New possibilities for nuclear spectroscopy at ILL: the FIPPS instrument and its first experimental campaign

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ISOLDE workshop
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The Institut Laue-Langevin (ILL) – since 1971

- 58 MW high flux reactor with intense extracted neutron beams
- 13 member states (F, D, UK, E, CH, A, I, CZ, S, B, SK, DK, PL)
- > 40 instruments (mainly for neutron scattering)
- user facility (2000 scientific visitors from 45 countries per year)
• Introduction:
  • spectroscopy after slow neutron induced reactions: Nuclear Physics at the Institut Laue-Langevin
    • \textit{in-pile} targets (GAMS, Lohengrin)
    • “pencil-like” neutron beam (EXILL campaign, FIPPS)

• The FIPPS instrument:
  • instrument layout
  • news from the first experimental campaign
  • future perspectives, physics possibilities
**LOHENGRIN**

fission fragment separator

P. Armbruster et al., NIM 139, 213–222 (1976)
G. Fioni et al., NIMA 332, 175–180 (1993)

\[ \frac{E_{\text{kin}}}{q} = \frac{E}{2r_{\text{el}}} \quad \frac{mv}{q} = B r_{\text{magn}} \]

\[ \rightarrow \quad \frac{\Delta A}{A} = 3 \times 10^{-4} - 3 \times 10^{-3} \]

\[ \rightarrow \quad \frac{\Delta E}{E} = 10^{-3} - 10^{-2} \]

up to \( 10^5 \) s\(^{-1} \) mass-separated fission fragments, \( T_{1/2} \geq \mu s \)

**GAMma–ray Spectrometer (GAMS)**

E. Kessler Jr et al., NIMA 457, 187–202 (2001)

High–resolution γ–ray facility
EXogam @ ILL (EXILL) – “pencil-like” neutron beam

→ Highly collimated neutron beam from ILL reactor (PF1B guide)

→ High efficiency and resolution Ge array (up to 52 Ge crystals, 6% @ 1.3MeV)
  + LaBr$_3$ detectors for fast timing

→ Fully digital electronics, trigger-less (>10 kHz/crystal)

→ 2 reactor cycles (∼ 100 days)

→ 14 stable (rare) and 3 actinide targets

M. Jentschel et al., submitted to JINST (2017)
A. Blanc et al., EPJ Conf. 93, 01015 (2015)
P. Mutti et al., EPJ Conf. 62 (2013)
J. Regis et al., NIMA 763 (2014)
Low-lying isovectorial octupole excitations in $^{144}$Nd: branching and mixing ratios, $^{143}$Nd($n_{\text{cold}}, \gamma\gamma$)

From the EXILL array:
Combination of inpile (GAMS) + neutron beam (EXILL)


$\delta_{\text{Lit.}} = 0.37^{+17}_{-11}$
$\delta_{\text{Fit}} = 0.54(4)$

courtesy of M. Jentschel

M. Thuerauf et al., to be published (2017)
Low-lying isovectorial octupole excitations in $^{144}$Nd: lifetime measurements with the GRID method

Lifetime (GAMS) + branching (EXILL) + angular correlation (EXILL):

$B(M1; 3^-_3 \rightarrow 3^-_1) = 0.13^{+3}_{-4}\mu_N^2$
$B(E2; 3^-_3 \rightarrow 3^-_1) = 40^{75}_{28}$ W.u.

Comparison with other MS states

$\tau_{Fit} = 59^{(18)}_{15}$ fs
The EXILL campaign: 
(n,γ) reactions on (rare) stable targets

Spectroscopy and lifetime measurements with fast-timing techniques

courtesy of S. Leoni
Nuclear structure around $^{208}$Pb

$^{210}$Bi

very complex level scheme
40 new transition, 33 new excited states

N. Cieplicka-Oryńczak et al., PRC 93, 054302 (2016)
Nuclear structure around $^{208}\text{Pb}$

$^{210}\text{Bi}$

very complex level scheme
40 new transition, 33 new excited states

→ comparison with large scale shell model calculations

$E_{\text{ex}} < 2 \text{ MeV}: \text{valence particle couplings;}$

$E_{\text{ex}} > 2 \text{ MeV}: \text{single part-phonon excitations}$

FIG. 10. The energy-spin distribution of states observed in the decay following cold-neutron capture on $^{209}\text{Bi}$ and having their calculated counterparts.

