An overview of the research activities: Recent results

Laboratori Nazionali di Legnaro

Nuclear Physics
Accelerator technologies
Gravitational waves and General Physics
Interdisciplinary researches

On-Line Trap for Fr
- Few- and multi-nucleon transfer reactions
- Coulex, elastic and inelastic excitations
- Near- and sub-barrier fusion of heavy systems

Ionization chamber
MWPPAC array

Focal plane of the PRISMA spectrometer
The magnetic spectrometer PRISMA installed at LNL
**Design Characteristics of the PRISMA Spectrometer**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
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<tbody>
<tr>
<td>angular acceptances</td>
<td>$\Delta \theta \sim 12^\circ$ $\Delta \phi \sim 22^\circ$</td>
</tr>
<tr>
<td>solid angle</td>
<td>$\Delta \Omega \sim 80$ msr</td>
</tr>
<tr>
<td>distance target-focal plane</td>
<td>7 m</td>
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<tr>
<td>energy acceptance</td>
<td>$\pm 20%$</td>
</tr>
<tr>
<td>max rigidity</td>
<td>70 MeV amu</td>
</tr>
<tr>
<td>dispersion</td>
<td>$\sim 4$ cm/%</td>
</tr>
<tr>
<td>mass resolution</td>
<td>$\sim 1/300$ FWHM</td>
</tr>
<tr>
<td>event rate</td>
<td>up to 100 kHz</td>
</tr>
</tbody>
</table>
First experiments: multinucleon transfer reactions

X vs. TOF matrix

2p stripping, 2n pick-up

In-beam matrix of TOF vs. focal plane X position.
Population of the neutron-rich $^{60}$Cr nuclide

4p stripping

$^{60}$Cr/17$^+$

260 MeV $^{64}$Ni+$^{124}$Sn

$\theta_{lab}=68^\circ$
Neutron-rich nuclei populated by means of multinucleon transfer and deep-inelastic reactions.

PIAVE beams highly needed!

With the PIAVE Xe beams

With present ALPI beam

$^{64}\text{Ni (390 MeV)} + ^{238}\text{U}$
### Changing Magic Numbers

**Relevant for astrophysics**

The monopole part of the effective force induces drastic changes in the single-particle energies. The neutron magic numbers at $N = 8,20$ changes into $N = 6,16$. These changes seems to originate from the strong attractive $\pi-\nu$ interaction between spin-orbit partners.

Approaching the neutron-drip line, a decrease of the average potential towards large radial values might occur. From solar abundances a drastic effect on nuclear shell structure is expected.

The figure compares the stable isotope $^{30}\text{Si}$ with the exotic nucleus $^{24}\text{O}$. Due to the monopole part of the effective $\pi-\nu$ interaction, the well known $N=20$ gap is reduced and a new gap appears at $N=16$. 

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**Diagram:**

- **N/Z**
  - $^{30}\text{Si}$: $Z=16$, $N=24$
  - $^{24}\text{O}$: $Z=8$, $N=16$

- **Extreme single-particle energy for neutrons (MeV):**
  - $^{30}\text{Si}$: $0d_{3/2}$, $1s_{1/2}$, $0d_{5/2}$
  - $^{24}\text{O}$: $0d_{3/2}$, $1s_{1/2}$, $0d_{5/2}$
The \( \pi - \nu \) interaction scheme can not account for a sizeable reduction of the N=50 shell gap.

Can one extraxct from the systematics of the 2\(^+\) energies around N=50 the Shell gap?
Persistance of the N=50 shell gap at Z~32

Only medium and high spins are sensitive to the core breaking.

Energy Gap ~ 4.5 MeV, about 650 keV quenching?
EXOTIC: a project to produce light exotic beams by inverse kinematics reactions at LNL by high intensity beams from the XTU Tandem accelerator –\textit{MI, NA, PD, U}

**Production reactions**

- \( p(^{17}\text{O}, ^{17}\text{F})n \)
- \( ^{3}\text{He}(^{6}\text{Li}, ^{8}\text{B})n \)
- \( ^{7}\text{Li}(^{9}\text{Be}, ^{6}\text{He})^{10}\text{B} \)
- \( p(^{7}\text{Li}, ^{7}\text{Be})n \)
- \( p(^{14}\text{N}, ^{14}\text{O})n \)
- \( ^{3}\text{He}(^{16}\text{O}, ^{18}\text{Ne})n \)

**Typical quantities to be measured**

- Elastic cross section.
- Break-up cross section.
- Transfer reaction.
- Low energy soft modes.

