….. some selected highlights since NN2012

Angela Bracco

Università di Milano and INFN
Interlinks of these fields to address questions such as:

- What is the influence of meson and hadron properties in the Quark-gluon plasma?

- What are the nuclear structure effects influencing the nucleosynthesis and low energy nuclear reactions?
Ultra relativistic heavy ion collisions

From the beginning

the big bang …..

the hot compressed matter and the properties of the hot quark gluon plasma
What do we want to learn from HIC?

Some results

Future

Exploring QCD under extreme conditions, where the strong interaction is really strong,

**The aim**

Weakly interacting plasma / ideal gas of (quasi-free) quarks & gluons

Partons are deconfined (not bound into composite color neutral hadrons)

Chiral symmetry is restored (partons ≈ massless, vanishing gluon condensate)

**The tools**

Relevant degrees of freedom (and experimental observables) at high T: ordinary hadrons are not sufficient
Heavy ion Collisions: matter under extreme conditions

Central activity of contemporary Nuclear Physics.

Energy increase by factor $10^4$ in ~30 years.

Total center-of-mass energy versus time.

By J. Schukraft.
No quasi free gas!!

From Collective properties

Future: What is the dynamics

‘Where is the onset? size & energy density? 

Increasingly precise measurements of macroscopic properties

\[ \eta/S, \xi, q^, e^, D, \text{EoS, } c_s, \]

2004: \(4\pi \eta/s < 10\)

2014: \(4\pi \eta/s \approx 1 - 2\)

'Macroscopic' piece of matter with amazing properties

- reaches thermo/hydro equilibrium incredibly fast & in small volumes (< 1 fm)
- tiny viscosity reveals density fluctuations in the initial state, event-by-event!
Reconcile: Perfect Fluid
(the relevant dof (particles, excitations, ..) are NOT free quarks & gluons)
and
Weak coupling (deconfinement) at short distances (from QCD)

\[ R_{AA} \]

\[ J/\Psi \] production

\[ W, \text{ and } Z \text{ production} \]

\[ J/\Psi \text{ coalescence} = \text{color conductivity}, \]
\[ Y \text{ suppression} = \text{resonance melting} \]

\[ \Rightarrow \text{less suppression than RHIC (PHENIX, } 1.2 < y < 2.2, p_T > 0) \]

\[ \Rightarrow \text{weaker centrality dependence} \]

\[ \Rightarrow \text{new regime } c\bar{c} \text{ coalescence?} \]
What do we want to learn from HIC?

Chiral symmetry Restoration?

Some evidence in low masses (rho) (indirect)

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strangeness, Behavior of multi strange barions

p-Pb smoothly bridges \( \Xi, \Omega \) abundances from pp to Pb-Pb values!

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Future planned measurements focusing mainly on heavy quarks with increased precision!
$^6\text{Li} + ^{12}\text{C}$
invariant mass distributions of $d + \pi$
and $t + \pi$

Properties of $\Lambda - n$ for Neutron stars

Lifetime estimation of the possible bound states yielding $d + \pi$
$t + \pi$

$181 \pm 30$ ps
$190 \pm 47$ ps
$(260$ ps lifetime of Lambda$)$

These states may be interpreted as the 2-body and 3-body decay of a neutral bound state:
2 neutrons and a hyperon, $^3\Lambda n$-
**Equation of state of Nuclear matter and neutron stars**

**EOS**: Constrains from isoscalar modes, as the GMR (nuclear compressibility), heavy ion collisions

Recent result on $^{68}$Ni for the GMR (GANIL- Active target Maya and RIB at 50 MeV/u)

**EOS Asymmetric term constrained by**:
- Heavy Ion collisions
- Neutron Skin polarizability (GDR and pygmy)
- P-REX experiments
- Nuclear masses

Soft mode? compressibility of the skin?

