Structure of Ca isotopes between doubly closed shells

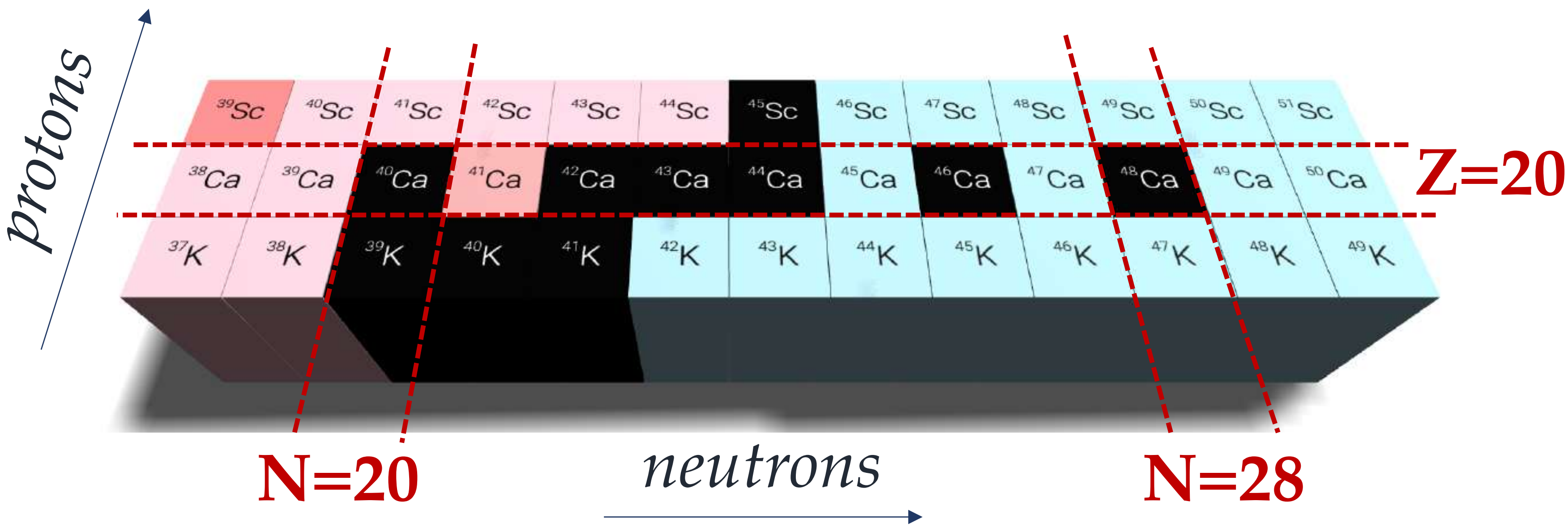
Simone Bottoni
Università degli Studi di Milano and INFN

Warsaw, Mar. 4th 2021

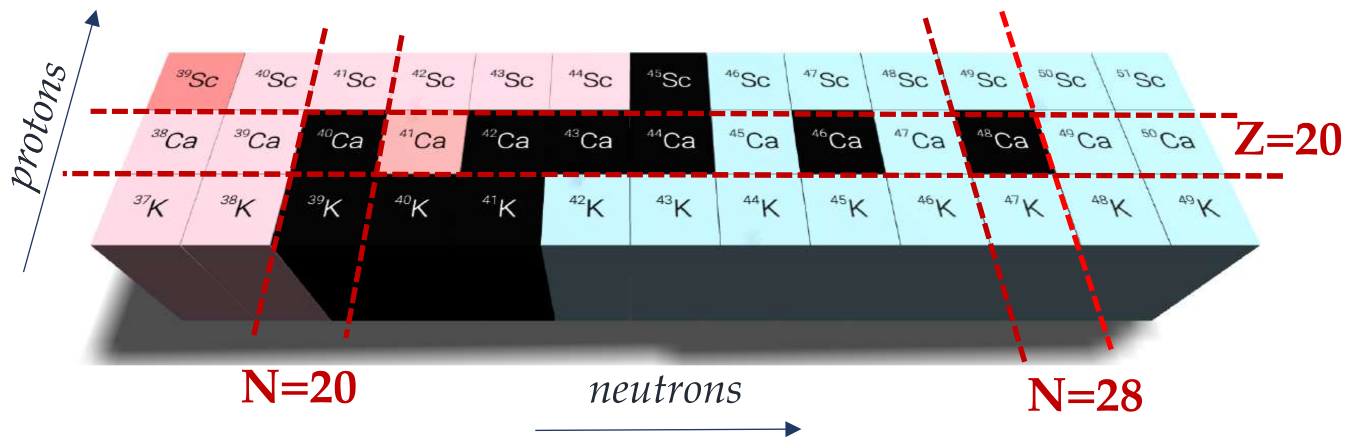
Collaboration

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

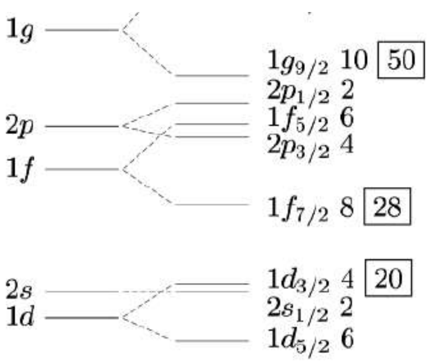
Introduction



Ca isotopes: coexistence of complex structures

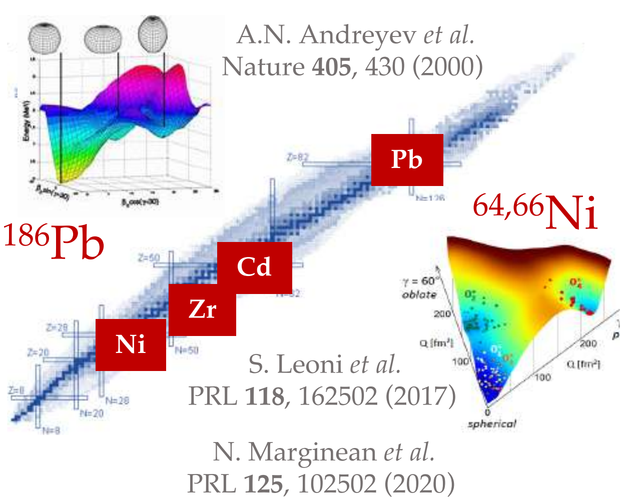


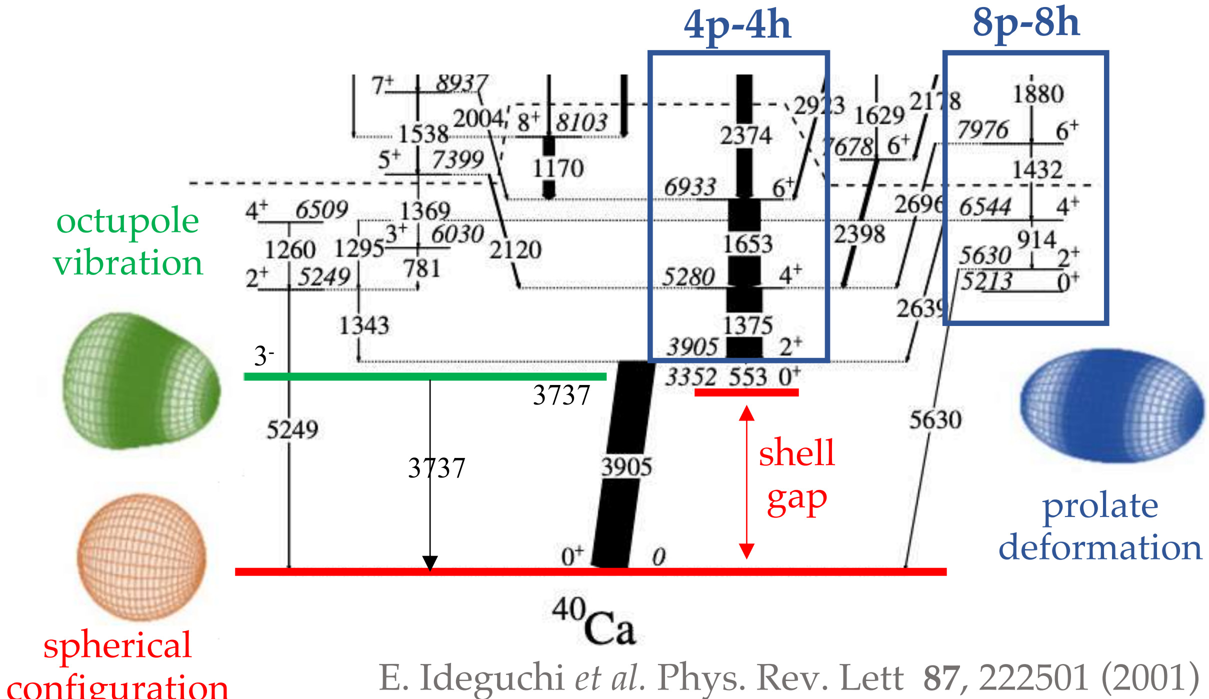
Active π-ν shells



Evolution of complex excitations from symmetric to neutron-rich nuclei

Shape coexistence across the nuclide chart





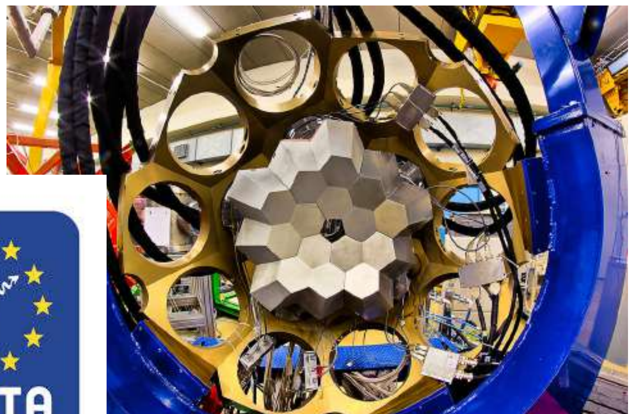
E. Ideguchi *et al.* Phys. Rev. Lett **87**, 222501 (2001)