**Detection system**

- Most of the requirements to evidence the peculiarities of the exotic nuclei are fulfilled using a magnetic spectrometer, such as PRISMA, to detect heavy ejectiles, coupled with arrays of position sensitive detectors for light ejectiles and gamma-rays.
**EXOTIC**: beam line layout

Limit of the experimental hall

- **A** Production target
- **B** 1st quadrupole triplet
- **C** 1st slit system
- **D** Bending dipole magnet
- **E** 2nd slit system
- **F** Wien filter
- **G** 2nd quadrupole triplet
- **H** 3rd slit system
- **I** Scattering Chamber
- **L** PRISMA target
EXOTIC : separator specifications

- Energy acceptance $\Delta E/E = \pm 10\%$
- Momentum acceptance $\Delta p/p = \pm 5\%$
- Horizontal angle acceptance $\Delta \theta = \pm 60 \text{ mr} [\pm 3.4^\circ]$
- Vertical angle acceptance $\Delta \phi = \pm 90 \text{ mr} [\pm 5.2^\circ]$
- Magnetic rigidity $B\rho = 0.98 \text{ Tm}$
- Solid angle $\Delta \omega \sim 20 \text{ msr}$
- $^{17}\text{F Trasmission (}\Delta E/E= \pm 10\% \text{ )} \ 20 \%$
- $^{17}\text{F Trasmission ( }\Delta E/E= \pm 1\% \text{ )} \ 5.6 \%$
EXOTIC: view of the beam line from the 1st quadrupole triplet towards PRISMA
EXOTIC: the gas target with the dedicated vacuum system and the first quadrupole triplet
- Clustering and reflection asymmetric shapes
- Collectivity and shell model
- Isospin symmetries and mirror pairs
- Isospin mixing in N=Z nuclei
- High spin states and superdeformation
- Chiral Symmetry in Nuclei

- Shell stability and shell evolution
- Spectroscopy at the dripline
N=Z nuclei and Mirror Simmetries

Electromagnetic spin-orbit term?

Ekman et al.

92Pd
the heaviest N=Z nucleus where excited states are known

N. Marginean et al.
Transition Matrix Elements in mirror pairs

Level Schemes

$^{51}\text{Fe}$

$\tau = ?$

$^{51}\text{Mn}$

$\tau = 130\text{ps}$

$\tau = 2.87\text{ns}$

$\tau = 2.07\text{ns}$

Decay curves of $27/2^+$ states

$^{51}\text{Mn}$

Preliminary

$130\text{ ps}$

$^{51}\text{Fe}$

$\sim 90\text{ ps}$

$R_1$ as a function of $e_{pol}^{(1)}$

Associated lifetimes of $27/2^+$ state in $^{51}\text{Fe}$ indicated

C. Fahlander et al.
Isospin mixing in medium mass N=Z nuclei

Impact on corrections to test Unitarity of CKM matrix

Transition matrix elements in mirror nuclei

For $T_z=\pm 1/2$ nuclei the isovector amplitude is $\neq 0$. The difference between the E1 strengths comes out from the interference between the induced isoscalar term and isovector term.
Hyperdeformation and exotic nuclear molecules

Quasi-molecular states in Atomic nuclei and clustering

Close to the particle threshold
Quasi-molecular states in nuclei?

Limits of the present spectroscopy

At the limit of the particle threshold
Signatures: Regular bands and parity doublets

Thummerer et al.

\[ \Psi = \begin{bmatrix} \gamma_1 \\ \gamma_2 \\ \gamma_3 \end{bmatrix} \]

\[ R(\omega) |\Psi\rangle = |\varphi\rangle \]

\[ R(\omega) |\Psi\rangle \neq |\Psi\rangle \]

Gamma-Ray Spectrum

Energy (keV)
Critical-Point Symmetries

Observed in $^{134}\text{Ba}$

Observed in $^{152}\text{Sm}$
X5 symmetry in $^{176,178}$Os at GASP

A. Dewald et al.
The Y(5) Symmetry


- Corresponds to the critical point of the phase transition from axially deformed to triaxial shape

Axially deformed  $\rightarrow$  Y(5)  $\rightarrow$  Triaxial
$^{170}$Er: A case of Y5 symmetry?

