Recent developments and perspectives in NUCLEAR STRUCTURE by gamma and particle spectroscopy

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INFN: G. Benzoni, B. Blasi, C. Boiano, S. Brambilla, B. Million, O. Wieland, E. Vigezzi

INFN-CNS3-GAMMA: MI, PD, LNL, FI, PG
International collaborations within EUROPE, JAPAN, USA

CONGRESSO DEL DIPARTIMENTO DI FISICA

Milano, 28-29 June 2017
INTRODUCTION

Challenges in Nuclear Physics

- The Physics – more than 7000 Nuclei!
- Interdisciplinarity - Astrophysics
- Dedicated Facility/Detection Setups – γ spectroscopy

FOCUS on NUCLEAR STRUCTURE

Selected Recent Highlights

- Shape Coexistence
- Collective Excitations – Resonances
- Complex Excitations – Coupling Particles and Phonons

OUTLOOK – how to pin down the nuclear force …
Our Challenge: UNIFIED Description of ALL Nuclei in the Universe

(EXOTIC) NUCLEI

Neutron number N
Proton number Z

248 Stable

~3000 discovered

> 7000 estimated to exist in the Universe

Enormous Discovery Potential !!!

BASIC SCIENCE
Many Body Quantum System
Symmetry Principle
Effective Nuclear Force

Our Challenge: UNIFIED Description of ALL Nuclei in the Universe

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(EXOTIC) NUCLEI

Excitations

SHELL Structure
Magic Numbers

Shapes

Clusters

Halos

Neutron SKIN

DIPOLE

Neutron number N
Proton number Z

\( ^{208}\text{Pb} \)

Very compact object
up to \( \sim 250 \) nucleons
SIZE \( \sim 10^{-45} \) m\(^3\)
DENSITY \( \sim 10^{17} \) kg/m\(^3\)

BASIC SCIENCE

Many Body Quantum System

Symmetry Principle

Effective Nuclear Force

Effective Nuclear Force

Many Body Quantum System

Symmetry Principle

\( n \rightarrow p \)

Effective Nuclear Force

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Many Body Quantum System

Symmetry Principle

\( n \rightarrow p \)

Effective Nuclear Force

Many Body Quantum System

Symmetry Principle

\( n \rightarrow p \)

Effective Nuclear Force
... in STAR explosions...

248 Stable

β-decay towards stable isotopes

Rapid Capture of FREE Neutrons

From EXOTIC To STABLE Nuclei

Neutron number N

Proton number Z
Heavy Elements ABUNDANCES depends on Structure of UNKNOWN EXOTIC Nuclei

Magic Numbers, Shapes

\[ \tau_{\beta}^{\text{Spherical}} \approx 10 \times \tau_{\beta}^{\text{Deformed}} \]
\[ \rho_n^{\text{Spherical}} \approx 0.5 \times \rho_n^{\text{Deformed}} \]

APPLICATIONS
Radio isotopes, Reactors, ...

BASIC SCIENCE
Many Body Quantum System
Symmetry Principle
Effective Nuclear Force

Proton number \( Z \)

STRONG Interdisciplinary with ... ASTROPHYSICS
A World Wide Effort to Expand the Nuclear Chart ...

- **PRODUCTION**: stable and radioactive ion beams, neutron beams, ...
- **INVESTIGATION of Nuclear Structure**: gamma and particle spectroscopy

**Theory**
- Institute of Nuclear Physics
  - SEATTLE (USA)

**Theory**
- ECT*
  - European Center
  - TRENTO (ITALY)

**Map**
- TRIUMF
- MSU
- Argonne
- GANIL
- GSI
- ISOLDE-CERN
- Orsay
- ILL-Grenoble
- Bucharest
- LAB Legnaro
- LAB Sud
- LAB Gran Sasso
- OSAKA
- RIKEN
LONG TRADITION OF $\gamma$-SPECTROSCOPY
Arrays based on Compton suppressed Ge detectors

Starting from the 80’s:

TESSA (Daresbury)
OSIRIS (Berlin)
ARGONNE-ND ARRAY (Argonne)
NORDBALL (Copenhagen)
JUROSPHERE (Jyvaskyla)
EUROGAM (Strasbourg)
CLARION (Oak Ridge)
GASP/GALILEO (Legnaro)
EUROBALL (Legnaro, Strasbourg)
GAMMASPHERE
STATE of the ART Ge ARRAYS

AGATA
(Advanced-Gamma-Tracking-Array)

LNL, 2011
S. Akkoyun et al, NIMA 668 (2012) 26-58

GRETA
(Gamma-Ray Energy Tracking Array)

