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• History & Motivation
• The State of the Art: Lessons & Challenges
• New Directions: Learning from the Lattice
• from SQM to FQM: Expanding the Horizon
• What’s Next?
... We thus conclude that strangeness abundance saturates in a sufficiently excited quark-gluon plasma ($T>160$ MeV, $E>1$ GeV/fm$^3$), allowing us to utilize enhanced abundances of rare, strange hadrons (__, __ etc.) as indicators for the formation of the plasma state in nuclear collisions.
Purpose of this Talk

(quoted from invitation...)

• summary talk on theoretical advances and challenges

• not intended to be a repeat of the talks presented during the sessions

• summarize the big picture that we can grasp from experimental measurements and theoretical ideas with emphasis on new investigations and challenges that the field is facing
Topics not covered in this talk, but reviewed by:

- Walter Greiner: Extension of the Periodic System
- S. Reddy: Strange Star Surface
- J. Schaffner-Bielich: Astro-Strangeness & Exotica
  - Pulsar measurements indicate a *hard* EoS
- J. Aichelin: EoS & Strangeness Probes at SIS
  - Kaon measurements indicate a *soft* EoS
  - Possible solution to quandary: a SH EoS (pulsar EoS sensitive to higher densities than Kaon EoS)
- H. Stoecker: LXD-BHs in RHICs at LHC
State of the Art: Lessons & Challenges

- hadron yields & ratios:
  - probes of chemical equilibration?
- excitation functions:
  - expectations vs. reality...
- Transport models:
  - dynamics of non-equilibrium phenomena
- elliptic flow systematics:
  - resolving hadronization
Hadron Yields & Ratios: Lessons from the Statistical Model

- SM fits work well even for p+p and e+e!
- generic feature of particle production?
- fit does not work for strangeness (w/o \( s \))!
- success of A+A fit: chemical equilibration
  - high charge-density from jet-quenching & hydro evolution suggests that equilibration occurred in the deconfined phase!
- BEWARE: mechanism for chemical equilibration in deconfined phase a mystery!
  - why does the SM fit work?
  - what about medium effects?
  - lessons from resonances?
  - can different SM scenarios be unambiguously verified/falsified?
- Theorists: need to develop understanding of underlying physics!!

Andronic, Braun-Munzinger & Stachel, nucl-th/0511071

- use SM model to fit yields & ratios:
- works very well from AGS to RHIC!

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also Cleymans, Torrieri, Caines...
Lattice at non-vanishing $\mu_B$

- net-quark susceptibility diverges near the tri-critical point – experimentally accessible via fluctuation measurements
- beam energy region sensitive to this effect (assuming SM f.o. curve) is $\approx 0.7$ GeV

- progress in calculating EoS at finite $\mu_B$
- splitting of chem f.o. and phase boundary near transition point from meson to baryon dominated matter
  - design or coincidence?

C. Sasaki et al.

$\chi_q^{(\text{crit})} / \chi_q^{(\text{free})}$

K. Redlich

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SQM 2006: Theory Summary #7
Excitation Functions

- plenty of excitation functions available: useful for systematic understanding!
- so far, only smooth, gradual changes observed
- widely differing opinions on energy resolution for TCP observations:
  - 1 GeV to 5 GeV in sqrt(s)_{NN} (Redlich, Stephans)
- new application: J/\_yield may provide info on dissociation vs. recreation
  - expectation of sharp peaks or minima may be naïve!

(temperature profiles, core vs. corona, beam energy resolution etc.)

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SQM 2006: Theory Summary  #8
Nuclear Fluid Dynamics

- transport of macroscopic degrees of freedom
- based on conservation laws: $\partial_x T = 0$, $\partial_x j = 0$

- for ideal fluid: $T = (u + p) u - p g$ and $j_i = u_i$
- **Equation of State** needed to close system of PDE’s: $p = p(T, u_i)$
  - connection to Lattice QCD calculation of EoS

- initial conditions (i.e. thermalized QGP) required for calculation
- assumes local thermal equilibrium, vanishing mean free path
  - applicability of hydro is a strong signature for a thermalized system

- simplest case: scaling hydrodynamics
  - assume longitudinal boost-invariance
  - cylindrically symmetric transverse expansion
  - no pressure between rapidity slices
  - conserved charge in each slice
3D-Hydro: Results

- 1st attempt to address all data w/ 1 calculation

Nonaka & Bass, nucl-th/0510038 & ms. in preparation

b=6.3 fm
Hydro: Challenges

- centrality systematics of $v_2$ less than perfect
- no flavor dependence of cross-sections
- separation chemical and kinetic freeze-out:
  - normalize spectra by hand
  - PCE: proper normalization, wrong $v_2$

Viscosity:
- success of ideal hydro argues for a low viscosity
- compatible with AdS/CFT bound of $1/4n$
- need full 3D viscous hydro comparison to data to experimentally determine
- note that viscosity will change as function of temperature during collision
Full 3-d Hydrodynamics

