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THE PROSPECTIVE EUROPEAN ISOL-TYPE RADIOACTIVE BEAM FACILITIES

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ABSTRACT

The planned West-European radioactive ion beam (RIB) facilities based on the ISOL-type two-accelerator method ~~will be~~ discussed in conjunction with the report of the Nupecc Study Group on radioactive beams. Special attention ~~will be~~ paid to the different aspects entering into an ISOL-type facility. The relative merits of the proposed facilities ~~will be~~ discussed and the main conclusions of the Nupecc Study Group ~~will be~~ presented.

1. Introduction

During the last few years interest has increased worldwide in the physics with accelerated radioactive ion beams. This is reflected on the one hand in the many conferences and workshops on this topic [1–4], and on the other in the large number of radioactive beam facilities that are proposed or under construction. In Western Europe alone there are five based on the ISOL-type (Isotope Selection On-Line) two-accelerator method: ARENAS[3] at Louvain-la-Neuve, CERN-ISOLDE at Geneva, EXCYT at Catania, GANIL-PLUS at Caen, and PIAFE at Grenoble. As was concluded by Nupecc in its Report **Nuclear Physics in Europe – Opportunties and Perspectives** physics with radioactive beams is one of the foremost frontiers of nuclear physics. In view of the strong interest in radioactive ion beams (RIB) Nupecc established a Study Group in 1992 to advise it on the proposed facilities. In my talk I would like to report on the work of this Study Group and give an overview of the planned European facilities.

2. The Nupecc Study Group

A Study Group on the proposed European radioactive beam facilities based on the two-accelerator method was established with th author as convenor at the International Workshop on the "Physics and Techniques of Secondary Nuclear Beams" at Dourdon in March of last year with the author as convenor. The Study group has met five times since and presented its report to the board of Nupecc in February of this year. The report together with the conclusions by the board of Nupecc will appear in print shortly [5].

The questions asked by the board of Nupecc were

- What is the physics case for radioactive beams.
- What are the relative merits of the proposed facilities.
- What is the R&D required to reach the desired goals.

With respect to the first question it was decided not to reinvent the physics case in view of the extensive literature on this topic. On the other hand it was realized that the physics case is the yardstick against which the different proposed facilities must be assessed, and therefore a condensed description of the physics case was presented. Among the many proposals and documents on radioactive beams the report on "The Isospin Laboratory" [6] as the ultimate radioactive beam facility has been a landmark which has strongly influenced the current thinking on the subject.

In order to be able to make a meaningful intercomparison of the different proposed facilities it was deemed essential to have benchmark numbers for the production of radioactive ions, taking into account the different proposed schemes of primary beams, targets and ion sources. To this end a working group chaired by H. Ravn was established, and it was an important achievement of this group to come up with benchmark numbers of selected beams on which a general consensus among the members of the working group was reached. In my talk I will heavily rely on the material presented by this group.

3. The Physics Case

An important and very attractive feature of the physics with radioactive beams is the strong interdisciplinary interest in RIB's. Besides the nuclear physics topis of nuclear structure and reactions, there are such fields as nuclear astrophysics, nuclear chemistry and solid state physics, as well as more applied research such as tribology. Pure nuclear physics research amounts to about 50% of the total interest [7] in accelerated RIB's.

In nuclear structure physics we mention the severe constraints imposed by extrapolating models and effective interactions to regions far off the stability line, the possibility to extend the study of the interesting N≅Z nuclei (neutron-proton pairing, isospin breaking) all the way to the proton drip line, proton and two-proton radioactivity, the possibility to study neutron matter in halo nuclei, new regions of octupole, super- and possibly hyper-deformation that can be reached, and the possibility to do "complete spectroscopy" including both low and high spin states in the same nucleus.

In the study of nuclear reaction dynamics we mention the possibility to produce "cold" nuclei with high angular momentum by imploying high spin isomeric beams, the systematic investigation of sub-Coulomb fusion enhancement, enhanced multiple neutron pair transfer in the collision of a neutron rich with a neutron poor nucleus, and exploratory studies into the synthesis of very heavy nuclei with neutron rich beams.

