The ν-ball project at ALTO

Jonathan Wilson, Matthieu Lebois, Nikola Jovancevic, Liqiang Qi, Damien Thisse
IPN Orsay
Why study atomic nuclei?

Reduction vs. emergence (the challenge of the XXIst century)

Life & complexity

Elemental diversity

Nuclear processes and properties

Nuclear astrophysics

Nucleons in medium binding energy $\approx$ MeV/u

Quarks & gluons medium explains nucleon mass $\approx 1000$ MeV

Higgs process explains mass of quarks $\approx 5$ MeV

The origin of the mass of ($\approx 90\%$ of) visible universe: due to *in-medium* (interacting) elementary particles

Emergence nowadays theoretically addressed via effective theories

... we are experimentalists
Experimental study of emergent phenomena at $10^{-14}$m

only possible strategy:
- vary the *in medium* conditions
- explore 3 axes of the nuclide chart
The ALTO facility

ALTO typically delivers ~3000 hours of beam time per year

- Trans National Access Facility (ENSAR2, ARIEL)
- ALTO international PAC
The ν-ball spectrometer @ ALTO

v-ball international collaboration
153 researchers from 16 countries and 37 institutes, including 80 Ph.D students

v-ball experimental campaign
Nov. 2017-June 2018. 10 experiments
3000 hours of beam time

Innovations
✓ Hybrid Spectrometer (Ge/BGO/LaBr3)
  high resolution, high efficiency
✓ Coupling with the LICORNE directional neutron source
✓ Calorimetry for reaction studies/selection
✓ Fully digital, 200 channels, including BGO
✓ Modes Triggered or Triggerlesss

24 Clover Ge + BGO
10 Coaxial Ge + BGO
20 LaBr3
or 36 PARIS phoswich
What physics questions does ν-ball address?

- To understand the **detailed nuclear structure** of very neutron-rich isotopes far from nuclear stability

- To study precisely **fast-neutron-induced nuclear fission** using new techniques to extract new observables and new correlations

- To further develop state-of-the-art **fast timing techniques** to measure **sub nanosecond lifetimes**, study nuclear isomerism, extract nuclear moments

- To facilitate diverse spectroscopy experiments proposed by the national and international users of the ALTO facility
A hybrid LaBr₃-Ge array for fast timing spectroscopic studies at the IPN Orsay

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¹³University of Oslo, Norway
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¹⁵European Commission JRC-IRM, Geel, Belgium
The first nu ν-ball workshop, May 2016
- building the ν-ball international collaboration
ν-ball time line

Conception phase
(Building international collaboration and physics cases)

2015
nu-ball LOI presented to ALTO PAC

2016
First nu-ball workshop @ IPN Orsay

2017
Delivery of Ge clovers

2018
Construction

2019
Experimental campaign

Dismantling + shipment of Ge clovers

2020
Data analysis and exploitation of results

2021
Start of nu-ball2 campaign

nu-ball2 workshop @ JRC-Geel, Belgium
The $\nu$-ball International Collaboration

153 researchers from 16 different countries, 37 institutes, including ~80 thesis students

