Topic 8:
Radioactive in-flight decays and continuum spectroscopy by particle emission

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1. Science case

1.1 Research objective

The joint proposal EXPERT (EXotic Particle Emission and Radioactivity by Tracking) is
suggested by the consortium GSI (Darmstadt, Germany) – FLNR JINR (Dubna, Russia) –
University of Warsaw (Warsaw, Poland) – PTI (Ioffe Physics-Technical Institute of Russian
Academy of Science, St. Petersburg, Russia) – KI (National Research Center “Kurchatov
Institute”, Moscow). The structure is open for other institutes to join. It is aimed at studies of
the nuclear landscape beyond the proton and neutron driplines and intends to push researches up
to limits of nuclear existence.

By combining the EXPERT instrumentation in different scenarios, the phenomena of
radioactivity, resonance decays, beta-delayed decays and exotic excitation modes can be studied
via observations of particle emissions, including the $2p$, $4p$, $6p$, $n$, $2n$, $4n$, $6n$ channels. Therefore
the main objectives of the EXPERT proposal are:

- Exotic $2p$ radioactivity studies and search for novel types of radioactive decays: $4p$, $2n$, $4n$.
- Studies of $p$, $2p$, $4p$, $6p$, $n$, $2n$, $4n$, $6n$ resonance decays coupled with spectroscopy of
  continuum.
- Quest aimed to discover the limits of existence of nuclear structure. Search for systems
  located far beyond the driplines aimed to answer for the basic question: “Where is the borderline
  between a resonant behavior and continuum response of nuclear matter”?
- Studies of beta-delayed particle (multi-particle) emission from exotic isotopes near and
  beyond the driplines.

For the systems whose ground states decay by (multy-) nucleon emission, the proposed
setup covers two important lifetime ranges of $1 \text{ s} – 100 \text{ ns}$, and $1 \text{ ps} – 100 \text{ ns}$ by applying the
implantation-decay and decay-in-flight techniques, respectively. For the short-lived systems, the
resonance properties and information about continuum dynamics are extracted on the basis of the angular correlations between the decay products. The above types of measurements are augmented with information on $\gamma$-deexcitation and $\beta$-delayed particle emission of the decay products.

Below we discuss some aspects of the proposed physics program in more details.

1.1.1 Particle radioactivity studies: $p$, $2p$, $n$, $2n$, $4n$

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 ($2p$) radioactivity were predicted by Goldansky in 1960 [gol60]. Soon the proton radioactivity was first observed as a $\beta$-delayed process [bar63,kar63], and about 20 years later the direct proton decay was discovered as radioactivity of an isomeric state, $^{53m}\text{Co}$ [jack70]. Later on, numerous one-proton decays were identified (see [pfu12] for a recent review). It took about 42 years until $2p$ radioactivity has been observed in $^{45}\text{Fe}$ [pfu02], and then in $^{54}\text{Zn}$ [bla05], $^{19}\text{Mg}$ [muk07] and $^{48}\text{Ni}$ [pom11]. The specific feature of the latter phenomenon is that its mechanism in general cannot be reduced to a sequence of one-proton emissions (thus sometimes it is called “true 2p decay”), and correlations between three decay products are important, which can be addressed by the adequate few-body theory [gri00]. Unexpectedly long half-lives are reported for all measured $2p$-emitters, which exceeds the diproton model predictions by factor of three orders of magnitude. A quantum-mechanical theory of the $2p$ radioactivity based on a three-body model [gri00,gri03a] 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 predictions, a number of $2p$-radioactivity candidates has been predicted for light- and medium- mass isotopes, in particular $^{26}\text{S}$, $^{30}\text{Ar}$, $^{34}\text{Ca}$, $^{38}\text{Ti}$, $^{41,42}\text{Cr}$ [gri03,gri03a]. The $2p$-radioactivity candidates, $^{26}\text{S}$, $^{30}\text{Ar}$, and $^{34}\text{Ca}$ are feasible for future studies at the fragment separator FRS and few others radioactive-beam facilities. So far, the isotopes $^{38}\text{Ti}$ and $^{41,42}\text{Cr}$ can be accessible 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 [ols13] based on the nuclear density functional theory, the global landscape of ground-state $2p$ 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 $^{103}\text{Te}$-$^{110}\text{Ba}$, where the competition between $2p$ emission and alpha decay is predicted [ols13]. 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 the $2p$-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 $^{103}\text{Te}$ (where $\alpha$- and $2p$- decay competition is predicted) is requested whose production rate at the Super-FRS is estimated to be $\sim$3 ions/h (produced in fragmentation of a primary $^{124}\text{Xe}$ beam at energy of 1.8 GeV/u and intensity of $10^{12}$ pps). The corresponding experimental scenario is described in the Section 2.3.1.