Ca isotopes: coexistence of complex structures

SUPERDEFORMED AND TRIAXIAL STATES IN ^{42}Ca

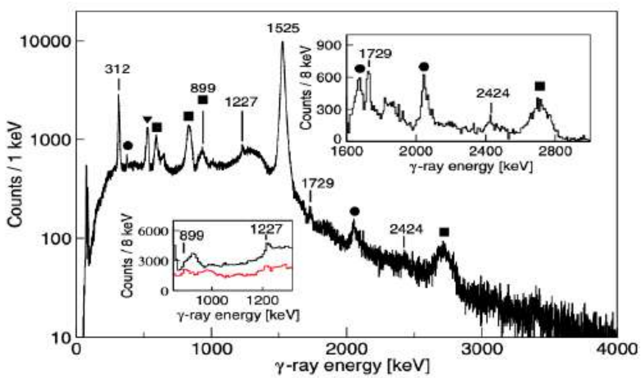
COULOMB EXCITATION @ LNL

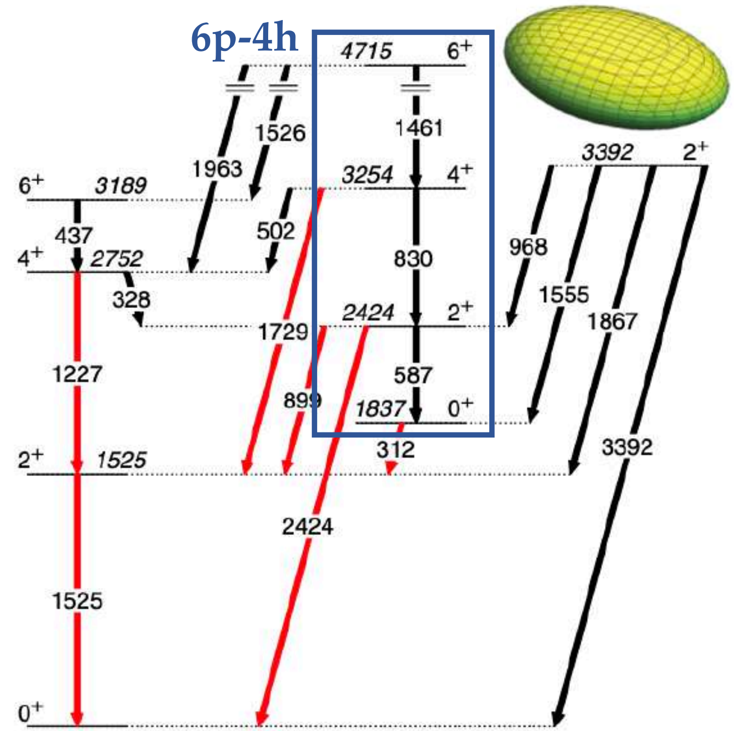
^{42}Ca+^{208}Pb / ^{197}Au



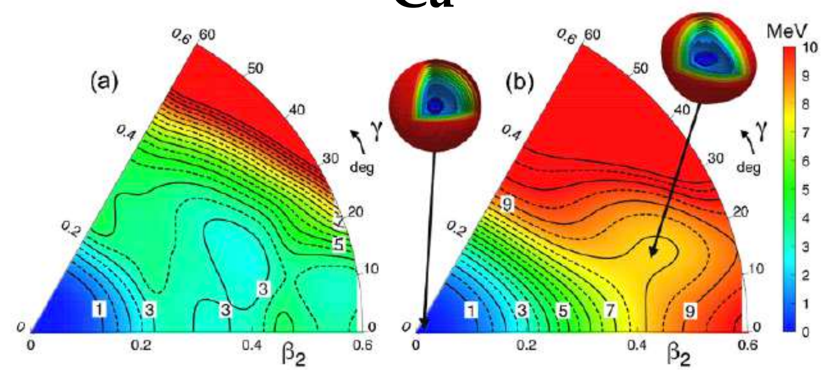
AGATA
ADVANCED GAMMA TRACKING ARRAY

AGATA-DANTE setup





^{42}Ca



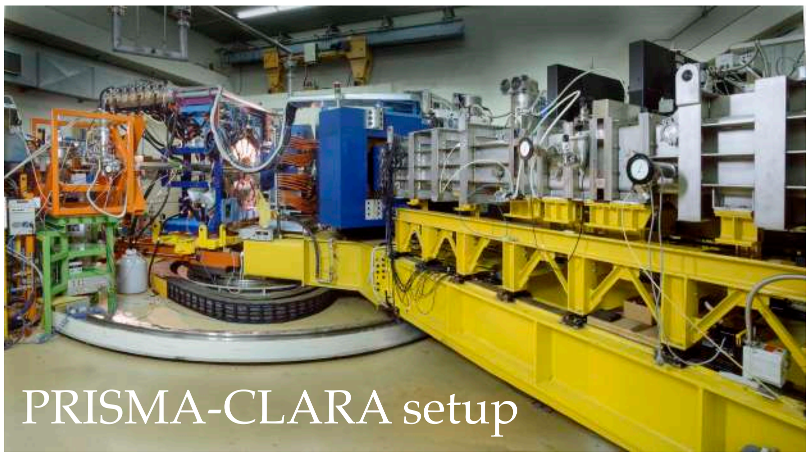
K. Hadyńska *et al.* Phys. Rev. Lett. **117,** 062501 (2016)

Ca isotopes: coexistence of complex structures

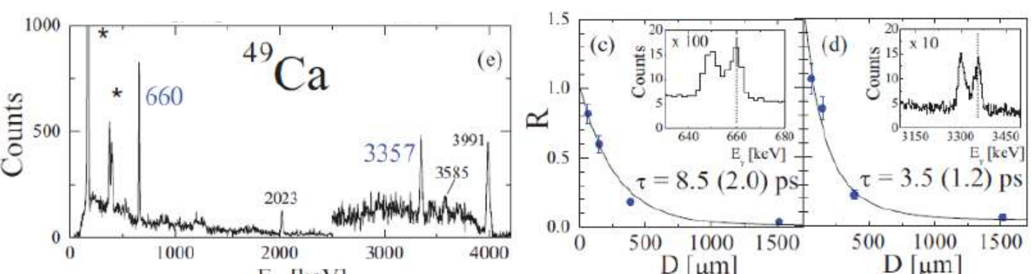
PARTICLE-VIBRATION COUPLING IN ^{49}Ca

MULTINUCLEON TRANSFER @ LNL

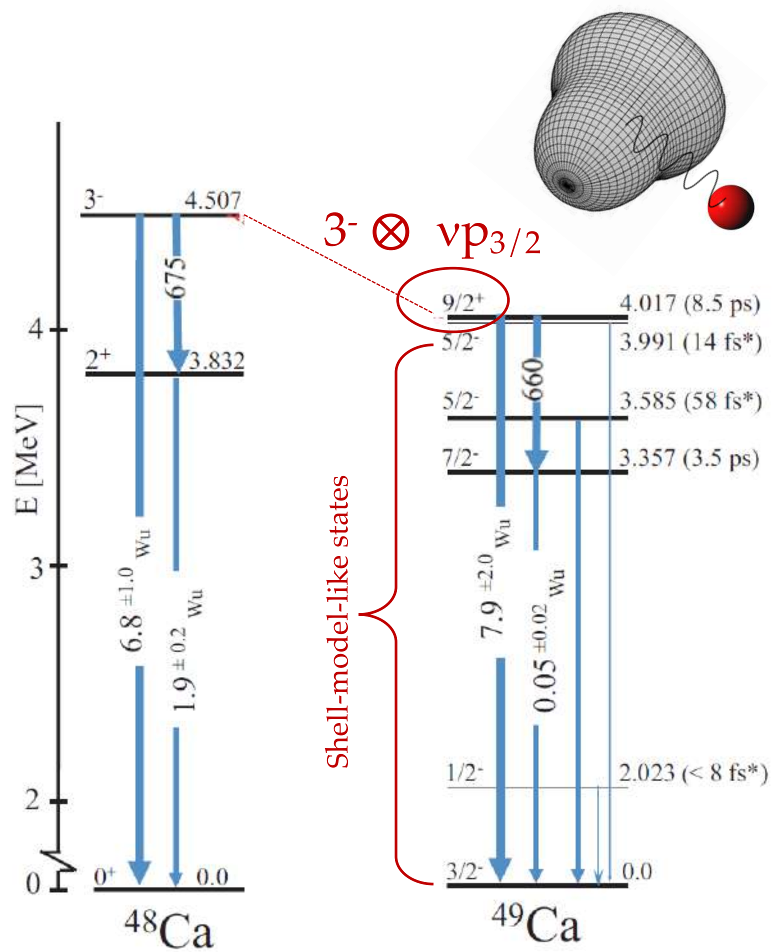
^{48}Ca+^{64}Ni / ^{208}Pb



γ-ray spectroscopy and lifetime measurements



^{49}Ca = ^{48}Ca + 1ν

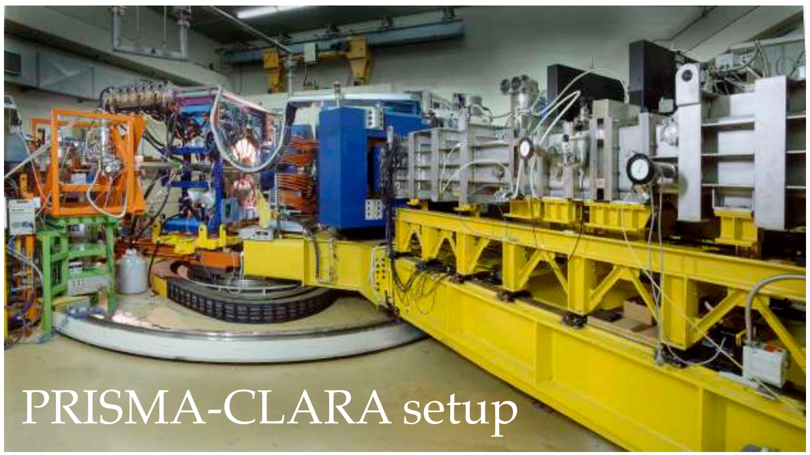


D. Montanari, S. Leoni, D. Mengoni *et al.* Phys. Lett B **697**, 288 (2011)

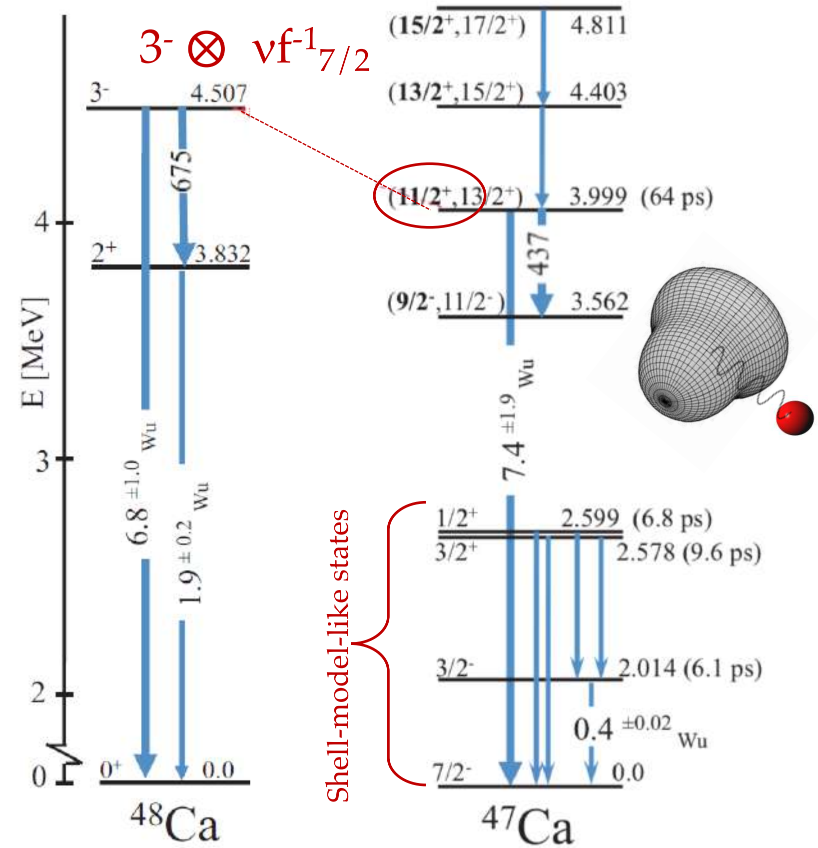
PARTICLE-VIBRATION COUPLING IN ^{47}Ca

MULTINUCLEON TRANSFER @ LNL

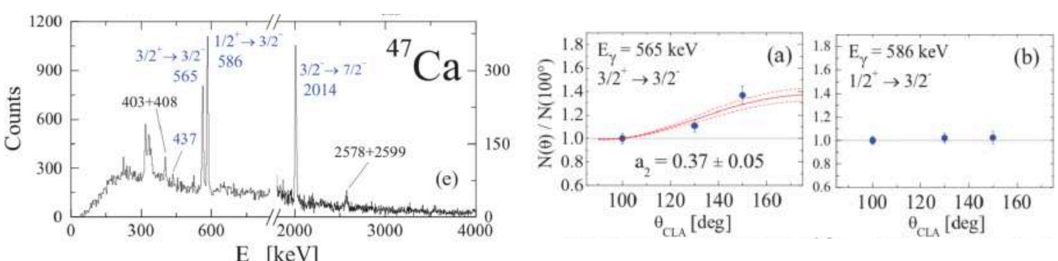
^{48}Ca+^{64}Ni / ^{208}Pb



$$^{47}\mathrm{Ca} = {}^{48}\mathrm{Ca} + 1\nu^{-1}$$



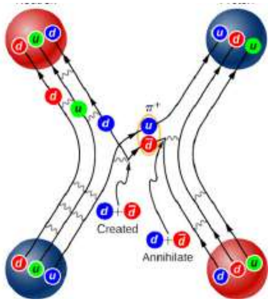
γ-ray spectroscopy and lifetime measurements



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

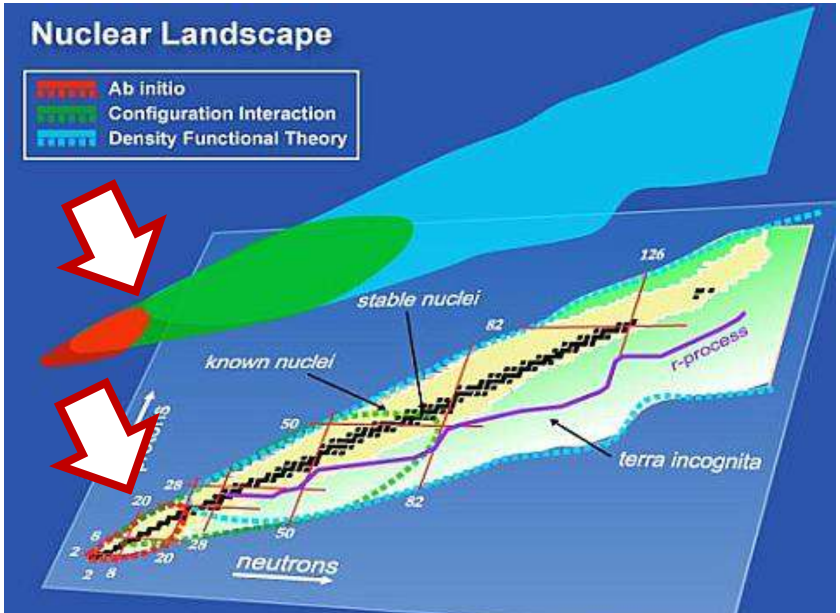
NEED OF AN UNIFIED DESCRIPTION OF NUCLEAR STRUCTURE

AB INITIO METHODS



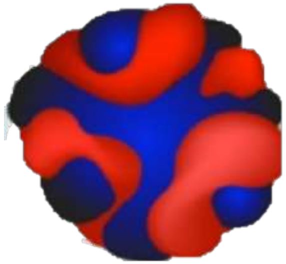
N-N interaction derived from first principles (QCD)

