From d-Bars to Antimatter- and Hyperclusters

J. Steinheimer, Zhangbu Xu, P. Rau, C. Sturm and H. Stöcker

Abstract The Facility for Antiproton and Ion Research (FAIR) is going to be constructed within the next six years adjacent to the existing accelerator complex of the GSI Helmholtz Centre for Heavy Ion Research at Darmstadt/Germany, expanding the research goals and technical possibilities substantially. Providing a broad spectrum of unprecedented fore-front research at worldwide unique accelerator and experimental facilities, FAIR will open the way for a large variety of experiments in hadron, nuclear, atomic and plasma physics as well as applied sciences which will be briefly described in this article. As an example the article presents research efforts on strangeness at FAIR using heavy ion collisions, exotic nuclei from fragmentation and antiprotons to tackle various topics in this area. In particular the creation of hypernuclei as well as metastable exotic multi-hypernuclear objects (MEMOs) and anti-matter will be investigated.

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1 The FAIR Project

The Facility for Antiproton and Ion Research, FAIR [1–3], will provide an extensive range of particle beams from protons and their antimatter partners, antiprotons, to ion beams of all chemical elements up to the heaviest one, uranium, with in many respects world record intensities. As a joint effort of 16 countries the new facility builds, and substantially expands, on the present accelerator system at GSI, both in its research goals and its technical possibilities. Compared to the present GSI facility, an increase of a factor of 100 in primary beam intensities, and up to a factor of 10000 in secondary radioactive beam intensities, will be a technical property of the new facility.

After the official launch of the project on November 7th, 2007, on October 4th, 2010, nine countries[1] signed the international agreement on the construction of FAIR. Civil work for the first buildings of FAIR will start during this year and first beams will be delivered in 2018. The start version of FAIR, the so-called *Modularized Start Version* [4, 5], includes a basic accelerator SIS100 (module 0) as well as three experimental modules (module 1–3) as it is illustrated in Fig. 1. The superconducting synchrotron SIS100 with a circumference of 1100 m and a magnetic rigidity of 100 Tm is at the heart of the FAIR accelerator facility. Following an upgrade for high intensities, the existing GSI accelerators UNILAC and SIS18 will serve as an injector. Adjacent to the SIS100 synchrotron are two storage-cooler rings and experiment stations, including a superconducting nuclear fragment separator (Super-FRS) and an antiproton production target. The Modularized Start Version secures a swift start of FAIR with outstanding science potential for all scientific pillars of FAIR within the current funding commitments. Moreover, after the start phase and as additional funds become available the facility will be upgraded by experimental storage rings enhancing capabilities of secondary beams and upgraded by SIS300 providing particle energies 20-fold higher compared to those achieved so far at GSI.

2 The Experimental Programme of FAIR

The main thrust of FAIR research focuses on the structure and evolution of matter on both a microscopic and on a cosmic scale. The approved FAIR research programme embraces 14 experiments, which form the four scientific pillars of FAIR and offers a large variety of unprecedented forefront research in hadron, nuclear, atomic and plasma physics as well as applied sciences. Already today, over two 2500 scientists and engineers are involved in the design and preparation of the FAIR experiments. They are organized in the experimental collaborations APPA, CBM, NuSTAR, and PANDA.

[1] In alphabetical order: Finland, France, Germany, India, Poland, Romania, Russia, Slovenia and Sweden

Fig. 1 On the *left* the existing GSI facility is shown. Displayed in color is the so called Modularized Start Version of FAIR including module 0, 1, 2 and 3. Coloring: the 100 Tm super conducting synchrotron SIS100 (module 0)—*green*; the experimental area for CBM/HADES (module 1)—*red*; the NuSTAR facility including the Super-FRS (module 2)—*yellow*; The Antiproton facility including the PANDA experiment (module 3)—*orange*. Not shown is the additional experimental area above ground for the APPA community (module 1)

2.1 APPA—Atomic Physics, Plasma Physics and Applications

Atomic physics with highly charged ions [6] will concentrate on two central research themes: (a) the correlated electron dynamics in strong, ultra-short electromagnetic fields including the production of electron-positron pairs and (b) fundamental interactions between electrons and heavy nuclei—in particular the interactions described by Quantum Electrodynamics, QED. Here bound-state QED in critical and supercritical fields is the focus of the research programme. In addition, atomic physics techniques will be used to determine properties of stable and unstable nuclei and to perform tests of predictions of fundamental theories besides QED.