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, $\beta$-delayed one-, two- and three- neutron emissions have been identified in light nuclei (e.g., see the recent review [pfu12]). As for the direct neutron emission, all known nuclear ground states (e.g., $^5\text{He}$, $^{10}\text{Li}$, $^{13}\text{Be}$ 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 [gri11] 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 [boh95], 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.

With the experimental progress in reaching the neutron dripline, the interest to nuclei beyond this limit is increasing. There is a possibility that neutron(s) 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 Refs. [gri11]. 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 $2n$ 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 ($2p$ 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 $2n$ and, especially, of $4n$ radioactivity is plausible, since the energy windows corresponding to the radioactive timescale is estimated to be reasonably broad. The estimates show that the decay-energy conditions for true $4p$ emitters are rather un-favourite and that the $4p$ decays are most likely to occur in a form of sequential $2p$-$2p$ emission. In contrast, the decay-energy conditions for true $4n$ emission are likely fulfilled in $^7$H and could be fulfilled in several other neutron-rich isotopes, e.g. $^{18}$Be, which is in reach at the modern radioactive beam facilities. The feasibility of an experimental search for long-lived true $2n$ and $4n$ emitters (i.e. with sufficiently small decay energy) by using a method of in-flight-decay and tracking of the decay products is discussed in [gri11].

Soon after this publication, the first indication on $2n$ radioactivity of isotope $^{26}$O (whose lifetime is reported to be about 4.5(3) ps) has been published [koh13]. The upper limit of the corresponding decay energy was measured to be less than 120 keV [lun12,cae13] and even less than 10 keV [kon14]. The followed theoretical three-body interpretation of the $^{26}$O system [gri13] has demonstrated that the reported lifetime value of $^{26}$O should correspond to a very small value of the decay energy of 1 keV [gri13], which is very difficult to be measured by using the present neutron detectors. This conclusion is based on a general phenomenon in three-body systems where even small configuration mixing (due to ‘core’ recoil, n-n final state interaction etc.) causes an appearance of an $s$-wave configuration which reduces the precursor’s lifetime dramatically.

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. For such small relative energies of the decay fragments, the neutrons are not well separated in space and time. In particular, the recent measurement of the $^{26}$O decay [lun12] clearly demonstrates that the conventional invariant-mass method (which detects all decay neutrons in coincidence with a heavy fragment) has a problem when distinguishing $2n$ events from $1n$ double re-scattering (i.e. “cross-talk” effect) at $2n$-decay energies below 100 keV. We suggest the neutron detection method to be free of the mentioned complications, which is described in Section 2.3.4.

1.1.2 Resonance decay and continuum spectroscopy studies
Nuclear structure remains rather unexplored beyond the proton drip line where nuclei exist only as resonances in continuum. In light nuclei, resonances dominated by single-particle configurations are usually expected to be very broad due to low Coulomb barriers. In particular, the ground states of $^{13}$F or $^{10}$Be-N are seen as broad $s$-wave proton resonances. However, some states beyond the drip line could exist as very narrow resonances due to more complicated structure. For example, the measured $1p$, $2p$ decays of the excited states of $^{13}$F and $^{16}$Ne give evidence on relatively stable nuclear configurations beyond the proton drip line [muk09]. 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. The corresponding theoretical model calculations of the mentioned $2p$ decays should take into account both parent nuclear structure and three-body decay boundary conditions. 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. [muk09] are obtained by analysing the same data measured in the $^{19}$Mg radioactivity search [muk07] and are one of additional by-products of this experiment as well as the results on seven first-time observed resonances in $^{16}$Na and $^{19}$Mg [muk12]. Therefore future experiments aimed to find new cases of $2p$ radioactivity will provide in addition rich information on short-lived resonances located around the $2p$ precursors.

