Noyaux exotiques : production propriétés et spécificités

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NOYAUX EXOTIQUES: PRODUCTION, PROPRIÉTÉS ET SPÉCIFICITÉS

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RESUME:

La production de faisceaux radioactifs est présentée. Les deux méthodes principales (séparation en ligne suivie d'une post-acceleration et séparation en vol) sont comparées et leur complémentarité est soulignée. Quelques expériences sont présentées et leur impact sur la structure nucléaire des noyaux "exotiques" est discuté.

ABSTRACT:

The production methods of energetic radioactive ion beams are reviewed emphasising the complementary aspects of the two principle production methods: isotope separation on-line followed by post-acceleration (ISOL) and in-flight separation (IFS). Examples of experiments related to exotic nuclei using both methods are given.

I.-INTRODUCTION

The radioactive nuclei building up the nuclear chart have, since the discovery of radioactivity a century ago, been the corner stones of many different studies in fundamental research and of many applications in various fields. Of course they have played and are still playing a central role in the development of nuclear- and particle physics. Nuclear-structure studies aim at a deeper understanding of the strongly interacting finite quantum many-body system and of the relation between the forces acting between the nucleons in the atomic nucleus and the fundamental forces. Recently, the nuclei at the boundaries of the nuclear chart - near the proton- en neutron driplines - have received an increased interest. The balance between protons and neutrons of these so-called *exotic* nuclei is so far from equilibrium - i.e. from the Z/N-ratio in

the valley of stability - that it is questionable if nuclear models, valid close to stability, survive at these boundaries. Experiments with these close-to-drip line nuclei will reveal critical information to guide the developments of theoretical models and to test their applicability. Furthermore, many of these still unknown nuclei are lying on nucleosynthesis paths; the reaction-, decay- and ground-state properties of some of these nuclei can play a key role in the development of reliable nucleosynthesis scenarios.

Exotic nuclei are extremely difficult to produce and study because of their extremely low production cross section and the overwhelming production of unwanted species in the same target. But recent technical developments have made it possible to produce a whole series of exotic nuclei in conditions that allow the study of their properties.

In this paper we will put the production of energetic radioactive ion beams of exotic nuclei in perspective and describe the two complementary production processes that are used nowadays: Isotope Separation On-Line (ISOL) followed by post-acceleration, and In-Flight Separation (IFS) (section II). After a general description of the process we will focus on recent technical developments in the field. In the subsequent section III, we give some "typical" examples of physics cases that are addressed with exotic beams. The examples are chosen not only because of their physics importance but also to demonstrate the complementary aspects in the production process and the detection systems. Clearly this overview will not be complete and the reader is referred to literature (see list of references) for further information, nor is the lecture intended to give an overview of all the efforts that are taking place in the field by mentioning every project separately.

One last remark about the name "exotic" before serving the main course. In 1966 a symposium on Nuclides far off the Stability Line was organised in Lysekill, Sweden. In the introduction to the proceeding of this conference Igmar Bergström wrote: "... *the nuclei to be discussed belong to a certain group which we, lacking a better name, have called nuclei far off the stability line. It is certainly not necessary to emphasise that we mean the line of beta stability.*" It is clear that choosing a name for these short-lived, close to the drip-line nuclei has not been easy and some might think that the term "exotic" nuclei has been chosen because it is trendy. Still according to "The Concise Oxford Dictionary"[1] exotic means: 1. Introduced from or originating in a foreign (especially tropical) country / 2. Attractively or remarkably strange or unusual; bizarre / 3. Of a kind newly brought into use. Some justification of the tem "exotic" can be found in explanation nr. 2 and 3.

II-THE PRODUCTION OF EXOTIC NUCLEI.

In ideal conditions the exotic nuclei should be available in copious amounts, free of any contamination, well defined in energy (the energy being variable), occupying a small phase-space volume (excellent ion-optical quantities). This is a dream of course, but we can try to make reality as close as possible to our wishes.

Various nuclear reactions in a broad energy range are used for the production of the radioactive nuclei. The most commonly used primary beams are neutrons, protons, deuterons and heavy ions and the energy varies from thermal energies over Coulomb barrier energies to relativistic energies. After the production phase the radioactive nuclei are manipulated and prepared for the experiment. This whole process must therefore fulfil as good as possible the following criteria:

1. *High production rate.*

As the cross section is a nature given number we have to optimise the beam-target combination. Furthermore, accelerators have to be used that can deliver the highest beam intensities and target systems have to be developed that can cope with the power deposition of the primary beam and of the secondary reaction products.

2. *High efficiency.*

The production rate of the very exotic nuclei will always be marginal. Therefore any manipulation of the reaction products - e.g. purification, transport to the detection system - has to be very efficient in order not to loose the few precious nuclei that we want to study.

3. *Fast.*

One general property of all near-drip line nuclei is their extremely short half life (μ-second to second range). Therefore all processes that take place between the production process and the experiment must be extremely fast in order not to loose to much of the primary activity.

4. *Selective.*

The production process is in general not selective and the exotic nucleus of interest is only a fraction of the total amount of produced nuclei. As the peak to background ratio in every experiment is crucial, the beam delivered to the experimental set-up must in an ideal case only consist out of the nuclei of interest. Therefore the whole production process must be element and isotope selective.

In fig. 1 we show very schematically how the production process can take place.

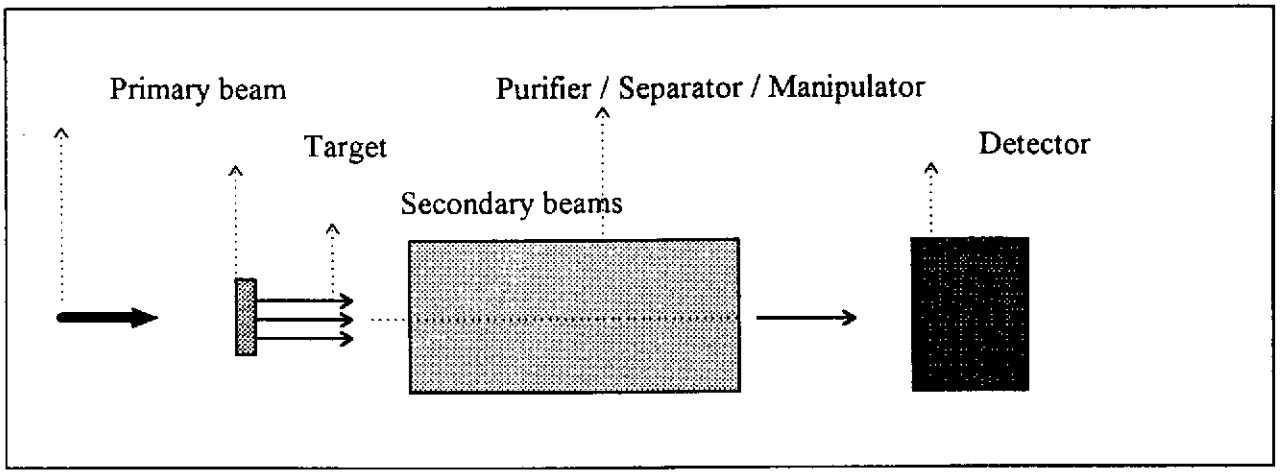

Fig. 1: Schematic drawing of an experiment to study exotic nuclei.

