NUCLEAR PHYSICS: CHALLENGES AND OPPORTUNITIES

W. GELLETLY

Physics Department, University of Surrey, Guildford GU2 7XH,
Surrey, U.K.

(Received June 15, 2005)

Abstract. The status of nuclear physics is first reviewed. The article then focuses on our goals in trying to understand the structure of atomic nuclei. We see that we must still have recourse to a variety of nuclear models to try to understand nuclear structure and the main goal is to study nuclear properties over a wide range of excitation energy, angular momentum, proton and neutron number in order to provide a platform on which we can erect a comprehensive theory. Some of the main questions facing us in nuclear structure are reviewed. From this it is clear that the main lacunae in our knowledge lie in the properties of nuclei far from stability. To progress further one must have recourse to beams of radioactive nuclei. The two methods that have been developed for the creation of beams of radioactive ions are then reviewed. Two major facilities, FAIR and SPIRAL II are now in the early stages of design and construction. Their main features and future experimental programmes are outlined in terms of how they will address the open questions before us.

Key words: Nuclear physics, nuclear structure; radioactive beams.

1. INTRODUCTION

Perhaps the best place to start is to ask the apparently simple question “What is Nuclear Physics?”, Like many apparently simple questions it is not so easy to answer. One way to begin to answer is by reference to Fig. 1. This shows a simple picture of the hierarchical structure we believe exists in the microscopic World. Our everyday world is made up of atoms and molecules with a positively charged nucleus at the heart of each atom surrounded by negatively charged electrons. The nucleus is, in turn, made up of positively charged protons and uncharged neutrons. At the next layer down these nucleons, the generic name for protons and neutrons, consist of quarks interacting via gluons.

The structure of atoms is only affected to a limited extent by the existence of the nucleus. Its presence is signalled by effects in hyperfine structure in atomic spectra for example, but they are small. This puts an upper bound, in terms of length scale, to the province of nuclear physics. If we think of nuclear physics as our attempt to understand the properties of nuclei then the smallest nucleus is, of course, the nucleon. Here our initial question is re-defined as “Where does Particle Physics end and nuclear physics begin?” The answer lies in the nature of the force
Fig. 1 – On the left we see a simple schematic picture showing the hierarchy of structures in the microscopic world; atoms, nuclei, nucleons and quarks. On the right we see a schematic picture of the phase diagram for nuclear matter showing the boundary between the quark-gluon plasma and nuclear matter. It also shows how we might explore this diagram.

between quarks. At high energies, short distances, the force is very weak and Quantum Chromodynamics (QCD) gives an adequate description in terms of perturbation theory. On the dimensions of the nucleon ($10^{-14}$ m) the force becomes very strong and the use of perturbation theory is out of the question. So the boundary can be thought to lie at the point where we must abandon perturbation theory. To paraphrase, when the going gets rough nuclear physics takes over. The structure of the nucleon lies within the purview of nuclear physics and can now be seen as a distinct specialism within it, now usually called hadron physics. There are many open questions here. Thus we would like to know how the mass of the nucleon is made up of the masses of its constituents. Similarly how is the spin of the nucleon made up? Do glueballs and hybrids exist and many more. Thus hadron physics constitutes one of the frontiers of nuclear physics. At another frontier lies our attempts to map out the phase diagram of nuclear matter. This is crudely shown as an inset in Fig. 1 where the nuclear temperature is plotted as a function of net baryon density. At low temperatures and densities we have nuclei, made up of nucleons as described above. In studies of heavy ion collisions we have shown that at relatively low temperatures there is a phase transition from liquid-like behaviour to a Fermi gas. At much higher temperatures we expect a phase transition to a regime where the quarks are de-confined just as in the Early Universe. The main approach to studying this phase transition has been by the attempts at CERN and RHIC to look at what happens in the central fireball in ultra-high energy collisions of heavy ions. There have been reports that the phase transition has been observed but that its character is not as expected. Such experiments will continue and it will also be possible in future at FAIR (Facility for Anti-proton and Ion Research), the facility currently under construction at GSI, Darmstadt, to look at this phase transition at much higher densities. In other words it should become possible to
map out the phase diagram, determine the nature of any transitions and look for critical points.

The third frontier is nuclear structure physics. This will be the main concern of this article and so we will deal with its nature and the questions to which it needs answers in the next section.

