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Radioactive beam facilities: European perspectives

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Abstract. During the last ten years, the cooperation in Nuclear Physics between the different European countries has significantly increased, in particular through extensive discussions initiated by NuPECC, the Nuclear Physics European Collaboration Committee. In this context, perspectives in physics with radioactive beams have been reviewed and a high priority has been given to the developments of performing facilities in Europe including both in-flight and ISOL facilities. In this presentation, the main challenges are recalled and the various existing national and transnational projects are reviewed as well as the accompanying research and development programs. A special attention is given to the EURISOL project, a European program aiming at a preliminary design study of a second-generation European ISOL radioactive beam facility.

PACS. 29.17.+w Electrostatic, collective, and linear accelerators – 29.25.Rm Sources of radioactive nuclei

1 Introduction

After 100 years, there are still quite fundamental questions to answer in nuclear physics, which, in fact, have consequences well beyond our field. A careful and detailed study of elementary constituents of matter and their interactions is needed to better understand how the nucleus is built. The understanding of the structure of the nucleus is of great importance not only for our field but such finite systems are an extremely rich laboratory for studying the general concept of complex systems. Finally laboratory experiments may improve a lot the comprehension of the universe, namely the formation of the elements since the big bang.

In this general context, rare-isotope (radioactive, exotic...) beam (RIB) facilities are essential tools to progress towards the understanding of the properties of nuclear matter. It is not the aim of this presentation to detail the main scientific directions with rare-isotope beams. Such an overview can be found in several reports and the reader may refer for instance to the NuPECC reports [1, 2] or the OECD Megascience Forum on Nuclear Physics [3]. Europe has been for years at the forefront of such research with major facilities such as GANIL, GSI and ISOLDE and recent initiatives on the definition of second-generation facilities, both in-flight and ISOL types, have been taken by NuPECC which will be discussed later in this paper.

This paper intends to briefly recall the current status of first-generation facilities. Perspectives for the middle term and associated new projects will be described. Finally the long-term strategy in Europe for second-generation facilities will be discussed. This short paper is not aiming at an exhaustive overview of the present situation. The scientific case is intensively discussed by the other contributors to this conference and as far as the projects are concerned, additional information can be found elsewhere [4,5].

2 The present situation: first-generation facilities

Several facilities are operational or at a commissioning phase in various European laboratories.

In-flight facilities rely on the use of medium- or high-energy heavy-ion driver accelerators. They give an easy access to very short-lived isotopes with a high acceptance and the main operating facilities of this type are GANIL (with the SISSI device and the LISE spectrometer), GSI (with the FRS recoil spectrometer) and the JINR-Flerov laboratory (with Acculina and Combas systems). Low-energy RIB ($E < 30$ MeV/u) are normally excluded.

ISOLDE at CERN has used ISOL type method for many years without any post-acceleration of the produced isotopes. The pioneer facility using a post-accelerator is located at Louvain-La-Neuve. It uses a 30 MeV proton driver (170 μA) and the isotopes (close to the β-stability line) are produced mainly by transfer reactions. They are then post-accelerated using two types of cyclotrons (CYCLONE 44 and 110) which may provide beams either at very low energy for astrophysical purposes (0.2–0.8 MeV/u) or on the higher energy range (1–5 MeV/u) [6].

REX-ISOLDE will use the RIB produced by the existing ISOLDE facility which will be then accumulated,

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cooled and bunched using a Penning trap, ionized with an EBIS source and post-accelerated up to 2 MeV/u using a linear accelerator [7]. The facility should be operational by mid-2001.

SPIRAL at GANIL [8] is based on the use of the existing heavy-ion cyclotrons as a driver. Primary heavy-ion beams with high intensities, up to 10^{13} pps and 100 MeV/u are produced. In the first phase, RIB are produced by fragmentation of the primary heavy-ion beams stopped in a thick C target. After ionization in a compact ECR source, the RIB will be post-accelerated in a new cyclotron CIME in the energy range 1.7–25 MeV/u. The facility is now ready to operate (tests of the target-ion source system and of the CIME cyclotron have been successfully achieved. The public hearing procedure has been favorable and one is now waiting for the final authorizations from the safety authority. The facility should be operational before summer 2001. At the same time, two very performing devices are being constructed through European collaborations which will be ready for experiments during 2001 (EXOGAM [9], a large γ-array detector, and VAMOS [10], a large acceptance spectrometer).

