How advances in Nuclear Physics are driven by new experimental methods

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Abstract:-This article has two main aims. Firstly we look at examples of how the introduction of new methods drives nuclear physics forward. Secondly it looks at the exciting new developments in accelerator facilities that produce beams of radioactive ions.

Introduction

This article is based on the first, introductory lecture to be given at the 34th Joliot-Curie School to be held near Perpignan in September/October 2015. The title of the 2015 school is "Instrumentation, detection and simulation in modern nuclear physics". The title of this article is exactly that given by the organisers in their email inviting the author to talk and warning that acceptance required this article as well to provide a record for the students of what was said in the lecture.

Why this particular talk? Perhaps a clue to the answer lies in their request that the talk should describe the "evolution of experimental techniques during the 20th Century from a historical point of view, up to the main large projects in Nuclear Physics in Europe and World-wide." Firstly it is clear that the organisers' main aim for the school is to bring the attendees up to date with the developments that have led to the current building of the extraordinary new facilities that will allow us to study the properties of nuclei and nucleons in their most exotic states. All of the other speakers are well qualified to do that; each bringing a wealth of experience and knowledge of some topic or technique that is vital to our success in these ventures.

So what is this article to be about? The title is fine but covers too large a canvas. To do it justice would require a book, not the kind of article the organisers have in mind. Accordingly I shall focus on nuclear spectroscopy, an area where I have some direct knowledge of how the subject has progressed. Sadly this means that the very exciting developments at Jefferson Laboratory, ALICE at the LHC and the underground laboratories such as Gran Sasso will not be covered. The last part of what I write will be devoted to the huge effort world-wide to create facilities that will deliver intense beams of radioactive nuclear species. It turns out that the genesis and evolution of such facilities follow a general pattern one can discern in the

events of the past. Thus I will focus first on some examples of past developments and innovations in experimental technique that opened the window on whole areas of the subject. I have chosen just a few examples but they illustrate clearly the way our subject progresses.

At this stage I should say that I heartily approve of the theme of the school. Normally when we attend conferences, workshops and graduate schools all the emphasis is on the latest results and our theoretical attempts to explain them. As a result the sudden jumps in experimental capability or the evolutionary improvements in what we can do get lost. Here instead we will be concerned with the advance of experimental technique and we will see how that drives nuclear physics forward. That is our main theme but there are some minor themes as well. The organisers may not be aware of it but their aims were summarised in an article published by Ernest Lawrence, the inventor of the cyclotron, based on a talk he gave at the University of Ohio in 1935 [1]. Fig.1 shows the relevant part of his talk. He also anticipated one of our sub-themes, namely the applications that flow from our advances in technique. He wrote "some of my medical colleagues think it quite possible that the discovery of artificial radioactivity will ultimately be of great importance to medicine." So it has turned out and it is just one of many examples of how improvements in our methods have produced applications of importance in other fields. How well their predictions have been fulfilled can be seen in the contribution by Ferid Haddad to this school [2].

EXPERIMENTAL METHODS

But before discussing experimental results, it is desirable to say something about experimental methods for accelerating protons and deuterons to high speeds. There is a natural tendency to relegate to the background the experimental methods and techniques and to regard the results brought to light in nuclear investigations as of first importance. It is so easy to forget that the nuclear investigations are made possible by the development of experimental methods and techniques. How greatly was nuclear physics enriched by the cloud chamber of C. T. R. Wilson!

Fig.1:- **An excerpt from E.O.Lawrence, Ohio journal of Physics 35, Issue 5, 388(1935)**

Anyone who is interested in history knows how unreliable both oral and written sources can be. Delving into the history of Nuclear Physics is no exception. The writers of textbooks like a "beautiful" story that helps the student to take in the physics message. It is not necessarily the way it happened and one must take the standard tales with a pinch of salt. A few examples will be noted as we pass them by. In general the message for students is that they must be both curious and sceptical. It is common in our subject to make use of the information in the large databases that have been accumulated on nuclear properties. They can indeed be very useful but one would be well advised to go back to the original papers if one is interested in the reliability of the information. If you have not read it then I would

recommend “Surely you’re joking, Mr Feynman” [3], where one sees the importance of curiosity and the desire to get at the essential facts.

I. The Cloud Chamber

As we see in fig.1 Lawrence gives the cloud chamber invented by C.T.R.Wilson as an example of how important experimental advances are. The tale of how Wilson became fascinated by the formation of clouds whilst working as a summer student at an observatory on Ben Nevis in Scotland appears in many places [4]. It is best to learn about it from the man himself [4*homepages.abdn.ac.uk/npmuseum/article/CTRWbroadcast.pdf*].Wilson made his expansion chamber to allow him to study the meteorological processes involved. It is

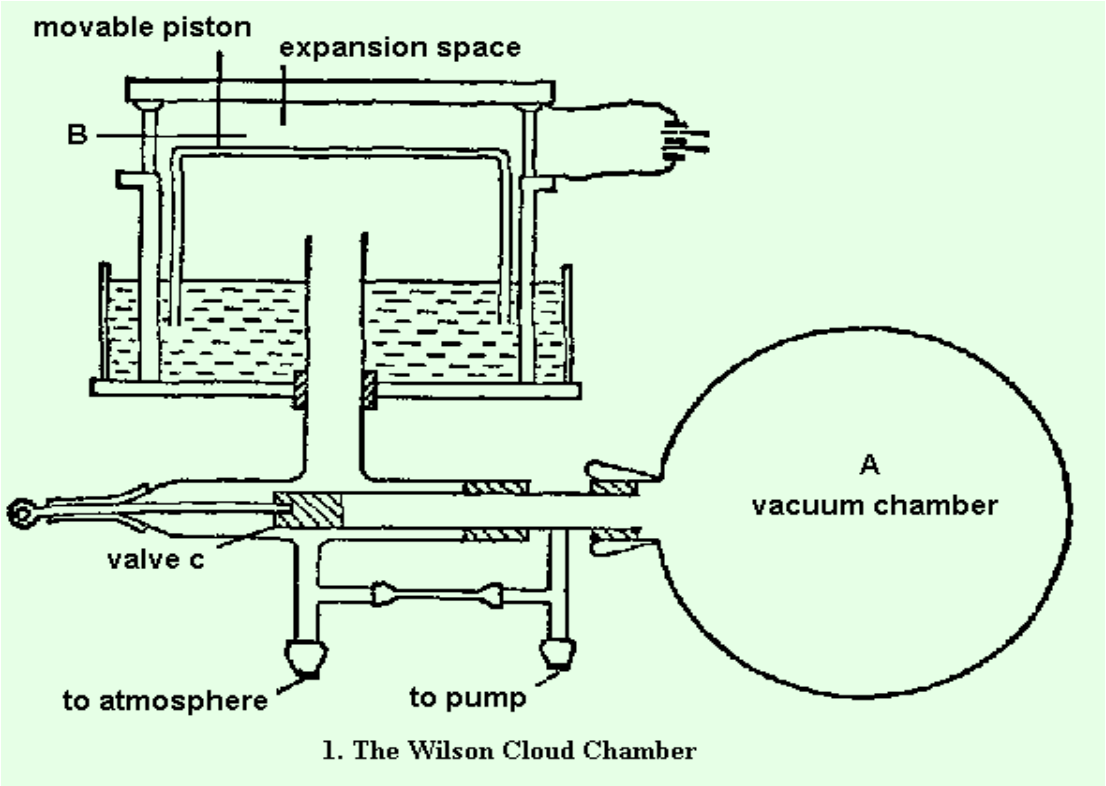


Fig.2:- **A version of the early expansion chambers made by C.T.R.Wilson.**

inherently a simple device. It consists of a sealed chamber with air saturated with water vapour. If the piston is suddenly lowered in an adiabatic expansion the air cools and the water vapour condenses on dust particles and, as Wilson found, also on ions in the air. In the version shown the lower chamber is evacuated and sealed with the valve c. When the valve is removed the decrease in pressure causes the piston to fall and the sudden expansion cools the air. The supersaturated vapour will now condense on dust particles or Aiken particles as Wilson would have called them because of another Scot who had experimented with such phenomena at home. The important aspect of Wilson’s work is that he found that when the air was dust free, which it will be after many expansions, the water vapour condenses on fine, hair-like tracks. He correctly recognised that it was condensing on ions. He spent many years refining the technique [5].

The great significance of the Cloud Chamber was that it allows one to "see" the phenomena that many people were trying to study. It became a major force in the study of cosmic rays and the instrument of many discoveries. Fig.3 shows an excellent example of an expansion where one sees the tracks of an alpha particle, a proton and low and high energy electrons. The characteristic δ-rays, electrons ejected from the atoms of the gas in the chamber because of the Coulomb interaction with the passing proton are also clearly seen. Wilson was awarded the Nobel prize in 1927 along with Arthur Compton for the Compton effect and one can imagine why the Nobel committee put them together in that Wilson's cloud chamber allowed one to see the scattered electron in the Compton process.

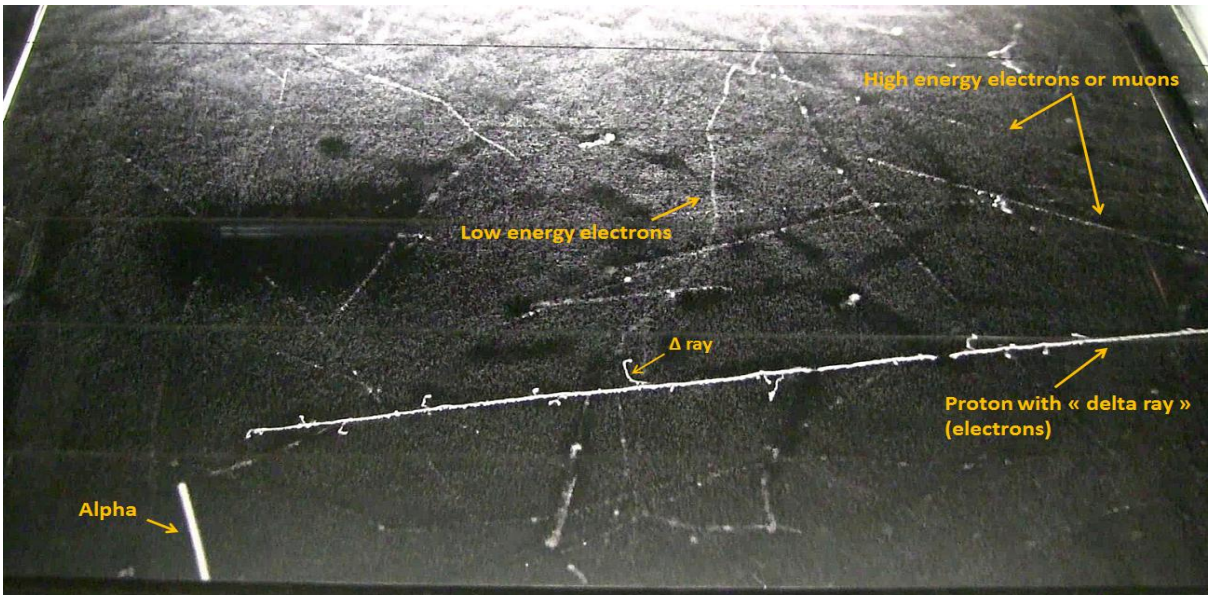
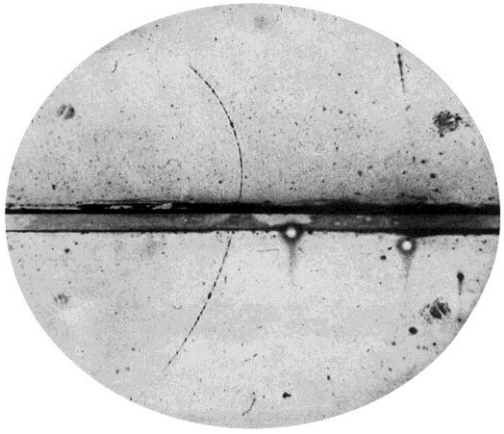


Fig.3:- A cloud chamber picture showing a variety of particle tracks.

Wilson's chamber played a major role in many discoveries. One such discovery [6] was of the positron by Anderson in 1932. In fig.4 the chamber sits in a magnetic field at right angles to the picture. We see the positron travelling upwards in the chamber, its direction obvious because the curvature of the track changes after it loses energy in traversing the Lead sheet. Otherwise it has all the characteristics of an electron. The story of its discovery is an example of how the textbooks like to tell a good story. Earlier Dirac had published his work on the relativistic wave equation for massive spin ½ particles, the Fermions.



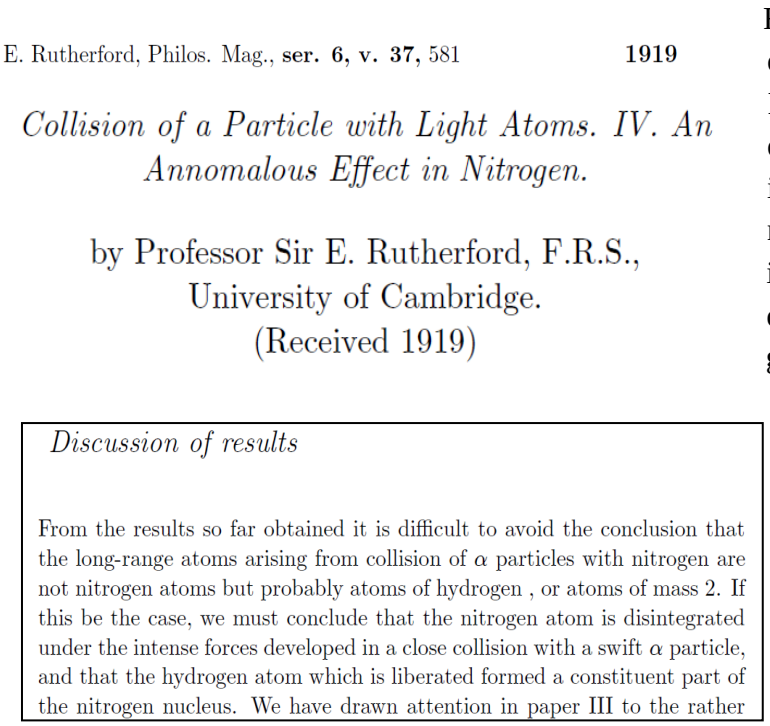
The interpretation of this equation gives as a prediction the existence of anti-particles, the positron in the case of the electron. In the textbook or popular view Anderson knew all about this and was searching for the positron. However Anderson himself said that this prediction played "no part whatsoever in the discovery of the positron." [7]. Yet another

Fig.4:-Anderson's picture of a positron [6].

example of how questioning one should be of what one reads in texts and that is doubly true of what one finds on the web, where the provenance of the material is often highly questionable. The web is a magnificent resource but must be taken with a strong dose of common sense and scepticism.

II. Nuclear reactions and accelerators

In essence we have only two ways of studying the properties of atomic nuclei; in radioactive decay and in nuclear reactions. The earliest focus was, quite naturally, on the former. It was not until 1919 that Rutherford published [8] evidence of the occurrence of a nuclear reaction.



