Precision Studies of Relativistic Nuclear Collisions

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• Motivation
• Experimental approach
• Results
  Nuclear technology
  Nuclear structure
  Dissipation
  Excitation of the nucleon
  Equation of state
• Summary
Motivation: Production of heavy residues in relativistic nuclear collisions

- Design of ADS for transmutation of radioactive waste

- Production of rare isotopes (FAIR, RIA)

- Spallation in interstellar medium ...
• Physics of semi-peripheral nuclear collisions and spallation reactions

Spectators:

“Swiss-cheese like” Fermionic system
• Punching holes in Fermi sphere
• Thermalization
• Expansion – break-up – freeze-out
  o Nörenberg et al., EPJ A9 (2000) 327
• Evaporation and fission

Participants:
Hot and dense nuclear matter (EoS)
• Incompressibility (statics)
• Momentum-dependent mean field (dynamics)
The Experimental Approach: Inverse Kinematics

Conventional experiments detect target-like reaction products by gamma decay

Suffer from:
- Stopping of the products in the target
- Radioactive decay before detection

GSI-experiments investigate projectile-like reaction products in-flight

Requires:
- A powerful heavy-ion accelerator
- Adapted high-resolution in-flight detection devices
The GSI Facility

Installations used for the experiments:
The Fragment Separator (FRS)

- $A/Z$ identified by $(B\rho)_2$ and ToF in FRS

$$B\rho = p/q \sim A \cdot \gamma \cdot v/Z$$

- $Z$ identified by $\Delta E$ in ionization chamber

$$\Delta E \sim Z^2 / v^2$$

$\rightarrow Z$ and $A$ are exactly known.

- Velocity precisely determined by $(B\rho)_1$

$$B\rho = p/q \sim A \cdot \gamma \cdot v/Z$$

$\rightarrow$ Relative precision $5 \cdot 10^{-4}$
Nuclide Identification Pattern

$^{136}\text{Xe} + \text{Pb}, 1 \text{ A GeV}$

Complete separation in $A$ and $Z$

D. Henzlova, PhD thesis
Nuclide distributions

Cross sections of 1368 nuclides determined.

M. V. Ricciardi et al., in preparation

Systems investigated: (analyzed by)

$^{238}\text{U} + ^1,^2\text{H,Ti,Pb}$ (J. Taieb*, M. Bernas, M. V. Ricciardi*,
E. Casarejos*, J. Pereira*, T. Enqvist)

$^{208}\text{Pb} + ^1,^2\text{H, Ti}$ (T. Enqvist, B. Fernandez*, A. Kelic, L.Audouin*)

$^{197}\text{Au} + ^1\text{H}$ (F. Rejmund, J. Benlliure)

$^{124,136}\text{Xe} + ^1\text{H},^{208}\text{Pb}$ (P.Napolitani*, D.Henzlova*, M.Fernandez*)

$^{56}\text{Fe} + ^1\text{H,Ti}$ (C. Villagrasa*, P. Napolitani*)

$^{197}\text{Au} + ^{197}\text{Au}$ (V. Henzl*)

Energies: 0.2 to 1.5 A GeV

*PhD theses
Strongly enhanced production of even-even $N=Z$ nuclei

Evidence for neutron-proton pairing / alpha clustering
Evidence for transient effects in fission

- Motion from g.s. to saddle is critically damped.
Fission channels

• Z-distributions from e.m.-induced fission of 70 secondary beams (E* ~ 11 MeV).
• Transition from asymmetric to symmetric fission mapped.

Caloric curve from ALADIN
(An indication for the liquid-gas phase transition)

The 4 nuclides, entering into the analysis:
FRS Data: The Isospin Thermometer

- Memory on N/Z of projectile is preserved for all fragments.
- The data are reproduced with a three-stage model: Abrasion – Break-up – Evaporation.
- Indication for constant freeze-out temperature of ≈ 6 MeV.

M. V. Ricciardi, D. Henzlova, PhD theses
Nuclear Charge-Exchange Reaction

- Charge-exchange reactions: $^1H(^{208}Pb, ^{208}Bi)x$, $^2H(^{208}Pb, ^{208}Bi)x$ at 1 A GeV
- Quasielastic scattering and excitation of the $\Delta(1232)$ resonance
- Excitation of the nucleon in the nuclear medium

Participant's blast on the spectators

- Unexpected acceleration in violent collisions.
- Valuable information on the EOS of nuclear matter.
- Information on momentum-dependent mean field.

M.V. Ricciardi, V. Henzl, PhD theses
M. V. Ricciardi et al., PRL 90 (2003) 212302
L. Shi, P. Danielewicz, R. Lacey, PRC 64 (2001) 034601
The FAIR Project

Improved experimental possibilities for nuclear-reaction experiments by

- Higher beam intensities
- Higher beam energies
- New spectrometers and rings
Summary

- **In-flight investigations** of projectile-like reaction products at the GSI heavy-ion facility.

- Mapping of nuclide *production cross sections*.

- Relevance for nuclear technology and astrophysics

- Yields reveal *neutron-proton pairing*.

- Fission dynamics *critically damped*.

- Mapping of the *fission channels*.

- Indications for a *break-up phase* from $N/Z$ ratios.

- *Excitation of the nucleon* in the nuclear medium.

- **Acceleration** of projectile fragments (*EoS*).

- ... and many more observations
  (see also http://www-w2k.gsi.de/charms)
CHARMS Collaboration
(Collaboration for high-accuracy measurements of nuclear reactions with the FRS)


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