Anti- and Hypermatter Research at the Facility for Antiproton and Ion Research FAIR

J. Steinheimer1, Z. Xu2, K. Gudima4,5, A. Botvina4,6, I. Mishustin4,7, M. Bleicher4 and H. Stöcker4,8

1 Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
2 Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA
3 FIAS, Johann Wolfgang Goethe University, Frankfurt am Main, Germany
4 Institute of Applied Physics, Academy of Sciences of Moldova, MD-2028 Kishinev, Moldova
5 Institute for Nuclear Research, Russian Academy of Sciences, 117312 Moscow, Russia
6 Kurchatov Institute, Russian Research Center, 124182 Moscow, Russia
7 GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstr. 1, D-64291 Darmstadt, Germany

E-mail: jsfroschauer@lbl.gov

Abstract. Within the next six years, the Facility for Antiproton and Ion Research (FAIR) is built adjacent to the existing accelerator complex of the GSI Helmholtz Center for Heavy Ion Research at Darmstadt, Germany. Thus, the current research goals and the technical possibilities are substantially expanded. With its worldwide unique accelerator and experimental facilities, FAIR will provide a wide range of unprecedented forefront research in the fields of hadron, nuclear, atomic, plasma physics and applied sciences which are summarized in this article. As an example this 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 and antimatter is investigated.

1. The FAIR Project

The Facility for Antiproton and Ion Research, FAIR [1, 2, 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.

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). The superconducting synchrotron SIS100 with a circumference of 1100 meters 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 Program 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 program 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.

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 program. 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. 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.

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. 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. 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 dileptonic decays of the light vector mesons ($\rho, \omega, \phi$) 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. 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 \cite{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.

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, toward 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 program at FAIR \cite{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 A GeV, is the keystone for a competitive NuSTAR physics program. 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 \cite{17, 18, 19} will bring new fundamental knowledge in hadron physics by pushing the precision barrier toward 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 antimatter

In 1928, Dirac predicted the existence of negative energy states of electrons based on the application of symmetry principles to quantum mechanics. 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. Nuclei are abundant in the universe, but antinuclei 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 [20]. This offers the first opportunity for discovery of antihypernuclei [21] and heavier antinuclei [22] 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 1 compiles all the antideuteron production in $\gamma p$, $pA$ and $AA$ collisions [23]. 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 1 shows the matter and antimatter yields as a function of baryon numbers as measured by the STAR Collaboration at RHIC [22]. The fit lines yield the production reduction rate by a factor of $1.6 \times 10^{-3}$ ($1.1 \times 10^{-3}$) 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 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 [24]. 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. 1. This means that the $A = 6$ antinuclei are produced at a rate $2 \times 10^6$ 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 $^4$He/$^3$He = $3.1 \times 10^{-3}$ and $^4$He/$^3$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. 1 for the $|A| = 2$ over $|A| = 1$. 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: $^4$He$^*$ $\rightarrow$ t + p, $^4$Li$^*$ $\rightarrow$ 3 He + p, and $^5$Li $\rightarrow$ 4 He + 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 [25]. 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. 1 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 [26]. Exotic forms of deeply bound objects with strangeness have been proposed [27] as states of matter, either consisting of baryons or quarks. The H di-baryon was predicted by Jaffe [28] and later, many more bound di-baryon states with strangeness were proposed using quark potentials [29, 30] or the Skyrme model [31]. However, the non-observation of multi-quark bags, e.g. strangelets is still one of the open problems of intermediate and high energy physics. Hypernuclei however are known to exist and be produced in heavy ion collisions already for a long time [32, 33, 34, 35]. The interest in the field of hypernuclear physics was fueled by the recent discoveries of the first anti-hypertriton [36] and anti-α [37] (the largest antiparticle cluster ever reported).

It is of great interest to estimate the yields for hypernuclei, and comparably the proton and Λ yields, from a consistent model for heavy ion collisions. In such models 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 two distinct approaches which allow us to estimate the theoretical uncertainties associated with different treatment of the process. First we use a hadronic transport model (DCM model) to provide us with the phase space information of all hadrons produced in a heavy ion collision. This information then serves as an input for a coalescence prescription. Secondly we assume thermal production of clusters from a 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 [38]. More detailed information on the calculations performed for the results in this section can be found in [38, 39].

