Accelerated beams of radioactive nuclei

W Gelletly

The study of nuclear physics demands beams of energetic particles to induce nuclear reactions on the nuclei of target atoms. It was from this need that accelerators were born. Over the years nuclear physicists have devised many ways of accelerating charged particles to ever increasing energies until today we have beams of all nuclei from protons to uranium ions available at energies well beyond those needed for the study of atomic nuclei. This basic research activity, driven by the desire to understand the forces which dictate the properties of nuclei, has spawned a large number of beneficial applications. Amongst its many progeny we can count reactor- and spallation-based neutron sources, synchrotron radiation sources, particle physics, materials modification by implantation, carbon dating and much more. It is an excellent example of the return to society of investment in basic research.

All of these achievements have been realised by accelerating the 283 stable or long-lived nuclear species we find here on Earth. We see them in fig. 1, the black squares, plotted as a function of the numbers of protons (Z) and neutrons (N) that they contain. In recent years, however, it has become evident that it is now technically possible to create and accelerate unstable nuclei and, as we see in fig. 1, there are some 6-7,000 distinct nuclear species which live long enough to be candidates for acceleration. They are the nuclei within the so-called drip-lines, the point where the nucleus can no longer hold another particle. It needs little imagination to see that this development might not only transform Nuclear Physics but could lead to many new, undreamed of, opportunities in industry, medicine, material studies and the environment.

In this short article I would like firstly to outline the ways in which we can produce them and secondly to describe some obvious applications of such beams.

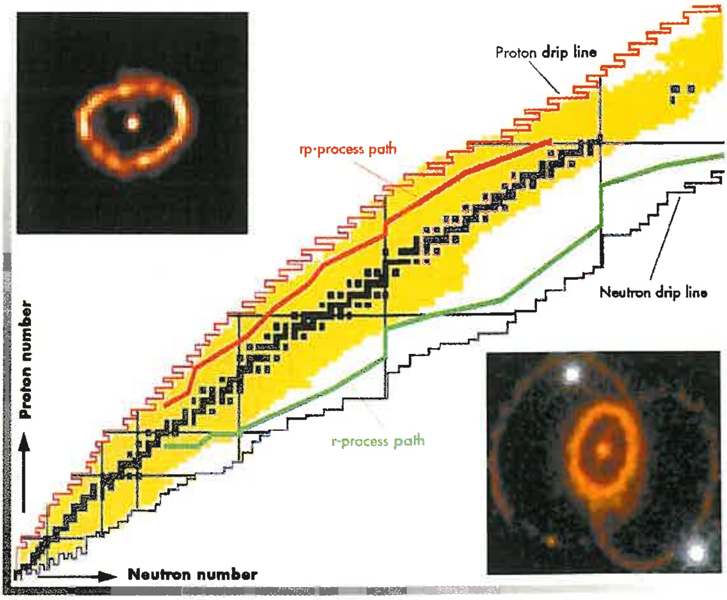

Fig 1: **A chart of the nuclides with the black squares, representing the stable nuclei, plotted as a function of the number of protons and neutrons in the nucleus. It also shows the limits of observation of nuclei, the drip-lines and the astrophysical r- and rp-process pathways. The insets show Hubble Space Telescope images of the nova Cygni 1992, a possible rp-process site, and the afterglow of SN1987A, an r-process site.**

How can we produce beams of unstable nuclei?

Fig. 2 shows schematically the two main methods of radioactive beam production which have been proposed. They are commonly known as the ISOL-Isotope separation on line – and In-flight techniques. In the ISOL method, we must first make the radioactive nuclei in a target/ion source, extract them in the form of ions and, after selection of mass by an electromagnetic device, accelerate them to the energy required for the experiments. In contrast, the in-flight method relies on energetic beams of heavy ions impinging on a thin target. Interactions with the target nuclei can result in fission or fragmentation, with the nuclei which are produced leaving the target with velocities close to those of the projectiles. A cocktail of many different species is produced which, since the ions have high velocities, does not need further acceleration to transport it to the secondary target. On route to the target the reaction products can be identified by mass, charge and momentum in a spectrometer (fragment separator). Thus a pure beam is not separated out from the cocktail. Instead each ion is tagged and identified by these primary characteristics and the secondary reactions are studied on an event-by-event basis. More recently US scientists have proposed a combination of the two methods in which the in-flight reaction products are brought to rest in a gas cell, sucked out and separated by mass and then re-accelerated to the required energy.