II-1 NUCLEAR REACTIONS TO PRODUCE EXOTIC NUCLEI

Several nuclear reactions are used to produce exotic nuclei. For convenience one defines the luminosity of the reaction (L) as the product of the primary beam intensity (N_p: particles/s) and the target thickness (N_t: atoms/cm^2):

$$L = N_p \, . \, N_t \; (s^{-1} \, cm^{-2})$$

Table 1 summarises possible luminosities obtained for the most common reactions used. From this table one concludes that the highest luminosities are obtained with the energetic neutrons while the lowest with heavy-ion fusion reactions.

The different reaction mechanisms lead also to different regions in the chart of nuclei. For example fission reactions produce neutron-rich nuclei while light ion induced spallation produces predominantly neutron-deficient nuclei south-west from the target nucleus. Projectile fragmentation produces nuclei south-west of the projectile nucleus.

Table 1: Typical luminosities of different reactions used to produce exotic nuclei. The numbers are approximate. Sometimes one uses for convenience as units for luminosity s^{-1} $barn^{-1}$.

Beam / reaction	Primary beam intensity (s^{-1})	# target atoms (cm^{-2})	Luminosity (s^{-1} cm^{-2})
low-energy protons (30 MeV) / fusion, fission	10^{15}	10^{22}	10^{37}
high-energy protons (1GeV) / fission, spallation, fragmentation [a]	10^{13}	10^{24}	10^{37}
heavy ions (5 MeV/u) / fusion	10^{13}	10^{19}	10^{32}
thermal neutrons / fission	$5\ 10^{14}$	$4\ 10^{21}$	$2\ 10^{36}$
energetic neutrons (100 MeV) / fission [b]	10^{15}	10^{24}	10^{39}
high-energy heavy ions / fragmentation			
E < 100 MeV/u	10^{13}	10^{22}	10^{35}
E > 100 MeV/u	10^{11}	10^{23}	10^{34}

a) example: p(1 GeV, 2 μA) + Sn-target → ^{110}In (σ~20 mbarn): $2\ 10^{11}$ atoms/s

b) Energetic neutrons are produced from 200 MeV deuteron beams like proposed by J. Nolan et al.[2)]

II-2 SEPARATING EXOTIC NUCLEI

After the production process we have to separate the exotic nuclei from the primary beam and from the other unwanted secondary beams. For this purpose two complementary techniques have been developed over the last decades: the so-called isotope separation on line (ISOL) technique eventually followed by post-acceleration and the so called in-flight separation (IFS) technique. The ISOL techniques rely on the availability of the radioactive species produced in a target and thermalised in a catcher consisting out of solid, liquid or gas material. Often the target and catcher are one and the same. The isotopes are subsequently extracted from the catcher material and ionised in an ion source. After extraction from the ion source the species are mass analysed using a magnetic dipole magnet and subsequently accelerated to the required energy. The IFS method makes use of the kinematics of the reaction and some combination of magnetic- and electrical fields, and atomic processes to separate the isotopes of interest from the primary beam or from other isotopes produced in the reaction.

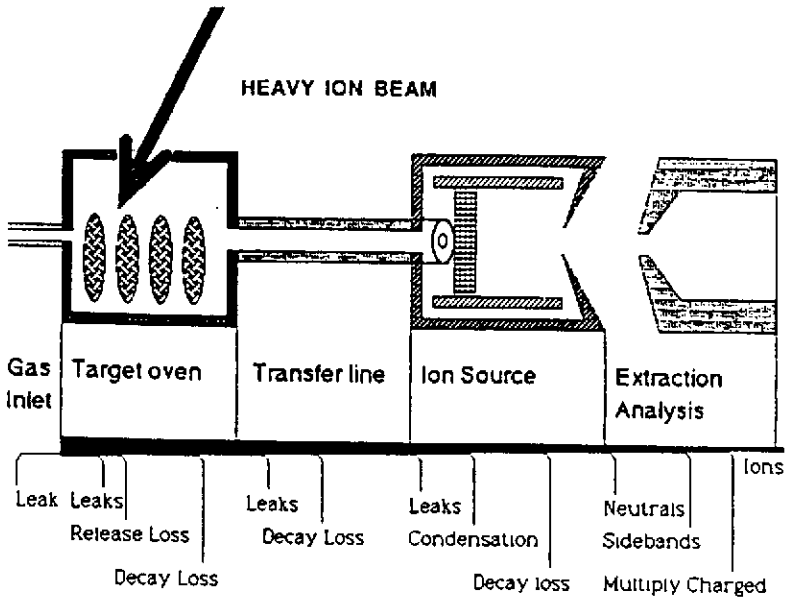

Fig.2: Schematic representation of a target-ion source system. The reaction products produced in the target have to diffuse from the target container to the ion source where they are ionised and extracted. The different loss mechanisms are shown in the bottom of the figure. The heavy ion beam indicates that these loss effects can be studied in a very precise way using energetic heavy ion beams [49].

II.2.1 THE ISOL TECHNIQUE: FROM FAST TO SLOW TO FAST.