Symmetry energy slope

**EDF with effective interactions**

PRL113(2014)032504
Heavy ion Collisions and the nuclear equation of state

The EOS, relationship between:

Thermodynamic and the bulk nuclear properties

is relevant in heavy ion collisions and environments of nucleosynthesis.

Evidence also of effects of **clusterization** on the Low-Density
(see e.g. *J P-G*41 (2014) 075108- (LNL)
and *J. P. G.* 420(2013) 012087 from LNS)

Equation-of-State:
For fluctuation and symmetry energy in nuclear fragmentation dynamics see M. Colonna, PRL110,042701(2013)
Neutron skin and its properties ....(pygmy-polarizability)

Virtual photon
Excitation of the dipole response

Low energy part
interpreted as oscillation of the skin or excitation of nucleons in the skin

Strength below binding –affecting nucleosynthesis in the r-process

Pygmy resonance

Nuclear Polarizability in $^{68}$Ni (GSI PRL111(2013)-242503)

Isospin character of the pygmy mode
Stringent test to theory

$^{17}$O inelastic scattering
AGATA at LNL
PRL113(2014)012501
Quantum montecarlo methods with chiral interactions

To be studied:

- Halo, radii, skins
  low energy scattering, break up high energy cross sections
- Binding energies (masses)
- The coupling of loosely bound nuclei to the continuum
  g.s and ex. resonances in very short lived b.s. (di-n and di-p decay)
- Excited states of light nuclei
- moments from measurements in traps

See e.g:
T. Otsuka et al. PRL 105(2010)
G.R. Jansen et al. PRL 113(2014) 142502

3N int. are needed .....pave the way to many-body systems
Halo nuclei, radii

Proton radii from charge changing reaction

PRL113(2014)132501

Two neutron decay
two proton decay

the heaviest halo: $^{37}$Mg
$S_n = 0.2$ MeV

Spectroscopic factors

Importance of p-wave
Change of the order level

$^{26}$O n-drip line

PRL113(2014)132501

$^{15}$Ne p-drip line

PRL112(2014)132502

$^{24}$O+n+n

Life time = 4.5 ps

$^{15}$Ne* 2n and 2p radioactivity
-no sequential decay

$^{14}$O

Spectroscopic factor purity of single particle

$^{14}$O(d, $^3$He) $^{14}$O(d, t)

GANIL
**Hoyle states $^{12}\text{C}$**

Particular attention to the problem of alpha clustering and of Hoyle states:

- 3 alpha decay
- Excited bands
- Form factors

Transition density from elastic scattering data

Hoyle state E0 form factor with Quantum Monte Carlo

Great success for theory!

$^{12}\text{C}$ – 3 alpha cluster

Deduce geometry
Data: spinning of an oblate equilater triangle

Charged radius larger than g.s.

PRL 113, 012502 (2014) $^{12}\text{C}(^{4}\text{He}; 3\alpha)^{4}\text{He}$-Birmingham

PRL 113(2014)102501

3 alpha decay 7.65 MeV 0+
0.2% direct branching

12C

Ground State Band

Bending Band

4+ Hoyle Band

5-

2-

4+ 4-

2+ 2-

1-

Triangular symmetry?

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Triangular symmetry?
Different excitation modes. Their properties need for description:

- Theoretical approaches overlap and bridges need to be built between them.
- Configuration interactions
- Density Functional Theory
- Dynamical symmetries

Super heavy beyond p drip line

Far from stability - New shells – and new magic numbers

shell disappearance - shell robustness

- Deformation- shape transition
- Shape coexistence
- Collective effects and particle vibration coupling
- Pairing interaction
The frontier: neutron-rich calcium isotopes

F. Wienholtz et al., Nature 498, 346 – mass

D. Steppenbeck et al., Nature 502, 207 - 2+ state

where ab-initio and DFT meet...

