Project B.5: Hadrons in Nuclear Matter

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introduction/motivation
the GiBUU transport model
off-shell transport
photoproduction of omega mesons on nuclei (CB/TAPS)
dileptons (CLAS/g7, HADES)
summary
Motivation: Hadrons in Medium

- how do vector mesons behave inside a hadronic medium?
- major prediction: mass shift $\leftrightarrow$ (partial) restoration of chiral symmetry in medium
- Brown/Rho (eff. Lagrang. approach): $m^*_V(\rho_0)/m_V \approx 0.8$
- Hatsuda/Lee (using QCD sum rules, neglecting width): $m^*_V(\rho)/m_V \approx 1 - \alpha(\rho/\rho_0)$, $\alpha \approx 0.16 \pm 0.06$
- mass shift $\leftrightarrow$ V-N potential $\leftrightarrow$ bound states?
other effects: collisional broadening, resonance structures, ...

collisional broadening (LDA):
\[ \Gamma_{\text{coll}} = \rho < \nu_{\text{rel}} \sigma_{VN} > \]
\( \Leftrightarrow \) absorption

extended sum-rule analysis by Leupold/Peters/Mosel, including finite width (NPA 628, 1998)

coupling to resonances can introduce additional structures in the spectral function (Post, 2003)
• semi-classical hadronic transport model
• unified framework for various types of reactions ($pA$, $\pi A$, $\gamma A$, $eA$, $\nu A$, $AA$) and observables
• modular and well-documented Fortran code
• collaborative effort, SVN-based multi-user environment
• publicly available releases (open source)
• http://gibuu.physik.uni-giessen.de

GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project
The BUU equation

- BUU equation describes time evolution of phase space density $f_i(\vec{r}, t, \vec{p}, \mu)$ for each particle species $i$ ($i = N, \Delta, \pi, \rho, ...$):

$$\left( \partial_t + (\nabla_{\vec{p}} H_i) \nabla_{\vec{r}} - (\nabla_{\vec{r}} H_i) \nabla_{\vec{p}} \right) f_i(\vec{r}, t, \vec{p}, \mu) = I_{coll}[f_i, f_j, ...]$$

- collision term $I_{coll}$:
  - depends on all $f_i$ ⇒ coupled-channel problem
  - decays and scattering processes (2- and 3-body)
  - low energy: resonance model
  - high energy: string model (PYTHIA)

- Hamiltonian $H_i$:
  - hadronic mean fields and potentials
  - “off-shell potential”

- model includes 61 baryons and 21 mesons

- solve numerically via test-particle method:

$$f = \sum_i \delta(\vec{r} - \vec{r}_i) \delta(p - p_i)$$
In-Medium Effects

Mass Shifts
- incorporated as simple scalar potential

Collisional Broadening
- in medium: \( \Gamma_{tot} = \Gamma_{vac} + \Gamma_{coll} \)
- \( \Gamma_{coll} = \rho \langle v_{rel} \sigma_{VN} \rangle \) (low density approx. in lab frame)
- contributing processes: \( VN \rightarrow \pi N, \pi \pi N, R, \ldots \)
- in practice: use \( \Gamma_{coll} = const. \) (from transparency measurements)

Off-Shell Transport
- density-dependent spectral functions need to be handled consistently
- smooth transition from in-medium to vacuum distribution
Off-Shell Transport

- off-shell EOM for test particles
  [Cassing/Juchem (NPA 665, 2000), Leupold (NPA 672, 2000)]:

\[
\begin{align*}
\dot{\vec{r}}_i &= \frac{\vec{p}_i}{E_i} + \frac{1}{2E_i} \left[ \frac{\partial}{\partial \vec{p}_i} Re(\Sigma_i) + \chi_i \frac{\partial \tilde{\Gamma}_i}{\partial \vec{p}_i} \right], \\
\dot{\vec{p}}_i &= -\frac{1}{2E_i} \left[ \frac{\partial}{\partial \vec{r}_i} Re(\Sigma_i) + \chi_i \frac{\partial \tilde{\Gamma}_i}{\partial \vec{r}_i} \right], \\
\chi_i &= \frac{m_i^2 - M^2}{\Gamma_i} = \text{const.}
\end{align*}
\]

- incorporate density-dependent self energies \( \Sigma_i, \tilde{\Gamma}_i \sim Im(\Sigma_i) \)
- Hamiltonian formulation: \( H_i = \sqrt{M^2 + \chi_i \tilde{\Gamma}_i + \vec{p}_i^2 + Re(\Sigma_i)} \)
- major difference to BUU model used by Mühlich (which relied on an old 'recipe' by Effenberger)
The CB/TAPS detector

