2.10 Status and Plans of HADES

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Abstract

HADES is operated at the SIS18 and investigates the microscopic properties of resonance matter formed in heavy-ion collision in the 1 A GeV energy regime. Important topics of the research program are the mechanisms of strangeness production, the emissivity of resonance matter and the role of baryonic resonances herein. The latter topic is addressed also by investigation of exclusive channels in proton and pion beam induced reaction, both for hadronic and semi-leptonic final states. To optimize the performance of the spectrometer for the FAIR Phase-0 campaign, several upgrade project are underway.

1. **Properties of Hadron Resonances and Resonance Matter**

   In central collisions of heavy ions at energies around a few A GeV , strongly interacting matter is substantially compressed and collective kinetic energy dissipated into intrinsic degrees of freedom. As a result, baryonic resonances are formed and in the final state of the reaction increasing abundances of mesonic states are observed as the beam energy rises. A scientific challenge is to understand the microscopic properties of the matter formed in the early stages of such collisions. Indeed, from studies using microscopic transport models, it is observed that the density in the interior of the collision zone may reach up to three times nuclear ground state density already at a beam energy of 1 A GeV. In such an environment hadronic states will likely change their properties compared to those observed in vacuum. Several experiments have tried to search for modifications of vector mesons states using their decay into lepton pairs. Although the results are not conclusive yet, a general trend examined is a strong broadening of vector meson states in the medium already for cold nuclear matter. A crucial question of QCD is under which conditions of density and temperature hadrons will ultimately lose their hadronic character and the system in such collisions will change from hadron gas into exotic states of strongly interacting matter? The situation at colliders (RHIC, LHC) is qualitatively very different. Due to the high gamma factors, the initial state at mid-rapidity is characterized by nearly instantaneous parton parton interactions which create a state of extreme energy density. The system then evolves through

   Figure 1 depicts a sketch of the phase diagram of strongly interacting matter. The experimental information is depicted by symbols localizing the chemical freeze-out region which depend on system size and on beam energy. They remarkably line up along a narrow corridor spanning from LHC ($T \simeq 160$ MeV, $\mu_B \simeq 0$ MeV) down to SIS18 energies ($T \simeq 50$ MeV, $\mu_B \simeq 800$ MeV) and are determined with the help of statistical hadronization models from final state particle abundances measured in these collisions. Also shown is the expectation value of the chiral condensate calculated in a Polyakov–Quark–Meson Model approach as a function of baryo-chemical potential (μb) and temperature [1]. The systematics of these freeze-out points suggests that a thermal spectrum of hadrons is observed even at low energies, where a quark gluon plasma is not formed.

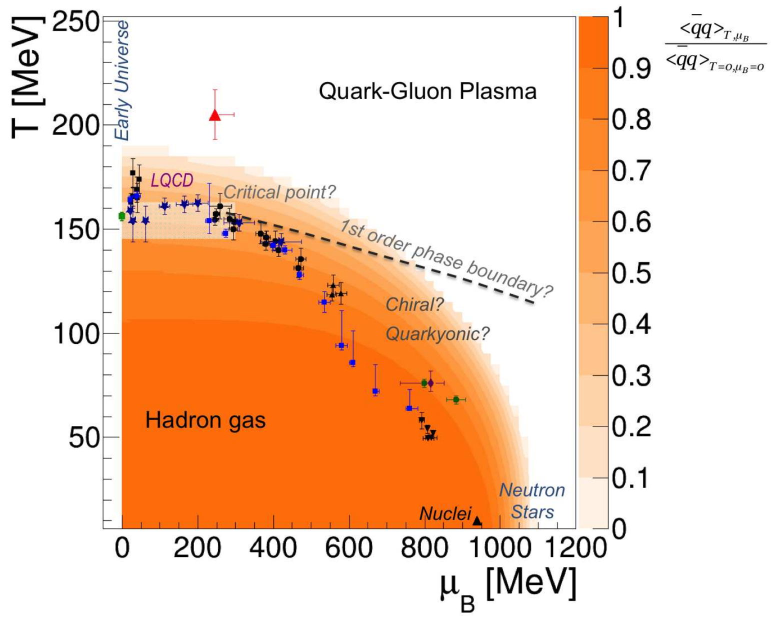

Figure 1: Sketch of the phase diagram of strongly interacting matter. The shaded area reflects the expectation value of the chiral condensate relative to its vacuum value. The data points are freeze-out configurations obtained by analyzing hadron final states in the framework of statistical hadronization models.