The first on-line isotope separators were built some thirty years ago and a vigorous development program for the target-ion source systems has been pursued since then. Fig. 2 gives a schematic drawing of the target - ion source system and points to the different limitations. After production and thermalisation in the target-catcher material the radioactive atoms have to diffuse out of the target-catcher material and effuse towards the ion source[3,4,5]. Different parameters determine the release and transport properties (temperature, chemistry, absorption- and desorption coefficients). The target-catcher material itself should not be evaporated of course and this limits the target-catcher choice to materials with very low-vapour pressure and good stability at high temperature. Furthermore as the diffusion and effusion should be as fast as possible, porous material is normally used. From this it is clear that, in general, this method can't be applied to make a beam of short-lived radioactive ions from refractory elements or elements that are used as target-catcher material. Exceptions to this rule exist of course, but it would lead us to far to dwell on this interesting subject. Let us just remark that the ion guide system in which the reaction products are thermalized inside a gas cell filled with a noble gas (like helium or argon) and swepted as 1^+ ions together with the helium gas into the front-end of the isotope separator,

overcomes this problem of chemical selectivity[6]. But as the reaction products have to recoil out of the target this system can only use thin targets. On the other hand one can use the physico-chemical properties of the radioactive atoms to make already some selection. The simplest example is cooling the transfer line between the target and the ion source. By doing this one avoid the non-gaseous elements to pass from the target to the ion source. They will stick to the wall of the cold transfer line and decay, while the isotopes from gaseous elements pass further to the ion source. This technique is very powerful and used very frequently at ISOLDE to produce beam of the noble gas elements[4]. Once in the ion source the atoms are ionised by electron bombardment, surface ionisation, or laser ionisation. We will not explain all the different ionisation mechanisms used in the ion sources as extended literature on this subject can be found in different textbooks[7]. We will only discuss two recent developments in ion source technology: Electron Cyclotron Resonance ion sources (ECR) and laser ion sources.

- ECR ion sources:

ECR ion sources are based on electron impact ionisation. The plasma is contained in a magnetic bottle structure usually made from a combination of solenoid fields (axial confinement) and multipole fields made with permanent magnets (radial confinement). In this way a "minimum B" structure is obtained, having a minimum magnetic field in the centre of the source[8]. High frequency radio frequency (RF) power is injected in the plasma and the electrons take their energy out of the RF field every time they pass the zone where the magnetic field B_{ECR} fulfils the following relation:

$$\nu_{RF} = \nu_{ECR} = e\, B_{ECR}/(2\pi m_e)$$

with ν_{RF} the RF frequency and, e and m_e the charge and mass of the electron. This zone is often called the ECR zone. On-line ECR sources have been developed at different places like Louvain-la-Neuve[9], GANIL[8] and Triumf [10]. These sources show very high efficiencies for singly- and multiple charged ions and have proven to be very effective for noble gases. Vigorous developments to use the sources also for non-gaseous elements is underway and using the source as a charge state multiplier is currently under investigation at Grenoble[11]. The fact that ECR sources produces beams of high charge state ions makes them interesting for post-acceleration as the length and thus the cost of the accelerator is much smaller.

- laser ion sources:

Resonant photo ionisation, whereby the atoms are stepwise excited by laser photons until they reach the continuum, is a very efficient and selective process. With the laser power obtained from nowadays commercial lasers one can ionise atoms of almost all elements. Furthermore by the

resonant character of these excitations one reaches a very high degree of element (eventually isotopic) selectivity. For an introduction in the field of resonant ionisation the reader is referred to the following references[12, 13]. The principle of laser ionisation has been successfully implemented in an on-line ion source for the production of beams of radioactive ions in two different ways[14]. At the ISOLDE facility, the laser light is shined into a hot cavity that is connected to the target container[15]. The atoms that diffused from the target material and enter the hot cavity are ionised through interactions with the laser light and are subsequently subtracted from the source. At the LISOL facility, the reaction products are thermalised in a gas cell [cfr. the ion-guide principle[6]] and photo ionised before they reach the exit hole of the gas cell[16]. The latter approach uses the "thin target" technique as the reaction products have to recoil out of the target which makes the total production rates limited. But it has the advantage that, for certain "refractory type" elements the long diffusion times in the "thick target" approach are avoided.

After ionisation depending on the charge state the ions are either directly used for experiments or injected into the accelerator. In case of the REX-ISOLDE project[17] further cooling in a Penning trap[18] and subsequently injected into an EBIS ion source[19, 20] for further charge state breeding is applied, prior to acceleration. This cooling and "manipulating" of radioactive ions improves substantially the beam quality and prepares the beams for specific experiments like further acceleration, injection into a high-precision trap for mass measurements, soft landing,... This development is rather new and carries a lot of potential for further developments and applications.

Finally, without going into details, different accelerator structures like cyclotrons (ARENAS[3 21], SPIRAL-GANIL [22]), linear accelerators (REX-ISOLDE [17], TRIUMF-Vancouver [23], INS-Tokyo[24]) and tandems (Oak-Ridge [25], EXCYPT-Catania [26]) are under construction at different places.

Note that most of the first generation R&D projects are based in an existing accelerator laboratory. It is natural that the local know-how has influenced the different technical choices.

II.2.2 In-flight separation

In-flight separation makes use of the kinematic properties of the reaction products after the nuclear reaction. Three types of nuclear reactions are used: fission, heavy-ion fusion and heavy-ion fragmentation.

In thermal neutron induced fission on a thin heavy target, like uranium, the reaction products have a typical recoil energy of a few tens of MeV. An example of a in-flight separator using thermal neutron induced fission is Lohegrin [27] at Grenoble.

Heavy-ion fusion result in a recoil velocity that can be approximated by:

$$v_R = A_P v_P / A_C$$

with v_R and v_P the velocity of the recoiling reaction products and the primary beam particles respectively and A_P and A_C the mass of the projectile and the compound nucleus respectively. As the cross sections for heavy-ion fusion are largest around the Coulomb barrier typical recoil energies vary from 0.2 to 3 MeV/u depending on the masses of the projectile and the target. The secondary products and the primary beam can be separated by a velocity filter like for example the FMA- in Argonne [28] or the gas-filled separator RITU [29] in Jyväskylä.

At higher energies, much higher then the Coulomb barrier, up to relativistic energies, fragmentation reactions dominate. After fragmentation the velocity of the primary and secondary products are approximately the same: $v_f \sim v_p$ (v_f and v_p are the velocities of the fragments and the primary beam particles respectively). The fragmentation reaction gives rise to a spread (σ) in momentum (p). The relative momentum spread (σ/p_F) can be approximated by:

$$\frac{\sigma}{p_F} = \frac{\sigma_0}{p_F}\sqrt{A_P - A_F}$$

with A_P and A_F the mass of the projectile and the fragment [30]. One notices that the larger the number of abraded nuclei (the larger the difference in mass between the projectile and the fragment) the larger the momentum spread. For fragmentation reactions of heavy nuclei (A>100) at E=500 MeV/u the typical relative momentum spread is 1% and the solid angle is 1 msr [31]. The separator must cope with this spread and solid angle.

