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LONG-RANGE PLANS FOR RESEARCH
WITH RADIOACTIVE ION BEAMS AT **JINR**

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Долговременные планы исследований
на радиоактивных ионных пучках в ОИЯИ

Дубненские радиоактивные ионные пучки (DRIBs) — это общее название для инициативной деятельности по созданию и развитию комплекса экспериментальных установок в Лаборатории ядерных реакций им. Г. Н. Флерова, благодаря которой в ОИЯИ (Дубна, Россия) появляется возможность проводить исследования с радиоактивными ионными пучками (РИП) на мировом уровне. Первая фаза этой деятельности (DRIBs-1) успешно осуществлена. Однако для того, чтобы отвечать современным требованиям научных исследований, была начата разработка нового проекта — DRIBs-3. Этот проект основан на методике производства РИП на лету с дополнительной второй стадией, выполненной по ISOL-методике. Новый фрагмент-сепаратор ACCULINNA-2, являющийся важной частью будущего проекта, находится в стадии строительства с ожидаемой датой его завершения в 2015 г. В данном документе обсуждаются долговременные планы по экспериментальным исследованиям на DRIBs-3, а также дальнейшее развитие этого проекта.

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Long-Range Plans for Research with Radioactive Ion Beams at JINR

Dubna Radioactive Ion Beams (DRIBs) is a general name for initiative to develop a complex of experimental facilities in the Flerov Laboratory of Nuclear Reactions, which should enable world-class research with Radioactive Ion Beams at JINR (Dubna, Russia). The first stage of this initiative (DRIBs-1) operates successfully. However, to meet the requests of the modern research, a new project DRIBs-3 is now being developed. It is based on the in-flight RIB production technique augmented with an ISOL-type second stage. The new fragment-separator ACCULINNA-2 comprising important part of the prospective facility is now under construction with an expected commissioning date in 2015. The long-range plans for experimental research at DRIBs-3 and the program for further development of this facility are discussed.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

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1. INTRODUCTION

One of the most challenging and fast developing fields in modern nuclear physics is connected to studies of nuclei located far from the β stability valley and even beyond the neutron and proton driplines. Such exotic nuclei often exhibit peculiarities unobserved in the vicinity of stability valley. Extreme conditions of large charge asymmetry and weak binding of valence nucleons in these nuclei provide stringent tests of the nuclear structure concepts formulated on the basis of data obtained for well-bound and almost charge symmetric systems. Present theoretical models make contradictory predictions about the dripline positions, on the energies of nuclear bound states in the dripline vicinity, excited states ordering and even shell closures. Even more uncertain are the theory predictions for the resonance states of nuclei situated close to and beyond the driplines.

To provide basis for contemporary theories which strive for a consistent description of such nuclear properties, experiments should provide comprehensive results characterizing long isotopic and isotonic nuclear chains extending even beyond the driplines. The last three decades, when radioactive ion beams (RIBs) became a practical tool in nuclear physics, a number of facts were established showing interesting new features of nuclear structure that were found in the most neutron-rich nuclei, such as neutron skins, neutron halos, and dramatic changes in level ordering eluding before any notion by standard nuclear models. A remarkable breakthrough achieved at the proton dripline was the discovery of the $2p$ radioactivity made in the last decade. A number of international nuclear centers having major RIB facilities — GANIL (France), GSI (Germany), RIKEN (Japan), NSCL (USA) contributed significantly in these accomplishments. During the last decade, major upgrades of RIB facilities were planned in many international nuclear centers. Such an upgrade has been performed several years ago at RIKEN (Japan), and other centers are actively preparing this (GSI \rightarrow FAIR, GANIL \rightarrow SPIRAL II, NSCL \rightarrow FRIB).

Some overall view of the current situation with the dripline study can be found in Fig. 1. The driplines are now experimentally achieved and reasonably studied only for the lightest nuclides. Already for $N > 5$ and $Z > 5$ information is sparse and often contradictory. It is expected that considerable efforts will

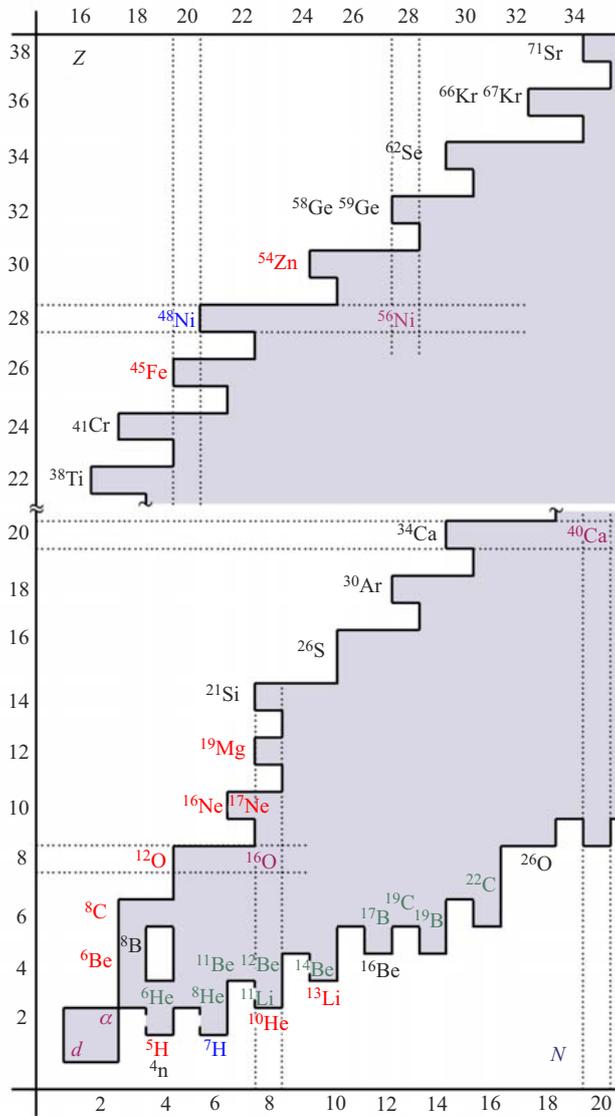


Fig.1 (color online). Driplines in the region of light nuclei achieved for today experimentally. Known isotopes with exotic properties are indicated by coloured labels: green for halo nuclei, red for $2p/2n$ emitters, blue for $4p/4n$ emitters. The gray colour indicates the predicted but not yet discovered exotic nuclei of the above kinds

be invested by scientific community in these studies in the coming years. We demonstrate that JINR has opportunity to join these efforts as an important player.