To learn more about the microscopic structure of matter in the region of high baryo-chemical potential HADES pursues a strategy, which relies on systematic measurements of strangeness production and virtual photon emission in heavy-ion collisions. The latter observable has the advantage, that this radiation is emitted through out the collision and hence is very sensitive to the properties of the dense and hot system. The disadvantage however is its small branching ratio and the fact that the spectrometer integrates the radiation over time. Consequently, contributions from the late stage of the collision have to be identified and subtracted before conclusions about the radiation from the dense phase can be drawn. Hadrons carrying strangeness are similarly interesting as their production threshold is high compared to the available energy in an NN collision at these beam energies. Consequently, their production requires a certain degree of collectivity, like it is the case in multi-particle processes or in deep off-shell production.

A central part of the physics program of HADES are measurements of rare meson production in heavy-ion collisions and in respective elementary collisions. The focus of the latter are the decay of baryonic resonances into intermediate ρ mesons and into final states with open strangeness thus addressing the observables utilized for the study of dense matter. The program includes in particular the reconstruction of exclusive hadronic and semi-leptonic final states. The paper is organized in the following way: In the next Chapter, selected results of experiments addressing virtual photons are presented. The examples address the concept of a reference spectrum in comparison to which medium-effects are addressed. In Chapter 3 few results on strangeness are shown emphazising the connection to virtual photon production and the role of baryonic resonance it. Chapter 4 gives a short status of the HADES campaign 2012–2014 and Chapter 5 provides an outlook on the upcoming physics program of HADES anticipated for the years 2018 to 2021 and the spectrometer upgrades planned for this campaign.

2. Dilepton Emission from Hadronic Systems

An important reference for the study of dilepton emission (here and in the following e^+e^- pairs) off strongly interacting matter is the production of dileptons in $p + p$ and $n + p$ collisions at energies below the threshold for η production. Expected contributions are then solely by conventional bremsstrahlung and due to Delta Dalitz-decay. HADES has observed a surprisingly large isospin dependence comparing $p + p$ with $n + p$ collisions at $T_{beam} = 1.25(\sqrt{s} = 2.4)$ GeV [2]. This strong deviation appears in the spectral distribution (dP/dM_{e+e-}) of the lepton pairs towards the kinematic limit. While conventional bremsstrahlung can not account for the effect, although there is a difference in $n + p$ and $p + p$ due to the absence of a electric dipole moment in the latter case, calculations including emission from the intrinsic charged pion line in an one-boson-exchange model for the $n + p$ case, and using a VDM form factor for the pion photon vertex, could reproduce the trend observed in the data. Charged pion transfer is only possible in $n + p$ reactions due to isospin restrictions. In a strict VDM picture such a process can be interpreted as the formation of a deep off-shell ρ-meson in the overlapping cloud of the by-passing baryons. To what degree such a production would rather proceed through an intermediate baryon resonance state, such as a $\Delta(1232)$ resonance, remains an open question. Indeed, calculations of the $\Delta(1232) \rightarrow Ne^+e^-$ electromagnetic transitiofrom factor in the kinematic region discussed above with the Spectator Quark Model [4] and a Two-component Model [5] show only little or moderate deviations from solutions assuming pure QED (point-like) transitions, respectively.

