EXPERT (EXotic Particle Emission and Radioactivity by Tracking) studies at the Super-FRS spectrometer

H. Geissel, O. Kiselev, I. Mukha[†], H. Simon, C. Sheidenberger, H. Weick, M. Winkler
GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, D-64291 Germany
[†]Corresponding author. E-mail: I.Mukha@gsi.de

A. Fomichev, S. Belogurov, A. Bezbakh, V. Chudoba, M. Golovkov, A. Gorshkov, Y. Itkis, G. Kaminski, A. Knyazev, G. Knyazheva, E. Kozulin, S. Krupko, S. Mianowski, S. Rymzhanova, S. Sidorchuk, P. Sharov, R. Slepnev, G. Ter-Akopian, V. Zagrebaev
Flerov Laboratory of Nuclear Reactions, JINR, Dubna, 141980 Russia

M. Pfützner, W. Dominik, Z. Janas, Ch. Mazzocchi, S. Mianowski
IEP, Faculty of Physics, University of Warsaw, Warszawa, 00681 Poland

A. A. Korsheninnikov, E. A. Kuzmin, E. Yu. Nikolskii
National Research Center "Kurchatov Institute", Moscow, 123184 Russia

I. Eremin, V. Eremin, N. Fadeeva, E. Terukov, Yu. Tuboltsev, E. Verbitskaya
Ioffe Physical-Technical Institute, St. Petersburg, 194021 Russia

S. N. Ershov, I. A. Egorova, A. K. Nasirov
Bogolyubov Laboratory of Theoretical Physics, JINR, Dubna, 141980 Russia

V. B. Dunin
Veksler and Baldin Laboratory of High Energy Physics, JINR, Dubna, 141980 Russia

G. D. Alkhazov, A. V. Dobrovolsky, A. V. Khanzadeev
Petersburg Nuclear Physics Institute, St. Petersburg, 188300 Russia

Yu. L. Parfenova
Skobel'tsyn Institute of Nuclear Physics, Moscow State University, 119991 Russia

X. Xu
Justus-Liebig-Universität, Gießen, Germany

G. Kaminski
Institute of Nuclear Physics PAN, Krakow, Poland

Y. Kopatch
Frank Laboratory of Neutron Physics, JINR, Dubna, 141980 Russia

for the Super-FRS Collaboration

The proposal EXPERT is suggested for the Super-FRS Collaboration physics program [1] in the NUSTAR Collaboration of the project FAIR (Facility for Antiproton and Ion Research) in Darmstadt, Germany. It is aimed at studies of the nuclear landscape beyond the proton and neutron drip-lines and intends to push researches up to limits of nuclear existence. By combining the EXPERT instrumentation (two tracking techniques applied for radioactivity and nuclear decays in-flight), the phenomena of multi-nucleon radioactivity, resonance decays in continuum, beta-delayed exotic decays and exotic excitation modes can be studied via observations of particle emissions, including the 2*p*, 4*p*, 6p, *n*, 2*n*, *4n*, *6n* channels.

Keywords: Radioactivity, multi proton-, neutron- decays; experiments at Super-FRS spectrometer; FAIR project.

The joint proposal EXPERT is suggested and developed by the consortium GSI (Darmstadt, Germany) – FLNR JINR (Dubna, Russia) – IEP (University of Warsaw, Poland) – PTI (Ioffe Physics-Technical Institute, St. Petersburg, Russia) – KI (National Research Center “Kurchatov Institute”, Moscow).

1. Scientific case

1.1. *The EXPERT research objectives*

- Study of exotic 2*p* radioactivity and search for unknown radioactive decays: 4*p*, 2*n*, *4n.*
- Studies of 2*p*, 4*p*, 6p, *n*, 2*n*, *4n*, *6n* nuclear decays by spectroscopy of their continuum.
- Quest aimed to discover the limits of existence of nuclear structure. Search for systems located far beyond the drip-lines is aimed to answer for the basic question: ***“Where is the borderline between resonance behavior and a continuum-like response of nuclear systems”?***
- Studies of beta-delayed multi-particle emission from exotic isotopes.

Below we discuss the proposed physics topics in detail.

1.1.1 Study of exotic 2p, 4p, 2n, 4n radioactivity

Nuclei with large excess of protons or neutrons become radioactive by emission of protons/neutrons. In past decades, impressive progress in studies of the proton-rich nuclei till limits of nuclear stability has been achieved. In particular, one-proton and two-proton (2*p*) radioactivity were predicted by Goldansky in 1960 [2]. Soon the proton radioactivity was first observed as a β-delayed process [3, 4], and about 20 years later the direct proton decay was discovered as radioactivity of an isomeric state, ^{53m}Co [5]. Later on, numerous one-proton decays were identified (see [6] for a recent review). It took about 42 years until 2*p* radioactivity has been observed in ^{45}Fe [7], and then in ^{54}Zn [8], ^{19}Mg [9] and ^{48}Ni [10]. The specific feature of the latter phenomenon is that its mechanism in general cannot be reduced to a sequence of one-proton emissions (*"true* 2*p decay"*), and correlations between three decay products are important, which can be addressed by the adequate few-body theory [11]. Unexpectedly long half-lives are reported for all measured *2p*-emitters, which exceeds the diproton model predictions by a factor of 1000. A quantum-mechanical theory of the *2p* radioactivity based on a three-body model [11, 12] explains them as a result of a considerable influence of few-body centrifugal and Coulomb barriers together with nuclear structure effects. By using this theory, a number of *2p*-radioactivity candidates has been predicted for light- and medium- mass isotopes, in particular ^{26}S, ^{30}Ar, ^{34}Ca, ^{38}Ti, ^{41,42}Cr [12,13]. The *2p*-radioactivity candidates, ^{26}S, ^{30}Ar, and ^{34}Ca are feasible for future studies at the fragment separator FRS GSI and few others radioactive-beam facilities. So far, isotopes ^{38}Ti and ^{41,42}Cr can be accessible only at the Super-FRS facility of NUSTAR where production rates of radioactive isotopes are planned to be higher by factor of 3-4 orders of magnitude in comparison with the FRS yields.

