Time like baryon transition studies with HADES

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for the HADES collaboration

QNP2022 - The 9th International Conference on Quarks and Nuclear Physics
Outline

❑ General motivations of the HADES experiment at GSI
   *From dense hadronic matter to hadron structure studies*

❑ Results for time-like electromagnetic baryon transitions in pion beam experiments

   *to be completed by*

Rafal Lalik, Hadron structure, Sept. 6 15:25 Hyperon studies
Szymon Harabasz, Heavy Ions, Sept. 8 12:30 medium effects in heavy-ion collisions
Fatima Hojeij, Heavy Ions, Sept. 8 13:35 exclusive channels in π−+C at 0.7 GeV/c

❑ Conclusions
HADES: exploring dense QCD matter

- Equation-of-State: First order transition? Search for a critical point
- Chiral symmetry restoration
- Microscopic structure of baryon dominated matter
- Role of baryonic resonances, hyperons
- Complementary to SPS, RHIC, ..

A+A: 1-3A GeV
\( \sqrt{s} = 2-2.4 \) GeV

Observables:
- Correlations and fluctuations
- Collective effects
- Strangeness
- Dileptons

T. Galatyuk, NPA-D-18-00411 (2018) QM18

B. Ramstein, QNP2022
Emissivity of baryon rich matter

- Moderate temperatures: $T < 90 \text{ MeV}$
- Baryon-dominated system ($N_\pi/A_{\text{part}} \approx 10\%$)
- Important role of vector mesons for low mass dilepton production

\[ \frac{dN_{ll}}{d^4xd^4q} = -\frac{\alpha_{em}^2}{\pi^2M^2} L(M^2) f^B(q \cdot u; T) \text{Im}\Pi_{em}(M, q; \mu_B, T) \]

McLerran, Toimela, PRD 31, 545 (1985)

Baryon Dalitz decay

Coupling of baryons to vector mesons is crucial
**Vector Meson Dominance in the baryon sector (I)**

Dalitz decay of baryonic resonances

\[ \rho, \omega, \phi \rightarrow \gamma^* \rightarrow e^+e^- \]

**Vector Meson Dominance Model**

Coupling constants

**Meson** Dalitz decays: (numerous data Crystal Ball/TAPS, A2, Na60 data)
many theoretical studies trying to connect VMD and the microscopic properties of QCD
"e.g. G. Adlarson et al., Phys. Rev. C95, 035208 (2017)"

**Baryon** Dalitz decays: almost unexplored, most calculations of etFF are based on Vector Meson Dominance.
Vector Meson Dominance in the baryon sector (II)

Various versions of VDM: equivalent for universal coupling

VDM2 : « strict VDM »
Sakurai, Phys. Rev 22 (1969) 981
- most commonly used in Heavy Ion transport models
- one single $\rho NN^*$ coupling
- Overestimation of baryon radiative decays

VDM1 : »two-component »
- $\rho$ contr. vanishes at $m_{\gamma^*}=0$,
- $\gamma N$ and $\rho N$ couplings fixed independently
- Phase between $\gamma$ and $\rho$ contributions to be fixed by data

\[ \Sigma_{VDM2} = \left( \frac{M_\gamma}{M_\rho} \right)^2 \Sigma^0_\rho \]

\[ \Sigma_{VDM1} = \left( \frac{M_\gamma}{M_\rho} \right)^2 \Sigma^0_\rho \]
Baryon electromagnetic transitions

Time-like electromagnetic form factors

\[ 4m_{ee}^2 < q^2 < (M_R - M_n)^2 \]

variable

No data are available

Limit at \( q^2 = 0 \) given by real photon decay

Space-like electromagnetic form factors

Data from Jlab (CLAS) up to \( -q^2 = 4 \text{ GeV}^2 \)

