Goals and status of the CBM experiment

Peter Senger

GSI Darmstadt, Germany

Abstract. The goal of the heavy-ion collision program at the future Facility for Antiproton and Ion Research (FAIR) in Darmstadt (Germany) is to explore the phase diagram of strongly interacting matter in the region of the highest baryon densities. The CBM research program addresses fundamental aspects of QCD such as the equation-of-state of highly compressed baryonic matter, the deconfinement phase transition and its critical endpoint, chiral symmetry restoration at high baryon densities, and the in-medium properties of hadrons. The corresponding key observables comprise low-mass vector mesons decaying into lepton pairs which serve as penetrating probes, hidden and open charm produced at threshold beam energies, (multi-) strange particles, and global features like collective flow and event-by-event fluctuations. The experimental task is to identify both hadrons and leptons and to detect rare probes in a heavy-ion environment. The experimental challenge is to select rare events in nucleus-nucleus collisions with charged particle multiplicities of about 1000 per central event at reaction rates of up to 10 MHz. Such measurements require fast and radiation hard detectors, fast and self-triggered read-out electronics, a high-speed data acquisition system, and online event selection based on full track reconstruction. The layout of the CBM detector system and the results of feasibility studies will be presented. More than 400 scientists from 50 institutions and 15 countries actually participate in the realization of the CBM experiment which represents a major international effort in future heavy-ion physics.

The participation at this summer school was partially supported by the HISS Dubna program of the Helmholtz association.

Fig. 1. The CBM experimental facility with electron detectors RICH and TRD (top panel) and with the muon detection system (bottom panel).

Experiments with dense nuclear matter

Peter Senger (GSI)

Outline:

Part I: Dense baryonic matter in the laboratory:

- Probing the nuclear equation-of-state by collective proton flow and strangeness production
- Measuring in medium properties of strange mesons

Part II: Towards highest baryon densities :

- Exploring the phases of QCD matter

HISS Dense Matter in HIC and Astrophysics, 14. - 26. 07. 2008, Dubna, Russia

„The challenge for the next century physics is:
explain confinement and broken (chiral) symmetry“
T.D. Lee

„But perhaps the most interesting and surprising thing about
QCD at high density is that, by thinking about it, one discovers
a fruitful new perspective on the traditional problem
of confinement and chiral-symmetry breaking“.
F. Wilczek

Fundamental Questions of QCD

- What is the equation-of-state of strongly interacting matter? (core collapse supernovae, neutron stars, early universe)
- What is the structure of strongly interacting matter as a function of T and ρ_B ? (hot and dense hadronic medium, deconfined phase, phase transitions?)
- What are the in-medium properties of hadrons as a function of T and ρ_B ? (partial restoration of chiral symmetry?)

The phase diagram of strongly interacting matter

Are heavy ion collisions the appropriate tool to study QCD matter ?

- Small, shortlived, dynamical systems: is equilibrated matter established?
- Particles freeze out at $\rho < \rho_0$: information on high density phase?
- Do signatures from the partonic phase survive hadronization?

The evolution of matter in the universe

Dense nuclear matter in nature: Core collapse supernova explosion

Symmetric nuclear matter at densities of 1 - 3 ρ_0

The Crab nebula and his pulsating heart

In 1054 chinese astronomers observed a "visiting star": As bright as the full moon for 1 month.

1968: discovery of a pulsating radiation source (30 Hz) in the center of the crab nebula

Strongly interacting matter in neutron stars

Questions:

- "Strangeness" of dense matter ?
- In-medium properties of hadrons ?
- Compressibility of nuclear matter?
- Deconfinement at high baryon densities ?

Hyperons in neutron stars

A. Akmal, V.R. Pandharipande, D.G. Ravenhall,
Phys. Rev. C 58 (1998) 1804

N. Glendenning, F. Weber, S. Moszkowski,
Phys. Rev. C 45 (1992) 844

Cold neutral matter in β -equilibrium:

Experiment: Hypernuclei

Antikaons in neutron stars

"Kaon condensate": $e^- \rightleftharpoons K^- + \nu_e, n \rightleftharpoons p + K^-$

G.E. Brown, H.A. Bethe, Astrophys. Jour. 423 (1994) 659
G.Q.Li, C.H. Lee, G.E. Brown, Nucl. Phys. A 625 (1997)

W. Cassing et al., Giessen: Hadron-String Dynamics (HSD):
mean field, hadrons + resonances + strings

The equation-of-state of (symmetric) nuclear matter

Equation of state:

$$PV \propto T \propto E$$

$$P \propto E/V \propto E/A$$

- $E/A(\rho_0) = -16 \text{ MeV}$

- $\delta(E/A)(\rho_0)/\delta\rho = 0$

- Compressibility:

$$\kappa = 9\rho^2 \delta^2(E/A)/\delta\rho^2$$

$$\kappa = 200 \text{ MeV: "soft" EOS}$$

$$\kappa = 380 \text{ MeV: "stiff" EOS}$$

Observable in HI collisions: collective flow (driven by pressure)

Dynamics of a semi-central Au+Au collision at 2 AGeV
(BUU calculation, P. Danielewicz, MSU)

Collective flow of nucleons: driven by pressure

Experimental determination of collision centrality

or Zero Degree Calorimeter: $E_{\text{ZDC}} = E_{\text{beam}} A_{\text{Pro-Spec}}$ and $A_{\text{part}} = 2 (A - E_{\text{ZDC}}/E_{\text{beam}})$

Experimental determination of the reaction plane

Transverse Momentum Method:

P. Danielewicz & G. Odyniec, Phys. Lett. 157 B (1985) 146

Dispersion of the reaction plane:

Sub-Event-Method: $\Delta\Phi = \Phi_1 - \Phi_2$

Azimuthal angular distribution of protons measured in Au+Au collisions at 1.15, 2, 4, 6, 8 AGeV

C. Pinkenburg et al., (E895),
Phys. Rev. Lett. 83 (1999) 1295

Rapidity: $y^{(0)} = y - y_m$
with $y = 0.5 \ln [(E + p_z)/(E - p_z)]$

Azimuthal angle distribution:
 $dN/d\Phi \propto (1 + 2v_1 \cos\Phi + 2v_2 \cos 2\Phi)$

Compressibility extracted from collective flow

P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592

Transverse in-plane flow:

$$F = d(p_x/A)/d(y/y_{cm})$$

Elliptic flow:

$$dN/d\Phi \propto (1 + 2v_1 \cos\Phi + 2v_2 \cos 2\Phi)$$

New data: Au + Au collisions at SIS energies

A. Andronic et al. (FOPI Collaboration) Phys. Lett. B612 (2005) 173

Summary: Collective proton flow in Au+Au collisions and the nuclear matter EOS

Beam energy AGeV	central density	flow observable	compressibility K
0.4 – 1.5	$\rho = 1 - 3 \rho_0$	transverse, elliptic	170 – 210 MeV
2 – 10	$\rho = 3 - 5 (7) \rho_0$	transverse	170 – 210 MeV
2 – 10	$\rho = 3 - 5 (7) \rho_0$	elliptic	300 – 380 MeV

Within microscopic transport models the collective flow is sensitive to:

- The nuclear matter equation of state
- In-medium nucleon-nucleon cross sections
- Momentum dependent interactions

Independent observables? particle production

Kaon production in Au+Au collisions at 1 AGeV

$$pp \rightarrow K^+ \Lambda p \quad (E_{\text{thres}} = 1.6 \text{ GeV})$$

K^+ mesons probe high densities
 K^+ mesons scatter elastically only

Probing the nuclear equation-of-state ($\rho = 1 - 3 \rho_0$)
 by K^+ meson production in C+C and Au+Au collisions

Idea: K^+ yield $\propto$ baryon density $\rho \propto$ compressibility κ

Transport model (RBUU)

Au+Au at 1 AGeV:

$$\kappa = 200 \text{ MeV} \Rightarrow \rho_{\text{max}} \approx 2.9 \rho_0 \Rightarrow K^+ \nearrow$$

$$\kappa = 380 \text{ MeV} \Rightarrow \rho_{\text{max}} \approx 2.4 \rho_0 \Rightarrow K^+ \searrow$$

Reference system C+C:

K^+ yield not sensitive to EOS

Experiment:

C. Sturm et al., (KaoS Collaboration),
 Phys. Rev. Lett. 86 (2001) 39

Theory:

Ch. Fuchs et al.,
 Phys. Rev. Lett. 86 (2001) 1974

The compressibility of nuclear matter

Experiment: C. Sturm et al., (KaoS Collaboration) Phys. Rev. Lett. 86 (2001) 39

Theory: QMD Ch. Fuchs et al., Phys. Rev. Lett. 86 (2001) 1974

IQMD Ch. Hartnack, J. Aichelin, J. Phys. G 28 (2002) 1649

Au/C ratio: cancellation of systematic errors both in experiment and theory

Outlook: determination of the nuclear EOS at very high ρ

Exploring the "nuclear" EOS at $3\rho_0 < \rho < 7\rho_0$

Measure excitation function of (multi-strange) hyperon production in heavy-ion collisions from 2 - 15 AGeV (no data yet):

Direct production:

Production via multiple collisions:

Strange mesons in dense matter

G.E. Brown, C.H. Lee, M. Rho, V. Thorsson,
Nucl. Phys. A 567 (1994) 937

T. Waas, N. Kaiser, W. Weise, Phys. Lett. B 379
(1996) 34

J. Schaffner-Bielich, J. Bondorf, I. Mishustin,
Nucl. Phys. A 625 (1997)

In-medium modifications of K^+ mesons

Data: M. Menzel et al., (KaoS Collab.), Phys. Lett. B 495 (2000) 26

K. Wisniewski et al., (FOPI Collab.), Eur. Phys. J A 9 (2000) 515

Reduced K^+ yield due to increased in-medium K^+ mass

K⁺ azimuthal emission pattern from A+A collisions

Data: Y. Shin et al., (KaoS Collaboration), Phys. Rev. Lett. 81 (1998) 1576
 F. Uhlig et al., (KaoS Collaboration), Phys. Rev. Lett. 95 (2005) 012301
 Calculations see A. Larionov, U. Mosel, nucl-th/0504023

Ni+Ni at 1.93 AGeV: π^- , K⁺ and K⁻ azimuthal distributions

F. Uhlig et al., (KaoS Collaboration), Phys. Rev. Lett. 95 (2005) 012301

Au+Au 1.5 AGeV semi-central collisions ($b > 6.4$ fm) K^+ and K^- azimuthal angular distributions

M. Płoskon, PhD Thesis 2005

$$dN(\phi)/\phi \propto 1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \dots$$

Elliptic flow of K^+ and K^- mesons: Comparison to off-shell transport calculations and in-medium spectral functions

Data: M. Płoskon, PhD Thesis, Univ. Frankfurt 2005

Off-shell transport calculations: W. Cassing et al., NPA 727 (2003) 59, E. Bratkovskaya, priv. com.

