FROM ALADiN-LAND TO R^3B AT GSI AND FAIR*

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This paper is directly based on the talk given at the conference and describes the evolution of our setup and experiments, being initiated and used at GSI, towards a dedicated experiment for various research studies with secondary beams at relativistic velocities for FAIR. Intermediate steps in the commissioning of the novel devices, together with the addressed physics questions, in the frame of Phase-0 beam times, are presented. Dedicated prototype studies at the SAMURAI setup in RIKEN are also presented. The general time-line for the Super-FRS facility at FAIR with intense SIS-18 and SIS-100 beams is discussed and prospects for associated physics studies are shown.

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1. Evolution and development of the R^3B setup

The R^3B setup is evolving from the (FRS-)ALADiN-LAND(-XBALL) setup at GSI since the 1990s in a continuous effort by the associated collaborations. Figure 1 shows the setup, being used by Panin *et al.* for pioneering work on exploring opportunities with $(p, 2p)$ reactions in inverse kinematics. The setup provides a very effective instrument for handling all kinds of reaction studies at relativistic energies. As relativistic focusing appears, the detectors in forward direction cover almost 4π solid angle for the peripheral reactions that are studied in several different classes of experiments, ranging from fission studies — where both charged fragments can be detected — halo physics, reaction studies, equation of state investigations based on interaction cross section and Coulomb excitation measurements, to short-range correlation studies.

An international R3B Collaboration comprising about 250 people from various countries has formed around the versatile setup and is aiming at improvements that will be implemented at the high-energy branch of the Super-FRS at FAIR. The configuration at FAIR is shown in Fig. 2 where

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all major components in the initial setup are shown. For that, several update steps have been already undertaken and devices could be tested in experimental campaigns, first at the RIKEN facility, at present, within the so-called FAIR Phase-0 experiments at the high-energy cave (HTC) at the FRS.

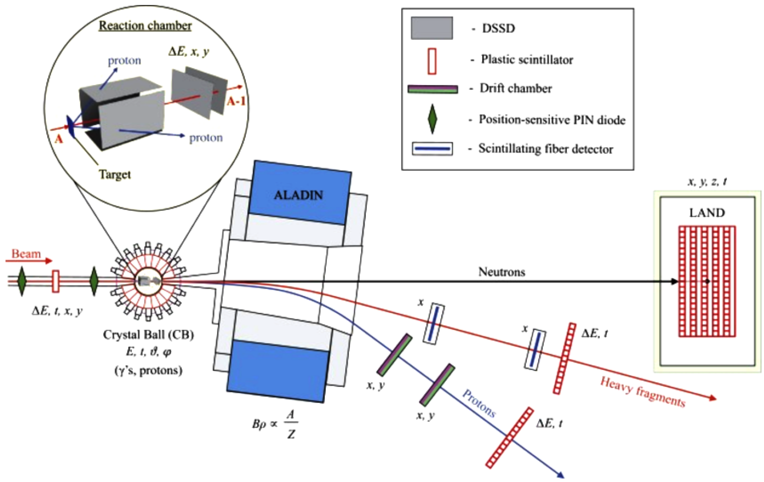

Fig. 1. ALADiN-LAND experiment ([1] and references therein) equipped with a box-type silicon DSSD-based target tracker, and still based on the ALADiN magnet, the X-Ball target calorimeter and the LAND neutron detector.

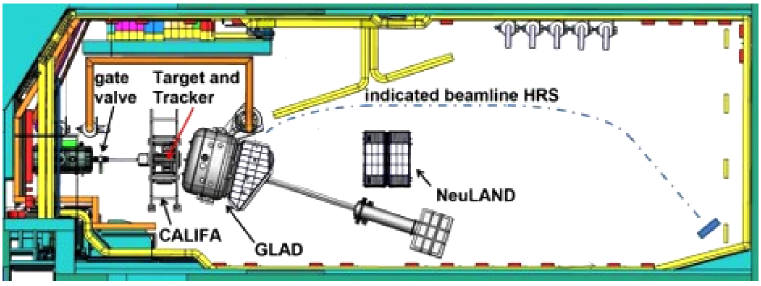

Fig. 2. R^3B at the high-energy cave (HEC) at FAIR. Major components are the superconducting spectrograph magnet (GLAD), a target section with a novel silicon tracker (L3T), and the CALIFA calorimeter together with an advanced particle tracking system and the NeuLAND neutron detector.

