Vector mesons in medium in transport-based approaches

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Outline

- vector mesons in medium: motivation & basic ideas

- theoretical models & simulation techniques:
  - hadronic transport models (example: GiBUU)
  - coarse graining (with UrQMD)

- results: light VM in medium
  - $\omega$ meson in $\gamma A$ (CB/TAPS)
  - $\rho$ meson in AA collisions (NA60, HADES)
  - $\phi$ meson in pA (KEK-E325 at 12 GeV)

- predictions for J-PARC E16 (pPb @ 30 GeV)
Hadron masses

- $m_{\text{had.}} \gg \sum m_q$
- $m_q \, (\sim \text{MeV})$ generated by Higgs mech.
- most of $m_{\text{had.}} \, (\sim \text{GeV})$ dynamically generated by QCD

- How do the hadronic masses come about? (rather well understood by lattice QCD)
- How to they change at large densities & high temperatures, i.e. in a hadronic 'medium'? (can be studied in nuclear react.)
• how do vector mesons change their properties inside a hadronic medium?
• Brown/Rho, Hatsuda/Lee: mass shift (restoration of chiral sym.)
  \[ m_V^*(\rho)/m_V \approx 1 - \alpha(\rho/\rho_0) \]
  \[ \alpha \approx 0.16 \pm 0.06 \]
• collisional broadening (LDA):
  \[ \Gamma_{coll} = \rho < v_{rel} \sigma_{VN} > \]
• QCD sum rules (Leupold, NPA 628, 1998)
• coupling to resonances can introduce additional structures in the spectral function (Post, 2003)
How to study in-medium properties?

- basic idea: observe decays $V \rightarrow ab$ inside the medium
- reconstruct in-medium mass from invariant mass of decay products: $m^*_V = \sqrt{(p_a + p_b)^2}$

we need:

- reasonably large medium:
  - either: 'cold' nucleus (e.g. $\gamma A$, pA: $\rho \approx \rho_0$, $T \approx 0$)
  - or: 'fireball' from heavy-ion collision ($\rho \gg \rho_0$, $T \gg 0$)
- short meson lifetime and/or low momentum
- FSI of decay products should be small (ideal: $V \rightarrow e^+ e^-$)
GiBUU: “The Giessen BUU transport model”

coupled-channel hadronic transport model, based on the Boltzmann-Uehling-Uhlenbeck equation (BUU)

microscopic, non-equilibrium description of nuclear reactions

unified framework for various types of reactions

- electroweak: $\gamma A$, $eA$, $\nu A$
- hadronic: $pA$, $\pi A$, $KA$
- heavy-ion collisions: $AA$

wide energy range: $\sqrt{s} \approx 100$ MeV to 100 GeV

implementation: large Fortran code ($\sim 100k$ lines of code)

publicly available releases (open source)

website: http://gibuu.hepforge.org

contributors: Mosel, Gallmeister, Gaitanos, Larionov, J.W., ...

similar models: UrQMD, HSD, JAM, ...

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THE BUU EQUATION

- BUU equ.: space-time evolution of phase-space density $F$
  (from gradient expansion of Kadanoff-Baym eq.)

$$\frac{\partial (p_0 - H)}{\partial p_\mu} \frac{\partial F(x,p)}{\partial x^\mu} - \frac{\partial (p_0 - H)}{\partial x_\mu} \frac{\partial F(x,p)}{\partial p^\mu} = C(x, p)$$

- Hamiltonian $H$:
  - hadronic mean fields, Coulomb, “off-shell potential”

- collision term $C(x, p)$:
  - decays and scattering processes (2- and 3-body)
  - low energy: resonance model, high energy: string fragment.

- test-particle method: $F = \sum_i \delta(\vec{r} - \vec{r}_i) \delta(p - p_i)$


GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project
Degrees of Freedom

- included hadronic states:
  - 61 baryons
    - non-strange: \( N, \Delta, 16 \ N^*, 13 \ \Delta^* \) states
    - single-strange: \( \Lambda, \Sigma, 12 \ \Lambda^*, 7 \ \Sigma^* \) states
    - multi-strange/charmed: \( \Xi, \Omega, \Lambda_c, \Sigma_c, \Xi_c, \Omega_c \)
  - 22 mesons
    - non-strange pseudo-scalars: \( \pi, \sigma, f_2, \eta, \eta', \eta_c \)
    - non-strange vectors: \( \rho, \omega, \phi, J/\Psi \)
    - strange: \( K, K^* \)
    - charmed: \( D, D^*, D_s, D_s^* \)

- each of those is an isospin multiplet
  (we assume isospin symmetry)

- plus antiparticles
low energies: resonance model
- $\sqrt{s} \lesssim 3\text{GeV}$
- assumption: cross sections dominated by resonance formation
- all res. parameters taken from Manley/Saleski PWA (Phys.Rev.D45,1992)

high energies: Lund string model
- PYTHIA 6.4 (Lund string model)
- hard pQCD interactions plus string fragmentation
Dilepton decays