In the theoretical survey [14] based on the nuclear density functional theory, the global landscape of ground-state 2*p* radioactivity has been qualified. This decay mode is found to be not an isolated phenomenon limited to a narrow range of light- and medium-mass nuclei, but a typical feature for the *2p*-unbound isotopes with even atomic numbers of almost all elements between argon and tellurium. The proton-unbound elements between tellurium and lead are predicted to decay by sequential emission of two protons. The upper end of the *2p*-decay territory is determined by alpha decay, which totally dominates above Z=82. The most interesting are nuclei around ^{103}Te–^{110}Ba, where the competition between 2*p* emission and alpha decay is predicted [14]. These two decay modes were never observed before to occur in the same nucleus. Such an observation would provide an excellent test of nuclear structure models and deeper understanding of the dynamics of charged particle emission from nuclei. Most of the new candidates for 2*p* radioactivity are located beyond the current experimental reach and have to wait for the facilities of the next generation, in particular the Super-FRS. As the first objective, the unknown isotope ^{103}Te (where α- and 2*p*- decay competition is predicted) is requested whose production rate at the Super-FRS is estimated to be ~3 ions/h (produced in fragmentation of a primary ^{124}Xe beam at energy of 1.8 GeV/u and intensity of 10^{12} pps). The corresponding experimental scenario is described in the Section 2.2.1.

Like in the case of proton decay, *one-neutron radioactivity* was first observed as a beta-delayed process, this disintegration mode playing an important role in the fission physics for reactors. Moreover, β-delayed one-, two- and three- neutron emissions have been identified in light nuclei (e.g., see the recent review [6]). As for the direct neutron emission, all known nuclear ground states (e.g., ^{5}He, ^{10}Li, ^{13}Be *etc.*) are either very short-lived or exist as virtual states only. The reason of such a difference between proton and neutron decays is in 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 lifetime. Simple estimates of one-neutron decay widths [15] show that a chance to identify neutron radioactivity exists only for the *d*-wave neutron precursors whose decay energy is less than 1 keV. There is a little chance that such a fine-located nuclide will actually be found. In particular the decay energy of ^{16}B is only 40(60) keV [16], which makes it a candidate for a neutron radioactivity probe. The better chances to find one-neutron radioactivity exist for *f*-wave or even higher-orbital-momentum configurations though the respective nuclear candidates are far from the current experimental reach.

There is a possibility that neutron emission from extremely neutron-rich nuclei may take the form of 2*n or 4n* radioactivity. The first theoretical estimates for searching of one- two- and four- neutron radioactivity have been proposed in Refs. [15]. It was argued that the observation of neutron radioactivity in *s-d* shell nuclei seems to be unrealistic, but sufficiently long lifetimes may occur in decays of heavier (*p-f* shell) systems. The estimated lifetimes for *true* 2*n emission* are much longer compared to the lifetimes of one-neutron emitters with the same energy due to the higher centrifugal barrier. A similar effect is already known for true *2p* emission (2*p* radioactivity) and understood theoretically. The trend towards longer lifetimes continues for *true four-nucleon emission*, which should be strongly hindered as compared to true two-nucleon emission with the same decay energy. For that reason the existence of 2*n* and, especially, of 4*n* radioactivity is plausible, since the energy windows corresponding to the radioactive timescale is estimated to be reasonably broad. The decay-energy conditions for true 4*n* emission are likely fulfilled in ^{7}H and could be fulfilled in several other neutron-rich isotopes. The feasibility of an experimental search for long-lived true 2*n* and 4*n* emitters by using a method of in-flight-decay and tracking of the decay products is discussed in [15].

The first indication on 2*n* radioactivity of isotope ^{26}O whose lifetime is reported to be about 4.5(3) ps has been published [17]. The upper limit of the corresponding decay energy was measured to be <120 keV [18, 19] and even

<10 keV [20]. The followed theoretical three-body interpretation of the ^{26}O system [21] has demonstrated that the reported lifetime value of ^{26}O should correspond to decay energy of 1 keV, which is very difficult to be measured by using the present neutron detectors.

The experiment which can prove existence of the phenomenon of the neutron radioactivity requires a facility with the highest production of exotic nuclei. Moreover, a construction of a neutron detector with unique properties which make it suitable for measurements of neutron decays with very low energies is mandatory. Indeed, measurements of very small decay energies of neutron precursors require special experimental methods because the neutrons are not well separated in space and time. In particular, the recent measurement of the ^{26}O decay [18] clearly demonstrates that the conventional invariant-mass method has a problem when distinguishing 2*n* events from 1*n* double re-scattering (i.e. “cross-talk” effect) at 2*n*-decay energies below 100 keV. We suggest the neutron detection method to be free of the mentioned complications, which is described in Section 2.2.4.