The fourth frontier can be seen as the application of the knowledge we have gleaned about nuclei from Nature. Such applications abound and are based sometimes on the phenomena of nuclear physics and sometimes on the techniques we have had to develop to study it. Nuclear astrophysics is a prime example. The chemical elements are made in nuclear reactions in stars apart from H and He and traces of a few other light elements which were made in the Big Bang. Up to mass 56 the elements are largely made in fusion reactions in Main Sequence stars. At this point fusion reactions become endothermic not exothermic and consequently the process of building nuclei of higher Z in this way comes to an end. This also marks the death of the heaviest stars since they can longer generate enough energy internally to balance gravity. The heavier elements are made in one or another of a series of nuclear reaction networks that have been identified by careful examination of the chemical abundance of the elements. One such process the s-process (slow neutron capture process) is thought to happen in the gentle flux of neutrons created in stellar He burning. In this case successive neutron captures are followed by beta decays with a slow and steady increase in A and Z as we creep up the line of nuclear stability. The other main processes are much more dramatic and involve the kind of explosions that can only occur on a stellar scale. The most important, in terms of making heavier elements, is the rapid neutron capture(r process) process. Although the site of the r process is unknown it involves such a high flux of neutrons that successive neutron captures occur before the slower beta decays can occur. Eventually when the neutron flux dies or we reach a point where the neutron capture cross-section is very small, the so-called waiting points, beta decay gets its chance and we decay back towards stability but much higher in Z since the most stable isobar with the same mass value lies at higher Z. If we are to understand where the r process occurs it is important to obtain information about the nuclei lying on the reaction pathway. It turns out that they lie a long way from stability and are very hard to reach experimentally. In novae and X-ray bursters heavier nuclei are also created in the rp (rapid proton capture) process. Again the reaction pathway lies through a region of nuclei well away from stability.

Nuclear physics has also been a prolific source of other applications. Nuclear physicists have created energetic beams of every known stable species and have lead to the building of nuclear reactors. These developments have led to spallation and reactor based sources of neutrons of considerable importance to the study of solids and biological systems. Similarly it led to the creation of synchrotrons that are the basis for synchrotron light sources. Particle physics is another of its many
progeny. Particle beams are also vital tools in terms of the manipulation of the properties of materials. Ion implantation has been very important in the semiconductor revolution that has transformed communications and many other aspects of our lives. Nuclear techniques have been important in both medical diagnosis and therapy. Positron emission tomography has become an important diagnostic tool and gamma rays and hadron beams have become important tools for the treatment of cancers. We are all familiar with carbon dating and in its modern form of Accelerator mass spectroscopy it has been applied not just to archaeological artefacts but to environmental samples, hydrology, biomedicine, geology, forensic medicine and much more [1].

In this article we shall concentrate on the structure of atomic nuclei. In the following section we will consider the goal of nuclear structure physics and the questions we must answer to make progress if we are to reach this goal.

2. THE STRUCTURE OF ATOMIC NUCLEI

Our goal in nuclear structure physics is to determine nuclear properties over a wide range of N, Z, T, ω (neutron number, proton number, temperature and rotational frequency) and find a consistent theoretical framework to describe the phenomena observed. In this enterprise there are many unanswered questions.

Before examining these questions it is worth considering the state-of-play as far as advances in nuclear theory are concerned. We start from the fact that we have no analytical formulation of the nuclear force so that we cannot start from this basis. However we do have very precise measurements of the nucleon-nucleon interaction. Thus we can carry out so-called ab-initio calculations starting with these empirical interactions. So far they have been done for nuclei up to about mass 12. The main result is that one cannot achieve any reasonable agreement with experiment unless one includes three-body interactions. Thus nuclear theory is even more intractable than one might fear. Beyond this one has recourse to effective interactions and this is the basis of the nuclear shell model. Its success is such that one cannot doubt that it has a real basis in reality. Again these calculations are limited because, in this case, of the restrictions imposed by the computing power available. For heavy nuclei Mean field models of various types still rule the roost. Thus, overall, we are still along way from goal.

This is mirrored by the many unanswered questions in experiment. One of the simplest sounding questions is “What are the limits to nuclear existence?” yet we are a long way from answering it. Fig. 2 shows a version of the chart of the nuclides. The stable nuclei appear as black squares plotted as a function of Z and N. The so-called magic numbers of neutrons and protons are marked by vertical and horizontal lines respectively. An estimate of the positions of the proton- and neutron-
Fig. 2 – A version of the Chart of the nuclides showing the Magic numbers of protons and neutrons, the drip-lines and an indication of the limits to our knowledge of unstable nuclei. The stable species are shown as solid squares.

drip lines is also shown. These are defined in terms of the locus of points where the appropriate single-nucleon separation energy goes to zero. In a loose sense nuclei beyond these limits are said not to “exist” although it may be possible to study some of them. We now have a reasonable idea of where the proton drip-line lies, partly because it is possible to make the relevant nuclei in fusion-evaporation reactions and partly because the decay gives a clear signal which can be detected with high sensitivity [2]. On the neutron-rich side our knowledge is much more limited. Fig. 2 also indicates those nuclei where we know something about them, either the mass or the half life, etc. We see that our knowledge stops short a long way from the neutron drip-line. Estimates of the position of the neutron drip-line rely on semi-empirical formulae of one kind or another. Fig. 3 shows the measured two-neutron separation energies for the Sn (Z = 50) nuclei and compares them with the results of a selection of semi-empirical estimates based on the measured masses. Not surprisingly they all do reasonably well for nuclei with measured masses, the nuclei near stability, but diverge rapidly as we extrapolate and estimates of the neutron drip-line for Sn can vary by as much as 20–30 mass units.

