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STUDYING BARYONIC MATTER WITH HADES AT GSI/FAIR*

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HADES at GSI/FAIR is a versatile detector operating with a few GeV proton, pion and heavy-ion beams. The highlights of the experimental programme and plans for future measurements within Phase-0 of FAIR are presented.

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1. Introduction

QCD describes nucleons as colorless states of three nearly massless quarks confined to a small volume due to the strong force. Building blocks are light (u, d) quarks with current mass of only a few MeV emerging from the famed Higgs mechanism. Their much larger constituent mass is generated by the coupling of the quarks to the non-trivial QCD vacuum and is attributed solely to properties of strong interactions. The underlying mechanism of mass generation is a spontaneous chiral symmetry breaking which leads to appearance of Goldstone bosons, identified with pions, and chiral parity doublets with large mass difference (for example, $\rho - a_1$), characteristic for the low-mass hadron spectrum. The order parameter of the chiral symmetry breaking is the non-vanishing expectation value of a quark–antiquark condensate related to the pion decay constant by the Gell-Mann–Oaknes–Renner relation. In cloudy bag models of nucleon, pion cloud is surrounding quark-core to counterbalance vacuum pressure exposed on the bag. Interaction of quarks with the pion cloud explains conservation of the quark handness (chirality) in the bag. Various model calculations predict significant changes of the expectation value of quark condensate as a function

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of temperature and baryon densities. Lattice calculations performed in the limit of vanishing baryo-chemical potential predict a crossover phase transition from the hadron gas to quark–gluon plasma at a critical temperature T_c which is accompanied by the chiral symmetry restoration (see Fig. 1 [1]). The latter is signalled by vanishing expectation value of the quark–antiquark condensate. First order phase transition is expected for QCD matter with non-vanishing baryo-chemical potential.

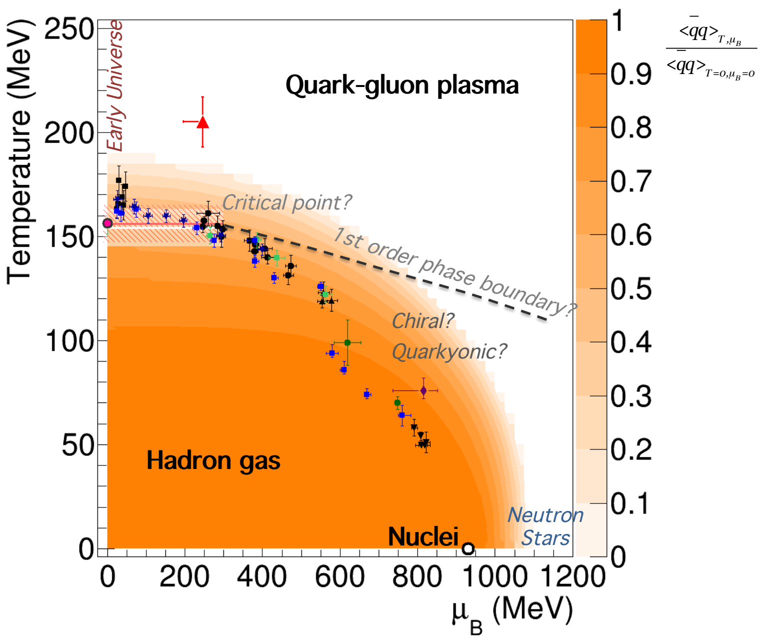

Fig. 1. (Colour on-line) Sketch of the phase diagram of QCD matter [1] including freeze-out data points in T and μ_B describing the final-state hadron abundances in a statistical hadronization model (blue squares and pink circle from [6, 7], light green squares from [8], black solid symbols from [9], dark blue stars from [10], green circles [11], lila diamond [12], as well as the Lattice QCD results from [5] (white curve) and [4] (red curve)). The red triangle is extracted from the measured invariant-mass slope of dimuons in the mass range of $1.2 < M_{\mu\mu} < 2$ GeV/c^2 in the dimuon measurement in In+In collisions at $\sqrt{s_{NN}} = 17.2$ GeV [13]. The expectation value of the chiral condensate relative to the vacuum is depicted as shaded gray/orange region [2].