1.1.3 Search for systems located far beyond the driplines which decay by $4p/6p$ emissions

In a quest for discovery of the limits of existence of nuclear structure, we propose searches of the most distanced from stability proton-rich nuclei which decay by $4p$ or $6p$ emissions. These systems are located 4 or 6 mass units beyond driplines, and their ground-state properties can provide important clues on behavior of nuclides far away from drip lines. The only known $4p$-emitter is $^8$C whose $4p$ decay was measured at MSU. This narrow resonance undergoes sequential $2p$-$2p$ decay via the intermediate nucleus $^6$Be [cha10]. There are several unobserved $4p$-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, $^{20}$Si→$^{18}$Mg+$2p$→$^{16}$Ne+$4p$→$^{14}$O+$6p$. The only way to produce $^{20}$Si is a reaction of a direct removal of a $2n$ pair from radioactive projectiles $^{22}$Si. The reaction of $2n$ removal ($^{22}$Si, $^{20}$Si) is similar to the reference case of ($^{11}$C, $^9$C) measured at high energies in the experiment S341 at GSI [holl]. The authors came to the conclusion that $2n$ 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 $^{25}$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 reactions of $2n$-pair removal have twice broader momentum distribution in comparison with products of conventional one-nucleon removal products. Therefore high energy and large acceptance of the Super-FRS result in reasonable transmissions of fragments, which is essential for feasibility of the experiment. We suggest to study the $^{20}$Si properties as one of the EXPERT flagship cases with the decay-in-flight technique described in Section 2.3.3.

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

The disintegration of nuclei far from the line of β stability generally 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 that nucleus. Most beta-delayed decay modes are enhanced at the drip lines since multi-nucleon separation energies are low there. The
enhanced role played by beta-delayed particle emission implies that the physics problems investigated via $\beta$ decay overlap reasonably with the ones investigated via reaction studies. The selection rules for beta decay provide a spin selectivity which is useful in the data interpretation. The specific example here is the population via beta decays of excited states whose properties are important in the astrophysical $rp$ process [wor94]. Additional 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., [lan03].

We suggest a study of beta-delayed multi-particle decays by implanting extremely exotic isotopes into the OTPC detector at the end of Super-FRS, which can be done in parallel with the experiments in the middle of the Super-FRS (they are described in Chapters 1.1.1, 1.1.2, 1.1.3). 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 Section 2.3.1, where one may also find references to the previous OTPC experimental results.

1.2 Experimental concept

The nuclei of interest are extremely exotic and are mostly unobserved yet. They can be best produced by utilizing secondary reactions with radioactive ion beams of high energy $\sim$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 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 “main separator” of the Super-FRS, see Figure 1. The corresponding locations at the present 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 SuperFRS (right panel) shown by the red dots.](image)

Unbound nuclei beyond the driplines either decay in flight or are radioactive by emitting nucleons, like the $p$, $2p$, $4p$ and $n$, $2n$, $4n$ channels. Their decay products to be measured by a combination of several compact experimental installations proposed in addition to the standard beam detectors of Super-FRS by applying the decay-in-flight and implantation-decay techniques. The proposed setup has a modular structure (see Fig. 2) allowing adaptation to a number of experimental conditions and a multi-purpose operation mode needed in extensive exploratory studies beyond the drip lines, see Section 2 for details.

1.3 Competitiveness
1.3.1 The EXPERT team research background

The authors of the proposal have the extensive expertise and considerable achievements in the studies of particle radioactivity and exotic particle emission modes gained in their previous unique experiments, including experiments at the FRS fragment separator in GSI. The list of the achievements includes: (i) the experimental discovery of $2p$ radioactivity at FRS [pfu02], (ii) developments of the first OTPC (optical time projection chamber) technology and first measurements of momentum distributions for $2p$ radioactive decays [mie07], (iii) the first application of the tracking technique applied for studies of the $2p$ radioactivity in flight [muk07], (iv) creation of the first consistent quantum mechanical theory of $2p$ radioactivity [gri00] leading nowadays to a comprehensive description of this decay mode [pfu12], (v) first predictions of $2n/4n$ radioactivity [gri11,gri13], (vi) promotions of new experimental and theoretical methods aimed to use fragment correlations in three-body decays as a spectroscopic tool [gol05, sid12].