<table>
<thead>
<tr>
<th>Country</th>
<th>Institutes and Universities</th>
</tr>
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<tbody>
<tr>
<td><strong>France</strong></td>
<td>IPN Orsay (16) CSNSM Orsay (6) CEA DAM/CEA Saclay (5) Subatech, Nantes (3) CENBG Bordeaux (6) IPHC Strasbourg (3) GANIL (2)</td>
</tr>
<tr>
<td><strong>UK</strong></td>
<td>University of Surrey (13) National Physical Laboratory (5) University of Brighton (2) University of West Scotland (4) University of Manchester (3) University of York (2)</td>
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<td><strong>Germany</strong></td>
<td>TU Darmstadt (7) IFK- Koln (9)</td>
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<td><strong>Poland</strong></td>
<td>IFJ-PAN Krakow (8) University of Warsaw (6)</td>
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<td><strong>Italy</strong></td>
<td>University of Milano (6) University of Padova (1) Legnaro (1)</td>
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<tr>
<td><strong>Finland</strong></td>
<td>Jyvaskyla (2)</td>
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<td><strong>Belgium</strong></td>
<td>JRC-Geel (3) Leuven (1)</td>
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<td>University of Oslo (6)</td>
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<td><strong>India</strong></td>
<td>Tata Institute (1)</td>
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<td><strong>Canada</strong></td>
<td>University of Guelph (4)</td>
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<td><strong>Serbia</strong></td>
<td>University of Novi Sad (1) University of Belgrade (1)</td>
</tr>
<tr>
<td><strong>South Africa</strong></td>
<td>iThemba (1)</td>
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<tr>
<td><strong>Japan</strong></td>
<td>Riken (1)</td>
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ν-ball management and human resources

**Scientific**
- Jonathan Wilson – DR2 (Responsable)
- Matthieu Lebois – MdC (Responsable)
- Nikola Jovancevic – Postdoc CNRS
- Liqiang Qi - Thesard
- Damien Thisse – Thesard
- Guillaume Mavilla - Technician NESTER
- Rhiann Canavan (Surrey) - Thesard
- Rosa-belle Gerst (Köln) - Thesard
- Joseph Nemer – Stagiaire
- Yannick Popovitch - Stagiaire

**Technical staff**
- Bernard Genolini – IR1 (Responsable)

**Mechanics**
- Christine Legalliard – IR1 (Responsable)

**Ge Detector Maintenance**
- Gabriel Charles – IR2 (Responsable)
- Nourredine Hammoudi - Al

**DAQ and Informatics**
- David Etasse (LPC Caen)
- Patrick LeJeannic (IPNO)
- Eric Legay (CSNSM)

**Administration**
- Pascale Pichot
- Celine Gaubert

**Estimated FTE = 6 person.years**
The \( \nu \)-ball core team
v-ball financing + equipment resources

Financing
2017 – AP in2p3 80 k euro
2018 – AP in2p3 72 k euro
2019 – AP in2p3 42 k euro
Total: 194 k euro

Renewal of ALTO DAQ
with ~180 channel state-of-the-art digital system

Essential equipment borrowed from:
24 Ge Clover detectors + holding frame + some cables (Gammapool, MOU 2017)
10 Ge Phase I detectors (Loan pool)
26 LaBr3 – Surrey + Madrid + Manchester Universities, UK
4 PARIS clusters – The PARIS collaboration (MOU 2018)
BGO HV supplies – Jyvaskyla University, Finland
$^{252}$Cf fission chamber – CEA DAM
Extra DAQ cards (coupling with PARIS) – LPC CAEN
100Tb data acquisition and buffer disk – CSNSM/P2IO Big data
Clover HV supplies – GANIL
Extra cables – Madrid University, Spain, Manchester University, UK
ν-ball project positive side effects

Renewal of the obsolete ALTO DAQ system

Renewal of the IPN Ge detector laboratory

Increase in the international visibility/attractivity of the ALTO facility
v-ball experimental campaign (Nov. 2017-June 2018)
3200 hours of beam time delivered

Heavy Ion Reaction $\gamma$ spectroscopy:
- Half-life measurement and isomer spectroscopy in the neutron-rich deformed nucleus $^{166}$Dy (1 week)
- Electromagnetic transition rates in the nucleus $^{136}$Ce (1 week)
- Pinning down the structure of $^{66}$Ni by 2n- and 2p-Heavy-ion transfer reactions and g-factor measurement (2 weeks)
- A study on the transition between seniority-type and collectivity excitations in the YRAST 4$^+$ state of $^{206}$Po (1 week)
- Measurement of the super-allowed branching ratio of $^{10}$C (2 weeks)
- Feeding of low-energy structures of different deformations by the GDR decay: the nuBall array coupled to PARIS (1 week)

