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Laboratory Portrait: The Institut für Kernphysik at Forschungszentrum Jülich • Feature Article: Long Range Structure of the Nucleon
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Cover illustration: The Coder Synchrotron COSY-Jülich with the three major internal experiments ANKE, PAX, and WASA.
NuPECC Long Range Plan 2010—Perspectives of Nuclear Physics in Europe

As announced in the April–June 2009 issue of the Nuclear Physics News International, the Nuclear Physics European Collaboration Committee of the European Science Foundation have now published their Forward Look on Nuclear Physics in Europe at a Presentation Conference in Brussels (under the Belgian EU Presidency) on 9 December 2010.

The goal of the NuPECC Long Range Plan 2010 was to bring together the entire Nuclear Physics community in Europe to formulate a coherent plan of the best way to develop the field in the coming decade and beyond.

Nuclear Physics projects are often “big science,” which implies large investments and long lead times. They need careful forward planning and strong support from policymakers. The Long Range Plan 2010 provides an excellent tool to achieve this. It represents the outcome of detailed scrutiny by Europe’s leading experts and will help focus the views of the scientific community on the most promising directions in the field and create the basis for funding agencies to provide adequate support.

The full Long Range Plan 2010 can be found at http://www.nupecc.org/, together with a booklet and a video that presents the case to the educated public. The report is based on the work of six expert sub-committees in the fields of Hadron Physics, Phases of Strongly Interacting Matter, Nuclear Structure and Dynamics, Fundamental Interactions, and Nuclear Physics Tools and Applications.

The main outcome of the exercise was a list of recommendations grouped under seven headers and shown below in an abbreviated version.

**ESFRI Facilities**

Complete in a timely fashion the construction of the nuclear physics facilities on the ESFRI list of large-scale research infrastructure projects in Europe:

a. FAIR at the GSI site, including its four pillars, the PANDA antiproton experiment, the NuSTAR radioactive ion beam (RIB) facility, the CBM dense baryonic matter experiment, and the atomic, plasma, and applied physics program APPA.

b. SPIRAL2 at GANIL, including high-intensity stable ion beams and ISOL RIBs to study exotic nuclei.

**Major Upgrades**

Carry out major upgrades of the following complementary large-scale nuclear physics facilities:

a. HIE-ISOLDE at CERN (RIBs).

b. SPES at INFN-LNL (RIBs).

c. The AGATA γ-ray detector to be used at the above facilities.

Figure 1. Roadmap for Nuclear Physics research infrastructure in Europe.
d. The Superconducting Linac at GSI to provide high-intensity stable ion beams for superheavy elements studies, for example.

ALICE Facility
Upgrade the nuclear beams program and the ALICE detector at CERN to extend the physics reach in investigations of quark-gluon matter.

Theory
Strengthen the theory support to experiment by developing collaboration between national theory groups through new transnational programs:

a. Strengthen the financial basis of the theoretical research infrastructure ECT* to increase its involvement in European theory initiatives.
b. Strongly support advanced studies related to the above experimental recommendations and improve the link between nuclear theory and quantum chromodynamics.
c. Invest in high-performance computing facilities dedicated to nuclear physics projects.

Existing Facilities
Fully exploit and upgrade existing large-scale research infrastructures (listed below in north to south order) to exploit fully past investment:

a. The lepton beam facilities at ELSA, MAMI, CERN-COMPASS, and DAFNE (INFN-LNF).
b. The hadron beam facilities at FZ Juelich-COSY and GSI.
c. The heavy ion beam facilities at JYFL, KVI, GSI,GANIL, IPN, CERN-ISOLDE, INFN-LNL, and INFN-LNS.
d. The nuclear astrophysics underground accelerator LUNA at INFN Gran Sasso.
e. The ELENA upgrade of the Antiproton Decelerator at CERN.

Fully exploit smaller-scale national and university nuclear physics laboratories in Europe.

Applications and Education
Secure and further develop the nuclear physics skills base in view of current and future needs, in particular regarding:

a. Novel developments in energy generation (nuclear fission and nuclear fusion), medicine (such as imaging and tumour therapy) and security.
b. Development of novel sources, micro-beams, high-power targets, and radiation detection instrumentation that will also be used in other fields of science and engineering, and in the life sciences.

Future Facilities
Continue the scientific and technical assessments for building new large-scale nuclear physics facilities in the future, and specifically promote:

a. The inclusion of the high-intensity ISOL facility EURISOL in future updates of the ESFRI list, based on the successful EURISOL Design Study in the EU Framework Programme 6.

b. Technical Design Studies for the intense RIBs facility ISOL@ MYRRHA, a polarized proton-antiproton collider (PAX) and an electron-nucleon/ion collider (ENC) at FAIR, and a high-energy electron-proton/ion collider (LHeC) at CERN.
c. The inclusion of nuclear physics programs at the multi-purpose facilities ELI (Extreme Light Infrastructure) and ESS (European Spallation Source).

This list of recommendations was then further condensed down into a roadmap for building new large-scale Nuclear Physics research infrastructure in Europe as shown in Figure 1, where facilities whose first phases have already been approved are colored in blue, future upgrades thereof in dark blue, and those that are still in the design or R&D phase in magenta.

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The Institut für Kernphysik at Forschungszentrum Jülich

The Forschungszentrum Jülich (FZJ) pursues interdisciplinary research that aims to solve the grand challenges facing society in the fields of health, energy, and the environment, and also information technologies. In combination with its two key competencies—physics and supercomputing—work at Jülich focuses on both long-term, fundamental, and multidisciplinary contributions to science and technology as well as on specific technological applications. With a staff of about 4,500, Jülich—a member of the Helmholtz Association—is one of the largest research centers in Europe. Located south-east of the city of Jülich it is close to the center of a triangle formed by the German cities of Aachen, Düsseldorf, and Cologne.

The Institut für Kernphysik (Nuclear Physics Institute; IKP) is dedicated to fundamental research in the field of hadron, particle, and nuclear physics. The aim is to study the properties and behavior of light hadrons in an energy range that resides between the nuclear and the high-energy regime.

The primary facility at the IKP is the COoler SYnchrotron COSY, a medium-energy accelerator complex with roughly 350 national and international users. With a maximum proton energy of about 2.8 GeV (~3.62 GeV/c) COSY allows the production of (strange) mesons up to the $\phi$ (1020). The accelerator complex comprises three major hadron-physics detector systems (ANKE, TOF, and WASA), as well as smaller experiments, which are mainly run by external groups (pdEDM). In addition, preparative studies for producing intense beams of polarized antiprotons are carried out (PAX).

In the upcoming decade, hadron physics will undergo a transition from light quark systems to hadrons with charm quarks, which will be pursued at the Facility of Antiproton and Ion Research FAIR (GSI Darmstadt). IKP is the leading institution of the consortium that designs and constructs of High-Energy Storage Ring (HESR) for antiprotons at FAIR. Also components of the PANDA experiment are developed and preparations for the PAX experiment proceed with a strong contribution of IKP.

COSY is a unique spin physics facility with hadronic probes and as such it is the ideal basis for searches for electric dipole moments (EDM) of light ions in storage rings.

The IKP is also involved in the development of novel accelerator technologies and concepts. For example, a 2 MV electron cooler will be installed in COSY and research on laser-driven particle acceleration is being performed.

Theory Activities—The Physics Case

Although very well tested at high energies, QCD, the theory of strong interactions, poses a great challenge to theory and experiment at low and at intermediate energies. Of paramount interest are the mechanism underlying quark and gluon confinement and spontaneous chiral symmetry breaking. The low energy regime, where

Figure 1. Inside the COSY accelerator hall.
only the lightest three quarks (up, down, strange) play a role, is largely controlled by the mechanism of spontaneous chiral symmetry breaking—the quark mass terms play a relatively little, but relevant role, while at higher energies, where also the charm and eventually the bottom quarks appear as dynamical degree of freedom, the quark mass terms has much more influence on hadronic properties. A systematic, consistent study of both regimes is the precondition for a deeper understanding of QCD in the non-perturbative regime.

The theoretical tools at our disposal are effective field theories (such as chiral perturbation theory for the light quark sector) and lattice gauge theory. While the former work with hadronic degrees of freedom, the latter numerically solves discretized QCD directly using quarks and gluons. Another promising route is the use of lattice techniques with hadronic degrees of freedom for nuclear structure studies—this allows one to solve the nuclear many-body problem without further approximations. On the one hand lattice studies allow one to solve the problems at hand exactly, the numerical effort is very involved and requires the use of supercomputers as they are available on campus in Jülich. On the other hand, effective field theories are technically easier to deal with, but require an increasing number of coupling constants when making the calculations more accurate. An important strategy is to use the lattice to determine theses constants that then allow one to make predictions for many other observables based on the properly tailored effective field theory. In addition what is needed are high accuracy experiments to test the predictions. Those are provided by modern experiments like those at COSY, to be described below, BES-III in China, Belle in Japan, KLOE in Italy, ELSA and MAMI in Germany, Jlab in the USA, LHC in Switzerland, and in the future from the accelerator complex FAIR.

The activities of the theory group at the IKP comprise hadron and nuclear physics. Current projects are the development of an effective field theory for nuclei and hyper-nuclei using both standard many body tools as well as lattice techniques, a systematic investigation of hadronic molecules involving all types of quark flavors—of direct relevance for COSY and FAIR—and a study of the implications of the quark masses on hadronic observables. For example, the quark mass induced piece of the proton-neutron mass difference was extracted from the experimental data on the forward-backward asymmetry in \( pn \rightarrow d\pi^0 \), the accuracy of this extraction will be further improved, once data on \( dd \rightarrow \alpha \pi^0 \) will be available from COSY. Further, a proposal was developed to extract the light quark mass ratio from certain bottomonia transitions—here the measurements could be performed with the LHCb detector at the LHC. This grew out of a systematic study of charmed meson loop effects in charmonium transitions that have led to a cornucopia of predictions to be tested with BES-III and PANDA. The theory group is also engaged in lattice QCD studies. For example there is currently a project under way to extract for the first time the width of the \( \Delta(1232) \), using the local Blue/Gene high performance computer. This will provide a highly non-trivial test of QCD in the non-perturbative regime.

COSY Accelerator Complex

The COSY cooler synchrotron and storage ring (Figure 1) provides polarized and unpolarized proton (deuteron) beams in the momentum range from 300 (600) MeV/c to 3.7 GeV/c for internal and external target experiments. The COSY accelerator complex includes H and D sources and the cyclotron JULIC for pre-acceleration. The negative charged ions are
injected via charge exchange into the COSY ring. COSY has a racetrack design, consisting of two 180° arc sections connected by 40 m straight sections. The total length of the ring is 184 m.

To prepare high-precision beams for internal and external experiments two different beam cooling techniques are utilized: electron cooling to increase phase-space density at injection energy by means of stacking injection in combination with transverse feedback, and stochastic cooling to counteract beam heating of stored ions due to interaction with internal targets. Stochastic cooling covers the momentum range from 1.5 GeV/c up to the maximum COSY momentum.

A new 2 MV electron cooler (Figure 2) for beam cooling up to maximum COSY momentum is being developed in cooperation with the Budker Institute in Novosibirsk and will be installed at COSY in 2011. The preparation of high-precision beams with increased luminosities above $10^{32}$ cm$^{-2}$ s$^{-1}$, using high-density internal targets, is the main applications for high-energy cooling at COSY. Technical developments for this electron cooler are also important steps toward the proposed 4.5(8) MV electron cooler of the HESR. The HESR electron cooler layout will strongly benefit from the experiences of the electron cooler operation at COSY.

Polarized beams are essential for the physics program at COSY. To keep the polarization during acceleration two different types of first-order spin resonances have to be overcome, namely imperfection resonances caused by magnetic field errors and misalignments of the magnets, and intrinsic resonances excited by horizontal fields due to the vertical focusing. For protons, in the energy range of COSY, five imperfection resonances have to be crossed. Vertical correction dipoles or a partial snake can be used to preserve polarization for this type of spin resonances by exciting adiabatic spin flips. To preserve the polarization at the intrinsic resonances, a fast change of the vertical betatron tune and therefore a fast crossing of the resonance is applied. For polarized deuterons no resonances are encountered in the energy range of COSY for regular vertical betatron tunes.

The main diagnostic tool to measure polarization of the internal COSY beam is the EDDA detector, primarily designed and used to measure the $pp$-scattering excitation function during synchrotron acceleration.

**Experiments at COSY**

**Experimental Facilities**

ANKE (Apparatus for studies of Nucleon and Kaon Ejectiles), is a large acceptance forward magnetic spectrometer (Figure 3) at an internal target station in the COSY ring. ANKE consists of three dipole magnets, acting as a chicane for the circulating COSY beam. The central dipole is movable to adjust the momentum of the detected particles independent of the beam momentum. ANKE is equipped with dedicated detectors for charged kaons that allow the identification of certain $K^+K^-$ final states in a more than 10 orders larger background. This capability has been recently exploited for a high-precision experiment on $\phi$ $(1020)$-meson production in nuclei. Using deuterium cluster targets, reactions on the neutron are tagged by detecting the low energy recoil “spectator” proton in a silicon tracking telescope in vacuum next to the target. A polarized internal target system comprising an atomic beam source, a Lamb-shift polarimeter, and a storage cell is in use at ANKE since 2005.