The Flerov Laboratory of Nuclear Reactions at the Joint Institute for Nuclear Research (FLNR JINR) has in the operation the Dubna Radioactive Ions Beams (DRIBs-1) complex, which includes the RIB fragment separator ACCULINNA [1] and the ISOL-type facility of two coupled cyclotrons U400M + U400 [2]. These facilities started the operation in 1996 and gained the full capacity in 2004. The obtained scientific results are recognized by the nuclear physics community and are available in numerous journal publications and conference proceedings [3, 4]. Some of the important results obtained with the 20–35 A · MeV RIBs of ACCULINNA are listed below.

- Di-neutron and two-triton configurations of the Borromean neutron-halo nucleus ${}^6\text{He}$ were experimentally established for the first time [5].

- Spectra of the ${}^3\text{H}({}^2\text{H},p){}^4\text{H}$ and ${}^3\text{H}({}^3\text{H},d){}^4\text{H}$ reaction products were ascertained and the parameters of the ${}^4\text{H}$ ground state resonance were for the first time derived in a consistent way [6].

- A new, lower limit for the ${}^7\text{H}$ decay energy was specified [7].

- The ${}^5\text{H}$ spectrum was extensively studied and the ground state of this unbound nuclear system was reliably established [8, 9].

- Spectroscopic data on the ${}^8\text{He}$ and ${}^9\text{He}$ resonance states were revised, although before the ACCULINNA started to work, the low-lying spectra of these nuclei were for more than one decade considered as reliably established [10, 11].

- New ACCULINNA data positioned the ${}^{10}\text{He}$ ground-state resonance at 2.1 ± 0.2 MeV above the three-body ${}^8\text{He} + n + n$ decay threshold and revealed in the ${}^{10}\text{He}$ spectrum prominent shell breaking effects as the onset of the intruder states and modification of the spin-orbital interaction [11, 12].

- Pioneering experimental investigation of the ${}^6\text{He}$ wave function was carried out by means of the quasi-free scattering experiments [13].

- New experimental methods, allowing the identification of overlapping broad resonance states, were developed [14] and successfully applied in the studies performed for the low-lying spectra of a number of unbound neutron-drip nuclei [9, 10, 12].

- New possibilities to study the ${}^8\text{He}$ β -decay into the $\alpha + t + n$ continuum or ${}^7\text{Li} + n$ channel were demonstrated with the use of an optical time projection chamber [15].

- A novel phenomenon — the isovector soft dipole excitation mode was uncovered in the ${}^6\text{Be}$ continuum in a charge-exchange reaction [16].

Experiments carried out at the DRIBs-1 ISOL facility, revealed extremely large enhancement of the sub-barrier fusion cross section for the ${}^6\text{He} + {}^{206}\text{Pb}$ system. The effect has been explained on the ground of a «sequential fusion» model assuming that a large energy release accessible for the two-neutron transfer is a factor which determines the fusion below barrier [4]. The study of interplay be-

tween fusion-evaporation and incomplete fusion reactions induced by 10 A · MeV ^6He and ^6Li beams provided essential information on the mechanisms of the breakup and incomplete fusion processes and on the wave functions of these loosely bound projectile nuclei [17].

The listed studies were important steps to gain deeper insights into the unusual structures of exotic nuclei and the role which proton and neutron dripline nuclei may play in the nucleosynthesis taking place at different sites in the Universe.

2. MOTIVATION FOR THE NEW DRIBs-3 FACILITY COMPLEX

During the years 2010–2016, the 7-year upgrade plan is in effect at JINR. The development of DRIBs-3 complex is the important part of this plan which will considerably strengthen and diversify the potential of the RIB research in Dubna. A number of factors inherent to the existing accelerators and projected upgrades inspire confidence in the success of the planned RIB research at FLNR JINR.

- The record, up to 5 pμA, intensities of comparatively low-energy heavy-ion beams of the U400M cyclotron provide prerequisites for future high-precision experiments with 10–50 A · MeV RIBs which will be obtained from the new fragment separator ACCULINNA-2 [18]. These RIBs will offer quite efficient conditions for experiments aimed to studies in the whole range of exotic nuclei with atomic numbers extending from $Z = 1$ to $Z \approx 40$.

- The energy range of the RIBs obtained from the fragment separator coupled with the U400M cyclotron is well suitable to stop exotic nuclei in a gas catcher (ion trap) thus making a universal source of 10–100 keV RIBs fitting well the goals of a new DRIBs-3 ISOL facility, as well as the demands of applied works in solid state physics.

- The RIBs obtained both from the fragment separator and from the ISOL facility will provide optimal conditions for nuclear structure studies using direct reactions, i.e., nucleon and cluster transfers, charge exchange reactions, elastic and inelastic scattering, etc.

- In particular, the relatively low RIB energy facilitates complete kinematical measurements resulting in the observation of very clean, background-free spectra of nuclei lying in the region and beyond the neutron and proton driplines.

- Essential consequence of the correlation measurements is a possibility of the unambiguous spin-parity identification for the observed resonance states.

- A great importance for the successful accomplishment of the Dubna research program in the region of extreme neutron-excess nuclei has the availability of unique cryogenic tritium targets and exotic solid-state targets of ^{10}Be , ^{14}C .

- Having 10–50 A · MeV RIBs one will take an advantage of the most effective use of such a technique as the Optical Time Projection Chamber having excellent capability to be an active target in the RIB experiments [15].

