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NUCLEAR PHYSICS AT THE WARSAW CYCLOTRON*

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Commissioned in 1994, the Warsaw Cyclotron is operated by the Heavy Ion Laboratory of the University of Warsaw as a "User Facility" with around 100 national and foreign users per year. The isochronous $K_{\max} = 160$ machine currently delivers around 3000 h of heavy ion beams per year, ranging from B to Ar, with energies between 2 and 10 MeV/nucleon. The current research programme comprises nuclear physics, atomic physics, materials science, solid state physics, biology, particle detector development and testing. In this article the experimental stations placed on the beam-lines of the cyclotron and some recent nuclear physics experiments are presented.

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1. Introduction

The Warsaw Cyclotron, jointly founded by the Ministry of Education, the Polish Academy of Sciences and the Polish Atomic Energy Agency and commissioned in 1994, is operated by the Heavy Ion Laboratory (HIL). Equipped with a 10 GHz ECR (Electron Cyclotron Resonance) ion source, the cyclotron provides beams of elements available as gases and gaseous compounds from ^{10}B up to ^{40}Ar with a maximum energy of 10 MeV/amu. The beam is extracted by the stripping method. The stripper can be positioned well inside the magnet in a continuous way allowing smooth changes in the extracted beam energy. The extracted beam intensities vary from tens of particle picoamperes to several hundred nanoamperes, depending on beam species, the accelerated ion charge state and ion energy. Further information about the Warsaw Cyclotron may be found in Ref. [1].

The Heavy Ion Laboratory is placed at the heart of the Ochota scientific Campus, where the research and teaching units of the University of Warsaw, the Polish Academy of Sciences and the Warsaw Medical Academy amicably coexist, forming a site with great interdisciplinary opportunities. Fig. 1 gives a current aerial view of the North part of the Campus. In the near future, new scientific and teaching units will appear there.

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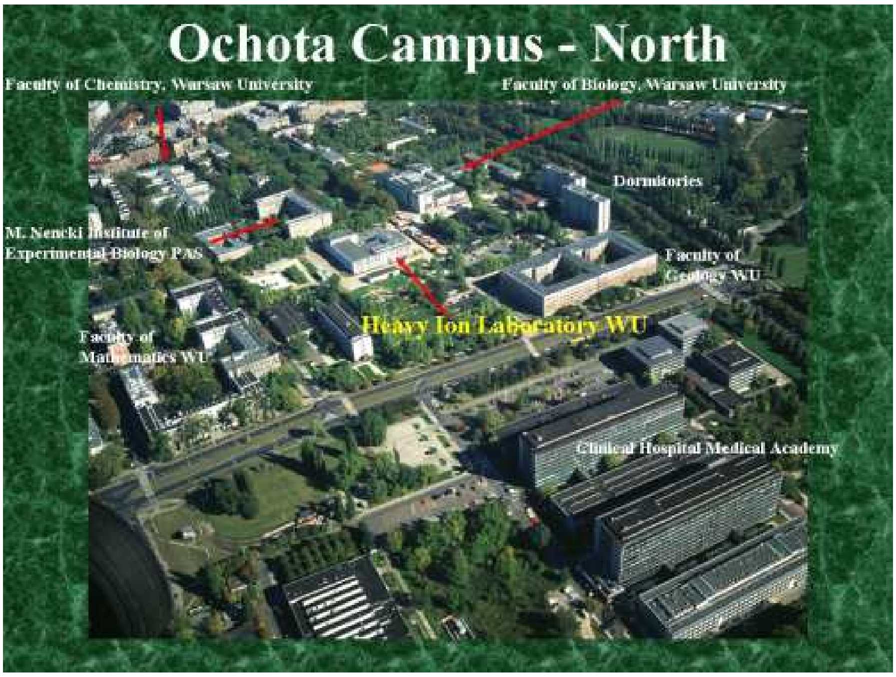

Fig. 1. Aerial view of the Ochota Campus-North.