- $V \to e^+e^-$ (with $V = \rho, \omega, \phi$) via strict VMD: $\Gamma(\mu) \propto \mu^{-3}$
- $P \to \gamma e^+e^-$ (with $P = \pi^0, \eta, \eta'$) [Landsberg, Phys.Rep.128, 1985]:
  \[
  \frac{d\Gamma}{d\mu} = \frac{4\alpha}{3\pi} \frac{\Gamma_{P \to \gamma \gamma}}{\mu} \left(1 - \frac{\mu^2}{m_P^2}\right)^3 |F_P(\mu)|^2,
  \]
- $\omega \to \pi^0 e^+e^-$ [Landsberg]:
  \[
  \frac{d\Gamma}{d\mu} = \frac{2\alpha}{3\pi} \frac{\Gamma_{\omega \to \pi^0 \gamma}}{\mu} \left[\left(1 + \frac{\mu^2}{\mu_\omega^2 - m_\pi^2}\right)^2 - \frac{4\mu_\omega^2\mu^2}{(\mu_\omega^2 - m_\pi^2)^2}\right]^{3/2} |F_\omega(\mu)|^2
  \]
- $\Delta \to Ne^+e^-$ [Krivoruchenko, Phys.Rev.D65, 2002]:
  \[
  \frac{d\Gamma}{d\mu} = \frac{2\alpha}{3\pi\mu} \frac{\alpha}{16} \frac{(m_\Delta + m_N)^2}{m_\Delta^2 m_N^2} \sqrt{(m_\Delta + m_N)^2 - \mu^2} \left[(m_\Delta - m_N)^2 - \mu^2\right]^{3/2} |F_\Delta(\mu)|^2
  \]

important: form factors well restricted for $\pi^0, \eta$ and $\omega$, but completely unknown for $\Delta$! (often neglected)

- NN Bremsstrahlung in soft-photon approximation
hadronic mean fields:

- usually: Skyrme-like potentials

\[
U_0(x, \vec{p}) = A \frac{\rho}{\rho_0} + B \left( \frac{\rho}{\rho_0} \right)^\gamma + 2C \sum_{i=p,n} \int \frac{gd^3p'}{(2\pi)^3} \frac{f_i(x, \vec{p'})}{1 + (\vec{p} - \vec{p'})^2/\Lambda^2} \]

+ \[d_{symm} \frac{\rho_p(x) - \rho_n(x)}{\rho_0} \tau_i\]

- or: relativistic mean fields (RMF)

- Coulomb potential

- “off-shell potential” (for density-dependent spectral functions)

- mean-field propagation with dynamical density evolution (according to test particle distribution)
Off-Shell Transport

off-shell EOM for test particles:

[Cassing/Juchem (NPA 665, 2000), Leupold (NPA 672, 2000)]:

\[
\begin{align*}
\dot{r}_i &= \frac{1}{1 - C_i} \frac{1}{2E_i} \left[ 2\tilde{p}_i + \frac{\partial}{\partial \tilde{p}_i} \text{Re}(\Sigma_i) + \chi_i \frac{\partial \Gamma_i}{\partial \tilde{p}_i} \right], \\
\dot{p}_i &= -\frac{1}{1 - C_i} \frac{1}{2E_i} \left[ \frac{\partial}{\partial r_i} \text{Re}(\Sigma_i) + \chi_i \frac{\partial \Gamma_i}{\partial r_i} \right], \\
C_i &= \frac{1}{2E_i} \left[ \frac{\partial}{\partial E_i} \text{Re}(\Sigma_i) + \chi_i \frac{\partial \Gamma_i}{\partial E_i} \right], \\
\chi_i &= \frac{m_i^2 - M_i^2}{\Gamma_i}, \quad \frac{d\chi_i}{dt} = 0
\end{align*}
\]

- needed to incorporate density-dependent spectral functions (self energy $\Sigma_i$, width $\Gamma_i \sim \text{Im}(\Sigma_i)$)
- test particles dynamically change their masses
- but: some approximations required
  - neglecting momentum dependence
  - only works 'close to mass shell'
Results I:

$\omega$ in medium

(with U. Mosel, V. Metag, M. Nanova, S. Friedrich)
CB/TAPS: $\gamma A \rightarrow \omega X$

