Studying in-medium hadron properties in baryonic matter with HADES

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Strangeness in NN and nuclear matter:
• \(\Lambda(1405)\) production and search for \(ppK^-\) in \(pp\) reactions
• kaons (K0), \(\Xi(1321)\), \(\phi\) production in A+A

\(\rho/\omega\) mesons in NN and p+A
High Acceptance Di-Electron Spectrometer

- Beams from SIS18: protons, nuclei, pions
  - $2.0 \text{ GeV} < \sqrt{s} < 3.2 \text{ GeV}$
- Spectrometer with high invariant mass resolution - 2% at $\rho/\omega$
- Versatile detector for rear probes:
  - dielectrons (e+, e-)
  - strangeness: $\Lambda$, $K^{\pm,0}$, $\Sigma(1385)$, $\Xi^-$, $\phi$
Kaons in nuclear matter

$K^0 / K^+$:

$K^+/K^0$ considered as good quasiparticle

✓ at SIS18 ($p_K < 1$ GeV/c) $\lambda_{K^+} \approx 5$ fm (weak absorption)

✓ $\Lambda(1405)$ physics: entry to $K^-$ in medium properties, kaonic clusters pp$K^-$..,
Λ (1405) doorway into bound K⁻ N

\[ p + p \rightarrow \Lambda(1405) + p + K^+ \]
\[ \Sigma^{+/-} + \pi^{+/-} \]
\[ \rightarrow n + \pi^{+/-} \]

- Pole shift? interference with non. res \( \Sigma \pi \)
- Lower pole stronger, \( \Lambda(1405) \)-N FSI?
Search for ppK\(^-\) bound state in p+p @ 3.5 GeV

\[ p+p \rightarrow ppK^- + K \]

\( \Lambda p \)

**PKW \( ^+\Lambda \) final state**

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**DISTO**

signal (\( M \approx 2.27\text{GeV} \))

PWA (Bonn-Gatchina) – (one example) \( N^*(1650)^+/N^*(1710)^+/N^*(1720)^+/N^*(1875)^+ /N^*(1900)^+ \) + non resonant

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**work in progress**

aim: global analysis of HADES/DISTO/COSY-TOF data
Case of A+A @ 1-2AGeV

1-2 AGeV: moderate densities but long system life time

**Baryonic matter:**

- \( \rho / \rho_N = 1-3, \ T < 80 \text{ MeV}, \ \tau \sim 12-14 \ \text{fm/c} \)
- nucleons, baryonic resonances (~30%) \( \Delta_{33} \)
- mesons(\( \pi^0 \)) ~10% "resonance (\( \Delta, N^* \)) matter"

- **Sub-threshold** production of (\( \omega, \phi, K^- K^+, \Xi \)):
  - confined to high density zone
  - Multi-step processes \( \sim \) Apart

  ex:
  - \( N+N \rightarrow N\Delta, \ \Delta+N \rightarrow N + N + \phi \)
  - \( N+N \rightarrow N K\Lambda, \ \pi\Lambda \rightarrow K N \)
  - \( P_{\rho/\omega \rightarrow e^+e^-} \approx 10^{-6} ! \)
$K^0_s$ and $K^+$ production in A+A

$K^0_s$ in Ar+KCl @ 1.756 GeV

$K^+$ in Au+Au @ 1.0 GeV

Transport models: $U_{KN} \approx 20-40$ MeV

Kaons are repealed from nuclear matter:
- flow out of plane: KAOS, FOPI
- reduced yield at low $p_t$ (p): FOPI, ANKE

...but usually assumed $m^* = m(1 - \alpha \rho_B / \rho_0)$ far too simple...

Results for $K^-$ are not yet conclusive...
φ and φ/ω ratio in Ar + KCl

- $R_{φ/ω}^{A+A} >> R_{φ/ω}$ in NN and πN reactions
- $φ → K^+K^-$
- $ω → e^+e^-$
- $OZI : φ/ω = tan^2 δ \cong 4.2 \cdot 10^{-3}$

\( R_{φ/ω}^{A+A} \) : enhanced vs NN and πN

φ and ω rates described by statistical hadronization models; no suppression for ss
Double strange $\Xi^-$ (1321) in Ar+KCl

**data:** PRL 103 (2009) 132310

- $\Xi^- \rightarrow \Lambda \pi^-$
- $\Lambda \rightarrow p \pi^-$

**Observation:**
- First measurement 640 MeV below NN threshold!
- Production significantly larger than transport & statistical hadronization models.