- $\gamma A \rightarrow \omega X \rightarrow \pi^0 \gamma X \rightarrow 3 \gamma X$
- Bremsstrahlung photon beam (tagged), $E_\gamma = 0.9 - 2.6 \text{GeV}$
- one setup at ELSA (Bonn), one at MAMI (Mainz)
- measure photon triples → demand that two make up a $\pi^0$
- → reconstruct $\omega$ mass
- mass resolution $\sim 25 \text{MeV}$
CB/TAPS: Early Results

Trnka et al., PRL 94, 2005:
- \( m^*_\omega = 722 \text{ MeV} \)
- \( \Gamma^*_\omega = 55 \text{ MeV} \)

Kotulla et al., PRL 100, 2008:
- \( T_A = \frac{12 \cdot \sigma(\gamma A \rightarrow \omega X)}{A \cdot \sigma(\gamma^{12}C \rightarrow \omega X)} \)
- \( \Gamma_{\text{coll.}} = 130 - 150 \text{ MeV} \)
Kaskulov/Oset, EPJ A31 (2007):

- CB/TAPS only weakly sensitive to in-medium effects (at full energy range of 0.9 - 2.6 GeV)
- but: rather sensitive to background subtraction
CB/TAPS: background channels

main background channels:

- $\pi^0 \pi^0 \rightarrow 4\gamma$ (missing 1 $\gamma$)
- $\pi^0 \eta \rightarrow 4\gamma$ (missing 1 $\gamma$)
- $n\pi^0 \pi^+$ misidentified as $3\gamma + p$

- S. Friedrich: describe background via GiBUU simulation
- take complete GiBUU output, feed through GEANT detector simulation
Photoproduction of $\omega$ mesons

$$\sigma_{\gamma N \to VN} = \frac{1}{16\pi k_{cm}s} \sqrt{s-m_N} \int_{m_\pi}^{\sqrt{s}} d\mu \left| M_{\gamma N \to VN(\sqrt{s})} \right|^2 A_V(\mu, \rho) p_{cm}(\mu)$$

$\gamma N \to \omega N$ in $^{40}$Ca nucleus (no FSI)

SAPHIR data

vac.

FM + PB

+ coll. broad.

+ 16% mass shift
Excitation Function

- measure total $\omega$ production cross section via $\pi^0\gamma$ final states as a function of $E_\gamma$ (including FSI/absorption)
- curves: GiBUU simulations, data: B. Lemmer
- data disfavor mass shift scenario

C

$\sigma/A$ (mb)

Incoming Energy (GeV)

preliminary

Nb

$\sigma/A$ (mb)

Incoming Energy (GeV)

preliminary
\( \pi^0 \gamma \) Spectrum: BUU simulations by P. Mühlich

- \( \gamma + ^{40}\text{Ca} \), 
  \( E_\gamma = 0.9 - 1.2 \text{ GeV} \)
- large low-mass tail

- \( \gamma + ^{40}\text{Ca} \), 
  \( E_\gamma = 1.5 - 2.2 \text{ GeV} \)
- almost to effects

recent simulations with GiBUU

Recent simulations show: effects do increase at threshold

but: Mühlich tails not reproduced

soon to be published [arXiv:1008.4520]
$\pi^0\gamma$ Mass Spectrum: Comparison to Data

$\gamma + \text{Nb}, E_\gamma = 900 - 1300 \text{ MeV};$ M. Nanova, J.W. et al. [arXiv:1008.4520]

$\Rightarrow$ statistics not sufficient to distinguish different scenarios!
Reasons for weak sensitivity

1. long $\omega$ decay length [few decays in medium]
2. strong broadening/absorption [smearing of in-medium peak]
3. nuclear density profile [very few decays at full density]

![Graph showing decay position of $\omega \rightarrow \pi^0\gamma$ for different simulations.
- vac. SF: $r<5\text{fm}$: 15.7%]
- 16% shift: $r<5\text{fm}$: 27.3%
- $\rho=\text{const}$: $r<6\text{fm}$: 39.1%]
**Dileptons from HADES**

- **HADES:** in-medium physics with protons and heavy ions
- **pp, pA, AA → e⁺e⁻X**
- e.g. pp@3.5GeV (base line for pNb@3.5GeV)
- open issue: time-like N-Δ transition form factor
- cross checks: dilepton $p_T$ spectra and pion spectra
- medium effects in p+Nb, Ar+KCl?
JLab: CLAS/g7

- new results on transparency ratio (preliminary)
- problems with background subtraction
  (Bethe-Heitler? $\rho$-$\omega$ mixing?)
- to be resolved ...

M. Wood et al. [arXiv:1006.3361]
VM properties in cold nuclear matter: a challenging problem!

GiBUU: a valuable tool to study in-medium physics

CB/TAPS: present data inconclusive

perspectives: improve statistics on $\pi^0\gamma$ line shape, measure $\omega$ excitation function