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



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

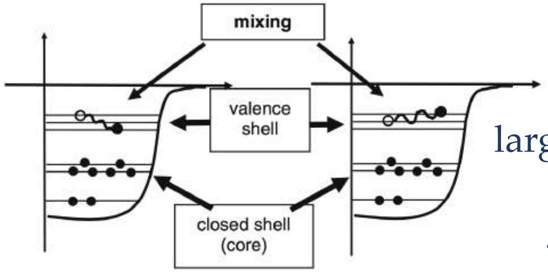
DENSITY FUNCTIONAL THEORY



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

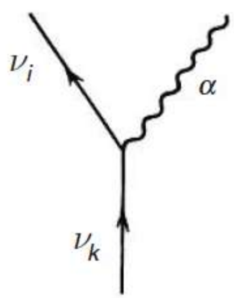


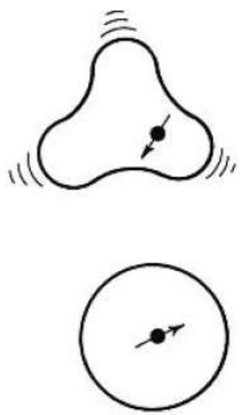
Effective and realistic interactions in large configuration spaces ($\geq 10^{10}$)

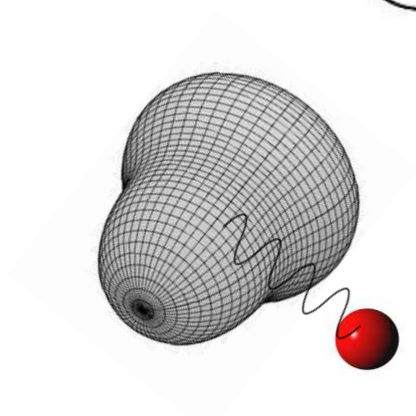
computational challenging

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

Nuclear physics
oscillations of the nucleon density

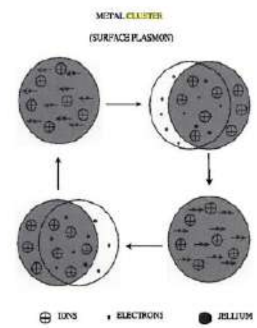


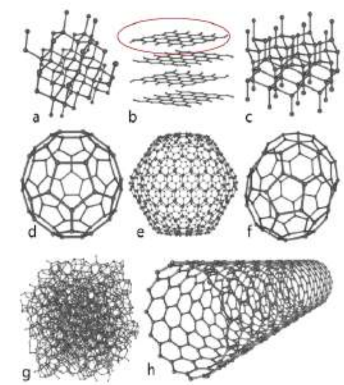


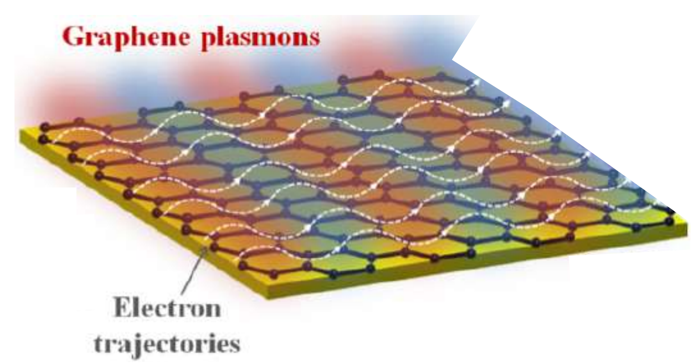


phonon-nucleon couplings

Solid state physics
oscillations of the free-electron density



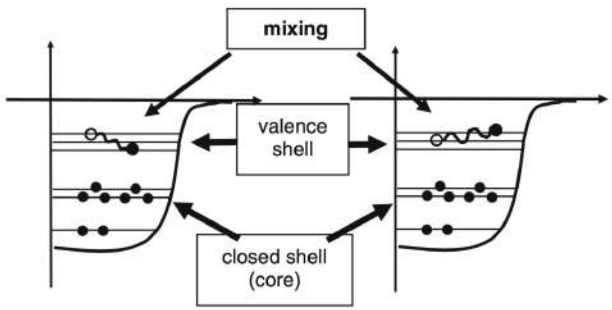


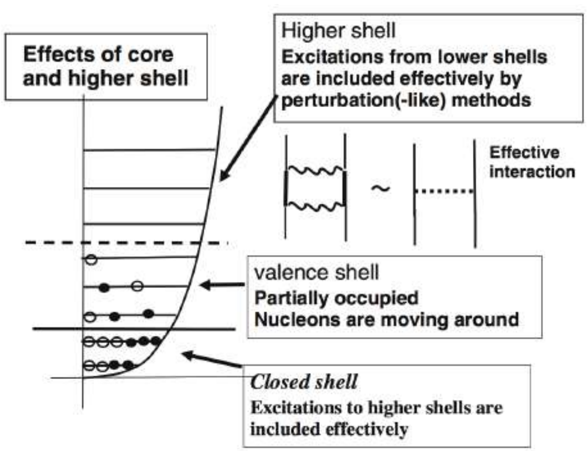


plasmon-electron couplings

Ca isotopes: benchmark for different theories

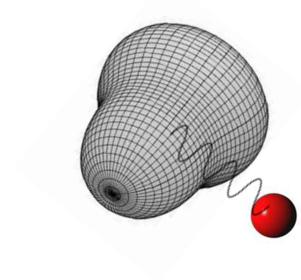
Shell model

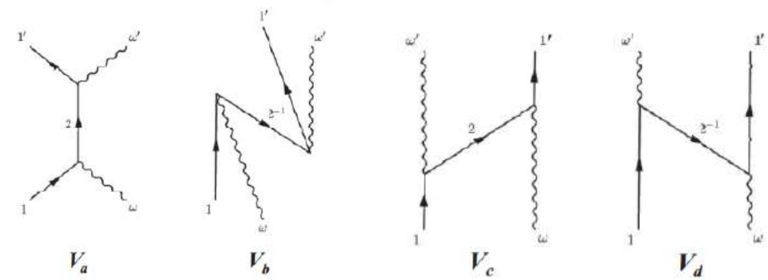




from T. Otsuka

Perturbative Particle-Vibration Coupling





$$\langle [j' \otimes J]_j \, | V_a + V_b | \, [j' \otimes J]_j \rangle = \sum_{j_1} \frac{1}{2j_1+1} \frac{\langle j_1 || V || j', J \rangle^2}{\varepsilon(j') - \varepsilon(j_1) + \hbar\omega_J}$$

$$\langle [j' \otimes J]_j \, | V_c + V_d | \, [j' \otimes J]_j \rangle = \sum_{j_1} \frac{2j'+1}{2j_1+1} \begin{Bmatrix} J & j' & j_1 \\ J & j' & j \end{Bmatrix} \frac{\langle j_1 || V || j', J \rangle^2}{\varepsilon(j_1) - \varepsilon(j') + \hbar\omega_J}$$

from A. Bohr and B. Mottelson

- **No collective excitations of the core**
- **Large increase of configurations involved**

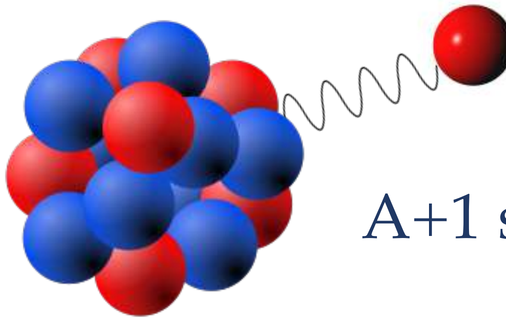
- **Phenomenological approach**
- **Weak coupling approximation**

THE HYBRID CONFIGURATION MIXING MODEL (HCM)

Microscopic model for odd-mass nuclei

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

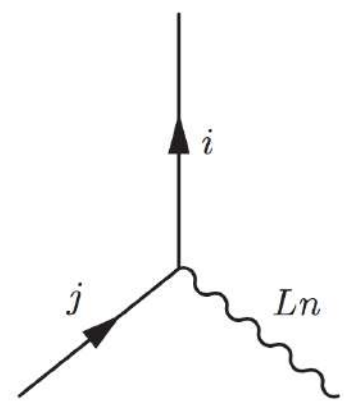
S. Bottoni et al., to be published



SKYRME HAMILTONIAN

$$
\begin{aligned}
H &= H_0 + V, \\
H_0 &= \sum_{jm} \varepsilon_j a^\dagger_{jm} a_{jm} + \sum_{NJM} \hbar\omega_{NJ} \Gamma^\dagger_{NJM} \Gamma_{NJM}, \\
V &= \sum_{jmj'm'} \sum_{NJM} h(jm; j'm', NJM) a_{jm} \left[a^\dagger_{j'} \otimes \Gamma^\dagger_{NJ} \right]_{jm}
\end{aligned}
$$

COUPLING VERTEX



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

BASIS

Single-particle/hole states (Hartree-Fock)

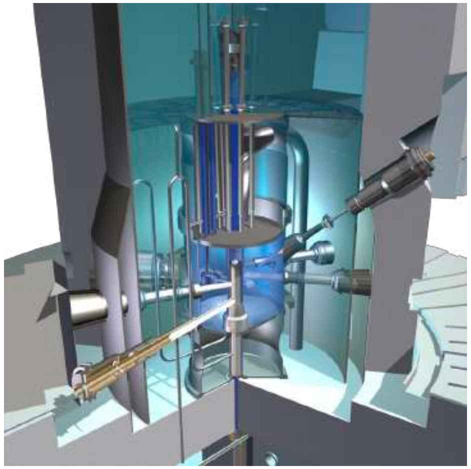
Collective phonons and
non collective 1p-1h excitations
(Random Phase Approximation)

The experimental campaign at Institut Laue-Langevin
Grenoble (France)

www.ill.eu

The Institut Laue-Langevin (ILL)

HIGH FLUX REACTOR

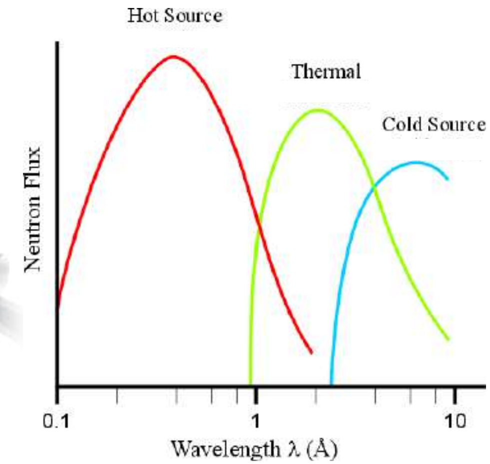


$1.5 \cdot 10^{15}$ neutrons / s / cm^2
(continuous beams)

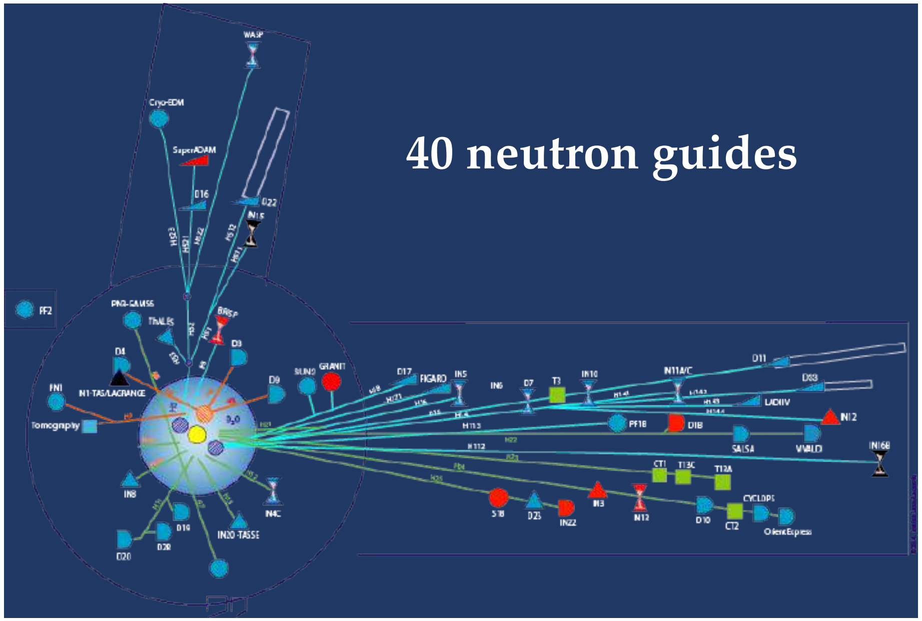
Thermal Power
58.3 MW

50-day cycles

NEUTRONS AT ILL



EXPERIMENTS AT ILL



FUNDAMENTAL SCIENCE:

Condensed matter physics

Material Science

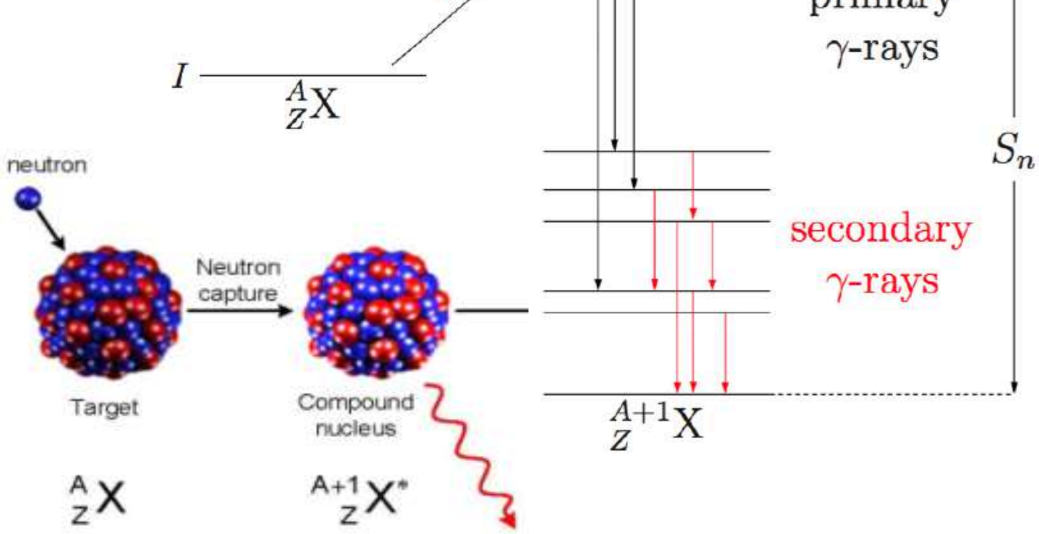
Chemistry and Biology

Nuclear and Particle physics

Experimental program at ILL

NEUTRON-CAPTURE REACTIONS

COLD AND THERMAL NEUTRONS



$$J_{I'} = J_I \pm 1/2$$

$$n + X = (X+1)$$

$$\underbrace{\cancel{T_n}}_{meV} + \underbrace{m_n c^2}_{GeV} + \underbrace{m_X c^2}_{GeV} = \underbrace{m_{X+1} c^2}_{GeV} + \underbrace{\cancel{T_{X+1}}}_{<<meV} + \underbrace{E^*_{X+1}}_{MeV}$$

$$E^*_{X+1} = (m_n c^2 + m_X c^2) - m_{X+1} c^2 \equiv S_n$$

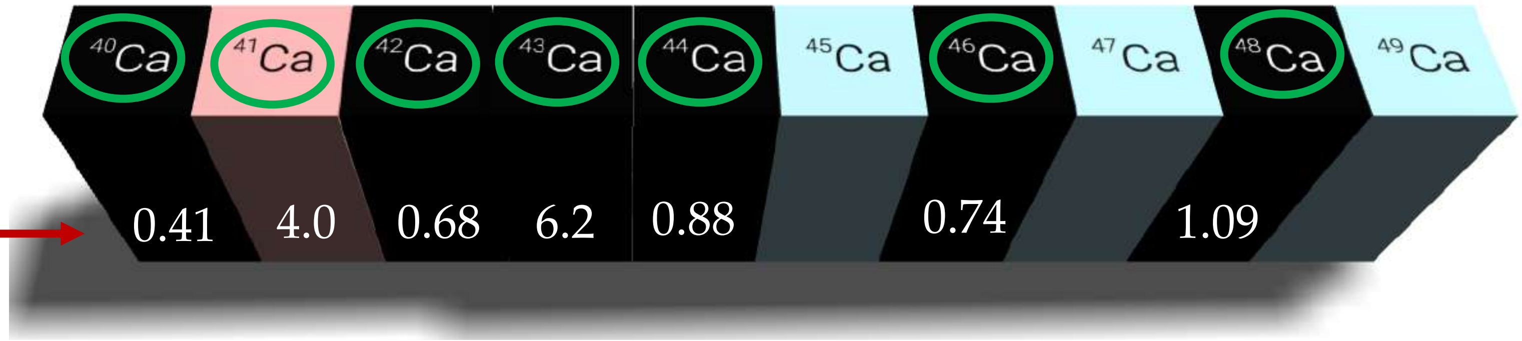
Complete low-spin γ-ray spectroscopy from the capture state to the ground state

Complementary to higher-spin spectroscopy with stable and radioactive beams

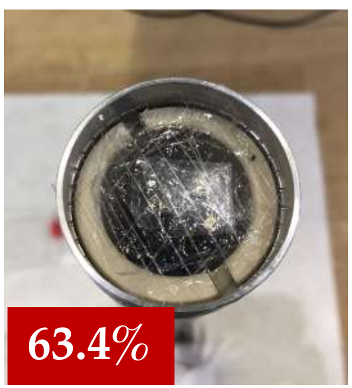
Experimental program at ILL

RARE AND RADIOACTIVE TARGETS

$\sigma(n,\gamma)$ [barn]



^{41}Ca



63.4%

$CaCO_3$

A ~ 2 MBq

m ~ 600 μg

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

made in 1975

^{46}Ca

31.7%

$Ca(NO_3)_2$

(40.6 mg)

Abundance

0.004%

made at PSI by A. Türler

^{48}Ca

60.5%

$CaCO_3$

(350 mg)

Abundance

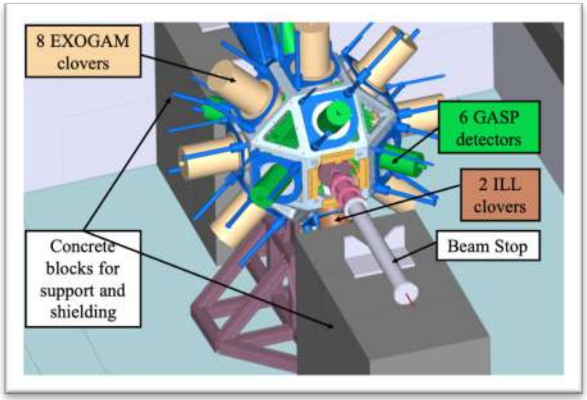
0.187%

made in 1979

Experimental program at ILL

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

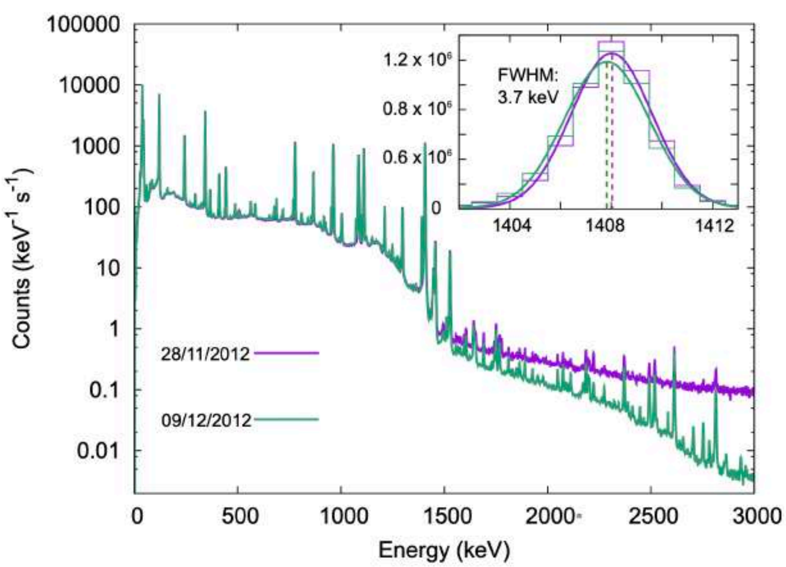
Promoted by W. Urban – ^{48}Ca(n,γ) first measurement

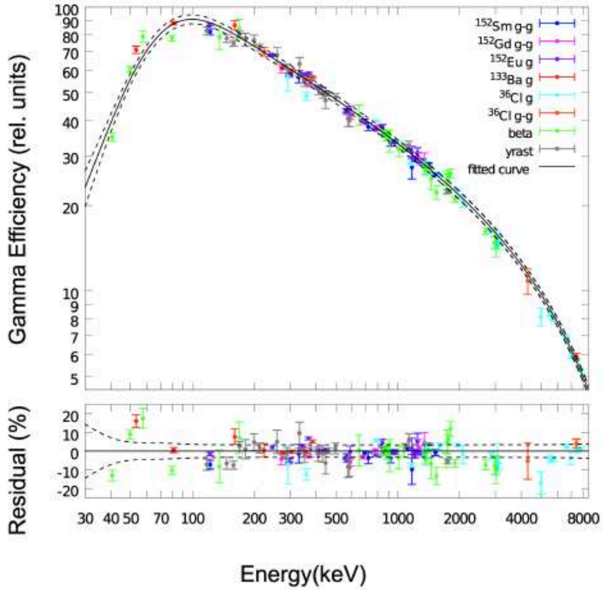


First campaign with a large γ array and a neutron beam (cold neutrons)

HPGe detectors

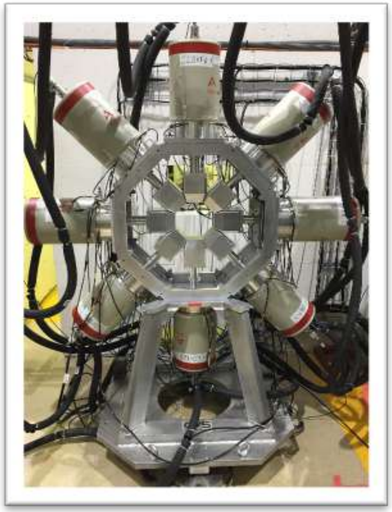
LaBr:Ce scintillators

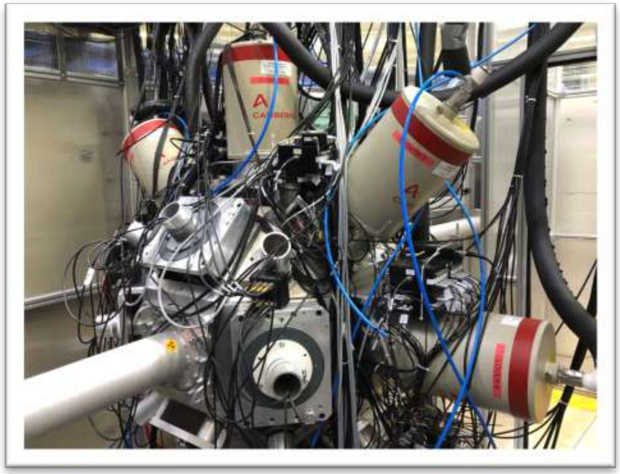




M. Jentschel *et al.*, J. Inst. **12**, 11003 (2017)

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



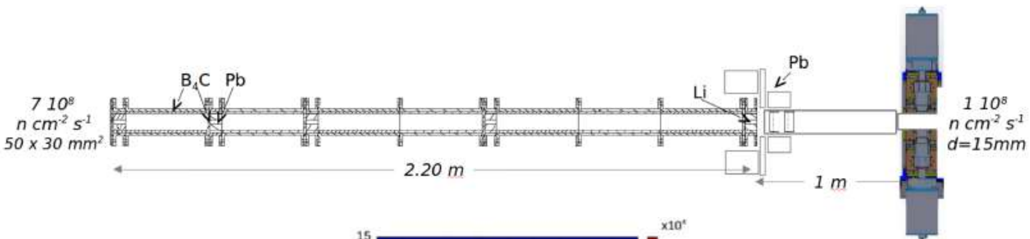


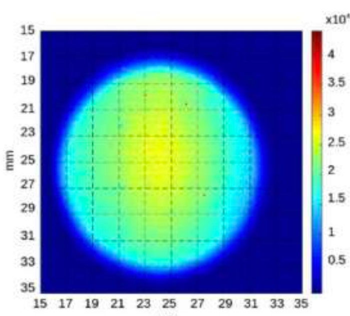
thermal neutrons

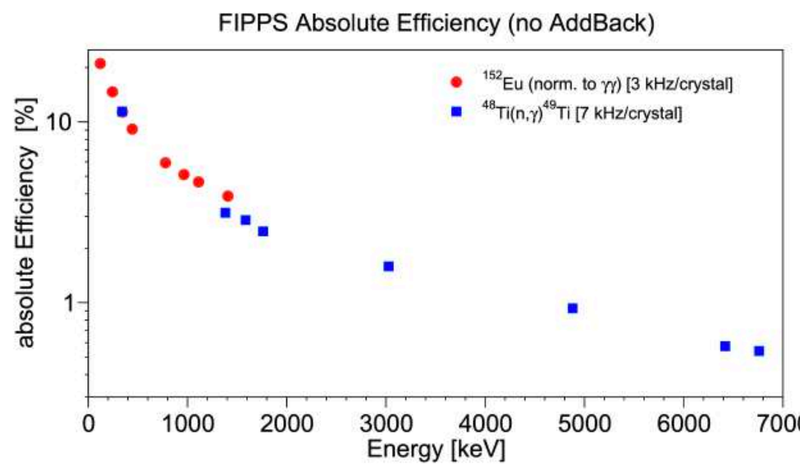
HPGe clover detectors + AC shields

Clover detectors from IFIN-HH (Bucharest)