TOF (Time-Of-Flight), is a non-magnetic spectrometer (Figure 4)
located at an external COSY beamline, combining excellent tracking capability with large acceptance and full azimuthal symmetry allowing to measure complete Dalitz plots. TOF is optimized for final states with strangeness. The strength of this high-acceptance spectrometer is the capability of delayed secondary displaced vertex detection, for example, from hyperon $\Lambda$, $\Sigma^+$, . . . decay products via a silicon micro-strip detector placed close to the interaction region. With the new straw tube tracking system recently commissioned, TOF has a significantly improved mass resolution and reconstruction efficiency.

WASA (Wide Angle Shower Apparatus), an internal $4\pi$ spectrometer (Figure 5) with large solid angle acceptance, is operated in the internal COSY beam. WASA comprises an electromagnetic calorimeter, a very thin superconducting solenoid, high granularity central and forward tracking detectors for reconstruction of charged and neutral decay particles and for angular and differential energy measurement. The target protons and deuterons are delivered by means of a unique frozen-pellet target system providing hydrogen or deuterium spheres with diameters of ~25 μm. The pellet target system provides a high density target with high purity necessary to measure rare meson decay processes at high luminosity. The close to $4\pi$ geometrical acceptance of WASA allows for an efficient search for rare final states. The measurement of exclusive final states represents the physics focus for the investigation of violation and breaking of basic symmetries. With the operation of WASA-at-COSY, high-statistics studies aiming at rare decays of $\pi$, $\eta$, $\omega$, and $\eta'$ are effectively turning COSY into a meson factory.

Recently a new internal target station has been set up for PAX (Polarized Antiproton eXperiments), which aims at providing an intense beam of polarized (anti-)protons by spin-filtering. The plan is to test and commission all equipment with protons at COSY before moving to CERN/AD for measurements with antiprotons.

In addition to providing beams for experiments with these detector systems, COSY is used for:

- Research and development of dedicated components, which are substantial for a successful operation of the HESR. In beam dynamics experiments at COSY their properties can be examined under similar conditions as at the HESR. Specifically, an improvement of the recently developed high sensitivity pickup and kicker structures in the frequency range 2 to 6 GHz for the HESR stochastic cooling system will be carried out. Their characteristics can be well investigated with a COSY beam. A novel design and construction of high frequency pickup and kicker structures for the collector ring CR at the FAIR facility will be performed. The structures will be tested with beam at COSY.
- Preparatory studies (polarimetry, beam lifetime, and spin coherence time measurements) for ($p$ and $d$) EDM searches at storage rings. In such measurements, the EDDA detector is used as a polarimeter.
- Tests of detector components and prototypes of the future large FAIR detector systems like CBM and PANDA.
COSY is unique on a worldwide scale in its possibility to store, accelerate, and manipulate polarized proton and deuteron beams and to use it for internal and external experiments. The major scientific issues for the ongoing hadron physics experiments are:

- Investigation of symmetries and symmetry violations, for example in rare meson decays;
- Hadron reactions, like $NN$ interactions, in particular the $np$ system and the di-proton ($pp$), final state, $YN$-interactions (spin-resolved $\Lambda N$ scattering lengths), and meson-nucleus interactions (e.g., (quasi-) bound states);
- Hadron structure and spectroscopy, like the investigation of $N^*$ resonances, in particular of those coupling to strangeness.

Selected Experimental Results from COSY (WASA and PAX)

Since the "standard" strong and electromagnetic decays are strongly suppressed for the $\eta$ (and $\eta'$) meson, the $\eta$ provides a perfect laboratory to search for decays that are forbidden by fundamental symmetries. At WASA-at-COSY the two complementary reactions $pp\to\eta p\eta$ and $pd\to^3He\eta$ have been investigated for hadronic $\eta$ production. They differ considerably in production cross section, however also in the contribution of multi-pion background, which is roughly 20 times larger for the ratio $\sigma(2\pi^0)/\sigma(\eta)$ in the $pp$ reactions and during the last two years, data sets from $pp$ and $pd$ interactions have been collected. The decay $\eta \to 3\pi^0$ forbidden by isospin conservation has been studied following the reaction $pp\to p\eta p\eta$ and the extracted data with more than $8\cdot10^5$ events $\eta\to 3\pi^0$ result in a slope parameter $\alpha = -0.027 \pm 0.008$(stat) $\pm 0.005$(syst) ($\text{Phys. Lett.} B 677:24–29 (2009)$) of the efficiency corrected radial density distribution of the Dalitz plot that compares well with results from other installations (CBall MAMI, Celsius/WASA, KLOE, CBall BNL). The measurement of the slope parameter allows for a sensitive test of QCD predictions, and the experimental findings show a strong discrepancy to the central value of current chiral perturbation-theory calculations (up to NNLO), where the large uncertainty, however, does not allow to decide the sign of the slope.

$\eta$ decays were studied using the $pd\to^3He\eta$ reaction at a beam energy of 1 GeV. An unbiased data sample of $1.1\cdot10^7$ $\eta$ meson decays was collected. Results to be published include the search for the box anomaly contribution in the decay $\eta \to \pi^\pm \pi^\mp \gamma$ (Ph.D. thesis C.F. Redmer, http://www.fz-juelich.de/ikp/wasa/theses.shtml). The decay $\eta \to \pi^\pm \pi^\mp \gamma$ was studied with the goal to test chiral QCD anomalies described by the Wess-Zumino-Witten (WZW) Lagrangian and to search for flavor conserving CP violation. To test the validity of the different models, not only the decay rate but also differential distributions of the Dalitz plot variables are compared with experimental data. As shown in Figure 6, the measured photon energy spectrum was found at variance with the simplest gauge invariant matrix element of $\eta \to \pi^\pm \pi^\mp \gamma$, but can be described by a Vector Meson Dominance ansatz. The pion angular distribution is consistent with a relative $p$-wave of the two-pion system. With $13740 \pm 140$ events these data represent the currently largest sample of an exclusive measurement. Up to now the $pd$ data sample was increased to $3\cdot10^7$ $\eta$ meson decays. Further results include symmetry-breaking decays ($\eta \to \pi^\pm \pi^\mp e^+ e^-$, $\eta \to \pi^0 e^+ e^-$), tests of chiral perturbation theory ($\eta \to 3\pi$,
η→π^0 γγ), and single and double electromagnetic transition form factors with the most ambitious goal being the search for new physics with the η→e^+e^- decay.

Due to 10–20 times larger production cross section (10 μb at 1.4 GeV) further progress toward rare η decays is being made by focusing on the pp→ppη reaction. Meanwhile, tagging on the pp→ppη reaction poses a challenge. A first investigation considers production reactions of η mesons as well as multi pion channels; see “Double-Pion Production in Proton-Proton Interactions” (Ph.D. thesis T. Tolba, http://www.fz-juelich.de/ikp/wasa/theses.shtml). The first long production run of 8 weeks for η meson decays in pp interactions was recently carried out. The data are presently being analyzed. The extension of the physics program to ω and η decay studies is anticipated in beam times scheduled for late 2010 and spring 2011.

On the road to the goal of the PAX collaboration to produce a polarized antiproton beam lie major technical challenges. Theoretical calculations found in literature predicted a very large low-energy lepton-hadron spin flip cross section and it was suggested that a viable method for producing polarized antiproton beams would be to use a co-moving lepton beam in conjunction with a stored hadron beam at small relative energy. However, in a recent COSY experiment the PAX collaboration showed that the spin-flip cross section was grossly overestimated, see Figure 7 and Phys. Lett. B6 74:269–275 (2009).

Thus the PAX collaboration will focus on the technique of spin-filtering as means to obtain a stored polarized antiproton beam. This method has been proven to work in an earlier measurement at the TSR ring in Heidelberg and a COSY experiment to determine the energy dependence of the process is being installed. Later it is planned to move the experiment to the AD ring at CERN where antiprotons are injected and decelerated.

**Preparations for the HESR Antiproton Ring**

The HESR is an essential part of the antiproton physics program at the FAIR project. It will provide antiprotons in the momentum range from 1.5 to 15 GeV/c for the internal target experiment PANDA. A consortium consisting of FZ Jülich, GSI Darmstadt, HIM (Helmholtz-Institute Mainz), University of Bonn, and ICPE-CA Bucharest is in charge of HESR design and construction.

Powerful phase-space cooling is needed to reach demanding experimental requirements in terms of luminosity and beam quality. Therefore, a broadband stochastic cooling system in the range from 2 to 4 GHz (with an upgrade option for longitudinal cooling to 4–6 GHz above 3.8 GeV/c) is developed. Due to the modularized construction concept of FAIR, the planned 4.5 MV electron cooling system is postponed to a later stage.

Various beam dynamics studies have been performed to guarantee the required equilibrium beam parameters, beam lifetime, and beam stability. Comprehensive beam dynamics experiments have been carried out to test the developed momentum cooling models. The interaction of the antiproton beam with an internal target and the fields of a barrier bucket cavity are included.

Magnet design of dipole, quadrupole, sextupole, and correction dipole magnets has been finalized. Three-dimensional field calculations have been performed to minimize the multipole components of the various magnet types. After negotiations with tenders
the magnet production is going to be started with a pre-series. A detailed concept for the vacuum system of the HESR has been worked out. Two test devices are manufactured. The first device to test the mechanical stability of the favored clamping flanges under ultra-high vacuum conditions is already operated. The second test facility will be a genuine cut-out of the arc from one center of a dipole to the next neighboring one.

Studies of beam behavior with pellet target, barrier bucket, and stochastic cooling have been performed at the cooler synchrotron COSY to benchmark simulation codes and test accelerator components for HESR. The mean energy loss induced by the interaction of a circulating beam with an internal pellet target cannot be compensated by phase-space cooling alone. To compensate the mean energy loss and thus to provide an antiproton beam with a significantly reduced momentum spread, a broadband barrier bucket cavity will be used in the HESR. Design, production, and assembly of such a cavity have been finalized and it is routinely operated in COSY (Figure 8, left). In order to avoid initial particles losses the beam can be pre-cooled by time-of-flight cooling. It has experimentally been confirmed that this cooling method has a larger cooling acceptance compared to usual filter cooling. New high-sensitivity pickups for stochastic cooling have been designed and built for the HESR (Figure 8, right). They have been successfully tested with COSY beam and have been proven their predicted performance.

**Preparations for the PANDA Experiment**

The PANDA experiment at the high energy storage ring (HESR) will perform high precision investigations of antiproton annihilation on proton and heavier ion fixed targets in order to pursue various topics around the weak and strong forces, exotic states of matter and the structure of hadrons. In order to serve the wide physics potential with antiprotons at HESR, PANDA is designed as a general purpose detector covering nearly the complete solid angle for both neutral and charged particles with good momentum and particle identification (PID) resolution as well as excellent vertex determination. IKP has taken over a key role in the preparation of the physics program, as well as focusing its instrumental activities on the interaction region and the surrounding inner detectors for charged particle tracking.

Together with partners from Moscow, IKP is developing an improved pellet target system. This system has an order of magnitude less divergence of the pellet stream, thereby allowing a finer focus of the HESR beam as well as lower expected fluctuations of the luminosity as compared to the WASA pellet target currently installed at COSY. The first detector outside of the interaction region will be a silicon pixel/strip Micro Vertex Detector (MVD) that will reconstruct (secondary) vertices with a precision below 50 micron. This device will enable events with the production of open charm to be tagged. Here IKP has taken over major aspects in the overall mechanical design and the development of the data transport systems. Detailed simulations of the radiation dose and expected spatial resolution have been performed, together with the development of the necessary software development for the data handling and reconstruction.

A Central Tracker (CT) will surround the MVD. At IKP a concept for the CT based on straw tube proportional chambers has been developed together with groups in LNF (Frascati, Italy) and Pavia (Italy). The design is based on the hardware of the straw tube tracker now in operation at the COSY-TOF experiment (Figure 9). Currently a full scale prototype is being assembled and new readout electronics are being developed to enable PID via specific energy loss in the active gas volume.

In order to achieve the optimal mass and width precision from resonance and threshold scans, the integrated luminosity must be determined with high precision. Therefore IKP has presented a concept for a luminosity
monitor based on measuring elastic scattering in the Coulomb-strong interaction interference region. This system is based on tracking the anti-protons scattered near the beam axis with multiple layers of silicon strip detectors.

Search for an Electric Dipole Moment (EDM) of Protons and Deuterons

Searches for EDM are a forefront research issue, because finding a non-zero EDM would be a major discovery pointing to physics beyond the Standard Model of elementary particle physics. Impressive upper limits (neutron equivalent in the order of $10^{-26}$ e·cm) have been obtained in recent years. These are further pushed by upgrading existing experiments on electrons and muons, heavy atoms and molecules, and in particular also the neutron, and by designing new ones.

The IKP is planning to search for EDM in a storage ring with a statistical sensitivity of few $10^{-29}$ e·cm per year, pushing the limits even further and with the potential of an actual particle-EDM discovery. For such studies a completely new approach has recently been proposed for protons, deuterons and possibly also $^3$He, which will rely on the time development of a horizontal spin component of these particles in a new class of storage rings. In the course of this, it has become obvious, that COSY—with its polarized beams, including the new hardware (like a low-$\beta$ section and a Siberian snake) and the target and detector systems—is very close to being a test-bench for polarimetry, spin coherence time investigations, and so on.

An R&D program at the COSY storage ring within an international collaboration (EDM@COSY) already proved the required sensitive and efficiency of deuteron polarimetry. All of the information gleaned during these studies will be incorporated into a design for a prototype polarimeter that will be tested on the COSY ring. The next step will be the investigation and optimization of spin coherence time in COSY. The natural spin coherence time of horizontal polarization needs to be determined and extended by bunching the beam and improvements to the ring lattice by means of high-order field corrections.

