# Bucharest Tandem Van de Graaff Accelerator

DOREL BUCURESCU, GHEORGHE CATA-DANIL, AND NICOLAE-VICTOR ZAMFIR 1

**Introduction**

The Tandem Van de Graaff accelerator is one of the main experimental facilities of the "Horia Hulubei" National Institute of Physics and Nuclear Engineering (IFIN-HH) in Bucharest-Magurele (http://www.nipne.ro). The institute, with more than 300 scientists, is the most significant player in the Romanian physics research landscape. Its activities cover a broad range of research in basic and applied nuclear physics and related areas:

- Theoretical Physics
- Atomic, Nuclear, and Particle Physics
- Life and Environmental Physics
- Radioisotopes and Radiopharmaceuticals
- Technological Irradiations
- Radioactive Waste Treatment and Storage
- Decommissioning of Nuclear Facilities
- Nuclear Engineering
- Training in nuclear activities

Since its foundation, more than 50 years ago, the institute, through its nuclear facilities, Cyclotron, Nuclear Reactor, and Tandem Accelerator, played the leading role in the formation and development of nuclear activities in Romania.

**Facility Description**

Nuclear physics research with accelerated ion beams is mainly performed in Romania at the Van de Graaff Electrostatic Tandem Accelerator (http://tandem.nipne.ro), a National Research Facility financed by the Romanian Authority for Scientific Research. Access to experiments is open to institutes and universities from Romania, as well as to groups from other countries on the basis of mutual agreements (beam-time requests can be submitted on-line through the accelerator Web page). The accelerator runs approximately 3600 hours/year and there are about 30 different users. Outside users can benefit from a high standard guest house, located close to the laboratory. Figure 1 is a general view of the Tandem Accelerator.

This accelerator was built by the High Voltage Engineering Corporation (USA) in 1973 and it was later upgraded from the original terminal voltage of 7.5 MV (FN type) to 9 MV. In order to operate the accelerator at 9 MV on the terminal, a new voltage divider was designed and installed, and an improved technique was applied for the analysis of the insulating gas composition [1]. Because it is located in a seismic area, the major earthquakes affected its structure. During the 1977 earthquake (magnitude 7.2 on Richter scale) due to the extremely high resonant mechanical stress, the inner structure collapsed inside the tank [2]. After only 9 years (1986) another earthquake (magnitude 6.8 on the Richter scale) deviated the acceleration column with 63 mm at the terminal position. As a consequence, a mechanical earthquake protection system was constructed and installed [3] (partially shown in Figure 2).

**Figure 1.** *A general view of the main vault of the Bucharest 9 MV Van de Graff Tandem Accelerator.*

**Figure 2.** *View of one of the four tank supports, part of the tandem earthquake protection system, equipped with an elastic GERB unit with springs and viscodampers.*

The accelerator currently delivers 28 ion species ranging from protons (intensities of 700 nA at 10 MeV) to gold (intensities of 10 nA at the maximum energy). Negative ions injected in the accelerator are produced by 3 ion sources: a duoplasmatron for p, $^{12}$C, $^{14}$N, $^{16}$O, $^{19}$F, $^{32}$S, a duoplasmatron source dedicated to $^{3,4}$He ions and a sputtering source for most of the elements. In addition there is in operation an ultra-clean sputtering source for Accelerator Mass Spectrometry (AMS) applications, followed by a 90 degrees magnetic analyzing and injection at zero degrees, shown in Figure 3.

There are seven beam lines for a wide variety of experiments, equipped with commercially available detectors for photons, charged particles, and neutrons, associated with standard nuclear electronics.

Presently, the machine is undergoing a major refurbishing process: the vacuum equipment, electrical power supplies, high voltage charging system, sputtering ion source are in the process of being replaced. Also the automatic control of the ion-optics elements (magnetic and electric lenses, analyzing, and bending magnets) and beam diagnosis will be installed according to updated technology in the near future.

In the Tandem experimental area, there is also installed a standalone 14 GHz *Electron Cyclotron Resonance Ion Source* (RECRIS), constructed in collaborations with scientists from Frankfurt University and CERN [4]. It can deliver a variety of highly charged ion beams (H, N, O, Ar) at low energies used for atomic physics and condensed matter studies. Figure 4 shows a view of the RECRIS setup.

**Research Program**

Over the years, a rich research program in both nuclear and atomic physics was developed, using beams accelerated by the Tandem accelerator. The nuclear physics studies in the first decade were centered on both nuclear reaction mechanisms and nuclear structure.