Data on Ti toward $^{60}\text{Ca}$

And for particle phonon coupling? They are now included in DFT
(see e.g. PRL113(2014)252501)

New Closures

N = 32 & 34

Ni isotopes-Beta decay

Magicity for p and n in $^{78}\text{Ni}$

PRL113(2014)102501

Evidence for neutron excitation

PRL112(2014)112503

MSU

PRL113(2014)182501

RIKEN
Quenching of shell, and robust shell closure

From $^{100}$Sn

- Shell energy
  - Tin region
  - Imber
  - RISING-GSI
  - $^{132}$Sn
  - Robust N=Z shell closure

- Lifetimes and cross sect. ORNL
- Isomers in Cd (RIKEN)
- Spin, $\mu$ (ISOLDE)

- PRL112(2014)172701
- PRL110(2013)172501
- PRL112(2014)092501

-$^{158}$Ta is beyond proton drip line but it has a spin trap-isomer!
- (multiparticle nature)
- $\gamma$ and $\alpha$ decay
- $\alpha$ decay at high $l$

Exp. JYFL

Spectroscopy done through the isomer!

The p drip line is blurred!!

Large deformations for Mg neutron rich N=

RISING-GSI

$^{132}$Sn

Shell N=80 in $^{132}$Sn as strong as in $^{208}$Pb

Life times

PRL111(2013)212502

Neutron Number N

$R_{4/2}$

$\Delta R_{4/2}$ Si
$\Delta R_{4/2}$ Mg
**Deformation, collectivity**

**Evolution of collectivity - rapid shape transitions**

- **Charged Radii of Au isotopes**
- **Hyperfine structure**
- **and alpha decay**

**Mapping**

- **Shape change**
- **Exp on Os isotopes**
- **Lifetime measured AGATA at LNL**

---

**Pairing**

**Search for a new type of superfluidity**

- **No T= 0 Pairing from Gamow Teller Strength Rising GSI**

**Importance of pairing in the 2n cross section LNL exp**

- **Giant pairing in $^{14,15}$C ?**
- **Other cases needed to conclude nccomms7743 (2015)**

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**Motivation for search for a non-zero EDM in $^{225}$Ra.**

- **Gaffney et al., Nature 497, 199 Exp at ISOLDE**
**Super-heavy**

Shell energy

<table>
<thead>
<tr>
<th>Proton nu</th>
<th>140</th>
<th>134</th>
<th>130</th>
<th>126</th>
<th>122</th>
<th>118</th>
<th>114</th>
<th>110</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron number</td>
<td>160</td>
<td>180</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Superheavy region

**Synthesis** \(^{48}\text{Ca} + ^{249}\text{Bk}\) (\(Z = 117\) fully identified)

**Chemistry**
(ionization potential)


**Spectroscopy**

of element 115

First level interpretation

From model

(PRL 111(2013) 112502)

Reactions are studied

PRL 112(2014) 172501

...discovery on 266Lr

\[ T_{1/2} = 0.70(3) \text{s} \]

\[ Q_{\alpha} = 10.10(1) \text{ MeV} \]

\[ E_{276\text{Mt}} = 9.60(1) \text{ MeV} \]

**Entry point**

much above yrast!

Fission barrier at 15 h similar to \(I=0\)

0.6 MeV different!

**Fission dynamics**

is needed

For super heavy

90% pre-fission n

PRL 113(2014) 262505

PRL 112(2014) 152702 n

How robust are shell in \(^{252}\text{No}\) nucleus?

Entry point much above yrast!
Fission barrier at 15 h similar to \(I=0\)
0.6 MeV different!

Pre-fission neutron in \(Z=108\)

ANL
Around the barrier

Reactions

Fusion and fission

Fusion Hindrance for a Positive-Q-value $^{24}$Mg + $^{30}$Si
LNL-PRL113(2014)022701

LNS data
Very low-energy loosely bound and diffuse surface affect the potential
Role of the continuum

$^{11}$Li break-up at Coulomb barrier -TRIUMF
(PRL110(2013)142701)

Fusion reaction and structure at finite T - LNS
PRC90(2014) 054603

GDR

Interplay between orientation of the deformed nucleus and quantum shell
Canberra-data on quasi fission
Nuclear landscape and nucleosynthesis

The Big Bang created only Hydrogen and Helium.