Experimentally, the structure of the QCD phase diagram is studied by means of heavy-ion collisions. At energies of around 1 A GeV, strongly interacting matter is compressed to two–three times the nuclear density and collective kinetic energy is dissipated into intrinsic degrees of freedom. As a result, some nucleons are excited to baryonic resonances and in the final state of the reaction, mesonic states are observed with increasing abundances as the center-of-mass energy of the collision rises. Compressing nuclear matter can lead to a significant overlap of baryons which at some densities start to share their pion cloud content. At the other extreme, at largest energies probed at the LHC and top RHIC energies, creation of deconfined matter consisting of quarks and gluons (quark–gluon plasma) is expected. In both cases, hadron states lose their hadronic character and are forming exotic phases of strongly interacting matter. A scientific challenge, both to theory and experiment, is to understand the microscopic properties of such exotic matter over a broad range of temperature and baryo-chemical potential.

Figure 1 [1] shows the expectation value of the chiral condensate (gray/orange gradient) for QCD matter in a diagram of temperature *versus* baryo-chemical potential ($\mu_{\rm B}$) obtained from the Polyakov–Quark–Meson Model [2]. At temperatures around 150 MeV and vanishing baryon-chemical potential, the chiral condensate is vanishing and the phase transition occurs, as also confirmed by lattice calculations [4, 5]. There are also freeze-out points determined from fits to particle abundances measured in various experiments by various statistical hadronization models (SHM) [6–11]. They reach temperatures around 160 MeV at vanishing $\mu_{\rm B}$ (LHC and top RHIC energies) and extend down to around 50 MeV at high $\mu_{\rm B}$ for collision systems at the SIS18 energies. As the chiral condensate seems to drop rapidly beyond these freeze-out points, it is assumed that the nuclear fireball spends most of its time in a phase with a substantially reduced chiral condensate.

As a matter of fact, the direct observation of strong in-medium modifications of hadrons and formation of exotic states in such shortly lived matter is a demanding task. It is realized by comprehensive studies performed with different experiments over a broad energy region. In this context, the low-energy frontier characterized by medium temperatures but large baryon density is of large interest but is only poorly explored. Recently, it attracts a lot of attention by dedicated programs at RHIC (BES), FAIR and NICA.

2. HADES experimental programme

The HADES experiment operating at GSI/FAIR is currently the only experiment pursuing comprehensive and systematic investigations at the low-energy frontier. The strategy relies on measurements of bulk properties and rare probes such as strangeness and dielectrons. Hadrons carrying strangeness are specifically interesting as their production threshold at the SIS18 energies is mostly below the energy available in a single (free) $N+N$ collision. Therefore, their production requires a certain degree of collectivity, like multi-particle (or multistep) processes which are enhanced in dense medium and depends on in-medium potentials. Dilepton emission, on the other hand, is a penetrating probe providing a measure of the emissivity of the compressed and hot matter created in the course of heavy-ion collisions. At low invariant masses, spectral distributions are mainly determined by the in-medium spectral function of ρ meson [14]. At higher masses, beyond low vector meson poles, the emission rates are determined by multi-pion scattering and (at higher beam energies) semileptonic decays of open charm, Drell–Yann and QGP radiation. Studies of the low-mass region give a unique opportunity to investigate the in-medium spectral function of ρ meson. It is of fundamental importance since it is related to properties of the quark condensate by means of QCD and Weinberg sum rules [15–17].

Measurements of e^+e^- pairs in heavy-ion collisions are complemented with measurements of meson production. In addition, meson and dilepton emission is studied in elementary collisions using proton and pion beams. The latter are crucial to establish significant reference spectra in comparison to which true medium effects can be demonstrated. Furthermore, they provide an important insight into the role played by baryonic resonances in meson production, essential at the SIS18 energy regime. Using these reactions, HADES also performs first direct studies of the resonance dielectron decays. The latter are important for the understanding of Vector Meson Dominance in the description of the radiative decays of baryons. This Ansatz is a salient feature in the description of the ρ–baryon interactions being a driving force for a dramatic broadening of the in-medium spectral function.

Among the most important results obtained by HADES in its first measurement campaign (2002–2012) are:

— Excess radiation of virtual photons above cocktail of hadronic sources in the low invariant-mass range (0.2–0.7 GeV/c^2) in Ar+KCl collisions at 1.76 A GeV [18]. This radiation can be understood as being due to a thermal-like emission originating from a dense and hot phase of the collision. The invariant mass distribution of the dielectrons is consistently described by calculations predicting a significantly broadened spectral function of the ρ meson [19, 20].