The proposed setup is based on the cumulative experience of all accomplishments in this field within the last decade. We also bring together different instrumentations with the large “internal synergy” effect and maximum efficiency of the proposed experiments.

1.3.2 Proposal features which make it unique for operation at SuperFRS

- The tracking/angular measurement part of the proposal requires a narrow 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 SuperFRS of high-energy secondary/tertiary 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/SuperFRS fragment separators provide sufficient space for such an operation, contrary to e.g. the BigRips separator.
- According to the EXPERT proposal, the last stage of the fragment separator 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, e.g. the R3B setup.

1.3.3 Unique features of the proposed experiments at Super-FRS

- The EXPERT setup is unique for radioactive $p$ and $2p$ decays for secondary reaction products within the 100 ms – 100 ns lifetime range.
- The EXPERT setup is unique for extremely low-energy (few-) neutron decay studies making it very suitable for 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 radioactive decays, with large “internal synergy” effect.

1.3.4 Additional advantages of the proposed initiative

- The highest yields of $p/n$, $2p/2n$ precursors due to extremely thick primary and secondary targets, up to 10 g/cm$^2$.
- Relative simplicity of the setup resulting in a short time required for the data analysis.
1.3.5 Motivation for the proposal as a “first day” experiment at the SuperFRS

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 [muk07, muk08, muk09, muk10a, muk12]. Thus several experimental purposes can be attained simultaneously. This option ensures a 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. 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 crossed 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 the R3B setup.

1.3.6 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 resembles the functionality of the R3B components (this is defined by a use of reactions at relativistic energy). However, the main scientific focus of the EXPERT – radioactivity studies – is complementary to the R3B setup and its experimental program. The major functionality of a secondary-target area components (tracking) corresponds to inclusive measurements mainly. Information about resonances and excitation modes obtained by EXPERT is in a limited kinematics range and thus cannot provide few-body correlations (e.g., tetra-neutron correlation). This part of EXPERT activity can be seen as preliminaries for studies at R3B.

The high resolution spectrometer is not accessible at R3B in the observable future. In a while, the EXPERT setup would provide limited in several respects but realistic opportunities for experiments requiring such instrumentation.

The silicon detectors for beam tracking can be used practically in all future experiments of NUSTAR. The respective R&D will cover essential features like the Si radiation hardness against intense beams of high-energy ions, sensitivity for the low energy ions, and stability of the detector performance in respect of parasitic irradiations.

2. Experimental techniques

2.1 Setup

The proposed EXPERT initiative components are schematically shown in Figure 2. Two experimental situations are illustrated: (i) two-proton ground state emitter is populated in one-neutron knockout and (ii) two-neutron ground state emitter is populated in one-proton knockout.
Fig. 2. Schematic layout of the proposed experiments for exploratory studies of nuclei beyond the proton and neutron driplines. 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 EXPERT components and subsystems

There are three main components for measurements of decays-in-flight of exotic nuclei:

(1) **Radiation-hard silicon strip detectors SSDs.** These compact and universal beam detectors of the SuperFRS 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 for studies radioactive decays-in-flight and provide information on trajectories of all charged decay products, which is sufficient for determination of half-life values in the range of 1 ps – 100 ns as well as on decay energies and angular correlations of decay products.

(3) **The NeuRad (Neutron Radioactivity) fine-resolution detector of neutrons.** Together with μSi detectors, this small-size 40x40x100 cm³ 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 yet phenomenon of neutron radioactivity is suggested to be probed in the decay energy range of 0.1-100 keV).

The EXPERT components augmenting the tracking subsystem are:

(4) **The GADAST (Gamma-ray Detectors Around Secondary Target) array.** It measures gamma-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 gamma emission). The GADAST demonstrator has been successfully tested in the FRS experiment “Two-proton decay of ³⁰Ar” [muk13].
The OTPC (Optical Time Projection Chamber) for radioactivity studies by the implantation-decay method. The detector measures trajectories of all charged fragments of radioactive precursors with lifetimes in the range $1 \text{s} – 100 \text{ns}$.

**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 \cite{gri00, gria, gri13} make strong motivation for performing high-risk pioneering studies \cite{muk07}.

