Second Andean School (2014)

Nuclear Structure and Gamma Spectroscopy

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DFN–IFUSP
Brazil
Introduction

- About my group @ LAFN/IFUSP
- Why to study nuclear physics
- Why to study nuclear structure
- Why to use gamma-spectroscopy
Personnel: J. R. B. O., N. H. Medina, L. Gasques (profs); J. Alcántara-Núñez (Post-Doc); V. Zagatto, V. Aguiar, A. Souza, J. Duarte (grad. students); undergraduate students; and, Many collaborators: (IFUFF, IPEN, UNAL, LNS).

Our spectrometer (Saci Perere)

Pelletron Tandem Accelerator (8MV), LAFN (Laboratório Aberto de Fís. Nuc.)

Research topics: odd-odd nuclei, chiral bands, isomers, LSSM tests, nuclear reaction mechanisms with γ-particle coincs. and weakly bound nuclei, nuclear rainbow scattering
The 4 forces of nature

- **Gravitational**
- **Electromagnetic**
- **Weak**
- **Strong, or Nuclear**

Electroweak unification

These 3 have a role in Nuclear Physics
Quantum electrodynamics

- Feynman diagrams

\[ \alpha = \frac{1}{137} \quad \alpha^2 \ll \alpha \]

Electron g-factor

\[ g_{\text{exp}}(e) = -2.00231930436153(53) \]
Standard Model

Particles and interactions

<table>
<thead>
<tr>
<th>Three Generations of Matter (Fermions)</th>
<th>Higgs</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass: 2.4 MeV</td>
<td>171.2 GeV</td>
</tr>
<tr>
<td>charge: +(\frac{1}{2})</td>
<td>0</td>
</tr>
<tr>
<td>spin: (\frac{1}{2})</td>
<td>0</td>
</tr>
<tr>
<td>name: u</td>
<td>c</td>
</tr>
</tbody>
</table>

Quarks: 
- u (up) 4.8 MeV \(\frac{1}{2}\) \(\frac{1}{2}\) down \(\frac{1}{2}\) \(\frac{1}{2}\)
- d (down) -0.17 MeV \(-\frac{1}{2}\) \(-\frac{1}{2}\)
- s (strange) 1.27 GeV \(\frac{1}{2}\) \(\frac{1}{2}\)
- b (bottom) 4.2 GeV \(\frac{1}{2}\) \(\frac{1}{2}\)
- g (gluon) 91.2 GeV 0

Leptons: 
- e (electron) 0.511 MeV \(-\frac{1}{2}\) \(\frac{1}{2}\)
- \(\bar{e}\) (electron neutrino) 0.17 MeV \(-\frac{1}{2}\) \(-\frac{1}{2}\)
- \(\mu\) (muon) 106.7 MeV \(\frac{1}{2}\) \(\frac{1}{2}\)
- \(\bar{\mu}\) (muon neutrino) 1.27 GeV \(-\frac{1}{2}\) \(-\frac{1}{2}\)
- \(\tau\) (tau) 1.777 GeV \(\frac{1}{2}\) \(\frac{1}{2}\)

Bosons (Forces):
- \(\gamma\) (photon) 0 | 0 |
- \(Z^0\) (weak force) 91.2 GeV | 0 |
- \(W^\pm\) (weak force) 80.4 GeV |

Color: RGB

Hadrons - color neutral:
Mesons \((q\bar{q})\) - ex: \(\pi^+ (u\bar{d})\);
Baryons \((3q)\) - ex: nucleons \(p(u\bar{d}\bar{d}); n(u\bar{d}\bar{d})\)
Strong interaction, QCD

- Confinement x asymptotic freedom

\[ \alpha = \frac{1}{137} \]

Unification

\[ Q \quad 1 \quad 10 \quad 100 \]

\[ \alpha_s(Q) \]

