Applications and societal benefits – WG6

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Introduction

Nowadays, it is obvious that society largely benefits from the large investments done in basic Nuclear Physics research. Recent achievements in particle- and radio-therapy within the new paradigm of theranostic approach are some of the most striking examples of the benefits from Nuclear Physics.

Improvements in nuclear applications were obtained thanks to an increase of the basic knowledge on nuclear structure and decay, nuclear reactions and nuclear system properties but also thanks to the developments performed in the related technologies: accelerator, instrumentation and high-performance computing.

The Nuclear Physics community has been and is still able to be mobilized to answer fundamental needs and questions addressed by the society specifically on energy, health and security. This has led to a new transverse discipline of Applied Nuclear Physics research.

Reliable, up-to-date and well-structured data libraries are indispensable not only for the Applied Nuclear Physics research, but also for Fundamental Nuclear Physics researchers who need the data to improve their knowledge and plan future activities that may lead to new discoveries The key issue that needs to be addressed by the European Nuclear Physics community as a whole is how to develop and maintain a high level of expertise in the area of nuclear data to meet the data needs of a continuously developing European nuclear physics landscape.

In this chapter we try to review the achievements done in this domain since the last Long Range Plan in 2010 together with the highlights and open problems. We formulate specific recommendations in each section and general recommendations to proceed within an international and European context by the end.

The chapter is divided according to the different domains of applications:

1. Energy
2. Health
3. Environment and Space
4. Society
5. Cross-disciplinary impact in other domains

1. Energy applications

Due to the large amount of energy released during a nuclear process, the use of nuclear reactions offers the best energy-density solution to produce energy. Therefore nuclear reactions are widely used in terrestrial reactors and envisaged in space missions to produce electricity. With a predicted growing of the energy world-demand and the development of carbon emission-free energies in the next decades, nuclear energy could help to reduce the dependence on fossil fuels and their impact on the world global warming. Despite the large amount of work done since the discovery of the fission process and its use for civil energy generation there are still key questions and related key issues that the Nuclear Physics community could contribute to address.

Key questions

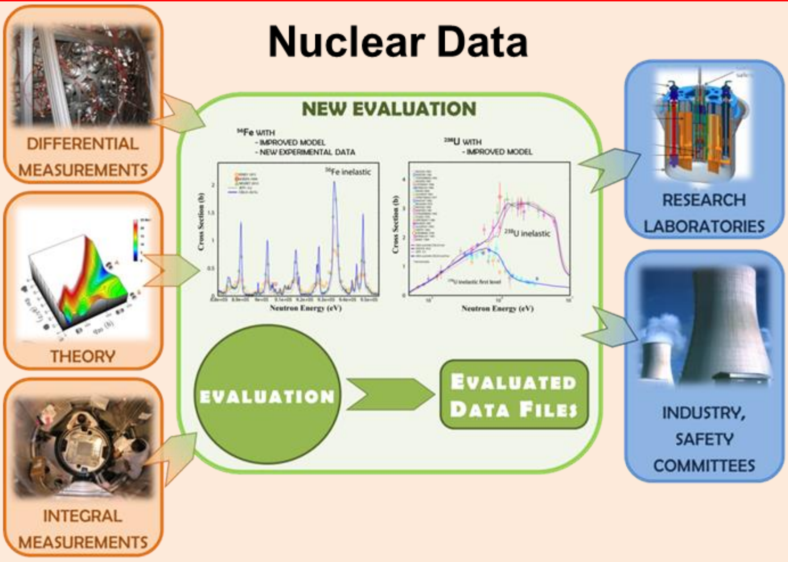
- *How can advance nuclear systems help to the sustainability and acceptability of nuclear energy generation?*
- *How can safety of current nuclear reactors be improved?*
- *How can nuclear power source be provided for space applications?*

Key issues

- *Accurate nuclear data and predictive modeling of nuclear reactions (induced by neutron and charged particle and decay)*
- *Design and construction of high-power and reliable accelerators and targets.*
- *Stability of components in extreme environments (radiation and chemically reactives)*
- *Synergies with other fields (radioisotope production, silicon doping, fuel and material testing, fundamental research)*

1.1 Next-generation fission reactors

Nuclear fission is an important source of electricity production that will still play an important role in the future. However, the sustainable production of energy using nuclear power relies on improvements in safety standards of current nuclear reactors and, more importantly, on the development of advanced systems, characterized by an optimized use of natural resources, minimized production of radioactive waste to be disposed of in geological repositories, increased safety and reduced proliferation risks, as well as economic competitiveness. Generation IV fast reactors, Accelerator Driven sub-critical Systems (ADS) and new nuclear fuel cycles are some of the most promising options being investigated.



In absence of predictive and reliable models able to describe nuclear reactions with the accuracy needed to fulfill the requirements imposed by nuclear systems in operation, Nuclear Data are the key ingredients in the simulation codes to assess the performance of innovative nuclear systems in normal and accidental conditions. Indeed, any calculation or simulation of the behavior of a nuclear system, and its safety limits, heavily relies on the production and transport of neutrons, photons, charged particles and recoil nuclei. Improving the accuracy of neutron-induced reaction cross section data for a variety of isotopes and over a wide range of energies is, for example, fundamental for the neutronics of the core and the production of radioactive elements. Similarly, improvements in the accuracy of fission yields and decay data are necessary to calculate the energy deposition inside the fuel element, the decay heat in case of urgent stopping and to predict the evolution and assess the safety of spent nuclear waste. An important part of the activity is related to nuclear data evaluation, with complete uncertainty and covariance analysis needed, as well as compilation and continuous maintenance of nuclear data libraries as the JEFF European library.

The European Nuclear Physics community can rely on a number of infrastructures and laboratories that can allow for some challenging measurements. This is the case, for example, of the high-flux neutron facilities of ILL, Grenoble, n_TOF at CERN and NFS at GANIL, complementing the well-established EU facilities for nuclear data in the Joint Research Centers (in particular IRMM in Geel, Belgium). Fission yields and decay data can be collected in various laboratories around Europe, such as Lohengrin at ILL, ISOLDE at CERN, or the future SPIRAL2 and SPES radioactive ion beam facilities. Finally, experiments at reactor facilities are important to constraint nuclear data evaluation. The key facility for integral data is the VENUS-F reactor at SCK·CEN, which is in 2016-2017 the only operational fast spectrum zero-power reactor in the world. MASURCA in France and BFS in Russia are under reconstruction.

Together with the development of new systems, in the wake of the Fukushima accident it has become of high priority in Europe to improve safety standards of existing nuclear reactors, as well as of fuel fabrication and waste management installations. In particular, the performance and safety limits of present and future nuclear power plants have to be evaluated not only in standard operation mode, but also under extreme external conditions. The accident in Japan, together with the stress test performed on EU nuclear reactors after the Fukushima event, have posed new challenges on the predictive power of tools and methods currently used for reactor calculations, as well as on the accuracy and reliability of available nuclear data and simulations for systems in extreme conditions.

Nuclear data and models are among the key ingredients for the assessment of the performance of nuclear systems in normal and accidental conditions. Although important progresses have been made in the last few years in this respect, at the European and International level, thanks to new facilities, advanced detection and acquisition systems and improved evaluation methods, the accuracy of nuclear data and reliability of models and simulation tools is still far from satisfactory and large efforts are needed to improve this situation, as demonstrated by the long-standing needs for data in the NEA High Priority Nuclear Data Request List. Among isotopes needing better data are several actinides and fission fragments, particularly those most difficult to measure. When dealing with safety, uncertainties and covariance matrices are needed and should be carefully evaluated within nuclear data and carefully implemented within simulation codes.

It should be emphasized that nuclear data uncertainties is the ultimate limit of the precision of the simulation systems.

Recent developments have made simulation tools more flexible and suitable for a wide range of applications, but the accuracy of the simulation results depends essentially on the predictive power of underlying models and, especially, on the accuracy of the nuclear data they rely on.

1.2 Accelerator Driven sub-critical Systems

The production and management of long-term radioactive hazard in nuclear fission reactors is one of the crucial points to be addressed for the public acceptance of this energy production. Accelerator Driven sub-critical Systems (ADS) for nuclear waste transmutation represent the possibility to solve this problem efficiently. The system based on a sub-critical reactor with a spallation neutron source provided by a high-power accelerator with a heavy metal target will be inherently safe. This will be ensured thanks to a robust and accurate online monitoring of the sub-criticality level. However, before the first concept of ADS is realized and its feasibility proven, many challenges have to be overcome. The main needs concerns improvement of nuclear data libraries and nuclear reaction models (mainly for neutron-induced as well as for spallation reactions), the development of structural materials able to sustain harsh environment of liquid heavy metal coolant pool, the construction of reliable high intensity accelerators, resilient and save spallation targets and effective minor actinide burning technologies.

In past years, the key ADS spallation target development project was the **Mega**Watt **Pi**lot **E**xperiment (MEGAPIE) at PSI. After almost 15 years MEGAPIE has reached its final phase – the Post Irradiation Examination (PIE) of the target structural materials and the Lead-Bismuth-Eutectic (LBE). In total the project has undergone ten main phases, from the first idea and design of the spallation target and ancillary systems through the target construction at ATEA, the integral test of the target system behavior and licensing to its operation in the spallation neutron source SINQ at PSI with the MegaWatt proton beam provided by the High Power Accelerator (HIPA) to the MEGAPIE system dismantling and disposal. The final stage, the Post Irradiation Examinations (PIE), is currently carried out in Hot Laboratories in Belgium, France, Japan, Switzerland and the USA and provides precious information on structural materials and LBE behavior under irradiation for future spallation sources. Results on the production of radioactive isotopes will help to constraints simulation codes.

In Europe, the key ADS demonstration project is MYRRHA at SCK·CEN. The project started in 1998 and since then the design has evolved into a multi-purpose, large-scale, flexible facility comprising the radioactive ion beam installation ISOL@MYRRHA.

A mock-up of the MYRRHA reactor core was already studied within the GUINEVERE project (2007-2011) and the coupling to a GENEPI-3C accelerator in the FREYA project (2011-2016). The methodologies for online reactivity monitoring of an ADS as well as nuclear data and neutronic codes has been validated (MCNP, Serpent, ERANOS) within these experiments. In experimental campaigns with many various configurations, highly enriched uranium fuel, solid lead as a coolant simulator, various types of reflector materials and thermal spectrum in-pile sections were used. Reactivity effects like coolant void and fuel Doppler effects have been measured. The investigation will continue and extend to instrumentation optimization within the MYRTE project, when the VENUS-F core will be loaded with bismuth and fast spectrum in-pile sections.

Other tasks being performed within the MYRTE project (2015-2019) are the R&D of the MYRRHA accelerator (reliability analysis, injector and superconducting cavities demonstration, beam diagnostics development), as well as the study of thermal hydraulics phenomena in the MYRRHA reactor pool, of the chemistry of volatile radionuclides (polonium and fission products, e.g. I, Te, Ru, Cs) and of the properties of actinide $(U,Am)O_2$ fuel are studied. In the next few years, all this activity is expected to provide important information on the feasibility of the ADS concept and eventually lead to the final design of a transmutation system.

1.3 Fusion reactors

Fusion is being considered the holy grail of production of cheap and "clean" energy and during the last decades enormous progress has been made on plasma confinement on fusion devices.

One of the biggest challenges currently being addressed is the construction of the

International Thermonuclear Experimental Reactor (ITER) in Cadarache, France. Among the many problems that have to be faced is the effect of the extremely high flux of high-energy neutrons on the structural material. The extremely high neutron flux in a fusion reactor will have a large impact in limiting the lifetime of various structural components inside the reactor itself. To this end, an accurate nuclear database is necessary to study the damage in the structural reactor materials. In this respect, the envisaged construction of a test facility to produce 14 MeV neutrons, like the ones produced in the d-t fusion reaction, is mandatory. In the medium and long term plan, neutron irradiation facilities, like the International Fusion Materials Irradiation Facility and/or DEMO-Oriented Neutron SOURCE (IFMIF/DONES) will play a key role in providing fundamental data to assess the level of radiation damage in the various components of the fusion reactors, and estimate their life-time. Such irradiation facilities will also be very useful for testing and validating models and calculations on irradiation effects in fusion power plants, as well as for space research.