N. Cieplicka-Oryńczak et al., PRC 93, 054302 (2016)
Transitions multipolarity from angular correlations:

- almost pure M1 character for the 320 keV transition
- reduction of the uncertainty on the $^{209}$Bi$(n,\gamma)^{210}$mBi, $^{209}$Bi$(n,\gamma)^{210}$gBi cross sections

Multivariable analysis of angular correlations:
The EXILL campaign: \((n,\text{fission})\) reactions on actinides

\[ ^{235}\text{UO}_2, \sigma_f = 586 \text{ b} \]
Layer sandwiched between Zr or Be backings

\[ ^{241}\text{PuO}_2, \sigma_f = 1010 \text{ b} \]
Layer sandwiched between Be backings

Total proj. spectrum: \(\gamma\)-rays from more than 150 different nuclei

\[ \rightarrow \text{multiple } \gamma\text{-ray coincidences, also with fission partners} \]
Single-particle vs. collective phenomena around $^{132}\text{Sn}$: delayed $\gamma$-ray spectroscopy of n-induced fission fragments

Selected highlight from the EXILL fission campaign:

- Prompt-delayed $\gamma$ coincidences across the isomer
- Lifetimes from $\text{LaBr}_3$ data (FATIMA campaign)
- New microscopic approach to particle-core couplings

G. Bocchi et al., PLB 760, 273–278 (2016)

→ New event-builder for cross-isomer coincidences
New microscopic approach to particle–core excitations around $^{132}$Sn

→ more and more fragmented wave functions with increasing angular momentum

Theoretical calculations: Hybrid Configuration Mixing (HCM) model

G. Bocchi et al., PLB 760, 273–278 (2016)
The new ILL instrument FIPPS (phase I)

✓ intense thermal neutron pencil beam
✓ stable, radioactive and actinide targets
✓ $\gamma$-ray detection:
  → high-resolution HPGe clovers
  → symmetry around target position
  → digital electronics, list-mode data
✓ ancillary detectors
The neutron beam

- thermal neutron guide (H22)
- n flux \([n/cm^2/s]\): \(7 \times 10^8\) prior collimation \(\rightarrow\) \(1 \times 10^8\) at target pos.
- external \(\gamma\)-ray background 5 to 10 times better than at PF1b (EXILL)
The HPGe detector system. FIPPS efficiency

✓ 8 HPGe clovers (4x50x80)
✓ target-to-clover distance = 9 cm
✓ FWHM @ 1.3 MeV ($^{60}$Co) ≈ 2 keV
✓ digital electronics (100 MHz, CAEN V1724) → high count-rate

Add-Back factor:
1.11 (2) @ 340 keV
1.27 (3) @ 1.4 MeV
1.55 (6) @ 6.8 MeV

FIPPS Absolute Efficiency (no AddBack)

$^{152}$Eu (norm. to $\gamma\gamma$) [3 kHz/crystal]
$^{48}$Ti(n,$\gamma$)$^{49}$Ti [7 kHz/crystal]

4 % @ 1.4 MeV
FIPPS performance: angular correlations

use individual crystals in order to increase the number of angular combinations

$^{115}\text{Sn}(n,\gamma)^{116}\text{Sn}$
gate on 1293 keV $\rightarrow$ 463 keV

$q_2 = 0.90(3)$
$q_4 = 0.825(12)$

$f(\theta) = 1 + a_2 q_2 P_2(\theta) + a_4 q_4 P_4(\theta)$
FIPPS first experimental campaign (Dec. 2016, Jan.-March 2017)

6 experiments, \( \approx 30 \) users, 11 universities and labs (EU, US, CAN)
\( \gamma \)-ray spectroscopy after \((n,\gamma)\) reactions on stable isotopes (15 targets):

- collectivity phenomena in atomic nuclei
- structure around magic nuclei
- nuclear methods (lifetimes)
$^{205}$Tl$(n,\gamma)^{206}$Tl: nuclear structure around $^{208}$Pb

We expect to populate the states with spins values from 0 to 3

Capture state at neutron binding energy

$^{205}$Tl

1/2+ 0

(0+,1+)

6.5 MeV

$^{206}$Tl

0


exp. 17-3-8, N. Cieplicka et al.
$^{205}\text{Tl}(n,\gamma)^{206}\text{Tl}$: nuclear structure around $^{208}\text{Pb}$

exp. 17-3-8, N. Cieplicka et al.
$^{205}$Tl(n,γ)$^{206}$Tl: nuclear structure around $^{208}$Pb

A preliminary comparison — good agreement with theoretical calculations.

Clear correspondence between theory and experiment including the group of 6 states around 1.4 MeV.