Data | Theory
--- | ---
Deep Inelastic Scattering | $\Lambda_{\text{MS}}^{(5)}$ | $\alpha_s(M_Z)$
$e^+e^-$ Annihilation | QCD | 245 MeV | 0.1209
Hadron Collisions | | 210 MeV | 0.1182
Heavy Quarkonia | | 180 MeV | 0.1155
Weak interaction

Beta decay

\[ \beta^- : \text{Carbon-14} \rightarrow \text{Nitrogen-14} \]

\[ \beta^+ : \text{Carbon-10} \rightarrow \text{Boron-10} \]

\[ n \rightarrow p + e^- + \bar{\nu}_e \]

\[ p + p \rightarrow ^2H + \nu_e + e^+ \]

\( \Delta m_\nu \neq 0 (!?) \)

p−p cycle
energy (and neutrino)
production at the Sun
Why Nuclear Physics

Nuclear force is the poorest understood of all the forces of nature

It is peculiarly STRONG – cannot be treated in perturbation theory like electro-weak interactions (except at very high energy)

It is very complex, and (therefore) very rich, particularly at low energy: short range central force, strong spin-orbit interaction, tensor force, pairing, 3-body forces...

Etc.
The atomic nucleus scale

Consists of p & n (lightest baryons)

Energy

radius

0.5 nm

5 fm

~1 fm

<<1 fm

Atom

Nucleus

3 val. quarks

nucleon

partons
The N-N force

Meson theory
Yukawa, 1935
\[ \Delta t \Delta E \approx \hbar \quad \Delta E = mc^2 \]
\[ c \Delta t mc^2 \approx \hbar c \]
\[ \Delta R = c \Delta t \approx \frac{\hbar c}{mc^2} \]

Pion

\[ \hbar c \approx 200 \text{ MeV.fm} \]
\[ m_\pi c^2 \approx 140 \text{ MeV} \]
\[ \Delta R \approx 1.4 \text{ fm} \]

Paris potential
(cenral part)

S - singlet (S=0)
T - triplet (S=1)
E - even (L=0, 2...)
O - odd (L=1, 3...)
(TE, SO) T=0; (TO, SE) T=1
Other terms of N.F.

- **Tensor**
  - Attractive: $\uparrow \downarrow$
  - Repulsive: $\uparrow \uparrow$

- **Spin-orbit**

- **3-body**
Why nuclear structure

Because it has interesting peculiarities (at low energy):

1 - The nucleus is a many-body system (but not "too-many", like in condensed matter physics: $A < 300 \ll N_A = 6 \times 10^{23}$)

2 - It presents an interplay between collective and single-particle degrees of freedom

3 - It (and only it - together with nuclear reactions) involves the nuclear force (at low energy)

4 - It involves geometric and dynamical symmetries

5 - It can provide precise tests of beyond-standard-model physics (e.g. double-$\beta$ decay)

6 - It is important for nuclear astrophysics
Nuclear Astrophysics

- Primordial nucleosynthesis
- pp cycle (Sun)
- CNO cycle
- $r$ (supernova) and $rp$ procs.

Ciclo CNO
**Why γ-spectroscopy**

- Nucleus is too small – we cannot measure with mechanical or electrical instruments

- Gamma (electromagnetic interaction) is very well known (QED)

- Provides access to detailed information of the quantum states of the nucleus (level scheme)
Typical γ-spect. experiment

Fusion-evaporation reactions

Target nucleus

Beam Nucleus

Fusion

10^{-22} \text{sec}

Compound Formation

Rotation

Cooling

10^{-15} \text{sec}

Groundstate

2^{-} \quad 1848 \quad 18375^{+} \quad 1829

10^{-19} \text{sec}

Fast Fission

\gamma

Level scheme

Model

High resolution detectors

in-beam γ spectra
Level schemes

Manifest the nuclear structure
Nuclear Models

- Liquid Drop
- Shell Model
- Pairing
- Collective models
- Nilsson
- CSM, TAC
- IBM
Binding energy per nucleon

\[ E_B/A = (NE - ZM_H - M(Z,A))c^2 \]

\[ E = Mc^2 \]

