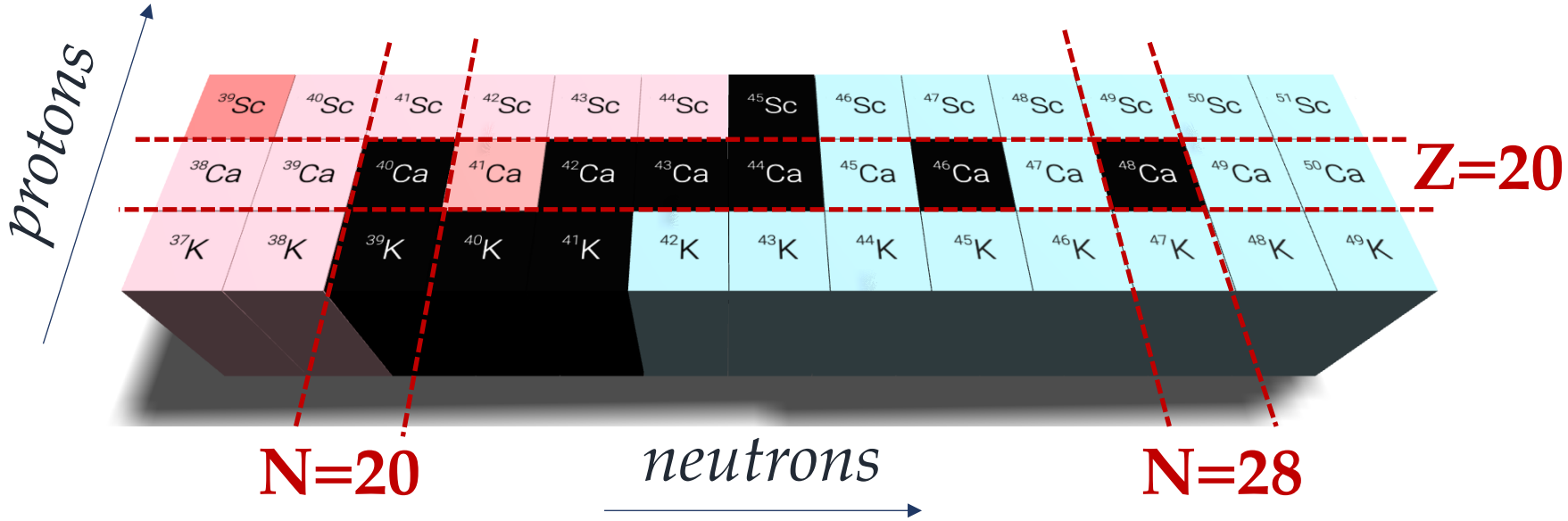
Structure of Ca isotopes between doubly closed shells

Simone Bottoni
Università degli Studi di Milano and INFN

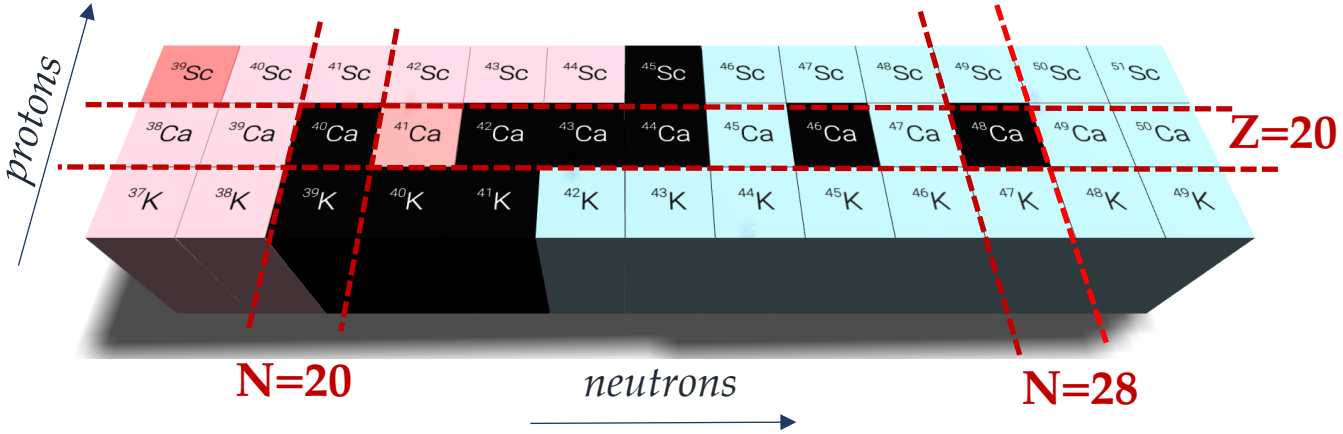
Collaboration

S. Leoni, S. Bottoni, G. Bocchi, G. Benzoni, A. Bracco, F. Camera, G. Colombi, F.C.L. Crespi, L. Iskra, B. Million, C. Porzio, S. Ziliani
G. Colò, P.F. Bortignon
Università degli Studi di Milano and INFN, Milano, Italy
B. Fornal, N. Cieplicka-Orynczak et al.
Institute of Nuclear Physics, PAN, Krakow, Poland
C. Michelagnoli, U. Köster, F. Kandzia, Y-H. Kim, M. Jentschel, P. Mutti, T. Reygadas, T. Soldner et al.
Institut Laue-Langevin, Grenoble, France
N. Marginean, C. Mihai, C. Costache, R.E. Mihai, S. Pascu, L. Stan, A. Turturica et al.
Horia Hulubei National Institute, Bucharest, Romania
M. Sferrazza
Univeristé Libre de Bruxelles, Bruxelles, Belgium
J-M. Regis, J. Jolie, L. Knafla et al.
Institut für Kernphysik, Univsersität zu Köln, Köln, Germany
G. de France et al.
GANIL, Caen, France
C. Ur
ELI-NP, Bucharest, Romania
W. Urban et al.
University of Warsaw, Warsaw, Poland
D. Bazzacco, D. Mengoni et al.
Università degli Studi di Padova, Padova Italy
A. Türler et al.
Univeristät Bern and PSI, Villigen, Switzerland
Y. Niu
Lanzhou University, Lanzhou, China

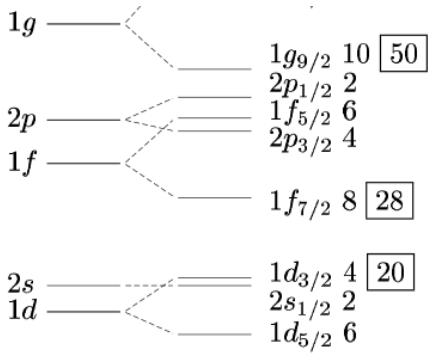
Introduction



Ca isotopes: coexistence of complex structures

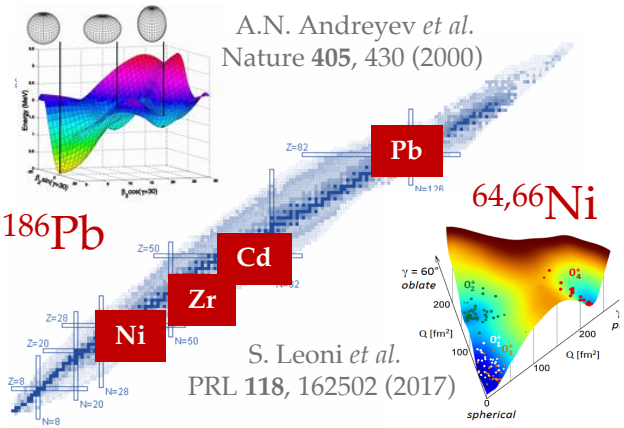


Active π-ν shells



Evolution of complex excitations from symmetric to neutron-rich nuclei

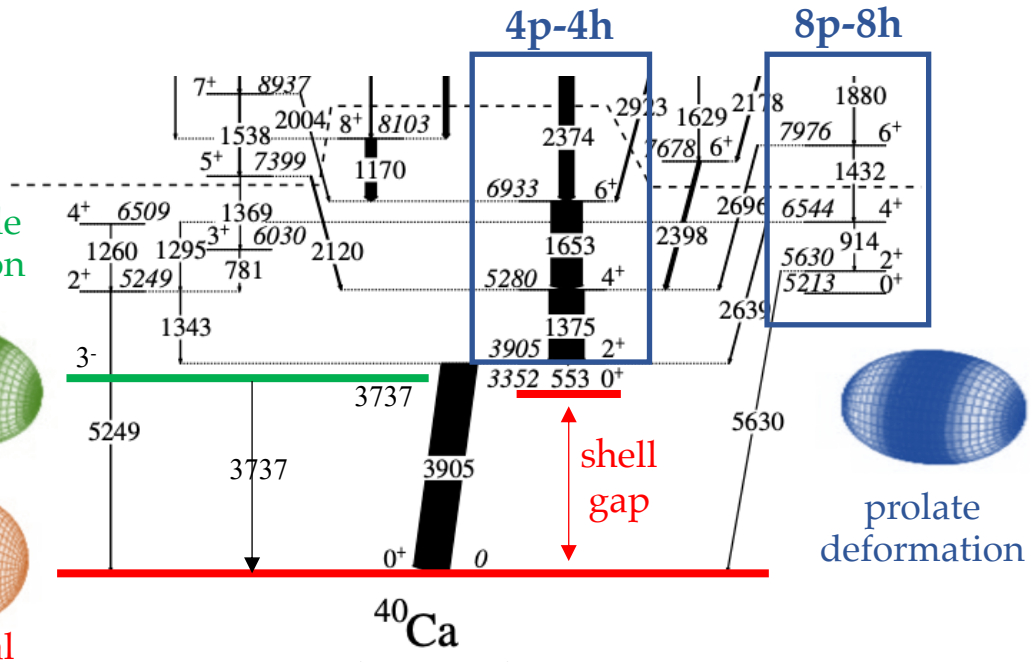
Shape coexistence across the nuclide chart



A.N. Andreyev *et al.*
Nature **405**, 430 (2000)

S. Leoni *et al.*
PRL **118**, 162502 (2017)

N. Marginean *et al.*
PRL **125**, 102502 (2020)



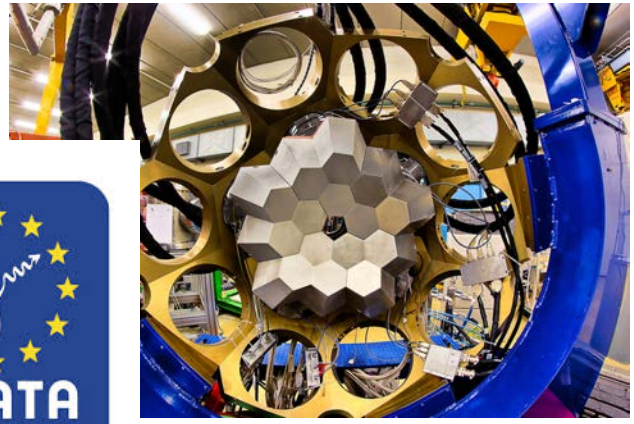
E. Ideguchi *et al.* Phys. Rev. Lett **87**, 222501 (2001)

