NuPECC Meeting

Nuclear Physics Research Programs
at LNS (Catania)

E. Migneco

Frascati 5-6 Dec. 2003
LNS in numbers

INFN Laboratori Nazionali del Sud are located in the Catania University campus area

- Total surface: 35000 m²
- Total volume: 97000 m³
- Staff members: 109
- Associated researchers: 82
- Users: 212
- Foreign users: 106
- Scientific production: about 150 published works/year
- Budget: about 11200 KEuros/year
Layout of the LNS accelerators

- Tandem Cyclotron
- Target
- Tandem injector
- Ion source
### 2001-2003 beam statistics

#### 2001
- **January-July**
- **October-December**

#### 2002
- **January-July**
- **November**

#### 2003
- **January-July 18**
- **July 20-31**
- **ECRIS exp.**

**Cyclotron beam**
- **2569 h**
- **2485 h**
- **2177 h**

**Tandem beam**
- **1085 h**
- **2075 h**
- **2288 h**

**Setting and beam development**
- **1424 h (CS)**
- **1161 h (CS)**
- **1020 h (CS)**

**Failures (Cyclotron)**
- **975 h**
- **587 h**
- **597 h**

**Failures (Tandem)**
- **200 h (Tand)**
- **222 h (Tand)**
- **417 h (Tand)**

**ECRIS experiment**
- **288 h**

**Notes:**
- **January-July 2001**
- **October-December 2001**
- **January-July 2002**
- **November 2002**
- **January-July 2003**
- **July 20-31 2003**

**2001-2003 beam statistics**
2003 Experiments at the Cyclotron

- Nuclear Physics: 1266 hours
- Applications: 911 hours
- Total: 2177 hours

2003 Experiments at the Tandem

- Nuclear Physics: 1368 hours
- Applications: 920 hours
- Total: 2288 hours
Cyclotron beams developed up to October 2003

**AX**

- $^2\text{H}^+$: 62
- $^2\text{D}^+$: 62
- $^4\text{He}$: 25
- $^7\text{Li}$: 50
- $^{12}\text{C}$: 23, 62
- $^{13}\text{C}$: 45
- $^{14}\text{N}$: 62
- $^{16}\text{O}$: 25, 62
- $^{18}\text{O}$: 15
- $^{19}\text{F}$: 35, 40, 50
- $^{20}\text{Ne}$: 40, 45
- $^{32}\text{S}$: 19.5
- $^{35}\text{Cl}$: 19.5
- $^{40}\text{Ar}$: 15, 40
- $^{40}\text{Ca}$: 10, 25, 40
- $^{58}\text{Ni}$: 16, 23, 25, 30, 35, 40, 45
- $^{62}\text{Ni}$: 25, 35
- $^{86}\text{Kr}$: 15, 25
- $^{93}\text{Nb}$: 15, 17, 23, 30, 38
- $^{112}\text{Sn}$: 15, 5, 35
- $^{116}\text{Sn}$: 23, 30, 38
- $^{120}\text{Sn}$: 40
- $^{124}\text{Sn}$: 15, 25, 30, 35
- $^{197}\text{Au}$: 10, 15, 20

- $^{12}\text{C}$ 80 MeV/a.m.u. beam to be developed in 2004
Heavy ion collisions are the only terrestrial tool to create hot and compressed nuclear matter and to gather information on the EOS.

Thermodynamical properties in finite rapidly evolving systems.

Multifragmentation observed in H.I.C. at intermediate energies ⇒ possible signature of the liquid-gas phase transition.

Probes and observables sensitive to the time evolution of the nuclear phase-space density and to thermodynamical properties of the system ⇒ very large and complex detector arrays (γ and particle measurement and ID, collective observables …) are needed.
1200 detectors arranged in 35 rings. The forward 18 rings cover polar angles from 1° to 30°. Their distances from the target increase with increasing polar angle from 100 to 350 cm. The other 17 rings form a sphere with 40 cm radius and cover the angular range from 30° to 176°.