Even-even Er isotopes

“I call any geometrical figure, or group of points, chiral, and say it has chirality, if its image in a plane mirror, ideally realized, cannot be brought to coincide with itself.” - Lord Kelvin 1904

Examples of chiral systems are found in:

- **Chemistry**: molecules with opposite handedness react differently in similar environments
- **Biology**: DNA has right and left-handed “screws”
- **Particle Physics**
Nuclear Physics: Current distributions in nuclei

The energies of the excited states for the left-handed and right-handed systems should be identical.

\[ J^\pi, J^z, \mathcal{P} \]

The energies of the excited states for the left-handed and right-handed systems should be identical.

\[ \mathcal{P} = 1 \]

\[ 8^+, 7^+, 6^+, 5^+, 4^+ \]

V. I. Dimitrov et al, PRL 84 (2000) 5732
Does Chiral symmetry exists in nuclei?

Planar to a-planar phase transition?

Limit of the present spectroscopy.
No sign of phase transition

D. Tonev et al.
120/180 segmented HPGe’s
40/60 cryostats (3 capsules)
Radius ~ 17/22 cm
Solid Angle Coverage ~ 72/80%
4440/6660 Digital Electronic Channels

Efficiency ~ 40% (M=1) and 25% (M=30)
Peak/Total ~ 65% (M=1) and 50% (M=30)

Effect of position resolution

$^{56}\text{Fe} (240 \text{ MeV}) + ^{208}\text{Pb} \Rightarrow ^{56}\text{Fe}^* (v/c=0.08) + \gamma$

$^{56}\text{Fe}^*$ detected by Phobos
$\Delta \theta \sim 2.0^\circ$

$\gamma$’s measured by MARS detector (25 segments)
$\Delta \theta \sim 2.0^\circ$

Doppler broadening drastically reduced !!

Doppler Corrected using reconstructed interaction points
FWHM = 4.5 keV

Corrected using center of Ge crystal
FWHM = 16.5 keV
Solid Angle = 80 msr  Energy accept. 20%
$\Delta m/m = 1/300 \quad \Delta E/E=1/1000$

First phase of AGATA
15 clusters ($1\pi$)
4 x efficiency
larger selectivity

- The limits of nuclear shape
- New symmetries in nuclei
- Isovector effects in nuclei

$^{64}\text{Ni} (390 \text{ MeV}) + ^{238}\text{U}$

With present ALPI beam

With the PIAVE Xe beams
Atomic Parity Non Conservation

Francium trapping to measure APNC (Atomic Parity Non Conservation):

a. test of the Standard Model at low momentum transfer
b. signatures for physics beyond Standard Model

SM Weak Charge: \( Q_W = -N + Z (1 - 4\sin^2 \theta_W) \)

Techniques: PNC-STARK Interference - OPTICAL ROTATION

e-\nu correlations in \( \beta \) decay

\[ \frac{d^2W}{d\Omega_e d\Omega_\nu} = 1 + a (p_e \cdot p_\nu/E) + <J> \cdot [A(p_e/E) + ...] \]

\( a_F = f(\text{Scalar,Vector}) \quad \text{Fermi} \)

\( a_{GT} = f(\text{Axial,Tensor}) \quad \text{Gamow-Teller} \)

\( p_e \) and \( p_\nu \) with electron and nuclear recoil

<table>
<thead>
<tr>
<th>Lab</th>
<th>Atom</th>
<th>Produced</th>
<th>Trapped</th>
<th>Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Los Alamos</td>
<td>(^{82}\text{Rb} )</td>
<td>( 10^8 ) s(^{-1} )</td>
<td>( 5 \times 10^5 ) s(^{-1} )</td>
<td>( \text{e}^+ - \nu )</td>
</tr>
<tr>
<td>Stony Brook</td>
<td>(^{210}\text{Fr} )</td>
<td>( 5 \times 10^6 )</td>
<td>( 10^4 )</td>
<td>APNC</td>
</tr>
<tr>
<td>TRIUMF</td>
<td>(^{37}\text{K} )</td>
<td>( 10^7 )</td>
<td>( 10^4 )</td>
<td>( \text{e}^+ - \nu )</td>
</tr>
<tr>
<td>Berkeley</td>
<td>(^{21}\text{Na} )</td>
<td>( 10^8 )</td>
<td>( 4 \times 10^4 )</td>
<td>( \text{e}^+ - \nu )</td>
</tr>
<tr>
<td>Legnaro</td>
<td>(^{210}\text{Fr} )</td>
<td>( 10^7 )</td>
<td>( 10^6 ) (goal)</td>
<td>APNC</td>
</tr>
</tbody>
</table>

\[
\langle \vec{J} \cdot \vec{p} \times \vec{q} \rangle \neq 0 \quad ?
\]

\[
E_{\text{meas}} = \frac{(\vec{p} + \vec{q})^2}{2M_{\text{recoil}}} \quad \text{eV} \times 100
\]
Test for exotic couplings in the electroweak interaction:
- Scalar currents
- Tensor currents

\[ ^{18}\text{Ne} \rightarrow ^{18}\text{F} + e^+ + \nu_e \]

