

The Alto Tandem and Isol Facility at IPN Orsay

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Alto is an infrastructure for experimental nuclear physics in France that comprises both an on-line isotope-separation facility based on the photofission of uranium and a stable-ion beam facility based on a 14.5-MV tandem accelerator. The isotope-separation on-line section of Alto is dedicated to the production of neutron-rich radioactive ion beams (RIB) from the interaction of the γ -flux induced by a 50-MeV 10- μ A electron beam in a uranium-carbide target. It is dimensioned for 10^{11} fissions per second. The RIB facility is exploited in alternating mode with the tandem-based section of Alto, capable of accelerating both light ions for nuclear astrophysics and heavy ions for γ -spectroscopy. The facility thereby offers the opportunity to deliver beams to a large range of physics programmes from nuclear to interdisciplinary physics. In this article, we present the Alto facility as well as some of the highlights and prospects of the experimental programme.

KEYWORDS: radioactive ion beams, resonant laser ionisation, stable beams, transfer reaction

1. Introduction

The isotope separator on-line (Isol) technique relies on the production of radioactive isotopes by intense beams hitting thick targets. The next generation of radioactive ion-beam facilities of the Isol family has been designed on the assumption of higher yields than presently available. To meet the demand for higher luminosity, it is essential to achieve ever higher primary beam intensities or possibly denser targets.

Two traditional approaches to reach the most exotic nuclei on the neutron-rich side are embodied in fission induced by protons (like Isolde at Cern) and by thermal neutrons (like for instance ILL at Grenoble). Fast neutrons produced in the break-up of deuterons have been proposed for future facilities (Spiral-2 at Caen). Over the last years, photofission has emerged as a particularly attractive alternative. In this technique an electron beam is slowed down in a thick uranium target that act as a converter. The bremsstrahlung that is generated excites the giant dipole resonance of the uranium nuclei, provoking photofission. Compared to the competing methods, photofission offers the advantage of a low cost for the electron accelerator, while the cross sections are not dissimilar.

An experimental programme to investigate the implementation of photofission was initiated at IPN Orsay at the beginning of the century. Isotopic cross sections were measured with a 50-MeV electron beam from the LEP Pre-Injector (LPI) at Cern [1], a machine that was subsequently transferred and installed at Orsay in 2005. The first electron beam at the new site was accelerated in 2006. After a long development programme including reinforcement of the radiation shielding around the target and a major facelift of the Parrne mass separator, the licence for operation at the full nominal intensity of 10 μ A was granted in 2012.

Next to the electron accelerator, the 14.8-MV tandem accelerator is an electrostatic Van de Graaff machine that is in use at Orsay since 1973. It delivers stable beams from protons

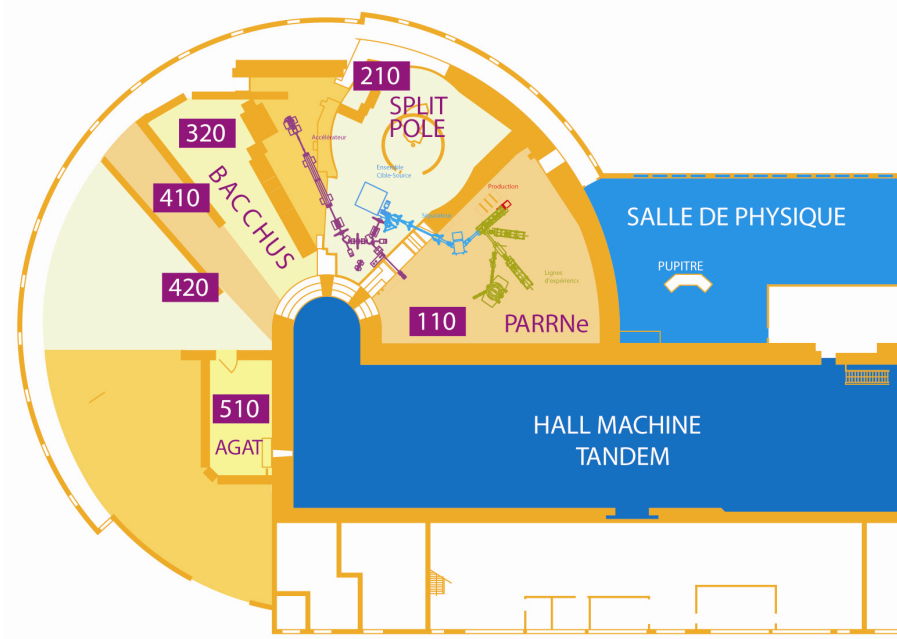


Fig. 1. Layout of the Alto facility. The tandem complex includes areas 210 to 510. The electron accelerator (its outline drawn in purple) and the Isol target (in blue) are outlined in area 210, the mass separator (blue) and low-energy beam lines (yellow) in area 110.