First experiments on *reaction mechanisms* at low energies exploited the good energy resolution of the tandem beams. One such direction was the study of the isobaric analogue resonances (IAR). As an interesting result, intermediate structures were observed near some IAR and there were related to configurations (hall-ways) in which very likely the number of excited particles and holes is larger than that for the door-way states, but much smaller than in the case of the compound nucleus configurations. Isobaric analogue resonances were observed for the first time in the actinide region by proton scattering on a $^{238}$U target [5]. A resonance analog to a parent state in continuum (in $^{13}$C) was observed in $^{13}$N, by means of the $^{12}$C(p,p) excitation function, thus pointing to a more general concept of IAR. In another series of experiments, the (p,n) threshold anomaly, that is, an anomalous behavior of the cross-section occurring at the opening of a neutron channel, was predicted and observed in the proton elastic scattering from *sd*-shell nuclei [6]. This anomaly from the (p,p) channel is induced by the 2*p* wave zero-energy neutron analogue state.

With the first heavy ion beams, reaction mechanism studies were extended to incomplete fusion processes. A study of nonequilibrium processes, and, in particular, of the projectile breakup channel, was made for various projectiles ($^{11}$B to $^{19}$F) of 3 to 5 MeV/A on light targets, and a strong dependence on the projectile was evidenced [7].

Gamma-ray spectroscopy at Tandem appeared as a natural continuation of the previous studies performed for several years at the Cyclotron with alpha-particle beams [8]. With the availability of heavy ion beams at Tandem, *nuclear structure* studies were mainly performed with in-beam gamma-ray techniques and fusion-evaporation reactions, to study medium-mass nuclei, including: lifetimes measured with the recoil distance method (see, for example Ref. [9]); magnetic moment

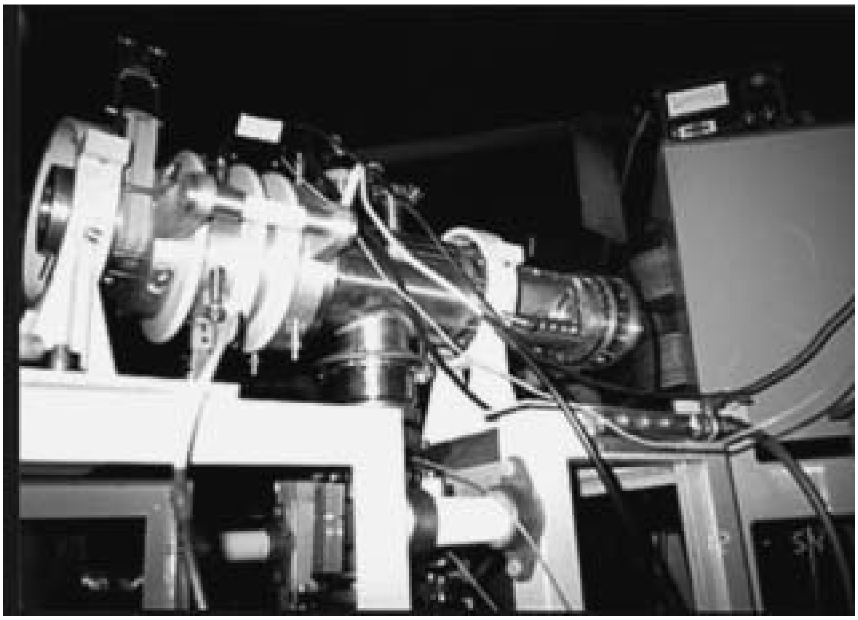

**Figure 3.** *The Sputtering Source dedicated to AMS studies.*

(g-factor) measurements by means of the recoil-into-gas integral perturbed angular correlation technique [10]; and study of new isomeric states [11].

The *atomic physics* studies concentrated on the experimental determination of atomic collision parameters such as: integral and differential ionization cross-sections of the inner (K and L) shells; integral and differential alignment parameters; multiple ionization effects; double vacancy production in the inner shells (see, for example, Ref. [12]).

Currently, the experimental program at our Tandem accelerator is concentrated mainly on three directions: nuclear structure, atomic physics, and applied nuclear physics. Some recent results will be briefly outlined.

Many research themes are related to strong international collaborations with other laboratories, such as Köln, Munich, Yale, Legnaro, Padova, Orsay, Dubna, GANIL, GSI, and RIKEN. It is worth mentioning that the Tandem accelerator was the main facility of the European (Framework Program–5) Centre of Excellence *Inter-Disciplinary Research and Applications based on Nuclear and Atomic Physics (IDRANAP)*. Presently the research activity is connected to European Projects in the Framework Program–6: EURONS, EURISOL, EURATOM.