The present project includes the creation of the next generation fragment separator ACCULINNA-2 to be installed on a primary beam line of the upgraded cyclotron U400M. This separator will be a more universal and powerful instrument aimed to produce secondary 10–50 A · MeV RIBs. The new separator should be capable to serve as the first stage among the facilities intended for the production of high quality beams of radioactive nuclei with energy of 10–100 keV well suitable for applied works in solid-state physics and for injection into an ion trap for mass-spectrometry and/or charge radii measurements. The main goal will be the practical realization of the new DRIBs-3 ISOL facility, i.e., the injection of the low energy (10–30 keV) RIBs into the upgraded variable energy cyclotron U400R for the further acceleration up to 5–20 A · MeV.

3. RESEARCH PROGRAM

Near the proton or neutron driplines the lowest nucleon threshold comes close to the ground state or, beyond the driplines, these thresholds are below the ground state. The proposed project is mainly focused on the studies of nuclear properties far from the stability valley and on the studies of RIB-induced nuclear reactions. The phenomena, comprising one of the goals of this program, should be following.

3.1. Nucleon Haloes, Neutron Skins. Weakly bound few-body exotic systems show properties which are very different from the «normal» nuclei, i.e., those nuclei which are not too far from the β stability. The light nuclei exhibiting one-neutron and two-neutron halo structures became the subject of a tremendous number of both theoretical and experimental studies. The study of neutron halos is important for a better understanding of nuclear structure close to the driplines. Examples of halo (skin) nuclei include ${}^6,8\text{He}$, ${}^{11}\text{Li}$, ${}^{11}\text{Be}$, ${}^{14}\text{Be}$, ${}^{17}\text{B}$, ${}^{19}\text{B}$, and ${}^{19}\text{C}$. With the exception of ${}^{11}\text{Be}$, which turned out to be a benchmark for the study of the one-neutron halo, not so much became known from experiments about the excitation spectra of these nuclei.

Along the neutron drip line, the relatively small enhancement of the total binding for paired neutrons has an important impact. The properties of the interleaving neutron-unbound nuclei will provide important insights into the neutron–nucleus interaction far from stability, the coupling to the continuum in neutron-rich systems, and the delicate structure of multineutron halos or skins. Studies of the adjacent neutron-unbound (odd- N) nuclei can yield single-particle information crucial for the characterization of the heavier bound nuclei. In relation to the drip line nuclei of beryllium, boron and carbon this means that specifically interesting are the spectra of ${}^{13}\text{Be}$, ${}^{16}\text{B}$, ${}^{18}\text{B}$, and ${}^{21}\text{C}$.

Nucleon knockout and the more traditional transfer reactions are complementary approaches for this case. While knockout reactions mainly probe *hole*

strengths, nucleon transfer reactions like (d, p) , (t, d) , (t, p) , and $({}^3\text{He}, d)$ populate *particle* levels. One can also populate hole states in exotic nuclei in nucleon pickup reactions from the RIB projectile nuclei, e.g., reactions of the $(d, {}^3\text{He})$, (p, d) , and (p, t) types. Orbital angular momentum quantum numbers, the relative location of single-particle states, and spectroscopic factors are accessible with experiments employing direct reactions. Transfer reactions access many excited states simultaneously, and their strong kinematic matching allows the optimization of the reaction choice for population of states with orbital angular momentum of the interest. Nucleon transfer and charge-exchange reactions, such as (p, n) and $(t, {}^3\text{He})$, offer a robust way to perform thorough studies of the halo nuclei.

3.2. Exotic Neutron Decays (Two-Neutron Virtual States, Two- and Four-Neutron Radioactivity). Beyond the driplines we get to the regions of strong nuclear instability. Here the experimental observations could be especially confusing for the light neutron-rich systems. In the absence of strong potential barriers the observables for neutron decays often become sensitive to reaction mechanisms. Also the appearance of novel forms of dynamics is not impossible here. These include the possible existence of hypothetical two-neutron virtual states [19] and two/four-neutron radioactivity [20]. The search for the few-neutron radioactive decays is inspired by the discovery of two-proton ($2p$) radioactivity. In contrast with situation on the proton dripline, the long-lived one-neutron emitters are practically impossible, while two- and four-neutron emitters may have much longer lifetimes, even falling in the radioactivity timescale. Discovery of such a novel type of radioactive decay is a challenging task requiring also application of novel experimental approaches.

Example of successful research on one- and two-neutron emitters beyond the neutron dripline, conducted at ACCULINNA, are the studies of neutron decays of states in ${}^5\text{H}$, ${}^8\text{He}$, ${}^9\text{He}$, and ${}^{10}\text{He}$. Refined data on the ${}^3\text{H}({}^8\text{He}, p){}^{10}\text{He}$ reaction, obtained at the ACCULINNA separator in the year 2011 [12], confirmed the results reported in [11]. The new data positioned the ${}^{10}\text{He}$ ground-state resonance at 2.1 ± 0.2 MeV above the three-body ${}^8\text{He} + n + n$ decay threshold and revealed prominent shell breaking effects in the ${}^{10}\text{He}$ spectrum as the onset of intruder states and changing the spin-orbital interaction. The extension of these works to similar systems with $Z > 2$ will receive a firm instrumental basis with the occurrence of the RIBs provided by DRIBs-3. The excitation spectra of ${}^{11-13}\text{Li}$, ${}^{13-16}\text{Be}$, ${}^{16-19}\text{B}$, and ${}^{19-22}\text{C}$ will be a first-priority task for ACCULINNA-2. The study will include precise determinations of ground-state masses of these nuclei. It is worth noting that currently none of the neutron separation energies are known to better than 10% for these nuclei. Transfer reactions of the (t, p) and (d, p) type, studied in inverse kinematical conditions, are the most suitable ones for the precise mass measurements. High statistics data will be accessible for complete kinematic measurements performed for the resonant states of these so far little-studied nuclei.