to iodine as well as clusters from carbon to gold. The beams can be sent to a range of set-ups, which include a split-pole and a zero-degree spectrometer, a semi-permanent γ detector array and a mono-energetic and directional neutron source. The photofission Isol installation together with the tandem accelerator constitute the bipedal Alto facility, the layout of which is shown in Fig. 1. It is covered by the Ensar framework of the European Union and was officially inaugurated in spring 2013. It is scheduled to deliver more than 4000 hours of beam a year, out of which 10% are radioactive beams.

2. The split-pole spectrometer

The split-pole spectrometer is an Enge magnetic spectrometer that consists of two pole pieces contained within a single coil [2]. The gap between both poles is designed such that it enables horizontal and vertical focussing to second order. Its maximum rigidity is 1.65 Tm. At the focal plane sits a position-sensitive proportional counter that is used for the localisation and the identification of the particles. It is frequently requested for nuclear astrophysics and continues to contribute to nuclear structure studies. Here we present the example of a transfer experiment that was part of a research project on the nuclear structure of exotic isotopes.

To put the matter in context, a RIB experiment had been carried out at the Ganil laboratory in Caen some time earlier that had aimed at the single-particle structure of neutron-rich copper isotopes by means of the $^{72}\text{Zn}(d, ^3\text{He})^{71}\text{Cu}$ proton pick-up reaction in inverse kinematics. In order to assure a consistent treatment of optical potentials and analysis procedures between the new measurement and available literature results on lighter isotopes [3], the $^{70}\text{Zn}(d, ^3\text{He})^{69}\text{Cu}$ reaction in direct kinematics was proposed to be performed at the Orsay tandem.

A deuteron beam of 27 MeV of energy and 200 nA of average intensity was sent on an

enriched ^{70}Zn target of $18.7(9) \mu\text{g}/\text{cm}^2$, supported by a carbon backing. The acceptance of the spectrometer amounted to 1.16 msr and an energy resolution of $\sigma = 18 \text{ keV}$ was obtained, corresponding to a resolving power of $E/\Delta E = 1140$. We reconstructed the excitation-energy spectrum of ^{69}Cu and measured the angular distributions of the emitted ^3He particles. Spectroscopic factors were deduced from comparing the measured differential cross sections to distributions that were calculated in the Distorted-Wave Born Approximation (DWBA). Elastic scattering was measured in order to validate the optical potential of the incoming channel, for which the relativistic Daehnick parametrisation was chosen [5]. For the outgoing channel, we took the potential by Perey and Perey [6].

While the previous results from the literature were largely reproduced at low energy, new additional strength for the relevant $\pi f_{7/2}$ hole state was found above 2 MeV of excitation energy. The cumulative amount of measured strength thereby increases from 39 to 68%. It now allows to constrain the centroid of those levels that contain fragments of the single-particle force with higher reliability, such that a better comparison with shell-model calculations is possible. At the same time, the optical potentials are also better defined and it serves as a solid reference in direct kinematics for the experiment with the radioactive ^{72}Zn beam in inverse kinematics and it underlines the continuing role for transfer experiments at classic spectrometers.

The split-pole also plays an important part for experimental nuclear astrophysics. The search for and the absence of resonant states in $^{10,11}\text{C}$ through the $^{10}\text{B}(^3\text{He},t)^{10}\text{C}$ and $^{11}\text{B}(^3\text{He},t)^{11}\text{C}$ reactions showed that these mechanisms cannot explain the deficit in the primordial abundance of ^7Li [7]. The $^{27}\text{Al}(p,p')^{27}\text{Al}$ reaction came under intensive scrutiny to probe the spectroscopic properties of ^{27}Al states above the α and neutron-emission thresholds [8]. It yielded better constraints for the nucleosynthesis of ^{26}Al , which is a tracer of massive stars in the galaxy, and in turn it contributes to an improved understanding of the chemical and dynamic evolution of the galaxy.