QGP evolution

Hydrodynamics

- ideally suited for dense systems
  - model early QGP reaction stage
- well defined Equation of State
- parameters:
  - initial conditions
  - Equation of State

+ micro. transport (UrQMD)

- no equilibrium assumptions
  - model break-up stage
  - calculate freeze-out
  - includes viscosity in hadronic phase
- parameters:
  - (total/partial) cross sections

matching condition:

- use same set of hadronic states for EoS as in UrQMD
- generate hadrons in each cell using local T and $_B$

Bass & Dumitru, PRC61,064909(2000)
Teaney et al, nucl-th/0110037
Nonaka & Bass, nucl-th/0510038
Hirano et al. nucl-th/0511046
3D-Hydro+UrQMD: Results

- Good description of cross section dependent features & non-equilibrium features of hadronic phase.
Recombination+Fragmentation Model

basic assumptions:

- at low $p_t$, the quarks and antiquark spectrum is thermal and they recombine into hadrons locally “at an instant”:

  - features of the parton spectrum are shifted to higher $p_t$ in the hadron spectrum

- at high $p_t$, the parton spectrum is given by a pQCD power law, partons suffer jet energy loss and hadrons are formed via fragmentation of quarks and gluons

  - shape of parton spectrum determines if recombination is more effective than fragmentation
  - baryons are shifted to higher $p_t$ than mesons, for same quark distribution

  - understand behavior of baryons!

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C.M. Ko
R.J. Fries
P. Sorensen

SQM 2006: Theory Summary  #14
Parton Number Scaling of $v_2$

- $v_2/n$ vs. $KE_t/n$ combines hydro w/ reco scaling
- _ meson exhibits $n=2$ scaling

- smoking gun for recombination
- measurement of partonic $v_2$!
Scaling Corrections & Correlations

• detailed study of CQN scaling reveals systematic deviations on the 5-10% level

• Recombination approach allows for two-particle correlations, provided they are contained in the parton source distributions:

\[ \sum_{1234} \mathbf{A}_{AB} \mathbf{B}_{AC} \mathbf{D}_{BD} \mathbf{N}_{D} \mathbf{P}_{D} \mathbf{W}_{\sigma \phi \phi} \mathbf{\sigma \phi \phi} \mathbf{\otimes \otimes} = \int \mathbf{R.J. Fries} \]

• can be understood by taking hadron wave-function, higher Fock-states & resonance decays into account

P. Sorensen, C.M. Ko

Greco & Ko, PRC 70, 024901 (04)

Fries, Bass & Mueller
PRL 94 122301 (2005)

R.J. Fries

SQM 2006: Theory Summary #16
string/hadron based transport models cannot reproduce elliptic flow @ RHIC

• UrQMD: AQM Dynamics
  - cross section scales with number of q's with _\h = _q, valence and _s < _u, d
  - V²/n scaling in UrQMD: _ < _N

• view UrQMD as toymodel for system of particles w/o phase-transition:
  - v² scales w/ cross-section
New Directions:

• experimental data on spectral functions
• probing the structure of matter with susceptibilities
• (strange) quarks and the glasma
• two viscosities: near perfect fluid w/o the “s”
Spectral Functions: Theory Status

- **BR in above calculation:**
  - version used in mid-90ies to describe CERES
  - no modification of resonance-width
  - term "BR" controversial, better: mass-scaling

- **medium effects on _ _ dominated by broadening of width**

- **improved version of mass-scaling w/ consistent width cannot currently be ruled out**

A. Foerster

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SQM 2006: Theory Summary  #19
different degrees of freedom introduce different correlations between conserved charges

- assumption: conservation of charge @ hadronization local in rapidity
- introduce baryon-number × strangeness correlation:

\[
\langle \langle \langle \rangle \rangle \langle \langle \rangle \rangle \langle \langle \rangle \rangle \approx -2/3
\]

- system of particles:

- connection to Lattice susceptibilities:

\[
C_{BS}: \text{V. Koch, A. Majumder & J. Randrup, PRL95 182301 (2005)}
\]

\[
\text{BS-QGP: E. Shuryak, I. Zahed, PRC70 021901 (2004); PRD70 054507 (2004)}
\]

QP-QGP: \(C_{BS}=1\)
HG: \(C_{BS} \approx 2/3\)
BS-QGP: \(C_{BS} \approx 0.61\)
$C_{BS}$ & $C_{QS}$: Lattice & Lessons

Gavai, Majumder

$T > T_c$: $C_{BS} = 1$
- mesonic as well as baryonic bound-states ruled out via $C_{BS}$ and $C_{B}$-derivatives thereof
- Lattice confirms quasi-quark nature of flavor carriers in the deconfined phase

**Wroblewski Factor:**
- significant deviations from 1 in RHIC domain!
- when is strangeness produced?
  - is $\xi$ fixed early on?
  - or at hadronization?

