Organisation for Economic Co-operation and Development (OECD)

Global Science Forum

Report of the
Working Group on Nuclear Physics

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OECD Global Science Forum

The Organisation for Economic Co-operation and Development (OECD) groups thirty Member countries committed to democratic government and the market economy, and provides a venue where governments can compare and exchange policy experiences, identify good practices and agree on decisions and action recommendations. Dialogue, consensus, peer review and peer pressure are at the very heart of the OECD's procedures. The Organisation's mission is essentially to help governments and society reap the full benefits of globalisation, while tackling the economic, social, environmental and governance challenges that can accompany it. It places a high priority on deciphering emerging issues and identifying policies that work in actual practice. In addition to the analysis and advice it provides on a vast range of economic issues, the OECD is one of the world's largest and most reliable sources of comparable statistical economic and social data. OECD databases span areas as diverse as national accounts, economic indicators, trade, employment, migration, education, energy, and health. The OECD produces internationally agreed instruments, decisions and recommendations in many areas, such as combating bribery in international business transactions, information and communications policy, taxation and environmental protection. Non-members are invited to subscribe to these agreements and treaties. Helping ensure development beyond the OECD's membership has been part of the Organisation's mission from the start. The Organisation maintains active relationships with some 70 non-member economies, along with businesses, labour organisations, civil society and parliaments. These stakeholders benefit from, and make valuable contributions to, the work of the OECD.

The Global Science Forum (GSF) is a venue for consultations among senior science policy officials of the OECD member and observer countries on matters relating to fundamental scientific research. The Forum's activities produce findings and recommendations for actions by governments, international organisations, and the scientific community. The GSF's mandate was adopted by OECD science ministers in 1999, and an extension until 2009 was endorsed by ministers in February 2004. The Forum serves its member delegations by exploring opportunities for new or enhanced international co-operation in selected scientific areas; by defining international frameworks for national or regional science policy decisions; and by addressing the scientific dimensions of issues of social concern.

The Global Science Forum meets twice each year. At these meetings, selected subsidiary activities are reviewed and approved, based on proposals from national governments. The activities may take the form of studies, working groups, task forces, and workshops. The normal duration of an activity is one or two years, and a public policy-level report is always issued. The Forum's reports are available at www.oecd.org/sti/gsf. The GSF staff are based at OECD headquarters in Paris, and can be contacted at gsforum@oecd.org.

Executive Summary – Findings and Recommendations

The OECD Global Science Forum (GSF) established the Working Group on Nuclear Physics in March 2006 for a period of two years. Its charge was to gather information and to discuss and analyze the following topics: the plans for nuclear physics in the various countries and regions; the mechanisms and rationales that underlie priorities and strategies; the needs and opportunities for enhanced international collaboration and coordination. A report was to be delivered to the GSF in March 2008. Eleven OECD governments (plus the European Commission) nominated delegates who, in turn, invited the following partners that became full members of the Working Group: two non-OECD countries, two intergovernmental organisations involved in nuclear physics research, and representatives from two independent scientific organisations (see Appendix C). Four meetings were held, with the location rotating from the United States to Italy to Japan to France. Important scientific background information was provided by recent science-community papers and planning documents, revealing how nuclear physics has evolved significantly over the last decade in a manner that sets the future directions of the field.

The primary goal of nuclear science is to understand the structure, dynamics, and properties of nuclear matter at the most fundamental level, i.e., to explore and explain how the basic constituents of matter—the quarks and gluons— combine to determine the properties of the particles and nuclei found in nature, to learn how nuclei behave under both normal and extreme conditions of neutron to proton ratio, temperature and density, and to establish what are the limits of nuclear existence. This includes understanding the origin of the chemical elements in the cosmos (such astrophysical settings often provide the most severe tests of modern theories of nuclei) and the fundamental forces of nature.

Major discoveries and technological advances have been made during the past decade that address the fundamental questions of the field. These advances were made possible by significant investments in frontier research facilities, exploiting technological advances which were initiated more than a decade ago. Notably, nuclear physicists have experimentally detected an exotic state of matter, the quark-gluon plasma, which is believed to have existed in the very first moments of the Universe. They have validated the standard solar model and established that neutrinos have mass. High-precision measurements of the quark structure of the nucleon are challenging existing theoretical understanding. Nuclear physicists have started to explore a completely unknown "terra incognita" of nuclei with extreme proton to neutron ratios, including very neutron-rich isotopes that play a critical role in the formation of many of the chemical elements. Measurements and computational simulations have revealed new structures and behaviours of nuclei, including the discovery of the new elements much heavier than any that are naturally occurring. This progress provides information and insight on astrophysical phenomena (for example, supernovae and neutron stars).

Scientific progress has been driven largely by advancements in technology that have enabled the construction of novel particle accelerators and experimental instrumentation. Dramatic increases in computational capabilities have played an equally important role, making possible increasingly realistic simulations of the strongly interacting many-body systems of nuclear matter. As perhaps never before, the scientific discoveries and technological advancements of nuclear physics have significant relevance and impact on society and on other scientific fields: astrophysics, cosmology, particle physics, condensed matter research, and others.

In this report, the findings of the working group are indicated in italics and summarized in abbreviated form in this Executive Summary. Recommendations are given in bold face type.

The Nuclear Physics Enterprise Today

There is a significant global effort in basic nuclear physics research, involving around 13,000 scientists and support staff with funding of approximately 2 billion US$ per annum. Countries support nuclear physics research in order to be at the frontier of discovery science as well as for strategic reasons. Any country with a modern economy needs facilities at which personnel can be trained in nuclear science, given its important role in many sectors of the economy–energy, security, industry–as well as in modern medicine. *The Working Group finds that the breadth of nuclear physics and its strong links with other sciences and national need result in the boundaries being defined differently in different countries.* This finding is particularly true for neutrino physics and other interfaces with particle and astro-particle physics.

Recommendation: International coordination in nuclear physics must take into account the national differences in the definition of its boundaries with closely related research fields.

A recent International Union of Pure and Applied Physics/Working Group 9 survey listed nuclear physics research facilities with external user groups operating at 90 institutions in 26 countries, with the largest concentration in Europe, Japan, and the USA. There is a wide diversity in the size, complexity, and costs of the existing facilities, which include accelerators, reactors, and underground laboratories. *The Working Group finds that this diversity has evolved to meet the needs of the individual countries and regions.* There exist a select number of major facilities that are technically complex and costly and that are operated as international user facilities. Some medium sized facilities operate in a similar manner. Small, and in many cases university-based, facilities play important roles for specialized nuclear physics studies and as training grounds for young scientists. The medium and smaller sized facilities, in general, often serve society at large through applied nuclear physics programmes and nuclear medicine**.**

Recommendation: It should be recognized that there are important roles for nuclear physics research facilities with a wide diversity in both size and type. As major new facilities are planned, an appropriate balance of facilities must be maintained.

Basic nuclear physics research as conducted today is truly international. *The Working Group finds that about 30% (in some cases more than 50%) of the users of the large and medium sized facilities are from outside the country where the facility is located. Support for the operations of these facilities has historically been provided by the host country or region with a policy of free and open access by the international scientific community and with beam time allocated based upon the merit of the proposed research.* Agencies in other countries have contributed to the research programs at these facilities by supporting their researchers who participate in developing new capabilities and experiments and by contributing experimental instrumentation. The international character of nuclear physics research is not limited to the accelerator facilities. For example, most underground nuclear physics experiments today are carried out by collaborations composed of researchers from several countries with investments from multiple agencies and countries.

Recommendation: Free and open access to beam usage should continue to be the international mode of operation for nuclear physics facilities.

The participation of the national nuclear physics communities in international collaborations takes place naturally if the countries have advanced industrialised economies, strong academic institutions, and well-established systems for funding and administering science. *The Working Group finds that in many developing and emerging countries the situation is much more difficult with regard to participation in research at the major, front-line facilities.* Yet these nuclear physics communities have bright young researchers who could significantly contribute to the science at these facilities, contingent on the establishment of appropriate access to programmes.

Recommendation: Funding agencies and research institutions are encouraged to create and support mechanisms that provide access to large-scale facilities by scientists from emerging or developing countries where no major facilities exist.

Advances in nuclear physics techniques and accelerator technology have made significant contributions to national and societal priorities, including new approaches in energy, national security, industry, and medicine. *The Working Group finds that the contributions of nuclear physics can be enhanced through explicit mechanisms to make nuclear scientists and the broader community more aware of how the insights and techniques of nuclear physics can be applied.*

Recommendation: The nuclear science community, funding agencies, and professional societies should continue to encourage interactions to make nuclear scientists and the broader community more aware of how the insights and techniques of nuclear physics can be applied. The nuclear science community should increase its efforts to better articulate the relevance and benefits of nuclear physics to national needs and society.

Success in basic research and its applications (for example, nuclear power generation or the development of instrumentation in the national security domain) relies on systematic, accurate measurements and accumulation of nuclear data in certified, reliable databases. In some areas, such as nuclear energy, there is strong international coordination through agencies such as the OECD Nuclear Energy Agency, the International Atomic Energy Agency (IAEA), and the U.S. Nuclear Data Program. *However, the Working Group finds that gaps exist in the international plans for the coordination and oversight of these databases, and that available resources are insufficient.*

Recommendation: The national agencies should work together with international organisations, such as the OECD Nuclear Energy Agency, the International Atomic Energy Agency, and the international science community, to create a more comprehensive international plan to acquire and curate nuclear data for the wider community.

Nuclear physics research has provided a pool of highly qualified personnel with skills that are important for a wide range of high priority areas of modern life (medicine, energy production, engineering, national security). During the last decade it is estimated that over 5,000 students received Ph.D. degrees in nuclear physics. Although there are significant variations from country to country, about one-third of these Ph.D. recipients are now at universities or national laboratories involved in basic nuclear physics research, another third in national laboratories or in government work in related applied areas, and the remaining third in the private sector. *The Working Group finds that training in nuclear physics is a good career option in most countries because of the opportunity to participate in discovery science and the wide range of applied areas where the acquired knowledge and experience is valued.*

The Global Roadmap for Nuclear Physics

There is an international consensus on five key questions that motivate future research in nuclear physics: (1) Is quantum chromodynamics (QCD) the complete theory of the strong interaction? (2) What are the phases of nuclear matter? (3) What is the structure of nuclear matter? (4) What is the role of nuclei in the evolution of the universe? and (5) What physics is there beyond the Standard Model?

What is in effect a global roadmap for nuclear physics emerges from matching the proposed new and upgraded facilities planned by the various countries and regions to the highest priority scientific opportunities. *The Working Group finds that this global roadmap reflects a high degree of coordination in optimizing the available resources for the world-wide nuclear physics programme.*

The new facilities and upgrades that are now under consideration will ensure the continuing success of nuclear physics, with an estimated investment worldwide of four billion US$ during the next decade. The discoveries and technical advancements that will result from the implementation of the global roadmap for nuclear physics will make important contributions to other scientific fields and national and societal priorities. The forefront research facilities in the global roadmap are needed to attract and train a next generation of scientists for research and national needs.

Recommendation: The proposed new and upgraded facilities within the global roadmap for nuclear physics are well coordinated and will produce outstanding science and discoveries. Their implementation is recommended.

Strategic Planning for Nuclear Physics

The major policy challenge that confronts scientists and policymakers is the increasing cost of the tools needed for achieving progress at the scientific frontier. The scientific community has done an outstanding job of identifying the scientific opportunities and the research capabilities needed to exploit them. However, the large cost and intense competition with other national priorities for resources have led to pressure on all funding agencies to examine opportunities for international cooperation, to optimize the use of the available resources, and to avoid duplication of efforts and research capabilities.

The planning processes used by funding agency officials for priority-setting and decision-making (e.g., established national advisory mechanisms) have worked well for making decisions about the use of existing facilities, new facilities under construction, and proposed facilities. Within Europe, these processes have been taken to the next stage under the European Commission, and regional priorities have been developed. The processes have been instrumental for producing the global roadmap that reflects the worldwide consensus of the research community regarding the most challenging scientific questions and the experiments that can provide answers to those questions. *The Working Group finds, however, that given the desirability of ensuring a globally coherent and efficient evolution of nuclear physics beyond that which is currently foreseen, it would be useful for agency officials to be informed on an ongoing basis about future major facilities. The information and advice should come from a forum that involves the world-wide nuclear physics community.*

Recommendation: A forum should be established to discuss, on a regular and ongoing basis, national and regional science-based roadmaps and to articulate a global scientific roadmap for nuclear physics. It should be organised by the International Union of Pure and Applied Physics /Working Group 9 (IUPAP-WG9) and composed of representatives of WG9 itself, the major national and regional scientific planning bodies (Nuclear Science Advisory Committee [NSAC], Nuclear Physics European Collaboration Committee [NuPECC], the Nuclear Physics Executive Committee of Japan [NPEC]) with proportionate participation from all other countries that are not members of one of the latter.

Looking beyond the timescale of the current roadmap, there is a possible need for major facilities that would be planned, designed, implemented, and utilized via a global-scale collaboration of interested countries.

Recommendation: The Working Group supports the OECD Global Science Forum's activities aimed at facilitating international consultations regarding the potential establishment of large-scale international facilities.

