Program
for Experimental Studies
at Cyclotron Center Bronowice IFJ PAN Kraków

version 1.0

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Foreword

In December 2012 a new Proteus-235 proton cyclotron, delivered by the Belgian company Ion Beam Application (IBA), will become operational at the Institute of Nuclear Physics PAN in Kraków. This cyclotron, partly financed by the structural funds of the European Union within the Operational Programme "Innovative Economy", was to be used mainly for proton radiotherapy of eye cancers. Now, within the National Centre of Hadron Radiotherapy project, the proton beam is also planned to be used with a special rotating gantry, allowing treatment of complicated cancer cases with a precise scanning beam.

Protons of initial energies ranging between 60 MeV and 250 MeV when stopping in the irradiated tissues, will deposit most of their energy (or dose) at their stopping ends, a phenomenon known as the Bragg peak. Also, unlike in photon beams, proton ranges are extremely well defined by their initial energy, thus critical organs or healthy tissues immediately behind the tumour volume can be spared by carefully adjusting the proton energy. Protons are able to deliver a much higher dose of ionizing radiation to the tumour volume and are able to better spare the neighbouring critical organs or healthy tissues than other radiotherapy modalities. This is of particular importance to paediatric patients in whom the possible occurrence of secondary radiation-induced cancer should be minimized.

In addition to medical applications, an experimental hall has been designed for research in the field of nuclear physics, radiobiology, dosimetry and medical physics. The new cyclotron equipped with a dedicated energy selector will be able to deliver a fairly monoenergetic beam of protons in the energy range between 70 MeV and 230 MeV, and currents between 1 nA and 500 nA. We plan a nuclear physics research programme using this beam, including gamma-ray spectroscopy (giant resonances, isomer decays, etc.), nuclear reactions (three-body forces, studies of nuclear symmetries, fission and spallation mechanisms, etc.), and other studies in this area. We are also considering in-beam tests of radiation detectors.

We are looking forward to your ideas and to collaborating with you!

Marek Jeżabek, Adam Maj and Paweł Olko

Preface

Installation of a new cyclotron facility at the Institute of Nuclear Physics Polish Academy of Sciences in Kraków opens new possibilities for experimental nuclear physics in Poland. Creation of the Cyclotron Center Bronowice (CCB), equipped with the new cyclotron, delivering beam of protons with energies up to about 250 MeV to an experimental area dedicated for fundamental physics research, will enable scientists and students to participate again in domestic, top-class research.

Well before the accelerator itself comes to its foreseen position, in parallel with building of the whole complex, scientists start to propose a number of projects which should be conducted at CCB. The first call for expressing interest in using CCB infrastructure for fundamental research showed that the need for such a facility has existed in the community since a long time and that we are ready to take full advantage of the forthcoming possibilities. The Editorial Committee of the Physics Case has put together outlines of projects which can be realized at CCB and acknowledges their high scientific importance. They are presented in the following, on purpose limited to just short abstracts, to be easily looked at in full by wide audience. Already now the potential program is very rich, covering fundamental studies of several persisting problems, as well as addressing issues of applied nuclear physics. CCB can also become testing laboratory for devices developed by international collaborations for projects planned at large facilities like FAIR or SPIRAL.

The Physics Case Group and the User Board will try to attract even more interesting projects and scientific groups from all over the world, to eventually construct out of the best projects a top-rated physical program for the new facility. But the activities planned for CCB can be viewed in an even wider scope. The foreign partners of the presented projects express interest in forming and international network of nuclear physics laboratories, in which complementary studies can be performed, exploiting different facilities. Realization of such prospects will lead to a new, truly global community of nuclear physics research.

Maria Kmiecik and Stanisław Kistryn
(Editors and Coordinators
of the Physics Case Group)

Dynamics of few-nucleon systems

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We propose a research program in the domain of few-nucleon systems to be performed with proton beams at the new cyclotron facility of the Cyclotron Center Bronowice. We aim at precise measurements of the differential cross sections of the elastic scattering and the kinematically complete deuteron breakup processes in proton-deuteron collisions. The studies, carried out over a wide range of beam energies, in almost the whole phase space, would provide very rich, worldwide unique data sets for systematic verifications of current and future approaches to describe the interaction details in few-nucleon systems.