1.1.2 Resonance decay and continuum spectroscopy studies

Isotopes beyond the drip line could exist as very narrow resonances due to more complicated structure in comparison with single-particle configurations. For example, the measured *1p, 2p* decays of the excited states of ^{15}F and ^{16}Ne give evidence on relatively stable nuclear systems [22]. The observed states have much smaller widths compared to those expected due proton shells coupled to undisturbed nuclear core. 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. The excited-core daughters are in turn open to *1p* decays. Such a phenomenon may be general for nuclei beyond the proton drip line where *1p, 2p* thresholds are very low. Accurate predictions of resonance positions and widths are crucial in studies of stellar nucleosynthesis. It is important to note, that the results of Refs. [22] are obtained by analysing the same data measured in the ^{19}Mg radioactivity search [9] and are one of the additional by-products of this experiment as well as the results on seven first-time observed resonances in ^{18}Na and ^{19}Mg [23].

1.1.3 Search for systems located far beyond the drip-lines decaying by 4p/6p emissions

In a quest for discovery of the limits of existence of nuclear structure, we propose searches of the most distant from stability proton-rich nuclei which decay by 4*p* or 6*p* emissions. These systems are located 4 or 6 mass units beyond drip lines, and their ground-state properties can provide important clues on behavior of nuclides far away from drip lines. The only known 4*p*-emitter is ^{8}C whose 4*p* decay was measured recently. This narrow resonance undergoes sequential 2*p*-2*p* decay via the intermediate nucleus ^{6}Be [24]. There are several unobserved 4*p*-unbound isotopes like ^{21}Si or ^{18}Mg whose properties together with ^{8}C may establish a 4p-decay pattern. Phenomenon of 6p emission has not been observed so far. There is a prospective candidate to observe such a phenomenon, ^{20}Si which is open in respect to the decay chain, $^{20}\mathrm{Si}\rightarrow{}^{18}\mathrm{Mg}+2p\rightarrow{}^{16}\mathrm{Ne}+4p\rightarrow{}^{14}\mathrm{O}+6p$. The way to produce ^{20}Si is a reaction of a removal of a 2*n* pair from radioactive projectiles ^{22}Si. The reaction (^{22}Si, ^{20}Si) is similar to the reference case of (^{11}C, ^{9}C) measured at high energies in the experiment S341 at GSI [25]. The 2*n* removal from ^{11}C proceeds as a direct reaction with the measured cross-section of 2.9 mb, which is comparable with the predicted cross-section by using the Cohen-Kurath spectroscopic factor of the *2n* pair. With the beam intensity of ^{22}Si of ~2500 pps produced in fragmentation of primary 1.5 GeV/u ^{28}Si beam at Super-FRS, there are realistic chances to populate ^{20}Si in the secondary reaction (^{22}Si, ^{20}Si) with a sufficient rate. The products of 2*n*-pair removal reaction have twice broader momentum spread in comparison with one-nucleon removal products. Therefore high energy and large acceptance of the Super-FRS result in high transmissions of fragments, which is essential for the experiment. We suggest studying the ^{20}Si properties as one of the EXPERT flagship cases by using the decay-in-flight technique described in Section 2.2.3.

1.1.4 Studies of beta-delayed multi-particle emission from exotic isotopes

The disintegration of nuclei far from stability proceeds not only to the ground state of the respective daughter nucleus but has a complex feeding pattern including multi-particle emission from highly excited states of daughter nucleus. Most beta-delayed decay modes are enhanced at the drip lines since multi-nucleon thresholds are low there. The enhanced role played by beta-delayed particle emission implies that the physics problems investigated via β decay overlap reasonably with the ones investigated via reaction studies. The specific example here is the population of excited states whose properties are important in the astrophysical *rp* process. Beta-decay rates are also needed in astrophysics for modelling of processes where weak interactions dominate.

We suggest a study of beta-delayed multi-particle decays by implanting exotic isotopes into the OTPC detector at the end of Super-FRS, which can be done simultaneously with the experiments in the middle of the Super-FRS. The OTPC technology has demonstrated high sensitivity in studies of radioactivity and ability to provide information at rates as low as few decays per week of measurements. Its implementation is described in the Sections 2.2.1-2.2.2, where one may also find references to the previous OTPC experimental results.

1.2 Experimental concept

The extremely exotic nuclei of interest are mostly unobserved yet. They can be best produced by utilizing secondary reactions with radioactive ion beams of high energy ~1.5 GeV/u impinging a secondary target at the middle focal plane of Super-FRS. Then the Super-FRS is used as a radioactive-ion beam separator in its first half and as a reaction spectrometer in its second half which is set for registering of the secondary-reaction fragments. The instrumentation of the

EXPERT setup is localized in the middle FMF2 and final FHF1, FRF1 focal planes of the Super-FRS, see Fig. 1. For comparison, the corresponding locations at the fragment separator FRS are at the focal planes S2 and S4.

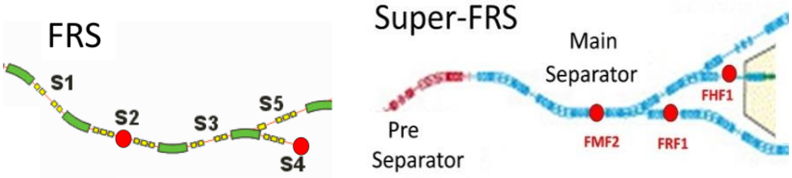

Fig. 1. Location of the EXPERT detectors in experiments at the fragment separators FRS (left panel) and Super-FRS (right panel) shown by the red dots.

Unbound nuclei either decay in flight or are radioactive by emitting nucleons like the *p*, 2*p*, *4p* and *n*, 2*n*, *4n* channels. The proposed setup covers two important lifetime ranges: of 1s – 100ns, and of 1ps – 100ns by applying the implantation-decay and decay-in-flight techniques, respectively. For the short-lived systems, the resonance properties and information about continuum are retrieved from the angular correlations between the decay products. These measurements to be augmented with data on γ de-excitation and β-delayed particle emission of the decay products. The setup has a modular structure with compact detector components (see Fig. 2), which allows for a number of experimental scenarios, see details in Section 2.2.