For Plasma physics the availability of high-energy, high-intensity ion-beams enables the investigation of High Energy Density Matter in regimes of temperature, density and pressure not accessible so far [7]. It will allow probing new areas in the phase diagram and long-standing open questions of basic equation of state

(EoS) research can be addressed. The biological effectiveness of high energy and high intensity beams was never studied in the past. It will afford to investigate the radiation damage induced by cosmic rays and protection issues for the Moon and Mars missions. Furthermore, the intense ion-matter interactions with projectiles of energies above 1 GeV/u will endorse systematic studies of material modifications.

2.2 CBM/HADES—Compressed Baryonic Matter

Violent collisions between heavy nuclei promise insight into an unusual state in nature, that of highly compressed nuclear matter. In addition to its relevance for understanding fundamental aspects of the strong interaction, this form of matter may exist in various so far unexplored phases in the interior of neutron stars and in the core of supernovae. The mission of high-energy nucleus-nucleus collision experiments worldwide is to investigate the properties of strongly interacting matter under these extreme conditions. At very high collision energies, as available at RHIC and LHC, the measurements concentrate on the study of the properties of deconfined QCD matter at very high temperatures and almost zero net baryon densities. Results from lattice QCD indicate that the transition from confined to deconfined matter at vanishing net baryon density is a smooth crossover, whereas in the region of high baryon densities, accessible with heavy-ion reactions at lower beam energies, a first-order phase transition is expected [8]. Its experimental confirmation would be a substantial progress in the understanding of the properties of strongly interacting matter.

Complementarily to high-energy nucleus-nucleus collision experiments at RHIC and LHC, the CBM experiment [9, 10] as well as HADES [11, 12] at SIS100/300 will explore the QCD phase diagram in the region of very high baryon densities and moderate temperatures by investigating heavy-ion collision in the beam energy range 2–35 AGeV. This approach includes the study of the nuclear matter equation-of-state, the search for new forms of matter, the search for the predicted first order phase transition to the deconfinement phase at high baryon densities, the QCD critical endpoint, and the chiral phase transition, which is related to the origin of hadron masses. In the case of the predicted first order phase transition, basically one has to search for non-monotonic behaviour of observables as function of collision energy and system size. The CBM experiment at FAIR is being designed to perform this search with a large range of observables, including very rare probes like charmed hadrons. Produced near threshold, their measurement is well suited to discriminate hadronic from partonic production scenarios. The former requires pairwise creation of charmed hadrons, the latter the recombination of c-quarks created in first chance collisions of the nucleus-nucleus reaction. Ratios of hadrons containing charm quarks as a function of the available energy may provide direct evidence for a deconfinement phase.

The properties of hadrons are expected to be modified in a dense hadronic environment which is eventually linked to the onset of chiral symmetry restoration at high baryon densities and/or high temperatures. The experimental verification of this theoretical prediction is one of the most challenging questions in modern strongly interacting matter physics. The dileptonic decays of the light vector mesons (ρ, ω, ϕ) provide the tool to study such modifications since the lepton daughters do not undergo strong interactions and can therefore leave the dense hadronic medium essentially undistorted by final-state interaction. For these investigations the ρ meson plays an important role since it has a short lifetime and through this a large probability to decay inside the reaction zone when created in a nucleus-nucleus collision. As a detector system dedicated to high-precision di-electron spectroscopy at beam energies of 1–2 AGeV, the modified HADES detector at SIS100 will measure e^+e^- decay channels as well as hadrons [13, 14] up to 10 AGeV beam energy. Complementarily, the CBM experiment will cover the complete FAIR energy range by measuring both the e^+e^- and the $\mu^+\mu^-$ decay channels.

