Exotic excitations of nuclei and three-body forces - basic nuclear physics research at the CCB

The Proteus C-235 cyclotron at the CCB (Cyclotron Centre - Bronowice) is not only suitable for medical applications - it is also an excellent tool for basic research in the area of nuclear physics.

Atomic nuclei are many-body objects the properties of which are determined by the coexistence of strong, weak and electromagnetic fundamental forces. Despite their structural complexity, nuclei are highly ordered and can be well described by theoretical models. Here, the characteristic feature is that two complementary approaches can be successfully applied in describing the atomic nucleus: the microscopic approach, where individual nucleons are viewed as being acted upon by the nuclear mean-field potential - this results in their shell structure, and the mesoscopic approach where the nucleus is considered as a complex system, characterized by specific symmetries and by collective properties. To unravel the interplay between these different approaches to the structure of the atomic nucleus is a major challenge of modern nuclear physics. The research programme, implemented by using proton beams from the CCB Proteus-235 cyclotron is aimed at clarifying certain aspects of these complementarity issues.

Our research focuses around two areas of experimental nuclear physics: on gamma spectroscopy of exotic excitations of the nucleus, and on many-body interactions occurring in the atomic nucleus. The first area of this research involves measurements of gamma quanta emitted, e.g. during the decay of a giant or “pygmy" resonance. Giant resonances have long been known to be basic excitations of atomic nuclei at energies of 10-20 MeV, much higher than the neutron separation energy; they appear to be synchronous oscillations of all protons relative to neutrons. Such excitations convey important information about the structure of the nucleus. Pygmy resonances, which have been discovered only recently, represent another collective state of atomic nuclei, at energies close to the neutron binding energy (7-10 MeV). These excitations are usually interpreted to be oscillations of the neutron skin relative to the remaining core of the nucleus; however, experimental confirmation of this hypothesis is yet rather inconclusive due to the present lack of sufficiently precise experimental data.

Pygmy resonances can be excited by Proteus C-235 cyclotron-accelerated protons interacting with target nuclei along their paths. To register high energy gamma quanta emitted from excited nuclei, the HECTOR detection system will be used, working in coincidence with the KRATTA detection system, which allows light charged particles to be identified and their energy measured. Gamma quanta can also be measured using "phoswich” type scintillation detectors which are implemented in the PARIS state-of-art detection system. PARIS is being constructed within an international collaboration coordinated by IFJ PAN, bringing together physicists from 18 countries. The uniqueness of research in this area at the CCB is in the special ability of the Proteus cyclotron to supply intensive proton beams with energies up to 230 MeV, but with rapid variation (within seconds) of their energy and intensity, combined with our unique detection system for measuring gamma quanta of high-energy.

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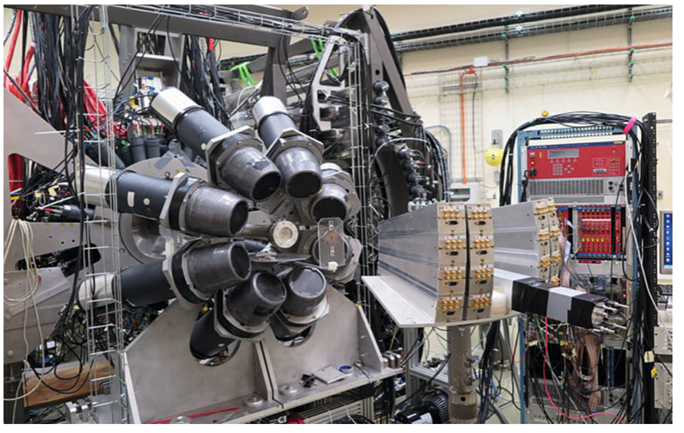
The planned research on excitations of nuclei in the (p,2p) reaction also concerns the above-discussed domain. The (p,2p) process may result in the ejection of a proton located in a deep single-particle state, leading to a highly excited hole state in the nuclide, which has one proton less than the target nucleus. The decay of such highly excited single-particle states has not yet been sufficiently investigated, though it could provide key information on the contribution of direct processes against processes leading to thermodynamic equilibrium. At the CCB it will be possible to measure the decay of highly excited single-particle states by employing the combination of a technique for the detection of two protons emitted at a relative angle close to 90 degrees (KRATTA) in coincidence with gamma quanta (HECTOR or PARIS), the spectrum of which will determine the cross sections of final products of this reaction.



The main experimental detection systems at the CCB: HECTOR (left), KRATTA (right) and BINA (rear)

Experimental study of many-body interactions in the nucleus is another research project of concern to us. In theoretical models of the atomic nucleus, it has so far been assumed for simplicity that the nucleus, which is a many-body system, can be accurately described through interactions between pairs of nucleons alone. It is known, however, that in systems of complex objects, such as are atomic nuclei, three-body forces appear. It has recently been shown that indeed three-body forces are necessary to describe light atomic nuclei in ab-initio calculations, and that use of three-body forces in the description of heavy nuclei can significantly improve the quality of predictions, e.g. of their binding energy. In this context, experimental determination of the parameters used to describe three-body forces is of paramount importance.

Three-body forces can be tested, e.g. by colliding a proton with a system of two nucleons, such as a hydrogen nucleus with one neutron, i.e. a deuteron. Research in this area using the proton beam from the CCB cyclotron and a deuterium target is currently under way and will continue. The detection system in this case is the BINA detector, which is used to record the direction and energy of the two protons emitted after proton - deuteron collisions. The range of proton energies available from the Proteus C-235 cyclotron and the possibility of their rapid changes makes the CCB laboratory an ideal and unique place in Europe for research on many-body forces. The planned construction of a polarized target, to be mounted on the Proteus C-235 beam, will further extend the range of this research.

The proton beam at the CCB is also used for testing advanced detection systems constructed within large international experiments in nuclear physics. The first measurements in which teams from France, Spain, Japan, Germany, Poland, Romania, Sweden, Turkey, Hungary and Italy participated, took place in March 2013.

Individual research programmes are coordinated by internationally recognised specialists from Poland and abroad. The scientific merits of projects are assessed by the IAC (International Advisory Committee), in which globally recognised nuclear physicists participate, several being leaders of major nuclear physics laboratories in Europe, the USA and Japan.