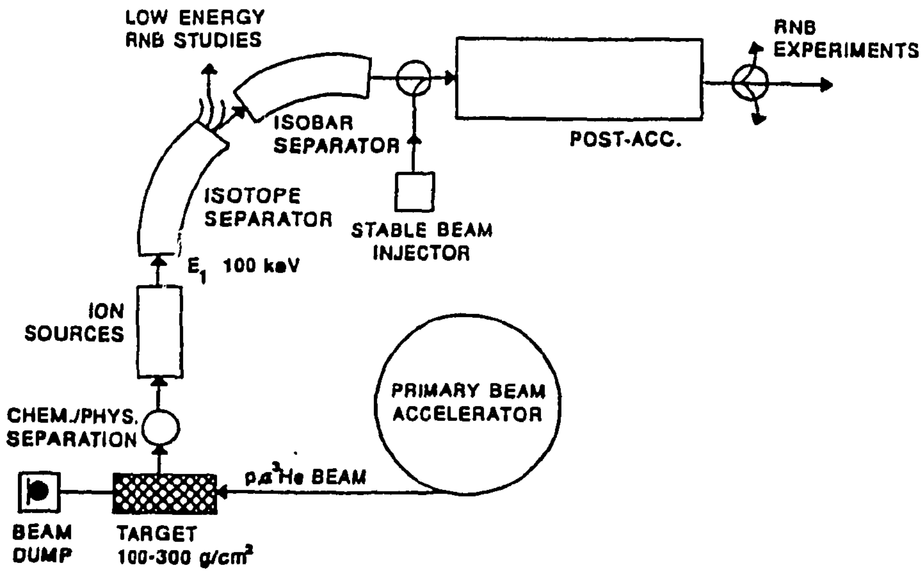

Fig. 1: Schematic drawing of an ISOL-type RIB facility

In summary the physics with radioactive beams promises to be a very rich field that is attracting many scientists. In Western Europe alone the number of senior scientists interested in this field was estimated by the Study Group to be between 200 and 300. In the Study Group's view nuclear physics studies with RIB's will lead to strong new impulses to nuclear structure physics. Moreover, it will ensure the continuation of high level research in the field of low-energy nuclear physics, a field which is very important for the applications of nuclear methods to other fields.

4. ISOL-Type versus Fragmented Beams

The facilities discussed by the Study Group are all based on the two-accelerator method. Such a facility is schematically shown in fig. 1, borrowed from Wiescher [8]. It consists of an accelerator for the primary beam, production target, ion source, and mass separator, followed by the post-accelerator. An alternative method to produce energetic RIB's is projectile fragmentation. At this point It may therefore be worthwhile to look at the relative merits of the two production methods.

At energies below and around the Coulomb barrier, and for not too short-lived isotopes, ISOL-type facilities will be superior both in intensity and in the quality (energy resolution and energy variability) of the beam. On the other hand beams from projetile fragmentation are required for very short-lived isotopes and/or high energies, as they are needed to study the excitation of giant resonances, charge exchange and many transfer reactions in inverse kinematics. Moreover, with the addition of cooler–storage rings after the fragment separator as, is done at SIS–ESR, some of the shortcomings of the fragmented beams, i.e. the lower beam intensities and the poorer energy resolution, can be remedied. A very interesting scheme based on projectile fragmentation and cooler rings has been proposed here at Dubna [9,10]. In conclusion both schemes, ISOL-type facilities and projectile fragmentation combined with cooler–storage rings, must be viewed as being complementary.

5. General Considerations on ISOL-Type Facilities

As seen from fig. 1 the ISOL-type RIB facility basically consists of three parts, (i) the primary beam accelerator, (ii) production target, ion source and mass separator, and (iii) the post-accelerator. Obviously all three parts cannot be treated in isolation. The choice of primary beams will determine the production target, and the type of post-accelerator will put constraints on the ion source. In the following paragraphs I will discuss the different aspects entering into the design of an ISOL-type RIB facility.

5.1. Primary beams and production cross sections

The use of a variety of primary beams ranging from thermal neutrons to heavy ions has been proposed. In all cases the choice of the primary beam has been dictated by the availability of an accelerator (reactor) that produces these beams.

Neutrons. The use of reactor neutrons has been proposed for the PIAFE project in Grenoble. In principle very high neutron fluxes ($\phi \leq 10^{15} cm^2 s^{-1}$) can be obtained. Radioactive ions are produced via the fission of ^{235}U which has very large cross sections for the production of neutron rich isotopes in the $80 < A < 140$ mass region. A restriction is the limited mass and isotope range of the fission products, but in this range the potentially largest yields for neutron rich isotopes might be obtained. A complication is the hostile environment close to the reactor core, in particular if the ion source is to be placed in the vicinity of the target.

Low-energy protons. Low energy protons as primary beams are being employed at Louvain-la-Neuve with a medical cyclotron as booster ($E_p \leq 30 MeV$). With this machine very large beam currents can be obtained (up to 500μA), the limiting factor being the power in the target that can be dissipated safely. This maximum power presently is 6 kW, and the aim is to reach 10 kW. The production process with low-energy protons is selective with high yields for channels close to the stability line. Strong channels are fusion-evaporation and direct transfer as well as charge exchange. Because of the selectivity, the production of unwanted activities is restricted.

