparticle-decorated carbon nanomaterials (carbon nanotubes, graphene and oxidized graphene), photocatalysts, metal-oxide semiconductor systems with high dielectric constants, thin-layer solar cells, special polymer structures and studies of corrosion resistance in the passive layers on structural components in the primary circuit of pressurized-water nuclear power plants. The scientific activity of the Laboratory extends to the R&D on novel methods of electron spectroscopy, electron spectrometers and excitation sources.



The VG ESCASCOPE electron spectrometer for XPS, monochromated XPS and laterally resolved XPS measurements.



The high-energy home-built ESA-31 electron spectrometer for XPS, XAES, HAXPES, REELS and EPES measurements.

COOPERATION

- > Institute of Physical Chemistry, Polish Academy of Sciences, Warsaw (Poland)
- > Institute of Technical Physics and Materials Science, Hungarian Academy of Sciences, Budapest (Hungary)
- > University of Miskolc, Miskolc (Hungary)
- > University of Pannonia, Veszprém (Hungary)

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PHOTON- AND CHARGED-PARTICLE-INDUCED ELECTRON EMISSION, ELECTRON TRANSPORT NEAR SOLID SURFACES

Fundamental processes of photon- and charged-particle induced ionization and the excitation of atoms and molecules embedded in the surface and interface layers of solids, as well as the transport processes of the excited electrons near surfaces and interfaces are studied using electron spectroscopy.

In the Electron Spectroscopy Laboratory, various methods of electron spectroscopy are used for studying ionisation processes and the accompanying excitations induced by photons and charged particles in surface and interface layers of solids. Attention is focused on the effects of the atomic environment on the local electronic structure. The excitation phenomena studied include those localized around the hole induced in the atomic inner shell, as well as collective (e.g. plasmon) excitations. The high-energy-resolution HAXPES experimental studies and model calculations cover hole creation in deeply bound electron shells in semiconductors and in 3d transition metals. Some experiments (e.g., studies of resonant excitations)

are performed using synchrotron radiation elsewhere. Electron scattering phenomena taking place in solids are studied both experimentally and theoretically.

The electron-transport processes within the near-surface layers of solids are investigated. The physical parameters of the processes that are relevant to quantitative surface analysis with electron spectroscopy are derived from the analysis and simulation of the high-energy-resolution electron spectra of backscattered electrons. The energies of the primary electrons in the backscattering experiments range up to 10 keV. (Methods: reflection electron energy loss spectroscopy – REELS, elastic peak electron spectroscopy – EPES).

COOPERATION

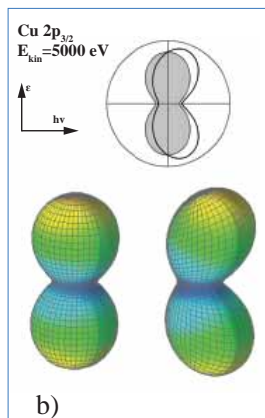
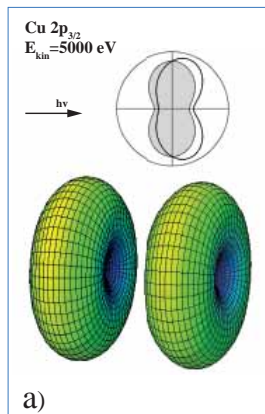
- > DESY, Hamburg (Germany)
- > Bariloche Atomic Center and Instituto Balseiro, (CNEA), Bariloche (Argentina)
- > Graduate School of Advanced Integration Science, Chiba University (Japan)
- > Institute of Applied Physics, TU Wien, Wien (Austria)
- > Université Libre de Bruxelles, Service de Métrologie Nucléaire, Brussels (Belgium)
- > Department of Physics and Chemistry, University of Southern Denmark, Odense, (Denmark)

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Nondipole effects in the angular distribution of hard X-ray excited Cu $2p_{3/2}$ photoelectrons (bottom) compared to the dipole approximation (top): a) for circularly polarized or unpolarized X-rays; b) for linearly polarized X-rays. After M. Novák et al., J. Electron Spectrosc. Relat. Phenom. 185 (2012) 4.