While at a proton beam energy of around 1 A GeV essentially $\Delta(1232)$ resonances are active in electron-pair production, the situation changes substantially at an energy of 3.5 A GeV . Fig. 2 shows the inclusive dilepton yield obtained by HADES in the channel $p+p \rightarrow e^+e^-X$ as a function of the dilepton invariant mass. The cocktail shown has been calculated with a microscopic transport model and represents only prompt dileptons while the data contains also contributions from Dalitz- and direct decays of long-lived mesons (dominantly π^0, η and ω). In the model, prompt dileptons stem solely from (off-shell) ρ meson production produced in baryonic resonance decays. The treatment of off-shell ρ–meson propagation leads to a modified mass distribution of the mesons governed by phase space constraints. The higher the resonance mass, the more prominently the ρ pole emerges, yet, the resulting spectral distribution of ρ mesons from baryonic resonance decays (all res.) significantly differs from a distribution obtained if prompt, non-resonant production is assumed (Phytia). The thin solid curve going through the data is the sum of mesonic and prompt dileptons. Although the model has a number of parameters which have to be adjusted, it illustrates how dilepton production might proceed through strict vector meson dominance and how important a detailed understanding of resonant ρ–nucleon coupling is for the theoretical description of dilepton production in heavy-ion collisions.

Indeed, the preparation of a reference spectrum based on elementary inclusive cross sections

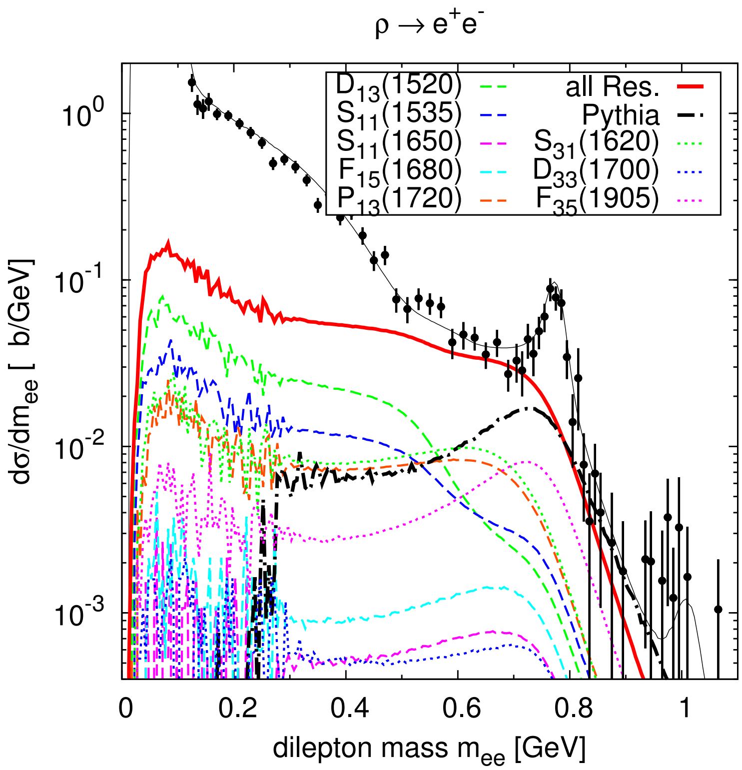

Figure 2: Dilepton invariant mass spectrum from $p + p$ collisions at 3.5 GeV (HADES data) compared to a calculation using a resonance model as implemented in microscopic transport codes. The cross sections for the excitation of the different baryonic resonances are obtained from a fit to data on meson production. All baryonic resonances, except the $\Delta(1232)$, produce lepton pairs via explicit decay to an intermediate ρ meson and subsequent annihilation into a pair of electrons. Figure taken from Ref. [3].

provided a conventional explanation for the inclusive electron pair spectra observed in $C+C$ collisions at 1 and 2 A GeV by HADES [6–8] and earlier by the DLS Collaboration [9], which could not be reproduced in microscopic model calculations at the time the DLS data was taken (DLS puzzle). It later turned out that within $\simeq 20\%$ uncertainty, $C+C$ collisions at these energies essentially appear as mere superposition of individual $N+N$ collisions, while a true excess radiation could only be observed in the heavier $Ar+KCl$ ($Ca+Ca$ in case of DLS) reactions at 1.76 A GeV .