3.3. Soft Excitation Modes. Based on the neutron halo hypothesis, existence of a new low-lying dipole resonance mode, the so-called soft dipole mode, has been suggested [21] for the halo systems. Its appearance is connected to the suggested low-frequency oscillations of the halo neutrons against the core, giving rise to low-lying dipole excitations. Assuming this hypothesis, large electromagnetic dissociation (EMD) for ^{11}Li incident on heavy targets was predicted [22]. The large cross-sections expected for Coulomb dissociations of the Borromean halo nuclei have been confirmed experimentally later (see, for example, [23]). It should be noted, that at least for the lightest Borromean halo-nuclei ^6He and ^{11}Li the low-lying dipole excitations are not a resonant ones (so, these are rather ordinary low-lying continuum states). However, it does not mean that these states cannot have resonant character in other halo nuclei.

The study of the soft mode showing up in the ^8He spectrum, performed in [24], demonstrates how deep one can get into the mechanism of this excitation created by the low-frequency oscillations of the halo neutrons against the nuclear core. In particular, the possible nature of the near-threshold anomaly above 2.14 MeV in the ^8He missing mass spectrum was explained by population of a 1^- continuum (soft dipole excitation) with a peak energy value of about 3 MeV.

High precision and high statistics data on the three-body $\alpha + p + p$ continuum of ^6Be were obtained recently in the charge-exchange $p(^6\text{Li}, ^6\text{Be})n$ reaction [16]. The ^6Be spectrum up to $E_T = 16$ MeV was well described by the population of three main structures in ^6Be , i.e., the 0^+ state at 1.37 MeV, the 2^+ state at 3.05 MeV, and a mixture of $\{0^-, 1^-, 2^-\}$ continuum in the E_T range from 4 to 16 MeV. The negative-parity continuum was interpreted as a novel phenomenon, the isovector nonresonant soft dipole mode offering new opportunities in the nuclear structure studies.

Transfer and charge-exchange reactions, studied at beam energies of 20–35 A · MeV will grant excellent conditions for such a research.

3.4. New Magic Numbers and Intruder States. It should be noted that there are several basic problems in the field of exotic nuclei, for which this project will provide very favourable conditions to be studied in detail. One example is the problem of the closed neutron shell breakdown at $N = 8$ and manifestation of s-d intruder states in the neutron-rich nuclei $^{9,10}\text{He}$, $^{10,11}\text{Li}$, $^{11,12}\text{Be}$. Clarification of filling sequences of the s-d neutron shell in a number of neutron-excess nuclei (e.g. ^{15}Be , $^{16,18}\text{B}$, $^{17,19}\text{C}$) and the interplay of s- and d- wave states in their even- N neighbours is another basic problem, which calls for thorough investigation. On the proton-excess side, similar phenomena call for the study of the possible two-proton halo structure, with a ^{15}O core, predicted by theory for ^{17}Ne . Of special interest is the clarification of the termination of the s-d shell filling occurring in the C, N, O, F, and Ne nuclei in the vicinity of neutron number $N = 16$. Quite high intensities of the 20–30 A · MeV beams of ^{24}O , $^{26,27}\text{F}$, $^{28-30}\text{Ne}$ offered by

this project, provide very good conditions for the study of resonant states of the corresponding isotopes (e.g., $^{24-26}\text{O}$) lying near and beyond the dripline.

3.5. Two-Proton Radioactivity (Few-Body Decays in More General Terms).

With the advent of the DRIBs-3 complex, the whole series of proton-rich nuclei with $Z \leq 36$, lying close and beyond the proton dripline, will become a subject for investigation of these rare decay modes. These include a number of nuclei predicted to exhibit $2p$ radioactivity. Furthermore, the $2p$ decay of resonant states gives rise to profound interest in the dynamics of this decay mode. The clear examples to be studied are the resonant states of ^6Be , ^{12}O , ^{16}Ne , ^{26}S , ^{30}Ar , ^{48}Ni , etc. The finding and measurement of the $2p$ -decay branch for the first excited state of ^{17}Ne will clarify the issues related to the $Z = 8$ waiting point affecting the rp-process in the sites of hot stellar burning.

The proton dripline is quite well known for nuclei with atomic numbers ≤ 36 . Only a few isotopes remain unknown here but could exist with half-lives comparable with the time-of-flight through a fragment separator. Recently, the ACCULINNA group performed dedicated search for the dripline nucleus ^{26}S produced in fragmentation of a $50.3 \text{ A} \cdot \text{MeV}$ ^{32}S beam [25]. An upper half-life limit of $T_{1/2} < 79 \text{ ns}$ was set for ^{26}S in this study. The other example is ^{48}Ni which was studied in 2011 by means of an imaging time projection chamber [26]. As a result, for the first time a $2p$ -decay branch was observed and the half-life of ^{48}Ni was determined to be 2.1 ms. No dedicated search has been performed yet for the neighbor nuclei with even Z : ^{21}Mg , ^{30}Ar , and ^{34}Ca , which could exist with half-lives shorter than 100 ps. The properties of these nuclei can be ascertained well due to the excellent choice of RIBs provided by DRIBs-3. The quest for ^{21}Mg and ^{26}S is challenging because it is very probable that $2p$ radioactivity is the main decay mode of these nuclei. Quite detailed studies of the $2p$ -decay mode will be feasible for the nuclei having lifetime $T_{1/2} \geq 50 \text{ ps}$. This becomes realistic because one can produce the needed nuclei in transfer reactions induced by the ACCULINNA-2 RIBs. The (p,d) - and (p,t) -type reactions are favorable for this task. For the searched nuclei, their formation and decay, occurring in-flight, are established by the detection of the daughter nucleus and the two emitted protons. The decay time is derived from the distance between the target and the vertex position defined as intersection point of the momentum vectors of the two emitted protons with the daughter nucleus trajectory.

The suggested approach works well also when the $2p$ -decay lifetimes are very short with the lower limit coming close to the characteristic nuclear lifetime. This is true for the excited states of the searched $2p$ emitters. Precision measurements of $2p$ - and p -decay characteristics made for a dozen of nuclei with $Z \leq 36$ lying beyond the proton dripline should be included in the DRIBs-3 research program.