Fig. 3 – The measured two neutron separation energies for the Sn isotopes are shown as Stars. The lines represent various semi-empirical formulae derived from them. Note the very different predictions of the position of the neutron drip-line.
The third boundary is of course the limit in terms of how heavy can a nucleus be. Up to \( Z = 112 \) the elements identified at GSI have been confirmed by experiments elsewhere. The observation of \( Z = 113 \) in cold fusion reactions has been reported by Morita et al. [3]. Elements up to \( Z = 118 \) have also been reported by Oganessian and his colleagues [4] in reactions involving heavy, radioactive targets. The isotopes created in these experiments are more neutron-rich and thus closer to the expected centre of stability of superheavy elements. The increasing half lives suggest that this centre is indeed being approached. The main difficulty in confirming these results is that the decay chains used to identify the nucleus made do not end in known alpha decays of lighter nuclei but in fission. Accordingly it is harder to confirm these exciting results. Clearly we are a long way yet from defining this particular limit.

One might think that the nuclear radius is an easy quantity to measure. Indeed the essence of how to measure it can already be seen in the experiments of Geiger and Marsden [5], namely in the scattering of charged particles from the nucleus. The charge radius, effectively the radius occupied by the protons, can be readily measured in electron scattering and over many years precise measurements of the charge radii of stable nuclei have been made. The results can be found in any undergraduate textbook. The nuclear radius is said to be \( R = R_0 A^{1/3} \) where \( R_0 \) is a constant. In addition the charge and matter radii are almost indistinguishable.

Although this is an excellent rule of thumb for nuclei near stability it was found to be hopelessly wrong for light neutron-rich nuclei like \( ^{11}\text{Li} \) as soon as beams of such nuclei became available. Measurements [6] of their total interaction cross-sections at relativistic energies showed that their radii were much larger than this formula. Analysis [7] in terms of the adiabatic approximation revealed that \( ^{11}\text{Li} \) has a radius of 3.53 [10] fm much larger than the 2.67 fm we would expect from the formula.

The results are interpreted as being due to an extensive halo of neutrons around a core of \( ^9\text{Li} \). We now know of quite a few light nuclei with such haloes and there are examples [8] of nuclei with proton haloes as well.

As nuclei get larger one would anticipate that the halo would become a less prominent feature and become rather a skin of neutrons. Although less prominent a feature we may anticipate that it will have profound consequences for nuclear properties. In essence what is a two fluid system near stability becomes a three fluid system in the nuclear equivalent of the Outback. Now we might expect a whole range of collective motions with these fluids moving against each other. Fig. 4 shows some simple examples.

Earlier we mentioned the magic numbers. They represent values of \( N \) and \( Z \) associated with extra stability. If one doubts the evidence one need only look at Fig. 5 where the energy of the first excited \( 2^+ \) state in even-even nuclei is plotted as a function of \( Z \) and \( N \) together with a plot of the corresponding \( B(E2; 2-0) \) values.
The highest energies clearly occur at the well known magic numbers consistent with what we would expect if they are spherical. However we have known for some time that the idea of shells is a labile one. In essence the magic numbers for the stable nuclei are the result of large energy gaps determined by the spin-orbit interaction. What happens to this interaction in nuclei far from stability? If one calculates the single particle levels as a function of nuclear deformation, as in the Nilsson model, then the energy gaps associated with closed shells change in N and Z. For example, naively we would expect that $^{40}$Zr with both neutrons and protons filling the $N = Z = 40$ subshell should be spherical but it turns out [9] that it is well
deformed in its ground state and is close to the centre of a region of deformed nuclei. Similarly, calculations with the cranked shell model reveal that the energy gaps move with rotational velocity. Accordingly we might not be surprised if varying the ratio of neutrons to protons also moves the shell or energy gaps. As we move away from stability the nuclear potential will soften. In the neutron-rich nuclei we will have a lower density surface associated with the skin of neutrons. As a result, the spin-orbit interaction which lowers the energy of the higher j spin-orbit partner, will become weaker and thus we may look forward to a gradual disappearance of the energy gaps as we move away from stability.