Gavai & Gupta, PRD 73, 14006, 2006

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SQM 2006: Theory Summary #21
The Quark & the Glasma

Color Glass Condensate (CGC):
- saturated gluon wave-function of a nucleus at RHIC+ energies

Glasma:
- initial state of a heavy-ion collision consisting of a coherent color field based on CGCs of colliding nuclei
- note that original CGC/Glasma do not contain quarks!
  ➢ solve Dirac eqn. for $\bar{q}q$ creation in coherent (longitudinal) color field
- For $Q_S \approx 1.3$ GeV one obtains roughly thermal $q$&$g$ population: 400 gluons, $100 \times N_f$ $q$ & $100 \times N_f \bar{q}$

Gelis, Kajantie & Lappi PRL 96 032304 (2006)
Color Fields: Anomalous Viscosity

collisional viscosity:
• derived in HTL weak coupling limit

anomalous viscosity:
• induced by turbulent color fields, due to momentum-space anisotropy
• with ansatz for fields:

Collisional vs. Anomalous Viscosity

Mueller

initial state
pre-equilibrium
QGP and hydrodynamic expansion
hadronization
hadronic phase and freeze-out

viscosity: 

- cross sections are additive
  - $\sim f^{-1/\gamma}$

(sumrule for viscosities:

smaller viscosity dominates in system w/ 2 viscosities!

temperature evolution:

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SQM 2006: Theory Summary #24
\(_B\): stable equilibrium

- Longitudinal flow induces momentum anisotropy \(_B\):

- Anisotropy grows with shear viscosity \(_B\):

- Color-magnetic fields are proportional to \(_B\):

- However, \(_B\) is inversely proportional to \(\langle B^2 \rangle\):

- Shear viscosity \(_B\) stabilizes due to:
From SQM to F(lavor)QM:

- production of charm & bottom
- probes of the medium
- quarkonium structure
Heavy Quark Production in pA & AA

I. Vitev:
- Higher Twist Shadowing in DIS
- process-dependent power corrections
  - well developed pQCD formalism

K. Tuchin:
- charm production in d+A using the color dipole model
- estimate for charm production timescale @ RHIC:

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Heavy-Quark Energy Loss

- radiative energy loss alone cannot account for $R_{AA}$ of non-photonic electrons when $b$-contributions are taken into account
- full calculation needs to account for:
  - multiple interactions w/ medium
  - transition radiation
  - collisional energy loss (M. Mustafa)

- Wicks, Horowitz, Djordjevic & Gyulassy, nucl-th/0512076

also Wiedemann

SQM 2006: Theory Summary #28
Diffusion of Heavy Quarks in a Hydrodynamic Medium

- propagation of heavy quarks in a QGP medium resembles a diffusion process
- use evolution of 3D-Hydro as medium
  - $T$, $\rho$, and $v_{\text{flow}}$ are known as function of $r$ & $\tau$
  - describe propagation with a Langevin Eqn:

\[
\kappa \xi + \Delta = -\Delta + \Delta
\]

- drag coefficient $\Delta/2T$ can be locally calculated from 3D hydro evolution

- Gossiaux, Guiho & Aichelin, JPG 31, 1079 (2005)
- Van Hees, Greco & Rapp: nucl-th/0508055
- Bass, Asakawa & Mueller in preparation
Heavy-Quarks as Medium Probes

- introduce resonant $cq$ interaction (Rapp)
- calculate drag & diffusion coefficients for Langevin evolution:
  - $R_{AA}$: characteristic leveling-off
  - $R_{AA}$: factor 3-4 from resonances
  - $v_2$: large resonance effects

- determine transport coefficients from data (Gossiaux)
Lattice: Survival of the J/\( \psi \)

Petreczky

- 1S charmonia states survive to unexpectedly high temperatures
- 1P state melts near \( T_C \)
  - need to reevaluate picture of charmonium physics at SPS and RHIC
    - dissociation mechanisms?
    - broadening effects?

Potential Models:

- Cornell potential not compatible with Lattice-correlators (Mocsy)
- new potential with parameters fit to Lattice EoS can reproduce spectral functions (Wong)
Charmonium Elliptic Flow

- measurement of significant Charmonium elliptic flow would indicate charm thermalization & charmonium regeneration via recombination
- strong sensitivity to in-medium interaction!

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in-medium formation of $J/\psi$:
- Thews, Schroedter & Rafelski, PRC63 (2001) 054905
The Happy End

• 25 years ago strangeness entered the stage as a single-purpose QGP signature

• strangeness has now developed into a versatile tool to comprehensively study the properties of the hot & dense QCD medium

• exciting new developments:
  • susceptibilities, charm collective flow

➢ need to extend toolbox to include heavy flavors

Good luck for the next 25 years!!
The End