Physics – Uspekhi **62** (7) 675 – 690 (2019)

INSTRUMENTS AND METHODS OF INVESTIGATION

PACS numbers: 21.10.Ft, **29.20.–c**, 29.25.Rm

Scientific program of DERICA — prospective accelerator and storage ring facility for radioactive ion beam research

L V Grigorenko, B Yu Sharkov, A S Fomichev, A L Barabanov, W Barth, A A Bezbakh, S L Bogomolov, M S Golovkov, A V Gorshkov, S N Dmitriev, V K Eremin, S N Ershov, M V Zhukov, I V Kalagin, A V Karpov, T Katayama, O A Kiselev, A A Korsheninnikov, S A Krupko, T V Kulevoy, Yu A Litvinov, E V Lychagin, I P Maksimkin, I N Meshkov, I G Mukha, E Yu Nikolskii, Yu L Parfenova, V V Parkhomchuk, S M Polozov, M Pfutzner, S I Sidorchuk, H Simon, R S Slepnev, G M Ter-Akopian, G V Trubnikov, V Chudoba, C Scheidenberger, P G Sharov, P Yu Shatunov, Yu M Shatunov, V N Shvetsov, N B Shulgina, A A Yukhimchuk, S Yaramyshev

DOI: https://doi.org/10.3367/UFNe.2018.07.038387

Contents

L V Grigorenko (1, 2, 3, *), **B Yu Sharkov** (1, 4, †), **A S Fomichev** (1, 4, ‡), **A L Barabanov** (3, ♯), **W Barth** (2, 5, 6), **A A Bezbakh** (1), **S L Bogomolov** (1), **M S Golovkov** (1, 4), **A V Gorshkov** (1), **S N Dmitriev** (1, ⋄), **V K Eremin** (7), **S N Ershov** (1, ∘), **M V Zhukov** (8), **I V Kalagin** (1), **A V Karpov** (1, 4), **T Katayama** (9), **O A Kiselev** (5), **A A Korsheninnikov** (3, ¶), **S A Krupko** (1), **T V Kulevoy** (1, 10), **Yu A Litvinov** (5), **E V Lychagin** (1, ♣), **I P Maksimkin** (11), **I N Meshkov** (1, ♡), **I G Mukha** (5), **E Yu Nikolskii** (1, 3), **Yu L Parfenova** (1), **V V Parkhomchuk** (12, ♠), **S M Polozov** (2), **M Pfutzner** (13), **S I Sidorchuk** (1, 4), **H Simon** (5), **R S Slepnev** (1), **G M Ter-Akopian** (1, 4), **G V Trubnikov** (1), **V Chudoba** (1, 14), **C Scheidenberger** (5), **P G Sharov** (1), **P Yu Shatunov** (12), **Yu M Shatunov** (12), **V N Shvetsov** (1), **N B Shulgina** (1, 3), **A A Yukhimchuk** (11), **S Yaramyshev** (2, 5)

(1) Joint Institute for Nuclear Research, ul. Joliot-Curie 6, 141980 Dubna, Moscow region, Russian Federation
(2) National Research Nuclear University MEPhI, Kashirskoe shosse 31, 115409 Moscow, Russian Federation
(3) National Research Center Kurchatov Institute, pl. Akademika Kurchatova 1, 123182 Moscow, Russian Federation
(4) State University Dubna, ul. Universitetskaya 19, 141982 Dubna, Moscow region, Russian Federation
(5) GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, 64291 Darmstadt, Germany
(6) Helmholtz Institute Mainz, Staudingerweg 18, 55128 Mainz, Germany
(7) Ioffe Institute, , ul. Politekhnicheskaya 26, 194021 St. Petersburg, Russian Federation
(8) Chalmers University of Technology, SE-412 96 Göteborg, Sweden
(9) Nihon University, 7-24-1 Narashinodai, Funabashi, Chiba 274-8501, Japan
(10) Alikhanov Institute for Theoretical and Experimental Physics, National Research Center Kurchatov Institute, ul. Bol'shaya Cheremushkinskaya 25, 117218 Moscow, Russian Federation
(11) Russian Federal Nuclear Center – All Russian Research Institute of Experimental Physics, prosp. Mira 37, 607188 Sarov, Nizhny Novgorod region, Russian Federation
(12) Budker Institute of Nuclear Physics, Siberian Branch of the Russian Academy of Sciences, prosp. Akademika Lavrent'eva 11, 630090 Novosibirsk, Russian Federation
(13) Institute of Experimental Physics, University of Warsaw, ul. Pasteura 5, 02-093 Warszawa, Poland
(14) Silesian University in Opava, Na Rybnicku 626/1, 746 01 Opava, Czech Republic

E-mail: * lgrigorenko@yandex.ru, † sharkov@jinr.ru, † Boris.Sharkov@itep.ru, ‡ fomichev@jinr.ru, ♯ a_l_barabanov@mail.ru, ⋄ dmitriev@jinr.ru, ∘ ershov@theor.jinr.ru, ¶ korsheninnikov@mail.ru, ♣ lychag@nf.jinr.ru, ♡ meshkov@jinr.ru, ♠ parkhomchuk@inp.nsk.su

Received 10 May 2018, revised 13 July 2018
Uspekhi Fizicheskikh Nauk **189** (7) 721 – 738 (2019)
DOI: https://doi.org/10.3367/UFNr.2018.07.038387
Translated by L V Grigorenko; edited by A M Semikhatov

Abstract. Studies of radioactive ions (RIs) are the most thriving field of low-energy nuclear physics. In this paper, the concept and the scientific agenda of the prospective accelerator and storage ring facility for RI beam (RIB) research are proposed for a large-scale international project based at the Flerov Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research. The motivation for the new facility is discussed and its characteristics are briefly presented and shown to be comparable to those of advanced world centers, the so-called "RIB factories". In the project, the emphasis is made on studies with short-lived RIBs in storage rings. A unique feature of the project is the possibility of studying electron–RI interactions in a collider experiment to determine the fundamental properties of nuclear matter, in particular, electromagnetic form factors of exotic nuclei.

Keywords: radioactive ion beam factory, radioactive ion beam research, heavy-ion LINAC, gas stopping and reacceleration systems for ions, ion synchrotron, heavy ion storage ring, electron and radioactive ion beam collider, electromagnetic form factors of nuclei

1. Introduction

The structure, properties, and transmutations of atomic nuclei are the main subjects of fundamental research in low-energy nuclear physics. A comprehensive understanding of the structure of atomic nuclei is a prerequisite for describing astrophysical processes, including nucleosynthesis, and for investigations of various cross-disciplinary problems where the nuclear structure plays a key role. More than three thousand radioactive isotopes (RIs) have been synthesized over the history of nuclear physics. However, according to theoretical estimates, from 2000 to 3000 more isotopes are still awaiting discovery (see Fig. 1). Thus, we have no answer yet to even the most fundamental question of nuclear physics: where does the nuclear stability borderline run in the major part of the nuclear chart. The dripline is only known for the lightest nuclei (with number of protons $Z < 32$ or the number of neutrons $N < 20$). But even for these regions, our knowledge barely extends beyond the dripline and hence the fundamental question of the bounds to the existence of the nuclear structures remains unanswered.

Radioactive isotopes are characterized by an excess of neutrons or protons compared to the nuclear stable nuclides and often have unusual properties. A substantial modification of the structure of nuclei far from the 'stability valley' has already been observed experimentally: the discovery of a new type of nuclear structure (a neutron or proton halo), changes in the shell structure of nuclei caused by the disappearance of old and the emergence of new magic numbers. Although many radioactive isotopes are very short-lived, they play a crucial role in the nuclear reactions that occur during explosive nucleosynthesis. During supernovae explosions and collisions of neutron stars, these processes supply the interstellar space with elements heavier than lithium. As a result, such processes determine the chemical composition of planetary systems and hence the world surrounding us.

Another question, important for understanding star evolution processes, concerns the properties of neutron matter that define the life cycle of neutron stars. Ordinary nuclear matter is almost symmetric because it consists of

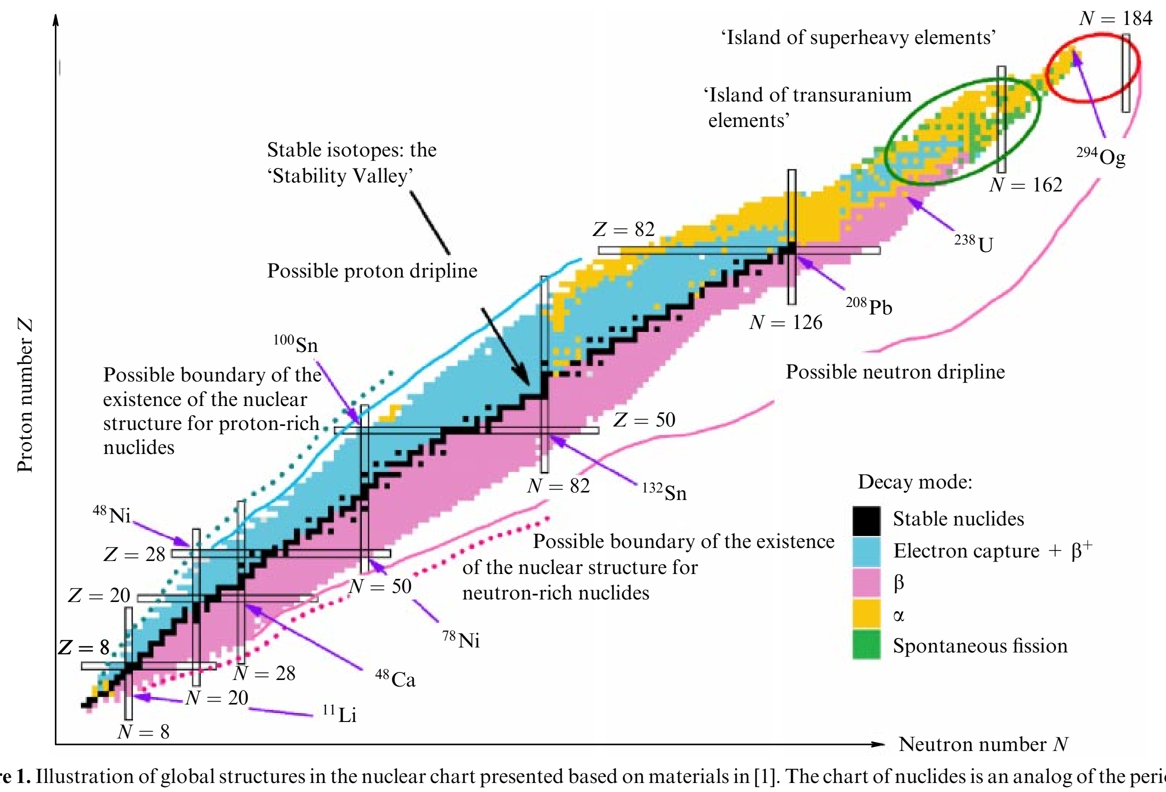

Figure 1. Illustration of global structures in the nuclear chart presented based on materials in [1]. The chart of nuclides is an analog of the periodic table for nuclear physics. In atomic physics, the main regularities are connected with the order in which the electron shells in atoms are filled. In nuclear physics, similar dependences are connected with the sequence in which the nuclear shells are filled for two types of particles, protons and neutrons. Vertical and horizontal bands indicate the 'magic' numbers corresponding to the number of protons Z and the number of neutrons N. Some 'special' nuclides are indicated by arrows: ^{11}Li is a nuclide with one of the most developed 'Borromean' two-neutron haloes, double-magic nuclides in long isobaric chains; ^{294}Og is the heaviest nuclide known today.

almost equal numbers of protons and neutrons (the typical ratio N/Z is in the range $1 < N/Z < 1.6$). Therefore, studies of stable nuclei do not answer this question. Studies of heavy exotic nuclear systems with a considerable excess of neutrons ($N/Z > 1.6$) can be a basis for the experimental investigation of extremely asymmetric neutron nuclear matter.

The search for the answers to the mentioned fundamental questions requires studies of unstable isotopes synthesized in laboratory conditions. For this reason, the construction of radioactive ion beam (RIB) 'factories' is currently the highway of the development of low-energy nuclear physics. RIB factories are multi-purpose centers of RI research with a typical construction budget of about \$ 600–1500 mln. For the last two decades, the total development budget for facilities in this field approaches \$ 10 bln, indicating both significant interest in this research and the growing costs. The scientific program of the world's largest project FAIR (Darmstadt, Germany), being developed with considerable participation of the Russian Federation, has been recently discussed in *Advances in Physical Sciences* [2].