High-energy protons. Traditionally high energy proton beams have been the preferred beams for ISOL facilities. Because of the large range of the energetic protons, very thick targets can be used: at the new ISOLDE at CERN with a 1 GeV beam from the CERN booster typically 140 g/cm^2 versus 5 g/cm^2 for a heavy ion target or for low-energy protons. Also the power density in the target is low as compared

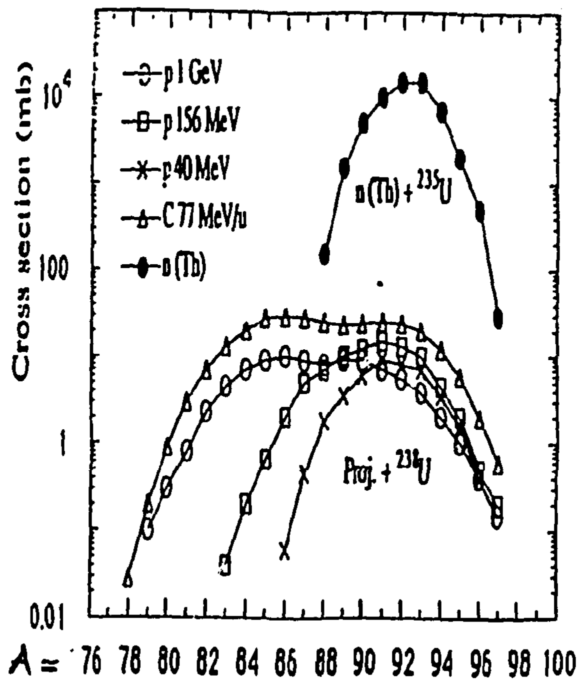

Fig. 2: Cross sections for the production of rubidium isotopes.

with other beams. The production process is target fragmentation. It is non-selective and therefore a wide range of isotopes can be produced.

Intermediate energy heavy ions. Intermediate energy heavy ion beams with energies of E/A≈100 MeV offer an interesting alternative to high-energy protons, though the power density in the target is much higher, and the useful target thickness is considerably smaller (5 g/cm^2 versus 140 g/cm^2 for 1 GeV protons). Mass distributions for E/A=77 MeV ^{12}C are similar to those obtained with 1 GeV protons, and the cross sections seem to be typically larger [11] by a factor of 2 to 5 (fig. 2). The important quantity for fragmentation thus appears to be the total energy dumped into the combined system target plus projectile. Also shown in (fig. 2) are the cross sections for thermal neutron fission.

With intermediate energy heavy ions both target and projectile fragmentation can be used as the production process. For certain neutron rich isotopes an increase in yield by more than an order of magnitude was observed [12] at the old ISOLDE with E/A=77 MeV ^{3}He and ^{12}C beams as compared with 600 MeV protons. Intermediate energy heavy ions as primary beams will be used at GANIL-PLus with projected beam currents up to 10pμA and at EXCYT-Catania with beams $\leq$ 1 pμA.

5.2. Production yields of radioactive ions

The production cross sections are obviously not the whole story in order to obtain

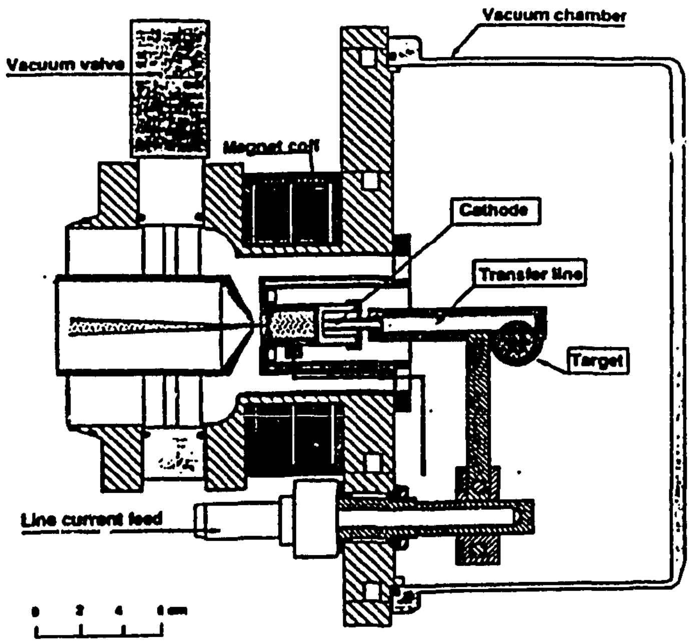

Fig. 3: A typical target and ion source unit.