LBNL, 2011
S. Paschalis et al, NIMA 709 (2013) 44-55

The “Ultimate” Ge Arrays

✧ EFFICIENCY: 43% $M_\gamma = 1$ and 28% $M_\gamma = 30$ (@ 1 MeV, FULL BALL)
✧ COUNT RATE capabilities (100s KHz)
✧ ANGULAR RESOLUTION of the $\gamma$ interaction point ($\theta \sim 1^\circ$)
✧ “PERFECT” DOPPLER CORRECTION (6 keV @ 1 MeV, $\beta = 50\%$)
The Gamma Tracking Array Concept

**HARDWARE**

1. Highly segmented HPGe detectors

2. Digital electronics to record and process segment signals
   - 14 bit, 100 MS/s
   - 37 signals/crystals
   - Raw Data Read Out: 10 kB/evt/crystal

**SOFTWARE**

3. Pulse Shape Analysis to decompose recorded waves

4. Identified interaction points
   \[(x_i, y_i, z_i, E_i, t_i)\]

5. Reconstruction of tracks evaluating permutations of interaction points

6. Reconstructed gamma-rays + Correlation with other detectors
AGATA Inauguration: 9th April 2010 – Legnaro National Laboratory INFN

Physics Campaign @ LNL (2010-2011)

Most Relevant Results from Milano
1 Review Paper
Several Phys. Rev. C
The AGATA Evolution Towards $1\pi$

LNL: 2010-2011
15 crystals
Total Eff. ~6%

GSI: 2012-2014
22 crystals
Total Eff. ~10%

GANIL: 2015-2019
up to 45 crystals
Total Eff. ~22%

Demonstrator + PRISMA
“backward”
STABLE BEAMS
20 experiments

AGATA + FRS
“forward”
RELATIVISTIC EXOTIC BEAMS
7 experiments

AGATA+VAMOS+ ...
“backward”
EXOTIC (ISOL) & STABLE BEAMS
6 experiments in 2015

From 2020 at Legnaro-INFN (SPES Radioactive ISOL Beams)
AGATA - FULL Detector

180 crystals segmented (6480 segments)
60 triple clusters
2.5 tons
FULLY DIGITAL electronics

Solid ang. 82%
Eff. 43% ($M_\gamma = 1$)
P/T 58% ($M_\gamma = 1$)

AGATA represents the state-of-the-art in gamma-ray spectroscopy and is an essential precision tool underpinning a broad programme of studies in nuclear structure, nuclear astrophysics and nuclear reactions. AGATA will be exploited at all of the large-scale radioactive and stable beam facilities and in the long-term must be fully completed in full 60 detector unit geometry in order to realise the envisaged scientific programme. AGATA will be realised in phases with the goal of completing the first phase with 20 units by 2020.
Detection Systems (State of the Art)
Very Powerful and Complete Experimental Setups ...
Selected Recent Highlights of $\gamma$ spectroscopy

Excitations

Pygmy Resonances

Couplings
Particle-Phonon

$^{133}Sb = ^{132}Sn + 1$ proton

Shape Coexistence
$Ni$ - isotopes

Neutron number $N$

Proton number $Z$
Appearence of DIFFERENT SHAPES in the SAME NUCLEUS at low excitation energy

Secondary Minima in the Potential Energy Surface – PES METASTABLE Configurations

SHAPE ISOMERS in actinide $A=240$, Polikanov – 1973

TWO SEPARATE WORLDS

Present Challenge in Nuclear Physics: MICROSCOPIC description Emergence of SHAPES and DEFORMATION in a pure SHELL Model framework (individual nucleons + interaction)
MICROSCOPIC Structure of Nuclei: a computational challenge ...

Shell Structure for p and n

Divergent Dimension of Configuration Space

\[
\binom{K}{A} = \frac{K!}{(K-A)!A!}
\]

Number of ways to distribute \( A \) nucleons over \( K \) orbitals

**Number of configurations**

- \( N=Z \)
  - 44 \( ^{88}\text{Ru} \) \( \approx 10^{28} \)
  - 28 \( ^{56}\text{Ni} \) \( \approx 10^{10} \)
  - 24 \( ^{48}\text{Cr} \) \( \approx 10^7 \)
  - 22 \( ^{44}\text{Ti} \) \( \approx 10^4 \)

State-of-the-art SHELL Model possible for \( A<100 \)

new calculations scheme

Monte Carlo Approach

Effective N-N interaction

very powerful computer

10^6 parallel processors

K-Computer
Tokio University
(Prof. Taka Otsuka’s group)
Monte Carlo SHELL Model (T. Otsuka’s Group)

$^{66}\text{Ni} - ^{70}\text{Ni}$: COEXISTENCE of spherical, oblate and prolate SHAPES

Best Candidate for SHAPE isomerism
HINDERED $\gamma$-decay
PROLATE $\rightarrow$ SPHERICAL

Confirmed by Experiment !!!
$^{18}\text{O} + ^{64}\text{Ni} \rightarrow ^{16}\text{O} + ^{66}\text{Ni}$, below Coulomb barrier

1425

$^+ 1$

Spherical g.s.