The Flerov Laboratory of Nuclear Reactions (FLNR) is the only place among the JINR member countries, including Russia, where RIB studies are currently performed; they are carried out at the ACCULINNA and ACCULINNA-2 facilities driven by the U-400M accelerator. The last achievements of and scientific plans for these facilities were recently presented in *Advances in Physical Sciences* [3]. These low-budget (around \$ 10 mln) facilities are able to deliver world-class results due to a specifically selected narrow scientific 'ecological niche'. This ecological niche is the correlation studies of direct reactions with RIBs at intermediate energies. However, the scientific opportunities provided by existing facilities do not match the complexity of the wider prospective agenda of RIB studies.

An analysis of the situation shows that one of the most important and prospective research fields was missed by all projects of modern RIB factories, both realized and under construction: the development of RI storage ring complexes with the ultimate goal of investigating the exotic nuclei properties in electron–RI collision experiments. Promoting this research field would provide maximum 'dividends' in domestic and world science with modest investments.

The advantages of studies of the nuclear structure in reactions with electrons originate from the nature of the electromagnetic interaction, which underlies the process of electron scattering. This interaction, which is well understood theoretically, is relatively weak. As a result, various effects of multiple scattering are suppressed and the reaction mechanism is reasonably simple. This makes a description of the electron interaction with the protons in the nucleus reliable within the lowest orders of the perturbation theory. The efficiency of the reactions with electrons for nuclear structure studies has been known for a long time, since the pioneering experiments of Hofstadter [4]. They have opened a new era in research on the properties of stable nuclei and were awarded the Nobel Prize in physics in 1961. The use of electron scattering provides unique opportunities for studying the properties of radioactive nuclei and has outstanding development prospects.

In RIB physics, the use of a collider mode for the electron–RIB scattering studies is necessary because the creation of sufficiently dense static targets consisting of short-lived RIs is extremely difficult.

In high-energy physics, the development of electron–ion colliders is considered a very important tool for deeper understanding of quantum chromodynamics [5]. Here, investigations of both protons and heavy ions are relevant, and the need for collider experiments is related to the possibility of a flexible choice of kinematical conditions for collisions and the possibility of using polarized beams.

2. Status and prospects of storage ring facilities for RIB studies

The idea of electron–RI collider experiments appeared quite a long time ago, reached a stage of well-developed projects, and for more than two decades repeatedly attracted the attention of researchers. We briefly consider the history and status of projects in this field and the status of storage ring complexes for RI studies in general.

The K4-K10 [6] was an upgrade project of the FLNR transformation into an advanced RI factory. It was completely accepted in 1990, but has not been implemented because of dramatic changes in the economic situation in the country. The complex included two rings, K4 (storage ring/accelerator with $B\rho_{\text{max}} = 4$ Tm) and the experimental ring K10 (with $B\rho_{\text{max}} = 10$ Tm).

The MUSES (Multi USe Experimental Storage rings) [7] project (two rings: storage/cooler ring and an experimental ring) was an important part of the RIB factory development at RIKEN (Japan). It was also canceled for nonscientific reasons in favor of more easily implementable projects. Now, attempts to attack this problem at RIKEN are being continued within the SCRIT (Self-Confining Radio-Isotope Ion Target) project, which involves electron scattering on a 'fixed target' consisting of RIs stored in an electromagnetic trap [8].

The most ambitious modern project, ELISe [9], is a part of the scientific program of the international FAIR facility. However, the project was not included in the 'modularized starting version' of FAIR and is now frozen until at least 2030. At the moment, the NUSTAR collaboration of FAIR, which is responsible for the low-energy nuclear-physics part of the FAIR scientific program, supports the acceleration of work on the electron–RIB collision topic within the DERICA project. The heavy-ion storage ring ESR is perhaps the most advanced facility of this kind, and it successfully continues operation at GSI, the host institute of FAIR. Recently, ESR was complemented with the low-energy CRYRING (CRYogenic RING), shifting scientific interests of the whole facility in the opposite direction from the scientific objectives of the ELISe project.

Many of the ideas of the K4-K10 were realized in the storage ring complex at the IMP (Institute of Modern Physics) (Lanzhou, China). However, because of the weak 'driver' accelerator, the luminosity achieved there is insufficient for collider studies of electron–ion collisions. Plans for a considerable upgrade of this facility are uncertain: the upgrade is technically complicated by the dense urban surroundings of the facility site. The attention of the RI community in China is now focused on the HIAF project (High-Intensity Heavy Ion Accelerator Facility). Two storage rings are planned at this RIB factory for entirely different purposes: for studies of the reaction of fully ionized heavy nuclei in 'merged beam' kinematics [10].

The TSR (Test Storage Ring) project at ISOLDE [11] at CERN was postponed indefinitely in order to better concentrate efforts on research in the fields of the physics of ultra-high energy (LHC (Large Hadron Collider), etc.) and antimatter (AD (Antiproton Deceleration), ELENA (Extra Low ENergy Antiprotons), etc.).

Thus, there is great interest in problems that can be solved with the use of storage ring facilities and hence in the development of such facilities. Nevertheless, the specific task of new facility development aimed at studies of radioactive nuclei properties in electron–RI collisions in storage rings remains unexplored. Focusing on this ultimate goal, it is possible to create a facility with a world-class scientific program at JINR within a rather modest budget.

The DERICA (Dubna Electron–Radioactive Ion Collider fAcility) project aims to construct a unique accelerator and storage ring facility for pioneering low-energy nuclear physics studies. These include the synthesis of still unknown RIs, measurements of their mass, studies of RI decay modes, fission barriers of heavy nuclei, studies of nuclear reaction dynamics, and determining the structure details of exotic nuclei, i.e., measurements of charge and matter radii with a high accuracy. The key role in this project is assigned to the studies of electron collisions with exotic nuclei, providing information on the spatial charge distribution in RIs, and, possibly, to an evaluation of the electromagnetic transition form factors of nuclear excitations with high selectivity to different multipolarities.

In collaboration with other Russian nuclear physics centers and institutes of its member countries, JINR has all the prerequisites for DERICA implementation. World-class studies with RIBs have been conducted in the FLNR for the last 25 years [3]. Significant experience has been gained in developing new facilities involving the cooperation of domestic and foreign scientists [12, 13]. The Budker Institute of Nuclear Physics (Novosibirsk) is one of the world leaders in constructing electron accelerators, electron coolers, and electron colliders [14, 15]. Experts from BINP played the leading role in preparing technical documentation of the ELISe project [9] and even carried out tests of some prototypes. They have also mastered the major part of the design and production of the CR ion storage ring for FAIR. As a result of joint efforts among JINR, the National Research Nuclear University (NRNU) MEPhI, and the Alikhanov Institute for Theoretical and Experimental Physics (ITEP) (which is part of the National Research Center Kurchatov Institute — NRC KI), the design methods and technologies for constructing 'warm' linear ion accelerators were developed [16]. In 2016, two linear particle accelerators were successfully commissioned for the NICA project (Nuclotron-based Ion Collider fAcility [17, 18]) in the High Energy Physics Laboratory at JINR. The LU-20 injector linac with spatially uniform Radio-Frequency Quadrupole (RFQ) focusing was designed by ITEP in collaboration with NRNU MEPhI [19–21]. The linear RFQ accelerator — an injector in the buster synchrotron of NICA — was manufac-

Figure 2. Possible location of the new laboratory on JINR's territory next to the Flerov Laboratory buildings. Arrows indicate the major FLNR facilities: U-400 cyclotron (superheavy element synthesis program), U-400M cyclotron (program of light exotic nucleus studies at the ACCULINNA-2 facility), and a recently constructed building of the 'superheavy element factory'. The available area near the FLNR is more than sufficient for the current DERICA project and for possible future upgrades.

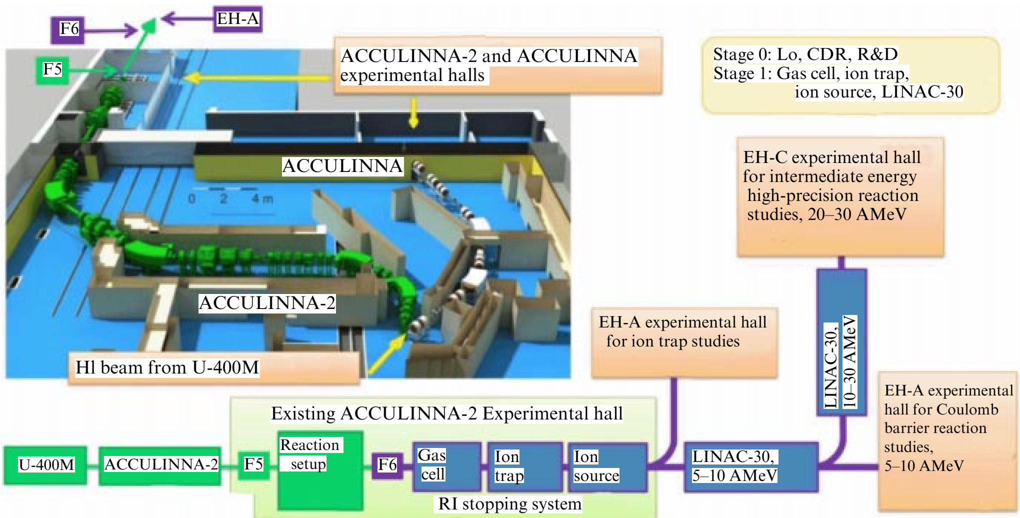

Figure 3. Concept of the DERICA project, stages 0–1. The RI stopping system and LINAC-30 accelerator are mounted downstream from the F6 focal point of the existing ACCULINNA-2 fragment separator. This makes R&D work and experimental studies possible already at the early stage of the project. LINAC-30 is shown separated in two sections with different scientific programs: 5–10 MeV/nucleon energies with fine tuning of the outgoing beam energy and 10–30 MeV/nucleon energies with coarse tuning.

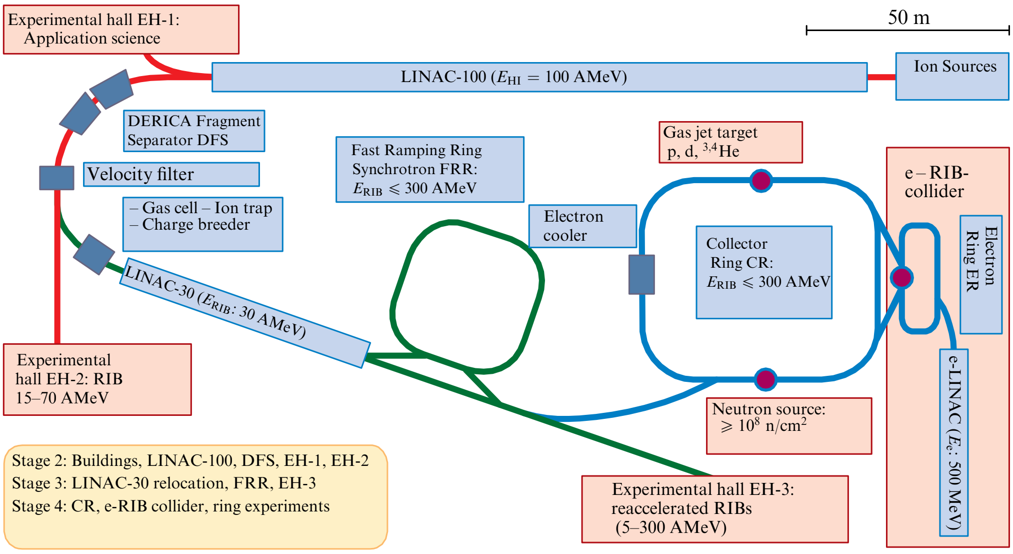

Figure 4. RIBConcept of the DERICA project, stages 2–4. Different stages of the project are indicated by color of the beamlines. At the first stage, experiments can be conducted in the experimental halls EH-1 (applied research using stable beams 25–100 MeV/nucleon) and EH-2 (direct reaction studies with RIBs at intermediate energies of 20–70 MeV/nucleon). At the second stage, high-quality post-accelerated RIBs in a broad energy range (5–300 MeV/nucleon) become available in experimental hall EH-3. At the third stage, three experimental halls at the CR collector ring are added.

tured by BEVATEC (Germany). The development of high-frequency superconductivity technologies has been started in Russia [22]. These developments can find application in both the 'driver' linear accelerator and the post-accelerator for RI. Thus, there are currently all the prerequisites to realize the research program originated in 1990 with the K4-K10 project [6] at a qualitatively new level.