Most of the rare probes like lepton pairs, multi-strange hyperons and charm will be measured for the first time in the FAIR energy range. The goal of the CBM experiment as well as HADES is to study rare and bulk particles including their phase-space distributions, correlations and fluctuations with unprecedented precision and statistics. These measurements will be performed in nucleus–nucleus, proton–nucleus, and proton–proton collisions at various beam energies. The unprecedented beam intensities will allow studying extremely rare probes with high precision which have not been accessible by previous heavy-ion experiments at the AGS and the SPS.

2.3 NuSTAR—Nuclear Structure, Astrophysics and Reactions

The main scientific thrusts in the study of nuclei far from stability are aimed at three areas of research: (i) the structure of nuclei, the quantal many-body systems built by protons and neutrons and governed by the strong force, towards the limits of stability, where nuclei become unbound, (ii) nuclear astrophysics delineating the detailed paths of element formation in stars and explosive nucleosynthesis that involve short-lived nuclei, (iii) and the study of fundamental interactions and symmetries exploiting the properties of specific radioactive nuclei.

The central part of the NuSTAR programme at FAIR [15, 16] is the high acceptance Super-FRS with its multi-stage separation that will provide high intensity mono-isotopic radioactive ion beams of bare and highly-ionized exotic nuclei at and close to the driplines. This separator, in conjunction with high intensity primary beams with energies up to 1.5 AGeV, is the keystone for a competitive NuSTAR physics programme. This opens the unique opportunity to study the evolution of nuclear structure into the yet unexplored territory of the nuclear chart and to determine the properties of many short-lived nuclei which are produced in explosive astrophysical events and crucially influence their dynamics and associated nucleosynthesis processes.

2.4 PANDA—AntiProton ANnihilation in Darmstadt

The big challenge in hadron physics is to achieve a quantitative understanding of strongly interacting complex systems at the level of quarks and gluons. In $p\bar{p}$-annihilation, particles with gluonic degrees of freedom as well as particle-antiparticle pairs are copiously produced, allowing spectroscopic studies with unprecedented statistics and precision. The PANDA experiment at FAIR [17–19] will bring new fundamental knowledge in hadron physics by pushing the precision barrier towards new limits. The charmonium ($c\bar{c}$) spectroscopy will take advantage by precision measurements of mass, width, decay branches of all charmonium states. Particular emphasis is placed on mesons with open and hidden charm, which extends ongoing studies in the light quark sector to heavy quarks, and adds information on contributions of the gluon dynamics to hadron masses. The search for exotic hadronic matter such as hybrid mesons or heavy glueballs gains enormously by precise scanning of resonance curves of narrow states as well. Recently, this field has attracted much attention with the surprise observation at electron-positron colliders of the new X, Y and Z states with masses around 4 GeV. These heavy particles show very unusual properties, whose theoretical interpretation is entirely open. Additionally the precision gamma-ray spectroscopy of single and double hypernuclei will allow extracting information on their structure and on the hyperon-nucleon and hyperon-hyperon interaction.

3 The Creation of Anti-Matter

The history of antimatter is a brief and fascinating history of scientific discoveries. In 1928, Dirac predicted the existence of negative energy states of electrons based on the application of symmetry principles to quantum mechanics. The states were recognized as antimatter partner of electrons (positrons) discovered by Anderson in the cosmic rays in 1932. The constructions of accelerators have provided the necessary energy and luminosity for the discoveries of heavier antimatters. The extension of Dirac's theory implied the existence of antimatter protons and neutrons, and both particles were discovered at Bevatron in 1955. The scientific investigation of antimatter has three major focuses since then:

(a) Antiparticles are produced as by-products of high-energy particle collisions. Many particle and antiparticle pairs are created in such collisions through strong or electromagnetic processes. Antiparticles are merely part of the energy and chemical (baryon, isospin or lepton) conservation laws.
(b) Precise measurements of particle and antiparticle properties, which can provide insights into the fundamental CPT conservation and baryon asymmetry in the Universe.
(c) Constructing more complex system of antimatter.