1.3 Competitiveness

1.3.1 The EXPERT team research background

The proposal team has the extensive expertise and considerable achievements in the studies of particle radioactivity and exotic particle emission modes. The list of the achievements includes: (i) the experimental discovery of 2*p* radioactivity at FRS [7], (ii) developments of the first OTPC (optical time projection chamber) technology and first measurements of momentum distributions for 2*p* radioactive decays [26], (iii) the first application of the tracking technique applied for studies of the 2*p* radioactivity in flight [9], (iv) creation of the first consistent quantum mechanical theory of 2*p* radioactivity [11] leading nowadays to a comprehensive description of this decay mode [6], (v) first predictions of 2*n*/4*n* radioactivity [15,21], (vi) promotions of new experimental and theoretical methods aimed to use fragment correlations in three-body decays as a spectroscopic tool [27,28]. The proposed setup is based on the cumulative experience of all accomplishments in this field. We also bring together different instrumentations with the large “internal synergy” effect and maximum efficiency of the proposed experiment.

1.3.2 Advantages of the EXPERT operation in the Super-FRS

- The tracking/angular measurement part of the proposal requires a strong focusing of the reaction/decay products in forward direction, which is possible only with high-energy (above 500 *A* MeV) secondary beam. This condition matches a unique advantage of the Super-FRS of high-energy secondary beams.

- The EXPERT experiments require the most exotic nuclides to be produced and efficiently separated as secondary beams. The intended extremely thick primary and secondary targets inside the Super-FRS are important conditions in achieving the highest yields of such nuclides.

- The tracking part of the EXPERT setup must be operated inside the fragment separator, which requires about of 1m space in its middle focal plane. So far, only the FRS/Super-FRS fragment separators provide sufficient space for such an operation, contrary to e.g. the Big Rips separator.

- In the EXPERT setup, the last stage of the Super-FRS must be operated as a high-resolution spectrometer for the reaction/decay products. The alternative location of the tracking system beyond the Super-FRS demands an additional high-resolution spectrometer after it. No such option is available in observable future at other NUSTAR facilities.

- The EXPERT setup is unique for radioactive *p* and 2*p* decays for secondary reaction products within the 100 ms – 100 ns lifetime range.

- The EXPERT setup is planned for unique extremely low-energy (few-) neutron decay studies and a (few-) neutron radioactivity search in the range from 100 keV/neutron down to 0.1 keV/neutron.

- Simultaneous utilization of the same secondary beam both for decay-in-flight studies and implantation studies of radioactivity has large synergy effect.

- The EXPERT setup works well on the poor “cocktail” beams due to a precise identification of the heavy fragment produced in the decay by the last stage of the fragment separator used as a high-resolution spectrometer. Several nuclides present in cocktail can be investigated simultaneously. This opportunity is proved in a series of the pioneering works [9, 22, 23, 29, 30]. Thus several experimental purposes can be attained simultaneously. This option ensures very efficient beam-time utilization. This allows also a conduction of “low risk” experiments, when valuable information can be obtained at some “experimental stations” even if the other stations fail due to lack of beam intensity.

- The shortest-possible beam times will be requested due to a usage of extremely thick targets, up to 10 g/cm^2. We can afford very thick both primary and secondary targets because the invariant-mass spectra are not reconstructed in our method, only the angular distributions. Multiple scattering in a target affects information obtained from the measured angular correlations is much smaller degree than e.g., energy losses of fragments influencing the invariant-mass reconstruction. Thus disadvantage of the method connected with obtaining of kinematics-limited information is excessed by surplus of a thick-targets use. All in all, the method is very efficient in exploratory studies which clarify the experimental conditions before detailed experiments at NUSTAR.

1.3.3 Synergy with the other NUSTAR experiments

The decay spectroscopy setup (DESPEC) is planned for the low-energy branch (LEB) of NUSTAR. The proposed EXPERT setup aims first of all at relatively short-lived radioactive species and resonances not accessible at LEB.

Functionality of the EXPERT setup resembles the functionality of some components of the R^3B setup of NUSTAR (such similarity is due to a use of reactions at relativistic energy). However, the main scientific focus of the EXPERT – radioactivity studies – is complementary to the R^3B setup and its experimental program. Information about resonances and excitation modes obtained by EXPERT is in a limited kinematics range and thus cannot provide e.g., tetra-neutron correlations.

The EXPERT setup fits for experiments requiring a strong-field high-resolution spectrometer. In particular, the bending power of the Super-FRS magnets is three times larger in comparison with the GLAD magnet of R^3B.

The silicon detectors for beam tracking (i.e., position, time and energy loss of every ion) can be used practically in all future experiments of NUSTAR. The respective R&D will cover essential features like the Si radiation hardness and stability of the detector performance with intense beams of high-energy.

2. Experimental techniques

The proposed detectors and components of EXPERT are sketched in Figure 2.

2.1 The EXPERT components and subsystems

The main detectors in measurements of decay in-flight of exotic nuclei are:

(1) *Radiation-hard silicon strip detectors SSDs.* These compact and universal beam detectors of the Super-FRS provide information on time-of-flight, position and energy loss of ions, and they will be used for tracking of the secondary beam impinging the secondary target.

(2) *Micro-strip silicon (μSi) tracking detectors.* The detectors are essential for applications of tracking technique to decays in-flight and provide data on trajectories of all charged decay products, which is sufficient for determination of half-life values as well as of decay energies and angular correlations.