the yields of radioactive ions prior to the injection into the post-accelerator. Besides the intensity of the primary beam ϕ in particles/s and the target thickness N in atoms/cm^2, the product release and transfer efficiency ϵ_1, the ion source efficiency ϵ_2, and the delay transfer efficiency ϵ_3, taking into account the radioactive decay losses, have to be considered. The yield of radioactive ions is thus given by the expression

$$Y = \sigma \cdot \phi \cdot N \cdot \epsilon_1 \cdot \epsilon_2 \cdot \epsilon_3 \tag{1}$$

A typical target ion source arrangement [13] is depicted in fig. 3 showing the target, transport line and ion source. The delay transfer efficiency ϵ_3 is determined by the diffusion out of the target, the effusion along the transport line, and sticking times at the walls of the source. Obviously these effects become the more critical as the lifetime of the radioactive isotope decreases. As an example the overall efficiencies for some non-volatile elements as a function of halflife are shown in fig. 4. These data were obtained at GSI [14] by implanting stable heavy ions into the ion source and folding the corresponding halflifes into the data. Saturation is reached for halflifes larger than 100s. For palladium the overall efficiency is seen to drop by almost two orders of magnitude for a change of halflife from 100 to 1 second.

5.3. Ion sources

A variety of ion sources are in use. Desirable properties are high ionization efficiencies, element selectivity and short delay times. In addition there is a high premium on multiply charged ions for post-acceleration, since q/A determines the heaviest

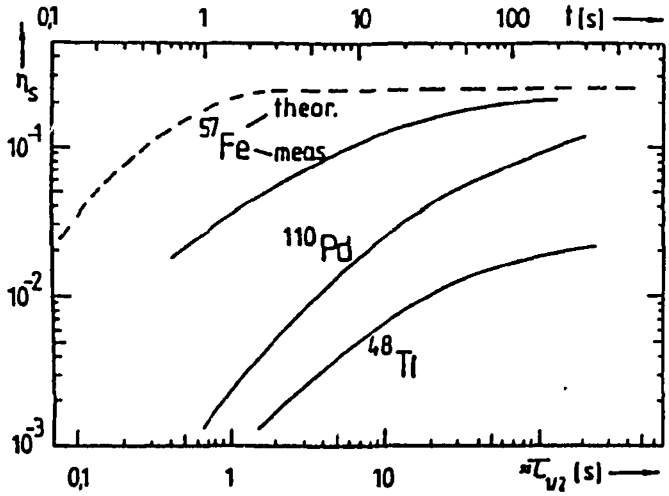

Fig. 4: Overall efficiencies of Ti, Fe, and Pd as a function of halflife.

masses that can still be accelerated both in LINAC's and cyclotrons. Moreover, the maximum energies per nucleon that can be reached are proportional to q/A for linear accelerators and to $(q/A)^2$ for cyclotrons.

In general, different ion sources will be needed for different groups of elements (see e.g. [13]). The various schemes employed are discussed in a recent review by van Duppen et al. [15]. These are (i) ionization through electron impact in plasmas, (ii) surface ionization sources, (iii) multistep photo-ionization with lasers and (iv) the ion guide system in which the reaction products are ionized while recoiling into a helium gas cell.

The plasma sources (i) include low-pressure gaseous-discharge ion sources and the ECR-source. Both sources have high ionization efficiencies, but have no or little chemical selectivity. The ECR source is the only source capable of producing highly charged ions in sufficient quantities. As yet, however, there is little experience with the production of radioactive, multiply charged ions which are crucial for certain post-acceleration schemes. Important and as yet insufficiently explored factors in the production of multiply charged radioactive ions of non–gaseous elements with an ECR source are the delay times due to sticking to the walls and the sensitivity to gas loads. Both the surface ionization (ii) and multistep photo–ionization sources with lasers (iii) are element selective but give singly charged ions only.

5.4. The post-accelerators

Tandem Van de Graaffs, LINAC's and cyclotrons are proposed as post-accelerators.

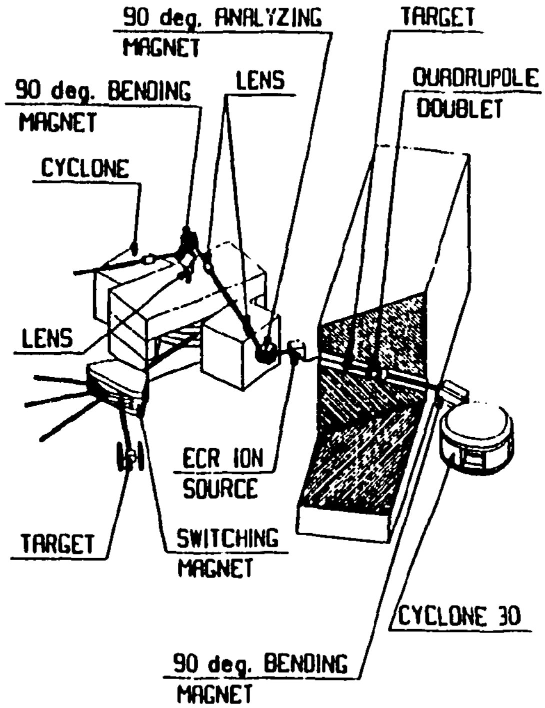

Fig. 5: Schematic drawing of the ARENAS facility.