Neutron induced reaction $\gamma$ spectroscopy:
- Spectroscopy of the neutron-rich fission fragments produced in the $^{238}$U(n,f) and $^{232}$Th(n,f) reactions (5 weeks)
- Spectroscopy above the shape isomer in $^{238}$U (2 weeks)
LICORNE/ν-ball coupling principle
Primary beam: $2 \times 10^{11}$/s

Target: $^{7}\text{Li}$ (16 MeV)

$3 \times 10^{20}$ atoms/cm$^2$

Target Material: $^{238}\text{U}$

Secondary beam: $2 \times 10^7$/s

$1.5$ MeV neutrons

Sample:
- $10^5$ fissions/s
- $^{238}\text{U}$
- $^{232}\text{Th}$ ~$100$ g
Anomalies in the charge yields of fission fragments from the $^{238}\text{U}(n,f)$ reaction
J.N. Wilson, M. Lebois, L. Qi et al.,
$^{238}$U(n,f) Fission Fragment Selection

- $^{140}$Xe (4.2%)
- $^{150}$Ce (0.8%)
- $^{138}$Te (0.8%)
- $^{98}$Sr (1.8%)
- $^{94}$Kr (0.8%)
- $^{82}$Ge (0.16%)

Graphs showing γ-ray energy distributions for different fission fragments.
$^{238}\text{U}(n,f)$ Gamma Multiplicity Distributions correlated with A/Z
Average gamma multiplicities

\[ \text{Detected } \langle M_\gamma \rangle \]

\[ \text{Mass (A)} \]

\[ {}^{252}\text{Cf(SF)} \]
Average gamma multiplicities

![Graph showing the relationship between mass (A) and average gamma multiplicities for various elements, including Ge, Zr, Mo, Te, Xe, and Ba. The graph uses symbols to represent different reactions, such as $^{238}$U(n,f) and $^{252}$Cf(SF).]
**Exotic Nuclei Production/Study from Fission Reactions**

**Spontaneous Fission**

$^{252}\text{Cf(SF)}, ~^{248}\text{Cm(SF)}$

(Gammasphere, Euroball)

**Fission induced by thermal neutrons**

$^{235}\text{U(n}_{\text{th}},f)$, $^{241}\text{Pu(n}_{\text{th}},f)$

(EXILL Exogam@ILL)

**Fission induced by fast ~2 MeV neutrons**

$^{238}\text{U(n,f)}, ~^{232}\text{Th(n,f)}$

(LICORNE @ IPN Orsay)
Spectroscopy above $^78$Ni

M. Lebois (Zn, Ge, Ga)
B. Fornal (Ge, Ga)
A. Korgul (Ge, Se)

Shape coexistence around N=60
A. Blahzev (Kr)
G. Georgiev (Rb)
D. Ralet (Sr)
L. Iskra (Y)
S. Bottoni (Sr, Zr)
P. Regan (Zr)

Onset of deformation
T. Kroll (Xe)
G. Benzoni (Ba, Ce, Nd)

Neutron-rich nuclei around $^{132}$Sn
S. Leoni (Sn, Sb)
L. Fraile (Sn, Sb, Te)
R. Lozeva (Sb, Te, I)
Production and study of neutron-rich nuclei above $^{78}$Ni with LICORNE/nu-ball

$^{232}$Th(n,f) reaction products

Yield
- $>$ 1%
- 0.1 – 1%
- 0.01% - 0.1%

Number of known excited states: 1

"$^{78}$Ni revealed as a doubly magic stronghold against nuclear deformation"
$^{96}$Sr Low-Z boundary of the Island of Deformation at N=60

J. Dudouet et al.
PRL 118, 162501 (2017)
Previous results confirmed

T. Rzaca-Urban et al.

$^{248}\text{Cm(SF)}$

$^{238}\text{U + Pb @ 350 MeV/A}$
$^{94}$Kr spectrum gated on the $2^+ \rightarrow 0^+$ transition (665 keV)