Intense R&D work has also to be performed before the design of the final EDM ring can be started. Main objectives are the development of high-sensitivity beam positioning monitors and combined electrostatic/magnetic field deflectors with cutting-edge field quality. The coil and conductor plate configuration has to be optimized with respect to field quality and stability and a prototype deflector to be build and tested to ensure its performance.

Laser-Particle Acceleration

The physics of laser-plasma interactions has undergone dramatic improvements in recent years. By directing a multi-TW, ultra-short laser pulse onto a thin foil or a gas, it is now possible to produce high-energy proton, ion, and electron beams. It is a yet untouched issue whether the laser-generated beams are or can be spin-polarized and, thus, whether laser-based polarized sources are conceivable. One may either think of a spatial separation of certain spin states by the huge magnetic field gradients that are inherently generated in the laser-generated plasmas, or of pre-polarized target particles that

Figure 8. Barrier bucket cavity installed in the COSY ring (left) and octagonal slot-coupler for stochastic beam cooling in HESR (right).

Figure 9. Prototypes of straw detectors for the PANDA experiment.
maintain their polarization during the rapid acceleration procedure.

Making use of its experience in polarized beams and targets as well as in building fast on-line detectors, IKP has established a working group that is carrying out exploratory studies aiming at the realization of a laser-based source for (un-)polarized beams in the COSY-injection energy regime. This work is carried out at the 300 TW Ti:Sa laser facility Arcturus at Düsseldorf University where currently proton energies of up to 10 MeV are achieved.

The preparation of accelerator components, comprising a set of dipole and quadrupole magnets, for beam catching has begun at the IKP. Such a trimmed, stable beam could later be injected into a conventional accelerator like COSY, provided that its injection energy of 40 MeV is reached.

Up to now the beams exhibit broad energy and angular distributions. It is known that via special target engineering quasi mono-energetic protons can be generated due to the spatial reduction of the accelerating field. Improved coupling efficiency and thus maximum proton energies can be achieved by using limited-mass targets, like small liquid drops or pellets. Such frozen pellet targets are currently being used for COSY experiments and seem to be a promising tool also for the effective generation of laser-generated particle beams.

Summary

COSY in combination with its complementary experimental facilities and polarized hadronic beams and targets provide unique opportunities to investigate a broad physics program holding the potential to significantly contribute to our understanding of hadron physics in the light quark sector. Experiments on the structure and interaction of baryons and mesons will continue at ANKE and COSY-TOF. This comprises the quantitative analysis of the observed baryon states and the polarization degrees of freedom as well as neutron interactions using deuteron beams or targets and spectator detection. With the WASA-at-COSY, a detector has become available that allows high-statistics studies aiming at very rare decays of \( \eta \) and \( \eta' \) regarding fundamental questions such as symmetries and symmetry violation within and outside the standard model. A particular strength is the close collaboration between experiment and the theory groups at IKP and other institutions.

COSY users, together with the IKP, will play a crucial role in the design, construction, and exploitation of the HESR and PANDA at FAIR (GSI Darmstadt). COSY plays a decisive role in the education of future hadron physicists in ongoing experiments. This will also enable them to prepare for and make optimum use of the future opportunities offered by FAIR. For further and comprehensive details on the current COSY physics program refer to Ref. [1].

Reference


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Long Range Structure of the Nucleon*

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Introduction: Ranges

Many physicists have the following picture of the structure of the nucleon: In the inner region at “short range” reside quarks bound by gluons, in the outer region at “large distances” live mesons and in particular pions. The nucleon consists of constituents (i.e., “constituent quarks” and pions), as the atom consists of a nucleus and electrons, and the nucleus of protons and neutrons. The range of the inner “colored” region, frequently called “confinement radius,” is rather elusive. It is a model parameter in the old bag model or models for the nucleon resonances based on the constituent quarks. One can estimate it from experiment by identifying it with the “annihilation radius” of the antiproton–proton system. Only quark–antiquark annihilation in the overlap region of color can contribute to annihilation [2]. It amounts to approximately 0.8 fm, in reasonable agreement with the mentioned model parameters. However, it cannot be easily identified with the root-mean-square (rms) radius of the electric charge of the proton, since the pion cloud will contribute to the charge distribution. A rough idea of the range of this contribution may be gotten by the Compton wave length of the pion which is of the order of 1.4 fm.

However, this picture fails in two ways. Firstly, the nucleon moves after the scattering in most experiments at relativistic velocities and therefore its structure looks different in different reference frames. The simplest example is the transformation of the magnetic moment into an electric dipole moment. This situation makes it particularly difficult to compare experiments to model calculations based on rest frame wave functions. These wave functions have to be “boosted” to the correct momentum transfer and there is no consistent way of doing that. Secondly, at relativistic energies particle-antiparticle (i.e., quark–antiquark), pairs have unavoidably to be considered making the picture much more involved.

These two aspects will be discussed in the third section.

The relativity destroys the simple picture also in another way. We usually relate ranges with momentum transfer via Heisenberg’s uncertainty relation. However, since in relativistic mechanics space and time are intimately connected no relativistic uncertainty relation exists [3]. Therefore the assignment of ranges to quantities depending on the negative four momentum transfer squared $Q^2 = -q^2$, as for example, in some plots of the running coupling constant, is rather misleading. We shall, therefore, in this article distinguish between the non-relativistic picture derived at small momentum transfers and the relativistic case where we have to use the relativistic quantum field theoretic description. At small momentum transfers we can approximate the four momentum transfer $q$ with the three momentum transfer $q^2 = -q^2$ and maintain the familiar interpretation of form factors (next section). In the third section we shall show how we can connect the non-relativistic picture to the underlying quark–gluon structure. We shall see that new experiments in just the relativistic domain are needed in order to clarify how nucleons are made up of quarks and gluons or, more precisely, how hadrons emerge from QCD.

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*This is an abridged version of Ref. [1].

Figure 1. The electric FF of the proton $G_{Ep}/G_D$ obtained from a direct fit to the cross sections with the spline model to data measured with the 3-Spectrometer set-up at MAMI. The FF is normalized to the dipole form given in the text. The 1 σ-error band is shown for the indicated errors.
Nonrelativistic Interpretation of Nucleon Form Factors

We begin with form factors of the nucleons and summarize what we know up to 2009 (see, e.g., Refs. [5–7] for some recent reviews on nucleon form factors). The pre-2000 data suggest that the magnetic and electric form factor of the proton follow a universal form, the “dipole form”

\[ G_D(Q^2) = \frac{1}{1 + Q^2/\Lambda^2_D}^{2}, \]

with the scale parameter \( \Lambda_D = 0.843 \) GeV approximately equal to the mass \( m_r \) of the \( \rho \) meson. The case was closed and considered to be textbook material. This finding was the basis for the much discussed “vector dominance model” in strong interactions. (For a recent discussion see Ref. [8].) The \( \rho \) meson mass defines a “small range” of an exponential distribution, somewhat unphysical due to its discontinuity at \( r = 0 \). It was believed that the dipole form would also describe the long ranges characterized by the rms radius of the proton. A measurement at the High Energy Physics Laboratory HEPL at Stanford gave \( \sqrt{\langle r^2 \rangle} = 0.805(11) \) fm \( = \sqrt{12 / m_r} \) [9]. Today the CODATA06 value 0.8768(69) fm is based mostly on measurements of electronic atoms [10]. This value is confirmed by a recent high precision determination at the Mainz Microtron (MAMI) yielding [4]:

\[ \sqrt{\langle r^2 \rangle} = 0.879(5)_{\text{stat}}(4)_{\text{syst}}(2)_{\text{model}}(4)_{\text{group}} \text{ fm} \tag{1} \]

As discussed in Ref. [11] this value is significantly larger than the largest value derived from dispersion relations [12] and is unexplained in most nucleon models. On the other hand, a recent study of the Lamb shift in muonic hydrogen at the Paul-Scherer Institute (PSI) in Zuerich yielded a very precise value as low as 0.84184(67) fm [13] in agreement with the upper bound of the dispersion-relations calculations [12]. Taken the CODATA06 value together with the new determination from electron scattering the combined mean value changes hardly, but, the deviation has now a significance of 7 standard deviations. Since the theoretical description of the Lamb shift in muonic hydrogen is rather matured the explanation of the difference is a puzzle so far.

Considering the focus on “long ranges” the question arises how much of the rms radius is possibly due to a pion cloud. There were weak indications that the pion cloud could be directly seen in the FFs in a similar way as the shell structure of the nucleus. This indication came from a coherent analysis of the data available until 2003 for the electric and magnetic FFs of the proton and neutron [14]. Since 2003 the data base has improved so much that we want to base this discussion on the most recent measurements.

Figure 1 shows the electric FF of the proton as derived from a direct fit of a FF model to data obtained with the 3-Spectrometer set-up at MAMI. This method takes advantage of modern computers and fits the theoretical cross section (Rosenbluth formula) to a large set of angular distributions measured at six energies 180, 315, 450, 585, 720, and 855 MeV. All together about 1,400 settings were measured. In this way the “measurement at constant \( Q^2 \)” (i.e., the old Rosenbluth separation), becomes obsolete and a very broad kinematic range can be covered indeed. A point of concern may be the analytical model used for the electric form factor \( G_E \) and magnetic form factor \( G_M \) in the direct FF fits. Here about a dozen different forms have been used, all yielding essentially the same results [4]. The rms radius is, however, somewhat dependent on them and the second systematic error in Eq. (1) reflects this dependence.

It is evident that these form factors show some structure after the gross dependence, assumed to be given by the standard dipole form, has been divided out. In Figure 1 one observes two slopes for \( G_E/G_D \). The steep negative slope at small \( Q^2 \) is reflected in the large rms radius discussed earlier. The reverse is true in Figure 2 for the rms radius of \( G_M/(m_p G_D) \). A shoulder structure is indicated in both FFs at \( Q^2 = 0.15 \) GeV\(^2\). It is shifted compared to the bump structure derived by Friedrich and Walcher [14] from the pre-2003 data and cannot be identified with it. However, just considering the scale of the rms radius and the scale of the
results from the MIT Bates measurement with the BLAST summary can be found in Ref. [11]. A detector at the South Hall Ring at small the electric rms radius of the neutron is a subtle interplay contribute to the small electric form factor. It turns out that mentioned recoil effect causes the magnetic moment to as in the case of the proton in first place. However, the in the neutron charge distribution. This means that the pion cloud should be more clearly visi-
ble again as a signal at large radii distributions in the rest frame system. The three-dimensional charge distribution of a spher-
ically symmetric non-relativistic system is obtained as:

\[ \rho_{\text{rest}}(r) = \int_0^{\infty} \frac{dk}{2\pi^2} k^2 j_0(rk) \tilde{\rho}(k), \]

(2)

where \( \tilde{\rho}(k) \) is an intrinsic FF. As already pointed out the relativistic effects do not allow for a simple interpretation of the electric and magnetic FFs in terms of charge and magnetic density distributions in the rest frame system. However, there is a special reference system, the Breit or brick-wall system, defined by having no energy transfer \( \nu \) to the nucleon, in which the charge operator for a non-relativistic (static) system is only expressed through the electric FF \( G_E \). In this system the four-momentum transfer squared becomes \( q^2 = \nu^2 - \bar{q}^2 = -\bar{q}^2 \). However, the rest frame systems (laboratory systems) for different \( q^2 \) move with different velocities with respect to the Breit system. For a relativistic system, to relate its intrinsic FF \( \tilde{\rho}(k) \) and density to the Breit frame in which the system of mass \( M \) moves with velocity \( \nu = \sqrt{1 - \gamma^2} \), requires a Lorentz boost relating \( k' = Q^2/(1 + \gamma) \). This relation shows that for \( Q^2 \rightarrow \infty \), there is a limiting largest intrinsic wave vector \( k' = 2M = 2\pi\hbar_{\text{rest}} \). In this picture, no information can be obtained on distance scales smaller than this wavelength due to relativistic position fluctuations (known as the

Figure 3. A compilation of the recent data for the neutron electric FF, \( G_{e_n} \), obtained at NIKHEF (triangle), Bates MIT (stars), JLab (squares), and MAMI Mainz (circles), with the quasi free \( \bar{e}p \rightarrow p\pi^0 \) and the \( \bar{e}^3\text{He} \rightarrow ppm \) reactions. The curves correspond with a new fit of a phenomenological model (solid red curve) [14], and of a Generalized Parton Distribution parametrization (dotted black curve) [15].
Zitterbewegung). For a non-relativistic system as for example, \( ^{16}O \) \( \lambda_{\text{in}} \) is below 0.04 fm, whereas for the nucleon, it corresponds with \( \lambda_{\text{in}} \approx 0.66 \) fm. Extracting the density for a relativistic system as the nucleon, therefore requires a prescription in order to relate the intrinsic FFs \( \alpha(k) \) in Eq. (2) to the experimentally measured FFs (see Ref. [18]). To see the transitional region from the distance scales where relativistic position fluctuations hamper our extraction of rest frame densities to distances where the concepts of a non-relativistic many-body system can be approximately applied, we visualize the charge density in Figure 4. It depicts the Fourier transform Eq. (2) using the fit in Figure 3 (solid red curve). One notices a negative charge density at distances around and larger than 1 fm. With all caveats we may interpret the negative charge as a “pion cloud” in the nonrelativistic limit since it extends beyond the confinement radius of about 0.8 fm.

Relativistic Picture

We now turn to the relativistic picture and see how it does complicate matters, however, for the benefit of a deeper insight. As already mentioned both, the size and the shape of an object, are not relativistically invariant quantities: observers in different frames will infer different magnitudes for these quantities. Furthermore when special relativity is written in a covariant formulation, the density appears as the time component (zero component) of a four-current density \( J^\mu = (\rho, J) \) (in units in which the speed of light \( c = 1 \)).