(3) *The NeuRad (Neutron Radioactivity) fine-resolution detector of neutrons.* Together with μSi detectors, this small-size 40x40x100 cm^3 neutron detector can 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 (e.g., an unobserved phenomenon of neutron radio-activity is suggested to be probed in the decay energy range of 0.1-100 keV).

(4) *The GADAST (Gamma-ray Detectors Around Secondary Target) array.* It measures γ-rays and light particles emitted instantaneously after secondary reaction. In the context of the proposal it could allow to disentangle the decays channels with a heavy fragment resulted in an excited state (and thus

instantaneously de-excited by γ emission). The GADAST demonstrator has been successfully tested in the FRS experiment [31].

(5) *The OTPC (Optical Time Projection Chamber) for radioactivity studies by the implantation-decay method.* The detector measures trajectories of charged fragments of radioactive precursors with lifetimes in the range 1 s – 100 ns.

(6) *Theoretical/Simulation framework.* In order to obtain physics results, the information provided by tracking/angular measurements needs the detailed theoretical analysis followed by Monte Carlo simulations. Moreover, solid theoretical predictions like the first theory of 2p and 2n radioactivity [11, 15, 21] make strong motivation for performing high-risk pioneering studies [9].

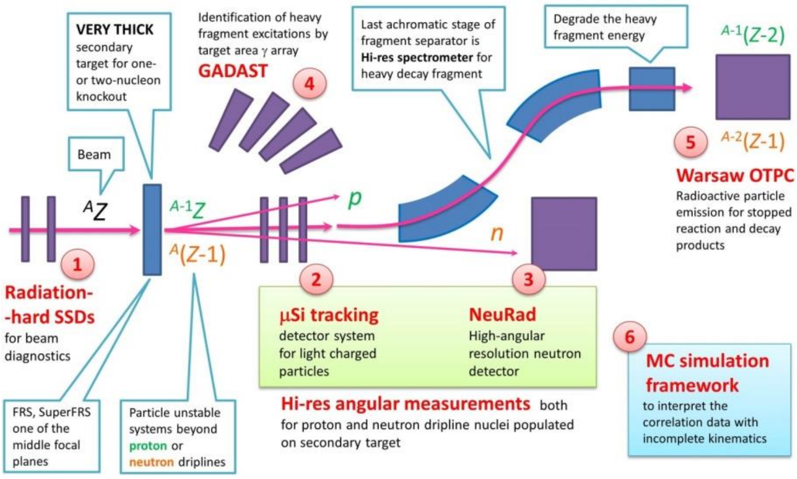

Fig. 2. Schematic layout of the proposed experiments for exploratory studies of nuclei beyond the proton and neutron drip-lines. The illustrated scenario suggests a population of two-proton (green) or two-neutron (orange) precursor in a secondary reaction of one-nucleon knockout by using radioactive beam. Theoretical/MC simulation framework is mentioned in this graph as a component of the proposal required in most considered experimental scenarios.

2.2 Experimental scenarios

We intend to populate proton/neutron precursors in reactions of one nucleon knockout on the secondary target (see Figure 2). The products of two-nucleon and even three-nucleon knockout are produced as well with the expected relative yields of 10^{-2} and 10^{-4}, respectively. Such processes may lead to a population of extremely exotic systems located by two or three mass units further away from the drip lines. Below we present several scenarios of the related experiments.

2.2.1 Radioactive decays beyond the proton drip-line with $T_{1/2} > 100$ ns.

Radioactive nuclides with $T_{1/2} > 100$ ns are populated in the secondary target at FMF2. In this case, the produced nuclei are able to reach the final focal plane FHF1 and stop in the OTPC, see Fig. 2, item 5. The OTPC is here the main detector. The OTPC technology has demonstrated high sensitivity in studies of radioactivity and ability to provide information at rates as low as few decays per week of measurements [6, 10, 26]. The examples of the measured decays are shown in Fig. 3 where the cases of two-proton radioactivity (a), beta-delayed triton (b) and beta-delayed three-proton (c) emissions are illustrated. The flagship experiment with ^{103}Te (see Section 1.1.1) is planned with OTPC.

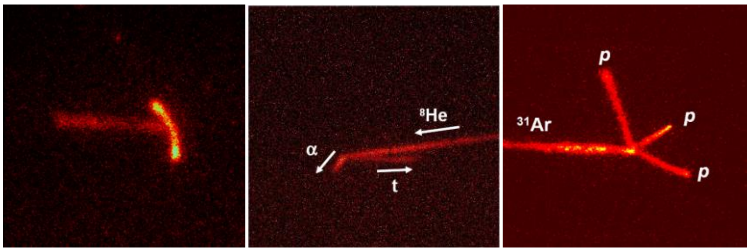

Fig. 3. Radioactivity observations made by the OTPC. On left: Two-proton radioactivity of ^{45}Fe [26]. Middle: β-delayed $\alpha+t+n$ emission from ^{8}He [32]. On right: $3p$-emission following β-decay of ^{31}Ar [33].

2.2.2 Radioactivity of the proton precursors with 100 ns > $T_{1/2}$ > 1 ps.

Radioactive nuclide with half-lives in the range of 100ns > $T_{1/2}$ > 1ps are populated in the secondary target at FMF2. In this case, the μSi system (see Fig.2, item 2) is invoked as the main detector. It is operated in the “tracking mode”, which allows for a decay vertex reconstruction. The distribution of the vertexes along beam direction is directly related to the lifetime of the precursor, see Fig. 4. At the final focal plane FHF1, the OTPC is invoked for studies of radioactivity of the secondary-beam ions which can reach OTPC, see the measured examples in Fig.3.