$^+ 2$

$^+ 3$

$^+ 4$

Prolate

$\rightarrow 20(7)$ ps

0.2 W.u.

STEP FORWARD in understanding MICROSCOPIC origin of deformation
$\rightarrow$ VALIDATION of PREDICTIVE POWER of Most Advanced SHELL Model predictions

Complementary studies in Ni chain by $\beta$-decay: G. Benzoni et al., ...
Selected Recent Highlights of $\gamma$ spectroscopy

Excitations

Pygmy Resonances

Shape Coexistence

Ni - isotopes

Neutron SKIN OSCILLATION

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Neutron SKIN OSCILLATION
The DIPOLE Response In Nuclei

Relevant ENERGY window for ($\gamma$,n) reactions in STARS

STRONG Impact on Element Abundance

Exp

with pygmy

Theory

Neutron Pressure from SKIN

Relevant for NEUTRON STARS Radii

ASTROPHYSICS Implications

- Nucleosynthesis
- Neutron Stars

Relevance in Nuclear Structure

- Complex Microscopic Nature
Pygmy Resonances in STABLE NUCLEI
Heavy-Ion Inelastic Scattering: a probe sensitive to the surface

LNL Campaign
AGATA + Si Telescopes + Scintillators (LaBr3)

$^{17}\text{O} @ 20 \text{ MeV/A}$
on $^{208}\text{Pb, 124Sn, 90Zr, 140Ce}$
STABLE targets

Pygmy Strength (E1)
1-3% EWSR isoscalar E1

See POSTER
F. Crespi
A NEW OBSERVATION: $^{124}\text{Sn}$ – QUADRUPOLE PYGMY

Multitude of $2^+$ discrete states

$^{124}\text{Sn}(^{17}\text{O},^{17}\text{O}'\gamma)$

AGATA

Concentration of E2 Strength much below the GIANT QUADRUPOLE resonance

- In agreement with Quasi-phonon Model predictions -

Pygmy Resonances in EXOTIC NUCLEI
Relativistic Coulomb Excitation: high selectivity for E1 excitation

Experimental Area
Ion Source

Up to 1 GeV/nucleon (90% c)
3-20 MeV/nucleon (8-20% c)

GSI

First Case: EUROBALL + BaF2 Setup

PYGMY Strength: 5-9% EWSR

68Ni

O. Wieland, A. Bracco et al., PRL 102, 092502 (2009)

AGATA + LaBr3 Setup

v/c = 73%

Preliminary ... 64Fe
Above background

R. Avigo, O. Wieland, ... in preparation
Complementary program at RIKEN-Japan

PYGMY studies in the MOST EXOTIC Nuclei:
\[ ^{20,22,24}\text{O},
^{50,52}\text{Ca},
^{70,72}\text{Ni},
^{128,132}\text{Sn} \]

Evolution of PYGMY strength along isotopic chains

Ongoing Experimental Campaign ... (A. Bracco, F. Camera, F. Crespi, O. Wieland, ...)
Selected Recent Highlights of $\gamma$ spectroscopy

- **Excitations**
- **Pygmy Resonances**

- **Couplings**
  - Particle-Phonon
  - $^{133}\text{Sb} = ^{132}\text{Sn} + 1\ \text{proton}$

- **Shape Coexistence**
  - Ni - isotopes

- Neutron number $N$
- Proton number $Z$

- Selected Recent Highlights of $\gamma$ spectroscopy

- Couplings

- Ni - isotopes

- $^{133}\text{Sb} = ^{132}\text{Sn} + 1\ \text{proton}$
Couplings between Particle and Collective Degrees of Freedom

**In NUCLEI**

**Particle-Phonon Couplings**

**PHONONS = Vibrations of MAGIC Core**

\[ ^{133}\text{Sb} = ^{132}\text{Sn} + 1 \text{ proton} \]

Key Ingredient for:
- Anharmonicity of vibrational spectra
- Damping of Giant Resonances