Besides the relativistic kinematic effects, as, for example, the length contraction, the concept of size and shape in relativistic quantum systems, such as hadrons, is also profoundly modified as the number of degrees of freedom is not fixed anymore. In relativistic quantum mechanics the number of constituents of a system is not constant as a result of virtual pair production. We consider as an example a hadron such as the proton which is probed by a space-like virtual photon, as shown in Figure 5. A relativistic bound state as the proton is made up of almost massless quarks. Its three valence quarks making up for the proton numbers, constitute only a few percent of the total proton mass. In such a system, the wave function contains, besides the three valence quark Fock component \( |q\bar{q}q\rangle \), also components where additional \( q\bar{q} \) pairs, the so-called sea-quarks, and (transverse) gluons \( g \) contribute leading to an infinite tower of \( |qqq\bar{q}\rangle, |qqqg\rangle, \ldots \) components. When probing such a system using electron scattering, the exchanged virtual photon will couple to both kind of quarks, valence and sea, as shown in Figure 5a and b. In addition, the virtual photon can also split into a \( q\bar{q} \) pair, leading to a transition from a \( 3q \) state in the initial wave function to a \( 4q\bar{q} \) state in the final wave function, as depicted in Figure 5c. Such processes representing non-diagonal overlaps between initial and final wave functions are not positive definite and do not allow for a simple probability interpretation of the density \( \rho \) anymore. Only the processes shown in Figure 5a and b, with the same initial and final wave function yield a positive definite particle density allowing for a probability interpretation.

This relativistic dynamic effect of pair creation or annihilation fundamentally hampers the interpretation of density and any discussion of size and shape of a relativistic quantum system. Therefore, an interpretation in terms of the concept of a density requires suppressing the contributions shown in Figure 5c. This is possible when viewing the hadron from a light front reference frame allowing for a description of the hadron state by an infinite tower of light-front wave functions [19]. Consider the electromagnetic (e.m.) transition from an initial hadron (with four-momentum \( p \)) to a final hadron (with four-momentum \( p' \)) viewed from a light-front moving towards the hadron. Equivalently, this corresponds to a frame where the hadrons have a large momentum-component along the z-axis chosen along the direction of the hadrons average momentum \( P = (p + p')/2 \). One then defines the light-front plus (+) component by \( a^+ = a^0 + a^3 \), in a general four-vector \( a^\mu \), which is always a positive quantity for both quark or anti-quark four-momenta.

Figure 4. Charge distribution of the neutron as derived from the Fourier transform of the \( G_{\text{En}} \) fit (solid red curve in Figure 3). The dashed part of the curve is for \( r < \lambda_{\text{in}} = 2\pi/(2M) \), where one is intrinsically limited to resolve the density due to the “Zitterbewegung” of the nucleon.
in the hadron. When we now view the hadron in a so-called Drell-Yan frame [20], where the virtual photon four-momentum $q$ satisfies $q^0 = 0$, energy-momentum conservation will forbid processes in which this virtual photon splits into a $q \bar{q}$ pair. Such a choice is possible for a space-like virtual photon, and its four-momentum or “virtuality” is then given by $q^2 = -\vec{q}_\perp^2 = -Q^2 < 0$, where $\vec{q}_\perp$ is the transverse photon momentum lying in the $xy$-plane. In such a frame, the virtual photon only couples to forward moving partons, that is, only processes such as in Figure 5 (a) and (b) are allowed. We can then define a proper density operator through the $+$ component of the four-current by $J^+ = \rho^0 + J^0$ [21]. For quarks it is given by

$$J^+ = \bar{q}\gamma^+ q = 2q_+q_+,$$  \hspace{1cm} (3)

where we introduced the $q_+$ fields through a field redefinition from the initial quark fields $q$ involving the ± components of the Dirac gamma matrices. The relativistic density operator $J^+$, as defined in Eq. (3), is a positive definite quantity. For systems consisting of, for example, light $u$ and $d$ quarks, multiplying this current with the quark charges yields a quark charge density operator given by $J^+(0) = +2/3u(0)\gamma^+ u(0) - 1/3d(0)\gamma^+ d(0)$. Using this charge density operator, one can then define quark (transverse) charge densities in a hadron as [22–23]:

$$\rho_0(b) \equiv \frac{d^2q_+}{(2\pi)^2} e^{-i\vec{q}_\perp \hat{b}} \frac{1}{2P^+} \times \left( P^+, \frac{\vec{q}_+}{2}, +\frac{1}{2} \left| J^+(0) \right| P^+, -\frac{\vec{q}_-}{2}, +\frac{1}{2} \right)$$  \hspace{1cm} (4)

where the hadron is in a state of definite (light-front) helicity. In the two-dimensional Fourier transform of Eq. (4), the two-dimensional vector $\hat{b}$ denotes the quark position in the $xy$-plane relative to the position of the transverse centre-of-momentum of the hadron. It represents the position variable conjugate to the hadron relative transverse momentum, which equals just the photon momentum $\vec{q}_\perp$.

The quantity $\rho_0(b)$ has the interpretation of the two-dimensional unpolarized quark charge density at a distance $b = |\hat{b}|$ from the origin of the transverse e.m. system of the hadron. In the light-front frame, it corresponds to the projection of the charge density in the hadron along the line-of-sight. It is important to mind this difference to the interpretation in the non-relativistic case.

The quark charge density in Eq. (4) does not fully describe the e.m. structure of the hadron, because we know that there are two independent e.m. FFs describing the structure of the nucleon. In general, a particle of spin $S$ is described by $(2S + 1)$ e.m. moments. In order to fully describe the relativistic structure of a hadron one needs to consider additionally the charge densities in a transversely polarized hadron state yielding a transverse charge distribution $\rho_{T \perp}$. We denote the transverse polarization direction by $S_\perp = (\cos \phi S_\zeta + \sin \phi S_\zeta)$. The transverse charge densities can then be defined through matrix elements of the density operator $J^+$ in eigenstates of transverse spin as [24–26]:

$$\rho_{T \perp} (b) \equiv \int \frac{d^2\vec{q}_\perp}{(2\pi)^2} e^{-i\vec{q}_\perp \hat{b}} \frac{1}{2P^+} \times \left( P^+, \frac{\vec{q}_+}{2}, s_\perp | J^+ | P^+, -\frac{\vec{q}_-}{2}, s_\perp \right)$$  \hspace{1cm} (5)

where $s_\perp$ is the hadron spin projection along the direction of $S_\perp$. Whereas the density $\rho_0$ for a hadron in a state of definite helicity is circular symmetric for all spins, the density $\rho_{T \perp}$ depends also on the orientation of the position vector $\hat{b}$, relative to the transverse spin vector $S_\perp$. Therefore, it contains the information on the hadron shape, again projected on the plane perpendicular to the line-of-sight.

As summarized in the previous section, e.m. FFs of the nucleon are well measured experimental quantities. We will, therefore, discuss the relativistic spatial shape as derived from these FFs. For a nucleon in a state of definite helicity, the transverse quark charge density is obtained
from Eq. (4) by taking the two-dimensional Fourier transform of its Dirac FF \( F_1 = (G_E + \tau G_M)/(1 + \tau) \) as [22–23]:

\[
\rho_0(b) = \int_0^\infty \frac{dQ}{2\pi} Q J_0(bQ) F_1(Q^2),
\]

where \( J_n \) denotes the cylindrical Bessel function of order \( n \). Note that \( \rho_0 \) only depends on \( b = |\vec{b}| \).

On the other hand, the information encoded in the Pauli FF \( F_2 = (G_M - G_E)/(1 + \tau) \) is connected to a nucleon in a transverse spin state. For a nucleon polarized along the positive \( x \)-axis, the transverse spin state can be expressed in terms of the light front helicity spinor states by:

\[
| s_\perp = +1/2 \rangle = \frac{1}{\sqrt{2}} \left( |\lambda = +1/2 \rangle + e^{i\phi} |\lambda = -1/2 \rangle \right),
\]

The second term, which describes the deviation from the circular symmetric unpolarized charge density, depends on the orientation of the transverse position vector.
In order to extract charge densities, one requires a form factor parametrization over all values of $Q^2$. Because the Bernauer et al. [4] data only provide a precision measurement of $G_{Ep}$ and $G_{Mp}$ for $Q^2 \leq 0.4$ GeV$^2$, to fully quantify their impact on quark charge densities requires a new global analysis combining the previous data with these new data. Here we will perform a first estimate of this by using a parametrization that smoothly connects the new high precision data at low $Q^2$ and the Arrington et al. [27] parametrization at larger $Q^2$. This interpolation function is used to extract the two-dimensional quark charge density in a proton in Figure 7. One readily sees that the new high precision data have a direct impact on the extracted charge densities at large distances, typically larger than about 1.5 fm. By comparing the extracted density, using the previous fit to world data with the new fit, one sees that the new data lead to a significant reduction of the densities at distances larger than about 2 fm. This is a direct consequence of the flatter behavior in $Q^2$, for $Q^2 \leq 0.3$ GeV$^2$, which the new data display for both $G_{Ep}$ and $G_{Mp}$.

In Figure 8, we show the corresponding large distance behavior of the quark charge density in the neutron. The transition between the dashed blue curve and the solid red curve in Figure 8 shows the impact of recent precision data at low $Q^2$ for the neutron FFs. These lead to a sizable enhancement in the extracted densities at distances larger than 1.5 fm. It is also of interest to compare these light-front densities with the static densities as discussed in the second section. For a non-relativistic system, one can extract the two-dimensional quark charge density in a proton in Figure 7. One readily sees that the new high precision data have a direct impact on the extracted charge densities at large distances, typically larger than about 1.5 fm.

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Figure 7. Large distance behavior of the unpolarized quark transverse charge density in the proton. The dashed blue curve uses the Arrington et al. parametrization [27]. The solid red curve shows the impact of recent high precision data at low $Q^2$ by using a smooth connection between the Bernauer et al. [4] fit at low $Q^2$ and the Arrington et al. fit at larger $Q^2$. For comparison, the dotted black curve is the 2-dimensional projection of the static charge distribution according to Eq. (8), using the interpolating fit for $G_{Ep}$.

In Figure 6, the transverse charge densities in a nucleon, polarized transversely along the $x$-axis (i.e., for $\phi_0 = 0$), are extracted based on the empirical information on the nucleon e.m. FFs which, however, does not yet contain the most recent data presented in the second section. For the proton e.m. FFs, the empirical parametrization of Ref. [27] is used, whereas for the neutron e.m. FFs, the empirical parametrization of Ref. [28] is taken. One notices from Figure 6 that polarizing the proton along the $y$-axis equivalent to the anomalous magnetic moment

\[ \vec{b} = b(\cos \phi_0 \hat{e}_x + \sin \phi_0 \hat{e}_y) \]

relative to the transverse spin direction.

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\[
\rho_{2d}(b) = \int_{-\infty}^{\infty} dz \rho_{2d}(\sqrt{b^2 + z^2}),
\]

\[ = \int_0^{Q^2} \frac{dQ}{2\pi} Q J_0(bQ) G_E(Q^2). \]  

One notices that this static 2-dimensional density has the same form as the light-front density, see Eq. (6), with the crucial difference that in the static density the Sachs electric FF $G_E$ appears, whereas for a relativistic system, the proper light-front charge density involves the Dirac FF $F_1$. Since the large distance behavior is mostly impacted by the low $Q^2$ data, where $G_E$ is dominated by $F_1$, one expects a qualitatively similar behavior at large distances between both pictures. This is illustrated in Figures 7 and 8 where the light-front densities (solid red curves) are depicted.
along with the 2-dimensional static densities (dotted black curves). One notices that for the proton, both densities approach each other at large distances pointing to a large tail in the charge distribution. The corresponding picture for the neutron shows that both light-front and static densities display a negative charge density for distances larger than about 1.6 fm, which can be associated with a negative pion cloud in the outer region of the neutron.

A combination of the FF data for the proton and neutron allows one to perform a quark flavor separation and map out the spatial dependence of up and down quarks separately. The flavor separated FFs, invoking isospin symmetry, are defined as

\[
F_{1,2u} = 2F_{1,2p} + F_{1,2n}, \\
F_{1,2d} = F_{1,2p} + 2F_{1,2n},
\]

(9)

For the Pauli FFs, it is convenient to divide out the normalizations at \(Q^2 = 0\), given by the anomalous magnetic moments \(\kappa_u = 2\kappa_p + \kappa_n\), \(\kappa_d = \kappa_p + 2\kappa_n\).

Using Eq. (6), we can then extract the ratio of up/down quark densities in the nucleon, which is displayed in Figure 9. If the down and up quarks would have the same spatial distribution in the nucleon, the ratio as displayed in Figure 9 would be one. We see, however, that in the center region of the proton, at distances smaller than about 0.5 fm, down quarks are less abundant than up quarks. The down quarks have a much wider distribution and are shifted to larger distances, dominating over up quarks between 0.5 to 1.5 fm. At large distances, larger than about 1.5 fm, one clearly sees the impact of the recent data, which results in a factor 2 change in the density as compared to previous fits to world data. Although the contribution of the large distance region to the total charge is very small, the new data allow one to precisely map out the charge densities in the region well beyond the confinement radius, where the charge density can in turn be interpreted as a measure of the contribution of the pion cloud.