3 Reflections for the middle-term perspectives: new projects

In the meantime reflections are underway to imagine real second-generation facilities for the next decade (2010 and beyond) and several projects are presently under construction or being discussed for the middle term, aiming at an operation around 2005-2006.

In the U.K. the SIRIUS project at Rutherford Appleton laboratory intends to use the ISIS accelerator (800 MeV p, 100 μA) which could be coupled to an RFQ and a LINAC to post-accelerate the rare beams up to 10 MeV/u. Maximum intensities for RIB close to the stability line would be close to 10^{11} pps, while exotic beam intensities like ^{132}Sn will be 10^8 pps. Another project is presently under discussion in Daresbury.

The SPIRAL Phase-II project is now in its phase of detailed elaboration. A project group has been settled which has in charge a preliminary detailed study of a facility for the production and acceleration of n-rich fission fragments. Two production methods are in competition. The first is based on the use of a primary deuteron beam (80 MeV, 500 μA) followed by a Be converter for the production of a high neutron flux inducing fission in a thick uranium target [11]. A European R&D program (RTD SPIRAL Phase-II) has been testing this concept during the last two years and promising results have been obtained in particular with the PARRNE system developed at Orsay.

The alternative to deuteron beams is the use of a LINAC electron accelerator (50 MeV, 500 μA). The principle is in this case the bremsstrahlung-induced fission of uranium [12]. Photofission mostly occurs in the Giant Dipole Resonance region and therefore leads to a very small angular spread ($\alpha < 3°$) and consequently to the use of a very small-size U target. Diffusion times could then be largely reduced. The fission flux could be as high as 10^{13} fissions/s and the production of ^{132}Sn higher than 10^{11} pps. The main difference between the two methods is the fission distribution (symmetric in the case of fast deuterons, asymmetric with the electron solution).

The relative merits of the two methods are being investigated and the final choice will be made by mid-2001. Similar projects based on the production of fission fragments are planned. The SPES project in Legnaro is based on the use of a high-power 200 MeV deuteron primary beam (100 kW) coupled to a linear superconducting accelerator. The MAAF project [13] is based on the use of thermal neutrons from the FRM-II Münich reactor and a project of an electron driver is envisaged at Dubna.

4 Long-term strategy in Europe for second-generation facilities

Quite decisive moments for the future of our field are coming. These have led NuPECC to initiate a large reflection and establish a working group on the long-term future of the physics with rare-isotope beams and investigate the main options for two types of second-generation RIB facilities. The conclusions of the study group have been recently published [2].The main conclusion is identical to the one of the OECD Megascience Forum on Nuclear Physics held in 1999 and strongly recommends the construction of one second-generation facility of each type (in-flight and ISOL). It is clearly considered by NuPECC that the existence of such performing facilities is a key-tool for the future of nuclear physics. The main improvement compared to present facilities is an increase of the RIB intensities by at least three or four orders of magnitude. It should be specified that similar discussions have been held in Japan and USA, both countries having presently quite ambitious projects (Radioactive Beam factory at RIKEN [14] and RIA in the United States [15]).

Two projects are being settled in Europe. The first one, located at GSI is dealing with an upgrade of the present in-flight facility [2,16]. The choice has been made for the driver of a new synchrotron which seems to be appropriate both for operation cycles of the storage ring and for use in slow extraction modes for studies with a new fragment separator. The new high-intensity synchrotron (200Tm) will consist of fast-cycling superconducting magnets and will provide for RIB production 10^{12} $^{238}U^{7+}$/s beam at 1 GeV/u. The fragmentation of this U beam will provide intense RIB beams over a broad mass spectrum. The project also includes the possibility of electron-ion collider for nuclear structure studies. An European R&D (R3B) is associated with this project intending to design a next-generation set-up for reaction studies with relativistic radioactive beams including a secondary liquid target (H, D, He) and a new spectrometer. The formal decision concerning this GSI upgrade has not been made yet. Such a facility, which will allow the acceleration of any beam (proton to uranium) up to 60 GeV protons and 33 GeV/u uranium, will be also used for nuclear matter studies at very high baryon densities, study of QCD structure of baryons and origin of the nuclear force and also plasma physics at extreme pressures and temperatures.