The detector is assembled in the large (70 m³ volume, 6m length and 4 m diameter) CICLOPE scattering chamber and started operation in January 2003.
Z identification up to Z=50
Z - A identification up to Z=9

N.LeNeindre et al, NIM A490 (2002) 251
Experiments approved by the LNS Scientific Committee and performed with CHIMERA in January - July 2003

SEARCH FOR ALPHA CLUSTER CONDENSATION (B. Borderie)

ISOSPIN EFFECTS
CLUSTER FORMATION \{ \}

(A. Pagano)

THERMODYNAMICAL STUDIES OF EQUILIBRATED NUCLEI (R. Bougault)

THERMODYNAMICAL COORDINATES OF EXCITED NUCLEAR SYSTEMS
(M. Bruno)

STUDY OF NONEQUILIBRIUM EMISSIONS IN SEMIPERIPHERAL REACTIONS
(G. Poggi)

TWO BODY DISSIPATION IN NUCLEUS - NUCLEUS COLLISIONS (J. Wilczynski – A. Pagano)

LIMITING EXCITATION ENERGY OF NUCLEAR MATTER (G. Cardella)

Total beam time: 1068 hours (beams: $^{40}$Ca, $^{58}$Ni, $^{112,124}$Sn, $^{197}$Au + calibration beams)
Experiments approved for 2004

NUCLEAR TRANSPARENCY AT FERMI ENERGIES (Z. Basrak)

ISOSPIN DEPENDENCE OF NUCLEAR EOS (W.G. Lynch)

CLUSTER EMISSION AND A NEW TYPE OF PHASE TRANSITION
(W.U. Schroeder)

STUDY OF NONEQUILIBRIUM EMISSIONS (G. Poggi)

R&D ON PULSE SHAPE DISCRIMINATION TO IMPROVE THE
DETECTOR PERFORMANCES (G. Politi)
SOLE
Superconducting Solenoid
$0^\circ \leq \theta \leq 6^\circ$

MACISTE
24 detectors
$\theta \leq 6^\circ$

MULTICS
162 detectors
$3^\circ \leq \theta \leq 28^\circ$

MEDEA
180 detectors
$30^\circ \leq \theta \leq 180^\circ$
Pre-equilibrium emission: 30 A MeV Ni + Ni

Quadratic dependence of extremely energetic proton multiplicity on the mean number of participants: an evidence of cooperative effects.

Two components are observed in the high energy photon energy spectra. The “thermal” component produced along the path versus equilibration is seen to be an important fraction (∼50%) of the total yield for 25<Eγ<40 MeV.

IMF-γ anticorrelation: a “clock” for multifragmentation (Ni + Au 45 AMeV)

\[ 1 + R_{γ,IMF} = \frac{<m_γ m_{IMF}>}{<m_γ> <m_{IMF}>} \]

anticorrelation (values < 1) are only observed for thermal photons, IMF’s in the parallel velocity window W1 and central collisions.
The anticorrelation observed in 45A MeV Ni+Au central collisions is an evidence of ‘prompt fragmentation’. BNV simulations of this reaction show that, once the system enters the spinodal region, in ~ 80% of the events local density fluctuations lead the composite system to multifragmentation preventing the second compression and, consequently, the thermal photon production.

Density oscillations from BNV simulations of 45 A MeV Ni + Au central collisions.

First compression → direct photon production
Expansion → prompt IMF emission (at $t=t_0$, the system enters the spinodal region)
If the system survives:
Second compression → thermal photon production, HHS formation, statistical IMF’s

IMF-γ anticorrelation: a “clock” for multifragmentation (Ni + Au 45 AMeV)
Signatures of dynamical effects
Strong mid-rapidity emission (ternary/binary about 30%) of low-Z IMF’s in peripheral ($b/b_{max} > 0.7$) collisions. The comparison with stochastic BNV calculations indicate a dynamical origin of the IS contribution.
A progressive quenching of the GDR γ emission as a function of the excitation energy is predicted and has been observed in our previous experiments. A cut-off energy of \( E^* \approx 250 \text{ MeV} \) must be introduced to reproduce the data.