Dynamical symmetries also play a major role in nuclear structure; they are best understood in terms of the Interacting Boson Model (IBM) introduced by Arima and Iachello [10]. In this algebraic model based on Group theory we treat even-even nuclei as being made up of bosons, each consisting of pairs of fermions. The model predicts the existence of dynamical symmetries which coincide with the geometrical shapes associated with the rotation of a deformed, prolate nucleus, a spherical harmonic oscillator and an oblate deformed rotor. Examples of all of these cases have been found in Nature. The model has also been extended to the prediction [11] and observation of supersymmetry where systems of even-even, even-odd and odd-odd nuclei are connected by a common structure. Although eagerly sought in other systems it is only in nuclei that supersymmetry has been shown to exist. More recently Jolie et al. [12] have looked at nuclei lying between these limits in terms of phase transitions between the different geometrical structures and have applied Landau’s theory of second order phase transitions to them. Iachello [13] has developed analytical expressions for the energies and transition probabilities in nuclei at the critical points.

Fig. 6 shows an example of the so-called E(5) critical symmetry prediction compared with the experimental level scheme. The only parameter here is the energy of the first 2+ state. We see excellent agreement. Again all of this is near

![Fig. 6](image-url)
stability. What happens far from stability? Will we find new examples of the dynamical symmetries? Will we find new symmetries in a three fluid system? Will we find examples of co-existing phases? The interested reader will find a nice summary of the topic in [14].

3. HOW CAN WE STUDY ATOMIC NUCLEI?

Compared with most physical systems nuclei are difficult to study. The reason lies in the strength of the nuclear interaction, which results in a very tightly bound system. Accordingly we cannot easily proceed, as in atomic physics, to study the wavefunctions of electrons in individual objects by bombarding the atom with photons or electrons or X-rays and then measure the energies, momenta, angular momenta etc of the ejected electrons. To do the equivalent thing for nuclei demands photons or particles of high energy to overcome the nuclear binding, which is typically 8 MeV per nucleon. Similarly atoms are readily affected by electric and magnetic fields that we can generate in the laboratory. Such fields have little effect on nuclei.

How then can we proceed?

The answer is that we have two ways in which we learn about nuclear properties, namely radioactive decay and nuclear reactions. The former is an important source of information; it often provides the first information on any newly produced nucleus. It is often the basis for precision tests of the Standard Model [15] and other things. Thus it is extremely useful. However we have no control over radioactive decay; in essence it is immutable. Decay rates can be altered under some circumstances but, in general, it is not a profitable way to proceed.

Fig. 7 shows in cartoon form some of the many possible outcomes of nuclear collisions, ranging from simple elastic scattering to quite complex reactions such as fragmentation or fission where there are many possible outcomes. Which reaction dominates depends on the nuclei involved and the bombarding energy. Which reaction we choose to study depends on what we want to learn. Thus if the bombarding energy is significantly below the Coulomb barrier the cross-section for Coulomb excitation will be high and since the interaction is via the well understood electromagnetic force it is an ideal choice if we wish to excite the low-lying states and measure their electromagnetic decay probabilities. Similarly if we wish to study the single-particle composition of low-lying states in the nucleus transfer reactions are the ideal tool. The main point is that in nuclear reactions we have control of some of the key quantities we want to study such as the excitation energy, angular momentum etc of the nuclei we want to study.

In Section 2 we examined some of the open questions in the study of atomic nuclei. The discerning reader will have noticed that the key to answering most of
these questions lies in the study of nuclei with a neutron-proton ratio well away from that of the stable nuclei. It is possible to make and study such nuclei already but only in a limited way and many of the reactions we would like to study are not possible. For example at first sight multiple Coulomb excitation of a nucleus such as $^{40}$Zr to determine the $B(E2; 2-0)$ to check its deformation is not possible because we cannot do the experiment with a target made of such a short-lived nucleus. All of this would change if we had beams of radioactive nuclei. Thus if we had a beam of $^{40}$Zr ions we do not need such an exotic target. We direct the beam on to a target such as $^{208}$Pb and measure the gamma rays emitted. In the jargon, we can use inverse kinematics. It will not escape the astute reader that we are in the same situation with many of the reactions we believe are important in explosive nucleosynthesis. In stars we have a gas or plasma of both types of nucleus involved in the reaction. In the laboratory we can study such reactions in inverse kinematics if we can create the relevant beam. In short, if we are to find answers to our questions about nuclear structure we need beams of radioactive nuclei. How can we create them?

4. CREATING BEAMS OF RADIOACTIVE IONS

Two methods have been found so far. In generic terms they are known as the Isotope Separator On-Line (ISOL) and In-flight techniques. There are variants of both but all the functioning or proposed systems can be fitted into these two categories. Fig. 8 summarises the main facts about both of them.

The basis of the ISOL system has been around for a long time and has been used to produce beams of radioactive nuclei at low energy (60 keV). The archetypal system is the ISOLDE facility at CERN which has all the main characteristics of
such a facility. The radioactive nuclei are produced in nuclear reactions with a beam of particles from a primary accelerator. Any beam of particles with energy above the Coulomb barrier would do; neutrons from a reactor or produced as secondary particles can also be used.