One of the major components is the superconducting GLAD magnet that improves the magnetic bending power from $B\ell = 2$ Tm to $B\ell = 4.8$ Tm. The higher rigidity allows to bend energetic neutron-rich beams and their fragments with high acceptance to angles that are even for large beam energies of 1–2 A GeV preventing to create a background in the novel neutron time-of-flight neutron spectrometer NeuLAND [2], that is covering an 80 mrad neutron cone downstream of the target.

Experiments at the reaction setup were initially conveniently carried out with solid-state targets. The experimental need to replace complex absorptive target nuclei with protons as an elementary probe in inverse kinematics was met with the use of plastic targets and later on with a liquid-hydrogen target. In order to study momentum transfer to the proton in reactions of halo nuclei, a first try has been performed as shown in Fig. 3 where — though the detection had proven to be successful for a very limited solid angle coverage — it became apparent that only a dedicated and optimized setup would later allow improving recoil proton detection considerably for the future.

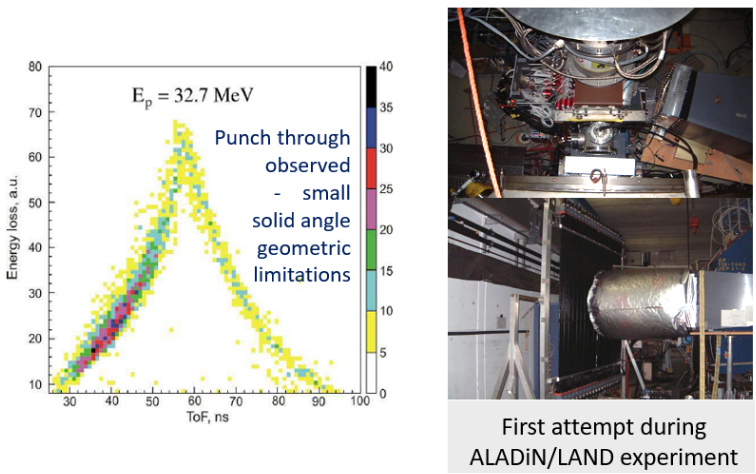

Fig. 3. The need for a dedicated recoil proton experiment was already shown in the year 2001 during an experiment using a liquid-hydrogen target replacing the previously used carbon target for inducing nuclear breakup reactions on halo nuclei (S135 proposal). At the time, the target recoil detection system consisted of a Multi Wire Drift Chamber watching a 5 cm long liquid-hydrogen target cell in vacuum, a helium bag, and parts of a scintillator-based proton time-of-flight detector (see photographs on the right). For details, see the text.

Meanwhile, first results on (p, pn) and $(p, p\alpha)$ reactions on ^{6}He could be obtained as shown in Fig. 4 by using the active hydrogen target IKAR. Clear kinematical correlations could be observed in the recoiled proton detection as well as the quasi-free scattering process could be established.

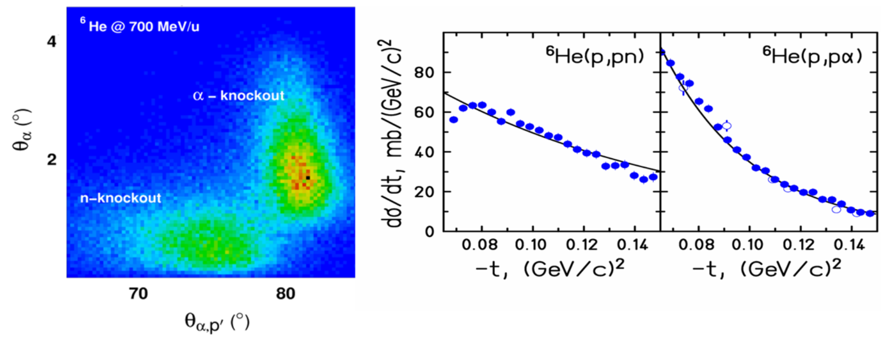

Fig. 4. Kinematical correlations (left panel) and differential cross sections depending on the relativistic momentum transfer ($-t$, right panel) observed [3] in ^{6}He elastic scattering at relativistic beam energy. The scattering of the bound α in ^{6}He on a proton (right plot, right panel, closed symbols) is compared to a previously measured free α scattering experiment and exhibits strong similarities.