We assume that the undergoing negotiations with foreign partners (Swiss laboratories at Uni Basel and PSI, KVI, FZ Jülich) will be successfully completed with decisions of transferring different experimental equipment to Cracow. The main purpose is to obtain the whole detection setup BINA from KVI, which includes liquid target assembly, the detector system (wire chamber and scintillation hodoscope) with the complete electronics.

Below we present the headlines of the planned research. In the first phase, tests with the AIC-144 beam at the old experimental hall are to take place, and, provided their outcome concerning the beam characteristics allows, also certain measurements are performed. Moreover, investigations towards optimization of the system for the second phase are foreseen. The main activity is grouped in the second phase, that is measurements with the optimized setup at the new CCB facility. We consider also possible extensions of the program as the third phase.

1. <u>Stage I</u>

- **Feasibility studies**

  As the first step AIC-144 beam studies at the old experimental hall are considered, with the focus on optimizing beam collimation and beam profiles.

- **Performance tests of detector elements**

  With the optimized beam, tests of specific parts of the detection systems are foreseen. Development of the measuring procedures and methods (e.g. beam energy degradation, precise intensity monitoring) is to be carried out. Upgrade of relevant detector elements is to be performed on the basis of the test results.

- **Measurements**

  If the beam parameters are found to be satisfactory, it is conceivable to perform the elastic scattering and breakup reaction measurements at selected kinematical configurations, with a number of semiconductor telescopes positioned at specific angles in a vacuum scattering chamber; they arrangement should be based on theoretical advises, pointing at the most interesting (showing the highest sensitivity to certain effects) phase-space configurations. Even discrete geometries can be very valuable in studies of e.g. three-nucleon force effects or Coulomb force influences.

2. Stage II

- **Feasibility studies at the new cyclotron**

  The tested previously detector elements and the simple experimental setup will be used to verify and optimize beam properties and investigate background conditions at the experimental station in the new CCB hall. After installation of the BINA setup, performance of all experimental subsystems will be checked (liquid target assembly, detector electronics, the full trigger electronics and data readout/acquisition system, including on-line monitoring software).

- **Elastic scattering in proton-deuteron system**

  Elastic scattering can be investigated with the test scattering chamber (only selected registration angles) and LD_2 target, providing physical results and a benchmark for measurements with the BINA system. Scan over beam energies will allow for relative normalization to the precisely known cross section values at several energies, eliminating in this way systematic uncertainty due to limited precision of the liquid target effective thickness determination.

- **Cross section measurements with BINA**

  After BINA detection system is installed and brought into operation, the measurements of elastic scattering and breakup reactions will be carried out, with an almost complete phase-space coverage (full detection efficiency for charged particles). These studies, performed over wide range (70 – 230 MeV) of proton beam energies, will provide the first (world wide) so consistent and systematic data base for investigating 3N continuum at medium energies.

- **Electromagnetic reactions in 3N system**

  Including detection of gamma-quanta will enable to study also processes of radiative capture, like $p + d \rightarrow {}^3He + \gamma$.

3. Possible extensions – stage III

- **New detector for few nucleon systems studies**

  Development of possibly optimal detection system, having all advantages of BINA, but even more versatile and avoiding its shortcomings (lower energy threshold, increased neutron detection efficiency).

- **Four nucleon systems**

  An extension of studies to four nucleon systems, i.e. measurements of two-, three- and, ultimately, four-body exit channels in reactions induced by proton beams on A=3 nuclei.

- **Measurement of analyzing powers in proton-deuteron collisions**

  Demanding and ambitious task is a development of vector and tensor polarized deuterium target (cryogenics, strong magnetic field). International collaboration partners are currently being identified.

- **Proton scattering on light nuclei**

  Studies of proton-induced reactions on light targets, leading to few-body exit channels.

Study of particle and gamma decays of high-lying resonance states by inelastic scattering of 200 MeV protons