The Working Group finds that planning for the future of nuclear physics should be a globally-coherent response to recognized scientific challenges, using an optimal set of national, regional, and, if needed, global-scale projects. To achieve this goal, funding agency officials should consider establishing a venue where they can discuss the future of the field, with special emphasis on the role of large programmes and projects.

Recommendation: National, regional, and global planning should be done at the agency level among interested parties to optimize the science and international collaboration, taking into account the global scientific roadmap of the community. The establishment of a forum for nuclear physics funding agencies should be considered for discussing plans for new large scale facilities and for optimizing communication and cooperation at a global level.

Rationale

Nuclear physics is the study of atomic nuclei and nuclear matter and of the fundamental forces responsible for their properties and behaviour. It is the quest to understand the origin, evolution, and structure of the matter of the universe that leads to galaxies, stars, and planets, including the Earth, the terrestrial environment, and ourselves. Nuclear physics is important to society because of its extensive applications for energy, national security, health, environmental protection, and industry. Countries have historically supported basic nuclear physics research both in order to advance the scientific field and to develop the expertise, technology, and trained workforce that are needed for their national nuclear-technology related activities.

This report presents the new science opportunities and focuses on the roles and opportunities for international collaboration in the field of nuclear science. The field has seen the emergence of new research frontiers over the last decades. They arise from the new insights and developments in the fundamental underpinnings of nuclear physics, as well as from the development of novel tools that allow scientists to push the energy, intensity, and precision frontiers. These latter tools are mostly in the form of new, powerful accelerators that vastly extend the science reach over that of previous-generation machines. These accelerators are at the forefront of technology and require a substantial expert workforce for development, engineering, construction, and operation. They are also quite costly.

The scales of the technical challenges and, thus, the necessary human expertise as well as the cost strongly suggest the need to consider pooling resources and collaborating broadly on an international scale. This need is not fundamentally new to the field where, over the last decade, nuclear research has been characterized by extensive international collaborations, in particular in large-scale experiments. The tradition of free and open access to major nuclear research facilities has been a key factor facilitating international cooperation in the field.

Collaborations range from informal groupings to address specific research topics to more formal ones governed by joint proposals, memoranda of understanding, or, as within the European Union Framework Programmes, legal contracts for R&D, networking, and facility access. Yet the size, cost, and timescales of future facilities make it important to consider whether cooperation and co-ordination needs to go beyond what has been done until now, both geographically—on a global scale—and with mechanisms for co-ordinated development, construction, and operation of selected facilities and their research programmes overall. These resource issues imply joint strategic planning and priority setting before a project is launched. The present report addresses these issues and discusses venues to establish suitable frameworks and mechanisms for creating global roadmaps for strategic planning and priority setting and for co-ordination and collaboration in facility construction and utilization on a regional and global scale.

The report first describes the field of nuclear physics, including the science opportunities, facilities, workforce, and investment world-wide. The scientific vision for the future is summarized by the key research questions, as developed by various national and regional documents of the scientific communities and advisory committees, and the new capabilities that are planned to address them. A few examples illustrate the importance of nuclear physics to other sciences and to society. The current collaborative structures and strategic planning mechanisms which have served the field well in the past are discussed. For future major facilities, the challenges of international collaboration on planning and construction of large scale facilities and projects to reach the scientific vision are examined. Potential mechanisms for cooperation and communication are suggested that could achieve a co-ordinated realization on an international or, possibly, global scale.

The international discussion of these questions is timely. The last such discussion for this field was the OECD Global Science Forum (GSF) (formerly the Megascience Forum) Working Group on Nuclear Physics (1996-1999), chaired by Dr. Bernard Frois of France. Its report has been useful for the last round of large investments in this field. The present Working Group on Nuclear Physics (WGNP) was established in 2006 for a period of two years. It includes representatives from 13 countries (Australia, Belgium, Brazil, Canada, China, France, Germany, Italy, Japan, Korea, Norway, United Kingdom, and United States), the European Commission, two intergovernmental organizations (European Organization for Nuclear Research [CERN], Geneva and the Joint Institute for Nuclear Research [JINR], Dubna) and two independent scientific organisations (IUPAP/WG9 and NuPECC). The WGNP met four times during the two year period to generate this report.

Acting on behalf of the Global Science Forum, its Bureau (the Chair and Vice-Chairs) reviewed and accepted this report in May 2008.

An Overview of Nuclear Physics

The Scientific Field of Nuclear Physics

Nuclear physics extends the understanding of the atomic nucleus in two directions: towards smaller distances (by investigating the structure of the constituents of nuclei, i.e., protons, neutrons, and mesons) and towards larger distances (by exploring the very limits of nuclear stability and existence). In parallel, this understanding is applied in other areas of scientific study

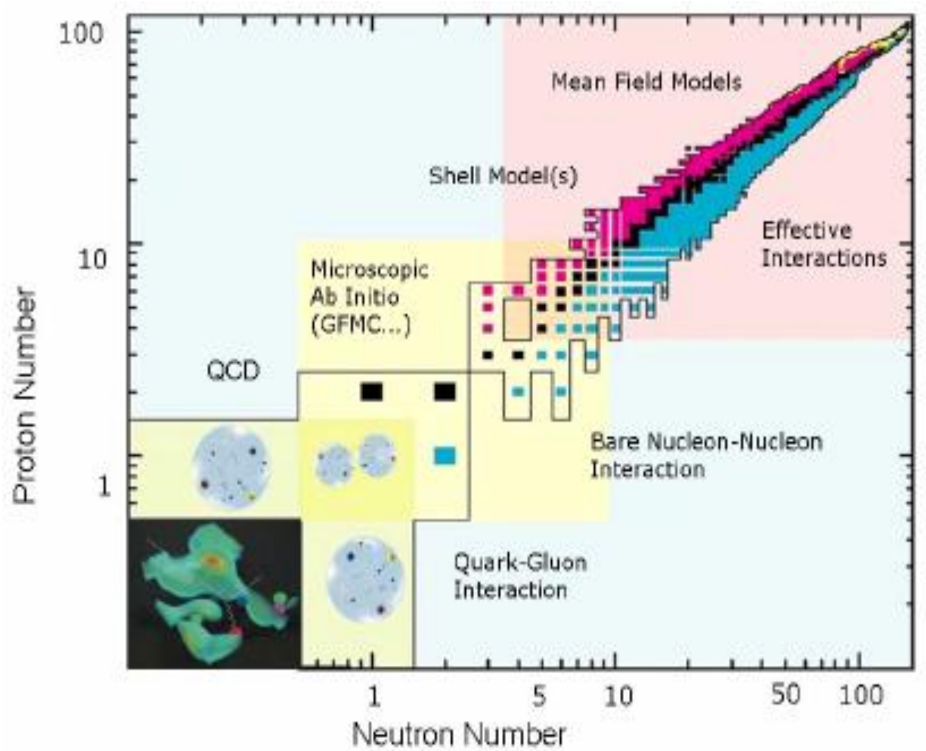

Figure 1: The landscape of nuclear research, where each box, characterized by the number of protons and neutrons, represents a nucleus for which some information is known. The labels and colours indicate the theoretical approaches that are typically used to describe these nuclei.

(e.g., in astrophysics to investigate the synthesis of elements and the production of energy in stars) or in practical applications (e.g., in nuclear medicine for diagnostic and therapeutic purposes).

The nucleus is made up of strongly interacting neutrons and protons, together called nucleons. The nucleons are part of the larger family of hadrons, tightly bound systems of quarks, anti-quarks, and gluons. Of the many hadrons that exist, only the nucleons are stable (inside the nucleus) and make up almost all visible matter. Many aspects of the physics of hadrons are still not well understood: for example, that quark masses contribute less than 2% to the mass of a nucleon, that quark spins make up only about 1/3 of the spin of a proton, and that free quarks are never observed. Solutions to these puzzles are needed to obtain a complete understanding of the strong force at nuclear distances and of the behaviour of hadronic matter under extreme conditions of temperature and density. Other key questions are the nature of the phase transition which occurred after the Big Bang, when the quarks and gluons, originally roaming free, condensed into hadronic matter and the nature of the unconfined phase. Experimentally, these latter questions are being addressed by the study of relativistic heavy ion collisions.

Towards the larger scale, the way in which neutrons and protons combine to form different nuclei is a central issue in the field. Why do some nuclei exist and not others? Why do they exhibit different decay modes, and why do they absorb energy in different ways? This aspect of nuclear physics research has been revolutionized in recent years with the development of the technology to produce beams of radioactive nuclei. These are beams of artificially-produced nuclei with unusual properties (for example, large excesses of neutrons or protons) that make them unstable (hence, "radioactive"). Theoretical models make testable predictions about these exotic nuclei. Using radioactive beams, scientists are now able to deliberately induce and study reactions, a key technique in nuclear physics, directly on nuclei other than the stable ones that Nature provides.

It is already known from preliminary studies that new phenomena emerge as experiments move beyond the limited realm of the naturally-occurring stable nuclei. The next generation of nuclear physics facilities will enable further exploration to the limits of nuclei with an excess of protons and well out into the unknown nuclear landscape of excess neutrons, where the ultimate limit that Nature sets on neutron binding is still a subject of much speculation. Tied into this effort is the exciting investigation of the ultimate limit of nuclear mass. Pioneering studies have already pushed well beyond uranium, the heaviest naturally-occurring nucleus. The tantalizing prospect still exists to reach the theoretically predicted "island of stability" where "super-heavy" nuclei may exist. If such novel nuclei can be produced in the laboratory, their atomic and chemical properties would be of enormous interest.

Nuclear astrophysics is a multi-disciplinary activity which involves nuclear physics, astrophysics, and astronomy. The goal is to understand the origin of the naturally-occurring elements and the energy generation processes that power astrophysical objects. While it has been possible for some time to study the key nuclear reactions which occur in stars like the Sun (albeit usually at energies above those relevant for stars), it has not been possible to study many of the reactions involved in extremely powerful explosive processes in Nature, such as novae, X-ray bursters, and supernovae. In these violent environments, key reactions occur between unstable nuclei. Before the development of radioactive beams, such reactions simply could not be studied in the laboratory.

Current Nuclear Physics Efforts and Facilities

Tools of nuclear physics

Most investigations of the structure of nucleons and nuclei involve the use of accelerators that generate high energy beams of particles which strike a target or collide into each other. Sophisticated detectors can separate out and identify the new particles or nuclei produced in the collisions. Some investigations require beams of neutrons and neutrinos; for these, reactor sources may also be used. As the field has developed, so has the complexity of the accelerator facilities and detectors. Many modern accelerator facilities are too large for university groups and, instead, are housed in national research centres or laboratories. These facilities attract many international users, individually or in groups. Similarly, the detectors are so complex that their cost and technical demands often require the financing and expertise from multiple international sources for construction and operation.

The recent IUPAP report, “Research Facilities in Nuclear Physics,” prepared by the IUPAP/WG9 on International Cooperation in Nuclear Physics (http://www.jlab.org/~sbrown/Handbook_rev3.pdf), provides a summary of current research activities and a comprehensive compendium of the facilities with external users groups worldwide. This inventory of resources is continually changing, as new facilities are opened and existing ones are upgraded or closed. Particular features of the decade since the last OECD report have been the steady shift towards larger facilities and the increasing number of facilities that produce radioactive beams.

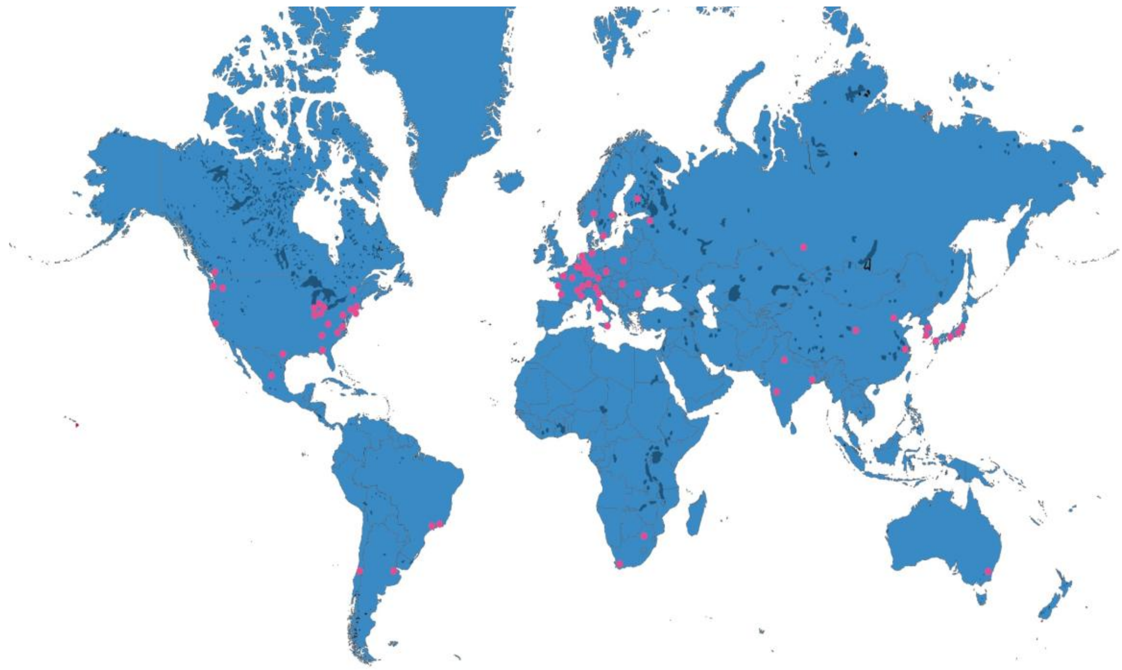

Figure 2: A worldwide map of the research facilities in nuclear physics with external users groups compiled by the Working Group 9 of IUPAP. A number of these facilities are primarily used for applications of nuclear techniques.