LOW-TEMPERATURE PHYSICS

Electromagnetic and optical measurements are carried out at low temperatures in high magnetic fields.

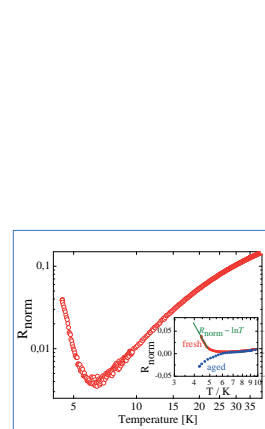
Atomki's activities in low-temperature physics involve experiments in high magnetic field at low temperatures. The magnetic structure and magnetic properties of samples can be studied by DC and AC susceptibility measurements. The main research fields of the laboratory that concern magnetic measurements are superconductivity, magnetism and thin-film physics. Temperatures are extended down to the mK range by a dilution refrigerator equipped with an 1.5 T superconducting magnet. This equipment is suitable for experiments with oriented nuclei.

There is a new possibility of carrying out optical measurements at low temperatures, in collaboration with the University of Debrecen. Using an optical cryostat,

the process of surface pattern formation in photosensitive nano-multilayers can be studied at low temperatures. This helps us to understand the mass-transport mechanism in these thin layers. The study of surface-relief formation by electron spectroscopy at low temperatures gives us a unique possibility to understand the mechanism.

We have a team of low-temperature specialists, with considerable experience in low temperature physics and technique, that studies superconductivity and magnetism.

In order to guarantee a supply of liquid helium, a new high-tech automated helium liquefier (ATL 160) was commissioned in January 2014.



Low-temperature normalized resistance of an electrodeposited Co-Pb thin film. The inset shows the difference between the fresh and aged states (*J. Alloys Comp* 545 (2012) 111.)

COOPERATION

- > University of Debrecen
- > MTA Wigner Research Centre for Physics, Budapest (Hungary)

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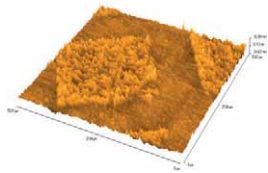
Sándor Mészáros, e-mail: meszaros.sandor@atomki.mta.hu



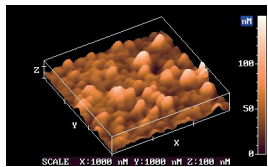
The dilution refrigerator for experiments in mK temperature range

APPLIED RESEARCH WITH HIGHLY CHARGED IONS

The ECR ion source of Atomki routinely produces and delivers highly-charged ion beams, not only for atomic physics research, but for applications.



Zirconium sample used in dentistry, bombarded with low-energy silicon ions through a mask to produce irradiated surface and non-irradiated part (for reference).



3-dimensional atomic-force-microscope (AFM) picture of Ti surface after treated with heavy ions.

Functionalizing the surfaces of solids by altering their structure and composition provides the key to a wide range of versatile applications of materials, from electronics to chemistry and medicine. The ion beam of the ECR ion source is used for the creation of nano-structured surfaces of light-sensitive and biocompatible materials useful in optics, plasmonics or dentistry. The investigations involve the production of the plasma and ion and molecular beams, and control of their interaction with the selected materials to form new surfaces or layers. Solid materials are functionalized via their composition and structure at the atomic (nano- and microscopic) scale, in respect of irradiation, stimulated

structural transformations and/or biocompatibility. Recently, several heavy ions (e.g., Ag, Au, Ca, Ce, C, Si, C_{60}) with different charge states and energies became our main interest as species interacting with surfaces.

The substrates, in most cases, are chalcogenides, titanium oxides or, more recently, zirconium ceramics. The work focuses on the physical parameters of these materials after irradiation, such as surface morphology, nano-structuring, plasmonic effects, etc. The biological activity of the treated surfaces is also a challenging task to be investigated, especially in case of dentistry materials.