Coupled channel G-Matrix approach (K- spectral functions): L. Tolos et al., NPA 690 (2001) 547

$$dN(\phi)/\phi \propto 1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \dots$$

Antikaon spectral function in nuclear matter

self-consistent coupled channel calculation with mean field (s,p,d waves)

M.F.M. Lutz, C.L. Korpa, M. Möller, nucl-th/07071283

Strangeness production in proton - nucleus collisions

W. Scheinast et al., (KaoS Collaboration)
Phys. Rev. Lett. 96 (2006) 072301

Comparison of p+A data to transport calculations

Transport calculation: H. W. Barz et al., Phys.Rev. C68 (2003) 041901

Summary Kaon production

Excitation function of K^+ production in A+A collisions ($\rho = 1-3 \rho_0$):

↳ The nuclear matter equation-of-state is soft ($K \approx 200 \text{ MeV}$)

Yield and elliptic flow of K^+ mesons in A+A collisions:

↳ The in-medium potential of K^+ mesons is repulsive

Yield of K^- mesons proton-nucleus collisions:

↳ Evidence for a K-N in-medium potential of $U_K \approx -80 \rho/\rho_0 \text{ MeV}$

Yield and elliptic flow of K^- mesons in A+A collisions:

↳ Quantitative interpretation of data requires off-shell transport calculations and in-medium spectral functions

The Kaon Spectrometer at SIS (1991 - 2002)

KAOS

Collaboration

GSI Darmstadt:

P. Koczoń, F. Laue, M. Płoskon,
E. Schwab, P. Senger, C. Sturm

TU Darmstadt:

A. Förster, S. Lang, H. Oeschler,
A. Schmäh, F. Uhlig

Univ. Frankfurt:

Y. Shin, T. Schuck, H. Ströbele

Univ. Marburg:

I. Böttcher, B. Kohlmeier,
M. Menzel

Univ. Kraków:

M. Dębowski, G. Surówka, W. Waluś

FZ Rossendorf:

F. Dohrmann, E. Grosse, L. Naumann,
W. Scheinast, A. Wagner

Facility for Antiproton and Ion Research (FAIR)

Compressed Baryonic Matter

Peter Senger (GSI)

Towards highest baryon densities :
➤ Exploring the phases of QCD matter

Dense Matter in HIC and Astrophysics, 14. - 26. 07. 2008, Dubna, Russia

Facility for Antiproton and Ion Research (FAIR)

Cost of the FAIR project: ~ 1.2 Billion € (25% from foreign partners).

15 FAIR member states:

Austria, China, Finland, France, Germany, Great Britain, Greece, India, Italy, Poland, Romania, Russia, Slovenia, Spain, Sweden,

German Federal Government has approved budget over 10 years

FAIR project start: Nov. 2007

First beams planned for 2014 - 2015

Research programs at FAIR

Rare isotope beams; nuclear structure and nuclear astrophysics

nuclear structure far off stability
nucleosynthesis in stars and supernovae

Beams of antiprotons: hadron physics

quark-confinement potential
search for gluonic matter and hybrids
hypernuclei

high-energy nucleus-nucleus collisions: compressed baryonic matter

baryonic matter at highest densities (neutron stars)
phase transitions and critical endpoint
in-medium properties of hadrons

short-pulse heavy ion beams: plasma physics

matter at high pressure, densities, and temperature
fundamentals of nuclear fusion

atomic physics and applied research

highly charged atoms
low energy antiprotons
radiobiology

accelerator physics

high intensive heavy ion beams
dynamical vacuum
rapidly cycling superconducting magnets
high energy electron cooling

Exploring the QCD phase diagram

The QCD Phase diagram: facts and speculations

Experimental results:

- > Freeze-out curve (T, μ_B)
- > $T_{fo} = 161 \pm 4$ MeV at ($\mu_B = 0$)
- > new state of matter = perfect liquid?

L-QCD Predictions:

- > $T_c = 151 \pm 7 \pm 4$ MeV (Z. Fodor, arXiv:0712.2930 hep-lat)
- > $T_c = 192 \pm 7 \pm 4$ MeV (F. Karsch, arXiv:0711.0661 hep-lat)
- > crossover transition at $\mu_B = 0$ (Z. Fodor, arXiv:0712.2930 hep-lat)
- > 1. order phase transition with critical endpoint at $\mu_B > 0$

High-energy heavy-ion collision experiments:

RHIC, LHC: cross over transition, QGP at high T and low μ

Low-energy RHIC: search for QCD-CP with bulk observables

NA61@SPS: search for QCD-CP with bulk observables

MPD@NICA: search for the QCD mixed phase with bulk observables

CBM@FAIR: scan of the phase diagram with bulk and rare observables

Trajectories from Transport models

UrQMD: L.V. Bravina et al.,
Phys. Rev. C60 (1999) 044905

3-fluid hydro:

Y. Ivanov, V. Russkikh, V. Toneev,
Phys. Rev. C73 (2006) 044904

FAIR beam energies:

A+A collisions up to 45 (35) AGeV, $Z/A=0.5$ (0.4)

(p+p and p+A collisions up to 90 GeV)

U+U 23 GeV/A

$t=17.14$ fm/c

UrQMD Frankfurt/M

Messengers from the superdense phase ?

U+U 23 AGeV

Up to date only freeze-out probes have been measured in A+A collisions at 2 - 40 AGeV

Possible signatures of QGP in heavy-ion collisions

taken from the book:
Quark-Gluon-Plasma:
 from big bang to little bang
 by
 Kohsuke Yagi,
 Tetsuo Hatsuda,
 Yasuo Miake (2006)

adapted from an original
 by Shoji Nagamiya

Search for discontinuities
 in excitation functions
 of various observables !

How much are the signals
 diluted by finite size,
 short lifetimes,
 and hadronization ?

Discontinuity in strangeness production:
signature for phase transition ?