E. Rutherford, Philos. Mag., **ser. 6, v. 37**, 581 **1919**

Collision of a Particle with Light Atoms. IV. An Annomalous Effect in Nitrogen.

by Professor Sir E. Rutherford, F.R.S.,
University of Cambridge.
(Received 1919)

Discussion of results

From the results so far obtained it is difficult to avoid the conclusion that the long-range atoms arising from collision of α particles with nitrogen are not nitrogen atoms but probably atoms of hydrogen , or atoms of mass 2. If this be the case, we must conclude that the nitrogen atom is disintegrated under the intense forces developed in a close collision with a swift α particle, and that the hydrogen atom which is liberated formed a constituent part of the nitrogen nucleus. We have drawn attention in paper III to the rather

Fig.5 shows the relevant section of his paper in Philosophical Magazine. It was one of a series of papers on how alpha particles interact with matter. In this paper, no. IV in the series, he shows incontrovertibly that what he has observed in bombarding nitrogen gas with alpha particles is the

^{14}N (^{4}He, p) ^{17}O reaction

This work opened the way to the effective study of nuclei and paved the way for a host of applications including the understanding of how the chemical elements

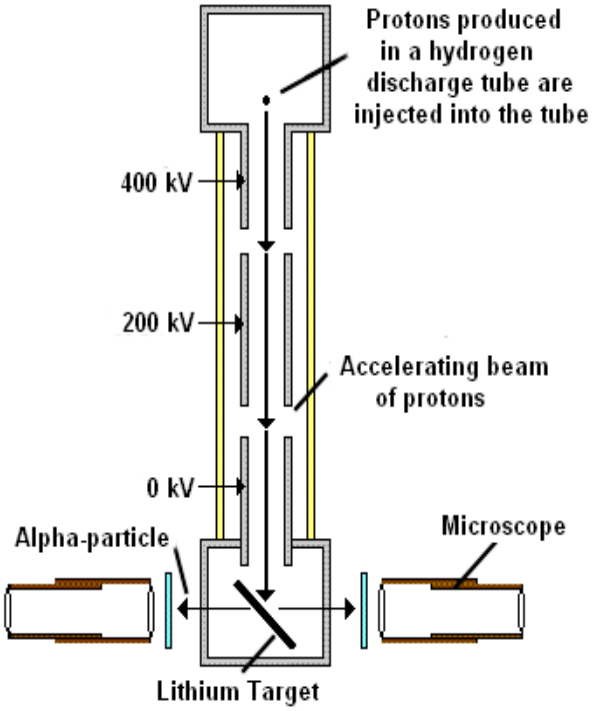
Fig.5:- Part of Rutherford's paper on the observation of the first nuclear reaction

were and are being formed in stars and explosive stellar processes. Alpha particles provided a convenient source of particles to bombard atoms and had, of course, been used to great effect by Geiger and Marsden [9] in their scattering experiments that Rutherford had interpreted [10] in terms of the nuclear atom.

It was immediately obvious that to make use of reactions to study nuclei we needed more flexible tools; projectiles of different types and energies. It was not long before Rutherford was encouraging his younger colleagues to do just that. Lawrence [1] again summarises the efforts needed very clearly and simply. By the time he is writing three approaches have been adopted, that he calls a) the ***High Voltage*** method, b) the ***Surf board*** approach and c) the ***resonance method***. From his description we easily recognise them as the Cockcroft-Walton, linear and cyclotron accelerators. They have all been developed and improved in many ways

and the ideas behind them still underpin the accelerators we use today. We now have available machines that can accelerate everything from electrons and protons up to uranium

ions in mass to energies well beyond anything needed for the original purpose of studying the gross properties of atomic nuclei. At the time of writing the LHC at CERN has just started to provide beams to allow proton-proton collisions at 13TeV. Nevertheless this is still a very long way from the energies seen in the cosmic rays and we continue to need information from their study.



The first successful accelerator was produced at Cambridge by Cockcroft and Walton [11] and they were able to use it to accelerate protons and bombard light elements such as Li and Be. Fig.6 shows schematically the set up Cockcroft and Walton used to study the first artificially induced reaction. They used a chain of rectifier diodes and capacitors to produce a high DC voltage of about 700 keV from a lower transformer AC voltage. They bombarded Li with the protons and observed the breakup of the resulting ^{8}B into two alpha particles emitted back-to-back. They had observed the $^{1}\mathbf{H} + {}^{7}\mathbf{Li} \rightarrow {}^{4}\mathbf{He} + {}^{4}\mathbf{He}$ reaction. Shortly afterwards Lawrence and Livingston [12] had produced the first cyclotron.

Fig 6.:- Schematic view of the setup used by Cockcroft and Walton [11]

Accelerator developments followed thick and fast from then on and continue today. By and large most of the machines that have been built fit into the three categories that Lawrence described [1]. The only exceptions are those based on laser Wakefield acceleration. It is outwith our brief to follow up the importance of this "new" method of acceleration although it seems likely that it will be important for many applications including nuclear physics. Suffice to say here that the concept on which laser plasma acceleration is based was proposed by Tajima and Dawson [13] in 1979 and there are now strenuous efforts to develop the idea in many places.

We shall return to the role of accelerators after a diversion to look at how gamma-ray spectroscopy has developed.

III. The development of modern Gamma-ray spectroscopy.

The existence of gamma rays was established by Villard in 1900 in studies of the emissions from Radium [14]. Rutherford had established the classification of the emissions in terms of their penetrating power and so γ clearly followed α and β in this hierarchy. Villard showed quite clearly that they were uncharged since they were not deflected in electromagnetic fields. In early experiments gamma rays and other radiations were detected by the use of a

spinthariscope, a simple device introduced by Sir William Crookes [15]. It relied on the observation of the fluorescence emitted from a ZnS screen bombarded by a particle. In scientific use these flashes of fluorescent light were observed with a microscope. It was hard and painstaking work to make these observations. First one had a long period of dark adaptation of the eye. Secondly it is hard to concentrate for the long periods needed for the observations. Anyone who has had their peripheral vision tested will testify to the latter. Nevertheless many important discoveries were made this way.

The first important breakthrough came in 1944 but was not published in the open literature until 1948. Curran and Baker took the newly developed photomultiplier tube and attached one to a piece of scintillator. This allowed one to measure the current generated by a particle hitting the ZnS screen. The work was done in 1944 and appeared in an internal report as part of the Manhattan project at Los Alamos and could not be published until 1948. Different scintillator materials and electronics were developed rapidly and now scintillation counters have a multitude of uses and applications and play a significant role still in Nuclear physics.

The second major development was the semiconductor detector. Fig.7 shows a schematic diagram of a p-i-n junction. Pell [17] produced detectors of this form by diffusing Li into a bar of n-type Si. He showed that Li will drift for a considerable distance into the n-type. material.

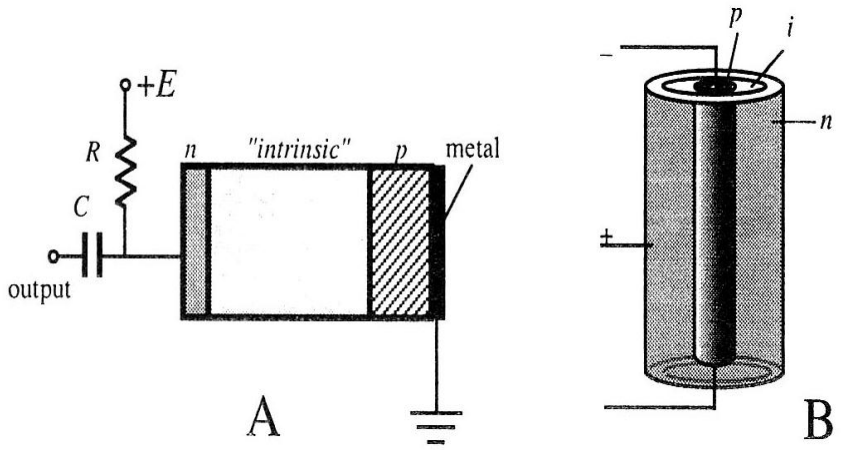
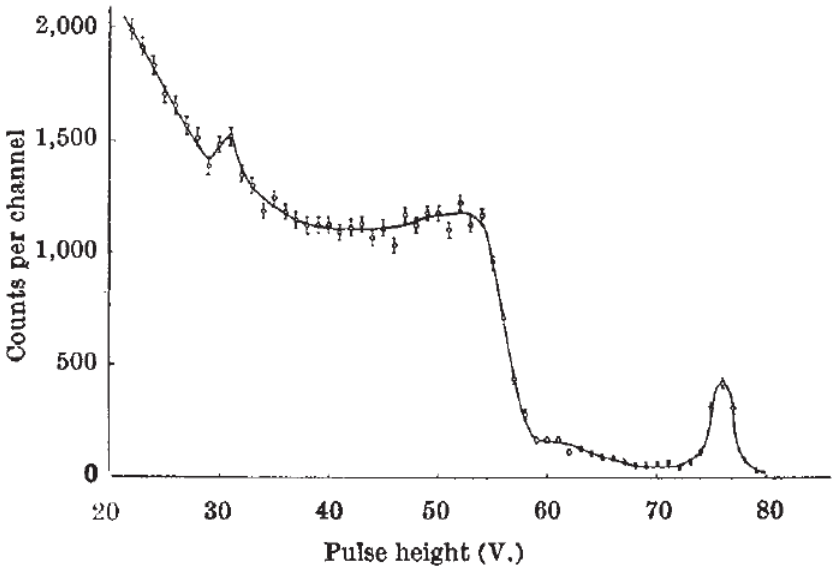


Figure 7: A-schematic of a p-i-n diode, B- a diode in cylindrical form.

Applying reverse bias, namely +ve/-ve connexions to the n- and p-type regions greatly extends the neutral, intrinsic region. Such a lithium-drifted diode (Si(Li)) can be used to detect photons but Si is too light to be really useful for γ-ray spectroscopy since the detector has too low an efficiency. A heavier semiconductor material is needed.

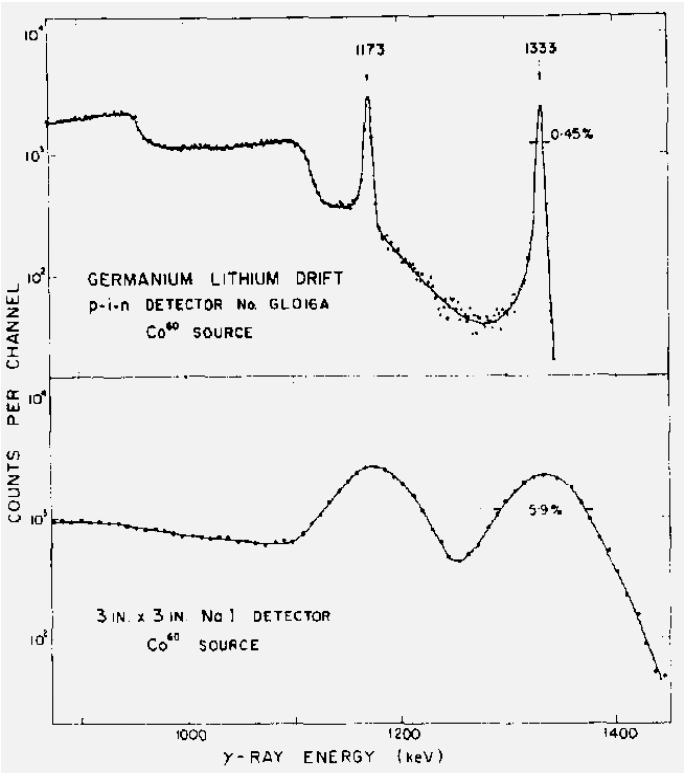
Freck and Wakefield[18] took the next step by producing a Ge based p-i-n junction. The spectrum from a ^{137}Cs source recorded with the detector is shown in fig.8. This is the first published γ-ray spectrum with a Ge(Li) detector.



Not surprisingly this first published Ge(Li) spectrum has a resolution of 21 keV. The height of the photopeak is only about one third that of the edge of the Compton distribution because of the small size of the detector.

Fig.8:- Pulse height spectrum in a Ge p-i-n diode [18]

As an aside it is worth noting that the spectrum was recorded with a single channel pulse height analyser and a scaler. The present author began his Ph.D. in 1961 and his spectra were recorded in the same painstaking way, the Nuclear Physics equivalent of the Neolithic period.



There followed a period in which many people attempted to produce bigger and better Ge(Li) detectors. A lot of attention was paid to the Lithium drift process and the surfaces involved. By the time the present author had finished his Ph.D. and moved as a post-doctoral fellow to Chalk River in Canada the first Ge(Li) detectors of sufficient quality to allow real spectroscopy had been produced at Chalk River by Tavendale and Ewan[19]. The spectrum they obtained from a ^{60}Co source is shown in fig.9, where it is compared with the same spectrum recorded with a 3"x 3" NaI(Tl) scintillation counter.

Fig.9:- The first Ge(Li) spectrum of real spectroscopic quality[19]. The recorded ^{60}Co spectrum is compared with the spectrum from a 3" x 3" NaI(Tl).

Now the energy resolution is 6KeV at ≈ 1 MeV. The Chalk River group quickly showed how useful such detectors could be in studying high energy γ – rays [20]. They demonstrated how versatile the detectors were by showing that one could measure the linear polarizations of reaction γ-rays with a single detector [21].

As they said in [20] "The high resolution, combined with the simplicity of the detector, will make possible many new experiments with reaction and neutron capture γ-rays."

This prediction was to be amply fulfilled because, by this time, accelerators of all kinds were now available in many laboratories and it was possible to study γ-rays from many different kinds of reaction. Fig.10 shows the γ-ray spectrum from the $^{156}Gd(^{4}He,4n)^{156}Dy$ reaction measured with a NaI(Tl) detector. A beam of 52 MeV alpha particles from a cyclotron was used to bombard a $^{156}Gd_2O_3$ target. The spectrum was recorded with and without Lead absorbers in front of the detector to eliminate background by subtraction. The final spectrum in fig.10 is that shown by the darker dots.

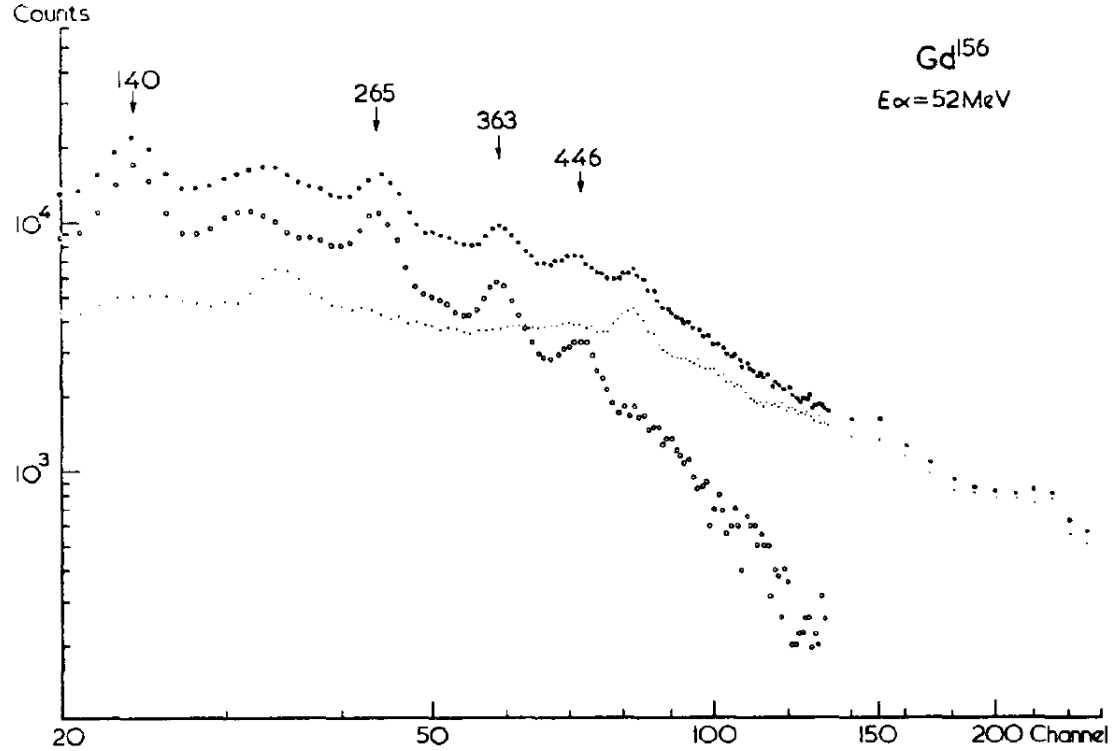


Fig.10:- The γ-ray spectrum from the $^{156}Gd(^{4}He,4n)^{156}Dy$ reaction[22].