Region of very stable nuclides

Fusion

Fission
Liquid Drop Model

- **Nuclear radius:** \( R = R_0 A^{1/3} \) \( (R_0 = 1.2 \text{ fm}) \)
  - \( \rho_0 \approx 0.17 \text{ fm}^{-3} \)
  - \( r_{NN} \approx 1/\sqrt[3]{\rho_0} = 1.8 \text{ fm} \)

- **Semi-empirical mass formula**

\[
E_B = a_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(N - Z)^2}{A} - \delta(A, Z)
\]
Magic Numbers

N: 2, 8, 20, 28, 50, 82, 126

... at least near the stability valley!
The shell model

3D harmonic oscillator

Mean field

Independent particle

\[ s_z = \pm \frac{1}{2} \]

degeneracy

\[ E^*(n) = (n + 3/2) \hbar \omega \]

Occupation

Parabolic potential well

Magic numbers

<table>
<thead>
<tr>
<th>n</th>
<th>l</th>
<th>(n+1)(n+2)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>0, 2</td>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>1, 3</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>0, 2, 4</td>
<td>30</td>
<td>70</td>
</tr>
<tr>
<td>5</td>
<td>1, 3, 5</td>
<td>42</td>
<td>112</td>
</tr>
</tbody>
</table>
Shell model with spin-orbit

Spin-orbit interaction

\[ H_{so} = k l.s \]

\[ l = r \times p \]

Magic numbers OK!
Realistic Shell Model

Woods-Saxon pot. for n & p + V(Coul.)

\[ V_{WS}(r) = \frac{V_0}{(r-r_0)} \left(1 + e^{\frac{r-a}{a}} \right) \]

Ex. \(^{116}\text{Sn}\)

Characteristic Level-scheme

\( E = \sum E_i(p.b.) \)

p.b. excitation

\( T \approx 1 \text{ W.U.} \)

\( 0^+ \)

\( j_1 \)

\( j_2 \)
Pairing correlations – beyond mean field.
Nucleus is analogous to a superconductor.
Large Scale Shell Model (LSSM)

- SM+realistic residual interactions between valence particles (exs.: KB3, SDPF...)

Ex. $^{46}$Ti: Core: $^{40}$Ca (N=Z=20) PhysRevC.70.034302
LSSM transition probabilities

Reduced t. p. in $^{46}$Ti

Ground-state band

- LSSM calcs

PR C 70, 034302 (2004)

Negative parity band ($K^\pi = 3^-$)
Collective models

Parameters for description of deformed shapes

Hill-Wheeler

\[ R(\theta, \phi) = R_0 \left( 1 + \beta \sqrt{\frac{5}{16\pi}} \left( \cos \gamma (3 \cos^2 \theta - 1) + \sqrt{3} \sin \gamma \sin^2 \theta \cos 2\phi \right) \right) \]

Lund convention

Quadrupole deformations

Prolate collective

Oblate non-collective

Triaxial collective

Spherical
Vibrational Model

Vibrations of the nuclear surface

Level scheme

\[ E^*(n) = n \hbar \omega \]

Harmonic quadrupole vibration

\[ \beta = \beta(t) \]

Spherical equilibrium deformation

\[ T \propto n \gg 1 \text{ W.U.} \]
Rotational model

Quadrupole deformation rotating perpendicularly to symmetry axis

\[ T = T(J) \gg 1 \text{ W.U.} \]
\[ E_{\text{rot}} = \frac{\hbar^2 J(J+1)}{2I} \]

\[ E_{\text{rot}} = \frac{1}{2} I \omega^2 \]
\[ L = I \omega \]
\[ E_{\text{rot}} = \frac{L^2}{2I} \]

\[ E_{\text{rot}} = \frac{\hbar^2 J(J+1)}{2I} \]
\[ E_y = \Delta E_{\text{rot}} (\Delta J = 2) \]

\[ \Delta E_y = \frac{4 \hbar^2}{I} \]

\[ \hbar \omega = \frac{E_y}{2} \]