In-flight separators use electrical and magnetic fields, or a combination of them, to separate the primary from the secondary beams, and the wanted from the unwanted secondary beams. By placing the magnet and electrical fields in different configurations one obtains separation according to the velocity, independent of the mass over charge ratio or visa versa. In fig.3 a schematic lay-out of a fragment separator is shown. It consists out of focusing elements

(quadrupole triplets) and magnetic dipole elements. The magnetic dipoles delivers a M/Q selection. This selection is hampered by the charge state dispersion after the nuclear reaction (different Q-values). A solution to this problem is going to much higher primary energies, where the reaction products are fully stripped. For example a primary beam of 1 GeV/u (typical energy of the GSI synchrotron) allows fully stripped ions up to Z~80 [31]. The symmetric set-up of a fragment separator and the high energy of the secondary beam allows for another separation mechanism. By placing a piece of material (degrader) in between the two symmetric sections, the secondary beam looses a certain amount of energy per nucleon $\propto Z^2/A_F$. Thus isotopes with different Z will have different energy when they have passed the degrader. As a consequence they will be separated by the subsequent dipole magnet section. By shaping the piece of material in a wedge one can even get monochromatic, achromatic or homogeneous beams [31].

Finally, one should note that because of the high energy of the secondary beams they are ideally suited for being detected in transmission detector arrays. The energy loss, position and the "time of flight" (TOF) information helps identifying and tracking the secondary particles in a unique way and is one of the most powerful elements of the fragment separation technique.

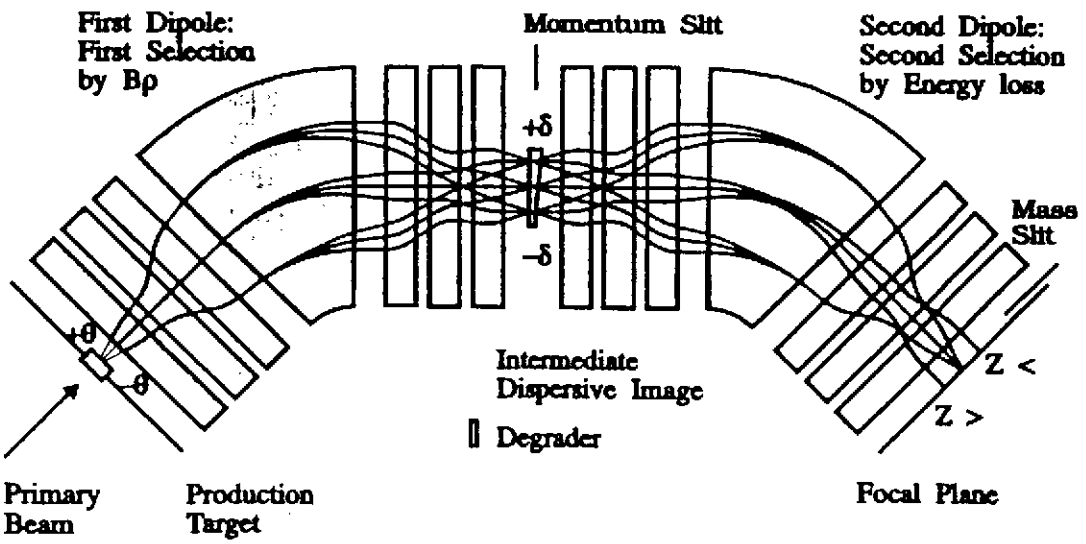

Fig. 3: Schematic representation of a fragment separator [50]

III. THE PHYSICS

In this chapter we will give a few examples of experiments that have recently been performed using radioactive ion beams. The examples are chosen to address the complementary aspects of the two different production methods [32].

III.1 SINGLE-NEUTRON STATES IN ^{133}SN

Properties of doubly-closed shell nuclei and nuclei in their neighbourhood are of importance for fine-tuning and understanding the shell model. Unfortunately, the number of doubly-closed shell nuclei is very small. This is especially true for the heavy nuclei: $^{48, 56, 78}$Ni, ^{100,132}Sn and ^{208}Pb. The latter is the only stable one and it is thus not surprising that the most complete information has been obtained for this nucleus. Still vigorous experimental programs are pursued in this region of the chart of nuclei. The situation around ^{132}Sn (Z=50, N=82) is much less understood partly due to a lack of experimental data. For example, singly particle states in ^{133}Sn have only been found recently in an experiment at ISOLDE [33]. By studying the β-delayed neutron decay of ^{134}In, levels in ^{133}Sn were populated and their subsequent gamma decay was studied (fig. 4).

The ^{134}In nuclei were produced in proton (1 GeV) induced fission on a uranium carbide target. After surface ionisation the low-energy (60 keV) beam was sent to a detection station where its β-decay was studied. A combination of gamma, beta and neutron detectors was used resulting in a gamma-ray spectrum that was gated by neutron conditions as shown in fig. 5. These spectra could only be obtained because of the high degree of beam purity, the good beam intensity and the high-quality of the beam spot. From these data one was able to extract information on the single neutron states around N=82. These type of data are not only useful to test the nuclear shell model but acts as input values in realistic nuclear structure calculations.