V. Egorov et al.
NPA621(97)745
Test of the standard model

Test of the trapping efficiency

On–Line Trap for Fr

Trapping of Francium atoms
MOT: Light pressure and magnetic fields can confine and cool atoms

A MOT has been built improving the trapping efficiency. Such Technique is based on the LIAD (Light Induced Atomic Desorption) effect from siloxane composites used as cell coatings. Twofold property:
- low adsorption coefficient
- desorption of atoms triggered by non resonant light

Trapping efficiency up to 76% and loading time of 40 ms have been achieved

These results will be applied to a MOT for radioactive Francium atoms in order to increase the trap population.
Sub-barrier fusion:
Fusion dynamics and nuclear structure

Break-up of
Exotic light nuclei

Deformed proton emitters

Fission dynamics
Symmetry energy and stellar collapse

GDR response probing shapes and non uniform charge and mass distributions in nuclei

Multifragmentation at low excitation energy

N=Z

132Ce
N/Z=1 N/Z=1.25 N/Z=1.28

+ γ γ

96Mo
100Mo
32S
36S

\( D(t=0) = 18.2 \text{ fm} \)

\( D(t=0) = 1.7 \text{ fm} \)
Fission dynamics in the super-heavy mass region

Influence of Q.F. on fusion process

\[ ^{48}Ca + ^{168}Er \rightarrow ^{216}Ra \]

E (a.u.)

Scattered beam

Fusion

\[ E^* = 40.4 \text{ MeV} \]
Fission dynamics in Super-Heavy region

Neutrons 12 scintillators

Fission Fragment 2 PPAC, MWPC

Charged particles

Multi-source fit to the experimental neutron and a energy spectra

pre- and post-scission multiplicities

Fission delay time $t_D$
Evaporation residues and fragments measurement: from fusion to multifragmentation

With the last upgrade? → also Isotope identification:
- 3rd coordinate in the phase space
- Temperature information of the emitting source

Signals already at lower energy 11AMeV

Isotope Identification
The use of Carbon ions for radiotherapy is particularly interesting due to the high ionization density induced by these ions at the end of the range and to their high biological effectiveness. Little information is available on nuclear cross sections in this energy range:

Theoretical predictions are based on the few experimental references:

Cross Section measurements of $^{12}$C on equivalent tissue materials have been performed at LNL (GARFIELD APPARATUS) and at LNS (MEDEA + MULTICS APPARATUS):
Interdisciplinary Researches

High reflectance mirrors for solar corona

Detection of explosives

Tissue equivalent proportional counters

Detection of explosives

Surface analysis

MOT traps

Radiation biology

Spatial resolution < 100 µm

Images of seven holes 300 µm in diameter and 100 µm spaced

Detector technology
Radiobiological studies:

- Light ion broad-beam irradiation facility at the 7MV Van de Graaff CN electrostatic accelerator (protons, deuterons, helium-3 and helium-4 ions; E: 0.8-12 MeV)

- Heavy ion broad-beam facility at the Tandem-ALPI accelerator complex (A>4; E: 5-26 MeV/amu)

- Light single-ion microbeam facility for single-cell irradiation at the 7MV Van de Graaff CN electrostatic accelerator (protons, deuterons, helium-3 and helium-4 ions; E: 0.8-12 MeV)

- Fully equipped biology Laboratory

Main Activities at LNL

- Cell inactivation
- Gene mutation
- Mutation characterization
- Chromosome aberration
- Influence of chromosome architecture in aberration formation
- Protein expression in normal and tumoral cells.

...Particular emphasis on the low-dose and low-dose rate effects... ...bystander effects and cell-to-cell communication.