**Question:**
- What is the production process?
- $K^- \Upsilon \rightarrow \pi \Xi^-$?
Statistical hadronization model at work

data: Ar+KCl HADES: EPJA 47 (2011) 21

calculation with Thermus (SHM): strangeness: canonical ensamble with suppression induced via strangeness conservation column (R_C)
• enhanced \( \eta \) (2), \( \phi \) (hidden strangeness)
• enhanced \( \Xi \) (~25)
• overall \( \chi^2/n.d.f \) ~2.3

• what is the mechanism of thermalization?
**ρ** -meson in vacuum and nuclear matter

**e+e-** annihilation into 2 pions: charged pion form factor

*ρ meson dominance*

1967: Sakurai

Vector Meson Dominance

**π^+ π^-** annihilation into e+e- in hot nuclear matter (HI collisions)

*ρ meson gets very broad!*

Melting of the meson in nuclear matter
Vector mesons in medium & ChS restoration


\[ m^* \approx m \left( \frac{\langle \bar{q}q^* \rangle}{\langle \bar{q}q \rangle} \right)^\mu \]

T. Hatsuda / S. Lee: QCD sum rules
PRC46(1992)R34

\[ m^* = m (1 - \alpha \rho^*/\rho) \]
p+p vs p+Nb @ 3.5 GeV

- large acceptance at small $M_{e^+e^-}$ and p ($<1$ GeV/c) (first measurement at low p!)
- p+p cocktail: based on known sources fixed to data $\pi^0/\eta/\omega/\rho$
- underestimated $e^+e^-$ yield below VM pole $\rightarrow$ missing component? $\rightarrow$ higher resonances ($\Delta$, $N^*$)

Nuclear modification factor

$$R_{pA} = \frac{d\sigma^{pNb}}{d\sigma^{pp}} \frac{\langle A^p_{part} \rangle}{\langle A^{Nb}_{part} \rangle} \frac{\sigma^{pp}_{reaction}}{\sigma^{pNb}_{reaction}}.$$
e+e- excess in p+Nb

- "slow" (p<0.8 GeV/c) pairs
- "excess over pp reference"

- Clear excess in p+A below VM pole & absorption of $\omega$ (observed also in $\gamma$+A exp)

- Secondary reactions: $\pi$+N $\rightarrow$ N$^*$ (1520), N$^*$ (1720), $\Delta$ (1620) $\rightarrow$ N$\rho$ $\rightarrow$ Ne+e- (i.e. transport models)

- Or/and in medium $\rho$ modification?

- First $R$ $\rightarrow$ pe+e- decay process must be understood!
Baryon resonance structure

Space-Like el. Transition Form Factors

\[
\begin{align*}
\text{e}^- + p &\rightarrow \pi^0 + \gamma^* + p \\
q^2 &< 0
\end{align*}
\]

studied at JLab/CLAS/MAMI, ...

Time-Like el. Transition Form Factors: Dalitz decays

\[
\begin{align*}
\text{e}^- + p &\rightarrow \pi^- + R + \text{e}^+ \\
q^2 &> 0
\end{align*}
\]

pion electroproduction

Dalitz Decays: poorly known!

\[
\begin{align*}
\text{e}^- + p &\rightarrow \text{e}^- + N + \pi \\
q^2 &< 0
\end{align*}
\]

\[
\begin{align*}
\text{N}^* &\rightarrow \text{N} + \text{e}^+ + \text{e}^- \\
\text{directly related to:}
\end{align*}
\]

\[
\begin{align*}
V &\rightarrow D & M &\text{Dominance Model} \\
2M_N &\text{q}^2
\end{align*}
\]
e+e- from Baryon Resonances in vacuum

**pp->ppπ⁰  @3.5 GeV**

- Resonance contribution estimated from ppπ⁰ and pnπ⁺ channels

**pp->ppe+e-  @3.5 GeV**

- Resonances (R) with Mass up to 2 GeV included
- Calculations with point-like RNγ* does not describe data
- eTFF(Me⁺e-) dependence very important -> Vector Meson contribution!

**eTFF-em. Transition Form Factors**
pion beams at SIS18: HADES in 2014

Badly need for hadron physics to improve our understanding of baryon resonance properties!

For physics discussed in this talk:

- $\pi^+ \pi^-$ production: coupling of $\rho$ to resonance

Old "Manley" analysis PRD30, (1984) 904

$1.3 < \sqrt{s} < 2$ was based on 240,000 events (differential; distributions not available)

Full excitation function can be measured with HADES within 2 weeks!