3.6. Spectroscopy of Exotic Nuclei. One of the most advanced features of the dripline nuclei studies in the recent years at ACCULINNA was the application

of correlation techniques in transfer reactions to the spectroscopy of exotic nuclei. The main idea of this method is not very new: in somewhat less general form such technique was applied to spin-parity identification of excited states emitting spinless particles at their decay. In the works performed at ACCULINNA, the method was further developed [9, 14] and its applicability was demonstrated in some complicated experiments [9–14, 16]. The point is that highly aligned states are produced in the direct reactions. The highest alignment effect is obtained in the rest frame of the produced exotic nucleus in respect to axis parallel to the transferred momentum vector. If the researcher is lucky, the decay of the aligned configuration may produce sharp correlation patterns. If one is lucky even more, the interpretation of the observed correlations may appear to be unique (this was the case, for example, with the spectrum of ^9He populated in the (dp) reaction). This «unstable» aspect of this approach depends on such details of reaction mechanism and spectral densities of different states, which are not possible to predict in advance.

Resonance states of light dripline nuclei (especially on the side of the neutron dripline) are frequently quite broad and thus overlapping. Therefore correlation shapes are often affected by interference. In this situation even weakly populated states may become apparent due to their contribution into the interference patterns. Addition of amplitudes acts in this situation as a kind of «quantum amplifier» giving access to the details of the spectrum which would be complicated to uncover otherwise. This aspect makes very prospective the technique based on the studies of the interference/alignment induced correlations as a novel approach in the RIB research.

The benefits, derived from the correlation aspect of spectra populated in direct transfer reactions, are always implied by default in the consideration of the ACCULINNA-2 research program.

3.7. Cluster States. Definition of dripline is that first particle breakup threshold becomes lower in energy than the ground state of corresponding nucleus. In proximity to the decay thresholds, clusterization phenomenon becomes increasingly important: some states possess expressed cluster structures, and new forms of nuclear dynamics arise. Such states have been found, for example, in Be isotopes — the observed excited states form rotational bands with a well-expressed molecular structure, characterized by a large deformation. Good candidates for such studies are the heavy isotopes of He, B, C, O, Ne, etc.

The correlation measurements, complete kinematics studies, discussed above as specific strong feature of ACCULINNA, are the most common tool for elucidating clustering aspect of nuclear dynamics. The importance of the OTPC [28] should be specially emphasized here. It gives opportunity to make complete kinematics measurements in experiments where the «useful» counting rates are just units and tens of events. This is a very important feature for the studies of extremely exotic nuclear systems attainable with extremely low production rates.

There were a number of successful experiments with OTPC at ACCULINNA. As it was shown in [15] the evidence for neutron emission after β decay of ^8He to a highly excited ^8Li state, indicates that the early reported decay scheme of ^8He is not complete. The methods based on OTPC offer a unique possibility of studying rare decay branches: the β decay of ^8He into $\alpha + t + n$, $^7\text{Li} + n$ and $^6\text{He} + d$. Information obtained with the use of the OTPC will allow one to clarify mechanisms of such decay processes. Another field for the cluster structure studies concerns the states in ^6He with a $(t + t)$ -structure and a possible $^5\text{H}-^3\text{H}$ clustering of ^8He .

Quasi-free scattering (QFS) is another technique sensitive specifically to the clustering aspect of nuclear structure. In this class of reactions the selection of a quasi-free knock-out channel explicitly defines the clustering partition of the studied nucleus. The quasi-free scattering reactions studied in [13] could be effectively applied for the determination of halo structures in ^6He , ^8He and other exotic nuclei. It should be noted that an original approach to the QFS was realized in this work. While typically a valence nucleon is knocked out in the QFS, the $(\alpha, 2\alpha)$ knock-out of the halo nucleus ^6He core was examined in [13] elucidating other aspects of nuclear structure.

3.8. Reactions with Halo Nuclei. Fusion reactions with halo nuclei have been of increased interest from experimental and theoretical points of view. In particular, much effort has been devoted to studying near-barrier fusion of light, weakly bound projectile nuclei. Unusual effects are expected here both from the halo structure of these nuclei and from the specific tunneling mechanism of the composed weakly bound system, which is of general interest for quantum theory. One example of this type of effects represents the recent study of the fusion reaction $^6\text{He} + ^{206}\text{Pb}$, which was carried out at the DRIBs-1 facility in Dubna [4]. DRIBs-3 will provide higher intensity and higher quality beams of ^6He nuclei and also a variety of other exotic beams (^8He , ^9Li , ^{12}Be , etc.) thus offering new prospects for insights into the process of low-energy fusion and multinucleon-transfer reactions of light exotic nuclei hitting heavy targets.

3.9. Astrophysical Applications. Nowadays the nuclear astrophysics research is an integral part of the novel forms of nuclear dynamics study. Finite nuclear matter is the only directly accessible «testing ground» for theoretical models that are meant to look into the states of the infinite stellar matter. The further the experimental knowledge is extended beyond the drip-lines, the more precise testing and tuning of theoretical models are possible in this field. The required data involve:

- masses and level schemes close to the neutron, proton, and alpha breakup thresholds;
- EC and β^\pm -decay lifetimes;
- partial proton, neutron, α, γ widths of low-lying resonances to calculate resonant radiation capture and (n, α) or (α, n) reaction rates;

- electromagnetic E1 and E2 strength functions to calculate the nonresonance radiation capture, extracted from the data on the electromagnetic dissociation of corresponding nuclei.

Nuclear reactions in stars involve short-lived proton-rich and neutron-rich nuclei that can be studied only with radioactive beams. The cross sections of the interest have to be studied indirectly by resonance reactions in inverse kinematics on the hydrogen and helium target nuclei and by transfer reactions in order to determine the level schemes and spectroscopic properties of nuclear states. This includes peripheral transfer reactions to measure the quantities called Asymptotic Normalization Coefficients (ANCs), which determine stellar capture rates. Transfer reactions performed with the RIBs delivered by DRIBs-3, such as (d, n) , (d, p) , (t, d) , (p, d) , or $({}^3\text{He}, d)$ can be used to extract proton spectroscopic factors, ANCs, or neutron spectroscopic factors in mirror nuclei.