The next step shown in Fig. 5 was to come up with a dedicated recoil detection setup based on silicon double-sided strip-detectors (DSSDs) in a box geometry around the target in the forward direction. Panin *et al.* [1] could show that the method in inverse kinematics works for the well-known test case ^{12}C in inverse as well as in direct kinematics.

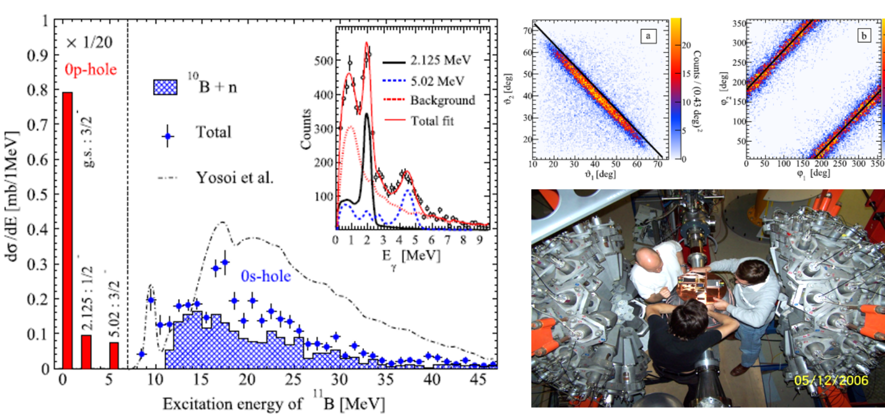

Fig. 5. First experiment establishing the $(p, 2p)$ mechanism in inverse kinematics at relativistic beam energies [1] on ^{12}C. The reconstructed excitation spectrum in ^{11}B by calorimetry and continuum spectroscopy is shown in the left panel. The clean kinematical correlations for both measured protons confirming the $(p, 2p)$ mechanism are visible in the right panel together with a photograph showing the insertion of the Si box tracker in front of a CH_2 target mounted inside the X-Ball calorimeter.

A successful later application of the method is shown in Fig. 6 where a study on $(p, 2p)$ quasi-free scattering on the potential two-proton halo nucleus ^{17}Ne has been performed. In the relative energy spectra, the halo proton removal contribution could be clearly singled out, and by studying the momentum distributions, the $2s^2$-wave contribution to the halo could be evaluated to be as low as 35%, so that the formation of the expected halo is seemingly suppressed.

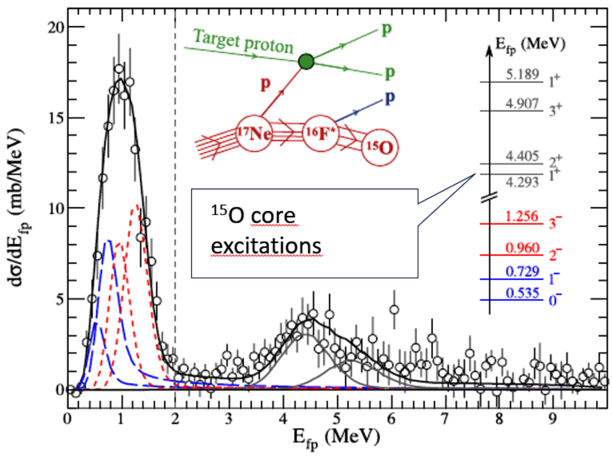

Fig. 6. Recent application [4] of the $(p, 2p)$ reaction mechanism in the investigation of the $2p$-halo character of proton-rich ^{17}Ne. The deduced rather small $2s^2$-contribution in the ground-state wave function for the protons indicates suppression of the halo.