### 2.3 Experimental scenarios

We intend to populate proton/neutron precursors in reactions of one neutron/proton knockout on the secondary target (e.g., one-nucleon knockout case is illustrated in Figure 2). It is evident that the products of two-nucleon and even three-nucleon knockout become available simultaneously with one-nucleon knockout products with the expected relative yields around $10^{-2}$ and $10^{-4}$, respectively. Such processes may lead to a population of extremely exotic systems which are located by two or three mass units further away from the drip lines. Below we present several scenarios of possible experiments and possible experimental situations. The incoming beam monitor consisting of radiation-hard SSDs (Fig. 2 item 1) and GADAST (Fig. 2 item 4) are always present in the EXPERT setup and their use is the same in all scenarios.

#### 2.3.1 Radioactive decays beyond the proton dripline when the precursor $T_{1/2} > 100 \text{ ns}$

Long-lived (radioactive) nuclides with $T_{1/2} > 100 \text{ ns}$ are populated in the secondary target at FMF2. In this case the produced nuclei are able to reach the final focal plane FH1 and stop in the OTPC, see Fig. 2 item 5. The OTPC is invoked here as the main detector as 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 \cite{pfu12, mie07, pom11}. Three 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. Radioactive decay observations made by the OTPC. (a) Two-proton ground state radioactivity of $^{45}$Fe \cite{mie07}. (b) $\beta$-delayed $\alpha+t+n$ emission from $^{4}$He \cite{mia10}, (c) $3p$-emission following $\beta$-decay of $^{31}$Ar \cite{pfu12a}.]

#### 2.3.2 Radioactivity of the proton precursors with $100 \text{ ns} > T_{1/2} > 1 \text{ ps}$

Radioactive nuclide with a shorter half-life value in the range of $100 \text{ ns} > T_{1/2} > 1 \text{ ps}$ is populated in the secondary target at FMF2. In this case, the $\mu$Si tracking 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 (because we measure its velocity), see Fig. 4. At the final focal plane FH1, the OTPC is invoked for studies of radioactivity of the secondary-beam ions which can reach OTPC, see the measured examples in Fig. 3(b,c).
2.3.3 Studies of short-lived proton resonances

Short-lived nuclides with \( T_{1/2} < 1 \text{ps} \) can be studied by the \( \mu \text{Si} \) tracking system (see Fig. 2 item 2) which is invoked as the main detector. It is operated 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 for the three-body \( 2p \) decays are reconstructed from the angular correlations proton-“heavy fragment” as well, though the results depend on a decay mechanism. It can be either “true” or sequential emission of protons, see Fig. 5(a,c). More details about the analysis procedures can be found in Refs. [muk07,muk08,muk09,muk10a,muk12]. At FHF1, the OTPC is invoked for studies of the \( \beta \)-delayed particle emissions similarly to the scenario of the Section 2.3.2.

2.3.4 Radioactive and resonance decays of the neutron-unbound precursors

The NeuRad and the \( \mu \text{Si} \) tracking detectors are invoked as the main measuring devices, see Fig. 2, item 3. The measurements of the angular HI-neutron correlations can provide unambiguous identification of lifetime or/and decay mode under certain experimental conditions. The method is similar to the technique applied in the investigations of \( 2p \) precursors by tracking their decay products in flight [muk07, muk08, muk09, muk10a, muk12]. The obtained angular correlation of just one proton (out of \( 2p \)) and a heavy fragment was sufficient for a measurement of the low \( 2p \)-decay energy with high precision [muk10a]. Similarly, a detection of \( 2n/4n \) decays in flight by the tracking technique with the measured angular correlations between one neutron and a heavy fragment allows for precisely-derived low decay energies, see Fig. 6. In such experiment the neutron detector must have a high granularity in transverse spatial coordinates.
and reasonable 1n-detection efficiency together with a relatively low efficiency of the n/4n 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.

