AN OVERVIEW OF RADIOACTIVE BEAM FACILITIES

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Abstract

Radioactive beams have become an extraordinary tool for modern nuclear physics. The present overview aims at a short, synthetic description of the basic technical aspects exemplified by the facilities which are either in operation, under construction or planned. From this, the main directions for future developments are concluded.

1 INTRODUCTION

Today, a century after the discovery of the phenomenon of radioactivity, about 3000 (particle-bound) combinations of protons and neutrons have been investigated, some in a very detailed way, whereas for others only their existence has been established. According to today's theoretical predictions, about as much nuclei await discovery and study, in particular very neutron-rich species (part of the nuclear landscape nowadays often referred to as "terra incognita"). The aim is to appreciate the full dimension of the nuclear many-body problem with the ultimate goal of a unified theoretical description. This vision is intimately related to a comprehension of nucleosynthesis in astrophysical sites and thus of the origin of the elements we and our world are made of. This is the fascinating physics which is made at radioactive beam facilities of which the technical aspects are discussed in the following, keeping in mind that it the performance of the tools which conditions the advance of physics. The progress of both, experiment and theory, have been reviewed at the recent INPC 98 by Hofmann [1], Langanke [2], Nazarewicz [3], Tanihata [4] and myself [5].

2 MAKING RADIOACTIVE BEAMS AND ASSOCIATED EXPERIMENTS

2.1 ISOL

The historically first developed method for making radioactive beams is called ISOL (Isotopic Separation On-Line). In this technique, the unstable nuclei are produced by charged-particle beams or neutrons which bombard a target that in general is sufficiently thick (else a catcher is used) to stop the recoiling reaction products. The latter are then transported (diffusion, jet transport...) into an ion source (surface ionization, plasma, laser...) providing element separation through chemical selection. After extraction (of the desired charge-state), the wanted mass is then obtained through electromagnetic separation. Thus the ISOL technique provides high-quality low-energy (a few tens to a few hundred of keV) beams of radioactive nuclei that are ideally suited for nuclear decay spectroscopy experiments, but also for many solid state physics applications.

Two other uses of ISOL beams are especially noteworthy. Pioneered at CERN's ISOL facility ISOLDE [6], they are presently very extensively used.

First, optical spectroscopy on the ISOL beams allows the study of the hyperfine spectra and isotope shifts, in particular by means of high-resolution laser techniques. This provided already a tremendous wealth of nuclear spins, moments and charge radii, see e.g. [7]. It is further remarkable that laser techniques, with the advent of laser ion sources, have considerably enlarged the scope of ISOL facilities, see, e.g., P. van Duppen [8].

A second example for the direct use of ISOL beams concerns high-precision nuclear mass measurements where two ingenious methods have been developed during the last years. Trap techniques have been pioneered with ISOLTRAP [10], reaching resolving powers in excess of 10^6, whereas MISTRAL [11] allows a very fast measurement, at some what lower resolution, of the cyclotron frequency of the radioactive beams by means of two coherent, high-harmonic radio frequency excitations of an ion orbit inside a magnetic field.

More general technical information on the use of ISOL beams as well as the demanding, but highly promising R&D efforts for the ISOL technique itself, can, e.g., be found in the proceedings of the EMIS conference series [12]. "Classical" ISOL separators can be found at many places in the world, e.g. at CERN, Jyväskylä (Finland), Louvain-la-Neuve (Belgium), Orsay (France), Warsaw (Poland), Oak Ridge (USA), TRIUMF (Canada), CIAE Beijing (China),...see, e.g. [12], and the reviews [14-16].