Ca isotopes: coexistence of complex structures

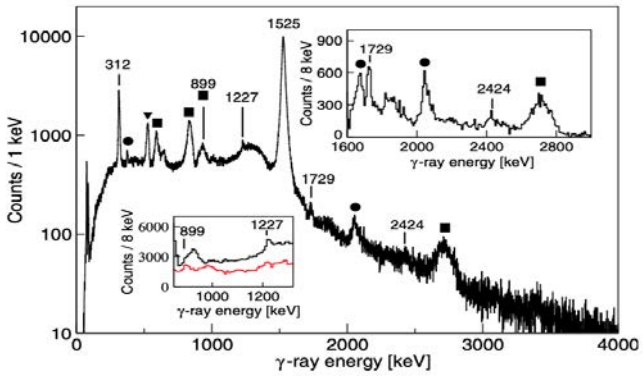
SUPERDEFORMED AND TRIAXIAL STATES IN ^{42}Ca

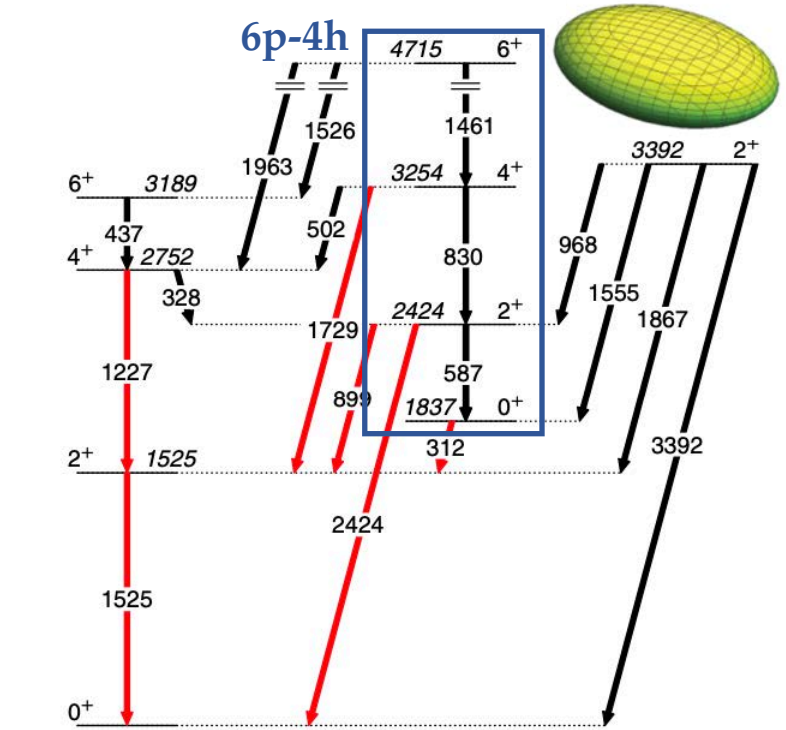
COULOMB EXCITATION @ LNL

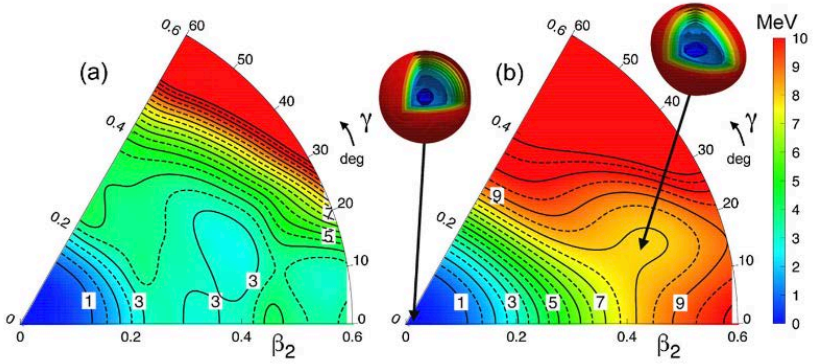
^{42}Ca+^{208}Pb / ^{197}Au



AGATA-DANTE setup







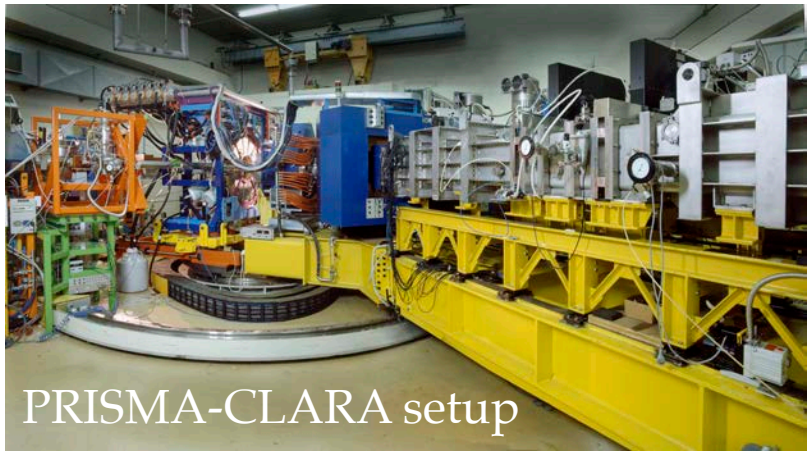
K. Hadyńska *et al.* Phys. Rev. Lett. **117,** 062501 (2016)

Ca isotopes: coexistence of complex structures

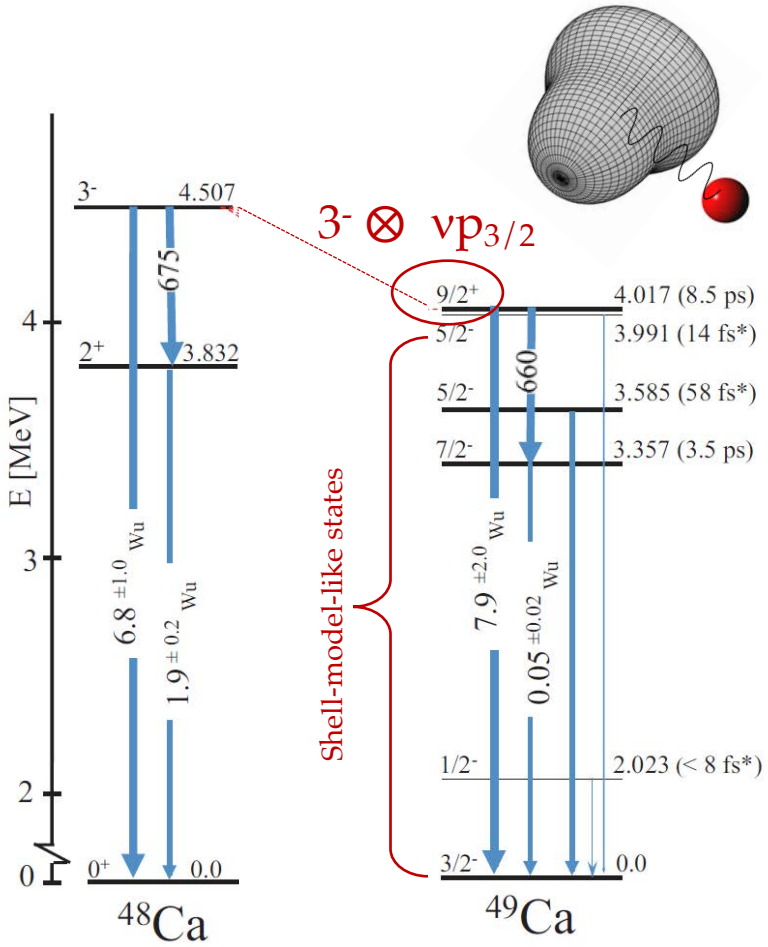
PARTICLE-VIBRATION COUPLING IN ^{49}Ca

MULTINUCLEON TRANSFER @ LNL

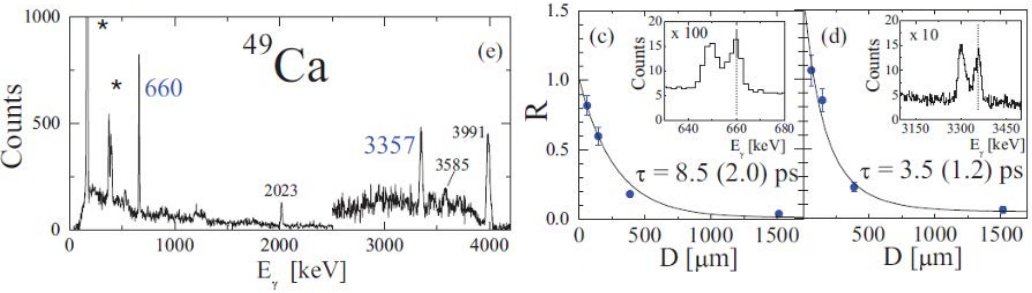
^{48}Ca+^{64}Ni / ^{208}Pb



^{49}Ca = ^{48}Ca + 1ν



γ-ray spectroscopy and lifetime measurements

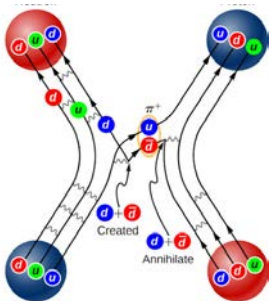


D. Montanari, S. Leoni, D. Mengoni *et al.* Phys. Lett B **697**, 288 (2011)

Ca isotopes: benchmark for different theories

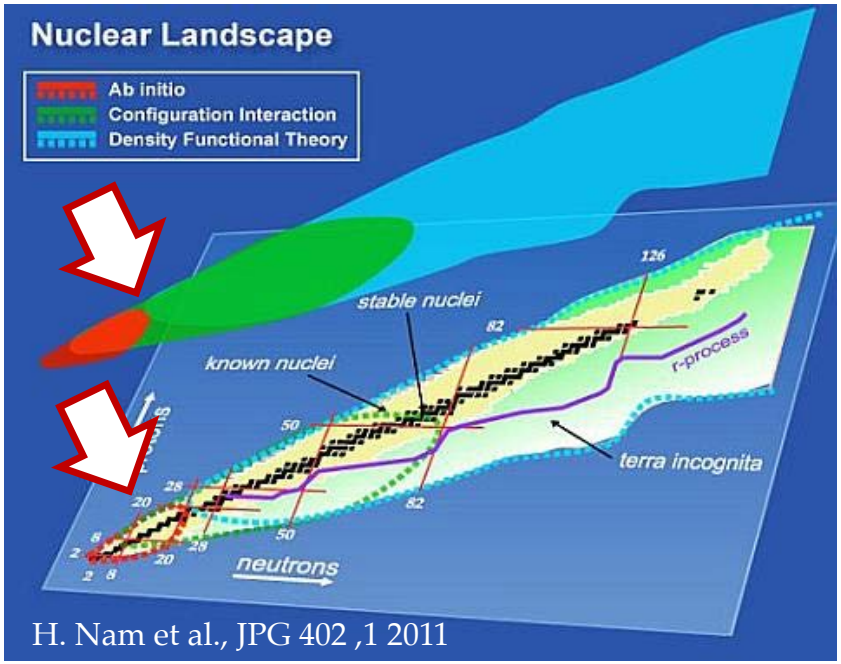
NEED OF AN UNIFIED DESCRIPTION OF NUCLEAR STRUCTURE