It is clear that all these three topics are related to each other with a different emphasis for each subject. Although it may sound trivial to define what antimatter is, its definition is not without controversy. There are particles and antiparticles (such as μ^+ and μ^-), which annihilate when put together. However, neither of them annihilates the ordinary matter. Antonino Zichichi (2008) argues that there is a basic difference between antiparticle and antimatter, and even anti-hydrogen is not antimatter. In this proceeding, we mainly focus on constructing more complex systems of antimatter: antinuclei and antihypernuclei.

After the discoveries of antiprotons and antineutrons, one of the important questions was whether the building blocks in the antimatter world have the same force to glue together the antinucleons into nuclei and eventually anti-atoms by adding positrons. Figure 2 depicts the history of the discoveries of antimatter. We note that the antimatter project span eight decades with four decades per step in our discoveries. There are effectively three periods in these 80 years. The first discovery was made in the cosmic ray in 1932. The second period of discovery was between 1955 and 1975 when the fixed target accelerators provided increasing intensity and energy for producing heavier and heavier antimatter. The third period was made possible with high energy relativistic heavy-ion collider at RHIC and at the LHC. At the same time, the technology advance also enables us to decelerate antiproton beams and trap antimatter hydrogen. The necessity of the long term commitment was expressed by Walter Greiner (2001) in 'Fundamental Issues in the Physics of Elementary Matter': "The extension of the periodic system into the sectors of hypermatter (strangeness) and antimatter is of general and astrophysical importance. [...] The ideas proposed here, the verification of which will need the *commitment for 2–4 decades of research, could be such a vision* with considerable attraction for the best young physicists." [20].

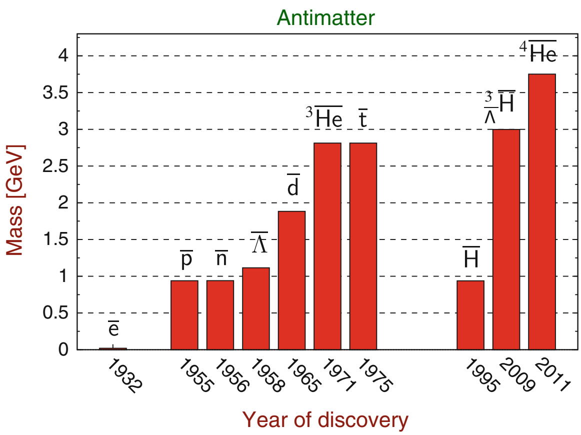

Fig. 2 Discovery year of the antimatter and its associated mass

Understanding the asymmetry of antimatter and matter is one of the frontiers of modern physics. Nuclei are abundant in the universe, but anti-nuclei with $|A| \geq 2$ have not been found in nature. Relativistic heavy ion collisions, simulating the condition at the early universe, provide an environment with abundant antinucleons and antihyperons and produce antinuclei and antihypernuclei by coalescing them together [21]. This offers the first opportunity for discovery of antihypernuclei [22] and heavier antinuclei [23] having atomic mass numbers (or baryon numbers) $|A| > 2$. The production of antimatter nuclei can be explained by coalescence of antiprotons and antineutrons close in position and momentum. Figure 3 compiles all the antideuteron production in e^+e^-, γp, pp, pA and AA collisions [24]. The results are shown for $\bar{d}/\bar{p}$ ratio as a function of beam energy. One can see that this ratio increases from 10^{-5} at low energy to 10^{-3} at high energy. Each additional antinucleon into the heavier antimatter decreases its production rate by that same penalty factor. At a center of mass energy of 100 GeV and above, this factor is relatively flat at slightly below 10^{-3}. It is interesting to note that this effective measure of antibaryon density shows no difference among pp, pA and AA collisions. In heavy ion collisions, more antiprotons are produced in each collision than in pp collisions. However, if more pp collisions are collected to match the amount of antiproton yields in heavy-ion collisions, one can essentially produce the same amount of heavy antimatter in pp and heavy-ion collisions. Now we understand that there are two deciding facts that RHIC discovered the last two heavy antimatters: sufficient energy to provide the highest antibaryon density for antinuclear production, and high luminosity heavy-ion collisions for effective data collection and particle identification.