$^9$Be($^{238}$U,f)

(courtesy of J. Dudouet)

$v/c = 0.1$

$v$-ball/LICORNE@ALTO

$^{238}$U(n,f)
The diagram represents the $\nu$-ball/LICORNE $^{238}\text{U}(n,f)$ reaction data. The nucleus $^{94}\text{Kr}$ is shown with various transitions and energy levels labeled. The half-life $T_{1/2} = 31 (3)$ ns is indicated for one of the transitions.

The diagram includes transition levels with associated energies such as 853, 836, 471, and 736 keV, among others. The parity assignments for the levels are indicated with $K_\pi = 9^- = n_{11/2}$ [505] $\otimes$ $7/2^+$ [404] and $K_\pi = 7^- = n_{11/2}$ [505] $\otimes$ $3/2^+$ [411].

The graph on the right shows a decay curve with a linear fit, indicating the decay behavior of the system.
Above the isomer in $^{94}\text{Kr}$
v-ball in context

Fission studies

DANCE @ Los Alamos
(neutron-induced fission calorimetry)

Big RIPS @ RIKEN (Pb(238U,f))

FIPPS @ ILL
235U(n,f) 241Pu(n,f)

AGATA/VAMOS@GANIL
9Be(238U,f)

nu-ball @ ALTO
232Th(n,f), 238U(n,f)

The structure of neutron-rich nuclei
Strengths

- Excellent new scientific opportunities, unique (worldwide) to the ALTO facility
- High impact scientific production potential, but with low cost
- Correctly dimensioned for ALTO facility. Internationally attractive. Lots of available beam time
- Excellent technical support from IPN Orsay and LPC Caen (DAQ)
Weaknesses

- Poor local informatics infrastructure (data transfer bandwidth, local data storage, etc.) lags behind current needs. Informatics support for longer-term data storage at CC-Lyon is practically inexistent.

- The nu-ball project has far too much dependence on mutualized resources (e.g. Gamma Pool detectors) that maximizes the amount of work (for IPNO) and minimizes the availability of the device.
nu-ball coupled to the LICORNE directional neutron source presents clear and unique opportunities to perform precision in-beam spectroscopy of fast neutron-induced reactions.

When nu-ball/LICORNE is fully optimized, it can (or has already) become a world-beating device in three separate domains:

- Research into new fission process observables and their correlations
- The detailed study of the nuclear structure of very neutron-rich nuclei (high spin)
- Sub nanosecond fast timing to study nuclear isomerism and nuclear moments
The heavy dependence of the project on mutualized, internationally-used, resources gives an inherent lack of predictability about the future development of the project, and introduces extra unnecessary and preventable risks to the project timeline and future campaign(s)

v-ball is vital instrumentation for the ALTO facility
We envisage asking for in2p3 support for a ν-ball2 campaign in 2021 and 2022.
Backup Slides
v-ball2 campaign forseen 2021 - 2022

New Configurations

**v-ball/PARIS**
GDR studies. High energy gamma detection for light nuclei (ALTO high intensity $^{6,7}$Li, $^{14}$C beams)

**v-ball/OUPS plunger and/or charged particle detector**
RDM lifetimes

**v-ball/Fast Timing**
24 clovers coupled with 40 FATIMA for best hybrid array performance. Lifetime measurements 10-ps 10ns range for weakly populated states

**v-ball/LICORNE**
Improve fission technique: Reduce gamma backgrounds from the source and intrinsic target activity. More primary beam. Low density targets for DPM lifetime measurements. $^{252}$Cf IC
ν-ball Ge detector maintenance

Operations
• Failure diagnostic
• Pumping
• Annealing (80°C)
• FET replacement (Clean room required)
• HV Filter replacement
• Charge preamplifier test and replacement
• Replace ORTEC’s obsolete preamplifier by Canberra material

11 detectors were repaired during the campaign. 25 FET’s replaced.