- $\gamma A \rightarrow \omega X \rightarrow \pi^0 \gamma X \rightarrow 3\gamma X$
- measure photon triples
  $\rightarrow$ demand that two make up a $\pi^0$
  $\rightarrow$ reconstruct $\omega$ mass
- mass resolution $\sim 25\text{MeV}$
- transparency-ratio measurement (Kotulla et al., PRL 100, 2008)
- $T_A = \frac{12 \cdot \sigma(\gamma A \rightarrow \omega X)}{A \cdot \sigma(\gamma^{12} C \rightarrow \omega X)}$
- revealed strong broadening/absorption $\Gamma_{coll.} = 130 - 150\text{MeV}$
GiBUU simulations showed: CB/TAPS has insufficient sensitivity to spectral modifications of the $\omega$

reasons: FSI of $\pi^0$ and strong broadening of $\omega$
(and limited statistics)

conclusion: CB/TAPS detector can make no statement about $\omega$ mass shift, but has established strong broadening
Results II:

\( \rho \) in medium

(with S. Endres, H. van Hees, M. Bleicher, U. Mosel)
**Heavy-Ion Collisions: “Coarse Graining”**

- PhD project of S. Endres
- put UrQMD simulation onto space-time grid
- for each cell, determine baryon and energy density
- use equation of state to calculate local temperature and baryo-chemical potential
- calculate thermal dilepton rates using Rapp-Wambach spectral function (Rapp 1997, NPA 617)

![Diagram](image-url)
good agreement with NA60 data, essentially reproducing earlier results by Rapp/Hees (in a simple fireball model)

- benchmark/proof of principle
- plus: more realistic description of collision dynamics
very good agreement
• dominant \( \rho \) in-medium contribution
• baryonic effects are crucial

HADES: \( \text{Ar}+\text{KCl} \) at 1.76 GeV
\( \rho \) shape already nontrivial in pp collision due to production
• in-medium properties of $\rho$ dominated by coupling to $N^*$ resonances (coll. broadening!)
• in-medium physics at SPS connected to vacuum physics at SIS
Results III:
\( \phi \) in medium

(KEK E325, J-PARC E16)
KEK E325: $p + Cu$ at 12 GeV

- $\rho/\omega$: 9% mass shift, no broadening [Naruki et al, PRL96, 2006]
- In conflict with NA60 and CB/TAPS!
- $\phi$: 3.4% mass shift, broadening factor 3.6 [Muto et al, PRL98, 2007]
- One of the few experiments claiming mass shifts of the vector mesons, heavily debated in the community
solid: vacuum SF

dashed: 9% mass shift, no broadening

cuts:
  - 0.6 < y < 2.2
  - $p_T < 1.5$ GeV
  - $50^\circ < \theta_{ee} < 150^\circ$
  - $\beta \gamma < 1.25$

mass resolution: 11 MeV

todo:
  - do various checks
  - take care of detector acceptance
  - compare with data
Benchmark: \( pA \to \pi X \) (HARP)

- GiBUU nicely describes inclusive pion production data by the HARP collaboration (Gallmeister et al., NPA 826, 2009)
J-PARC E16: $p + Pb$ at 30 GeV

- planned experiment at the high-momentum beamline of J-PARC
- will expand on E325 results, confirm or reject them
- mainly aims for the $\phi$ (could measure also $\rho/\omega$ region?)

![Diagram of experimental setup]

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\( p + Pb \) at 30 GeV: simulation

- “first shot”
- no cuts
- resolution: 5 MeV
- 3.4\% mass shift
- moderate effects visible
\( \beta \gamma = p/m \)

- proposed: cut on small \( \beta \gamma \) selects low-momentum \( \phi \) mesons
- larger prob. to decay inside the nucleus
- add. effect: enhanced production of low momenta for shifted \( \phi \)
- cut on \( \beta \gamma < 0.5 \)
- selects a very small fraction of all produced \( \phi \) mesons
- mass shift of 3.4%
- no broadening
- huge effect
- in-medium peak is stronger than vacuum peak

\( p + \text{Pb at 30.0 GeV} \)

**GiBUU total**
- \( \rho \rightarrow e^+e^- \)
- \( \omega \rightarrow e^+e^- \)
- \( \phi \rightarrow e^+e^- \)
- \( \omega^0 \rightarrow \pi^0e^+e^- \)
- \( \pi \rightarrow e^+e'^\gamma \)
- \( \eta \rightarrow e^+e'^\gamma \)
- \( \Delta \rightarrow N^+e' \)
mass spectrum with $\beta \gamma$ cut

- mass shift + broadening (factor 3.6)
- much smaller effect
- phase-space enhancement of low momenta not so strong in this scenario
Summary / Conclusions

- exp. situation of VM in-medium properties is still confusing
  - NA60 sees broadening of $\rho$ in AA collisions
  - CB/TAPS established strong broadening of the $\omega$ meson in $\gamma A$
  - KEK-E325 claims to see mass shifts of all light VMs

- transport models are an important tool to understand and interpret exp. results

- J-PARC E16 will hopefully help to clarify the situation
- has good chance to verify or exclude mass shift of the $\phi$
- provided it collects enough statistics to make hard cuts