**APPROVED**

**JINR DIRECTOR**

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**" " \_\_\_ 2023**

**SCIENTIFIC AND TECHNICAL REASONING FOR THE OPENING**

**OF PROJECT**

**IN RESEARCH AREA WITHIN THE TOPICAL PLAN FOR JINR RESEARCH**

**1. General information on the project**

* 1. **Theme code** 3-5-1130-2017

**1.2 Project**

**1.3 Laboratory**

Flerov Laboratory of Nuclear Reactions

**1.4 Scientific field**

Heavy ion physics

**1.5 The name of the Project**

Light exotic nuclei at the borders of nuclear stability.

**1.6 Project Leaders**

G. Kaminski, S.I. Sidorchuk

**1.7 Project Deputy Leaders**

V. Chudoba, A.S. Fomichev

**2 Scientific rationale and organizational structure**

**2.1 Annotation**

With the development of modern accelerator techniques and computational techniques, it is now possible to take nuclear physics far away from the area close to stability both in theory and in practice. Nuclear systems far from stability are in a geographical analogy called exotic nuclei. Exploration of exotic nuclei and unbound nuclear systems at the borders of nuclear stability have been possible largely due to the development of Radioactive Ion Beams (RIB’s) at accelerator facilities. To study radioactive species with short half-lives, they must first be produced in the laboratory. This field of physics is being actively explored in the world's leading centers (RIKEN, GSI, GANIL, MSU) [1]. At FLNR, JINR, the research program for studying light exotic nuclei by the in-flight fragmentation method at the ACCULINNA separator started in 1996 at the U400M cyclotron [2]. In 2017, the FLNR experimental complex was extended by commissioning a new generation of in-flight facility – the ACCULINNA-2 separator. It has opened a wide range of new experimental possibilities for studies of light exotic nuclei using secondary beams at the energy range of 5-50 MeV/nucleon.

The ACCULINNA-2 separator is equipped with the radio-frequency filter (RF kicker) for additional purification of secondary beams, the zero-degree spectrometer for separating reaction products, an array of neutron detectors based on stilbene crystals, and detection systems for registration of charged particles. The experiments performed at the new separator already resulted in new data on extremely neutron rich nuclear systems such as 6,7H,7,9He,10Li [3-6]. The realization of the experimental program was stopped in 2020 for an upgrade of the U400M cyclotron. By 2024 the upgrade of the cyclotron should be finished. Then the upgraded cyclotron complex will offer new quality, intensive heavy ion beams for light exotic nuclei study.

The research program is focused in studying the structure of light nuclei and nuclear systems near and beyond the borders of nuclear stability by means of transfer reactions, investigation of rare decay modes and the influence of the reaction mechanisms on the observed characteristic of studied nuclei. The successive application of transfer reactions to study the structure of nuclei near the borders of nuclear stability can lead to obtaining the most reliable information and revising existing knowledge.

The experimental program will be realized at the ACCULINNA-2 facility, taking the advantages of work with intensive beams, separator key equipment (RF-kicker, zero-degree spectrometer) and cryogenic target complex [7].

The ACCULINNA facility will be used for tests measurements, detectors testing and applied studies (samples irradiation, etc.) that do not require a high quality of the secondary beam (intensity, purification from impurities, transverse size).

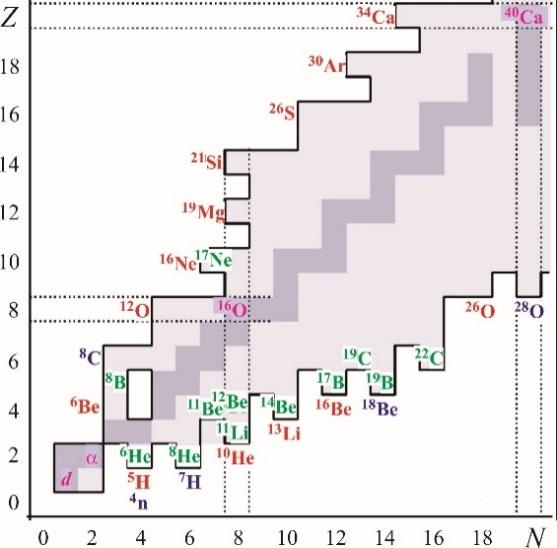
**2.2 Scientific justification (**purpose, relevance and scientific novelty, methods and approaches, methodologies, expected results, risks).

**Area of interest – light exotic nuclei at the borders of nuclear stability.**

Advancing towards the boundaries of nuclear stability in the study of neutron-rich and neutron-deficient nuclei has been and remains a top priority in nuclear physics over the past half-century. Investigating the properties of these nuclei is crucial for understanding the nature of nuclear forces, astrophysical processes, and the formation of chemical element nuclei.

The current status of research on light exotic nuclei in the region *Z* ≤ 20 is shown schematically in Fig.1. The limits of nuclear stability have been reached only for the lightest nuclei, and the properties of these nuclei (5,6,7H, 9,10He, 11,13Li, 16,18Be, 17,19B, etc.) are intensively studied in the world's leading centers [1]. Among the most interesting objects of research, it is necessary to mention the so-called Borromean nuclei with a two-nucleon halo, two-proton radioactivity, cluster structure and three body decays [8]. As known, nuclear structure models were formulated on the basis of data obtained for nuclei in the vicinity of the *β*-stability line. The predictive power of these models dramatically decreases when going to the unknown region of the nuclei chart. Therefore, one of the particular interests of the study of exotic nuclei with a low binding energy of valence nucleons and an anomalous *N/Z* ratio is to provide new data for nuclear structure models probing.

Carrying the experiments with exotic nuclei requires high energy and high intensity secondary beams. But high energy, in turn, imposes restrictions on the reaction mechanism. With the energy increase the cross-sections for a nucleon transfer are falling, while for knockout are increasing, respectively. As a result, experimental information on the nuclear structure and decay channels of the lightest nuclei is rather poor and highly contradictory as the existing data were collected for different reaction mechanisms.