**Conclusion**

We have presented two ideas about the long-range structure of the nucleon. The first is nonrelativistic in terms of a “bare nucleon” plus a pion cloud, and the second relativistic in terms of quarks and gluons. One may be tempted to believe that the second is more fundamental since it uses the elementary fields of the standard model of particle physics. The quantum theory of quarks and gluons, QCD, describes a very large domain of strong interaction physics indeed. However, at sufficiently low energies, hadrons may be described by effective field theories formulated in terms of fields with discrete quantum numbers. These fields may be viewed as elementary in a certain domain of validity (i.e., sufficiently low energies here). One prominent example of such an effective field is just the pion in Chiral Perturbation Theory emerging as the Goldstone Boson of the spontaneous breaking of chiral symmetry of QCD.

In fact, we are not able to devise a quantitative description of the nucleon-nucleon force in terms of quarks and gluons. On the other hand, the meson exchange idea allows for a very precise description of this force. Therefore, it may be futile to ask the question which description is more correct. Frequently in physics we have to be content with a model allowing a description in a limited domain and, following from this, limited predictive power.

This sometimes confusing situation is also revealed by the two extreme reference frames in which we have considered the structure of the nucleon: the brick-wall system implying an infinitely heavy nucleon and the light-front frame implying a nucleon moving with approximately the speed of light. As we demonstrated in both frames, the long distance structure of the nucleon reflects the physics of the pion cloud. However, whether we will ever be able to devise a “final theory” in terms of the elementary fields is an open question. Actually, most physics is understood.
in terms of emergent effective degrees of freedom as the examples of condensed matter physics and nuclear physics show overwhelmingly.

Acknowledgments

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Figure 9. Ratio of down over up quark densities in the proton. The dashed blue curves represent a previous fit to world data, whereas the solid red curves show the impact of recent high precision data at low $Q^2$ as described in the text. The dotted black curves represent the results of a Generalized Parton Distribution parametrization [15] of up and down quarks.

The European Strategy Forum on Research Infrastructures (ESFRI) and its roadmap [1] aim to integrate national resources into a common, pan-European effort. Currently the ESFRI roadmap, first issued in 2006 and updated in 2008, lists 43 large-scale projects selected from all science and engineering areas. Under the 7th Framework Programme the European Commission has funded the preparatory phases for 34 projects included in the 2006 ESFRI roadmap. In the area of physical sciences besides the two radioactive beam facilities FAIR (at GSI/Germany) and SPIRAL2 (at GANIL/France) also the project “Extreme Light Infrastructure” (ELI) [2] was selected. Already one year before the end of ELI’s 7th Framework Preparatory Phase a decision was made in October 2009 to implement ELI as a joint European consortium of 17 nations consisting of three laser facilities that will be consolidated under the joint ELI project. The prime objective is to build a unified infrastructure based on three mutually supporting pillars.

One pillar will be located in Prague (Czech Republic), focusing on building a novel generation of secondary sources from high energy laser beams for interdisciplinary applications in physics, medicine, biology, and material sciences [3]. The second pillar, concentrating on the physics of ultrashort optical pulses on the attosecond scale, is scheduled for location in Szeged (Hungary) [4]. Finally, the third pillar will be built in Magurele, close to Bucharest (Romania) and will be dedicated to (photo-)nuclear physics [5], therefore termed ELI–Nuclear Physics (ELI–NP). With the termination of ELI’s Preparatory Phase end of November 2010 and with funding of 280 million Euros in the process of being allocated from EU structural funds for ELI–NP in Romania, ground breaking for ELI–NP should start as early as 2011.

The laser backbone of ELI–NP will consist of several arms of high-power, short-pulse lasers, each of them providing 10 Petawatt laser power (Table 1). These “APOLLON”-type lasers are currently being developed by the group of Gerard Mourou and coworkers at the École Nationale Supérieure de Techniques Avancées (ENSTA) in Paris [6]. Here, a future fourth pillar of ELI is prepared, where many APOLLON lasers are envisaged to be combined for high-field science. The second source of ELI–NP, the γ-beam facility (Table 1), will be developed and provided by the group of Chris Barty at Lawrence Livermore National Laboratory (LLNL). Brilliant, intense, and energetic photon beams will be generated via Compton backscattering of laser photons from a high-quality electron beam [7]. The Livermore group is presently building a similar facility called MEGa-ray [8], with a normal-conducting electron linac

Table 1. Characteristics of the ELI–NP linear Compton back-scattering γ source and the high-power lasers.

<table>
<thead>
<tr>
<th>Parameters of γ-beam</th>
<th>Value</th>
<th>Parameters of APOLLON lasers</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>max. e energy</td>
<td>600 MeV</td>
<td>power</td>
<td>2 · 10 PW</td>
</tr>
<tr>
<td>max. γ energy</td>
<td>13.2 MeV (19.5 MeV)</td>
<td>OPCPA front end</td>
<td></td>
</tr>
<tr>
<td>norm. emittance</td>
<td>0.18 mm mrad</td>
<td>Ti:Sapphire</td>
<td></td>
</tr>
<tr>
<td>γ-energy spread (FWHM)</td>
<td>10⁻³</td>
<td>high energy end</td>
<td></td>
</tr>
<tr>
<td>total flux (ph/s)</td>
<td>10¹³</td>
<td>100 TW</td>
<td>10 Hz</td>
</tr>
<tr>
<td>pulse repetition (macro p.)</td>
<td>12 kHz (120Hz)</td>
<td>1 PW</td>
<td>≥0.1 Hz</td>
</tr>
<tr>
<td>pulse duration</td>
<td>2 ps</td>
<td>10 PW</td>
<td>1/min</td>
</tr>
<tr>
<td>γ source size</td>
<td>10 μm</td>
<td>max. intensity</td>
<td>10²⁴ W/cm²</td>
</tr>
<tr>
<td>peak brilliance</td>
<td>1.5 · 10¹⁴</td>
<td>max. field strength</td>
<td>≈10¹⁵ V/m</td>
</tr>
<tr>
<td>ph/(mm² mrad² s 0.1% BW)</td>
<td></td>
<td>pulse duration</td>
<td>15 fs</td>
</tr>
<tr>
<td>average brilliance</td>
<td>4 · 10¹²</td>
<td>contrast (10 ps before)</td>
<td>10⁻¹²</td>
</tr>
<tr>
<td>ph/(mm² mrad² s 0.1% BW)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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The experiments can be grouped into three categories: stand-alone $\gamma$-beam experiments, stand-alone APOLLON-type laser experiments, and combined experiments making use of both drivers, for example, the 600 MeV electron beam (for the $\gamma$-beam) and the high power lasers.

The layout of the ELI–NP facility, covering an area of about two football fields, is shown in Figure 1. It consists of two 10 PW lasers, shown in the upper part of the figure, which can be added phase-synchronized into a common focus. In the lower part the normal-conducting electron linac is shown, delivering $\gamma$ beams from two beam ports. The high spatial accuracy of the beams requires a special design of the concrete base plate of the building to prevent vibrations. The laser hall will require clean-room conditions of class 6. The large amount of radio-protection concrete shielding is designed in a modular way to accommodate the planned experiments with a maximum of flexibility. Finally, an architect’s vision of the ELI–NP facility is shown in Figure 2.

Nuclear Physics and Astrophysics

Experiments with Stand-Alone APOLLON-Type Lasers

The origin of the heaviest elements (e.g., gold, platinum, thorium, uranium) remains one of the 11 greatest unanswered questions of modern physics, according to a recent report by the U.S. National Research Council of the National Academy of Science [11]. A recent paper [12] outlines in detail, how dense, laser-accelerated ion beams open up a new access to very neutron-rich nuclei, relevant to this element production. In this proposal, we introduced the new “fission–fusion” nuclear reaction process that allows one to produce the decisive extremely neutron-rich nuclei in the range of the astrophysical $r$-process (the rapid neutron-capture process around the waiting point $N = 126$ [13, 14] by fissioning a dense, laser-accelerated thorium ion bunch in a thorium target (covered by a polyethylene layer), where the light fission fragments of the beam fuse with the light fission fragments of the target. So far the astrophysically relevant nuclei are about 15 neutrons away from the last known isotope of a given element and nothing is known about their nuclear properties (Figure 3).

Via the “hole-boring” (HB) mode of laser Radiation Pressure Acceleration...
(RPA) [15, 16] using a high-intensity, short pulse laser bunches of $^{232}$Th with solid state density can be generated very efficiently from a Th layer (approx. 0.5 μm thick), placed on a deuterated diamond-like carbon foil $[\text{CD}_2]_n$ (with approx. 0.5 μm thickness), forming the production target. Laser-accelerated Th ions with about 7 MeV/u will pass through a thin $[\text{CH}_2]_n$ layer placed in front of a thicker second Th foil (both forming the reaction target) closely behind the production target and disintegrate into light and heavy fission fragments. In addition, light ions (d,C) from the $[\text{CD}_2]_n$ backing of the Th layer will be accelerated as well, inducing the fission process of $^{232}$Th also in the second Th layer. The laser-accelerated ion bunches with near solid state density, which are about $10^{14}$ times more dense than classically accelerated ion bunches, allow for a high fusion probability of the generated fission products when the fragments from the thorium beam strike the thorium layer of the reaction target.

In contrast to classical radioactive beam facilities, where intense but low-density radioactive beams of one ion species are merged with stable targets, the novel fission–fusion process draws on the fusion between high-density, neutron-rich, short-lived, light fission fragments both from beam and target. Moreover, the high ion beam density may lead to a strong collective modification of the stopping power in the target by “snowplough-like” removal of target electrons, leading to significant range enhancement, thus allowing one to use rather thick targets.

Using a high-intensity laser with 300 J and 32 fs pulse length, as, for example, envisaged for the ELI–Nuclear Physics project in Bucharest (ELI–NP), order-of-magnitude estimates promise a fusion yield of about $10^3$ ions per laser pulse in the mass range of $A = 180 - 190$, thus enabling to approach the $r$-process waiting point at $N = 126$. The produced nuclei from the fission–fusion process will

![Figure 2. Architect’s view of the ELI–NP facility.](image)

![Figure 3. Nuclidic chart, showing the different nucleosynthesis processes like the $r$-process, the $s$-process, or the fusion processes in stars together with contour lines of the new fission–fusion process for producing very neutron-rich nuclei close to $N = 126$ waiting point of the $r$-process.](image)
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be injected into a Penning trap to measure their nuclear binding energy, a measure for shell quenching, with high accuracy [12]. This information will constrain possible sites for the astrophysical r-process decisively.

**Experiments with γ-Beams**

Employing intense, brilliant γ beams the fine structure of many E1 and M1 excitations can be probed in detail with their many decay branches. Specific parity-violating mixtures between parity doublets (e.g., 1⁺ and 1⁻ states) allow a very sensitive access to parity violating nuclear forces [17]. The gateway states to switch from the ground state via γ-excitation–deexcitation to a longer-lived isomer or from one isomer to the next with still higher spin and K quantum number can be explored in detail. The transition from regular nuclear motion at lower energies to chaotic nuclear motion at higher excitation energies, which recently has been reviewed in detail [18], can be studied by many tools like nearest-neighbor level distributions or Porter-Thomas width distributions. Very high-resolution γ spectrometers, similar to the GAMS spectrometer at ILL [19], will become more important. Once we reach excitation energies with particle unstable states, fine structures like the Pygmy Dipole Resonance (PDR) become important for astrophysical processes.

**Fundamental Physics**

*Pair Creation from the Vacuum with 600 MeV Electrons Seeding a very Intense Laser Focus*

The typical quasi-static threshold electric field for pair creation from the vacuum is \( E_s = \frac{m^2 c^3}{e\hbar} = 1.3 \times 10^{18} \) V/M, which correspond to laser intensities of \( 4.3 \times 10^{29} \) W/cm². Due to the very strong exponential dependence of the pair production rate [20] in the focused laser fields of ELI–NP, we cannot reach pair creation with the laser field alone. Here, Nina Elkina and colleagues [21] of Hartmut Ruhl’s group (LMU, Munich) performed detailed simulations focussing 600 MeV electrons as seeds into the focus of two counter-propagating circularly polarized APOLLON-type lasers. By strongly non-linear quantal effects the electrons emit hard γ rays (up to 500 MeV) in the laser focus, which then in a second step decay into \( e^+e^- \) pairs. These pairs are re-accelerated, resulting in further hard γ rays and pairs. Elkina’s simulations showed a quadratic increase of pairs in the laser focus with time, less than exponential, due to the loss of electrons and positrons from the focal laser region. At ELI–NP this strong radiation damping, the predicted spectra and angular distributions of hard γ rays, electrons and positrons will be compared to experimental data, resulting in conclusive tests of the computer simulations for strong laser-field interaction.

**Searching for Light Elementary Particles with High Power Lasers**

In stand-alone experiments with the APOLLON-type lasers the fundamental properties of vacuum can be probed. Here, Kensuke Homma and colleagues [22] have proposed new experiments: Very light elementary particles below 1 eV (like candidates of dark energy) couple very weakly to matter and have not been detected until now. Here, the very intense semi-macroscopic laser fields may open a new window to find these new particles via coupling to laser photons, by observing the generation of second-harmonic radiation in the quasi-parallel colliding system of a single focused laser. Schematically this experiment is shown in Figure 4.

**Applications**

With the γ beam of ELI–NP several new applications can be developed, giving many nuclear excitation cross-sections a new importance. Many of the applications (e.g., in medicine or radioactive materials and radioactive waste management) open new perspectives in a socioeconomical context.