— Observation of virtual photon radiation off the internal charged pion line in $n+p$ collisions below the η-meson production threshold. This process explains the strong difference in the virtual photon production between $p+p$ and $n+p$ reactions and appears crucial for the extraction of the excess radiation in $A+A$ collisions [21–23].

— The first measurements of Dalitz decays of baryonic resonances in the exclusive processes: $pp \to p\Delta^+ \to pp\,e^+e^-$ [23] and $\pi^-p \to N^* \to ne^+e^-$.

— Indication of a nearly complete disappearance of the ω signal and appearance of a dielectron excess relative to the $p+p$ reference [24] below the vector meson pole in $p+\mathrm{Nb}$ collisions for virtual photon momenta below 0.8 GeV/c [25].

— Search for a dark photon candidate in dielectron spectra measured in the reactions $p+p$ and $p+\mathrm{Nb}$ at 3.5 GeV, as well as Ar+KCl at 1.76 A GeV with an upper limit at 90% C.L. on the mixing with photon $\epsilon^2 = \alpha'/\alpha$ in the mass range of $M_U = 0.02$–0.6 GeV/c^2 [26].

— Evidence of the repulsive interaction of K^0_{S} within cold nuclear matter measured in proton-induced reactions and extracted from the comparison of the meson spectra with models precisely calibrated to $p+p$ reactions [29].

— ϕ-meson production in $A+A$ which is compatible with no strangeness suppression [30, 31] and appears as an important source of K^-.

— Unexpectedly large yields above SHM expectation for Ξ^- in Ar+KCl (1.76 A GeV) and $p+\mathrm{Nb}$ (3.5 GeV) reactions [32, 33].

All the observations in heavy-ion collisions are in accordance with a picture describing the fireball as a resonance gas with strong in-medium effects. To further scrutinize these observations, HADES focuses next on larger collision systems at the maximum SIS18 energy (Au+Au and Ag+Ag) and on reactions with hadronic beams (pions and protons) on proton and nuclear targets. The reactions with protons will be performed at maximum SIS18 energies ($\sim E_{\mathrm{kin}} = 4.5$ GeV) and will constitute an important reference for the future measurements at SIS100.

3. HADES experiment

HADES is a unique apparatus installed at the heavy-ion synchrotron SIS18 at GSI Darmstadt [34]. It has a large acceptance for charged particles and is optimized to identify very rare electrons and positrons in a hadron rich environment, which exceeds the electron signal by many orders of magnitude in multiplicity. The HADES spectrometer (see Fig. 2) consists of six identical sectors covering the full azimuth and polar angles from 18° to 85° measured relative to the beam direction.

Each sector of the spectrometer contains a Ring-Imaging Cherenkov Detector (RICH) operating in a magnetic field-free region, two drift chambers (MDCs) in front of the magnetic field, and two outer MDCs behind the magnetic field, time-of-flight (ToF) detectors, based for $\theta > 45°$ on scintillator rods and for $\theta < 45°$ on resistive plates (RPC), combined with an

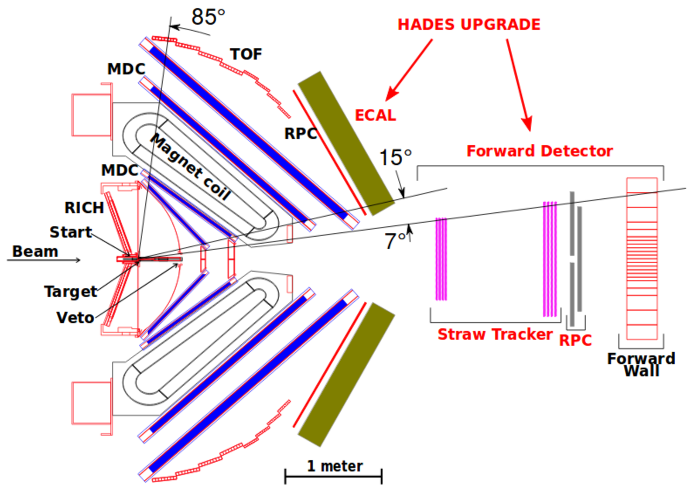

Fig. 2. Schematic side view of the HADES detector showing its compact design. The detectors are symmetrically arranged in the azimuthal angle around the beam axis. The distance to the target of the forward wall is typically 6 m.