**Fig.1.** Status of research at the light nuclei for *Z* ≤ 20. Halo nuclei are highlighted in green, two protons or neutron emitters are in red, 4*n*/4*p* emitters are in blue, the *β*-stability line and regions of nuclear stability are highlighted in gray and light gray, respectively. Dotted lines indicate closed shells for neutrons/protons.

One of the main sources of information about the structure of exotic nuclei are experiments on measurement of fragmentation or stripping at a relatively high energy. These data are often contradictory to the results from the transfer reactions (for example, 5H or 10He). One of the possible explanations is the influence of the structure of the input state and the reaction mechanism on the formation of the final state spectra. The successive application of transfer reactions to study the structure of nuclei near the borders of nuclear stability can lead to obtaining the most reliable information and revising existing knowledge. Moreover, it is necessary to concentrate on the complete kinematic experiment to obtain the most reliable information about the nuclear structure. Additionally, the energy range of the U400M accelerator is optimal for studying direct transfer reactions, which, in turn, are the most reliable source of information about the nuclear structure.

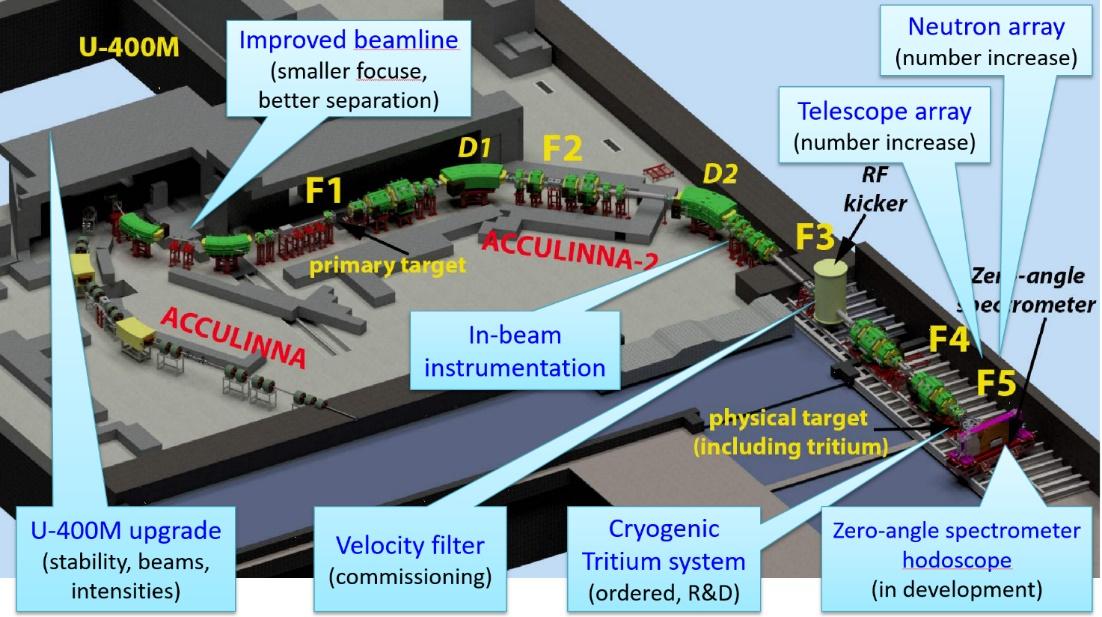
Availability of cryogenic targets of hydrogen and helium isotopes offers an opportunity to move toward more exotic, more neutron rich nuclei via one- and two-neutron transfer (*d*,*p*), (*d*,*n*), (*d*,3He), (*d*,3H), (*p*,*d*), (*p*,*t*), (3He,*n*), (*t*,*p*), (*t*,*α*), which are characterized by a relatively high cross section at energies of 10–50 MeV/nucleon [1].

Transfer reactions in the energy range available at the FLNR are also perspective for studying clusterization structures in light exotic nuclei. As a prominent tool for this purpose measurement of an alpha particle transfer in (6Li,*d*) reactions are considered. Inverse kinematics reactions with registration of the angular distribution of charged decay products of the excited states of studied nucleus can be used to determine the spins and parities of alpha cluster states. A measurement of cluster structure in 14C at the excitation energy range 12–20 MeV is one of the first planned experiments.

**Experimental base at the FLNR**

At the Flerov Laboratory of Nuclear Reactions (FLNR) JINR, the research program on light exotic nuclei obtained by the in-flight fragmentation method began in 1996 at the ACCULINNA-1 fragment separator with the U-400M heavy ion accelerator. This program was limited by a narrow range of available primary beams, the simple construction of the separator and relevant technical parameters (acceptance, purification degree, length). However, this facility consistently produced scientific results during the period 1996-2016 [1] due to the following key factors: (a) the presence of high-intensity primary heavy ion beams at the U-400M cyclotron; (b) the use of new methods for analyzing correlation data; (c) the application of a cryogenic tritium target for studying nuclei 5H, 8He, 10He in the (*t*,*p*) reaction.

Further, in 2018, a new fragment of the separator - ACCULINNA-2 [4] was commissioned (Fig. 2), and in 2019-2020, the first experimental results were obtained on it [3,9,10]. In particular, it was possible to shed light to the long-standing landmark problems of experimental nuclear physics – the detection of the isotopes 6H and 7H, as well as to advance in the study of a new mode of spontaneous nuclear decay with the simultaneous emission of 4n. In terms of "productivity" of radioactive beams, ACCULINNA-2 outperforms ACCULINNA-1 by about 30 times, and the improvement in the degree of beam purification can reach a factor of 100. The characteristics of ACCULINNA-2 are generally comparable to facilities of the same class, such as RIPS (RIKEN, Japan) and LISE (GANIL, France).