Figure 3 shows the matter and antimatter yields as a function of baryon numbers as measured by the STAR Collaboration at RHIC [23]. The fit lines yield the production reduction rate by a factor of 1.6×10^{-3} (1.1×10^{-3}) for matter (antimatter) for each additional nucleon (antinucleon). The sensitivity of current and planned space based charged particle detectors is below what would be needed to observe antihelium

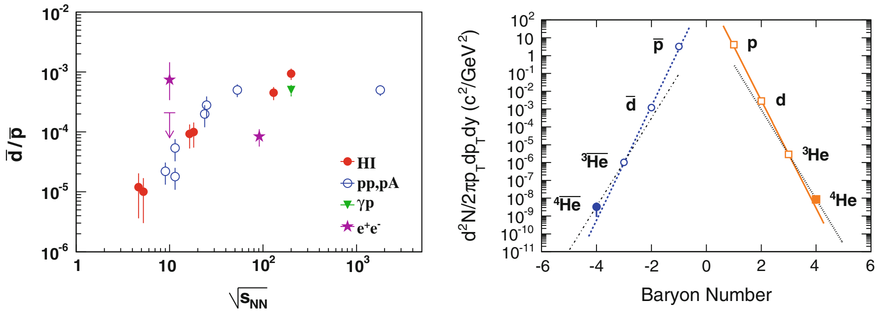

Fig. 3 *Left* antideuteron and antiproton yield ratio as a function of the center of mass energy of the colliding target and projectile particles. *Right* matter and antimatter invariant differential yields as a function of the baryon number. The *solid* and *dashed lines* are a fit to all the experimental data. The *dotted* and *dotted dash lines* are extrapolations from the yields of $|A| = 3$ and $|A| = 4$.

produced by nuclear interactions in the cosmos. This implies that any observation of antihelium or even heavier antinuclei in space would indicate the existence of a large amount of antimatter elsewhere in the universe. In particular, finding antimatter ^{4}He in the cosmos is one of the major motivations for space detectors such as the Alpha Magnetic Spectrometer [25]. We have shown that antimatter ^{4}He exists and provided a measure of the background rate in nuclear collisions for possible future observations in cosmic radiation.

The next stable antimatter nucleus would be $A = 6$ (^{6}He; ^{6}Li). However, the penalty factor on the production rate for an additional antinucleon is about 1500 as shown in Fig. 3. This means that the $A = 6$ antinuclei are produced at a rate 2×106 lower than that of an $A = 4$ antialpha particle. Unless production mechanisms or collider technology change dramatically, it is unlikely that $A = 6$ antinuclei can be produced in collider or fixed-target experiments (STAR 2011). On the other hand, the ratio of the $^4\text{He}/^3\text{He} = 3.1 \times 10^{-3}$ and $^4\overline{\text{He}}/^3\overline{\text{He}} = 2.4 \times 10^{-3}$. There is a factor of 2 higher yield of $|A| = 4$ over $|A| = 3$ than the extrapolation from the fit. The excess is visible even in a log-scale plot of 13 orders of magnitude. This ratio is also much higher than that shown in Fig. 3 for the $|A| = 2$ over $|A| = 1$. It has been argued that a more economic way of producing heavier antimatter and/or nuclear matter containing large amount of strange quark contents is through excitation of complex nuclear structure from the vacuum or through strangeness distillation from a QGP. Is this enhanced yield an indicative of a new production mechanism or a minor deviation due to trivial configuration of nuclear binding? Where do we go from here into the future in search and construction of heavier and more exotic antimatter? The indicative enhancement of higher antialpha yields suggests that even higher enhanced yields of heavier antimatter. Besides the possible high yields of $|A| = 6$ antimatter, the heaviest antimatter that can be produced and detected with a tracking detector in high-energy accelerators are likely to be $A = 4$ or 5 unstable antinuclei: $^4\text{He}^* \rightarrow \text{t} + \text{p}$, $^4\text{Li} \rightarrow {}^3\text{He} + \text{p}$, and $^5\text{Li} \rightarrow {}^4\text{He} + \text{p}$. New trigger scheme and high data acquisition rate have been proposed to improve the effective data taking rate by two orders of magnitude in STAR during the heavy ion collisions [26]. This should confirm if the enhancement indeed exists and provide a possible path for discovering even heavier antimatter. In addition, as mentioned in the previous section, the antimatter yield reduction factor is similar in $p{+}p$ and AA collisions. One expects that the penalty factor to persist for antimatter heavier than antideuteron in $p{+}p$ collisions. A comparison between the antimatter yields as shown in Fig. 3 in $p{+}p$ and $A{+}A$ collisions will provide a reference for whether the enhancement seen in antialpha production in AA collisions is due to new production mechanism. Both RHIC and LHC have sufficient luminosity in $p{+}p$ collisions to produce antialpha. The only experimental issue is how to trigger and identify those particles. STAR has proposed a new trigger and TPC readout schemes for heavy antimatter search by using the Electromagnetic Calorimeter (EMC) for charged hadrons and only readout small sector of TPC associated with that struck EMC.