3. DERICA project concept

There are some basic qualitative features of the DERICA project that must be emphasized. In the K4-K10, MUSES, and ELISe projects, a 'hot' beam of RIs produced by a fragment separator is injected into the storage ring and is cooled there until it reaches the required quality for the experiments or for injection into the next experimental ring. In the MUSES and ELISe projects, stochastic cooling of the beam in the storage ring was proposed. The stochastic cooling time (in seconds) can be estimated via the phenomenological expression

$$t_{st} \sim \frac{20N}{\Delta\omega}\,,$$

where N is the number of particles in the orbit, and $\Delta\omega$ is the bandwidth of the stochastic cooling system (in Hz), optimistically evaluated as 2–4 GHz. For the simultaneous injection of 10^8–10^9 particles, the cooling time should be about ~ 0.5–10 s, and during this time further RI production is inefficient. Thus, this strategy of RI facility operation leads to a controversy between the high luminosity request and the expected short lifetime of the RI being investigated.

In the DERICA project, the RIBs produced by DFS (DERICA Fragment Separator) (see Fig. 4) are stopped in a gas cell, accumulated in the ion trap, and then transferred to the ion source/charge breeder (these components form the 'RI stopping system'). The charge breeder provides the highest possible charge state for further effective acceleration (see Fig. 3). In recent years, gas cell technologies have been improved significantly [23]. Projects for the post-acceleration of a 'cold' beam of RIs based on gas cells are successfully realized in the HIE-ISOLDE (High-Intensity and Energy) at CERN and ISAC (Isotope Separation and Acceleration) at TRIUMF (Vancouver, Canada) and are planned to be implemented in the SPIRAL2 at GANIL (Caen, France). However, the production of radioactive ions in all these projects is based on the ISOL (Isotope Separation On-Line) technology. In the DERICA project, the RIB stopped in a gas is reaccelerated by the LINAC-30 superconducting linear accelerator to the energy ~ 30 MeV/nucleon. For some tasks, higher energies are required. In particular, the effective operation of the electron–RI collider requires the energies of the ions to be about 100–300 MeV/nucleon. For these purposes, further acceleration from ~ 30 to ~ 300 MeV/nucleon is performed by the booster synchrotron FRR (Fast Ramping Ring), featuring a high ramping rate of the magnetic field (duty cycle can be less than 0.1 s). The duty cycle of the RI stopping system is 0.1–0.3 s. Depending on the setup of the post-acceleration (only LINAC-30 or LINAC-30 + FRR), the time before injection into the experimental ring of the CR is 0.1–0.5 s. Compared to approaches suggested previously, the DERICA concept allows significant improvement in the time preceding the start of measurements. This can be crucial for the studies of short-lived RIBs (with $T_{1/2} < 1$–5 s).

The basic DERICA components could be located on unused territory at JINR (see Fig. 2). The project implementation is envisioned to have several stages (see Figs 3, 4). At stage 1, the ACCULINNA-2 fragment separator [3, 12] will be used for R&D and experiments. This facility, driven by the U-400M accelerator, has recently been commissioned at the FLNR. The use of the existing FLNR scientific infrastructure will accelerate and technologically safeguard the project, because the key technologies of RIB extraction and post-acceleration can be tested at the early stage of development. Moreover, the unique scientific opportunities would become available already at this stage of the project. The upgrade of the U-400M cyclotron, planned for 2020–2021, should significantly improve the performance of the ACCULINNA-2 facility and provide opportunities for the full-fledged RIB research program for the period of further DERICA construction. A staged implementation of the DERICA project implies the appearance of new fundamental and applied research opportunities at each stage (see Figs 3 and 4). For the total duration of the project construction, 10–15 years after the decision is made, the first new scientific instruments will become available for experiments in just 3–5 years. The construction phases and new scientific opportunities are distributed among the stages as follows:

— At stage 0 of the project, the scientific agenda is fully formulated, the technological concept is formulated, and required R&D is carried out.

— At stage 1.1 (RI stopping system, experimental hall EH-A), the RI stopping equipment is placed in the F6 area of the ACCULINNA-2 facility (see Fig. 3). After commissioning this system, experiments with stopped RIs in electromagnetic traps become possible.

— At stage 1.2 (LINAC-30, experimental halls EH-B and EH-C, see Fig. 3), the system of RI reacceleration based on the LINAC-30 is put into operation. In experimental halls EH-B and EH-C, high-quality post-accelerated RIBs with energies of 5–10 and 20–30 MeV/nucleon become available.

— At stage 2.1 (LINAC-100, experimental hall EH-1, see Fig. 4), applied studies with high-intensity stable-ion beams in experimental hall EH-1 can be performed.

— At stage 2.2 (DFS, experimental hall EH-2, see Fig. 4), studies of reactions with RIBs at intermediate energies (20–70 MeV/nucleon) at the experimental site EH-2 become possible. It is expected that for this energy range and this type of experiment, the RIBs with world-record (or close to it) intensities would become available.

— At stage 3.1 (gas cell), the equipment of the RI stopping system is relocated from the ACCULINNA-2 to DFS. After its commissioning in this new location, experiments with RIBs in electromagnetic traps become available.

— At stage 3.2 (LINAC-30, Experimental hall EH-3), the LINAC-30 accelerator is relocated from the ACCULINNA-2 to the DFS. High-quality post-accelerated RIBs with energies that can be varied in the range 5–30 MeV/nucleon become available in the experimental hall EH-3. Intensities of the RIBs at this stage would exceed those available at stage 1.2 by orders of magnitude.

— At stage 3.3 (FRR), in the experimental hall EH-3, high-quality post-accelerated RI beams with energies in the range 5–300 MeV/nucleon become available.

— At stage 4 (CR), experiments can be performed at three independent experimental areas of the CR storage ring: (1) collider experiment on electron scattering, (2) reactions in a gas jet target [24], and (3) reactions with thermal neutrons or neutrons from the D + T reaction in 'merged beams' kinematics.

The technological requirements for the heavy-ion accelerators LINAC-100 and LINAC-30 are specified in Appendix 1. Appendix 2 provides estimates of the precision of electron–RIB scattering experiments in the collider as a function of luminosity. Appendix 3 provides estimates of the luminosity of several experiments with RIs in storage rings and in the electron–RIB collider. The possibility of using so-called 'ordered' (or 'crystalline') beams in collider experiments are discussed in Appendix 4, as are special requirements for the high-energy storage ring CR that must be met to use this operation mode. A brief summary of the DERICA project stages is given in Appendix 5.

4. Scientific program of the DERICA project

The ultimate goal of the DERICA project is the measurement of RI charge form factors and, in particular, the determination of their charge radii. In addition, implementation of the project will open up broad opportunities for advanced research in other fields of modern nuclear and atomic physics. It is expected that the RIB intensity at the endpoint of the DFS fragment separator will be record-high (or close to it) among the RIB factories worldwide, which would provide important opportunities for direct-reaction studies with RIs at intermediate energies (20–70 MeV/nucleon).

An attractive feature of the project is the possibility of various experiments with post-accelerated RI beams both on a fixed target (in the experimental hall EH-3) and in the CR storage ring in three physically important energy ranges: (i) $E_{\rm RIB} \sim$ 5–10 MeV/nucleon, for near-barrier and resonant reactions, (ii) $E_{\rm RIB} \sim$ 20–30 MeV/nucleon, direct reactions at intermediate energies (knock-out, transfer, pick-up, etc.), (iii) $E_{\rm RIB} \sim$ 100–300 MeV/nucleon, direct reactions at high energies (knock-out, elastic and quasi-free scattering, etc.).

4.1 Studies using the electron–RIB collider

The question of the size and shape of nuclei is among the most fundamental questions in nuclear physics. In Fig. 5, matter radii (averaged over all nucleons) and charge radii of light nuclides from deuterium to ^{32}Mg are schematically shown. We note that even for rather well-studied light nuclei, there are many gaps in this information. It is a remarkable fact that the dripline nuclei such as ^{11}Li and ^{22}C have the sizes of 'valence' nucleon orbitals comparable to those of very heavy nuclei, for example, ^{208}Pb. An exact description of the nucleon density shape of RIs is the critical test of our understanding of nuclear structure.

For many RIs, the matter radii (related to distributions of both neutrons and protons) are determined from the analysis of data on elastic scattering on protons and stable nuclei. However, these results are model dependent. The electron–nucleon interaction, which is well described by quantum electrodynamics, allows extracting information on the charge distribution within the nucleus in a model-indepen-

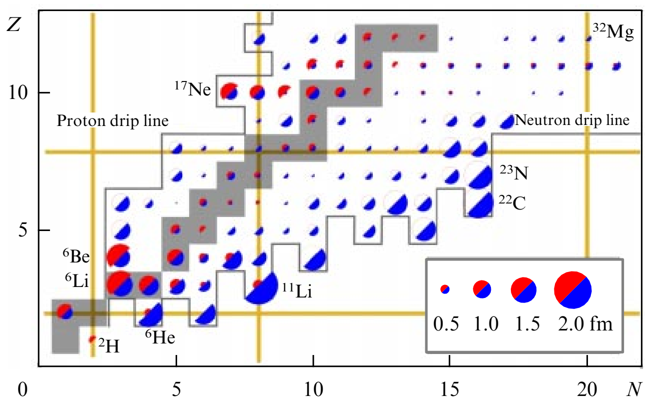

Figure 5. Information on matter (blue semicircles) and charge (red semicircles) radii of isotopes for nuclides lighter than ^{32}Mg. The values $\Delta r_{\rm blue} = r_{\rm matter} - r_0 A^{1/3}$ and $\Delta r_{\rm red} = r_{\rm charge} - r_0 A^{1/3}$ are shown, which illustrate deviations in the values from those expected within the liquid drop nucleus model. The value $r_0 = 0.93$ fm (somewhat smaller than the standard values in the liquid drop model: $r_0 = 1.2 - 1.25$ fm) is chosen so as to use ^{4}He nuclide as a 'baseline' with $r_{\rm matter} = 1.47$ fm (corresponding to $r_{\rm charge} = 1.67$ fm).

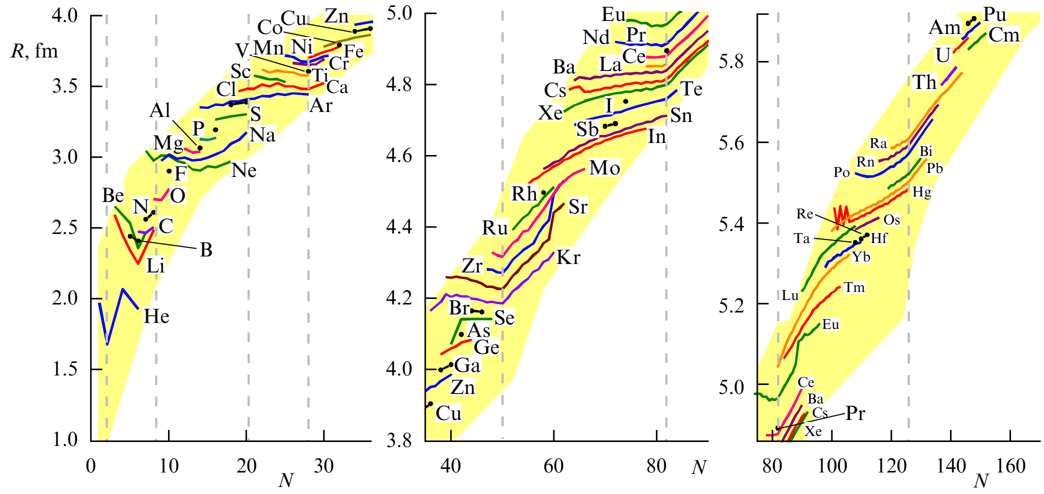

Figure. 6. Status of charge radius studies according to Ref. [33]. The charge radii of about 900 isotopes among the known 3100 isotopes are now measured. The shaded area corresponds to the region of nuclear-stable isotopes based on estimates in Ref. [34] and assuming the dependence $R \sim A^{1/3}$ for nuclear radii.

dent way and, for example, verifying a possible depression of the charge density in the interior of some exotic nuclides.