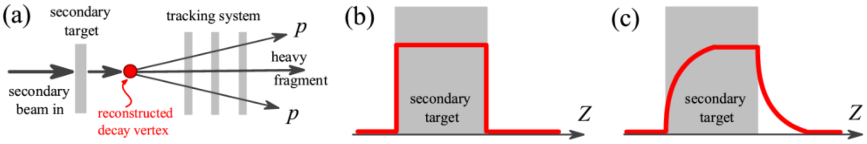

Fig. 4. (a) Basic idea of lifetime determination of $2p$ radioactive precursors, which is plausible in the range 100 ns > $T_{1/2}$ > 1 ps [9]. (b) Ideal sketch of a vertex reconstruction of promptly emitted protons. (c) Ideal vertex reconstruction of radioactive $2p$ precursors (delayed emission).

2.2.3 Studies of short-lived proton resonances

Short-lived nuclides with $T_{1/2}$ < 1ps can be studied by the μSi tracking system (see Fig. 2 item 2) which is invoked as the main detector in the high-resolution angular mode. Then energies of the $1p$ resonances are reconstructed from the measured angular correlations of a proton with a heavy fragment, see Fig. 5(b). Energies and particle correlations of 2p decays are derived from the angular correlations proton-“heavy fragment” as well, though the results depend on a decay mechanism. It can be either “direct $2p$” or sequential emission of protons, see Fig. 5(a,c). Details of data analysis can be found in [9, 22, 23, 29, 30]. At

FHF1, the OTPC is invoked for studies of the β-delayed particle emissions similarly to the above-described scenario in the Section 2.2.1.

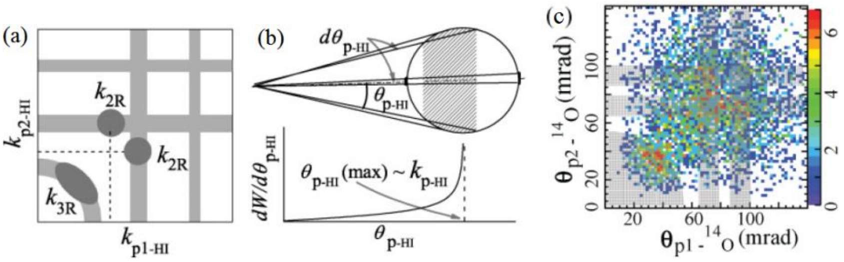

Fig. 5. Identification of ground and excited states by using the measured angular correlations of products of 2p decays in-flight. (a) Schematic view of momentum correlations between a heavy ion (HI) and protons *(p1,p2)* in the cases of "true" *2p* decays (k_{3R}) and sequential *2p* decays (k_{2R}); (b) "Kinematical focusing" near the maximal angle between decay products illustrated by ratios of c.m. and lab solid angles. (c) The measured correlation plot of 2*p* decays of ^{16}Ne states populated in a neutron knockout from ^{17}Ne projectiles [29]. Shaded areas of the circular sector and bands indicate the true 2*p* decay of the ground state and the sequential decays of excited states via the intermediate ^{15}F states.

2.2.4 Radioactive and resonance decays of neutron-unbound precursors

The NeuRad and the μSi tracking detectors are employed, see Fig. 2, item 3. The angular HI-neutron correlations provide information on lifetime and decay mode. The method is similar to the technique applied to 2*p* precursors by tracking products of their decay in flight [9, 22, 23, 29, 30]. The obtained angular correlation of just 1*p* (out of 2*p*) with a heavy fragment allowed for determination of 2*p*-decay energy with high precision [30]. Similarly, a detection of 2*n*/4*n* decays in flight by the tracking technique allows for precisely-derived decay energies. In such an experiment sketched in Fig. 6, the neutron detector must have high granularity and reasonable 1*n*-detection efficiency together with a relatively low efficiency of the *n*/4*n* detection. The first feature is needed to access the smallest correlation angles, and the latter two features allow avoid the cross-talk problem in detecting multiple neutron decays.

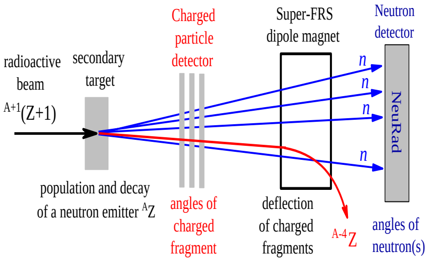

Fig. 6. Scheme of a setup for studies of long lived neutron emitters by tracking. The high-resolution neutron and charged-particle detectors should provide the heavy-fragment vs. neutron correlations with high angular accuracy. The setup is implemented in the Super-FRS as shown in Fig. 1. It must have the secondary target and the angular detector of fragments at FMF2 as well as the neutron detector at FRF1 located at FMF2. The moments of heavy fragments are measured at FHF1.

The simulations in Fig. 7 show a distinctive correlation pattern, which helps to identify the decay mode [15]. Two cases are considered, the 2*n* decay of ^{26}O and the 4*n* decay of ^{28}O (the upper and lower panels in Fig. 7, respectively).

Both parent nuclei are assumed to be unbound either by 20 keV (as predicted in Refs. [15] for ^{26}O) or by 150 keV (the upper-limit value measured [12]). These precursors decay to the ^{24}O ground state by 2*n*/4*n* emissions. The nuclei of interest are assumed to be populated in one-proton knock-out from ^{27,29}F projectiles at intermediate energies of 700 *A* MeV. The simulated angular distributions of the decay products shown in Fig. 6 display very narrow peaks located at the smallest angles, down to 1 mrad. It was demonstrated for true 2*p* decays [9, 22, 29], that such characteristic correlation peaks are indeed formed which allows to identify the decay mechanism and to measure the decay energy provided all decay products are tracked accurately.