**Fig.2** The ACCULINNA and ACCULINNA-2 separators in the hall of the U-400M cyclotron. The insets show the main subsystems of the ACCULINNA-2 that require launching/debugging to increase the luminosity of experiments with radioactive beams and expand their range.

Detailed information on the status of the ACCULINNA-2 facility and a possible program of the first experiments with RI beams are provided in review [9]. The main advantages of ACCULINNA-2 complex compared to world analogues of in-flight separators are: (a) a relatively low range of ion energies (from 5 – 7 MeV/nucleon to 50 MeV/nucleon); (b) the ability to work as a physical target with all helium and hydrogen isotopes (including tritium) in a wide range of thicknesses (from 1019 to 1021 atoms/cm2), achieved by choosing the phase state of the substance - gas or liquid. Moreover, the energy range of heavy ion beams available at the U400M accelerator is optimal for studying direct transfer reactions, which, in turn, could deliver the most reliable information about the nuclear structure.

In the period 2024-2028 realization of this project is proposed at the new upgraded U400M cyclotron experimental complex. Studies of the structure of nuclei with a large excess of protons or neutrons and rare channels for their decay will be carried out on secondary beams of radioactive ions obtained in the fragmentation of beams of stable nuclei with Z ≤ 36 accelerated to energy of 30 – 60 MeV/nucleon. The primary beryllium target and the existing radiation shielding make it possible to operate with a beam power of heavy ions up to 4 kW. Since mid-2020, the upgrade of the U-400M accelerator has been underway, aimed at increasing the accelerator operation stability, increasing the energy, intensity, and quality of heavy ion beams. Therefore, in 2024 due to availability of new quality radioactive ion beams it is expected that the program of research with unstable nuclei will be resumed at a qualitatively new level.

**Exploring borders of nuclear stability**

The scientific program aims to study the properties of isotopes at the boundaries of stability. It can be divided into several main topics. The following are proposed:

1. Investigation of hard-to-access neutron-rich nuclei along with their isobar analogs or mirror nuclei. Isobar analogues are important for studying the properties of atomic nuclei and for testing nuclear models. By comparing the properties of isobar analogues, one can gain insights into the underlying nuclear forces and interactions that govern the behavior of atomic nuclei. Studies of mirror nuclei have been used to test the symmetry properties of the nuclear forces, and to investigate the role of isospin symmetry in nuclear structure. They also play an important role in astrophysics, as mirror nuclei can be used to study the nucleosynthesis of light elements in stars.
2. **5He-5H:** This topic takes advantage of using the same combination of beam+target for conducting of the **6He(d,3He)5H** and **6He(d,3H)5He** reactions in inverse kinematics. Both isotopes are characterized by a two-neutron decay, which is essential for understanding the interactions between neutrons in such systems. By investigating the behavior of the t+*n*+*n* correlations, we can gain insights into the structure of 5H and the dynamics of the two-neutron decay process. Like 5H, 5He also exhibits a two-neutron decay, which in this case corresponds to the 3He+*n*+*n* channel. Investigating the behavior of this decay mode can shed light on the structure of 5He and the interactions between neutrons in neutron-rich nuclei.
3. **7H-7He-7B:** All these isotopes are undoubtedly of great interest. The available combinations of beams and targets provide us with the possibility to populate low-lying states through different reaction mechanisms and investigate their impact on the structure of these states. Neutron-rich isotopes, such as 7H and 7He, can be populated in reactions with 6He and 8He beams hitting proton, deuterium, or tritium targets, such as **8He(*p*,*d*)7He**, **6He(*d*,*p*)7He**, **8He(*d*,3H)7He**, **8He(*d*,3He)7H**, and **8He(*t*,4He)7H**, in inverse kinematics. Low-lying states of 7B can be populated through the neutron transfer reaction **8B(*p*,*d*)7B** or the charge-exchange reaction **7Be(*p*,*n*)7B**. Investigating the 7B nucleus, a mirror nucleus for 7He, offers better experimental access to 7He properties.  
   Moreover, due to the employment of a neutron detection wall, we will be able to detect all particle products. Additionally, the expected decay chain 7B→6Be →5He will provide further access to the 5He isotope mentioned above.

These experimental approaches not only contribute to our understanding of the properties and structure of neutron-rich isotopes but also help refine theoretical models used to describe nuclear systems. By carefully selecting appropriate combinations of beams and targets, one can investigate the behavior of these isotopes in various reaction mechanisms, gaining valuable insights into the fundamental forces governing nuclear interactions and the limits of nuclear stability.

1. **10He-10Li-10N:** These isotopes represent some of the most complex and hardly accessible isobars with a mass number A=10. They can be populated through **8He(*t*,*p*)10He**, **9Li(*d*,*p*)10Li**, and **9C(*d*,*n*)10N** reactions. The use of a liquid tritium target allows for larger statistics of 10He, enabling more detailed studies of its properties and decay modes. Measuring all reaction products for both mirror nuclei, 10Li and 10N, will allow for comparative analyses of their nuclear structure properties. This comparison can provide valuable insights into the behavior of these exotic isotopes and their interactions, helping to refine theoretical models that describe their properties and decay mechanisms.
2. First experiments with tritium target: 13Li; 16Be;

Within the Project, we plan to conduct a few experiments from the aforementioned list, with an approximate rate of one-two experiments per year. The specific experiments to be carried out will be determined by the readiness of our equipment (see Risks).