LaBr:Ce scintillators





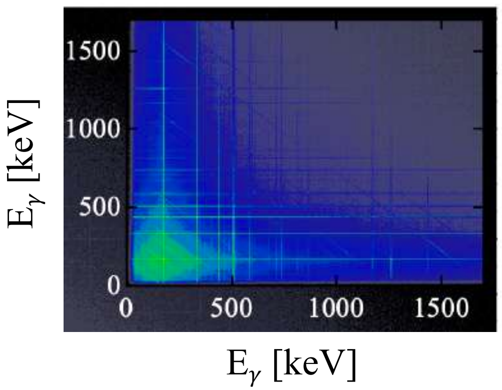


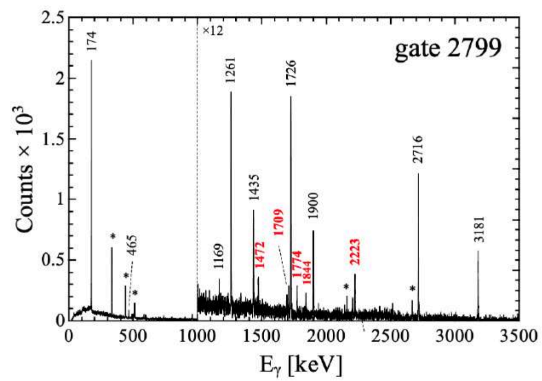
C. Michelagnoli *et al.*, EPJ **193**, 04009 (2018)

Experimental program at ILL

EXPERIMENTAL TECHNIQUES

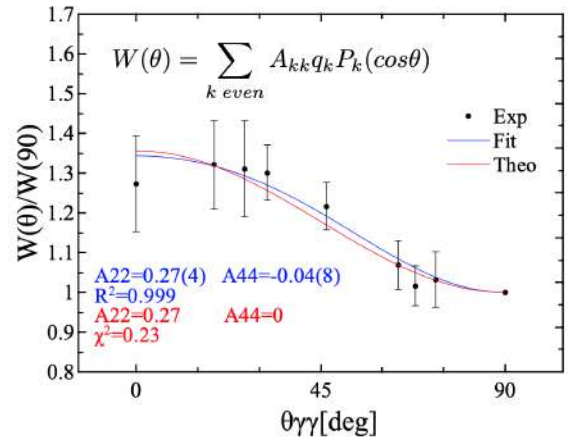
High-resolution γ-ray spectroscopy





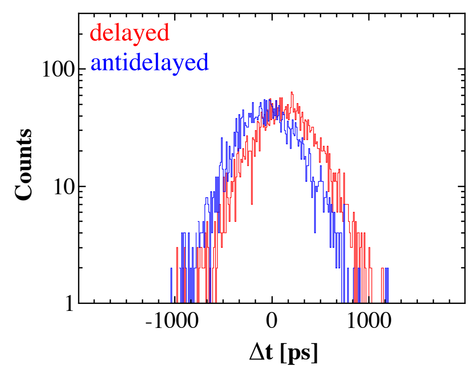
γ- γ coincidences
Prompt-Delay correlations
Level and decay schemes
γ-ray intensities

Angular correlations



γ-ray multipolarities
Spin assignments

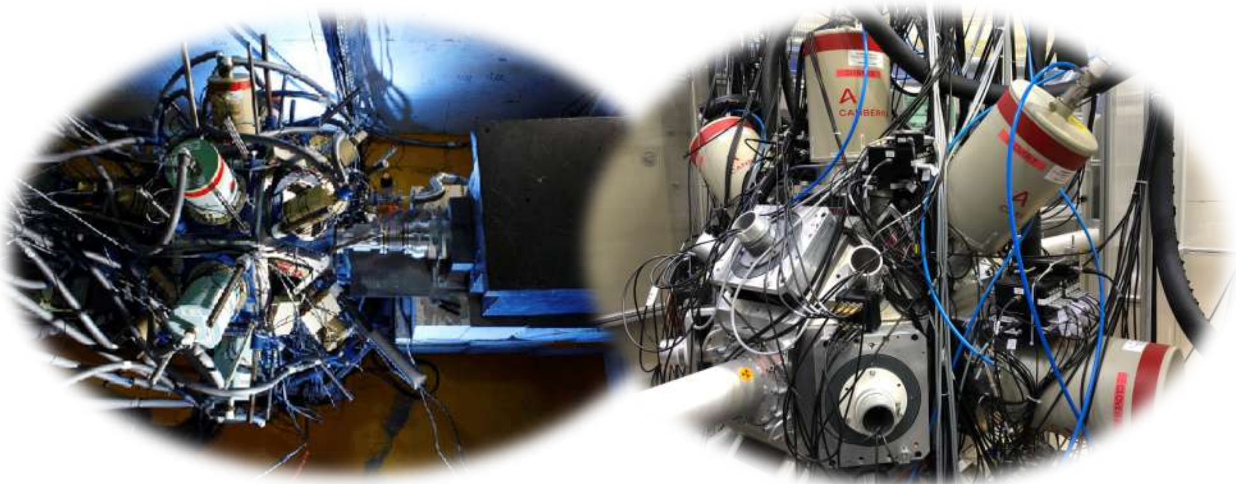
Lifetime measurements



LaBr:Ce detectors
Fast-timing techniques
Piscosecond range

Information on state wave function

Recent results



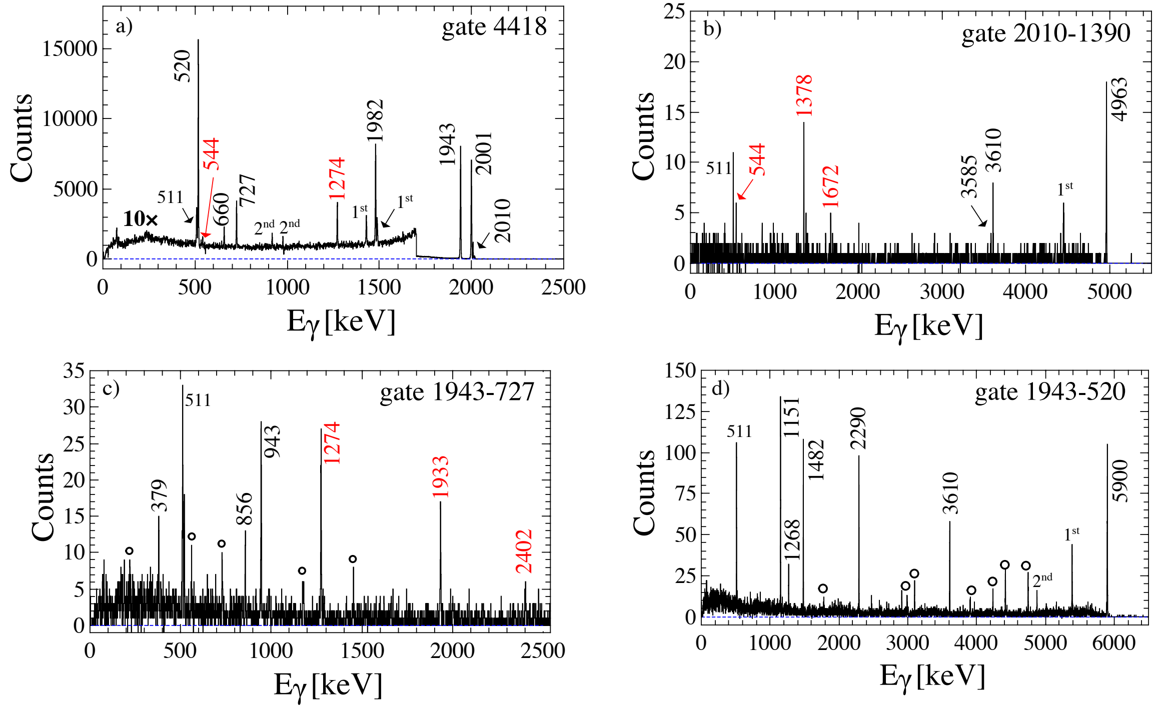
EXILL **FIPPS**

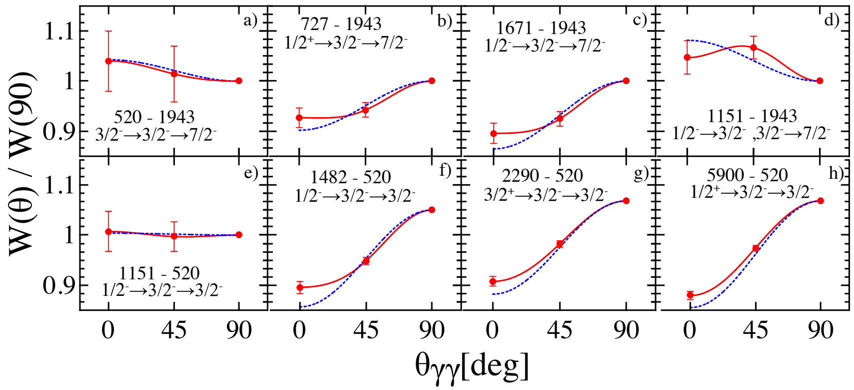
PHYSICAL REVIEW C **103**, 014320 (2021)

Low-spin particle-core and hole-core excitations in ^{41,47,49}Ca isotopes studied by cold-neutron-capture reactions

S. Bottoni,[1,2,*] N. Cieplicka-Oryńczak,[3] S. Leoni,[1,2] B. Fornal,[3] G. Colò,[1,2] P. F. Bortignon,[1,2] G. Bocchi,[1,2] D. Bazzacco,[4] G. Benzoni,[2] A. Blanc,[5] A. Bracco,[1,2] S. Ceruti,[1,2] F. C. L. Crespi,[1,2] G. de France,[6] E. R. Gamba,[7,2] Ł. W. Iskra,[2,3] M. Jentschel,[5] U. Köster,[5] C. Michelagnoli,[5] B. Million,[2] D. Mengoni,[8,4] P. Mutti,[5] Y. Niu,[9] C. Porzio,[1,2] G. Simpson,[5] T. Soldner,[5] B. Szpak,[3] A. Türler,[10] C. A. Ur,[11] and W. Urban[12]

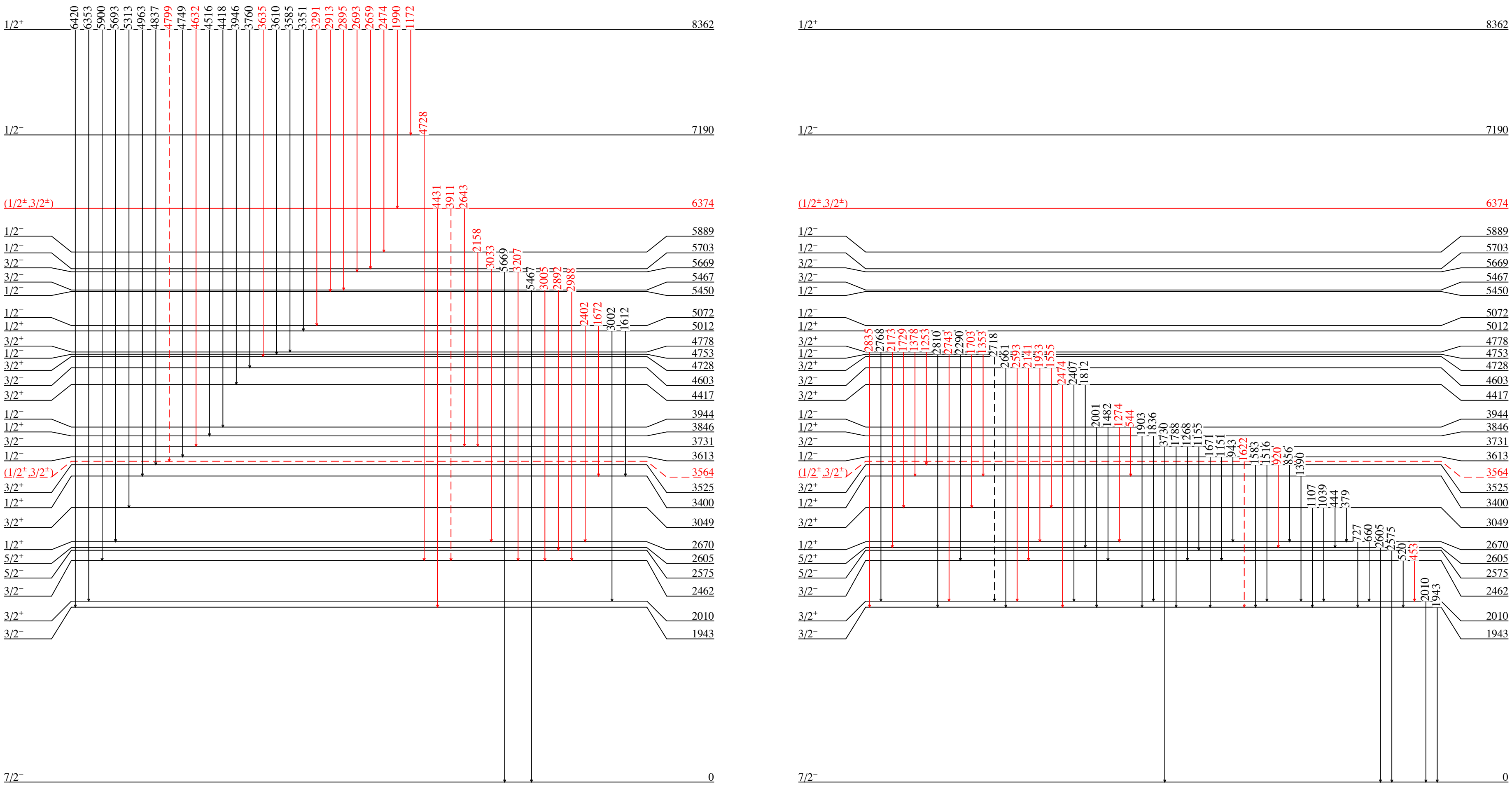
^{41}Ca


a)
gate 4418
Counts
Eγ [keV]
520
544
511
660
727
10×
2nd 2nd
1274
1st
1st
1982
1943
2001
2010
b)
gate 2010-1390
511
544
1378
1672
3585
3610
1st
4963
c)
gate 1943-727
511
379
856
943
1274
1933
2402
d)
gate 1943-520
511
1151
1268
1482
2290
3610
1st
2nd
5900