From the upper panel in Fig. 7 one may conclude that 2*n* decay energies as low as 1 keV can be reached provided the experimental setup has an angular resolution less than 1 mrad. The true 4*n* decay presented in the lower panel of Fig. 7 is characterized by a single peak, which corresponds to a uniform sharing of the decay energy among all neutrons. The correlation pattern is sensitive to the decay mechanism, as the sequential 2*n*-2*n* decay via the ^{26}O g.s. provides a two-peak correlation distribution. Similarly, for the simulated 4*n* decay, the necessary angular resolution of the neutron detectors should be <1 mrad as well. Existing neutron detectors like the large neutron detectors at RIKEN or GSI provide an angular resolution of ~10 mrad. Thus, implementation of the NeuRad aimed for registration of neutrons from decays in-flight with extremely low decay energies is essential. This relatively compact detector is built as a bunch of straw-like scintillation fibers (each with a small cross area of 3x3 mm^2) will provide the necessary angular resolution already at 10–20 m distances from the decay point [34]. Tests of the NeuRad prototype are under way [35].

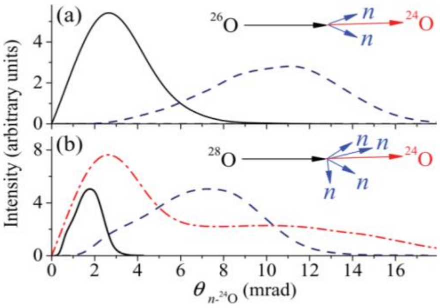

Fig. 7. Illustration of a way to identify 2n and 4n emission modes by measuring angular HI-neutron correlations [15]. Monte Carlo simulations of the angular distributions between the heavy fragment and one of the neutrons for decay energies of 20 keV (solid curves) and 300 keV (dashed curves): (a) spectra for the true 2n decay of ^{26}O; (b) spectra for the true 4n decay of ^{28}O. The dash-dotted curve in (b) refers to a sequential 2n-2n decay of ^{28}O via the ^{26}O g.s. with 4n- and 2n- decay energies of 300 and 20 keV, respectively.

The general lay-out of the experiment searching for neutron radioactivity includes the μSi tracking detectors at FMF2, the NeuRad detector at FRF1 (its position corresponds to zero-degree angles of reactions occurred at FMF2), and standard beam detectors at FHF1 needed for HI measurements.

2.3 Theoretical/Simulation framework

The hardware developments within EXPERT initiative are augmented with relevant theoretical research. Moreover, the progress in this research is integral part of the future success of the whole project. The aims of the theoretical/simulation developments for EXPERT are :

- In majority of the EXPERT scenarios, measurements of several particles in coincidence are expected. The (multi-particle) registration efficiency and, especially, the reconstruction of correlation distributions are strongly affected by the design of the experimental setup. Monte Carlo (MC) simulations of the experimental setup response are the only realistic method to resolve the problem. Importance of the MC procedures is emphasized when kinematically incomplete information is obtained, and it can be interpretable only in certain model assumptions about the “missing” kinematic variables.

- Many systems beyond the nucleon drip-lines have opened few-body decay channels and demonstrate exotic few-body nuclear dynamics, see Fig. 8 for a review. Theoretical issues of few-body continuum and of few-body decay dynamics are mostly unresolved. The rapid experimental progress in this field challenges the adequate theoretical methods for a treatment of this physics field.

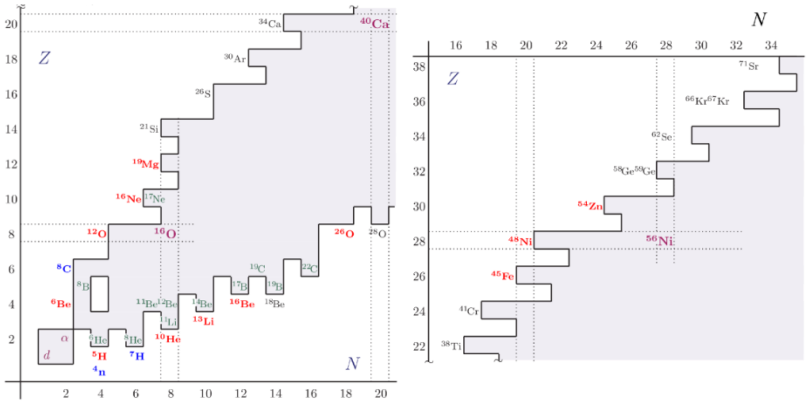

Fig. 8. Location of the systems characterized by exotic (including few-body) nuclear structure in proximity of the known drip-lines The color coding: red – “true” 2p/2n emitters, blue – 4p/4n emitters, green – halo systems.

- Conjugation of the theoretical calculations with the experimental data can be very complex in this field, especially when the specific reaction mechanisms are important. E.g., the 8-fold differential cross section has to be simulated in the case of three-body decay. The development of software providing a theoretical input for experimental data in a form of the quantum-mechanical theoretical MC simulations is active in our collaboration during several years. The formal title for this development is TEG-DDR (Three-body event generator for decays and direct reactions). Power of the method is demonstrated in the recent publications [6, 28, 36, 37], where the discussed developments were successfully applied.