At ISOLDE the primary beam consists of $4 \mu A$ of $1.4 \text{ GeV}$ protons from the PS Booster, the workhorse of CERN’s accelerator stable. They impinge on a thick target where they are brought to rest. The target is maintained at high temperature, partly by beam heating. As a result the nuclei diffuse out of the target relatively quickly and effuse into an ion source. Following ionisation an electric field is used to accelerate them to $60 \text{ keV}$ and extract them into a mass separator, where they are separated by $A/q$. This is the equivalent of mass separation by $A$ since they are all singly charged. The beam can now be directed to experiments or it can be injected into a second post-accelerator to take its energy to that required to induce the nuclear reaction of interest. The two main advantages of the ISOL method are that it allows the use of a thick target and hence maximises the yield of nuclei of interest and that it provides beams of high quality, comparable or identical to that obtained with stable beams. The main disadvantage is that it depends critically on the chemistry of the species of interest. Despite 30 years of development at ISOLDE some elements, notably the refractory elements, are not available as beams. If the half life of the species is very short, of the order of ms, then many of the nuclei decay before reaching the ion source, with a corresponding loss in intensity.

The basis of the in-flight system results in beams complementary in many ways to the ISOL beams. The main facilities world-wide are all based on
accelerators capable of producing intense beams of high energy, heavy ions and are located at MSU (USA), RIKEN (Japan), GANIL (FRANCE) and GSI (Germany). In these cases the high energy primary beam is incident on a relatively thin target. In peripheral collisions with target nuclei part of the projectile is sheared off and a cocktail of projectile-like nuclei with different $A$ and $Z$ values flies in the forward direction with the velocity of the beam. They are directed into a Fragment Recoil Separator (FRS) like the one shown in Fig. 9. In general the cocktail of species passes through the entire system and experiments are carried out on an event-by-event basis with each ion being identified by $A$, $Z$ and charge state. Typically the $B\rho$ of the magnets, the time-of-flight through the system and the rate of energy loss in the final detectors serve to tag the ion which is tracked on to the target. The great advantages of this method lie in the fact that it is independent of chemistry so that all species are available and all species with half lives greater than the flight time through the FRS survive. In rare circumstances even shorter lived species survive [16]. The main disadvantages are that the beam quality is poor and that thin targets are used with a resulting loss in intensity.

![Fig. 9](image)

It is clearly evident that the two methods are entirely complementary, each having advantages for certain types of experiment. They are both subject to variants. The Rare Isotope Accelerator (RIA), the next generation machine to be built in the U.S.A aims to combine the two methods. Using primary beams of 400 MeV it can function as a fragmentation-based facility or a straight ISOL facility or it can be used with a thin target with the ions recoiling into a gas catcher, where they are stopped, ionised, extracted and injected into a post-accelerator. In
this way it is hoped to capture the best of both systems. A second hybrid, sometimes called the Argonne method, involves the creation of a forward focussed beam of high energy neutrons resulting from the breakup of deuterons in a carbon target. The neutrons then impinge on a dense $UC_x$ target where the radioactive species are produced in fission. The neutron-rich fission fragments are then extracted and treated as described above. This is the basis of the SPIRAL II facility to be built at GANIL.

One could catalogue all of the facilities planned or under construction around the World but it would be a somewhat pointless exercise. The interested reader can find the details in successive proceedings of the Radioactive Beam series of conferences [17]. Instead I shall discuss below the two second generation facilities to be built in Europe, namely FAIR and SPIRAL II. This is partly because they represent Europe’s main contribution in the near future to this field and partly because of personal involvement.

5. THE NEXT GENERATION OF MACHINES IN EUROPE

It would be equally pointless to regale you with every detail of these two machines since they are readily available on the Web. Instead I will endeavour to pick out their main features and how they will help to answer the questions outlined in section 2.

5.1. FAIR

Fig. 10 shows both the present GSI facility and the outline of the future facility. It is aimed not just at producing radioactive beams but beams of anti-protons for hadron physics; relativistic, heavy ion beams to allow an exploration of the nuclear phase diagram at higher net baryon density than studied so far; plasma physics and atomic physics. As far as nuclear structure is concerned the aim is an improvement of a factor of 10$^4$ in beam intensity over the current facility to be achieved by an increase in both primary beam energy and intensity. Radioactive nuclei will be produced in both fragmentation and fission of the primary beams.

Fig. 11 shows the layout of the new Super-FRS and its three experimental branches. At the time of writing the main outlines of the Super-FRS and the associated equipment and programmes are clear but the detailed design continues. A large collaboration, involving ~ 800 scientists, called NuSTAR has been formed to design, fund and build the equipment needed.