**Structure of drip line isotopes in (*d*,*p*) and (*d*,*n*) reactions**

Single nucleon transfer reactions have, for many decades, played a major role in the development of the understanding of the structure of nuclei. Reactions such as (*d*,*p*) have served as fundamental tools for studying the properties of single particle states in nuclei throughout the periodic table. The kinematics selectivity and high cross-section of one-neutron transfer (at small angles close to 0°) of the (*d*,*p*) reaction in particular have made it one of the most heavily used reactions for the experimental determination of spin-parity, and for probing the wave functions of single-particle states in nuclei. Interest in direct transfer reactions such as (*d*,*p*) has been renewed and invigorated with the possibility to test new, powerful theoretical methods for calculating nuclear structure, as well as the ability to address new questions in nuclear astrophysics. Such a tool is particularly important while there is a lot of contradictory data on the same nuclear systems which need to be clarified. The candidates for such studies are 7,9He,10Li.

For this purpose a detailed study of the spectrum of low-lying 7,9He, 10Li levels populated in (*d*,*p*) reactions, using the zero degree spectrometer and an upgraded neutron detection wall will be performed. The main advantages of new measurements in comparison to the first measurements at the ACCULINNA-2 are:

* expected better statistics due to higher primary beam intensity,
* better energy resolution and significant background suppression due to use of the zero-degree spectrometer.

**Nuclear structure with tritium target system**

Availability of a cryogenic tritium target complex offers a unique possibility to explore borders of nuclear stability and beyond with cryogenic T2 target by means of 2*n*-transfer reactions. 3H is seen as a prominent source of 2*n* to be transferred and as light recoil as p, for effective registration of light nuclei (Z<=6) in the range of a small angles in center of mass system (characterized by a larger cross section) in correlative measurements. In such an approach the structure of a group of light neutron dripline nuclei could be probed. Moreover, tritium may be used as a receiver of proton in (*t*,4He) reaction which is characterized by large cross sections. Usage of 3H as a target is an effective way (relatively large cross sections) to probe low lying states at nuclear resonances as 7H, 10He, 13Li,16Be.

**7H:**

Study of the 7H levels spectra and decay channels with successive and democratic emission of 4*n*, obtained in the cross reaction 8Hе(26 MeV/A)+3H→4Hе+7H, refinement of data from [3,4]. Advantages compared to the existing literature data: 1) the population of 7H in such a reaction, which is characterized by a more favorable energy balance in comparison with the reaction 8Hе+2H→3Hе+7H; 2) measurements with a higher energy resolution is expected (an improvement by a factor of 2 in comparison with the experiment [4]) due to the registration of all fragments in the exit channel. The 7H levels spectra will be studied in the (*t*, *α*) transfer for the first time.

**10He:**

Study on 10He level spectra and 2*n*-decay channel in the reaction 8Hе(26 MeV/A)+3H→1H+10He, refinement of data from [11]. Advantages: 1) Higher statistics due to the use of a liquid tritium target ~3\*1021 atom/cm2 thick, 3-5 times thicker than before) and high 8He intensity ~2\*105 1/s (before ~104 1/s); 2) higher energy resolution due to the complete kinematics measurements, i.e. correlation data will be obtained from triple and quadruple coincidences *p*-8He-*n*-*n*.

**13Li:**

Study of low-lying levels in the spectrum of 13Li in the 11Li(26 MeV/A)+3H→1H+13Li reaction. Advantages in comparison with the known literature data: 1) the population of 13Li in the reaction (*t*,*p*) with a known (i.e., well-studied) mechanism of two-neutron transfer will be done for the first time; 2) due to the detection of *p*-*n*-11Li and *p*-*n*-*n*-11Li coincidences with a statistics of about 100 events for the ground state a high energy resolution is expected.

**16Be:**

Measurement of precision data on the spectrum of low-lying 16Be levels and decay channels with 2*n* emission will be conducted using the 14Be(*t*,*p*)16Be reaction in inverse kinematics. Comparison with the results of work [12], where 16Be was populated in the proton stripping reaction 17B(53 MeV/A) on a beryllium target, will be performed. It is worthy to mention that the contribution (influence) of the initial states of the projectile 17B on the final states of 16Be is excluded.

Lighter neutron-rich isotopes like 6,8Не, 11Li, 11-14Be are also in the zone of interest.

**Exotic radioactivity - search for 2*p* radioactivity**

Commissioning of the RF filter will open ways to the whole series of proton-rich nuclei with *Z*≤36, lying close and beyond the proton drip-line. These include a number of nuclei predicted to exhibit 2*p*-radioactivity. Furthermore, great interest is in the dynamics of the 2*p* decay of resonant states, e.g., of 6Be, 12O, 16Ne, 26S, 30Ar, etc. Nevertheless, only a few could have half-lives long enough for detection by means of the TOF method. Unknown isotope 26S, is expected to decay by two-proton (2*p*) emission, was already studied theoretically and was searched experimentally at ACCULINNA-1 [13]. In these studies, a half-life upper limit for 26S of T1/2<79 ns was set.

Study of the 2*p* decay mode in such short living nuclei (17Ne, 26S) should be feasible in transfer/charge exchange reactions (*p*,*d*), (3He,n), (*p*,*n*) induced by RIBs, and will be included in the research program.

**26S:**

Study of 26S level spectra and search for the 2*p* decay channel from the 26S ground state in the reactions 27S(30 MeV/A)+1H→2H+26S, 24Si(32 MeV/A)+3He→*n*+26S, 26P(28 MeV/A)+1H→*n*+26S. Advantages in comparison with the data known in the literature and the data obtained at ACCULINNA-2 [13]: 1) this approach to the study of 26S has not been used before; 2) Operation of the RF-kicker will significantly improve the purity desired secondary beam 27S/26P/24Si by a factor of ~50 comparing to the ACCULINNA-1. 3) there will be improved beam tracking to a physical target due to low-pressure coordinate detectors; 4) The unambiguous determination of the output channel (i.e., the 24Si core from the 26S→24Si+p+p decay will be identified against the background of incident beam, among which there is 24Si) due to the use of the zero-degree spectrometer. Refinement of data from [13].