All the other elements are created in a continuing cosmic cycle which involves the birth, life and death of stars.

Various nucleo-synthesis processes in different regions of the nucleal chart!
Reactions - Cross section measurements for astrophysics

\[ ^{13}\text{C}(\alpha,n)^{16}\text{O} \]

Neutron source for s process role of 3 keV Subthreshold res

Gamma-ray astronomy
Production of \(^{26}\text{Al}\) in massive stars

Data = previous calculation X40

\[ ^{18}\text{F}(\alpha,p)^{15}\text{O} \]

3 new states in \(^{19}\text{Ne}\) to explain rate production

s-process study – isotope \(^{67}\text{Zn}\) abundance

\[ d(\alpha,\gamma)^{6}\text{Li} \]

Data in agreement with BBN
**Lifetime γ-ray for bottleneck reaction in CNO**

**MSU-GRETINA**
X-ray burst – the rp process

57\(^{\text{Cu}}(p,\gamma)\)\(^{58}\text{Zn}\) among TOP 20 reactions

**GANIL**
β-delay p-γ competition

**LNL – AGATA**
Lifetime γ-ray for bottleneck reaction in CNO

**Core-collapse (Type II) Supernovae**
e-capture dominated by GT

**OSLO**

**Hi γ's lab.**

**Star dust**

Level density and gamma strength for r- and s-processes

\[^{86}\text{Kr}/^{84}\text{Kr}\] (γ,n)

86\(^{\text{Kr}}/84\text{Kr}\)

PRL 112(2014) 222501

PRL 112(2014)032502

PRL 113(2014)032502

PRL 111(2013)112501
Nuclear Physics Laboratories around the world

Major upgrades and new facilities are under construction!
LNL : SPES- CYCLOTRON for the production of radioactive beams

<table>
<thead>
<tr>
<th>Main Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerator Type</td>
<td>Cyclotron AVF 4 sectors</td>
</tr>
<tr>
<td>Particle</td>
<td>Protons (H⁻ accelerated)</td>
</tr>
<tr>
<td>Energy</td>
<td>Variable within 30-70 MeV</td>
</tr>
<tr>
<td>Max Current Accelerated</td>
<td>750 µA (52 kW max beam power)</td>
</tr>
<tr>
<td>Available Beams</td>
<td>2 beams at the same energy (upgrade to different energies)</td>
</tr>
<tr>
<td>Max Magnetic Field</td>
<td>1.6 Tesla</td>
</tr>
<tr>
<td>RF frequency</td>
<td>56 MHz, 4&lt;sup&gt;th&lt;/sup&gt; harmonic mode</td>
</tr>
<tr>
<td>Ion Source</td>
<td>Multicusp H⁻ I=15 mA, Axial Injection</td>
</tr>
<tr>
<td>Dimensions</td>
<td>Φ=4.5 m, h=1.5 m</td>
</tr>
<tr>
<td>Weight</td>
<td>150 tons</td>
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Cyclotron assembled and operated with 700 µA at 1MeV
Applications: in many fields

Applications in medicine get a great attention

$^{149}\text{Tb}$: targeted alpha therapy. 2014 tests establishing safe usability limits, e.g. kidney damage

$^{155}\text{Tb}$: Very promising results about the effect of Auger electrons for therapy.

NuPECC Report
Efforts in different directions

- Experiment different observables to pin down new effects
- Theory mutual feedbacks with experiments
- Technical developments ties and implications with other research fields
- Interconnections and mutual inspiration
My presentation addresses only few of the interesting results
Apologies…. Hope a flavor is given for a very lively field!!

For this week we are looking forward for:

• Presentations of the interesting ongoing work
• Discussions for the future plans
• Active participation of students and young researchers

Many thanks to the organizers
and enjoy the NN2015 conference!!!