The prominent peaks at 140, 265, 363 and 446 keV were interpreted as being the 2-0,4-2,6-4 and 8-6 transitions within the rotational band built on the ground state of ^{156}Dy. Clearly states of medium to high spin were being populated in the reaction and one could observe the gamma rays depopulating these states. It did not take long before the new Ge(Li) detectors were drafted into use in such experiments and produced exciting new results.

Fig.11 shows the γ-ray spectrum from the $^{156}Gd(^{4}He,4n)^{156}Dy$ reaction at a bombarding energy of 43MeV with a beam from the Stockholm cyclotron. The spectrum is again dominated by the intraband transitions in the ground state band of ^{160}Gd but now we see the

transitions up to the 18+ state in the band. The sequence and positions of the gamma rays within the band were confirmed by observations of γ-γ coincidences. A cursory examination of the spectrum reveals that the energy level sequence does not follow the simple I(I+1) relationship that one expects for a simple rotor. As we move to higher spins the levels crowd closer together. Suffice to say that the results would be interpreted [23] in terms of "backbending", the breaking of a pair of particles because of the Coriolis force they experience under rotation.

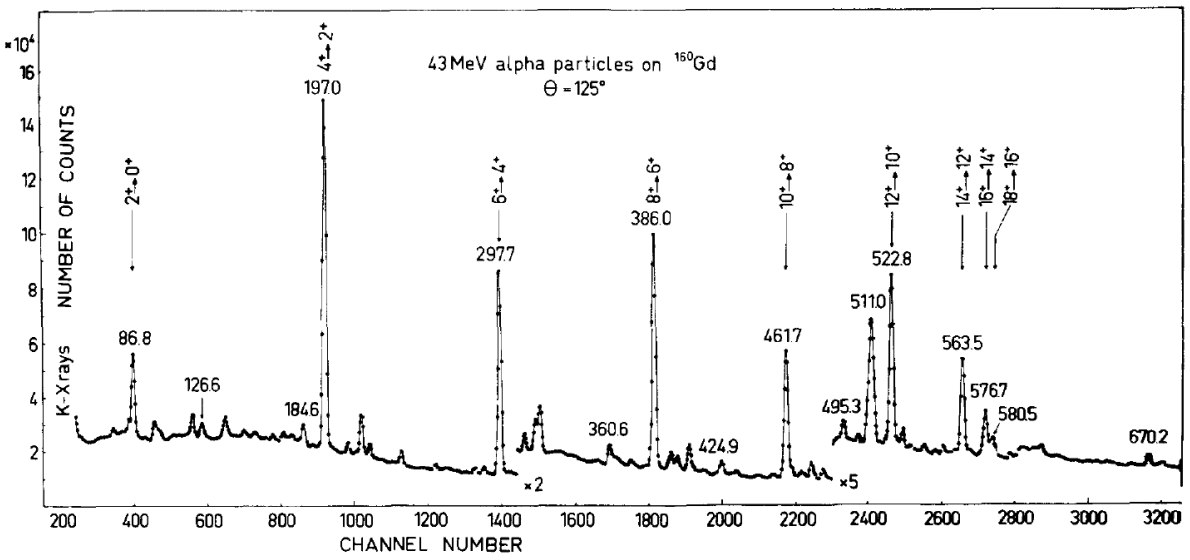
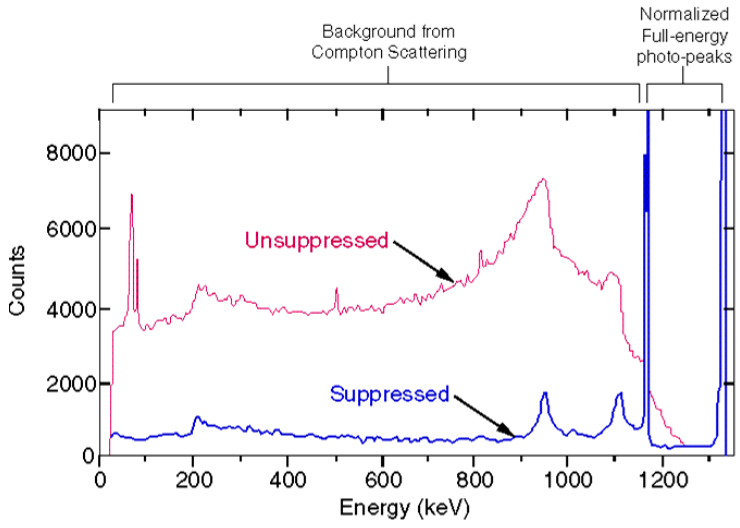


Fig.11:- The γ-ray spectrum from the ^{160}Gd(^{4}He,4n)^{160}Dy reaction at 43 MeV [23].



The quality of the spectra obtained in such studies was constrained by Compton scattering. A large fraction of the γ-rays incident on the detector undergo Compton scattering and the scattered γ-ray leaves the detector carrying some of the energy with it. The effect is clearly seen in figs 8, 9 and 12. The solution adopted around 1970 was to surround the detector with a scintillator.

Fig.12:- The ^{60}Co spectrum recorded in a Ge(Li) detector with and without escape suppression.

This shield had only two holes in it. One to allow the insertion of the Ge detector and the other for the entrance of the gamma rays. Any scattered gamma-ray leaving the Ge detector is recorded in coincidence with the main detector and the event is vetoed. This *escape*

suppression is highly effective as we can see in Fig.12, where the same spectrum from ^{60}Co, with and without escape suppression, is shown. Tavendale and Ewan [19] had already recognised how effective such an active shield would be in their pioneering work The Ge(Li) detector was the detector of choice until ~ 1980. By then developments in the semiconductor industry meant that there was a supply of high purity n- and p-type Ge and one could now make detectors from this HPGe(hyper-pure Ge) material. Typically such detectors require the level of impurities to be below $5x10^{9} – 2x10^{10}cm^{-2}$. In the case of n-type material the diode is formed by Li diffusion on one end and the depletion layer is limited by B implantation on the other end. In p-type material it is the other way round. By ~ 1980 the volumes of HPGe detectors were comparable with or exceeded the volumes of Ge(Li) detectors. It turns out that n-type material is less affected than p-type to neutron damage. As a result from 1980 or so most commercial detectors were n-type HPGe detectors and they have remained the work horse until today. Many different shapes were tried but the most commonly adopted shape was co-axial with one closed end. All the modern gamma ray arrays (see below) are based on n-type HPGe detectors of this shape. HpGe detectors had a number of advantages over Ge(Li) detectors. Firstly production was faster and easier since the slow drift process was not involved. Secondly the detectors still had to be operated at T < 110K but they could be stored at room temperature. Thirdly they could be made with larger volumes, another key element in reducing Compton scattering and hence improving the photopeak/total ratio.

As we saw earlier [23] the use of Ge(Li) detectors in coincidence was a powerful tool for determining level schemes since it allows one to pick out sequences of γ-rays from a large background of unrelated transitions. The use of escape suppression shields helped to improve the sensitivity of such measurements but more was needed. The solution was clear. More detectors were needed. This led to the construction of what have been termed arrays of gamma-ray detectors. The first of these [24] was set up at Riso in Denmark by a collaboration from the Niels Bohr Institute and Liverpool University. It consisted of five escape-suppressed detectors. Fig.13 shows a descendant of this TESSA (the Escape Suppressed Spectrometer Array) array namely TESSA-2 [25]. This development rapidly led to the building of many different arrays with different capacities and characteristics. NaI was replaced by Bismuth Germanate ($Bi_4Ge_3O_{12}$) as a shielding material because of its higher efficiency and the fact that it allowed one to build a more compact and efficient array. The technical development of arrays and the Physics that underpins it has been very ably summarised in [26].

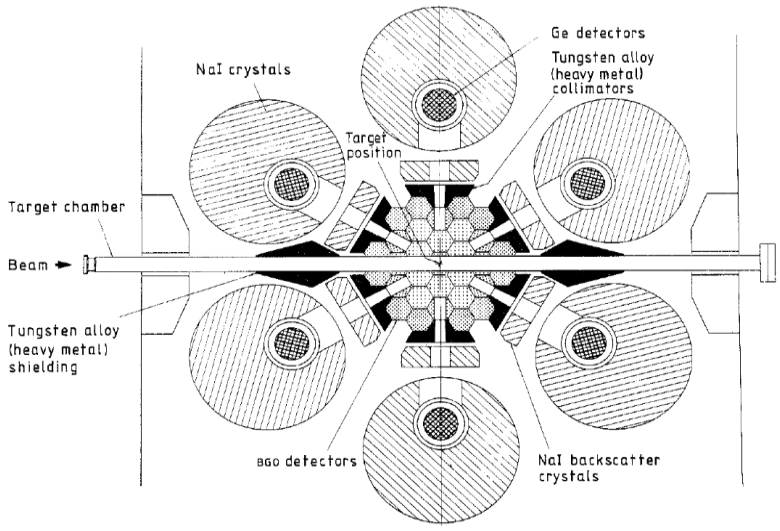


Fig.13:- A cross-section through the TESSA-2 array[25] showing the HPGe detectors, NaI shields, backscattering crystals and an inner array of BGO crystals.

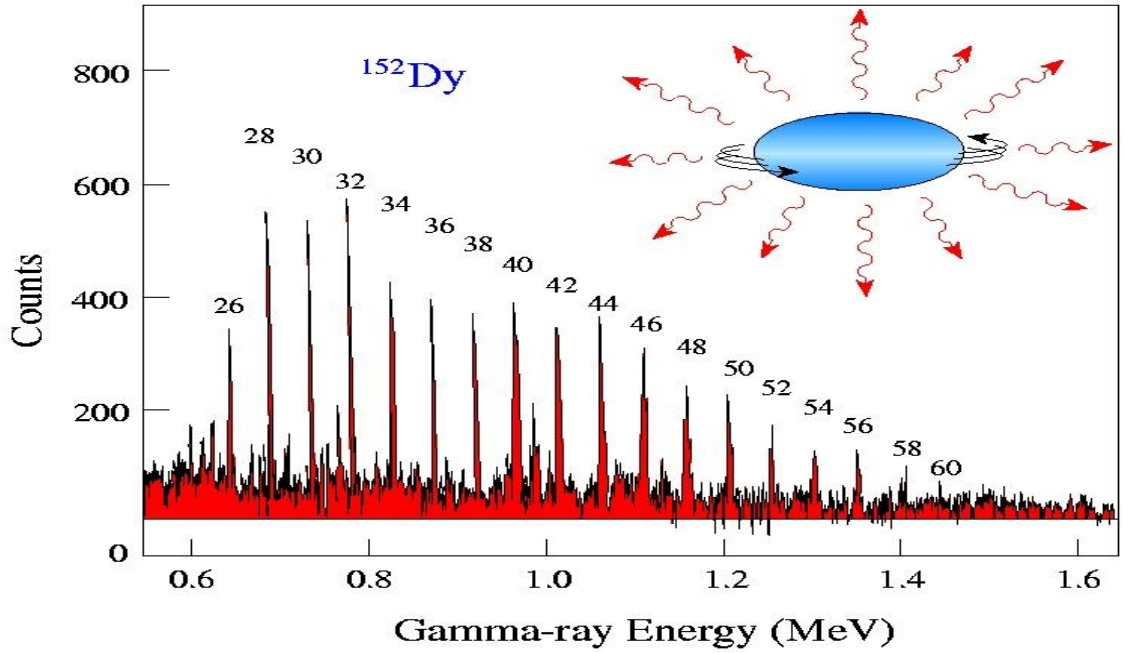


Fig.14:- The first observed spectrum of a discrete-line superdeformed band [27].

The experiments with these arrays produced a veritable explosion of results and information about high spin states in nuclei.

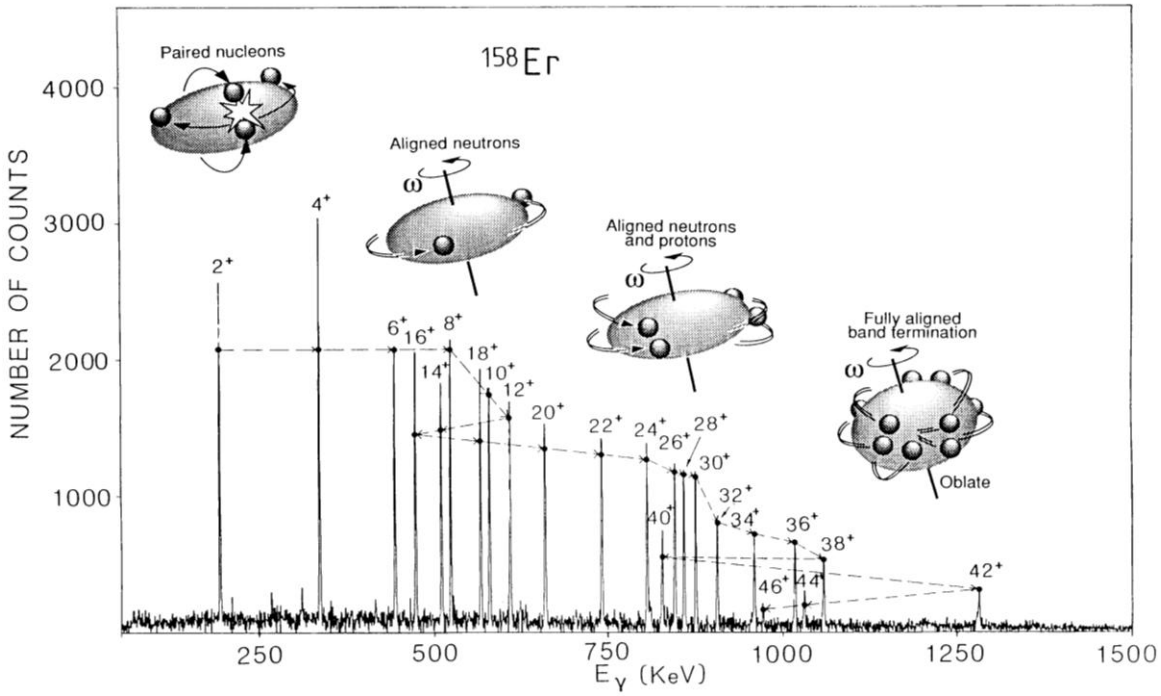


Fig.15:- The observation of the termination of a rotational band in ^{158}Er [28]. (see text)

Fig.14 shows the first observation of the discrete transitions in a superdeformed band. The transitions were observed with the TESSA3 spectrometer [29] with an inner BGO ball. The states in the band were populated in the ^{108}Pd(^{48}Ca,4n) ^{152}Dy reaction at 205 MeV bombarding energy. One is observing the de-excitation of a series of rotational levels for a prolate ellipsoid with an axis ratio of 2:1.