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 antiparticle cluster approaches that of the particle cluster. Figure 2 shows the results for antiparticle 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. We show only results for the UrQMD hybrid model because the DCM calculations are restricted to energies up to $E_{lab} = 160$ A GeV where the statistics needed for a meaningful estimate are quite significant. The yields of the antiparticle clusters show a monotonous increase with beam energy. They show that, at the highest RHIC energy (and at the LHC) the reconstruction of $^{3}\Lambda$He might be a feasible task.

As another promising experimental observable the double ratio $R_H$ defined as:

$$R_H = \frac{3}{\Lambda} \frac{H/3He \cdot p}{p/\Lambda}$$

for collisions of Pb+Pb/Au+Au and a wide range of beam energies. This ratio is especially interesting, as it has been proposed to be sensitive on the local correlation of strangeness and baryon number, therefore being a measure of the baryon-strangeness correlation $c_{BS}$ [40].

Our results for $R_H$ are shown in figure 3 as an excitation function of the beam energy $\sqrt{s_{NN}}$. $R_H$ is evaluated for the mid rapidity region of most central ($b < 3.4$ fm) heavy ion collisions. The lines depict results from the UrQMD-hybrid model and the symbols denote DCM coalescence results. Experimental data are depicted as green symbols with error bars. For the hadrons the feed down from resonances is taken into account as well as the feed down to the $^3He$ from the hypertriton. Because experiments usually cannot distinguish between $\Lambda$'s and $\Sigma^{0}$'s, we show $R_H$ in the cases where the $\Lambda$ yield includes $\Sigma^{0}$'s (black solid line and squares) and where the yield is corrected for the $\Sigma^{0}$ (red dashed line and circles). This is in fact important as there is no experimental indication for a bound $^{3}\Sigma_{0}H$ hypernucleus.

**Figure 2.** (Color online) Yields of antiparticle clusters with $|y| < 0.5$ 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).
Figure 3. The Strangeness Population Factor $R_H = (\frac{3}{\Lambda} H/3 He) \cdot (p/\Lambda)$ as a function of $\sqrt{s_{NN}}$ for most central collisions of Pb+Pb/Au+Au. We compare results from the thermal production in the UrQMD hybrid model (lines) with coalescence results with the DCM model (symbols). The red line and symbols denote values of $R_H$ where the $\Lambda$ yield has been corrected for the $\Sigma^0$ contribution.

The double ratio $R_H$ from the hybrid model turns out to be almost energy independent. The same behavior has been observed in previous thermal calculations [41]. On the other hand, the coalescence result increases with decreasing beam energy and is in general larger than the thermal result. This observation leads to the conclusion that the information on correlations of baryon number and strangeness is lost in the thermal calculation because here $R_H$ essentially only depends on the temperature. On the other hand, in the microscopic treatment the correlation information survives and $R_H$ captures the trend of $c_{BS}$.

5. Summary

After about ten years of negotiations, R&D and writing reports, on 4th of October nine countries finally 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 and first beams will be delivered in 2018. The initial version of FAIR, the so-called Modularized Start Version, includes the superconducting synchrotron SIS100 and three experimental modules to perform experiments for all research pillars. It will allow to carry out an outstanding and world-leading research program in hadron, nuclear, atomic and plasma physics as well as applied sciences. Due to the high luminosity, exceeding current facilities by orders of magnitude, it will be possible to conduct experiments that could not be done anywhere yet. FAIR will expand the knowledge in various scientific fields beyond current frontiers. Moreover, the exploitation of exiting strong cross-topical synergies promise novel insights.

6. Acknowledgments

This work was supported by HGS-HiRe and the Hessian LOEWE initiative through the Helmholtz International center for FAIR (HIC for FAIR). Computational resources were provided by Frankfurt Center for Scientific Computing (CSC). J. S. acknowledges a Feodor Lynen fellowship of the Alexander von Humboldt foundation. This work was supported by the Office of Nuclear Physics in the US Department of Energy’s Office of Science under Contract No. DE-AC02-05CH11231. I.M. acknowledges partial support from grant NS-215.2012.2 (Russia).