The three experimental branches are aimed at different types of experiment although their physics goals overlap. The low energy branch is based on the idea of slowing down or stopping the ions resulting from fragmentation or fission from the
Super-FRS and then using them. It will involve a magnetic spectrometer designed to focus the slowed down ions. If they are stopped in an active or passive stopper their decay can be studied. Since experiments of this kind may involve only a few ions per second or less the detection systems must be as efficient as possible. The so-called RISING campaign at the present facility gives an example of what one might expect. In Fig. 12 we see at the top, the decay schemes for a series of isomers
in Pt nuclei populated in the fragmentation of a 1 GeV/u beam of $^{208}$Pb. Below, on the left, we see the identification plots for the ions that have passed through the FRS and stopped in an inclined Al plate viewed by a set of Ge detectors, on the right, we see gamma-ray spectra in coincidence with various individual gamma rays emitted in the decay of the isomer in $^{200}$Pt.

The increase in beam intensity and gamma-ray detection efficiency would mean that the same experiment at FAIR would result in the gamma ray peaks in the spectrum having $\sim 10^5$ counts in them instead of 20–30. One can look at this in two ways; either one will do the experiment much better or alternatively one will be able to do similar experiments on nuclei much further from stability.

The second, high energy branch is devoted to reaction studies with fixed targets. Fig. 13 shows the layout schematically. The beams will be used directly, impinging on a fixed target. This will be surrounded by a high-efficiency, gamma-ray detector. A large magnetic dipole behind the target will allow the direction of the heavy ejectiles into either a high-acceptance detector subtending a large solid angle or, in the other direction, into a magnetic spectrometer with a momentum resolution of about $10^{-4}$. Lighter fragments such as neutrons or protons will be detected with high efficiency. The overall aim is kinematically complete measurements of reactions
Fig. 13 – The layout of the high energy branch of the Super-FRS.

with the high energy radioactive nuclear beams from the Super-FRS. It will allow studies *inter alia* of light ion elastic, inelastic and quasi-free scattering and charge exchange in inverse kinematics as well as break up and knockout reactions. In essence this particular programme has a sound foundation built on current experiments at GSI. An example of the results [8] of one type of experiment to be carried out this way are shown in Fig. 14.

Fig. 14 – The upper panel shows (points) the measurement of the inclusive longitudinal momentum distribution for 7Be ejectiles in the knockout of a proton from 8B at relativistic energies [8]. The lower panel shows the same results but for ejectiles in coincidence with gamma rays from the first excited state in the ejectile. The widths are shown on the figure. The curves represent the results of three-body calculations.
The main aim here is to determine the configuration of the ground state of $^8$B using the present Fragment Recoil Separator at GSI. A primary beam of 1 GeV/u $^{12}$C ions from the SIS heavy-ion synchrotron was used to produce a beam of $^8$B nuclei by fragmentation at 936 MeV/u at the entrance to the spectrometer. The FRS was used in its energy-loss mode to transmit the $^8$B ions to a carbon target placed at the intermediate focus of the spectrometer where the $^8$B breaks up into $^7$Be + p. The $^7$Be is then transmitted to the final focal plane where they are identified and detected in a position sensitive, time projection chamber and their longitudinal momentum distribution measured. An array of 32 NaI detectors was set up behind the target at the intermediate focal plane. This was used to record the $^7$Be ions in coincidence with prompt gamma rays.

Fig. 8 shows the longitudinal momentum distributions of all fragments and also those in coincidence with the 429 keV gamma rays de-exciting the $\frac{1}{2}^-$, first excited state in $^7$Be. These measurements allow one to determine the amounts of the $^7$Be ground state and first excited state in $^8$B. The latter makes up 13 $\pm$ 3% of the total cross-section. The results are interpreted in terms of $^8$B as a three-body system made up of an alpha plus $^3$He plus a proton. From the longitudinal distribution in momentum one can deduce the corresponding spatial distribution of the protons in $^8$B. The conclusion of the analysis of the results is that $^8$B has a proton halo.

The third branch is unique to FAIR. It consists of a complex of storage ring shown schematically in Fig. 15. Although the present experimental programme at the ESR (experimental storage ring) is highly successful it is limited partly by the

Fig. 15 – The complex of storage rings to be built at FAIR. See text.
intensities of the available secondary beams from the FRS and partly by the poor matching of the emittance of the FRS and acceptance of the ESR. As a result many experiments are ruled out by the low luminosity. The increase in the primary beam intensity and energy at FAIR will lead on average to radioactive beams some $10^4$ times more intense and this huge improvement will make many new experiments feasible and push the boundaries of experiment further away from stability just as in the case of the other two branches. As stated earlier the largest improvement is in the matching of the beam characteristics with the acceptance of the rings.

