The EXPERT project: part of the Super-FRS Experiment Collaboration

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Abstract. The EXPERT project is subtopic of the Super-FRS Experiment Collaboration, being part of NUSTAR@FAIR. The experiments will be aimed at the nuclear systems in the most outer regions of the nuclear landscape. Special attention will be payed to few-body decays which are expected to be a regular phenomena in the vicinity and beyond the driplines. Studies of rare and not yet observed (multi-)nucleon radioactivity, many-body decays of resonance states of unbound nuclei as well as beta-delayed decays and search for exotic excitation modes will be carried out. The scientific program will be performed using the modular detector system containing the methods for detection of all particle and radiation types.

1. Introduction
The EXPERT project [1] is a part of the scientific program of the Super-FRS Experiment collaboration in the frame of NUSTAR@FAIR [2]. It is aimed at studies of the nuclear landscape beyond the proton and neutron dripline and intends to push researches up to limits of nuclear existence. The program will be realized by means of a compact modular detector setup supplementing the Super-FRS facility which will be employed in a separator-spectrometer mode [3]. Employment of the EXPERT instrumentation in different scenarios will allow to investigate phenomena of radioactivity, resonance decays, beta-delayed decays and exotic excitation modes either by means of in-flight or implantation-decay techniques.

2. Physical case
Arbitrary combination of protons and neutrons does not give a stable nucleus. If more and more nucleons of the same type is added to nucleus, a boundary of stability is reached and newly formed nucleus will undergo an immediate emission of the nucleon (proton or neutron). Boundaries of nuclear particle-stability are called driplines. The nuclei beyond the driplines still show individual states and may have half-lives exceeding far the characteristic nuclear time $10^{-21}$ s. Those unbound states are called resonances, and their lifetimes defined by the centrifugal and Coulomb barriers are strongly affected by nucleon correlations. The main objectives of the EXPERT project are focused on the nuclei in the vicinity of the driplines and may be schematically enumerated as:

(i) Exotic 2p radioactivity studies and search for novel types of radioactive decays: 4p, 2n, 4n.
(ii) Studies of p, 2p, 4p, 6p, 1n, 2n, 4n, 6n resonance decays and spectroscopy of continuum states.
(iii) Search for systems located far beyond the driplines aimed to answer the basic question: Where is the border-line between a resonant behavior and continuum response of nuclear matter?

(iv) Studies of beta-delayed particle (multi-particle) emission from exotic isotopes.

Radioactivity is a spontaneous decay of elements (it means of long-lived nuclear states) and nuclei with large excess of protons or neutrons become radioactive by their emission. One-proton (1p) and two-proton (2p) radioactivity were predicted already in 1960 [4]. It has first been discovered for $^{45}$Fe [5], and further observations of 2p-radioactivity reported for $^{54}$Zn [6], $^{19}$Mg [7], $^{67}$Kr [8], $^{48}$Ni [9] have confirmed unexpectedly large half-lives of 2p-decay precursors. The first quantum-mechanical theory of 2p radioactivity which uses a three-body core+p+p model [10] interprets this observation as being due to a considerable influence of Coulomb and centrifugal barriers together with nuclear structure effects, and is able to predict the regular existence of considerably long-living 2p-decay precursors. Number of 2p-radioactivity candidates has been predicted using the theory presented in Ref. [10] for light- and medium-mass isotopes, in particular $^{26}$S, $^{34}$Ca, $^{38}$Ti, $^{41,42}$Cr. Such a general feature of proton-unbound nuclei with a three-body structure may be of general interest, e.g. for nuclear astrophysics: the inverse reaction to 2p decay, namely 2p radiative capture, may play an important role in the synthesis of heavy elements in the Universe, possibly bridging some waiting points in the hot rp-process, see e.g. [11, 12]. The measurements of 2p decays are the only way of studies of 2p radiative capture so far.

As for the direct neutron emission, all known nuclear ground states (e.g., $^{5}$He, $^{10}$Li, $^{13}$Be etc.) are either very short-living or exist as virtual states only. The reason of such a difference between proton and neutron decays is in the absence of a Coulomb barrier in the latter case. Thus even small admixture of an s-wave configuration in the neutron precursor (i.e., the system without a centrifugal barrier) causes a dramatic reduction of its life-time [13]. There is a possibility that (multi-) neutron emission may take the form of 2n or 4n radioactivity. The first theoretical estimates for searching of one- two- and four- neutron radioactivity which are expected for exotic extremely neutron-rich nuclei have been proposed in Ref. [13]. The estimated lifetimes for simultaneous emission of two neutrons are much longer compared to the life-times of one-neutron emitters with the same energy due to the higher centrifugal barrier. A similar effect is known for true 2p emission (2p radioactivity) and understood theoretically and the trend towards longer lifetimes continues for true four-nucleon emission.

In light nuclei beyond the proton dripline, resonances dominated by single-particle configurations are usually expected to be very broad due to low Coulomb barriers. However, some states could exist as very narrow resonances due to their more complicated structure. Their structure may be understood as proton orbits built on excited-core configurations whose 1p-decay branches into the excited core are larger than those to the respective ground states. Such a phenomenon may be general for nuclei beyond the proton drip line where 1p, 2p thresholds are very low.