Although, in general, the highest possible incident beam energies are preferable for the Coulomb dissociation reaction studies, for low-energy beams anticipated in the presented DRIBs-3 project a list of relatively low energy (e.g., at energies of ~ 50 A · MeV and below) studies exists for the dripline nuclei. The low-energy case is more challenging from theoretical point of view and requires more theoretical contribution for data interpretation. However, problems arising here are known to be tractable. Coulomb dissociation cross sections are straightforwardly related to the rates of the astrophysical nonresonant radiation. The Coulomb dissociation reactions and, e.g., transfer reactions populating continuum states could be also regarded as the representatives of a broader class of the processes capable to elucidate the continuum excitation properties. An interesting possibility is to study the breakup reactions in complete kinematics for the breakup products. Breakup processes on light targets can be considered as alternative to the Coulomb dissociation reactions. They are characterized by strong Coulomb-nuclear interference and could be much more complicated for interpretation. However, such reactions have different selectivity in quantum numbers compared to the Coulomb dissociation, which almost exclusively populates E1 and E2 states. Good examples are the actively discussed three-body virtual states. The ground states of ${}^{10}\text{He}$ and ${}^{13}\text{Li}$ could be such three-body virtual states. Just as it occurs with ordinary two-body virtual states, these objects resemble rather the final state interactions than the real resonance states characterized by a compact size and a definite lifetime.

Two-proton radiative capture is a process which importance along the r -process path is poorly understood so far. This process is directly related to two-proton radioactive decay. This means that limited information about $2p$ radioactivity and all complexities of this phenomenon are projected to this field as well. A particularly important region that will become accessible to experiments is that around the critical waiting points ${}^{64}\text{Ge}$, ${}^{68}\text{Se}$, and ${}^{72}\text{Kr}$. These waiting points shape the light curves of the X-ray bursts and determine the amount of heavier

nuclei produced. Another case important for the passage of the rp-process is the ^{15}O waiting point. The fact that the two-proton capture is a possible alternative to the (α, p) reaction as a pathway for the rp-process, makes topical the search for a weak $2p$ -decay branch of the first excited $3/2^-$ state in ^{17}Ne . Such a search carried out at a level of $\Gamma_{2p}/\Gamma_{\gamma} \approx 10^{-5} - 10^{-6}$ predicted by theory will be feasible with the use of intense $Z = 8 - 10$ RIB beams provided by DRIBs-3.

4. THREE STAGES OF DRIBs-3 DEVELOPMENT

The proposed development of the ACCULINNA-2 fragment separator [6] suggests the creation of a more universal scientific instrument giving a variety of clean and well-prepared secondary beams limited only by the choice of the primary beams provided by the U400M cyclotron. An important task of the ACCULINNA-2 project is the realization of a beam usage concept at FLNR complying with the modern trends inherent to large RIB facilities. The fragment separator, together with the beam diagnostics system, should become a standard instrumentation for the laboratory. The idea is that the exotic beam is delivered for users into the low-background experimental area (F3 or F5 focal planes in Fig. 1) with full particle-by-particle identification and complex diagnostics (energy and trajectory). The ACCULINNA-2 is not intended to compete with the new large in-flight RIB facilities in the world (see Table 1). It should be complementary to the existing/constructed facilities in certain fields. Namely, ACCULINNA-2 should provide high intensity RIBs in the lowest energy range attainable for in-flight separators. We emphasize the scientific importance of this specific field of researches and choose a cost-effective technical solution for this project. The prime objectives of ACCULINNA-2 are to provide good energy resolution and high efficiency for correlation measurements. The latter, combined with the selection of certain reaction mechanisms and the choice of specific kinematical conditions, could provide accurate spin-parity identification of the corresponding

Table 1. Characteristics of in-flight RIB separators; $\delta_P = \Delta P/P$ is the momentum acceptance, and $P/\Delta P$ is the first-order momentum resolution, obtained at a 1 mm object size

Facility Laboratory	ACC FLNR	ACC-2 JINR	LISE GANIL	A1900 MSU	RIPS RIKEN	BigRIPS RIKEN	FRS	SuperFRS GSI
$\Delta\Omega$ (msr)	0.9	5.8	1.0	8.0	5.0	8.0	0.32	5.0
δ_P (%)	2.5	6.0	5.0	5.5	6.0	6.0	2.0	5.0
$P/\Delta P$ (a.u.)	1000	2000	2200	2915	1500	3300	8600	3050
$B\rho_{\max}$ (T·m)	3.2	3.9	4.3	6.0	5.76	9.0	18	18
Length (m)	21	38	42	35	21	77	74	140
E_{\min} (A·MeV)	10	5	40	110	50	100	220	300
E_{\max} (A·MeV)	40	50	80	160	90	400	1000	1500

nuclear states. The fragment separator, together with the beam diagnostics system, should become a *standard multiuser instrument* for the laboratory.

The development of DRIBs-3 facility is planned to proceed in three stages.

4.1. Stage 1. Layout and Major Features of the ACCULINNA-2. The main contractor for ACCULINNA-2 fragment separator is French company SIGMAPHI. In accordance with the Contract №500/1535 dated 28.09.2011 between JINR and SIGMAPHI, the ACCULINNA-2 will be fully commissioned at the end of 2014 (with the exception of the RF-kicker which is planned for years 2015–2016). The layout of ACCULINNA-2 within the U400M cyclotron hall is shown in Figure 2. A beam of radioactive nuclei leaving the production target at F1 is captured by a short focusing quadrupole triplet Q1–Q3 and transported through the magnetic dipoles D1–D2 and magnetic quadrupoles Q4–Q14 up to the final focal plane F5. The F2 nonzero momentum dispersion plane is intended for the installation of a wedge-shaped energy degrader. In the achromatic focal plane F3, separation of the secondary beams with mass A and charge Z is taking place according to the ratio $A^{5/2}/Z^{3/2}$ (bare nuclei are implied). This ratio arises from the cumulative effect of the A/Z separation in the F2 plane after passing the D1 dipole and the charge/mass dependence of the energy losses in the wedge. For the light neutron-rich nuclei this is typically enough for preparing quite pure RIBs. The most important second- and third-order aberrations in the F2 and F3 focal planes are corrected by the magnetic multipoles M1–M5 having corresponding sextupole and octupole components. As a result, the main second-order aberrations become very small in the F2 and F3 planes.