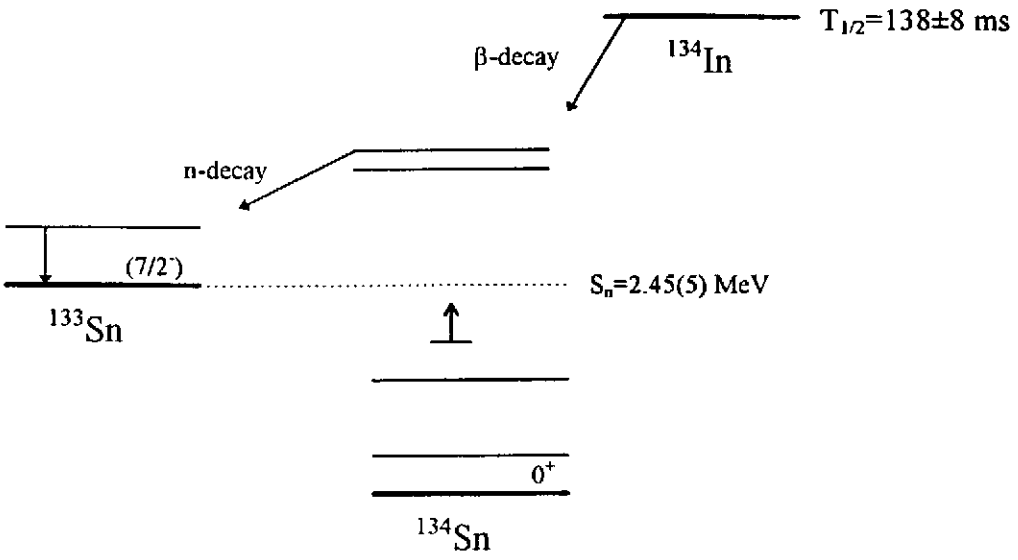

Fig. 4: Schematic drawing of the decay of ^{134}In

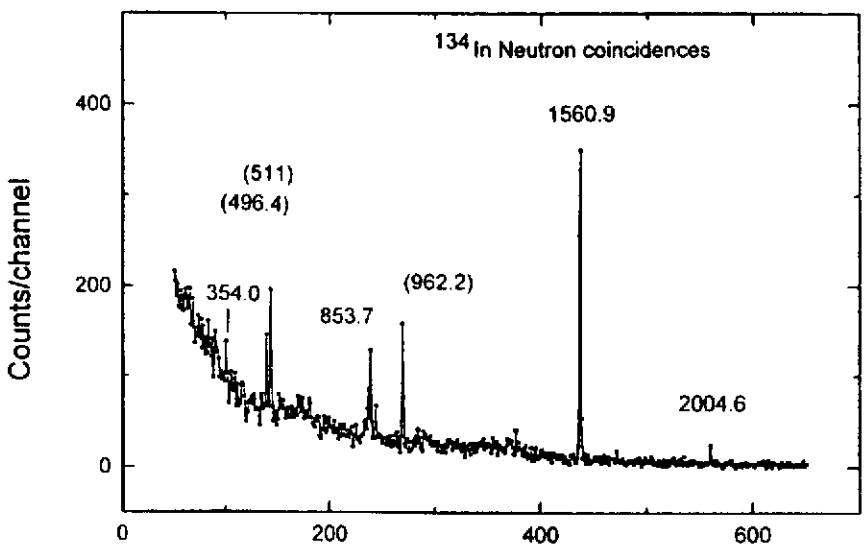

Fig. 5: Part of the neutron gated gamma spectrum obtained at mass 134 [33]

III.2 SHAPE COEXISTENCE AROUND Z=82

Since long experimental evidence exists for shape coexistence around the neutron deficient Pb (Z=82) nuclei. The coexisting structure are believed to be based on proton multi-particle-multi-hole excitation across the Z=82 shell gap [34]. In-beam as well as decay studies have delivered complementary information. For example extensive alpha decay studies were performed at several on-line isotope separators (LISOL: Louvain-la-Neuve, Belgium; ISOLDE: CERN, Geneva, Switzerland; and GSI: Darmstadt, Germany) and have revealed a large set of low-lying 0^+ states [35]. The decay characteristics have been identified as fingerprints for the underlying structure of the connected states. More recently the efforts in this field of research have been shifted from on-line isotope separators to in-flight separators because of the short half-life limitations at on-line isotope separators. Fine structure studies have revealed for example recently the first excited 0^+ state in ^{188}Pb and the intensity of the alpha line feeding the excited 0^+ state indicates a strong mixing of the regular and deformed states in the ground state of ^{192}Po [36].

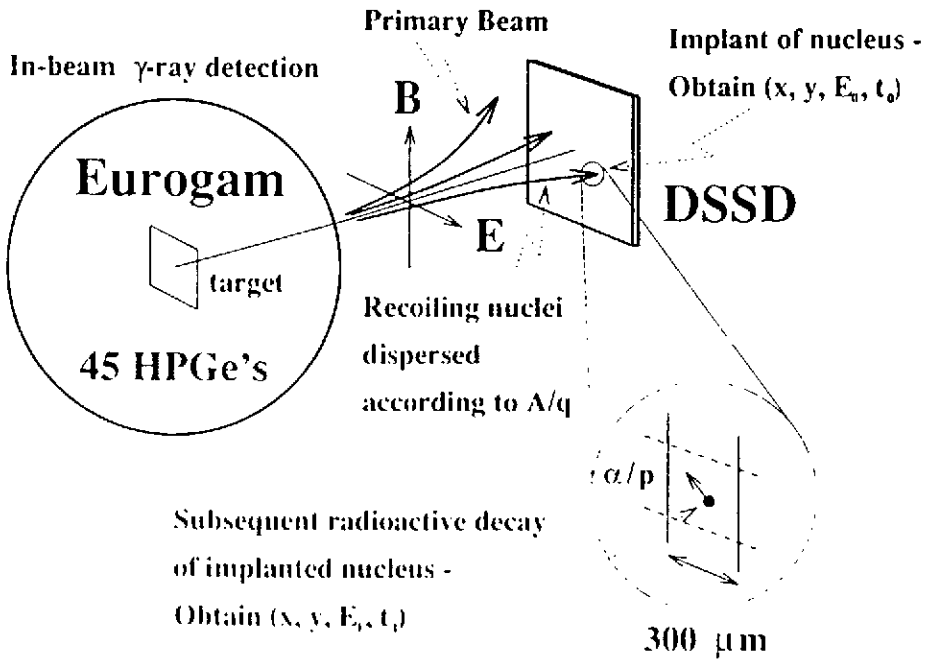

Fig. 6: The principle of recoil-decay-tagging method. Prompt γ rays from the in-beam reaction are detected by a Ge-array (in the case shown it was the Eurogam detector). The recoiling evaporation residues are injected into an in-flight separator (in this case the late Daresbury recoil separator) and are after suppression of the unwanted beam (mainly the primary beam) implanted in a double sided silicon strip detector (DSSD). After a certain time the implanted radioactive nucleus alpha-decays. By correlating the alpha decaying events with the γ events, one obtains extremely clean γ spectra and the alpha decay energy uniquely identifies the nucleus they belong to [37].

Another very successful application in this region of the chart of nuclei are in-beam studies using the so-called recoil-decay-tagging method. This method, originally developed by E.S. Paul et al. [37], is explained in fig. 6. At the RITU in-flight separator of Jyväskylä, recently, a very extensive set of experiments have been performed getting in-beam data on several neutron-deficient Pt, Hg, Pb, Po and Rn nuclei. In fig. 7 we show as an example the gamma spectrum taken for ^{192}Po using the RDT method [38]. From these spectra one can conclude that indeed the deformed structure in ^{192}Po has become the ground state. Similar experiments have been performed at the FMA in Argonne. The difference being that the RITU gas-filled separator only suppresses the primary beam and has no mass selectivity. But the RDT method identifies the nucleus in a unique way.