Level scheme

\( J^\pi \)

<table>
<thead>
<tr>
<th>( J^\pi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>8^+</td>
</tr>
<tr>
<td>6^-</td>
</tr>
<tr>
<td>4^+</td>
</tr>
<tr>
<td>2^+</td>
</tr>
<tr>
<td>0^+</td>
</tr>
</tbody>
</table>

Permanent \( \beta \) deformation

152Dy

SD

No. of Counts

\( \gamma \)-ray energy (keV)
Rotational or vibrational?

Nuclide chart

Ratio of energies between $4^+$ and $2^+$ states
(even-even nuclei)

$E_{4^+}/E_{2^+}$

Vib. = 2.0
Rot. = 3.3

Www.nndc.bnl.gov
Nilsson model

Single particle shell model states in a deformed potential

\[ K = \sum \Omega_i \]

\[ ^{140}\text{Gd} \]
Cranking shell model - CSM

Nilsson+Coriolis interaction

Routhian \( e' = e - \omega J_x \)

Energy in the intrinsic frame
"Backbending" at high spins

- Coriolis induced pair breaking

Level scheme

\[ H_{\text{Coriolis}} = -\hbar \omega j_x \]

\[ \hbar \omega = \frac{E_y}{2} \]
Band termination

Alignment of all the valence particles
Chiral symmetry breaking

Tilted Axis Cranking

$^{105}$Rh

Nearly degenerate M1 bands

Energia de excitação (MeV)

$I (h)$

Quiralidade no sistema intrínseco

partícula(s)

caroço triaxial

buraco(s)

$j_\pi$

$R//2$

1

$3 2 1$

$3 2 1$
Example of study at IFUSP

J.A. Alcántara-Núñez, PhD, IFUSP, 2003

Saci Perere spectrometer – Pelletron accelerator
**Symmetry and phase transitions**

- IBM: s, d bosons
- Dynamical symmetries

- Ex. X(5) critical point of the rotation-vibration phase transition

![Casten triangle](image)

![Diagram](image)
LSSM x Collective rotation

Rotor behavior built up from SM + residual interactions

Backbending

1f_{7/2}
Effective interactions ($\chi$EFT) from bare NN and NNN interactions – No Core Shell Model

J.P. Vary
ntse-2014
(Nucl. Theory in the Supercomputing Era), Russia
Precision theoretical calculations
Gamma spectroscopy

- Gamma detectors and Electronics
- Coincidence technique
- Compton suppressor
- Large spectrometers (Why so complex?)
- The concepts of resolving power and observational limits
- Tracking arrays
- Other techniques
**Hiperpure Germanium detector**

- **HPGe semiconductor crystals**

- **Liquid $N_2$ T=77K**

- **Energy resolution 2–3keV**

- **Time resolution 20 ns**

- **High Voltage (2–5 kV)**

- **1k$/$%
Basic electronics

- Energy spectrum

Diagram:

- Det.
- Pre
- Amp. Spec.
- ADC
- PC
- HV
- FA
- CFD

Canal

Analog to digital conversion

Analog pulse
From Spec. Amp. (linear)

Analog pulse
From Spec. Amp. (linear)
Comparison between “ideal”, NaI(Tl) and HPGe

Energy resolution (FWHM)
γ-γ coincidence circuit
Todays electronics

- Ex.: Gretina Digitizer and Timing & control modules
\[ \gamma - \gamma \text{ Matrix} \]

Biparametric spectrum \( E_1 \times E_2 \)

Matrix in perspective

Event: \( E_1, E_2, T_2 - T_1 \)

Total Projection

\[ \Delta t = 20 \text{ ns} \]
The Compton Supressor

- Anti-coincidence with BGO signals (b)
Typical $\gamma$ spectrometer system

Why is it so complex?