**New Medical Radioisotopes Produced with γ-Beams**

In Ref. [23] about 50 radioisotopes are described, which can be produced with better specific activity and absolute activity by γ beams compared to present production schemes, being of interest for medical diagnostic and/or therapeutic purposes. With the narrow bandwidth γ beams we will find specific gateway states or groups of resonant states for many of the isotopes, if
where the production cross-sections can be increased by 2–3 orders of magnitude compared to the existing average cross-sections [23], making them even more interesting for large-scale industrial applications. Here we shall focus on some of the most interesting isotopes to give a flavor of the new possibilities.

\[^{195}\text{Pt}\]: Determining the efficiency of chemotherapy for tumors and the optimum dose by nuclear imaging

In chemotherapy of tumors most often platinum cytotoxic compounds like cisplatin or carboplatin are used. We want to label these compounds with \[^{195}\text{Pt}\] for pharmacokinetic studies like tumor uptake and want to exclude “nonresponding” patients from unnecessary chemotherapy, while optimizing the dose of all chemotherapy treatments. For such type of diagnostics a large-scale market can be foreseen, but it would also save many people from painful but useless treatments. It is estimated in Ref. [23] that several hundred patient-specific uptake doses could be produced with a γ beam facility per day. However, this probably may be increased to \(10^5\), if optimum gateway states can be identified by scanning the isomer production with high γ beam resolution.

\[^{117}\text{Sn}\]: An emitter of low-energy Auger electrons for targeted tumor therapy

Auger-electron therapy requires targeting into individual tumor cells, even into the nucleus or to the DNA, due to short range (below 1μm) of Auger electrons; however, this method is of high relative biological efficiency (RBE) due to the shower of many (typically 5–30) Auger electrons produced. On the other hand, Auger radiation is of low toxicity, while being transported through the body. Thus Auger-electron therapy needs special tumor-specific transport molecules like antibodies or peptides. Many of the low-lying high spin isotopes produced in \((\gamma\gamma')\) reactions have strongly converted transitions, which trigger these large showers of Auger cascades.

A variety of other important medical radioisotopes can be produced (see Ref. [23]): New “matched pairs” of isotopes of the same element become available, one for diagnostics, the other for therapy, allowing to control and optimize the transport of the isotope by the bioconjugate to the tumor. Also new therapy isotopes become available, such as \[^{225}\text{Ac}\], where four consecutive α decays can cause much more efficiently DNA double-strand breaking. Developing these techniques and applications is a promising task of ELI–NP with a strong societal impact.

New Brilliant, Intense Micro-Neutron Source Produced by Intense, Brilliant γ-Beam

ELI–NP includes the proposal to develop a brilliant, low-energy neutron beam from the γ beam. In Ref. [24], it is described in detail, how low-energy neutrons will be released without moderation and without producing a broad range of fission fragments as in nuclear reactors, or a broad range of spallation products as in spallation neutron sources. Thus, the new neutron facility has the advantage of producing only small amounts of radioactivity and radioactive waste and thus requires only moderate efforts for radioprotection, therefore being very different from present reactor or spallation facilities. The new source can be operated as a multi-user neutron facility and could deliver several orders of magnitude larger isomer production.

Figure 5. Schematic picture of the new neutron production scheme, using the γ beam to excite neutron-halo isomers with a neutron separation energy \(S_N\) below the binding energy \(E_B\). The left level scheme shows the increasing number of compound nuclear resonances as a function of the excitation energy. The halo isomer is fragmented into several high-lying resonances, resulting in halo isomers with different binding energies. The two blue arrows indicate the width of the γ beam. Then in a second step, a photon beam of much lower energy, shown in red, generates the neutron beam by dissociating the neutron halo states.
more brilliant neutrons compared to the best existing neutron sources. When producing the neutrons, we envisage to use a two-step process: with the high-energy $\gamma$ beam in a first step neutron-halo isomers will be populated, while in a second step neutrons are released from the stopped neutron-halo isomers by a second photon pulse (Figure 5).

For the realization of such a neutron source we first plan to study the new neutron-halo isomers in detail. We propose to search for neutron-halo isomers populated via $\gamma$ capture in stable nuclei with mass numbers of about $A = 140–180$ or $A = 40–60$, where the $4s_{1/2}$ or $3s_{1/2}$ neutron shell model states reach zero binding energy. These halo nuclei can be produced for the first time with the new $\gamma$ beams of high intensity and small bandwidth. This production scheme thus offers a promising perspective to selectively populate these isomers with small separation energies of 1 eV to a few keV. Similar to single-neutron halo states for very light, extremely neutron-rich, radioactive nuclei [25], the low neutron separation energy and short-range nuclear force allows the neutron to tunnel far out into free space, much beyond the nuclear core radius. This results in prolonged half-lives of the isomers for the $\gamma$-decay back to the ground state in the 100 ps-μs range. Similar to the treatment of photodisintegration of the deuteron, the neutron release from a neutron-halo isomer via a second, low-energy, intense photon beam has a much larger cross-section with a typical energy-threshold behavior. In the second step, the neutrons can be released as a low-energy, pulsed, polarized neutron beam of high intensity and high brilliance.

Similar to the situation 30 years ago, when synchrotron sources led to increases in brilliance of x-ray beams by many orders of magnitude, the production of pulsed neutron beams with extremely high brilliance will lead to a dramatic leap in the field of neutron scattering. The well focused beams of highest intensity will allow the accurate determination of the structure of biological samples, heterostructures, and of new functional materials. These materials are often only available in small quantities. The exceptionally strong scattering of neutrons by hydrogen and other light materials will provide key information concerning the functionality of bio-materials, which cannot be easily obtained using synchrotron beams or existing neutron sources. In addition, the brilliant neutron beams will allow for the first time the investigation of collective excitations (i.e., magnons and phonons), and relaxation as well as diffusion processes in samples that are only available in smallest quantities. Moreover, the by orders of magnitude smaller duration of the neutron pulses will allow for the investigation of time-dependent processes and the dynamics in systems far away from equilibrium. The new neutron beams will therefore open completely new scientific opportunities in the fields from biology to hard condensed matter to geosciences and nuclear physics. In Ref. [24] many new possibilities are described in more detail.

**Nuclear Resonance Fluorescence of Nuclear Materials and Nuclear Waste Management**

The non-destructive detection of materials hidden by heavy shields such as iron with a thickness of several centimeters is difficult. Such detection of clandestine materials is of importance, for example, for applications in nuclear engineering: the management of nuclear materials produced by nuclear power plants, the detection of nuclear fissile material in the recycling process, and the detection of explosive materials hidden in packages or cargo containers. A non-destructive assay [26] has been proposed with the extremely high-flux Laser Compton Scattering (LCS) $\gamma$ source. The
Facilities and methods

Elemental and isotopic composition is measured using nuclear resonance fluorescence (NRF) with LCS γ-rays. Figure 6 illustrates how characteristic resonances of these elements can be identified via NRF.

Here, one has to stress the political importance of this project. Measuring remotely and precisely isotopes like 239Pu, 235U or dominant fission products is very important for radioactive waste management. The handling of radioactive waste and its long-term storage are partially unsolved problems not only in Europe but worldwide, as exemplified by the strong interest and encouragement by IAEA on this development.

Acknowledgments

A large number of persons have contributed to the development of the ELI–NP project, but also to ELI in general, to all of them we are very grateful. However, we cannot name these people individually, since, for example, more than 100 people have contributed to the ELI–NP Whitebook and to the main components of the ELI–NP infrastructure. We thank the EU for funding the ELI Preparatory Phase within the 7th Framework Programme.

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Laboratory of Neutron Activation Analysis at the Nuclear Physics Institute of the ASCR, Řež

**Introduction**

In addition to analytical methods with ion and neutron beams described in the previous issue of *Nuclear Physics News* [1], neutron activation analysis (NAA) has been traditionally pursued at the Nuclear Physics Institute (NPI). NAA as the most important radioanalytical technique for determination of trace elements in bulk samples of various matrices has been utilized at NPI since the end of the 1960s, after the advent of Ge semiconductor detectors for high-resolution γ-ray spectrometry. In this period, attention was paid especially to analysis of the materials of mineral origin, for example, tektites [2], meteorites [3], minerals, rocks, and lunar samples (from the Apollo 11 and 12 expeditions) [4]. The introduction of non-destructive, so-called instrumental neutron activation analysis (INAA) opened the possibilities of application of this technique in many other fields, namely environmental control and monitoring, biological, medical, nutritional, material, and archaeological research, in analytical quality assurance, and so on. To be able to utilize the potential of NAA for analyses of various materials effectively, many technical advances and methodological improvements have been made.

**Technical Description of the Laboratory Facilities**

Neutron irradiation is carried out in the LVR-15 research reactor of the Nuclear Research Institute Řež, Plc. operated at 8–10 MW thermal power, in which thermal, epithermal and fast neutron fluence rates of up to $7 \times 10^{13} \text{n cm}^{-2}$, $7 \times 10^{13} \text{n cm}^{-2}$, and $6 \times 10^{13} \text{n cm}^{-2}$, respectively, are available in vertical channels. One of these channels is equipped with a pneumatic transport system for short-time irradiation, in which polyethylene containers can be irradiated for 10 s–3 min with the transport time of 3.5 s. In several other channels long-time irradiation in Al cans can be carried out for several hours to several weeks. Both short- and long-time irradiation can be performed in special containers made of or inlaid with a 1-mm Cd shield to screen out thermal neutrons and to achieve selective activation with epithermal neutrons (epithermal neutron activation analysis—ENAA) and/or fast neutrons (fast neutron activation analysis—FNAA). For measurement of the induced activities, the laboratory is equipped with a Canberra Genie 2000 γ-spectrometric system, which comprises several coaxial HPGe detectors with relative efficiency in the range of 20 to 78% and FWHM resolution of 1.75 to 1.87 keV for the 1332.5 keV photons of $^{60}\text{Co}$, one planar HPGe detector with the effective area of 500 mm$^2$, thickness of 15 mm, FWHM resolution of 550 eV at 122 keV, and one well-type HPGe detector with the active volume of 150 cm$^3$, FWHM resolution of 2.02 keV at 1332.5 keV, well dimensions 16 × 50 mm. For a dynamic correction of the dead-time and pile-up effects, Canberra 599 Loss Free Counting modules are used. To facilitate

**Figure 1. Block diagram of strategies for self-verification in NAA [7].**
counting of large batches of solid samples, two coaxial HPGe detectors are equipped with a pneumatic sample changer. Contamination-free sample preparation is carried out at a clean bench, which provides Class 10 working environment. Ordinary chemical laboratories, as well as radiochemical laboratories with disposal systems for both solid and liquid radioactive waste are integral parts of the laboratory of neutron activation analysis at NPI.

**Methodological Developments**

**Self-Verification Principle**

Among the many favorable features of NAA [5], the possibility to determine a particular element using different neutron induced reactions of its isotopes is a very salient one, which has no analogy in other analytical techniques. Since it forms the basis for a unique ability to verify analytical data that NAA produces, this special property has been termed the self-verification principle [6]. Figure 1 shows the basic elements of the self-verification principle in NAA. The primary source of the independence of the analytical data is the essentially isotopic nature of NAA, that is, activation of different isotopes of the same element, and the possibility of using different, again essentially independent, isotopic nuclear reactions, such as \((n, \gamma)\), \((n,p)\), \((n,\alpha)\), \((n,2n)\), \((n,\beta)\) in NAA. It has been shown [6] that more than 25 elements most frequently assayed in biological and environmental matrices can be determined by at least two independent reactions giving gamma emitting radionuclides. Figure 2 illustrates an example of self-verification of INAA results for Se in human red blood cells using two independent nuclear reactions \(^{74}\text{Se}(n,\gamma)^{75}\text{Se}\) and \(^{76}\text{Se}(n,\gamma)^{77}\text{mSe}\) [7].

In addition to the undoubted independence of analytical data provided by NAA using different isotopic reactions, other elements of independence exist in NAA methods. Internally independent routes to analytical information in NAA can be provided by several ways:

- using the different modes of NAA non-destructive, instrumental NAA (INAA) or radiochemical NAA (RNAA)
- using selective activation with thermal, epithermal, and fast neutrons (TNAA, ENAA, and FNAA, respectively)
- using selective measurement techniques (\(\alpha\), \(\gamma\), and X-ray spectrometry, Compton suppression counting in \(\gamma\)-ray spectrometry, \(\gamma-\gamma\) or \(\beta-\gamma\) coincidence counting, \(\beta\) and Cherenkov counting, and delayed neutron or fission track counting for determination of fissile elements and/or nuclides)
- using combinations of the above.

Other examples of various strategies of the self-verification principle have been published elsewhere [7].

**NAA as a Primary Method of Measurement**

Due to a higher potential for accuracy compared with other methods of elemental analysis, especially for trace element analysis, NAA has been denoted for a long time as a “reference, arbitrary, independent” method. However, only recently the case has been made for NAA as a primary method to the Consultative Committee on the Amount of Substance (CCQM) of the International Committee for Weights and Measures (CIPM) [8]. Although the final recommendations are not yet finalized, it appears that CCQM has agreed to consider NAA as a primary method of measurement. This has been achieved because the method satisfied the CCQM’s definition that “a primary method of measurement is a method having the highest metrological properties, whose operation can be completely described and understood, for which a complete uncertainty statement can be written down in terms of SI units” [9, 10].

![Figure 1](image1.png)

**Figure 1.** The basis for a unique ability to verify analytical data that NAA produces, this special property has been termed the self-verification principle [6].

![Figure 2](image2.png)

**Figure 2.** Self-verification of INAA results for Se in human red blood cells using two independent nuclear reactions [7].