At present, however, the effect of neutron irradiation on the various structural components of the future fusion reactors can only be estimated with models, which in turn heavily rely on cross section data. It is therefore important, in the short-medium term, to collect accurate data on neutron-induced reaction on various elements. Apart from producing defects as a result of elastic scattering, neutron induced reactions will be responsible for transmutation of elements in the structural components, activating them and modifying their integrity and stability. Furthermore, neutron reactions leading to charged particle production will be responsible for gas production, in particular Helium, in the material, which could produce modification of the geometry, for example due to the formation of bumps, as well as of the thermo-mechanical properties, leading to swelling and embrittlement. This is particularly true for (n,α) reactions. The list of involved elements is rather long from light to heavy elements: Be, Fe, V, Cr, Mo, Nb, Ta, Zr and W.

In order to improve models of damage produced by neutron irradiation in fusion reactors, differential and integral data in a wide neutron energy range should be collected, and an accurate database constructed and maintained. Neutron facilities like n_TOF at CERN, NFS at GANIL, and smaller mono-energetic neutron facilities can be exploited in this respect. The optimization of models will at the end rely on the irradiation facilities, but improvements in the nuclear physics input, both in terms of data and theories, on which these models are based, should be pursued with high priority in the next few years.

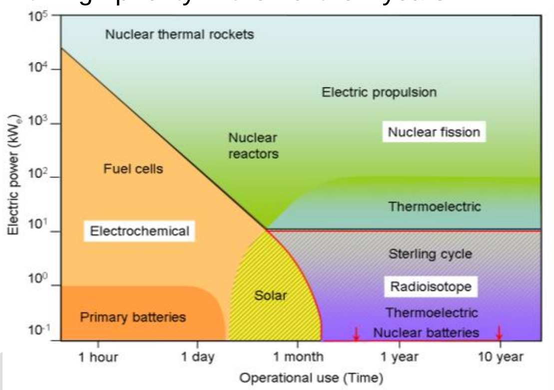


Figure 1: A comparison between nuclear power sources and other forms of space power, which maps the most suitable power technologies for different power level ranges and mission duration. In general, RPS are best suited for applications lasting more than several months and power levels up to one to 10 kilowatts.

1.4 Nuclear power sources for space applications

Photovoltaic cells are well established as the appropriate primary power source for most space missions. They are a relatively inexpensive, reliable, well established technology. However, they are not practical for future science missions to the outer planets or for missions with planetary Landers or mobile explorers. For deep space missions, the major problem is that the power they generate is inversely proportional to the square of the distance from the Sun. Thus for an array of a given size, the power it can generate at, say, Jupiter will be less than 4% of the power it generates at the Earth and at Saturn less than 1.5%. Even closer to the Sun the usefulness of photovoltaic arrays on long duration planetary landers and explorers may be limited due to long day/night cycles, atmospheric attenuation and/or dust storms. The nuclear power systems are the only viable alternative to photovoltaic arrays for the long–term production of power in space. Space nuclear power systems can be conveniently divided into three categories. In order of increasing complexity, these are:

(i) Direct production of heat by radioactive decay. Typically they are low power devices producing between 1 and 10W of heat and are placed directly where heat is required.

(ii) Radioisotope Power Sources (RPS) which generates electrical power by converting the heat released from the nuclear decay of radioisotopes into electrical energy *via* one of many conversion processes. To date, space missions have largely relied on Radioisotope Thermoelectric Generators (RTG), in which the conversion process is mediated by the Seebeck effect using an array of thermocouples, providing a typical power output up to a few hundred Watts electrical.

(iii) Nuclear reactor systems. Power systems based on nuclear fission provide a more cost effective solution than RTG's, if power requirements exceed ~ 1 kW electrical.

At the present time, research is concentrating in several key areas. In Europe the major emphasis is on developing new fuel and production technology to replace ^{238}Pu which, as a by-product of nuclear weapons production, is no longer available. Current efforts concentrate on ^{241}Am, extracted from civilian waste stocks. Complementary efforts are also underway in improved electrical energy extraction (up to 100W_e) through the development of new, matched thermo-electric materials and efficient and reliable heat engines.

In addition to macro power sources in the range ~10-100 W_e, a need for miniaturized nuclear power sources has also recently arisen, largely fueled by the growing interest in small satellites and technical developments in nano-technology. These extend from 1 watt devices for powering systems and instruments down to milli-watt nuclear batteries for powering nodes in wireless network-based spacecraft. Promising candidates are based on direct energy conversion; so-called alpha and beta-batteries. These utilize active semiconductors to convert the radioactive emissions generated by embedded alpha and beta sources directly into electron-hole pairs and then into usable power *via* a resistive load.

Lastly, although there has been continual interest in nuclear propulsion, its realization must be considered very long term, in view of the current low technology readiness levels, coupled with perceived safety issues and the continued lack of significant funding.

1.5 Future perspectives and recommendations

Addressing the challenging needs posed by the Fukushima accident and by the subsequent policy shift towards reactor safety will be one of the main priorities for the next several years for the Nuclear Physics community of experimentalists, theoreticians and evaluators involved in energy applications.

Together with new measurements, the development of predictive and reliable models and simulation tools is mandatory for nuclear energy systems. Since regulators and operators rely significantly on modeling and simulation for safety assessment and licensing, it is of outmost important for the Nuclear Physics community to devote a large efforts to refine modeling, simulations and other predictive methods, so that they can provide reliable predictions both in standard and extreme conditions. This can be done only by a strong cooperation between experimentalist, theoretician and evaluators. Considering the large effort required on the evaluation process, it is important that a continuous support be ensured to the evaluation community, at present rather weak, with fresh new forces needed all over Europe. In this respect, the training of a new generation of young researchers is becoming mandatory.

The European research funding program brings together the majority of European neutron sources. The FP7 projects (ERINDA, CHANDA, ANDES …) help to prepare the methodologies, facilities, detectors, interpretation and tools to produce and use nuclear data with very high quality. Such intensive cooperation is the main reason of significant improvement of the experimental (EXFOR) and evaluated (ENDF) databases and the TALYS code during last years. It will be important to use the Horizon 2020 program in the same way.

In the next years it is of paramount importance to maintain and optimize the use of available European nuclear data facilities and maintain and support smaller facilities for specific needs, such as for example detector tests and training of young researchers. It is also important to facilitate the access and integration of experimental teams, which are normally multinational, and support the development of innovative methodologies and instrumentations.

Recommendations

- *Support efforts in nuclear data measurements, evaluation and modeling.*
- *Continue developments for high power and high stability particle accelerators.*
- *Maintain a high level of competence in applied nuclear physic through training and education of young researchers.*
- *Exploit synergies with other fields (detectors, accelerators,…).*
- *Support specific projects as MYRRHA and IFMIF/DONES in Europe.*

2. Health applications

Ionizing particles strongly damage the DNA of tissue cells, ultimately causing their death. Cancerous cells are particularly vulnerable to ionizing particles because of their reduced ability to repair damaged DNA. This property is used since many years for cancer treatment. Different techniques are developed using external accelerated charged particles, X- or gamma-rays or internal radioactive decaying nuclei. In parallel imaging techniques using radiation properties are also developed to improve the diagnostics and the efficiency of the treatment. The Nuclear Physics community is mobilized to improve the existing techniques and developed new ones to address the key questions and related key issues in this field.

Key questions:

- *How cancer treatment efficiency can be improved, reducing the dose to the patient?*
- *How diagnostic methods can be improved?*
- *What are the risks of low-dose radiations?*

Key issues:

- *To develop new methods to better target the treatment on the tumor cell.*
- *To improve the quality of imaging technologies decreasing the dose to the patient.*
- *To develop radiobiology studies.*

2.1 Particle therapy

Charged particle therapy has been largely driven and influenced by nuclear physics. The increase in energy deposition density along the ion path in the body allows reducing the dose to normal tissues during radiotherapy compared to photons. Clinical results of particle therapy support the physical rationale for this treatment, but the method remains controversial. The therapy systems currently installed allow treatment delivery with scanned ion beams with cyclotrons and in some installations synchrotrons as the underlying accelerator. Installations are no longer restricted to huge, multi-room environments but can reach down to single room installations that can physically fit into bunkers originally designed for conventional X-ray therapy. The costs for particle therapy systems, however, are still not yet in the range that allows further spread to smaller clinical centers. The high cost remains the main hindrance to the diffusion of particle therapy.

The vast majority of radiotherapy patients are still treated with X-rays. Over 100,000 cancer patients have been treated with protons worldwide. Approximately 20,000 patients have been treated with other ions, generally ^{12}C. There are currently five C-ion facilities in operation in Japan, two each in China and Germany, and one in Italy and Austria. Several others are under construction or planned, including one in the USA. All of them are synchrotron-based and thus allow the implementation of ions other than protons and carbon ions that are currently used in parallel in the European centers. Investigations on alternative ion species focus on helium and oxygen. Helium has similar biological effectiveness as protons, but reduced lateral scattering, which leads to sharper dose fall-off. Implementation into treatment planning system is ongoing on a research basis but not yet commercially available. Oxygen is interesting for its high biological effectiveness, which could make it a tool for highly radioresistant and hypoxic tumors. The drawback of this ion is its potential toxicity in the normal tissue, which is instead not a major problem for helium.

Boosting of tumor sub-volumes is one type of adaptive treatment schemes. Fundamental necessities of such treatments are adequate imaging capabilities and seamless integration into the workflow. In comparison to photon beam therapy installations particle therapy centers still lack in volumetric imaging capabilities. Some of the recent installations feature in-room CT scanners in diagnostic quality or cone-beam CT systems which are standard for medical electron/photons linacs since several years. Upgrade of existing machines with volumetric imaging or at least installation of such devices in all future particle centers is essential to allow at least patient positioning comparable to photon beam therapy and potentially adaptation of treatment plans on a daily level, to, e.g., allows boosting of changing hypoxic regions or quick adjustment of the treatment plan to shrinking or moving target volumes. In photon beam therapy the currently most advanced system is magnetic resonance (MR)-guided therapy, which is already clinically used in combination with ^{60}Co γ-ray sources and will be available as a combination of linac and magnetic resonance tomography (MRT) soon. With the same arguments as above it is thus at least of academic interest to integrate particle therapy and MRT and initial studies in that direction are ongoing.

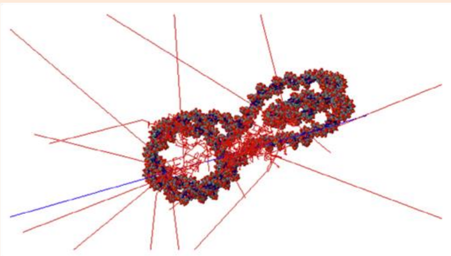
Another important issue with respect to accelerators and treatment planning is handling of patient changes within a treatment fraction (intra-fractional). Such changes are of main concern if structures moving with respiration are treated with a scanned beam since the resulting interference can result in under-dosage of the clinical target volume. Several beam delivery solutions have been proposed in the last decade. Among them are gating, rescanning, and tracking but also quick treatment delivery options. All techniques should be used in combination with (daily) 4DCT imaging and 4D treatment planning in particular 4D dose calculations to allow a dosimetric estimation of the interplay effect. Facilities with scanned beam delivery need an individual strategy to deal with organ motion and thus the implementation of 4D dose delivery into (commercial) treatment planning systems might be of even higher priority than expansion of accelerator techniques for the mitigation of interplay effects since it can be universally achieved if the delivery parameters (scan time, energy change time, …) are handled as parameters. Further details are provided in the section 2.2. Individual facilities can then model the interference patterns on a patient specific level and in addition design technical solutions such as fast rescanning, tracking or reduction of scan times towards breath-hold based treatment delivery.