AB INITIO METHODS



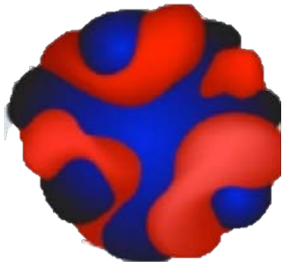
N-N interaction derived from first principles (QCD)

J. D. Holt, J. Menendez, J. Simonis, and A. Schwenk, Phys. Rev. C **90**, 024312 (2014)



H. Nam et al., JPG 402 ,1 2011

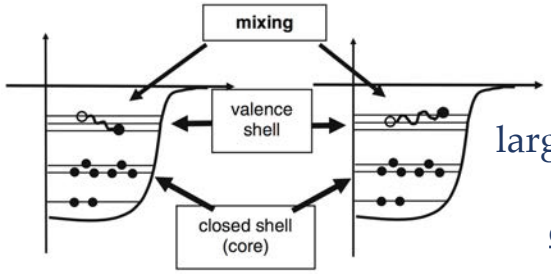
DENSITY FUNCTIONAL THEORY



Energy Density Functionals based on effective interactions (Skyrme, Gogny, …)

M. Bender, P.-H. Heenen, P.-G. Reinhard Rev. Mod. Phys. 75, 121 (2003)

SHELL MODEL CALCULATIONS



Effective and realistic interactions in large configuration spaces ($\geq 10^{10}$)

computational challenging

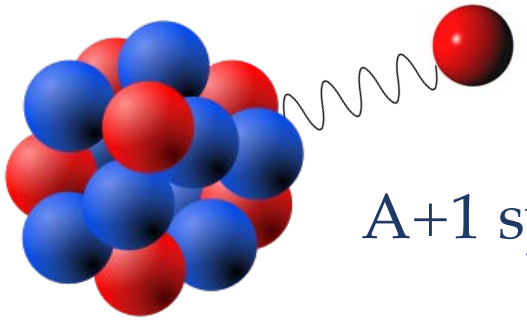
Y. Utsuno, T. Otsuka, B. A. Brown, M. Honma, T. Mizusaki, and N. Shimizu, Progr. Theor. Phys. Suppl. **196**, 304 (2012)

THE HYBRID CONFIGURATION MIXING MODEL (HCM)

Microscopic model for odd-mass nuclei

G. Colò *et al.*, Phys. Rev. C. **95**, 034303 (2017)

S. Bottoni et al., to be published



single particle

A+1 system

doubly-magic core

SKYRME HAMILTONIAN

$$H = H_0 + V,$$

$$H_0 = \sum_{jm} \varepsilon_j a^\dagger_{jm} a_{jm} + \sum_{NJM} \hbar\omega_{NJ} \Gamma^\dagger_{NJM} \Gamma_{NJM},$$

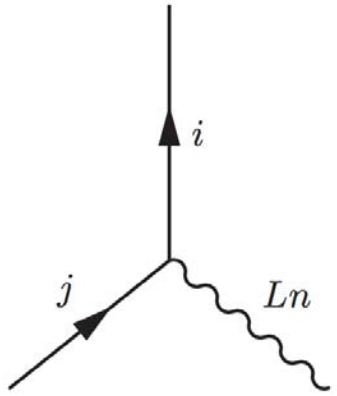
$$V = \sum_{jmj'm'} \sum_{NJM} h(jm; j'm', NJM) a_{jm} \left[a^\dagger_{j'} \otimes \Gamma^\dagger_{NJ} \right]_{jm}$$

BASIS

Single-particle/hole states (Hartree-Fock)

Collective phonons and
non collective 1p-1h excitations
(Random Phase Approximation)

COUPLING VERTEX



G. Colò, H. Sagawa and P.F. Bortignon
Phys. Rev. C **82**, 054307 (2010)

The experimental campaign at Institut Laue-Langevin

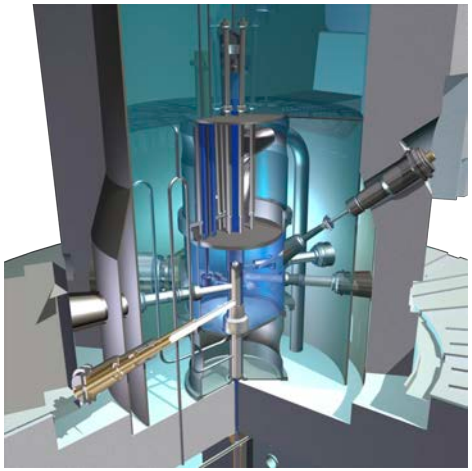
Grenoble (France)

www.ill.eu

See also: C. Porzio and Ł. Iskra talks

The Institut Laue-Langevin (ILL)

HIGH FLUX REACTOR

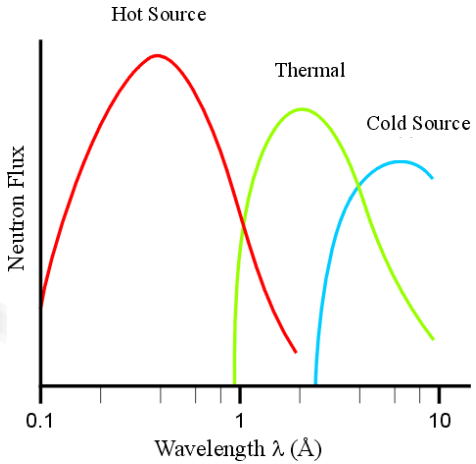


$1.5 \cdot 10^{15}$ neutrons / s / cm^2
(continuous beams)

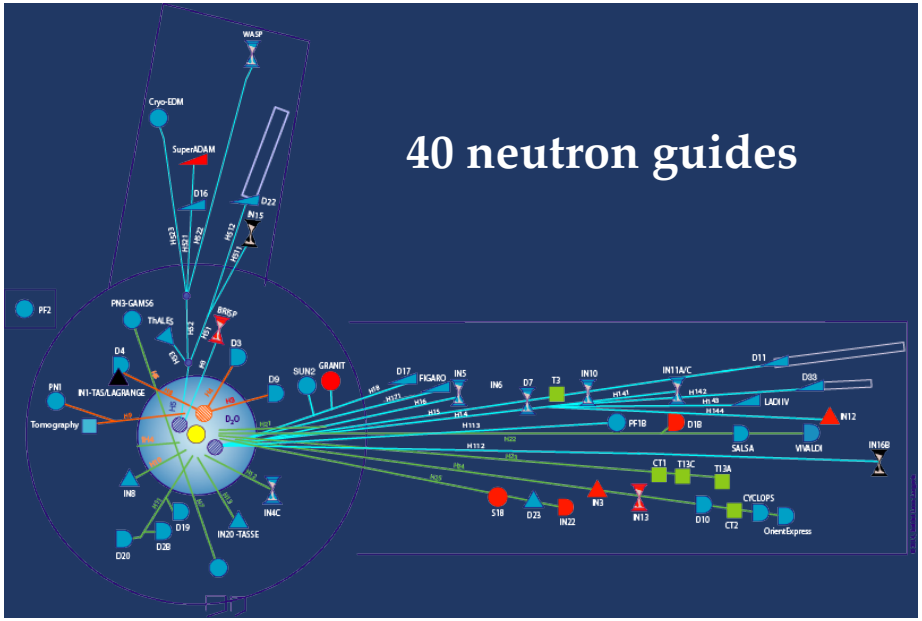
Thermal Power
58.3 MW

50-day cycles

NEUTRONS AT ILL



EXPERIMENTS AT ILL



FUNDAMENTAL SCIENCE:

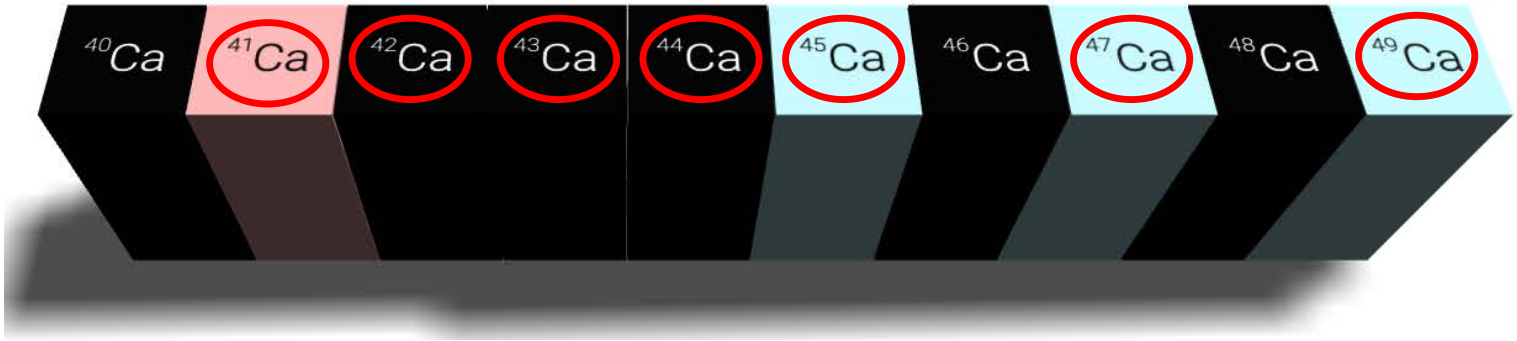
Condensed matter physics

Material Science

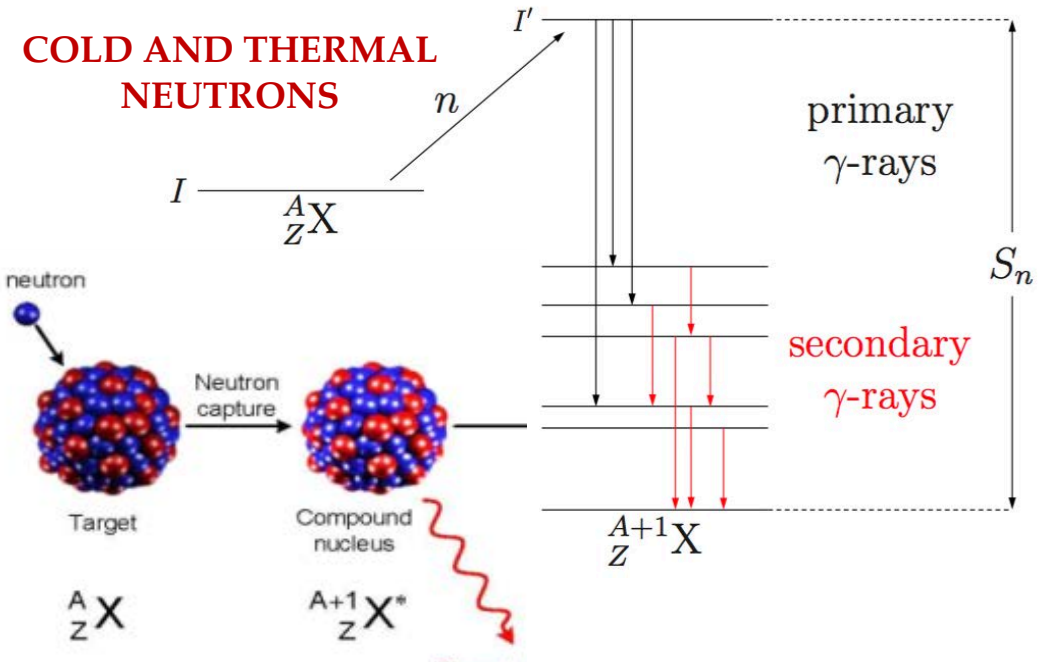
Chemistry and Biology

Nuclear and Particle physics

NEUTRON-CAPTURE REACTIONS



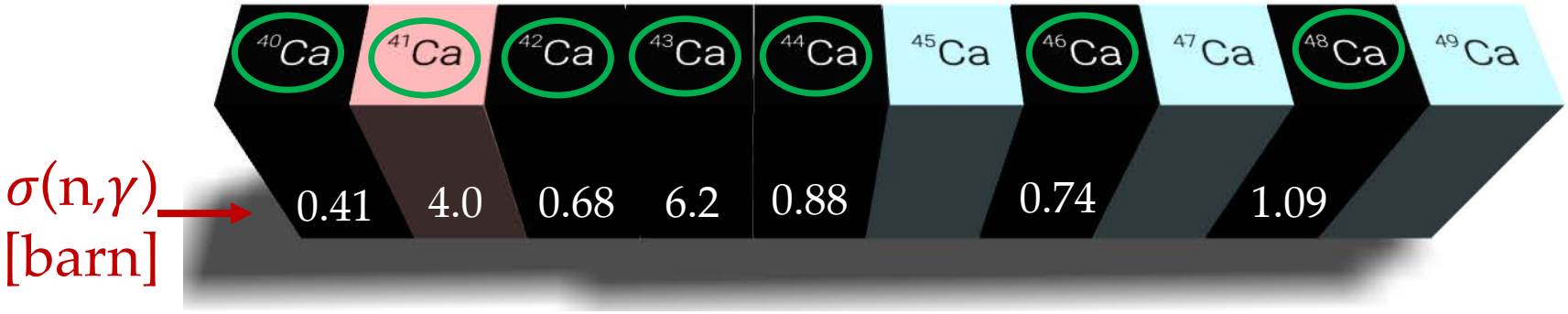
COLD AND THERMAL NEUTRONS



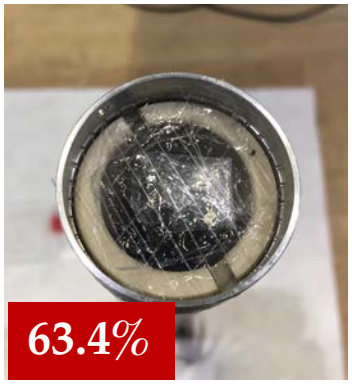
Complete low-spin γ-ray spectroscopy from the capture state to the ground state

Complementary to higher-spin spectroscopy with stable and radioactive beams (e.g. AGATA experiments)

RARE AND RADIOACTIVE TARGETS



^{41}Ca



$CaCO_3$

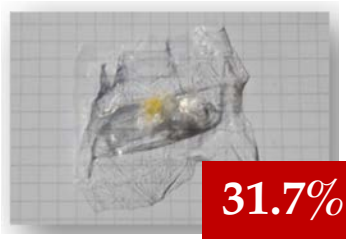
A ~ 2 MBq

m ~ 600 μg

$t_{1/2} \sim 10^5$y

made in 1975

^{46}Ca



$Ca(NO_3)_2$
(40.6 mg)

Abundance
0.004%

made at PSI by A. Türler

^{48}Ca

60.5%

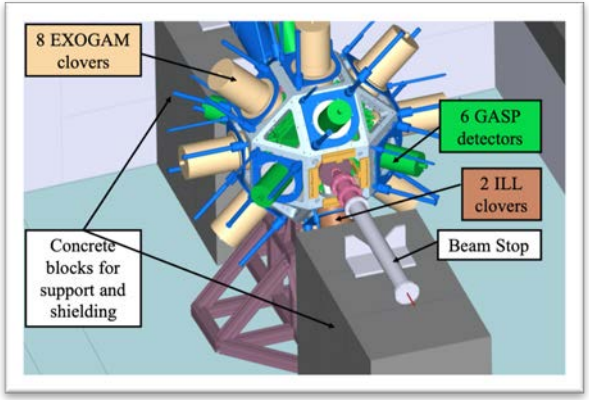
$CaCO_3$
(350 mg)

Abundance
0.187%

made in 1979

Experimental program at ILL

THE **EXILL** CAMPAIGN (2012-2013)

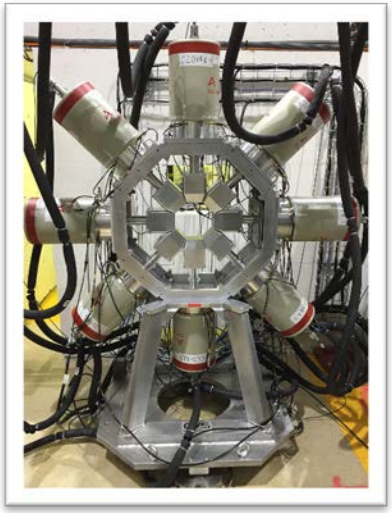


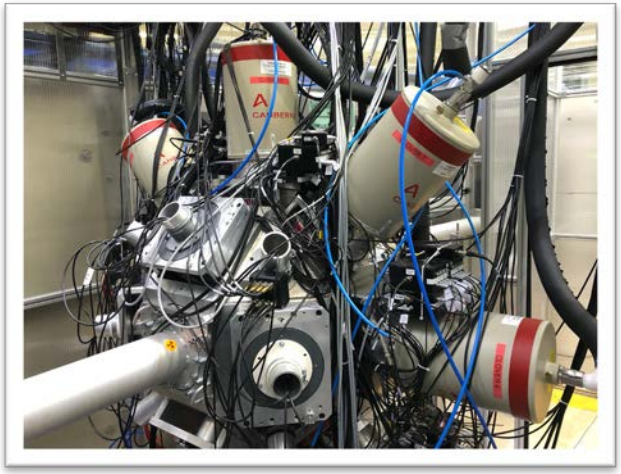
First campaign with a large γ array and a neutron beam (cold neutrons)

HPGe detectors

LaBr:Ce scintillators

THE **FIPPS** PERMANENT SETUP (SINCE 2016)





thermal neutrons

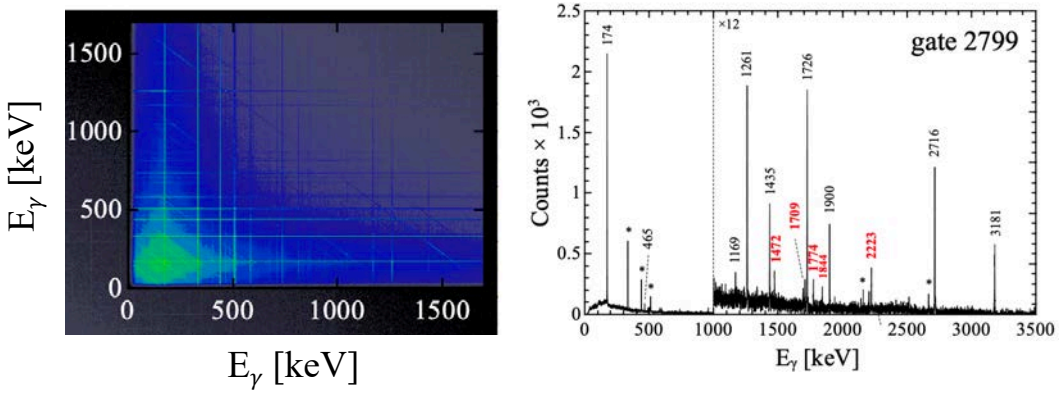
HPGe clover detectors + AC shields

Clover detectors from IFIN-HH (Bucharest)

LaBr:Ce scintillators

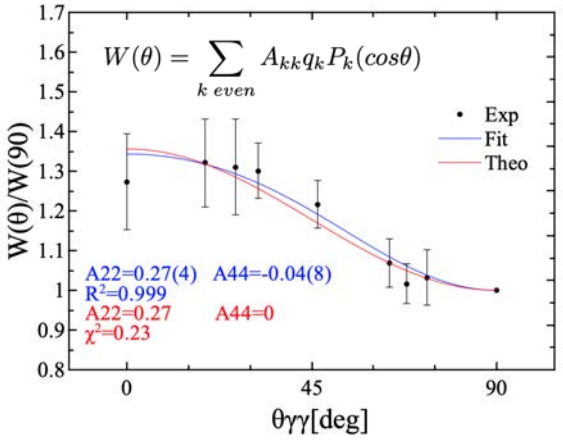
EXPERIMENTAL TECHNIQUES

High-resolution γ-ray spectroscopy



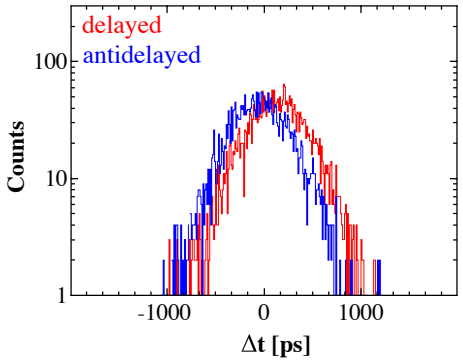
γ- γ coincidences
Prompt-Delay correlations
Level and decay schemes
γ-ray intensities