+ Many others like: $\pi^- p \rightarrow \pi^- p$, $\pi^- p \rightarrow K^0 \Lambda$, $K^+ \Sigma^-$

Needed for PWA and coupled channel calculations

- $e^+ e^-$ never measured

Resonance Dalitz decays $R \rightarrow N e^+ e^-$ (electromagnetic Transition Form Factors)

- Meson production of nucleus: $K^\pm$, $\rho$, $\omega$, $\phi$

differential distributions are even more scarce (or missing)
Radiation from baryonic matter

Vacuum

\[ \Delta(N^*) \rightarrow Ne + e^- \]

Dense matter 2-4\(\rho_0\) :

- baryon resonances + nucleons +
- (20-30\%) pions

1) How does the \(\gamma^*(e^+e^-)\) couple to resonance?

1) How does the radiation from "resonance" matter look like?

superposition of NN reactions?

multistep processes (transport) ?

thermalized system ?
CC compared to NN reference.

- NN and C+C normalized to the individual $N(\pi^0)$
- C+C data (1 and 2 AGeV!) reproduced (within 20%) by superposition of NN interactions (reference) – no room (within error bars) for in-medium effects.
e+e- pairs from Ar+KCl @ 1.756

Cocktail with „freeze-out” comp.

excess related to radiation from inside of the fireball

radiation from short lived resonance states propagating in matter?

\[ \tau_{\text{fireball}} \sim 8-10 \text{ fm/c} > \tau_\Delta \sim 1.3 \text{ fm/c} \rightarrow N_{e^+e^-} \sim \tau_{e^+e^-} \text{ Volume} \]
Summary:

- new $K^0_S$ data support repulsive $KN$ in-medium potential; $\Lambda(1405)$ is crucial for antikaon properties in nuclear matter -> pp data waits for comparison with microscopic calculations
- enhanced $\phi$ production w.r.t. NN/$\pi$N data
- enhanced (above SHM predictions) production of double strange $\Xi(1321)$
- in-medium effects on $\rho$ (p+A) are not clear yet:
  
  determination of $\rho$-meson shape in N-N collisions („vacumm”) is far from trivial and requires better understanding of $\Delta/N^* - \rho$ couplings → el. Transition Form Factors, work is in progress
  
  Properties of baryon resonances in nuclear matter are strongly related to the in-medium $\rho$ properties
- pion beam programme essential for understanding of vector meson in-medium properties & kaon production
The Collaboration

Cracow (Univ.), Poland
Darmstadt (GSI), Germany
Dresden (FZD), Germany
Dubna (JINR), Russia
Frankfurt (Univ.), Germany
Giessen (Univ.), Germany
München (TUM), Germany
Moscow (ITEP,RAS), Russia
Nicosia (Univ.), Cyprus
Orsay (IPN), France
Rez (CAS, NPI), Czech Rep.
Sant. de Compostela (Univ.), Spain
LIP, Portugal
N+N reference (II): e+e- in n+p


- η production – fixed by COSY, WASA data
- bremsstrahlung pn→pne+e- (non resonant), why it is so much different from pp?
charge pion exchange & pion eFormFactor

for example:

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Resonance reconstruction
strangeness

Ar + KCl @ 1.75 AGeV: excellent rec. capabilities

\[ K^0_s \rightarrow \pi^+ + \pi^- \]

\[ \Lambda \rightarrow p^+ + \pi^- \]

\[ \phi \rightarrow K^+ + K^- \]

\[ \Xi \rightarrow \Lambda + \pi^- \]

first observation at SIS
Vector mesons in cold matter - experiments

**Direct: \( \rho \) meson line shape**

- No mass shift
- \( \rho \) broadening

\[ \Gamma_{\rho} \approx 217 \text{ MeV} \]

\( \gamma + A \) line shape

\( m^*/m_0 = 1 - 0.09 \rho_N/\rho_0 \)

\( \rho \) mass shift

**Indirect: Transparency**

\[ T_A = \frac{\sigma_{\gamma A \rightarrow VX}}{A \cdot \sigma_{\gamma N \rightarrow VX}} \]

\( N_{e+e-} \propto \Gamma_{e+e-} \tau_{\text{meson}} = \frac{\Gamma_{e+e-}}{\Gamma_{\text{tot}}} \)

\( \Gamma_{\omega}^{*} \sim \rho_N v_\omega \sigma_{VN} \)

\( \Gamma_{\phi}^{*} \sim 33 - 50 \text{ MeV} \)

\( \phi \) meson (SPRING8, ANKE)

Large \( \omega \) absorption

\( \Gamma_{\omega \text{tot}}^{*} \approx 210 \text{ MeV} \)
Strangness production in ArKcl

Boltzmann fit:

\[
\frac{1}{m_t^2} \frac{d^2M}{dm_1 dm_2} = C(y_{cm}) \exp \left( \frac{-(m_t - m_0)c^2}{T_B(y_{cm})} \right).
\]

\[\rightarrow \text{inverse slopes } T_B(y_{cm})\]