The 90 institutes and laboratories listed in the IUPAP report are located in 26 countries, principally in Europe, North America, and Japan. While the main motivation for advancing nuclear physics has been scientific, there are also practical and strategic reasons why countries invest in the construction and operation of the facilities. Any country with a modern economy needs some facilities at which personnel can be trained in nuclear science, given its pervasive presence in important sectors of the economy: energy generation, defence, industry, as well as in modern medicine.

The IUPAP report reveals a spread in the scale of facilities from small university-based, through medium sized at national laboratories, to a small number of facilities which operate effectively as international centres. The scale of the major facilities makes them costly to operate, but there are key scientific questions that need this level of investment. The 18 major accelerator facilities described in Appendix A represent the major capability enhancements planned for the field. However, medium-sized and small-scale facilities also play a vital role. They provide a cost-effective way of addressing some of the open questions where the ultimate in beam energy or intensity is not needed, and they also provide the absolutely essential training ground where junior scientists acquire research skills.

The IUPAP report also illustrates the international character of nuclear physics research today. For a number of operating and proposed facilities, large fractions of the user community come from outside the host country. Examples include the Gesellschaft fuer Schwerionenforschung (GSI, 40% of the 1300 users per year), the Relativistic Heavy Ion Collider (RHIC, 50% of the 1000 users per year), the Continuous Electron Beam Accelerator Facility (CEBAF, 40% of the 1300 users per year), and TRIUMF (66% of the 600 users per year). Beyond explicit user participation, there are broad international networking activities in almost all aspects of the science, including topical discussions and planning for both theory and experiment. These examples illustrate three important points. These scientists want and need to work at the facilities with the optimum capabilities to address their research goals. They bring considerable resources, both in manpower and equipment, to the execution of the scientific programme at the host laboratory. As a result of the international character, there is broad and open sharing of ideas, plans, and techniques.

Nuclear Physics Workforce

Nuclear Physics research is carried out at universities, research institutions, and national laboratories. There is a good record of cooperation between scientists engaged in basic and applied research. The complex facilities required in nuclear physics (accelerators, advanced instrumentation, and large scale computing) create a need for a large pool of support personnel– people with advanced technical and administrative skills. In addition, nuclear physics has always been an intellectually attractive subject, and the field is notably characterized by the presence of many students and postdoctoral fellows. Those who choose to leave the field are able to contribute in numerous ways to society and the modern knowledge-based economy.

The Working Group compiled an estimate of the size of the nuclear physics workforce worldwide. For Europe, it made use of a NuPECC survey and, for North America, data were provided by the U. S. Department of Energy (DOE), the National Science Foundation (NSF), and the Canadian Natural Sciences and Engineering Research Council (NSERC). For South America, the Asian region, and Australia, the data were collected by members of the working group. The Working Group did not succeed in obtaining data for Russia, which is a country with a significant nuclear physics effort.

The results of the survey should be interpreted with caution. The figures are an underestimation and probably only accurate to 10%. Funding mechanisms and employment practices differ greatly between countries, so that the classification of engineer, technician, and researcher can be blurred. There are also considerable differences between countries over where the boundaries are drawn between nuclear physics and related fields such as neutrino physics, particle physics, and astrophysics. Finally, there is some inconsistency in the way support staff and facility operations staff are counted.

The data are summarized by region in Table 1. Allowing for the countries for which no data could be collected, it is estimated that over 13,300 individuals are actively engaged in nuclear physics research (including some 3,800 in supporting roles), with approximately 6,600 Ph.D. scientists and about 2,900 graduate students—a major research enterprise indeed. The European community is the largest, about one half; the North American, about one third; and the Asian Pacific community, about one fifth.

For Europe and North America it was possible to compare the data with similar surveys taken about 10 years ago. These comparisons reveal that the number of researchers and Ph.D. students has remained broadly similar over this period (a drop in theory activity balanced by an increase in experimental work) but that the number of support staff has dropped. This latter fact may, in part, reflect the efficiency savings associated with the closure of some small scale facilities and the shift to larger, multi-user facilities.

Table 1. Data on Estimated size of Nuclear Physics Workforce

Region	Theory Ph.D.	Experiment Ph.D.	Ph.D. students	Support	Totals
Europe	650	2260	1400	2210	6520
North America	350	1360	900	1150+	3760+
South America	70	100	120	100+	390+
Asia Pacific	~ 610	~ 1190	~ 520	300+	~2620
Total	~ 1680	~ 4910	~ 2940	3760+	13290+

~ indicates that some data has been estimate

+ indicates that only partial data existed for some countries (so a lower limit)

Europe comprises data from Austria, Belgium, Croatia, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Netherlands, Norway, Poland, Portugal, Romania, Spain, Sweden, Switzerland, and the United Kingdom. North America comprises data from Canada and USA. South America comprises data from Argentina, Brazil, Chile, Colombia, and Venezuela. Asia Pacific comprises data from Australia, China, India, Japan, Korea, and Taiwan.

Support for Nuclear Physics

The Working Group gathered data on the funding for nuclear physics activities worldwide, but it encountered significant difficulties. The challenges are the following: (1) funding models differ greatly between countries with, for example, workforce costs included in some estimates and not in others; (2) capital funding is accounted for in different ways; (3) some major, costly facilities are used for other research activities, so the attribution of funding for nuclear physics is not always clear; (4) major differences exist in the cost of living between countries. An analysis of the available figures suggests that the total spending is approximately $2B (US) per year. The regional breakdown broadly follows that for the workforce given above, i.e., North America at two thirds the level of Europe and the Asian region at about half the level of Europe. Thus, on average, a nuclear scientist is supported at approximately $200k (US) per annum in the major industrial countries.

Achievements over the Last Decade

Major discoveries and progress have been made in nuclear physics over the last decade; these have been reported extensively in recent reports by the regional science advisory groups (see e.g., NuPECC Long range Plan 2004 (http://www.nupecc.org) and the 2007 NSAC Long Range Plan (http://www.sc.doe.gov/np/nsac/nsac.html). A few selected examples are given here as an indicator of the vigour, importance, and breadth of the field.

By colliding nuclei at the very highest energies achievable, physicists have discovered a new state of matter, the quark-gluon plasma (QGP). In this state the neutrons and protons that make up our everyday world dissolve into a mixture of quarks and gluons (which are believed to be among the most fundamental particles in Nature). This is the form in which matter is believed to have existed soon (around 1 microsecond) after the Big Bang. The ability to perform experiments on this primordial material is of enormous interests to astrophysicists and cosmologists.

By detecting neutrinos (uncharged particles emitted in nuclear decays) coming from the sun, nuclear physicists have discovered that these particles have mass (albeit very small). Up until this point, the dominant theory of fundamental physics (the "Standard Model of particles and interactions") had been based on the neutrinos having no mass, so this discovery is of the most fundamental significance and requires a renewed effort to uncover the truly fundamental laws of Nature.

By making precise measurements of the quark structure of the nucleon, nuclear physicists have found evidence that existing theories of strongly interacting matter may not be able to adequately account for even basic properties of hadrons, such as their internal charge distribution. Again, these experimental results are motivating scientists to seek a better, more complete theoretical understanding of the physical world, possibly involving an entire paradigm shift away from current models. These same investigations have also led to significantly improved limits on the mass scale associated with physics beyond the Standard Model.

By developing the technology to produce accelerated beams of short-lived radioactive nuclei, physicists are now able to study the unstable nuclei and nuclear reactions that occur in some of the most spectacular events in the Universe: the stellar explosions that occur in novae, X-ray bursters, and supernovae. This new capability, coming at the time when new satellite missions can study the gamma ray emission from these objects, has revolutionized the ability of researchers to understand and model these amazing objects. Among the unusual properties these exotic nuclei reveal are such features as highly deformed shapes and neutron skins (which may be a way to probe the material which makes up the exotic neutron stars which populate the universe).

Finally, at facilities in Germany, Japan, Russia, and the USA, nuclear physics groups have been competing and collaborating to create "super-heavy" nuclei larger and heavier than those that Nature provides. These new nuclei form a group of elements which have never before been observed (or even named), and there is much interesting atomic physics and chemistry to be learnt from them.

Findings and Recommendations:

There is a significant global effort involved in basic nuclear physics research today, involving some 13,000 scientists and support staff, with funding of approximately $2B per annum. *The breadth of nuclear physics and its strong links with other sciences and national need result in the* *boundaries being defined differently in different countries.* This finding is particularly true for neutrino physics and other interfaces with particle and astro-particle physics.

International coordination in nuclear physics must take into account the national differences in the definition of its boundaries with closely related research fields.

Major discoveries and advances have been made during the past decade, addressing the fundamental questions of the field. This progress was made possible by significant investments in frontier research facilities and technological advances which were initiated more than a decade ago.

A survey finds nuclear physics research facilities are operated at 90 institutes in 26 countries, with the largest concentration in Europe, Japan, and the USA. There is a wide diversity in the size, complexity, and costs of the facilities needed, which include accelerators, reactors, and underground laboratories. *The Working Group finds that this diversity has evolved to meet the needs of the individual countries and regions.* There exist a select number of major facilities that are technically complex and costly and that are operated as international user facilities. Some medium sized facilities operate in a similar manner. Small, and in many cases university-based, facilities play important roles for specialized nuclear physics studies and as training grounds for young scientists. The medium and smaller sized facilities, in general, often serve society at large through applied nuclear physics programmes and nuclear medicine**.**

It should be recognized that there are important roles for nuclear physics research facilities with a wide diversity in both size and type. As major new facilities are planned, an appropriate balance of facilities must be maintained.

The Working Group finds that about 30% (in some cases more than 50%) of the users of the large and medium sized facilities are from outside the country where the facility is located. Support for the operations of these facilities has historically been provided by the host country or region with a policy of free and open access by the international scientific community and with beam time allocated based upon the merit of the proposed research.

Nuclear physics research has provided a pool of highly qualified personnel with skills important for a wide range of important areas of modern life (medicine, energy production, engineering, national security).

The Working Group finds that training in nuclear physics is a good career option in most countries because of the opportunity to participate in discovery science and the wide range of applied areas where the acquired knowledge and experience is valued.

Scientific Vision for the Future

Future Directions

The previous section provided the basis of where the field of nuclear physics stands today. For the future, there is international consensus on five key questions that motivate future research directions in nuclear physics. Work underway at existing facilities around the world can provide partial answers to these broad questions; however, new facilities and the development of new theoretical tools are required to obtain the deeper understanding that is needed to fully answer them. Global planning and the construction of major new facilities are intimately linked to the questions. Thus, they provide a logical framework for laying out a roadmap for the field. The questions are highlighted in the next few paragraphs. For orientation, some of the newly upgraded and future facilities designed to address them are mentioned in each section. Appendix A gives a summary of the major facility plans by region.

(a) Is QCD the complete theory of the strong interaction?

A central problem in nuclear physics is to connect the observed properties of the hadrons to the underlying theoretical framework of quarks, gluons, and the theory of their interactions, Quantum Chromodynamics (QCD). How these properties change when the hadrons are placed in a nuclear environment—be it a heavy nucleus or a fireball of hot and dense nuclear matter, which might recreate, in the laboratory, the environment found throughout the universe shortly after the Big Bang—is also of fundamental interest. These problems can only be solved by precision experiments that can be compared to QCD predictions, ultimately testing whether QCD is, indeed, the complete theory of the strong force.

Addressing these objectives is a driving force for future facilities, such as the Japan Proton Accelerator Research Complex (J-PARC), the international Facility for Anti-proton and Ion Research (FAIR) at the GSI Laboratory, the 12 GeV Continuous Electron Beam Accelerator Facility (CEBAF) Upgrade at the Jefferson Lab, the Mainz Microtron (MAMI), A Large Ion Collider Experiment (ALICE) at CERN, and RHIC II at Brookhaven National Laboratory (BNL). In the longer term, discussion is under way at Jefferson Lab, BNL, and CERN to build an international high energy electron-ion collider to probe the glue which binds quarks into nucleons and nuclei, yielding an unambiguous understanding of their internal structure.

(b) What are the phases of nuclear matter?

Our present understanding of the nuclear phase diagram suggests that nuclear matter will exist in a very different form at extreme values of temperature and density. This new form of matter, often referred to as the quark-gluon plasma, is under intense investigation experimentally at RHIC and has shown quite surprising properties. It also will be the focus of the ALICE experiment at the Large Hadron Collider (LHC) at CERN and future research at FAIR.