Angular correlations



γ-ray multipolarities
Spin assignments

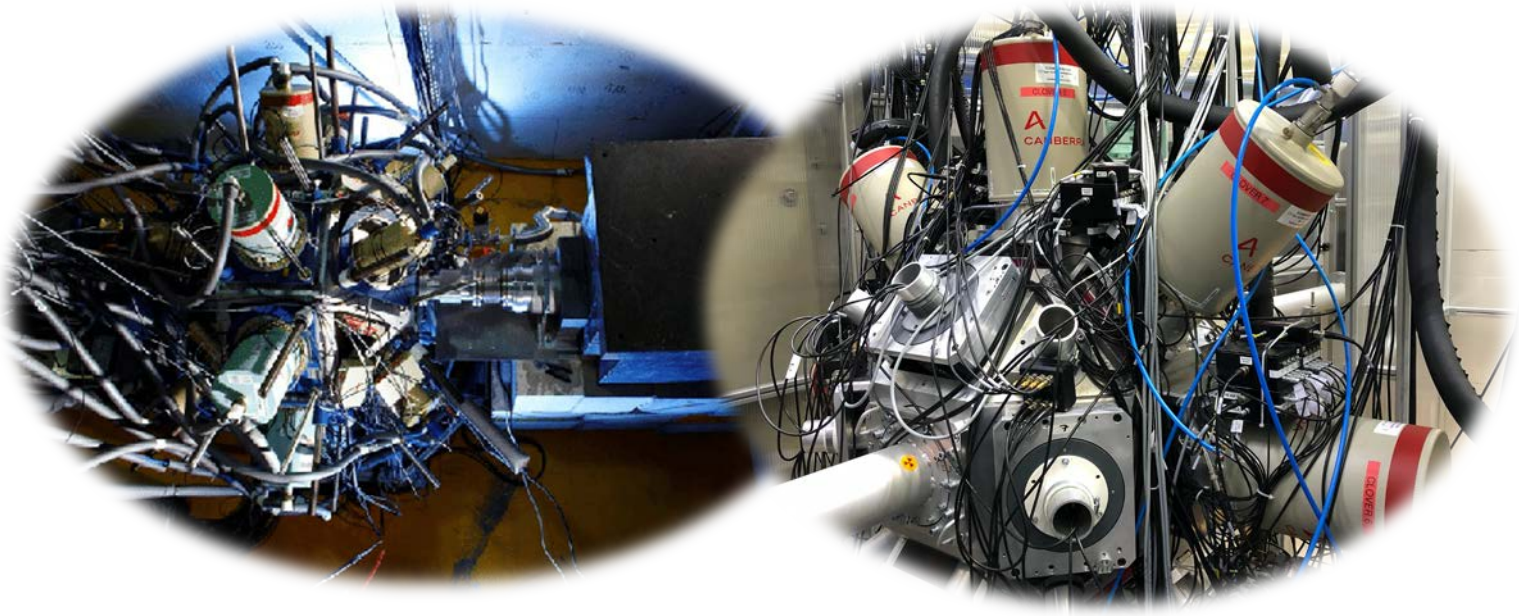
Lifetime measurements



LaBr:Ce detectors
Fast-timing techniques
Piscosecond range

Information on state wave function

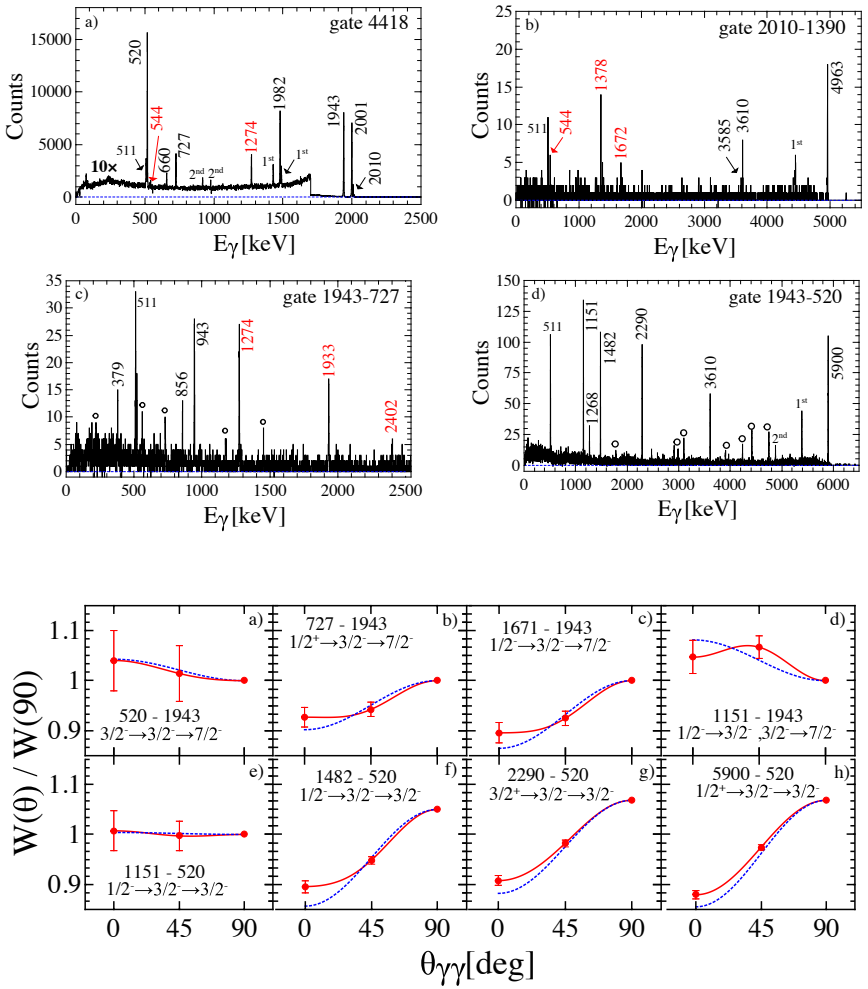
Recent results

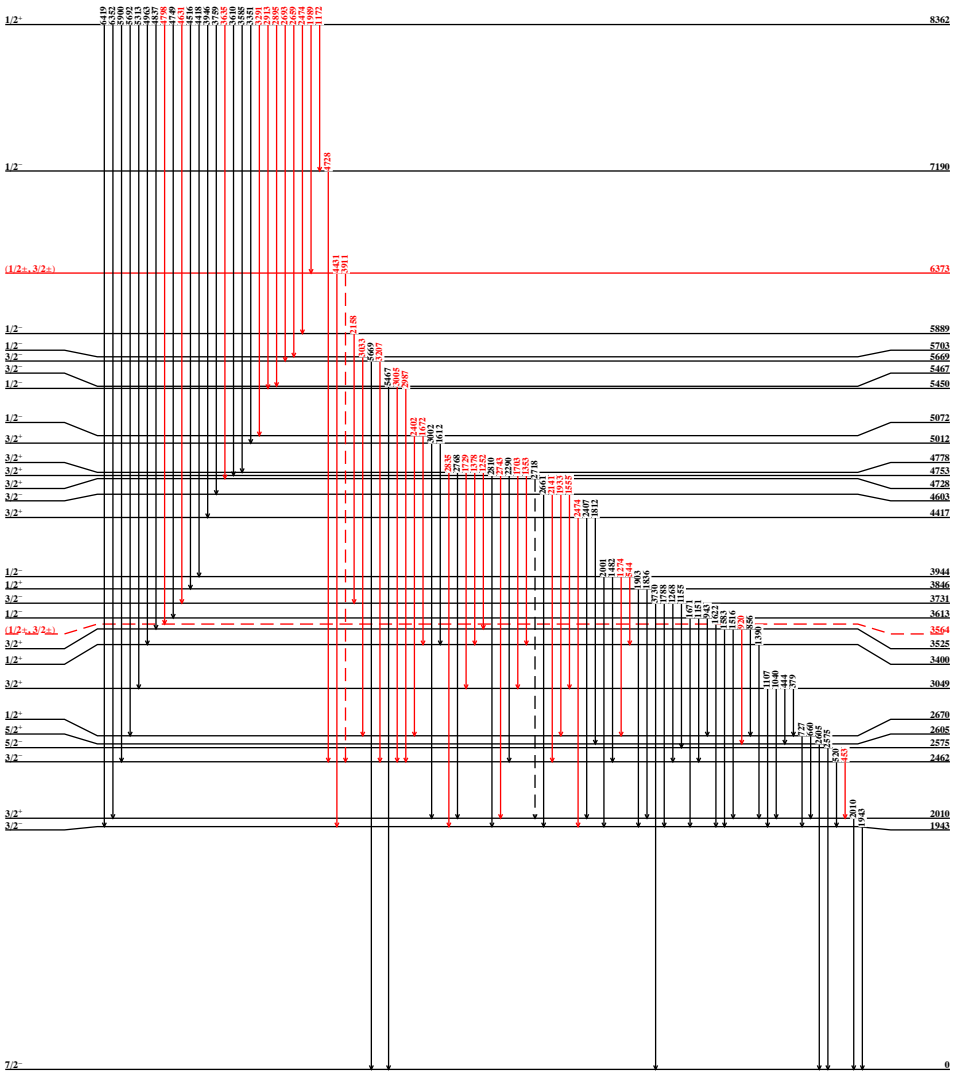


EXILL
(2012-2013)

FIPPS
(SINCE 2016)

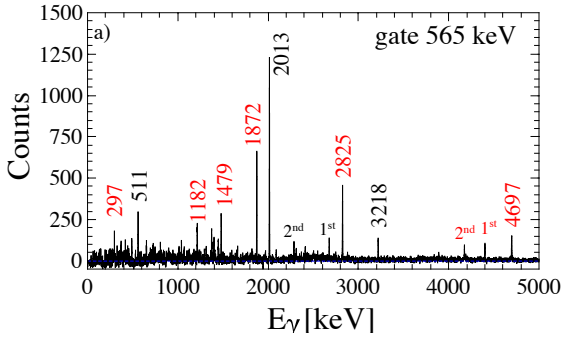
^{41}Ca

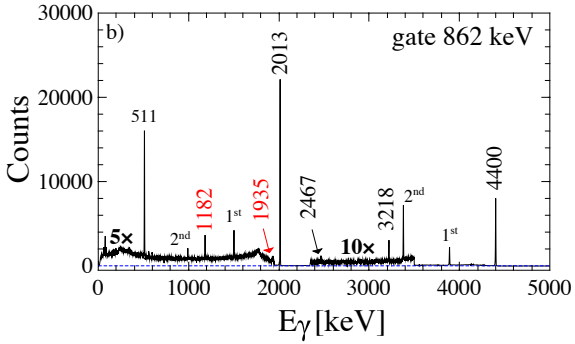

a)
gate 4418
520
544
660
727
1274
1982
1943
2001
2010
511
10×
Counts
Eγ[keV]
b)
gate 2010-1390
1378
1672
3585
3610
4963
511
544
1st
c)
gate 1943-727
379
856
943
1274
1933
2402
511
d)
gate 1943-520
1151
1268
1482
2290
3610
5900
511
2nd
1.1
1
0.9
W(θ) / W(90)
520 - 1943
3/2⁻→3/2⁻→7/2⁻
727 - 1943
1/2⁺→3/2⁻→7/2⁻
1671 - 1943
1/2⁻→3/2⁻→7/2⁻
1151 - 1943
1/2⁻→3/2⁻ ,3/2⁻→7/2⁻
1151 - 520
1/2⁻→3/2⁻→3/2⁻
1482 - 520
1/2⁻→3/2⁻→3/2⁻
2290 - 520
3/2⁺→3/2⁻→3/2⁻
5900 - 520
1/2⁺→3/2⁻→3/2⁻
0
45
90
θγγ[deg]