Components are expensive
HV Filter - 860 euros
FET - 180 euros
Preamplifier - 1600 euros

Timeline was very tight
New technique developed in 2018 to replace Preamplifier components rather than whole board
Gammapool Problems

Gammapool: International committee of 12 members existing since 2002
Deployment of ~20M euros of ex-Euroball detector resources

- Conflicts of Interest (e.g. Members voting themselves equipment for their own research)
- Committee members from non-French countries unaccountable to their funding agencies (e.g. Seats can be transferred between friends or colleagues - no appointment procedure)
- Seats for life. No obligation to sit for fixed term mandates.
- Lack of French representation (only 8% or 16% of committee) (Over 50% of nu-ball equipment was originally financed by France)
- Poorly written MOU with no end-of-life clause. Resources and MOU are considered eternal
- Unlike Loanpool, countries who contributed nothing to Gammapool and borrow equipment are not required to pay any rental costs
- The scientific context in which the 2002 MOU was written has changed dramatically
First preliminary results: $^{252}\text{Cf}$ ionisation chamber + $\nu$-ball
$\nu$-ball calorimetry

$^{152}\text{Eu}$ beta decay events

$^{252}\text{Cf}$ fission events

$\gamma$ multiplicity

Sum Energy
First preliminary results: $\nu$-ball calorimetry
First preliminary results:

$^{252}\text{Cf}$ ionisation chamber + $\nu$-ball

RIKEN

Isomer in $^{164}\text{Gd}$ discovered at BIGRIPS focal plane in 2017

$^{164}\text{Gd}$ isomer identified after only 48 hours of data < 0.01% of the total yield

Decays from states above the isomer observed for the first time

Prompt decays impossible to observe
### Summary of nu-ball/LICORNE fission experiments:

<table>
<thead>
<tr>
<th>Expt.</th>
<th>Target mass</th>
<th>$^7$Li Current</th>
<th>$E_n$</th>
<th>Fission Rate</th>
<th>Time</th>
<th>Data</th>
<th>Total Fissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{252}$Cf(SF)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3 kHz</td>
<td>2 days</td>
<td>50Gb</td>
<td>$5.2 \times 10^8$</td>
</tr>
<tr>
<td>$^{238}$U(n,f)</td>
<td>81 g</td>
<td>10 nA</td>
<td>1.7 MeV</td>
<td>8 kHz</td>
<td>9 days</td>
<td>11Tb</td>
<td>$6.0 \times 10^9$</td>
</tr>
<tr>
<td>$^{232}$Th(n,f)</td>
<td>129 g</td>
<td>80 nA</td>
<td>1.7 MeV</td>
<td>26 kHz</td>
<td>19 days</td>
<td>80Tb</td>
<td>$4.0 \times 10^{10}$</td>
</tr>
<tr>
<td>$^{238}$U(n,f)</td>
<td>81 g</td>
<td>100 nA</td>
<td>3.4 MeV</td>
<td>28 kHz</td>
<td>7 days</td>
<td>25Tb</td>
<td>$1.7 \times 10^{10}$</td>
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</table>
The search for neutron radioactivity
Neutron radioactivity

A-1X → n → high-spin isomer → neutron-emission threshold → γ decay → A^X

g.s.
Occurrence of microsecond isomers in the known nuclei

Potential existence of isomers lying above neutron-separation energy

- $^{208}$Pb
- $^{132}$Sn
- $^{78}$Ni

A.K. Jain, B. Maheshwari, S. Garg, M. Patial, and B. Singh

ATLAS OF NUCLEAR ISOMERS
Nuclear Data Sheets 128 (2015) 1–130
Yields of products from the fast-neutron induced fission of $^{232}$Th

Thermal neutron induced fission of $^{235}$U

Spontaneous fission of $^{248}$Cm