electromagnetic calorimeter (ECAL) that replaces the pre-shower detector in previous campaigns. At forward angles $\theta < 8^{\circ}$, the detection of charged particles will be this year extended by two straw tube tracking stations, developed for the PANDA detector, and RPC ToF wall comprising together Forward Detector. Momentum measurement of charged particles in HADES is achieved by tracking the particles in front of and behind the toroidal field generated by six superconducting coils arranged symmetrically around the beam axis. A powerful and flexible trigger system selects events with defined multiplicity or topological pattern of charged hits in the ToF detectors. A major improvement of the spectrometer in terms of granularity and particle identification capability was achieved with the new RPC time-of-flight detectors. The Forward Detector increases significantly the acceptance for hyperon reconstruction in proton induced reactions.

The rate capabilities of the HADES DAQ system depend on the particle multiplicity of the collisions under investigation. The current rate capabilities of HADES are presented in Fig. 3 together with the existing and planned heavy-ion experiments exploring the high μ_{B} region of the QCD phase diagram. In the last Au+Au run, the DAQ system was operated at peak rates of 14 kHz. For lighter collision systems like Ag+Ag one expects to achieve rates of about 10 kHz and for elementary reactions up to 20 kHz. One central limiting factor, especially in the case of elementary collisions, is the current front-end electronics of the MDC. Its replacement by state-of-the-art modules will enable to increase this speed to about 80 kHz without changes to the current read-out procedures.

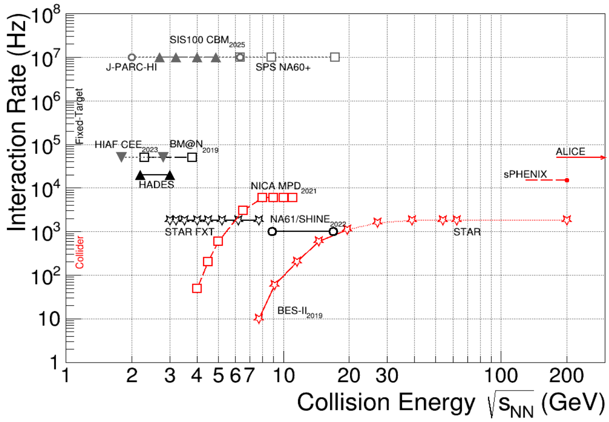

Fig. 3. Interaction rates achieved by the existing and planned heavy-ion experiments exploring the high μ_B region of the QCD phase diagram as a function of center-of-mass energy [35]. High-rate experiments are also proposed at J-PARC [36] and at the SPS [37], but are still in a conceptual stage.

4. The physics program for FAIR Phase-0

The goal of the HADES physics program is to explore the microscopic structure of dense baryonic matter. The focus is placed on investigations of hadron properties embedded in dense and hot baryonic matter and characterization of bulk properties. An important part of this program is to carefully define the reference against which modifications of the hadrons are measured and to study elementary processes relevant for understanding of in-medium effects. As main probes, we use virtual photons detected via dielectrons, which directly couple to the electromagnetic current of hadrons, and the production of strange hadrons. HADES will fully exploit the opportunities of FAIR Phase-0 to address in particular the following physics topics:

4.1. Emissivity of baryonic matter in the vector meson mass region

To advance our understanding of the emissivity of strongly interacting matter, studies of the ρ meson spectral functions will be pursued with higher statistics. Moreover, the identification of the narrow vector mesons ω and ϕ, and the spectroscopy of continuum radiation above vector meson poles in the dielectron invariant-mass distribution is planned. By comparing the ϕ multiplicity in the e^+e^- and K^+K^- decay channels, one can directly address the question whether narrow ϕ states exist before the system freezes out. With the set of measurements anticipated for Phase-0, HADES will study this question both in $A + A$ and $p + A$ collisions, *i.e.* in a hot and dense as well as in a cold matter. In a similar way, HADES can study the ω multiplicity in the e^+e^- decay channel. While collecting the statistics necessary to accomplish this task, HADES will also have access to the continuum radiation above the vector mesons poles, *i.e.* $M_{ee} \simeq 1\,\mathrm{GeV}/c^2$. This mass region is of particular interest since besides the in-medium ρ spectral function also multi-pion processes start to contribute, like $\pi + \rho \rightarrow a_1$, driving chiral vector–axial mixing. The latter processes are not expected to be important in $p + p$ collisions but should significantly contribute in $A + A$. Hence, the comparison to this reference will provide important information for the understanding of emissivity of QCD matter and shed light on unexplored in-medium properties of a_1 vector meson, the chiral partner of the ρ. Moreover, the double-differential investigation of the continuum radiation, *i.e.* inspecting the slopes of transverse momentum distributions for several bins of the growing invariant mass ($\mathrm{d}^2N/\mathrm{d}m_\mathrm{t}/\mathrm{d}M_{ee}$), will allow to conclude on the dependence of effective temperatures on the invariant mass.