A good description of this excess radiation can be obtained if emission out of thermalized system is assumed [10]. Under this assumption, the emissivity of matter at not too high temperatures is given by the thermal average of the in-medium ρ propagator for which ρ–baryon couplings are fundamentally important [11]. The spectra observed in experiments is then given as a four-volume integral over the emissivity, *weighted* with the time-dependent temperature and density profile of the hot and dense system. The latter can, e.g., be derived by coarse graining a microscopic transport code. Fig. 3 shows the dilepton excess radiation, obtained from the $Ar+KCl$ data by subtracting all known sources from long-lived mesons decay, compared to a calculation assuming thermal emission and coarse graining UrQMD [12, 13]. The calculations agree well with data and the spectra show nearly exponential shapes, although the calculations are entirely based on VDM and hence dominated by large by off-shell ρ meson.

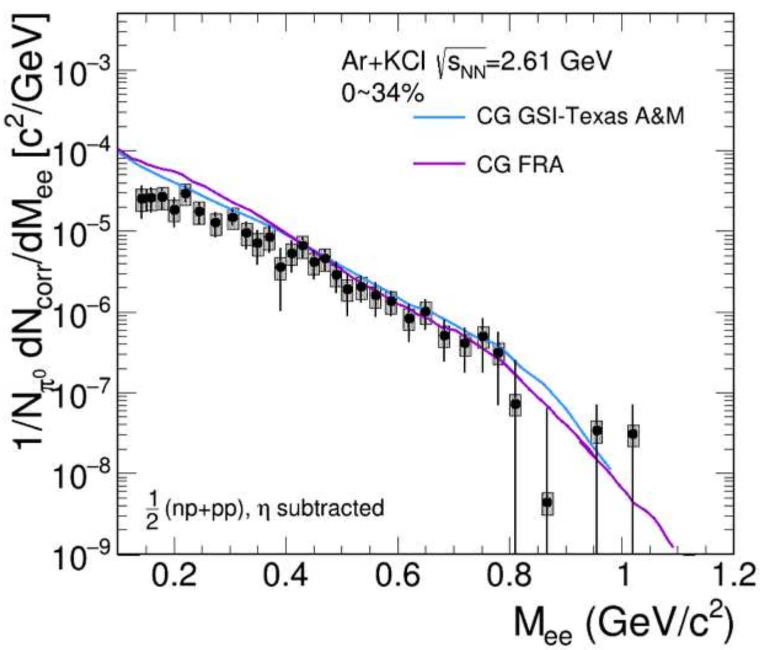

Figure 3: Dilepton excess radiation observed in $Ar + KCl$. Contributions from first chance NN collisions and late η–Dalitz decays have been subtracted from the data. The yield is normalized to the number of produced π^0 (to remove trivial A_{part} dependences). The colored lines show the results of two versions of corse grained UrQMD calculations using different concepts for obtaining the thermal parameters. The data has been analyzed for the 34% most central events.

3. Selected Results on Strangeness Production

Similarly important are baryonic resonances for the description of strangeness production in heavy-ion collisions, in particular at beam energies where the total energy in a single $N + N$ collision is not sufficient to produce a final state with strangeness. If instead binary collision occur, which include secondary (or even higher generation) baryonic resonance states, the kinematic constraints can be lifted beyond the effect of fermi motion. A theoretical description of secondary interactions beyond the low-density approximation is difficult but desirable as the collision frequencies are as high that asymptotic states are not easily reached between subsequent collisions.

A particular role in the production and propagation of strangeness is played by the $\Lambda(1405)$ resonance. The existence of this resonance influences the interaction of antikaons propagating through a baryonic medium since this resonance can be understood as a dynamically produced antikaon-nucleon quasi-bound state [14]. Such a picture is also supported by lattice data if the strange magnetic form factor of the resonance is investigated [15]. The $\Lambda(1405)$ has been observed by HADES in $p+p$ collisions at 3.5 GeV collisions 4. The broad structure is attributed to the formation of the $\Lambda(1405)$ state which appears a little bit shifted, a hint that the state is a molecule and its appearance depending on the reaction dynamics.