The global status of the nuclear charge radii is illustrated in Fig. 6. The behavior of the charge radius as a function of the neutron number can be quite complicated. The shell effects are clearly seen. The results for RIs are mainly obtained in experiments with ion traps, where the charge radius is determined by an isotopic shift of the hyperfine splitting of atomic levels. The used method determines the range of the studied isotopes: some isotopic chains are investigated in detail, while for other isotopes the data are very limited. The electron–RI scattering research can expand the range of isotopes available for study. It can be regarded not only as an alternative method for determining the charge radius but also as a means to obtain much more detailed information on the charge distribution, in particular, via determination of the charge form factors (see Appendix 2).

The use of electrons for studying RI properties is dictated by the great difficulty in creating the RI target. In the DERICA project, an approach is used in which the relativistic RI beam in an orbit in the storage ring becomes a target. In this case, the advantage of the electron–ion scattering mentioned above turns into a considerable technical difficulty because the low cross sections lead to stringent requirements on luminosity. The luminosity estimates for some types of experiments (including collider ones) in the DERICA project are given in Appendix 3. In Appendix 4, the possibility of a substantial increase in luminosity in the collider experiment due to realization in the storage ring CR of an ordered state of ions in the beam (so-called 'crystalline beams') is discussed. Such a suggestion was first considered in the MUSES project [25–27]. The specific organization of the electron–RIB collider operation in this mode is also briefly described in Appendix 4.

4.2 Synthesis of new isotopes

The primary information about any isotope is just the fact of its existence. Synthesis of new isotopes is intensively carried out all over the world, and the nuclear chart is annually replenished by 3 to 10 new isotopes. In recent decades, new isotopes were mainly discovered in experiments with fragment separators. For such studies, the isotope lifetime has to be $\tau \geqslant 100$ ns, which corresponds to a typical time-of-flight through the fragment separator. Isotopes with shorter lifetimes can only be studied in nuclear reactions (see Section 4.5). Commissioning the new generation 'RIB factories' (RIBF (Radioactive Isotope Beam Factory) in Japan is already running, FRIB (Facility for Rare Isotope Beams) in the USA and FAIR in Germany are under construction) would certainly intensify this work. The DERICA project will have reasonably high production rates, which are necessary for these studies. As was already mentioned in the Introduction, from 2000 to 3000 isotopes remain unknown according to theoretical estimates, and this field of activity is broad enough for all possible 'players'. The DFS fragment separator and LINAC-100 should be able to provide excellent opportunities for these studies. Besides, the DERICA project will create unique opportunities for the synthesis of heavy neutron-rich isotopes in multinucleon transfer reactions (see Section 4.8).

4.3 Measurements of masses and lifetimes of short-lived nuclei

The second most important piece of information on an isotope is its mass and lifetime.

The technology of RIB stopping in a gas cell [24] and further accumulation of RIs in an ion trap perfectly fits with the technique of mass measurements using electromagnetic traps (Penning traps) or/and Multiple-Reflection Time-of-Flight (MR-ToF) mass spectrometers [28].

Another technique of mass measurement can be based on the isochronous mode of the CR storage ring [29]. Clear advantages of this method are the sensitivity and short measurement time. Injecting just one short-lived particle is sufficient to determining its mass with a relative accuracy of about 10^{-6}. Because the low-energy beam injection from LINAC-30 or the FRR synchrotron is assumed in the DERICA project, it will be possible to keep the nuclei of isobaric multiplets in the ring in the same charge state. In this case, more stable nuclides with more precisely measured masses will be available for calibration. Thus, the accuracy of the mass measurement will probably be higher than in the other higher-energy 'ring projects', where questions of calibration remain open [30].

4.4 Study of radioactive decays

Nuclei located outside the stability valley transmute into more stable systems due to the 'weak' processes, β^- and β^+ decays or electron capture. Because of the structural peculiarities of isobaric neighbors, weak transitions tend to mainly populate excited states of the daughter systems. If these states are above the thresholds for nucleon or cluster emission, then we have the β-delayed emission of particles [31]. Studies of β-decays and β-delayed emission of particles in the DERICA project can be carried out (i) by implantation into the detecting system in the EH-2 experimental hall, (ii) with the use of electromagnetic traps behind the gas cell, and (iii) in experiments with the CR storage ring, which open interesting possibilities [11]. In particular, we note the possibility of studies at the borderline between nuclear and atomic physics [32]: studies of the exotic decay modes of nucleus + electron systems and studies of atomic effects in the radioactive decays of highly charged ions.

A special class of radioactive decays is represented by the 'strong' decays proceeding via emission of one or several particles: $\alpha, p, 2p, n, 2n$. It is also possible that a heavier cluster is emitted (e.g., ^{10}Be-cluster radioactivity) or the simultaneous emission of four neutrons occurs (4n-radioactivity). While α decay is among the three basic types of radioactivity (α, β, and γ) already discovered by Becquerel in 1896, the discoveries of p-radioactivity (1982, GSI) and 2p-radioactivity (2002, GSI, GANIL) are among the quite recent achievements of RIB physics. The question of the possibility of unusual types of radioactive decay with the emission of several neutrons (2n or 4n) still has no answer. 'Strong' radioactive decays in the DERICA project can be investigated in the transfer or knock-out reactions populating the ground states of nuclear systems located beyond the nuclear stability borderline.

4.5 Studies of ultra-short-lived RIs in nuclear reactions. Reactions with a tritium target

Nuclear reactions due to their diversity are the most flexible tool of nuclear physics. Synthesis and studies of the structure and decay modes of ultra-short-lived RIs (for example, those far beyond the dripline) or short-lived nuclear states with $\tau < 100$ ns can only be carried out with the use of nuclear reactions. The DERICA project gives very ample opportunities for studies of nuclear reactions.

Nuclear reactions at intermediate energies (20–70 MeV/nucleon) on a fixed target can be investigated in the EH-2 experimental hall. In this case, a 'hot' beam of RIs from a DFS fragment separator (nonmonochromatic, divergent, with the transverse diameter of 2–3 cm) can be used. Each incoming particle should be fully characterized and the event-by-event reconstruction of interactions performed. This requirement imposes a restriction on the intensity of the secondary RIBs to be less than around $\leqslant 2 \times 10^6$ s^{-1} and hence on the level of beam purification from admixtures.

In the EH-3 experimental hall, it is possible to conduct various experiments with post-accelerated RIBs on a fixed target in three physically important energy ranges: 5–10 MeV/nucleon for near-barrier and resonant reactions, 20–30 MeV/nucleon for direct reactions at intermediate energies (knockout, transfer, pickup, etc.), and 100–300 MeV/nucleon for direct reactions at high energies (knockout, elastic and quasi-free scattering, Coulomb excitation on heavy targets, etc.). For these studies, the post-accelerated beam has a very small diameter (~ 1 mm), low emittance, and nearly 100% purity. All these factors would have a very positive impact on the quality of experiments. Also, there is no above-mentioned restriction on the RIB intensity.

In the CR storage ring, reactions with RIs can be investigated with gas jet targets [35, 36]. Despite the limited choice of target composition (p, d, ^{3}He, and ^{4}He), a wide range of reactions is covered here:

— Elastic scattering reactions (which at high energies can be used, e.g., to determine the matter radii of RIs).

— Reactions of one- and two-nucleon transfer (problems of astrophysical interest at low energies and nuclear spectroscopy at intermediate energies).

— Knockout reactions and quasifree scattering (problems of nuclear structure and nuclear spectroscopy at high energies).

The important feature of reactions with RIBs in storage rings is the possibility of using infinitely thin gas jet targets (10^{13}–10^{16} cm^{-2}). Combined with beam cooling, this allows considerably improving the experimental angular and energy resolutions [35, 36]. For studies of elastic and quasifree scattering at high energies, this opportunity can be crucial (for example, in elastic scattering studies, a high resolution allows the inelastic contributions to be disentangled). Estimates of the luminosities for some nuclear reaction experiments in the DERICA project are presented in Appendix 3.

Although reactions with a tritium target are a very specific subject, they deserve a special discussion; it is a matter of the unique opportunities provided by the use of this 'tool': the reaction of the proton transfer to tritium is uniquely energetically favorable (the energy release of the reaction is ~ 19 MeV), reactions with the tritium target, studied in parallel with reactions with an ^{3}He target, are extremely convenient for studies of isobaric symmetry, and two-neutron transfer from tritium is a highly effective tool for studies of neutron-rich systems beyond the dripline. This research is complicated by the radiation hazard of tritium ($T_{1/2} =$ 12.32 years): work with tritium in the gaseous/liquid phases is usually available in very few (defense-related) scientific centers.

At the FLNR, the program of RIB studies with cryogenic tritium gas/liquid targets has been successfully realized at the ACCULINNA facility in collaboration with experts from the All-Russian Research Institute of Experimental Physics (Sarov) [3]. A similar program is under development at the ACCULINNA-2 facility [3, 37]. Naturally, cryogenic tritium targets can be used in the experimental halls EH-2 and EH-3 of the DERICA complex.

Construction of a gas jet tritium target for use in the CR accumulative ring is a unique and even more interesting possibility. Estimates show that 10^3 cm^3 of gaseous tritium (which is about 2.7 kCi, i.e., the standard for rooms of class II radiation safety in the Standards of Radiation Safety-99 of Russia) would be enough for the functioning of the gas jet target from 20 days to 2 years (depending on the flux density). Thus, conditions may appear for unique long-duration measurements with a thin tritium target.

4.6 Studies of nuclear reactions for astrophysical applications

The major astrophysical application of nuclear data is the use of the cross sections of certain processes in the 'network' calculations of various nucleosynthesis scenarios. The data most in demand are the following:

— Cross sections of the resonance and nonresonance radiative capture (p,γ), (α,γ) using gaseous hydrogen and helium targets for applications in studies of r- and rp-processes in stars [38]. Cross sections of the photo-dissociation reactions (γ,p), (γ,n), (γ,α) can be obtained from these data;

— Cross sections of transfer reactions with deuterium, tritium, and helium-3 targets, which are often used in indirect methods for determining important astrophysical characteristics, for example, in the 'Trojan Horse' method, used to determine asymptotic normalization coefficients;

— Emission process of β-delayed neutrons (protons), which are sometimes needed in network calculations as a reciprocal process for the radiative capture of neutrons (protons);

— Data on the hyperfine structure and the gross structure of spectra populated in the course of the β-decay of nuclei in chains of astrophysical slow and rapid processes (s- and r-processes);

— Study of level density variations in 'magic number' nuclei with an excitation energy in the range 1–25 MeV.

The use of a storage ring for studies of astrophysical reactions is especially attractive for the following reasons:

— The use of localized gas jet targets of very small thickness (10^{13}–10^{16} cm^{-2}) and sizes (< 1 mm^2) allows achieving a high angular resolution;

— Energies of the accumulated beams can be precisely controlled by cooling the beam and using thin targets, which make it possible to find and investigate narrow resonances in the cross sections;

— Radioactive ions can be accumulated with an energy exactly corresponding to that of a 'Gamow window' for the relevant astrophysical processes. For the r-process (2–8 MeV/nucleon), similar experiments have been performed on the ESR [36, 38]. For many reasons, the ESR is not an optimal ring for such measurements. Similar measurements form the basis of the physical program of the TSR@ISOLDE [11] and CRYRING@ESR [39] projects. There, a gradual decrease in ion energies to less than 1 MeV/nucleon is planned, which will allow reaching the energy range of rapid proton capture (rp-process);

— In the case of storage ring studies, a sufficient luminosity is provided by circulation of RIBs in the ring with a frequency of $\sim$ 1 MHz.

We emphasize that the storage of highly charged ions at low energies imposes serious requirements on the vacuum of the storage ring. Similarly to the CRYRING case, the average residual gas pressure of $\sim 10^{-12}$ mbar is required for this type of experiment. Application of an injection scheme similar to that proposed for TSR [11] will not only maintain the average RIB intensity in the ring but also gradually accumulate additional ions.