One of the main programmes to be followed with the rings involves the measurement of masses and lifetimes of exotic nuclei. As we saw earlier such measurements are important for nuclear astrophysics and also in determining where the drip-lines lie. As Fig. 3 shows, measurements along chains of isotopes and isotones reveal where shell gaps occur. Measurements on the $N \sim Z$ nuclei will shed light on the role of neutron-proton pairing. It will also be possible to measure masses and lifetimes for isomeric states and indeed to produce pure beams of isomers.

Technically the experiments are demanding. The production cross-sections are low and the beams from the Super-FRS have a large emittance and large longitudinal momentum spread. We must also remember that the nuclei far from stability are very short-lived. Two methods of measuring masses have been developed at GSI, namely Schottky Mass Spectrometry (SMS) [18] and Isochronous Mass Spectrometry (IMS) [19]. These measurements are both based on determination of the frequency of rotation which characterises the charge-to-mass ratio of the circulating ions. The difference between SMS and IMS is that in SMS the momentum spread of the beam is reduced by both stochastic and electron cooling whereas in IMS the optics of the ring is tuned to an isochronous mode such that the ions with different velocities follow different, compensating trajectories. These methods do not reach the high level of precision made with Penning traps but are ideally suited to measure a broad swathe of the mass surface at once.

Nuclear lifetimes can be measured by counting the changes in intensity of the stored mother and daughter ions in SMS. Alternatively the numbers of daughter nuclei can be recorded with particle detectors placed near the orbit of the mother nuclei and monitoring the intensities of the mother nuclei by SMS. In both cases we obtain redundant information.

The Collector Ring(CR) and New Experimental Storage Ring(NESR) will accept the full phase space of the fragments delivered by the Super-FRS.

The CR operated in Isochronous mode will involve nuclei with very short half-lives, down to $\mu$s. Precise measurements of the revolution frequency will be possible using time-of-flight detectors and sensitive resonant Schottky probes. For longer-lived nuclides, nuclei with half-lives longer than 1 s, they will be pre-cooled stochastically in the CR and then transferred via the RESR to the NESR. They will then be cooled further by electron cooling and mass measurements will be made by
SMS. The pre-cooling in the CR will reduce the time for electron cooling considerably in the NESR.

Fig. 16 shows an example of the spectra obtained with the present ESR at GSI. A large number of fully stripped ions are captured in the ring. In essence their masses are measured by time-of-flight over many revolutions in the ring and so the relevant measurement is one of frequency. Since there are many nuclei of known mass as well as those whose masses are sought one does not need to seek far for calibration. The inset to Fig. 16 shows how good the resolution is in that one can distinguish ions in the ground state and 754 keV excited state of $^{143}\text{Sm}$. The sensitivity is such that we see in this inset the signals from just a single ion in each of the two states. The reader can have no doubt that this is a very powerful tool. All of these measurements will transform our knowledge of the masses of nuclei far from stability.

The NESR will also allow the first real programme of reaction studies with exotic nuclei in a ring. The cooled beam of radioactive ions will interact with a gas jet or pellet target. This programme will complement that at the high energy branch. It will again aim for kinematically complete measurements but with the great improvement that a very thin target can be used. Fig. 17 shows a schematic of the proposed detection system. In part, magnets of the NESR lattice can be operated as a spectrometer for the projectile-like heavy ions. The design is not yet complete and is technically demanding but it is envisaged that part of the ring will
help act as an element of the spectrometer needed to analyse the spectrum of heavy ejectiles and light particles and gamma rays will be detected with high precision. Taken altogether the aim is that the detector system will handle a wide range of different types of reaction. What can we expect from this first real programme of reaction studies with exotic nuclei in a ring? The range of possibilities is large and includes elastic scattering to give nuclear matter radii and distributions, which will provide information about haloes, skins and central densities.

Studies of inelastic scattering will provide information on surface collective states, electric giant resonances and bulk properties in asymmetric matter, compressibility and soft collective excitation modes. Charge exchange will allow access to Gamow-Teller and spin-dipole resonances, as well as spin-isospin excitations leading to better understanding of the properties of neutron skins, spin excitations and stellar weak interaction rates.

Measurements on transfer reactions will give spectroscopic factors for single particle- and hole-states as well as pair transfer. The idea will be to shed light on single-particle structure, the changing spin-orbit interactions and the pairing interaction. Studies of quasi-free scattering will also allow the measurement of single particle spectral functions and cluster knockout providing detailed information on single particle structure, nucleon-nucleon correlations and in-medium interactions.