PRISMA-CLARA
LNL-INFN
Complexity of the spectra

Ex.: Fusion-evaporation reaction

Compromise: efficiency x resolving power (R)
The resolving power concept

- The P/B ratio improves each time a gate selection is made.
- The improvement factor is the resolving power: \( R = \frac{SE_\gamma}{\Delta E_\gamma} \frac{P}{T} \)

- \( SE_\gamma \) is the average energy separation between \( \gamma \) peaks within a cascade.
- \( \Delta E_\gamma \) is the energy resolution.

- \( P/T \) is the peak to total ratio of the detector.
Multiple $\gamma$ coincidences

- $\alpha$: observational limit of the spectrometer

$R$ – Resolving power
$\varepsilon_{ph}$ – Photo-peak efficiency

$$R = \frac{SE_{\gamma}}{\Delta E_{\gamma}} \frac{P}{T}$$

$$\alpha_{back} = \frac{(P/B)_F}{R_0 (kR)^F}$$

$$\alpha_{stat} = \frac{N_F}{N \varepsilon_0 (k \varepsilon_{ph})^F}$$

$N_F = 100; (P/B)_F = 0.2$

Optimum: $\alpha_{back} \approx \alpha_{stat}$
γ-spectrometer examples

- Multi-detector GeHP/CS systems
  - HERA - LBL
  - 20 GeHP
  - Gammasphere LBNL/ANL
  - ~100 GeHP
The Saci-Perere spectrometer

IFUSP

- Sistema Ancilar de Cintiladores (Saci)
- Pequeno Espectrômetro de Radiação Eletromagnética com Rejeição de Espalhamento (Perere)

4 GeHP c/ AC

11 $\Delta E-E$ (85% of $4\pi$)
Ancillary systems

- Charged particle detectors \((4\pi)\)

SACI - sistema ancilar de cintiladores plásticos
(phoswich)
Plastic Phoswich scintillators

- Two types, with different decay time constants

Charged particle
Energy loss

\[ \Delta E \]

PMT

\[ E \]

\[ \Delta E \text{ gate} \]

\[ E \text{ gate} \]

\[ \Delta L \]

Saci

\[ {}^{18}\text{O} + {}^{110}\text{Pd} \]

\[ \Delta E - E \]

\[ Z = 2 \]

\[ Z = 1 \]

\[ Z = 0 \]
Observacional limit of Saci-Perere

$1\% -$ typical SD band intensity
$\gamma - p \ (^{16}O + ^{27}Al)$

J.A. Alcántara-Núñez (Mestrado IFUSP)

$^{27}Al + ^{16}O \quad 40 \text{ MeV}$

- Projeção Total
- Janela em $1p$
- Janela em $1\alpha$
- Janela em $1\alpha 1p$
- Janela em $2p$
- Janela em $2c$

Energia (Canais)

Energia (MeV)

$^{38}K + \alpha n \quad 10.9\%$
$^{40}K + 2\text{pn} \quad 14.4\%$
$^{41}K + 2p \quad 9.8\%$
$^{37}Ar + \alpha \text{pn} \quad 10.2\%$

$^{42}\text{Ca} + \text{pn} \quad 19.7\%$
$^{40}\text{Ca} + 2\text{np} \quad 3.4\%$

$^{42}\text{Sc} + n \quad 0.2\%$
$^{42}\text{Ca} + p \quad 1.0\%$
$^{39}K + \alpha \quad 1.9\%$

$^{35}\text{Cl} + 2\alpha \quad 10.2\%$
$^{38}\text{Ar} + \alpha p \quad 18.5\%$
Composite/segmented $\gamma$ detectors

- Clover (4 segments) / Multi-segmented

EXOGAM (Ganil)

GRETA (USA)

AGATA (EU)
New generation: γ-ray tracking

- Positions of γ interactions in 3 dimensions with mm precision
- Reconstruction of the scattering sequence
- Pulse-shape discrimination
  DSP (FPGA)