Exploration of higher \( q^2 \) with CLAS12

A. D’Angelo Sept.5 10:30
K. Joo Sept.5 15:00

Role of quark core and meson cloud in the TL region?
Time-like Electromagnetic baryon transition Form factor models

- Covariant model (T. Pena and G. Ramalho) quark core + meson cloud
- Parameters fitted to space-like data
- Predictions for the time-like region


Quark core contribution:
- Quark form factors inspired by VDM

Meson cloud contribution:
- Based on pion electromagnetic form factor
- Dominant contribution in the time like region

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Access to Time-like eTFF via baryon Dalitz decay (I)

- **e⁺e⁻ invariant mass distributions** \((q^2 = M_{ee}^2)\):

\[
\frac{d\Gamma^{N^* \rightarrow Ne^+e^-}}{dM_{ee}} = \frac{2\alpha}{3\pi M_{ee}} \Gamma^{N^* \rightarrow N\gamma^*}(M_{ee}),
\]

\(\Gamma^{N^* \rightarrow N\gamma} \) = \frac{\sigma_+ 1/2}{m_+^{3/2} m_-^{1/2}} |G_T(q^2)|^2 \times \Gamma^{N^* \rightarrow N\gamma}

\(m_\pm = m_* \pm m_N\)

\(\sigma_\pm = m_\pm^2 - M_{ee}^2\)

**effective form factor**

**radiative decay width**

- **QED reference**: calculation for **constant covariant form factors** (point-like baryons)

extrapolation of radiative decay at finite \(q^2\)

- \(J^P = \frac{1}{2} -\) (e.g. N1535):

\(|G_T(q^2)|^2 = 2|G_E(q^2)|^2 + \frac{q^2}{2m^*2} |G_C(q^2)|^2\)

- \(J^P = \frac{3}{2} -\) (e.g. N1520):

\(|G_T(q^2)|^2 = |G_E(q^2)|^2 + 3|G_M(q^2)|^2 + \frac{q^2}{2m^*2} |G_C(q^2)|^2\)

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Access to Time-like eTFF via baryon Dalitz decay (II)

- Additional information from $e^+/e^-$ angular distributions:
  - spin density matrix formalism

M. Zetenyi et al. C 104, 015201 (2021)
A. Sarantsev priv. comm.

\[ |A|^2 \propto 8k^2 \left[ 1 - \rho_{11} + (3\rho_{11} - 1) \cos^2 \Theta \right. \\
\left. + \sqrt{2} \text{Re} \rho_{10} \sin 2\Theta \cos \phi + \text{Re} \rho_{1-1} \sin^2 \Theta \cos 2\phi \right] \]

related to helicity amplitudes or electromagnetic transition form factors

\[
\rho_{11} = \frac{1 + \lambda}{3 + \lambda} = \frac{A_\perp}{2A_\perp + A_\parallel} \quad \text{J=1/2} \\
\lambda = \frac{|G_{E/M}^+|^2 - |G_C^\pm|^2}{|G_{E/M}^\pm|^2 + |G_C^\pm|^2} \quad \text{J>1/2} \\
A_\perp = \frac{l+1}{l} \left| G_{M/E}^{\pm} \right|^2 + (l+1)(l+2) \left| G_{E/M}^{\pm} \right|^2 \\
A_\parallel = \frac{M^2}{m^2} \left| G_C^\pm \right|^2
\]
Δ(1232) Dalitz decay studies with HADES

First measurement of $\Delta(1232)$ Dalitz decay branching ratio ($\Delta^+ \rightarrow p e^+ e^-$) using information from PWA ($p n \pi^+$, $p p \pi^0$)

Sensitivity to the electromagnetic structure (form factor) of the N-Δ transition


Dominance of magnetic transition ($\gamma^*$ are transversely polarized)

$E=1.25$ GeV $pp \rightarrow ppe^+ e^-$

HADES PRC95, 065205 (2017)
Dalitz decay studies of heavier baryons with HADES

\[ p + p \rightarrow pp e^+ e^- \quad 3.5 \text{ GeV} \]