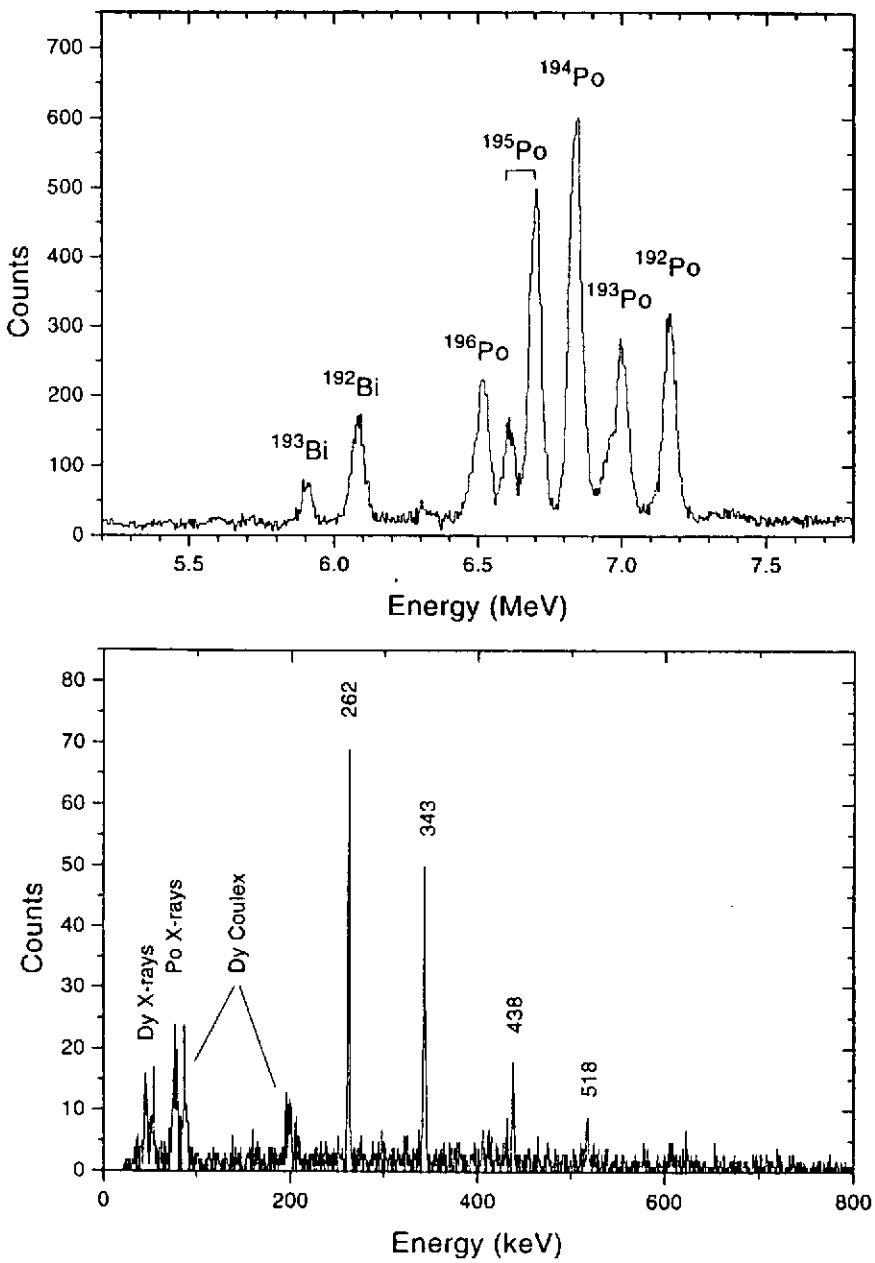

Fig. 7: The alpha spectrum recorded at the end of the RITU spectrometer in the segmented particle detector. The gamma ray spectrum obtained after correlations with alpha's from the decay of ^{192}Po [38].

III.3 ^{100}SN AND OTHER EXOTICS.

The doubly magic ^{100}Sn nucleus has since long been the "Holy Grale" of nuclear structure physicists. At least if one looks back into history and read some older proposals and conference proceedings. It is clear that its properties are important for our understanding of the atomic nucleus close to the proton drip-line: it is most probably the heaviest N=Z nucleus that we will be able to study experimentally. The rabbit that defended the Holy Grale in Monthy Pytton's film is this time disguised in the form of an extremely low-cross section. Furthermore every nuclear reaction (heavy ion fusion, fragmentation) produces copious amounts of unwanted nuclei from which one has to extract the few ^{100}Sn. In two independent experiments ^{100}Sn was identified at GSI and GANIL [39, 40]. Fig. 8 shows the identification plot obtained at GSI. In total 6 counts were attributed to ^{100}Sn. Because of the purity of the signal, already first decay properties of ^{100}Sn could be extracted. Note for example table 1 from ref. [41] where the decay properties of the six events are summarised. From these data a level scheme was deduced (fig. 9) and compared to a recent calculation of H. Grawe et al. [42] The errors on the deduced values are of course too large to make any significant comparison. Still it shows the power of the method and with increasing primary beam intensity, the statistics of these experiments can be improved by two orders of magnitude. It should be noted that the intensity of ^{100}Sn that can be obtained using a heavy ion fusion reaction at an on-line mass separator is much larger compared to the intensity at a fragment separator. Unfortunately the beam purity and possibilities for identification at IFS systems are superior over ISOL systems. This makes these experiments possible at the former and not (yet) at the latter. Still it is interesting to note that the first study of ^{101}Sn was performed at the GSI on-line isotope separator [43].

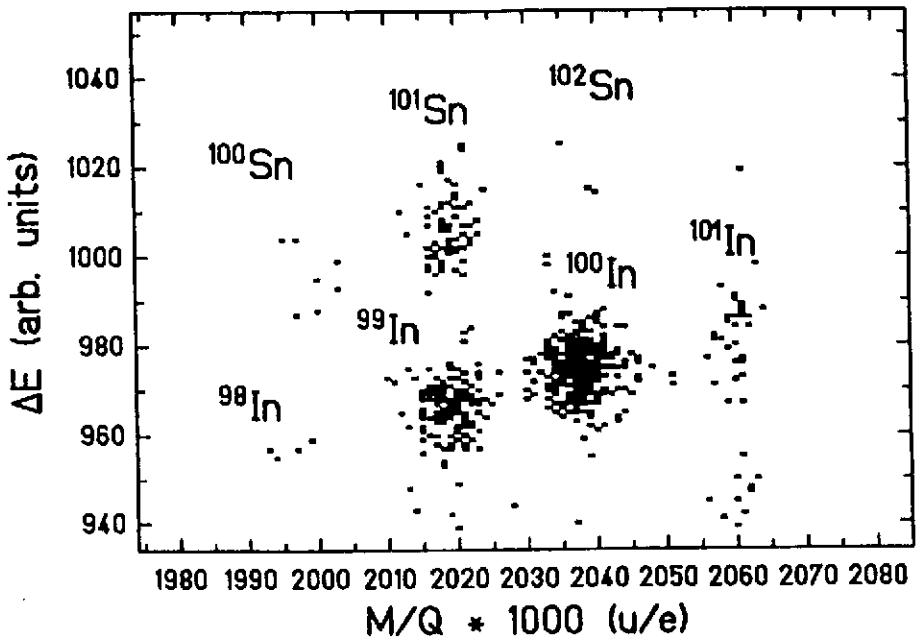

Fig. 8: Identification plot for ^{100}Sn [39]