Tandems have the highest beam quality but require negative ions as input. These are produced either by surface ionization, or when this is not possible, by charge transfer of positive ions. Both tandems and LINAC's allow for a continuous energy variation. Moreover, polarized ion beams might be produced via the tilted foil method prior to injection and acceleration with LINAC's.

As a first stage before the LINAC's, RFQ's are usually foreseen which still appear to require R&D. With singly charged ions the LINAC is restricted in its mass range to typically $1/A \leq 80$. Numbers on the achievable transmissions vary strongly in literature and range from 3% for the largest masses to close to 100%. They obviously depend on the type of accelerator structure that is chosen. For the cyclotron very high transmissions have been obtained, up to 60% at GANIL [16]. In addition the cyclotron acts as a mass separator. Except for the lightest ions, however, the availability of multiply charged ions is a condition "sine qua non" for cyclotrons and this restricts the choice of sources that can be employed with the cyclotron.

6. The Proposed Facilities

ARENAS[3], Louvain-la-Neuve [17,18]. Louvain-la-Neuve is the first and up to now only working radioactive beam facility with the two accelerator method. The present facility uses a medical cyclotron, CYCLONE 30, that can deliver up to 500μA

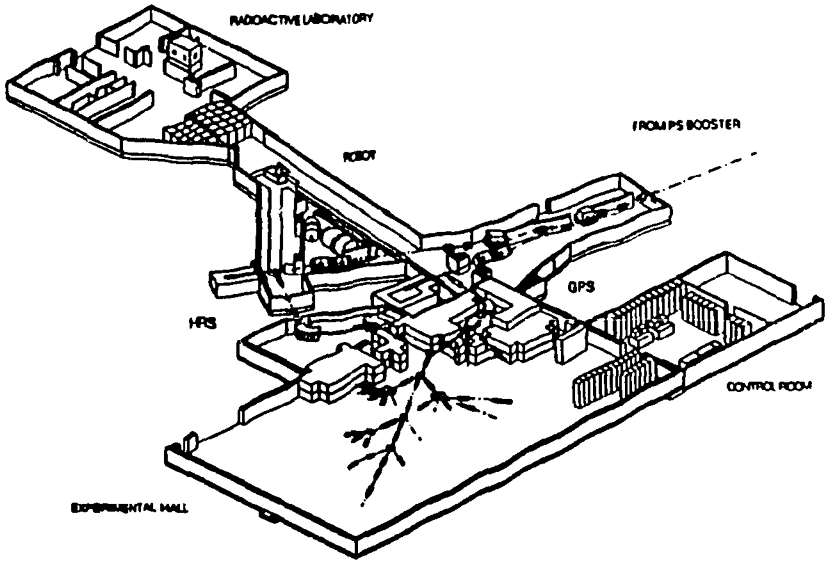

Fig. 6: The new ISOLDE facility

protons of 30 MeV as the primary accelerator, and the K=110 MeV variable energy cyclotron CYCLONE as post-accelerator. RIB's of ^{6}He, ^{11}C, ^{13}N, ^{19}Ne and ^{35}Ar have as yet been accelerated. The ARENAS[3] project , that is funded, foresees the construction of a new cyclotron with a high transmission (25%), that will allow to cover the energy range of strong astrophysical interest between 0.2 and 0.8 MeV/u for $(A/q)_{min}$ = 13 and $(A/q)_{max}$ = 6.5, respectively. With the new cyclotron in operation both CYCLONE 30 and CYCLONE can be used as primary accelerators. Fig. 5 shows a schematic drawing of the ARENAS facility.