4.2. Stage 2. Development of Beams and Instrumentation at the ACCULINNA-2. First experiments with radioactive beams at ACCULINNA-2 are planned for the beginning of 2015. Since that time, the focus of technical developments at ACCULINNA-2 will move to the broadening of scientific opportunities at the facility. The major topics are the intensity/quality/variety of secondary beams and the development of «integrated» instrumentation, presumed to be available to all prospective users by default.

The above discussion of RIB production at ACCULINNA-2 was based on the primary beams already available from the U400M cyclotron. Moderate investment into the cyclotron upgrade may lead to considerable increase of the versatility of the DRIBs-3 facility. The prime issues which can be foreseen here are development of sources and accelerator upgrade.

• **Development of Sources.** The technique of the primary beam fragmentation and in-flight separation has important limitations connected with the energy and charge of the primary beam. To provide RIBs of heavier isotopes higher energies are required due to higher energy losses in fragmentation target and in the in-line instrumentation. More powerful ECR source, effectively providing the injection of the higher charge states for heavier isotopes into the cyclotron, may significantly increase the opportunities provided by ACCULINNA-2.

- **Accelerator Upgrade.** The operation of the fragment separator is very sensitive to the quality of primary beam at F1. More advanced beam extraction from the U400M cyclotron providing better defined primary beam may drastically improve the performance of the facility in all modes.

The full-scale operation of the ACCULINNA-2 and broad versatility for a full scale of possible reaction studies with secondary beams can be achieved only after several additional pieces of scientific hardware are developed and installed. These are:

- **RF-Kicker.** The single-stage achromatic fragment separator in many cases produces quite contaminated beams. In our case of the relatively low-energy operation this problem is worsened by the presence of different charge states in the RIB. This problem is especially important for production of maximally exotic species or to the cases when maximal intensity of the chosen secondary beam should be provided for reaction studies. To clean the RIBs, especially the proton-rich ones which can be strongly contaminated by the primary beam «tail», the velocity filter is required. The proposed upgrade of the ACCULINNA-2 includes the addition of a radio-frequency filter (the so-called «RF-kicker»). The TOF transport line (F3–F5) has an allocated space for this device and the design of the line is optimized for its operation. The construction of the RF-kicker can be accomplished in 2015–2016.

- **Neutron Wall.** A number of important experiments were performed at ACCULINNA using the DEMON facility [27]. At the moment there is an activity to develop neutron detection abilities using stilbene detectors. Having good properties, these detectors have small solid angle coverage (considering the necessary TOF base). The situation may be developed extensively, providing considerably more stilbene modules, or considering different options for wide-solid-angle neutron detection.

- **Zero Angle Spectrometer.** Many reactions with exotic nuclei lead to formation of projectile-like final-state fragments. These fragments travel more or less together with other species of the secondary beam. In the case of an intense secondary beam this fact may lead to impossibility of registering these fragments, leading to severe limitations on the types of experiments which can be performed by the facility. Zero angle spectrometer nowadays belongs to the class of standard instrumentation at the leading RIB facilities around the world (ALLADIN at GSI, A1900 at NSCL, SAMURAI at RIKEN, etc.). As a minimal option the installation of the existing MSP-140 magnetic spectrometer can be considered downstream of the F5 plane of ACCULINNA-2.

- **Modern OTPC.** The optical time projection chamber [28] has been successfully used at ACCULINNA. Following this experience, an improved version of the OTPC for ACCULINNA/ACCULINNA-2 is now under construction in collaboration with the Warsaw University group. It is proposed also to develop this technique into an active target similar to MAYA [29] in which, instead of

a standard TPC unit with electronic readout, an optical TPC will be used. This should include the use of hydrogen, deuterium, and helium as components of the gas mixture in the active OTPC target. A possible first-day experiment could be the study of the reaction $^{11}\text{Li} + ^2\text{H} \rightarrow ^{10}\text{He} + ^3\text{He}$, where the energy and angle of the ^3He particle stopped in the gas will be measured. On the proton drip side, the first priority will be given to studies of structures inherent to ^{19}Mg and ^{26}S via $^{20}\text{Mg} + ^1\text{H} \rightarrow ^{19}\text{Mg} + d$ and $^{28}\text{S} + ^1\text{H} \rightarrow ^{26}\text{S} + t$ reactions (with hydrogen as a component of the gas mixture).

4.3. Stage 3. ISOL Complex of DRIBs-3. The ISOL complex of DRIBs-3 will be upgraded as a result of the reconstruction of its second-stage, the U400 cyclotron. An increased choice of RIBs will be delivered by this complex for experiments. The U400 cyclotron upgraded into U400R will result in a considerable improvement of the beam quality and will give a new option of the