Another development path was carried out with respect to the neutron detection capabilities of the original setup. The basic limitation of the original LAND detector is the limitation to detect and separate more than two showers from neutrons impinging on the detector material of scintillator with interspersed iron converter slabs. After optimization of geometry, granularity, and by going to a fully active detector with 3 m depth comprising 5×5 cm^2 detector bar, a prototype assembly shown in Fig. 7 could be used to ascertain the performance of the full detector. The experiments were carried out in the years 2014–17 at the SAMURAI reaction experiment at RIKEN, where the prototype detectors were successfully used to significantly improve the performance of the already existing neutron detection system. The very interesting quest for the four-neutron nuclear system could be addressed [5] in the same setup in a missing mass analysis without neutron coincidences, due to limitations in obtainable statistics, improving on previous results [6] also from RIKEN.

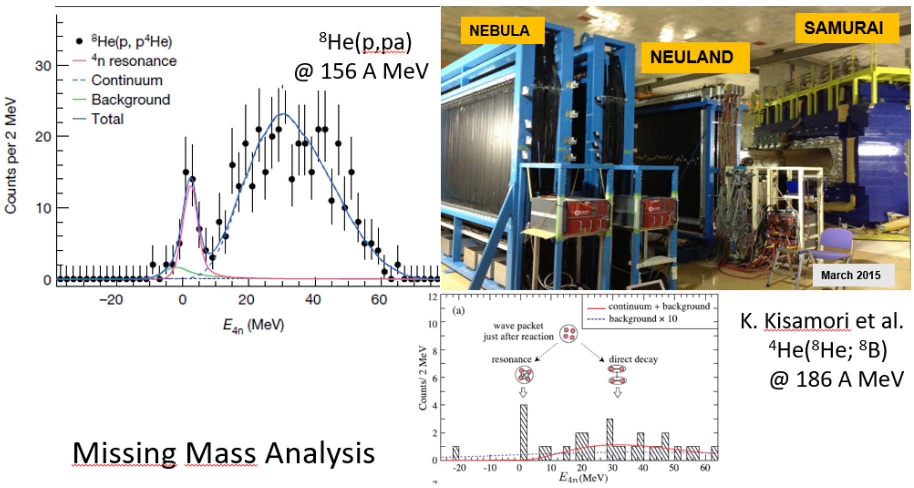

Fig. 7. Investigation of the unbound $4n$ system [5, 6] using the missing mass method. The quasi-free scattering method by Duerr *et al.* [5] was carried out in the SAMURAI setup at RIKEN. From 2014–17, 4 (of 30 for the full detector) prototype double planes were characterized and tested at the same setup.

The full assembly of NeuLAND shown in Fig. 8 will allow for coincident detection of four neutrons, allowing for fully exclusive measurements of the $4n$ channel and introducing for the first time an efficient measurement of four neutron correlations.

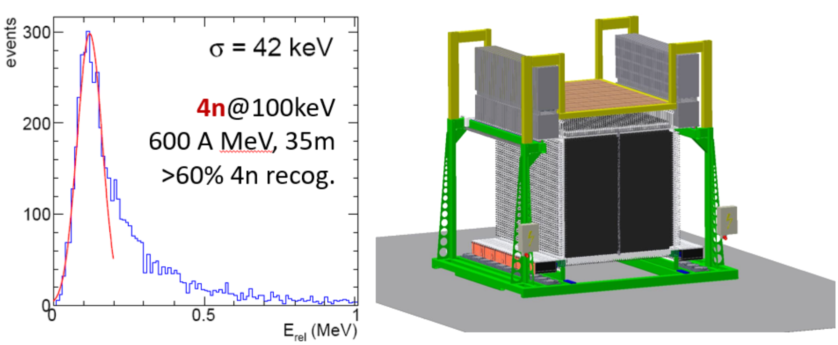

Fig. 8. Performance plot and drawing of the NeuLAND Neutron Detector [2] for the R^3B experiment at FAIR. The system will allow for an unprecedented $4n$ separation efficiency with high resolution and minimized background contributions from lower neutron multiplicity channels. Exclusive measurements of the $4n$ channel will become available with unprecedented efficiency for coincident $4n$ detection in kinematically complete experiments.

Figure 9 eventually shows the expected configuration of an initial experiment that could be set up at FAIR premises.