C. Blume et al. (NA49 at CERN-SPS), nucl-ex/0409008

Low energy run at RHIC: remeasurement of K/ π (incl. e-by-e)
CBM: Precise excitation function of multistrange particle production and propagation (collective flow)

Hadron elliptic flow at FAIR

AMPT calculations: C.M. Ko at CPOD 2007

Partonic scattering enhances elliptic flow

Approximate constituent quark number scaling !

Charmonium dissociation in the quark-pluon plasma ?

Quarkonium dissociation temperatures:
(Digal, Karsch, Satz)

state	J/ψ(1S)	χ _c (1P)	ψ'(2S)	Υ(1S)	χ _b (1P)	Υ(2S)	χ _b (2P)	Υ(3S)
T _d /T _c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

Upper bounds on dissociation
temperatures : A.Mocsy, P. Petreczky

state	χ _c	ψ'	J/ψ	Υ'	χ _b	Υ
T _{dis} ≤ T _c ≤ T _c	1.2T _c	1.2T _c	1.3T _c	2T _c		

sequential dissociation of J/ψ and ψ'?

➤ measure excitation functions of J/ψ, ψ', D, Λ_c production
in p+p, p+A and A+A collisions (incl. p_T-spectra, flow)

Charm production

Hadronic transport models: parameterization of measured cross sections

O. Linnyk, E. Bratkovskaya, W. Cassing, H. Stöcker, Nucl. Phys. A786 (2007) 183

The creation of charm in hadronic transport calculations

The creation of charm via hard collisions (gg and qq) in a partonic phase

Formation of D mesons, charmed hyperons and charmonium via coalescence (e.g. statistical hadronization)

Charmonium and open charm production by statistical hadronisation in nuclear collisions

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, arXiv:0708.1488

1. c - $\bar{c}$ production in hard collisions,
2. statistical hadronization according to the temperature and the baryochemical potential

Charm production in partonic and hadronic matter

Charmed particle ratios (ψ/D , Λ_c/D , D/D_s , ...) are sensitive to the medium they are formed in

In-medium properties of open charm

Statistical hadronization model:
A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel,
arXiv:0708.1488

Kinetic rate equation in thermal fireball:
L. Grandchamp, R. Rapp, G.E. Brown,
Phys. Rev. Lett. 92 (2004) 212301

HSD microscopic transport model:
W. Cassing, E. Bratkovskaya, A. Sibirtsev,
Nucl. Phys. A 691 (2001) 753

Looking into the fireball ...

... using penetrating probes:

short-lived vector mesons decaying into
electron-positron pairs

Dilepton radiation from the deconfined phase?

Data: R. Arnaldi, et al. [NA60 Collaboration], Phys. Rev.Lett. 96, 162302 (2006);

Calculation: J.Ruppert, C. Gale, Th. Renk, P. Lichard, J. I. Kapusta, arXiv:0706.1934

Inverse slope parameters as function of mass

R. Arnaldi et al., (NA60),
arXiv: 0711.1816v1 [nucl-ex]
to appear in PRL

N. Xu, Int. J. Mod. Phys. E16 (2007) 715

$M < 1 \text{ GeV}/c^2$: radial flow generated in the late hadronic phase
 $M > 1 \text{ GeV}/c^2$: messengers from the early partonic phase?

Searching for the modification of hadron properties via dilepton measurements

Calculations: H. van Hees, R. Rapp, arXiv:0711.3444v1 [hep-ph]

no $\rho, \omega, \phi \rightarrow e^+e^- (\mu^+\mu^-)$ data between 2 and 40 AGeV
 Electrons: access to $M_{inv} < 200 \text{ MeV}/c^2$ Muons: better statistics (trigger)
 no $J/\psi, \psi' \rightarrow e^+e^- (\mu^+\mu^-)$ data below 100 AGeV

Information needed in addition to dileptons from A+A:

- $\pi, K, p, \Lambda, \dots$ to constrain the fireball evolution
- $\rho \rightarrow \pi\pi, \phi \rightarrow KK$ to measure the freeze-out contributions
- p+A collisions to determine the contribution of primordial p's

The quest for the critical endpoint: Search for dynamical fluctuations in the E-by-E kaon/pion ratio

NA49 Preliminary

Measure the particle yields ratio
in an event : K/π

Relative width of distribution : $\sigma = \text{RMS} / \text{MEAN}$

$$\sigma_{\text{data}}^2 = \underbrace{\sigma_{\text{fin}}^2 + \sigma_{\text{exp}}^2}_{\text{background}} + \sigma_{\text{dyn}}^2$$

Event mixing: no two tracks coming from
one real event $\Rightarrow \sigma_{\text{mixed}}$

$$\sigma_{\text{dyn}}^2 = \sigma_{\text{data}}^2 - \sigma_{\text{mixed}}^2$$

Fluctuations from NA49

nucl-ex/0403035

- dynamical fluctuations reported by NA49
- increase towards low energies
- K/π : not reproduced by UrQMD
- p/π : correlation due to resonance decays

Summary: CBM physics topics and observables

The equation-of-state at high ρ_B

- collective flow of hadrons
- particle production at threshold energies (multistrange hyperons, open charm?)

