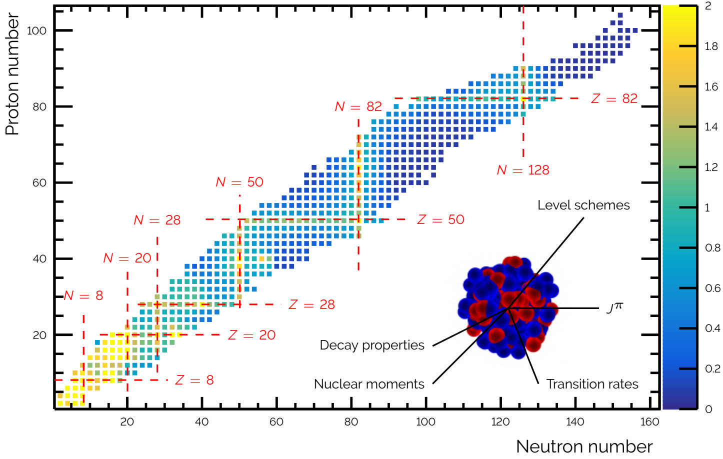
γ-ray spectroscopy at LNL: past, present and future

Alain Goasduff, Ph.D. - alain.goasduff@lnl.infn.it
April 23rd, 2020

Why studying nuclear structure?

A first glance to the nuclear structure: the energy of the first 2^+ in even-even nuclei



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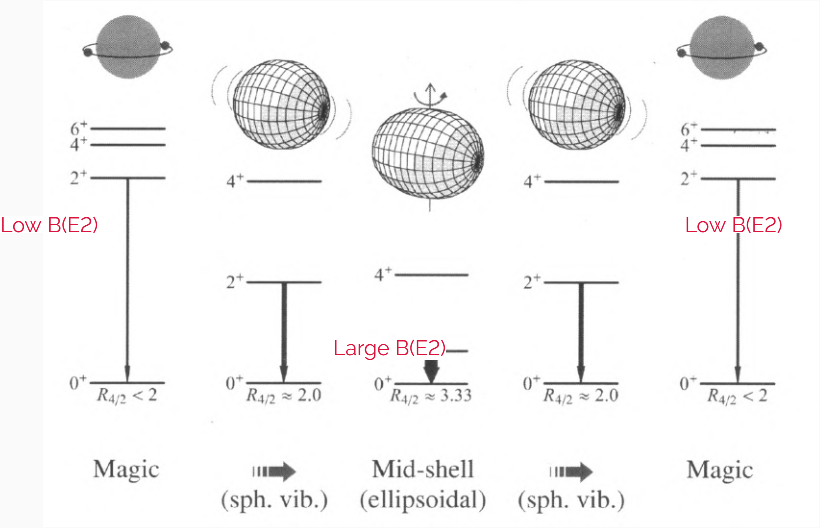
Evolution of the nuclear structure



How to study it?

How can we study the nuclear structure?

One of the easiest way to study the nucleus $\Longrightarrow$ γ-spectroscopy:

- Relatively simple and well-known operator
- In a first (and good) approximation: 1-body operator
- Gives access to:
  - Level scheme $\Longrightarrow$ γ-ray energy
  - Spin and parity of the states $\Longrightarrow$ γ-ray angular distribution
  - Electromagnetic moments of the excited states $\Longrightarrow$ Several experimental methods ...

Quantities can be compared to theoretical models once wave functions are computed.

High resolution spectroscopy

- But generally limited efficiency
- Based on semi-conductor
- Low to medium energy γ-rays
- Complex low energy structure

High efficiency spectroscopy

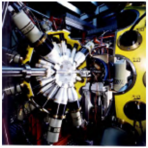
- But generally limited resolution
- Based on inorganic scintillation materials
- Medium to high energy γ-rays
- Resonant structures

New devices reuniting the two aspects:

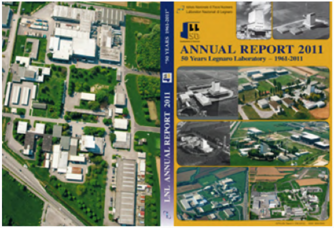
The AGATA tracking array

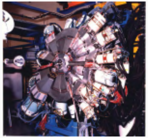
γ-spectroscopy at LNL

γ-spectroscopy at LNL - A long story (short)