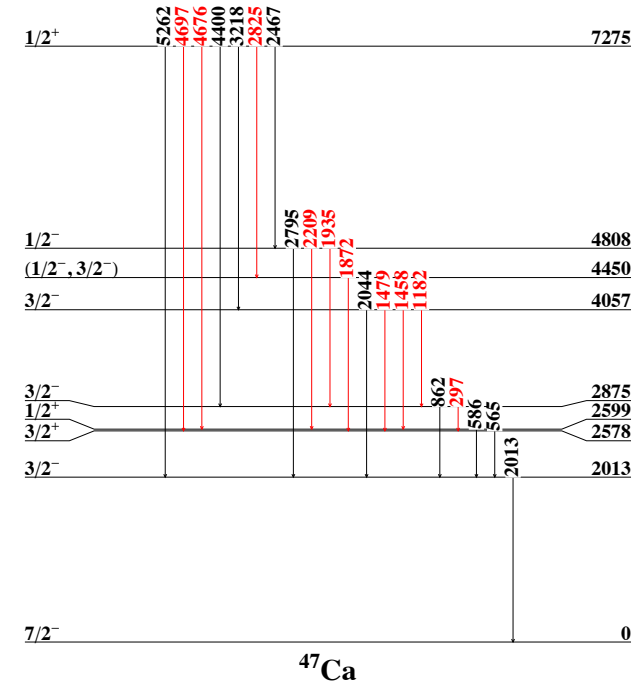

1/2⁺
8362
1/2⁻
7190
(1/2±,3/2±)
6373
1/2⁻
5889
1/2⁻
5703
3/2⁻
5669
3/2⁻
5467
1/2⁻
5450
1/2⁻
5072
3/2⁺
5012
3/2⁻
4778
3/2⁻
4753
3/2⁻
4728
3/2⁻
4603
3/2⁺
4417
1/2⁻
3944
1/2⁺
3846
3/2⁻
3731
1/2⁻
3613
(1/2±,3/2±)
3564
3/2⁻
3525
1/2⁻
3400
3/2⁺
3049
1/2⁻
2670
5/2⁻
2605
5/2⁻
2575
3/2⁻
2462
3/2⁻
2010
3/2⁻
1943
7/2⁻
0

^{41}Ca

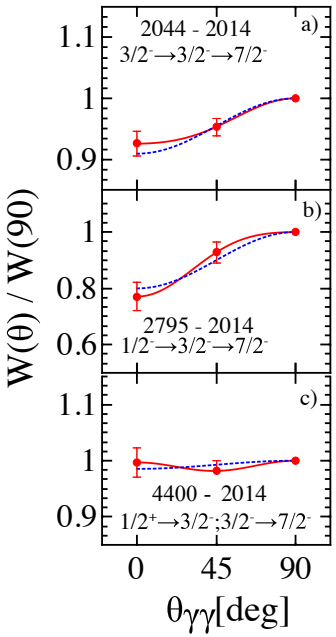
^{47}Ca



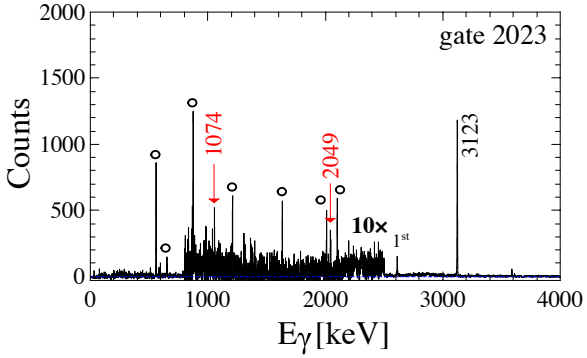


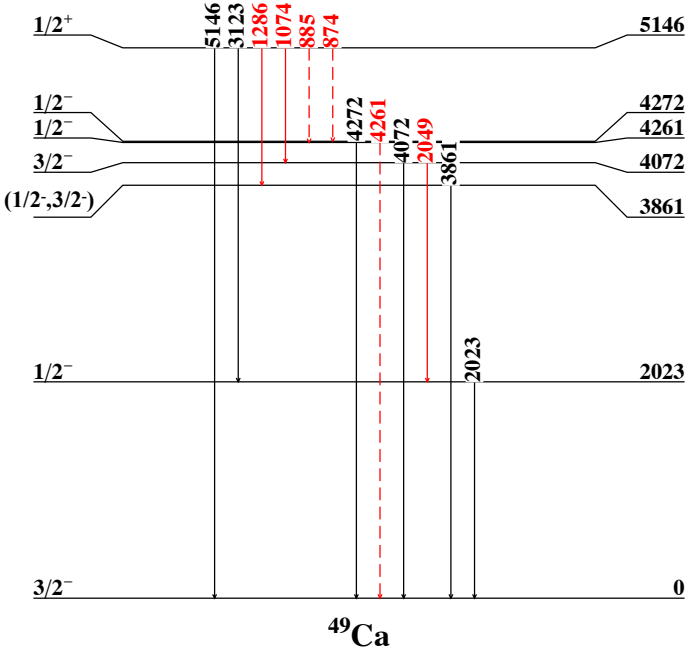


^{47}Ca



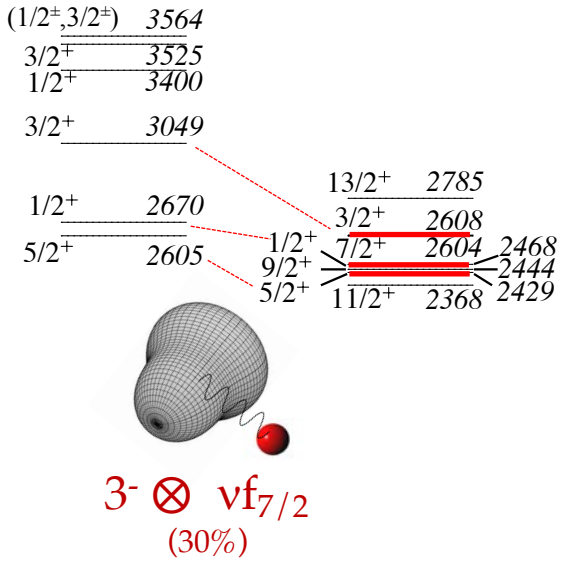
^{49}Ca

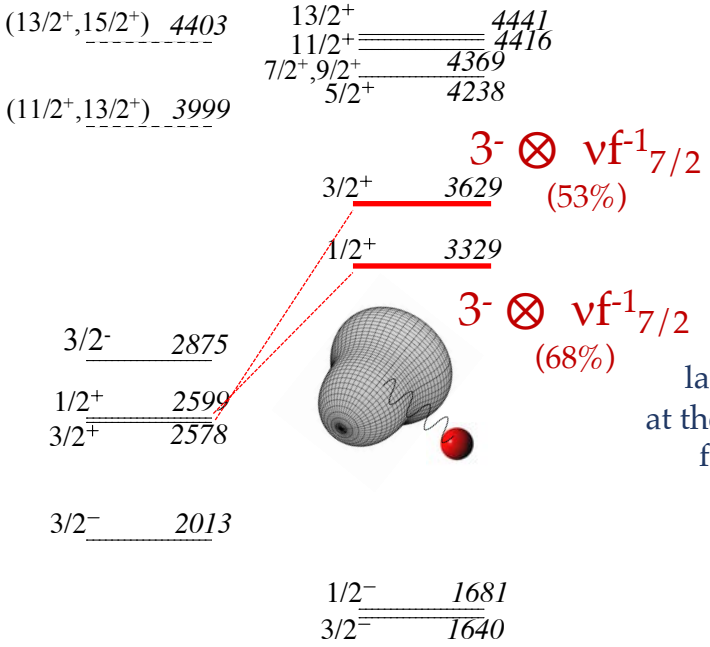


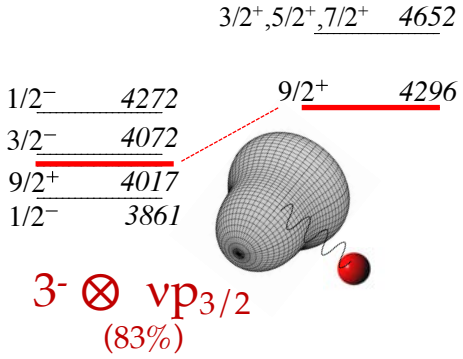


^{49}Ca

Comparison with HCM model







agreement with Utsuno's large-scale shell-model calculations at the limit of computational capabilities for collective octupole excitations

