THE FUTURE OF NUCLEAR PHYSICS IN EUROPE AND THE DEMANDS ON ACCELERATOR TECHNIQUES

Walter F. Henning, GSI, 64291 Darmstadt, Germany

INTRODUCTION

Nuclear physics has undergone a major reorientation in its research goals during the last decade or so [1]. There are two, or maybe three major reasons for that.

The first one results from the fact that nucleons and mesons, the basic building of nuclei and their fields, have substructure. Understanding the quark-gluon structure of hadrons, how and to what extent this partonic substructure affects the behavior of nuclei and nuclear matter, and to what extent we have a full and quantitative understanding of these features through the theory of strong interaction, quantum-chromo-dynamics (QCD), is at the center of much of the activity in nuclear physics. The length and energy dimensions involved with hadrons and nuclei require the non-perturbative treatment within QCD, and also the extension to finite temperature and chemical potential.

A second important new area has been the development of accelerated beams of short-lived nuclei (sometimes called 'radioactive', 'rare isotope' or 'exotic' beams) at useful intensities. Much of what we know about nuclei comes from nuclear reactions. Consequently these studies have been essentially restricted to stable nuclei where reaction targets could be built and exposed to beams of particles, in particular light ones (protons, deuterons, helium nuclei etc.). Energetic beams of short-lived nuclei now allow to reverse the reaction kinematics and thus, with targets of light nuclei, to study nuclei away from, and up to the limits of stability in nuclear reactions.

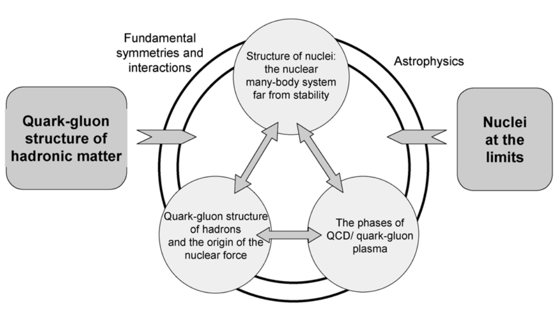

Figure 1: Current research frontiers in nuclear physics.

The third area of interest is the exploration of the limits of the Standard Model. For the strong interaction sector this connects to the QCD discussion above. For the weak sector, the discovery of neutrino oscillations and mass has placed new emphasis on an area which started with Davis' solar neutrino searches in radiochemical experiments several decades ago [2]. Both solar and galactic neutrinos as well as neutrinos from high-intensity accelerators are of broad interest now. Rare decays and direct symmetry violation studies requiring intense primary and secondary beams are also pushing accelerator performance and design.

The areas of interest just described have overlap and intersections with each other. One way of summarizing the overall situation could be the schematic shown in Figure 1.

RESEARCH AREAS, FACILITIES AND BEAMS

The new research programs require new experimental capabilities and new facilities and beams, and these then, in turn, define new and very challenging requirements for accelerator instrumentation, in particular beam diagnostics - the subject of this conference.

The substructure of the stable nucleons, protons and neutrons, and of stable nuclei is directly accessible via studies with beams of hadrons, leptons and photons. Other hadrons, mesons and excited baryons, need to be produced in reactions.

Beams of leptons, and in particular electrons, are preferred probes for the ground state structure of nucleons since they are point-like and the electromagnetic interaction is well understood. Structure functions, including in particular spin, have been and are intensely studied. Quark and gluon contributions to the spin are being studied at existing high-energy facilities (HERMES at DESY [3] and COMPASS at CERN [4] for example) but in particular also at the dedicated high-intensity cw electron-beam facility CEBAF at JLAB [5]. Current interest is being focussed on skewed parton distributions and the measurements of DVCS, deep virtual Compton scattering, which promises to provide information on parton correlations and, possibly, structure functions of excited hadrons. These studies, plus the exploration of the transition from perturbative to non-perturbative QCD, are asking for high-duty cycle electron machines up to several tens of GeV laboratory energy. In addition, concepts are being developed for future e-A colliders at tens to 100 GeV center-of-mass energy [6,7].

Facilities for studies of QCD with intense hadronic probes are being developed in Japan and Europe: the Japanese Hadron Facility (J-PARC) [8] with intense proton beams and primary interest in research with secondary beams of kaons and neutrinos; the future facility proposed for the GSI Laboratory in Germany with intense antiproton beams and in particular a high-energy antiproton storage ring with electron cooling [9]. The goals of these facilities in hadron physics are in tests of the Standard Model and neutrino physics for the J-PARC, and in studies of QCD and chiral symmetry in nuclear matter for the GSI facility.