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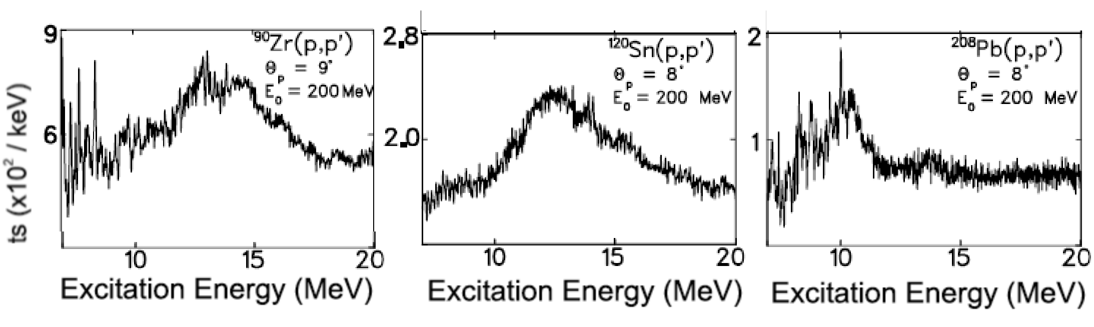
Giant Resonances are fundamental high frequency modes of excitation of nuclei, providing basic information on nuclear structure and on the effective nucleon-nucleon interaction. They can be excited employing different probes (protons, alphas, photons and heavy ions) and can decay directly by emission of particles and γ's.

Inelastic scattering of protons at 200 MeV has been shown to successfully populate the Giant Quadrupole Resonance in a number of stable targets, as for example ^{208}Pb, ^{56}Ni, ^{90}Zr and ^{124}Sn. This is illustrated in the figure below, showing high resolution proton spectra detected in a magnetic spectrometer [1]. Besides the pronounced resonance structure of quadrupole nature (in the 10-15 MeV region), the proton spectra give evidence for a number of lower-lying states of dipole nature (below particle threshold), which have been associated to the so called "pygmy" dipole resonance, arising from the oscillation of the neutron excess with respect to the proton-neutron inert core [2].

The previous observations call for additional investigation of these resonance states. In particular, their particle and gamma decay has never been investigated in details, although it would provide additional/basic information on the microscopic structure of such states and on the damping mechanisms into more complex degrees of freedom.

We therefore propose to measure particle and gamma decays of giant resonances produced by inelastic scattering of protons at 200 MeV. The experimental setup will consist of an array of 8 large volume BaF_2 detectors (HECTOR array) for the measurements of high-energy γ-rays, while the scattered protons will be detected by a system of E-ΔE Si telescopes, which will also allow to detect particles emitted by the resonance states of interest.



[1] A. Shevchenko et al., Phys . Rev. Lett. **93**, 122501-1 (2004).
[2] J. Endres et al., Phys. Rev. Lett. **105**, 212503 (2010).

Giant Dipole Resonances in hot nuclei studies using proton beams

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The Giant Dipole Resonance (GDR) is the collective excitation of nucleus described by the oscillations of neutrons against protons. It delivers information on nuclear structure, for example, single particle levels evolution, effective shapes of hot nuclei as a function of temperature/spin, damping mechanism and isospin mixing. These are experimentally obtained from the measurement of high-energy gamma rays emitted in the GDR decay.

In heavy ion fusion reactions, GDR gamma decay is used to probe nuclear shape/deformation and the temperature dependence of GDR damping mechanism. The nuclei produced in such processes are characterized with spin and temperature distributions and therefore it is difficult to distinguish the spin induced phenomena from the temperature one.

The use of proton beams provides an alternative approach for the investigation of nuclear structure using the GDR as a probe. In proton induced fusion-evaporation reactions, the fused compound nuclei have an extremely low angular momentum values, making possible the study of nuclei at a well-defined temperature. Performing fusion-evaporation reactions using high energy proton beams offers the possibility to investigate nuclei in a high temperature region without the influence of angular momentum.

We propose to study the temperature evolution of the GDR properties. Such study will be performed using the compound nuclei produced in fusion reactions using proton beams of energies up to 200-230 MeV. The predicted maximum temperature is of the order of 3-6 MeV, depending on the mass, of the selected compound nucleus. As stated before, the angular momentum transferred in such reactions is small (up to 10-18 $\hbar$) and doesn't change significantly with beam energy. The high energy gamma rays from the GDR decay could be measured by large volume BaF_2 crystals from HECTOR array or $LaBr_3$/NaI phoswich detectors from PARIS prototype. For very high beam energy other reactions e.g. fission, spallation, multifragmentation are possible to occur. In such cases, events corresponding to the compound nucleus decay could be chosen by the discrete transitions measured in evaporation residues identification or by tagging the fusion residue.