At the highest densities, yet at still rather low temperatures, the quarks making up the nucleons may form another new state of matter—colour superconductivity—where they condense into pairs like the electrons in a superconducting material. As the density rises, one may also find that a large fraction of matter is made up of hadrons that incorporate strange quarks, which do not occur in normal matter. Such states of matter may indeed occur in neutron stars, which can be viewed as gigantic nuclei with a radius of about 10 km.

(c) What is the structure of nuclear matter?

A key goal for nuclear physics is to develop a comprehensive understanding and a predictive theory of complex nuclei. Worldwide, this goal has driven the development of various cutting edge facilities for experiments with short-lived rare isotopes in order to provide data and discover new phenomena against which theoretical predictions have to be tested. Rare isotope beams (RIB) are obtained by complementary techniques, either through the isotope-separation-on-line

(ISOL) process or through in-flight production.[1] Major advances in the field will come through the extended reach in proton-to-neutron ratio of planned new or upgraded facilities, including the Radioactive Isotope Beam Factory (RIBF) at Rikagaku Kenkyusho (RIKEN), FAIR at the GSI Laboratory, the HIE-ISOLDE facility at CERN, Système de Production d'Ions Radioactifs en ligne 2 (SPIRAL2) at Grand Accelerateur National D'ions Lourds (GANIL), the facility for the Study and Production of Exotic Species (SPES) at INFN Legnaro, the Isotope Separation and Acceleration II (ISACII) at TRIUMF, and the planned Facility for Rare Isotope Beams (FRIB, USA) with capabilities for fast, stopped, and unique reaccelerated beams. Complementary facilities with very high-intensity low-energy reaccelerated beams for astrophysics, such as the more conceptual European Isotope Separation On-line Radioactive Beam Facility (EURISOL), are envisioned as cornerstones of future international efforts. A multi MW driver accelerator for an ISOL facility producing very intense radioactive beams for re-acceleration and secondary fragmentation may only be possible within a global context.

All these facilities will provide new and important insights into the structure of nuclei and are expected to discover new phenomena that will lead to major progress towards a unified description of nuclei.

(d) What is the role of nuclei in shaping the evolution of the universe?

Another central objective of nuclear physics, together with astrophysics, is to explain the origin and abundances of the chemical elements in the universe. Tied to this pursuit are challenging questions such as the mechanism of core-collapse in supernovae; the structure, cooling, and presence of strange matter in neutron stars; the origin, acceleration, and interactions of the highest energy cosmic rays; and the nature of galactic and extragalactic gamma-ray sources.

New tools in astronomy and nuclear physics, such as the aforementioned RIB facilities, already are paving the way for a much better understanding of these questions. Nuclear astrophysics has benefited enormously from the advent of rare isotope beam facilities dedicated to the measurement of nuclear reactions involving short-lived nuclides of particular relevance to astrophysics. These include measurements of the various nuclear capture processes and the determination of masses, half-lives, and structures of rare nuclei that occur in cataclysmic stellar environments. However, a major fraction of the nuclei involved in the synthesis of most of the heavy elements through the so-called r-process, believed to occur in core-collapse supernova explosions, can only be studied with the future RIB facilities. Experiments at those facilities may finally provide the answer as to the origin of the heavy elements.

(e) What physics is there beyond the Standard Model?

Nuclear physicists have long tested the Standard Model of particle and nuclear physics with precision experiments. While the Standard Model has proven remarkably resilient to these tests, recent measurements of neutrino properties coupled with astronomical observations indicating the presence of dark matter and dark energy provide strong evidence for physics beyond it. Likely associated with physics beyond the Standard Model is the observation of an obvious imbalance between matter and antimatter in the universe. An essential ingredient in solving this enigma is the presence of new interactions which may be measurable in the properties of mesons, neutrons,

[1] Leading ISOL facilities: ISOLDE at CERN, HRIBF at ORNL (USA), ISAC at TRIUMF (Canada), SPIRAL at GANIL (France). Leading in-flight facilities: GANIL (France), GSI (Germany), NSCL at MSU (US) and RIKEN (Japan).

and atoms, e.g., via the occurrence of static electric dipole moments. Different types of precision experiments searching for indications of additional forces that were only significant in the initial moments after the Big Bang will, in the future, be possible at Jefferson Lab with its 12 GeV CEBAF upgrade, J-PARC, and at the aforementioned rare isotope facilities.

Finally, resolving the solar and atmospheric neutrino puzzles by the Sudbury Neutrino Observatory (SNO) and Super-Kamiokande—thereby confirming that neutrinos change their character, or oscillate—has opened up possibilities for exciting discoveries in the neutrino sector. The nature of the identified neutrino oscillations may be best addressed by a future international neutrino factory or beta-beam facility, while an observation of neutrino-less double beta decay would revolutionize the understanding of the true character of neutrinos and could determine their mass scale. Many of these experiments, which involve both nuclear and particle physicists, benefit by going deep underground to reduce the backgrounds from cosmic radiation. Indeed, nuclear scientists were the leaders in this area 40 years ago with the pioneering solar neutrino measurements of Ray Davis. Existing and future underground laboratories play an essential role in the search for the neutrino-less double beta decay, the decay of the proton, and for the understanding of enigmatic dark matter. Underground research at a number of facilities including Kamiokande (Japan), Gran Sasso (Italy), and SNOLAB (Canada) has made dramatic discoveries, but the current facilities are heavily oversubscribed. A new Deep Underground Science, and Engineering Laboratory (DUSEL) is under design in the United States to significantly increase the space available at the greatest depths for such measurements.

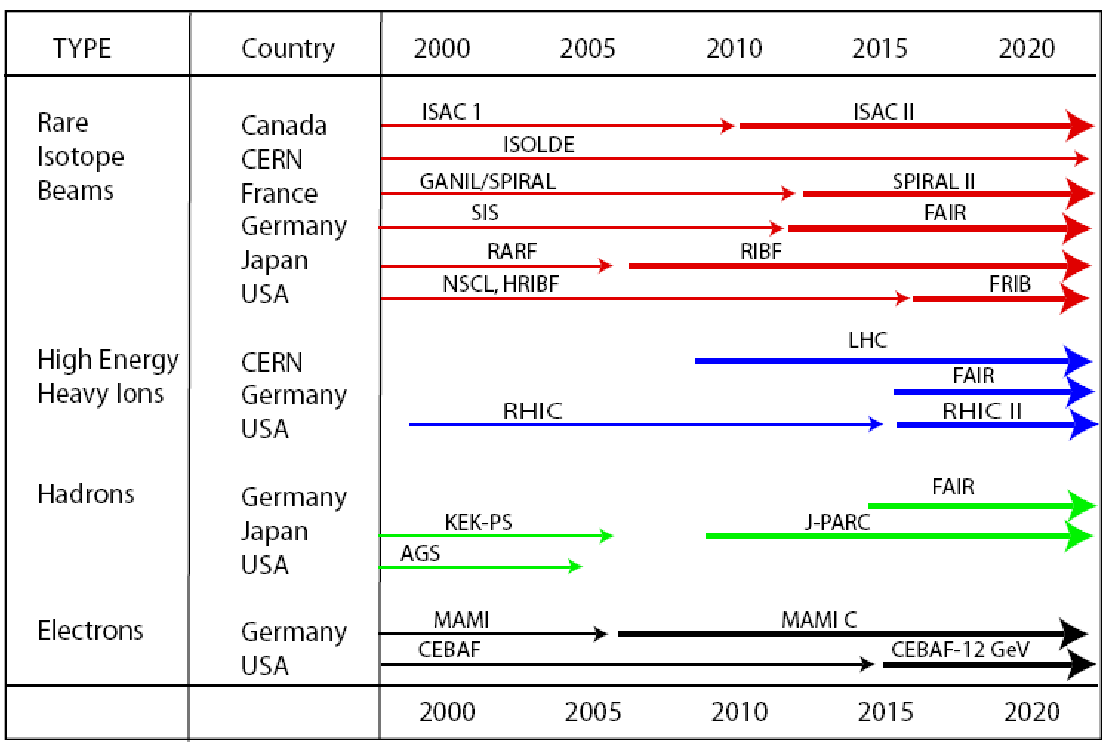

Figure 3: Summary of large-scale accelerator facilities in nuclear physics for the countries participating in this Working Group—existing, estimated starts of operation, or proposed starts of operation for the period 2007-2020.

The Global Roadmap for Nuclear Physics

The global roadmap for nuclear physics, which emerges from matching the proposed new and upgraded facilities planned by the various countries and regions to the highest priority scientific opportunities, shows a remarkable degree of coordination in optimizing the available resources for the world-wide nuclear physics programme. Figure 3 shows most of the larger accelerator facilities that comprise this roadmap.

As noted above, nuclear physics is not a completely self contained discipline, but is intertwined with other areas of study such as particle physics and astrophysics; the definitions of these areas also vary from country to country. Examples of non-accelerator-based facilities at which nuclear physics shares a role (and in some countries a significant role) are underground laboratories. Figure 4 shows the present status of the larger (areas greater than 400 m^2) existing and planned facilities of interest to nuclear physics. These laboratories can serve nuclear physics, particle physics, and astrophysics, as well as areas outside the physical sciences, and are large enough that they can figure into planning processes at the national level and beyond.

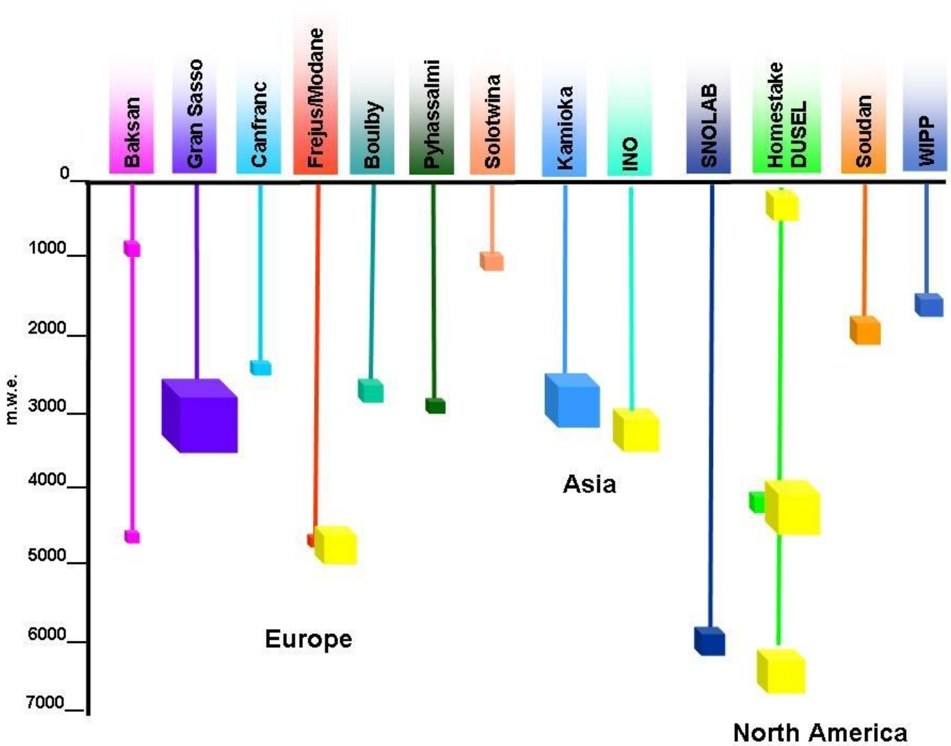

Figure 4: Volumes of existing and planned space in underground laboratories worldwide, as a function of depth (expressed in meter water equivalent, mwe). The laboratories shown are all above 400 m^2 in footprint area. The volumes shown in the graph are those exploited for research that is directly relevant to nuclear physics (thus, for example, existing spaces or planned extensions devoted to gravity wave experiments or geology experiments are not shown). At three facilities (Homestake/DUSEL, Fréjus/Modane, INO), new development or expansion projects are in advanced stages of authorisation, and are depicted in yellow. Additional plans and proposals are under discussion in other countries.

The importance of the complementary nature of the various facilities (including those provided primarily by other fields) cannot be overstressed. It is essential for progress. To someone outside the field, some of the distinctions between capabilities may appear subtle, but they are not. Indeed this roadmap highlights the extent of collaboration and cooperation among the scientists and the fact that plans for future facilities have been developed by scientists working together with funding agencies in their region with full appreciation of the world-wide scene. The processes in place appear to have worked well in developing this suite of new research capabilities. Because the research portfolio is broad and funding in each country is limited, the most important tasks in the future will be to explore mechanisms of how to utilize these facilities most effectively and coordinate R&D investments for future facilities in order to obtain the maximum output for the field of nuclear physics.

Findings and Recommendations:

There exists an international consensus on five key questions that motivate future research directions in nuclear physics, i.e., (1) Is QCD the complete theory of the strong interaction? (2) What are the phases of nuclear matter? (3) What is the structure of nuclear matter? (4) What is the role of nuclei in shaping the evolution of the universe? and (5) What physics is there beyond the Standard Model?