W(θ) / W(90)
θγγ[deg]
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⁻

$^{40}Ca(n,\gamma)^{41}Ca$ - EXILL

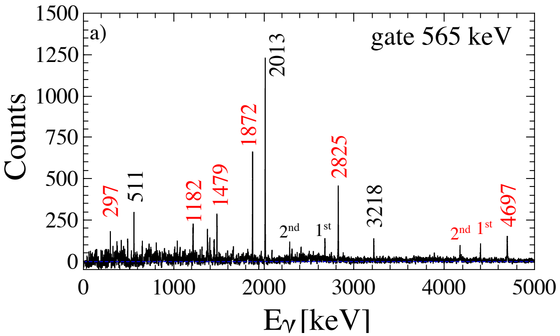
^{41}Ca

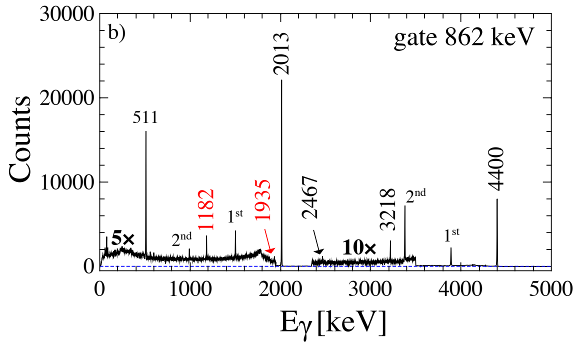


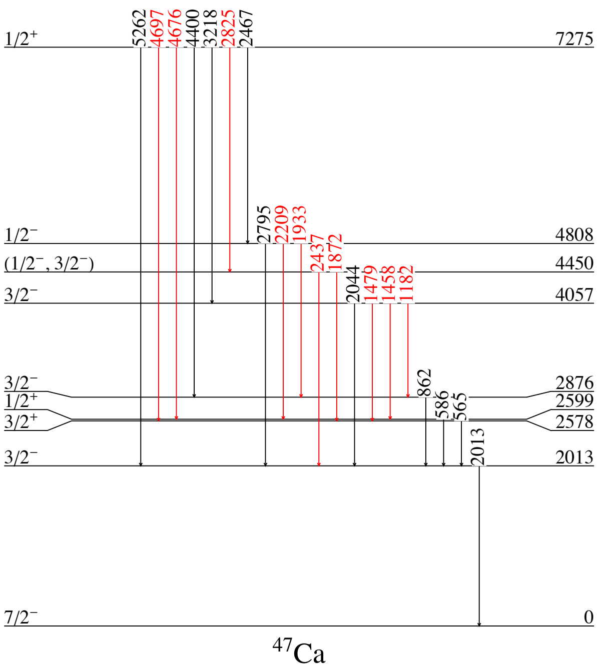
41 new transitions

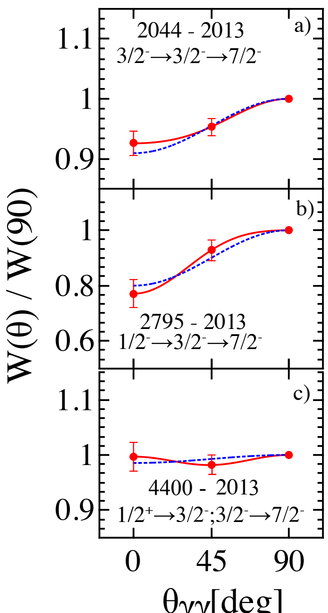
$^{46,48}Ca(n,\gamma)^{47,49}Ca$ - EXILL