GASP

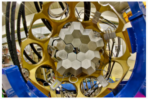




EUROBALL

CLARA

- 80 % of nuclear physics research
- 50 % γ-ray spectroscopy
- Neutron-deficient and neutron-rich nuclei



AGATA

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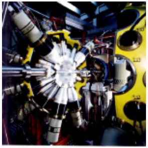

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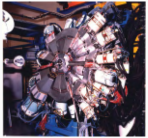

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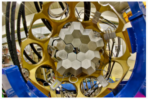


AGATA

Exploring the low energy structure of the nuclei

VOLUME 74, NUMBER 6 PHYSICAL REVIEW LETTERS 6 FEBRUARY 1995

N = 40 Neutron Subshell Closure in the ^{68}Ni Nucleus

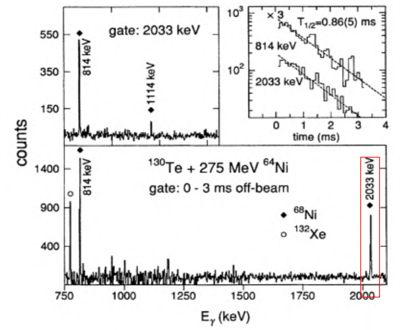
R. Broda, B. Fornal, W. Królas, and T. Pawłat
H. Niewodniczański Institute of Nuclear Physics, PL-31-342 Kraków, Poland

D. Bazzacco, S. Lunardi, C. Rossi-Alvarez, and R. Menegazzo
Dipartimento di Fisica dell'Università di Padova and INFN, I-35131 Padova, Italy

G. de Angelis, P. Bednarczyk, J. Rico, and D. De Acuña
INFN Laboratori Nazionali di Legnaro, I-35020 Legnaro, Italy

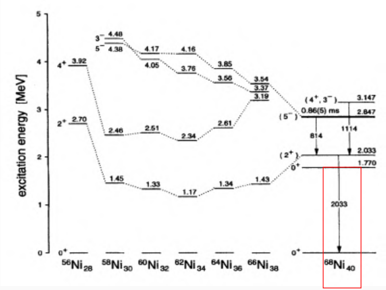
P. J. Daly, R. H. Mayer, and M. Sferrazza
Chemistry Department, Purdue University, West Lafayette, Indiana 47907

H. Grawe, K. H. Maier, and R. Schubart
Hahn-Meitner-Institut Berlin, D-14109 Berlin, Germany
(Received 28 June 1994)



GASP experiment

Deep-inelastic reaction ^{64}Ni + ^{130}Te



Large increase of the E(2^+) at $N = 40$

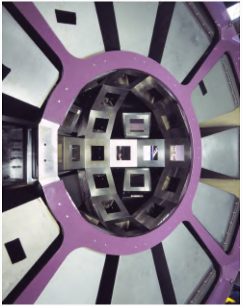
→ subshell closure

→ Evolution of the magicity far from stability

Coupling the γ-spectrometer with complementary setup

Deep-inelastic and multi-nucleon transfer reaction $\Longrightarrow$ Population of moderately neutron-rich nuclei BUT:

- Identification in thick target experiment is limited
- Doppler-broadening
- What to do with weak reaction channel?



CLARA γ-ray array
25 Compton-suppressed Ge Clovers
$\epsilon = 3\%$ for single 1 MeV γ

PRISMA Magnetic spectrometer
$\Omega = 80$ msr
Z, A, q clean identification of the fragments

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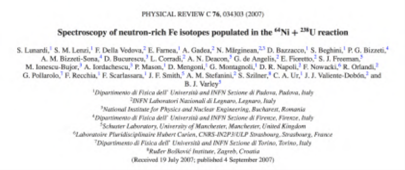
From the $N = 40$ subshell closure down to an island of deformation