A global roadmap for nuclear physics emerges from matching the proposed new and upgraded facilities planned by the various countries and regions to the highest priority scientific opportunities. *The Working Group finds that this global roadmap reflects a high degree of coordination in optimizing the available resources for the world-wide nuclear physics programme.* The new facilities and upgrades that are now under consideration will ensure the continuing success of nuclear physics, with an estimated investment worldwide of $4 billion (US$) during the next decade.

The proposed new and upgraded facilities within the global roadmap for nuclear physics are well coordinated and will produce outstanding science and discoveries. Their implementation is recommended.

Relevance of Nuclear Physics to Society

As discussed above, nuclear physics is the science of atomic nuclei and their constituent particles. The ever-broadening scope of nuclear physics since the 1930's has generated sub-fields such as particle physics, neutron scattering, accelerator science, and broad ranges of applications in chemistry, physics, the environment, and medicine. Most recently, in addition to nuclear energy, its applications to archaeology and national security have grown in importance. In some areas the main scientific thrusts of nuclear science are irrevocably intertwined with other areas of science such as the QCD structure of matter with particle physics or the origin of the elements with astrophysics and cosmology, to name only two examples. In other areas, the skills and techniques of the field, both theoretical and experimental, become of immense value in new settings.

With such a broad scope in fundamental and applied nuclear physics, a multi-skilled workforce has been generated initially by curiosity driven research. Surveys of the field have shown that of the over 5,000 students that received their Ph.D. degrees in nuclear physics, about 1/3 are in national laboratories or in government work in related applied areas and about 1/3 are in the private sector workforce where their training is considered to be valuable and is being utilized.

A thorough accounting of the connections of nuclear physics to other sciences and the relevance to society would require far more space than is available here. Instead, this diverse scope of current areas of fundamental scientific interest and societal impact is illustrated with four examples: the impact of nuclear physics results in basic research in the creation of the heavy elements in supernova explosions and, on the applied side, the power of nuclear physics methods in medical, environmental science, and nuclear energy.

Astrophysics and astronomy provide a first example where the science is inextricably linked to nuclear science as seen in the fourth question of the section on the Scientific Vision for the Future. When astronomers look at what stars are made of, they see evidence that over half the elements heavier than iron are created in a very neutron-rich environment that may occur in supernova explosions. Few of the nuclei involved have ever been seen in the laboratory, yet the pattern of element abundances (Figure 5) provides a characteristic fingerprint of their structure. New nuclear techniques are providing the means to synthesize these rare isotopes in the laboratory. Also the properties of neutrinos determine how energy is carried away from the explosion. Coupled with astrophysicists advancing models of supernova explosions and nuclear and high energy physicists achieving new insight into the effects of the properties of neutrinos, these results on rare isotopes will help us understand these grand fireworks in the sky and where the elements on earth originated.

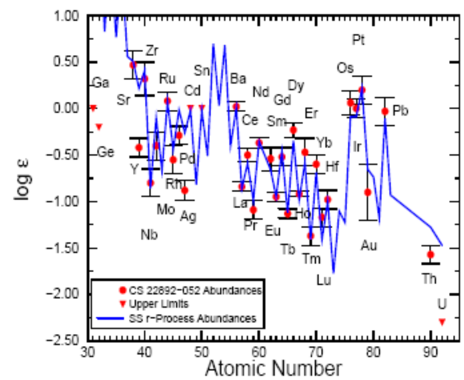

Figure 5: The distribution of elements measured in a distant star reveals a characteristic fingerprint of the properties of nuclei.

The applications of nuclear physics methods in medicine are now indispensable to diagnosis and treatment of disease. In 1931, Ernest O. Lawrence invented the cyclotron, which developed into a powerful particle accelerator. Its offshoots are the sector-focusing cyclotron, the synchrocyclotron, and the synchrotron used for basic nuclear physics research and, increasingly, for applied nuclear science. Shortly after its invention, the cyclotron was used to produce a plethora of radioactive isotopes, and now hospitals and clinics have their own instruments to produce short lived isotopes on site for medical diagnostics and treatment. Medical imaging is another example of translated nuclear technology. Nuclear magnetic resonance (MRI) is an offshoot of Rabi's fundamental studies on nuclear moments. Computer assisted tomography (CAT) and positron emission tomography (PET) spring from the programmes of nuclear particle detector construction. Radiation treatment of disease—including gamma-ray, neutron, proton, and ion-beam therapy—are well developed technologies stemming from accelerator technology and an understanding of energy deposition by particle beams.

Figure 6: A clear (bottom) and smoggy (top) day in Sydney Australia. Fine particulates in the air are a significant health risk and can be well characterized by proton-induced x-ray emission.

In the environmental area, smoggy conditions are of great concern in many industrial areas. For example, Figure 6 illustrates a clear day and a (rare) smoggy day in Sydney, Australia. In 2005 Australia set new National Environmental Protection measures for fine particles in the atmosphere at 8 $\mu g/m^3$ annual average and 25$\mu g/m^3$ 24 hour maximum. These guidelines recognize the increased importance of fine particle pollution for human health. Proton induced x-ray emission (PIXE) is an ideal nuclear technique for characterizing fine particles in air and finding their sources. At the Australian Nuclear Science and Technology Organisation, 40,000 filters from Australia and Asia have been analyzed for 25 different chemical species over the past 15 years. PIXE techniques are now routine for state, local council, mining, and industrial environmental protection agencies.

The challenge to the nuclear power industry is to create a new generation of reactors that are safer, sustainable, resistant to proliferation, and that allow a solution to the nuclear waste issue that is acceptable to society. A number of new concepts are under consideration, and there is great interest in improving the knowledge of the basic nuclear properties to better predict their behaviour. New facilities, such as the neutron Time of Flight (nTOF) facility at CERN and exotic beam facilities, are designed to measure the important cross sections and characterize the properties of the fission fragments. Coordinating and archiving these results effectively is an important international responsibility. One of the promising approaches to dealing with the nuclear waste is to “burn” it with intense neutron beams either from fast reactors or by proton induced spallation using high power nuclear accelerators. These techniques can reduce the amount of very-long lived activities that must be stored for many generations. Accelerator transmutation of waste is one application (accelerator stimulated sub-critical reactors is another) that emerges directly from the development of high-power particle beams for fundamental research.

Findings and Recommendations:

Advances in nuclear physics techniques and accelerator technology have made significant contributions to national and societal priorities, including new approaches in energy, national security, industry, and medicine.

The Working Group finds that the contributions of nuclear physics can be enhanced through explicit mechanisms to make nuclear scientists and the broader community more aware of how the insights and techniques of nuclear physics can be applied.

Recommendation: The nuclear science community, funding agencies, and professional societies should continue to encourage interactions to make nuclear scientists and the broader community more aware of how the insights and techniques of nuclear physics can be applied. The nuclear science community should increase its efforts to better articulate the relevance and benefits of nuclear physics to national needs and society.

The basic and applied sciences, such as nuclear energy and national security instrumentation, rely on the accumulated, systematic, and accurate measurement of nuclear data. Databases of evaluated nuclear data are essential to provide nuclear results to the broader interested communities. In some areas, such as nuclear energy, there is strong international coordination of this activity through agencies such as the OECD Nuclear Energy Agency, the IAEA, and the U.S. Nuclear Data Program. *However, the Working Group finds that gaps exist in the international plans for the coordination and oversight of these databases, and that available resources are insufficient.*

The national agencies should work together with international organisations, such as the OECD Nuclear Energy Agency, the International Atomic Energy Agency, and the international science community, to create a more comprehensive international plan to acquire and curate nuclear data for the wider community.

International Cooperation and Strategic Planning

International issues were the primary concern of the OECD Working Group on Nuclear Physics. These issues can be grouped into two categories: (1) collaboration in research at the level of individual scientists, scientific groups, and research institutions/laboratories and (2) coordination of strategic planning by governmental and intergovernmental institutions (typically, funding agencies). These are discussed separately below.

Collaboration in Nuclear Physics Research

Nuclear physics began in the late nineteenth century as “bench top science” conducted by individuals or very small groups using radioactive sources and small detectors to study nuclear decays and low-energy scattering. Rather quickly though—and because of the importance of being able to artificially induce nuclear reactions—accelerators became the key instrument of research[2]. This factor, together with the development of the associated complex detector systems, led to major new requirements for facilities and equipment and provided greatly expanded incentives and opportunities for collaboration across institutional and national boundaries. Thus, since the emergence of very large dedicated nuclear physics accelerators in the 1960s, levels of collaboration evolved from small unstructured exchanges of ideas, progress reports, research goals, and independent (possibly coordinated) work on common research objectives to joint shorter-term studies and joint proposals, to longer term joint R&D and research, to institutional collaborations on joint projects, and, most recently, to joint construction and operation of research facilities.

[2] The key development, which had many repercussions for both basic and applied research, was the invention of the cyclotron by Ernest Lawrence in 1931.

A key principle governing this productive history of cooperation was that of free and open access to facilities. According to this principle (which is by no means universal in science but has proven its worth in other domains, notably high energy physics[3]) the use of research facilities is allocated based on the importance and quality of the research proposed (and related criteria such as the likelihood of success and the scientific qualifications of the researchers) regardless of nationality or institutional affiliation of the proposers. In addition, the operating costs of the facility are borne by the facility itself, with external users only being expected to pay for their specialised experimental equipment, certain consumables, plus travel and subsistence. It should be noted that the application of this principle is far from being a trivial matter; it may, for example, result in the turning down of proposals from researchers who are nationals of the country that owns and operates the facility and who may even be permanent employees of the facility. Over many decades and without any formal international agreement in place, the provision of free and open access to nuclear physics facilities is a remarkable example of commitment to excellence and to the universal values of science. Without the required discipline and dedication, it would have been possible for the system to break down if only one country decided to begin practicing "scientific protectionism" with regard to the use of its own facilities.

Extensive international consultations and interactions among scientists (including, most significantly, collaboration in actual experimental and theoretical research) have created an ongoing, evolving, global consensus about the scientific priorities for nuclear physics and the research agenda for the future. This consensus is described, in greatly abbreviated form, on pages 16-21 of this report. Its realisation depends on the provision and exploitation of an optimal set of facilities which requires, in turn, the commitment and cooperation of national and regional funding bodies.

Existing National and Regional Mechanisms for Strategic Planning and Priority-Setting

Numerous strategic planning and priority-setting activities take place at institutional, national, regional, and global levels. For the purposes of this report (i.e., for formulating recommendations for new actions) it is important to distinguish three classes of ongoing activities, as described below. Collectively and considered in their global totality, the results of the activities are reflected in the roadmap. The Working Group's recommendations are aimed at ensuring that the roadmap can be translated into reality as efficiently as possible and that the health and vitality of nuclear physics be maintained well beyond 2015.

(1) National activities under the aegis of governments

These national activities are conducted under the aegis of governmental bodies (funding agencies) in close association with chartered scientific groups whose mandate is to define scientific priorities and to offer information and advice to the decision-makers. The members of the scientific groups are usually prominent scientists. Examples of these groups include the following:

- In the United States, the Nuclear Science Advisory Committee (NSAC) to the Department of Energy (DOE) and the National Science Foundation (NSF);

[3] The principle of free and open access originated in the high energy physics community and is embodied in the "ICFA Guidelines" of the International Committee for Future Accelerators. (http://www.fnal.gov/directorate/icfa/icfa_guidelines.html). It became a recommendation of IUPAP in 1996 (http://www.iupap.org/ga/ga22/majfacil.html) .

- In Canada, the Subatomic Physics Long Range Planning Committee to the Natural Sciences and Engineering Research Council (NSERC);
- In Germany, the Komitee fuer Hadronen und Kerne (KHuK) which advises the Ministry of Education and Research;
- In Japan, the Nuclear Physics Executive Committee (NPEC) which reports to the Ministry for Education, Culture, Sports, and Science and Technology;
- In Poland, the Commission for High Energy (and Hadron) Physics of the National Atomic Energy Agency;
- In Sweden, France, Italy, and the United Kingdom, similar advisory bodies.

The cooperative planning and priority-setting activities between agencies and the scientific community have been very beneficial to the field of nuclear physics, and the numerous studies and reports produced by the scientific advisory groups are a valuable resource to policy-makers and to anyone interested in the steady accumulation of knowledge and insight into the workings of nuclear matter.

(2) Inter-governmental activities (chiefly at the European level)

The oldest inter-governmental organisation dedicated to cooperation in nuclear physics is CERN, the European Organisation for Nuclear Research, established in 1954. Currently, it has a strong focus on elementary particle physics, but its mandate and experimental programmes still encompass facilities and experiments in nuclear physics. For example, one of the four collider detectors (ALICE) of the LHC is designed for studying hot, dense nuclear matter and the quark-gluon plasma, and the ISOLDE facility produces beams of exotic nuclei.

In 1956, the Joint Institute of Nuclear Research (JINR) was established in Dubna, near Moscow.

With the establishment of the European Union, the situation qualitatively changed for international cooperation for science in Europe. With a formal governmental structure, the encouragement of international activities and planning in science paralleled similar interests in other areas. Perhaps equally important, the governing structure provided a funding mechanism to encourage this cooperation.