4.7 Studies in a storage ring with a neutron target

While studies of RIB reactions with protons and heavier nuclear targets can be carried out by various methods, studies of reactions with neutrons are so far limited only to stable or long-lived nuclides. The cross sections of various reactions with neutrons are necessary for understanding almost all astrophysical processes and, in particular, the r-process. Knowledge of the cross sections of RI reactions with neutrons is important not only for fundamental science but also for modeling modern nuclear reactors.

A unique opportunity can arise in the framework of the DERICA project if the development of powerful new neutron sources allows the future implementation of experiments dedicated to the studies of neutron interaction with RIs in storage rings. At present, the concept of a new fourth-generation neutron source is being developed in the Frank Laboratory of Neutron Physics at JINR. The neutron source is based on a 1 GeV proton superconducting accelerator with a current of about 0.1 mA. The concept also includes subcritical fast assembly with several target stations. The peak density of the neutron flux can be about 10^{17} cm^{-2} s^{-1}, while the averaged density of the thermal neutron flux can be as large as 3×10^{14} cm^{-2} s^{-1} [40, 41]. Under certain conditions, this will allow the use of such a source for studies of collisions with RIBs. We note that experiments with neutrons in the merged-beam kinematics, which could be performed, for example, with use of extremely high-flux neutron D-T generators, are of special interest. In general, nowhere in the world have experiments with a neutron target in inverse kinematics been realized: there are only estimates and proposals [42, 43].

4.8 Production and study of heavy neutron-rich nuclei in multinucleon transfer reactions

Fragmentation reactions are the major method currently used for production of heavy neutron-rich nuclei. This method has a number of limitations. First, ^{238}U is the heaviest nucleus available for the primary beam. Corresponding nuclei obtained in fragmentation reactions have $Z \leqslant 92$ and $N \leqslant 146$. Second, the production cross sections (and hence the yields) of heavy neutron-rich isotopes rapidly decrease with the number of removed nucleons. For example, the most neutron-rich nucleus with $N = 126$ known today is ^{202}Os. It has been produced in the fragmentation of ^{238}U and ^{208}Pb with a cross section of a few picobarns [44, 45].

The alternative method for production of heavy neutron-rich nuclei is based on the use of multinucleon transfer reactions (MTRs) in heavy-ion collisions at energies near the Coulomb barrier. It is predicted in Refs [46–50] that the cross sections of MTRs decrease much more slowly than the cross sections of fragmentation reactions. That makes MTRs much more favorable for producing nuclei far away from the β stability line. Besides that, only in such reactions can neutron-rich nuclei heavier than uranium, up to super-heavy nuclei, be obtained. The use of beams of neutron-rich nuclei as primary beams will allow additionally increasing the production cross sections of interesting exotic nuclei and thereby stepping into the poorly studied area of neutron-rich heavy and super-heavy nuclei.

The following new opportunities for studies of MTRs show great promise within the DERICA project:

— Search for unknown heavy nuclei, in particular, in the region of $N = 126$, which is the last 'waiting point' in astrophysical nucleosynthesis; study of their structure and the decay features.

— Search for unknown neutron-rich nuclei heavier than uranium; study of their nuclear-physical properties. Measurement of the fission barriers is of special interest here.

— Studies of the multinucleon transfer reaction dynamics in a wide range of masses and energies of the colliding nuclei.

4.9 Studies of fission barriers of heavy nuclei with $Z > 98$ and $A > 250$

The fission barriers of actinides (from ^{230}Th to ^{249}Bk), the structures of their excited states, and the density of levels above the fission barrier and in the second potential well can be studied with nucleon transfer reactions (d, pf), (t, pf), (^{3}He, df), (t, αf) (see review [51]). Extending such studies to the regions of atomic numbers and neutron numbers $Z \geqslant 100$, $N = 154$–162, and then to $N > 162$ will open a path to detailed studies of the barrier properties of super-heavy nuclei located within the recently discovered 'island of stability' of super-heavy elements [52].

Intense and pure RIBs (^{10,11}Be, $^{14-16}$C, $^{20-22}$O, $^{21-23}$F, ^{24}Ne, ^{25,26}Na, ^{28}Mg, ^{29,30}Al, $^{32-34}$Si, $^{35-37}$P) will be available in the experimental hall EH-3 of the DERICA facility. The transfer reactions of clusters ^{5,7}H, ^{6,8}He, ^{9,11}Li, ^{12,14}Be, ^{13,15}B to the heavy targets ^{248}Cm, ^{249}Bk, ^{251}Cf, ^{254}Es are of special interest here. Implementation of this research program will for the first time allow investigating the fission barrier structure for the heaviest, previously unknown isotopes with atomic numbers $Z = 99$–104.

4.10 Other nuclear physics tasks

Beside the points noted above, the scientific program of the DERICA project at various stages of implementation includes the following topics:

— Studies of transfer reactions (with deuterium, tritium, and helim-3 targets); some examples of such reactions have been calculated for the TSR@ISOLDE project [11];

— Studies of emissions of β-delayed neutrons (protons) for nuclear structure problems, the theory of β decay, and decay dynamics. Tentative calculations were performed to evaluate the possibility of such experiments for the ESR storage ring [53];

— Studies of scattering on an internal gas jet target. In these experiments, studies can be carried out efficiently in the regime of small momentum transfers [36];

— Studies of reactions with a selective population of either ground or isomeric states [30];

— Production and spectroscopy of unknown heavy nuclei with $Z = 100$–106 in fusion reactions with intense RIBs.

4.11 Atomic physics studies

As has already been mentioned, the following problems reside on the borderline between nuclear and atomic physics:

— Studies of exotic decay modes of 'nucleus plus electron' systems;

— Studies of atomic effects in radioactive decays of highly charged ions.

The project will allow the following studies to be carried out:

— laser spectroscopy for atomic physics problems;

— study of di-electron recombination for atomic physics problems and for the problem of determining nuclear radii;

— high-precision experiments in quantum electrodynamics, studies of parity violation in atomic transitions.

4.12 Potential of RI use for producing intensive neutrino beams

Radioactive isotopes moving in a storage ring with high values of the Lorentz factor γ and decaying via β^- and β^+ emission and also by electron capture emit a neutrino preferentially in the flight direction, thus becoming sources of collimated neutrino beams (so-called β-beams). Beta-beams have a number of advantages: they are 'pure', i.e., solely consist of a neutrino of one type (electron antineutrinos in the case of β^- decay and electron neutrinos in the case of β^+ decay and electron capture), and their spectrum can be precisely calculated and can be smoothly varied by changing the Lorentz factor γ. The spectrum can include one or several monochromatic lines (if electron capture is considered), and some of these lines can be subjected to time modulation (see [54, 55] and the references therein). There are a number of neutrino physics problems that can be explored by using β-beams (a discussion of problematic topics can be found in review [56]). However, all these opportunities were understood rather recently (after the pioneering publication [57]), and the sources of β-beams have not been constructed yet.

There is a detailed project of a generator of neutrino β-beams of very high energies aimed mainly at studies of neutrino oscillations. This proposal is based on decays of the radioactive ions ^{6}He, ^{8}Li, ^{8}B, and ^{18}Ne accelerated to ultrarelativistic energies ($\gamma > 100$) and accumulated in a storage ring [58]. There is no certainty that this project will be implemented, because there is reason to believe that other high-intensity neutrino sources are preferable for studies of oscillations [59]. However, smaller-scale generators of pure neutrino β-beams with relatively low energies based on RIs accelerated to Lorentz factors from 1 to 100 are of great interest. Such generators can be used for studies of neutrino physics problems such as neutrino coherent scattering on nuclei, mechanisms of the elastic and inelastic neutrino interaction with nucleons and nuclei, the resonant neutrino interaction with nuclei, refining the weak coupling constant, searching for new effects beyond the Standard Model, and others. Rare-earth (and close to them) RIs are of special interest here because they relatively intensively decay via the electron capture and therefore form monochromatic neutrino lines.

Within the DERICA project, different methods of production of intense RIBs — potential sources of high-intensity neutrino β-beams — can be tested. Such studies are necessary for the design of the high-intensity neutrino β-beam generator optimized to use the most suitable radioactive isotopes. Moreover, by using hydrogen-like ions accumulated in the storage ring and decaying via electron capture, the technique of modulation of an emitted neutrino beam by means of electromagnetic (laser) radiation can be developed. This problem is directly related to the 'atomic-physics problems' discussed in Section 4.11 (in particular, with laser spectroscopy of ionized radioactive nuclei).

4.13 Applied studies

The implementation of the DERICA project will contribute to the development in Russia of modern technologies for the design and construction of charged particle accelerators, detectors, and other physical equipment in demand in the world.

Using the beams of stable nuclei with the energy of up to 100 MeV/nucleon, applied research on radiation physics can be performed. First and foremost, this is the simulation of the heavy-ion component in the cosmic ray spectrum in testing microelectronics parts used in the space industry. These beams can also be used to calibrate tracking detectors used to measure high-energy cosmic rays for studies of the 'velocity effect' in the formation of tracks and for appropriate radiobiological experiments. The radiative effects of high-energy heavy ions in thin targets are not only and not so much dependent on the energy losses of an ion in a substance; they are more sensitive to the charge state of the ion. This research topic is still poorly investigated. Therefore, studies of the effect of highly stripped heavy ions on different materials, in particular on 2D structures, are of great interest.

Large mean free paths of ions with high energies will allow planning experiments on modification of massive materials in the bulk, as well as the development of high-performance technology for irradiating multilayer targets.

5. Conclusion

The heyday of the physics of radioactive ion beams, which made it the main focus in the development of low-energy nuclear physics in the world in the late 1980s and early 1990s, coincided with a period of considerable difficulties in domestic science. A noticeable lag from global centers in this field of research can be traced to that time. The situation is partly compensated by Russia's significant participation in the international FAIR project (construction of an advanced RIB factory in Germany). However, it seems necessary to construct and maintain a full-fledged infrastructure of advanced RIB research in Russia.

The implementation of the DERICA project will make it possible to establish a laboratory at JINR that will not only be among the world leaders according to certain parameters but will also provide unique scientific opportunities for specialists from Russia, the JINR member states, and foreign partners. The relatively low cost of the project in comparison with comparable ones throughout the world is due to the rejection of the broadest universalism of modern RIB factories and concentrating on several fundamental areas of research. Notably, the ultimate goal of the project, unique on a global scale, should be a program to study the properties of exotic nuclei in collider experiments on the scattering of electrons and radioactive isotopes. Despite the rejection of universalism, the DERICA project covers a very wide range of tasks of modern nuclear, atomic, and applied physics. It should become a place of attraction for domestic and foreign scientists, as well as a center for training specialists in a broad range of fields (fundamental nuclear physics and astrophysics, accelerator technology, materials science, and other applied studies).

The feasibility potential of the project is high, as it relies, in general, on proven technologies and successfully operating scientific organizations. Realization of the scientific program discussed above requires the implementation of advanced technological solutions that will promote the development of physical experimental techniques and technological culture in general and, in particular, promote developments in a number of key areas, such as ultra-high vacuums, high-frequency superconductivity, and electromagnetic traps.

The approximate project cost is $ 300 mln (in 2017 prices). In 2019–2021, conceptual and technical designs of the project will be performed together with the development of prototypes for LINAC-100, which is the basic facility of the project. The project construction period is 2022–2031 (for a startup in 2022).

Potential participants in the project are **Russia:** JINR (Dubna), BINP (Novosibirsk), NRC KI (Moscow), NRC KI — ITEP (Moscow), NRC KI — PNPI (Gatchina), INR (Moscow), RFNC (Sarov), PTI (St. Petersburg), NRNU MEPhI (Moscow), FIAN (Moscow), SINP (Moscow); **Germany:** GSI (Darmstadt), Johannes Gutenberg University Mainz, Forschungszentrum Jülich, University of Frankfurt; **France:** GANIL (Caen), CEA. (Saclay), INP (Orsay); **Japan:** RIKEN (Wako, Saitama), RCNP (Osaka); **Netherlands:** KVI, University of Groningen; **Sweden:** Lund University, Chalmers University of Technology (Gothenburg); **South Africa:** iThemba LABS, Stellenbosch University; **Canada:** TRIUMF (Vancouver); **Italy**: LNL INFN (Legnaro).

