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Status of the present radioactive beam facilities and perspectives for second generation installations

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Abstract. Radioactive nuclear beams offer very new opportunities in the domain of nuclear physics for the investigation of the isospin degree of freedom very far away from the β-stability line. The present situation with respect to the first generation Radioactive Beam Facilities (RIB) will be described. Intensity limitations of such facilities have led to the development of several projects all aiming at the increase by several orders of magnitude the RIB intensities. Innovative solutions are being explored and very ambitious projects are now discussed in Japan, USA and Europe. The main trends and goals of these projects will be reviewed.

INTRODUCTION

The understanding of the structure of nuclei and related properties of nuclear matter requires exploring extreme states of nuclear matter, especially along the isospin degree of freedom. The later is connected with the production and detailed studies of the properties of exotic nuclei far beyond the β-stability line and the present proceedings indeed stress the very intense undergoing activity in this domain.

One of the main tools for such nuclear structure studies, which will improve significantly our understanding of nuclear matter, is the development of dedicated radioactive ion beam (RIB) facilities. With such facilities, one is willing to focus on a number of fundamental questions: What is the limit for the existence of nuclei? What is the behavior of nuclear matter with respect to the strong interaction near the limits of stability? The structure of exotic nuclei may contradict existing standard nuclear models. How to understand this structure far from the β-stability line? What can we learn in connection with the nucleosynthesis problem? An overview of the main scientific directions as well as the various possible solutions can be found in several reports. The reader may refer for instance to the NuPECC report (1) or the OECD Megascience Forum on Nuclear physics (2).

This paper intends to present the current status of the first generation Radioactive Beam Facilities (RIB), the detector developments as well as the undergoing R&D for developing innovative solutions for future second generation RIB facilities. Giving the large number of existing or planned facilities, it is excluded to give an exhaustive

overview of the present situation. The reader may also refer to ref. (3)(4)(5) for details on the physics as well as on the facilities. Special emphasis will be given here to the developments in Europe and to the NuPECC initiatives.

PRODUCTION TECHNIQUES: ISOL AND IN-FLIGHT METHODS; EXISTING FACILITIES

Two methods are heavily used for the production of radioactive ion beams, which are quite complementary, the ISOL and the In-Flight techniques.

The ISOL method (Isotopic Separation On-Line) has been extensively used especially in Europe, the most well known facility being ISOLDE at CERN (6). With such a method, the radioactive ions are produced in a thick target where the primary beam (light charged particles or heavy ions) as well as usually the reaction products are stopped. The radioactive species are then extracted, ionized and the needed mass is obtained trough an electromagnetic separation before to be possibly post-accelerated in a dedicated accelerator. The advantage of the ISOL method is that various drivers can be used (light particles as well as heavy ions) and the use of a post accelerator allows to deliver low energy RIB of high optical qualities as good as with stable beams. On the other hand, selective ion sources should be used and the access to very short lived species (below several msec) is somewhat limited to the time release from the production target except maybe with the IGISOL method used at Jyväskylä.

The main existing facilities of this type without post-acceleration are ISOLDE (6), IGISOL (7) and TISOL at TRIUMF (8). Facilities using a post accelerator are Louvain-La-Neuve (LLN) and HRIBF at Oak Ridge. At LLN, the pioneer post accelerated RIB facility (9), the driver is a high intensity (170μA) 30 MeV proton machine. RIB are produced by transfer reactions and post accelerated in a cyclotron up to a few MeV/u. Light beams as ^{13}N are produced with good intensities (10^5-10^7 pps). A new cyclotron, dedicated to astrophysics is presently under commissioning.

In-flight facilities rely on the use of medium and high-energy heavy-ion driver accelerators. The RIB are essentially produced in peripheral collisions by projectile fragmentation, transfer reactions and even projectile-fission. These products are very forward focused and the use of an on-line fragment separator as LISEIII (10) at GANIL allows to get a purified beam. The production of in-flight RIB gives easily access to very short periods and the acceptance is quite high due to the forward focusing of the products. Giving the high energy, those products can be easily identified. However, the optical quality might be limited and it is difficult to get access to low energies (E<30 MeV/u), except for some specific applications using a storage ring as in GSI.

The main operating facilities (all coupled with performing fragment separators) are GANIL (SISSI and LISE), MSU (A1200), RIKEN (RIPS), Dubna (Acculina and Combas) Lanzhou (RIBLL) at medium energies and GSI (FRS) at high energy.