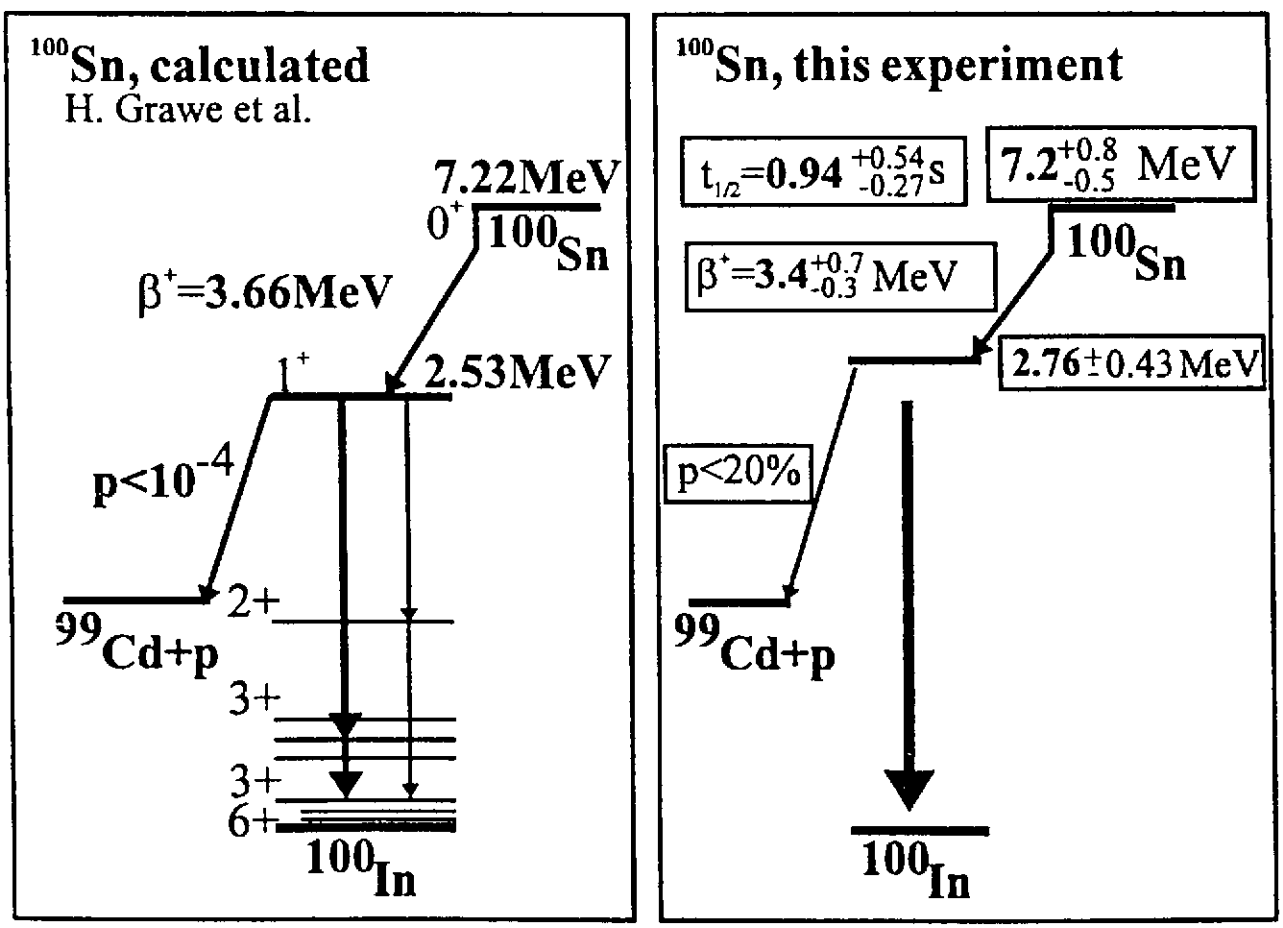

Fig. 9: Comparison of the experimental results in the decay study of ^{100}Sn with shell-model calculations [41, 42]

III.4 COULOMB EXCITATION MEASUREMENTS

The region around the closed N=20 and N=28 neutron shell and proton number between Z=8 and Z=20 marks an interesting region in the chart of nuclei. For example, recent self-consistent mean field calculations performed by Werner et al. [44] suggest that the sulphur isotopes (Z=16) are moderately deformed even in the presence of the "closed shell" N=28. Experimentally this region of the chart of nuclei is not easy to access. To obtain detailed spectroscopic information like excitation energies and B(E2) transition probabilities one needs beams of radioactive ions.

One drawback using radioactive ion beams is the low intensity. Consequently the first experiments one can perform with the secondary beams are decay experiments or study reactions with a high cross section. Coulomb excitation measurements are therefore of particular interest.

At the Riken facility Motobayashi et al. [45] performed a Coulomb excitation measurements using a ^{32}Mg beam produced in a fragmentation reactions. They could show that ^{32}Mg, although having a closed neutron number (N=20), was strongly deformed in its ground state ($|\beta_2|$~0.5). More recently a series of experiments was performed at the Michigan State University Cyclotron where a position sensitive NaI(Tl) detector array was used to perform Coulomb excitation measurements on even mass isotopes of argon and sulphur [46]. The secondary beams were produced in the fragmentation of 80 MeV/u ^{48}Ca and ^{40}Ar beams. Fig. 10, taken from ref. [46], shows part of the gamma spectra obtained. The top panel shows the spectra prior to Doppler correction while the lower panel the Doppler corrected spectra are displayed. Note that the ^{42}S data were obtained with a beam intensity of only 1800 atoms/second. From these data the authors could conclude that the ^{40,42}S isotopes are deformed but that the N=28 shell gap at least persists down to Z=18.