A possibility of using the NESSI detector at CCB and spallation reaction measurements with proton beam of ~ 200 MeV energy

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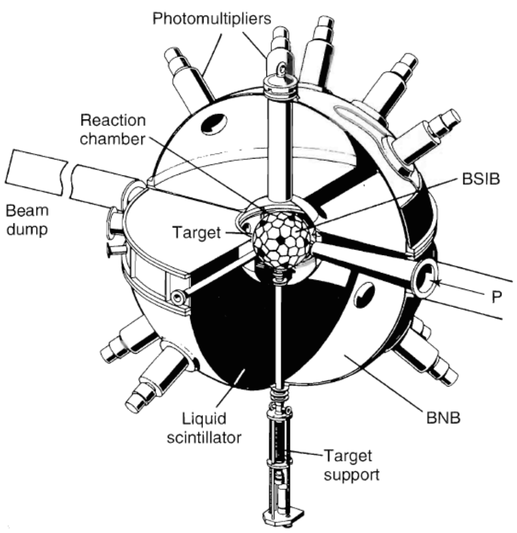
NESSI – NEutron Scintillator and SIlicium detector BNB – Berliner Neutron Ball,



Volume: 1.5 m^3
Diameter: 140 cm
Diameter of reaction chamber: 40 cm
Liquid scintillator: NE343 + 0.4% Gd (gadolinium)
Number of PM: 24
BSiB – Berliner Silicon Ball,
162 silicon detectors,
Acceptance: 90% from 4π
Radius: 10 cm
Single detector
Active surface: 763 mm^3
Thickness: 500 μm
Energy resolution < 100 keV
BSiB – improvement,
6 detectors in BSiB for angles between 30^o and 150^o were replaced by the telescopes consisted of two silicon detectors ΔE (80 μm and 1000 μm thicknesses, full depletion) and CsI scintillator with thickness 7 cm and photodiode readout.

In interaction of proton beam with energy much greater than 100 MeV with nuclei, besides of fusion-fission reaction, the **spallation** process becomes important. Spallation processes products can dissipate energy in evaporation of nucleons and light charged particles or by fission.

POSSIBLE EXPERIMENTS WITH PROTON BEAM OF 200 MeV ENERGY USING THE „SYRENA" EXPERIMENTAL SETUP (HIL Warszawa).

Investigation of the nucleon distribution in nuclei.

The nucleons distribution in nuclei can be deduced from experiments of elastic scattering of high energy protons on nuclei. Experiments can be performed with different targets (A = 6 – 238). The classical ΔE – E method together with scintillation NaI detectors can be used in these experiments.

Investigation of cluster structure of light nuclei.

High energy protons can produce clusters x in collisions with A nuclei. This A(p,px)Y reaction can be used for investigation of the cluster structure of light nuclei. The experiments can be inclusive with classical ΔE – E method and also correlation experiments ΔE – E with registration of px and/or xY correlations and energy spectra of the reaction products.
The experimental data should be analyzed with the CRC (Coupled Reaction Channels) method with using the spectroscopic factors of x clusters.

Search for the Giant Pairing Vibrations

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It has long been predicted that in nuclei there should exist a collective mode of excitation based on the coherent superposition of 2–particle (or 2–hole) states in the second major shell above the Fermi surface (it is analogous to the giant resonances of nuclear shapes which involve the coherent superposition of p-h excitations). This mode is called Giant Pairing Vibration (GPV) and should manifest itself as a concentration of strength, with L=0 character, in the high–energy region (~10 MeV) of the pair–transfer spectrum. Despite efforts using conventional transfer reactions, the GPV has never been identified.

We would like to undertake a search for GPV by using the (p,t) neutron-pair transfer reactions on various targets and at various beam energies. A proton beam would be delivered from the cyclotron at the Centrum Cyklotronowe Bronowice. As the GPV may have a gamma-decay branch, we propose to measure coincidences between the outgoing tritons and gamma rays emitted from the pair-transfer product in the energy range of 4 - 20 MeV. Tritons would be detected in a set of silicon telescopes covering a sizable solid angle. Gamma rays would be measured with the help of an array consisting of BaF_2 and $LaBr_3$ scintillator detectors.

Studies of isomers populated in proton induced fission of ^{238}U and other heavy targets

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We propose to search for nano- and microsecond isomers in neutron-rich nuclei produced in proton induced fission of heavy targets. The distribution of products for fission induced by energetic 230 MeV protons differs from that of spontaneous fission. Thus, the exotic isotopes that will be produced with sufficient yield and studied are to large extent unknown. For many of those nuclei the only information available comes from the beta decay studies in which the structure of low-lying and usually low-spin states is revealed. The aim of our experiment is to search for nano- and microsecond isomeric states of yrast character which will be populated in fission and will decay by cascades of gamma-rays. Identification of such states and their decay modes carries important spectroscopic information.

