CURRENT AND FUTURE EXOTIC NUCLEI RESEARCH AT ACCULINNA/ACCULINNA-2 FACILITIES

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1.1. *Introduction*

ACCULINNA is in-flight fragment separator based on U-400M cyclotron at Flerov Laboratory of Nuclear Reactions (FLNR, JINR, Dubna, Russia). In the recent years there was a successful line of research at FLNR dealing with light dripline systems. Novel results were obtained for such isotopes as ^{5}H [1-4], ^{7}H [5], ^{6}He [6], ^{8}He [7], ^{9}He [8], ^{10}He [7,9], ^{6}Be [10], and ^{26}S [11]. These studies focus on continuum properties (including continuum properties of three-body systems), studies of specific correlations, and practicalities of connection between theory and experiment. They allowed important insights connected to spectroscopy, structure and decay dynamics of exotic nuclei.

The important part of scientific plans for FLNR for the nearest 5-7 years includes development of DRIBS-3 initiative (Dubna Radioactive Ion BeamS). In the framework of this initiative the ACCULINNA facility is currently being replaced with much more powerful ACCULINNA-2 fragment separator (commissioning is planned for 2015). The main scientific objective of the ACCULINNA-2 facility is to strengthen the most successful research line of ACCULINNA which is direct reaction studies with light exotic secondary beams in the energy range 20-40 A MeV. With ACCULINNA-2 coming to operation the ACCULINNA should be gradually converted to applied activities (biology and material research).

1.2. *ACCULINNA fragment separator and collaboration*

The schematic view of the U-400M cyclotron hall including ACCULINNA facility is given in Figure 1. This is a single achromatic stage fragment separator accomplished with 8 m long ToF transport line for particle-by-particle identification. Possessing very moderate characteristics as spectrometer ACCULINNA enjoys record-high primary beam intensities form the U-400M cyclotron and make possible certain range of the pioneering research.

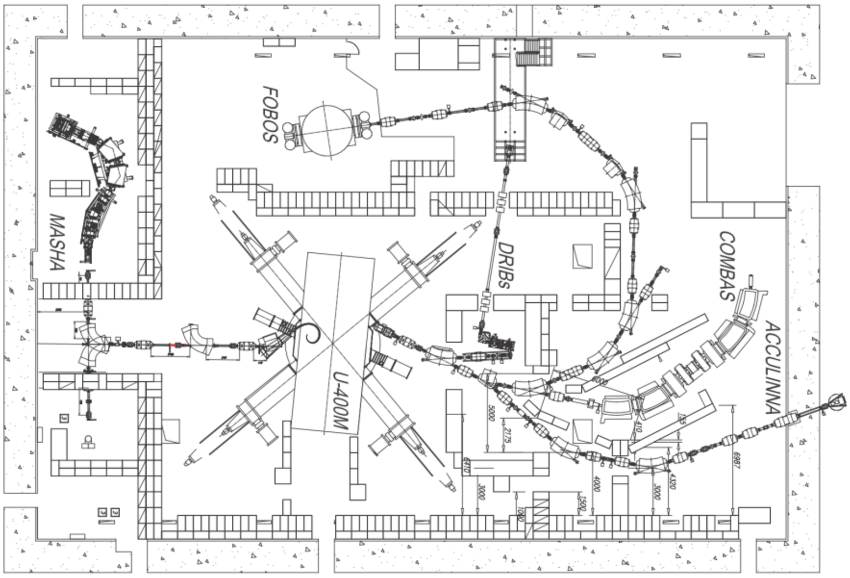

Fig.0. Schematic view of the U-400M cyclotron hall with existing experimental facilities.