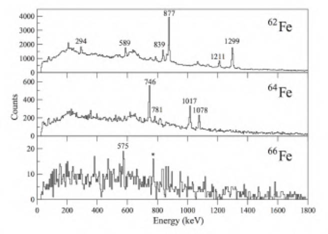

PHYSICAL REVIEW C **76**, 034303 (2007)

Spectroscopy of neutron-rich Fe isotopes populated in the $^{64}Ni + ^{238}U$ reaction

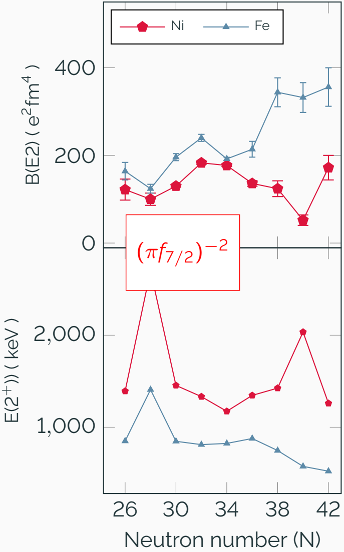
S. Lunardi,[1] S. M. Lenzi,[1] F. Della Vedova,[2] E. Farnea,[1] A. Gadea,[2] N. Mărginean,[2,3] D. Bazzacco,[1] S. Beghini,[1] P. G. Bizzeti,[4] A. M. Bizzeti-Sona,[4] D. Bucurescu,[3] L. Corradi,[2] A. N. Deacon,[5] G. de Angelis,[2] E. Fioretto,[2] S. J. Freeman,[5] M. Ionescu-Bujor,[3] A. Iordachescu,[3] P. Mason,[1] D. Mengoni,[1] G. Montagnoli,[1] D. R. Napoli,[2] F. Nowacki,[6] R. Orlandi,[2] G. Pollarolo,[7] F. Recchia,[1] F. Scarlassara,[1] J. F. Smith,[5] A. M. Stefanini,[2] S. Szilner,[8] C. A. Ur,[1] J. J. Valiente-Dobón,[2] and B. J. Varley[5]

[1]*Dipartimento di Fisica dell' Università and INFN Sezione di Padova, Padova, Italy*
[2]*INFN Laboratori Nazionali di Legnaro, Legnaro, Italy*
[3]*National Institute for Physics and Nuclear Engineering, Bucharest, Romania*
[4]*Dipartimento di Fisica dell' Università and INFN Sezione di Firenze, Firenze, Italy*
[5]*Schuster Laboratory, University of Manchester, Manchester, United Kingdom*
[6]*Laboratoire Pluridisciplinaire Hubert Curien, CNRS-IN2P3/ULP Strasbourg, Strasbourg, France*
[7]*Dipartimento di Fisica dell' Università and INFN Sezione di Torino, Torino, Italy*
[8]*Ruđer Bošković Institute, Zagreb, Croatia*

(Received 19 July 2007; published 4 September 2007)



S. Lunardi et al., PRC **76**, 034303 (2007).
S. M. Lenzi et al., PRC **82**, 054301 (2010).
W. Rother et al., PRL **106**, 022502 (2011).

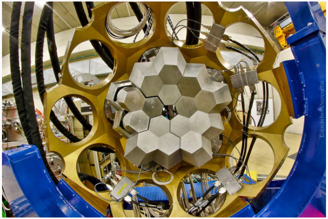


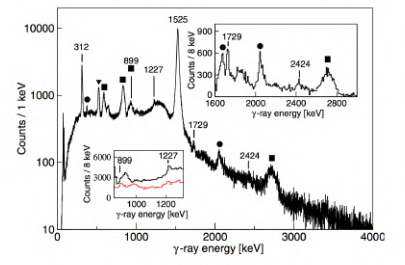
Going deeper into the nuclear structure with the electromagnetic moment measurement

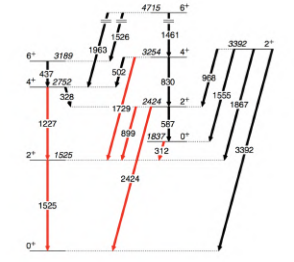
PRL 117, 062501 (2016) PHYSICAL REVIEW LETTERS week ending 5 AUGUST 2016