The relative high energy of the fragmentation beams makes the Doppler broadening a real problem. On the other hand post-accelerated radioactive ion beams (energies below or around the Coulomb barrier) combined with highly segmented Ge detector arrays makes the Doppler correction more accurate and the peak to background ratio will improve considerably. Coulomb excitation measurements are underway at different places like the SPIRAL project at GANIL [22] using the so-called EXOGAM detector array and at the REX-ISOLDE facility [17] using the Ge-mini ball array [47].The Ge-mini ball detector will consist out of 6 clusters of 7 detectors that are 6-fold segmented electronically: 252 individual detector energy signals.

The spatial resolution will even be further improved by radial information extracted from the rise time of the detector signal (fig. 11). First experiments at these facilities are expected in 1999.

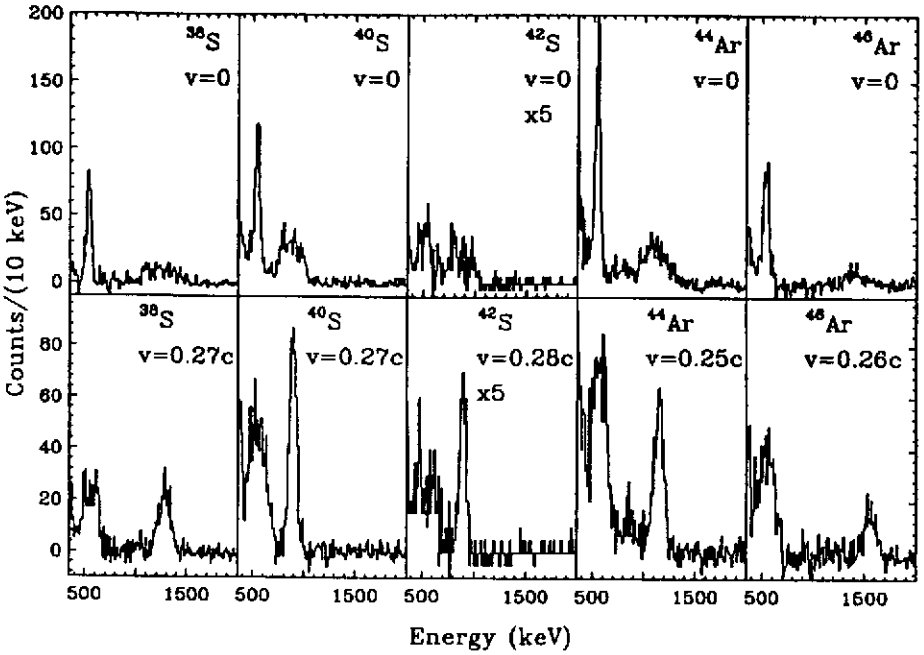

Fig. 10: Part of the gamma-ray spectra obtained in the Coulomb excitation measurement using fragmented beams of $^{38-42}S$ and $^{44,46}Ar$. The top panel shows the spectra prior to Doppler shift correction, the lower panel shows the same spectra after proper Doppler shift correction [46].

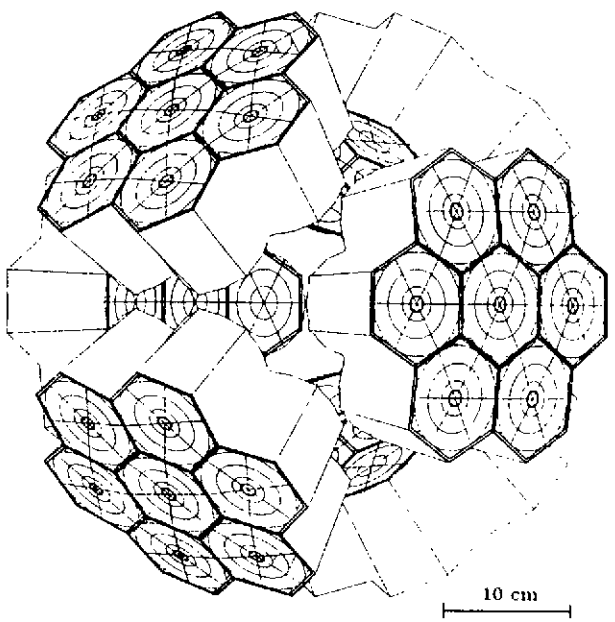

Fig. 11: Schematic drawing of the Ge-mini ball detector [47]. The six-fold segmented cluster detectors form a cube configuration.

III 5. AND OTHER REACTION WORK.

With the fragment products extensive reaction studies have been performed at relativistic energies in the framework of "halo" nuclei [31] and they are discussed by N. Orr in these proceedings. Recently, first reaction studies using a post-accelerated radioactive ^{6}He beam have been performed at Louvain-la-Neuve; the elastic scattering of ^{6}He on ^{4}He, looking for the transfer of the two neutrons [48]. These are the first experiments in a series that will start as soon as other ISOL+post accelerator type of facilities come into operation.

IV CONCLUSION AND OUTLOOK

In this lecture we have tried to give a comprehensive overview of the efforts that are taking place world-wide in the research field of exotic nuclei. We have discussed the two different approaches that are developed and used for the production of energetic beams of these exotic nuclei and showed the complementary aspects of both methods. From this discussion it can be concluded that the field of in-flight separation is a mature field where different facilities are preparing for intensity upgrades of the primary beam intensity (MSU, GSI, RIKEN). The field of on-line isotope separation + post-acceleration is still in full development and several first generation facilities, that are now operational, under construction or planned, are performing important R&D work to answer the different technical issues that are raised. These efforts will finally result in the optimum design for second generation facilities.

The physics cases that have been discussed briefly have been chosen for didactical purposes to show how the different technical aspects of the production methods are related to the physics results obtained in the experiments. Interesting to note here is the fact that even with limited statistics (in case of decay studies for example) still unique information can be obtained.

Let me finally note that these radioactive ion beam developments have also an impact in other research fields like nuclear medicine, solid-state physics and atomic physics.

I hope I have convinced the reader that the field of "exotic nuclei" is a very lively field that got a new impulse with the availability of (energetic) radioactive ion beams of good quality (purity, ion optical properties, time structure) and intensity. Also the theoretical work in this far from stability region has regained interest and new developments are expected there as well. May be there will come a time that the nuclei we plan to study nowadays aren't any longer "exotic" in the sense of ref. [1] ("attractively or remarkably strange or unusual; bizarre; of a kind newly

brought into use"). At that moment we will have taken a major step in the understanding of the nuclear structure and thus in the understanding of the manifestation of the strong and weak interactions in the nuclear medium under extreme conditions.

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