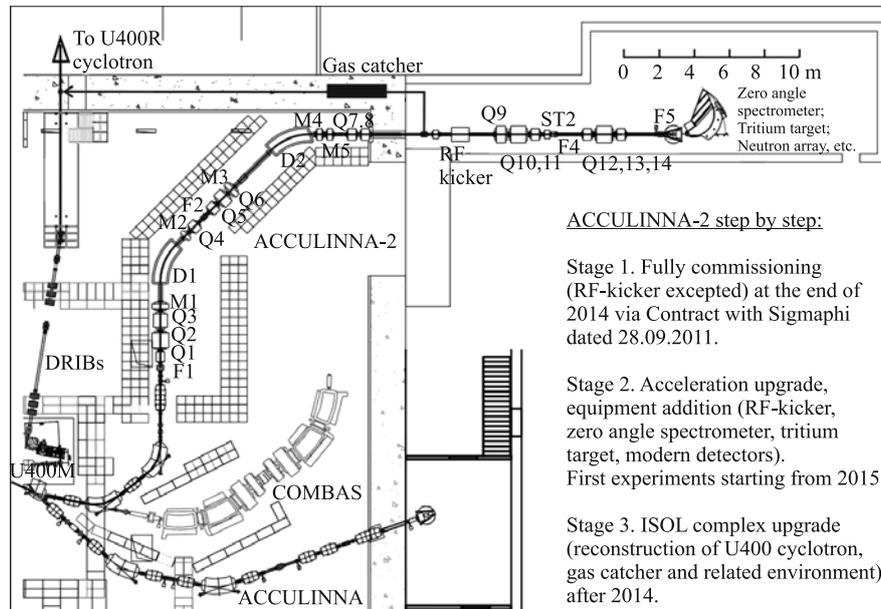


Fig. 2. Layout of the new fragment separator ACCULINNA-2 in the U400M cyclotron hall. The gas catcher, installed to produce the low-energy (10–50 keV) and high quality RIBs intended for the further injection in an ion trap or in the DRIBs beam line to be transported for injection in the U400R cyclotron for the further acceleration to 5–20 A · MeV, is shown near the achromatic F3 focal plane. Zero-angle magnetic spectrometer could be useful for spectroscopy of reaction products emitted from the target in the forward direction in a range of $0^\circ - 15^\circ$. Installation of additional equipment (RF-kicker, cryogenic tritium target, multidetector systems, etc.) is foreseen starting from 2015

RIB energy variation in the range of 5–20 A · MeV. The list of RIBs accelerated at DRIBs-3 will include new species due to the new options offered by the extraction and shaping of the RIBs, obtained from the gas catcher installed at ACCULINNA-2 (see caption to Fig.2). Some RIB species which will be delivered by the DRIBs-3 complex are shown in Table 2.

The ACCULINNA-2 project realization is scheduled for the years 2011–2016. The tentative work plan includes two phases: (phase 1) the construction of

Table 2. RIBs accessible from the upgraded DRIBs-3 complex. Beam energies will be smoothly variable in a range of 5–20 A · MeV

RIB	⁶ He	⁸ He	⁹ Li	¹² Be	⁸ B	¹⁶ C	¹⁷ F	³⁴ Si	⁴⁶ Ar
Intensity, pps	$1 \cdot 10^8$	$3 \cdot 10^5$	$5 \cdot 10^5$	$7 \cdot 10^5$	$3 \cdot 10^5$	$6 \cdot 10^5$	$7 \cdot 10^6$	$2 \cdot 10^5$	$3 \cdot 10^5$

Table 3. RIB yields from a ⁹Be production target with thickness, optimized for the specific cases. «Purity» is the part of the RIB of interest in the total secondary beam current as obtained in focal plane F3. After the passage through the RF kicker, in plane F5, the parts of all the desired beams in the total RIB current will make $\geq 60\%$ and at the same time their intensities will be reduced by a factor of three

Primary beam	Maximum intensity, pμA	Energy, A · MeV	Secondary beam	Energy, A · MeV	Intensity, pps/pμA	Purity (%)
⁷ Li	5	34	⁶ He	21.7	$4.1 \cdot 10^7$	99
			⁶ He	12.7	$1.1 \cdot 10^7$	99
¹¹ B	5	33	⁸ He	21.9	$8.6 \cdot 10^4$	99
			⁸ He	15.6	$3.7 \cdot 10^4$	99
¹⁸ O	3	48	¹¹ Li	31.3	$7.4 \cdot 10^3$	81
			¹⁴ Be	34.6	$1.6 \cdot 10^3$	99
²⁰ Ne	5	54	¹³ O	24.2	$1.5 \cdot 10^6$	10
			¹⁷ Ne	29.0	$5.4 \cdot 10^6$	69
³⁶ S	3	49	¹¹ Li	30.4	$1.3 \cdot 10^4$	80
			²⁴ O	23.4	$2.5 \cdot 10^3$	62
			¹⁵ B	27.0	$5.5 \cdot 10^4$	47
			¹⁸ C	25.5	$1.9 \cdot 10^4$	11
⁴⁸ Ca	1	42	³⁶ Mg	28.1	$1.2 \cdot 10^2$	2
			¹⁵ B	25.9	$1.7 \cdot 10^4$	18
			¹⁷ B	26.2	$3.4 \cdot 10^2$	19
			¹⁷ C	25.1	$3.6 \cdot 10^4$	14
³² S	3	52	²⁴ Si	11.3	$7.2 \cdot 10^3$	31
			²⁷ S	21.7	$3.7 \cdot 10^2$	1

achromatic part of the fragment separator and (phase 2) the RF-kicker installation. The main separator (phase 1) is planned for realization within the first 3–4 years. After that the physical program formulated above can be started. The installation and commissioning of the RF-kicker part (phase 2) can be done in parallel with the experimental runs.

5. CONCLUDING REMARKS

Radioactive ion beam research is the «major highway» of the modern nuclear physics. Flerov Laboratory of Nuclear Reactions (JINR, Dubna) is the only lab in Russia and JINR member states, where such research is conducted nowadays. The first stage of the new radioactive ion beam initiative DRIBs-3 developed in FLNR is construction of the in-flight fragment separator ACCULINNA-2. This facility is planned to occupy a specific «ecological niche» among the world leading facilities providing the unique opportunities for certain type of investigations. First of all, these are studies of the direct nuclear reactions with light exotic nuclei in the energy range 6–60 A · MeV and Z up to 40, correlation studies of cluster degrees of freedom and exotic decays, precision experiments for needs of nuclear astrophysics. According to schedule, the ACCULINNA-2 is commissioned in 2015, so the planning of the «first day» experiments and forthcoming technical developments is now due. In this report we provide the preliminary DRIBs-3 research program focusing at ACCULINNA-2 opportunities and discuss the long-range plans for developing the research with radioactive ion beams at JINR.

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