Superdeformed and Triaxial States in ^{42}Ca

K. Hadyńska-Klęk,[1,2,3,4] P. J. Napiorkowski,[1] M. Zielińska,[5,1] J. Srebrny,[1] A. Maj,[6] F. Azaiez,[7] J. J. Valiente Dobón,[4] M. Kicińska-Habior,[2] F. Nowacki,[8] H. Naïdja,[8,9,10] B. Bounthong,[8] T. R. Rodríguez,[11] G. de Angelis,[4] T. Abraham,[1] G. Anil Kumar,[6] D. Bazzacco,[12,13] M. Bellato,[12] D. Bortolato,[12] P. Bednarczyk,[6] G. Benzoni,[14] L. Berti,[4] B. Birkenbach,[15] B. Bruyneel,[15] S. Brambilla,[14] F. Camera,[14,16] J. Chavas,[5] B. Cederwall,[17] L. Charles,[8] M. Ciemała,[6] P. Cocconi,[4] P. Coleman-Smith,[18] A. Colombo,[12] A. Corsi,[14,16] F. C. L. Crespi,[14,16] D. M. Cullen,[19] A. Czermak,[6] P. Désesquelles,[20,21] D. T. Doherty,[5,22] B. Dulny,[6] J. Eberth,[15] E. Farnea,[12,13] B. Fornal,[6] S. Franchoo,[7] A. Gadea,[23] A. Giaz,[14,16] A. Gottardo,[4]







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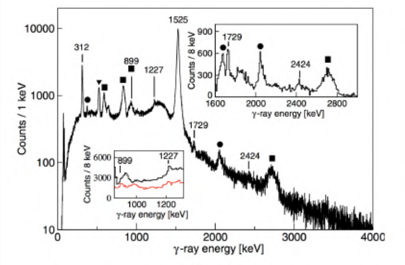
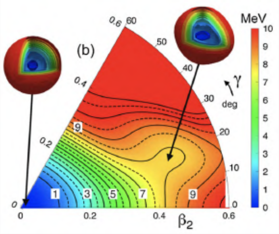
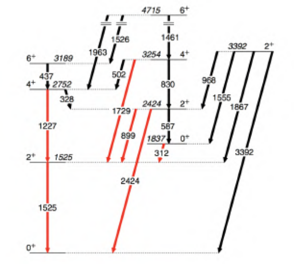


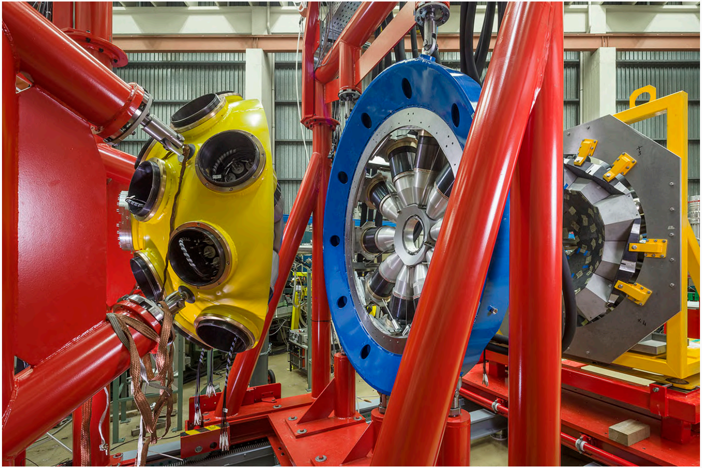




GALILEO: The working horse

Phase 1 - The present implementation

25 HPGe (GASP) + AC + Complementary detectors



A. Goasduff et al., to be submitted Nucl. Inst. Meth. A

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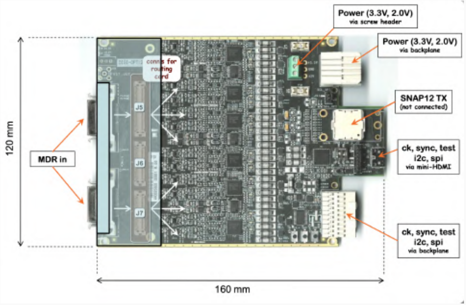
GALILEO Electronics