It has been demonstrated in Ref. [gri11] that a distinct correlation pattern leads to an unambiguous identification of the decay mode, see the results of simulations in Fig. 7. Two cases are considered, the 2n decay of $^{26}$O and the 4n 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. [25] for $^{26}$O) or by 150 keV (the upper-limit value measured in Refs. [12]). Both precursors decay to the $^{24}$O ground state by 2n/4n 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 2p decays [muk07, muk08, muk09], 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 2n decay energies as low as 1 keV can be reached provided the experimental setup has an angular resolution less than 1 mrad. The true 4n 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 2n-2n decay via the $^{26}$O g.s. provides a two-peak correlation distribution. Similarly, for the simulated 4n decay, the necessary angular resolution of the neutron detectors should be < 1 mrad as well. Existing neutron detectors, like the present large-area neutron detectors at RIKEN, GSI and MSU, 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 built as a bunch of straw-like scintillation fibers (each with a small cross area of 2x2 mm$^2$) will provide the necessary angular resolution already at 10–20 m distances from the decay point [muk14]. Its dynamical range is limited to small decay energies only, which makes no competition to large-energy-range invariant-mass detectors like the NeuLAND detector of R3B NUSTAR. Tests of the NeuRad prototype are under way [muk14a].

All in all, the general lay-out of the dedicated experiment searching for (multy-) neutron radioactivity includes the $\mu$Si 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 identification and its momentum measurements). In addition, the OTPC is invoked for studies of the exotic radioactivity of implanted secondary beam at FHF1, similarly to the scenario of Section 2.3.2.
Fig. 7. Illustration of possibility to understand 2n and 4n emission modes by measuring angular HI-neutron correlations [gri11]. 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.

2.4 Theoretical/Simulation framework development

It is presumed that the hardware developments within EXPERT initiative are augmented with relevant theoretical research. Moreover in certain aspects the progress in this research is integral part of the future success of the whole project.

The aims of expected theoretical/simulation developments within EXPERT initiative are:

- In majority of the EXPERT scenarios measurements of particle in coincidence are expected. The more exotic the situation under investigation the more particles in coincidence should (or could) be registered. The (multiparticle) registration efficiency and, especially, the reconstruction of correlation distributions are strongly affected by specific of experimental setup. MC simulations of the experimental setup are the standard (and seem to be the only realistic method) to resolve the problem. In EXPERT experiments importance of the MC procedures emphasized by the fact that kinematically incomplete information is obtained, which means that it can be interpretable only in certain model assumptions about “missing” degrees of freedom.

- On theoretical side many of the systems beyond the nucleon driplines have opened few-body decay channels and demonstrate exotic few-body nuclear dynamics, see Fig. 8 for overall view of the situation. Many theoretical issues of few-body continuum population and few-body decay dynamics are still unresolved. The rapid experimental progress in this field challenges our ability to provide the adequate theoretical methods for treatment of this physics.

- Conjugation of the theoretical calculations with the needs of experiment in this field can be very complex, especially, when the details of the reaction mechanisms begin to play important role. E.g. for the three-body decay the 8-fold differential cross section is to be simulated. The program of development of the software providing theoretical input for experimental MC simulations in the form of fully Quantum-Mechanical theoretical MC simulations is in progress for several years in our collaboration. The formal title for this development is TEG-DDR (Three-body event generator for decays and direct reactions). Potential power of the corresponding method can be understood from the recent publications (e.g. Refs. [pfu12,sid12,ego12,fom12a]), where the discussed developments were applied on various levels of sophistication.
3. Implementation

The proposed EXPERT initiative includes the following components (itemizing provides the major functionality, R&D status, current financing sources, and delivery plans):

3.1 Radiation hard SSDs
- **Recent publications**: [ere12,kis12].
- **Development “roadmap”**: New generation of radiation hard SSDs has been developing at PTI-RIMST consortium (RIMST – Research Institute of Material Science and Technology, Zelenograd, Russia) in frame of Program for basic research of Russian Academy of Science together with GSI and ACCULINNA group (JINR) since 2013.
- **Available resources**. To be applied via the Russian in-kind contribution, partially by BMBF.
- **Tests with beam, pilot experiments**. Tests of prototypes in 2014, 2015 at ACCULINNA, JINR.

3.2 μSi tracking system
- **Recent publications**: [muk12].
- **Development “roadmap”**: New 6 detectors with improved characteristics are available at GSI (with 20% share by JINR). Upgrade of electronics will be complete in 2014.
- **Available resources**. Manpower and additional materials (from GSI and JINR).
- **Tests with beam, pilot experiments**. S414 experiment (awaiting beamtime).