Deconfinement phase transition at high ρ_B

- excitation function and flow of strangeness (K , Λ , Σ , Ξ , Ω)
- excitation function and flow of charm (J/ψ , ψ' , D^0 , $D^\pm$, Λ_c) (e.g. melting of J/ψ and ψ')
- excitation function of low-mass lepton pairs

QCD critical endpoint

- excitation function of event-by-event fluctuations ($K/\pi, \dots$)

Onset of chiral symmetry restoration at high ρ_B

- in-medium modifications of hadrons ($\rho, \omega, \phi \rightarrow e^+e^-(\mu^+\mu^-), D$)

CBM Physics Book in preparation

Meson production in central Au+Au collisions

W. Cassing, E. Bratkovskaya, A. Sibirtsev, Nucl. Phys. A 691 (2001) 745

Experimental challenges

Central Au+Au collision at 25 AGeV (UrQMD + GEANT4):
160 p 400 π^- 400 π^+ 44 K $^+$ 13 K $^-$

- up to 10^7 Au+Au reactions/sec
- determination of (displaced) vertices with high resolution ($\approx 50 \mu\text{m}$)
- identification of leptons and hadrons
- fast and radiation hard detectors
- selftriggered readout electronics
- high speed data acquisition and online event selection

The Compressed Baryonic Matter Experiment

Conceptual design and feasibility studies

Software tools:

- Framework FAIRroot, VMC
- Transport codes GEANT3&4, FLUKA
- Event generators UrQMD, HSD, PLUTO
- Fast track reconstruction algorithms for online event selection

Simulation input:

- realistic signal and background multiplicities (e.g. central coll. Au+Au 25 AGeV)
- realistic detector layout and response

Hyperon detection with STS (no p, K, π identification)

- Silicon tracker: 2 hybrid pixel (750 μm each), 4 microstrips (400 μm each)
- Strips with 50 μm pitch and 5° stereo angle
- full event reconstruction

central Au+Au collisions at 25 AGeV:

total efficiency 10.6%

2.1%

1.0%

Benchmark for Vertex-Tracker performance:
D mesons and Λ_c from Au+Au central collisions at 25 AGeV

- Full track reconstruction:
- 2 MAPS (150 μm thickness each)
 - 6 Silicon micro-strip detectors
 - proton identification via TOF

D and Λ_c multiplicity from HSD
Hadronic background from UrQMD

Vector meson identification via electron pairs in CBM

central Au+Au collisions at 25 AGeV

particle	S/B	ϵ (%)	σ (MeV)
ω	0.15	7.5	14
ϕ	0.13	9.1	14
ρ	0.002	4	
J/ψ	10	12	38
Ψ'

Vector meson identification via muon pairs in CBM

Central Au+Au collisions at 25 AGeV

particle	S/B	ϵ (%)	σ (MeV)
ω	0.11	4	10
ϕ	0.06	7	12
ρ	0.002	3	
J/ψ	18	13	21
Ψ'	1	16	27

Estimated particle yields for minimum bias Au+Au collisions at 25 AGeV

particle, mass (MeV)	N	decay mode	BR	R/s (MHz)	T	ϵ (%)	Y/s	Y/10 w
η (547)	6.6	$\mu^+\mu^-$	$5.8 \cdot 10^{-6}$	0.25	y	3	0.28	$1.7 \cdot 10^6$
K^+ (494)	8	-	-	0.025	n	20	$4 \cdot 10^4$	$2.4 \cdot 10^{11}$
K^- (494)	2.6	-	-	0.025	n	20	$1.3 \cdot 10^4$	$7.8 \cdot 10^{10}$
K_S^0 (497)	5.4	$\pi^+\pi^-$	0.69	0.025	n	10	$9.3 \cdot 10^3$	$5.6 \cdot 10^{10}$
ρ (770)	4.6	e^+e^-	$4.7 \cdot 10^{-5}$	0.025	n	5.4	0.29	$1.8 \cdot 10^6$
ρ (770)	4.6	$\mu^+\mu^-$	$4.6 \cdot 10^{-5}$	0.25	y	2.7	1.4	$8.6 \cdot 10^6$
ω (782)	7.6	e^+e^-	$7.1 \cdot 10^{-5}$	0.025	n	7.2	1	$6 \cdot 10^6$
ω (782)	7.6	$\mu^+\mu^-$	$9 \cdot 10^{-5}$	0.25	y	3.7	6.3	$38 \cdot 10^6$
ϕ (1020)	0.256	e^+e^-	$3 \cdot 10^{-4}$	0.025	n	9.6	0.18	$1 \cdot 10^6$
ϕ (1020)	0.256	$\mu^+\mu^-$	$2.9 \cdot 10^{-4}$	0.25	y	6	1.	$6.7 \cdot 10^6$
Λ (1115)	6.4	$p \pi^-$	0.64	0.025	n	10.6	$1.1 \cdot 10^4$	$6.5 \cdot 10^{10}$
Ξ^- (1321)	0.096	$\Lambda \pi^-$	0.999	0.025	n	2.1	50.4	$3 \cdot 10^8$
Ω^- (1672)	0.0044	ΛK^-	0.68	0.025	n	1	0.75	$4.5 \cdot 10^6$
D^0 (1864)	$7.5 \cdot 10^{-6}$	$K^- \pi^+$	0.038	0.1	y	3.25	$8.5 \cdot 10^{-4}$	$5.1 \cdot 10^3$
$\bar{D}^0$ (1864)	$7.5 \cdot 10^{-6}$	$K^- \pi^+ \pi^- \pi^-$	0.075	0.1	y	0.37	$2.1 \cdot 10^{-4}$	$1.3 \cdot 10^3$
$\bar{D}^0$ (1864)	$2.3 \cdot 10^{-5}$	$K^+ \pi^-$	0.038	0.1	y	3.25	$2.6 \cdot 10^{-3}$	$1.6 \cdot 10^4$
D^+ (1869)	$8 \cdot 10^{-6}$	$K^- \pi^+ \pi^+$	0.092	0.1	y	4.2	$3.1 \cdot 10^{-3}$	$1.9 \cdot 10^4$
D^- (1869)	$1.8 \cdot 10^{-5}$	$K^+ \pi^- \pi^-$	0.092	0.1	y	4.2	$7 \cdot 10^{-3}$	$4.2 \cdot 10^4$
Λ_c (2285)	$4.9 \cdot 10^{-4}$	$p K^- \pi^+$	0.05	0.1	y	0.5	$1.2 \cdot 10^{-2}$	$7.4 \cdot 10^4$
J/ψ (3097)	$3.8 \cdot 10^{-6}$	e^+e^-	0.06	1-10	y	14	0.032 - 0.32	$1.9 \cdot 10^{5-6}$
Ψ' (3686)	$5.1 \cdot 10^{-8}$	e^+e^-	$7.3 \cdot 10^{-3}$	1-10	y	15	$5.6 \cdot 10^{-(5-4)}$	$3.4 \cdot 10^{2-3}$
J/ψ (3097)	$3.8 \cdot 10^{-6}$	$\mu^+\mu^-$	0.06	10	y	16	0.36	$2.2 \cdot 10^6$
Ψ' (3686)	$5.1 \cdot 10^{-8}$	$\mu^+\mu^-$	$7.3 \cdot 10^{-3}$	10	y	19	$7.1 \cdot 10^{-4}$	$4.3 \cdot 10^3$