Research in applied nuclear physics, including nuclear interactions, dosimetry, image guidance, range verification, novel accelerators and beam delivery technologies, can significantly improve the clinical outcome in particle therapy. Measurements of nuclear fragmentation cross-sections, including those for the production of positron-emitting fragments (used for imaging and range verification), and attenuation curves are needed for tuning Monte Carlo codes, whose

High-performance computing Monte-Carlo codes

High precision open source software has traditionally accompanied the development of cutting-edge radiation detectors, in order to accurately model particle-matter interactions. These software toolkits are incredibly flexible, simulating wide varieties of physical interactions across a range of energies. Their open source nature has contributed greatly to their success, allowing their extension to new physical domains, and their validation by a global community comprised of hundreds of physicists.

A case in point is the Geant4 Monte Carlo simulation toolkit. This software platform, initially developed for high energy physics applications has evolved to become a general-purpose simulation platform, usable in a variety of application domains with potential societal benefits. The GEANT ("GEometry ANd Tracking") series of toolkits began their development at European Organization for Nuclear Research (CERN, Switzerland) in 1974 and has grown to be amongst the widest used open source open source simulation platform in the world. Unlike its predecessors, Geant4 adopts object-oriented programming technology (C++), which naturally and progressively broadened its domain of applicability to other research domains involving particle-matter interactions. These extended across the space sciences, where the toolkit is used to simulate the response of satellite-born detectors, across medical physics, where it is used to simulate radiation treatments and even to radiobiology, where the toolkit can be used to predict DNA damage from radiation sources.



Example of Geant4-DNA result: atomistic view of a dinucleosome in liquid water irradiated by a single 100 keV proton

Geant4 is scaled to be used in high-performance computing, incorporating recent technological advances such as multi-core processors. It is also largely used on computing grids and has been ported to GPU based high performance systems. The ease with which the Geant4 license allows anyone to build software on top of Geant4 has enabled the creation of more user-friendly simulation platforms for the medicine community, through the GATE (http://www.opengatecollaboration.org) and TOPAS (http://www.topasmc.org) collaborations.

Geant4 is not an isolated example. The ROOT toolkit (http://root.cern.ch) provides leading data analysis tools to an array of researchers, and beyond this, scientists form the core of a wide variety of numerical and analysis libraries scattered across a plethora of programming languages. The Fluka package also developed at CERN is another example of general code for calculations of particle transport and interactions with matter, covering an extended range of applications. Given the immense benefit to both the research and wider communities that comes from an open-source culture, it is vital that the development of these projects be encouraged.

use in clinical environments is rapidly increasing thanks to fast calculation methods. Existing cross sections and codes are indeed not very accurate in the energy and target regions of interest for particle therapy. These measurements are especially urgent for new ions to be used in therapy, especially He and O as noted above. Furthermore, nuclear physics hardware developments are frequently finding applications in ion therapy due to similar requirements concerning sensors and real-time data processing. Part of the European efforts in the field have been coordinated in the past years by the ENLIGHT platform, based at CERN. Several National efforts are also under way, such as the ARCHADE project in France, which includes the installation of innovative accelerators for therapy in GANIL (Caen), and the FOOT experiment proposed in Italy (INFN) for the measurement of nuclear fragmentation cross-sections. At GSI/FAIR in Darmstadt, the combination of the UNILAC, SIS18 and future SIS100 in conjunction with the supporting infrastructures represents a unique R&D environment for advancements in the field of ion beam therapy.

2.2 Imaging

Atomic and nuclear imaging is used in aiding diagnosis and guiding radiation therapies. Anatomical information is acquired from Computed tomography (CT) and Magnetic Resonance Imaging (MRI) whilst molecular information can be derived from Single Photon Emission Computed Tomography (SPECT) and Positron Emission Tomography (PET). Developments in detector technologies such as fast scintillators ($LaBr_3$) and solid-state detectors (APDs, MPPCs and SiPMs) have evolved these systems to include Time-of-Flight (TOF)-PET and hybrid PET/MRI, SPECT/MRI capabilities. The improvement of coincidence resolving time (CRT) below 500 ps has significantly reduced the signal-to-noise ratio of TOF-PET images. Further improvement of CRT will provide new opportunities for PET attenuation corrections, whilst 10 ps would provide a new frontier that could lead to reconstructionless PET.

Monte-Carlo simulation is an essential tool for the design and optimization of these new devices and analysis of their data, through informing data correction and image reconstruction processes. GATE, a GEANT4-based package developed by a collaboration of nuclear and particle physicists, is a commonly used platform, with recent upgrades to model light transport in order to support the simulation of optical imaging techniques. Extensive efforts have been made to improve their computational efficiency through the implementation of variance reduction techniques and parallelization on computer clusters or graphics processing units (GPU). In the near future, Monte Carlo will tackle simultaneous imaging and dosimetry issues, and soon case system Monte Carlo simulations may become part of the diagnostic process.

Statistical image reconstruction maximizing the log-likelihood of the measured data using expectation maximisation (e.g. ML-EM, OSEM) or a gradient descent optimisation has become a clinical realty for about a decade in emission tomography, most often combined with a resampling algorithm (e.g. FORE) of the measured data into sets of 2D sinograms in the case of 3D PET. As an application of the Bayes' theorem, a regularization term can be introduced to limit the expansion of noise through successive iterations. These approaches and list mode reconstruction techniques require an accurate knowledge of the system matrix describing the imaging device, which can be calculated or estimated by Monte Carlo. Predicted physics effects such as scatter and attenuation can be input directly into the reconstruction algorithm. Image reconstruction software packages have arisen for PET (e.g. STIR) and fan-beam or cone-beam (CB)CT (e.g. RTK) thanks to dedicated collaborative initiatives, providing access to various implementations of reconstruction algorithms running on different computing architecture, including GPUs. It is recommended that collaborative initiatives are supported with the aim to provide clinically informed, dedicated and maintained image reconstruction and Monte Carlo simulation software packages.

Development of X-ray photon counting cameras based on hybrid pixel detector and ASIC readout arrays provides the opportunity to evolve conventional X-ray CT to spectral CT, including K-edge imaging. Development of larger CdTe, CZT or GaAs detectors could facilitate translation to clinical practice.

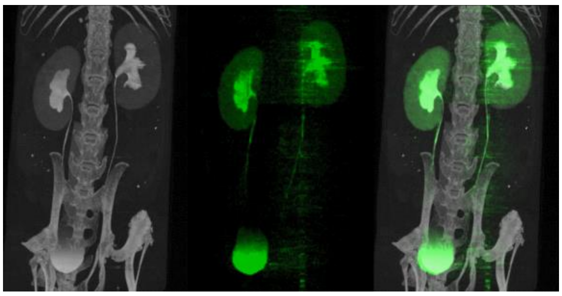


Figure 2: Preclinical K-edge imaging of a mouse injected with iodine, acquired with a photon counting

hybrid pixel camera XPAD3. The K edge image (green) was obtained using 3 x 3 composite pixels where energy thresholds were set above, under, and at the iodine K

Recent advances in the achievable precision of dose delivery in radiation therapy have promoted the development of instrumentation for in-situ image guidance, from simultaneous stereoscopic radiographic X-ray kilovoltage (kV) projections up to integrated volumetric X-ray kV imaging (CBCT, or fan beam CT on rail) and, so far limited only to very few installations, even MRI. This anatomical information of the patient position is used to determine positional corrections to be applied by a robotic positioning system for alignment to the original planning situation prior to irradiation. The new imaging-based representation of the patient can be used to assess anatomical changes, calling for an adaptation of the initial plan to the new situation for ensuring optimal tumour coverage and normal tissue sparing, so called adaptive therapy. Research is ongoing to enable improvements of image quality and computational speed for accurate and fast dosimetric calculations, ideally towards on-the-fly identification of the optimal plan to be delivered to the patient on a daily basis. In addition to anatomical image guidance prior to and, especially for organ motion, during irradiation, more recent developments also aim at devising information on the actual dose delivery. This is particularly important for emerging ion beam therapy techniques, which are extremely sensitive to anatomical variations and other sources of range uncertainties in the fractionated treatment course.

New imaging methods are currently being explored, which either aim at improving the knowledge of tissue stopping properties by using the ion beam itself in transmission imaging, or at indirectly measuring the ion beam range by exploiting secondary prompt or delayed emissions generated by nuclear reactions. Whereas the former approach has not yet reached clinical application and instrumentation development is still ongoing, different techniques and prototypes of nuclear-based in-vivo range verification based on PET and SPECT concepts are being evaluated clinically and will enable soon to draw conclusion on the method of choice, ideally towards real-time control of the dose delivery during therapeutic irradiation. Ongoing advances in imaging will likely impact the therapeutic workflows, substantially contributing to make the most of the high level of precision, which is currently achievable with modern techniques of radiation therapy.

Certain positron emitters emit high energy gamma rays in coincidence with the positron. For example, 99.9% of ^{44}Sc β^+ decays result in the emission of a 1157 keV gamma ray that can be used in conjunction with the detection of the 511 keV annihilation photons. This triggers the development of a novel imaging technique: the so-called 3-photon camera or gamma-PET, which determines the intercept between the line of response defined by the annihilation pair and the trajectory of the third gamma emitted by the radio-isotope. This latter is deduced from a cone of possible incidences given by a Compton camera, for which sophisticated detection techniques such as liquid xenon time projection chambers (TPC) or different combinations of solid-state and/or scintillator-based scatterers and absorbers can be used. Simulations have shown the possibility to achieve good energy and spatial resolutions with this approach and hence reduce drastically the dose injected to the patient.

Last but not least, additional imaging developments are envisaged concomitantly to the use of the bone cancer treatment drug XOFIGO, which is based on the decay chain of ^{223}Ra. In recent years, this radionuclide has been carefully characterized by a number of national measurement institutes and nuclear data collected during these studies can now be exploited by gamma-ray energy coincidence measurements in order to monitor the dose uptake of this drug.

2.3 Radioisotope production

Nuclear medicine describes the use of pharmaceuticals which consist of radioactive materials, either in elemental form or coupled to a molecular vector. This discipline was developed in the 50's with the use of ^{131}I for diagnosis and treatment of endocrine diseases (thyroid). Since then the use of radio-isotopes has been greatly extended to deal with many other pathologies. Over 30 million procedures per year based on radio-isotope compounds are used today in nuclear medicine worldwide. Around 90% of them are dedicated to diagnosis, with ^{99m}Tc representing the most demanded radio-isotope for SPECT. The use of radiopharmaceuticals in diagnosis and therapy is growing rapidly and the radio-isotope market is becoming an important economic driver within the pharmaceutical industry.

Radio-isotopes are used routinely in medicine for both diagnostic (mainly oncology, cardiology and neurology) and treatment (nearly exclusively oncology) purposes. The potential interest of a given radio-isotope in medicine depends on a number of different factors:

(i) the specific decay properties of the radio-isotope to be used (which dictate its capability for imaging and/or therapy);

(ii) its radiological decay half-life (which must be long enough to reach the target but short enough to avoid unnecessary radiation exposure);

(iii) transport constraints (for example from the production site to the hospital);

(iv) chemical properties (~~need~~ different chemical properties are required for different medical applications; bond strength, direct labeling or via chelators);

(v) the ease of production (quantity, quality, cost effectiveness, availability).

Apart from a few exceptions, the required radio-isotopes have to be artificially produced i) in nuclear reactors providing fission products or using neutron capture reactions or ii) in light ion induced reactions at accelerator centres (medical cyclotrons / LINACs).

Most short-lived PET isotopes are produced in a decentralized way at over 700 cyclotrons world-wide. On the other hand the supply of the ^{99}Mo/^{99m}Tc "workhorse" for imaging by gamma cameras and SPECT is presently assured by a limited number of research reactors and processing plants of irradiated ^{235}U targets. To alleviate this potential production and supply shortage, the IAEA has recognized the need to increase worldwide capacity for radio-isotope production and distribution. New facilities can be based on fission reactors, cyclotrons and high-intensity linear accelerators.