FIRST GENERATION FACILITIES: FACILITY UNDER CONSTRUCTION, UPGRADES AND PROJECTS

Several projects of post-accelerated RIB based on the ISOL concept are presently under construction.

SPIRAL at GANIL (11) will be using the present GANIL cyclotrons as a driver. A vigorous R&D program (SIRA) on the production and ionization of the radioactive species produced by projectile fragmentation has been pursued since several years. This has led to the concept of a universal specially designed carbon target and to the development of performing ECR sources. Highly charged RIB will be injected in a new cyclotron CIME to be post-accelerated in the energy range 1.7-25 A.MeV. Beam tests with stable beams have been successfully achieved. For example, typical expected beam intensities for Ar isotopes are ranging from 2.10^8 pps for ^{35}Ar, 10^5 for ^{33}Ar and 10^3 for ^{32}Ar. The facility is ready to operate and waiting for authorization from the safety authorities.At the same time, the primary beam intensities have been increased up to 10^{13} pps and will finally reach a beam power close to 6KW.

At the same time, very performing experimental equipments are under construction trough large European collaborations, EXOGAM (12), a large γ-array detector and a large acceptance spectrometer VAMOS (13).

Prospects for a second phase of SPIRAL are underway. This second phase could be based on the use of a deuteron beam followed by a Be converter for the production of a high neutron flux which then induces fission in a thick U target. Intense fission fragments beams are expected to be produced (for instance 10^9 pps ^{91}Kr and 2.10^5 pps ^{78}Ni for a 6KW d beam at 200 MeV)[14]. A European Union RTD program[15] has been settled to experimentally test this concept of a deuteron based system and the first results are very promising (16)(GANIL, IPN Orsay, Jyväskylä, Groningen, Louvain-La-Neuve). This idea of using fast neutrons was first suggested by Argonne (17) and similar projects based on the use of thermal neutrons from reactors have been planned (the former PIAFE project and now the MAFF project near the FRM-II reactor at Munich (18).

Another facility is under construction at CERN. This is the REX-ISOLDE project (19) which will use the RIB produced by the existing ISOLDE facility. These RIB will be then accumulated, cooled and bunched using a Penning trap, ionized with an EBIS source and post-accelerated up to 2 A.MeV. The installation should be completed by the middle of 2000. At the same time, a new high efficiency γ-array (MINIBALL) will be operating.

Other ISOL projects presently under construction are ISAC (8) at TRIUMF (500 MeV p driver up 100μA and a post-accelerator up to 1.5 A.MeV) and EXCYT at LNS Catania (20) (heavy-ion superconducting cyclotron driver and a tandem post-accelerator).

Several other projects are being discussed but not founded yet. Among them, one may mention:

- The two projects at Argonne and Oak Ridge (see next section on second generation facilities)

- The Dubna project (possible use of two different drivers, heavy-ions for light RIB production and 25 MeV electrons for the production (by photofission) of intense fission fragments beams (21).
- SIRIUS at Rutherford Laboratory (22), a 800 MeV p driver up to 100μa followed by a linear post-accelerator up to 10 A.MeV. For example, intensities for ^{132}Sn should be close to a few 10^8 pps.
- Legnaro (high intensity 200 MeV d driver and a linear post-accelerator) (23).
- E-arena project at KEK (24) a 3GeV p driver up to 10 μA and a linac post-accelerator up o 6.5 A.MeV; expected intensities reach 10^9 at ±5 units from the stability).

As far as the In-Flight facilities are concerned, two main installations are being upgraded. The NSCL K1200 superconducting cyclotron will be coupled to the K500 cyclotron. Primary beam intensities up to 1pμA will be available with energies of 200 A.MeV for light beams and 100 A.MeV for Uranium. Gains of several orders of magnitude in the RIB intensities are expected to be achieved (25). At the same time, the A1200 fragment separator will be replaced by an improved system, the A1900 beam analysis system with a higher bending power more adapted for very n-rich beams. The project is scheduled to be completed in 2001.
The GSI complex will be also significantly improved; the UNILAC injector will be reconstructed and the SIS synchrotron will be filled up to its incoherent space charge limit (26). Intensities as high as 10^{10}pps for ^{238}U will then be achieved. This upgrade is expected to be operational in 2000.