Acknowledgments
We are grateful to Professors V L Varentsov and E Kolomeitsev for the fruitful discussions and useful comments. Special thanks go to O Suckhareva for technical assistance. This work was supported in part by the Russian Science Foundation grant No. 17-12-01367.

Appendix 1. Requirements for heavy-ion (LINAC-100, LINAC-30) and electron accelerators

The LINAC-100 and LINAC-30 accelerators (Tables 1 and 2) should be designed to accelerate the ions of elements of almost the entire Periodic Table.

To produce the widest range of secondary RIBs, it is necessary to accelerate the primary stable ions ($Z = 5$–92) to an energy of ~ 100 MeV/nucleon. In addition, to provide flexibility in choosing the conditions for producing RIBs and the operation of the accelerator for applied research, it is desirable to ensure the capacity to adjust the beam energy in a wide range and to provide at least three operating modes of the accelerator: with maximum ion energies of 100, 75, and 50 MeV/nucleon. The main purpose of LINAC-100 is the acceleration of intense continuous wave (CW) primary beams of stable ions (from boron to uranium) with a beam current of 1 pμA and higher for the production of RIBs by fragmentation.

The maximum rate of RIB production at the LINAC-100 plus DFS stage will reach $\sim 10^9$–10^{10} particles/s. Then, as explained above, they will be stopped and collected in a trap

Table 1. Expected intensities of primary beams in the LINAC-100 accelerator with an energy of 100 MeV/nucleon.*

Ion	A/Z	I, pμA
$^{11}B^{2+}$	5.5	10 or more
$^{18}O^{3+}$	6.0	10 or more
$^{20,22}Ne^{4+}$	5.5	8 or more
$^{32,36}S^{6+}$	6.0	5 or more
$^{36}Ar^{6+}$	6.0	5 or more
$^{40,48}Ca^{7+}$	6.0	5 or more
$^{56,64}Ni^{11+}$	5.8	5 or more
$^{86}Kr^{15+}$	5.7	5
$^{132}Xe^{22+}$	6.0	5
$^{160}Gd^{27+}$	5.9	5
$^{209}Bi^{37+}$	5.65	4
$^{238}U^{40+}$	5.95	~ 0.8**

* The maximum available charge states of Bi and U ions correspond to the performance of superconducting ECR sources with a 28 GHz working frequency. It is possible to use several ion sources (for example, specialized for Kr–U heavy ions or a simpler one for lighter ions B–Ni) with different operation principles.
** Performance of modern ECR sources with a 28 GHz working frequency can be ~ 1 pμA for $^{238}U^{40+}$ [60].

Table 2. Typical secondary beams of RI in the LINAC-30 accelerator.*

Element	Range of A	Charge	Range of A/Z
B	8–19	5+	1.6–3.8
O	13–24	8+	1.63–3.0
Ar	31–46	16+	1.94–2.88
Sn	100–132	38+	2.63–3.47

* The range of the mass numbers is defined by the known stability boundaries for these isotopes. The maximum accessible charges of ions are shown based on the capabilities of the ECR ion sources.

with subsequent stripping to high-charge states and acceleration in LINAC-30. LINAC-30 will provide acceleration of RIB bunches with a repetition rate of 2–20 Hz. The RIBs accelerated in LINAC-30 are either used directly for measurements (in the experimental hall EH-3 or in the experimental ring CR; see Fig. 4), or are injected into the FRR synchrotron for further acceleration. For injection into the synchrotron, the pulse duration for the ion beam from LINAC-30 has to be in the range 1–50 μs.

For the experiments carried out in experimental hall EH-3, the possibility of varying the energy of RIBs accelerated in LINAC-30 is required. For the physical program of the project, there are two important energy ranges: (1) the near-barrier energies 5–10 MeV/nucleon and (2) the range convenient for studying direct reactions at intermediate energies of 20–30 MeV/nucleon. In these energy ranges, the LINAC-30 accelerator should provide an acceleration of the whole spectrum of secondary RIBs available for production in the fragment separator, with a capability of smooth energy tuning with a step of ~ 0.1 MeV in the first energy range and ~ 1.0 MeV in the second one.

At least in the initial section of the accelerator, the main objective is the acceleration of primary beams of ions with the maximum ratio $A/Z \approx 6$. Modern ion sources deliver beams of the heaviest ions of required intensities with the mass-to-charge ratio $A/Z = 5.5$–6.0 ($^{209}\mathrm{Bi}^{37+}$, $^{238}\mathrm{U}^{40+}$). The required intensities of heavy ions (especially in the maximal charge state of $37+$ for Bi and $40+$ for U) can be provided by modern electron cyclotron Resonance (ECR) cryogenic sources [60]. In Table 1, we present ions that are most interesting as primary beams with the mass-to-charge ratio $A/Z = 5.5-6.0$. Furthermore, after a certain beam energy is reached, it is possible to increase the rate of acceleration using strippers. In this regard, as a possible alternative, it is advisable to consider the use of a cyclotron as the driver of the primary beam or the implementation of the CYCLINC concept (cyclotron + linear accelerator) to reduce the cost of the driver accelerator.

A structure with spatially uniform quadrupole focusing (radio frequency quadrupole, RFQ) is traditionally used as the initial part providing beam bunching. The bunching is needed to increase the capture coefficient for the acceleration regime. It also provides the initial acceleration to several hundred keV per nucleon.

Linear superconducting (SC) structures are currently used as the main part of linear accelerators. SC linear accelerators are usually based on the so-called modular principle, when identical short (usually 2–5 accelerating gaps) SC resonators with an independent power supply are used, with SC solenoids and quadrupoles placed between the resonators for focusing. For a large length (and hence high output energy), it is appropriate to split the accelerator into several groups consisting of identical resonators and solenoids. In this case, the effective acceleration of particles with different charge-to-mass ratios is possible due to adjustment of the amplitude and phase of the RF field in each resonator. Moreover, the simultaneous acceleration of several types of isotopes with close Z/A values is possible in such a universal accelerator without losses. The general trend of SC accelerator development is to start the SC part of the accelerator from the lowest possible velocity of the accelerated beam. However, for intermediate-energy acceleration between RFQ and SC resonators, one or several normally conducting sections with drift tubes are required.

For the objectives of the DERICA project, the required energy of the electron beam is rather low, only about 500 MeV, which significantly simplifies construction of the electron accelerator. The major requirement is delivery of an intense electron beam to the ring orbit ($\sim 5 \times 10^{11}$ s^{-1}). At such energies and intensities, it seems reasonable to use a linear accelerator up to the final electron energy (so-called 'top-up injection') and a storage ring (in order to avoid dumping of the electron beam). With a standard acceleration rate of 25–30 MeV m^{-1}, the linear accelerator will be no more than 20 m in length. It will be able to accelerate electron bunches with charges up to 1–2 nC, with the bunch duration of not more than 1 ps, and small longitudinal and transverse beam emittances. The radio-frequency power supply system of the storage synchrotron with top-up injection will be simple enough because it will only compensate for the electron energy loss due to the synchrotron radiation.

Appendix 2. Estimates of the precision of experiments at the electron–RIB collider

We consider the problem of the charge density evaluation from the cross section of elastic electron scattering on ions. In the leading Born approximation the cross section of the elastic scattering on a charged object with a distributed charge is expressed as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q} = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}q}\right)_{\mathrm{Mott}} F^2(q)\,, \tag{1}$$

where $(\mathrm{d}\sigma/\mathrm{d}q)_{\mathrm{Mott}}$ is the Mott cross section on a point-like nucleus,

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}q}\right)_{\mathrm{Mott}} = \frac{2\pi (Z\alpha)^2}{k^2}\,\frac{1}{q}\left(4\,\frac{k^2+m_{\mathrm{e}}^2}{q^2} - 1\right), \tag{2}$$

and $F(q)$, called the charge form factor, is responsible for the dependence of the cross section on the charge density ρ:

$$F(q) = \frac{1}{4\pi}\int \rho(r)\exp(\mathrm{i}qr)\,\mathrm{d}^3 r = \int_0^\infty \rho(r)\,\frac{\sin(qr)}{qr}\,r^2\,\mathrm{d}r\,. \tag{3}$$

We determine the accuracy of the charge radius r_{ch},

$$r_{\mathrm{ch}}^2 = \int_0^\infty \rho(r)\,r^4\,\mathrm{d}r\,, \tag{4}$$

depending on the luminosity in the experiment. For this, using the Monte Carlo (MC) method, events are generated corresponding to the cross section of electron scattering on ions with the assumed charge distribution (see Fig. 7). Based on these data, the initial charge distribution is then reconstructed. The electron spectrometer acceptance is supposed to be about 5%, which is a quite conservative value. We disregard other experimental biases, such as the energy and angular resolutions. We assume a collision of the electron beam with an energy of 500 MeV with the 300 MeV/nucleon RIB. For a statistical analysis of the 'experimental data' and determination of the confidence intervals, we use the maximum likelihood method.

We consider ^{48}Ca as the object of studies with the charge radius $r_{\mathrm{ch}} = 3.478$ fm. We use three simple model parameterizations for the charge density: the uniformly charged sphere, the Gaussian, and the exponential distributions. Any realistic distribution is expected to have statistical properties somewhere between the uniform sphere and exponential distributions. The estimated accuracy as a function of the luminosity is given in Fig. 8. We see that a luminosity of about

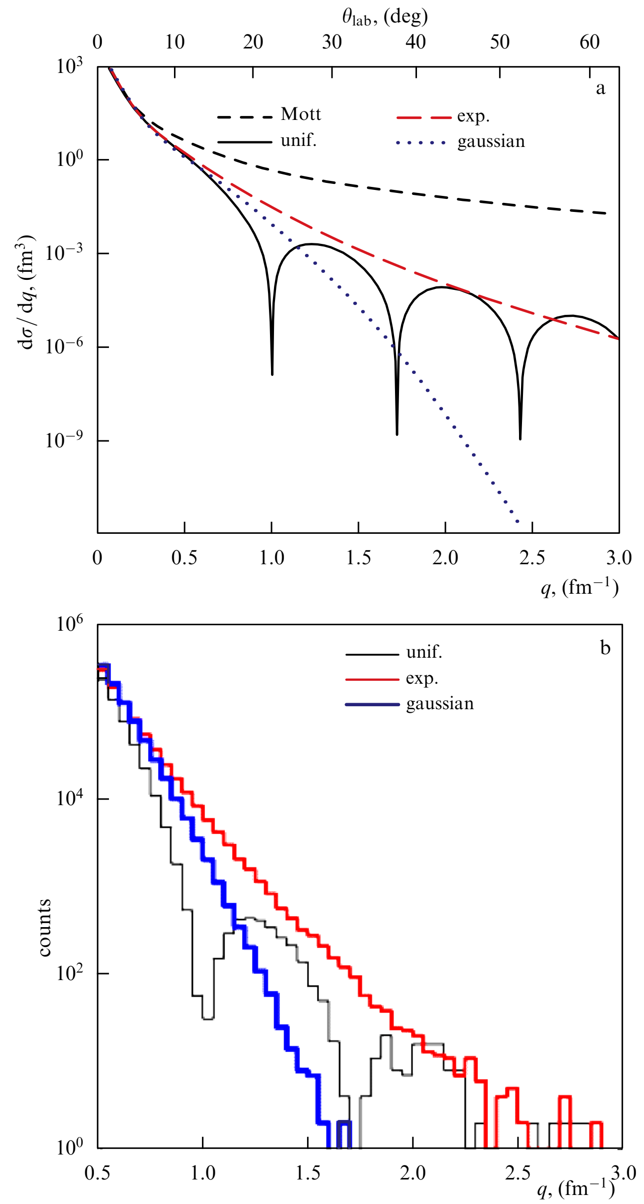

Figure 7. Scattering cross section (Eqns (1) and (2)) for three model charge distributions (a uniform sphere, and Gaussian and exponential distributions): (a) theoretical curves, and (b) results of MC simulation for a 10-day experiment with the luminosity 10^{28} cm^{-2} s^{-1}.

10^{28} cm^{-2} s^{-1} guarantees determination of charge radius with an accuracy of better than 1%.