4 Hypermatter

Relativistic heavy ion collisions are an abundant source of strangeness. As strange quarks have to be newly produced during the hot and dense stage of the collision, they are thought of carrying information on the properties of the matter that was created [27]. Exotic forms of deeply bound objects with strangeness have been proposed [28] as states of matter, either consisting of baryons or quarks. The H di-baryon was predicted by Jaffe [29] and later, many more bound di-baryon states with strangeness were proposed using quark potentials [30, 31] or the Skyrme model [32]. However, the non-observation of multi-quark bags, e.g. strangelets is still one of the open problems of intermediate and high energy physics. Lattice calculations suggest that the H-dibaryon is a weakly unbound system [33], while recent lattice studies report that there could be strange di-baryon systems including Ξ's that can be bound [34]. Because of the size of these clusters lattice studies are usually very demanding on computational resources and have large lattice artifacts, therefore an experimental confirmation of such a state would be an enormous advance in the understanding of the hyperon interaction.

Hypernuclei are known to exist and be produced in heavy ion collisions already for a long time [35–38]. The recent discoveries of the first anti-hypertriton [39] and anti-α [40] (the largest anti-particle cluster ever reported) has fuelled the interest in the field of hypernuclear physics. Metastable exotic multi-hypernuclear objects (MEMOs) as well as purely hyperonic systems of Λ's and Ξ's were introduced in [41, 42] as the hadronic counterparts to multi-strange quark bags [43, 44].

In the work presented in this section we will focus on the production of hypernuclei in high energy collisions of Au+Au ions. In such systems strangeness is produced abundantly and is likely to form clusters of different sizes. Hypernuclear clusters can emerge from the hot and dense fireball region of the reaction. In this scenario the cluster is formed at, or shortly after, the (chemical-)freeze out of the system. A general assumption is, that these clusters are then formed through coalescence of different newly produced hadrons. To estimate the production yield we can employ thermal production of clusters froma fluid dynamical description to heavy ion collisions. Though thermal production differs significantly in its assumptions from a coalescence approach one would expect to obtain different results, depending on the method used. However it can be shown that both approaches can lead to very similar results [49]. More detailed information on the calculations performed for the results in this section can be found in [50].

Figure 4 shows our results for the mid rapidity yields ($|y| < 0.5$) of di-baryons and hypernuclei as a function of the beam energy E_{lab}. In our calculations we considered most central ($b < 3.4$ fm) Pb+Pb/Au+Au collisions at $E_{\mathrm{lab}} = 1$–160 AGeV. In addition, Fig. 4 shows the Λ yield (black lines and squares) for the model compared to data [46–48]. In these figures, the UrQMD hybrid model calculations are shown as lines. At lower energies the cluster production should be suppressed additionally due to the non-equilibrium of strangeness. In the thermal calculations restrictions of energy and momentum conservation, resulting in a phase space reduction for produced strange particles, strongly decreases strange particle yields [51–53]. This behavior was also observed in a core-corona implementation in the hybrid model [54].