*Nuclear Structure Physics*

Nuclear Structure studies at the Bucharest Tandem Accelerator are mainly dealing with the gamma-ray spectroscopy of low-lying, yrast and non-yrast excited levels.

*Study of high-spin states populated with heavy-ion fusion-evaporation reactions*. High-spin structures were studied in medium-mass (A ~ 70–130) slightly neutron-deficient nuclei, in fusion-evaporation reactions induced by ion beams from Li to F, by in-beam gamma-ray spectroscopy experiments (gamma-ray excitation functions, angular distributions, $\gamma$-$\gamma$, charged

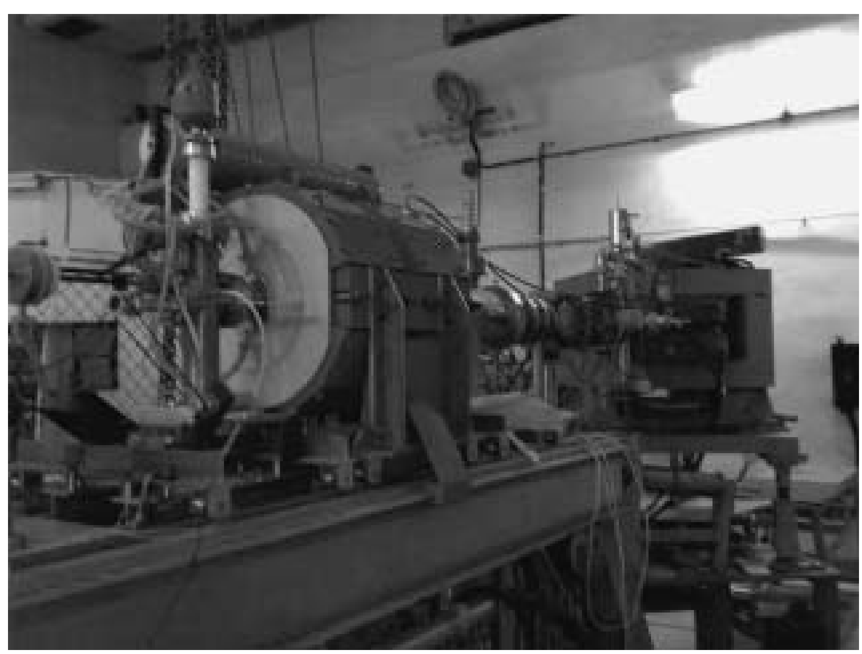

**Figure 4.** *The ECR ion-source RECRIS setup.*

particle – γ, and neutron – γ coincidences, lifetimes of excited states by the Doppler shift attenuation (DSA) and recoil distance (RD) methods). Different nuclear structure phenomena were observed and studied. "Transitional" nuclei in the A~80–90 region were studied rather systematically. In many of these nuclei high spin states were studied for the first time, thus enriching the picture of the systematic evolution of nuclear structure over isotopic and isotonic chains. Such systematics allowed extensive comparisons with different nuclear structure models, and especially the algebraic models (interacting boson and boson-fermion models). Isomeric states were also observed and studied, as is the case of two new short-lived isomeric states observed in $^{84}$Y. The decay scheme was determined in experiments at the Tandem, and their lifetimes and magnetic moments were measured in experiments at the Cyclotron of our Institute [13]. A new setup was recently developed for lifetime measurements of isomeric states by using an autocorrelation single-crystal scintillation time spectrometer. Some experiments performed at our accelerator complemented experiments at large-scale facilities. For example, high-spin band structures were measured in $^{96}$Tc first in Bucharest experiments, with spin assignments in the lower part of the level scheme based on detailed gamma-ray angular distributions and DCO-ratios; these structures were then extended to higher spins by analyzing data from a EUROBALL experiment. Another example is the study of high-spin states in $^{91}$Y and $^{95}$Nb; the first gamma-rays of band-like structures in these nuclei were assigned in Bucharest by γ-γ, neutron-γ, and charged particle-γ coincidence experiments, and extensions at higher spins were obtained in an experiment with the GASP array (Legnaro) [14].