4.2. Search for in-medium modification of the light vector mesons by inspecting their line shape

Strong medium modifications are expected due to the coupling of (vector) mesons to baryons. Due to their resonant character, they are strong only if the relative momenta between these mesons and the (baryonic) medium are not too high. In the measurement of proton-induced ω production off nuclei, HADES found a strong disappearance effect when selecting e^+e^- pairs with moderate laboratory momentum ($p < 800$ MeV) (see the previous section). Yet, the acquired statistics was by far not enough to address modifications of the line shape. In the case of proton-induced reactions, the omegas are produced with substantial recoil in the laboratory frame. In a pion-induced reaction, the kinematics is more favourable for the recoiless production, hence it will allow to study the meson production with small momenta where in-medium modifications are enhanced. Now, with the improved SIS18 performance, increased pion beam intensity is expected. HADES, therefore, aims for a long run using a medium-heavy target to optimize the ratio of in-medium/vacuum decays. The optimal choice is silver since this nucleus will also be investigated in $A + A$ collisions.

4.3. Multi-strange baryon production

The comprehensive study of strange-hadron production by HADES, including the most recent data in Au+Au at $1.23\,A$ GeV, unravelled unexpected features so far not consistently described by models based on microscopic transport theory. Most notable are the high yields of (hidden-strange) ϕ mesons and double-strange Ξ hyperons. These findings can potentially put into question former results based on comparisons of data to such transport models eventually biased by wrong assumptions. Yet, the situation is still not fully conclusive. To scrutinize further our understanding of strangeness production in our energy regime, error bars have to be substantially reduced, in particular for inclusive K^-, ϕ and Ξ spectra. The collision system Ag+Ag is best suited since it provides a maximum $A_{\rm part}$ around 200 while the beam energy can be raised by almost $0.5\,A$ GeV w.r.t. our previous Au+Au run, which will substantially increase the overall strangeness ($s\bar{s}$) production.

Attempts to better describe strangeness production with transport models include conjectures about unknown decay branches of heavy baryonic (non-strange) resonances and excited hyperon states into final states with open strangeness. Hence, the above measurements need to be accompanied by reference measurements using exclusive final states in $p+p$ reactions and inclusive production off cold nuclear matter. A simultaneous description of strangeness production by microscopic transport off cold matter and in hot and dense matter can provide strong evidence for the validity of the models used.

4.4. Electromagnetic structure of excited baryons and hyperons

Our recent studies of the baryon resonances in the exclusive channel $\pi^-p \to e^+e^-n$ and $NN \to NNe^+e^-$ revealed patterns of far off-shell ρ production followed by dielectron decay. This raises the question to what extent the baryon meson cloud is instrumental in transferring excitation energy into a virtual photon with invariant mass m_{e^+e-}. This question is related to the structure of the so-called transition form-factors of the resonances in the (soft) time-like region, where $0 < q^2 = (m_{e^+e^-})^2 < (M_{\rm R} - M_N)^2$ with $M_{\rm R}$ and M_N the resonance and the nucleon mass, respectively. Indeed, not too much is known about such time-like baryon transition form-factors. In particular, the role played by vector mesons in these transitions is of major importance. With the secondary pion beams [39] and the HADES detector, one has a unique opportunity to explore radiative and Dalitz decays of baryon resonances. Similar programme is also planned to be extended to excited hyperon states Λ^*, Σ^* which can be produced in proton-induced reactions at the maximum SIS18 energies [40]. These states will also be measured in hadronic final states with large statistics. Especially, the $\Lambda(1405)$ is the one unanimously considered to be, at least partially, a molecular meson–baryon state. Measurements of $\Lambda(1405)$, also in pion-induced reactions, will provide important information to constrain the model calculations and to unravel the nature of $\Lambda(1405)$. In the spirit of the discussed extended structure of baryons such investigations are highly interesting. A better understanding of the coupling of baryonic resonances to intermediary ρ mesons is also mandatory to validate emissivity calculations for hadron-resonance matter. Such studies can, therefore, pave the way for searching new states of matter with the upcoming Compressed Baryonic Matter program at FAIR's SIS100.