Radio-isotopes for therapy

While the use of radionuclides for diagnostic purposes (SPECT and PET) is a mature field in nuclear medicine, the therapeutic use of radionuclides is still less evolved. So-called "targeted therapies" target specifically receptors that are present at the surface of the tumor cells or relevant biomolecules overexpressed in the development of a pathological process. Once in the vicinity of the cancer cells, treatment efficacy resides in the specific radioactive decay properties. Hence, in order to pave the way to a more personalized treatment strategy, radiation types which span different energy deposition ranges within the human body and different associated Linear Energy Transfers (LET) are required. Excellent overall response rates, survival benefit and strongly reduced adverse reactions have been demonstrated compared to standard care, but the clinical use of such targeted therapy has, to date, been limited to niche applications with relatively low incidence, such as thyroid cancer, non-Hodgkin's lymphoma or gastro-entero-pancreatic neuroendocrine tumors.

New applications are currently being developed with new vectors (antibodies, peptides, folates, etc.) targeting more frequent types of cancer such as prostate cancer, lung cancer, melanoma, etc. which kill over 100000 patients in Europe annually. These new developments open the opportunity to combine at an early stage the new vector with a radionuclide of optimized decay properties. For applications where single cells should be targeted, (e.g. non-solid cancers such as leukaemia or lymphoma, micro-metastases of various cancer types), and also for adjuvant treatment of minimal residual disease (i.e. individual cancer cells or cell clusters circulating in the body after surgery or other therapies capable of removing or destroying large, visible metastases) or targeting of chemo- and radiation resistant cancer (e.g. glioblastoma), high-LET particles such as alpha particles or Auger electrons are very promising since their ranges are comparable to the cancer cell diameter (alpha) or to chromosome sizes (Auger electrons) and therefore, a few particles are sufficient to kill even a "radio-resistant" cancer cell.

The challenge for nuclear physics lies in finding ways to provide the most promising radionuclides for such applications since many alpha- or Auger electrons-emitters are indeed "supply-limited".

The theranostic approach

An important challenge of nuclear medicine is to find new techniques able to provide effective cancer diagnostics and treatment at the very early stages of the disease. To achieve this goal, new highly-selective radio-pharmaceuticals are under development, which integrate various diagnostic and therapeutic functionalities:

- selective identification of key precursors of the tumour process;
- early diagnostics of oncologic diseases by using molecular imaging;
- transport and delivery of radio-pharmaceuticals to targeted tumour cells without damaging surrounding healthy tissues;
- real-time monitoring of therapeutic effects during the treatment to redirect/adjust it.

The theranostic approach aims at combining diagnostic and therapy. For nuclear medicine, this translates into combining therapy to efficiently target the cells of interest and highly sensitive and complementary morphological imaging techniques.

This new paradigm in nuclear medicine allows in principle to:

- Select patients that will respond to a given treatment: optimizing the treatment for each patient;
- assess the staging of the disease;
- perform dosimetry to adjust the therapeutic activity to inject;
- assess the efficiency after treatment.

With such a personalized approach, a better treatment efficacy for the patient and a lower societal economic cost should be achieved.

To this end, specific radio-isotopes need to be developed:

- radionuclides which possess identical (^{44}Sc/^{47}Sc, ^{64}Cu/^{67}Cu, ^{152,155}Tb/^{149,161}Tb) or similar (^{99m}Tc/^{188}Re) chemical properties so that they can be linked to the same molecule
- a single radionuclide for both imaging and therapy (^{117m}Sn; ^{223}Ra);

This is why the whole "nuclear alphabet" involving $\alpha, \beta^{-/+}$, conversion and Auger electrons and α radiations finds useful applications in nuclear medicine, implying the development of numerous radio-isotopes with different decay properties (LET, Q value, $T_{1/2}$) in addition to good chemical properties to ease chemistry with the specific vectors.

Production and mass separation techniques

A necessary condition to promote and develop a personalized strategy is the availability, in a sufficient amount, of high purity and high specific activity of these radio-isotopes.

a. Production:

These nuclei are produced in nuclear reactors and accelerator centres. Production mechanisms (reaction channels, target / projectile properties, energy) and properties (cross sections, contaminants) should be studied in great detail to assess the interest of potential candidates or vice-versa to enlarge the choice of possible radionuclides.

To be used in nuclear medicine, large radionuclide production is required which implies the use of highly intense particle beams (hundreds to thousands of µA) or secondary neutron sources. Targetry to be used in such conditions (kW of power over few cm^2) are not an easy task requiring dedicated developments. Such R&D activities are ideally suited to be performed in nuclear physics research laboratories. Production capabilities of some specific nuclei using electron and gamma beams should also be investigated.

b. Purity:

A key characteristic of radionuclides for medicine is "purity". Different types of "purity" have to be considered and first of all the radionuclide purity. The amount of impurities depends primarily on the reaction mechanism itself: reactions induced by low energy projectiles open very few reaction channels, hence tends to result in less impurity, while higher energy projectiles may increase the production yield, though often at the expense of more numerous products. Chemical separation is usually employed to remove unwanted species but it is inefficient for isotopic impurities. Sometimes a suitable combination of irradiation/decay times might lead to a sufficient purity. A second aspect concerns the specific activity. This describes the dilution of the desired radionuclides by stable isotopes of the same element. In particular receptor targeted therapies require high specific activity to avoid saturation of the limited number of receptors per cancer cell by stable atoms. A new approach is the use of physical separation (on- or off-line) using mass separators like at ISOLDE and CERN-MEDICIS for instance. Isobaric separation can provide final products of high specific activity, even in cases where no other way of non-carrier added production exists (production from (n,γ) reaction for example).

2.4 Radioprotection

Nuclear physics has largely contributed to radiation protection through the development of detectors and calculation tool. The goals of the radioprotection studies are to evaluate the health risks associated to low-dose radiation exposure and to develop mitigation strategies. In the past few years, radiation protection research has been organized within a European Joint Programme Co-fund Action (EJP). The aim of the EJP is to bring together relevant funding agencies from the EC and the Member States to integrate European research and to administer calls for research proposals in radiation protection on behalf of the European Commission. This activity will build upon the Strategic Research Agendas (SRAs) from different European radiation protection research platforms and aims to establish interaction and synergies between the different areas of expertise. The radiation protection platforms are: the Multidisciplinary European Low Dose Initiative (MELODI), dedicated to low-dose radiation risk research; European Radioecology Alliance (ALLIANCE) for radioecology and environmental radioactivity research; the European Platform on preparedness for nuclear and radiological emergency response and recovery **(**NERIS), for radiological emergency management; and the European Radiation Dosimetry group (EURADOS), dealing with all Dosimetry issues. The SRAs define the roadmap and priorities for research to be supported by the European Commission. The latest MELODI SRA (2015) focuses on three key research questions:

(i) dose and dose-rate dependence of cancer risk, especially the shape of the dose-response curves at doses below 100 mSv, where epidemiological evidence is scarce;
(ii) non-cancer effects, including cardiovascular and central nervous system late effects;
(iii) individual radiation sensitivity.

The most recent EURADOS SRA covers five topics for future research:

(i) fundamental dose concepts and quantities;
(ii) radiation risk estimates deduced from epidemiological cohorts;
(iii) dose assessment for radiological emergencies;
(iv) integrated personalized dosimetry in medical applications;
(v) improved radiation protection of workers and the public.

All these topics require an interdisciplinary effort, including medicine, biology, chemistry, ecology, and of course physics. The EURADOS SRA is particularly addressing the issues of personalized dosimetry, nuclide-specific information in dose rate measurements in the environment, micro- and nano-dosimetry, and accurate dosimetry of neutron fields, where the nuclear physics contribution is essential.

2.5 Recommendations

- *Develop Monte-Carlo approaches which combine and validate contemporary imaging, dosimetry and diagnostic processes.*
- *Development of new tools and techniques to improve the quality and computational speeds leading to more accurate and faster dosimetric calculations in real time, thereby optimising patient treatment planning and throughput.*
- *Promote the development of accelerators and targetry towards intense beams and consider in the design or upgrades of existing facilities the production of innovative radiopharmaceuticals. Develop related mass separation techniques to obtain high purity radio-isotopes.*
- *Promote the study of radionuclide production using suitable and focussed types of nuclear reactions in order to enlarge the choice of available radionuclides*
- *Take advantage of alternative radionuclide properties to develop new "theranostic" concepts in imaging and therapy*
- Promote interdisciplinary research groups and radiobiology

3. Environmental and space applications

The interaction of energetic charged particles with atoms can create defects and damages in materials and human bodies. The knowledge of the near-Earth environment in terms of cosmic-radiation is of prime importance for spacecraft operations and astronaut safety. On the other hand, low energetic charged particles are largely used for elemental analysis. Nuclear Physics techniques and knowledge can strongly contribute to get a clear understanding of the Earth and near-Earth environments, which has significant societal and political impacts, and to address the following key questions and related key issues.

Key questions

- *What is the part and what is the impact of anthropogenic activities on climate change and modification of our environment?*
- *What is the radiation content of near-Earth environment and its impact on human activities?*

Key issues

- *To develop efficient technologies (ion-beam analysis, radiation detection, radiotracers,…) for elemental and radionuclide analysis and to monitor environment changes.*
- *To reconstruct the past atmospheric concentration of mineral dust to correlate its variations with climatic change.*
- *To study and identify aerosol sources on a global and local scale and their effects on climate and environment*

- *Investigate the origin of cosmic radiations and their impact on near-Earth environment*

3.1 Climate and Earth science

In environmental sciences, Nuclear Physics plays an important role through the measurement of the elemental composition of the aerosol, in particular with Particle Induced X-Ray Emission (PIXE, sometimes complemented by other Ion Beam Analysis techniques, IBA), which is a very sensitive method for detecting trace elements. There is an increasing concern in European citizens about the problems related to the high levels of Particulate matter (PM) in our cities, which affects human health. Aerosol also affects climate change, directly by scattering and absorption of solar radiation and indirectly by impacting on cloud processes. A large number of abatement measures are beneficial for mitigating both impacts. However there are some measures that may be beneficial for mitigating climate change but increase emissions of the key urban air pollutants, and vice versa.

Regarding atmospheric aerosols, a better knowledge of their composition could help to identify their sources. This would bring valuable information to help epidemiological studies or constraint climate models. PIXE has several prominent features:

(i) All the elements with Z > 10 are simultaneously detected in very short measuring time (~ 60 sec respect to several minutes or hours typical of other competitive techniques), therefore hundreds of samples can be analyzed in one day (any study needs the analysis of a big number of samples to obtain reliable results, of the order of 100-1000, depending on the specific problem which is studied). Among the detectable elements, there are also important markers of anthropogenic (e.g., V, Ni, Cu, Zn, Pb) or natural sources (Na, Cl, Al, Si, Ca, Fe, Ti, Sr). Multi-elemental data set as a whole (which comprises data for various tracers) can be used for disentangling the contributions from different source categories by applying multivariate receptor modelling.

(ii) Thanks to the capability of detecting all the crustal elements (which are not detected by AMS, Aerosol Mass Spectroscopy, or with difficulty by ICP-MS), PIXE is unrivalled in the study of mineral dust: consequently it is very effective in the study of natural aerosols, like, for example, mineral dust archived in polar ice cores (for environmental and paleo-climatic studies) and Saharan-dust transport.

(iii) It is possible to analyze samples with very low mass: samples collected with high time resolution (e.g. 1 hour instead of 24 hours) to follow the temporal evolution of the aerosol components, as well as size-segregated aerosol samples to assess real human exposure.