→ emergence of COMPLEX excitations

**Common many-body diagrammatic techniques**

**Different energy scales ...**

**In CONDENSED MATTER**

**Electron-Phonon Couplings**

**Phonons and Plasmons**

Key Ingredient for:
- Electromagnetic Response
- Superconductivity

in Metal Clusters, Fullerenes, ...
Particle-Phonon Couplings around EXOTIC and Doubly Magic $^{132}$Sn

Neutron-induced FISSION

$n + ^{235}U$

$n + ^{241}Pu$

$^{133}$Sb: $^{132}$Sn + 1 $\pi$
One-valence Proton nucleus

$^{132}$Sn

$r$-process

$^{78}$Ni

$^{133}$Sb
The γ-spectroscopy campaign @ ILL-Reactor (Grenoble)
2012-2013: 100 days, 95% DATA taking

Dedicated ballistic neutron guide
highly collimated beam (1 cm²)
cold neutrons (meV)
Φₙ = 2×10⁸ n cm⁻² s⁻¹

MOST INTENSE
Continuum neutron source
In pile
Φₙ = 5×10¹⁴ n cm⁻² s⁻¹

10 EXOGAM
6 Ge GASP

58 MW

Reactor hall ILL 5
Experimental level (C)
Fission Data

$^{133}\text{Sb} = ^{132}\text{Sn} + 1$ proton

Lifetime measurements with fast scintillators

<table>
<thead>
<tr>
<th>$\frac{15}{2}^+$ → $\frac{13}{2}^+$</th>
<th>$\frac{13}{2}^+$ → $\frac{11}{2}^+$</th>
<th>B(M1) [W.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.24$</td>
<td>$0.004$</td>
<td></td>
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$< 20$ ps

$31(8)$ ps

$17 \mu$s

Nature of the States is COMPLEX and DIVERSE

Interpretation NOT Doable by SHELL Model:

Too LARGE space

→ Alternative Approach
The New “HYBRID” Model (G. Colò, P.F. Bortignon - Milano)
CORE Excitations (Phonons-RPA) + single particle (Hartree Fock)

$^{133}\text{Sb}: ^{132}\text{Sn} + 1\pi$

Coupling Matrix Elements between SINGLE PARTICLE and CORE excitations consistently calculated

NO FREE PARAMETERS - Same SkX Interaction

The New “HYBRID” Model (G. Colò, P.F. Bortignon - Milano)
CORE Excitations (Phonons-RPA) + single particle (Hartree Fock)

\[ {^{133}\text{Sb}}: {^{132}\text{Sn}} + 1\pi \]

- **GOOD Reproduction of Exp.**
- **MIXED** States based on Collective and Non-Collective Excitations of \(^{132}\text{Sn}\) CORE

STARTING POINT for extended investigation in MEDIUM/HEAVY Nuclei **NOT possible with SHELL MODEL !!!**


See POSTER S. Bottoni

2016 HIGHLIGHT Institut Laue-Langevin (ILL)
OUTLOOK: pinning down the NATURE of the nuclear force

Major problem in Nuclear Physics:
detail composition of the nuclear force is NOT known !!!

In HEAVY-Systems:
**Effective N-N Interaction**
Corrections are needed due to the presence of other Nucleons

**Bare N-N interaction**
can be derived from QCD

**QCD**

LIGHT systems ONLY (up to C, O, Ne, ...) can be computed by **ab-initio calculations:**
→ they are sensitive to details of the N-N interaction (2 body and 3 body terms)

\[ \tau \ (2+) \]

0.25 ps 0.08 ps

2 body 3 body

AGATA exp. in GANIL - in 10 days:
\[ ^{18}\text{O} \ (141 \text{ MeV}) + ^{238}\text{U} \ (10 \text{ mg/cm}^2) \]
\[ \gamma \text{-spectroscopy of n-rich B-C-O-F nuclei} \]

High Precision Lifetimes measurements
\[ \tau = 100 \text{ fs} – 10’s \text{ ps} \]
Conclusions

- **NUCLEAR STRUCTURE PHYSICS** aims at a unified description of > 7000 Nuclei in the Universe less than half are known ... very high discovery potential !!!

- Several BASIC questions to be answered
  
  Microscopic Origin of shapes and deformations
  
  Nature of Resonance Excitations – neutron skins ...
  
  Emergence of complex excitations – particle-phonon couplings ...
  
  **Outlook**: sensitivity to details of nuclear force

- **Strong Interdisciplinarity** – Astrophysics

- **State-of-the-Art SETUP**: AGATA, large volume scintillators, …

- **A Major Challenge for THEORY** …

**Thank You for the Attention** **