GALILEO benefits from the developments made for AGATA and GASP detectors:

- Dedicated differential pre-amplifier with fast-reset capabilities
- ADC: DigiOpt-12



A. Pullia et al., 2015 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC)
A. Pullia et al., 2012 IEEE Nuclear Science Symposium and Medical Imaging Conference Record (NSS/MIC)
D. Barrientos et al., IEEE Transactions on Nuclear Science **62** (2015) 3134

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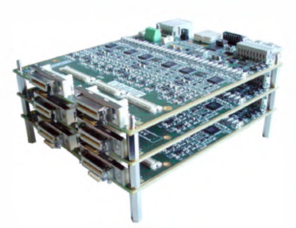

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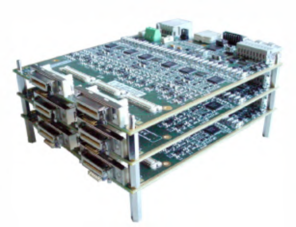

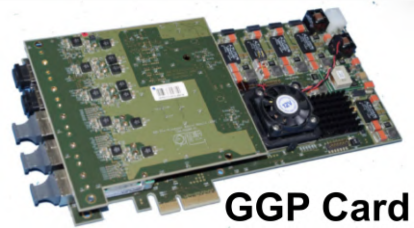

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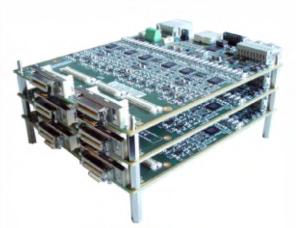
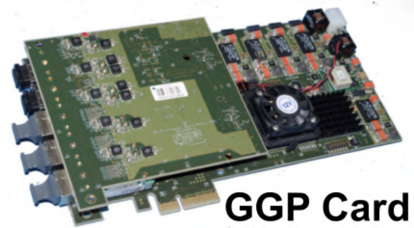
- Synchronization: Global Trigger and Synchronization (GTS)





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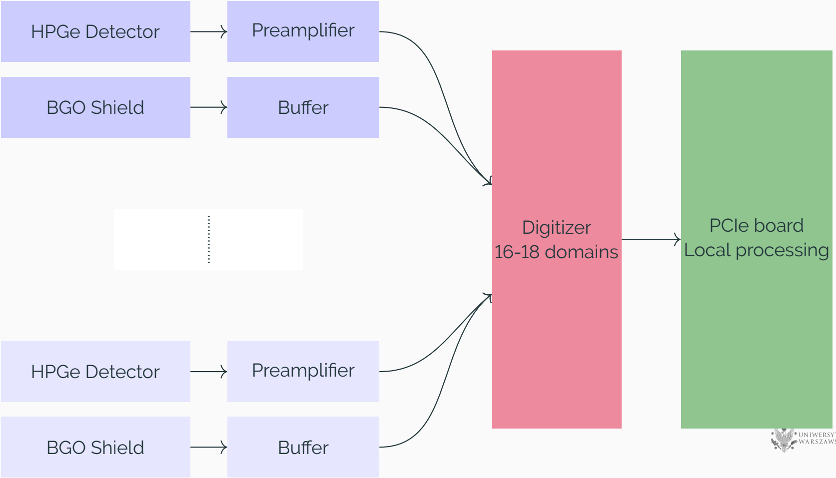
GALILEO Digital electronics