**17Ne:**

Study of 17Ne level spectra and search for the 2*p*-decay channel of the first excited state of 17Ne (3/2¯), refinement of the data of work [14], namely, a significantly (about 50 times) lowering of the limit of the ratio of partial widths Γ2*p*/Γγ of the first excited state of 17Ne (Jπ=3/2¯), obtained in [14] as Γ2*p*/Γγ < 1.6(3)х10-4. These data play an important role for astrophysics, in particular, for the theoretical description of combustion in stars. Promising reactions: 18Ne(35 MeV/A)+1H→2H+17Ne, 15O(38 MeV/A)+3He→n+17Ne, 17F(35 MeV/A)+1H→n+17Ne. Advantages: 1) significant (factor of ~25) improvement in the beam purification at ACCULINNA-2 with RF kicker compared to ACCULINA-1 for the settings on 18Ne/17F/15O in the producing reaction 20Ne(53 MeV/A)+Be; 2) improved beam tracking to a physical target due to installation of a low-pressure coordinate detectors; 3) background reduction of projectile-like fragments by applying additional fragments separation at the zero-degree spectrometer.

**Methodology**

Proposed project of study of light exotic nuclei requires operation at gaseous and liquid targets at cryogenic temperatures, operation with higher purification level of the radioactive ion beams, commissioning and implementation of essential equipment and new detector systems to the experimental base.

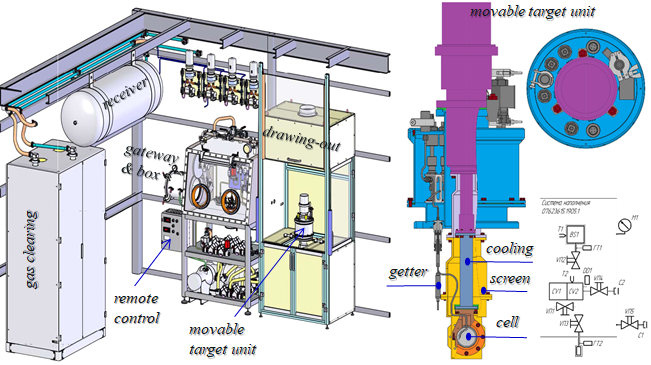
Currently, most of the experimental installations are in working condition; however, several aspects require additional refinement and development. The following system elements can be improved or implemented to increase the efficiency of research and expand capabilities:

1. Construction and commissioning of a tritium target.
2. Development and implementation of 1,2H and 3,4He cryogenic targets.
3. Commissioning of the RF filter to increase the purity of radioactive beams, as well as detection efficiency.
4. Development and construction of zero-degree spectrometer based on existing D3 magnet for measuring energies and angular distributions of heavy fragments from reaction products.
5. Beam diagnostics system for radioactive ions using PPAC detectors [citation].
6. Neutron detector wall based on plastic scintillators for registering neutrons emitted as a result of decay or recoil from the (*d*,*n*) reactions.
7. Silicon strip detectors for measuring coordinates and energies of charged particles.
8. Microstrip detectors for providing high spatial resolution and large detection area.
9. Software for conducting experiments and data analysis (e.g., ExpertRoot, Go4, etc.) enabling the processing and interpretation of obtained results.

Implementation and optimization of the aforementioned equipment and instrumentation elements will significantly increase the efficiency of research and expand the capabilities for studying the properties of exotic nuclei.

**Tritium target**

To carry out the experiments with radioactive beams at the ACCULINNA-2 separator, a complex of cryogenic physical targets with isotopes H2, D2, T2, 3He, 4He in gas, liquid and solid (for hydrogen) phases has been created (Fig. 3) [15]. The project developed in collaboration with VNIIEF (Sarov), DZHM (Dzerzhinsk), and VNIPIET (Sosnoviy Bor) is at the final stage of realization. A conceptual design of the tritium-target complex is presented in (Fig. 3).



**Fig. 3.** A complex of cryogenic physical targets. Scheme of the gas-vacuum system (left) and the tritium target cell with related subsystems (right).

It includes a comprehensive gas-vacuum and tritium safety system for the supply, cooling-heating, control, radiation safety, and utilization of unwanted gases. The complex will provide operation at gaseous and liquid targets at cryogenic temperatures.

The design of the cryogenic tritium target cell, gas vacuum system is on the stage of the equipment ordering and manufacturing. The technical design of the special ventilation system of the experimental cabin is under technical expertise for safety rules at the approval stage. The design of the system of utilization of liquid radioactive waste is under technical expertise to fulfill the safety rules. The targets of all long-living isotopes of hydrogen (including tritium) and helium with the thickness being in a wide range (1020÷5\*1021 atoms/cm2) will be available for use in experiments since 2026. The activity of tritium will achieve up to 2.7 kCi. The riskiest stage of this project is impossibility/delay in obtaining a certificate for work with tritium target complex.

**RF-Kicker**

In 2018-2020, as a continuation of development of essential experimental equipment for the ACCULINNA-2 beam line the radio-frequency filter (RF kicker) was designed and installed [1]. In 2024 commissioning of the RF-kicker system is planned. Operation with RF-kicker will open up new possibilities of investigations in the proton-rich region of unstable nuclei. The upgraded ACCULINNA-2 beam line will result in reduction of the unwanted ions at the settings on the settings of 27S/26P/24Si by a factor of ~ 50 compared to analogous settings at ACCULINNA-1 [13]. A control system for RF-kicker should be developed.