COOPERATION

- > Departments of Dentistry and Physics of University of Debrecen (Hungary)
- > Institute of Oral Science (Taiwan)
- > Bio-Nano Electronics Research Center, Toyo University, Tokyo (Japan)

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PHYSICS OF THIN FILMS AND SURFACE/INTERFACE LAYERS

The research programme consists of both fundamental research and the application of thin films. It is aimed at understanding better the surface atomic motion and atomic migration through interfaces in the study of ion–surface interactions.

In thin-film physics, knowledge of the depth distribution of elements is an important question. Depth profiling is an established technique for the determination of in-depth compositions near surfaces and through interfaces. If a layer thickness is greater than 10–15 nm, sputter-based depth profiling is required to reveal the layer structure. In nanoscale physics, it is desirable to use a depth-profiling technique with a depth-resolution of 1 nm. The surface roughness and crater shape play important roles in sputter-based depth profiling, and they determine the ultimate depth resolution. Compositional depth profiling is used for studying solar cell structures. The efficiency of a thin-film solar cell depends partly on the layer structure and partly on the p–n junction and doping levels. Depth-profile analysis is suitable for checking the cell fabrication process, i.e., to determine these parameters.

COOPERATION

- > University of Debrecen, Department of Solid State Physics (Hungary)
- > National Technical University of Ukraine, KPI, Kiev (Ukraine)
- > Institute of Materials for Electronics and Magnetism, Parma (Italy)
- > Lviv National Polytechnic University, Department of Electronics and Computer Technologies, Lviv (Ukraine)
- > University of Málaga, Department of Applied Physics (Spain)

REFERENCES

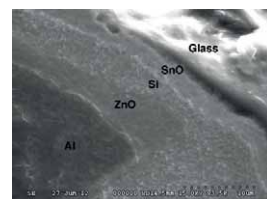
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CONTACT

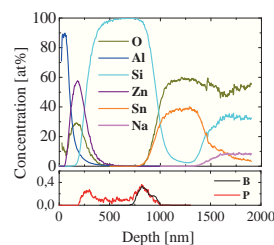
Kálmán Vad, e-mail: vad.kalman@atomki.mta.hu

Designing and carrying out an accelerated life-time testing procedure, to determine the correlation between the degradation of p–n junctions and lifetime also require depth-profile analyses.

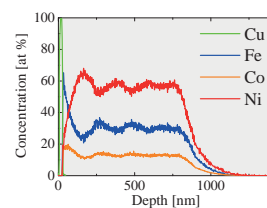
Nanometre-thick layers, prepared by electrochemical deposition, can be studied using reverse depth profiling. This method produces new information about the nanometre-scale electrochemical deposition process. In thin-film physics, the surface of a thin layer can play an important role. X-ray photoelectron spectroscopy (XPS) and low-energy ion scattering (LEIS) methods are used to obtain information about the surface structure, surface atomic migration, ion–surface interaction and the chemical states of the surface ions. Our research programmes in the field of materials science rely on the results of thin-film physics.



A solar cell structure.



Depth profiling of a solar cell



Depth distribution of constituents of a FeCoNi thin film produced by electrochemical deposition



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Environmental physics

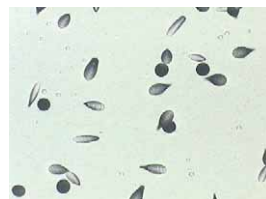
This area of scientific activity is mainly concerned with the so-called environmental isotopes and trace elements. This term denotes isotopes, both stable and radioactive, that are present in the natural environment, either as a result of natural processes or human activities. In environmental research, isotopes are generally applied either as tracers or as age indicators.

NOBLE GAS AND STABLE-ISOTOPE GEOCHEMISTRY, ISOTOPE HYDROLOGY

Noble gas and stable isotopes are ideal tracers of environmental processes.