We discuss the possibility of obtaining more detailed information on the charge form factors than on the charge radius. For this, we use the analytic two-parameter charge density in the generalized shell model [4]

$$\rho(r) = \frac{8k^3(1+\alpha k^2 y^2)}{\sqrt{\pi}\,(2+3\alpha)} \exp(-k^2 y^2)\,,$$
$$k = \left[\frac{3(2+5\alpha)}{2(2+3\alpha)}\right]^{1/2}, \qquad (5)$$

where $y = r/r_{ch}$. The attractive feature of this model is that it describes the situation of an increase or decrease in the charge density in the central region of the nucleus (see Fig. 9). The description of such features of charge distributions is a sensitive test for theoretical models of the nuclear structure.

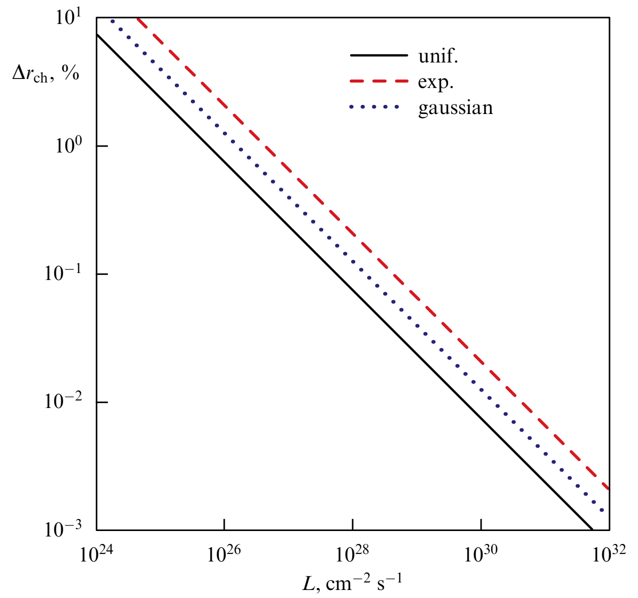

Figure 8. Statistical precision of the charge radius determination according to Eqn (4) for the three model charge distributions (a uniformly charged sphere, and Gaussian and exponential distributions) as a function of the luminosity for a 10-day experiment.

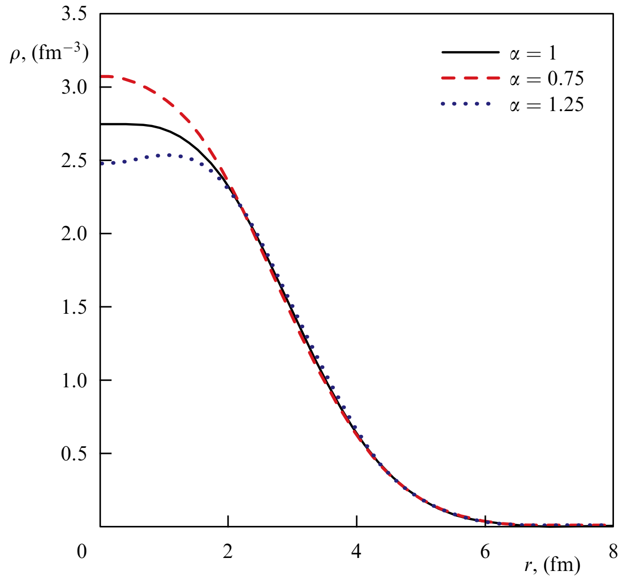

Figure 9. Charge density in the generalized shell model (5) for different values of the parameter α. The charge radius $r_{ch} = 3.478$ fm corresponds to the model of ^{48}Ca.

The results of simulations given in Fig. 10 show that we are capable to reliably disentangling situations with very insignificant variations in the density in the central region of a nucleus with luminocities about 10^{27}–10^{28} cm^{-2} s^{-1}.

We note once again that all the estimates are performed under the assumption of a realistic electron spectrometer acceptance and a 'modest' experiment duration of 10 days.

Appendix 3. Luminosity estimates for experiments with some RIBs

A major feature of the DERICA project is the possibility of systematically investigating properties of RIBs (including quite short-lived ones) in long isobaric and isotonic chains.

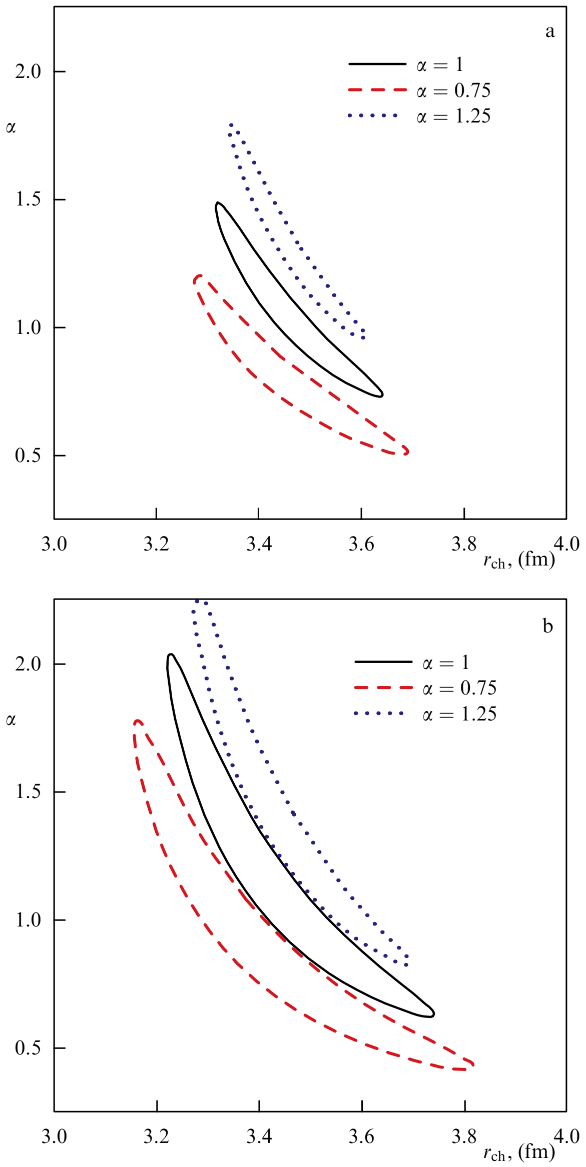

Figure 10. Contour plots of the confidence interval dependence on the parameters r_{ch} and α, obtained for charge distribution (5) in the generalized shell model with different (actual) values of the parameter α. The real charge radius $r_{ch} = 3.478$ fm corresponds to ^{48}Ca. The confidence interval 1σ (68%) is given in panel (a). The confidence interval 2σ (95%) is presented in panel (b). Duration of the experiment is 10 days with a luminosity of 7×10^{27} cm^{-2} s^{-1}.

Luminosity for different experimental scenarios (see Table 3) is estimated based on the following assumptions. The LINAC-100 accelerator gives the 10 pμA current of primary ions at the energy of 100 MeV/nucleon. For estimates of yields of secondary RIBs, the LISE++ program is used, set up for the ACCULINNA-2 fragment separator. It is supposed that the DFS fragment separator of the DERICA project will have an acceptance 5 times higher than that of ACCULINNA-2. The efficiency of the RI stopping system is assumed to be 15% and time of accumulation is taken to be 0.2 s (in fact, it should be 0.1–0.3 s, depending on the ion). The estimated acceleration time in the synchrotron FRR is 0.3 s.

Parameters of the CR storage ring (with the circle length about 220 m) and of the electron collider facility are taken similar to those of the ELISe project. Velocities of particles in the ring in the cases of 7, 30, and 300 MeV/nucleon beams are 0.121 s, 0.247 s, and 0.652 s, respectively. The corresponding circulation frequencies are 0.166, 0.337, and 0.890 MHz.

The average flux $\bar{j}'$ of RIBs with a half-life $T_{1/2}$ downstream from the post-acceleration system (RI stopping system–LINAC-30–FRR) is

$$\bar{j}' = \frac{j\varepsilon T_{1/2}}{\Delta t \ln 2}\left(1 - 2^{-\Delta t/T_{1/2}}\right), \qquad (6)$$

where Δt is the time of accumulation and post-acceleration, j is the input flux from the fragment separator, and the efficiency of the RI stopping system is ε. In this case, the average number $\overline{N}_{stor}$ of RIs circulating in the storage ring is

$$\overline{N}_{stor} = \frac{T_{1/2}}{\ln 2}\,\bar{j}' = \frac{j\varepsilon}{\Delta t}\left(\frac{T_{1/2}}{\ln 2}\right)^2\left(1 - 2^{-\Delta t/T_{1/2}}\right). \qquad (7)$$

Appendix 4. Special requirements for the CR storage ring

Attempts to use 'ordered' (or 'crystalline') ion beams with extremely small emittance (0.2 nm and smaller) in colliders have been discussed since the turn of the 20th century [25–27]. However, as estimates showed, the low linear density typical of ordered beams, something like 10–100 ions/m, does not allow reaching the level of collider luminosity that is of interest for experimental studies. Gradually, interest in this option was lost. However, recently there was a proposal [61] to use deeply cooled ionic beams in a 'super-crystalline' state. In such a state, preserving 'quasi-ordering', the beam emittance grows proportionally to the linear density to the power 2/3, and remains quite a small value. Experiments have shown [61] that such a structure of the beam can be maintained by electron cooling, even in the case of an increase in its linear density up to 5×10^5 ions/m. As a result, it is possible to reach a luminosity of about 10^{27} cm^{-2} s^{-1} in the electron–ion collider. Also, in this mode, it is possible to use a coasting ion beam, significantly simplifying the beam formation. Bunching of the beam can still be required when operating at an extremely low ion intensity. In this case, the linear density of the ion beam should not exceed the limit value quoted above. Otherwise, the beam emittance (the cross size) would increase, leading to a decrease in luminosity.

One of the problems with an electron–ion collider with bunched electron and ion beams is the necessity to provide synchronization of the electron and ion bunches at the collision point [61, 62]. This problem is typical of all asymmetric colliders. As a result, the ion energy variation in such a collider is only admissible with a step inversely proportional to the number of bunches in the rings. There is no such problem with coasting ion beams.

The major limitation of the electron–ion collider luminosity is related to the so-called 'beam–beam collision effect' — scattering of particles of one beam in the field of the other beam in the collision region. In an electron–ion collider, this effect, which determines the stability of the moving particles, is considerable for ions. This is because achieving the maximum luminosity requires maximizing the electron bunch intensity in accordance with the so-called Laslett criterion (shift of oscillation frequency of particles in the field of their own bunch). At the same time, the beam intensity of rare and/or radioactive ions is most likely limited by their 'generator', and this beam does not affect the intensity of the electron beam.

Among the advantages of the coasting ion beam is an opportunity to reduce the electron–ion beam collision effect

Table 3. Estimates of luminosity for various experimental scenarios.*

Ion	$T_{1/2}$, s	j, c^{-1}	L_1	$\overline{N}_{stor}$ (1)	L_2	L_3	$\overline{N}_{stor}$ (2)	L_4	L_5
^{11}Be	13.7	5.0×10^9**	3.7×10^{29}	1.5×10^{10}	2.4×10^{28}	2.5×10^{31}	1.5×10^{10}	6.5×10^{31}	1.4×10^{29} **
^{12}Be	0.02	1.0×10^9**	1.1×10^{28}	6.2×10^5	1.0×10^{24}	1.1×10^{27}	2.5×10^5	1.1×10^{27}	
^{16}C	0.7	1.5×10^9**	1.0×10^{29}	2.1×10^8	3.4×10^{26}	3.5×10^{29}	1.8×10^8	8.0×10^{29}	
^{17}C	0.19	2.5×10^8	1.3×10^{28}	7.3×10^6	1.2×10^{25}	1.2×10^{28}	4.7×10^6	2.1×10^{28}	
^{18}C	0.09	3.0×10^7	1.1×10^{27}	3.0×10^5	4.9×10^{23}	5.0×10^{26}	1.5×10^5	6.6×10^{26}	
^{19}C	0.05	3.8×10^6	9.6×10^{25}	1.4×10^4	2.3×10^{22}	2.3×10^{25}	6.0×10^3	2.6×10^{25}	
^{32}Ar	0.098	2.0×10^6	8.0×10^{25}	2.3×10^4	3.8×10^{22}	3.8×10^{25}	1.2×10^4	5.2×10^{25}	
^{33}Ar	0.17	4.0×10^7	2.1×10^{27}	1.0×10^6	1.7×10^{24}	1.7×10^{27}	6.3×10^5	2.8×10^{27}	
^{34}Ar	0.84	2.0×10^9**	1.4×10^{29}	3.4×10^8	5.5×10^{26}	5.6×10^{29}	3.0×10^8	1.3×10^{30}	
^{35}Ar	1.77	1.0×10^{10}**	7.2×10^{29}	3.7×10^9	6.1×10^{27}	6.2×10^{30}	3.5×10^9	1.5×10^{31}	2.8×10^{28} ***
^{40}S	8.8	2.0×10^9**	1.5×10^{29}	3.8×10^9	6.3×10^{27}	6.4×10^{30}	3.7×10^9	1.7×10^{31}	
^{41}S	2.0	7.0×10^8**	5.1×10^{28}	2.9×10^8	4.8×10^{26}	4.9×10^{29}	2.8×10^8	1.2×10^{30}	
^{42}S	1.0	2.0×10^8	1.4×10^{28}	4.0×10^7	6.7×10^{25}	6.8×10^{28}	3.7×10^7	1.6×10^{29}	
^{43}S	0.265	6.0×10^7	3.5×10^{27}	2.7×10^6	4.4×10^{24}	4.5×10^{27}	1.9×10^6	8.5×10^{27}	
Luminosity limit			10^{23}		10^{23}	10^{23}		10^{25}	10^{25}