Most beta-delayed decay modes are enhanced at the drip lines since multi-nucleon separation energies are low there. Need in beta-decay data arises in astrophysics for processes where weak interactions play dominating role, either directly as beta-decay rates or indirectly where neutrino interactions are important (see e.g. [14]).

3. Experimental methods

We intend to populate proton and neutron precursors in reactions of one- or two-nucleon knockout on the secondary target located at middle focal plane (FMF2) of the Super-FRS separator. The intended experiments will be generally carried out using either ion-implantation or the in-flight decay method, in dependence on the decay precursors life-time. The implantation
technique is feasible for the half-live intervals from $10^{-7}$ to $10^{-2}$ s. The in-flight decay method by tracking technique may be employed for the half-lifes from $10^{-7}$ to $10^{-12}$ s. We are going to take an advantage of employment both of them together with the measurement of gamma coincidences. We want to emphasize the uniqueness of our experiment when employment of these two alternative (and overlapping with regard to boundary time) methods covers a range of 10 orders of magnitude of half-life measurements of the unknown precursors.

When using the ion-implantation method, radioactive nucleus is firstly stopped in a detector and its subsequent activity is measured. With this technique, the 2p-radioactivity of the $^{45}$Fe ground state was discovered at GSI and GANIL [5]. We intend to use the similar method with the Optical Time-Projection Chamber (OTPC) which has been developed in the frame of the EXPERT project being part of Super-FRS Experiment Collaboration. Ions at the final focal plane (FHF2), after passing through the standard in-flight identification detectors will be slowed down in a wedge degrader and implanted into the OTPC [15]. The OTPC detector will record charged particles emitted during the decay of the stopped ions. While at the intermediate focal plane the production of nucleus of interest by means of one- or two-nucleon removal proceeds, the unreacted beam ions may be implanted into the OTPC at the final focus plane, where their decays will be recorded. Such an approach was proven efficiently and successfully at the FRS facility [16].

The conventional in-flight decay method aims at detecting fragments of a short-lived precursor in missing-mass or invariant mass measurements. A special in-flight decay method where all fragments are tracked and the decay vertices are recovered from the measured trajectories was first-time performed at GSI [7]. The method gives us possibility to extract rich information on investigated nucleus: life-time in range from $10^{-12}$ to $10^{-7}$ s can be ascertained; present few-body decay channels may be identified; and moreover the energy spectrum of precursor can be reconstructed. Such a tracking technique has proven to be a precise and effective tool for 2p-radioactivity studies which led to the discovery of the $^{19}$Mg [7, 17] and $^{30}$Ar [16] isotopes and their spectroscopy. The more detailed information on the method can be found e.g. in Ref. [18]. We intend to use the already proven technique using new tracking detectors developed within the EXPERT project.

4. Hardware

The nuclei of interest, extremely exotic and mostly unobserved yet, will be best produced in secondary reactions on radioactive ion beams of high energy 1.5 GeV/A impinging a secondary target at the middle focal plane of Super-FRS. The instrumentation of the EXPERT setup (see Fig. 1) will be localized in the middle FMF2 and final FHF1, FRF1 focal planes of the the Super-FRS facility. The decay products of unbound nuclei will be measured by a combination of several compact experimental appliances which will be installed in addition to standard Super-FRS beam diagnostic detectors. Experimental setup of the EXPERT equipment will be adapted to a number of experimental conditions and the main advantage will be taken of the versatile modular structure of particular components.

There are five main detector arrays allowing us to perform different experimental scenarios:

(i) Radiation-hard silicon strip detector (SSD) will provide information on time-of-flight, position and energy loss of ions, and it will be used for tracking of the secondary beam impinging the secondary target. The same type of detector will be used for the Super-FRS beam diagnostics.

(ii) The microstrip silicon ($\mu$Si) tracking system is a new generation detection system, similar to the other systems to be used at the several large facilities of FAIR, e.g. by the CBM, EXL, R3B, HISPEC/DESPEC collaborations and at the Super-FRS. Therefore, the unique experience gained by tracking charged particles in a very broad dynamic range (in our case,
Figure 1. Schematic layout of the proposed experiments for exploratory studies of nuclei beyond the proton and neutron driplines. Two illustrated scenarios suggest that incident $^{A}Z$ secondary beam is stripped of one neutron or proton on the thick secondary target. These processes populate either particle-unstable proton-rich $^{A-1}Z$ precursor or particle-unstable neutron-rich $^{A-1}(Z-1)$ precursor. They decay via proton or neutron emission producing an $^{A-2}(Z-1)$ heavy-ion fragment. Theoretical and Monte Carlo (MC) simulation framework is mentioned in this scheme as a component of the proposal required in most considered experimental scenarios.

it is the simultaneous detection of several protons and heavy ions) will provide a valuable reference in planning of the mentioned FAIR experiments.