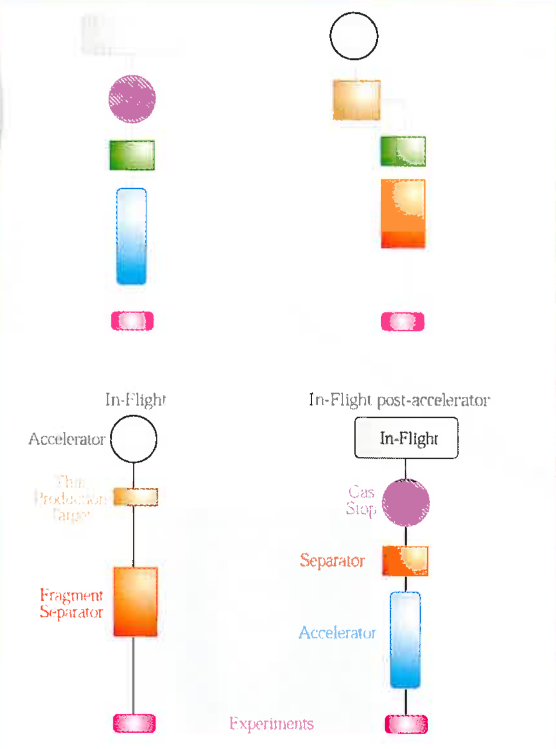

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Fig 2: **A schematic view of the basic methods of producing radioactive nuclear beams. At the top we see the ISOL method with and without a post-accelerator. Below we see the In-flight method and the proposed hybrid in which fragments are caught in a gas cell and then re-accelerated.**

The ISOL and in-flight methods are complementary in almost every respect. With the ISOL technique one can produce beams of high quality, comparable to that of stable beams. Since we start with ions at the temperature of the target/ion source the process is similar to the way the beam is generated in a stable beam accelerator so one can produce beams of similar quality. Strong ISOL beams can be produced but the intensity varies markedly according to a) the chemical species involved and b) how far from stability they are. Refractory elements such as Zirconium and Molybdenum are extremely difficult to ionise and are not suitable for the method at present. This technique also relies on the diffusion and effusion of the radioactive atoms in the target, which is maintained at high temperatures (~2500°C) to speed the process up. Such diffusion processes vary a lot in speed. For short-lived nuclear species, with half-lives of milliseconds or less, this is often the limiting factor in intensity because the atoms decay before they reach the final target.

In contrast, in-flight facilities can produce all chemical species with half-lives greater than about 150ns, the time of transit through the fragment separator, and since the beams are produced at high energy they do not need re-acceleration. The main drawbacks of this method however are that a) the beams are weak, b) they are not separated physically – the individual ions are simply tagged electronically by A, Z and momentum and c) they are of poor quality in terms of energy and focussing.

The idea of combining the ISOL and in-flight methods by stopping fragmentation products in a gas cell is clearly aimed at getting the "best of both worlds". In principle the method should work but it requires considerable development to show that it is effective.

Uses of Radioactive Beams

What can we do with beams of radioactive ions? It turns out that they provide an analytical tool which can be used to probe the structures of atomic nuclei and materials as well as having applications in nuclear astrophysics, bio-medicine and the environment.

Thus ion implantation is widely used to modify the properties of materials. It is a versatile tool and can be used to alter the mechanical, electrical, optical, magnetic and chemical nature of materials. The process is independent of the normal solubility or alloying rules. Thus it has been used to create a wide range of semiconductor devices as well as machine tools and replacement parts for the human body which are wear resistant.

In general the modification required is achieved empirically. How much better, however, if we could determine where the implanted ions end up. We can do that by implanting radioactive ions of the same chemical species under exactly the same experimental conditions. As illustrated in fig. 3 the radiation pattern of the implanted ions is influenced and altered by the electric and magnetic fields in the material of the host. By monitoring these changes with various techniques we can obtain information on the nature of the sites they occupy and their surroundings. In some sense we can see the radioactive ions as "spies" on the microscopic environment. The information our spies glean allows us to understand the implantation process and hence design better devices.

Radioactive decay involves chemical transformation and is characterised by its half life. Thus it can provide a chemical signature at the atomic level. Many standard spectroscopic techniques used in materials studies, such as photoluminescence, electron paramagnetic resonance and deep level transient spectroscopy, are chemically blind. If they are used with radioactive implants this "chemical blindness" can be cured for these techniques by following the growth and decay of the signals. In other words using radioactive implants will take the "informed" guesswork about chemical species out of the use of these techniques.

Almost everyone must be aware of the widespread use of nuclear techniques in medicine for diagnosis and therapy. A simple example is the use of radioactive tracers in vivo. This has been done for a long time but is not fully exploited because of limitations on the range of tracers. Positron emitters provide the basis of PET (Positron Emission Tomography). Its use

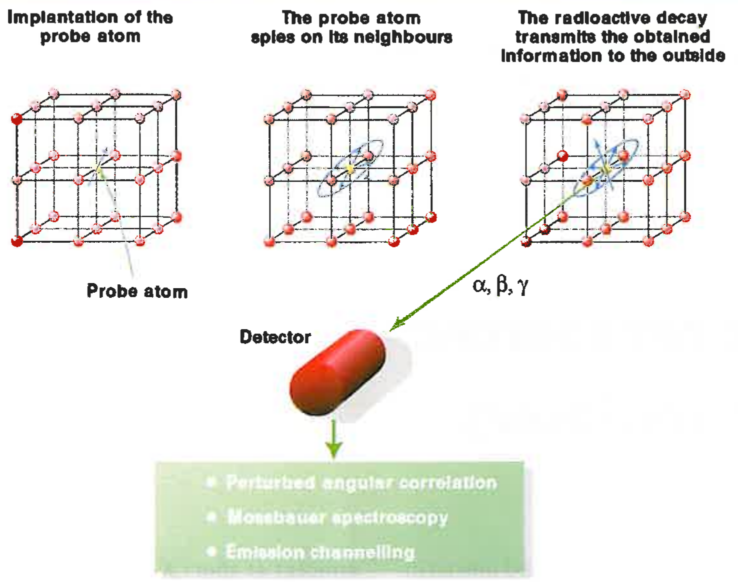

Fig 3: **An illustration of how radioactive probe atoms implanted in a solid can act as "spies" on their microscopic environment. The properties of the probe atom are modified by the local microscopic environment and that information is carried away by the radiation emitted in the radioactive decay that follows.**