1/2− 2023

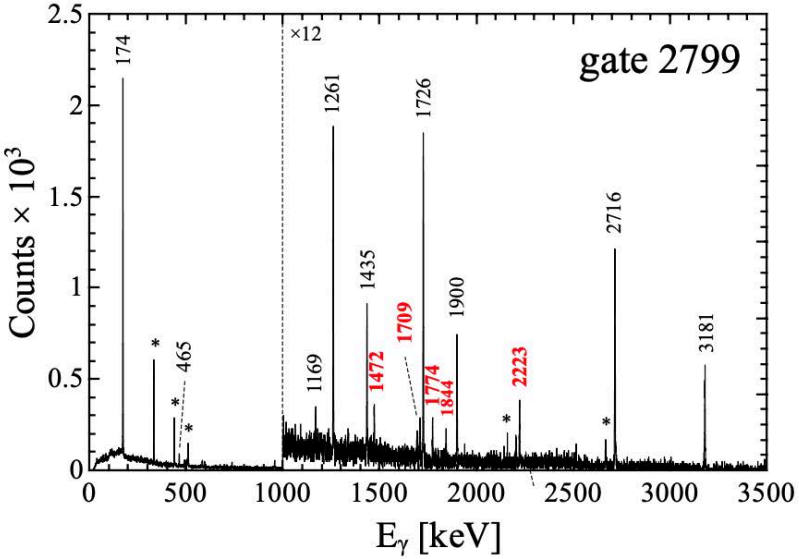
1/2− 1835

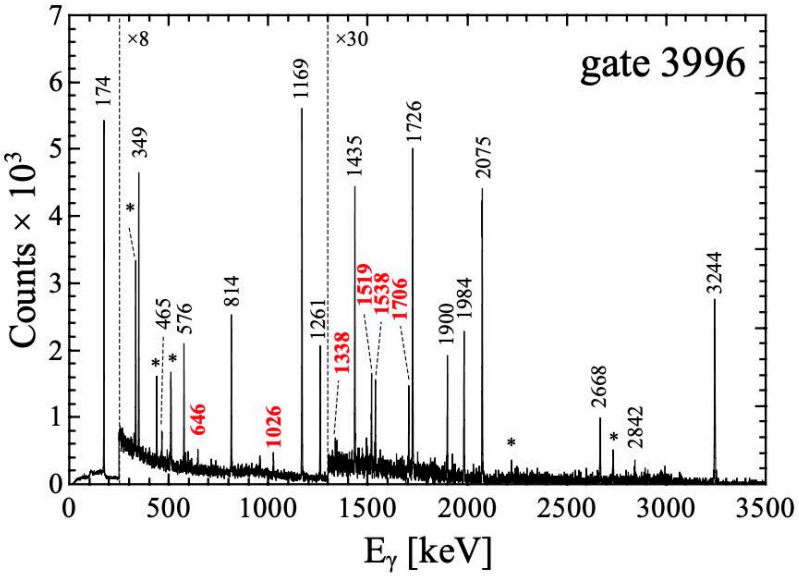
7/2− 0 7/2− 0
EXP HCM
^{41}Ca

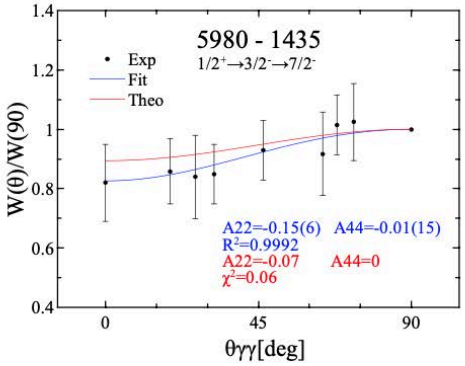
7/2− 0 7/2− 0
EXP HCM
^{47}Ca

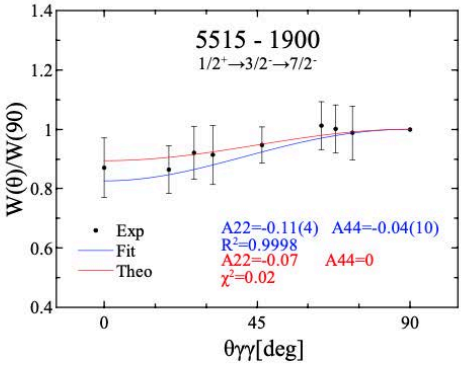
3/2− 0 3/2− 0
EXP HCM
^{49}Ca

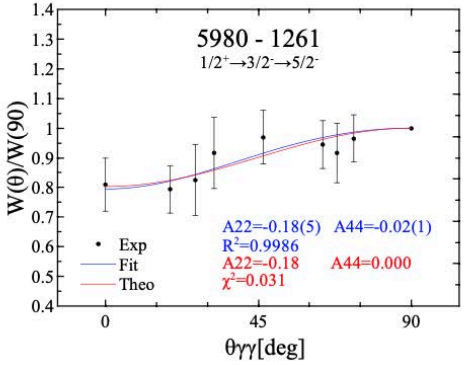
$^{44}Ca(n,\gamma)^{45}Ca$ - FIPPS

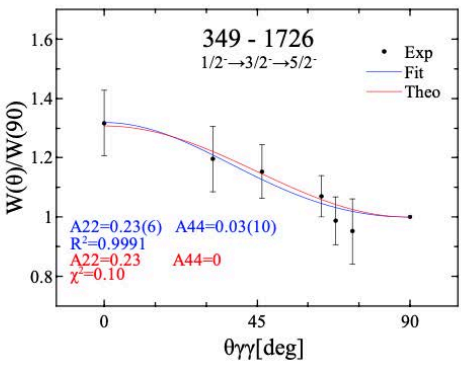


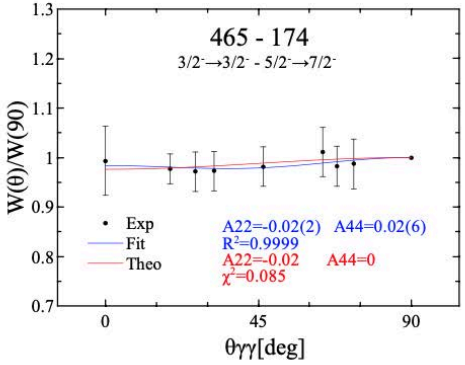


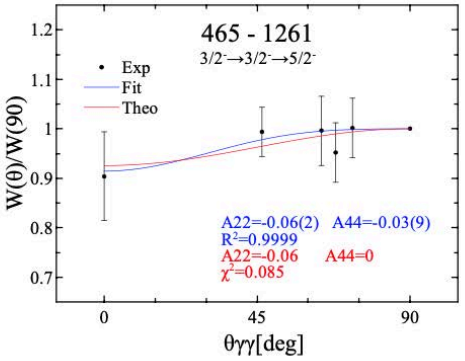




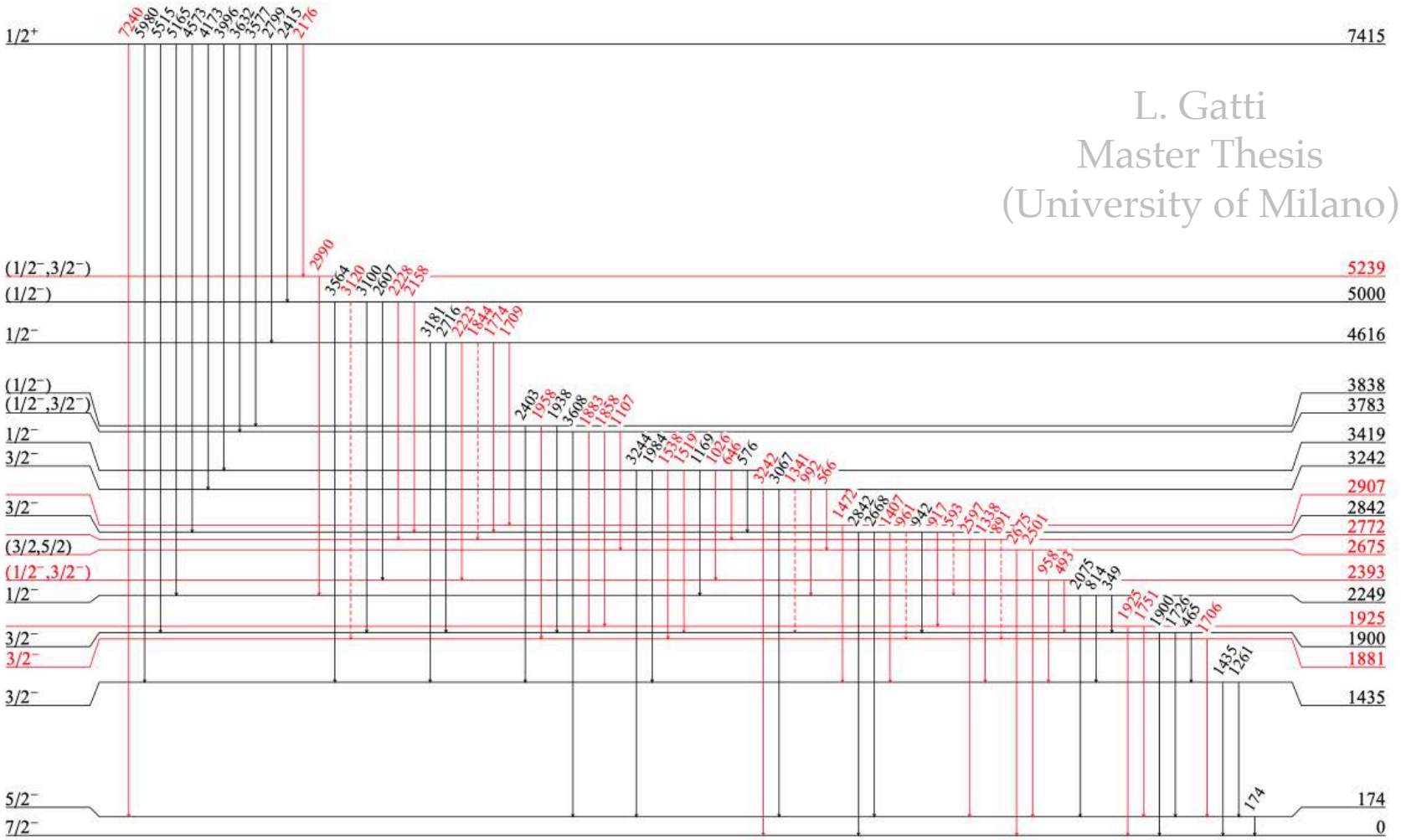






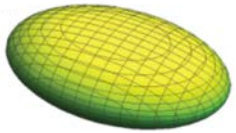


OPEN SHELL NUCLEUS – SUPERFLUID PROPERTIES



^{45}Ca

ONGOING EXPERIMENT (31/08/2020 – 21/09/2020)