Fig.15 shows the transitions de-exciting states in the ground state band of ^{158}Er [28]. The dashed lines joining the transitions de-exciting successive levels in the band show clearly a series of "backbends". We start from the prolate ground state with all of the valence nucleons paired. Firstly a pair of neutrons aligns, then a pair of protons and eventually all of the valence nucleons are aligned above $j\pi = 42+$. All of these newly aligned particles are orbiting the "equator " and one can see from the cartoon shown as an inset that the overall shape will now be oblate.

These and many other exciting new physics results were reviewed and placed in the context of the development of γ-ray arrays up to 1998 in [30]. The physics is interesting but constitutes a digression from our main themes here.

The evolution of gamma-ray spectroscopy has not ended but the evolutionary process is now being driven by needs other than searching for the weak signals of transitions de-exciting rotational structures and has re-focussed as a tool for studying nuclei far from stability [31]. As we will see later this puts an even greater premium on total absorption efficiency, peak-to-total ratio and granularity but because of the high velocities of the nuclei produced in fragmentation reactions and fission there are new demands related to reducing the spread in γ-ray energy due to the Doppler effect.

- 1960:- First Ge(Li) detector - Freck and Wakefield
- 1963:- First Ge(Li) detectors of spectroscopic quality – Tavendale
- late 1970s:- HPGe detectors take over from Ge(Li)
- 1981:-first TESSA array with NaI(Tl) suppression shields - Riso
- 1985:- BGO suppression shields introduced
- 1994:- Cluster detector
- 1996:- Clover detector
- 2003:- MINIBALL with Digital processing of preamplifier signals
- ≈2000:- Gamma ray tracking [32,33]

Fig.16:- The steps towards modern γ-ray spectroscopy

Naively one's first response to the need for increased efficiency for γ-ray arrays is to think of a complete shell of Ge. The main groups working in this area considered the idea but it is impractical both because of cost and because of scattering between the granules that would make up the detector. The main problem is being able to distinguish between signals in two adjacent detectors that may have come from interactions with two separate γ--rays or from scattering between the detectors. The granularity could be increased and the shell moved further form the target to minimise this effect but this would mean even greater expense.

Instead the solution adopted in Europe and the U.S.A is the idea of γ-ray tracking, an idea that was put forward [32,33] by the group at Berkeley. In essence the AGATA and GRETA arrays, designed and being built in Europe and the U.S.A respectively, are based on the same principles. They make use of highly segmented detectors and the physics of Compton scattering. In both cases the idea is to surround the target or source by a shell of about 100-200 position-sensitive detectors. Using digital electronics and pulse-shape analysis one can identify every interaction point in energy deposited, time and position as the γ-ray scatters from segment to segment and is finally absorbed in the whole shell. Each event is then reconstructed in software using the Klein-Nishina formula. Both AGATA and GRETA will have high efficiency because of the total volume of Ge, provide good correction for Doppler broadening since the angle of emission form the target is measured from the first interaction point and very good peak-to-total ratio. Both systems have been used and are being refined in early implementation forms based on the availability of a limited number of detectors. Fig.17 shows schematically an idea of how AGATA will look with its full complement of 180 detectors and also the improvement expected compared with a conventional array.

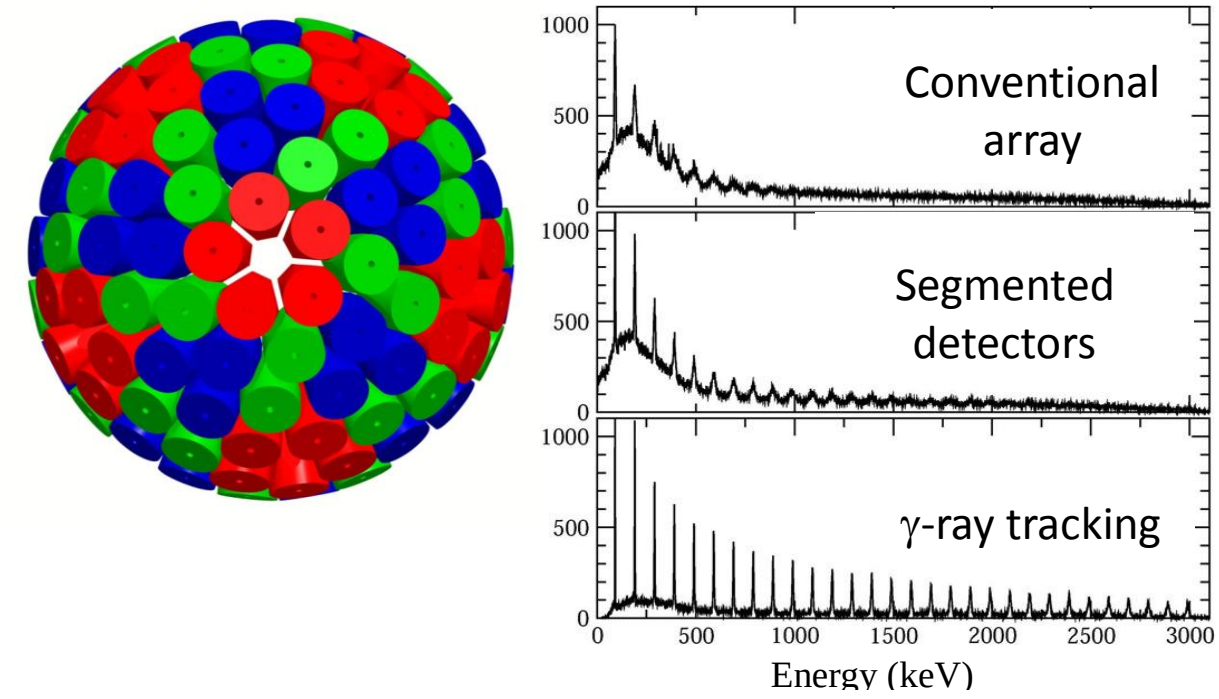


Fig.17:- On the left a schematic view of AGATA with its 180 large-volume Ge Detectors with 36 segments. On the right an example of the expected improvement in performance.

As one can see in Fig.17 the improvement in performance will be particularly important in studies of γ-rays from the products of fragmentation reactions and fission (see later). Our cursory look at the development of γ-ray spectroscopy has only touched the surface. Any reader who wants the detail should read [26, 34].

The reader may wonder why I have spent quite a lot of space on the question of how γ-ray spectroscopy has developed. The answer is straightforward. I could have used other areas of nuclear physics to provide an example but I am personally familiar with this particular area and I believe that it has developed in just the way that many other parts of Nuclear physics has developed.

The developments listed in fig.16 were all important milestones on a path that led from an initial breakthrough to the capabilities we have today. Undoubtedly it needed Freck and Wakefield's [18] first Ge(Li) to kickstart the process. Modern γ-ray spectroscopy was certainly born with that device but once it existed Tavendale and others soon turned it into a device that would lead to a rich harvest of information on nuclear structure. This pattern of an initial "breakthrough" or development followed by a steady evolutionary process over a long period is typical of how our experimental methods develop and improve. It is equally true of the development of accelerators. Rutherford[8] had shown that a swift projectile could overcome the Coulomb barrier and that a means of delivering a range of projectiles with various energies was needed to study reactions. Electrostatic accelerators, cyclotrons and linacs followed and have been steadily improved ever since. The process of improvement has not come to an end in either case. We shall now turn our attention to the latest development in accelerator technology and we will see clearly that accelerators continue to evolve and that the tools to look at the products produced in the reactions they induce are also still evolving and will continue to do so.

One of our sub-themes was how our advances in experimental method lead to new applications within and beyond the academic pursuit of knowledge. The accelerators eagerly sought for use in studying atomic nuclei are now ubiquitous. They provide beams for radiation therapy, the modification of materials, forensic analysis, the production of radioisotopes for medical imaging and therapy, analysis of archaeological artefacts and art objects and much more. Our detectors are used for imaging, security purposes and space science applications. This brief summary only scratches the surface. Lawrence and his colleagues [1] certainly saw a future that has become a reality.

IV The advent of beams of radioactive nuclei

As I sit here in Culross in Scotland and write what you will read at your leisure a vast effort is underway around the Globe to produce machines that will provide beams of radioactive nuclei. In this section of the article we shall look briefly at the scientific dreams and hopes that drive this activity, how it started and the methods that have been employed up to now, ending with the present state-of-play.

The drive to produce beams of radioactive nuclear species is readily understood [35,36]. With stable beams and targets we are limited in the range of atomic nuclei that we can produce. If

their properties did not change much with Z and N that would be of no great concern. It turns out, however, that nuclear properties can change rapidly with the addition or subtraction of a few nucleons. Even with the beams of unstable nuclei we have today we have already seen a range of phenomena hidden from our view before. Nuclear radii do not follow the simple $A^{1/3}$ rule that all the simple textbooks report [37,38]. The familiar shell structure near the line of stability changes radically as we move to larger values of isospin (the third component of isospin in nuclear physics is defined as $T_Z = (N-Z/2)$). Understanding the forces in nuclei with extreme isospin is a major challenge. We are still a long way from reaching the limits of existence of nuclei, particularly for neutron-rich species and for the heaviest elements. Finding these limits of existence is in itself important. The idea of the neutron drip-line is a simple one but our nuclear models struggle to say what it is. Element 118 has been produced [39] in the laboratory and we have convincing evidence that the "Island of Superheavy nuclei" exists but we have not reached there yet. Quite apart from what the properties of nuclei far from stability will tell us about nuclear structure their study is important in nuclear astrophysics.

Nuclear reactions and decays play an important part in the births, lives and deaths of stars[40]. It is these same reactions that are involved in the production of the chemical elements. In broad terms [41] we have had a picture of how the elements are made for some time. We still lack much of the detail we need to understand the observed abundances of the elements not just in the solar system but in other star systems as well. We do not yet know where all of the heaviest elements are produced and we cannot model supernovae. We also lack information about the reactions on light nuclei that fuel main sequence stars. Not all of the information will come from the use of beams of radioactive nuclei but many of the elements are produced in explosive stellar processes and the reaction networks lie amongst the unstable nuclei in the Segre chart. Our only means of studying them is to produce beams of unstable nuclei and use them to induce reactions on light, stable targets. The study of this type of so-called inverse reaction is critical to improving our understanding of stellar processes. We will also need the information from underground laboratories where we can study reactions at the lowest energy in the lowest background possible.

In brief these are the main arguments for producing and using beams of radioactive nuclei.

IV.I The origins of Radioactive Beam Physics.

Human beings are fascinated by questions about who did something first. Who first climbed Mount Everest, who first crossed the Atlantic, who first reached the South Pole? Does it matter that the Vikings did it long before Columbus? Does it matter that Sherpa Tensing and Edmund Hillary had a strong support team? All of their feats were remarkable and repeating some of them today would still be remarkable. The newspaper headline or historical focus, however, is still on being first.

It is the same in Science, usually couched in terms of who discovered something. Where then did radioactive beams first see the light of day? You can probably find other possibilities but I can see three places where we could award the crown. Firstly there seems to be no doubt

who first made an on-line isotope separator work and one can argue that provides the basis for an ISOL-based radioactive beam facility. O.Koefed-Hansen and K.O.Nielsen [42,43] can be seen in Fig.18.

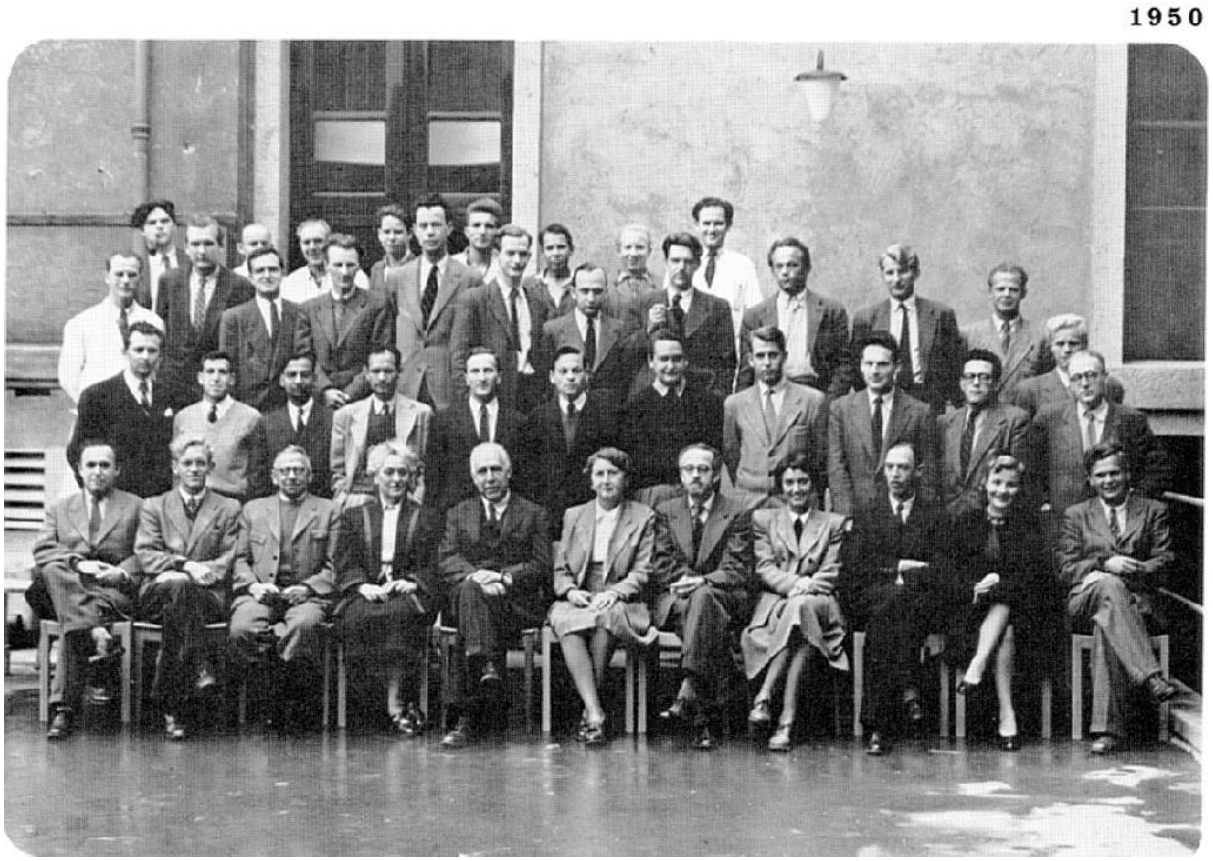


Fig.18:- In this photograph of the staff at the Niels Bohr Institute in 1950 we see O.Kofoed-Hansen (5th from right in the 2nd row) and K.O.Nielsen (2nd from right in the third row).

Their paper in Physical Review [42] even defines the meaning of on-line separation in the phrase " The cyclotron and the isotope separator were operated simultaneously—" They studied the decay of several Kr isotopes that had been produced in the fission of Uranium by a deuteron beam. There is no doubt that this was the genesis of ISOLDE at CERN, driven by Scandinavian expertise and interest. Isolde began operations at CERN in 1967 and has gone from strength to strength. Any similar facility has to benchmark itself against the sterling performance of ISOLDE. It may be on a different scale from the LHC but the quality of the science is just as high. As we have noted before the primary motive was to study the properties of nuclei but CERN-ISOLDE has contributed to Science in many other areas.