Mainly performed in the framework of INFN and EU Contract projects.
INFN-LNL Single-ion microbeam facility for single cell irradiation
INFN-LNL Radiobiology Laboratory
ADVANCED THIN FILM MATERIALS

Synthesis and Process Development

- Plasma Sputtering Deposition
- Plasma Diagnostics
- Ion Implantation

- Low Friction, High Hardness Nanoscaled Materials and Multilayers

- Extreme UV and soft X-ray optics development

- Insulating Oxides and High Performance Plastics
Characterization of Physical Properties

Composition
- Ion Beam Analysis (RBS, NRA, ERDA, PIXE)
- Microbeam (Micro-PIXE 2-D trace element analysis)

Mechanical Characterization
- Nano Hardness / Stress
- Adhesion (Micro Scratch)
- Atomic Force Microscopy
New Cryogenic system
• to avoid the noise of boiling liquid He we choose $T > 1.5\, \text{K}$

New Suspension
• main component: 4 columns
  attenuation 180 dB at 1 KHz
• no mechanical resonances between 645-1380 Hz
• CuBe cable that supports the bar from its center of mass:
  suppression of the low frequency motion
• high mechanical Q materials (AL, CuBe)
• to avoid creeping the working point of the suspension materials is $< 25\%$ Yield stress

New capacitive transducer + double stage dc-SQUID

New daq and data analysis systems

AURIGA bar detector: the new design
(of all the components of the detector except the main cryostat and the bar)

READY to START: cool down at the end of 2003
Upper Limit on the Rate of gravitational waves bursts from the GALACTIC CENTER random arrival times and amplitude $\geq$ search threshold $h$


The Area under the blue curve is excluded with a coverage $> 95\%$

rate $[anni^{-1}]$

search threshold $h$

$h \sim 2 \times 10^{-18}$ $\longleftrightarrow$ $\Delta E \sim 0.02 M_{\odot}$ converted @ 10 kpc
DUAL detectors estimated sensitivity at SQL

[M. Bonaldi, et Al. Phys. Rev. D (in press); gr-qc/0302012]

Science with HF GW
- BH and NS mergers and ringdown
- NS vibrations and instabilities
- EoS of superdense matter
- Exp. Physics of BH
- Normal modes of relativistic stars
  - g-modes (fully GR perturbation)
  - p-modes (pressure)
  - w-modes (space-time)
  - r-modes (rotation)
- New born NS (EOS for hot (T>10^8 K) nuclear matter)

\[ M_{\text{Tot}} \geq r_1 \cdot Q / T \quad \text{(in press)} \]

\[ r_1 = 0.25 \, m \quad r_{2-\text{int}} = 0.26 \, m \quad r_{2-\text{ext}} = 0.47 \, m \]
\[ h = 2.35 \, m \quad \text{Tot mass} = 16.4 \, t \]

**Molybdenum**
\[ Q / T \geq 2 \cdot 10^8 \, K^{-1} \]

**Silicon Carbide (SiC)**
\[ Q / T \geq 2 \cdot 10^8 \, K^{-1} \]
\[ r_1 = 0.82 \, m \quad r_{2-\text{int}} = 0.83 \, m \quad r_{2-\text{ext}} = 1.44 \, m \]
\[ h = 3 \, m \quad \text{Tot mass} = 62.2 \, t \]
Nuclear Physics Perspectives at LNL

Tandem+Alpi
A Superconductive Linac as a test bench for Eurisol
Nuclear Structure and Dynamics at the limits (spin and isospin)

High intensity stable beams
Moderately neutron rich nuclei by means of high intensity stable beams
Multi-nucleon transfer and deep-inelastic collisions as a way to access n-rich nuclei: The Clover array + PRISMA

from SPES to Eurisol
Medium size next generation RIB facility, a way to Eurisol
Advanced Gamma ray Tracking Array and other Integrated Infrastructure Initiatives
- Fission induced by fast n
- $3 \times 10^{13}$ fissions per second.
- The p beam power (~100 kW) is dissipated in the first target (converter), while the second target (production target) only withstands the fission power (few kW).
- The production target consists of $^{238}\text{U}$, in the UCx form.
- The (p/n) converter is a thick Be target.
The SPES-BNCT project
An experimental neutron beam facility
aimed at the treatment of skin melanoma

Neutron source:
- reactor
- charged particle accelerator

GBM TAC slice
(Macroscopic examination)

The Boron-Phtalocyanine:
the new boron carrier

Glioblastoma Multiforme (GMB)  Melanoma
ALPI Output Energy

0 10 20 30

E/A [MeV/u]

Tandem (G-F) (1-10 pnA)
PIAVE+Alpi (40-200 pnA)

New Injector

Tandem
Euroball and GASP
Nuclear Structure

Experimental halls
XTU Tandem
Piave
Alpi

Hot nuclei and low energy multifragmentation

8πLP

Garfield

Reaction mechanisms at the Coulomb barrier

RMS
PRISMA
Hot nuclei and low energy multifragmentation

Garfield
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