^{47}Ca

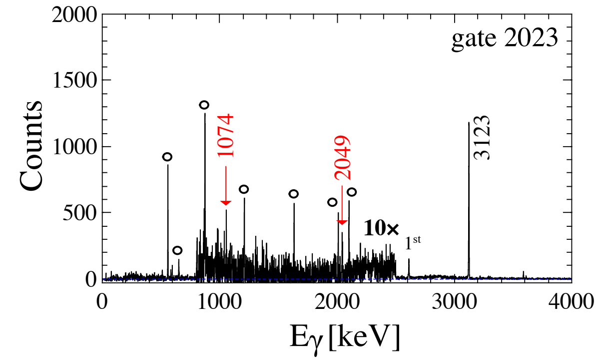


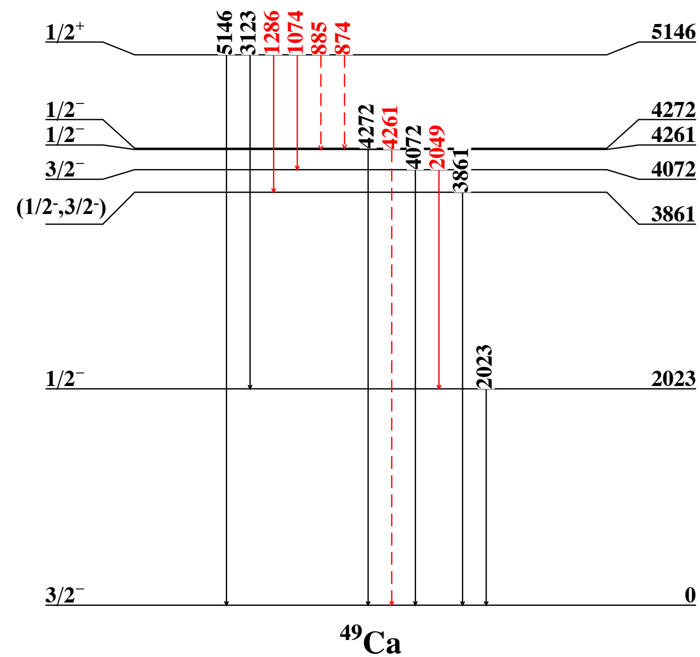




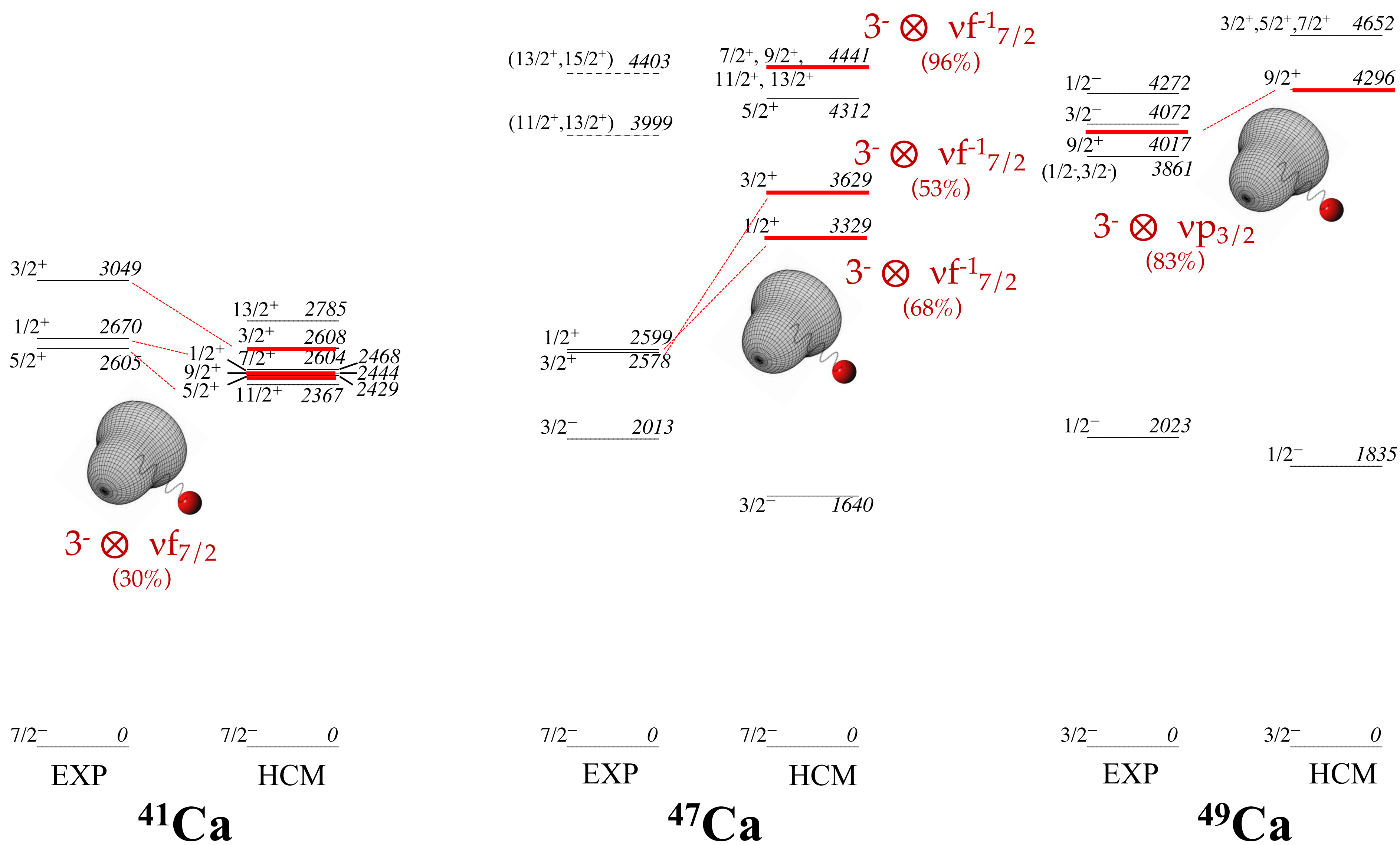


^{49}Ca





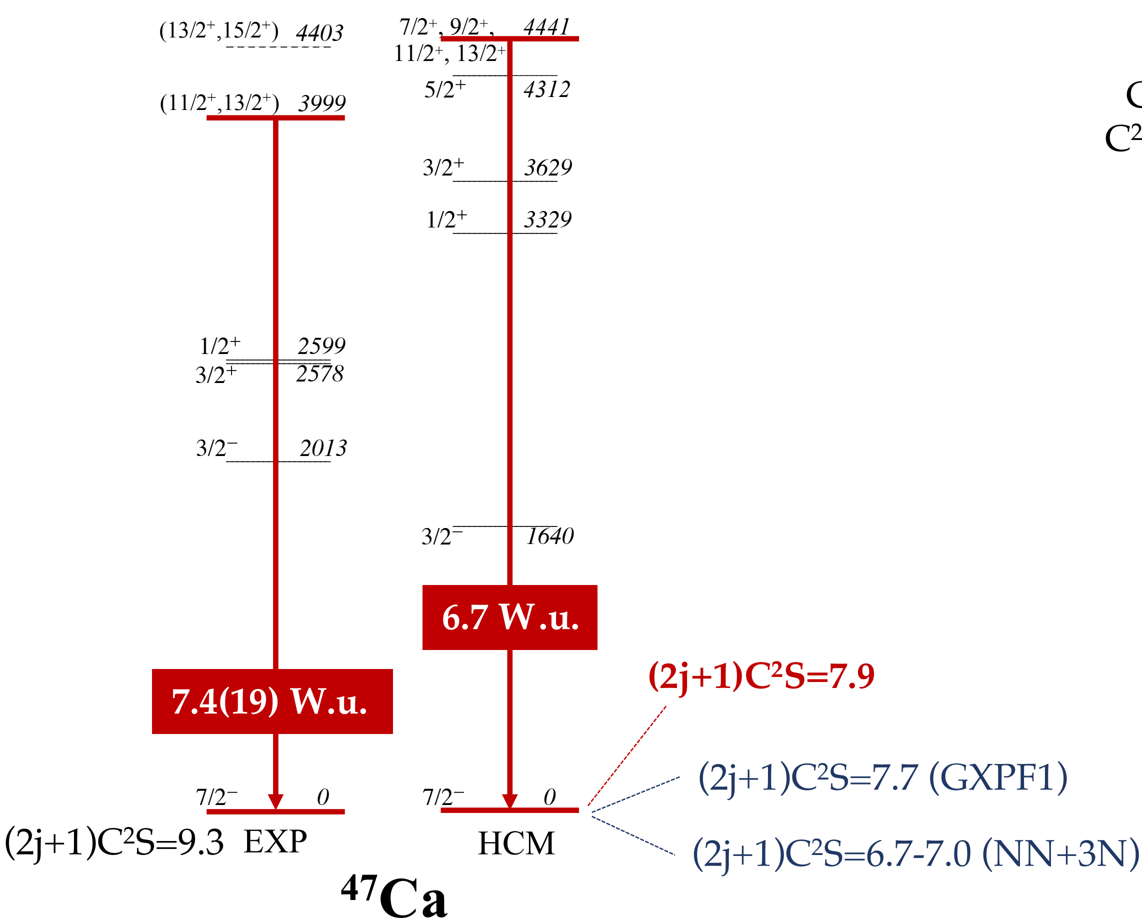
Comparison with HCM model

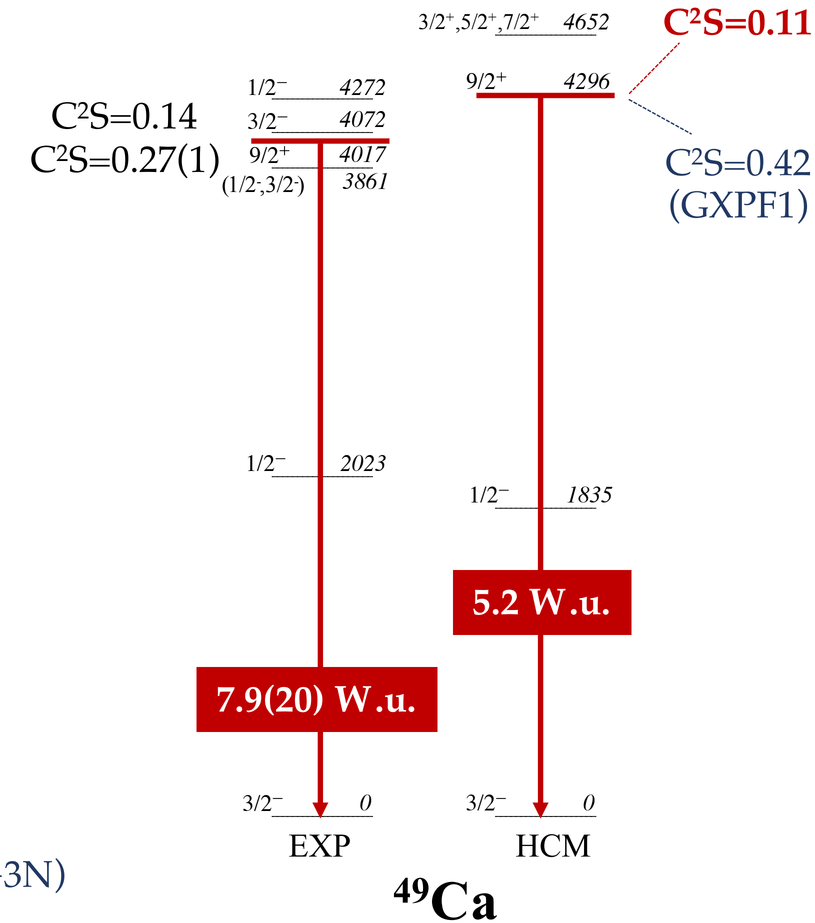


Comparison with HCM model

$^{47}Ca = {}^{48}Ca + 1\nu^{-1}$

$^{49}Ca = {}^{48}Ca + 1\nu$





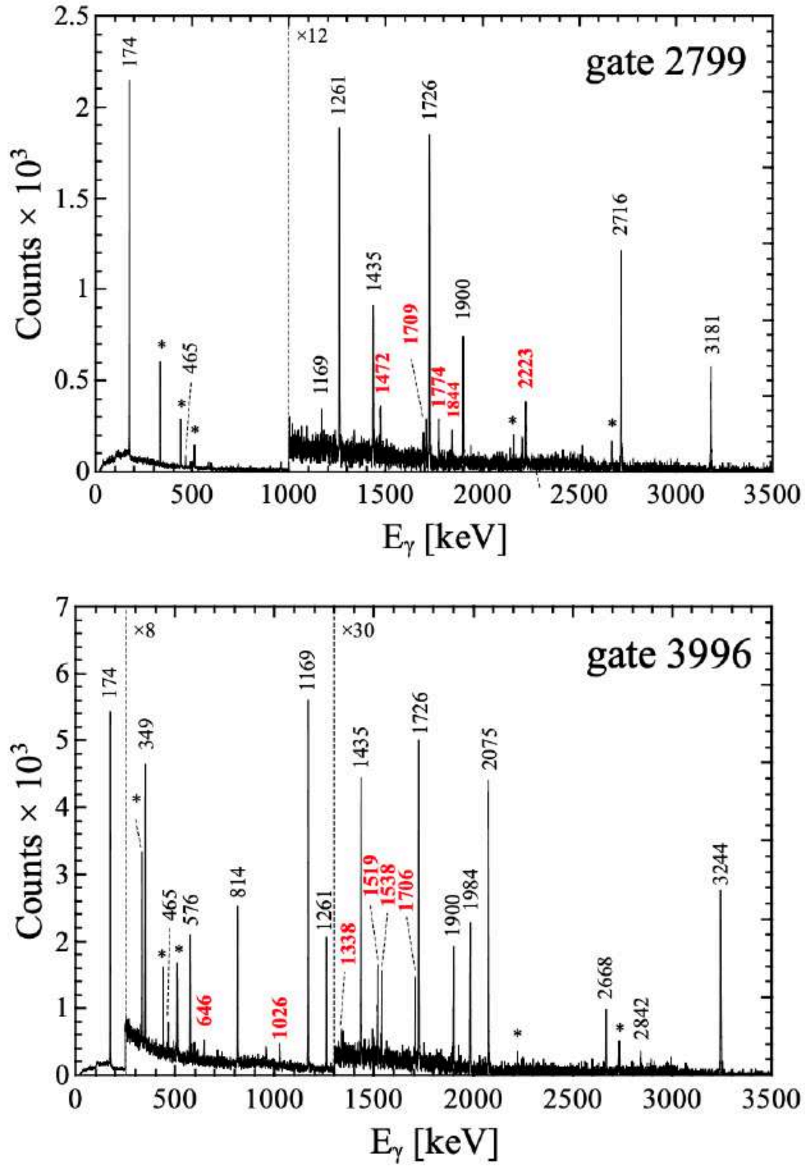
H. L. Crawford et al., PRC 95, 064317 (2017)

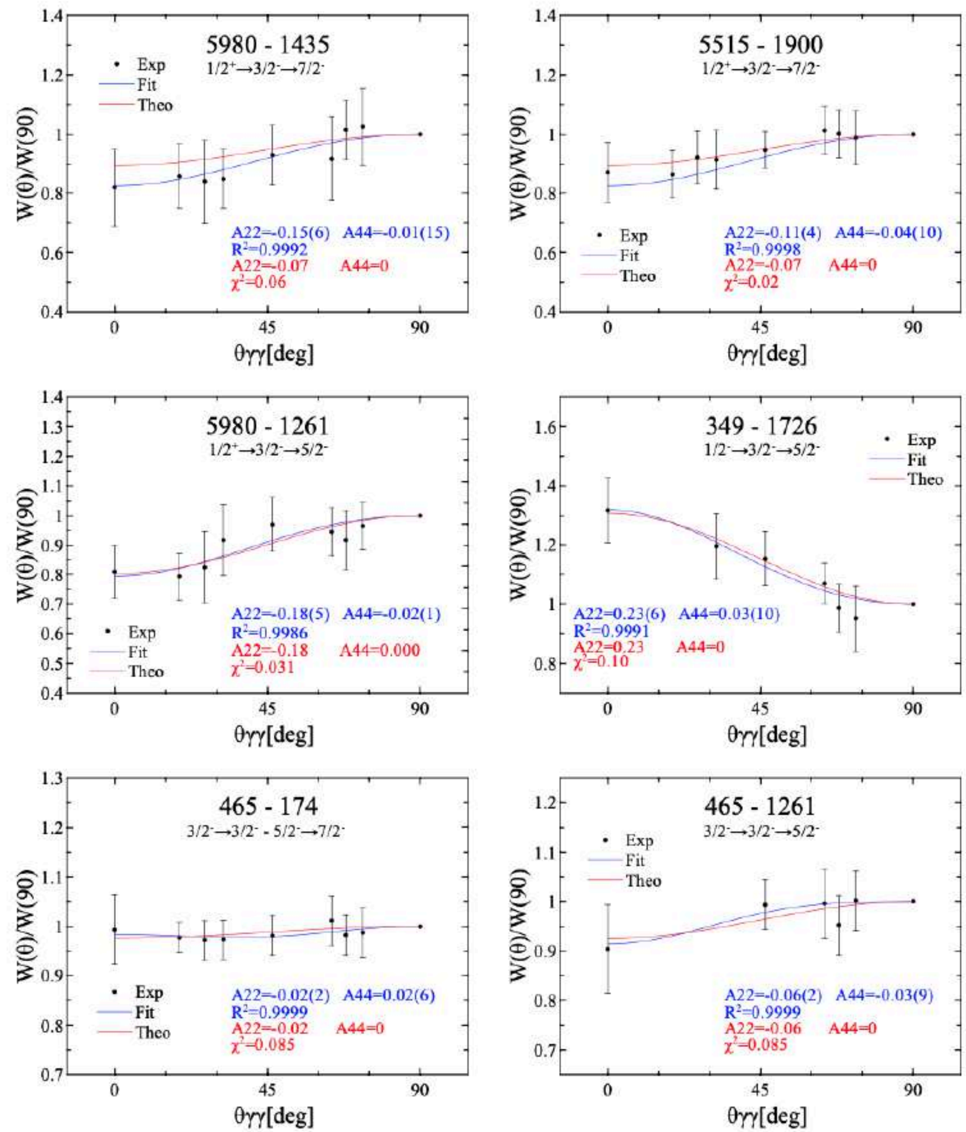
Y. Utsuno, et al, Progr. Theor. Phys. Suppl. **196**, 304 (2012)
J. D. Holt, et al, Phys. Rev. C **90**, 024312 (2014)

A. Gade et al., PRC 93, 031601(R) (2016)

^{44}Ca(n,γ)^{45}Ca - FIPPS

^{45}Ca



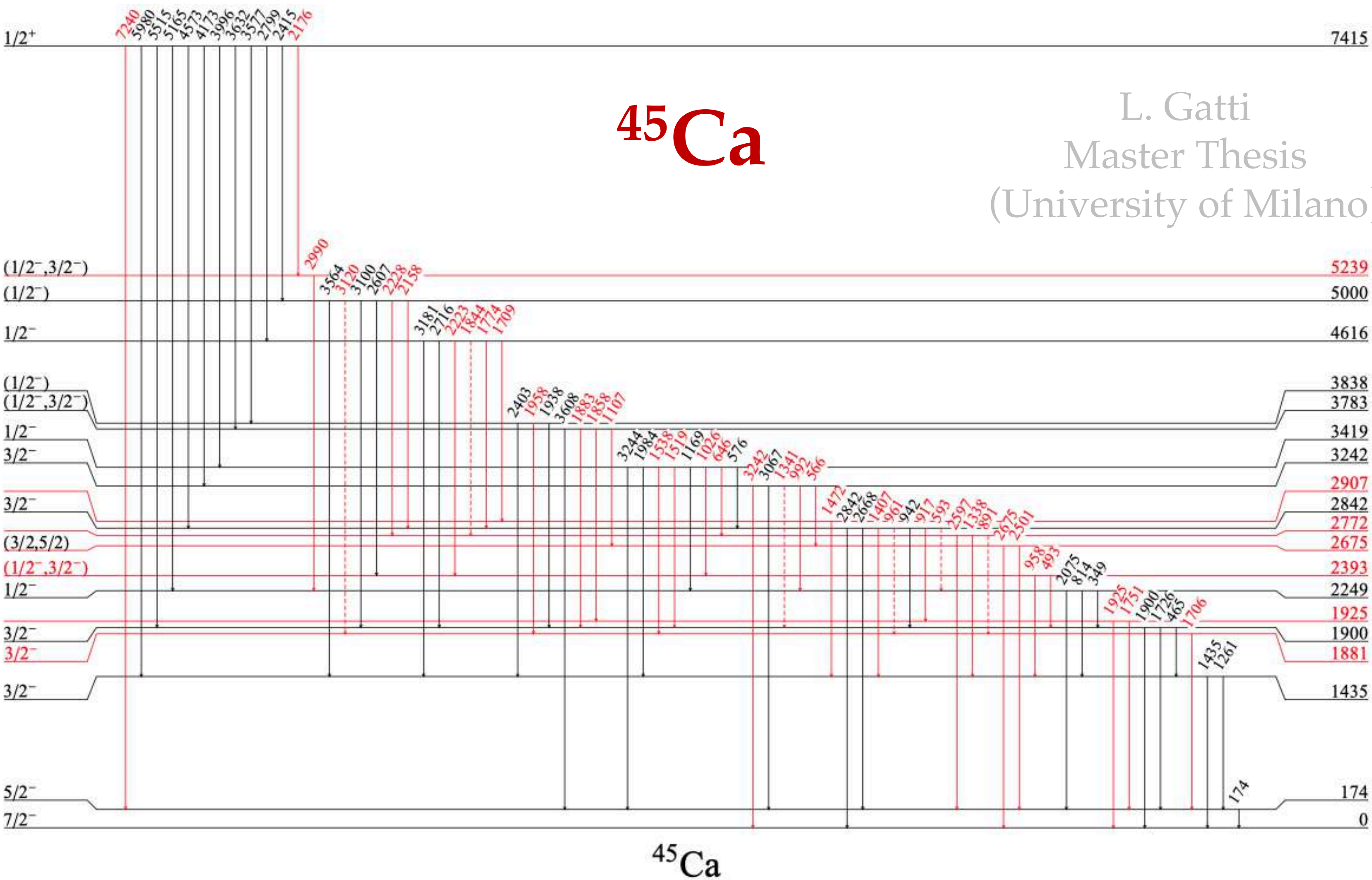


OPEN SHELL NUCLEUS – SUPERFLUID PROPERTIES

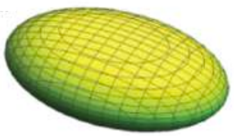
Extension of the HCM model within quasi-particle formalism (Y. Niu)