Other experimental work at the tandem complex includes γ -spectroscopy with stable beams. The existing Orgam array has recently been upgraded with the arrival of eight triple clusters from the Miniball detector, which were temporarily moved from Isolde to Orsay in 2014, and now reaches 8% of efficiency at 1332 keV. The experimental programme of this Minorca campaign, including the use of LaBr_3 scintillators and a freshly designed plunger device [9], is presently under way. A neutron source known by the name of Licorne started operating in 2013 [10]. A 100-nA ^7Li beam of 13 to 17 MeV is shot onto a polypropylene target and for a given beam energy and emission angle produces a mono-energetic beam of $10^7 \text{ s}^{-1}\text{sr}^{-1}$ neutrons set at a value between 0.5 and 4 MeV. Coupled to the Orgam or Minorca array, the γ -emission after the fission of fertile and fissile isotopes can be studied at neutron energies that are relevant for the design of Generation-IV nuclear reactors. Finally, also carbon-cluster and molecular beams for atomic physics are available at Alto.

3. The photofission facility

After the initial measurements of photofission production yields at Cern [1], the LPI electron accelerator was brought to Orsay and implanted in an existing building on the campus of the university of Paris-South. A thermo-ionic electron gun creates pulses of 60 mA, while a klystron at 30 MW delivers the RF wave that brings the beam up to 50 MeV. The target was installed in the same experimental area as the split-pole spectrometer. To match the infrastructural constraints, a double deviation was inserted to bend the electron beam over 130° such that it reaches the target. A radiation bunker was constructed around the target, while additional shielding was added for the mass separator. Inside the bunker,

the Isol target and its surrounding chamber are based on the standard design at Isolde. The target is housed in a cylinder that is filled with UC_x pellets with a density of 3.5 g/cm^3 . The effective density can be lower as the spacing between pellets is increased, the total length varying between 12.5 and 19 cm. The resulting amount of uranium is 60 g. The target is heated to a temperature of 2000°C or 10% beyond.

For a 50-MeV electron beam of $10 \mu\text{A}$, the resultant bremsstrahlung easily excites the giant dipole resonance of ^{238}U , which is centered at 15 MeV. To the photofission cross section of 160 mb, one should add the indirect yield that is due to secondary neutrons from (γ, n) and $(\gamma, 2n)$ reactions. Since the production mechanism is inherently colder than fission induced by protons, less neutrons are evaporated in the process and the final fission fragments are expected to be richer in neutrons.

With the parameters given above, the total rate in the target reaches 10^{11} fissions per second. Yields for several isotopes have been measured [11] and have been extrapolated to the full range of accessible fission fragments [12]. The obtained numbers at 100 nA of electrons were comparable to those of earlier measurements at Orsay for a deuteron beam of 14 MeV and $1 \mu\text{A}$, confirming the prospect of an increased output of the facility by a factor of 100 when Alto is run at its nominal intensity of $10 \mu\text{A}$. Since the mean free path of the incident electrons is less than 3 cm, the fission rate moreover saturates for a target length of about 7 cm [13]. It will therefore be possible to optimise the target length further such that shorter release times are obtained.

Three types of ion sources are currently available for the extraction of radioactive beams at Alto. The surface ion source consists of a simple tube of a refractory material with an appropriate work function to ionise the atoms of interest upon contact with the hot surface. In the Febiad ion source the atoms are ionised in a hot plasma by the impact of energetic electrons. Resonant laser ionisation relies on the unique level structure of the electron shells of every atomic element to excite electrons in a stepwise manner till ionisation is achieved. Because of the ability to tune the laser wavelength to the energy of almost any atomic transition, it is near-universal and highly selective. Research for combinations of target and ion source that takes place at IPN Orsay includes furthermore the development of high-density uranium-carbide targets and the extraction of fluorinated molecular beams to speed up the release of lanthanides and other chemically reactive elements. In the next section, we give more details on the laser ion source and the laser system, which has recently been purchased and put into operation.

4. The laser ion source

The resonant-ionisation laser ion source at Alto, referred to as Rialto, includes two dye lasers with a wavelength range of 540 to 850 nm. They are pumped by a 532-nm Nd:YAG laser at a repetition rate of 10 kHz and a pulse width of 10 ns. Frequency-doubling units based on a BBO crystal allow to access ultraviolet wavelengths from 270 to 425 nm. The laser beams are transported to the ion source over a path of 13 m. After an initial feasibility test in 2011 with an older laser set-up had shown an enhancement over surface ionisation of a factor of 8 in the spectrum of ^{79}Ga and its descendants, illustrated in Fig. 2, a new laser set-up was acquired and commissioned with further delivery of gallium beams in 2012 and zinc beams in 2013.