We will use a number of Germanium detectors for gamma coincidence measurements supplemented by a tagging device, possibly a Delta E – E Si detector for Z identification of fission products which will be implanted into the Si detector in front of the Germanium detectors setup. This idea is similar to the Isomer-scope concept for experiments with neutron-rich radioactive ion beams at Oak Ridge and GANIL. For the Germanium detectors, sufficient efficiency can be obtained using a set of 4 segmented Clover detectors. For the Delta E – E telescope, we propose to use 20 microns thick 50x50 mm Delta E detectors coupled to a CD type thick Si detector serving as an active catcher.

Investigations of nuclear reactions relevant in cancer therapy

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Goal of the proposed investigations is creation of the experimental database of cross sections for nuclear reactions in p+^{12}C, ^{14}N, ^{16}O and ^{12}C+^{12}C, ^{14}N, ^{16}O systems, in a broad energy range of 40-400 MeV/nucleon. The charged reaction products as well as neutrons and γ's will be measured. The data will be parametrized or general reaction models will be constructed. The results will be utilized in GEANT4 code, which will be adopted for precise calculations of the dose in hadron therapy. In parallel, studies on applications of the secondary reaction products to monitoring the deposited dose will be carried out.

One of the most important aspects in hadron therapy is a precise calculation of the dose during the therapy planning and real dose monitoring during irradiation itself. Both these aspects are of importance since small uncertainties caused by tissue in-homogeneity can result in a displacement of the Bragg peak into an adjacent organ and hence a corresponding undesirable irradiation of healthy tissue. These problems arise in the therapy with the proton beam as well as with the ^{12}C beam, however there are specific differences depending on the applied projectiles. The electromagnetic processes responsible for beam energy loss and the corresponding energy deposition in the tissue are well known. However, in order to achieve sufficient precision detailed knowledge of the nuclear reactions induced by beam in the tissue material is also required. For dose monitoring the secondary nuclear reaction products may be used. Presently, investigations are performed on the application of PET method utilizing reaction products with β^+ activity. Disadvantages of this method are a long time necessary for the measurement and displacement of the produced isotopes due to biological processes. These disadvantages may be eliminated when monitoring is based on neutrons or γ's, which emerge from the patient body without large distortions.

The best method for measuring the charge reaction products is the use of inverse kinematics. Therefore such measurements will be performed at GSI or Heidelberg, in collaboration with the group from RWTH Aachen University. At present a detection system for these measurements is constructed. At CCB measurements with the proton beam are proposed, with the detection of neutrons and γ's. The aim of these investigations is validation of the irradiation simulations and measurement of cross sections for neutron and γ emission. In these measurements a part of the presently being constructed system can be used. Test measurements of the detection systems constructed for the dose monitoring during irradiation are also planned.

There is a possibility to start measurements with the currently operating cyclotron at CCB. For that purpose a detection system for γ's with energy up to 20 MeV is necessary. Such measurements would deliver information about γ spectra and γ production cross sections close to the Bragg peak. Such experiments can be continued at FZ Juelich at higher beam energies. The results will form a very good basis for construction of a detection system for dose monitoring purposes.

In beam tests at CCB of acceleration components for the EURISOL radioactive beam facility

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EURISOL program aims at delivering radioactive ion beams, the tool that can be used by physicists to reach exotic nuclei and will help to investigate the nuclear structure at the extremes of the nuclear landscape. The R&D being performed in the framework of the EURISOL project will lead to a solution enabling a production of exotic fragments by irradiation of heavy targets with intense proton beams, separation and further acceleration.

In the first step it is investigated a possibility to use of intense H- beam at 1GeV energy, that will allow for multiple extraction and simultaneous irradiation of several target stands. It is however required that after splitting the beam emittance will be preserved.

We propose to build in IFJ PAN a prototype of a "Magnetic Chicane" [1] and perform in beam tests at CCB in order to evaluate its influence on the beam emittance. It seems that the excellent beam parameters required for the proton therapy will make the CCB proton beam particularly useful also for such applications.

[1] A.Facco et al., Phys. Rev. Special Topics - Accelerators and Beams **10**, 091001 (2007).