A second contender for the accolade of being first is the ISOL-based radioactive beam facility [45] built at the University of Louvain-la-Neuve. Sadly it was closed down long before its usefulness expired. It was based on two cyclotrons. A K =30 cyclotron was used to produce up to 0.5 mA of 30 MeV protons to produce short-lived species in a target/ion source, which were then injected into a second K = 130 cyclotron and re-accelerated for use in reaction studies. Fig.19 shows schematically the layout of the facility.

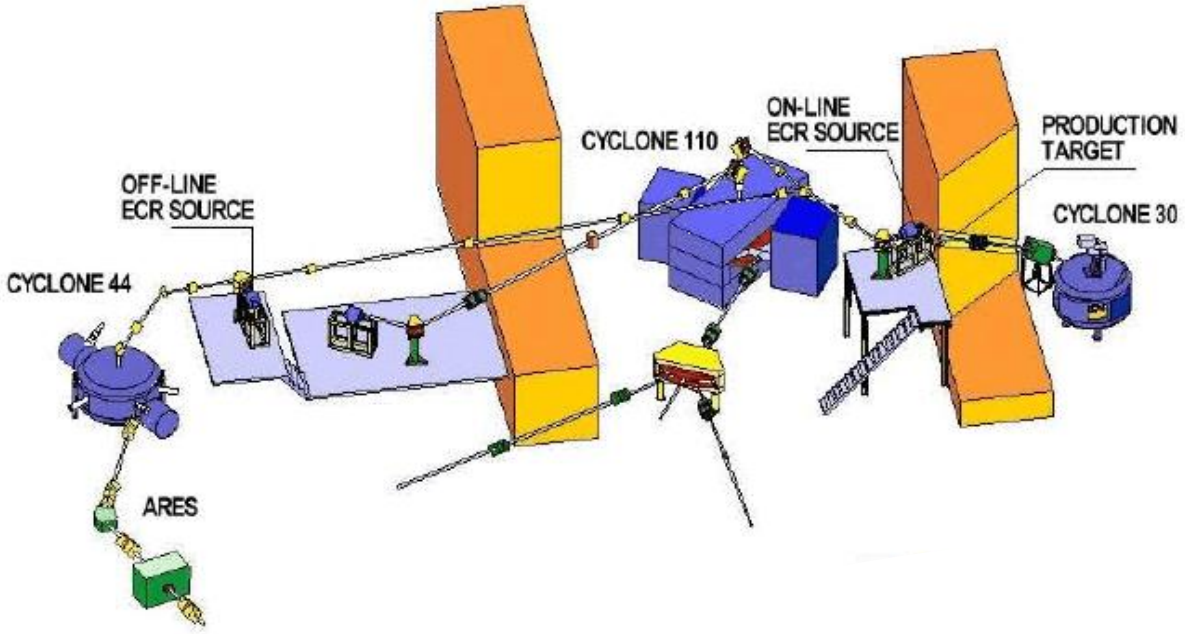


Fig.19:- The layout of the first ISOL-based radioactive beam facility [45] at Louvain-la-Neuve.

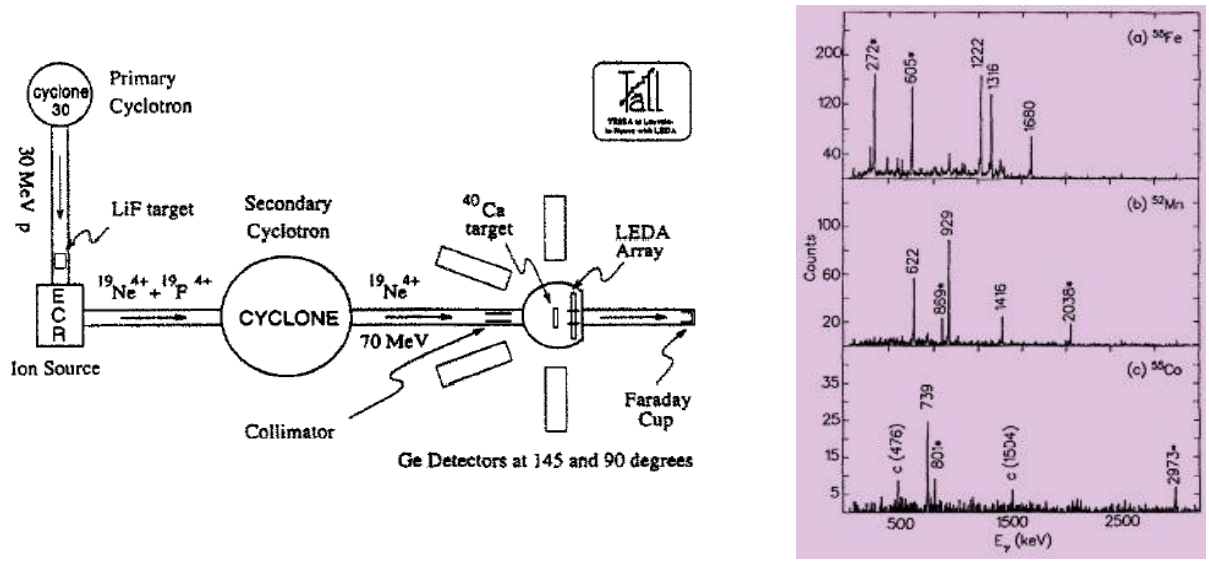


Fig.20:- On the left hand side we see the layout for the first study of γ-rays from a fusion-evaporation reaction induced by radioactive ions [46-48]. On the right hand side we see the γ-ray spectrum from ^{19}Ne(^{40}Ca,3pnγ)^{55}Fe at the top.

The Louvain-la-Neuve facility shows all the basic features of an ISOL-based accelerator system. There are three main elements namely a primary accelerator used to create the radioactive species of interest in a target/ion source (the second element) and the ions are then injected into a second accelerator to produce a beam with the requisite properties in terms of energy and intensity.

Many pioneering experiments were carried out at Louvain-la-Neuve. One example is an experiment led by our group at Surrey [46-48]. Fig.20 shows schematically the experimental setup for a study of the ^{19}Ne(^{40}Ca,3pnγ)^{55}Fe reaction. The resulting γ-ray spectra from ^{55}Fe, ^{52}Mn and ^{55}Co are shown on the right. Following this brief excursion into self-promotion or at least group promotion we turn to the third possibility for first radioactive beam experiments. In the 1970s at Berkeley Ghiorso pushed the coupling of the SuperHilac linear accelerator to the BEVATRON in order to produce beams of relativistic heavy ions. The joined up system was re-named the BEVALAC. The nature of fragmentation reactions was then explored in a whole series of experiments at the BEVALAC. At energies of ~1 GeV per nucleon the fragmentation of a heavy nucleus on a light target such as Be leads to the production of a cocktail of many different nuclear species with a velocity close to the projectile velocity and emitted into a narrow cone. The cross-sections for individual species range from a few hundred mb to μb depending on the target and projectile. At energies of 400 MeV per nucleon and above, many of the individual nuclear species are produced with σ > 1μb [49].

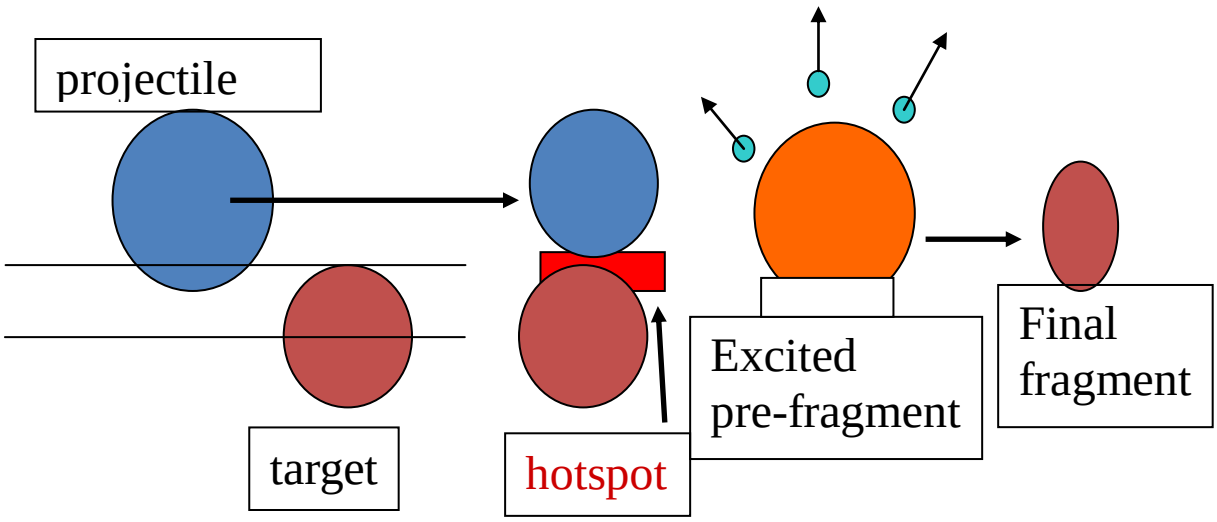
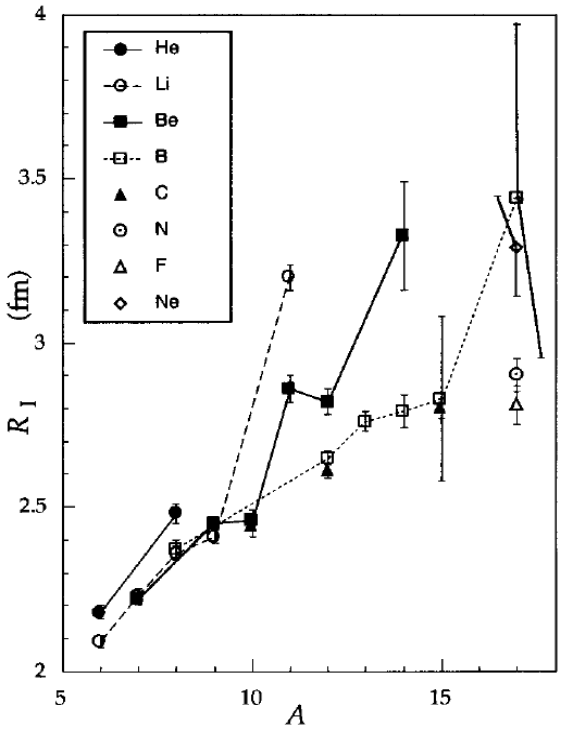


Fig.21;- A cartoon showing what happens in a peripheral collision between a high energy heavy ion and a light nucleus (see text). Courtesy of Z.Podolyak.

Fig.21 gives a simple picture of what happens in peripheral collisions between a high energy, heavy ion and a light nucleus. It is often described in terms of a process of abrasion followed by ablation. Given the high velocity of the projectile the interaction takes place over a very short time, part of the projectile is sheared off but in the short time there is an exchange of nucleons. The remnant will lose some nucleons by evaporation and finally we end up with a range of species. In other words we have a cocktail of different nuclei, that goes forward into a small cone. Effectively we have a beam of exotic nuclei although not of ideal quality.



The new BEVALAC beams were exploited by Tanihata et al. [37] to produce beams of light nuclei and then use them to determine interaction cross-sections first for stable and unstable He isotopes and then Li , Be and B isotopes. The results came as a complete surprise. Instead of following the simple well-established $A^{1/3}$ rule we find in all the textbooks, that works well for stable and near-stable nuclei, it is clear that the radius is much larger for nuclei such as ^{11}Li.

Fig.22:- Interaction radii for some light nuclei measured [37] at the BEVALAC.

The measured radius of 3.5F for ^{11}Li compared with the expected value of 2.7F is the most striking result. Tanihata and his colleagues concluded that "It suggests the existence of a large deformation and/or a long tail in the matter distribution in ^{11}Li ." This question was settled by a measurement [50] of the ground state spin and magnetic moment at CERN-ISOLDE using fast collinear laser spectroscopy and the sensitive detection of optical pumping. The nuclear wave function is extended.

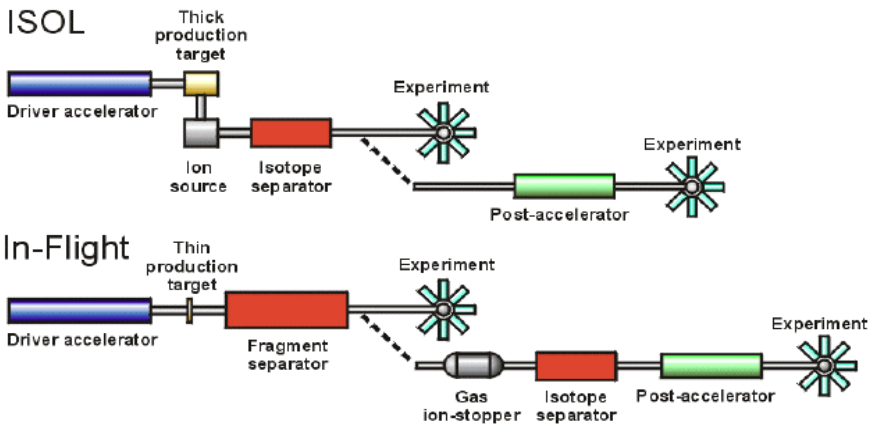
The interpretation of these results in terms of a neutron halo is due to Hansen and Jonson [51]. They coined the term "neutron halo" for the effect and explained it in terms of pairing and the weak binding of the last neutron.

The results of Tanihata et.al. and the subsequent interpretation in terms of the neutron halo led to a ferment of both theoretical and experimental activity. Studies of light nuclei where the haloes had been observed became one of the main reasons cited to justify the building of new and better radioactive beam facilities.

IV.I Radioactive Beams of atomic nuclei-the current situation

Which was the first radioactive beam facility is not a particularly important question but we have learned a number of useful and interesting things from the last section. Just as we saw earlier (sections I-III) the process begins with a breakthrough, usually on a small scale, and then steadily evolves by many steps to the current state-of-the-art. This is as true of radioactive beam facilities as for our earlier examples.

We have also touched on the two main methods of producing such beams, namely the ISOL-based facility and the in-flight facility. There are now a significant number of examples of both types. Fig.23 shows, in cartoon form, the main elements of both kinds of facility.



The figure ignores the vital and essential detail such as the complex technology involved in the target/ion source in an ISOL facility and the crucial fragment recoil separator in the in-flight facilities.

Fig.23:- This shows the essential elements of both an ISOL-based and an in-flight radioactive ion beam facility.

In both cases two accelerators are required. The primary accelerator is needed to create the short-lived species of interest. In the case of an ISOL facility this primary accelerator could be replaced by a nuclear reactor as was proposed [51] at the FRM-II reactor in Munich. Here the source of neutron-rich nuclei would have been from the bombardment of a thin ^{235}U target with thermal neutrons.

Isolde provides an excellent example of an ISOL facility. The primary accelerator, now the PS-BOOSTER at CERN, delivers 1.4 GeV protons to a thick target. Following diffusion and effusion in the hot target the ions enter an ion source, which can be of a variety of types. Following ionisation the ions are extracted into a mass separator. The separated beam can then be directed to the experimental apparatus in use. Alternatively, after a series of manipulations the ions can be injected into the REX post accelerator [52,53] and used to study reactions. Initially the REX linear accelerator re-accelerated the beams to a maximum of 3MeV /nucleon. As part of an upgrade of ISOLDE the Linac is being lengthened and under its new name of HIE-ISOLDE will first take the energy to 5.5 MeV/nucleon and then later 10 MeV/nucleon. At the time of writing the first of these steps should be completed during the winter of 2015.