*Study of low-spin states populated with non-selective reactions*. Such studies, complementary to those with heavy-ion beams, were performed for different medium mass nuclei (A ~ 70–150) with the (p,nγ) reaction at low energies. Due to its lack of selectivity, this reaction allowed the observation of complex level schemes, which are quasi-complete for a certain spin window. In spite of the rather small velocity of the recoiling nuclei, level lifetimes can be also determined in such reactions, with the DSA method because at incident energy close to the threshold of the studied levels, one avoids the problem of the cascade feedings. An illustration of this type of study is in Ref. [15], where many new low-spin levels were observed in $^{139}$Ce with the (p,n) reaction, while high-spin structures were studied with the $^{12}$C+$^{130}$Te reaction.

*Nuclear structure investigations by off-beam gamma-ray spectroscopy*. Gamma-ray spectroscopy following beta decay is very useful in cases where a detailed level scheme at low spins and excitation energies is necessary in order to assess the validity of certain theoretical model predictions. Such a case, of outstanding current interest, is the search for fingerprints of nuclear structure paradigms such as dynamical symmetries, and critical shape phase transition points (like E(5), the critical point between the U(5) and O(6) dynamical symmetries, and X(5), between U(5) and SU(3), respectively). Very often, information on such low-lying states (such as their spin value, or branching ratios of their decay) can be obtained through gamma-ray spectroscopy following beta-decay. Such studies were done, very often, 30–40 years ago and, in order to have precise data, new measurements should be performed using modern tools, especially high resolution coincident gamma-ray spectroscopy. We have used for such studies beta emitter sources prepared by different reactions, which, depending on the parent nucleus lifetime, were measured either by using a beam chopping system, or were simply transported aside from the beam line, in front of the gamma-ray detectors. Such an approach was used to study the level schemes of $^{100}$Ru, $^{124}$Te, and $^{64}$Zn, which is proposed as a good candidate for the E(5) symmetry [16].

*Atomic Physics*

Atomic Physics studies in recent years concern mainly heavy ion–atom collision mechanisms at intermediate energies. Recent experimental studies approached the ionization in the K-K and K-L level matching regions, namely: 2pσ and 3dσ molecular orbitals ionization cross-sections and vacancy transfer probabilities [17]. Multiple ionization probabilities of the outer shells of the target atom and equilibrium charge states of the projectile in the solid target were also obtained.

*Applications of Nuclear Methods*

A large fraction of the beam time at the Tandem accelerator is dedicated to the use of IBA (Ion Beam Analysis) methods in a wide spectrum of applications for different scientific or economic domains. The methods include PIXE (Particle Induced X-Ray Emission), PIGE (Particle Induced Gamma ray Emission), RBS (Rutherford Back-Scattering), NRBS (Non-Rutherford Back Scattering spectrometry), ERDA (Elastic Recoil Detection Analysis), and offer high precision capabilities for materials analysis and characterization.

PIXE type of analysis was used in archaeometrical researches, to study the composition of ancient Greek, Roman, and Dacian silver and gold coins, and Neolithic obsidian tools and ceramics pigments [18]. Part of these studies were performed within the frame of the European Union Actions COST G1 ("Ion Beam Study of Art and Archaeological Objects") and G8 ("non-destructive analysis and testing of museum objects"). PIXE and related IBA techniques have been implemented for the characterization of biomineral structures such as bones, dental enamel, and biomaterials. Use of wide beam, thick target PIXE on such materials for which good reference materials are missing, and the complementary ERDA method allowed the evaluation of relative concentrations of up to 20 elements with $Z > 14$ per specimen [19]. Analysis of the trace and dominant element concentrations allowed the discrimination of diabetes-induced changes in bones, and the study of dental enamel demineralization. Studies now in progress extend the application area of IBA methods to those mentioned before and other related biological materials. A high potential of the PIGE method for precise measurements of Carbon in steels was recently demonstrated [20]. ERDA capability for studying the profile of helium implanted in different materials is also important to assess the behavior of nuclear matrices where helium is produced by the disintegration of actinides. Such studies were performed, for example, for ceramics, which are considered promising materials for nuclear waste immobilization and/or transmutation. Recoil spectrometry has been extended to the analysis of hydrogen and helium, which are important elements in a wide variety of thin film materials [21]. One should also mention radiation damage studies performed with irradiation of materials with different beams. As an example, samples of KU1 quartz glass (a candidate for optical transmission components of future thermonuclear reactors) were irradiated with 12 to 15 MeV protons, in order to study the degradation of their optical transmission properties, as a part of the cooperation in the frame of the EURATOM program [22].