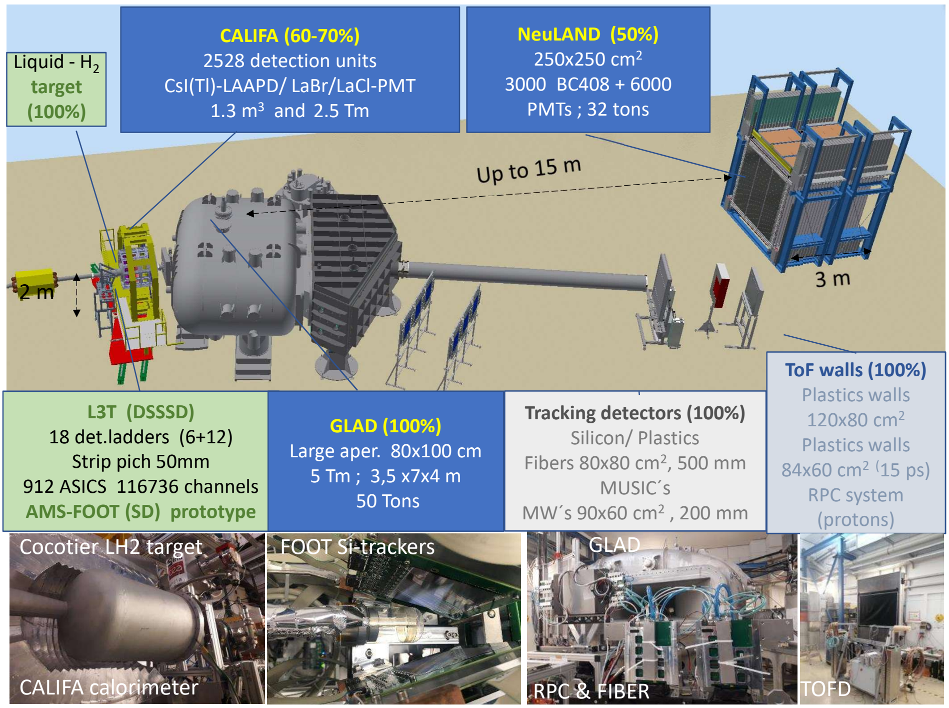

Fig. 9. R^{3}B setup configuration as anticipated when moving into the new location at the High Energy Branch of the Super-FRS at FAIR. The photographs show systems that are currently readily being used (*e.g.* NeuLAND or the advanced ToF as part of the charged particle tracking system [2, 7]) for experiments within the Phase-0 Research Programme.

2. Moving to FAIR, status of the facility

The FAIR project is a major accelerator endeavour aiming for the nuclear structure community (NUSTAR) at intensities 3–4 orders of magnitude higher[1] than at the present facility. Beam energies are basically kept to the current level going for still affordable large acceptance magnetic systems in the separator form 18 Tm (FRS) to 20 Tm (Super-FRS). As shown in Fig. 10, the increase of intensity is to be achieved with an increase of primary beam intensity together with a substantially improved acceptance for secondary beam in the Super-FRS.

[1] Here, 1–2 orders of magnitude are expected from the primary beam intensity increase and 1–2 orders of magnitude come from the better transmission through the separator and into the experimental locations.

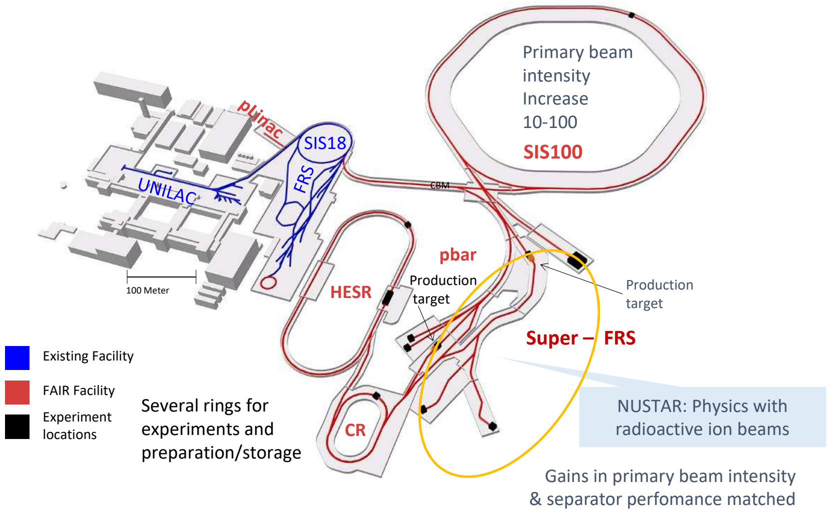

Fig. 10. FAIR facility layout for the intermediate objective [8] with a focus on nuclear structure experiments (NUSTAR).