Our interest concerns mainly noble gases dissolved in sources of water in the environment. The so-called noble-gas recharge temperatures can be calculated from noble-gas concentrations in water. To complete the age-distribution pattern of the study area, a radiocarbon tracer of the dissolved organic and inorganic carbon is usually applied. The stable-isotope signature of environmental water reflects that of the water that had been infiltrated in an earlier, colder climate. Our mass spectrometers (VG5400 and

Delta^{XP} Plus) are able to determine noble-gas abundances (He, Ne, Ar, Kr, Xe) with high precision, and variable stable ratios from samples of different materials. Etched-track type detectors are used to measure spatial and temporal variations of the radon and thoron gas in underground natural (caves, soils) and artificial (mofettes, wine cellars, mines) environments in order to trace subsurface flow processes and to estimate risks associated with the inhalation of radon daughters in underground workplaces.



Optical microscopic image of etched α particle tracks in polycarbonate due to radon gas



Measurement of radon and thoron gas in the air of a Tokaj-hegyalja wine cellar

COOPERATION

- > Section of Hydrology, University of Miskolc, Miskolc (Hungary)
- > Isotope Hydrology Laboratory, IAEA, Vienna (Austria)
- > Babes-Bolyai University of Cluj Napoca, Cluj Napoca (Romania)
- > Hospital of Cardiology, Covasna (Romania)

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VG5400 noble gas mass spectrometer

RADIOCARBON DATING AND ENVIRONMENTAL RESEARCH

Radiocarbon is commonly used for archaeological dating, geological, ground-water, soil, carbon-cycle, atmospheric and climate research, and metabolism studies in life sciences.



Sample preparation for C-14 AMS analyses



Graphitized samples for C-14 AMS analyses



MICADAS type C-14 AMS (ETHZ)

Radiocarbon is a cosmogenic isotope (^{14}C), a natural radioactive tracer of atmospheric carbon. It is distributed in all the living organisms and in practically all parts of the Earth's surface through the carbon cycle. Because it is a very rare carbon isotope (the $^{14}\text{C}/^{12}\text{C}$ ratio is about 10^{-12} in modern carbon) with a medium-length half-life (5730 y), it is ideal for archaeological dating, and for many different scientific and industrial applications. The Radiocarbon Laboratory of Environmental Studies has a three-decade track record of internationally recognized activity in radiocarbon dating.

A state-of-the-art ^{14}C analysis technique with a compact MICADAS type AMS with a fully equipped sample-preparation laboratory has been available in Atomki since 2011. Applications ranging from basic scientific research (such as carbon-cycle studies) to nuclear environmental monitoring and biological studies have been running at the ^{14}C AMS facility. One of the features of the Laboratory is that the MICADAS AMS system has an enhanced gas ion source interface, which uniquely allows reliable AMS ^{14}C analyses of ultra-small (0.1-0.01 mg C) samples to be carried out.

COOPERATION

- > ETHZ (Zürich, Switzerland)
- > NSF AMS Laboratory of Arizona University, Tucson (USA)
- > Nuclear Physics Institute AS CR, Prague (Czech Republic)
- > University of Debrecen, Debrecen (Hungary)
- > University of Szeged, Szeged (Hungary)
- > MTA Research Centre for Astronomy and Earth Sciences, Budapest (Hungary)
- > Hungarian Meteorological Service, Budapest (Hungary)

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K–Ar GEOCHRONOLOGY

The K–Ar method used for dating geochronological events such as volcanism, metamorphism and mineralization is being developed at Atomki.

The K–Ar method is based on the measurement of the concentration of accumulated radiogenic ^{40}Ar , which is formed in the decay of ^{40}K in minerals. It can be used for dating volcanics, magmatic rocks solidified beneath the surface, metamorphic processes of different grades, (ore) mineralization, the time of tectonic displacement of greater rock bodies, as well as several other processes. Geochronological questions from many areas (from over 100 areas) have been solved, and methodological research has been performed to improve the interpretation of the derived dates of rocks with

a complex history and composition. The first results of a completely new application – the detection of soil degradation resulting from the use of fertilizers – has been published. Some instrumental innovations related to the K–Ar method have also been proposed and/or elaborated.