Dalitz decays of point-like baryonic resonances constrained by \( pp\pi^0 \) and \( pn\pi^+ \) channels: QED reference

+ “direct” \( \rho \) and \( \omega \)

Effect of electromagnetic transition Form Factors for light baryonic resonances \((N(1520), \ldots)\)
Specific motivations for pion beam experiments with HADES

Production of resonance with given mass in s-channel \( M_R = \sqrt{s_{\pi p}} \)

HADES + GSI pion beam is an ideal (unique in world) tool to
- Study the unknown time-like electromagnetic structure of baryons
- Complete the very scarce pion beam data base for hadronic couplings
- Test description of in-medium dilepton production

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In medium vector meson spectral functions


S. Harabasz Sept. 8 12:30

Strong **broadening of in medium** $\rho$ spectral function

**Observed from LHC to GSI energies!**

**Vector Meson Dominance**

$$D_\rho(M,q,T,\mu_B) = \frac{I}{M^2 - m_\rho^2 - \Sigma_{\rho\pi} - \Sigma_{\rho\phi} - \Sigma_{\rhoN}}$$

Pion loop: $\pi N$ interactions

$\Sigma_{\rho\pi} = \rho + \Sigma_{\pi}$

$\Sigma_{\rhoN} = \rho$

$\Sigma_{\rho\phi} = \rho$

$\Sigma_{\rhoB} = \rho$

$\Delta; N(1520), \ldots$

Baryonic loop

- sensitive to $\rho NN^*$ couplings
- related to baryon Dalitz decay $\Delta/N^* \rightarrow Ne^+e^-$

**can be best accessed via $\pi N$ reactions**

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B. Friman et al. NPA617 (1997) 496.
R. Rapp and J. Wambach EPJA 6 (1999) 415

$\Delta \rightarrow N^* \rightarrow Ne^+e^-$
High Acceptance Di-Electron Spectrometer

Experiments (2004-2022)

**Hadronic matter studies**
- C+C 1 and 2A GeV, Ar+ KCl 1.75A GeV,
- Au+Au 1.25 AGeV, Ag+Ag 1.65A GeV

**Cold matter:**
- p+Nb 3.5 GeV, $\pi^-$+C/W 1.7 GeV/c

**Elementary reactions:**
- p+ p 1.25, 2.2, 3.5 GeV, 4.5 GeV d+p 1.25 GeV/nucleon
- $\pi^-+\text{CH}_2/C$ 0.7 GeV/c

before lepton selection

after lepton selection
Pion beam at GSI

- Primary beam: $6 \times 10^{10}$ Nitrogen ions/s at $E = 2\text{A GeV}$
- Momentum acceptance = 2 % (rms)
- Momentum range $p_\pi = 0.65 - 1.5 \text{ GeV/c}$
- Secondary pion beam: $2 \times 10^5 \pi/s$ for $p_\pi$ around 0.7 GeV/c


Measurements on CH2 and C targets
- $\pi^- p \rightarrow \pi^+ \pi^- n$ and $\pi^- p \rightarrow \pi^- \pi^0 p$
  (4 measurements $\sqrt{s} = 1.46-1.55 \text{ GeV/c}^2$)
- $e^+e^-$ production $\sqrt{s} = 1.49 \text{ GeV/c}^2$
- data on C target also used for cold matter studies F. Hojeij, Sept. 8 13:35

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Partial Wave Analysis in $2\pi$ production channels

**HADES data** ($\pi^- p \rightarrow n\pi^+\pi^-$ and $\pi^- p \rightarrow p\pi^0\pi^-$ at 4 energies) + photon (CB-ELSA, MAMI) and pion (Crystal Ball) data base included in Bonn-Gatchina Partial Wave Analysis

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- total $3/2^-$
- $N(1520) \ 3/2^-$
- total $3/2^-$
- $N(1440) \ 3/2^-$
- total $1/2^-$
- $N(1535) \ 1/2^-$