**Zero Degree Spectrometer**

In 2017 the dipole magnet of the zero-degree spectrometer had been installed at the ACCULINNA-2 beamline. In the period of 2024-2028 further development of a particle tracking system based on multiwire proportional chambers (MWPC), parallel plate avalanche counters (PPAC) (front detector), particle hodoscope (backward detector) and plastic scintillators is planned. The particle tracking system will provide reconstruction of charged particle trajectories with a good position resolution and high detection efficiency. Moreover, usage of the particle tracking system for diagnostics of RI beams and the ion-optical tuning is planned. It is crucial to measure particle trajectory with high-resolution *Bρ* determination to achieve excellent particle identification power of the ACCULINNA-2 separator.

**Detectors**

New detector systems and related electronics have been developed as well. It include the following items: a) detector array for detection of neutrons based on stilbene crystals and plastic scintillators [16]; b) radiation-hard and extremely fast silicon strip detectors providing excellent time resolution (σ ~ 50 ps) for RIB diagnostics [17]; c) scintillation arrays of CsI(Tl), LaBr3(Ce), etc. crystals for detection of gamma-rays and possible detection of charged particles; d) new generation of micro-strip silicon detectors dedicated for tracking of charged particles [17]. Actually, the construction of particle tracking systems for the zero-angle spectrometer, together with hodoscope detectors and neutron array at the final focal plane F5, has started.

A modification of the detector array intended for the study of nuclei undergoing decay with the multi-neutron emission is planned. The modification assumes the use of the assembly of 100 BC-404 scintillators which are at the disposal of the ACCULINNA group. The proposed detector system, together with the existing array of stilbene modules [18], will significantly increase the luminosity of the ACCULINNA-2 setup, which plays a key role in the experiments with radioactive beams [1,5].

**Risks:**

In the risk analysis for this project, we identify two main categories of risks that could potentially impact the project's timeline and success. The first category pertains to the planned and scheduled construction and commissioning of equipment, where unforeseen challenges, delays, or technical difficulties may arise, affecting the project's progress. The second category revolves around external circumstances, including factors such as the possibility to purchase detectors, electronics, and vacuum techniques, as well as potential issues with the certification of tritium targets. These external factors can introduce uncertainties and complications, which may, in turn, influence the execution and outcomes of the project. By identifying and addressing these risks early on, we aim to mitigate their impact on the project and ensure its successful completion.

In our risk analysis, we consider the potential challenges associated with key items of equipment and propose suitable mitigation strategies:

1. Construction and commissioning of a **tritium target** pose a **medium level of risk**, as there is a possibility that certification may not be granted. In such an event, the possible solution would be to conduct experiments that do not require the use of a tritium target, thereby ensuring the project's progress despite this setback.
2. The development and implementation of **1,2H and 3,4He cryogenic targets** may encounter a **low level of risk**, primarily resulting from potential delays in construction. To address this risk, the project team could utilize existing target cells, allowing experiments to continue as planned while new target cells are being developed.
3. The **commissioning of an RF filter** to enhance the purity of proton-rich radioactive beams presents a **medium level of risk**. Potential challenges include the complexity of constructing radiation protection and obtaining certification for operation. To mitigate this risk, the project is considering conducting experiments with neutron-rich beams, which would allow for continued progress in the research while the RF filter is being certified.
4. The development and construction of a **zero-degree spectrometer** may face potential troubles with the availability of silicon strip detectors in sufficient amount and quality, posing a **medium level of risk**. A solution to this challenge is the purchase of silicon strip detectors developed and produced in markets not affected by sanctions.
5. Implementing a beam diagnostics system for radioactive ions using **PPAC detectors** may face potential troubles due to a lack of manpower, presenting a **low level of risk**. As a solution, the project could employ the existing tracking system based on MWPC, thereby ensuring progress in the project.
6. Developing a **neutron detector wall based on plastic scintillators** could face potential troubles due to a lack of electronics in sufficient amounts for the construction of all scintillation modules, presenting a **medium level of risk**. To mitigate this risk, the existing neutron wall based on stilbene monocrystals in conjunction with the available plastic scintillators may be used within the project.
7. **Silicon strip detectors** for measuring coordinates and energies of charged particles may face potential troubles, as these detectors are consumable parts and will deteriorate in performance when irradiated, or damaged during manipulation, posing a **high level of risk**. A solution to this challenge is to search for new suppliers of silicon strip detectors from the beginning of the project duration.
8. **Microstrip detectors** may face potential troubles as they are currently available for JINR within the SuperFRS Experiment Collaboration as part of NUSTAR within FAIR. At the moment, detectors cannot be provided for use in the territory where the JINR is located, posing a **high level of risk**. However, the impact on the project's progress is minimal, and the project may continue to work with strip detectors, obtaining results of high quality.

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**2.3 Estimated completion date**

2024-2028.

**2.4 Participating JINR laboratories**

FLNR

**2.4.1** **MICC resource requirements**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Computing resources** | **Distribution by year** | | | | |
| 1st year | 2nd year | 3rd year | 4th year | 5th year |
| Data storage (TB)  - EOS  - Ribbons |  |  |  |  |  |
| Tier 1 (core-hour) |  |  |  |  |  |
| Tier 2 (core-hour) |  |  |  |  |  |
| SC Talker (core-hour)  - CPU  - GPU |  |  |  |  |  |
| Clouds (CPU cores) |  |  |  |  |  |

**2.5. Participating countries, scientific and educational organizations**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Organization** | **Country** | **City** | **Participants** | **Type**  **of agreement** |
| VNIIEF | Russia | Sarov | Yukhimchuk A.A.+4 persons | Contract |
| VNIPIET | Russia | Sosnoviy Bor | Nesvetaylov S.A.+4 persons | Contract |
| SINP MSU | Russia | Moscow | Eremenko D.O.+2 persons | Protocol |
| IE NASB | Belarus | Minsk | Baev V.G.+1 person | Protocol |
| PTI NASB | Belarus | Minsk | Zaleski V.I.+1 person | Protocol |
| IOP VAST | Vietnam | Hanoi | Li Hong Him+1 person | Protocol |
| HCMUS | Vietnam | Ho Chi Minh | Vo H.H.+1 person | Protocol |
| GSI-FAIR | Germany | Darmstadt | Scheidenberger C.+3 persons | Protocol |
| INP | Kazakhstan | Alma-Ata | Burtebaev N.+3 persons | Protocol |
| PKU | China | Beijing | Yanlin Ye +1 person | Protocol |
| KU | South Korea | Sejong | Park H.K.+2persons | Protocol |
| iThemba LABS | South Africa | Somerset West | Jones P.+2 persons | Protocol |
| UNISA | South Africa | Pretoria | Lekala L.M.+2 persons | Protocol |