The ACCULINNA group includes 15 staff members and 7 young associate researches. There are experimentalists from the Kurchatov institute and GSI participating in our research program on a more or less constant basis. The experimental group of Warsaw University has and an active program of rare decay mode studies based on their “flagship” development of the Optical Time Projecting Chamber [12]. There is a long-term collaboration with Vanderbilt University (Nashville, USA) connected with extensive research program for spontaneous fission of ^{252}Cf. Scientists from ACCULINNA group actively participate in experiments at other facilities, such as GSI (Germany), GANIL

(France), Legnaro (Italy), iTEMBA (South Africa). The ACCULINNA group is involved in the range of R&D activities connected to NUSTAR part of the FAIR facility at Germany. These activities are supported via German contribution to JINR, German BMBF grants, and by FAIR-Russia Research Center, established several years ago to facilitate participation of Russian scientists in FAIR-connected projects.

The ACCULINA group has sizable theoretical "subsystem" providing mainly the reaction theory research and studies of exotic decay modes. There is a long-term theoretical collaboration including scientists from BLTP (JINR), Chalmers Technical University (Geteborg, Sweden) and Moscow State University.

1.3. *Dripline research at ACCULINNA. Novel experimental approaches for low-energy direct reactions.*

Near and beyond the driplines we often face quite specific forms of nuclear dynamics, such as standard shell structure breakdown, appearance of new shells and new magic numbers, nucleon haloes and skins, true few-body decays (with two-proton radioactivity as one of the forms), and soft excitation modes. Nowadays, the nuclear driplines are achieved up to $Z \sim 30$ for proton and up to $N \sim 30$ for neutron rich sides of the nuclear chart. It is natural also to extend our knowledge to the systems beyond the driplines, which are so far typically poorly studied. We are going to illustrate the scientific opportunities provided by ACCULINA just by one important example of research in this field.

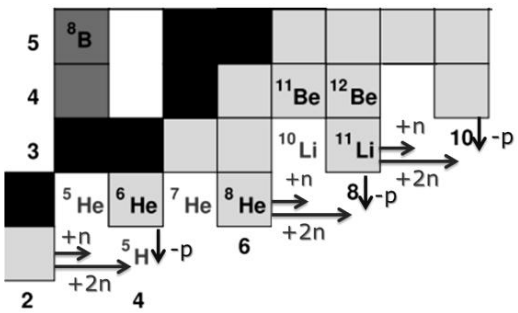

Fig.2. Schematic illustration of difference in experimental approaches populating exotic systems beyond the driplines in (mainly high-energy) knockout reactions (blue vertical arrows) and in relatively low-energy transfer reactions (red horizontal arrows).

The majority of the modern experimental studies of the systems beyond the driplines are provided by “high-energy” radioactive ion beam facilities. Here population of such systems is taking place via knock-out reactions from the secondary beam nuclides residing straight next to the dripline. For relatively low-energy secondary beams available at ACCULINNA the direct transfer reactions provide a natural alternative way for population of extremely neutron/proton-rich particle-unstable systems. The difference between these two approaches is schematically illustrated in Figure 2.

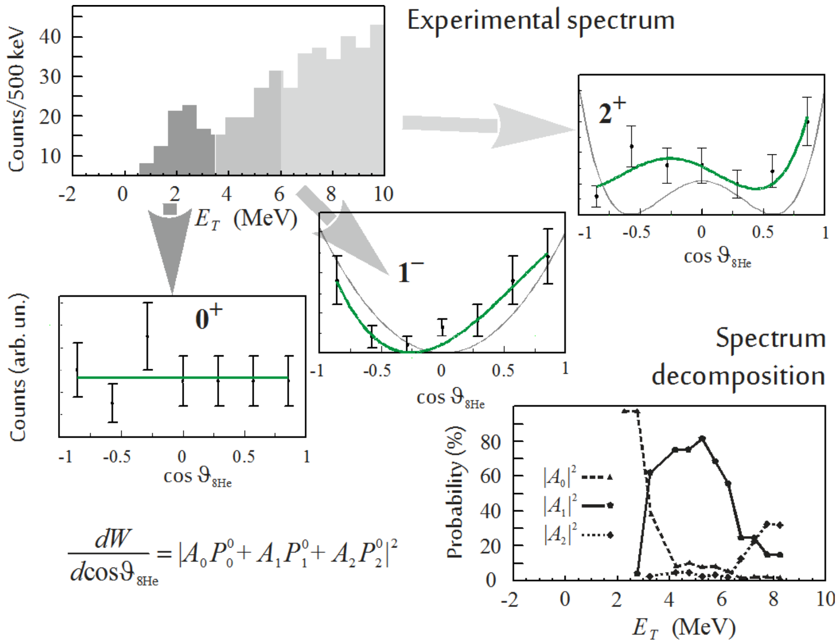

Fig.3. Spectrum and correlations in ^{10}He. Qualitative illustration for usage of correlation information in analysis of data from population of the systems beyond the driplines.

The additional opportunities opened by the transfer reactions are illustrated in Fig.3 by example of ^{10}He studied in the two-neutron transfer reaction on ^{8}He [9]. These opportunities are connected with possibility of specific correlations in the direct reactions. In the case of the direct reaction mechanism the only selected direction for the reaction products is the direction of momentum transfer. In the frame bound to the momentum transfer vector the transferred angular momentum should always have only zero-th projection on the Z axis

$M_z = 0$. In the case of good luck this strong transferred angular momentum alignment may lead to expressed correlation patterns for various decay products. In certain conditions such correlation patterns may have unambiguous (or at least not very uncertain) explanation (see, e.g., Ref. [4] for details). The ^{10}He invariant mass spectrum shown in Fig. 3 has an expressed ground state peak at about 2.1 MeV. The higher-energy spectrum is quite featureless represented presumably by superposition of broad overlapping continuum states. However, the correlation studies allow us to make some more detailed conclusions about the nature of this continuum. The most interesting information is provided by ^{8}He angular distribution in the reference system connected with momentum transfer vector. Under certain assumptions connected with the mechanism of the 2n transfer [9] such angular distributions can be represented as coherent sum of ordinary Legendre polynomials. Energy evolution of coefficients of this decomposition indicates presence of 1^- state at about 4-6 MeV and 2^+ state at about 6-8 MeV and above. Such level ordering is anomalous and indicates the breakdown of the expected shell structure. On one hand this continues the trend of the shell structure breakdown in $N = 8$ isotone already known for ^{12}Be nucleus. On the other hand this is an important finding considering the fact that ^{10}He nucleus is double-magic one.

The correlation studies of this kind were for the first time used in the investigation of ^{5}H system [4] and later successfully applied in the studies of ^{9}He [8], ^{8}He [7], and ^{6}Be [10]. These studies require high quality (good energy-angular resolution) data with relatively high statistics and development of advanced theoretical tools for data treatment. Our research promote correlation studies as one of most important prospective tools for studies of particle unstable systems beyond the driplines and continuum excitations for systems close to the driplines.

1.4. *Scientific motivation for ACCULINNA-2*

Successful light exotic nuclei research program at ACCULINNA inspired the design of a more powerful facility ACCULINNA-2. The new facility was to fit very tight budget, fit existing experimental hall and more fully utilize opportunities provided by U-400M cyclotron. The new project should enhance the positive features of ongoing research program, but provide also important new opportunities allowing maintain at FLNR world-class research of light exotic systems at least within the next decade.

It is expected that a complete range of “conventional” nuclear physics research with radioactive secondary beams will be accessible at the new facility, like elastic/inelastic scattering, resonant elastic scattering, studies of radioactive decays and nuclear spectroscopy . However, the scientific focus of the prospective facility is the direct reactions in the energy range 20-40 A MeV providing high-precision (including correlation) data for nuclear structure and nuclear astrophysics. These include direct transfer reactions and other “well controlled” types of reactions, such as charge-exchange and quasi-free scattering reactions.

The mentioned above controversial requirements defined the compromises of ACCULINA design. The fragment separator retained the single achromatic stage design of ACCULINNA because of the low energy of the available primary beams. To provide opportunities of the better secondary beam purification which are especially important for formation of the proton-rich secondary beams, the opportunity of the velocity filter (“RF-kicker”) was considered after F3 focal plane. A 14 meter long transport line for secondary beams suggests much better energy and angular resolution for the secondary beam particles.