Figure 11 shows the full separator layout with its main advantages. The slightly increased energy, which is world-wide the highest one with respect to existing facilities, will allow for experiments with high transmission using thick production targets. The energies will be high enough to provide suit-

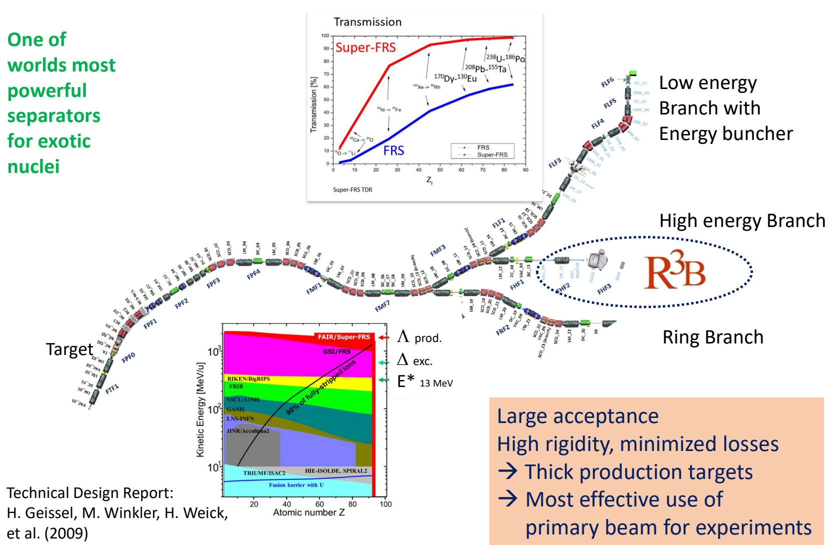

Fig. 11. Super-FRS layout [9, 10] for the secondary beam facility. For details, see the text.

able Coulomb excitation energies via the virtual photon spectrum created by the electric field of a high-Z target nucleus. It will also be sufficient to excite the Δ-resonance or produce λ-baryons during reactions. This will open new opportunities in physics studies as will be exemplarily shown later in this manuscript.

The Covid pandemic and in particular the Russian warfare in Ukraine and related effects on international markets and energy prices, together with sanctions of the EC have affected the FAIR project at a late stage of implementation. Although all Russian in-kind contributions for the Super-FRS can be meanwhile provided via alternative suppliers, the related cost and time impact leads to stage implementation of the project as shown in Fig. 12 in order to keep the availability of the new facility to a conveniently early date between Q4/2026 or Q1/2027 depending on ongoing FAIR council decisions.

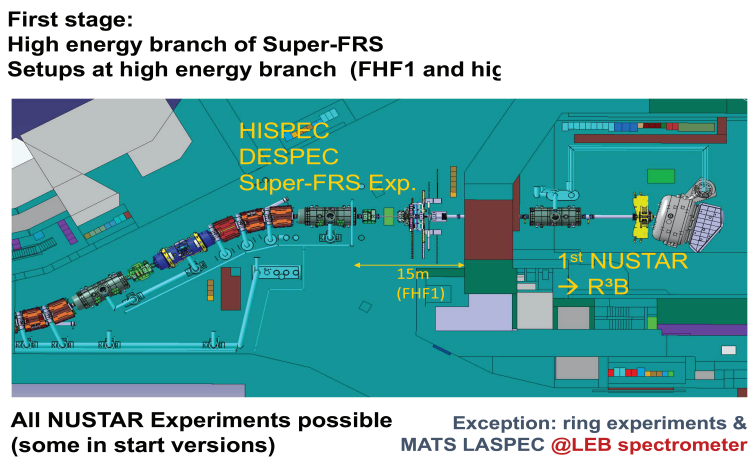

Fig. 12. Initial configuration of the Super-FRS experimental areas [9, 10] in order to be able to provide an early science programme for the NUSTAR experiments. As indicated, the 15 m long area in front of the high-energy cave can be initially used to set up first versions of the HI/DESPEC experiments in the final focus of the Super-FRS Main Separator — similarly to at the existing facility in the FRS-S4 area, whereas the Super-FRS experiments will be installed throughout the Super-FRS.