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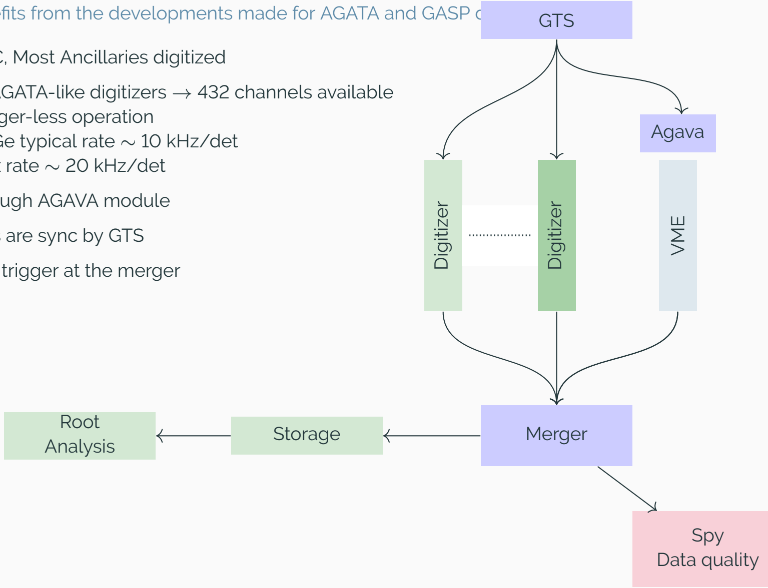
GALILEO readout

GALILEO benefits from the developments made for AGATA and GASP c

- HPGe, AC, Most Ancillaries digitized
  - 12 AGATA-like digitizers → 432 channels available
  - Trigger-less operation
  - HPGe typical rate ∼ 10 kHz/det
  - Max rate ∼ 20 kHz/det
- VME through AGAVA module
- Branches are sync by GTS
- Software trigger at the merger



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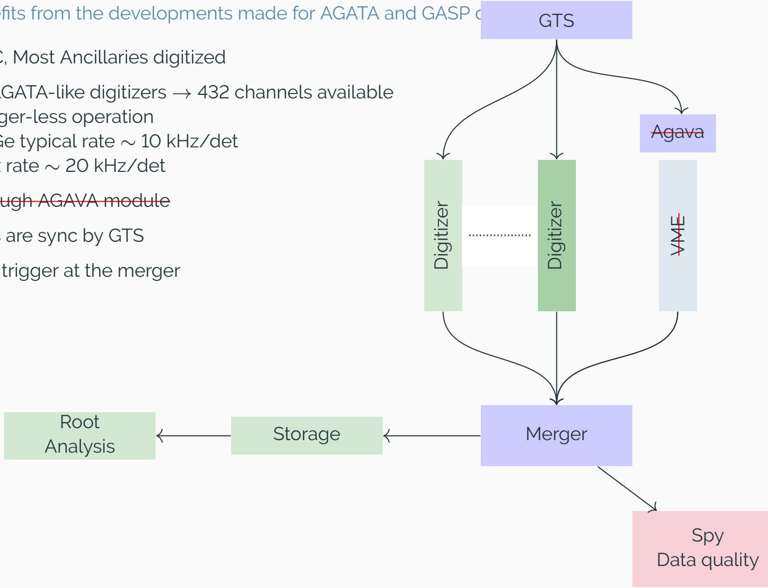

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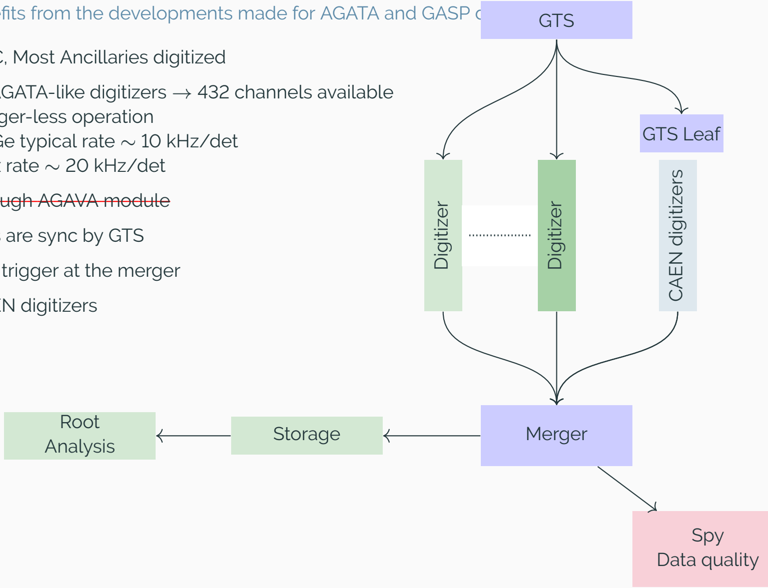
  - HPGe typical rate ∼ 10 kHz/det
  - Max rate ∼ 20 kHz/det
- ~~VME through AGAVA module~~
- Branches are sync by GTS
- Software trigger at the merger
- New CAEN digitizers