CERN-ISOLDE [20,21]. The present ISOLDE facility uses 1 GeV protons from the CERN PS-Booster Synchrotron as the primary beam (max. average current 2.1 μA). ISOLDE can look back to 25 years of highly successful research with low-energy RIB's and it is probably the most experienced laboratory in the production of radioactive ions. The design of the post-accelarator for ISOLDE is still under consideration. Currently a RFQ plus superconducting LINAC with intermediate stripping is being favoured. The accelerator should accept q = 1^+ ions and have a maximum energy of E/A = 5 MeV for A$\approx$80, the highest mass that can be accelerated. The choice of the LINAC as post-accelerator will allow to make use of the whole range of ion sources available at ISOLDE. Transmission drops from 30% for the lightest ions to 3% for the heaviest. Realisation of this project will strongly depend on the support in R&D and infrastructure CERN is able to provide. The lay-out of the ew ISOLDE facility

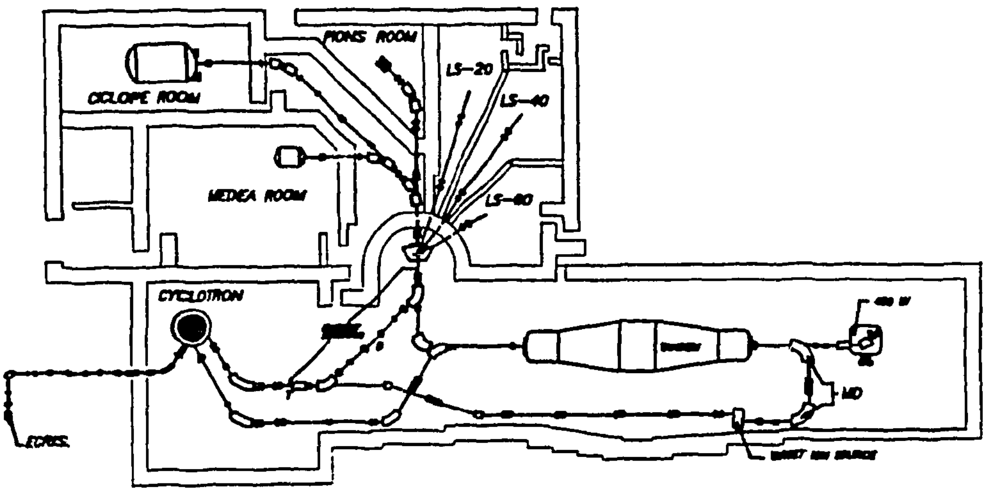

Fig. 7: The proposed EXCYT facility in Catania

is given in fig. 6.

EXCYT-Catania [19]. This facility will make use of the Catania k=800 MeV superconducting cyclotron, which is under construction, as the primary accelerator, and of the 15 MV tandem as post-accelerator (fig. 7]. This project is very similar to the Oak Ridge scheme [22]. The goal is to be able to extract up to 1 pμA of partially stripped ions from the cyclotron. The production target and ion source will be on a 300 kV platform that is the injector into the tandem. Beams with energies above the Coulomb barrier will be restricted to A$\leq$40. The use of the tandem as post-accelerator will assure the highest quality beams. Funds for this project have been set aside but not yet allocated.

GANIL-PLUS, Caen [5,23]. The present GANIL accelerator complex will deliver the primary beams by accelerating heavy ions to a maximum energy of 95 MeV/u for q/A = 0.5. Maximum beam currents of 10 pμA are aimed for. Both projectile and target fragmentation can be used to produce the radioactive nuclei. As the post-accelerator a K = 260 MeV compact cyclotron is foreseen with an energy range from E/A=2.7 MeV to 29 MeV for q/A = 0.1 and 0.5, respectively. (The most recent numbers are from 2 to 25 MeV/u). The post-acceleration relies on the availability of multiply charged ions to be injected into the cyclotron. The transmission through the cyclotron will be $\geq$40%. If funded in 1994, the aim is to be able to perform first experiments in 1997. The a part of the present GANIL facility together with the