^{45}Ca

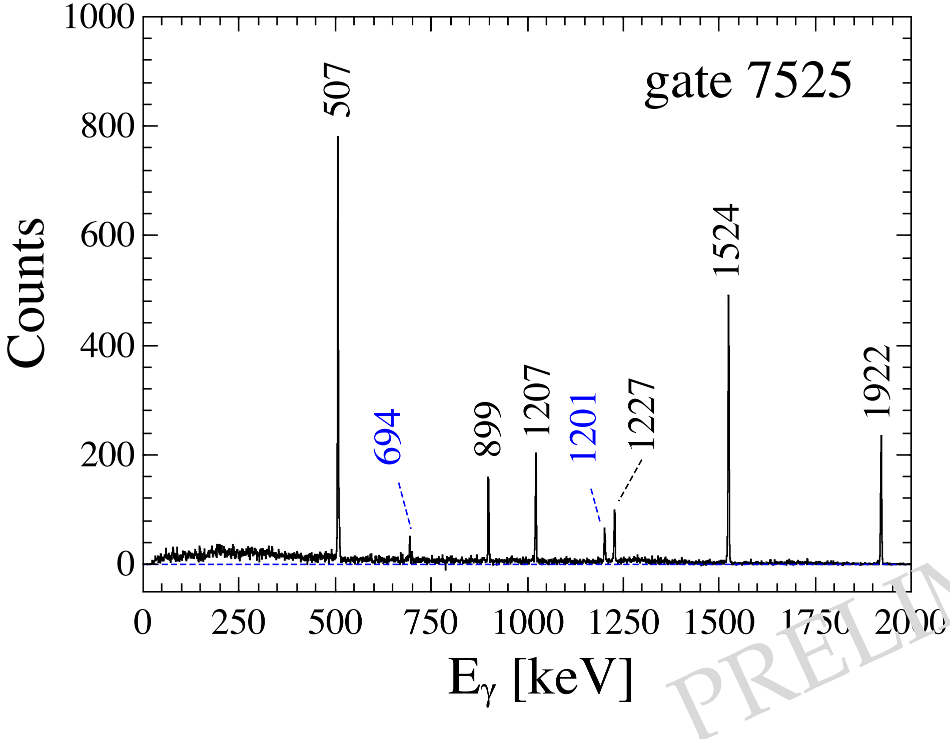
L. Gatti
Master Thesis
(University of Milano)

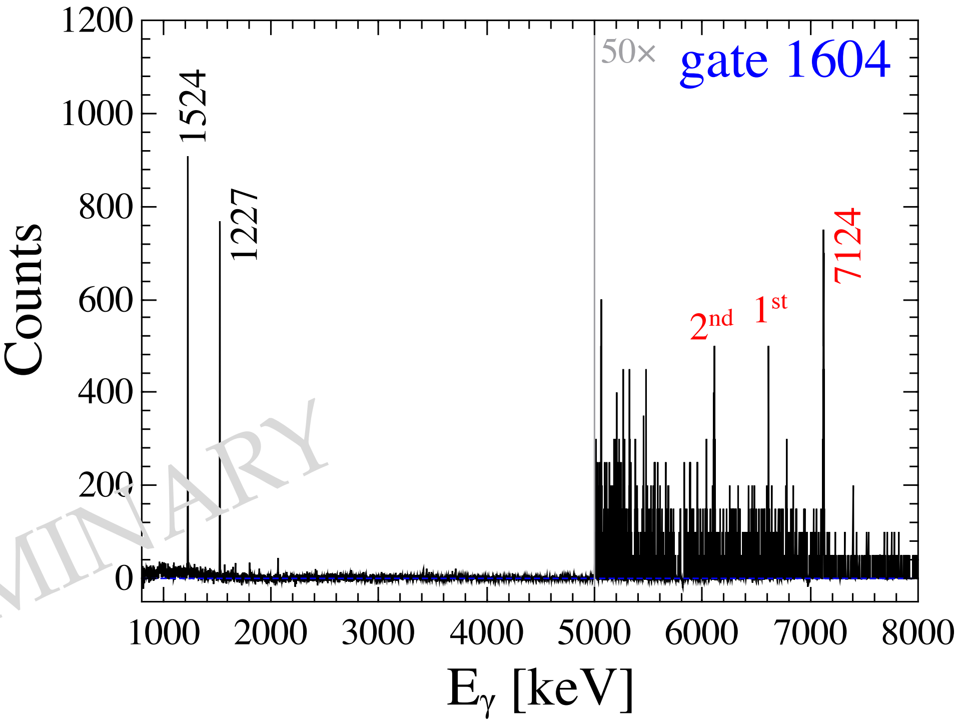


good statistics and selectivity already after 4 hours



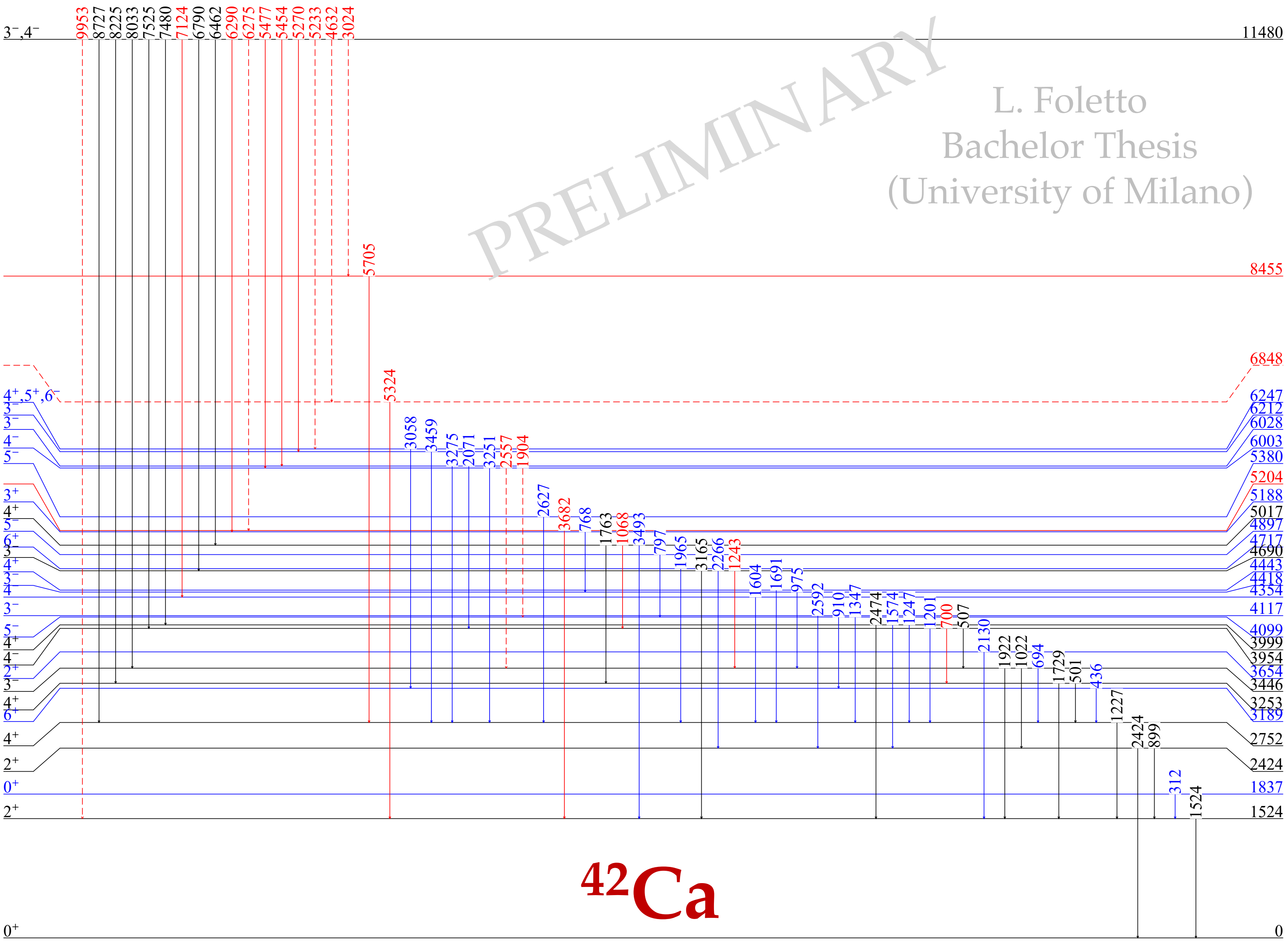
K. Hadyńska *et al.*
Phys. Rev. Lett. **117**, 062501 (2016)



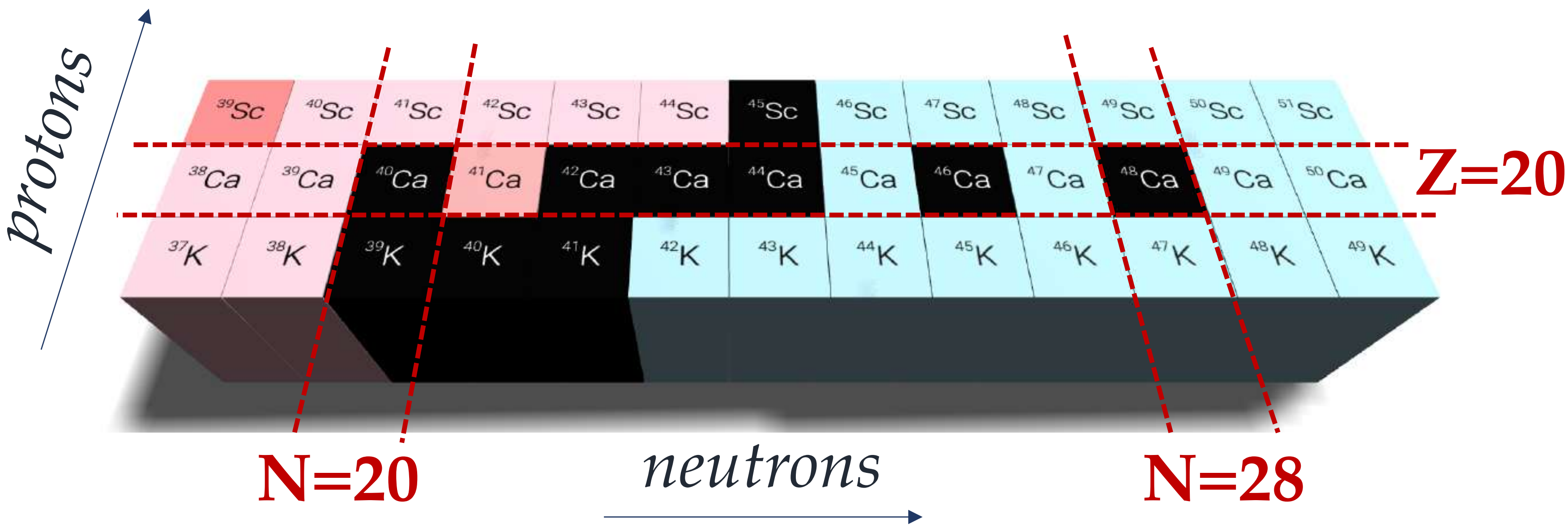


^{42}Ca

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