**s-channel $3/2^-$ $N(1520)$ is dominant**

**Branching ratios** of $N(1440)$, $N(1535)$, $N(1520)$ to $2\pi$ channels ($\Delta \pi$, $\sigma N$, $\rho N$) → **8 new entries** (4 first + 4 additional entries)
Selection of quasi-free $\pi^- p \rightarrow$ ne$^+ e^-$

- Selection of the exclusive $\pi^- p \rightarrow$ ne$^+ e^-$ channel using missing mass
- Quasi-free treatment of $\pi^- C$ interactions $\sigma_C/\sigma_p = 3.3 (\sim Z^{2/3})$
- Subtraction of residual $\pi^0$ contribution
Comparison to the QED reference

QED reference:
- Dalitz decay of $J^P=3/2^-$ or $1/2^-$ (largest contr. to $\pi p \leftrightarrow n\gamma$ and $\pi p \rightarrow \rho n$) with constant covariant form factors
- Cross section deduced from $\sigma(\pi p \rightarrow n\gamma)$

• $\sigma(\pi p \rightarrow n e^+ e^-) = 2.14 \pm 0.06$ (data) $\pm 0.23$ (QED ref) $\mu b$
  
  $\sigma = 1.16 \ast \sigma_{\text{QED}}$

• $M_{ee} < 200 \text{ MeV}/c^2$ consistency with QED reference
• Strong excess at larger $M_{ee}$ (up to a factor 5)
• Effective time-like transition form factor
  
  $R_{\text{QED}} = (d\sigma/dM)/(d\sigma/dM)_{\text{QED}}$

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**Data comparison with VDM2/VDM1 models**

**VDM1/VDM2 test:**
- Large overestimation of measured yields with VDM2
- Two component (direct $\gamma + VDM1$) with constructive interferences gives a better description of the full spectrum

**Ideal case:**
$\rho \rightarrow \pi^+\pi^-$ extracted from the same experiment (PWA)

Direct test of VDM models based on known $\rho$ contribution


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**HADES coll. arXiv:2205.15914 [nucl-ex]**

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Two-component Lagrangian model

Microscopic calculation of $\pi^- p \rightarrow n e^+ e^-$


Strong contribution of the Born terms

Here, « Kroll-Lee-Zuminio » « VDM1 » Lagrangian is use

→ Shape and yield sensitive to the interference between the $\gamma$ and $\rho$ contributions
Invariant mass distribution: comparison to models

**Lagrangian model:**
- based on VDM1 for various baryon transitions
- shown with phase $\phi=90^\circ$
- very promising, but needs to be confronted to $\pi p \rightarrow \pi\pi N$ data

**Covariant form factor model** (quark core+meson cloud)
- $n-N1520$ and $n-N1535$ transitions
- dominant pion cloud contribution: baryon transition form factor strongly related to the pion electromagnetic form factor

T. Pena Sept. 9 12:00

**More calculations:**
- A. I. Titov and B. Kämpfer, EPJ.A12, 668 217 (2001) ($\rho/\omega$ prod. amplitudes)
  Inverse Pion Electroproduction (dipole or Gaussian FF)
Analysis of $e^+/e^-$ angular distribution spin density matrix elements

\[ \frac{|A|^2}{\sigma} = \frac{1}{N} \left( 8m_e^2 + 8|k|^2 \left[ 1 - \rho_{11}^{(H)} + \cos^2 \theta (3\rho_{11}^{(H)} - 1) + \sqrt{2}\sin(2\theta)\cos \phi \Re \rho_{10}^{(H)} + \sin^2 \theta \cos(2\phi) \Re \rho_{1-1}^{(H)} \right] \right) \]