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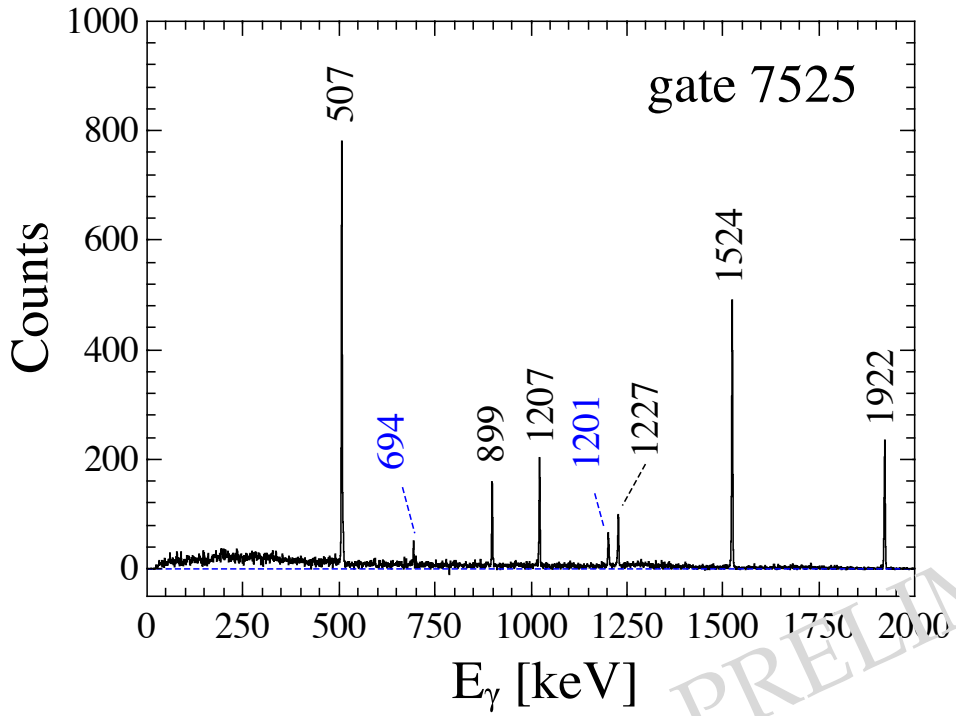
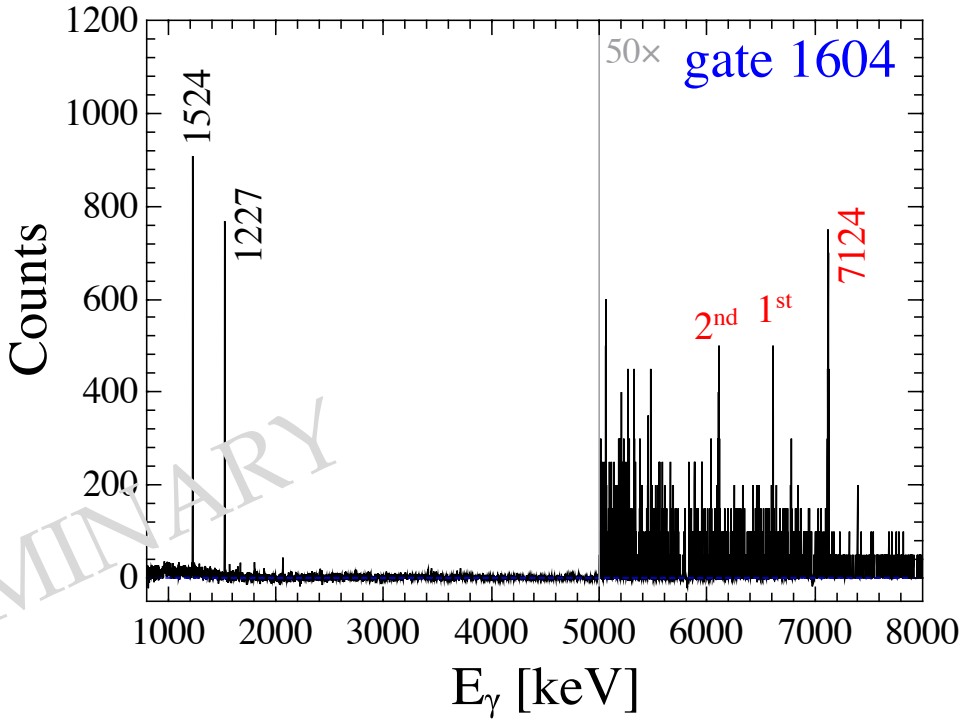
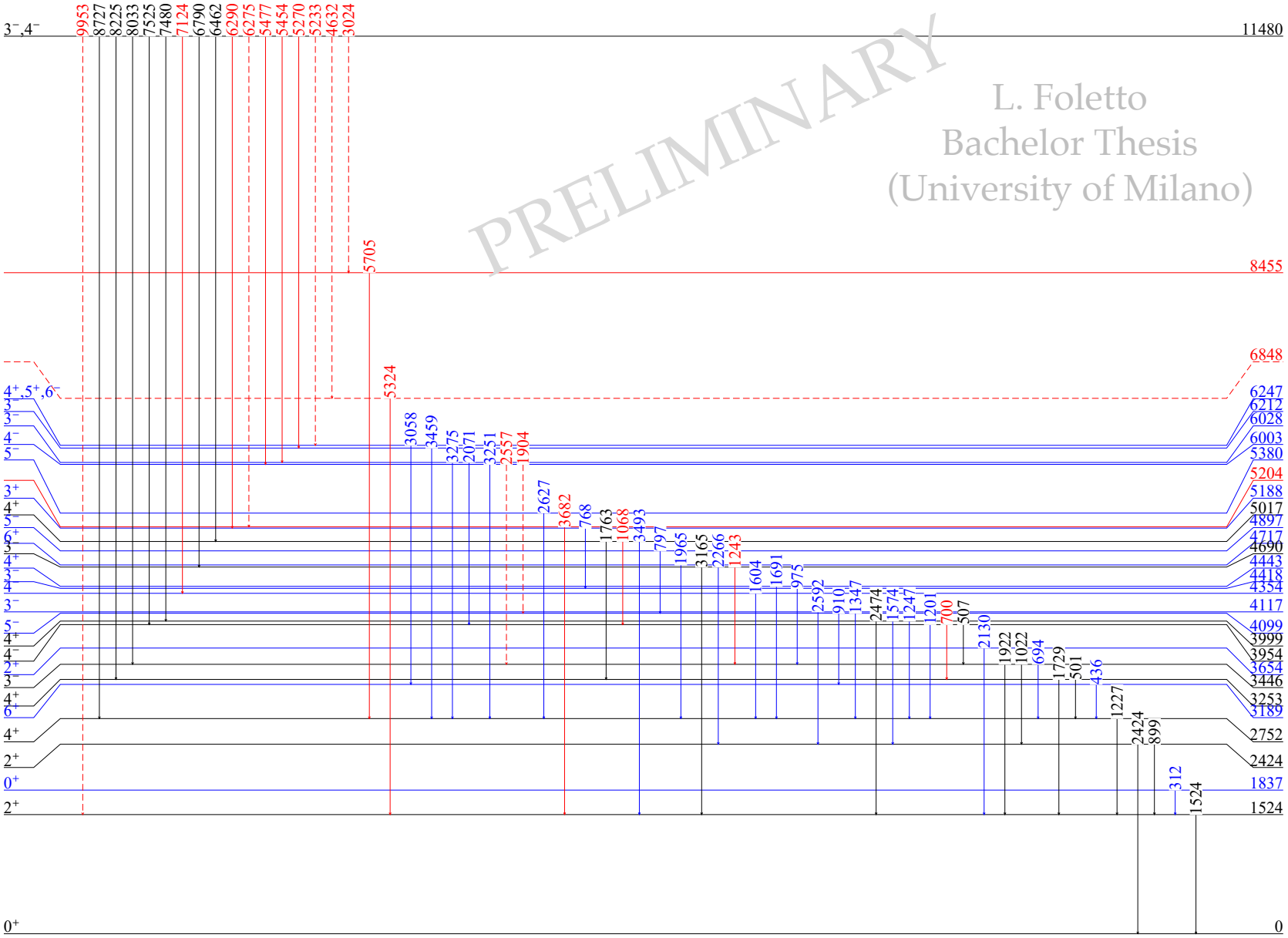
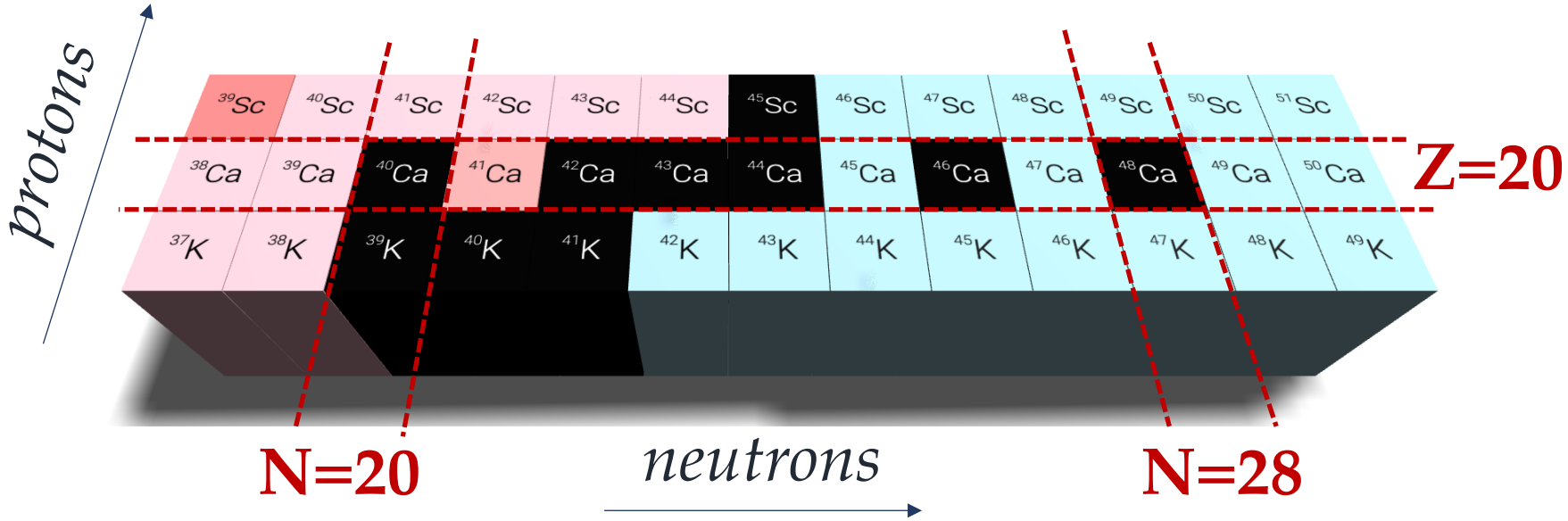




$^{41}Ca(n,\gamma)^{42}Ca$ - FIPPS



Conclusions and future perspectives



Conclusions and future perspectives

Evolution of complex structures along Ca isotopes

Microscopic origin of nuclear deformations and core-coupled states

Important benchmark for different theory approaches:

from state-of-the-art large-scale shell-model calculations to newly-developed models (Hybrid model) which allow to reach heavier mass regions

———•———

Extensive experimental campaign at Institut Laue-Langevin

Neutron-capture reactions with rare and radioactive targets

High-resolution γ-ray spectroscopy and lifetime measurements

Importance of complementary experimental approaches to reach a complete picture of the complex world of nuclear structure

Thank you for your attention

Simone Bottoni
Università degli Studi di Milano and INFN