First experiments

Experimental campaign: Started in fall 2015

Shape coexitence:
→ ^{60}Zn, D. Mengoni et al.
→ ^{66}Zn, M. Rocchini et al.
→ ^{116}Sn M. Siciliano et al.
→ ^{58}Ni K. Hadyńska-Klęk et al.

Reaction studies:
→ ICF vs CF on Li G. Zhang et al.
→ ICF ^{6}Li G. Zhang et al.

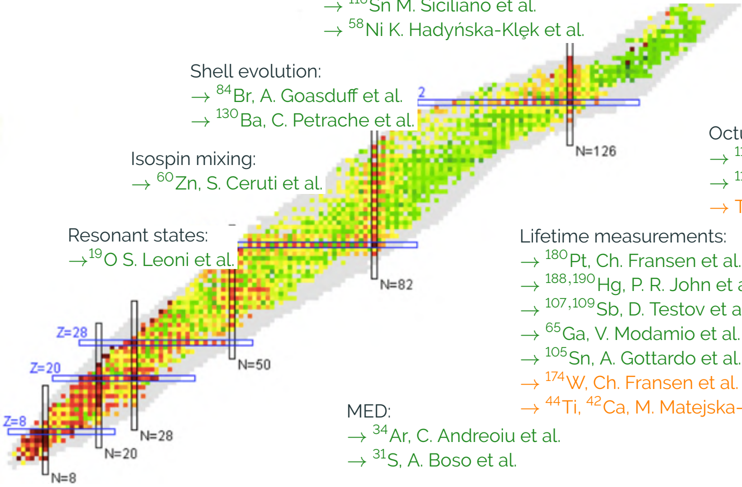
Shell evolution:
→ ^{84}Br, A. Goasduff et al.
→ ^{130}Ba, C. Petrache et al.

Isospin mixing:
→ ^{60}Zn, S. Ceruti et al.

Resonant states:
→ ^{19}O S. Leoni et al.

Octupole deformation:
→ ^{114,116}Ba, J. Smith et al.
→ ^{118}Ba, J. Valiente et al.
→ Th isotopes, J. Smith et al.

Lifetime measurements:
→ ^{180}Pt, Ch. Fransen et al.
→ ^{188,190}Hg, P. R. John et al.
→ ^{107,109}Sb, D. Testov et al.
→ ^{65}Ga, V. Modamio et al.
→ ^{105}Sn, A. Gottardo et al.
→ ^{174}W, Ch. Fransen et al.
→ ^{44}Ti, ^{42}Ca, M. Matejska-Minda et al.



MED:
→ ^{34}Ar, C. Andreoiu et al.
→ ^{31}S, A. Boso et al.

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Summary:
16 exp. performed
3 exp. to be done

Ancillaries

GALILEO complementary detectors

Study of weak reaction channels with stable beams:
High efficiency + High resolving power + High CR capabilities

- Light charged particle detectors
  Euclides, GALTRACE
- Neutron detector
  NeutronWall
- Lifetime measurements
  Dedicated plunger IKP-LNL
- Heavy-ion detectors:
  Spider
- Fast timing or high-energy γ-ray detector
  Large volume $LaBr_3$

Commissioned dets

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- Light charged particle detectors
  Euclides, GALTRACE
- Neutron detector
  NeutronWall, NEDA
- Lifetime measurements
  Dedicated plunger IKP-LNL
- Heavy-ion detectors:
  Spider, RFD, PLASTIC
- Fast timing or high-energy γ-ray detector
  Large volume $LaBr_3$, FT $LaBr_3$