2. Experimental stations

The large switching magnet in the cyclotron hall directs the heavy ion beam towards one of the seven beam lines (see Fig. 2). The currently operating experimental stations are:

- IGISOL — based on a Scandinavian type isotope separator with a laminar helium flow gas cell (helium chamber for the IGISOL device) guiding the ions to the separator ion source [2]. Its efficiency for stopping, guiding and extracting heavy ion reaction products is about 6%, measured using ^{213}Rn produced in a reaction induced by a 6 MeV/amu ^{14}N beam. The IGISOL system is shown in Fig. 3.

- OSIRIS II — a gamma-ray multidetector system consisting of 12 Compton-suppressed HPGe counters, a 50 element BGO γ-multiplicity filter, a four-sector HPGe polarimeter and a 4π Silicon Ball for charged-particle multiplicity measurements. Recently, a conversion-electron spectrometer was built [3] and successfully tested inside the multidetector system, as well as a charged-particle detection set-up using 110 silicon PiN diodes dedicated to Coulomb excitation studies [4]. The OSIRIS II system is shown in Fig. 4.

- JANOSIK, a multidetector system for the study of Giant Dipole Resonances. It consists of a large, high-purity lead-shielded NaI(Tl) crystal (25.4 cm×29.0 cm) and a 32-element multiplicity filter (barium fluoride and NaI(Tl) detectors). It is designed to detect photons in the range from 4 to 40 MeV. A movable arm allows angular distributions of the radiation resulting from heavy ion bombardment to be studied. The JANOSIK system is shown in Fig. 5.
- ICARE — a charged particle multidetector system consisting of a 1 m diameter reaction chamber in which 48 $E - \Delta E$ gas, CsI and semiconductor telescopes are installed. TOF (time-of-flight) set-up with MCP (microchannel plates) detectors can be conveniently installed for coincidence experiments using about a 1 m flight base line. The ICARE multidetector system was designed and constructed at IRES (Strasbourg) and recently moved, installed and tested at the HIL. The ICARE detector set-up is shown in Fig. 6.
- SYRENA — a large, 80 cm diameter, universal scattering chamber equipped with silicon and gas detector telescopes allowing angular distributions of charged particles to be measured and used for light particle-light target nuclear reaction studies. Currently being progressively replaced by the ICARE system.
- CUDAC — a small scattering chamber, equipped with an array of backward semiconductor detectors (PiN diode type) and forward monitoring Si counters. The compact geometry of this chamber allows the use of external gamma-ray detectors for Coulomb excitation studies. CUDAC is also used for measurements of fusion barrier height distributions.

3. The current nuclear physics research programme

The Heavy Ion Laboratory is a typical "User Facility" with around 100 national and foreign users per year. The cyclotron delivers around 3000 h of beam on target, of which about 70% is devoted to nuclear physics research. Currently, the following investigations are being vigorously pursued:

- Electromagnetic properties of rotational bands resulting from chiral symmetry breaking in odd–odd nuclei. Using the OSIRIS II multidetector system and the Doppler-shift attenuation method the lifetimes of excited states in nuclei of mass around 130 are determined. The resulting transition probabilities in supposed chiral partner bands ("yrast" and "side") are compared [5–12]. The chiral symmetry breaking contribution to these bands is then deduced.

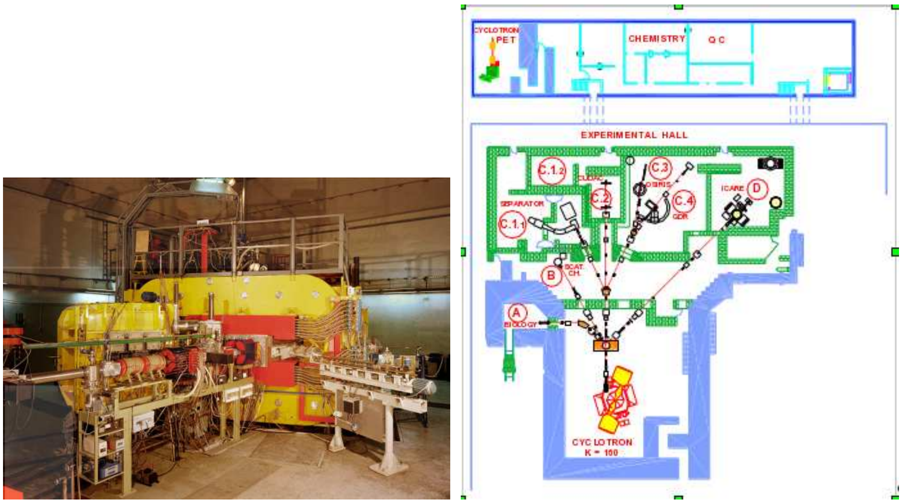

Fig. 2. The $K_{\max} = 160$ heavy-ion cyclotron and the layout of the beam lines with the experimental stations. The upper part of the layout shows schematically the PET Radiopharmaceuticals Production Centre (see Sec. 4).