Segmented Ge detectors
Tracking spectrometers

- **Gretina/Greta (USA)**
  - Large efficiencies (50%)
  - Excellent resolution (2keV)

**Agata (EU)**

The AGATA sub array – PRISMA setup installed at LNL.
Evolution of the resolving power
Other γ spectroscopy techniques

- Angular distributions and correlations
- Lifetime measurements
- g-factor measurements
Angular distributions $\rightarrow \Delta J$

\[ \vec{l} = \vec{r} \times \vec{p} \]
\[ m_l = 0 \]

$\lambda = 1$ (M1, E1)

$\lambda = 2$ (M2, E2)

Beam

Compound nucleus

$W(\theta)$

Target

$E_1$

$E_2$

M1

M2

$M_1$

$M_2$

$W(\theta)$

$W(\theta)$
Directional correlation

QDCO versus mixing ratio $\delta$

(Q - Stretched quadrupole gate)

\[ \begin{align*}
Q & \rightarrow \text{gate} \\
2 & \rightarrow 1+2 \\
5 & \\
4 & \\
2 & \\
\end{align*} \]

Saci-Perere $37^\circ/101^\circ$

\[ \begin{align*}
\text{DCO} & \quad \text{relative to mixing ratio } |\delta| \\
0 & \quad 10^{-3} \\
0.2 & \quad 10^{-2} \\
0.6 & \quad 10^{-1} \\
1.2 & \quad 10^{0} \\
1.6 & \quad 10^{1} \\
2 & \quad 10^{2} \\
\end{align*} \]
Doppler shift attenuation method

Lineshapes

\[ E_{\gamma} = E_0 \left( 1 + \beta \cos \theta \right) \]
**Plunger (~ns)**

- **Recoil distance method - RDM**

  \[ \text{Recoil velocity} \quad \begin{array}{c} \text{beam} \\ \theta \end{array} \]

  \[ d = vt \]

  \[ E_\gamma = E_0 \left(1 + \frac{v}{c} \cos \theta\right) \]

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**L.G.R. Emediato (IFUSP)**

\(^{133}\text{Ce Triax. PRM x IBFM}

PRC 55 (1997) 2105
RSM - "SISMEI"

- $\gamma-\gamma(t)$, $p-\gamma(t)$ coincidences
- Time spectra - 20ns-10μs

Dennis Toufen – Mestrado IFUSP
**g-factor measurements**

\[ \mathbf{\mu} = g \mathbf{J} \]

- **Larmor precession**

![Diagram](image)

Modulation spectra for $^{176}$W in Pb. $B=27.2\,\text{kG}$

TDPAD

Application—Hauser Alloys ($^{114}$In)

\[ E_r=240+351+440+558 \, \text{keV} \]

\[ 0 \quad 25 \quad 50 \quad 75 \quad 100 \quad 125 \quad 150 \quad 175 \quad 200 \quad 225 \]

Time [\text{ns}]

\[ P(t) \]
A. Stuchbery (ANU) 2012

\[ \vec{B} = 0 \quad \vec{B} \sim 10^3 \text{T} \]

Detector ring
Azimuthal angle $\phi$

Beam

$^{130}\text{Te} + ^{12}\text{C}$ ORNL (Hyball+Clarion @ HRIBF)

Non-perturbed
$\vec{B} = 0$

Perturbed
$\vec{B} \sim 10^3 \text{T}$

\[ |g| \]

S electron
Transient magnetic field

- Triple target
- Rotation of \( W(\theta) \)
- \( B_{\text{ext}} \Rightarrow \text{polarization} \)
- \( B_T \sim 1000 \text{ T} \) (\( \tau \sim \text{ps} \))
- Polarized unpaired \( s \) electrons
Measurement

\[ \vec{H} \uparrow \downarrow \]

Proposal LAFN
Unal/USP