In addition, the important questions of QCD relating to confinement and chiral symmetry restoration are being persued in relativistic heavy-ion collisions. Reaching the region of the quark-gluon plasma promises studies of matter fully deconfined and chirally symmetric. Major advances are expected at RHIC at Brookhaven [10] and at the ALICE experiment at the LHC [11] and - to some extent - at the future GSI facility [9].

In Japan (RIKEN [12]), Europe (GSI [9] and EURISOL [13]) and the USA (RIA [14]) there are plans to build new large-scale facilities to provide intense beams of short-lived nuclei. The science interest arises from the fact that this will allow the studies of the nuclear many body system to be extended up to the limits of binding. As in any physical system, pushing it to its limits - here in isospin or neutron to proton ratio - may reveal particular sensitivities. In addition, the paths of explosive nucleosynthesis and thus the generation of all nuclei and chemical elements heavier than iron proceed through the regions of unstable nuclei far from stability. Finally, the high secondary intensities expected from the future facilities promise new and sensitive experiments on fundamental symmetries and features of the fundamental interactions through the use of specific nuclei and their weak decays.

The production of secondary beams of short-lived nuclei proceeds through nuclear reactions, either in flight and in a thin target (projectile fragmentation facilities) or on-line in a thick target with subsequent slow extraction at thermal energies from an ion source (ISOL or isotope separation on-line) and re-acceleration. In the recent RIA scheme, the IGISOL technique, originally developed at Jyväskylä [15], is further expanded [14], allowing for the two approaches being combined to a multi-purpose, powerful future facility.

Use of secondary beams in storage rings has been shown to be particularly powerful for optimising beam quality, for multiple use of the re-circulating beam with an internal target, and precision experiment with cooled beams. Storage rings are envisioned for the RIKEN facility in Japan and for the planned future facility at GSI. Filling the storage rings will probably be more efficient for a synchrotron-injected facility than for a dc primary beam driver such as a cyclotron.

With these facilities it will be possible to reach regions of nuclei far from stability, extending to the rapid neutron capture process (r-process) with useful intensities and the neutron drip line up to medium mass nuclei.

AN EXAMPLE: THE FUTURE FACILITY AT GSI

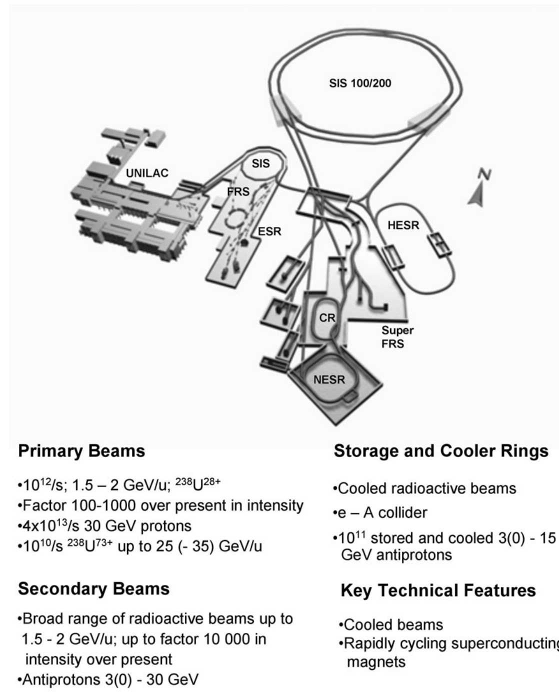

Figure 2: The existing GSI facility (left) with the linear accelerator UNILAC, the heavy-ion synchrotron SIS18, the fragment separator FRS and the experiment storage ring ESR; and the new project (right) with the double-ring synchrotron SIS100/200, the high-energy storage ring HESR, the collector ring CR, the new experiment storage ring NESR, the super-conducting fragment separator Super-FRS and several experimental stations. The present UNILAC/SIS18 complex serves as injector for the new double-ring synchrotron.