Fig. 3. The IGISOL device, based on a Scandinavian type isotope separator with an additional gas catcher ion guide.

- Distribution of fusion barrier heights and their description by currently available reaction codes. Fusion barrier distributions are extracted from excitation functions of the sum of the cross-sections of all quasielastic channels (elastic and inelastic scattering and transfer reactions). The experimental programme till now was mainly concentrated on reactions with strongly deformed ^{20}Ne projectile, impossible to accelerate in electrostatic devices. A simple reaction chamber (CUDAC (see Fig. 2) [13, 14]) and recently the ICARE multidetector system with the set-up for TOF measurements are employed [15].

- Coulomb excitation studies. A systematic study of the electromagnetic properties of even–even molybdenum isotopes has been performed at the HIL using CUDAC and the OSIRIS II set-up. A large number of electromagnetic matrix elements for the low-spin states in ^{96,98,100}Mo have been determined. Quadrupole deformation parameters, including triaxiality, were deduced indicating different shapes for the ground and low-lying 0^+ excited states [4, 16–18]. The Coulomb excitation data analysis software GOSIA is maintained and developed by a HIL-Rochester collaboration.

- Light projectile-light target nuclear reaction studies. This large experimental programme led by Kiev in collaboration with Kraków and Warsaw aims at the determination of nuclear optical potential parameters for the exotic nuclei produced in transfer reactions. An impressive number of systems have been studied such as: ^{7}Li+^{18}O [19], ^{7}Li+^{10,11}B [20, 21], ^{11}B+^{14}C [22], ^{11}B+^{12}C [23] and analyzed by coupled-reaction-channels models. The results obtained have implications for studies of weakly-bound radioactive nuclei and the possible neutron-halo structure of their ground or excited states. The experiments were performed at the SYRENA experimental station [24] and are currently being moved to the ICARE set-up.

- Giant Dipole Resonance studies. Using the JANOSIK experimental station the high energy gamma rays issuing from the decay of compound nuclei with excitation energy E^* around 50 MeV and with Z from 16 up to 30 have been measured. A comparison of their intensities for the $T = 0$ entrance channel with those from the neighbouring $T \neq 0$ one indicates a strong Z dependence of the isospin mixing in hot nuclei [25–28].

- Trans-lead nuclear isomers investigated by isotope separation on-line. The efforts of the Warsaw IGISOL team in collaboration with Orsay and Jyväskylä were crowned with success after a long construction and testing period, with excellent efficiency being obtained in the IGISOL system for heavy ion induced reactions [2]. Recently [29] a new high-spin isomer in ^{216}Fr was discovered by studying the α-decay chains. Preliminary results of similar isomer searches in other trans-lead nuclei will be announced soon.

Fig. 4. OSIRIS II — Gamma-ray multidetector system.