(iv) No sample pre-treatment (e.g sample digestion) is necessary: this is especially important when samples with very low mass must be analyzed and therefore any contamination is dramatic (e.g mineral aerosol in polar ice cores for paleo-climatic studies)

(v) It is a non-destructive technique; therefore further analysis by different analytical techniques can be used.

In Europe, several low energy accelerators are operating but only two are particularly devoted to the analysis of aerosol samples, the PIXE Laboratory in Lund and the LABEC Tandem Laboratory in Florence. Other small energy laboratories are partially involved in these studies. In general, their scientific potentiality may cover the largest part of the needs but it is essential to maintain a high level of R&D in these laboratories in order to be able to provide an up-to-date analysis. IAEA, too, is supporting the development of IBA for the study of atmospheric aerosol composition.

Urban pollution

Accelerator based techniques have a role in the study of aerosol composition for the identification of aerosol sources, to give to policymakers the knowledge and the tools for a significant reduction in anthropogenic emissions. As examples of recent applications, the European project AIRUSE (http://airuse.eu/en/). The comparison of data obtained by both PIXE and other different techniques (e.g. ion chromatography, ICP-MS/AES) allowed a quality assurance control on the huge quantity of data obtained in the project. PIXE data have been used to reconstruct the average aerosol chemical composition and in multivariate receptor modelling to determine the aerosol sources and their impact on PM 10 and PM 2.5 mass. In particular the high sensitivity of PIXE for all the crustal elements allowed the direct determination of the Saharan dust contribution. The hourly samples analysed by PIXE helped in disentangling the contributions from different aerosol sources due to the capability of tracking rapid changes as the ones occurring in many particulate emissions as well as in atmospheric transport and dilution processes, thus confirming and reinforcing the identification of the aerosol sources obtained by the daily concentrations.

Natural aerosol

The interest in the study of natural aerosol is justified by the fact that Saharan dust is a major component of PM on a global scale and its atmospheric concentrations have relevant effects on climate and environment; in southern Europe, it gives an important contribution to PM and it can episodically increase significantly the PM 10 and PM 2.5 levels. The EU Air Quality Directives specify that PM 10 limit values have not to be applied to events defined as natural, which include 'long-range transport from arid zones'. Diffusion models and satellite images observation can be very effective in the study of Saharan-dust transport; however, the advection of air masses coming from Sahara does not necessarily imply high PM 10 concentrations at ground level. Therefore, only field campaigns, followed by elemental analysis, can assess the real impact of the Saharan-dust episodes on the air quality, so deserving a key role to the PIXE technique. An estimate of the soil dust component concentration can be calculated considering the crustal elements as oxides. Finally, natural dust contains Fe, an important nutrient in marine ecosystems; the deposition of dust-iron to the ocean affects the CO2 –carbon cycle and this in turn can affect climate.

Climate

A fine example of the contribution that can be provided by PIXE and complementary IBA techniques is the long-term work that is being done by the Lund PIXE group within CARIBIC (Civil Aircraft for the Regular Investigation of the atmosphere Based on an Instrument Container). The CARIBIC project is a multidisciplinary project to study gases and aerosols in the mid- and upper troposphere and lower stratosphere by using a civil aircraft on long-distance flights. A Lufthansa Airbus is used since 2004. The Lund group studied the sources of the increase in the lowermost stratospheric sulphurous and carbonaceous aerosol background concentrations, with implication in the areas of nucleation (new particle formation), aerosol optical properties and the role of aerosol particles in cloud formation and properties.

Ocean acidifications

Ocean acidification is a change in pH seawater; CO_2 reacts with water molecules (H_2O) and forms the weak acid H_2CO_3 (carbonic acid). It is estimated that if CO_2 continues to be released at the same rate as today, ocean acidity will increase by 170% compared to preindustrial levels. The changes are happening at least 10 times faster than at any moment in the geological past. Radiotracer applications are essential instruments in evaluating the changes in some key biological processes, e.g. primary production, growth and calcification rates. Programs based on the production and use of radiotracers like ^{45}Ca or ^{14}C are foreseen at radioactive ion beam facilities like SPES (I) and EURISOL-DF (EU). This knowledge is also essential for the risk assessment of coastal ecosystems and the management of the stock of commercial species and to understand the responses of organisms to pH changes. Taking into account the Blue growth as a key issue for EU, ocean acidification has also the potential to impact the food security and the ecosystem integrity.

Paleoclimatic studies

In order to reconstruct past solar activity, which represents a key variable in paleoclimatic research Accelerator Mass Spectrometry (AMS) provides an excellent tool via measurements of ^{10}Be produced in the atmosphere and extracted from ice cores drilled from stable ice shields, e.g. from Greenland. The reconstructed solar irradiation can then in turn act as a "geological clock" and used to search for its impact on other parameters of relevance for the climate or beyond. As an example, studies of the concentrations of oxygen isotopes could yield information on water temperatures and/or sea level changes.

Insoluble mineral aerosol deflated from continental surfaces is an important player in Earth's climate by its influence on the Earth-Atmosphere radiative budget. To reconstruct the past atmospheric concentration of mineral dust and to correlate its variations with climatic changes, dust stratigraphies have been obtained by the chemical and physical analyses on ice cores drilled in polar areas. For the Southern Hemisphere, ice core drilled in Antarctica can give relevant information on the hydrological cycles of the southern South America (the most relevant dust area for Antarctica during glacial periods) and on the different transport processes of air masses from medium latitude, as a function of the changes in the climatic belts. The isotopic and geochemical composition of Antarctic dust particles both in present-day aerosol and in ice cores is used to infer dust source locations and to study the geochemical evolution, in turn linked to paleo-environmental conditions, of dust at the source. The extremely low elemental concentrations usually present in the insoluble particulate in Antarctic ice cores (pg to µg per kg of ice) make these analyses particularly challenging. In this context, the PIXE technique has proven to be a reliable tool for major and minor elements investigation. Ice-core sections are melted and the liquid is filtered through a narrow-area membrane to concentrate the insoluble dust to obtain detectable concentrations. No other sample pre-treatment is needed, thus minimizing contaminations (compared to ICP-MS).

Perspectives and recommendations

Recently other competitive techniques, such as those based on atomization by induced coupled plasma and detection by atomic emission spectroscopy (ICP-AES) or mass spectrometry (ICP-MS), have been developed. Furthermore, traditional X-ray fluorescence (XRF) systems have been replaced by more efficient modern devices and synchrotron radiation XRF has started to be used for elemental analysis; therefore, the use of a proper experimental set-up is a prerequisite for a rational application of IBA for aerosol analysis otherwise there is no possibility to compete with the chemistry laboratories; recently the INFN LABEC laboratory in Florence has developed a dedicated setup which uses an array of new X-Ray detectors which has reduced the measuring time of a factor ten.

It is important to remember that nuclear techniques provide only part of the desired information with regard to the chemical composition (anyway very important). PIXE researchers should not limit themselves to PIXE and IBA analyses, but try to diversify their activities by performing also other chemical and/or physical and optical measurements and to establish collaborations with other groups (chemists, geologists, physicists….).

It is important to participate to all the phases of cross-disciplinary projects regarding urban air quality, climate research, ecology, meteorology and epidemiology.

3.2 Environmental radioactivity

An understanding of the origin and activity levels of radionuclides present in the wider European environment has significant societal impact, not least in ensuring public confidence in the applications of nuclear science. Accurate measurements of environmental radioactivity levels, traceable to internationally recognized primary standards ensure public confidence in all radionuclide applications. Such applications range from:

(i) assay and sentencing of medium and long-lived civilian nuclear waste materials including ^{90}Sr, ^{134,135,137}Cs, ^{237}Np and ^{241}Am;
(ii) evaluations of naturally occurring radioactive materials (NORM) concentrations with links to European and world-wide geology, erosion and climate change monitoring such as ^{3}H, ^{7}Be, ^{14}C, ^{208}Tl, ^{210}Po, ^{210}Pb, ^{214}Bi, ^{214}Pb, ^{222}Rn, ^{223}Ra, ^{226}Ra, ^{228}Ac, and ^{234,235,238}U;
(iii) industrially or Technologically Enhanced NORM levels arising from oil scale, produced water and related materials which have potential radiological impact on workers in the oil, gas and wider mineral production industries (e.g. ^{40}K, ^{219,220,222}Rn, ^{223,234,236,238}Ra, etc.) and;
(iv) the production, handling and disposal of important radiopharmaceutical isotopes such as ^{82}Rb/^{82}Sr, ^{89}Zr, ^{99m}Tc, ^{131}I, ^{211}At, ^{223}Ra and ^{227}Th.

Gamma-ray spectrometric measurements of environmental samples allows a careful evaluation of NORM levels across a range of naturally occurring radioisotopes and can also be used to determine uranium isotopic ratios which are signatures of uranium depletion or enrichment. There are also a number of cases where gamma-ray spectrometry is not suitable for such activity determinations and other techniques such as alpha-particle spectrometry are required including the direct decay of ^{238}U and ^{232}Th and/or liquid scintillation counting for ^{3}H and ^{14}C measurements. This public confidence in such pursuits stems from the parallel strands of accurate, traceable measurement underpinned by careful management and evaluation of nuclear decay data. Indeed, nuclear data are essential for many applications related to measurements of environmental radioactivity, including decay products from nuclear power production and verification of International Comprehensive Treaty Ban Organisation commitments through atmospheric measurements of signature fission and activation products such as ^{111}Ag, ^{125}Sb/^{125}Sn, ^{131}I, ^{140}La/^{140}Ba. The availability of reliable, up-to-date and well-structured data libraries, with user-friendly visualization and retrieval tools, are indispensable in this regard. Credible and reliable nuclear data libraries have a profound societal impact by connecting science and technology with society through dissemination of the results of basic nuclear physics research.

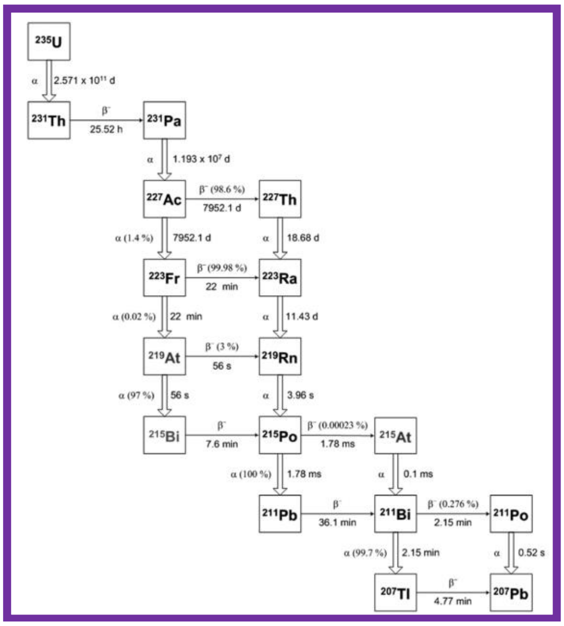


Figure 3: Evaluated decay data for the natural decay chain of ^{235}U.

Recommendations

The European nuclear physics community must upgrade its expertise in the measurement and characterisation of radioactive sources across the wider environment to ensure public confidence in applications of nuclear science. This includes a recommendation for up to date measurements on key nuclear decay data such as half-lives and gamma-ray emission probabilities values for a the most important environmental radioactive sources.

Reliable, recommended nuclear data libraries are required in a wide range of applications that possess strong, direct societal impact. We recommend strong support for nuclear data evaluation activities within the various topical fields included in the Long Range Plan.