- Models predict a reduction of the GDR yield which strongly affects the resulting yield in a region between 150 and 300 MeV.

- Our previous data are all in an excitation energy region higher than the one where this saturation of the yield is expected to set in.

- If the parameter governing the quenching is \( E^*/A \) or \( T \) in nuclei with \( A \approx 110 \) and a cut-off energy of \( E^* \approx 250 \text{ MeV} \):

\[
E^*/A \approx 2.2 \text{ MeV/A}
\]

- The \( E^* \) region to investigate in order to map the progressive disappearance of the GDR is:

\[
1.5 < E^*/A < 3 \text{ MeV} \\
A \approx 130 \quad 200 < E^* < 400 \text{ MeV}
\]
Evidence for a limiting temperature $T \approx 5.5$ MeV for the excitation of the dipole vibration

Spectra from 300 MeV and above can only be reproduced assuming a cut-off energy of 200 – 250 MeV for the $\gamma$-emission from the GDR decay independent of the initial $E^*$ of the nucleus produced

**CASCADE input parameter**
- $E^* = 500$ MeV, $A = 110$, $\Gamma = 12$ MeV
- $E^* = 350$ MeV, $A = 110$, $\Gamma = 12$ MeV
- $E^* = 250$ MeV, $A = 110$, $\Gamma = 12$ MeV
- $E^* = 300$ MeV, $A = 136$, $\Gamma = 12$ MeV
- $E^* = 200$ MeV, $A = 126$, $\Gamma = 12$ MeV
- $E^* = 160$ MeV, $A = 126$, $\Gamma = 12$ MeV

**Reactions**

<table>
<thead>
<tr>
<th>Reactions</th>
<th>$E_{\text{bea}}$ (MeV)</th>
<th>$E^*$ (MeV)</th>
<th>$A_R$</th>
<th>$E^*/A_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{116}\text{Sn} + ^{12}\text{C}$</td>
<td>17 MeV/A</td>
<td>160</td>
<td>126</td>
<td>1.27</td>
</tr>
<tr>
<td>$^{116}\text{Sn} + ^{12}\text{C}$</td>
<td>23 MeV/A</td>
<td>200</td>
<td>126</td>
<td>1.60</td>
</tr>
<tr>
<td>$^{116}\text{Sn} + ^{24}\text{Mg}$</td>
<td>17 MeV/A</td>
<td>300</td>
<td>136</td>
<td>2.19</td>
</tr>
</tbody>
</table>

**Spectra from 300 MeV and above**

- $E^* = 500$ MeV, $A = 110$, $\Gamma = 12$ MeV
- $E^* = 350$ MeV, $A = 110$, $\Gamma = 12$ MeV
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- $E^* = 300$ MeV, $A = 136$, $\Gamma = 12$ MeV
- $E^* = 200$ MeV, $A = 126$, $\Gamma = 12$ MeV
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**$\gamma$ multiplicities (12 – 20 MeV)**

- New data
- $^{36}\text{Ar} + ^{90}\text{Zr} \oplus 27$ MeV/A
- $^{36}\text{Ar} + ^{98}\text{Mo} \oplus 37$ MeV/A

**Natowitz et al. PRC65 (2003)**
The Trojan Horse Method can give hints on the bare astrophysical S(E)-factor and the electron screening effect, for many reactions of astrophysical interest.

Using the Trojan Horse Method, cross sections of reactions destroying the lithium content in astrophysics environment have been measured.

Relevant for primordial nucleosynthesis.

<table>
<thead>
<tr>
<th>$U_e^{(adiab)}$</th>
<th>$U_e^{(THM)}$ $^6$Li+d</th>
<th>$U_e^{(THM)}$ $^7$Li+p</th>
</tr>
</thead>
<tbody>
<tr>
<td>186 eV</td>
<td>340 ± 50 eV</td>
<td>330 ± 40 eV</td>
</tr>
</tbody>
</table>


- **Homogenous Big-Bang:** elements up to Lithium only produced in primordial nucleosynthesis
- **Inhomogenous Big-Bang:** much wider set of primordially born elements (up to carbon at least).

