Present and Future RIB Facilities

B R Fulton
Physics Department, University of York, York YO10 5DD, UK
E-mail: Brian.Fulton@york.ac.uk

Abstract. Over the past decade a range of facilities have been built which produce accelerated beams of short-lived radioactive nuclei. The advent of these beams has revolutionised nuclear physics research by removing the straightjacket that Nature had held us in when only the few stable nuclei were available to be used to initiate nuclear reactions. We can now probe further, and in more detail, towards the limits of nuclear stability, uncovering new structural phenomena and measuring the key nuclear reactions that control the energy output and element production in explosive astrophysical sites. A new generation of facilities is now under construction or planning that will have the capability to extend our reach ever further. In this talk we will survey the capabilities and time lines of these facilities, as well as looking at the science areas that each will address.

1. Introduction
As the recent OECD Global Science Forum report [1] on Nuclear Physics has revealed, we are a part of a truly enormous human endeavour. Worldwide, the annual spend on nuclear physics is $2B and the activity employs around 13,000 scientists and support staff. Approximately 3,000 PhD students are trained each year, providing young people equipped to provide the skilled technical workforce that society needs. The applications of our science also spread widely across society, covering power generation, medical procedures and industrial applications.
A defining feature in the development of our science over the last decade has been the development of radioactive beam facilities - accelerator complexes were we can produce intense, high quality, accelerated beams of short lived isotopes. The science drive towards this goal has long been recognised, since being constrained to carrying out studies using the 300 or so stable nuclides that Nature has given us greatly limits our ability to produce and study new nuclei, or to measure the rates of the reactions between nuclei. As a result our understanding of the nuclear landscape was until recently constrained to those (perhaps uncharacteristic) nuclei that lie close to the valley of stability on the Segre chart. With the new facilities removing this constraint, the whole range of some 7,000-8,000 nuclei between the drip lines becomes available for study and understanding.
Efforts to create, separate and study radioactive nuclei have of course been undertaken for many year. Setups were developed in many laboratories in which a beam impinged on a target to produce new nuclei. By designing the setup so that the target was inside some form of ion source, the short-lived, radioactive nuclei produced in the reactions could be ionised and accelerated to some tens of keV to enable mass analysis and selection of specific isotopes of interest. As well as enabling the ground state and decay properties of these nuclei to be studied, these low energy beams also found applications in a wide range of other sciences (atomic physics, surface science, solid state studies etc.).

Published under licence by IOP Publishing Ltd
While it is invidious to pick out one example from the many successful facilities, it is worth highlighting the ISOLDE facility at CERN where over 600 different nuclei have been produced and studied in this way over some three decades.

While much nuclear physics information can be gained from studies using these low energy accelerated beams, this is generally restricted to the ground state properties of the nuclei, and to the low lying states in any daughter nuclei which arise from their decays. To study the excited states we need to be able to accelerate these nuclei and use them in nuclear reaction studies and this provided one approach in the development of radioactive beams. This can be achieved by building a second accelerator which can take the short-lived radioactive beams from the ion source and re-accelerate them. This has become known as the “ISOL” approach (Ion Separation On-Line). Another quite separate approach was developed in parallel and is known as “In-Flight”. This avoids the use of the ion source and lets the nuclei produced in reactions in the target fly out of it and be used directly (after some form of magnetic separation). For this to work effectively the beam energy required in the primary accelerator has to be much higher so that the recoiling radioactive nuclei produced in the reactions are of high enough energy. We will look at these two approaches in more detail in the next section.

Figure 1  Worldwide distribution of radioactive beam facilities

Figure 1 shows the worldwide distribution of facilities which are either in operation or in construction. This presents an impressive picture of worldwide activity in the field. It is important to note that these developments have not occurred by accident, but as a result of a coordinated approach by the community, both on the regional and international level. For many years the planning of facilities in the USA and Europe has been guided by the Long Range Plans produced on roughly five year periods by NSAC (Nuclear Science Advisory Committee) [2] and NuPECC (Nuclear Physics European
Collaboration Committee) [3]. Previous reports by these committees set out the science case for a new generation of radioactive beam facilities, defined the ideal beam specifications and outlined the experimental instrumentation which would be needed to pursue the science. In particular, the NuPECC LRP published in 2002 established the aim, already alluded to in the previous LRP, that Europe should build two next generation radioactive beam facilities, based on the ISOL and In-Flight approaches. As an aside, it is pleasing to note that our Asian colleagues have recently established ANPhA as a coordinating body loosely based on the NuPECC model and it may be that ANPhA will in the future help guide the development of our science in the Asian region). This regional planning is further coordinated on an international level by studies carried out under the auspices of the Global Science Forum of OECD (Organisation for Economic Cooperation and Development). In particular, the report in 1999 was a key in providing the international drive towards radioactive beam facilities, a direction confirmed in the more recent 2008 report [4].