2.2 In-flight separation

The in-flight separation technique relies on the forward focusing present in peripheral (and certain other) nuclear reactions. The concept of in-flight "fragment-separators" was pioneered with relativistic-energy and intermediate-energy heavy ion-beams at Berkeley, USA [16] and GANIL, France [17], respectively. A high-energy ($E > 30$ MeV/u) heavy-ion beam impinges onto a relatively thin production target. The energy-loss of the wanted reaction products is generally kept below $\Delta E/E<10$ %. Under these conditions the latter, generally called fragments, exhibit a narrow momentum distribution and a substantial part of them may be directly collected by means of the optics ($\delta\Omega$ = a few msr) of a momentum selecting spectrometer. Designing this instrument doubly achromatic provides additional momentum-loss analysis after equipping the intermediate focal plane with a energy degrader. Pioneered with "LISE" (GANIL) [17], this feature introduces atomic number Z selection. Consecutively, other large devices for fragment separation have been constructed and put into operation: "FRS" (GSI, Germany), "A1200" (MSU, USA), "RIPS" (RIKEN, Japan) and "SISSI" (GANIL, France), "COMBAS" and "ACCULINNA" (JINR Dubna, Russia), "RIBLL" (Lanzhou, China) and "SBL" (Chiba, Japan). Brief information of all these instruments and the main references can be found in [13-15].

One has however to note that the optical quality of fragment beams is somewhat limited, in particular while aiming at a high transmission, which means privileging the angular and momentum acceptance of the separator. The situation is best at high energy, where also contamination of incompletely-stripped charge states is minimal, with an upper limit of about 1 GeV/u due to the increasing probability for "destroying" the wanted exotic nucleus by reactions in the various materials it passes (production target, Z-selective degrader, detector systems). Complementary to the ISOL technique, we stress here the following highly attractive features of In-Flight Separation: (i) the short-separation times, in the order of μs, without any dependence on the chemical nature of the transmitted nuclei, (ii) the possibility to inject into a storage ring and (iii) the high energy of the fragment beam that can be used for inducing secondary nuclear reactions.

The first feature has allowed to for synthesis and study of radioactive nuclei completely unknown hitherto. One may mention, in particular, mapping of the border lines of nuclear stability, and studies of regions of closed shell nuclei, see [3-5] and refs. therein. This advance is highlighted by the fact that in the last five years experiments at GANIL and GSI have been able to synthesize the long-awaited-for doubly magic nuclei ^{100}Sn [18,19], ^{78}Ni [20] and ^{48}Ni [21].

Concerning the second property of In-Flight Separation, note the paper by Katayama at this conference which is dedicated to this topic [22]. Here we mention just the highlighting example of experiments recently pioneered at GSI, the only facility in the world where heavy ion beams up to uranium are available with GeV/u energies and where the fragment separator FRS injects secondary exotic beams into the storage ring ESR. Direct mass measurements are made by means of two novel techniques [23]. Schottky spectrometry has been used to determine more than 100 new masses for neutron-deficient heavy nuclei ranging from xenon to polonium with a resolving power of 650 000. Alternately, the ESR can operated as an isochronous time-of-flight spectrometer for uncooled fragments, so that nuclei with lifetimes inferior to cooling times can be investigated (here resolving powers of 150 000 have already been observed)

The possibility to make nuclear reactions with secondary beams has brought a true revolution to the field which started with Tanihata's cross section measurements [24] on light neutron-rich nuclei leading to the discovery of the neutron halo [25]. An impressive number of new reaction-type experiments at the fragmentation facilities are presently under way, see e.g. [4,26-29].

2.2 Post-acceleration of radioactive beams

Up to now, the reaction experiments at the fragment separators have essentially been made down to a minimum energy of, say, 25 MeV/u. Slowing down by further passage of matter excludes to conserve, simultaneously, reasonable optical properties and the beam intensity. Deceleration in a storage cooler-ring is intensity- and time-limited, in particular for short-lived species. A technical solution for low-energy beams, of interest for many nuclear and astrophysical reactions, was developed since the mid-80's at Louvain-la-Neuve, Belgium [30]: Here, the secondary beams from an ISOL system, are injected into a second (cyclotron) accelerator for post-acceleration in the range 0.65-5 MeV/u.

This pioneering development has given rise to several analogue projects, see, e.g. the overviews [13], [14] and [15] containing the main references for the Asian, European and North-American projects respectively.

In the US "RIA" (*Rare Isotope Accelerator*) project [31] also a combination of ISOL and In-flight is foreseen as one of several possible production schemes. Here the in-flight separated projectile fragments would be stopped in a gas catcher feeding the ion-source of a post accelerator.