(iii) The NeuRad (Neutron Radioactivity) fine-resolution detector of neutrons. Together with $\mu$Si detectors, this small-size 40x40x100 cm$^3$ neutron detector will be able to provide precise information on angular correlations of decay neutrons with a charged fragment, which is used to derive the decay energy of exotic radioactive decays (for example an unobserved yet phenomenon of neutron radioactivity is suggested to be probed in the decay energy range of 0.1-100 keV).

(iv) The GADAST cluster (GAmma-ray Detectors Around Secondary Target) is the EXPERT component augmenting the tracking system for charged particles. It is a compact array of gamma-ray sensitive modules which will be located in the middle focal plane of the Super-FRS. The principal task of this array in the context of our physics program is to disentangle measurements of (few-)proton radioactivity by tagging the gamma-ray de-excitation of the heavy fragment in the excited state(s). In addition, due to its thickness, it is suitable to be used as the detector of charged particles. It will consist of three arrays of scintillation crystals. Two identical arrays of 64 trapezoidal CsI(Tl) crystals will cover the region characterized by the angles of more than 15 degrees in laboratory system. Around the beam axis, where much better energy resolution and counting rate is required, an annular array of 32 detectors based on LaBr$_3$(Ce) crystals will be positioned.

(v) The OTPC detector main features and principles of operation are described in Ref. [15]. In particular, a new concept of the signal readout using two CCD cameras will be implemented. This new feature is expected to improve the sensitivity and the efficiency of the OTPC to detect both proton and heavy ion at the final focus of the Super-FRS. In comparison with the
previous generation of OTPC, the gas mixture will be optimized to reach the best detection of the low-energy protons emitted by beta-delayed decays. This will yield much more precise information on investigated decays and it will facilitate a test of isospin symmetry. The length of the active volume along the beam direction is 35 cm. Primary electrons, resulting from the gas ionization by the stopping ion and by the emitted charged particles, drift with constant velocity toward the amplification section, passing through a gating electrode. At the anode plane electrons stimulate atoms of the gas to emit light which is recorded by a pair of digital cameras (CCD) and a photomultiplier (PMT). Having such an information, we will be able to reconstruct the tracks of all particles in three dimensions.

It is worthy to remark that the construction of all above mentioned components is already in process and their prototypes are tested at ACCULINNA and ACCULINNA-2 facilities [19] at Flerov Laboratory of Nuclear Reactions, JINR Dubna. Completion of all detectors and their test on radioactive ion beams provided at the ACCULINNA-2 facility is planned by end of year 2022. GADAST and OTPC detectors will be employed in experimental studies on proton-rich nuclei (e.g. \(^{17}\)Ne, \(^{26,27}\)S, \(^{28}\)Si) conducted at ACCULINNA-2 within the next few years.

5. Conclusion
The EXPERT project is aimed at research of exotic nuclear systems in the vicinity and beyond the driplines. It will take an advantage of the Super-FRS, the backbone facility for whole NUSTAR Collaboration, which will be supplemented by versatile and modular system of detectors. The proposed scenarios of experimental setup will allow to study properties of both proton- and neutron-rich nuclear systems characterized by few-cluster structure. The conception of measuring techniques, together with their readiness, will allow us to take a part in experimental campaign within FAIR-Phase-0.

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References
[1] Geissel H et al., Proc. Int. Symposium on Exotic Nuclei (EXON2014), World Scientific (2015) ISBN 978-981-4699-45-7, 579.
[2] http://www.fair-center.eu/for-users/experiments/nustar.html
[3] Winkler M et al., Nucl. Instr. Meth. B 266 (2008) 4183.
[4] Goldansky V I, Nucl. Phys. 19 (1960) 482.
[5] Pfützner M et al., Eur. Phys. J. A 14 (2002) 279; Giovannazzo J et al., Phys. Rev. Lett. 89 (2002) 102501.
[6] Blank B et al., Phys. Rev. Lett. 94 (2005) 232501; ibid 94 (2005) 249901.
[7] Mukha I et al., Phys. Rev. Lett. 99 (2007) 182501.
[8] Goigoux T et al., Phys. Rev. Lett. 117 (2016) 162501.
[9] Mukha I et al., Phys. Rev. Lett. 99 (2007) 182501.
[10] Schatz H et al., Phys. Rep. 294 (1998) 167.
[11] Grigorenko L V et al., Phys. Rev. C 72 (2005) 015803.
[12] Grigorenko L V, Mukha I, Scheidenberg Ch and Zhukov M V, Phys. Rev. C 84 (2011) 021303(R).
[13] Martinez-Pinedo G et al., Nucl. Phys. A 718 (2003) 452c.
[14] Pomorski M et al., Phys. Rev. C 90 (2014) 014311.
[15] Mukha I et al., Phys. Rev. Lett. 115 (2015) 202501.
[16] Mukha I et al., Phys. Rev. C 77 (2008) 061303(R).
[17] Mukha I et al., Phys. Rev. C 82 (2010) 054315.
[18] Grigorenko L V et al., Phys. Usp. 59 (2016) 321.