GSI provides us with an example of a major in-flight facility. The primary beams in this case are first generated in an ion source and injected into the UNILAC [54] linear accelerator, which can accelerate ions up to 2-11.4 MeV/nucleon. They are then injected into the SIS 18 synchrotron [55] taking the energy up to a maximum of 2GeV /nucleon. The extracted beams from the synchrotron are then directed on to a light target such as B to produce a cocktail beam of exotic nuclei.

As described earlier the cocktail beam of fragments flies forward in a narrow cone into the FRS (Fragment Recoil Separator) [56]. The FRS allows us to identify the fragments on an ion by ion basis. The layout of the FRS is shown in schematic form in fig. 24. The identification is established by the measurement of the energy loss in a MUSIC (multi-sampling ionization chamber) chamber[58], the time-of flight (TOF) between two scintillators SCI21 and SCI41 and the Bρ of the spectrometer magnets.

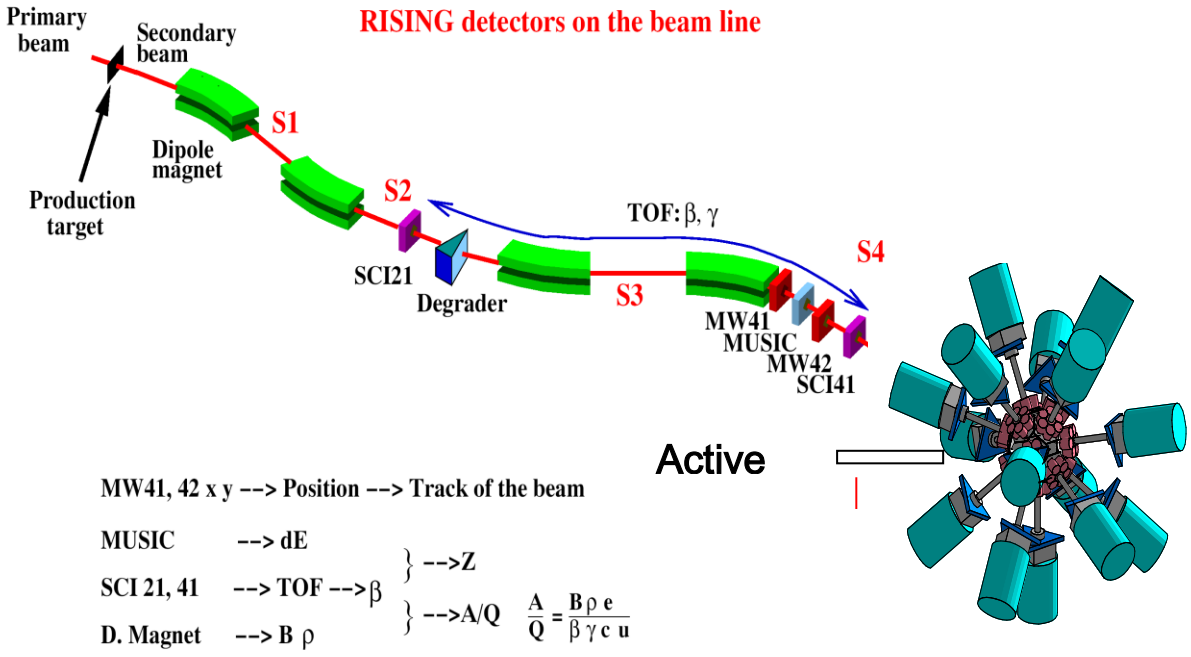


Fig.24:- A schematic drawing of the FRS [56]. Fragments from the production target are identified on an ion-by-ion basis using the ΔE signal from the MUSIC chamber, the time-of-flight(TOF) between scintillators 21 and 41 and the Bρ values of the magnets. The beam is implanted into a DSSSD detector in the case shown and is surrounded by the RISING [57] γ-ray array of cluster detectors.

A typical identification plot for the ions is shown in fig.25**.** In the case shown the spectrometer has been centred on the ^{52}Ni ions. They were produced in the bombardment of a 400 mgcm-2 Be target by a 680 MeV/nucleon beam of ^{58}Ni from the SIS 18 synchrotron.

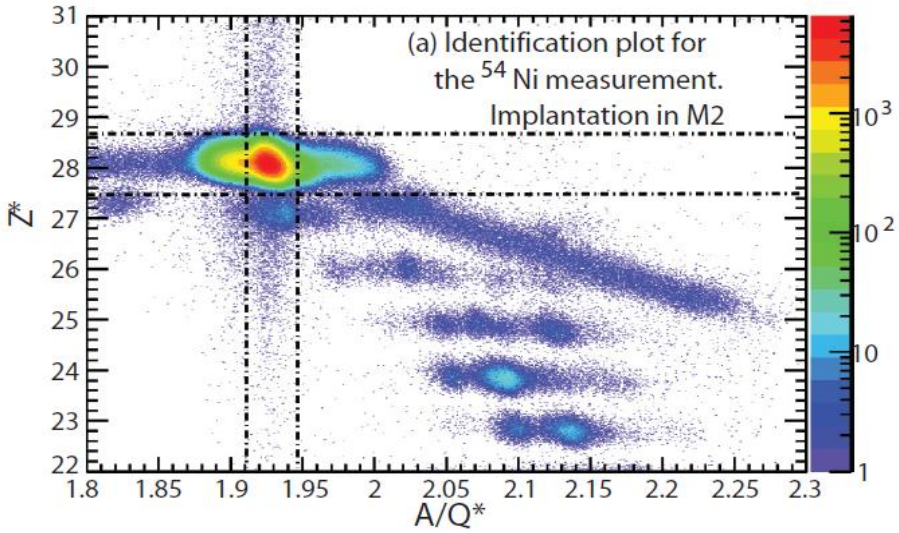


Fig.25:- An example of an identification plot[59] from a fragment recoil separator, in this case the FRS[56] at GSI. The separator was setup to centre on ^{54}Ni, one of the T_z =-1 nuclei whose beta decay was being studied.

The figure is taken from a study [59] of the beta decays of T_z =-1 nuclei for comparison with the Charge Exchange reaction on the corresponding stable, T_z =+1 nucleus.

The two methods have quite different characteristics and produce beams with different properties. In general ISOL-based facilities involve a light projectile on a heavy target. Many are like ISOLDE and make use of spallation of a heavy target by a light projectile. However some also involve a converter target with electrons or deuterons producing gammas or fast neutrons respectively that then strike a thick target of Uranium and induce fission. France boasts two such facilities in SPIRAL2 [60] and ALTO [61]. The main advantage of ISOL facilities is the high quality of the beams produced. Effectively the beam quality is the same as in a stable beam accelerator. It also makes maximum use of a thick target and a high beam current (up to 10^{16} pps) to produce beams as intense as possible.

The disadvantages are

• long extraction and ionization times in the target/ion source, which can be as long as ms. As a result the intensities of very short-lived activities are reduced.

• the processes involved are charge dependent and it has taken a large effort over many years to produce beams of some 60 elements at CERN-ISOLDE.

• there is a large heat load in the thick target.

• The high current means that there is heavy activation of the target and ion source .This means that complex handling mechanisms are needed to deal with the targets and ion sources.

In contrast the in-flight facilities usually involve a heavy projectile incident on a thin, light target. This means a short separation and identification time, effectively equal to the time of flight through the fragment recoil separator. Since the target is thin compared with the range of the projectile in the material the heat deposition is limited. The other main advantage is that the process is independent of chemistry.

The main disadvantages are

• the thinner target and low primary beam currents (10^{12} pps) mean that the beam intensities are low, in general.

• the beam is a cocktail of different species and this demands a highly sophisticated and expensive spectrometer to separate and identify the ions.

As we will see below many new facilities are in design or construction. From the above we can extract some key design criteria for these facilities. In general the production cross-sections are low. Accordingly the beam + target combinations to be employed are critical in terms of optimising the final beam intensities. At the same time the targets must be able to cope with the heat deposited. In addition the Physics demands access to the shortest-lived nuclear species possible, accordingly any delays in the production process must be

minimised. Again many unwanted nuclear species are produced in the primary reactions. Thus the selection and identification of the nuclei of interest must be effective and any manipulation of the beam must be efficient and minimise any losses.

Table 1 Current Main-line In-flight Facilities

Facility	Accelerators	Energy	Typical Beam	Spectrometer
GANIL	2 sep.sect.cyclotrons	≤100MeVu^{-1}	^{36}S 10^{13}pps	LISE
GSI	Linac + synchrotron	≤2GeVu^{-1}	10^{10} pps per spill	FRS
NSCL	2 supercond.cyclotrons	≤200 MeVu^{-1}	^{40}Ar 5x10^{11} pps	A1900
RIKEN	Ring cyclotron	≤100MeVu^{-1}	^{40}Ar 5x10^{11} pps	RIPS

Table 2 Current Major ISOL facilities

Facility	Driver Accelerator	Post Accelerator	Beam Energy	Beams
REX-ISOLDE	PS-BOOSTER 1.4GeV p	REX-LINAC	0.3-3.0MeVu^{-1}	large Variety
SPIRAL	GANIl cyclotrons	CIME cyclotron	2.7-25MeVu^{-1}	He,Ne,Ar,Kr, N,O,F
TRIUMF	Cyclotron 500 MeV p	ISACI+ISAC2 RFQ+LINAC	0.2-11 MeVu^{-1}	large variety

---

There are quite a large number of facilities in existence of both types. Tables 1 and 2 summarise briefly the main characteristics of what one might see as the principal current facilities. All of these facilities, apart from the GANIL in-flight facility, have major upgrades planned. We have already outlined the plans for ISOLDE above. At GANIL the new ISOL facility, called SPIRAL 2 [60], involves the building of a new superconducting Linac to deliver 5mA of deuterons at 14.5MeVu^{-1} and 1mA of ions with A/q = 3. The deuteron beam will interact with a C converter to produce neutrons that then impact on a UC_X target producing 10^{14} fissions sec^{-1}. Re-acceleration will take place in the current post-accelerator, the CIME cyclotron. The emphasis will be on neutron-rich nuclei although other reaction mechanisms will be used to produce neutron-deficient species as well.

TRIUMF is also involved in an ambitious upgrade [62] called ARIEL (Advanced Rare isotope Laboratory). A new high power superconducting electron linac will produce beams of 500kW of 50MeV electrons that will produce unstable nuclei via photofission. In addition there will be a new proton driver and appropriate target/ion source systems and beam transport lines for the new facility. When completed this will triple the beam time available and make it a multi-user facility.

Equally ambitious plans are aimed at upgrading the in-flight facilities at GSI and NSCL, with the new facilities being called FAIR [63] and FRIB [64] respectively.

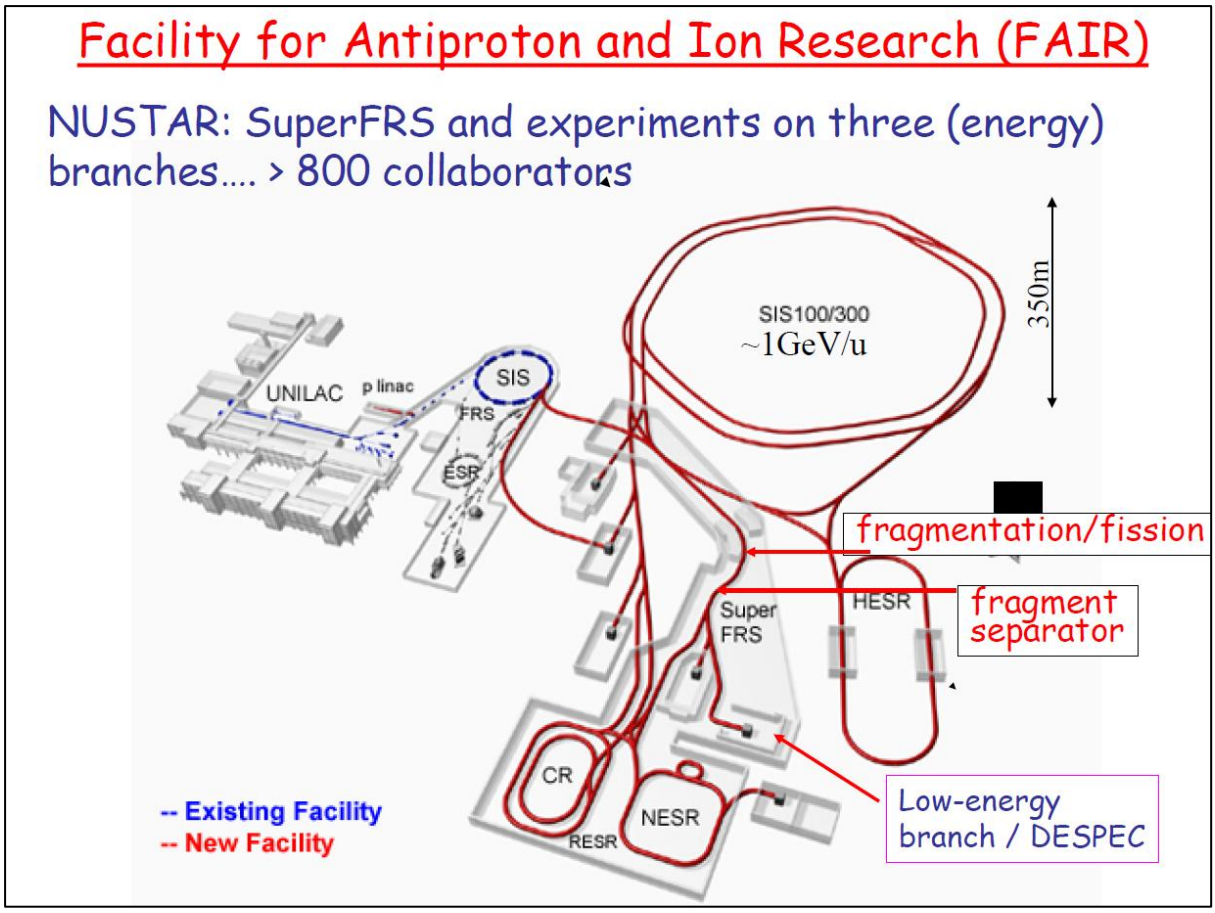


Fig.26:-Schematic picture of FAIR [63] and how it is grafted on to current GSI facilities.

FAIR is aimed not just at upgrading the current capabilities for producing exotic nuclei (under the banner of NuSTAR [65]) but also at new atomic physics, studies of the phase diagram of nuclear matter [66] and hadron physics via proton-antiproton collisions [67]. FAIR involves an upgrade to the UNILAC that will inject beam into SIS 18 and then into a new SIS 100 synchrotron that will take the beams of ions, up to U in mass, to energies of $\leq$ 2GeVu^{-1}. The facility will use both fragmentation and fission to produce the widest possible range of nuclei. A new fragment separator called the Super FRS will be built as part of FAIR. FAIR will also have several storage rings (see below).