An accelerator mass spectrometry (AMS) setup is being installed on one of the beam lines [23]. Experimental AMS studies were performed with $^{26}$Al (with a sensitivity level of $10^{-14}$ for the isotope to element ratio), and tritium and deuterium (for the diagnosis of fusion experiments).

Finally, we mention a medical application of nuclear methods, namely, the boron neutron capture therapy (BNCT). An experimental set-up was designed and is under development [24], to provide thermal and epithermal neutrons (from the (p,n) reaction on $^{7}$Li), to irradiate aqueous cells solutions.

**Plans for the Future**

The research program at the Bucharest Tandem Accelerator is increasingly related to the large European projects in Nuclear Physics: FAIR and SPIRAL2. It is based on the fact that such a small scale facility, together with the other similar facilities, is complementary in many respects to Large Scale Facilities (LSF):

- more "classical" research directions, which can still lead to important contributions to the field.
- represents an ideal place for educating young scientists; they go through all stages of an experiment and really achieve the desirable skills needed for future LSF groups.
- represents an appropriate place for developing instruments or experimental methods intended for a LSF.
- The Bucharest Tandem Accelerator is financed by Romanian authorities. This support may become stronger, if it is demonstrated that by developing the in-house activity, the participation of the Romanian groups at the European LSFs increases in efficiency.

In order to achieve these goals it is necessary to have a strong program of enhancing the experimental capabilities. Regarding the scientific program the main directions will be:

*In-beam Gamma-Ray Spectroscopy*

For this purpose, a small array of six (at present) HPGe detectors, with efficiencies between 30% and 60%, will be used, together with several Silicon detectors for charged particles and liquid scintillator detectors for neutrons. This system will allow the study, by $\gamma\gamma$ coincidences, of the high-spin states of other nuclei close to the stability line in the medium mass region, which are little known at present—such nuclei are populated with relatively low cross-sections in heavy ion induced reactions.

A modern plunger device for lifetime measurements with the recoil distance method is under construction.

*Off-Beam Gamma-Ray Spectroscopy for Nuclear Structure and Nuclear Astrophysics*

A transport system of the irradiated targets in a low-background area combined with a high efficiency array of gamma detectors and conversion electrons will serve to continue the off-beam studies in order to pin down nuclear structure details. These empirical parameters will contribute to further mapping of the evolution of nuclear collectivity. A parallel program will be devoted to measure cross-sections of reactions relevant for nucleosynthesis.

*Proton Induced Fission Studies on Actinides*

An array of 81 plastic scintillator detectors for neutrons (constructed and used in experiments at RIKEN) will be installed at the Bucharest Tandem, in connection with a VME acquisition system. It will be used to measure, for the first time, the correlation function of the neutrons emitted in proton induced fission, as well as neutron nuclear data.

*New Applications of IBA Methods*

More performing experimental setups are under development, using different beams both in vacuum and in air, for the analysis of a large variety of samples. Studies of the modification of properties of materials by irradiation with accelerated particle beams will be also continued.

*Atomic Physics*

New studies of the inner shell vacancy production and sharing in heavy systems at intermediate bombarding energies will be performed. Studies of atomic physics and material science will also be performed using our new facility of 14 GHz ECR ion source, TOF spectrometer, and position-sensitive detectors. Atomic processes in lower Z collision systems and energies, with relevance for plasma and fusion physics, will be studied.

*Testing Detectors and Experimental Methods for Large Scale International Projects (FAIR, SPIRAL2, AGATA, CERN, ITER)*

Active participation of the Romanian nuclear research groups in the Large Scale International Projects has and will have a high priority. In-house research in this direction could use Tandem accelerator beams for testing different new detection systems and experimental methods. These works will be performed mainly in large international research teams.

*Accelerator Mass Spectrometry*

The extremely high detection sensitivity of AMS in conjunction with the enhanced values observed for $^{129}$I relative to other fission products makes the measurement of $^{129}$I with AMS an efficient tool for nuclear safeguards, detecting and preventing accidental or deliberate discharge of small nuclear debris that otherwise would remain undetected by radioactivity measurements. The goal of future experiments is to measure, monitor, and investigate the transport of $^{129}$I in the vicinity of three nuclear power plants in Eastern Europe: Kozloduy (Bulgaria), Cernavoda (Romania), and Chernobyl (Ukraine).

The extensive refurbishing process presently being undertaken, the strong scientific program, together with the high level achievements and results, show that the Bucharest Tandem Accelerator is an active part of the European Infrastructure in Nuclear Physics.

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