In 2009, Zoltán Pécskay (senior scientist of K–Ar laboratory) was invited to join the international scientific expedition to King George Island, Antarctica. There, he carried out systematic sampling of magmatic rocks for K–Ar dating at Atomki.



Mass spectrometer for K–Ar isotope analysis.



Expedition to the King George Island, Antarctica.

COOPERATION

Results have been achieved and published in articles in cooperation with over 120 university departments and research institutes from 43 countries.

- > Institute of Geology, University of Tübingen (Germany)
- > Geological Institute of the Czech Academy of Sciences, Prague (Czech Republic)
- > Institute of Geological Sciences, Polish Academy of Sciences, Cracow Research Centre, Kraków (Poland)
- > Institute of Geodynamics, Romanian Academy, Bucharest (Romania)
- > Okayama University of Sciences, Okayama (Japan)

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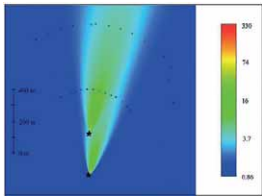
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THE STUDY OF SAFETY AND ENVIRONMENTAL EFFECTS IN NUCLEAR INSTALLATIONS

Monitoring anthropogenic pollution coming from the nuclear industry is a major activity for the Hertelendi Laboratory of Environmental Studies (HEKAL) in Atomki.



Concentration map around the power plant, calculated with the fitted mass transfer coefficient. The colour code shows the concentration on a logarithmic scale, in Bq/l. The stacks are shown with stars, and the samplers with plus signs.



Hermetic containers designed for gas generation measurements of drum L/ILW.

Nuclear power plants and radioactive waste-disposal facilities might emit radioactive isotopes, the abundances of which exceed the natural level. To detect these increased levels, creative sampling methods as well as state-of-the-art sample preparation and measurement techniques have been developed, and are used by the HEKAL group. Atomki developed the differential radiocarbon and tritium samplers that take integrated samples from the ambient air around the Paks Nuclear Power Plant. An automatic groundwater sampling device has also been developed in order to take separately anions and cations by means of ion-exchange resins. In addition to envi-

ronmental samples, hard-to-measure isotopes from low- and intermediate-level radioactive waste are also identified in our laboratory. These samples include ion-exchange resins and evaporation residues from the primary circuit of the nuclear power plant. Numerous chemical extraction procedures have been adopted and developed to separate different radioisotopes of interest from the relatively high radioactive isotope abundance. Well-shielded, high-purity Ge detectors, different ultra-low-background liquid scintillation spectrometers and several mass spectrometers (noble gas, IRMS, QMS and AMS) are used in this complex field.

COOPERATION

- > Paks Nuclear Power Plant Ltd: Environmental Monitoring Section, Water Chemistry Section, Waste Management Section (Hungary)
- > Public Limited Company for Radioactive Waste Management (Hungary)
- > Nuclear Physics Institute AS CR, Prague (Czech Republic)

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STUDY OF ATMOSPHERIC AEROSOLS

The properties and effects of atmospheric aerosols are studied with the use of nuclear micro-analytical techniques. Currently, we focus on the environmental and health impact of atmospheric aerosols including source characterization, indoor aerosols and personal exposure.

The systematic investigation of atmospheric aerosol samples has been carried out for 20 years using the accelerator-based PIXE elemental analytical technique. A continuously expanded database has been created relating to the PM₁₀ (particles with an aerodynamic diameter smaller than 10 μm) and PM_{2.5} (aerodynamic diameter smaller than 2.5 μm) aerosol mass, black-carbon content and main elemental components. On this basis, the elemental composition, size distribution, seasonal and long-term time variation, and sources of the atmospheric aerosol that are characteristic of the east-Hungary region have been investigated.