Fig. 18 also shows a small electron storage ring that can provide beams of electrons collinear with the radioactive ions stored in the NESR. This will allow studies of reactions of the electrons with the radioactive ions. One principal result will be direct measurements of the charge radii of the radioactive ions. Of course it will be limited in terms of how far from stability we can go because of the finite time to cool the ions in the NESR but it will provide unique information.
5.2. SPIRAL II

European aspirations in terms of the ultimate ISOL facility are embodied in a facility called EURISOL [20] facility would use at least 1 mA of 1 GeV protons on a thick target as the primary means of creating the radioactive nuclei. Technically this is beyond our present capabilities and demands a series of technical developments. One major step in this direction is represented by SPIRAL II, a second-generation facility to be built at GANIL, France.

Spiral II is based on the so-called Argonne method in which an intense (5 mA) beam of 40 MeV deuterons from a superconducting Linear accelerator (Linac) is directed on to a rotating carbon converter wheel where the deuterons break up, producing an intense beam of neutrons in the forward direction, with energies centred around 14 MeV, which strikes a thick UCX target. Neutron-rich nuclei are produced in the fission of Uranium in this target. Ions are produced at low energy as described in section 4.2 and then injected into the existing CIME cyclotron to be accelerated to the energies shown in Fig. 18.

![Fig. 18](image)

Fig. 18 – The range of energies for the radioactive ions produced by the CIME cyclotron, the post-accelerator of the SPIRAL II facility.

Fig. 18 shows the ranges of ions that will be provided by SPIRAL II using not just fission but various other reaction mechanisms to produce the ions using the heavy ion beams that will also be available from the Linac with high current, up to 1 mA, at up to 14 MeV/u and A/q = 3.
Fig. 19 shows the future overall layout at GANIL. The new linac and associated beamlines are seen at top right. A direct beamline from CIME to the G1 and G2 beam rooms means that operation of the present cyclotron complex is independent of the new ISOL beams. Overall it will be possible to produce five separate beams at different energies and places simultaneously. This will make very efficient use of the facilities.

At the time of writing the question of the new equipment needed to exploit the SPIRAL II beams is still under debate. However several major pieces have been added recently to an already formidable array of equipment. This includes the EXOGAM gamma-ray array [21], the TIARA Si detector array for light particles [22] and the VAMOS spectrometer [23]. These can be operated together to study a wide range of reactions.
The great advantage of ISOL beams, as stated earlier is the beam quality. Fig. 20 shows a gamma-ray spectrum of the multiple Coulomb excitation of a beam of $^{76}$Kr ions from the SPIRAL I accelerator facility at an energy of 4.4 MeV/u on a Pb target. The spectrum was recorded with EXOGAM. All of the observed transitions are E2 transitions and are labelled by the initial and final spin values of the levels in $^{76}$Kr. The spectrum has been corrected [on-line] in energy for the effect of the Doppler shift due to the motion of the emitting nuclei. This particular spectrum was recorded [24] in coincidence with the scattered Kr ions detected in an annular Si strip detector. The EXOGAM array consists of up to 16 clover Ge detectors. In each case the four leaves of the clover are segmented in four so that there are effectively 16 elements in each detector which means that Doppler correction can be carried out to good effect.

![Kr74 + Pb208](image)

Fig. 20 – The preliminary spectrum of gamma rays from the Coulomb excitation of $^{74}$Kr ions at SPIRAL. The gamma rays were detected in coincidence with Kr ions in an annular Si strip detector. (Courtesy of W. Korten and E. Bouchez).

6. SUMMARY

This is an exciting time to be a nuclear physicist. Now we not only have beams of all stable nuclear species up to energies well beyond anything we need in nuclear physics but we are now able to produce beams of accelerated radioactive
nuclei by two different methods. These methods complement each other. Here we have concentrated on the next generation of facilities to be built in Europe; FAIR and SPIRAL II represent big advances in the production of radioactive nuclear beams. They are not the only such facilities being built in Europe. At CERN-ISOLDE the addition of a post-accelerator, called REX-ISOLDE, allows the exploitation of many of the beams developed there over the last 30 years or so. In addition the original ISOL machine at Louvain-la-Neuve is still highly productive and the EXCYT project exists at Catania. Further afield the ISOL facilities at ISAC-TRIUMF and Oak Ridge are functioning and RIA, the Rare Isotope Accelerator, awaits the green light in the USA. The RIBF (Radioactive Ion Beam Factory) is under construction at RIKEN in Japan.

Space here is too limited to say anything about these two machines too. The emphasis here has been on radioactive ion facilities and on nuclear structure physics. The reader should not be carried away with the idea that this is all we need in the way of facilities. High quality, high intensity beams of stable nuclei also have a major role to play in future. As fig. shows we want to explore all of this diagram and that means the need for stable and radioactive species. Sometimes both will be needed as part of a single experiment. This can be done relatively easily at SPIRAL II for example. In addition radioactive beams have many uses other than for nuclear physics. The interested reader is referred to [25] for further information.

REFERENCES

15. See e.g., A. Garcia, Nuclear Physics, A746 (2004) 298c.
17. See e.g., Nuclear Physics, Vol. 746.