From the general overview just given, it is obvious that many important challenges await the construction of advanced beam diagnostics. It is also obvious that this brief overview does not cover the broad range of capabilities of the future facilities anticipated in any detail. We therefore consider one facility as an example: the GSI Future Facility [9]. The conceptual layout is shown in Figure 2, together with some key parameters. Major challenges for beam diagnostics are the very high (primary) beam intensities and the precision use of the secondary beams. In particular the cooling of beams leads to unprecedented precision in momentum spread and physical beam dimensions, requiring new approaches in beam diagnostics. Figure 3 illustrates this with a Schottky noise spectrum of a 'cocktail' of fragment nuclei, electron-beam cooled and circulating in the ESR at the present GSI facility [16]. The Fourier analysis determines precisely rotation frequencies of beams circulating with fixed velocity (namely that of the electron-cooler beam) and thus yields precise mass measurements. This is just one of many examples. For a more detailed discussion of the

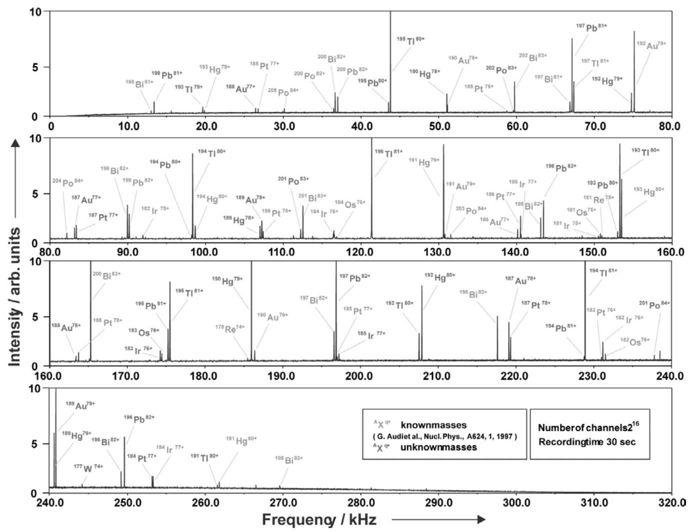

Figure 3: Schottky frequency spectrum of a collection of beams of heavy nuclei circulating in the ESR [16].

GSI Future Facility and its performance characteristics, please see the Conceptual Design Report [9].

OUTLOOK

In this paper a brief summary was given of major facilities under construction or in planning for the field of nuclear and hadron physics. Along one example, the GSI future facility, areas of particular importance for beam diagnostics were indicated. This by no means covers all areas where such future developments are needed. In fact, within the limited scope of this article, many smaller facilities in existence or being planned, could not be covered and often these facilities (with lower beam energies) pose severe demands on beam diagnostics. For example, low-energy beam tracking on a particle-by-particle basis which is desirable for the secondary beams with very low intensitiy but with possibly strong contamination, may be a major challenge to beam diagnostics. And in all the areas, the clear distinction historically made between beam diagnostics (and accelerator operation) and instrumentation of experiments may become diffuse or often nearly vanish.

REFERENCES

[1] NuPECC Long Range Plan, in preparation; NSAC Long Range Plan, Opportunities in Nuclear Science; April 2002, Berkeley Lab Technical and Electronic Information Department;
NRC Report on Nuclear Physics: The Core of Matter, The Fuel of Stars; National Academy Press, Washington, D.C. 1999

[2] Davis, Raymond, Jr., Harmer, Don S., Hoffman, Kenneth C., Phys. Rev. Lett. 20 (1968) 1205-1209; http://www.physicstoday.org/vol-55/iss-10/nobel.html

[3] http://www-hermes.desy.de/

[4] http://wwwcompass.cern.ch/compass/publications/welcome.html

[5] http://www.jlab.org/div_dept/physics_division/GeV.html

[6] Electron-Nucleon/Nucleus Collisions - Joint DESY/GSI/NuPECC Workshop, held at Seeheim, near Darmstadt, March 3/4 1997

[7] eRHIC: http://www.phenix.bnl.gov/ WWW/publish/abhay/Home_of_EIC/
EIC: Ya. Derbenev, Proc. of EPAC 2002, Paris, France, p. 314

[8] J-PARC: http://jkj.tokai.jaeri.go.jp/

[9] GSI: An International Accelerator Facility for Beams of Ions and Antiprotons; Conceptual Design Report, 11/2001; http://www.gsi.de/ GSI-Future/cdr/; this report is also available on CD. Mail to press@gsi.de to request a copy

[10] RHIC: http://www.bnl.gov/RHIC/

[11] LHC: http://lhc-new-homepage.web.cern.ch/ lhc-new-homepage/;
ALICE: http://alice.web.cern.ch/Alice/

[12] http://www.rarf.riken.go.jp/

[13] EURISOL: A Feasibility Study for a European Isotope-Separation-On-Line Radioactive Nuclear Beam Facility, EC contract No. HPRI-CT-1999-500001

[14] RIA: http://www.phy.anl.gov/ria/w.html

[15] IGISOL: http://www.phys.jyu.fi/research/igisol/

[16] Yu. A. Litvinov et al., Hyp. Int. 132, 283-289 (2001)