This research was broadened to cover time- and size-resolved aerosol investigations, and also the calculation of lung-

deposition probabilities, in order to obtain additional and more precise information about aerosol sources and estimates with regard to impact on health. Quantitative single-particle analysis has been carried out, using the Debrecen scanning nuclear microprobe, on samples that are interesting from the point of view of aerosol evolution, formation and ageing of particles, as well as health effects.

Recently, the aerosol research was extended to include the determination of fossil and non-fossil carbonaceous components of atmospheric particulate matter (APM), by using the novel accelerator mass spectrometry technique. Radiocarbon dating on APM is now routinely carried out at the new state-of-the-art MICADAS AMS.

COOPERATION

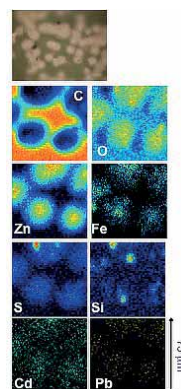
- > Hungarian aerosol research society (eg. ELTE, Department of Analytical Chemistry; University of Pannonia, Department of Environmental and Earth Sciences; MTA Centre for Energy Research; Environmental Physics Department, University of Szeged, Photoacoustic Research Group; Department of Environmental Physics, Institute of Chemistry, University of Debrecen; Hungarian Meteorological Service)
- > Regional Inspectorates for Environment, Nature and Water Ministry of Rural Development

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Optical image and PIXE elemental maps of an aerosol sample collected in indoor environment.



Aerosol sampling in cave



Deposit of fine aerosol particles with 2 h time resolution

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IMPRESSUM

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MAP

- I** > Administration and management
- > Section of Electron Spectroscopy and Materials Science
- > Section of Atomic Collisions

- II** > Section of Environmental and Earth Sciences
- > ECR Laboratory

- III** > Low-temperature Physics Laboratory

- IV** > Apartments

- V** > Tandetron Laboratory
- > Mechanical workshop

- VI** > Laboratory for Materials Science and Surface Physics
- > UD - ATOMKI Department of Environmental Physics
- > Section of Electronics

- VII** > Hertelendi Laboratory of Environmental Studies – AMS Laboratory

- VIII** > Section of Theoretical Physics
- > Library
- > Cafeteria

- IX** > Laboratory of Electrostatic Accelerators
- > Section of Ion Beam Physics

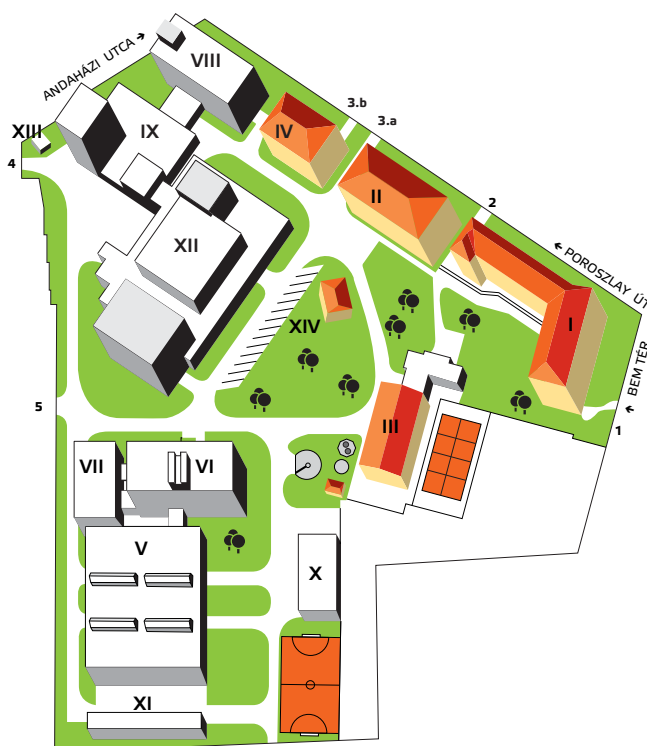
- X** > Garage

- XI** > Stores

- XII** > Cyclotron Laboratory
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- > Section of Cyclotron Applications
- > Lecture Hall

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- XIV** > Guest house



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