2. Methods of producing radioactive beam facilities

As mentioned earlier, there are two main approaches to producing accelerated radioactive beams – ISOL production and In-Flight production. A further method (batch production) is used on occasions for relatively long-lived nuclei where they are produced and chemically separated before being placed in the ion source of an accelerator, but we will not consider that approach here. Figure 2 shows a schematic outline of the production methods used in the two approaches and further details are given in the following sections.

3. The ISOL approach

In the ISOL method, the beam from a primary production accelerator is used to bombard a target which is incorporated into an ion source. The target/ion source assembly is maintained at a high temperature so that the radioactive nuclei produced by nuclear reactions in the target diffuse out of the target material and are ionised so that they can then be extracted for mass analysis and subsequent acceleration in a second accelerator. The key components of the system are shown in Figure 2 and comprise the primary accelerator, the target/ion source assembly and the secondary accelerator. The choice of the primary accelerator will depend on the beams which are required, which in turn is determined by the reaction process which is chosen (transfer reaction, fusion, fragmentation etc.). First generation facilities were usually built around existing accelerator facilities and the choice of reaction mechanisms depended on the beams available. In second generation, purpose built facilities high energy proton beams are a popular choice, exploiting spallation reactions on a wide range of different mass targets to access nuclei across the Segre chart. A third generation of facilities is now in the construction phase where deuteron beams are also used. The innovation here is to have a separate target upstream of the target/ion source assembly where the deuteron beam interacts to produce a neutron beam which can be used for neutron induced fission reactions (these have the ability to produce much more neutron rich radioactive nuclei than other reaction processes). A key feature of the primary accelerator will clearly be a high beam current, as the production rate will scale with this, but the limits on beam intensity more often come from what the target/ion source can cope with rather than the accelerator.

The target/ion source assembly is perhaps the most challenging aspect of the facility. The operation of this at high temperatures, under intense beam irradiation and in a hostile radioactive environment brings enormous technological challenges. The design of the assembly requires a deep knowledge of materials science, atomic physics and chemistry in ensuring the most efficient diffusion and effusion of the nuclei of interest, in preventing them being held in the source by chemical bonding and in ensuring that they are ionised in the most efficient way. The operation of the source is also a major challenge in terms of materials lifetime and remote handling. One advantage of the deuteron/neutron approach mentioned above is that the radioactive loading is restricted to the (relatively simple) upstream target, simplifying the problems for the main target/ion source assembly.

The mass analysis of the extracted radioactive nuclei to select the species of interest, and their subsequent reacceleration, is relatively straightforward, with the main technical challenges and innovations here being in implementing methods to charge breed the nuclei (higher charge states...
enable more efficient acceleration) and designing the accelerator emittance and low energy of the extracted ions.

4. The In-Flight approach
In the In-Flight approach the radioactive nuclei are not re-accelerated, but produced directly as fast moving products emitted from the target following fragmentation of a primary beam nucleus. In this case the beam nucleus must be relatively close in mass to the nucleus to be produced and must also be at a relatively high energy in order that the reaction products have the required energy. The target in this case is more conventional and the choice is partly determined by considerations of the reaction cross section, but mostly by the ability to withstand high beam currents.

Figure 2 shows a schematic layout of an In-Flight facility. The demands on the primary accelerator are that it be able to accelerate a wide range of beam species up to the heaviest masses, and to provide high intensity beams at the highest energies where the fragmentation cross sections are largest (typically 100’s of MeV/u). The main challenge in the facility is the secondary stage, where the beam of interest is selected out from the vast number of radioactive nuclei emerging from the reaction target. This is achieved by a complex arrangement of electromagnetic separation sections, incorporating selective energy loss sections to remove isobaric contaminations and using time-of-flight and particle tracking to uniquely identify each nucleus as it hits the secondary target where the reactions of interest take place.