International cooperation has received a major boost through the so-called "Framework Programmes" of the European Union. In 1989, under the Second Framework Programme for Community R&D, the European Commission introduced a scheme to help Europe's top and most promising researchers to conduct experiments at whichever facility in the European Union was best equipped for their research, irrespective of where it was located or who owned and operated it. To this end, since the late 1980s, successive Framework Programmes have contained an activity designed to promote access to outstanding facilities. Over successive Framework Programmes additional funding schemes have been added to support networking between research infrastructures and the conduct of joint projects for research and technical development.

Under the Sixth Framework Programme, all these support schemes were integrated within a single instrument called "Integrated Infrastructure Initiatives." In nuclear physics the following two programmes are presently supported by the EU: EURONS and Hadron Physics. EURONS addresses nuclear structure and nuclear astrophysics, and includes 8 research infrastructures. It involves approximately 1500 nuclear scientists from about 100 institutions in 27 countries. The access activities to the leading European nuclear physics facilities constitute the backbone of EURONS. Hadron Physics involves all relevant European facilities in this area of research and two leading high-performance computing centres, with a total of nine research infrastructures. More than 2000 researchers, both experimentalists and theorists, from about 140 research institutions participate. The networking activities of both programmes have a more prospective character with an emphasis on fostering future cooperation, pooling of resources (including human capital), stimulating complementarity, and ensuring broad dissemination of results.

A relatively new initiative of the European Commission is the ERANET programme which supports and strengthens the networking of funding agencies in specific fields of science. An ERANET proposal for nuclear physics was funded recently. The aim of such an ERANET is not only to provide a forum for discussion and information exchange but also to establish tools for, and to eventually implement, joint activities.

In 2002 the European Strategy Forum for Research Infrastructures (ESFRI) was formed, composed of delegates from 27 national research ministries and one representative of the European Commission. In 2006, the *ESFRI Roadmap* identified 35 priority research infrastructure projects of pan-European dimension for the next decades. These projects span a very broad scientific spectrum, including the social, life, energy, environmental, and materials sciences. There are two nuclear physics infrastructures on the roadmap: FAIR and SPIRAL2. Decisions on financial contributions from countries to any of the projects on the ESFRI Roadmap will continue to be taken at the national level, but the ESFRI process has been broadly welcomed as an important step in the ongoing process or European integration. Follow-on activity by ESFRI is already under way.

The progress in Europe has been dramatic. What is less clear is how to apply these successful European strategies to a global level, where there is not an over-arching governmental structure or a stable funding source for promoting internationalism.

(3) Activities undertaken by non-governmental organizations

The oldest organizations that are dedicated to fostering collaboration are the International Union for Pure and Applied Physics (IUPAP) and its Nuclear Physics Commission (one of 19 Commissions spanning all the sub-fields of physics). IUPAP sponsors and supports conferences but not research programmes and facilities. To complement the work of the Commissions, working groups have been established to deal with cross-disciplinary issues and to promote international coordination of programmes and facilities. These groups include the International Committee on Future Accelerators (ICFA), created in 1976, and the Working Group on International Cooperation in Nuclear Physics (WG9) set up in 2005.

WG9, whose membership includes the chairs of NSAC and NuPECC (described below) and representatives of the major laboratories world-wide, has an IUPAP mandate to provide a landscape of key science issues and future directions in nuclear physics, to organise and provide expert advice for governmental or inter-governmental organizations, and to encourage coordination of facility construction worldwide. However, WG9 is not formally connected to any funding agencies or governmental body and works strictly in an advisory capacity.

To foster cooperation in nuclear physics in Europe, the Nuclear Physics European Collaboration Committee (NuPECC) was formed. It was originally a representative board established by the science community and delegates from the major nuclear physics facilities in Europe. It is now a formal Expert Committee of the European Science Foundation, and its members are appointed with the help of national funding agencies and/or national research councils. The long range plans developed by NuPECC for Europe, as with the long range plans developed by NSAC for the U.S. and the other national activities, establish a reference frame that projects into the nuclear physics community worldwide. Together these plans can *de facto* be considered a first draft blueprint of a worldwide long range plan and science prioritisation.

In addition to the three classes of ongoing activities enumerated above, mention must be made of the OECD Working Group on Nuclear Physics, which was authorised for the period 1996-1999 by the Megascience Forum and for the period 2006-2008 by the Global Science Forum. This time-limited effort, bringing together all of the stakeholders at the global level (representatives of major funding agencies, advisory bodies, and the inter-governmental and non-governmental organisations), has been a venue for discussions about future directions and requirements of nuclear physics in a truly international context.

The Challenges of Future International Collaboration on Large Facilities and Projects

Regarding future facilities beyond the current roadmap, the critical question is whether some facilities are of such size and cost that they may only be implemented via a global-scale collaborative effort. The science-based deliberations of the OECD Working Group converged on two possible projects of this type: a very high power (multi-megawatt) ISOL-type rare isotope facility for producing beams of short-lived nuclei (EURISOL) and an electron-ion-collider.

In considering future facilities, it is useful to focus on the different generic stages of implementation: formulating the science case and research goals; defining facility scope and conceptual design; performing research and development (R&D) on critical technologies and components; engineering design and facility integration; (if appropriate) negotiating an international agreement, funding scheme and management structure; selecting the site; constructing the facility; commissioning; operating; upgrading; and decommissioning.

As noted, there is already a good history of international collaboration on the first two stages which principally involve members of the scientific community. Joint pre-construction R&D has, in the past, been mostly limited to experimental instrumentation rather than the accelerators themselves (with the important exception of efforts supported by the EU). For future major facilities (beyond the roadmap on page 18) a global R&D effort will probably be needed (an example is the enormous challenge of developing high-power ion sources and targets for ISOL), but it is by no means clear how this global R&D effort could be organised, funded, and managed. An approach similar to that of the European Union Integrating Infrastructure Initiatives (I3) might be feasible. In particular, the network components of the EU I3's, which finance travel and meeting costs for (nationally approved and financed) R&D activities at participating laboratories, might be appropriate models to follow.

There have been few formal partnerships for the construction of larger accelerator facilities. These have, to date, usually been implemented in a national framework and then made available to the broad international user community. Attempts of shared ownership of major facilities between international partners are being attempted just now (aside from the long-standing CERN laboratory). One example is a new approach developed with the FAIR project where presently 15 countries have agreed to jointly develop, construct, and operate a major nuclear physics project on a contractual basis and, thus, in joint ownership. In November 2007, representatives from the 15 countries officially celebrated the start for FAIR. Lessons-learned should be studied from recent experiences associated with projects in other physical sciences: the International Linear Collider (ILC), the International Thermonuclear Experimental Reactor (ITER), the Square Kilometre Array telescope (SKA), and the European X-ray Free Electron Laser (XFEL). A careful study of these projects would shed light on the issues, solutions, and, importantly, unanticipated difficulties and obstacles. The latter have to do with the very different rules and procedures in the different partner countries (political, legal, employment, staff rules, project management, budget, procurement, taxes, etc). At the regional level, the European Union has developed solutions which have proven to be quite effective in the end, albeit at considerable initial investments in funds and effort.

Sharing the operating costs of a facility following construction is a difficult and delicate topic and, possibly, one of the reasons why shared ownership in large research infrastructures is hard to achieve. But there are important successful precedents, such as CERN, the European Synchrotron Radiation Facility (ESRF), the Institut Laue-Langevin research reactor, the ALMA radio telescope array, the Auger cosmic ray observatories, and, most recently, ITER. For research facilities, such as the ones used in particle physics and in nuclear physics, there are certain aspects in facility operation which may need some re-definition. The operating cost can be broken down in very coarse categories according, for example, to the pie-chart shown (Figure 7). An important factor here is that in addition to running the accelerator and the site-infrastructure, operating the large and complex experiments simply for the data collection phase, i.e., not yet including data analysis and extraction of the science, is an important operating task. Generating what one might call the data summary tapes involves substantial effort and, thus, cost. This effort is a genuine contribution to facility operations by the respective partners and should be counted that way.

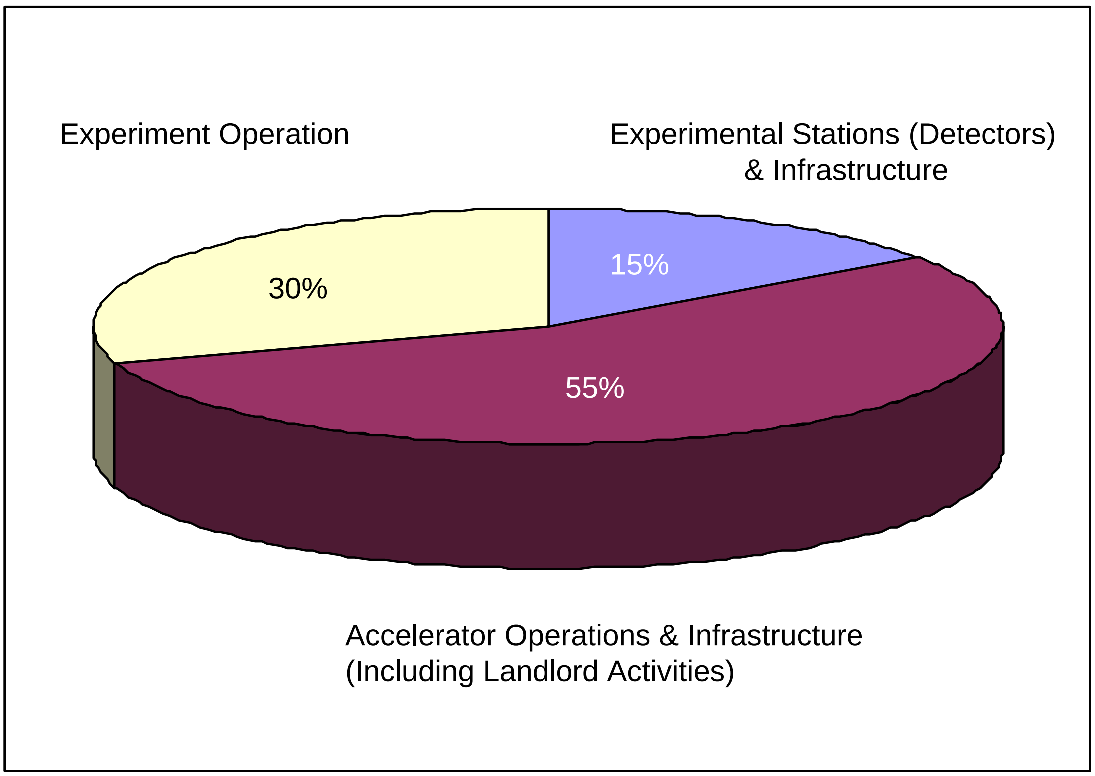

Figure 7: The typical relative fractions of operating costs are shown for a major user facility. In most cases the accelerator operations and infrastructure are supported by the host organisation while the experimental detectors and infrastructure, and the experimental operation to the stage where data summary archives can be distributed to home institutions for final research analysis receive major contributions from the user community.

In examining the prospects for future large facilities from a global perspective, it is important to not overlook that there are a considerable number of countries where such facilities do not exist and are unlikely to be built in the foreseeable future. The participation of the nuclear physics communities of such countries in international collaborations takes place naturally if the countries have advanced industrialised economies, strong academic institutions, and well-established systems for funding and administering science. Such is the case for many of the European, North American, or Asian countries. In many developing and emerging countries, however, the situation is much more difficult with regard to participation in research at the large, front-line facilities. Yet the nuclear physics communities in these countries have bright young researchers who could significantly contribute to the science at these facilities, contingent on the establishment of appropriate access programmes.

Possible Mechanisms for Coordinated Planning and Implementation

A significant issue regarding future large facilities for nuclear physics is the extent to which some of them can be planned and implemented via global-scale cooperation. It has already been pointed out that the international scientific community is well-integrated and endowed (via IUPAP/WG9 and NuPECC at the European level) with effective mechanisms for formulating the science case and for establishing the basic performance parameters. However, there are no standing mechanisms for coordination between regions and for extending strategic planning, roadmapping and priority-setting to worldwide scale[4]. An important responsibility of this OECD report is to provide a basis for discussions on whether and, if so, how to establish a worldwide strategy and priority forum in nuclear physics.

Several possibilities were considered on how to establish such a forum. One possibility could be to expand on the ESFRI process described for the European Union above and, possibly, on trial basis create such a forum for a predetermined period and a limited scope of goals (e.g., electron-ion collider or multi-MW-ISOL planning). Organisationally it might be attached to the European Union bodies for the trial period. Another possibility could be an informal funding agency forum comparable to the Funding Agencies for the Large Colliders (FALC) group for high-energy physics. A third possibility, which would have a stronger science community component, might be to expand the scope of the IUPAP/WG9 working group on nuclear physics (a role similar to ICFA) to help organise community and agency input into the strategic planning and roadmap development, and to ultimately help with the global coordination process for facility-plan development. Conceivably, the OECD Global Science Forum could play a continuing role in this context, possibly in conjunction with the community input organised by other groups such as the IUPAP/WG9 working group. Of course, this direction raises the question of membership in these forums which has to be broader than just the OECD membership of 30 advanced industrialised democracies. But the forums could serve to organise the process (town meetings, agency representative meetings, etc.) which then, in turn, would guarantee broadly based participation.