In this scenario the reaction path for nucleosynthesis is

\[ ^1\text{H}(n,\gamma)^2\text{H}(n,\gamma)^3\text{H}(d,n)^4\text{He}(t,\gamma)^7\text{Li}(n,\gamma)^8\text{Li}(\alpha,\gamma)^{11}\text{B}(n,\gamma)^{12}\text{B}(\beta\nu)^{12}\text{C}. \]

- $^8\text{Li}$ half-life = 840 msec - chain bottleneck

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**Test of $^8\text{Li}$ production by $^7\text{Li} + d$ and of the dedicated beam line**

**500 mbarn**

- $\pm 170$ mbarn $\pm 70$ mbarn
  - **Stat.**
  - **Syst.**

**measured $^4\text{He}(^8\text{Li},n)^{11}\text{B}$ cross section:**

- at $E_{cm} = 1.25$ MeV $\Rightarrow$ Elab = 3.75 MeV
EXCYT STATUS
Main tasks and deadlines

◆ Upgrade of CS to high intensity beams
  ◆ Installation of new electrostatic deflectors: 70 W of $^{20}\text{Ne}$ and 100 W of $^{13}\text{C}$ at 45 MeV/amu have been extracted
  
  100 W are now available!!!
  ◆ Completion of high intensity beam acceleration and extraction (autumn ’03)

◆ Target-ion source system for RIB’s production
  ◆ Test of the target-ion source assembly at GANIL in operating condition (up to 400 W $^{13}\text{C}@60 \text{AMeV}$) to test $^{8,9}\text{Li}$ production

◆ Assembling of the high resolution mass separator:
  ◆ High Voltage Platforms (Pre-separator and I stage) fully installed including the beam lines
  ◆ II stage assembling in progress, to be completed in December 2003 - January 2004
◆ Licensing
  ◆ Already authorized up to 100 W
  ◆ The authorization to work at full power (500 W) is in progress

◆ Commissioning of the facility and first experiment (2004)
  ◆ First scheduled RIB: $^{8,9}$Li for nuclear astrophysics and experiments with Magnex
  ◆ Expected intensities $10^4$-$10^6$ pps
Main parameters of MAGNEX

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum magnetic rigidity</td>
<td>1.8 Tm</td>
</tr>
<tr>
<td>Solid angle</td>
<td>51 msr</td>
</tr>
<tr>
<td>Momentum acceptance</td>
<td>± 10 %</td>
</tr>
<tr>
<td>Momentum resolution</td>
<td>1 / 5400</td>
</tr>
<tr>
<td>Mass resolution</td>
<td>1 / 300</td>
</tr>
<tr>
<td>Momentum acceptance (max)</td>
<td>1 / 2000</td>
</tr>
<tr>
<td>Mass resolution (90% acceptance)</td>
<td>1 / 200</td>
</tr>
</tbody>
</table>

The start detector

- Position sensitive start detector;
- Vertically focusing quadrupole;
- Bending magnet;
- Focal plane detector measuring ion direction, energy, charge and mass.

PSD based on microchannel plate technology

The FPD is under construction at GANIL. A prototype has already been realized and tested with Tandem beams at LNS.
The vertically focusing quadrupole

Some physics items
- Spectroscopy of weakly bound nuclei via reactions induced by EXCYT beams;
- Charge exchange near the neutron dripline at Tandem and Cyclotron energies;
- Nuclear astrophysics with stable and radioactive beams;
- β-delayed spectroscopy via EXCYT beams

E < 30 MeV/amu
2 < A < 40

E < 25 MeV/amu
40 < A < 93

The bending magnet

Scheduled activity
The installation started in June 2002. The apparatus will be commissioned in 2004.
LNS Superconducting Cyclotron is the unique machine in Italy and South Europe used for proton therapy.

A facility for the treatment of ocular tumours with 62 AMeV proton beams (named CATANA) has been developed in Catania.