**2.6. Co-executing organizations** *(those collaborating organisations/partners without whose financial, infrastructural participation the implementation of the research programme is impossible. An example is JINR's participation in the LHC experiments at CERN).*

**3. Staffing**

**3.1. Staffing needs in the first year of implementation**

|  |  |  |  |
| --- | --- | --- | --- |
| **№№**  **n/a** | **Category**  **employee** | **Core staff,**  **Amount of FTE** | **Associated**  **Personnel**  **Amount of FTE** |
| 1. | scientific staff | 31 | - |
| 2. | engineers | 13.25 | - |
| 3. | professionals |  | ~~-~~ |
| 4. | employees |  | ~~-~~ |
| 5. | workers |  | ~~-~~ |
|  | **Total:** | **44.25** | **-** |

**3.2. Human resources available**

**3.2.1. JINR core staff**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **№№ п/a** | **Category**  **of employees** | **NAME** | **Division** | **Position** | **Amount**  **of FTE** |
| 1. | scientific staff | Penionzhkevich Yuri Erastovich | FLNR | Head of sector | 1 |
| 2. | scientific staff | Bezbakh Andrey Anatolievich | FLNR | Head of group | 1 |
| 3. | scientific staff | Krupko Sergey Anatolievich | FLNR | Head of group | 1 |
| 4. | scientific staff | Sereda Yuri Mikhailovich | FLNR | Head of group | 1 |
| 5. | scientific staff | Grigorenko Leonid Valentinovich | FLNR | Chief Research Scientist | 1 |
| 6. | scientific staff | Ter-Akopian Gurgen Mkrtychevich | FLNR | Chief Research Scientist | 0.5 |
| 7. | scientific staff | Golovkov Mikhail Sergeevich | FLNR | Leading Research Scientist | 1 |
| 8. | scientific staff | Nikolskiy Evgeniy Yurievich | FLNR | Leading Research Scientist | 0.5 |
| 9. | scientific staff | Wolski Roman | FLNR | Leading Research Scientist | 0.5 |
| 10. | scientific staff | Belogurov Sergey Gennadievich | FLNR | Senior Research Scientist | 1 |
| 11. | scientific staff | Kononenko Gennadiy Alexandrovich | FLNR | Senior Research Scientist | 1 |
| 12. | scientific staff | Lukyanov Sergey Mikhailovich | FLNR | Senior Research Scientist | 1 |
| 13. | scientific staff | Maslov Vladimir Anatolievich | FLNR | Senior Research Scientist | 1 |
| 14. | scientific staff | Parfenova Yulia Lvovna | FLNR | Senior Research Scientist | 1 |
| 15. | scientific staff | Skobelev Nikolay Konstantinovich | FLNR | Senior Research Scientist | 1 |
| 16. | scientific staff | Smirnov Vladimir Ivanovich | FLNR | Senior Research Scientist | 1 |
| 17. | scientific staff | Sobolev Yuri Gennadievich | FLNR | Senior Research Scientist | 1 |
| 18. | scientific staff | Stepantsov Sergey Viktorovich | FLNR | Senior Research Scientist | 1 |
| 19. | scientific staff | Testov Dmitriy Alexandrovich | FLNR | Senior Research Scientist | 1 |
| 20. | scientific staff | Azhibekov Aidos | FLNR | Research Scientist | 1 |
| 21. | scientific staff | Gorshkov Alexander Vladimirovich | FLNR | Research Scientist | 1 |
| 22. | scientific staff | Knyazev Alexander Gennadievich | FLNR | Research Scientist | 1 |
| 23. | scientific staff | Mauey Bakytbek | FLNR | Research Scientist | 1 |
| 24. | scientific staff | Mendibaev Kayrat | FLNR | Research Scientist | 1 |
| 25. | scientific staff | Sharov Pavel Germanovich | FLNR | Research Scientist | 1 |
| 26. | scientific staff | Amer Akhmed | FLNR | Junior Research Scientist | 1 |
| 27. | scientific staff | Batchuluun Erdemchimeg | FLNR | Junior Research Scientist | 1 |
| 28. | scientific staff | Isataev Talgat | FLNR | Junior Research Scientist | 1 |
| 29. | scientific staff | Muzalevskiy Ivan Alexeevich | FLNR | Junior Research Scientist | 1 |
| 30. | scientific staff | Khirk Mishel | FLNR | Junior Research Scientist | 1 |
| 31. | scientific staff | Stukalov Sergey Sergeevich | FLNR | Junior Research Scientist | 1 |
| 32. | scientific staff | Chamidulin Bulat Radikovich | FLNR | Intern researcher | 0.5 |
| 33. | Engineers | Gorshkov Vladimir Alexandrovich | FLNR | Leading Engineer | 1 |
| 34. | Engineers | Slepnev Roman Stanislavovich | FLNR | Leading Engineer | 1 |
| 35. | Engineers | Vorontsov Andrey Nikolaevich | FLNR | Senior Engineer | 1 |
| 36. | Engineers | Klygin Sergey Alexandrovich | FLNR | Senior Engineer | 1 |
| 37. | Engineers | Aznabaev Dauren | FLNR | Engineer | 1 |
| 38. | Engineers | Butusov Ilia Vasilievich | FLNR | Engineer | 1 |
| 39. | Engineers | Ertaeva Dinara | FLNR | Engineer | 1 |
| 40. | Engineers | Gazeeva Elvira Mikhailovna | FLNR | Engineer | 1 |
| 41. | Engineers | Ismailova Arailym | FLNR | Engineer | 1 |
| 42. | Engineers | Mai Quynh Anh | FLNR | Engineer | 1 |
| 43. | Engineers | Rymzhanova Sofia Alexeevna | FLNR | Engineer | 1 |
| 44. | Engineers | Shakhov Aleksey Viktorovich | FLNR | Engineer | 1 |
| 45. | Engineers | Almanbetova Enlik | FLNR | Laboratory assistant | 1 |
| 46. | Engineers | Asemhan Kymbat | FLNR | Laboratory assistant | 0.25 |
| 47. | Engineers | Molotorenko Ksenia Dmitrievna | FLNR | Laboratory assistant | 1 |
|  | **Total:** |  |  |  | **44.25** |