The future nuclear physics facilities such as the multi-megawatt ISOL systems and electron-ion collider would also require a global R&D effort. As already stated, a bottom-up approach could be used similar to the European Union's Integrating Infrastructure Initiatives (I3). One of the most effective components of the I3 programme finances travel for experimentalists to regional research facilities. Such a programme, if developed on a wider scale, could open up regional labs for researchers from other regions, in particular from emerging economies or developing countries.

[4] The OECD Working Group, with its fixed mandate and time duration, is not a mechanism of this kind.

Findings and Recommendations:

The major issue identified as facing nuclear physics globally was the increasing cost of the tools needed to be at the scientific frontier. The scientific community has done an outstanding job of identifying the scientific opportunities and the research capabilities needed to exploit them. However, the large cost and intense competition with other national priorities for resources has led to pressure on all funding agencies to examine opportunities for international cooperation to optimize the available resources and avoid duplication of efforts and research capabilities.

The planning processes used by funding agency officials for priority-setting and decision-making (e.g., established national advisory mechanisms) have worked well for making decisions about the use of existing facilities, new facilities under construction, and proposed facilities. The processes have been instrumental for producing the global roadmap that reflects the worldwide consensus of the research community regarding the most challenging scientific questions and the experiments that can provide answers to those questions. *The Working Group finds, however, that given the desirability of ensuring a globally coherent and efficient evolution of nuclear physics beyond that which is currently foreseen, it would be useful for agency officials to be informed on an ongoing basis about future major facilities. The information and advice should come from a forum that involves the world-wide nuclear physics community.*

A forum should be established to discuss, on a regular and ongoing basis, national and regional science-based roadmaps and to articulate a global scientific roadmap for nuclear physics. It should be organised by the International Union of Pure and Applied Physics/Working Group 9 (IUPAG/WG9) and composed of representatives of WG9 itself, the major national and regional scientific planning bodies (e.g., Nuclear Science Advisory Committee [NSAC], Nuclear Physics European Collaboration Committee [NuPECC], Nuclear Physics Executive Committee of Japan [NPEC]) with proportionate participation from all other countries that are not members of one of the latter.

Looking beyond the timescale of the current roadmap, there is a possible need for large facilities that would be planned, designed, implemented, and utilized via a global-scale collaboration of interested countries.

The Working Group supports the OECD Global Science Forum's activities aimed at facilitating international consultations regarding the potential establishment of large-scale international facilities.

Planning for the future of Nuclear Physics should be a globally-coherent response to recognized scientific challenges, using an optimal set of national, regional, and, if needed, global-scale projects. To achieve this goal, funding agency officials should consider establishing a venue where they can discuss the future of the field, with special emphasis on the role of large programmes and projects.

National, regional, and global planning should be done at the agency level among interested parties to optimize the science and international collaboration, taking into account the global scientific roadmap of the community. The establishment of a forum for nuclear physics funding agencies should be considered for discussing plans for new large scale facilities and for optimizing communication and cooperation at a global level.

Historically, the field of nuclear physics has benefited enormously from the application of the principle of free and open access to large-scale research facilities. According to this principle, *the use of the facilities is allocated based on the importance and quality of the research proposed, regardless of nationality or institutional affiliation of the proposers. In addition, the operating costs of the facility are borne by the facility itself.*

Free and open access to beam usage should continue to be the international mode of operation for nuclear physics facilities.

The participation of the national nuclear physics communities in international collaborations takes place naturally if the countries have advanced industrialised economies, strong academic institutions, and well-established systems for funding and administering science. *In many developing and emerging countries the situation is much more difficult with regard to participation in research at the major, front-line facilities.* Yet the nuclear physics communities in these countries have bright young researchers who could significantly contribute to the science at these facilities, contingent on the establishment of appropriate access programmes.

Funding agencies and research institutions are encouraged to create and support mechanisms that provide access to large-scale facilities by scientists from emerging or developing countries where no major facilities exist.

Appendix A: Regional Description of the New Facilities in Nuclear Physics

Nuclear physics is a very broad field. No single accelerator facility can provide the capability needed to attack the full range of important problems, which span from determining how nucleons are assembled from quarks and gluons to understanding how the universe is evolving. Progress in experimental nuclear physics depends critically on having both large, state-of-the-art accelerator facilities and detectors as well as smaller facilities dedicated to specific problems. Today major advances in theory are being made through the use of powerful parallel processor computer arrays. For the field to advance in the future, experimental and theoretical developments must continue to go hand in hand. New major facilities—accelerators, detectors and computers—are needed to attack many of the fundamental questions in nuclear physics. But support for smaller regional facilities must also be maintained. Through careful national and regional planning, complementary major facilities are being developed throughout the world that will provide many of the tools needed for the future. Here a brief overview of the new or planned major facilities or upgrades of facilities is provided by region. Two major facilities that are considered to be further in the future are also discussed.

Major New or Planned Facilities in Asia

BRIF: At CIAE Beijing, China, the **Beijing Radioactive Ion Facility** is being constructed coupling a 100 MeV, 200 μA proton cyclotron with a 15 MV Tandem accelerator and a 2 MeV/u LINAC post-accelerator. BRIF will be completed in 2010. Future plans include upgrading the LINAC to ~14 MeV/u by 2017.

CSR: In China, the **Cooler Storage Ring** project at the HIRFL facility in Lanzhou has recently been commissioned. When fully operational, it is expected to accelerate protons to 3.7 GeV, and uranium ions to 500 MeV/u. The facility is based on a synchrotron, followed by a fragment separator and an electron-cooled storage ring. The research programme will focus on studies of nuclear and hadron physics, biology and materials science.

J-PARC: A new laboratory, the **Japan Proton Accelerator Research Complex**, located on the coast of the Pacific Ocean near Tokai, Japan, is currently under construction and is expected to start operations in 2009. The new laboratory will be a multi-purpose research and accelerator facility. The research programme includes neutrino, nuclear, and hadron physics with proton beams of up to 50 GeV. A high-intensity proton beam at 3 GeV will be used to produce secondary neutron and muon beams at a spallation facility for condensed matter and applied research (materials and life sciences) and for R&D on nuclear transmutation technology. There is already significant international participation in the J-PARC programmes. In nuclear and particle physics, a call for letters of intent in 2003 prompted 30 proposals with 478 collaborating scientists; of these about 2/3 were from abroad (30 % from Europe, 35% from North America, 5% from other countries in Asia). Among those, 142 members were on a neutrino programme. This programme has now grown to a group of 400 scientists with ¾ of the participants from outside Japan.

NLNS: In the Republic of Korea, a new heavy-ion facility is being proposed, the **National Laboratory for Nuclear Science** as part of the International Science and Business Belt, for the production of radioactive beams and for ion-beam treatment of cancer.

RIBF: Initial operation of the RIKEN (Rikagku Kenkyusho, The Institute of Physical and Chemical Research) **Radioactive Isotope Beam Factory** in Japan began in 2007. This in-flight facility is based on multiple coupled cyclotrons using the largest superconducting cyclotron worldwide. The ultimate design goal is to deliver beams up to uranium at 350 MeV/nucleon with 1 particle-μA beam current for projectile fragmentation and fission. Development of the experimental programme and related instrumentation involves joint R&D activities with other major laboratories worldwide. An example is the collaboration between RIKEN, GANIL, GSI and MSU scientists on the R&D of high-rigidity, large-acceptance, super-conducting fragment separators.

SLEGS: At the **Shanghai Synchrotron Radiation Facility**, a source for 1-25 MeV gamma-rays is being planned using Compton backscattering of laser photons. This source is expected to begin operation in 2009.

Major New or Planned Facilities in Europe

FAIR: The **Facility for Antiproton and Ion Research** is to be constructed next to the site of the GSI facilities at Darmstadt, Germany and will be built and operated as an international facility with contributions presently from 15 countries around the world. The project will comprise two new superconducting heavy-ion synchrotrons (SIS 100 and 300), a high energy storage ring for antiprotons, a large-acceptance fragment separator, and storage rings for radioactive ion beams as well as several fixed target stations. The physics programme covers the investigation of exotic nuclei, hadron spectroscopy in anti-proton induced collisions, nuclear matter at high densities as well as a wide programme in plasma and atomic physics. A formal starting event was held in November 2007. A start of construction is projected for autumn 2008 and will proceed in three phases until the end of 2015. FAIR (as well as the SPIRAL-2 project discussed below) has been selected by ESFRI as one of the 35 new projects to be pillars to strengthen European research. An International Steering Committee (FAIR-STI with working groups on scientific and technical issues as well as administrative and financial issues) has been set up, and the contractual basis for the involvement of partner countries has been established. Germany will finance up to 75% of the total construction costs. Approximately 2500 scientists worldwide have been participating in planning and designing this facility

ISOLDE: The **Isotope Separation On-Line** facility at CERN produces radioactive beams by the ISOL technique with driver beams from the CERN Proton Synchrotron Booster and, with the REX-ISOLDE upgrade, accelerates them up to 5.5 MeV/u. Future upgrades, such as the High Intensity and Energy at ISOLDE (HIE-ISOLDE) are expected to increase this to up to 10 MeV/u, and capitalize on a fivefold increase in driver intensity with the approved upgrade of the CERN low energy linac injector, and a faster cycling of the Proton Synchrotron.

LHC/ALICE: The **Large Hadron Collider** at CERN is a major facility for research in high energy physics and in relativistic heavy ion physics. The ALICE detector, focusing on relativistic heavy ion physics, is being built by an international collaboration of about 1000 scientists from 28 countries. All costs for ALICE are carried by the members of the collaboration, generally through in-kind equipment contributions and workforce allocations. A common fund has been established with a per capita contribution to cover experimental operating costs. The LHC is expected to start operation in 2008.

MAMI: The **Mainz Microtron** is a continuous wave electron accelerator at the University of Mainz. The facility was upgraded in 2006 (MAMI-C) to a maximum beam energy of 1.5 GeV.

SPES: The **Study and Production of Exotic Species** project at INFN LN Legnaro, Italy will complement the near term research options in exotic beam research.

SPIRAL-2: The **Système de Production d'Ions Radioactifs en ligne 2**, which is scheduled for completion in 2012, is a new isotope separation on-line (ISOL) facility to be built at the GANIL Laboratory in Caen, France. Based on the concept of a high beam power (200kW) superconducting linear accelerator, SPIRAL-2 will be a next generation ISOL facility delivering very intense secondary radioactive ions beams (RIB) to energies up to 20 MeV/u for the European and international scientific communities. This project (as well as the FAIR project discussed above) has been selected by the European Strategy Forum for Research Infrastructures (ESFRI) as one of the 35 new projects to be pillars to strengthen European research. France will finance 80% of the total cost of the project with the remaining contributions coming from European countries and countries outside Europe. Letters of intent, supervised by an International Steering Committee, have been developed in order to form international collaborations for the construction of new experimental devices. SPIRAL-2 is intended to become a European International facility.

Major New or Planned Facilities in the Americas

12 GeV CEBAF Upgrade Project: A major upgrade from 6 to 12 GeV electron beam energy is underway at the **Continuous Electron Beam Accelerator Facility (CEBAF)** at the DOE's Jefferson Lab (JLab) in the U.S. The 12 GeV CEBAF Upgrade, which is scheduled for completion in 2015, is one of the two major Nuclear Physics facilities funded by DOE. The user community at JLab includes about 30% of the U.S. nuclear physicists and has a strong international component (about 40%). It is expected that construction of new major detectors for the higher-energy electron and, in particular, photon beams will broadly involve international groups.

FRIB: Construction of a major **Facility for Rare Isotope Beams** is being planned in the U.S. for the period 2011-2017. The plans include a high-energy (200 MeV/nucleon) super-conducting driver linac providing 400 kW light and heavy-ion beams up to uranium. The concept for FRIB involves fast, stopped and unique re-accelerated beams. The present plans call for FRIB to be funded by DOE, and it is expected to attract a large international user community.

ISAC II: In 2006 the linear accelerator was commissioned for the **ISAC II** upgrade of the ISAC ISOL facility at TRIUMF in Vancouver, Canada. Beams can now be accelerated to 4.3 MeV/nucleon with 6.5 MeV/nucleon becoming available in the near future. Major future improvements will also include the development of a suite of new instrumentation by international collaborations and the use of actinide production targets with the 500 MeV proton beam at intensities up to 75 μA. TRIUMF is also planning a 50 MeV mega-watt class superconducting RF electron linear accelerator for photo-fission on actinide targets.

RHIC-II: The **Relativistic Heavy Ion Collider (RHIC)** at Brookhaven National Laboratory is a major DOE user facility with approximately 50% of the users coming from around the world.

There have been major contributions from partners within and outside the U.S. on R&D, construction, and operation of the experimental equipment. There are upgrades planned for RHIC detectors and the accelerator to provide higher luminosity (RHIC II). A unique aspect of international partnership at RHIC was the establishment of the RIKEN BNL Research Center in April 1997, which is funded by RIKEN. The Center is dedicated to the study of QCD, including spin physics, lattice QCD, and high-energy high-density physics through the nurturing of a new generation of young physicists.

