The electromagnetic response of resonance matter and other strange observations

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Baryonic matter at few GeV beam energy

- Baryon-dominated system throughout the evolution ($N_\pi/A_{\text{part}} \approx 10\%$)
- Comparatively long lifetime of the dense "fireball"

- Au+Au $\sqrt{s_{\text{NN}}} = 2.42$ GeV
- Long interpenetration times

Central cell (3x3x3 fm3) thermodynamic properties from coarse graining UrQMD

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HADES explores baryon-rich matter with rare and penetrating probes

- Emissivity of matter (dileptons)
  Vector meson spectral functions modified by coupling to baryons
  Play substantial role in ρ melting observed in UrHIC
  cf. R. Rapp, H. van Hees, PLB 753 (2016) 586

- Flavor production (strangeness)
  Strong kinematic suppression of direct K⁻ production
  K⁻ couples strongly to baryons

- Flow anisotropies
  Preferred out-of-plane emission due to shadowing

- Net baryon number fluctuations
  No antiprotons, additional terms when correcting for volume fluctuations
High Acceptance DiElectron Spectrometer at GSI, Darmstadt

HADES program:
- Excitation function for low-mass lepton pairs and (multi-)strange baryons and mesons
- Various aspects of baryon-resonance physics

- Large acceptance: full azimuthal coverage, 18°-85° polar angle
- Interaction rate capability: up to 50kHz trigger rate
- Mass resolution 2 % (ρ/ω region)
HADES event reconstruction (2.5×10^9 events)

Particle identification by means of:
- Velocity
- Momentum
- dE/dx in MDC and ToF
- RICH information

\[ \pi^0 \rightarrow e^+e^- \]
\[ \mu^+ \rightarrow e^+\nu_{e}\bar{\nu}_{e} \]
\[ \eta \rightarrow \gamma\gamma \]

\[ \phi \rightarrow K^+K^- \]
\[ \Lambda \rightarrow p\pi^- \]
\[ \Sigma^+ \rightarrow p\pi^+ \]

\[ \Xi^- \rightarrow K^-\pi^+\pi^- \]
\[ \Omega^- \rightarrow K^-\pi^+\pi^- \]
Final state
“Hadron-chemistry”
Strange particle production

- First comprehensive data set on strange particle productions from the Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV

- Far below (free NN) threshold $\Rightarrow$ strong constraints on production mechanism

- Universal scaling with participant number $A^{\alpha}_{\text{part}}$ ($\text{Mult} \sim A^{\alpha}_{\text{part}}$, with $\alpha > 1$)

- Production yields reflect matter properties
Macroscopic description of hadron production

- Grand canonical ensemble \((T, \mu_B, V)\)
- Strangeness canonically suppressed at low temperatures \(\Rightarrow\) needs additional parameter: \(R_c < R_V\)

- Hadron abundances described by four parameters \(T, \mu_B, R_V, R_c\)

- What is the mechanism responsible for system thermalization?
- “Matter” formed also at low energies (high \(\mu_B\)?)

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THERMUS v2.3
The role of $\phi$ meson: do $K^+$, $K^-$ freeze-out sequentially?

- Sizeable increase of $\phi$ meson to $K^-$ ratio around production threshold
  25% of $K^-$ are from $\phi$ decays

- Sufficient statistics to perform multi-differential analysis for $K^+$, $K^-$ and $\phi$

- Unique freeze-out criteria when $\phi$ decay kinematics is taken into account → no evidence for sequential freeze-out of $K^+$, $K^-$ support for statistical model

See also
Ar+KCl in HADES: PRC 86 (2010)
Al+Al in FOPI: EPJA 52 (2016)
Flow and its anisotropies

- Kinetic freeze-out parameters from blast wave fit to hadron spectra
- $T_{\text{kin}} = 62 \pm 10 \text{ MeV}, \langle \beta_r \rangle = 0.36 \pm 0.04$
- $\Lambda$ and $\phi$ fall out of the trend

- Global freeze-out parameters fit well into trend of world data
- $T_{\text{kin}} < T_{\text{chem}}$ also at low energies (high $\mu_B$)
(Net)-Proton Number Fluctuations
The experimental challenge ...

- Phase space region, not too large not too small
- Data need efficiency corrections! Note that efficiency = $\text{acc} \times \text{det.eff.} \times \text{rec.eff.}$
  → Two methods tested and validated with full MC simulations and realistic detector response
- Volume fluctuations due to centrality selection, no antiprotons, no terms cancel!