**3.2.2. JINR associated personnel**

|  |  |  |  |
| --- | --- | --- | --- |
| **№№ п/a** | **Category of employees** | **Partner organisation** | **Amount of FTE** |
| 1. | Scientific employees |  |  |
| 2. | Engineers |  |  |
| 3. | professionals |  |  |
| 4. | Workers |  |  |
|  | **Total:** |  |  |

**4. Financial support**

**4.1 Total estimated cost of the project**

Forecast of the total estimated cost (specify cumulatively for the whole period, excluding FPC).

The details are given in a separate form.

**4.2 Extra budgetary funding sources**

Estimated funding from co-executors/customers - total.

**Project Leader** \_\_\_\_\_\_\_\_\_\_/G. Kaminski/

**Project Leader** \_\_\_\_\_\_\_\_\_\_/ S.I. Sidorchuk /

Date of submission of the project to DSOA: \_\_\_\_\_\_\_\_\_

Date of decision of the laboratory's STC: \_\_\_\_\_\_\_\_\_ document number: \_\_\_\_\_\_\_\_\_

Year of the project opening: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

(for renewable projects) -- Project start year: \_\_\_\_\_\_\_

**Schedule proposal and resources required for the implementation   
of the Project**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Names of costs, resources,**  **sources of funding** | | | **Cost (thousands**  **of dollars)**  **resource requirements** | **Cost,**  **distribution by year** | | | | |
| 1st year | 2nd year | 3rd year | 4th year | 5th year |
|  | | International cooperation (IC) | 450 | 90 | 90 | 90 | 90 | 90 |
| Materials | 1 700 | 300 | 320 | 340 | 370 | 370 |
| Equipment and third-party services (commissioning) | 420 | 100 | 80 | 80 | 80 | 80 |
| Commissioning work | 80 | 30 | 30 | 20 | - | - |
| Services of research organisations |  |  |  |  |  |  |
| Acquisition of software | 175 | 35 | 35 | 35 | 35 | 35 |
| Design/construction | 50 | 20 | 20 | 10 | - | - |
| Service costs (*planned in case of direct project affiliation)* |  |  |  |  |  |  |
| **Resources required** | **Normo-hours** | Resources |  |  |  |  |  |  |
| * the amount of FTE, |  |  |  |  |  |  |
| * accelerator/installation, |  |  |  |  |  |  |
| * reactor,…. |  |  |  |  |  |  |
| **Sources of funding** | **Budgetary resources** | JINR budget *(budget items)* | It. 4 - 450  It. 5,6 – 2120  It. 9 – 80  It. 11 – 175  It. 18,19- 50 |  |  |  |  |  |
| **Extrabudgetary (supplementary estimates)** | Contributions by  co-contractors  Funds under contracts with customers  Other sources of funding |  |  |  |  |  |  |

Project Leader \_\_\_\_\_\_\_\_\_/ G. Kaminski /

Project Leader \_\_\_\_\_\_\_\_\_/ S.I. Sidorchuk /

Laboratory Economist \_\_\_\_\_\_\_\_\_/T.V. Mamonova /

**APPROVAL SHEET FOR PROJECT**

NAME OF THE PROJECT

DESIGNATION OF THE PROJECT

PROJECT CODE

THEME CODE

NAME OF THE PROJECT LEADER

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  |  |  | |
| AGREED |  |  |  | |
| JINR VICE-DIRECTOR | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | S.N. Dmitriev | \_\_\_\_\_\_\_\_\_  DATE |  |
| CHIEF SCIENTIFIC SECRETARY | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | S.N. Nedelko | \_\_\_\_\_\_\_\_\_  DATE |  |
| CHIEF ENGINEER | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | B.N. Gikal | \_\_\_\_\_\_\_\_\_  DATE |  |
| LABORATORY DIRECTOR | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | S.I. Sidorchuk | \_\_\_\_\_\_\_\_\_  DATE |  |
| CHIEF LABORATORY ENGINEER | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | I.V. Kalagin | \_\_\_\_\_\_\_\_\_  DATE |  |
| LABORATORY SCIENTIFIC SECRETARY  THEME LEADER | \_\_\_\_\_\_\_\_\_  SIGNATURE  \_\_\_\_\_\_\_\_\_  SIGNATURE | A.V. Karpov  S.I. Sidorchuk | \_\_\_\_\_\_\_\_\_  DATE  \_\_\_\_\_\_\_\_\_  DATE |  |
| PROJECT LEADERS | \_\_\_\_\_\_\_\_\_\_  SIGNATURE | G. Kaminski | \_\_\_\_\_\_\_\_\_  DATE |  |
|  | \_\_\_\_\_\_\_\_\_\_  SIGNATURE | S.I. Sidorchuk | \_\_\_\_\_\_\_\_\_  DATE |  |
| APPROVED BY THE PAC | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE | |