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Abstract. Project of a new in-flight fragment separator is proposed as a part of the third generation DRIBs facilities in Dubna. As compared to the existing separator ACCULINNA, beam intensity should be increased by a factor 10-15, the beam quality improved and the RIB assortment should broaden considerably at ACCULINNA-2. Research program and structure are outlined for the new instrument.

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INTRODUCTION

RIB research conducted at the ISOL type coupled cyclotron facility DRIBs [1] and fragment separator ACCULINNA [2] is being developed actively in the Flerov Laboratory of Nuclear Reactions (FLNR, JINR). Experiments performed at DRIBs on the ${}^6\text{He}+{}^{206}\text{Pb}$ reaction revealed [3] a large enhancement of the sub-barrier fusion cross section which could be explained as due to a sequential fusion mechanism [4]. Considerably increased cross sections were measured for transfer reactions induced by the ${}^6\text{He}$ and ${}^6\text{Li}$ beams in the vicinity of Coulomb barrier. This stimulates the extension of this study to other nuclei with cluster structures (${}^8\text{He}$, ${}^{7,9,11}\text{Li}$, ${}^{7,9-14}\text{Be}$, etc). The study of interplay between the fusion-evaporation and incomplete fusion reactions induced by 10 A·MeV beam provided essential information on the mechanisms of the breakup and incomplete fusion processes and the wave function of

the loosely bound ${}^6\text{He}$ projectile nucleus [5]. Using secondary 20-30 A·MeV RIBs provided by ACCULINNA (see in Ref. [1]) (1) the di-neutron and t+t configurations of the neutron-halo nucleus ${}^6\text{He}$ were experimentally established; (2) the ${}^4\text{H}$ nuclear system was studied in the ${}^3\text{H}({}^2\text{H},p){}^4\text{H}$ and ${}^3\text{H}({}^3\text{H},d){}^4\text{H}$ reactions and the ${}^4\text{H}$ resonance parameters were ascertained being consistent with those obtained using the charge-symmetric reflection of the ${}^4\text{Li}$ R-matrix parameters; (3) the ${}^5\text{H}$ spectrum was reliably established; (4) new experimental methods for the analysis of the three-body decays of spin-aligned states were developed and applied; (5) the knowledge about the ${}^8\text{He}$, ${}^9\text{He}$ and ${}^{10}\text{He}$ states was revised radically while, before the ACCULINNA works, the low-lying spectra of these nuclei have been considered as reliably established for more than a decade.

The DRIBs-3 project planned for 2010–2016 in FLNR relies on factors inherent to the existing accelerators and projected upgrades. These are: (1) record intensities of the primary cyclotron beams; (2) relatively low primary beam energies of the U-400M cyclotron making for precision studies of nuclear structures with 20 – 50 A·MeV RIBs; (3) the 20 – 50 A·MeV RIBs of a fragment separator coupled with the U-400M cyclotron meet conditions for the creation of a U-400M – U400R ISOL facility. Important for the successful accomplishment of the Dubna RIB research programme for neutron-excess nuclei is the availability of unique cryogenic tritium targets. The present project suggests the creation of a next generation fragment separator to be installed on a primary beam line of the upgraded cyclotron U-400M.

SCIENTIFIC PROGRAMME

RIB research is an important direction in modern nuclear physics. The knowledge of drip-line nuclei is necessary for the further development of nuclear theory and indispensable for nuclear astrophysics. Here, the nuclear structure and reaction mechanisms are intertwined more than ever before. The following major problems relevant to this field make the programme of the ACCULINNA-2 project.

- Nucleon haloes, neutron skins, Efimov states, etc. Making use of the (d,p), (t,p), (p, ${}^3\text{He}$), (p,2p), (α ,2 α), (t, ${}^3\text{He}$), (p,2p) and (α ,2 α) reactions occurring with 10–50 A MeV beams of ${}^8\text{He}$, ${}^{11}\text{Li}$, ${}^{14}\text{Be}$, ${}^{17}\text{B}$, ${}^{16}\text{C}$ will present exclusive conditions for getting the spectra of such nuclear objects as ${}^{10-12}\text{He}$, ${}^{11-13}\text{Li}$, ${}^{13-16}\text{Be}$, ${}^{13-19}\text{B}$, ${}^{25-28}\text{O}$ and for the study of extremely neutron-excess structures as hexaneutron and the barely known ${}^{6,7}\text{H}$, ${}^{11,12}\text{He}$, ${}^{12,13}\text{Li}$, ${}^{15,16}\text{Be}$, etc.
- Soft excitation modes (e.g., the soft mode of the giant dipole resonance). Transfer reactions studied at beam energies of 20 – 30 A·MeV grant excellent conditions for such research.
- New magic numbers and intruder states. Such basic problems as (1) the disappearance of the closed neutron shell N=8 and s-d intruder states in ${}^{9,10}\text{He}$, ${}^{10,11}\text{Li}$, ${}^{11,12}\text{Be}$, (2) the issue of the filling sequences of the s-d neutron shell in neutron-excess nuclei (${}^{15}\text{Be}$, ${}^{16,18}\text{B}$, ${}^{17,19}\text{C}$) and the interplay of s- and d-wave states in their even-N neighbours, (3) the two-proton halo predicted by theory for ${}^{17}\text{Ne}$, (4) the termination of filling the s-d shell at ${}^{24}\text{O}$, will receive favourable conditions to be studied at ACCULINNA-2.

- Two-proton radioactivity (few-body decays in more general terms). With the advent of this project a series of nuclei with $Z \leq 30$, lying close and beyond the proton drip-line, becomes a subject for such study. The 2p-radioactivity and the 2p decay of resonant states give rise to profound interest in the dynamics of this decay mode.
- Cluster states. Close to the thresholds, clusterization becomes increasingly important and new forms of nuclear dynamics arise. Objects for such studies are the heavy isotopes of B, C, O, Ne, the states in ${}^6\text{He}$ with a (t+t)-structure and the possible ${}^5\text{H}$ - ${}^3\text{H}$ clusterization in ${}^8\text{He}$.

The proposed project will favour nuclear astrophysics research which is an integral part of nuclear dynamics study. Data of interest are: (1) masses and level schemes close to the neutron, proton, and α breakup thresholds; (2) EC and $\beta^\pm$ -decay lifetimes; (3) partial p, n, α , γ widths of resonance states; (4) E1 and E2 strength functions. The cross sections of interest must be studied by resonance reactions in inverse kinematics on hydrogen and helium and by transfer reactions in order to determine the level schemes and spectroscopic properties of nuclear states. This includes peripheral transfer reactions to measure the Asymptotic Normalization Coefficients determining the stellar capture rates.

Excitation energy spectra of exotic RIBs become accessible with the use of the inelastic scattering reactions (p, p') and (α , α') directly related to the (p, γ) and (α , γ) reactions in stellar objects. The (α , α') reaction is an effective tool for the study of α -cluster states which are relevant to the very popular nowadays study of the Bose-Einstein condensation in nuclear systems. The investigation of the high-lying isobaric analogue states in ${}^9\text{Li}$ by the ${}^8\text{He}+\text{p}$ resonance scattering, recently carried out ACCULINNA, showed that this is an efficient way to infer knowledge on the properties of the lowest states in the neighbouring neutron-rich systems.

For drip-line nuclei, there is a list of low-energy (≤ 50 A·MeV) studies of Coulomb dissociation reactions directly related to the rates of the astrophysical non-resonant radiation. Moreover, the interplay between the Coulomb dissociation and transfer reactions, populating continuum states, could be regarded as a case of a broader class processes capable to elucidate the continuum excitation properties. The breakups on light targets, characterized by the strong Coulomb-nuclear interference and diffractive dissociation and having, perhaps, different selectivity, are an alternative to the Coulomb dissociation.

The higher intensity and quality of the ${}^6\text{He}$, ${}^8\text{He}$, ${}^9\text{Li}$, ${}^{12}\text{Be}$, etc., beams provided by the proposed DRIBs-3 project will greatly enhance the possibilities of studying low-energy fusion and multi-nucleon-transfer reactions. Beams of the heavy Li, Be, B, C isotopes on the neutron-rich side, and ${}^7\text{Be}$, ${}^8\text{B}$, etc., on the proton-rich side are suitable for measuring the probability of transfer of the clusters, found in these exotic nuclei.

PROPOSED ACCULINNA-2 SEPARATOR

ACCULINNA-2 (see Ref [6] and Table 1) is intended to provide high-intensity RIBs in the lowest energy range attainable for the in-flight separators thus complementing the world-wide facilities. The prime objectives are to provide good

energy resolution and high efficiency for correlation measurements of reaction products. The latter could provide spin-parity identification. The proposed development suggests the creation of a universal instrument giving a variety of clean and well-prepared secondary beams. The fragment separator, together with the beam diagnostics system, is intended to be a standard instrumentation for the laboratory. The exotic beam should be delivered into the low-background experimental area with particle-by-particle identification and energy/trajectory diagnostics.

The layout of ACCULINNA-2 is shown in Fig. 1. A beam of radioactive nuclei leaving the production target is captured by a short focusing quadrupole triplet Q1–Q3 and transported through the magnetic dipoles D1–D2 and quadrupole doublets Q4 – Q14 to the final focal plane F5. The F2 non-zero momentum dispersion plane is intended for the installation of a wedge-shaped energy degrader. In the achromatic focal plane F3 separation of the secondary beams with mass A and charge Z is taking place according to the ratio $A^{5/2}/Z^{3/2}$. This ratio arises from the cumulative effect of the A/Z separation in the F2 plane after passing the D1 dipole and the charge/mass dependence of the energy losses in the wedge. For the neutron-rich nuclei this is typically enough for preparing quite pure RIBs. The most important second- and third-order aberrations in the F2 and F3 focal planes are corrected by the magnetic multipoles M1 – M5 having appropriate sextupole and octupole components. As a result, the main second-order aberrations become small in the F2 and F3 planes.

To cope with contaminations inherent especially to the proton-rich RIBs a vertically deflecting radio-frequency (RF) kicker will be installed in-between F3 and Q9. Two steering magnets ST1 and ST2 compensate the shift of the beam of interest at the slit position F4 when the desired beam passes the RF-kicker on crest of the RF-wave. The most of the contaminant ion beams fall out of the F4 slit.

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

	ACC FLNR	ACC-2 JINR	LISE GANIL	A1900 MSU	RIPS RIKEN	BigRIPS RIKEN	FRS	SuperFRS GSI
$\Delta\Omega$, msr	0.9	5.8	1.0	8.0	5.0	8.0	0.32	5.0
p , %	2.5	6.0	5.0	5.5	6.0	6.0	2.0	5.0
$P/\Delta P$, a.u.	1000	2000	2200	2915	1500	3300	8600	3050
$B\rho_{\max}$, Tm	3.2	3.9	4.3	6.0	5.76	9.0	18	18
Length, m	21	38	42	35	21	77	74	140
$E_{\min}$, A·MeV	10	5	40	110	50		220	
$E_{\max}$, A·MeV	40	50	80	160	90	350	1000	1500

Comparison of the proposed ACCULINNA-2 separator with the other fragment separators, existing or projected, is made in Table. 1. Table 2 shows the parameters of some RIBs, which can be obtained at ACCULINNA-2.

The ISOL complex DRIBs will be upgraded as a result of the reconstruction of its second-stage, the U400 cyclotron, and an increased choice of RIBs will be delivered by this complex for experiments. The U400 upgrade into U400R, scheduled for 2010-11, will result in a considerable improvement of the beam quality and will give the new option of the RIB energy variation in a range of 5 – 20 A·MeV. The list of RIBs

accelerated at DRIBs will include new species due to the new options offered by the extraction and shaping of the RIBs, obtained from the gas catcher installed at ACCULINNA-2 (see caption to Fig. 1). Some RIB species which will be delivered by the DRIBs complex are shown in Table 3.

FIGURE 1. Schematic layout of the existing ACCULINNA and projected ACCULINNA-2 fragment separators in the U-400M cyclotron hall. Near the achromatic F3 focal plane is shown the gas catcher installed to produce the low-energy (10-50 keV), high quality RIBs intended for the further injection in an ion trap or in the DRIBs beam line to be transported for injection in the U400 cyclotron for the further acceleration to 5 – 20 A·MeV. The MSP-114 magnetic spectrometer could be useful for spectroscopy of reaction products emitted from the target in the forward direction in a range of 0°–15°.

TABLE 2: RIB yields from a ^9Be production target with thickness, optimized for the specific cases. “Purity” is the part of the RIB of interest in the total secondary beam current as obtained in focal plane F3. After the passage through the RF kicker, in plane F5, the parts of all the desired beams in the total RIB current will make $\geq 60\%$ and at the same time their intensities will be reduced by a factor of three.

Primary beam	Maximum intensity, pμA	Energy, A·MeV	Secondary beam	Energy, A·MeV	Intensity, pps/pμA	Purity (%)
^7Li	5	34	^6He	21.7	4.1×10^7	> 99
			^6He	12.7	1.1×10^7	> 99
^{11}B	5	33	^8He	21.9	8.6×10^4	> 99
			^8He	15.6	3.7×10^4	> 99
^{18}O	3	48	^{11}Li	31.3	7.4×10^3	81
			^{14}Be	34.6	1.6×10^3	> 99
^{20}Ne	5	54	^{13}O	24.2	1.5×10^6	10
			^{17}Ne	29.0	5.4×10^6	69
^{36}S	3	49	^{11}Li	30.4	1.3×10^4	80
			^{24}O	23.4	2.5×10^3	62
			^{15}B	27.0	5.5×10^4	47
			^{18}C	25.5	1.9×10^4	11
^{48}Ca	1	42	^{36}Mg	28.1	1.2×10^2	2.4
			^{15}B	25.9	1.7×10^4	18
			^{17}B	26.2	3.4×10^2	19
			^{17}C	25.1	3.6×10^4	14
^{32}S	3	52	^{24}Si	11.3	7.2×10^3	31
			^{27}S	21.7	3.7×10^2	1

TABLE 3: RIBs accessible from the upgraded DRIBs complex. Beam energies will be smoothly variable in a range of $5 \div 20$ A·MeV.

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

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