Algorithm taking into account acceptance and efficiency developed by A. Sarantsev
\[ \rho_{11}, \rho_{10}, \rho_{1-1} \] extracted in 3 bins in $\cos \theta_\gamma$

\begin{itemize}
  \item Significant longitudinal contributions at finite $q^2$
  \item Angular dependence of $\rho_{10}$ consistent with strong N1520 contribution
  \item Good agreement with Lagrangian model
  \item More precise data needed!
\end{itemize}
HADES upgrade: FAIR-Phase0

New ECAL (lead glass), $\Delta E/E \sim 5\%$

$\gamma \rightarrow$ neutral mesons

and $e^+/e^-$ detection

used in Au+Au exp. March 2019

New RICH photon detector & read-out

(coll. with CBM@FAIR)

Gain in $e^+/e^-$ efficiency $\times 5$

used in Au+Au exp. March 2019

FD: Forward detector (0.5-6.5°)

Straws + RPC TOF

(coll. with PANDA@FAIR)

$\sigma(x) \sim 150 \mu m$  $\sigma$(TOF)$\sim 70$ ps

used in p+p 4.5 GeV Feb. 2022

« Hyperon electromagnetic form factors with HADES » $Y \rightarrow \Lambda e^+e^-$, $Y \rightarrow \Lambda \gamma$

Rafal Lalik (JU Krakow), Hadron structure, Sept.6 15:25
Future pion beam experiments at SIS18

Exp. proposal at GSI/SIS18: 2023-2024: explore the third resonance region ($\sqrt{s} \sim 1.7$ GeV/$c^2$)

1. Baryon meson couplings $\pi\pi N$, $\omega n$, $\eta n$, $K^0\Lambda$, $K\Sigma$,.....
   Including neutral mesons thanks to the ECAL
   → Improve the poor pion beam data base (PWA)
   → Many baryon structure issues: confirmation of $N'(1720)$,
     Cascade decays ($R \rightarrow R'\pi/\eta \rightarrow N\pi\pi/ N\pi\eta$), $\eta n$ couplings
     A. Thiel  Sept.6 8:30

2. Time-like electromagnetic baryon transitions $\pi^- p \rightarrow n e^+ e^-$
   • Broad range of $q^2 = (M_{ee})^2 \rightarrow$ sensitivity to form factors
   • Check of Vector Dominance (both for $\rho$ and $\omega$)
   • Spin density matrix elements

3. Cold matter studies:  C, Ag targets
   • $\omega$ absorption
   • $\rho$ spectral function
   • Strangeness production
✓ Baryon resonance studies with the GSI pion beam + HADES detector (2\textsuperscript{nd} resonance region $\sqrt{s} \sim 1.5$ GeV)
  → improved knowledge of hadronic couplings
  → very new information on electromagnetic baryon transitions in the time-like region
  → phenomenological to be developed to extract information for single baryon transition!
✓ On-going analysis for hyperon Dalitz and radiative decays in pp reaction at 4.5 GeV

✓ Proposal for pion beam experiment in 2023 in the third resonance region
  → Investigate heavier resonances N(1620), N(1720),... in e\textsuperscript{+}e\textsuperscript{-} channels and many hadronic channels, e.g. $\pi p \rightarrow \eta n$, $K^0 \Lambda$, $K \Sigma$,....
✓ Experimental program at SIS18:
  Au+Au (0.2-0.8 GeV) (subm. proposal), p+A at 4.5 GeV, d+p energy scan,......

✓ After 2028: HADES experiments at FAIR with ion and proton beams

Status of FAIR: Y. Leifels Sept. 7 9:00
Thank you
Selection of quasi-free $\pi$-p→ne+e-

- Selection of the exclusive $\pi$-p→ne+e- channel using missing mass
- Quasi-free treatment of $\pi$-C interactions $\sigma_C/\sigma_p=3.3$ ($\sim Z^2/3$)
- Subtraction of residual $\pi0$ contribution
Precision data require accurate analysis procedures to establish the baryon spectrum.