3.3 Space radiations

Space radiation characterization and dosimetry

Understanding the near Earth and radiation belt environment composition and variability has important practical applications in the areas of spacecraft operations, spacecraft system design, mission planning and astronaut safety. The composition and origin of space radiation in the near-Earth environment are of different types, exhibiting high variability in intensity and energy spectrum. The main components are (i) galactic cosmic rays which originate outside the solar system, (ii) energetic and transient solar particle events which are emitted by the Sun, and (iii) the trapped radiation in the Earth radiation belts. Further contributions to the radiation field result from secondary particle in the spacecraft itself and from the interaction of energetic cosmic rays with the Earth's atmosphere including albedo neutron production. On Mars, secondary radiation is produced by the thin atmosphere and by the scattering on the planet's surface. On the Moon the nearly entire absence of an atmosphere results in a greater contribution of secondary production from cosmic ray interactions in the lunar soils and regolith. The resulting composition, intensity and energy spectra of the radiation field are very broad, exhibiting large gradients with altitude, which also show large temporal variations. The resulting absorbed dose rates reflect a corresponding broad spread (over many orders of magnitude for a Moon- or Mars-bound flight across the Earth's radiation belts) and time variability (also over many orders of magnitude for strong solar particle events). The recent measurements of the RAD detector on the Curiosity rover (Figure 4) on the route to Mars and on the planet, demonstrated that the total dose in a mission to Mars is close to 1 Sv, making radiation the major health risk for human exploration. In addition to passive solid-state instrumentation there is active in-situ dosimetry on board the International Space Station. Advanced instrumentation is also being deployed on payloads and spacecraft platform devices on-board satellites providing high-resolution radiation monitoring (examples include energetic particle telescopes (e.g. EPT) and integrated particle spectrometers, e.g. MagEIS and the Relativistic Proton Spectrometer both on board the Van-Allen radiation belt probes).

Ground-based research

Accelerator-based simulations are very important to perform space radiation protection experiments. Radiobiology studies in cells, tissues, and animals, can be performed at accelerators to predict health risk in long-term manned space missions. NASA sponsors a large program in the field at the Brookhaven National Laboratory in Upton, NY, and ESA has sponsored similar European activities called Investigation on Biological Effects of Radiation (IBER), based at the SIS18 synchrotron at GSI. Many experiments have been performed using ^{56}Fe at 1 GeV/n, being iron the most abundant very heavy ion on the galactic cosmic ray spectrum, and considering that these ions at this velocity have an LET around the peak of effectiveness for biological damage. In the future, the FAIR accelerator will be an ideal site for this research, given the higher energies of heavy ions that will be possible to reach there. FAIR will be indeed the only accelerator able to produce all beams at virtually all energies of interest for applications in space radiation research and medicine. High-energy proton and heavy ion accelerators can also be used for testing shielding materials. Attenuation of high-energy and high-Z beams gives indications on the quality of the shielding material. Light, hydrogen-rich materials, give stronger dose attenuation than high-Z shields at the same mass thickness (in g/cm^2). High-energy proton beams directed on thick shields simulate the production of secondary radiation, especially neutrons, in spacecraft and planetary bases. These data are also important to benchmark transport codes, especially Monte Carlo, used for space radiation. Low-energy accelerators have been used to test damage to microelectronics in space, and their role remains essential to measure single event upsets, latchout, burnout, etc. Recently high-energy particle tests for radiation hardness have also been performed. With high-energy beams entire, unopened devices can be tested, and range effects can be assessed before spaceflight.

Figure 4: The NASA Mars Science Laboratory (MSL) spacecraft had onboard the Curiosity and a radiation detector (RAD), which has been used to measure the dose in deep space during the transfer to Mars (November 2011-August 2012) and on the planet's surface (photo courtesy of NASA)

Cosmic ray physics

Current space radiation research includes dedicated studies of high-resolution characterization of the galactic cosmic rays. Experiments are motivated by astrophysics studies such as the origin of energetic cosmic-rays and particle propagation/transport in the solar system and at the galactic scale. The space-borne particle-physics experiment AMS-02, in LEO orbit since 2011 on board the ISS, performs high-resolution measurements of cosmic ray composition and spectra including measurements of the anisotropies of the positron and anti-proton distributions. Results include fundamental physics studies such as investigations of dark matter. The PAMELA cosmic ray space observatory, deployed since 2006, measures the composition and spectra of cosmic rays and trapped radiation in LEO orbit. A fully European project, PAMELA is the first satellite-based experiment dedicated to the detection of cosmic rays, with a particular focus on their antimatter component, in the form of positrons and antiprotons. Other objectives include long-term monitoring of the solar modulation of cosmic rays, measurements of energetic particles from the Sun, high-energy particles in Earth's magnetosphere and Jovian electrons.

Space weather, Earth magnetosphere

Related research includes space weather and the physics of Earth's geomagnetic field (and planetary) and the interplay with solar wind and energetic solar radiation. Earth bound SPEs and coronal mass ejections (CMEs) can strongly affect the magnetosphere and distort the distribution, composition and dynamics of Earth's radiation belts resulting in the energetic and highly variable phenomena of geomagnetic storms, which can potentially disrupt spacecraft systems and satellite navigation. The geomagnetic field serves primarily as shielding against energetic cosmic rays while it also accumulates charged particles, forming the radiation belts. Current research includes novel phenomena/processes of acceleration, depletion of the trapped radiation, creation of energetic charged particles in the Earth's belts. For this purpose dedicated space missions are being deployed in orbit such as the Radiation Belt Storm Probes (RBSP - also called Van Allen probes). Launched in 2012, the RBSP consist of twin spacecraft sampling the Earth belts along highly eccentric orbits reaching high altitudes enabling systematic and correlated measurements.

4. Societal applications

Nuclear techniques are high-precision nondestructive methods used to characterize samples at the elemental level bringing new insight compare to other methods. That is the reason why these methods are more and more used in the interpretation and the preservation of cultural heritage and for the control of radioactive materials.

Key questions

- *Which technical developments to strengthen the position of nuclear techniques compared to other methods?*

Key issues

- *Safe boundaries of nuclear techniques to minimise the side-effects of the applied radiation*
- *Develop and use instrumentations with more modalities*
- *Access to analytical facilities*
- *Better communicate with end-users?*

4.1 Heritage science

Heritage science is a multi-disciplinary domain dealing with the various aspects of cultural and natural heritage conservation, interpretation and management. It operates across the boundaries of arts and humanities, as well as science and technology. Nuclear physics contributes to the field with a wide range of analytical methods to determine the composition, or the age of tangible heritage. It also has a role in the preservation of art and archaeological objects.

Ion beam analytical techniques

IBA techniques have been used for decades to analyse archaeological and art objects. Their main strength is their analytical performance which reaches the trace elemental level, without sampling. The possibility to obtain the distribution of elements through mapping, depth information, and the capability to measure light elements are of great importance to preserve the position of these techniques in the plethora of analytical methods.

Although IBA considered non-destructive, since no sampling is needed, the irradiation may cause visible or non-visible, reversible or irreversible changes depending on the material and the experimental parameters. (This is also true for photon irradiation.) Therefore establishing the safe boundaries are of outmost importance. The IBA and the photon irradiation communities have launched an initiative to be more open about this issue, with the help of IAEA, and also as part of an IPERION CH (*Integrated Platform for the European Research Infrastructure ON Cultural Heritage)* research programme. More systematic investigations as well as specific guidelines are expected. One of the obvious mitigation strategies is to decrease the beam current and the time of acquisition. To do that, efficient detector systems are required. The AGLAE Laboratory, for example, has managed to gain a factor of ten for trace elements analysis with their new detector configuration.

The competition of synchrotrons and bench or even portable techniques has been increasingly stronger. However, the high quality of IBA results with their fully quantitative nature, and the adaptability of the experimental settings are still very attractive. Besides the most prevailing PIXE/PIGE/RBS methods, we can expect the increase of the applications of other modalities such as ionoluminescence, or X-radiography induced by PIXE. Although the majority of investigations in the field are performed with external beams, measurements in vacuum have also their use, especially when high spatial resolution, light element PIXE (down to C) or hydrogen detection are the goal (e.g. archaeogeology, research on consolidation materials, etc.)

Neutron techniques

The strength of neutron techniques is that they provide information about the inner structure and composition of objects in a non-destructive way. The methods cover elemental (or even isotopic) analysis, diffraction and imaging which are valuable tools to determine the characteristics of art and archaeological objects. Neutrons penetrate through the outer, often corroded or otherwise altered layer and travels through the selected volume. The different available methods can be combined such as in the radiography/tomography-driven Prompt Gamma-ray Activation Imaging facility, constructed in 2012, in the Budapest Neutron Centre. Neutron imaging is complementary to X-ray imaging as the transmittance differ for the elements; it is useful to also have an X-ray system in neutron facilities. Phase contrast imaging and energy selective imaging are among the new trends. The ability of the neutron techniques to look below the surface is highly thought-after but the accessibility of research reactors and spallation neutron sources is a limitation.

Carbon dating and preservation of cultural and natural heritage

Besides the composition and structure of tangible heritage, the two most important issues related to nuclear physics are dating and preservation. The number of AMS facilities is increasing in Europe and more compact facilities are also available. For heritage science applications the sample preparation is at least as important as the measuring part, special efforts (graphitization units, carbonate sampling systems, etc.) are required to ensure high quality. For bone samples, stable isotope measurements are also needed for a precise dating.

Preservation requires high intensity gamma-rays to kill bioactivity (disinfection) or for consolidation by radio-polymerisation. The number of dedicated facilities is small and side effects must be considered. But as irradiation acts on all biological aggressors and large amount of objects can be treated simultaneously, and the modification can be kept at an acceptable level with proper expertise, this is a valuable tool for conservators.

Access to analytical facilities

In the field of heritage science, the access to nuclear physics techniques is not always straightforward. After the successful EU CHARISMA project, currently the IPERION CH provides free of charge access to large scale facilities in France (AGLAE, SOLEIL) and Hungary (BNC, MTA Atomki) for users in the field. The CERIC consortium also accepts proposals from heritage science. Many laboratories have good personal contacts with museums and have recurrent users. Nevertheless, these techniques are still not as well-known as they should be. Many publications appear in technical journals which are beyond the usual pool of journals read by archaeologists, conservators and curators and these experts often do not feel encouraged enough to apply for these techniques. The EPS Nuclear Physics Cultural Heritage Topical Paper (2016) can be one possibility to reach out to stakeholders. A unique opportunity emerges with the acceptance of the E-RIHS initiative for the ESFRI Roadmap. E-RIHS will provide state-of-the art tools and services to the multidisciplinary communities of researchers working to advance knowledge about heritage and strategies for preservations. Techniques based on the principles of nuclear physics are embraced within E-RIHS as tools which can provide valuable insights into historical technologies, materials, chronologies, and degradation phenomena.

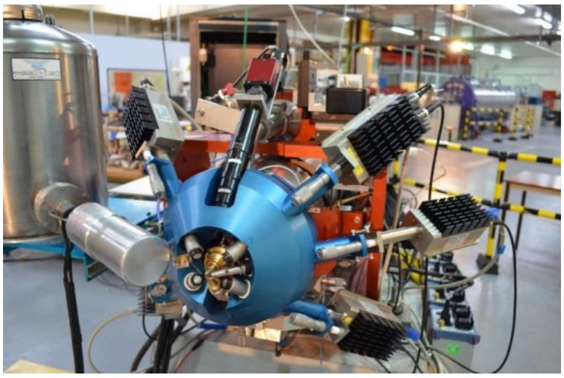


Figure 5: The multi-detector system on the AGLAE external beam (L. Pichon et al., NIMB 318 (2014) 27)

Recommendations

- *Using the maximum number of simultaneous modalities to gain the maximum information during the irradiation*
- *Upgrading detection systems for higher efficiency and safer irradiations*
- *More synergy with other physical and chemical techniques*
- *Better communication with stakeholders*
- *Participation in and support of E-RIHS, the dedicated European Research Infrastructure for Heritage Science*

4.2 Nuclear security and counter terrorism

The European Internal Security Strategy draws attention to the need to enhance capabilities against CBRNE (chemical, biological, radiological, nuclear, explosives) threats, including developing minimum detection and sampling standards.

The action plan focuses on three main strands:

- Prevention: ensuring that unauthorised access to CBRN materials of concern is as difficult as possible.
- Detection: having the capacity to detect CBRN materials in order to prevent or respond to CBRN incidents.
- Preparedness and response: being able to efficiently respond to incidents involving CBRN materials and to recover from them as quickly as possible.