Annual yields at RHIC II & LHC

10 weeks CBM

Au+Au 25 AGeV

from Tony Frawley
RHIC Users mtg.

at LHC: $(10-50) \times \sigma$ $\sim 10\%$ of $\mathcal{L}$ 25% running time

Hardware development

CBM DAQ Architecture

Compressed Baryonic Matter 2007

<http://www.gsi.de/fair/experiments/CBM>

PROGRESS REPORT

Coming soon: CBM Physics Book

Content:

- Bulk Properties of Strongly Interacting Matter
- In-Medium Excitations
- Collision Dynamics
- Observables and Predictions
- The CBM Experiment

400 - 500 pages,
about 50 authors,
Submission in Sept. 2008
to Springer,
"Lecture Notes in Physics"

CBM Collaboration : 52 institutions, ~ 400 members

Croatia:

RBI, Zagreb
Split Univ.

China:

CCNU Wuhan
USTC Hefei

Cyprus:

Nikosia Univ.

Czech Republic:

CAS, Rez
Techn.Univ.Prague

France:

IPHC Strasbourg

Hungaria:

KFKI Budapest
Budapest Univ.

India:

Aligarh Muslim Univ.
Panjab Univ.
Rajasthan Univ.
Univ. of Jammu
Univ. of Kashmir
Univ. of Calcutta
B.H. Univ. Varanasi

Korea:

VECC Kolkata
SAHA Kolkata
IOP Bhubaneswar
IIT Kharagpur
Korea Univ. Seoul
Pusan National Univ.

Norway:

Univ. Bergen

Germany:

Univ. Heidelberg, P.I.
Univ. Heidelberg, KIP
Univ. Heidelberg, ZITI
Univ. Frankfurt
Univ. Münster
FZ Dresden
GSI Darmstadt

Poland:

Jag. Univ. Krakow
Warsaw Univ.
Silesia Univ. Katowice
AGH Krakow

Portugal:

LIP Coimbra

Romania:

NIPNE Bucharest
Univ. Bucharest

Russia:

IHEP Protvino
INR Troitzk
ITEP Moscow
KRI, St. Petersburg
Kurchatov Inst., Moscow
LHE, JINR Dubna
LPP, JINR Dubna
LIT, JINR Dubna
MEPHI Moscow
Obninsk State Univ.
PNPI Gatchina
SINP MSU, Moscow
St. Petersburg P. Univ.

Ukraine:

T. Shevchenko Univ. Kiev

Acceptance for particles identified by TOF

Very important for the measurement of event-by-event fluctuations:
a large and azimuthally symmetric acceptance

100 % purity:

Dilepton measurements in heavy ion collisions: fixed-target versus collider experiments

1. Experimental setups
2. Multiplicities
3. Luminosities
4. Rates

Dilepton sources in Heavy-ion Collisions

Single electron spectra central Au+Au collisions 25 AGeV

Background sources

1. external pair conversion:
 $\gamma \rightarrow e^+e^-$
2. Dalitz-decays:
 $\pi^0 \rightarrow \gamma e^+e^-$ (BR = $1.2 \cdot 10^{-2}$)
 $\eta \rightarrow \gamma e^+e^-$ (BR = $4.9 \cdot 10^{-3}$)
3. Bremsstrahlung:
 $pn \rightarrow pn e^+e^-$
4. misidentified pions

Background in muon measurements: $\pi \rightarrow \mu\nu$, $K \rightarrow \mu\nu$

$\eta \rightarrow \gamma\mu^+\mu^-$ (can be determined by $\eta \rightarrow \mu^+\mu^-$)

The pioneering experiment: DLS at the Bevalac

G. Roche et al., Phys. Lett. B 226 (1989) 228

DiLepton Spectrometer

Acceptance for e^+e^- pairs: 0.3%
Mass resolution: $\Delta m/m = 10\%$

Ring Imaging Cherenkov detector (RICH)

Bestimmung der Teilchen-
Geschwindigkeit durch Messung
von θ (Ringradius des Lichtkegels)

$$\cos\theta = 1/(\beta n)$$

DLS data

HADES at GSI

HADES

CERES/NA45 at SPS

Electron-positron pairs from CERES

CERES 2000: 159 AGeV Pb+Au

beam intensity: 10^6 ions / spill

1 spill = 4 s beam and 15 s pause

targets: $13 \times 25 \mu\text{m}$ Au ($\sim 1\%$ interaction)

trigger: 8% most central

Event rate = 470 / spill ($\sim 25 \text{ Hz} = 15 \text{ Mio events/week}$)

Low mass vector mesons (CERES/CERN)

Data: ~ 180 signal pairs

Calculations by R. Rapp:

thick dashed line:
unmodified rhothick dashed-dotted line:
in-medium dropping rho massthick solid line:
in-medium spread rho width