5. Advantages of the ISOL and In-Flight methods
The two approaches are entirely complementary, which is why facilities based on each method are being constructed in each region.

The advantage of the ISOL approach is that a wider range of reaction processes can be employed, chosen to maximise the production in particular regions of the Segre chart. In addition the technique allows greater separation of the selected nuclei and the secondary acceleration enables the beam energy of the radioactive beam to be varied. The disadvantages lie in the target/ion source, not just the complexity of operation inherent in these sophisticated assemblies, but also in the fact that it takes a finite time to get the radioactive nuclei out of the source and so there is a limit on the half-lives of nuclei which can be re-accelerated (typically 10’s of ms). In addition, for some particularly reactive elements, chemical hold times in the source can prevent intense beams being produced.
By contrast, the In-Flight approach suffers from no chemical selectivity and because the nuclei remain fast moving, the effective limit on half-lives is considerably lowered. This advantage is offset by the fact that the beam emittance is poor and suffers an energy spread. In addition, the energy of the secondary beam is not variable as it is fixed by the primary beam energy, this limiting the types of secondary reaction studies that can be investigated. Recently techniques have been developed to circumvent these problems, with the secondary beams being stopped in gas cells from which they can subsequently be extracted (and even re-accelerated in a hybrid Fragmentation/ISOL approach) or injected into storage rings where their energy can be lowered and the beam energy spread and emittance reduced by cooling.

6. Operating facilities
There is a wide range of facilities operating at present, ranging from small university based to major national facilities. In the former class are the facilities at Calcutta (VECC-RIB), FSU (RESOLUTE), Notre Dame (TwinSol) and Sao Paulo (RIBRAS), which provide a limited range of beams, but occupy niche areas by exploiting particular reaction mechanisms or separation approaches. The larger facilities are often first generation facilities where an existing accelerator is used for the production stage (or re-acceleration for ISOL facilities). These include the facilities at Catania (EXCYT and FRIBS), CERN (REX-ISOLDE), GANIL (SPIRAL), GSI (FRS/SIS), MSU (NSCL), ORNL (HIRF), RIKEN (RIBF), Texas A+M (T-REX) and TRIUMF (ISAC). In a number of cases the facilities have planned upgrade projects which will enhance their capability for subsequent years.

7. Facilities under construction
A wide range of facilities are presently being constructed including ANL (CARIBU), Beijing (BRIF), CERN (HE-ISOLDE), GANIL (SPIRAL-2), GSI (FAIR), Legnaro (SPES), MSU (FRIB) Orsay (ALTO) and TRIUMF (ARIEL). Many of these are dedicated radioactive beam facilities which have been designed specifically for this purpose. They are all designed to deliver a wide range of beam species, over a wide energy range and with high intensities. Although all are nationally funded projects (FAIR is an exception here), most have a strong international aspect with the instrumentation for the facilities being planned by large international collaborations of experimenters. These facilities will come into operation during the present decade and ambitious and novel science programmes are outlined in the science cases prepared for these.

8. Facilities being planned
A number of exciting projects which will produce the third generation of facilities in the following decade are under discussion around the world. The projects are at differing stages of maturity, some are still paper exercises, others in the conceptual design stage and some fairly advanced and reaching the point where funding decisions will be sought.
In Europe the longer term aspiration centres on EURISOL, exploiting a high power (4MW) linac accelerator. This is an ambitious project to build a multi-beam facility capable of producing and accelerating beams of all masses to energies from a few to many hundred MeV per nucleon. Much work has already been done on the design and efforts are now underway to get this on the roadmap of European facilities and to generate the interest to garner the $1B+ funding required.
In Asia there are a number of projects being developed. The one closest to realisation is KARIA (Korean Rare Isotope Accelerator) facility. This is again a $1B plus scale facility which have both a fragmentation and ISOL capability. In China, CARIF (China Advanced Rare Ion-beam Facility) is a concept to accelerate fission fragments produced through fission by thermal neutrons from a new advanced reactor.

9. References
[1] http://www.oecd.org/dataoecd/35/41/40638321.pdf
[2] http://www.er.doe.gov/np/nsac/index.shtml
[3] http://www.nupecc.org
[4] http://www.oecd.org/dataoecd/35/41/40638321.pdf