Shell-Model calculations with realistic Kuo-Herling interactions

exp. 17-3-8, N. Cieplicka et al.
$^{205}\text{Tl}(n, \gamma)^{206}\text{Tl}$: nuclear structure around $^{208}\text{Pb}$

$^{205}\text{Tl}(n, \gamma)^{206}\text{Tl}$ – angular correlations of $\gamma$ rays

Multipolarity of the 5854-keV $\gamma$ ray (theoretical values for different spin hypothesis):

- $E1$ $0+ \rightarrow 1-$ $\Rightarrow A2 = 0.5$, $A4 = 0.0$
- $E1$ $1+ \rightarrow 1-$ $\Rightarrow A2 = -0.25$, $A4 = 0.0$

exp. 17-3-8, N. Cieplicka et al.
Gamma-ray Induced Doppler Shift Attenuation Method: Test Experiment

- from 29/01/2017 to 06/02/2017 on FIPPS

**PRINCIPLE:**

In a two-step cascade, the emission of a primary gamma-ray is inducing a recoil of several hundreds of eV on the emitting nucleus. The energy of a sufficiently fast emitted second gamma ray will be Doppler shifted.

- Comparison measured Doppler shifts to those calculated from simulations of the atomic slow down process yields information on the lifetimes of the nuclear levels.

**TARGETS used:**

- NaCl (\(^{36}\)Cl), Ti\(_2\)O\(_3\) (\(^{49}\)Ti), Ti metallic (\(^{49}\)Ti), NiF\(_2\) (\(^{59}\)Ni), Ni metallic (\(^{59}\)Ni)

Data from \(^{36}\)Cl associated to states with different lifetimes

Short lifetime → Long Lifetime

exp. 17-3-7, F.C.L. Crespi, M. Jentschel et al.
Strong similarity in structure of Cd and Te nuclei – properties of $0^2_+^+$ states in Te match intruder $0^+_1$ states in Cd

Population in % relative to gs in ($^3\text{He},n$) reactions

$0^+_1$ states identified as intruder band heads

exp. 17-3-3, P. Garret et al.
Requirement: seek missing low-energy transitions amongst states to aid in identifying intruder band – use the $^{123}$Te(n,$\gamma$) reaction

Exp. 17-3-3, P. Garret et al.
FIPPS: short-term plans

- Last proposal round: 14 proposals, 300 days (cf. 90 days to be scheduled in 2018)
- Jan.-May 2018:
  \((n,\gamma)\) on (rare) stable targets, test of \((n,fission)\) on \(^{233,235}U\) with active targets

Possibilities:

- installation of additional Ge detectors (up to 16 clovers) + anti-Compton shields
- progressive installation of ancillary methods (LaBr\(_3\), magnetic moment measurements, X-ray detectors...)
- \((n,fission)\) with \(^{233}U,\,^{235}U,\,^{239}Pu,\,^{241}Pu\) etc. targets
- test and use of fission tags (active targets, diamond detectors, ...)
- gaseous targets, radioactive targets and actinides (with fission veto)
✓ tight polycarbonate casemate (handling of radioactive targets)

✓ new C-fiber reaction chamber (future installation of low-energy X-ray dets)

✓ holding structure for LaBr₃ dets and additional HPGe clovers (up to 16)
FIPPS: longer-term plans

Study the structure of n-rich nuclei and fission mechanism

HPGe clovers + Gas-Filled-Magnet (GFM) for fission fragment selection

FIPPS phase II project submitted for *Endurance II*

\[ \Delta A/A = 2.2\% \]

acceptance:
0.4\% extracted beam;
full reconstruction of ion tracks using a low-pressure TPC
\[ \rightarrow 3.5\% \]

\[ \Delta A/A = 2.2\% \]

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A. Chebboubi PhD Thesis
G. Kessedjian et al.
FIPPS phase II: Ge array + GFM, proposed setup

HPGe clovers + Gas-Filled-Magnet (GFM) setup for fission fragment identification

Entrance/Exit positions + tracking => fragment mass
Gamma rays of the complementary fragment => Z
Possibility to add detectors at the focal plane
Time-of-Flight + Energy in IC => fragment kinetic energy
Concluding remarks

- Nuclear studies after slow-neutron induced reactions @ ILL: in-pile targets (Lohengrin, GAMS) vs “pencil-like” neutron beam (EXILL campaign, FIPPS) → structure of nuclei close to stability and n-rich nuclei produced in fission
- FIPPS is the new Nuclear Physics instrument of ILL for prompt gamma-ray spectroscopy after slow-neutron induced reactions → complementarity with the existing Lohengrin and GAMS instruments
- Promising results are coming from the first experimental campaign ((n,γ) on stable targets -^{206}\text{Ti},^{124}\text{Te})
- Rich experimental program for coming years ((n,γ) on radioactive targets, fission, ancillary devices, GFM... it depends strongly on your input!)

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