Di-baryon production rates have been calculated in a coalescence approach using the RQMD model for $\sqrt{s_{NN}}$ = 200 GeV collisions of Au nuclei [45]. To relate our calculations to these results, they are indicated as the colored bars on the right axis of Fig. 4. The RQMD model used was in particular tuned to reproduce multi strange particle yields (such as the Ξ) and the results are therefore close to the ones obtained with our thermal/hydrodynamic approach. When the beam energy of the collisions is increased, the system created becomes almost net-baryon free. This means that the probability to create an anti-particle cluster approaches that of the particle cluster. Figure 5 shows the results for anti-particle cluster production at mid-rapidity ($|y| < 0.5$) in collisions of Pb+Pb/Au+Au at center of mass energies of $\sqrt{s_{NN}}$ = 3–200 GeV. The yields of the anti-particle clusters show a monotonous increase with beam energy. They show that, at the highest RHIC energy (and at the LHC) the reconstruction of ${}^4_{\Lambda}$He might be a feasible task.

As another promising experimental tool for the production of antimatter clusters and hypernuclei we propose collisions of asymmetric sized nuclei, e.g. Ne+U, Ca+U.

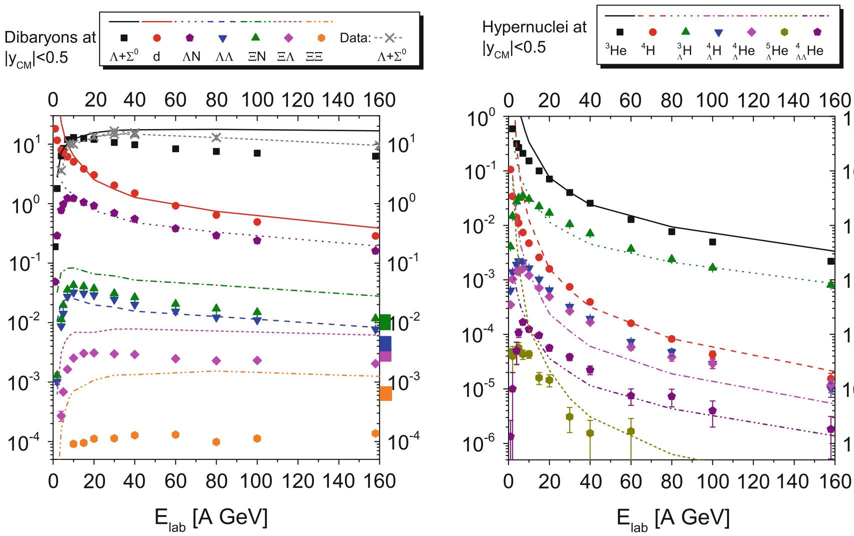

Fig. 4 *Left* yields of different di-baryons in the mid rapidity region ($|y| < 0.5$) of most central collisions of Pb+Pb/Au+Au. Shown are the results from the thermal production in the UrQMD hybrid model (*lines*) as compared to coalescence results with the DCM model (*symbols*). The *small bars* on the right hand axis denote results on di-baryon yields from a previous RQMD calculation at $\sqrt{s_{NN}}$ = 200 GeV [45]. In addition, the black lines and symbols depict results for the production rate of Λ's from both models, compared to data (*grey crosses*) from [46–48]. *Right* yields of different (hyper-)nuclei in the mid rapidity region ($|y| < 0.5$) of most central collisions of Pb+Pb/Au+Au. Shown are the results from the thermal production in the UrQMD hybrid model (*lines*) as compared to coalescence results with the DCM model (*symbols*)

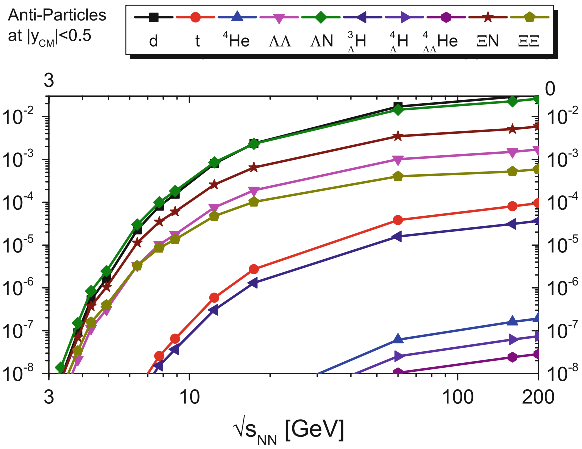

Fig. 5 Yields of anti-particle clusters in the mid rapidity region ($|y| < 0.5$) of most central collisions of Pb+Pb/Au+Au as a function of $\sqrt{s_{NN}}$. Shown are only the results from the thermal production in the UrQMD hybrid model (*lines* with *symbols*)