The ideas beyond the ACCULINA-2 design and quantitative information about expected characteristics are summarized in the Letter of Intent [12]. The ideas about prospective research program and some views of possible “first day” experiments can be found in the report [13]. The progress of construction works is reported in Ref. [14].

1.5. *On the way to ACCULINNA-2*

The contract for the ACCULINNA-2 construction was signed in the autumn 2011 with French ion-optics solution provider SigmaPhi. Because of the budgetary and workforce requirements the construction of ACCULINNA-2 will proceed in three stages. The first stage to be completed in the end of 2014 includes infrastructure works in the U-400M hall, construction and commissioning of the “bare” fragment separator. Since that moment operation of the facility starts. It is expected that much more intense secondary beams and much more favorable experimental conditions than at ACCULINNA are achieved, especially on the neutron-rich side of the nuclear chart.

On the second stage the cyclotron upgrade should make possible broader range of primary beams (up to krypton) and broader energy range for them.

ACCULINNA-2 facility itself should be augmented with various instruments boosting the performance and broadening the experimental opportunities. The two major instruments to be mentioned are: (i) velocity filter (“RF kicker” positioned next downstream the F3 focal plane) for more efficient operation on the proton-rich side of the nuclear chart and (ii) the target-area zero angle spectrometer to simplify work with beam-like reaction products. We are working now on the design of these devices and timely fund allocation.

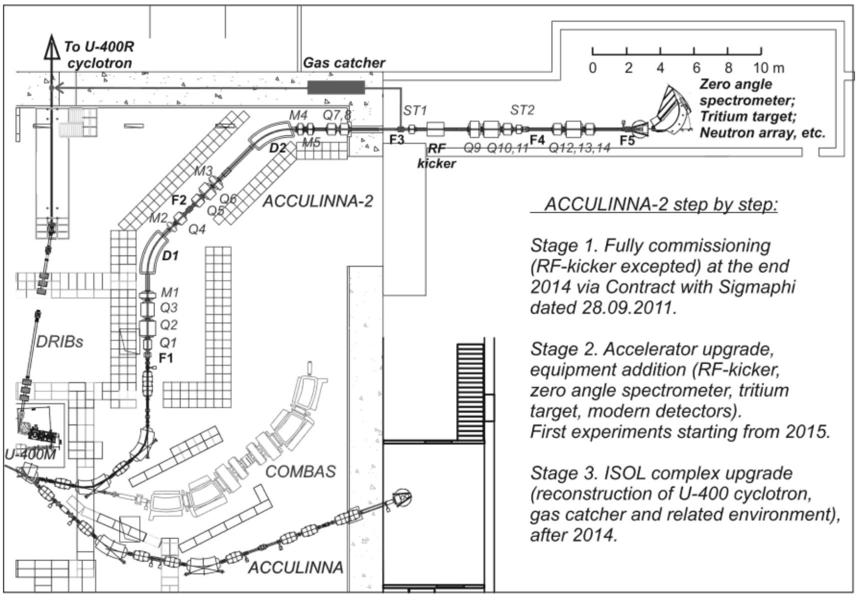

Fig. 4. Layout of the fragment separator ACCULINNA-2 in the U-400M cyclotron hall.

On the third stage it is planned that ISOL-type part of DRIBS-III is developed. It is expected to consist with of ACCULINNA-2 as “preseparator”, gas catcher cell with supersonic gas stream extraction system at focal plane F3, and transport line to U-400 cyclotron providing reacceleration of the secondary beam up to 5-10 A MeV.

1.6. *Welcome*

It is expected that ACCULINNA-2 will become truly international user-friendly facility opened “external” scientists under common well-defined procedure. We welcome all ideas and contributions concerning possible “first day" experiments and prospective scientific program of this new facility which is coming to operation quite soon.

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