D.Adamova et al., PRL 91 (2003) 042301

Muon identification: NA38/50/60

Concept of NA60: place a **silicon tracking telescope** in the vertex region to measure the muons **before** they suffer multiple scattering in the absorber and **match** them to the tracks measured in the muon spectrometer

Improved kinematics; dimuon mass resolution at the ω :
 $\sim 20 \text{ MeV}/c^2$ (instead of $80 \text{ MeV}/c^2$ in NA50)
 Origin of muons can be accurately determined

Dimuon pairs measured by NA60 (CERN)

RHIC Relativistic Heavy Ion Collider

Projectile ion: e.g. Au^{79+}
 Energy: $2 \times 100 \text{ GeV/u}$
 Magnetic dipol field: 6 T

$$s_{\text{NN}} = (E_1 + E_2)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2$$

collider: $\mathbf{p}_1 + \mathbf{p}_2 = 0 \rightarrow \sqrt{s_{\text{NN}}} = E_1 + E_2$

fixed target: $E_2 = m$, $\mathbf{p}_2 = 0$

$$s_{\text{NN}} = (E_{\text{kin}} + 2m)^2 - \mathbf{p}_1^2$$

$$s_{\text{NN}} = 2m \cdot (E_{\text{kin}} + 2m)$$

for $E_{\text{kin}} \gg m$: $\sqrt{s_{\text{NN}}} = 1.4 \cdot \sqrt{E_{\text{kin}}}$

If the incoming beam is simply slammed into a stationary target, much of the energy is taken up by the target's recoil.

PHENIX Physics Capabilities

designed to measure rare probes:

Au-Au & p-p spin

+ high rate capability & granularity
+ good mass resolution and particle ID
- limited acceptance

• 2 central arms:

electrons, photons, hadrons

- charmonium $J/\psi, \psi' \rightarrow e^+e^-$
- vector meson $\rho, \omega, \phi \rightarrow e^+e^-$
- high p_T π^0, π^+, π^-
- direct photons
- open charm
- hadron physics

• 2 muon arms:

muons

- "onium" $J/\psi, \psi', Y \rightarrow \mu^+\mu^-$
- vector meson $\phi \rightarrow \mu^+\mu^-$
- open charm

• combined central and muon arms:

charm production $DD \rightarrow e\mu$

PHENIX data

Low-Mass Continuum:

enhancement $150 < m_{ee} < 750$ MeV: $3.4 \pm 0.2(\text{stat.}) \pm 1.3(\text{syst.}) \pm 0.7(\text{model})$

Intermediate-Mass Continuum:

Single- $e \rightarrow p_T$ suppression & non-zero v_2 : charm thermalized?

PYTHIA single- e p_T spectra softer than p+p but coincide with Au+Au

Angular correlations unknown

Room for thermal contribution?

• Data absolutely normalized

• Cocktail filtered in PHENIX acceptance

• Charm from

- PYTHIA

- Single electron non photonic spectrum w/o angular correlations

$\sigma_c = N_{coll} \times 567 \pm 57 \pm 193 \mu\text{b}$

CERN and the Large Hadron Collider (LHC)

Protons and heavy ions (Pb)
Energy: $> 1 \text{ TeV}$
 Protons in the ring: 3×10^{14}
 Current: 0.5 A
 Beam energy: 3 MJ
Magnetic dipole field: 8 T

The ALICE experiment at CERN

Fig.1: Layout of the ALICE detector. The Transition Radiation Detector (4) is the cyan component placed between the TPC (3) and TOF (5).

Transition radiation

$$\text{Total energy} \propto \gamma$$

$$\Theta = 1/\gamma$$

Transition Radiation Detectors (TRD)

$$p = 1 \text{ GeV/c}$$

$$\gamma_e = 2000$$

$$\gamma_\pi = 7.1$$

Facility for Antiproton and Ion Research (FAIR)

primary beams

- $5 \times 10^{11}/s$; 1.5-2 GeV/u; $^{238}\text{U}^{28+}$
- factor 100-1000 increased intensity
- $4 \times 10^{13}/s$ 90 GeV protons
- $10^{10}/s$ ^{238}U 35 GeV/u (Ni 45 GeV/u)

secondary beams

- rare isotopes 1.5 - 2 GeV/u;
- factor 10 000 increased intensity
- antiprotons 3(0) - 30 GeV

storage and cooler rings

- beams of rare isotopes
- e – A Collider
- 10^{11} stored and cooled antiprotons
- 0.8 - 14.5 GeV

accelerator technical challenges

- Rapidly cycling superconducting magnets
- high energy electron cooling
- dynamical vacuum, beam losses

The Compressed Baryonic Matter Experiment

Electron identification with RICH and TRD

Mapping the QCD phase diagram with heavy-ion collisions

Critical endpoint:

Z. Fodor, S. Katz, hep-lat/0402006

S. Ejiri et al., hep-lat/0312006

crossover at small μ_B

Recent L QCD calculations:

$T_c = 150 - 190 \text{ MeV}$

baryon density:

$$\rho_B \approx 4 \left(\frac{mT}{2\pi} \right)^{3/2} \times \frac{\exp((\mu_B - m)/T) - \exp((- \mu_B - m)/T)}{\text{baryons} - \text{antibaryons}}$$

Meson production in central Au+Au collisions

Vector meson yields for central Au+Au collisions
at $\sqrt{s_{NN}} = 7.1$ GeV (25 AGeV)