Atomic gallium exists in the ground state and a metastable state that lies closely at 0.1 eV. For ionisation of the atom starting from its ground state we used rhodamine 6G dissolved in ethanol and after frequency doubling we produced a 287-nm transition to lift the atom resonantly to an excited state. Saturation was reached above 110 mW. A second

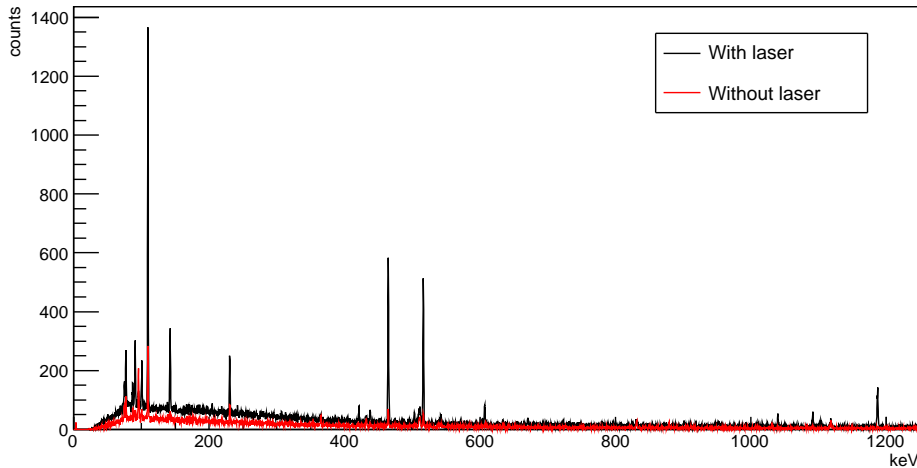


Fig. 2. Gamma spectrum after β -decay of ^{79}Ga with (black) and without (red) laser irradiation for an electron current of 160 nA and a measurement time of 5 minutes. The spectrum also includes daughter activity from the decay of ^{79}Ge .

step, for which we took 15 W of the 532-nm pump beam, brought it in non-resonant fashion to the continuum. The metastable state, representing half of the number of atoms at the working temperature of the ion source, was excited by replacing the first step by a transition at 294 nm. The latter was generated from dissolving pyrromethene in ethanol, stabilised with dabco to increase its lifetime. With the combined set-up of both schemes together, an enhancement factor for gallium of 17 was reached.

For the ionisation of zinc, we used a three-step scheme. DCM was dissolved in ethanol for both dye lasers. The first step was a transition at 214 nm, obtained after frequency tripling. It was followed by a second step at 636 nm and final ionisation into the continuum by means of the pump beam at 532 nm. The power in the UV transition, 20 mW before transport to the separator area, was not sufficient for saturation. The red transition saturated easily, before attaining 100 mW. The green pump beam carried up to 15 W of power before being transported to the source. The transport efficiency for all lasers was of the order of 25%.

The extracted radioactive ions were sent at an energy of 30 keV to the electromagnetic mass separator Parnne of a resolving power of $M/\Delta M = 1500$ and further to the Bedo experimental beam line, which is dedicated to $\beta\gamma$ -decay. The Bedo set-up essentially consists of a tape station, a 4π plastic scintillator mounted around the collection point that acts as a β -trigger with an efficiency of 55%, and four Exogam-prototype clover detectors supplemented with Eurogam detectors and with a total efficiency of 3% or more. BGO anti-Compton shields and LaBr₃ scintillators can be added, while a neutron detector called Tetra, assembling 90 ^3He counters, is available through a collaboration with the JINR laboratory in Dubna. Data were accumulated for $^{82,83,84}\text{Ga}$ [14] and for $^{79,80}\text{Zn}$ [15]. With the Febiad ion source, recently the β -decay of ^{82}Ge was investigated anew [16].

The Alto facility is set to expand through the construction of a new beam line for collinear laser spectroscopy. In this method, nuclear polarisation will be achieved through optical pumping. Two detection set-ups are foreseen. The first one concerns the measurement of ground-state properties such as spin, charge radius and electromagnetic moments through nuclear magnetic resonance and scans of the hyperfine structure. The second one will be tailored for β -decay spectroscopy of the polarised radioactive beams, giving access to the

spins of excited states. Like most of the instrumentation at Alto, they are built with the ability to move them later to the Desir hall of the Spiral-2 facility at Ganil, which is currently under construction at Caen in France.

Next to Desir, IPN Orsay is also actively involved in development for the Actar, Gaspard, and Paris detectors, and the Reglis gas cell for the new S3 spectrometer at Spiral-2. While Alto continues to exploit a niche with stable beams on one hand, its low-energy physics programme based on photofission on the other hand paves the way for R&D on Isol and RIB, instrumentation and methodologies, and training of a new generation of Isol physicists.

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