Treatment of the choroidal melanoma about 300 new cases/year in Italy.
Work in progress about treatment line, dosimetry and immobilization systems.

Treatment of macular degeneration.

Study and development of a new 250 AMeV Cyclotron for protons and ions to treat deep tumours.

Total number of patients (since March 2002): 52
The source was realised by electrodeposition of $^{210}$Po on a thin silver film. The source was sealed and it was certified as non contaminant.

The energy of the outcoming $\alpha$ particles is about 4.5 MeV.

The in-situ analysis of samples in the cultural heritage field has been up to now very successful and will continue in the future.

Next important goal:
The Archaeological Museum of Misurata (Libia) for the characterization of the “Misurata treasure” (110000 Roman Age silver-plated coins)
Interdisciplinary research at LNS

- **Nano-structures on superconducting films induced by radiation** (INFN – Sez. Torino, Politecnico di Torino, Dept. Of Physics)

  Study and optimization of irradiation of high-Tc superconducting films to create nanosize columnar defects, allowing to control the vortex behavior in superconductors. The aim is the design of the lay-out of medium-power superconducting devices.

- **Lithography: fabrication of micro opto-mechanical components with highly energetic heavy ion beams** (University of Brussels)

  Investigation of high energetic heavy ion beams as a suitable source for the creation of micro-features. Possible applications in the optical communication field.

- **Analysis of biological effects induced by heavy ion beams**

  Characterization of biological effects induced by proton beams. The aim is to find innovative anti-cancer strategies by coupling the effects of apoptosis with the balistic precision of proton beams.

  Study of DNA damage induction by carbon ions.

  Metabolic effects induced by proton irradiation of human tumor cells.

- **Radiation hardened power MOSFETs** (University of Naples, University of Cassino (FR) and ST-Microelectronics Catania)

  Failure mechanisms of power MOSFETs due to the impact with energetic particles in aero-space applications.
Perspectives

• EXCYT and MAGNEX commissioning: 2004

• Experiments with EXCYT: 2005 on

• Study of a new primary accelerator for EXCYT (10-20 KW) and possibility of using also CS as post-accelerator: 2005 (about 5 years realization time)
NEMO

The study of the Capo Passero site has been completed. A limited activity for monitoring and long term characterization will continue in the future.

The Astroparticle Physics European Coordination (ApPEC) has appointed a Peer Review Committee to evaluate the characteristics of the proposed sites for the km3 detector

*Presentation of the candidate sites in January 2003*  
*Recommendations expected by mid 2004*

As an intermediate step towards the km³ the NEMO collaboration has proposed a mid term program to test the feasibility of the technological solution proposed at the Catania Test Site

*Project jointly funded by INFN and MIUR*  
Call "68/2002 PON 2000-2006" - LAMS PROJECT - FUNDED 4.474.512,72 €  
1.474.512,72 INFN + 3.000.000,00 MIUR

Call "decreto direttoriale 1105/2002" - SIRENA PROJECT - 2.301.000,00 €  
500.000,00 INFN + 1.801.000,00 MIUR (submitted for approval)
Km3 detector architecture

Detector architecture
- Reduce number of structures to reduce connections and allow underwater operations with a ROV ⇒ non homogeneous sensor distribution
- Modularity

Reference layout used for the feasibility study

- 1 main Junction Box
- 8 secondary Junction Boxes
- 64 Towers
- 16 storeys with 4 OM (active height 600 m)
- 4096 OM

Total instrumented volume ≈1 km³
The NEMO Phase 1 project

This project aims at the realization of some critical components of the km3 neutrino detector