is limited by the positron emitters available. Beta emitters have great potential for radionuclide therapy but with a few exceptions those of therapeutic interest are not commercially available. ISOL-based radioactive beam accelerators could repair this deficiency. Amongst many possible topics, therapeutic effects are known to depend on specific activity and so systematic studies of the relationship between the specific activity of tracers and the biological response are important to clinical research. Again the radio-lanthanides are non-specific "tumour-seeking" tracers, which could be produced "carrier-free" and in sufficient quantities in ISOL systems. So far we have only scratched the surface in this general area.

Environmental problems can also be tackled. When we investigate how to isolate and store nuclear waste we immediately worry about leakage of the long-lived, fission products. The general thrust of this research is to incorporate the waste into a solid which is then contained within a concrete or rock barrier. To be sure there is no external contamination we need to know all about how the radionuclides are transported in these materials. This can be investigated by implanting ions of shorter-lived radioactive fission products and determining how they move in the storage material.

For the nuclear physicist these facilities are a cornucopia of beams for all sorts of purposes. Amongst the many delights is that they will allow us to probe the limits of existence of nuclei. Basic theoretical predictions of how heavy a nucleus can be, or how many neutrons or protons it can hold will be tested much more vigorously than before. We now have little doubt that the basic idea behind "superheavy" elements is correct. To date we are fairly sure that a few atoms of elements up to Z=112 have been detected and there has been exciting but as yet unconfirmed evidence of the detection of elements 114, 116 and 118. However the heart of the predicted island of superheavies has many more neutrons than the species which have been created so far. One route leading closer to the centre of the Island would be to use nuclear reactions induced by beams of radioactive nuclei rich in neutrons.

Similarly we have little idea of the point where we can no longer add another neutron to the nucleus. Intriguingly we believe that neutron stars exist and they are, in essence, gigantic nuclei made of neutrons. Hence we might think that we could add neutrons forever. However neutron stars are so heavy that gravity plays a major role in stabilising them. We believe that there are limits but our present best guesses vary by 20-30 neutrons in the case of tin (Z=50) isotopes. Beams of radioactive nuclei will allow us to narrow the range of guesses if not decide where the neutron-rich nuclei come to an end by precise measurements of nuclear masses and the separation energies for the last neutron. In exploring these questions we will also encounter many new phenomena. We expect to see skins and haloes of neutrons in nuclei far from stability and we anticipate that the quantum shells which underpin nuclear structure in stable nuclei will disappear in these exotic nuclei.

Beams of radioactive nuclei open a gateway to better understanding in nuclear astrophysics as well. The generation of energy in stars, which stabilises them, and the creation of the elements is the result of nuclear reactions. Fusion processes fuel the Main Sequence stars and create the elements up to ^{56}Fe/^{56}Ni. The process runs out beyond this point because it needs an input of energy for fusion to continue. In massive stars this is the root cause of their death in the massive explosions we see as supernovae. Most of the nuclear species beyond A=56 are created in type II supernovae. The death throes of these massive stars are accompanied by enormous fluxes of neutrons for short periods. This results in the rapid capture of many neutrons followed by beta decays ending up with heavy nuclei along the lines of stability. The pathway for this so-called r-process is shown in fig. 1. In other dramatic, explosive processes in stars such as novae and X-ray busters a similar process involving proton capture and beta decay, the rp-path (see fig. 1), may be involved in the creation of some of the proton-rich, stable nuclei. Testing these ideas requires the details of nuclear reactions and of the structure of nuclei involved. As we can see from fig. 1, the r- and rp-process pathways pass through large numbers of unstable nuclei. If a reaction involving such a nucleus is important to our understanding of what happens in stars the only way we can study them is to use a radioactive beam incident on a light target; hydrogen or helium. Hence the importance of radioactive beams for this field.

Where are they?

Given the ferment of ideas and activity in this field it is not surprising that there are many proposals to build new ISOL facilities around the World and to upgrade the four, major In-flight facilities at GSI (Germany), GANIL (France), RIKEN (Japan) and MSU (USA). It would be invidious to pick some out and not others and tedious for you the reader to list them all. If you are interested you can try the article by W Nazarewicz et al in Nuclear Physics News, Vol. 6, No. 3, p.17 (1996). Alternatively you can rest assured that "A Radioactive Beam Facility is coming soon to a neighbourhood near you!"