[1] H.H. Gutbrod et al. (Eds.), FAIR Baseline Technical Report, (2006).
[2] W. F. Henning, Nucl. Phys. A 805, 502 (2008).
[3] H. Stöcker, Proc. of 11th Europ. Part. Acc. Conf., Genoa, Italy (2008).
[4] C. Sturm, B. Sharkov and H. Stöcker, Nucl. Phys. A 834, 682c (2010).
[5] Green Paper of FAIR: The Modularized Start Version, www.gsi.de/documents/DQC-2009-Nov-124-1.pdf (2009)
[6] Th. Stöhlker et al., Nucl. Instrum. Meth. B 261, 234 (2007).
[7] I.V. Lomonosov and N.A. Tahir, Nucl. Phys. News 16 1, 29 (2006).
[8] B. Friman, C. Höhne, J. Knoll, S. Leupold, J. Randrup, R. Rapp, P. Senger (Editors), Lect. Notes Phys. 814, 1 (2011)
[9] P. Senger et al. [CBM Collab.], Phys. Part. Nucl. 39, 1055 (2008).
[10] P. Senger et al. [CBM Collab.], Prog. Part. Nucl. Phys. 62, 375 (2009).
[11] G. Agakishiev et al. [HADES Collab.], Eur. Phys. J. A 41, 243 (2009).
[12] J. Stroth et al. [HADES Collab.], Prog. Part. Nucl. Phys. 62, 481 (2009).
[13] I. Fröhlich [HADES Collab.], arXiv:0906.0091 [nucl-ex].
[14] P. Tlusty et al. [HADES Collab.], AIP Conf. Proc. 1322, 116 (2010).
[15] R. Krücken et al. [NuSTAR Collab.], J. Phys. G 31, S1807 (2005).
[16] B. Rubio and T. Nilsson [NuSTAR Collab.], Nucl. Phys. News 16, 9 (2006).
[17] Physics Performance Report for PANDA, arXiv:0903.3905v1 [hep-ex].
[18] K. Fohl et al. [PANDA Collab.], Eur. Phys. J. ST 162, 213 (2008).
[19] J. S. Lange [PANDA Collab.], Int. J. Mod. Phys. A 24, 369 (2009).
[20] J. Adams et al. [STAR Collab.], Nucl. Phys. A 757, 102 (2005).
[21] B. I. Abelev [STAR Collab.], Science 328 58 (2010).
[22] H. Agakishiev et al. [STAR Collab.], Nature 473, 353 (2011).
[23] H. Liu and Z. Xu, arXiv:nucl-ex/0610035.
[24] S. P. Ahlen, V. M. Balebanov, et al., Nucl. Instrum. Meth. A 350, 351 (1994).
[25] STAR decadal plan 2011, www.bnl.gov/npp/docs/STAR_decadal_Plan_Final.pdf.
[26] P. Koch, B. Müller and J. Rafelski, Phys. Rept. 142, 167 (1986).
[27] A. R. Bodmer, Phys. Rev. D 4, 1601 (1971).
[28] R. L. Jaffe, Phys. Rev. Lett. 38, 195 (1977).
[29] J. T. Goldman et al., Phys. Rev. Lett. 59, 627 (1987).
[30] J. T. Goldman et al., Mod. Phys. Lett. A 13, 59 (1998).
[31] B. Schesinger, F. G. Scholtz and H. B. Geyer, Phys. Rev. D 51, 1228 (1995).
[32] P. Braun-Munzinger and J. Stachel, J. Phys. G 21, L17 (1995).
[33] J. K. Ahn et al., Phys. Rev. Lett. 87, 132504 (2001).
[34] H. Takahashi et al., Phys. Rev. Lett. 87, 212502 (2001).
[35] A. Andronic, P. Braun-Munzinger, J. Stachel and H. Stöcker, Phys. Lett. B 697, 203 (2011).
[36] STAR Collab., Science 328, (2010) 58.
[37] STAR Collab., Nature 473 (2011) 353.
[38] J. Steinheimer, K. Gudima, A. Botvina, I. Mishustin, M. Bleicher and H. Stocker, Phys. Lett. B 714, 85 (2012)
[39] J. Steinheimer et al., Phys. Lett. B 676, 126 (2009).
[40] S. Zhang, J. H. Chen, H. Crawford, D. Keane, Y. G. Ma and Z. B. Xu, Phys. Lett. B 684, 224 (2010).
[41] A. Andronic, P. Braun-Munzinger, J. Stachel and H. Stocker, Phys. Lett. B 697, 203 (2011)