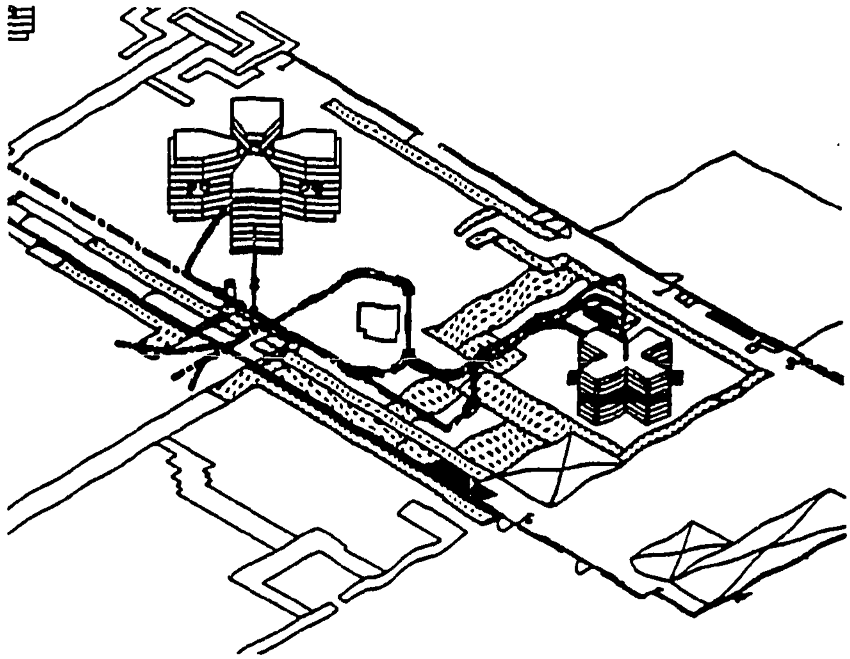

Fig. 8: The GANIL facility with the new cyclotron shown on the right.

proposed cyclotron is shown in fig. 8.

PIAFE, Grenoble [24].The activity will be produced via the fissioning of a ^{235}U target placed close to the core of the ILL reactor. Depending on the element, fission products will be ionized ($q=1^+$) in either an integrated target, thermionic/plasma source [26] or in an ECR source outside of the reactor shielding. After mass analysis the activity will be transported in a transfer line over 400m to the SARA accelerator complex consisting of a compact K=88 MeV injector cyclotron and a K = 160 MeV separated sector cyclotron. Before injection multiply charged ions have to be formed in an ECR source into which the 1^+ ions are fed. The overall transmission from the first ion source to the target is estimated to be 0.5% including all effects. The aim is to produce neutron rich nuclei with masses between 75 and 150 and with energies E/A between 2 and 10 MeV. The realisation of this ambitious project will still require considerable R&D that is actively being pursued in an international collaboration. A schematic diagram of the proposed PIAFE facility is shown in fig. 9.

7. Comparison of the Different Facilities

Starting with the production yields established by the working group chaired by H. Ravn (see sect.2) "beams on target" were calculated, taking into account the intensities of the primary beams, the target thicknesses, conversion to multiply charged ions

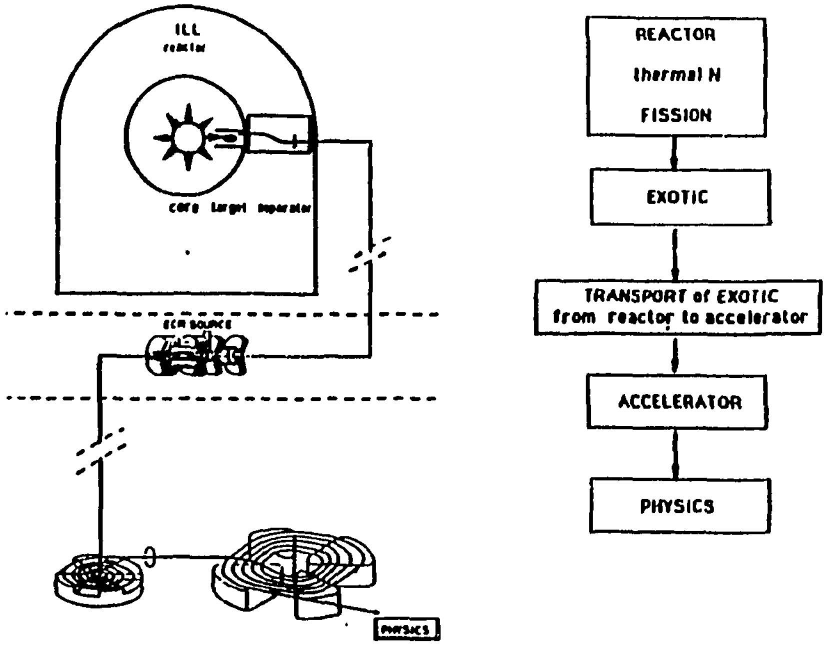

Fig. 9: Schematic diagram of the proposed PIAFE facility.

(in the case of cyclotrons) and the overall transmission through the post-accelerators. The predicted intensities [5] of the radioactive beams are listed in Table 1 for the proposed European facilities. The mass ranges and maximum energies of these facilities are shown in fig. 10. To arrive at these energies the most probable charge states (in particle currents) were taken, and moreover A and Z were chosen along the valley of stability. For cyclotrons as post-accelerators the maximum energies obviously strongly depend on the assumed q/A ratios.