* Notations: j — flux of RIs produced in the fragment separator, $\overline{N}_{stor}$ (1) and $\overline{N}_{stor}$ (2) — numbers of RIs accumulated in the CR after acceleration in LINAC-30 and FRR, respectively. L_1 — luminosity of the experiment in the experimental hall EH-3 for a fixed gas target 5×10^{20} cm^{-2} in thickness. L_2 — luminosity in the CR ring for a gas jet target 10^{13} cm^{-2} thick at an energy of 7 MeV/nucleon. L_3 and L_4 — luminosities in the CR ring for a gas jet target 5×10^{15} cm^{-2} thick at energies of 30 and 300 MeV/nucleon. L_5 — luminosity of the collider experiment in the CR ring at an energy of 300 MeV/nucleon. Primary beams for the Be, C, Ar and S isotopes are ^{15}N, ^{22}Ne, ^{40}Ca, and ^{48}Ca, respectively.

** Productivity of modern gas cells (stage of the RI stop in gas) is limited to the value $\sim 5 \times 10^8$ ions/s.

*** The corresponding estimated luminosities for ^{11}Be and ^{35}Ar in the ELISe project [9] are 2.4×10^{29} and 1.7×10^{27} cm^{-2} s^{-1}.

by violating the collision synchronization of ion and electron bunches, such that an ion can meet an electron bunch only after many revolutions in the ring, crossing the collision region in the absence of the electron bunch there.

To conclude, in the quasi-ordered ion beam mode, the luminosity of the electron–ion collider can be increased by up to 2 orders of magnitude with respect to the 'standard' mode of the storage ring (see Appendix 3). This can be achieved for relatively low-intensity ion beams, which is especially important in experiments with rare and short-lived RIs.

Appendix 5. Tentative plan stages for the DERICA project implementation

Table 4. Stages of the DERICA project construction*

Stage		Location	Equipment	Experimental possibilities	Section
1	1.1	ACCULINNA-2, final focal plane F6	RI stopping system	Experiments with RIBs in electromagnetic traps	4.3, 4.4
	1.2	EH-B and EH-C	Temporary building, LINAC-30	High-quality post-accelerated RIBs with the energies in two ranges: 5–10 and 20–30 MeV/nucleon	4.2, 4.4, 4.5, 4.6, 4.8, 4.9
2	2.1	EH-1	New building, LINAC-100	Applied researches with high-intensity beams of stable ions	4.13
	2.2	EH-2	Fragment separator DFS	Reactions with RIBs at intermediate energies (20–70 MeV/nucleon)	4.4, 4.5
3	3.1	DFS, final focal plane	RI stopping system is relocated from ACCULINNA-2 to DFS facility	Experiments with RIBs in the electromagnetic traps. Range of available RIBs is essentially expanded compared to the stage 1.1	4.2, 4.4
	3.2	EH-3	LINAC-30 is relocated from ACCULINNA-2 to DFS facility	Studies of nuclear reactions with high-quality post-accelerated RIBs for beam energies varied in a broad range of 5–30 MeV/nucleon. The RIBs intensities are orders of the magnitude higher than those available at the stage 1.2	4.2, 4.4–4.6, 4.8, 4.9
	3.3	FRR	Storage ring — Synchrotron FRR	Experiments using FRR as the low energy storage ring	4.3, 4.4, 4.6, 4.10, 4.11
		EH-3		Studies of nuclear reactions with high-quality post-accelerated RIBs for beam energies varied in a broad range of 5–300 MeV/nucleon	4.2, 4.4, 4.5
4	4.1	Experimental halls of the storage ring CR	Experimental storage ring CR	Experiments using CR as the high-energy storage ring	4.3, 4.4, 4.7, 4.10–4.12
	4.2		System of the electron–RIB collider	electron–RIB scattering experiments in collider	4.1

* For each stage of the construction, the following information is provided: the key part of the works, the equipment put into operation, and the experimental possibilities that become available at this particular stage (also with references to the respective parts of the experimental program).

References

1. National Nuclear Data Center. NNDC database, https://www.nndc.bnl.gov
2. Fortov V E et al. *Phys. Usp.* **55** 582 (2012); *Usp. Fiz. Nauk* **182** 621 (2012)
3. Grigorenko L V et al. *Phys. Usp.* **59** 321 (2016); *Usp. Fiz. Nauk* **186** 337 (2016)
4. Hofstadter R *Rev. Mod. Phys.* **28** 214 (1956)
5. Accardi A et al. *Eur. Phys. J. A* **52** 268 (2016)
6. Oganessian Yu Ts et al. *Z. Phys. A* **341** 217 (1992)
7. Katayama T, Suda T, Tanihata I *Phys. Scripta* **2003** (T104) 129 (2003)
8. Tsukada K et al. *Phys. Rev. Lett.* **118** 262501 (2017)
9. Antonov A N et al. *Nucl. Instrum. Meth. Phys. Res. A* **637** 60 (2011)
10. Ter-Akopian G M et al. *Int. J. Mod. Phys. E* **24** 1550016 (2015)
11. Grieser M et al. *Eur. Phys. J. Spec. Top.* **207** 1 (2012)
12. Grigorenko L, Fomichev A, Ter-Akopian G *Nucl. Phys. News* **24** 22 (2014)
13. JINR. ACCULINNA-2 project, http://aculina.jinr.ru/acc-2.php
14. Levichev E B, Skrinsky A N, Tumaikin G M, Shatunov Yu M *Phys. Usp.* **61** 405 (2018); *Usp. Fiz. Nauk* **188** 461 (2018)
15. Dikanskii N S, Meshkov I N, Parkhomchuk V V, Skrinsky A N *Phys. Usp.* **61** 424 (2018); *Usp. Fiz. Nauk* **188** 481 (2018)
16. Gusarova M A et al. *Phys. Part. Nucl. Lett.* **13** 915 (2016); *Pis'ma Fiz. Elem. Chast. At. Yad.* **13** 1425 (2016)
17. JINR. Nuclotron-based Ion Collider fAvility. NICA, http://nica.jinr.ru/
18. Agapov N N et al. *Phys. Usp.* **59** 383 (2016); *Usp. Fiz. Nauk* **186** 405 (2016)
19. Bazanov A M et al., in *Proc. of the 8th Intern. Particle Accelerator Conf., IPAC17, 14 – 19 May 2017, Copenhagen, Denmark*, paper TUPVA117
20. Plastun A et al., in *Proc. of the 28th Linear Accelerator Conf., LINAC16, 25 – 30 September 2016, East Lansing, MI, USA*, paper TUPLR060
21. Koshelev V et al., in *Proc. of the 28th Linear Accelerator Conf., LINAC16, 25 – 30 September 2016, East Lansing, MI, USA*, paper TUPLR050
22. Aliev K A et al. *Phys. Part. Nucl. Lett.* **13** 911 (2016); *Pis'ma Fiz. Elem. Chast. At. Yad.* **13** 1418 (2016)
23. Wada M *Nucl. Instrum. Meth. Phys. Res. B* **317** 450 (2013)
24. Grigoryev K *Phys. Scripta* **2015** (T166) 014050 (2015)
25. Meshkov I, Sidorin *Nucl. Instrum. Meth. Phys. Res. A* **532** 474 (2004)
26. Meshkov I et al., Preprint RIKEN-AF-AC-34 (2002)
27. Meshkov I et al. *Nucl. Instrum. Meth. Phys. Res. A* **532** 376 (2004)
28. Atanasov D et al. *Phys. Rev. Lett.* **115** 232501 (2015)
29. Zhang Y H et al. *Phys. Scripta* **91** 073002 (2016)
30. Walker P M, Litvinov Yu A, Geissel H *Int. J. Mass Spectrometry* **349 – 350** 247 (2013)
31. Pfützner M, Karny M, Grigorenko L V, Riisager K *Rev. Mod. Phys.* **84** 567 (2012)
32. Litvinov Yu A, Bosch F *Rep. Prog. Phys.* **74** 016301 (2011)
33. Angeli I, Marinova K P *Atom. Data Nucl. Data Tables* **99** 69 (2013)
34. Erler J et al. *Nature* **486** 509 (2012)
35. Moeini H et al. *Nucl. Instrum. Meth. Phys. Res. A* **634** 77 (2011)
36. Kiselev O A (EXL Collab.) *Phys. Scripta* **2015** (T166) 014004 (2015)
37. Yukhimchuk A A et al. *Nucl. Instrum. Meth. Phys. Res. A* **513** 439 (2003)
38. Mei B et al. *Phys. Rev. C* **92** 035803 (2015)
39. Lestinsky M et al. *Eur. Phys. J. Spec. Top.* **225** 797 (2016)
40. Aksenov V L, Commun. JINR E3-2017-12 (Dubna: JINR, 2017)
41. Aksenov V L et al., Preprint JINR P3-2016-90 (Dubna: JINR, 2016)
42. Reifarth R K et al. *Phys. Rev. Accel. Beams* **20** 044701 (2017)
43. Reifarth R, Litvinov Yu A *Phys. Rev. ST Accel. Beams* **17** 014701 (2014)
44. Steer S J *Int. J. Mod. Phys. E* **18** 1002 (2009)
45. Kurcewicz J et al. *Phys. Lett. B* **717** 371 (2012)
46. Dasso C H, Pollarolo G, Winther A *Phys. Rev. Lett.* **73** 1907 (1994)
47. Corradi L, Pollarolo G, Szilner S *J. Phys. G* **36** 113101 (2009)
48. Zagrebaev V, Greiner W *J. Phys. G* **34** 1 (2007)
49. Zagrebaev V, Greiner W *J. Phys. G* **35** 125103 (2007)
50. Karpov A V, Saiko V V *Phys. Rev. C* **96** 024618 (2017)
51. Bjørnholm S, Lynn J E *Rev. Mod. Phys.* **52** 725 (1980)
52. Oganessian Yu Ts, Utyonkov V K *Rep. Prog. Phys.* **78** 036301 (2015)
53. Evdokimov A et al. *Proc. Science NIC* **12** 115 (2012)
54. Barabanov A L, Titov O A *Eur. Phys. J. A* **51** 96 (2015)
55. Barabanov A L, Titov O A *Phys. Atom. Nucl.* **80** 1181 (2017); *Yad. Fiz.* **80** 702 (2017)
56. Bednyakov V A, Naumov D V, Smirnov O Yu *Phys. Usp.* **59** 225 (2016); *Usp. Fiz. Nauk* **186** 233 (2016)
57. Zucchelli P *Phys. Lett. B* **532** 166 (2002)
58. Wildner E et al. *Phys. Rev. ST Accel. Beams* **17** 071002 (2014)
59. Edgecock T R et al. *Phys. Rev. ST Accel. Beams* **16** 021002 (2013)
60. Zhao H W et al. *Rev. Sci. Instrum.* **89** 052301 (2018)
61. Meshkov I *Nucl. Instrum. Meth. Phys. Res.* **917** 56 (2019)
62. Meshkov I N *Phys. Part. Nucl. Lett.* **15** 506 (2018); *Pis'ma Fiz. Elem. Chast. At. Yad.* **15** 391 (2018)