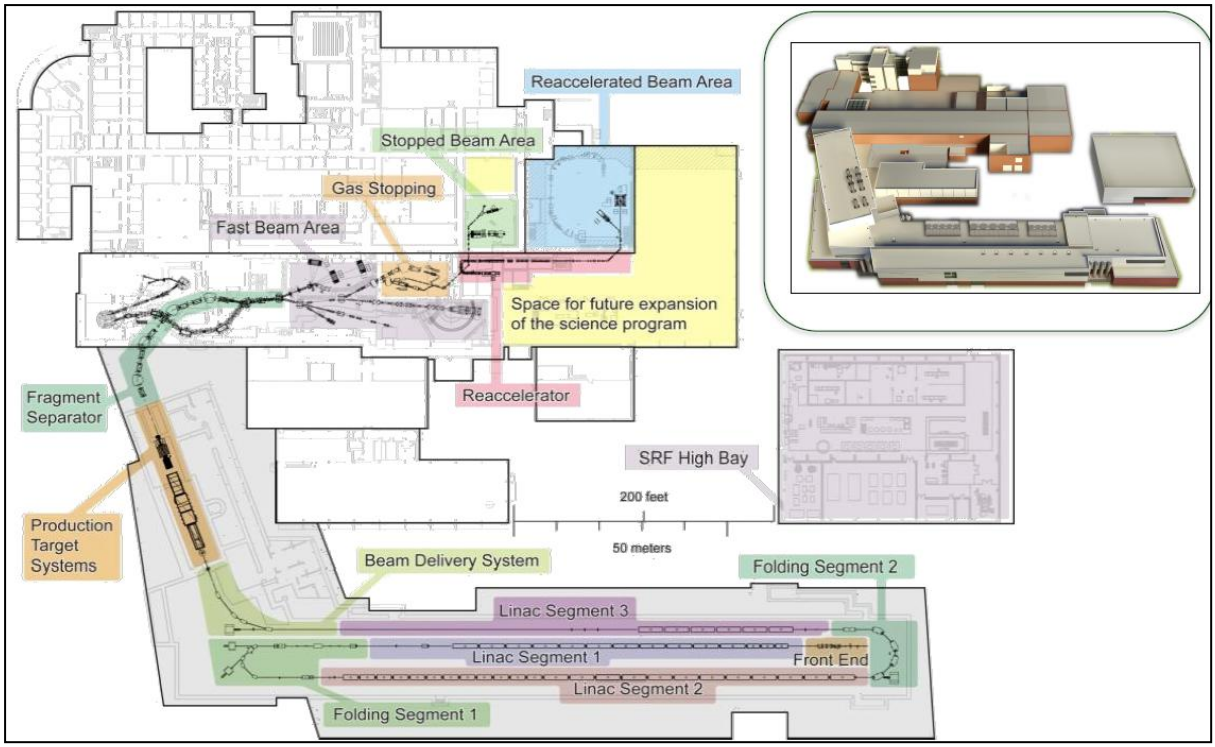


Fig.27:- Layout of FRIB[64]

In the United States the major effort in this area is the upgrade of NSCL's coupled cyclotron facility to FRIB [64]. Here the driver accelerator will be a superconducting-RF linear accelerator. It will produce beams up to ^{238}U ($5x10^{13}$ pps) with an energy $\leq$ 200 MeV u^{-1}. It will be possible to upgrade the energy readily to $\leq$400 $MeVu^{-1}$ in the future without major disruption of the experimental programme. There will be a new three-stage fragment separator with high momentum and angular acceptance that will provide high beam purity. It will operate in several different modes that will optimise acceptance close to or far from the line of stability. Overall there will be fast, stopped and re-accelerated beams. The layout for FRIB is shown in Fig.27.

One next-generation in-flight facility is already operating very successfully, namely the RIBF [68] at RIKEN in Japan. The RIBF consists of a linear accelerator followed by four cyclotrons to provide beams at 350 $MeVu^{-1}$. The goal in terms of intensity is 1pμA. the two-stage BigRIPS separator [69] separates and tags the ions from the production target on an event-by-event basis.

Another ambitious new project planned in Asia is the RISP project [70] at Daejong in South Korea. It will have a superconducting heavy ion linear accelerator that will provide U beams at 200 $MeVu^{-1}$ to a fragment separator. The same machine can accelerate light ions such as protons to 600 MEV and this beam can be directed into an ISOL target/ion source system and then separated in mass. There will be an alternative driver for the ISOL facility that consists of a 70 MeV cyclotron delivering 1mA of beam. The separated ISOL beams will be fed into a charge breeder and finally a superconducting linear accelerator providing beams up to

18MeVu^{-1}. Alternatively these beams can be fed into the main linac and accelerated to high energy for fragmentation studies with the aim of reaching even further from stability.

There is a particularly large amount of Research and Development for new radioactive beam Facilities underway in Asia. There is a nice summary of all this activity in [71] and I do not propose to repeat it here. Major projects are proposed in India, Japan and China in addition to the RIBF, RIKEN and RISP projects. The RIBF at RIKEN is the main fully operational next-generation project in the World not just Asia.

What I have written above focuses on major international projects. Despite all this activity there is still plenty of room for smaller, niche projects and there are plenty of them. There is one which has been rather successful and that is the IGISOL facility at the University of Jyvaskyla. It has some features that are worth emphasising for the benefits they bring to the physics programme.

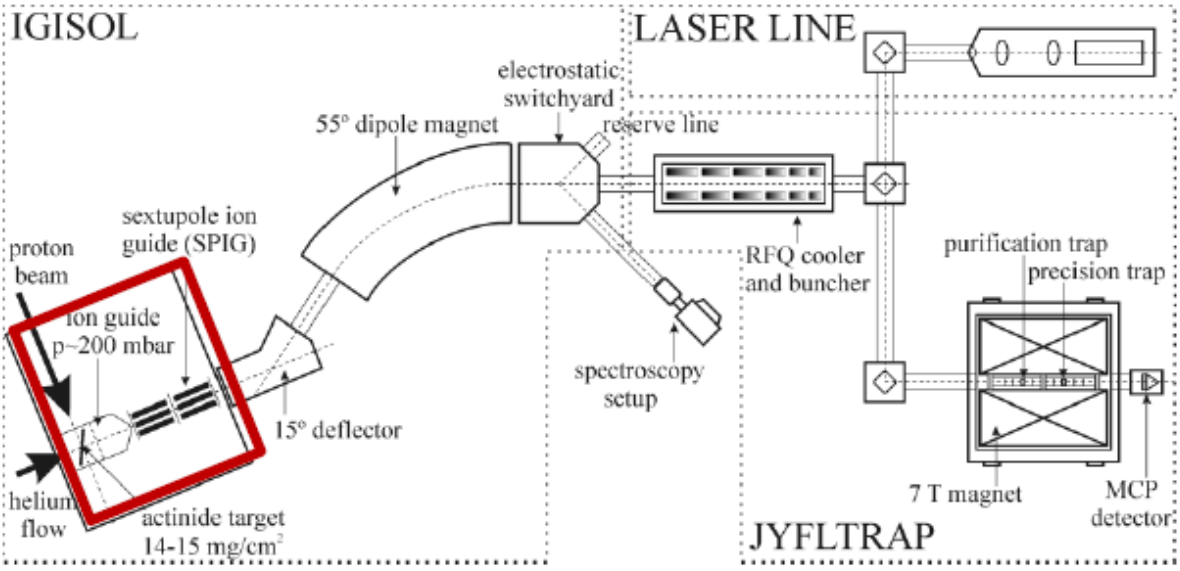


Fig 28:-A schematic view of the layout at the IGISOL facility [72] Jyvaskyla.

In its present re-incarnation, IGISOL-4, the target can be bombarded by beams from either the new K30 cyclotron or the existing K130 cyclotron. The beams most commonly used are of protons and induce fission in a target of ^{238}U or fusion-evaporation on other targets. The nuclei are stopped in a gas cell and are extracted at 30 kV. They can be used directly or, after an RFQ cooler and buncher, injected into a double Penning trap. The first trap is essentially a purification device and acts as an isobaric separator and the second acts as a precision measuring device. Reference [73] summarises the facility and its capabilities. For spectroscopy it is an excellent preparation tool since it can deliver isobarically separated activities to the experimental apparatus. Some recent work based on its use can be found in [74], where the purification was an essential element in the success of the work.

I have picked out the IGISOL from the smaller facilities that are operating or under construction simply because of the importance of gas catchers and traps for many radioactive beam facilities. They are an important element in beam preparation in some cases and important in the measuring systems in others.

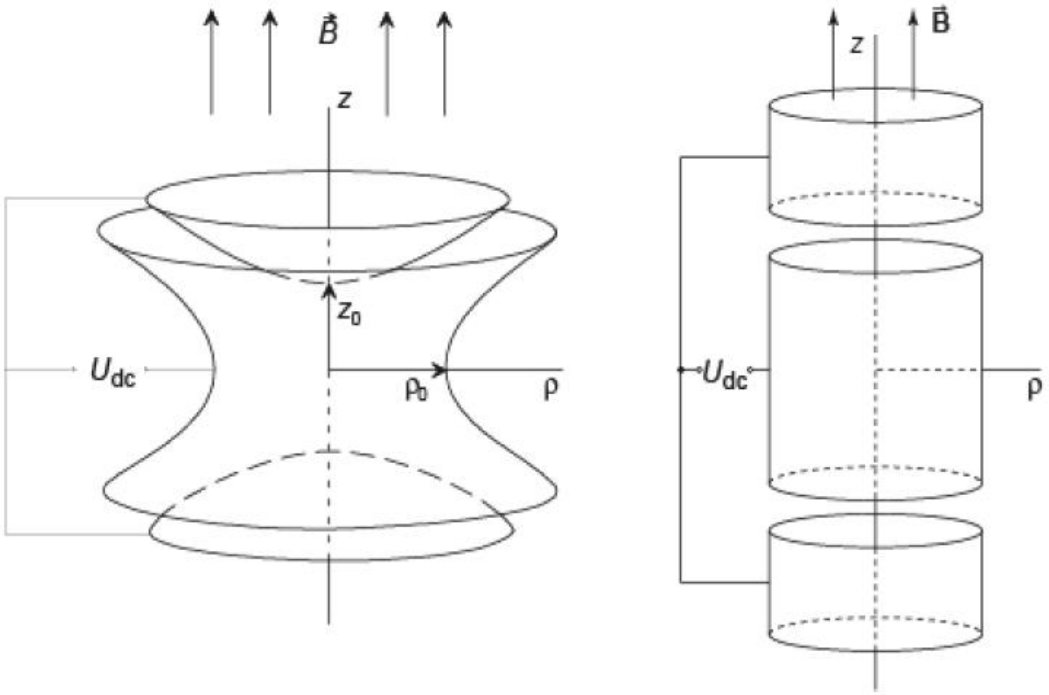


Fig.29:- Two possible geometries for a Penning trap. Hyperbolic geometry on the left and cylindrical geometry on the right.

Both Paul and Penning traps are important not just in nuclear physics but in many other applications. Here we are concerned with Penning traps and there is an excellent and readable summary of their properties and what can be done with them in [75]. The essential facts are straightforward. To confine an ion fully in all three spatial dimensions requires a potential minimum in the three directions. This requires a force on the ion which is proportional to the distance from the potential minimum and means that the ion will undergo simple harmonic motion about the minimum. This cannot be done with electrostatic fields alone. Instead one can use a strong, homogeneous magnetic field in the radial direction and a weak, electrostatic field in the axial direction as shown in fig.29. In the figure there is an electrostatic potential Udc between the end caps and the electrodes, which have a hyperbolic shape in order to produce a quadratic potential and the required linear force in the axial direction and the magnetic field confines ions in the radial direction. An alternative geometry is the cylindrical geometry shown on the right. This is much easier to manufacture and align. In the trap the ions perform a complicated motion consisting of a circular motion around the magnetic field with cyclotron frequency $\omega_C = (q/m)B$ plus two types of radial motion, usually called reduced cyclotron motion and magnetron motion. In essence mass measurements mean measuring ω_C.

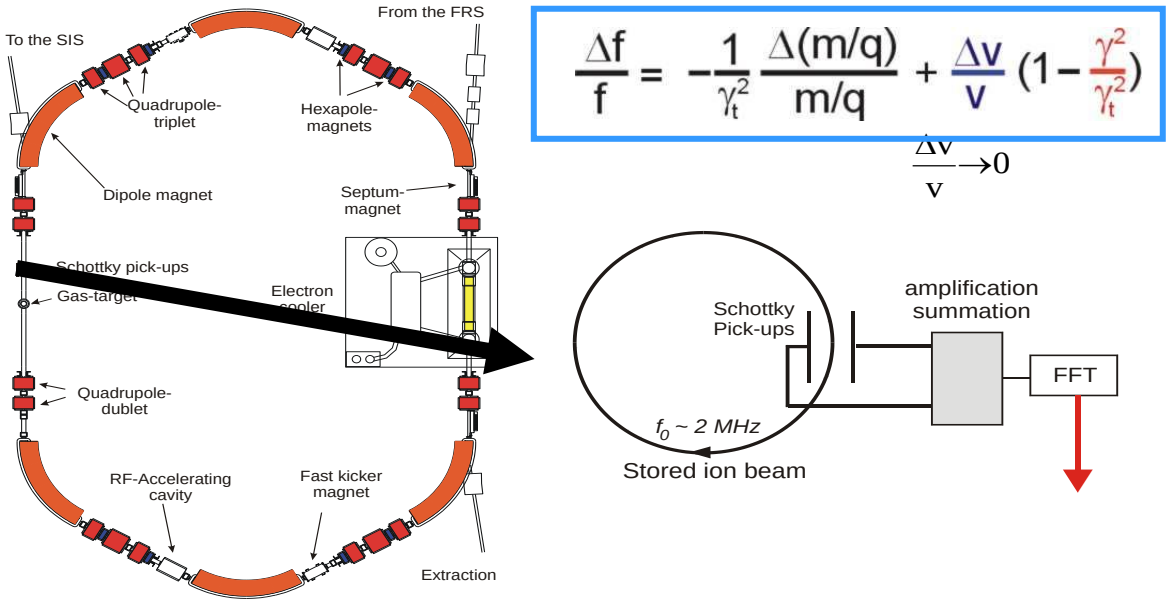


Fig.30 :-shows a schematic picture of the ESR storage ring [76] at GSI on the left. The cartoon on the lower right shows the setup used for Schottky mass spectrometry measurement of mass.

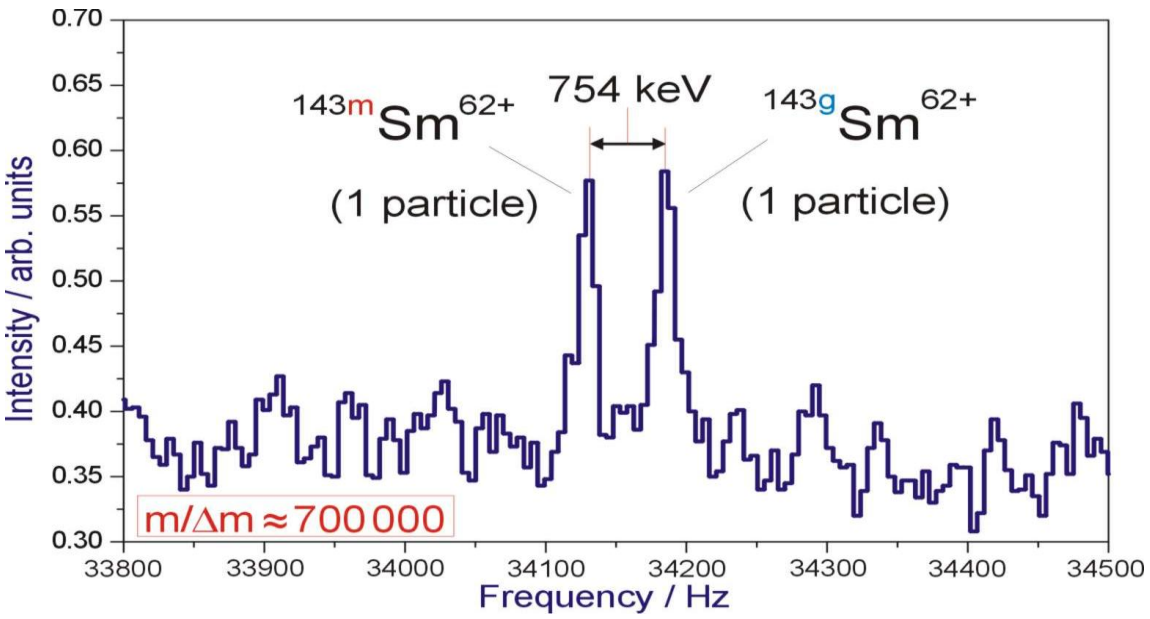


Fig.31:- Part of a Schottky frequency spectrum taken at the ESR[76] showing how good the mass resolution is with the ground state of 143Sm and an isomer at 754 keV excitation clearly separated.