3. Prospects

The FAIR facility and the Super-FRS experimental facilities will offer vast opportunities for R^3B experiments with intense and energetic secondary beams. The two following examples shown in Figs. 13 and 14 may serve as a good impression what can be expected in the future.

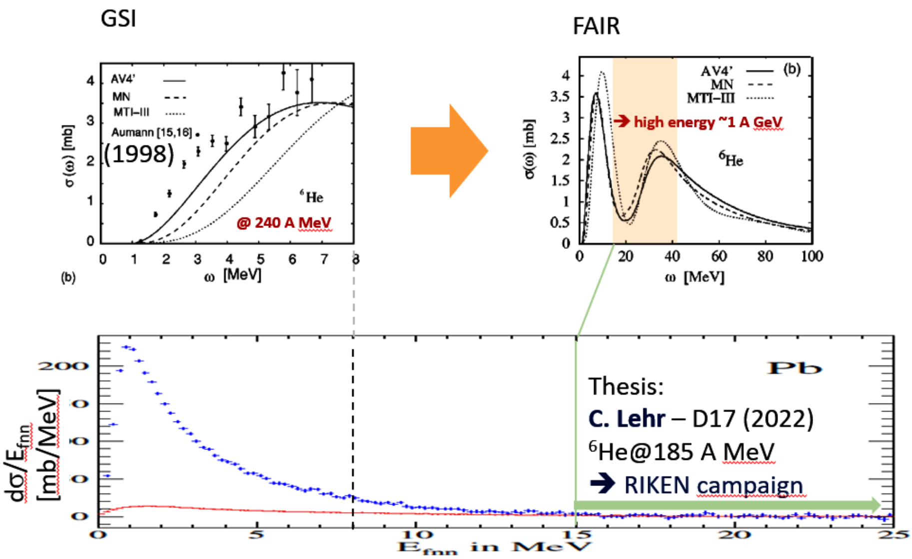

Fig. 13. Coulomb excitation of ^{6}He future (right [11]) and past (left [12]) compared to results obtained at the RIKEN facilities with restricted energy (C. Lehr, Ph.D. Thesis, TU-Darmstadt (D17, 2022)) though very high beam rates. The link from low lying excitations (halo) and GDR (core) are only accessible at GSI/FAIR energies.

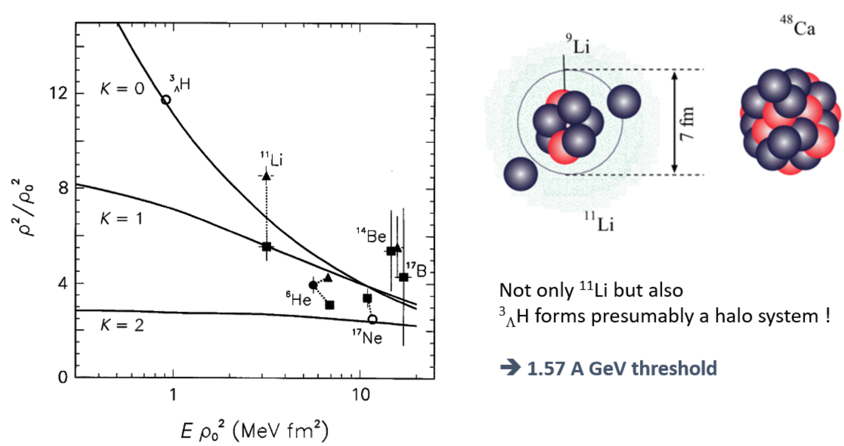

Fig. 14. The hypertriton may exhibit a halo as predicted by Jonson and Riisager [13] using a three-body formalism. Experiments may allow to measure the size of the system [14]. The strangeness channels in reactions require FAIR energies.

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