The second project is focusing on an ISOL facility. Under the initiative of NuPECC, a European program, supported by the 5th Research Program, has been launched, EURISOL [17], aiming at a preliminary design study of such a second-generation facility. The following laboratories or institutions belong to the collaboration: GANIL (coordinating laboratory), Chalmers University, K.U. Leuven, GSI, INFN, IPN Orsay, ISOLDE, Jyväskylä, RAL, and Saclay. The main objectives for the period 2001-2002 is to investigate scientific and technical challenges, identify the R&D required before the next step of a complete design, establish a cost estimate and running costs. Possible synergies with existing European installations and major European projects in other fields will also be carefully investigated.

As mentioned before, such a facility is aiming at a 10^4 increase of the intensity with respect to existing facilities. The main characteristics of the project, which are subject to changes as discussions continue, are the following:

The best option for a driver seems to be a one-GeV proton machine, most probably a superconducting linear accelerator. Intensities may range from 100 μA (if the proton beam is directly impinging the production target, in particular for the production of p-rich species) up to a few mA, that is several MW, when running in an indirect process mode (neutron-induced fission). Development of such high-intensity drivers may strongly benefit from existing synergies between various fields requiring also such accelerators (muon colliders and neutrino factories, condensed matter studies with neutron probe, nuclear waste transmutation and ADS system or even irradiation tools). Let us also mention the existing R&D program in France called IPHI between CEA and CNRS which deals with the construction of a 5 MeV (in a first step) proton injector for such a machine.

Different options are being studied for the target-ion source system (investigation of various types of targets, laser ion sources, ion guide ISOL systems...). A charge breeder system will be required aiming to study a universal system to convert 1^+ into N^+ ions, in order to significantly increase the efficiency of the post-acceleration phase. A large European collaboration has been settled for this specific and crucial point. As far as the RIB are concerned, the chosen solution should fulfill several conditions: deliver very low energy beams as well as accelerated beams up to 100 MeV/u with an easy energy tuning at low energies. The best solutions could be the coupling of a LINAC (for low energies) to a cyclotron (for the high-energy side). The advantage of having 100 MeV/u rare-isotope beams lies in the possibility to induce in-flight fragmentation of n-rich species. EPAX [18] calculations seem to indicate that a fragmentation reaction of ^{132}Sn could be extremely promising, indicating the possible production of more than 100 new very n-rich nuclides.

It is clear that the concept of such a new performing machine requires strong needs for technological developments in a coordinated way. They are summarized below:

- Accelerator R&D (high-intensity driver).
- High-power target and high intensity.
- Investigation of the production modes and cross-sections for exotic nuclei.
- Development of an efficient charge breeder system and of new sources for highly charged ions.
- Highly efficient handling of RIB including cooling, traps, separator…
- Definition of multi-beam devices.
- Conception of high-efficiency detectors.
- Careful study of radioactivity and safety problems related to the use of MW beams.

It is intended to have a decision taken to build such a European facility around 2005 after an intense R&D period. The final objective is to have the facility operational by 2010.

5 Conclusion

Europe has presently very ambitious projects for developing second-generation rare-isotope beam facilities. There is a need for one facility of each type, in-flight and ISOL types. The EURISOL project is a complementary facility to the new in-flight facility proposed at GSI. The future site of EURISOL remains to be decided but there are only a few potential possibilities. Many coordinated R&D programs have already started in Europe in addition to EURISOL and R3B which are dealing with specific areas related to key-technological or detector developements. The major ones are the charge breeding project, the innovative ECR ion-source project, the EXOTRAP project (different manipulations of radioactive beams) and the EXOTAG project (R&D related to the development of efficient and sensitive detectors for exotic nuclei).

As a tremendous effort is probably needed to overcome major challenging technological problems during the next decade, a world initiative to exchange information and define opportunities and partnerships for international cooperation is strongly needed.

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