3.3 NeuRad angular hi-res detector of neutrons.
- **Recent publications**: [gri11].
- **Development “roadmap”**: Tests of a light output of a 8x8 bundle of the BCF12 fibers with PMT have shown the registration threshold of 160 keV. Construction and tests of the 5% prototype are planned by the ACCULINNA group (JINR, Dubna, Russia) in 2014–2015.
- **Available resources**. Materials for a full-size detector are now available at GSI (financed by BMBF). Manpower (2 PhD students) is supported by the FAIR-Russia Research Center (4-years grant since 2014).
- **Tests with beam, pilot experiments**. First beam test of low-energy prototype is expected in 2015 at ACCULINNA, JINR.
3.4 GADAST target area gamma detector.

- **Recent publications:** [muk10].
- **Development “roadmap“.** Currently in production, 20 modules are built and tested, all components are available for 64 modules in total, which should be delivered by ACCULINNA group (JINR) by middle 2014.
- **Available resources.** Materials are financed by BMBF. Workforce (2 PhD students and one postdoc) are financed by FAIR-Russia Research Center (4-years grant since 2014).
- **Tests with beam, pilot experiments.** First beam test performed with 16-module demonstrator during S388 GSI experiment (August 2012). Full configuration run is planned for the S414 experiment (awaiting beamtime).

3.5 OTPC for stopped-beam studies

- **Recent publications:** [pfu12,pfu12a,fom12].
- **Development “roadmap“.** New generation Optical Time Projecting Chamber is built by the University of Warsaw. Several further improved and specialized designs are under consideration and development.
- **Available resources.** Financial support is via the Poland contribution to JINR.
- **Tests with beam, pilot experiments.** Invoked in the recent S388 GSI experiment in August 2012 [pfu12a]. Use of OTPC in the planned S414 experiment (awaiting beamtime). The beamtime is awaited in the end 2013/beginning 2013 at MSU.

3.6 Theoretical/Simulation framework

- **Recent publications:** [pfu12,ego12,fom12a]
- **Development “roadmap“.** Development of MC event generators TEG-DDR (Three-body Event Generator for Decays and Direct Reactions) by theoretical section of ACCULINNA group. For 2014 studies of prospects to incorporate channels with more than three outgoing particles are planned. In 2014-2015 the delivery of the public domain version of the code is planned.
- **Available resources.** Manpower (2 PhD students) is financed by the FAIR-Russia Research Center (4-year grant since December 2013).
- **Tests with beam, pilot experiments.** The latest versions have demonstrated the high performance for a number of the reaction mechanisms applied in analysis of the data obtained at GSI, JINR, MSU.

3.7 Nearest prospects of the setup usage or component tests summarized

The proposed EXPERT setup has a modular design: all the ingredients have their own applications in experiments. However, within the proposed initiative we expect a significant synergy effect. The EXPERT setup comprises an advanced version of the setup used in the successful S271 and S388 experiments at GSI (searches for 2p-radioactivity of $^{16}$Mg and $^{30}$Ar, respectively). All components of the proposed setup are under active developments. All of them (except the NeuRad) can be used in the possible nearest experiments at FRS. E.g., the proposal S414 “Search for two-proton radioactivity of $^{26}$S“ accepted at GSI in 2010 is awaiting beamtime. Continuation of this program in the next years at FRS might ensure confidence that by the moment of the SuperFRS 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 its $\alpha$- and 2p- decay branches. As the other nearest candidates for such studies could be following systems: $^{20-21}$Si, $^{38}$Ti, $^{34}$Ca, $^{31}$Cr, $^{58,59}$Ge, $^{62,63}$Se, $^{66}$Br, $^{71}$Rb and $^{7}$H, $^{16}$B, $^{18}$Be, $^{21}$B, $^{26,28}$O.
References


I. Mukha et al., *Gamma detectors around a secondary target GADAST at the middle of the fragment separator FRS*, Lol 49 (2010) to G-PAC GSI, unpublished.


I. Mukha et al., *New states in $^{18}$Na and $^{19}$Mg observed in the two-proton decay of $^{19}$Mg*, Phys. Rev. C **85** (2012) 044325.


M. Pfützner et al., *Observation of beta-delayed three-proton emission from $^{31}$Ar with the Optical Time Projection Chamber*, GSI Scientific Report 2012, PHW-ENNA-EXP-17, p.147, http://repository.gsi.de/record/52876.