4.5. Two-body particle correlations

The planned experiments will also allow to perform other types of measurements requiring high statistics such as the study of short-range NN correlations (SRC), two-particle correlation studies aiming at the determination of *e.g.* the Λ–p scattering parameters and phase shifts. SRC provide direct insight into the short-range part of the nucleon–nucleon interaction, while hyperon–nucleon correlations will give valuable information on the equation of state of neutron stars assuming the presence of strange hadrons in the core of these dense objects. In particular, thanks to the ECAL, also the Σ^0–p and Ξ^0–p correlation can be addressed in future measurements for the first time.

4.6. Correlations and fluctuations

The strong rise towards lower collision energies of the fourth moment of the event-by-event (e-by-e) net-baryon multiplicity distribution observed by the STAR Collaboration [41] has recently attracted a lot of attention. In view of theoretical studies of critical phenomena in the QCD matter phase diagram, this finding could signal the existence of a critical end point. To further scrutinize this interpretation, an extension of the respective excitation function to even lower collision energies is planned by HADES. At the SIS18 beam energies, the fraction of protons bound in light fragments (d, t, He) is large and the question to what extent these influence the role of protons as proxy for baryon number fluctuations remains to be clarified. Furthermore, effects of volume fluctuations [42–44] due to the finite resolution of HADES centrality selections have to be carefully studied.

Flow observables play a very important role in the field of heavy-ion physics, since they allow to gather information on the equation of state (EoS) of dense nuclear matter and also provide a means to extract medium properties such as the ratio of shear viscosity and entropy density η/s. While η/s is around the theoretical lower boundary at high energies (RHIC and LHC), a strong rise towards lower energies is expected. However, current analyses do not yet result in a consistent picture and more precise data, especially on higher-order flow coefficients, in the HADES energy region will help to narrow down the properties of the hadronic medium produced here.

With the high statistics data collected with 1.23 A GeV collisions and future runs with Ag+Ag at 1.65 A GeV, the investigation of higher-order flow harmonics will be possible. Multi-particle azimuthal correlation techniques can in addition be utilized to disentangle the contribution from collective and non-flow processes involved in the dynamical evolution of heavy-ion reactions. At low energies, v_1 and v_2, related to directed and elliptic flow, have been measured for pions, charged kaons, protons, neutrons and fragments at the BEVALAC and SIS18, but so far higher-order harmonics have not been studied.

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REFERENCES

[1] T. Galatyuk [HADES Collab.], *PoS* **INPC2016**, 354 (2017).
[2] B.J. Schaefer, J.M. Pawlowski, J. Wambach, *Phys. Rev. D* **76**, 074023 (2007).
[3] J.W. Holt, N. Kaiser, W. Weise, *Prog. Part. Nucl. Phys.* **73**, 35 (2013).
[4] S. Borsanyi *et al.* [Wuppertal–Budapest Collab.], *J. High Energy Phys.* **1009**, 073 (2010).
[5] O. Kaczmarek *et al.*, *Phys. Rev. D* **83**, 014504 (2011).
[6] A. Andronic *et al.*, *Nucl. Phys. A* **837**, 65 (2010).
[7] J. Stachel *et al.*, *J. Phys.: Conf. Ser.* **509**, 012019 (2014).
[8] F. Becattini *et al.*, *Phys. Lett. B* **764**, 241 (2017).
[9] J. Cleymans, H. Oeschler, K. Redlich, S. Wheaton, *Phys. Rev. C* **73**, 034905 (2006).
[10] L. Adamczyk *et al.* [STAR Collab.], `arXiv:1701.07065 [nucl-ex]`.
[11] G. Agakishiev *et al.* [HADES Collab.], *Eur. Phys. J. A* **52**, 178 (2016).
[12] X. Lopez *et al.* [FOPI Collab.], *Phys. Rev. C* **76**, 052203 (2007).
[13] H.J. Specht *et al.* [NA60 Collab.], *AIP Conf. Proc.* **1322**, 1 (2010).
[14] R. Rapp, J. Wambach, *Adv. Nucl. Phys.* **25**, 1 (2000).
[15] T. Hatsuda, Y. Koike, S.H. Lee, *Nucl. Phys. B* **394**, 221 (1993).
[16] J.I. Kapusta, E.V. Shuryak, *Phys. Rev. D* **49**, 4694 (1994).
[17] R. Rapp, J. Wambach, *Eur. Phys. J. A* **6**, 415 (1999).