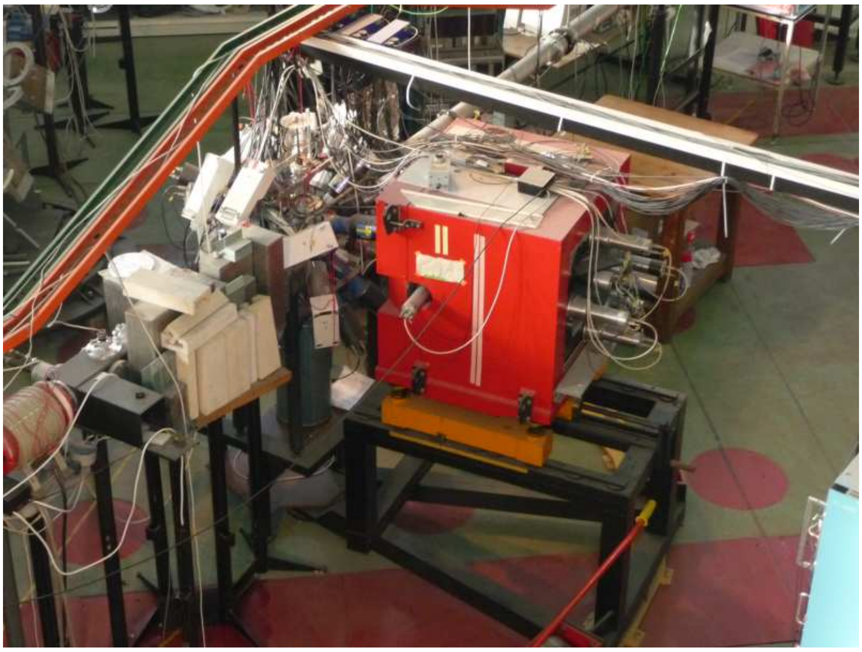

Fig. 5. JANOSIK, large NaI(Tl) crystal and its ancillary detectors for high-energy gamma ray studies.

- Nuclear structure studies using the OSIRIS II multidetector system. "Classic" studies of excited state properties, including level energies, spins, half-lives and branching ratios have been conducted almost from the beginning of operations at the Warsaw Cyclotron. Recently, data for neutron deficient Sn and Sb [30,31] and trans-lead nuclei [32] were published, including their band structure and transition probabilities. These experiments take advantage of the pulsed-beam structure of the cyclotron as well as the newly installed conversion electron spectrometer.

4. Ongoing new projects

Three large-scale laboratory development projects are currently underway:

- A new multidetector gamma-ray spectrometer EAGLE (central European Array for Gamma Level Evaluations) is currently at the construction and assembly phase. This array will be able to accommodate up to 30 HPGe detectors with anti-Compton shields together with a number of ancillary detectors, such as an inner-ball multiplicity and sum-energy filter, a conversion electron spectrometer and a Coulex chamber including 100 Si PiN diodes. Other detectors such as a recoil filter and a neutron wall are also being considered. In its first operational phase EAGLE will host the HPGe detectors from the OSIRIS II array. Later, collaboration with the European Gamma Pool is requested.

- A new ECR ion source (SUPERNANOGAN) has been ordered from PANTECHNIK (France) and will supply the Warsaw Cyclotron in parallel with the current home-made source. Metallic ion beams and higher beam intensities are expected.

- Radiopharmaceuticals Production Centre. Besides the heavy ion machine the Laboratory will soon be equipped with a second, low energy (16.5 MeV p) high current proton–deuteron cyclotron for the production of short-lived radiopharmaceuticals for Positron Emission Tomography (see the upper part of the laboratory layout in Fig. 2). This project is jointly funded by the Ministry of Science, the International Atomic Energy Agency, the Ministry of Health and European Structural Funds.

Fig. 6. The ICARE reaction chamber with vacuum and gas system.

5. Conclusions

The Warsaw Cyclotron is the largest nuclear physics facility in Central Europe. The Heavy Ion Laboratory attracts users not only from Poland, but also from a number of nuclear centres abroad, and is a significant element of the European Research Area. Besides the experimental programme in nuclear physics presented in this article, activity in other domains of science is pursued at the Laboratory using nuclear physics tools. In the near future it is expected to have a strong impact on nuclear medicine applications and teaching when the PET Radiopharmaceuticals Production Centre becomes operational.

I wish to dedicate this article to the memory of a number of wonderful and enthusiastic people who, with their knowledge and hard work, contributed to the success of the venture called "the Warsaw Cyclotron". Let me mention here some names: Sławek Chojnacki, Tomek Czosnyka, Jurek Dworski, Czesław Weychert, Lucjan Zemło and many others. Preparing the conference presentation and writing this text I was greatly helped by discussions with: Jarek Choiński, Kasia Hadyńska, Marta Kicińska-Habior, Janek Kownacki, Witek Kurcewicz, Jarek Perkowski, Eryk Piasecki, Krzysztof Rusek, Julian Srebrny, Agnieszka Trzcińska, Andrzej Wojtasiewicz and Kasia Wrzosek.

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