TOWARDS SECOND GENERATION FACILITIES

If one is willing to ultimately answer the question about the nuclear stability and the origin of the elements, an exploration of the nuclear landscape as close as possible from the neutron and proton drip lines is required. In that context, the main limitation of the first generation radioactive beam facilities is the beam luminosity. As mentioned by the OECD Megascience report (2), there is a worldwide interest in the construction of advanced radioactive beam facilities. True second-generation facilities are at least aiming at a 10^3 intensity increase with respect to the present facilities (or those under construction), a necessary condition for a real breakthrough with respect to the present facilities. This is a real challenge for the next millennium.

Two projects in United States and Japan fulfill this condition (the situation in Europe will be discussed later).

The most advanced project is the project of a Radioactive Beam Factory at RIKEN (27). The new accelerator system will consist, in addition to the existing ring cyclotron, of a 4 sector ring cyclotron (IRC) and a 6 sector superconducting cyclotron (SRC) in order to boost the energy into the range 150-400 A.MeV up to uranium and reach primary beam intensities as high as 1particle μA (corresponding to a beam power of 100KW). A new beam separator (RIPS II) will be constructed. With such a system, nuclei up to N/Z=3 should be available. This first phase of the project is

accepted and the IRC cyclotron is under construction. First beam from the SRC cyclotron is scheduled for 2003. The second phase of the project will consist of the MUSES complex (a booster synchrotron up to 1.4 A.GeV, an accumulator cooler, double storage ring for electron-RIB collisions). 2.5 GeV electrons will be provided by a LINAC. This very ambitious project is aiming at the production of more than 2000 nuclei with at least 10 pps. Preliminary schedule intends to achieve the whole project by 2006.

In United States, the high priority has been given by the NSAC to the definition of an advanced RIB facility. The main physics opportunities have been defined in the so-called Columbus white paper (28) and the present stage of the reflection with respect to a new project is the following (29): this is a projectile fragmentation based ISOL concept with a multiple heavy ion beam driver. The driver would be a 200 A.MeV heavy ion linear accelerator with an intensity of 1 particle μA (50-100KW-beam power). The radioactive products created by the in-flight method are then slowed down after passing through a fragment separator and stopped in a gas cell acting as an ion guide where they come to rest as 1^+ ions. The extraction is then possible in a few msec with a high efficiency independent of the chemical properties of the radioactive species. A linear post-accelerator is then boosting the ions up to a maximum energy of 15 A.MeV. This project is obviously at a very preliminary stage and may be modified in the following months.

What is the present situation en Europe? NuPECC has clearly considered that the existence of performing RIB facilities was a key-tool for the future of Nuclear Physics. A study group (first chaired by R.Siemssen and now by B.Jonson) has been settled in order to investigate the main options for two types of second generation RIB facilities in Europe (In-Flight and ISOL).

As far as the ISOL type is concerned, a large European Collaboration, supported by the EU 5th Research program, has been settled which intends to define a preliminary design study of the next generation European ISOL RIB facility (EURISOL collaboration: GANIL, Chalmers Univ., K.U.leuven, GSI, INFN, IPN Orsay, ISOLDE, Jyväskylä, RAL, Saclay). The first step is to investigate scientific and technical challenges, identify the required R&D, establish a cost estimate and look at possible synergies with other major European projects. This period should be followed by a vigorous R&D program on key technologies before to reach the point where the decision to build such a European Facility can be made.

Possible upgrade towards second generation facilities is under discussion. At GSI, one possibility has been studied implying the construction of a high intensity, high-energy synchrotron (with BR=50Tm) with an accumulator ring (with BR=18Tm). Intensities up to 10^{12} pps for 1A.GeV Uranium could be obtained. This facility could be also well suited for plasma physics studies.

At GANIL, it is presently thought to propose to add a new high intensity proton driver taking advantage of the existing R&D IFHI project of a linear proton accelerator for different purposes, in particular the developments of hybrid reactors for nuclear waste incineration. Discussions about the use of a 100mA, 30 MeV proton machine are underway which could at the same time favor crossdisciplinary developments.

All these ambitious projects require strong needs for technological developments. This concerns accelerator R&D, high power target, high intensity sources, highly efficient beam handling including cooling, traps, fragment separator, beam storage and instrumentation.

Many ongoing R&D programs have started in Europe, which should be supported and may be more coordinated. The OECD recommendations should be followed: it would be very positive to decide a world initiative of the funding agencies to exchange information and define opportunities and partnership for international cooperation.

There is a need in Europe for the next millennium to have two performing second-generation facilities based on ISOL and In-Flight methods. A positive decision for such very ambitious projects will be achieved only providing there is an agreement between the main laboratories and the funding agencies.

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