*Project jointly funded by INFN and MIUR*

Project completion foreseen in 2005 (junction boxes) and 2006 (towers)
<table>
<thead>
<tr>
<th>Beam</th>
<th>Projectile</th>
<th>Energy (MeV/amu)</th>
<th>Target</th>
<th>Intensity Pre-accelerated (pps/µA)</th>
<th>Intensity Post-accelerated (pps/µA)</th>
<th>Total 500W (pps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^8$Li</td>
<td>$^{15}$N</td>
<td>50</td>
<td>C</td>
<td>$6.7 \times 10^7$</td>
<td>$2.4 \times 10^6$</td>
<td>$1.6 \times 10^6$</td>
</tr>
<tr>
<td>$^{11}$C</td>
<td>$^{18}$O</td>
<td>50</td>
<td>C</td>
<td>$8.0 \times 10^7$</td>
<td>$2.2 \times 10^7$</td>
<td>$1.2 \times 10^7$</td>
</tr>
<tr>
<td>$^{13}$N</td>
<td>$^{14}$N</td>
<td>50</td>
<td>C</td>
<td>$2.1 \times 10^8$</td>
<td>$5.0 \times 10^7$</td>
<td>$3.6 \times 10^7$</td>
</tr>
<tr>
<td>$^{14}$O</td>
<td>$^{16}$O</td>
<td>50</td>
<td>C</td>
<td>$2.6 \times 10^7$</td>
<td>$1.1 \times 10^6$</td>
<td>$7.0 \times 10^5$</td>
</tr>
<tr>
<td>$^{15}$O</td>
<td>$^{16}$O</td>
<td>50</td>
<td>C</td>
<td>$1.5 \times 10^8$</td>
<td>$6.0 \times 10^7$</td>
<td>$3.8 \times 10^7$</td>
</tr>
<tr>
<td>$^{19}$O</td>
<td>$^{22}$Ne</td>
<td>50</td>
<td>C</td>
<td>$1.3 \times 10^7$</td>
<td>$4.7 \times 10^6$</td>
<td>$2.2 \times 10^6$</td>
</tr>
<tr>
<td>$^{22}$O</td>
<td>$^{26}$Mg</td>
<td>50</td>
<td>C</td>
<td>$8.0 \times 10^3$</td>
<td>$2.6 \times 10^3$</td>
<td>$1.0 \times 10^3$</td>
</tr>
<tr>
<td>$^{17}$F</td>
<td>$^{20}$Ne</td>
<td>50</td>
<td>C</td>
<td>$4.6 \times 10^5$</td>
<td>$1.3 \times 10^5$</td>
<td>$6.5 \times 10^4$</td>
</tr>
<tr>
<td>$^{18}$F</td>
<td>$^{19}$F</td>
<td>50</td>
<td>C</td>
<td>$1.2 \times 10^7$</td>
<td>$4.7 \times 10^6$</td>
<td>$2.5 \times 10^6$</td>
</tr>
<tr>
<td>$^{20}$Na</td>
<td>$^{24}$Mg</td>
<td>50</td>
<td>C</td>
<td>$1.0 \times 10^7$</td>
<td>$1.4 \times 10^4$</td>
<td>$6.0 \times 10^3$</td>
</tr>
<tr>
<td>$^{22}$Na</td>
<td>$^{19}$F</td>
<td>50</td>
<td>C</td>
<td>$6.0 \times 10^7$</td>
<td>$7.6 \times 10^4$</td>
<td>$4.0 \times 10^4$</td>
</tr>
<tr>
<td>$^{24}$Na</td>
<td>$^{19}$F</td>
<td>50</td>
<td>C</td>
<td>$1.6 \times 10^7$</td>
<td>$2.0 \times 10^4$</td>
<td>$1.1 \times 10^4$</td>
</tr>
<tr>
<td>$^{33}$Cl</td>
<td>$^{35}$Cl</td>
<td>50</td>
<td>C</td>
<td>$1.4 \times 10^6$</td>
<td>$3.1 \times 10^5$</td>
<td>$9.0 \times 10^4$</td>
</tr>
<tr>
<td>$^{34}$Cl</td>
<td>$^{35}$Cl</td>
<td>50</td>
<td>C</td>
<td>$1.1 \times 10^8$</td>
<td>$2.5 \times 10^7$</td>
<td>$3.2 \times 10^6$</td>
</tr>
</tbody>
</table>