The action plan includes both legal and technical measures to mitigate the threats related to malevolent use of nuclear technologies and terrorist attacks involving radioactive materials and to have an efficient control at border posts in order to trace any transport of radioactive material. Issues not currently being adequately addressed at European level include certification of radiation detectors, standardization of deployment protocols, response procedures and communication to the public. Existing techniques could be enhanced by reference to standards that would better support field teams when detecting and analysing radiological contamination. The idea would be to provide a framework within which experimental facilities and laboratories will share knowledge and expertise in order to harmonize test protocols throughout Europe, leading to better protection of critical infrastructures against all types of threats and hazards. The mission is to foster the emergence of innovative, qualified, efficient and competitive security solutions, through the networking of European experimental capabilities.

Future data acquisition systems shall enable the movement of detection data from first responders electronically to analysis centres rather than the costly and time consuming process of moving experts and/or samples. This new technology is especially useful in crisis events, when time and resources are sparse and increased analysis capacity is required. In order to utilise the opportunities opened by these new technologies, the systems have to be interoperable, so that the data from each type of detector can easily be analysed by different analysis centres. Successful interoperability of the systems requires that European and/or international standards are devised for the digitised data format. The basis of such a format is a list of registered events detailing an estimate of the energy of the detected radiation, along with an accurate time-stamp for recorded events (and optionally other parameters describing each event).

Improved radiation detection systems

In nuclear security, the detection of illicit trafficking of nuclear material (particularly plutonium) is at present based on the use of ^{3}He detectors for the detection of the characteristic neutron emanations in radiation portal monitoring systems. The recent significant increase in the demand for instrumentation related to nuclear security, coupled to the reduced production of nuclear weapons, has created an issue with ^{3}He detector supply from manufacturers, leading to an associated exponential price increase.

Recent research into alternative detection systems has given preliminary indications that some novel and promising alternatives may be employed. In the last 10 years a large number of new high light-yield scintillator materials have been discovered. The first and the most famous among them, the Lanthanum Halides, were already the target of an intense R&D, which provided the starting point for the design and development of several new high performance $LaBr_3$:Ce, $LaCl_3$:Ce based detector arrays. A suite of "new" detector technologies and systems are currently emerging as $CeBr_3$, SrI_2 but others as CLLB (Cs2LiLaBr6:Ce), CLYC (Cs2LiYCl6:Ce) or CYGAG:Ce (a transparent ceramic material exhibiting promising scintillation properties and offering the advantages of a ceramic in terms of robustness and chemical stability) require intense R&D activities in order to fully characterise their properties.

Combining two or more scintillator materials in a single compact detector can be a cost effective way of detecting gamma-rays, charge-particles and neutron radiations with the same detector. Adding a segmentation of the crystals could give also new imaging features that can help in detecting the angle of impact and thus the direction of the source relative to the detector.

List-mode data acquisition based on digital electronics

Time-stamped list-mode data format produces significant added value compared to more conventional spectrum format. It improves source localization, allows signal-to-noise optimization and noise filtering. List-mode approach also allows precise time synchronisation of multiple detectors enabling, for example, measurement of single gamma-rays in one detector and UV-gated gamma spectrometry in other ones. List-mode data is commonly used within the nuclear physic community but has up to now not been used in the area of nuclear security.

The development of Time- and Geo-stamped correlation is important to be able to scan big objects from a car or an aeroplane or large areas. Such technology is also needed to follow the movement of malicious activities over long time scale.

Remote-controlled radiation measurements

There is significant potential for the use of unmanned remote controlled systems in sampling and measuring radiological events. The main advantage is the protection of the involved human personnel. Depending on the size and the loading capacity of the unmanned system, appropriate sensors are necessary. The main envisaged applications are:

- repetitive/routine measurements;
- measurements in areas of high radiation;
- search, localisation and identification of possible radiation sources;
- gamma-ray mapping: dose rate, surface activities, point activities (including blank of critical infrastructures and sites);

- operation in dangerous and uncooperative environments (CBRNE scenarios, dirty bombs, inaccessible areas, etc.);
- collection of samples;
- decontamination and containment actions.
- forensic medical applications as in case of *radiological-dirty* crime.

Reachback and expert support
Most countries have emergency-plans to deal with accidents of different kind and scale. However, only major powers have the capability to keep continuous track and history over the RN measures within their borders and thus be able to search and prepare for criminal activity. For an efficient Reachback system which covers all the territories there is a need for standardizing data taking, storing, and the final distribution of the analysed data. A European centralized database where all information are stored and can be analysed from different laboratories should be created to have 24h 7/7 days control all over Europe.

Perspectives and recommendations
Efficient security and antiterrorism activities in nuclear domain require implementation of both, legal and technical actions. Legal activities to the large extent overlap with intellectual and commercial property protection as well as with the export control measures. It is thus possible to implement a common procedure allowing for rapid classification whether a given activity (e.g. sample transfer or data publication) may be freely conducted or may require additional verification.

Recommendations
- Need to develop detectors with directional detection and with simultaneous gamma-ray and particle identification.
- High priority should be given to the standardisation of list-mode data with Time and Geo-localisation.
- Lightweight detectors and manipulators shoulc be developed for remote-controlled radiation measurements.
- To foster the emergence of innovative, qualified, efficient and competitive security solutions, through the networking of European experimental capabilities.

5.Cross-disciplinary impact

Nuclei interact with matter mainly by electromagnetic interaction. The use of ion beams is then well suited to study the structure of materials and atomic matter even in extreme conditions as in plasma.

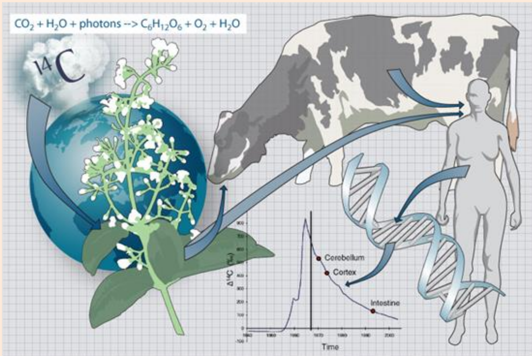
Key Questions
- *What are the local and long-range chemical and magnetic structures of materials?*
- *What are the dynamical properties of materials and how do ultrafast processes take place in materials?*
- *How do atoms and materials behave under extreme conditions?*
- *How can materials be modified by nuclear tools?*

Key Issues
- *Increasing sensitivity, increasing depth and lateral resolution of analytical techniques*
- *Extending the temperature, pressure and magnetic field range accessible for nuclear methods*
- *Controlled modification and nanostructuring of materials*

5.1 Materials sciences

Nuclear Analysis Methods and the Biomedical Bomb-peak dating

Nuclear methods and methods based on nuclear techniques are extremely efficient and, in many cases, unique tools for investigating the structure of materials and to characterize samples at the elemental level. These methods benefit from progresses in accelerator technology and instrumentation to increase their sensitivities.



Among them, Accelerator Mass Spectrometry (AMS) analysis is a powerful technique to measure the isotopic ratio of elements in materials. Coupled to the conventional carbon-14 dating method it offers new opportunities. Carbon-14 dating method is a robust and well established tool in the archaeological sciences, facilitating dating artefacts from tens of thousands of years ago to the middle of last century with an accuracy of a few tens of years. The so called "bomb-peak dating" addresses the interesting period of the last 60 years with an accuracy of about 2 years. The detonation of the atmospheric nuclear bombs during the cold war era, prior to the Test Ban Treaty in 1963, increased the amount of radiocarbon in the atmosphere significantly, providing a time marker.

By improving the sensitivity of AMS analysis from requiring milli-grams amounts of sample material to micro-grams, it has been able to address a number of hitherto uncharted scientific questions such as: "how old are the various cells in our body?" As an example, using purified DNA, the regeneration rates of neurons in hippocampus and striatum in the human brain have been measured showing high levels of renewals. Other highly controversial questions regarding the human cardiomyocytes (heart muscle cells), the adipocytes (fat cells), Oligodendrocytes (brain support cells) have now been resolved using this technique. In this domain, the objective is to have a complete regeneration map of the human cells in health and in disease.

Other applications can be found to provide court-of-law evidence for a number of actual forensic cases. For instance, human teeth have been dated to confirm the date-of-birth of the victims. An extreme sensitivity of AMS for 14C-labelled pharmaceutical substances in human blood in the zeptomole range (10-21 mole) has also been demonstrated. This is of pronounced interest in the pharmaceutical industry. Minute amounts of candidate drugs are administered directly to humans, yielding pharmacokinetic data which is critical in early drug development- the so called Microdosing method.

Nuclear physics has provided a number of valuable tools for materials science, the vast majority of which features the possibility for non-destructive analysis. An additional benefit is the fact that many of the methods yield quantitative results without the requirement of reference samples. Most commonly, keV and MeV ion beams provided by accelerators are employed for materials characterization or modification. In the field of ion-beam analysis (IBA) continuous development of the established methods is performed towards more sensitive systems with enhanced depth resolution to meet the ongoing trend of miniaturization in thin-film technology as well as to be able to employ the methods e.g. for soft-matter systems. Methods like medium-energy ion scattering (MEIS) or MeV-secondary-ion mass spectrometry (MeV SIMS) with micro-beams or for ambient conditions are examples of ongoing developments. A larger penetration of ion-beam based analytical tools into e.g. organic thin film chemistry can be expected, but requires active communication of the potential of the methodology beyond the established target communities.

There are also numerous non-ion-beam-based techniques which originated from nuclear physics and have great potential for materials characterization and for studying physical and chemical phenomena in materials.

Neutrons have been widely used as analytical tools in activation analysis and radiography of bulk materials. The main strength of thermal neutrons is their applicability in scattering experiments: diffraction methods being sensitive to long-range chemical and magnetic structure while small-angle scattering and reflectometry give insight to short-range properties of nanostructured materials. With the advent of ESS, Europe will further secure its leading role in neutron scattering in a period when, by decommissioning many nuclear reactors worldwide, we shall be faced with a dramatic shortfall of research neutrons.

Mössbauer spectroscopy (including nuclear resonant scattering of synchrotron radiation) and perturbed γ–γ angular correlation (PAC) are methods mainly based on hyperfine interactions. Especially Mössbauer spectroscopy has a wide range of applications including metallurgy, solid-state physics, magnetism, structural chemistry, nanosciences, life sciences, archaeology, etc. Besides, nuclear resonant scattering of synchrotron radiation comprising resonant forward scattering (both in time and energy domain), nuclear inelastic scattering and synchrotron radiation perturbed angular correlation has been recently extensively used for studying vibrational properties of materials, particularly at extreme conditions with an important impact to earth sciences. Mössbauer spectroscopy has traditionally been worldwide the strongest in Europe. Nuclear resonant scattering beamlines in Europe are available at

ESRF and PETRA III. With the envisaged upgrade of the ESRF beamline ID18 a beam size at the sample position of 150 nm × 50 nm and an energy resolution of 10 µeV can be reached, an unprecedented tool for studying nanosystems.

Muon-spin rotation (µSR) and positron annihilation spectroscopy are nuclear methods in a more general sense. µSR has a significant impact to diffusion and magnetic structure studies. The main strength of positron annihilation is its extreme sensitivity to defects in materials such as vacancies and dislocations. With the advent of slow-positron sources (both those based on radioactive sources as well as those based on LINACs or nuclear reactors), the method became surface-sensitive; an important aspect in nanoscience applications

The field of materials modification by nuclear physics methods is dominated by ion irradiation, most commonly with several ten to hundreds of keV, with large volume applications such as semiconductor doping or material amorphization. Research is expected to focus in two directions: first, materials modifications in rather extreme environments, i.e. under extreme doses or other complex environmental conditions is of relevance for research in fusion as well as next generation fission reactors and has applications in earth and planetary sciences. Second, shallow implantation of low doses with high lateral selectivity, in the best case controlled single ion implantation is of relevance for the growing research fields of spintronics and qubits in quantum computing.