In a few places there are heavy ion storage rings, notably at GSI. One can think of them as a kind of very large trap. In-flight facilities are well-suited to injecting into a storage ring. With a synchrotron as the main accelerator the fast extracted beam can be injected in well-defined secondary bunches. Further beam cooling is then required, usually there is a first step of

stochastic cooling followed by electron cooling. The ESR [76], the storage ring at GSI, has been used very successfully to measure many nuclear masses with Schottky mass spectrometry [77]. It is shown schematically in Fig.30. Storage rings do not require a synchrotron. The Japanese will add the RARE RI ring to the RIBF facility and it is proposed that the storage ring from Heidelberg will be moved to HIE-ISOLDE. At the time of writing this awaits final approval from the CERN council. The interested reader can consult [76] for more detail about storage rings and their capabilities.

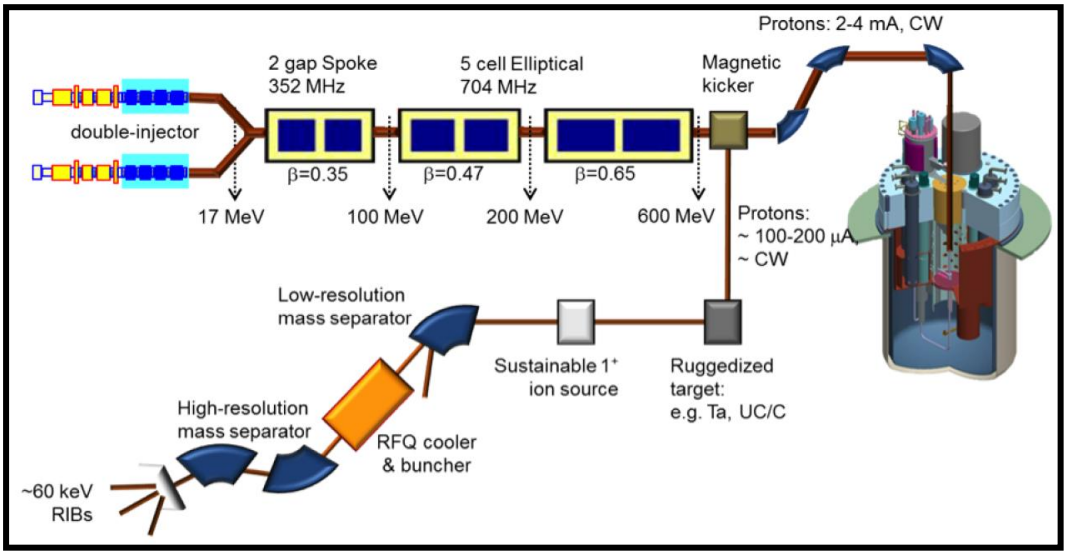


Fig.32:-shows a schematic picture of MYRRHA and its satellite ISOL@MYRRHA[78].

Before we conclude two other facilities are worth mentioning. The first is MYRRHA and with it ISOL@MYRRHA [78]. The former is a demonstrator for accelerator driven systems to "burn" nuclear waste.

MYRRHA, situated at Mol in Belgium, will be a flexible, fast spectrum research reactor. It is designed to operate in critical and sub-critical modes. The main design features of interest here are the beams of 600 MeV protons from a linear accelerator that is intended to operate for very long periods with an absolute minimum of interruption. A small fraction of the beam can be taken to the satellite facility ISOL@MYRRHA., designed as a typical ISOL facility. Since it will be able to run for long periods of time the idea is that it should be used for experiments that require very long beam times. This means that it could also entertain the use of experimental equipment of very low efficiency such as the Curved crystal spectrometers[79] in use at ILL. We often loosely call HPGe detectors high resolution detectors but, of course, they have much inferior resolution to diffraction-based spectrometers. Thus experiments that require this superior resoltion could be carried out at ISOL@MYRRHA and indeed it will be ideal for any experiment that requires very good statistics.

The second facility worth mentioning is, as yet, still an idea although a large amount of work has been put into ensuring that the proposed design will meet the requirements for the best

possible re-accelerated ISOL-produced beams. EURISOL, if it was built to the design, would mean a major step forward in terms of beam intensities. The proposed driver accelerator would be a superconducting CW linear accelerator that would accelerate H^- ions to 1 GeV.

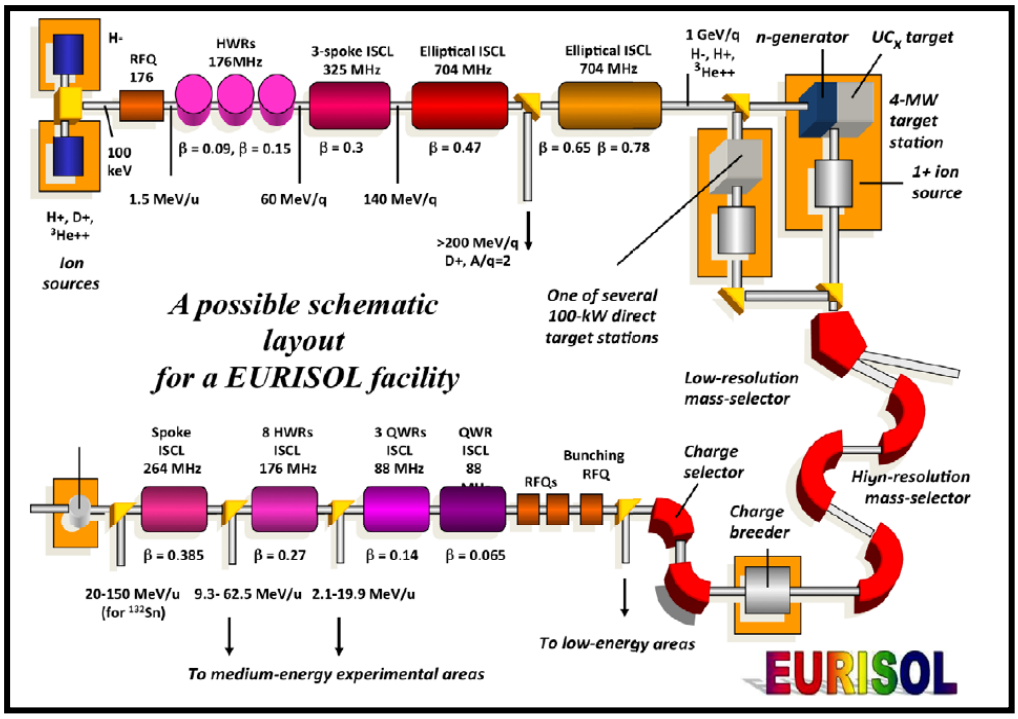


Fig.33:- A credible layout for the proposed EURISOL facility.

The beam would deliver a power of 4kW to a target station. Alternatively with a newly developed magnetic beam splitting system 100 kW can be delivered to three smaller target stations in parallel. A whole series of direct spallation targets and neutron converters plus a fissioning target will also be available. The post accelerator will be a superconducting linear accelerator with energy 150 MeV u^{-1}. This energy is sufficient for the beam to be used for further fragmentation.

Our focus in this section has been on the accelerators themselves. The success of all these facilities also depends on many other technical developments and improvements in traps, charge breeders, ion sources of all kinds, targets, storage rings, spectrometers etc. Many of these topics were covered by other speakers at the Joliot-Curie school and the reader will find an account of what they said in this volume.

Only one of the major next-generation facilities is in full operation, the RIBF at RIKEN. It has been very successful partly because of the beams available but also because of the quality of the BigRIPS fragment separator [69] and the experimental equipment, such as the EURICA γ-ray array assembled to exploit the beams. Fig.34 shows the EURICA array [81] at the end of BigRIPS with the author standing at the front of the picture. Fig.35 shows a typical identification plot [82].

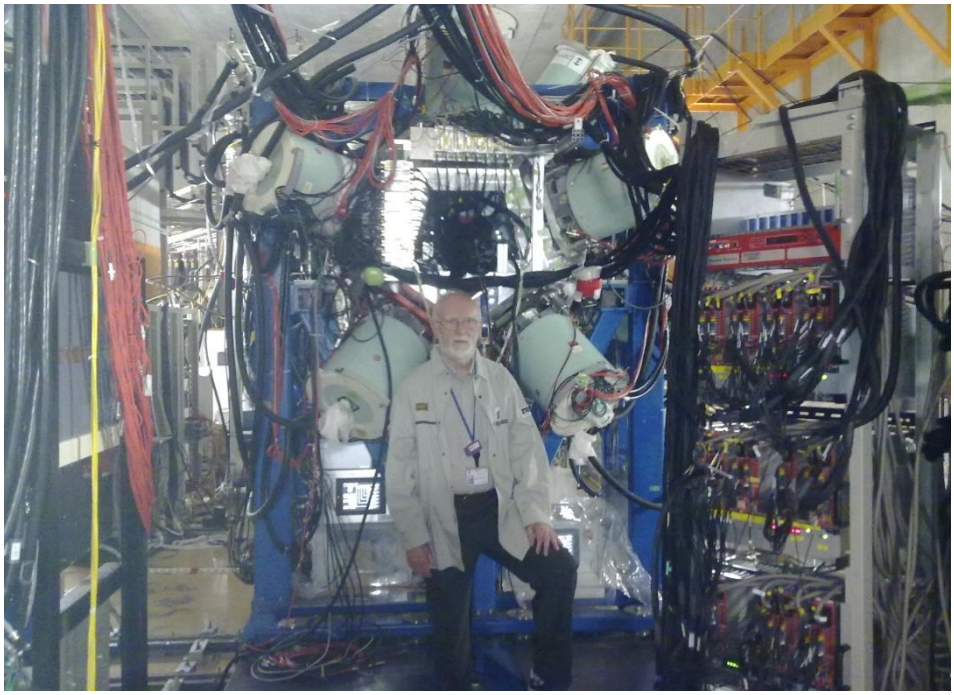


Fig.34:- The author standing in front of the EURICA array [84] situated at the end of the BigRIPS spectrometer [72] at the RIBF, RIKEN in 2015. The array is open to allow the adjustment of the implantation detector and the beam direction is out of the page.

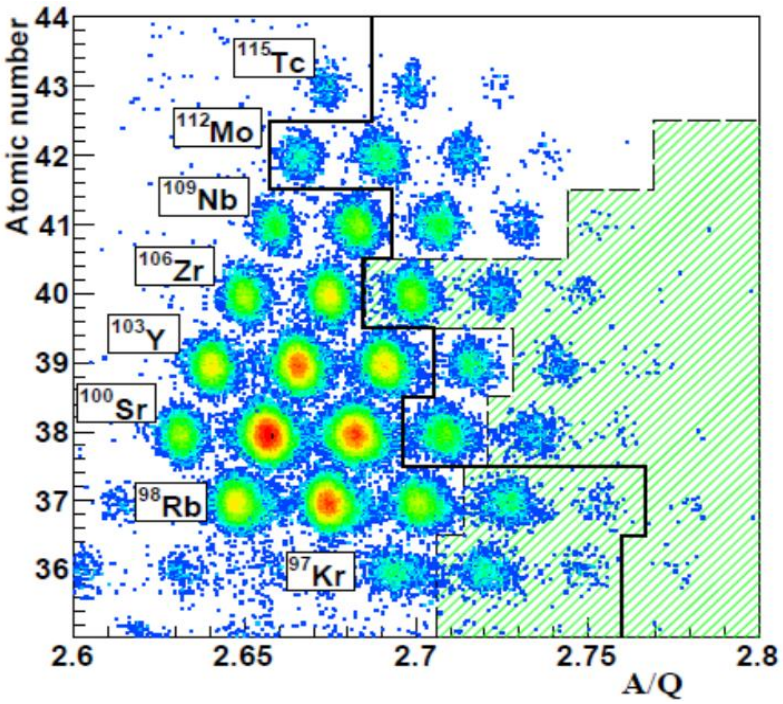


Fig.35.:- The figure shows the quality of the event-by-event tagging of exotic ions at the end of the BigRIPS spectrometer[69] at the RIBF, RIKEN. The nuclei were produced in the bombardment of a 345 MeVu^{-1} beam of ^{238}U on a 550mgcm^{-2} Be target. The half lives of the nuclei to the left of the black line were known prior to the experiment [82].

V Summary and conclusions

In the first half of this article our focus was on how Nuclear Physics develops because of the "evolution of experimental techniques". What we found is that the steps forward in the subject all start with something new but it takes a steady progression of many improvements over a longer period to get us to where we are now. This we could clearly see in the way that γ-ray spectroscopy has developed over the last 50 odd years. The same was true of the development of accelerators following Rutherford's discovery of nuclear reactions. Here and there we also noted that these same developments also opened up new applications of nuclear techniques and methods and there is no sign of this flow of new applications drying up.

I indicated in the beginning that this is an exciting time to be a nuclear physicist given the large amount of activity in building major new facilities for all areas of nuclear physics. In the second half of the article we found that radioactive beam facilities have developed in just the same way as the subject has developed historically. It was not appropriate here to discuss in detail each and every new accelerator but we covered most of the largest projects aimed at new radioactive beam facilities that are now underway. For the reader who wants more detail on the radioactive beam facilities reference [80] gives an excellent summary of what is still the current scene.

To my younger readers, or those young in spirit, I can say that you should have the curiosity of Feynman and the vision of a Lawrence. Be sceptical, check your facts and rely as little as possible on secondary sources. I spent three years working with Andy Sunyar at Brookhaven National Laboratory. I learned a lot from him but the thing I remember most is a comment he made when I arrived there to join the group. He said "for the moment we are not as well equipped as the other DOE labs. but we can be smarter than them." Having the best equipment is good but using your brain is even better. It is a message worth remembering.

Acknowledgements:- the material on which this article is based is drawn from an eclectic range of sources. John Simpson (Daresbury Laboratory) was particularly helpful in terms of providing pictures. I had not previously read E.O.Lawrence's article [1] but I was impressed by its quality, his breadth of vision and how quickly he grasped the possibilities that recent experiments had opened up. It is perhaps worth noting that his article appeared in a journal that administrators, obsessed with journal citation indices and h-indices, the false Gods that they imagine measure the quality of our Science, would have scorned. I suspect it would not have gone down well in his annual appraisal. There is a bias in my choice of references and examples. My colleagues in Surrey and Valencia are referenced more than others simply because the references were appropriate and came readily to hand.

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