In Fig. 6 we show the energy (a) and baryon number (b) density distributions in the reaction plane at $t = 16$ fm of a Ne+U collision at $E_{\text{lab}} = 15$ AGeV with an impact parameter $b = 4$ fm as calculated with a hydrodynamic model. At the collision zone

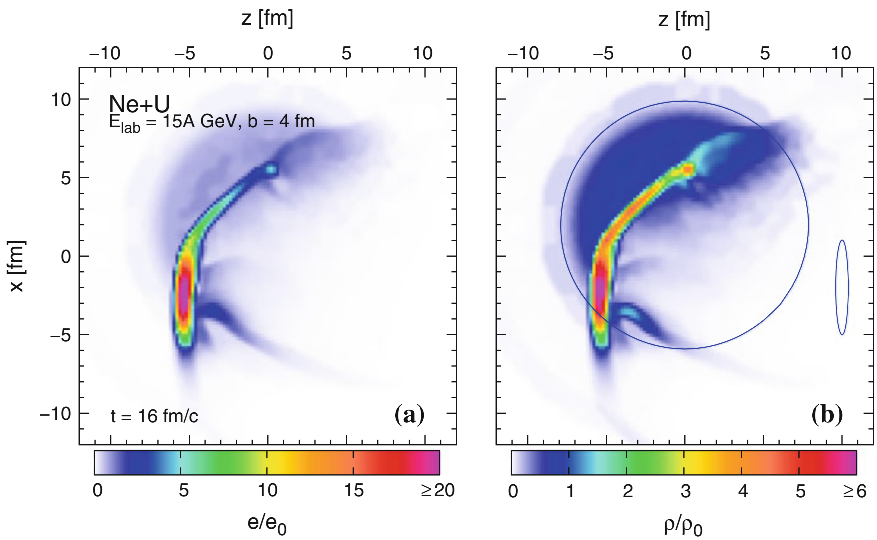

Fig. 6 Density distributions of the energy (**a**) and baryon number (**b**) in units of the nuclear ground state values e_0, ρ_0 in the reaction plane of the asymmetric collision Ne+U with an impact parameter $b = 4$ fm and $E_{\text{lab}} = 15$ AGeV. The *blue lines* in (**b**) show the initial setup of the colliding Ne and U nuclei for the calculation with a hydrodynamic model

a highly compressed Mach shock wave is created and propagates through the target nucleus causing a directed cone like emission of particles [55]. Depending on the underlying EoS [56] high densities above the phase transition are reached already at rather small beam energies. In this very dense and hot shock zone, antibaryons are abundantly produced. Due to the directed, correlated emission through the surface, many of those $\bar{p}$ and $\bar{n}$ are able to escape annihilation and coalesce to antimatter clusters. Similarly, multi hyperon clusters form and can be detected downstream.

5 Summary

On October 4th, 2010, and after about ten years of negotiations, R&D, and writing reports, nine countries signed the international agreement on the construction of the Facility for Antiproton and Ion Research FAIR. Construction of the first FAIR buildings will start in 2012, so that the first beams will be delivered in 2018. The start version of FAIR, the so-called *Modularized Start Version*, includes the superconducting synchrotron SIS100 as well as three experimental modules to perform experiments for all research pillars. It will allow to carry out an outstanding and world-leading research programme in hadron, nuclear, atomic and plasma physics as well as applied sciences. Due to the high luminosity which exceeds current facilities by orders of magnitude, experiments will be feasible that could not be done elsewhere. FAIR will expand the knowledge in various scientific fields beyond current frontiers. Moreover, the exploitation of exiting strong cross-topical synergies promise novel insights.

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