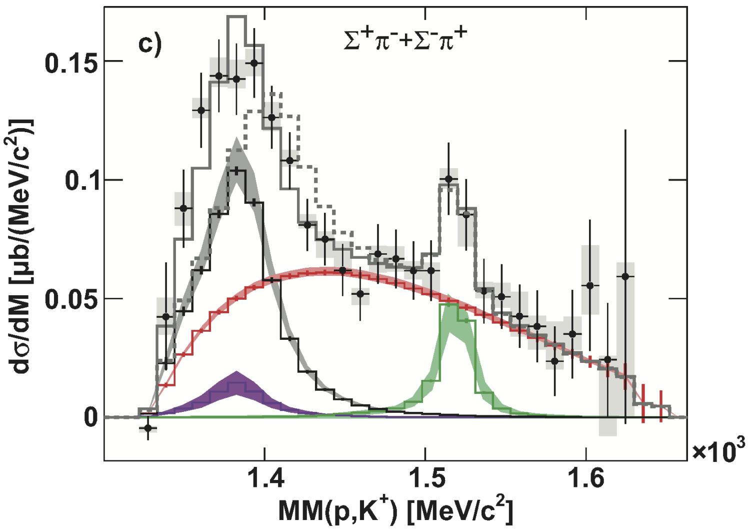

Figure 4: Missing mass distribution to the pK^+ subsystem of the exclusive final state $pK^+n\pi^+\pi^-$ reconstructed in $p+p$ reactions at 3.5 GeV. The distribution is interpreted in terms of contributions from $\Lambda(1405)$ and $\Lambda(1520)$, histograms shaded in grey and green, respectively, $\Sigma(1385)$ (purple) and channels not involving excited hyperons (red). The pole mass for the simulated $\Lambda(1405)$ contribution was fitted to the experimental distribution and favors a downward shift by 20 MeV/c^2 .

The resonant scattering, as well as the different NN thresholds for associated ($K\Lambda$) and direct ($K\bar{K}$) kaon production, suggests a rather complex structure of kaon production in heavy-ion collisions at SIS18 (”threshold-”) energies. Yet, the yields observed in $Ar + KCl$ collisions at 1.76 A GeV shows a very simple behaviour. The multiplicities of all observed hadrons an be explained assuming a break-up (freeze-out) of a thermalized hadronic system if strangeness is treated canonically by implementing a *strangeness correlation radius* R_c. The latter leads to suppression of hadronic states with open strangeness but not for states with hidden strangeness like the ϕ. Fig. 5 shows the reconstructed hadron multiplicities in comparison with a fit using the THERMUS code. All multiplicities including states involving strange quarks are reproduced assuming a temperature of $\simeq 76$ MeV and a baryochemical potential of $\simeq 800$ MeV, except for the double strange baryon Ξ [16]. Note that ϕ is produced abundantly as expected by the statistical model and holds up for $\simeq 30\%$ of the produced antikaons [17].

These observations, as well as those in dilepton production are accordance with a picture describing the fireball as *strongly* interacting resonance gas. The observed hadron multiplicities resemble thermalization although, e.g., the ow pattern of protons does not. That raises the question if the equilibration is driven by binary collisions of the (hadronic) constituents, as it is implied by the low-density approximation forming the basis of the model calculations used to describe heavy-ion collisions and medium-effects at these energies? Likely other mechanisms drive equilibration, like, e.g., a strong quantum mechanical entanglement [18]. To further scrutinize these observations, HADES focused on studying a heavy collision system at maximum SIS18 beam energy and on exploiting pion induced reactions.