Projects Farther in the Future

These projects are discussed as potential future projects in national or regional plans but due to their longer time scale, are not included in Figure 3.

Electron Ion Collider: In the longer term, there is strong interest in the construction of a high-energy **Electron-Ion Collider** to study protons and nuclei at the shortest distance scales. Plans are being developed at BNL and JLAB in the U.S. and at CERN in Europe.

EURISOL: EURISOL is a very ambitious future project under consideration which would provide Europe with the world's leading ISOL facility. The driver accelerator envisioned for it is a several-megawatt superconducting linear accelerator, and a second superconducting accelerator would be used to accelerate rare isotope beams. The beam power projected for EURISOL is orders of magnitude beyond present capabilities. EURISOL has a very large collaboration drawn from across Europe and is the subject of an EU funded Design Study. It is intended to be an international European facility.

Appendix B: Glossary

Beta Beam Facility A potential future facility for producing pure electron neutrino and antineutrino beams by the decay of radioactive nuclei such as ^{6}He or ^{18}Ne after these isotopes have been produced, accelerated and stored in a specially designed storage ring.

Big Bang The cosmic explosion that is believed to be the origin of our universe, about 14 billion years ago.

Dark Matter Unusual (non-baryonic) matter that does not emit light because of the peculiar nature of its interactions. The existence of dark matter has been detected through its influence on galactic dynamics and the cosmic background of microwave radiation from the early universe. Dark matter is believed to account for about 25% of the energy in the universe.

Dark Energy A form of energy that is believed to account for about 70% of the energy of the universe and is observed to exhibit a pressure that counteracts gravity. The exact nature of dark energy is still quite mysterious.

Electron Ion Collider A proposed new accelerator that would collide high energy beams of electrons with high energy beams of atomic nuclei. Such a facility is particularly well suited to understanding the behaviour of the glue in nuclei in a regime where the number of gluons becomes extremely large. One theoretical prediction is that all matter in this regime form a "coloured glass condensate" state.

Gluon The carrier of the force of the (coloured) strong interaction. The fact that the gluon (unlike the photon which mediates the electromagnetic interaction but is not electrically charged) also carries colour and interacts with other gluons is, in large part, responsible for the very unusual features of the strong interaction.

Hadron Any observable particle that interacts by the strong interactions. Some long-lived examples include the protons and neutrons that make up the atomic nucleus.

Halos Neutron-rich nuclei that are very weakly bound have a core of neutrons and protons surrounded by halos of almost pure neutron matter. Studies of these nuclei can help scientists understand the properties of neutron stars.

In-Flight Rare Isotope Production A technique to produce rare, unstable short-lived isotopes, where a fast beam of a heavy isotope shatters, like glass, on a nuclear target. This technique is especially suited for studying the nuclei farthest from stability that exist for only a brief time (milliseconds). The disadvantage is that the resulting ions tend to have a distribution of velocities near that of the incident beam, which is excellent for some experimental techniques but not suitable for others.

Isotope Production by Gas Stopping and Reacceleration Unstable short-lived isotopes are produced by in-flight techniques and then slowed down and stopped in helium gas. The resulting ions can be efficiently extracted and then reaccelerated in a second accelerator. This powerful technique uses the chemical element independence of in-flight techniques to produce high quality beams of isotopes that are very difficult to produce with the ISOL technique.

Isotope Separation On-Line (ISOL) Rare Isotope Production A technique to produce rare, unstable short-lived isotopes where a high-power beam, usually of light ions, strikes a heavy target. The isotopes produced in these reactions diffuse out of the hot target and are ionized in an ion source, then re-accelerated in a second accelerator. The advantage of this technique is that the quality of the beam of radioactive ions is similar to the quality of beams of stable ions. The disadvantage is that it is not efficient for very short-lived isotopes or isotopes that do not diffuse easily through the target (for example, refractory materials).

Meson A particle containing a quark and an anti-quark that in hadron models serves as the carrier of the strong interaction between protons.

Neutrino Neutrinos are very weakly interacting light neutral particles that are emitted from nuclei (and hadrons) in "weak interactions" (beta-decay). Until recently, neutrinos were believed to be mass-less. The clear observation of neutrino mixing in the past few years demonstrates that neutrinos must have mass. This was the first evidence that the Standard Model of particles and interactions was not correct and needed to be modified.

Neutrino-less Double Beta Decay A postulated but exceeding rare form of beta decay where a nucleus transforms into a final nucleus differing by two units of charge by emitting two and only two electrons. Detecting such a decay would provide strong evidence that a neutrino is its own antiparticle; moreover a measure of the decay rate can provide very sensitive information about the masses of neutrinos.

Neutron stars An exotic form of matter where stars of mass comparable to the mass of the sun collapse to diameters of about 10 Km. The crusts of such stars contain very neutron rich nuclei. It is an open question if the centres may be made of quark matter, strange matter, or neutron matter.

NSAC The Nuclear Science Advisory Committee, an expert panel that provides advice to the U. S. Department of Energy and U. S. National Science Foundation about nuclear physics issues. Approximately every 5 years, most recently in 2002 and 2007, NSAC prepares a Long Range Plan for U. S. Nuclear Science.

Nuclear Matter A generic term for a collection of strongly interacting matter, encompassing all nuclei and extending to the form of matter in neutron stars and the quark-gluon plasma.

Nucleus The nucleus is the positively charged centre of each atom. It is composed of neutrons and protons and, at a deeper level, of quarks and gluons. Nuclei were the first objects known that were bound by the strong interaction, which is now believed to be described completely by the theory of quantum chromodynamics in the Standard Model.

NuPECC Nuclear Physics European Collaboration Committee, an expert committee of the European Science Foundation whose objectives include the strengthening of European collaboration in nuclear science through defining a network of complementary facilities within Europe and encouraging optimization of their usage; providing a forum for the discussion of the provision of future facilities and instrumentation; and providing advice and recommendations to the ESF and to other bodies on the development, organisation, and support of European nuclear research and of particular projects.

Proton The simplest atomic nucleus at the centre of the hydrogen atom. Protons and their neutral counterpart, neutrons, are the constituents of all atomic nuclei.

Quark A "point-like" particle with no thus-far observed internal structure that in groups of three or more along with the gluon carriers of the strong interaction force makes up the protons and neutrons of atomic nuclei.

Quantum Chromodynamics (QCD) The theory of interactions between quarks and gluons based on the "colour charge" of each of these particles. QCD has a number of unfamiliar properties: it becomes weaker as particles get close together yet becomes so strong as coloured particles are separated that no free quarks and gluons have ever been observed.

Quark-Gluon Plasma A state of nuclear matter at high temperature or high density where quarks and gluons are free to travel large distances compared to the diameter of the proton. Recent experimental results show that the properties of this new state of matter that only existed previously in the first microseconds following the Big Bang are quite different than had been predicted by nuclear theory.

Radioactive or Rare Isotope or Exotic Beams of isotopes that are not naturally occurring on earth. While modern accelerators can create beams of any long-lived isotope of a nucleus, new techniques are required to produce beams of short-lived isotopes (with lifetimes less than several days). With these new concepts for isotope capture and acceleration that have been developed and tested, it is possible to create such beams and study a broad range of new nuclei, whose properties are important to understand the structure of all nuclei and the evolution of the formation of the chemical elements in the universe.

Shell Structure Just as atoms exhibit a shell structure that is responsible for the similarities in the chemical behaviour of the elements in columns of the periodic table, neutrons and protons in nuclei also appear to be orbiting a common central potential. One of the most intriguing features of nuclei far from stability is that this shell structure appears to change in neutron-rich nuclei leading to possible changes in the expected distributions of the chemical elements in cosmic explosions such as supernova.

Standard Model of Particles and Interactions The current accepted theory of the particles and interactions involved in the electromagnetic, weak (responsible for nuclear beta decay), and strong interactions (responsible for the binding of protons, neutrons and nuclei). While this theory is extremely successful, there are many reasons to believe it is incomplete, and one major direction of nuclear and particle research focuses on understanding where the theory may be wrong.

Strong Interactions – One of the four basic interactions in nature, the strong interactions provide the binding that hold protons and nuclei together. Quantum Chromodynamics is believed to be the underlying theory describing strong interactions.

Super-heavy Nuclei – The heaviest nucleus occurring naturally on earth is uranium (with 92 protons); in nuclear reactions, nuclei with up to 118 protons have been observed. Nuclear theorists predict that there may be especially stable configurations of "super-heavy" nuclei with, for example, 120 protons and 182 neutrons that may have much longer half-lives than their near-by neighbours. The observation of this "island of long-lived super-heavy nuclei' would tell us a great deal about how heavy nuclei behave.

Supernova – Supernova are huge cosmic explosions of stars. One type of these events (Type IA which are thermonuclear explosions of binary systems including a white-dwarf star) is used as a standard candle in cosmological studies. Another type (Type II) is believed to be the source of the production of about one-half of the heavy elements through the rapid neutron capture process.

X-ray Bursters – Observations of stars reveal bursts of x-ray production that are believed to be due to the accretion of material and the subsequent nuclear combustion on the surface of a neutron star.

Weak Interactions – One of the four basic interactions in nature (along with the strong interactions, electromagnetic interactions, and gravity) that is responsible for nuclear beta-decay. Neutrinos only interact with matter by the weak interaction and gravity which makes them extremely difficult to detect.

Appendix C: Participants

Country/ Organization	Name	Institution
Australia	John White	Australian Institute of Nuclear Science and Engineering
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	Jean Sacton	Brussels Free University
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	Alan Shotter/Nigel Lockyer	TRIUMF
CERN	Michael Doser	
	Mats Lindroos	
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	Ani Aprahamian	National Science Foundation
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	Bradley Keister	National Science Foundation
	Jehanne Simon-Gillo	U.S. Department of Energy
	Robert Tribble	Texas A&M University
OECD	Stefan Michalowski	Global Science Forum

Appendix D: Acronyms and Abbreviations

AGS	Alternating Gradient Synchrotron (BNL, USA)
ALICE	A Large Ion Collider Experiment (CERN, Geneva, Switzerland)
CAT	Computer Assisted Tomography
CEBAF	Continuous Electron Beam Accelerator Facility (JLab, USA)
CERN	European Organisation for Nuclear Research (Geneva, Switzerland)
DOE	Department of Energy (USA)
DUSEL	Deep Underground Science and Engineering Laboratory (USA)
ESFRI	European Strategy Forum for Research Infrastructures
EURISOL	European Isotope Separation On-line Radioactive Beam Facility
FAIR	Facility for Anti-proton and Ion Research (Germany)
FRIB	Facility for Rare Isotope Beams (USA)
GANIL	Grand Accelerateur National D'ions Lourds (France)
GSF	Global Science Forum
GSI	Gesellschaft fuer Schwerionenforschung (Germany)
HIE-ISOLDE	High Intensity and Energy at the Isotope Separation On-Line facility at CERN
HRIBF	Holifield Radioactive Ion Beam Facility (ORNL, USA)
IAEA	International Atomic Energy Agency
ICFA	International Committee on Future Accelerators
INFN	Istituto Nazionale di Fisica Nucleare (Italy)
INO	India Neutrino Observatory
ISAC	Isotope Separation and Acceleration (Canada)
ISOL	Isotope Separation On-Line
ISOLDE	Isotope Separation On-Line facility at CERN
IUPAP	International Union of Pure and Applied Physics

IUPAP/WG9	International Union of Pure and Applied Physics Working Group on International Cooperation in Nuclear Physics
JINR	Joint Institute for Nuclear Research (Dubna, Russia)
J-PARC	Japan Proton Accelerator Research Complex (Japan)
KEK-PS	High Energy Accelerator Research Organisation – Proton Synchrotron (Japan)
KHuK	Komitee fuer Hadronen- und Kernphysik (Germany)
LHC	Large Hadron Collider (CERN, Switzerland)
MAMI	Mainz Microtron (Germany)
MRI	Nuclear Magnetic Resonance Imaging
MSU	Michigan State University (USA)
NPEC	Nuclear Physics Executive Committee (Japan)
NSAC	Nuclear Science Advisory Committee (USA)
NSCL	National Superconducting Cyclotron Laboratory (USA)
NSERC	Natural Sciences and Engineering Research Council (Canada)
NSF	National Science Foundation (USA)
NuPECC	Nuclear Physics European Collaboration Committee
OECD	Organisation for Economic Co-operation and Development
PET	Positron Emission Tomography
PIXE	Proton-induced X-ray Emission
QCD	Quantum Chromodynamics
QGP	Quark-gluon plasma
RIB	Rare Isotope Beams
RIBF	Radioactive Isotope Beam Factory (Japan)
RIKEN	*Rikagaku Kenkyusho* (The Institute of Physical and Chemical Research, Japan)
SIS	Heavy Ion Synchrotron (GSI, Germany)
SNO	Sudbury Neutrino Observatory (Canada)
SNOLAB	

SPES Study and Production of Exotic Species (INFN-Legnaro, Italy)

SPIRAL -2 Système de Production d'Ions Radioactifs en ligne 2 (SPIRAL2, GANIL, France)

TRIUMF Canada's National Laboratory for Particle and Nuclear Physics

WIPP Waste Isolation Pilot Project (USA)