	J/ψ	ρ	ω	φ
multiplicity	$2 \cdot 10^{-5}$	23	38	1.3
BR ($\rightarrow \mu\mu$)	0.06	$4.6 \cdot 10^{-5}$	$9 \cdot 10^{-5}$	$3 \cdot 10^{-5}$
$\mu\mu$ multiplicity	$1.2 \cdot 10^{-6}$	$1 \cdot 10^{-3}$	$3.4 \cdot 10^{-3}$	$3.7 \cdot 10^{-4}$
$\mu\mu$ min bias	$3 \cdot 10^{-7}$	$2.5 \cdot 10^{-4}$	$8 \cdot 10^{-4}$	$9 \cdot 10^{-5}$

Collider Luminosity: $L = N_1 \cdot N_2 \cdot B / F \text{ [cm}^{-2}\text{s}^{-1}\text{]}$

N_1, N_2 = beam particles per bunch

B = number of bunch crossings per sec

F = beam size in cm^2

Typical numbers:

$$N_1 = N_2 = 10^9$$

$$B = 10^6 \quad \rightarrow L = 10^{27} \text{ cm}^{-2}\text{s}^{-1}$$

$$F = 10^{-3} \text{ cm}^2$$

Reaktion rate $R = L \cdot \sigma$

σ = reaction cross section

$$\sigma = \pi \cdot (2 \cdot R)^2 = 4 \pi \cdot (r_0 \cdot A^{1/3})^2 \quad \text{with } r_0 = 1.2 \text{ fm}$$

$$\text{Au+Au collisions: } A=197 \rightarrow \sigma = 6 \text{ barn, } 1 \text{ barn} = 10^{-24} \text{ cm}^2$$

Collider reaction rates for Au+Au:

$$R = 10^{27} \text{ cm}^{-2}\text{s}^{-1} \cdot 6 \cdot 10^{-24} \text{ cm}^2 = 6000 \text{ s}^{-1}$$

Fixed target Luminosity: $L = N_B \cdot N_T / F \text{ [cm}^{-2}\text{s}^{-1}\text{]}$

N_B = beam particles/sec

$$N_T / F = \text{target atoms/cm}^2 = N_A \cdot \rho \cdot d / A$$

with Avogadros Number $N_A = 6.02 \cdot 10^{23} \cdot \text{mol}^{-1}$,

material density $\rho \text{ [g/cm}^3\text{]}$,

target thickness $d \text{ [cm]}$

atomic number A

Typical numbers:

$$N_B = 10^9 \text{ s}^{-1}$$

$$\text{Au target: } \rho = 19.3 \text{ g/cm}^3, A = 197$$

$$d = 0.3 \text{ mm (1\% interaction rate)}$$

$$L = 1.8 \cdot 10^{30} \text{ cm}^{-2}\text{s}^{-1}$$

Fixed target reaction rates for Au+Au:

$$R = L \cdot \sigma = 1.8 \cdot 10^{30} \text{ cm}^{-2}\text{s}^{-1} \cdot 6 \cdot 10^{-24} \text{ cm}^2 = 10^7 \text{ s}^{-1}$$

Acceptances and Efficiencies

$$\varepsilon = \varepsilon_{\Delta\Omega} \cdot \varepsilon_{\Delta p} \cdot \varepsilon_{\text{Det}} \cdot \varepsilon_{\text{Trigg}} \cdot \varepsilon_{\text{DAQ}} \cdot \varepsilon_{\text{analysis}}$$

with

$\varepsilon_{\Delta\Omega}$ = angular acceptance

$\varepsilon_{\Delta p}$ = momentum acceptance

ε_{Det} = detector efficiencies

$\varepsilon_{\text{Trigg}}$ = trigger efficiencies

ε_{DAQ} = dead time correction of DAQ

$\varepsilon_{\text{analysis}}$ = efficiency of analysis

(track finding, cuts for background suppression , ...)

Typical values:

$\varepsilon_{\Delta\Omega} \approx 0.5$, $\varepsilon_{\Delta p} \approx 0.8$, $\varepsilon_{\text{Det}} \approx 0.9$, $\varepsilon_{\text{Trigg}} \approx 0.9$, $\varepsilon_{\text{DAQ}} \approx 0.5$, $\varepsilon_{\text{analysis}} \approx 0.3$,

$\varepsilon \approx 0.05$

Low-energy RHIC run at $\sqrt{s_{\text{NN}}} = 9$ GeV

peak luminosity $\sim 2 \cdot 10^{23} \text{ cm}^{-2}\text{s}^{-1}$

Reaction rate Au+Au ~ 1 Hz

further reduction:

average luminosity, large diamond

improvement by upgrades incl. e^- cooling

NICA collider

luminosity design value $\sim 1 \cdot 10^{27} \text{ cm}^{-2}\text{s}^{-1}$

Expected dilepton yields for
minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 7.1$ GeV (25 AGeV)

Assumption: experimental efficiency $\varepsilon = 10\%$

Multiplicity of J/ψ : $M \cdot \varepsilon = 3 \cdot 10^{-8}$

Multiplicity of ω : $M \cdot \varepsilon = 8 \cdot 10^{-5}$

Collider reaction rate 100 s^{-1}

Yield of J/ψ :

$3 \cdot 10^{-8} \cdot 100 \text{ s}^{-1} = 3 \cdot 10^{-6} \text{ s}^{-1} = 1.1 \cdot 10^{-2} \text{ h}^{-1} = 19$ in 10 weeks

Yield of ω :

$8 \cdot 10^{-5} \cdot 100 \text{ s}^{-1} = 8 \cdot 10^{-3} \text{ s}^{-1} = 29 \text{ h}^{-1} = 50000$ in 10 weeks

Fixed target reaction rates:

10^7 s^{-1} with J/ψ trigger: $1.9 \cdot 10^6 J/\psi$ in 10 weeks

10^5 s^{-1} without trigger: Yield of ω : $5 \cdot 10^7$ in 10 weeks