5.2 Atomic and Plasma physics

Upcoming large scale particle accelerator facilities such as the Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany and SPIRAL2 in Caen, France, provide outstanding and worldwide unique experimental conditions for extreme matter research in atomic and plasma physics. The associated research programs comprise interaction of matter with the highest transient electromagnetic fields and properties of plasmas and of solid matter under extreme pressure, density, and temperature conditions.

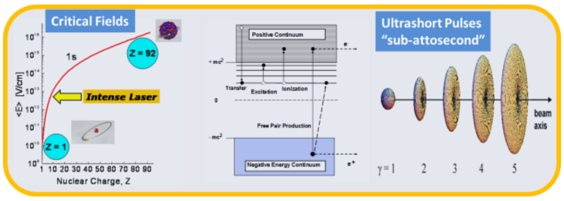


Figure 6: Left: electric field strength present for the ground-state electron in hydrogen-like systems as function of the nuclear charge. For comparison, typical field strengths provided by state-of-the-art high power lasers is also displayed. Middle: Dirac spectrum showing a variety of the atomic processes which can be studied in hitherto unexplored regimes. Right: electromagnetic field strength of a relativistic ion showing a strong enhancement in the transverse direction together with the compression in time.

A broad variety of dedicated experimental facilities, including experimental stations, storage rings, and traps, equipped with most sophisticated instrumentation will allow the atomic and plasma physics communities to efficiently exploit the unique research opportunities and to tackle the associated new challenges.

Atomic physics research will in particular focus on the study of atomic matter – ions, atoms and molecules- subject to extreme electromagnetic fields as well as atomic processes mediated by ultrafast electromagnetic interactions (see Fig. 5). A prominent example concerns the binding energies of electrons in high-Z one-electron ions where the K-shell electrons are exposed to transient electric fields (e.g. 10^{16} V/cm in U^{91+}) close to the Schwinger limit. In a concerted effort and in close collaboration with the leading expert groups in theory, a comprehensive research program has been initiated to accomplish a significant validity check of non-perturbative bound-state QED in regions $\alpha Z \approx 1$. Different experimental approaches will be applied (1s Lamb shift, 1s hyperfine structure, bound-state g-factor, mass measurements) thus probing QED at different mean-distances of the electron with respect to the nucleus. At the same time, highly precise atomic physics techniques will be applied as powerful tools for the determination of nuclear parameters such as nuclear radii and moments. Even high-precision determination of fundamental constants will be enabled.

At the high energy range, in particular FAIR will offer world-wide unique research opportunities to address a big variety of exciting topics. Here, highly-charged ions (HCI) can be stored and cooled at energies in the few-GeV/u range. These intense and high luminosity beams can then be coupled with dedicated internal multiphase targets as well as dedicated laser systems, including novel XUV, X-ray and high power lasers. This will enable us to explore a broad range of interesting physics phenomena. These include (among others):

- lepton pair-production in a nonperturbative regime;

- the negative continuum dielectronic recombination;
- radiative processes such as the radiative recombination and/or the radiative electron capture (REC) in up-to-now unexplored regimes;
- ionization dynamics and correlated electron motion induced by ultrafast extremely strong fields of relativistic ions;
- electron impact phenomena, such as excitation and ionization as well as the resonant coherent excitation process.

In addition, the coupling of various types of lasers with the ion beams in the high energy storage ring (HESR) would enable tests of bound-state quantum electrodynamics and the special theory of relativity with improved precision. Moreover, detailed experimental concepts have been worked out to explore parity non-conservation effects in highly charged ions and thus test the standard model.

Experiments at HESR at relativistic beam energies will be complemented by experiments at CRYRING and the HITRAP facilities at FAIR which focus on atomic and nuclear physics of exotic systems down to very low beam energies (< 10 MeV/u) and even at rest. Both CRYRING and HITRAP are coupled to the ESR which allows to decelerate ions from high energies (400 MeV/u) to the injection energy of both facilities providing in this way very-high Z ions in the bare or the few-electron state from a kinetic energy of 10 MeV/u continuously down to near- thermal energies. This scenario is worldwide unique and will e.g. deliver high-accuracy data for bound state QED (minimizing Doppler shifts) as well as the determination of fundamental constants. In addition, atomic collisions can be studied in the non-perturbative, adiabatic regime, even the electron dynamics in super-critical fields of transient super-heavy quasi-molecules will be accessible.

Furthermore, in the energy range of ~1-10 MeV/u the Fast Ion – Slow Ion Collisions (FISIC) project is planned and currently being developed at the S3 beamline of the SPIRAL2 facility. The project aims to utilize the intense ion beams provided by the SPIRAL2 facility in order to address the ion-ion collisions in the hitherto unexplored intermediate regime. Such studies are of fundamental interest as they will allow benchmarking the state-of-the-art atomic theories in the regime where most of the current standard approaches have not yet been applied. Furthermore, this regime is particularly interesting, because here cross sections for various atomic processes are of the same order of magnitude, the multiple processes become important and the ion stopping power is at maximum. Moreover, knowledge of the fundamental mechanisms at stake in the fast ion – slow ion collisions in atomic physics can provide a real breakthrough in the understanding of energy transfers in various plasmas such as inertial confinement fusion plasmas or stellar/interstellar plasmas. Indeed, ion-ion collisions are underlying many astrophysical phenomena in the universe but one of the least studied in laboratory. Here, it should be also mentioned that the low-energy branch of the FISIC experiment is generally mobile and can be transported and installed at CRYRING in order to extend the range of available ions into the high-Z range which would also be unique in many aspects.

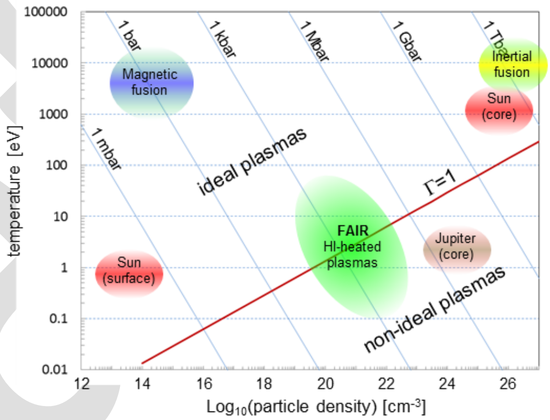


Figure 7: Schematic phase diagram showing the areas accessible with FAIR and other facilities as well as the conditions existing in cosmic objects. The red line separates the ideal and dense, strongly coupled plasma regimes (warm dense matter).

Bunched FAIR beams of highest intensities provide huge energy densities (hundreds of kJ/g) and allow novel experiments and unprecedented diagnostic capabilities. Matter exposed to FAIR beams experiences similar extreme temperature and pressure conditions as prevailing in the interiors of stars, brown dwarfs or giant planets (so-called warm dense matter). The research program will focus on the equation of state and on transport properties of different materials in so far unexplored warm dense matter and high-energy density regions of the phase diagram. Related to these major goals, phase transitions, hydrodynamics and instabilities are of great interest. For instance, particle coupling in dense plasmas changes significantly, leading to different properties that need to be experimentally investigated (see Fig. 6). Sophisticated computational tools have been developed to understand and predict the hydrodynamic processes of ion-beam heated matter. This allows to design special target configurations which enable a precise diagnostics of the target state with a minimum of measured quantities. State of the art optical and laser diagnostics will be applied to improve the understanding of atomic physics and thermodynamic properties of matter under these extreme conditions.

For the completion of the plasma physics research program at FAIR, the availability of a powerful probe (or driver) is essential. This probe can very advantageously be based on a high-energy laser that is matched to the requirements of experimental schemes, but also serve a much larger community within the FAIR research pillar APPA (Atomic Physics, Plasma Physics, and Applied Science). A project to build this laser, the so-called ''Helmholtz Beamline'', exists on the roadmap of infrastructure of the Helmholtz society and is currently in the planning stage. During this stage GSI together with the Helmholtz center in Dresden Rossendorf and the Helmholtz Institute Jena are conducting the necessary R&D in the fields of laser technology and laser-based diagnostics at their facilities. This includes experimental demonstrations and validations at the PHELIX facility.

5.3 Recommendations

- It is our vital interest to find schemes that link operators of applied nuclear facilities to potential user groups in materials sciences and related areas.

6. Summary and recommendations

Nuclear Physics is in the forefront of many applications which cover the range of the needs of Humanity in terms of energy, health, knowledge and protection. This is due to the peculiar properties of nuclear interactions with matter but also to the developments and the expertise developed by Nuclear Physics groups in accelerator technology, radiation detector technologies, high-performance computing, event reconstruction and 'big data'.

The main domains of applications have been reviewed in this chapter showing some important progresses and new orientations since the last Long Range Plan in 2010:

- In the nuclear energy domain, the safety of existing and future installations is became the main concern in the wake of the Fukushima accident. The main consequences are a need for accurate and predictive simulation codes based on reliable nuclear data.
- In the medical domain, the new theranostic approach leads to the development of adapted techniques for cancer treatment, in particular to the development of specific radio-isotopes, and more efficient imaging techniques. Thanks to the developments of high light-yield and fast scintillators coupled with high-performance computing Monte-Carlo codes the efficiency of diagnostics are improved and the dose to the patient can be reduced. Such developments should also permit to improve the detection techniques for nuclear security and counter terrorism.
- In the environmental domain, the global warming and urban pollution are become of main concern for our societies. Efficient low-energy accelerator-based techniques are used to trace aerosols and study their role and impact in these problematics.
- With the availability of high-intensity accelerators and new installations (Ganil, ESS, FAIR, HIE-Isolde) new studies in material, atomic and plasma physics will be possible, exploring matter in extreme conditions. Some of these installations will also be used to study and develop the production of new radioisotopes for medical use.

In the following we try to draw some recommendations for the future of Applied Nuclear Physics in Europe.

The compilation, evaluation and dissemination of nuclear data are laborious tasks that rely heavily on contributions from experts in both the basic and applied science research communities. Efforts carried out at national and international levels benefit from the coordination provided by international organisations such as the International Atomic Energy Agency (IAEA) in Vienna and the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (NEA-OECD) in Paris. The development and maintenance of nuclear data libraries, and dissemination of nuclear data to various user communities constitute major goals of the international networks associated with these agencies: the Nuclear Reaction Data Centres Network (NRDC/IAEA), the Nuclear Structure and Decay Data evaluators (NSDD/IAEA), and NEA Data Bank. The challenge facing the nuclear research and applications communities is to ensure that the new measurements performed in the European facilities are incorporated promptly into the available databases and are therefore used in both reaction modelling and evaluations that are important for energy and non-energy applications.

The complexity of applied nuclear methods, the special infrastructure needed in applications and, most importantly, the necessary knowledge in nuclear physics often prevents other communities from applying nuclear methods in materials sciences.

Recommendations

- *Maintain an adequate level of competence and expertise in the field of applied nuclear physics. In this respect training and education at all levels (Bachelor, Masters, PhD) of a new generation of researchers is fundamental*.
- *Strengthen the communication between Nuclear Physics community and end-users (stakeholders).*
- *Applied nuclear physics communities should be encouraged to build open-access networks offering their services (i.e., research infrastructure, knowledge and data) to potential users. Such networks as distributed and/or virtual research infrastructures should be integrated in the emerging European Open Science Cloud.*
- *Promote the activities in nuclear physics with applications in medicine, such as measurements of fragmentation cross-sections important for medical applications.*
- *Pursue the developments of novel accelerators and sensors for medical applications.*
- *Support activities related to the compilation, evaluation and dissemination of nuclear structure and decay data in Europe*
- *Maintain a high level of expertise in nuclear data evaluation to meet the requirements of a continuously developing European research and applied sciences landscape through targeted training and mentorship schemes*