3. Prospects of the EXPERT setup in near future

The proposed EXPERT setup has a modular design, and every component may be used in experiments independently. Thus, a significant *synergy effect* is expected. The EXPERT setup will be based on the successful S271 and S388 experiments at GSI (aimed for observations of 2*p*-radioactivity of ^{19}Mg and ^{30}Ar, respectively). All components of the proposed setup are under active developments and can be used in the possible nearest experiments at FRS GSI or ACCULINNA2 JINR [38]. E.g., the accepted proposal S414 “Search for two-proton radioactivity of ^{26}S” is awaiting beam-time at GSI. Continuation of this program in the next years at FRS and ACCULINNA2 might ensure confidence that by the moment of the Super-FRS commissioning the setup is ready to run. The first flagship experiment is proposed for a search of the unobserved isotope ^{103}Te and predicted competition of it’s α- and 2*p*- decay branches. The other nearest candidates for such studies are suggested: $^{20\text{-}21}$Si, ^{38}Ti, ^{34}Ca, ^{41}Cr, ^{58,59}Ge, ^{62,63}Se, ^{69}Br, ^{73}Rb and ^{7}H, ^{16}B, ^{18}Be, ^{21}B, ^{26,28}O.

References

[1] *Super-FRS Collaboration. Scientific program of the Super-FRS Collaboration: Report of the collaboration to the FAIR management*, GSI Report 2014-4, doi:10.15120/GR-2014-4.

[2] V.I. Goldansky, Nucl. Phys. **19** (1960) 482.

[3] R. Barton *et al.,* Canadian J. Phys. **41** (1963) 2007.

[4] V. Karnaukhov, G. Ter-Akopyan, V. Subbotin and L. Petrov, Journal of Experimental and Theoretical Physics (in Russian) **45** (1963) 1280.

[5] K. Jackson *et al.,* Phys. Lett. B **33** (1970) 281; J. Cerny *et al.,* Phys. Lett. B **33** (1970) 284.

[6] M. Pfützner, M. Karny, L. Grigorenko and K. Riisager, Rev. Mod. Phys. **84** (2012) 567.

[7] M. Pfützner *et al.,* Eur. Phys. J. A**14** (2002) 279; J. Giovinazzo *et al.,* Phys.Rev. Lett. **89** (2002) 102501.

[8] B. Blank *et al.,* Phys. Rev. Lett. **94** (2005) 232501; *ibid* **94** (2005) 249901.

[9] I. Mukha *et al.,* Phys. Rev. Lett. **99** (2007) 182501.

[10] M. Pomorski *et al.,* Phys. Rev. C **83** (2011) 061303(R).

[11] L.V. Grigorenko, R.C. Jonson, I. Mukha, I.J. Thompson and M.V. Zhukov, Phys. Rev. Lett. **85** (2000) 22.

[12] L.V. Grigorenko and M.V. Zhukov, Phys. Rev. C **68** (2003) 054005.

[13] L.V. Grigorenko, I. Mukha, M.V. Zhukov, Nucl. Phys. A **714** (2003) 425.

[14] E. Olsen, M. Pfutzner *et al.,* Phys. Rev. Lett. **110** (2013) 222501; *Errata*, Phys. Rev. Lett., **111** (2013) 139903.

[15] L.V. Grigorenko, I. Mukha, C. Scheidenberg and M.V. Zhukov, Phys. Rev. C **84** (2011) 021303(R).

[16] H.G. Bohlen *et al.*, Nucl. Phys. A **583** (1995) 775c.

[17] Z. Kohley *et al.,* Phys. Rev. Lett. **110** (2013) 152501.

[18] E. Lundenberg *et al.,* Phys. Rev. Lett. **108** (2012) 142503.

[19] C. Caesar for the R3B Collaboration, Phys. Rev. C **88** (2013) 034313.

[20] Y. Kondo *et al., Study of Two-Neutron Decay of* ^{26}*O at SAMURAI RIKEN, in preparation,* (2014).

[21] L.V. Grigorenko, I. Mukha, M.V. Zhukov, Phys.Rev.Lett.**111** (2013) 042501

[22] I. Mukha *et al.*, Phys. Rev. C **79** (2009) 061301.

[23] I. Mukha *et al.*, Phys. Rev. C **85** (2012) 044325.

[24] R. J. Charity *et al.*, Phys. Rev. C **82** (2010) 041304(R).

[25] M. Holl for the S341 Collaboration, *Two nucleon removal cross sections from* ^{11}*C,* unpublished.

[26] K. Miernik *et al.*, Phys. Rev. Lett. **99** (2007) 192501.

[27] M.S. Golovkov *et al.*, Phys. Rev. C **72** (2005) 064612.

[28] S. Sidorchuk *et al.,* Phys. Rev. Lett. **108** (2012) 202502.

[29] I. Mukha *et al.*, Phys. Rev. C **77** (2008) 061303(R).

[30] I. Mukha *et al.*, Phys. Rev. C **82** (2010) 054315.

[31] I. Mukha *et al.*, GSI Scientific Report 2012, PHW-ENNA-EXP-45, p.175, http://repository.gsi.de/record/52876.

[32] S. Mianowski *et al.*, Acta Phys. Pol. B **41** (2010) 449.

[33] M. Pfützner *et al.*, GSI Scientific Report 2012, PHW-ENNA-EXP-17, p.147, http://repository.gsi.de/record/52876.

[34] I. Mukha, Acta Phys. Polonica B **45** (2014) 1001.

[35] I. Mukha, D. Kulik, GSI Scientific Report 2013, p.110, doi:10.151.20/GR-2014-1-NUSTAR-FRS-13.

[36] I.A. Egorova *et al.*, Phys. Rev. Lett. **109** (2012) 202502.

[37] A.S. Fomichev *et al.*, Phys. Lett. B **708** (2012) 6.

[38] L.V. Grigorenko for the ACCULINNA-2 Collaboration, Book of Proceedings of The first International African Symposium on Exotic Nuclei, Cape Town, SA, December 2-6, 2013.