8. Testbed Facilities for High Current Targets

In addition to the proposed facilities there are experiments planned for testing target/ion source arrangements capable of withstanding currents one to two orders of magnitude larger than those currently employed, which are available at meson factories and neutron spallation sources. At the Rutherford-Appleton Laboratory such a testbed facility [21] is going to be installed at the ISIS facility, which is a spallation neutron source centered around an 800 MeV proton synchrotron with a maximum beam current of 200 μA. At the Paul Scherrer Institute there is a 590 MeV proton machine that is presently being upgraded to a maximum current of 1.5 mA. The development and testing of a thin target has been proposed at PSI [27], which in the initial phase is to work with a current of 20μA. Such a target is expected to

Isotope	ARENAS	CATANIA	CERN	GANIL	PIAFE
^{11}Li		$2 \cdot 10^3$	$1 \cdot 10^4$	$2 \cdot 10^4$	
^{13}N	$7 \cdot 10^{10}$		$4 \cdot 10^9$	$6 \cdot 10^9$	
^{15}O	$2 \cdot 10^{10}$	$5 \cdot 10^8$	$2 \cdot 10^9$	$3 \cdot 10^9$	
^{17}F		$1 \cdot 10^9$	$1 \cdot 10^9$	$1 \cdot 10^9$	
^{19}Ne	$3 \cdot 10^{10}$		$1 \cdot 10^{10}$	$2 \cdot 10^9$	
^{20}Na		$9 \cdot 10^6$	$4 \cdot 10^8$	$1 \cdot 10^8$	
^{34}Ar	$3 \cdot 10^9$		$4 \cdot 10^7$	$1 \cdot 10^8$	
^{78}Zn			$7 \cdot 10^4$	$1 \cdot 10^5$	$1 \cdot 10^3$
^{73}Se		$3 \cdot 10^8$	$5 \cdot 10^8$	$2 \cdot 10^8$	
^{91}Kr	$5 \cdot 10^7$			$9 \cdot 10^7$	$8 \cdot 10^9$
^{105}Cd				$1 \cdot 10^5$	
^{132}Sn				$3 \cdot 10^5$	$1 \cdot 10^6$
^{144}Xe				$5 \cdot 10^4$	$1 \cdot 10^7$

Table 1: Expected yields of RIB for selected isotopes for the different, proposed European facilities

deliver reaction products independent of their chemical properties.

9. Conclusions of the Nupecc Study Group

In the Study Group's view the proposed facilities must be seen as first generation facilities both in their expected currents of radioactive beams and in the range of beams they can produce and accelerate. They are largely complementary in their production methods, mass ranges and energies.

For a true second generation facility on a European level with beam currents at least two orders of magnitude larger, complete coverage of the mass range and energies up to the Fermi energy, much R&D is still required. In particular the picture of a "turn key" facility producing any desired radioactive beam on request seems overoptimistic at this moment. Moreover, first experiments with radioactive beams have shown these to be very time consuming and far from routine.

In view of the foregoing, the Study Group has come to the conclusion that a second generation facility on a European level would seem premature at this moment. Instead it has recommended to go ahead with first generation facilities on one hand and on the other to start a vigorous R&D program towards a true second generation facility. This should build on the experience gained with the first generation facilities, and an R&D and scientific network between the different laboratories working in the field should be established. The testbed facility at RAL and the proposed thin target studies at PSI are first and promising steps towards a second generation facility.

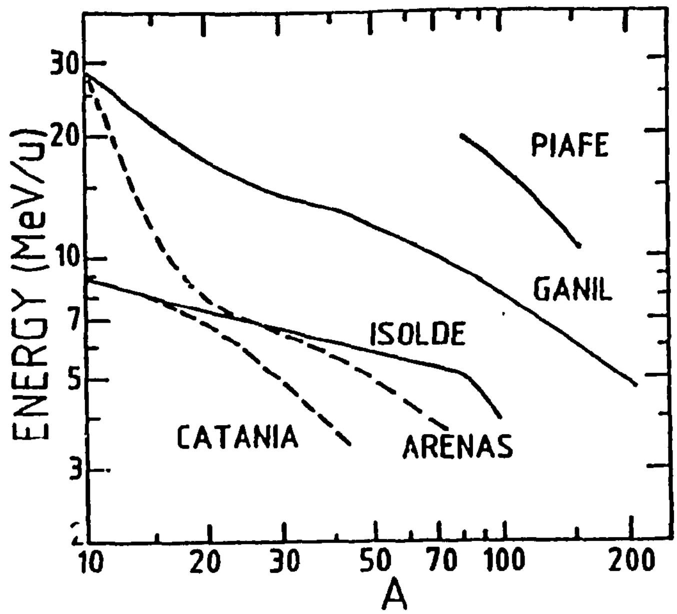

Fig. 10: Comparison of the different proposed European ISOL-type facilities.

10. Outlook

An overview of the planned European RIB facilites based on the two-accelerator method has been given. One is under construction and others are close to being funded. With these new and challenging experiments will become possible which will allow us to probe into the structure of nuclei far from stability which are unaccessible with present beams.

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