3 RADIOACTIVE BEAM INTENSITIES

3.1 Efficiency considerations

The intensity **I**, available for an experiment is obviously a prime requirement for any future progress. Often quite inferior to the in-target production rate, it is determined by: $\mathbf{I} = \sigma \times \phi \times N \times \varepsilon_1 \times \varepsilon_2 \times \varepsilon_3 \times \varepsilon_4 \times \varepsilon_5$, which contains the following factors: σ is the cross section of the production reaction, ϕ the primary beam intensity, N the thickness of the production target, ε_1 the efficiency of release from the target and transfer to the ion source, ε_2 the efficiency of this latter, ε_3 the efficiency of the separator, ε_4 the delay transfer efficiency due to radioactive decay losses and ε_5 the efficiency of the post-accelerator. The interdependence of these factors and their best combination is subject to intense debate among the specialists, e.g. [12, 32], but it is clear that maximizing the luminosity **L**, i.e. the product $\mathbf{L} = \phi \times \mathbf{N}$, is definitely the way of future progress.

For the fragment separators ε_3 is in the order of 1% to 80%, $\varepsilon_1 \times \varepsilon_2 \times \varepsilon_4 \times \varepsilon_5 = 1$ ($\varepsilon_1 \approx 1$ due to direct recoil out of the target, $\varepsilon_2=1$ since there is no ion source, $\varepsilon_4 \approx 1$ because of the short flight-time, $\varepsilon_5 = 1$ since there is no post-acceleration). In contrast, for the ISOL method, the total efficiency is extremely case dependant and lies between, say, a few % to 10^{-8} (ε_5 being 5% to 50% depending on the type of post-accelerator. However, at least for not too short-lived species with "benign" release properties, the ISOL technique can overcompensate its often lower efficiency due to its luminosity advantage (see below).

3.2 Luminosity considerations

For the production one uses (essentially charged-particle induced-) fragmentation/spallation, fusion, nucleon transfer, deep-inelastic and fission reactions. The luminosities are highest for proton-induced reactions, because of the high intensities of proton accelerators and the larger possible target thickness. Indeed, they presently reach 10^{13} $b^{-1}s^{-1}$ at ISOLDE or more than 10^{14} $b^{-1}s^{-1}$ at Louvain-la-Neuve whereas the luminosity four to six orders of magnitude lower for typical heavy-ion fragmentation reactions at GANIL or GSI, respectively.

One may note the great potential for substantial improvements at the heavy-ion facilities: GANIL is commissioning the acceleration of 95 MeV/u ions up to a beam power of 6 kW, GSI will have finished during the year 2000 its programme to boost the heavy-ion synchrotron up to its incoherent space-charge limit [33], RIKEN has started the construction of a new high-intensity facility [13, 22], the MSU upgrade will considerably increase the performance of the present facility [34]. In the context of the NuPECC working group, a European fragmentation facility with a luminosity of more than 10^{12} $b^{-1}s^{-1}$ for up to 1 GeV/u uranium primary beams is considered. Presently discussed up-grade plans at GSI [35] meet this requirement while the US RIA proposal [31] is in the same luminosity class but at the lower energy of 400 MeV/u.

A general limitation for RNB facilities, be it ISOL or in-flight, is given by the maximum heat-deposition in the target, due to the energy-loss of the primary charged-particle beam. Extensive R&D is under way at various places (CERN-ISOLDE, Rutherford Appleton Laboratory (RAL), IPN Orsay, GANIL-SPIRAL...) for the design of targets with minimized local thermal overstress [36]. The SIRIUS-facility design study [37] of the RAL relies, e.g. on this R&D.

3.3 Selected R&D topics for future facilities

In contrast to charged particles, neutrons will heat the target only through the energy released by the "useful" nuclear reactions. In particular neutron induced fission is a very promising reaction since the produced, very neutron-rich nuclei either allow a direct access to the "terra incognita" or via secondary reactions, like transfer, fusion and fragmentation, of the post-accelerated beams.

The fission cross sections for thermal neutrons on uranium (^{235}U) are extremely large in the top of the distribution. The success of this production method (for an overview of past experiments see [38]) has been at the origin the PIAFE project [39], now discontinued, and it is the basis for the MAFF project at Munich [40].

Nolen [41] recently proposed the use of fast neutrons on very thick ^{238}U targets where the luminosities may reach more than 10^{15} b^{-1} s^{-1} despite of the smaller fission cross sections and difficulty of efficient release from such targets.