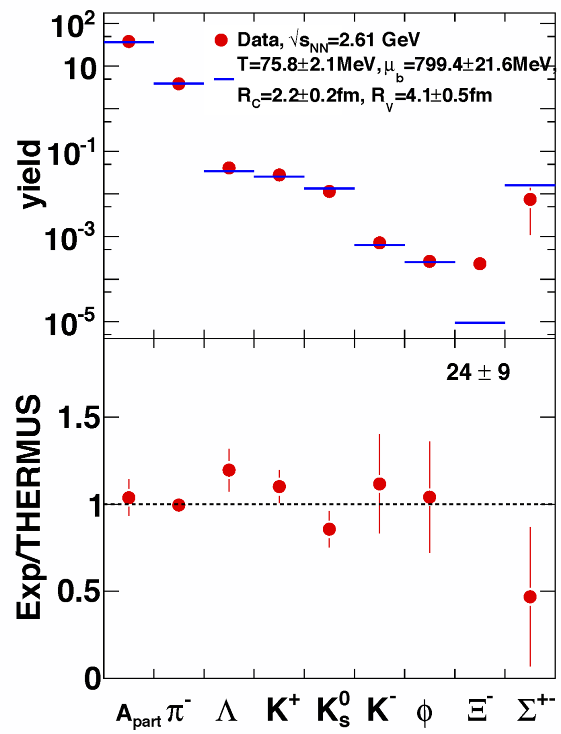

Figure 5: Hadron multiplicities in full phase space for 38% most central $Ar + KCl$ collisions at 1.76 A GeV. The data is compared to the expectation of a Statistical Hadronization Model (THERMUS). The extracted paramters for temperature and baryochemical potential fit weel in the systematics shown in Fig. 1.

4. The HADES campaign 2012–2014

During the first measurement campaign (2002-2007), HADES was operating with a 18-fold segmented inner time-of-flight detector system. This low granularity made runs with heavy collision systems impossible. In the shutdown period for SIS18, the HADES collaboration replaced this system by a RPC system with more than 1000 individual cells. Also replaced was the innermost layer of drift chambers.

In April 2012 HADES took 7.2×10^9 events during 30 days run for the collision system $Au + Au$ at 1.23 A GeV. For the first time, a nearly complete set of strange hadrons (ϕ, K^+, K^-, K^0) has been reconstructed at such low beam energies ($\sqrt{s}$ =2.4 A GeV). Again a large ϕ meson abundancy, which accounts for about 25% of the total K^- production, could be observed - note that a NN collisions at this beam energy is $\simeq 500$ MeV below the $NN\phi$ threshold. Ongoing analysis work focuses on a further reduction of systematic errors and on a comprehensive comparison to results from transport calculations.

As expected already, the yield of dielectrons reconstructed in these collisions shows a strong excess above a reference spectrum. Two different analysis strategies have been implemented, one focusing on highest purity, the other on highest efficiency for electron positron reconstruction. The results nicely agree, though the one with higher statistics comes with the price of an higher uncertainty in the overall normalization. The spectrum again drops off nearly exponentially.

A first experiment with the GSI pion beam has been realized in 2014 with two weeks of beam on target in total. The first run was dedicated to strangeness production in cold matter in pion-induced reactions on light (12C) and heavy (74W) nuclei at a beam momentum of 1.7 GeV/c. The goal of the second run was to measure both double pion and dilepton production in $\pi^{-}+p$ reactions around the pole of $N(1520)$ resonance using polyethylene and carbon targets. Data at four different pion beam momenta (0.656, 0.69, 0.748 and 0.8 GeV/c) were collected with the largest statistics in the case of 0.69 GeV/c momentum, aimed for dilepton production studies.

The two-pion production data samples have been included in the multichannel Partial Wave Analysis (PWA) developed by the Bonn-Gatchina group, which allows for the extraction of the various $2\pi N$ channels ($\Delta\pi, \rho N, \cdots$). The total (resonant+non-resonant) ρ is derived and converted into a $e^{+}e^{-}$ contribution using the Vector Dominance Model (VDM) assumption. Adding to this ρ contribution a cocktail of point-like baryonic sources, the exclusive dilepton production can be described quite nicely. This demonstrates the consistency between the dilepton and double pion production channels and suggests that the involved time like baryonic electromagnetic transitions can be described by VDM. The ρN couplings of the $N(1520)$ are also of high interest due to the connection with the expected medium modification of the ρ meson spectral function. Most of the new results will be presented on the upcoming Quark Matter Conference in February 2017.