![Figure 3](image3.png)

**Figure 3.** Section of \(\gamma\)-ray spectrum of a separated vanadium fraction in RNAA of blood. The \(^{52}\text{V}\) peak corresponds to \(\sim 50 \text{ pg mL}^{-1}\) of vanadium [12].
Two types of primary methods are distinguished: (1) A primary direct method: measures the value of an unknown without reference to a standard of the same quantity and (2) A primary ratio method: measures the value of a ratio of an unknown to a standard of the same quantity; its operation must be completely described by a measurement equation.

Obviously, NAA belongs to the latter category and extends the list of formerly recognized potentially primary methods of measurement, which comprise isotope dilution mass spectrometry (IDMS), coulometry, gravimetry, titrimetry, and determination of freezing point depression [10]. The recognition of NAA as a primary method of measurement has further accentuated its special position among other trace element analytical methods. The NAA laboratory at NPI has contributed to this recognition by one of the very first design of quantification of uncertainty in NAA [11].

**Radiochemical NAA (RNAA)**

Ordinary INAA of complex matrices may yield unsatisfactory detection limits and/or uncertainties of trace elements of interest due to the overwhelming activities of other radionuclides formed on neutron activation. There are various physical means of improvements of detection limits of elements, such as optimization of irradiation, decay and counting times, use of selective activation with thermal, epithermal and fast neutrons, use of specific counting techniques, and so on, which has been described in detail elsewhere [12]. However, it has been demonstrated that in cases where the induced radionuclides of trace elements are masked by matrix activity, radiochemical separation is very frequently the most effective means of optimization in NAA and yields the lowest detection limits and uncertainties, which are close to the theoretical ones [12]. Examples are given in Table I and Figure 3. Table I presents

| Table 1. Comparison of uncertainties of ENAA and RNAA for low-level determination of iodine in identical food samples [12]. |
|---|---|---|---|
| Sample | ENAA | RNAA |
| 1 | 32 | 12.6 | 39 | 5.7 |
| 2 | 58 | 27.3 | 69 | 5.0 |
| 3 | 62 | 27.3 | 58 | 5.2 |
| 4 | 130 | 27.3 | 124 | 4.5 |
| 5 | 178 | 12.6 | 164 | 4.0 |

*Combined relative uncertainty in which all standard uncertainties except for counting statistics are equal to ~3% and ~4% for ENAA and RNAA, respectively.

**Table 2. Single-element RNAA procedures [7and refs. therein].**

<table>
<thead>
<tr>
<th>Element</th>
<th>Nuclear reaction</th>
<th>Sample decomposition</th>
<th>Separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>$^{30}\text{Si}(n,\gamma)^{31}\text{Si}$</td>
<td>Alkaline-oxidative fusion with Na$_2$O$_2$ + NaOH</td>
<td>Distillation of SiF$_4$</td>
</tr>
<tr>
<td>V</td>
<td>$^{51}\text{V}(n,\gamma)^{52}\text{V}$</td>
<td>Pre-irradiation dry ashing in air followed by post-irradiation wet ashing in a mixture of H$_2$SO$_4$ + HNO$_3$ + HClO$_4$</td>
<td>Extraction with N-benzoyl-phenyl-hydroxylamine</td>
</tr>
<tr>
<td>Cr</td>
<td>$^{50}\text{Cr}(n,\gamma)^{51}\text{Cr}$</td>
<td>Wet ashing in a mixture of HNO$_3$ + HClO$_4$</td>
<td>Extraction with tribenzyllamine</td>
</tr>
<tr>
<td>Mn</td>
<td>$^{54}\text{Mn}(n,\gamma)^{55}\text{Mn}$</td>
<td>Wet ashing in a mixture of HNO$_3$ + HClO$_4$</td>
<td>Precipitation of hydrated MnO$_2$</td>
</tr>
<tr>
<td>I</td>
<td>$^{127}\text{I}(n,\gamma)^{128}\text{I}$</td>
<td>Alkaline-oxidative fusion with Na$_2$O$_2$ + NaOH</td>
<td>Extraction of elementary I with CHCl$_3$</td>
</tr>
<tr>
<td>Re</td>
<td>$^{185}\text{Re}(n,\gamma)^{186}\text{Re}$</td>
<td>Microwave assisted wet ashing in a mixture of HNO$_3$ + HF or alkaline-oxidative fusion with Na$_2$O$_2$ + NaOH</td>
<td>Extraction with tetraphenylarsenium chloride or methylheptylketone or solid extraction with trioctyl-methylammonium chloride</td>
</tr>
<tr>
<td>Pt</td>
<td>$^{198}\text{Pt}(n,\gamma)^{199}\text{Pt} \rightarrow ^{199}\text{Au}$</td>
<td>Wet ashing in a mixture of HNO$_3$ + HClO$_4$</td>
<td>Precipitation of elementary Au with Se by ascorbic acid</td>
</tr>
<tr>
<td>Tl</td>
<td>$^{202}\text{Tl}(n,\gamma)^{203}\text{Tl}$</td>
<td>Wet ashing in a mixture of HNO$_3$ + HClO$_4$ (+ HF)</td>
<td>Extraction with Na diethylthiocarbamate</td>
</tr>
</tbody>
</table>

---

a comparison of uncertainties for iodine determination in biological samples using ENAA and RNAA, while Figure 3 shows a result of RNAA for determination of vanadium in blood, in which selective radiochemical separation yielded the vanadium peak at virtually zero background. For this reason, a number of RNAA procedures were developed at NPI to be able to fully exploit the possibilities of NAA for determination of extremely low levels of elements. These procedures are briefly summarized in Tables 2 and 3. Thus, the laboratory of NAA at NPI became one of the world-leading institutions, where RNAA is available for determination of elements at trace and ultratrace levels in various matrices, which find many interdisciplinary applications.

Main Research Activities

The INAA and RNAA procedures developed are utilized in a wide variety of research activities, which are performed in close collaboration with Czech institutions and those abroad. INAA has been used in environmental control and monitoring, especially in analysis of ambient air aerosols, aerosols originating from combustion processes, and aerosols from occupational settings. This technique is being increasingly used in geo- and cosmochemical research to study the composition and origin of rocks, sediments, tektites [13] and meteorites [14]. One of these studies resulted in a new theory of moldavite formation [13]. A combination of short- and long-time irradiation and counting with coaxial and planar HPGe detectors using suitable decay and counting times yields information on contents of up to 35 major, minor, and trace elements. If RNAA is also used to determine Rb and Cs and almost all rare earth elements (which provide information about the origin and evolution of a rock or a meteorite), and instrumental photon activation analysis (IPAA) is employed for determination of some elements that cannot be assayed with INAA, contents of 42 elements can be determined in this type of samples [14]. A similarly large number of elements were also determined with INAA in an archaeological study on the origin of sandstone blocks used for the construction of Khmer temples in Angkor, Cambodia. The combination of INAA and RNAA proved to be useful in occupational and environmental health studies concerning evaluation of workers’ exposure in machining, assembling and welding of stainless steel constructions [15], and exposure of workers of a vanadium pentoxide production plant and that of general population living in the vicinity of the plant. The determination of vanadium in blood and urine of control subjects in the aforementioned studies by RNAA yielded improvements of our knowledge about normal, baseline levels in occupationally non-exposed population [16]. This is an example of vanadium determination at the ultratrace element level (~50 pg·mL⁻¹), which can hardly be achieved by any other analytical technique. Similarly low levels and/or amounts of elements in biological materials were also determined by RNAA in biomedical studies concerning dynamics of trace element concentrations during neurodegenerative processes in the brain, such as Alzheimer’s disease, studied in brains of mutant mice [17], or in studying the pharmacokinetics of cisplatin, an antitumor drug. In nutritional studies, INAA and RNAA were employed to assess the transfer of pollutants into agricultural crops and foodstuffs grown in the vicinity of a phosphate fertilizer production plant [18], while ENAA and RNAA were used for assessment of iodine intake from Asian diet samples [19]. Trace element determination in mushrooms by INAA and ENAA is at the borderline of purely mycological and nutritional

| Table 3. Multi-element RNAA procedures [7 and refs. therein]. |
|---------------------------------|---------------------------------|---------------------------------|
| **Element (nuclide)** | **Sample decomposition** | **Separation** |
| Rare earth elements | Alkaline-oxidative fusion with Na₂O₂ + NaOH | Precipitation with oxalic acid |
| Cu, As, Mo, Cd, Sb | Wet ashing in a mixture of H₂SO₄ + HNO₃ + H₂O₂ | Extraction with Zn diethylthiocarbamate |
| Co, Ni (⁶⁰Co) | Wet ashing in a mixture of HNO₃ + HClO₄ | Ion exchange chromatography using Dowex 2 × 8 |
| Hg, Se | Microwave assisted wet ashing in HNO₃ | Extraction with Ni diethylthiocarbamate and precipitation of elemental Se with ascorbic acid |
| I, Mn | Alkaline-oxidative fusion with Na₂O₂ + NaOH | Extraction of elementary I with CHCl₃ and precipitation of hydrated MnO₂ or Mn extraction with Na diethylthiocarbamate |
research (if edible mushrooms are concerned), and can also be used in environmental monitoring due to a special ability of some mushroom species to accumulate certain elements from their environment. Not only elements, but also some long-lived radionuclides can be measured with NAA for environmental monitoring. An example is assay of $^{129}$I, a long lived fission product with half-life of $15.7 \times 10^6$ years, with NAA employing a combination of pre- and post-irradiation separation of iodine to study the $^{129}$I distribution in the Baltic Sea [20] and in thyroids from Ukraine and Denmark [21]. In the view of a special potential of NAA for accuracy compared with other trace element analytical techniques, NAA has been used at NPI in chemical metrology, for quality assurance and in the preparation of reference materials (RM) of chemical composition a long time before the method has been recognized as a primary method of measurement. INAA and RNAA procedures were employed for homogeneity tests and certification of element concentrations in RM prepared by national and international bodies. Table 4 shows NPI activities in the preparation of reference materials of world-leading producers.

### Table 4. NPI activities in the preparation of reference materials of world-leading producers.

<table>
<thead>
<tr>
<th>RM code</th>
<th>Producer</th>
<th>Method</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single cell green algae RMs with managed levels of heavy metals IAEA-391, IAEA-392, IAEA-393</td>
<td>IAEA, Vienna</td>
<td>INAA, RNAA</td>
<td>Certification analyses for up to 22 elements</td>
</tr>
<tr>
<td>IAEA Reference Air Filters (RAF)-I, IAEA Reference Air Filters-II</td>
<td>IAEA, Vienna</td>
<td>INAA</td>
<td>Preparation of RAF, homogeneity testing and certification analyses for up to 35 elements, evaluation of the certification campaign</td>
</tr>
<tr>
<td>IRMM-530 Al-0.1% Au alloy</td>
<td>IRMM, Geel</td>
<td>INAA</td>
<td>New data on Au content</td>
</tr>
<tr>
<td>IRMM-540R, IRMM-541 Uranium-doped glass</td>
<td>IRMM, Geel</td>
<td>INAA</td>
<td>Certification analyses for uranium</td>
</tr>
<tr>
<td>NIST SRM-1515 Apple Leaves, NIST SRM-1515 Peach Leaves NIST SRM-1573a Tomato Leaves</td>
<td>U.S. NIST, Gaithersburg</td>
<td>INAA, RNAA</td>
<td>Certification analyses for 28 elements</td>
</tr>
<tr>
<td>NIST SRM-1570a Spinach Leaves</td>
<td>U.S. NIST, Gaithersburg</td>
<td>INAA, RNAA</td>
<td>Certification analyses for 20 elements</td>
</tr>
<tr>
<td>NIST SRM-2783 Air Particulate on Filter Media</td>
<td>U.S. NIST, Gaithersburg</td>
<td>INAA</td>
<td>Certification analyses for 23 elements</td>
</tr>
<tr>
<td>NIST SRM-1648 Urban Particulate Matter</td>
<td>U.S. NIST, Gaithersburg</td>
<td>INAA</td>
<td>New data for V and Mn</td>
</tr>
<tr>
<td>NIST SRM-1577c Bovine Liver</td>
<td>U.S. NIST, Gaithersburg</td>
<td>RNAA</td>
<td>Certification analyses for V and Ni</td>
</tr>
</tbody>
</table>

NAA has also many times helped in and the International Atomic Energy Agency (IAEA), Vienna. Table 5 compares RNAA results of certification analyses of ultratrace levels of V and Ni in the recently prepared NIST SRM-1577c Bovine Liver achieved at NPI with the NIST certified values. NAA has also many times helped in

### Table 5. Comparison of RNAA results for V and Ni with NIST certified values for NIST SRM-1577c Bovine Liver [22].

<table>
<thead>
<tr>
<th>Element, ng·g$^{-1}$</th>
<th>V</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPI result$^a$</td>
<td>8.4 ± 1.0</td>
<td>44.0 ± 6.4</td>
</tr>
<tr>
<td>NIST value$^a$</td>
<td>8.17 ± 0.66</td>
<td>44.5 ± 9.2</td>
</tr>
</tbody>
</table>

$^a$expanded uncertainties with coverage factor of 2 are given.
resolving of discrepant analytical data and there are also several examples that the consistent application of NAA advantages lead to the corrections of originally biased certified values. The NAA results helped in improving assigned values of Cu and Mn in IAEA RM A-11 Milk Powder [7]. While this case concerned the correction of data obtained in an open intercomparison, in another case the NAA results obtained at NPI differed from NIST values for Mn and V in NIST SRM-1648 Urban Particulate Matter [7]. This finding has led to a change of the original NIST values to new ones as given in Table 6. It is noteworthy that this was only the second case where data for environmental and/or biological RM obtained outside NIST has led to a correction of the NIST certified values of element contents.