[18] G. Agakishiev *et al.* [HADES Collab.], *Phys. Rev. C* **84**, 014902 (2011).

[19] T. Galatyuk *et al.*, *Eur. Phys. J. A* **52**, 131 (2016).

[20] S. Endres, H. van Hees, J. Weil, M. Bleicher, *Phys. Rev. C* **92**, 014911 (2015).

[21] G. Agakishiev *et al.* [HADES Collab.], *Phys. Lett. B* **690**, 118 (2010).

[22] J. Adamczewski-Musch *et al.* [HADES Collab.], `arXiv:1703.08575 [nucl-ex]`.

[23] J. Adamczewski-Musch *et al.* [HADES Collab.], *Phys. Rev. C* **95**, 065205 (2017); B. Ramstein *et al.* [HADES Collab.], *EPJ Web Conf.* **199**, 01008 (2019).

[24] G. Agakishiev *et al.* [HADES Collab.], *Eur. Phys. J. A* **50**, 82 (2014).

[25] G. Agakishiev *et al.* [HADES Collab.], *Phys. Lett. B* **715**, 304 (2012).

[26] G. Agakishiev *et al.* [HADES Collab.], *Phys. Lett. B* **731**, 265 (2014).

[27] G. Agakishiev *et al.* [HADES Collab.], *Phys. Rev. C* **87**, 025201 (2013).

[28] G. Agakishiev *et al.* [HADES Collab.], *Phys. Lett. B* **742**, 242 (2015).

[29] G. Agakishiev *et al.* [HADES Collab.], *Phys. Rev. C* **90**, 054906 (2014).

[30] G. Agakishiev *et al.* [HADES Collab.], *Phys. Rev. C* **80**, 025209 (2009).

[31] J. Adamczewski-Musch *et al.* [HADES Collab.], `arXiv:1703.08418 [nucl-ex]`.

[32] G. Agakishiev *et al.* [HADES Collab.], *Phys. Rev. Lett.* **103**, 132301 (2009).

[33] G. Agakishiev *et al.* [HADES Collab.], *Phys. Rev. Lett.* **114**, 212301 (2015).

[34] G. Agakishiev *et al.* [HADES Collab.], *Eur. Phys. J. A* **41**, 243 (2009) [`arXiv:0902.3478 [nucl-ex]`].

[35] T. Ablyazimov *et al.* [CBM Collab.], *Eur. Phys. J. A* **53**, 60 (2017).

[36] J-PARC-HI proposal `http://silver.j-parc.jp/sako/white-paper-v1.21.pdf`

[37] A. Dainese *et al.*, *Frascati Phys. Ser.* Vol. **62**, (2016).

[38] J. Adamczewski-Musch *et al.* [HADES Collab.], `arXiv:1812.07304 [nucl-ex]`.

[39] J. Adamczewski-Musch *et al.* [HADES Collab.], *Eur. Phys. J. A* **53**, 188 (2017).

[40] R. Lalik *et al.* [HADES Collab.], *J. Phys.: Conf. Ser.* **1137**, 012057 (2019).

[41] X. Luo [STAR Collab.], *PoS* **CPOD2014**, 019 (2015).

[42] V. Skokov, B. Friman, K. Redlich, *Phys. Rev. C* **88**, 034911 (2013).

[43] B. Ling, M.A. Stephanov, *Phys. Rev. C* **93**, 034915 (2016).

[44] P. Braun-Munzinger, A. Rustamov, J. Stachel, *Nucl. Phys. A* **960**, 114 (2017).