5. HADES at FAIR Phase–0

With the start of FAIR Phase 0 in 2018, most of the detector systems will reach an age of more than 15 years. Hence, we have started an upgrade program replacing the UV detector of the RICH by a detector based on MAPMTs. The development of this detector is a joint initiative between HADES and CBM, the same modules will later also be used in the CBM RICH. The pre-shower detector (polar angle coverage from 18 to 45 degree), which augmented electron/positron identification and also served as additional tracking detector in front of the low-granularity time-of-flight system during the first experimental campaign, will be replaced by an electromagnetic calorimeter (ECAL). This new detector is based on recycled lead glass crystal from the former OPAL calorimeter. For the first time, this will enable studies of radiative baryonic resonance decays with real photons. Moreover, the success of the experimental program addressing elementary reactions calls for an instrumentation of the acceptance region between polar angles of 2 to 8 degree in order to enlarge the phase space acceptance. This solid angle will be equipped with tracking stations and a new RPC-based time-of-flight wall. The tracking system will be based on developments for the

PANDA tracker which will be composed of by 5 mm straw tubes. Last but not least a moderate upgrade of the DAQ system will increase the band width such that interaction rates of up to 100 kHz are in reach for elementary reactions and around 20 kHz for heavy-ion reactions.

Further experiments on baryonic-resonance and cold-matter physics will be realized, taking advantage of foreseen improvement of the extraction and increase of the space charge limit. In addition, with the ECAL, the capacity of HADES to provide high precision data for PWA for baryonic resonances with masses up to 2 GeV/c^2 will be extended to exit channels with neutral mesons. HADES at the moment represents the only facility world-wide, which combines a pion beam with dilepton spectrometry and acts as a precursor in view of existing plans for meson beam facilities for baryon spectroscopy. Emphasis will be on the electromagnetic transition form factors of baryonic resonances, the coupling of vector mesons and kaons to baryons and medium effects in cold nuclear matter.

Measurements of hadron production off cold nuclear matter provide an important reference for understanding heavy-ion collisions. They also provide an ideal test bed for microscopic transport theory. HADES has already studied $p + Nb$ collisions at 3.5 GeV in 2007. Yet, many of the the interesting observation made suffer from statistical significance or call for multi-differential analysis. Moreover, particle identification in the 2007 run was limited since no fast start detector had been available at this time. Meanwhile, HADES has developed such detectors based on mono-crystal CVD diamond which combine high rate capability with excellent time resolution for minimum ionizing particles. A high statistics run would enable very important studies like, ϕ production and propagation both in the hadronic and leptonic final state, in-medium w-meson, multi-strange baryon production, short range correlation (SCA) and two particle correlation studies aiming at determining, e.g., the λp phase shifts.

The combined measurement of dielectrons and strangeness performed by HADES in $Ar + KCl$ and Au+Au collisions have provided new intriguing results which call for further systematic investigations. We propose an experiment which focuses on measuring a medium-heavy collision system at the maximum energy at SIS18, to increase the NN center-of-mass energy in favour of an enhanced strangeness production. Silver, e.g., can be stripped to charge state 45^+ behind the UNILAC and would then allow acceleration in SIS18 to 1.67 A GeV.

The main goals are to search for multi-strange baryons in connection to our finding in $p+Nb$ and $Ar+KCl$, and to extend the dielectron and strangeness excitation functions. Indeed, the unexpected high cascade yield is by now not explained theoretically and call for more data (see also above). In the dielectrons channel, we will focus on studies of properties of the low-mass excess as well as on vector meson (ρ, ω, ϕ) spectroscopy. The strangeness study will include ϕ meson production via the $K^+K^?$ decay channel, kaon production characteristics, $\Lambda(1115)$, $\Sigma(1385)$ and $\Xi(1321)$ strange baryon production, and HBT correlations.

The motivation for operating HADES as part of the Compressed Baryonic Matter program at SIS100 is two-fold: First, HADES can bridge the gap from the SIS18 energies to the SIS100 region were CBM acceptance is favourable. It enables the option to measure dilepton spectra in heavy-ion collisions with two different spectrometers to so minimize systematic uncertainties. Second, HADES can serve as ideal spectrometer to continue reference measurements focusing on cold matter studies. As medium-effects show a strong momentum dependence, the relevant phase space for meson production and propagation is near to the target rapidity.

Finally, HADES can also be operated with a liquid hydrogen target, which is not possible in CBM. Any reference measurements, as well as a continuation of the physics program of HADES at SIS18 is possible at the new experimental site.

6. **Acknowledgments**

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