It can be concluded that despite of the fast development of other trace element analytical techniques, such as atomic absorption and fluorescence spectrometry, and mass spectrometry, NAA is indispensable for solving special analytical tasks in many interdisciplinary applications.

This concerns especially the cases where a large number of elements is to be determined or where determination of very low elements levels with a low uncertainty is required.

### Table 6. Comparison of old and new values for Mn and V in NIST SRM-1648 Urban Particulate Matter.

<table>
<thead>
<tr>
<th>Element, ( \mu g \cdot g^{-1} )</th>
<th>Original NIST values(^a) [23]</th>
<th>NPI results [7]</th>
<th>New NIST values(^a) [23]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mn</td>
<td>(860)</td>
<td>768 ± 18</td>
<td>786 ± 17</td>
</tr>
<tr>
<td>V</td>
<td>140 ± 3</td>
<td>128 ± 4</td>
<td>127 ± 7</td>
</tr>
</tbody>
</table>

\(^a\)NIST values with uncertainty are certified; noncertified values are in parenthesis.

### References

*Jan Kučera*

Nuclear Physics Institute of the Academy of Sciences of the Czech Republic
Report on the FINUSTAR3 Conference

The winners of the FINUSTAR3 poster prize: Nassima Adimi (CENBG, Bordeaux), Gulfem Susoy (Istanbul University), and John Daoutidis (ULB, Brussels).

The 3rd International Conference on Frontiers In Nuclear Structure, Astrophysics, and Reactions (FINUSTAR 3) was held on the island of Rhodes, Greece from August 23–27, 2010. The venue was the Rodos Palace Hotel on the north-eastern coast of Rhodes, 2 km north of the capital city Rhodos. It was organized by the Institute of Nuclear Physics (INP) of the National Center for Scientific Research (NCSR) “Demokritos” (Athens, Greece) and the Department of Physics of the University of Jyväskylä (JYFL, Finland).

FINUSTAR3 was the third in a series of international conferences previously held in 2005 in the isle of Kos, Greece and in 2007 in Agios Nikolaos, Crete, Greece. Just like the previous ones, this conference covered a wide spectrum of research activities in nuclear structure, nuclear astrophysics, and nuclear reactions that due to common instrumentation and research facilities have been overlapping strongly over the last years:

- Nuclear structure at the extremes.
- Collective phenomena and phase transitions in nuclei.
- Exotic excitations.
- Synthesis and structure of the heaviest elements.
- Nuclear masses and ground state properties.
- Ab-initio calculations and the shell model.
- Mean field theories, cluster models, and molecular dynamics.
- Scattering and reaction dynamics at low and intermediate energies.
- Nuclear reactions off stability and indirect methods.
- Neutrinos in nuclear astrophysics and astro-particle physics.
- Nuclear astrophysics (Big-Bang nucleosynthesis, s-, r-, and p-process, & nuclide production).
- Radioactive and exotic relativistic beams.
- Facilities and instrumentation for the future.

The conference was attended by 150 physicists with a fair representation of all the major nuclear physics laboratories. There were a total of 131 contributions, 79 of them given as oral (20 invited talks and 10 invited contributions) and 52 as poster presentations. Ninety-eight of them were based on experimental and 33 on theoretical results. They were of excellent quality, also reporting on fresh new data and results and provoking lively discussions.

The conference was supported by the EU-FP7 project “Center of Excellence in Low-energy Ion-Beam Research and Applications—LIBRA” of the Tandem Accelerator Laboratory, INP, NCSR “Demokritos.” The best poster presentation in theory and experiment were elected by a committee consisting of members of the international advisory committee and awarded a prize of 500 euro. The winners were John Daoutidis (ULB, Brussels) and Gulfem Susoy (Istanbul University), respectively. An additional excellent poster prize, not accompanied with money, was awarded to Nassima Adimi (CENBG, Bordeaux) (see Figure).

The proceedings of FINUSTAR3 will be published in AIP Conference Proceedings Series.

SOTIRIOS V. HARISSOPULOS
Tandem Accelerator Laboratory
Institute of Nuclear Physics, NCSR “Demokritos”

RAUNO JULIN
Department of Physics
University of Jyväskylä

Nuclear Structure 2010

The conference “Nuclear Structure 2010” (NS2010) was hosted by Lawrence Berkeley National Laboratory, 9–13 August 2010. This was the thirteenth in this series of conferences, which are hosted once every two years by the North American National Laboratories. More than 140 people attended from over 50 institutions representing 20 different nations around the world. Nuclear structure physics remains an exciting, international affair.
Berkeley, with its long history as a home of progressive ideas and cutting-edge intellectual research, provided a perfect back-drop to the conference that played out at the beautiful Clark-Kerr Campus on the edge of the city. The program ranged over the latest research and developments in nuclear structure physics which covered diverse topics concerning the properties of nuclei at the extremes of isospin, mass, angular momentum, and excitation energy. In keeping with the tradition of the conference, only a handful of speakers were invited and most of the talks were selected from submitted abstracts. This resulted in a vibrant program with many young speakers, some giving their first talk at a major international conference, presenting the very latest research from their labs and universities. The program, talks, and many photos are available at the conference website: http://www.lbl.gov/nsd/conferences/nuclearstructure2010/.

The conference started with a special session devoted to halo nuclei, discovered twenty-five years ago at Berkeley by Tanihata and collaborators. Halo nuclei, which have spatially extended wavefunctions arising from a decoupling between the weakly bound valence nucleons and the core, are now a major research focus at many radioactive-ion beam facilities and provide a dramatic example of the type of new phenomena we hope to discover as we push to the edges of nuclear stability. Later sessions provided a snapshot of the newest results and latest ideas across the entire ambit of the field: from discussions of the decay of proton-rich isotopes to the shell evolution in nuclei with extreme neutron excess; from the microscopic understanding of the lightest systems to the observation of superheavy elements (including the latest element added to the periodic table, as reported by Krzysztof Rykaczewski of Oak Ridge National Laboratory on behalf of the collaboration that recently discovered element-117 at Dubna).

The final session was devoted to the latest experimental facilities being built in the United States and we heard about the progress toward the FRIB accelerator (Facility for Rare Isotope Beams to be hosted by Michigan State University) and the GRETINA gamma-ray tracking array (currently being assembled at Lawrence Berkeley National Laboratory). In the near future, it is clear these experimental advances, along with similar facilities being constructed elsewhere in the world, will create an exciting period of exploration and discovery in the field of nuclear structure.

In conclusion, I should like to paraphrase some comments from one of the great figures in the field (those attending the meeting should know to whom I refer), made at an earlier incarnation of this conference, also held in Berkeley, but repeated again by Mark Riley of Florida State University in his NS2010 summary talk. “I have the distinct impression that our subject is in the best possible shape. Mother Nature continues to shower us with her bounties and we remain continually amazed by the complexity and elegance of nuclei. We are enjoying ourselves, being very creative, and our techniques are powerful and beautiful. We are continually finding new phenomena and the theories we use have tremendous intellectual bite.” The truth of these words was clearly demonstrated at Nuclear Structure 2010. I look forward to the next conference in the series and I wish the local organizers of NS2012 at Argonne National Laboratory the very best.

RODERICK CLARK
Lawrence Berkeley Laboratory
International Agreement on the FAIR International Accelerator facility

Nine Countries are Involved in One of the World’s Largest Research Projects in Darmstadt, Germany

Nine countries signed the international agreement on the construction of the accelerator facility FAIR (Facility for Antiproton and Ion Research) on 4 October in Wiesbaden, Germany (see Figure). FAIR will be located at the GSI Helmholtz Center for Heavy Ion Research in Darmstadt, Germany. Signing the agreement were science ministers and state secretaries from Finland, France, Germany, India, Poland, Romania, Russia, Slovenia, and Sweden. The countries that could not yet join because of their internal ratification procedures (France, Poland, and Slovenia) are expected to do so within the next year. China, Saudi Arabia, Spain, and the United Kingdom are also planning to contribute to FAIR.

Immediately after the signing, FAIR GmbH was established as a company. The first shareholders are Germany, Russia, India, Romania, and the Swedish–Finnish consortium. In its first session, the council of the company appointed Boris Sharkov as scientific managing director and Simone Richter as administrative managing director. Beatrix Vierkorn-Rudolph was appointed as the first chair of the FAIR council.

FAIR will be one of the largest research projects and most sophisticated accelerator centers worldwide. The international agreement has now cleared the way for its realization. Germany will bear roughly three-quarters of the total costs of approx. €1 billion. Roughly 3,000 scientists from more than 40 countries are already working on the planning of the experiment and accelerator facilities. FAIR will generate antiproton and ion beams of a previously unparalleled intensity and quality. When completed, FAIR will comprise eight ring accelerators of up to 1,100 meters in circumference, two linear accelerators, and around 3.5 kilometers of beam pipes. The existing GSI accelerators will serve as preaccelerators for the new facility. FAIR will make it possible to conduct a wider range of experiments than ever before, enabling scientists from all over the world to gain new insights into the structure of matter and the evolution of the universe since the Big Bang.

INGO PETER
GSI Darmstadt

Representatives of the signatory countries in Schloss Biebrich, Wiesbaden (Photo: G. Otto, GSI).
The G.N. Flerov Prize is Awarded for Studies of Exotic Nuclei Near the Drip-Lines

The G.N. Flerov prize for 2009 is awarded to Sidney Gales, Dominique Guillemaud-Mueller, and Yuri Penionzhkevich for outstanding results achieved in the study of the properties of exotic nuclei near the nucleon drip-line (see figure).

The G.N. Flerov prize was established in 1992 in accordance with the resolution of the 71st Session of the Scientific Council of the Joint Institute for Nuclear Research (Dubna) in memory of the eminent physicist Georgy Nikolaevich Flerov (1913–1990).

The prize is awarded for the contributions in the field of nuclear physics related to Flerov’s interests connected with the experimental heavy ion physics including the synthesis of heavy and exotic nuclei using ion beams of stable and radioactive isotopes, studies of nuclear reactions, acceleration technology, and applied research.

RUMIANA KALPAKCHIEVA
JINR Dubna

G.N. Flerov prize winners, from left to right: Sidney Gales and Yuri Penionzhkevich.
April 3–8
Eilat, Israel. Nuclear Physics in Astrophysics 5
http://www.weizmann.ac.il/conferences/NPAS/

April 27–May 1
Vancouver, Canada. 10th International Conference on Low Energy Antiproton Physics (LEAP 2011)
http://leap2011.triumf.ca/

May 2–6
Saint Malo, France. FUSION11
http://fusion11.ganil.fr/

May 17–20
Newport News, Virginia, USA. The 18th International Workshop on the Physics of Excited Nucleons (NSTAR 2011)
http://conferences.jlab.org/nstar2011/

June 6–10
Bordeaux, France. Fourth International Conference on Proton-emitting Nuclei PROCON2011
http://www.cenbg.in2p3.fr/PROCON2011/

June 12–17
New London, NH, USA. Gordon Research Conference on Nuclear Chemistry

June 12–18
Crete, Greece. 11th International Conference on Applications of Nuclear Techniques
http://www.crete11.org/

June 27–July 2
Constanta, Romania. Advanced Many-Body and Statistical methods in Mesoscopic Systems

August 8–12
Manchester, UK. Rutherford Centennial Conference on Nuclear Physics
http://rutherford.ioconf.org/

September 5–9
Vienna, Austria. International Conference on Exotic Atoms and Related Topics - EXA2011
http://www.oead.ac.at/smi/research/talks-events/exotic-atoms/EXA-11/

September 11–18
Piastki, Poland. XXXII Mazurian Lakes Conference on Physics
http://www.mazurian.fuw.edu.pl/

October 11–15
http://www2.yukawa.kyoto-u.ac.jp/~ykis2011/ykis/index.html

November 23–28

2012
March 1–3
Phillip Island, Victoria, Australia. Astronomy with Radioactivities VII

March 10–11
Lund, Sweden. HIE-ISOLDE Spectrometer Workshop
http://indico.cern.ch/conferenceDisplay.py?confId=116915

May 31 – June 3
Agios Nikolaos, Crete, Greece. 4th International Conference on Chaotic Modeling, Simulation and Applications (CHAOS2011)
http://www.cmsim.org/

June 6–9
Ghent, Belgium. Second International Conference on Advancements in Nuclear Instrumentation, Measurement Methods and their Applications - ANIMMA
http://www.animma.org/

June 13–17
http://www.nuclear.kth.se/NCNP2011/Home.html

June 27–30
Padova, Italy. EGAN 2011 Workshop
http://egan.infn.infn.it/egan2011.html

June 30–July 2
RIKEN Tokyo, Japan. Joint International Symposium on Frontier of gamma-ray spectroscopy (gamma11)
http://www.cns.s.u-tokyo.ac.jp/gamma11/

July 4–10
St. Petersburg, Russia. Isomers in Nuclear and Interdisciplinary Research Meeting (INIR-2011)
http://onlinereg.ru/inir2011

September 4–9
San Sebastián, Spain. 2nd International Particle Accelerator Conference IPAC2011
http://www.ipac2011.org/

September 16–24
Erice, Sicily, Italy. Erice School 2011 “From Quarks and Gluons to Hadrons and Nuclei”
http://crunch.ikp.physik.tu-darmstadt.de/erice/

September 17–21
Bucharest, Romania. European Nuclear Physics Conference EuNP C2012
http://www.ifin.ro/eunpc2012/

More information available in the Calendar of Events on the NuPECC website: http://www.nupecc.org/