This important R&D issue, i.e. the optimization of $\varepsilon_1 \times \varepsilon_4$ is addressed by the PARRNe program at Orsay where the deuteron beam from the 15 MeV tandem is used to produce neutron fluxes of more than 10^8 s^{-1} with an energy around 10 MeV. The neutrons impinge on a ^{238}U target of the device PARRNe which allows extraction and collection of radioactive noble gases. Promising results have recently been obtained for targets of uranium carbide (containing up to 30 g of uranium) or molten uranium (up to 250 g) [42-45]. In order to investigate the best operational parameters for strong fission-fragment beams at the GANIL/SPIRAL facility based on the PARRNe developments, a European Union RTD Project has been started, with the collaborating laboratories GANIL, Jyväskylä, KVI Groningen, Louvain-la-Neuve and IPN Orsay [46].

Concerning the concomitant development of intense primary beams for the neutron generation, Important R&D efforts are presently done for the development of ultra-high current accelerators. an example are the 100 mA proton injector-accelerators IPHI, presently under construction in France [47, 48]. and LEDA under commissioning in Los Alamos [49]. Another important and most relevant effort is presently made for development of super conducting cavities for the high-energy section of such a multi megawatt class accelerator. Note that there is a certain synergy between the high intensity requirements for exotic beams, hybrid reactors for waste transmutation, spallation sources, neutrino factories and muon-colliders [51]. Such aspects will also be investigated in EURISOL design study (for which EU funding has just been obtained) for a next generation ISOL facility for Europe [52].

Yet another possibility for a fission based radioactive beam facility is the use of a low-energy (25-50 MeV) electron driver beam. The generated bremsstrahlung would induce photo-fission in the uranium targets [53, 54]

All these R&D activities are complemented by and important effort made by several groups for predicting reliably cross-sectios for the various envisaged production reactions. Among recent developments, the complementarity of different methods has been analyzed in calculations by Benlliure et al. [53] and modelling for fast particle induced fission is presently made by Rubchenya [54], Mirea [55] and Ridikas et al.[56].

4 FACILITIES

This concluding section contains a short (and by necessity somewhat superficial) "facility summary". However, most of the radioactive beam facilities and future projects commence to have very nice web-sites. For the interested reader, a good entry may be the EURISOL site, http://www.ganil.fr/eurisol/, from which one the links easily to other facilities and projects. Furthermore, since the borderline between a "major radioactive beam experiment" and a "radioactive beam user facility" is somewhat undefined, may those who feel that the following contains omissions forgive me.

The proposal of the **Argonne** National Laboratory, USA, is based on the existing ATLAS facility. which then would constitute the post-accelerator and associated equipment for the US **RIA** facility.

ARENAS3, at Louvain-la-Neuve, Belgium uses as driver the cyclotron CYCLONE 30 which delivers up to 0.5 mA of 30 MeV protons for producing intense radioactive beams no too far away from stability with the ISOL method. A K=44 cyclotron with 25% acceleration efficiency will delivers beams for the astrophysically interesting energy range 0.2-0.8 MeV/u, for higher energies the K=110 CYCLONE is used.

In Russia, the Flerov Laboratory at Dubna operates the **DRIBS** facility two cyclotrons, U400 (K=400-540) and U400M (K=450-630), reputed for their high intensity. Physics with light radioactive nuclei from in-flight fragmentation is presently made, ISOL + post-acceleration using one accelerator as driver, the second as post-accelerator is under installation, as well as the possibility of inducing photo-fission (see also section 3.3) by means of their 25 MeV, 20 μA electron-microtron.

The superconducting cyclotron (K=800) of the **Catania** National Laboratory in Italy delivers intermediate-energy heavy-ion beams which can be used in connection with the fragment separator ETNA or with the EXCYT facility (both under construction). This latter project, connects an ISOL system to the existing 15MV tandem.