HADES $y - p_t$ coverage for protons

Proton $m_t$ spectra

Proton multiplicity distributions

Analysis based on $40 \times 10^6$ Au+Au evts divided into 4 centrality classes
(Net)-Proton Number Fluctuations

Need to select a phase-space bite small enough to avoid spectators, but large enough to stay away from Poisson limit! \( \Delta y = 0.2 \)

How about bound protons? \( d/p = 0.3 - 0.4 \)
\( \rightarrow \) deuteron fluctuation analysis is ongoing

red/black = unfolding (preferred method) + vol. flucs. corr.
green = evt-by-evt eff correction of factorial moments + vol. flucs. corr.

QM2017, R. Holzmann
„If you want to detect something new, build a dilepton spectrometer“
S. Ting
Electromagnetic radiation

- No strong final state interactions
  - leave reaction volume undisturbed
- Encodes information on collisions \((T, \mu_B, \tau_{\text{coll}})\)

The vector correlator is directly accessible in HIC:

\[
\frac{dN_{\parallel}}{d^4xd^4q} = \frac{-\alpha_{\text{EM}}^2}{\pi^3 M^2} f_B^B(q_0; T) \text{Im}\Pi_{\text{EM}}^{\mu\nu}(M, q; \mu_B, T)
\]

- Unique direct access to in-medium spectral function
Virtual photon emission

Two independent analyses (red, black)

- First measurement of $e^+e^-$ for a heavy system in this energy regime
- Normalization to number of neutral pions
- Strong excess yield ($0.15 < M < 0.7$ GeV/$c^2$) above $e^+e^-$ cocktail components of meson decays at freeze-out and elementary baryonic reference observed

→ Medium radiation
Virtual photon emission – isolation of excess

- Isolation of excess radiation by subtracting experimentally measured contributions from first chance (NN reference) and late emission ($\eta$)

- Acceptance corrected excess yield

- $M_{ee} < 1$ GeV/c$^2$ ~ exponential fall-off - 'Planck-like'
  → measurement of radiating source temperature
Virtual photon emission – fireball thermometer

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- Fit $\frac{dN}{dM} \sim M^3 \exp\left(-\frac{M}{T}\right)$ to range $M=0.1-0.8 \text{ GeV}$

- $<T>_{\text{emitting source}} = 72 \pm 2 \text{ MeV/kB}$
Virtual photon emission – fireball chronometer

- Strong excess (\(\sim A_{\text{part}}^{1.3}\), interplay \(V \otimes \tau_{\text{coll}}\))
- Rapid increase of relative yield reflects the number of \(\Delta\)'s/ \(N^*\)'s regenerated in fireball
- Dilepton chronometer of the collision time

What is the nature of the excess?
- Regeneration of baryonic resonances
- Subsumed into spectral functions
Thermal dileptons at SIS18?

- Strong broadening of the in-medium $\rho$
- Thermal rates folded over coarse-grained UrQMD medium evolution works at low energies
- Supports baryon-driven medium effects at UrHIC (SPS and RHIC)!

$T_{\text{max}} = 85$ MeV, $\rho = 3 \rho_0$

$\frac{dN_{\pi^0}}{dM_{ee}}$ (GeV/c$^2$)

$\frac{1}{N_{\pi^0}} \frac{dN_{\pi^0}}{dM_{ee}}$ (c$^2$/GeV)

Excitation of the vacuum (melting of condensate) matches spectral medium effects!

$\langle \langle \bar{q}q \rangle \rangle(T, \mu_B) = 1 - \sum_h \frac{g_h^2 \sum_h}{m_h^2 f_h^2}$

HADES, collaboration review
Résumé …

- First measurement of acceptance corrected *excess spectrum* at low energies ⇒ *robust understanding* of low-mass dilepton excess radiation by $\rho$-baryon coupling.

- Analyzed *proton nb fluctuations* ⇒ *HADES data* allow to extend RHIC results towards low $\sqrt{s_{NN}}$, but interpretation needs input from theory.

- Unexpectedly high $\phi$ multiplicities. Feed down correction important when interpreting kaon spectra.

- Strange hadrons ⇒ *Universal scaling with participant number* $A_{\text{part}}$

- Completion of the excitation functions of flow, $T_{\text{chem}}$, $T_{\text{kin}}$ and $<\beta_T>$

- *Exciting results from* $\text{Au+Au collisions at } \sqrt{s_{NN}}=2.42$ GeV ⇒ *suggest “thermalize” strongly interacting medium created*
... and prospects

- Strong scientific program for FAIR Phase-0
- Important measurements to complement the exploration of the phase diagram and to provide a valuable reference measurements
  - $\pi+p/A \sqrt{s}=1.7 - 1.9$ GeV: EM structure of baryonic resonances
  - Ag+Ag at 1.65A GeV: multi-strange hadrons & intermediate-mass dileptons
- Continue physics program at higher energies SIS100
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~100 collaborators
Thank you for your attention!