The **GANIL** facility at Caen, France (two coupled K=380 cyclotrons) has, since 1984, a broad physics programme based on in-flight fragment separation of heavy-ion beams up to 95 MeV/u. A speciality are the high intensities available for very rare enriched isotopes from ECR sources. The new ISOL & post-accelerator **SPIRAL** relies on the existing GANIL as a driver. The project uses ECR techniques to inject highly-charged beams into the cyclotron CIME for post-acceleration to energies between 1.8-25 MeV/u. SPIRAL has recently been commissioned very successfully and the physics experiments should start this fall. The upgrade SPIRAL-II is presently under elaboration (see also 3.3).

GSI Darmstadt, FR Germany, exploits very successfully the combination of the fragment separator FRS and the storage ring ESR. An upgrade (see also section 3.2) will soon be terminated which will allow to fill the heavy-ion synchrotron SIS (GeV/u beams). Presently, discussions are underway for a new facility allowing novel experiments with in-flight fragmentation.

The **HRIBF** Facility at Oak Ridge, USA relies on the ORIC cyclotron (60 MeV protons, 50 μA) for production of the radioactive species. The recently constructed ISOL system is optimized for negative ions since the postacceleration is made by the pre-existing 26 MeV Tandem.

The **HIRFL** facility at Lanzhou (China) uses a K=540 separated sector cyclotron for making light radioactive beams up to 80 MeV/u by in-flight fragmentation by means of the separator RIBLL and plas the installation of a new storage-ring facility.

The **ISAC** facility at Vancouver, Canada uses the meson factory TRIUMF as driver accelerator of great potential. Ultimately it is envisaged to use 100 μA of 500 MeV protons for an ISOL facility connected to a warm linac, presently under construction, for energies between 0.2-1.5 MeV/u. ISAC phase-2 relies then of super-conducting cavities for reaching Coulomb barrier energies.

The "historical" **ISOLDE** facility at CERN, Geneva, Switzerland has delivered since almost 30 years 600 radioactive species as low energy ISOL beams. The 1.4 GeV PS booster acts as a driver with 2 μA average proton current. A post-accelerator, accepting the ISOLDE charge-state 1^+ beams up to mass A=80, is under construct: Prior to injection into a linear structure (RFQ, interdigital H-type, linac) bunching and charge-state breeding is assured by a novel scheme based on a Penning trap and an EBIS source.

ISOL Beams are also available from the **Jyväskylä,** Finland K=130 cyclotron. There is no post-accelerator at present, but the facility has an very active low-enery RIB physics programme and contributes to the R&D on the ISOL method (see also section 3.3).

The **NSCL** at Michigan State University, USA, uses the super-conducting cyclotron K1200 in connection with a super-conducting ECR source for the acceleration heavy-ion beams in the intermediate to pre-relativistic regimes with considerable intensities allowing a vast experimental programme based on the in-flight fragmentation method. An upgrade which has been started will give rise to a substantial gain in energy, or, likewise, in intensity for a given energy. The NSCL is also contender for **RIA**.

RIKEN in Japan provides presently intermediate energy radioactive beams for the fragment separator RIPS, the large experimental effort being accented in particular by physics with light neutron-rich nuclei. The new project, of which phase 1 is started will re-use the present installation, upgraded in intensity, as injector for a new machine: consisting of two separated sector cyclotrons. The second super-conducting, 30 Tm machine, will provide intense beams of energies of up to 400 MeV/u for in-flight fragmentation. Phase 2 would built the double intersecting storage rings MUSES. and a 2.5 GeV electron LINAC for collision experiments with the fragment beams.

We conclude this summary by mentioning the planned projects **SPES** at Legnaro National laboratory in Italy, **MAFF** in Munich, Germany, **SIRIUS** at the Rutherford Appleton laboratory, UK and **E-ARENA** in Japan

Legnaro would use the existing 16 MV tandem with its super conducting LINAC which provides 20 MeV/n beams up to the mid-mass region as post-accelerator for an ISOL system relying on a new intense light-ion driver to be built. At Munich the new high flux reactor FRM-II, presently under construction would allow (see also section 3.3) to use thermal neutrons as driver particles, whereas the SIRIUS design study of an ISOL system followed by a RFQ +super-conducting 10 MeV/u linac relies on the existing ISIS 800 MeV, 100 μA proton synchrotron as driver. Annother intense driver accelerator would be the linac of the KEK Jaeri Joint Project. The prototype for the E-Arena ISOL + post-accelerating linac had been built at the at INS during the last years.

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