Commissioned dets
Future dets

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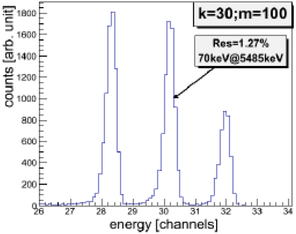
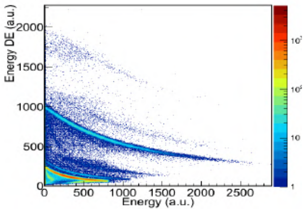
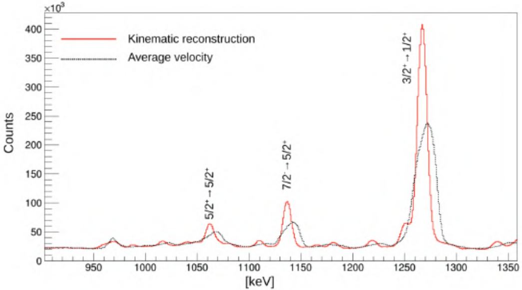
Light charged particles: EUCLIDES



- 110 Silicon detectors (80 % of 4π)
- $\epsilon_\alpha \sim 30\%$; $\epsilon_p \sim 50\%$
- $\sim$ 100% working, $\sim$ 80 keV FWHM
- New compact pre-amplifiers
- Digital electronics
- Trigger-less mode

Channel selection and Doppler correction





- Digital trigger
- Online trapezoidal filter 3 μs
- Offline short trace filtering 0.5 μs
- Trigger-less mode
- Max CR $\sim$ 40 kHz

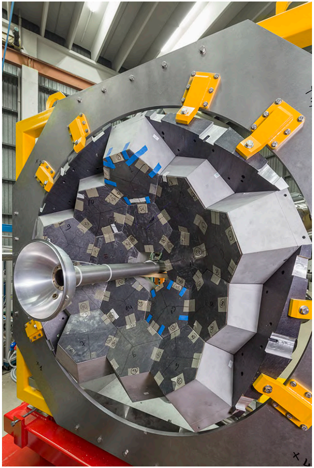
- Digital trigger
- Digital CFD
- Z separation

D. Testov et al., Eur. Phys. J. A **55** (2019) 47

Neutron detection: NWALL-NEDA

The NeutronWall array at LNL:

- 45 liquid scintillators detectors
- Analogue electronic providing three signals: ToF, ZCO and QVC
- VME readout



Ö. Skeppstedt et al., Nucl. Inst. Meth. A **421** (1999) 531.

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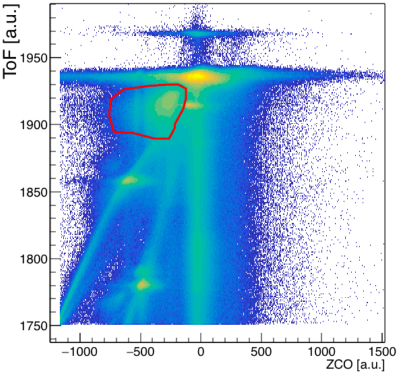

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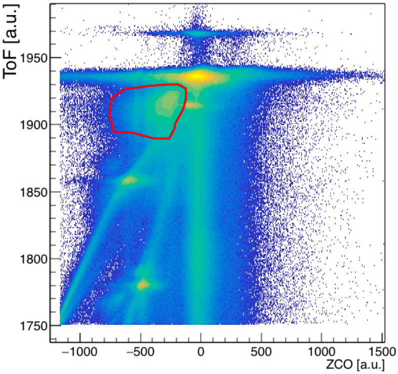

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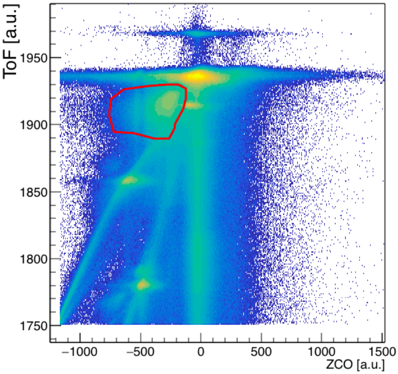

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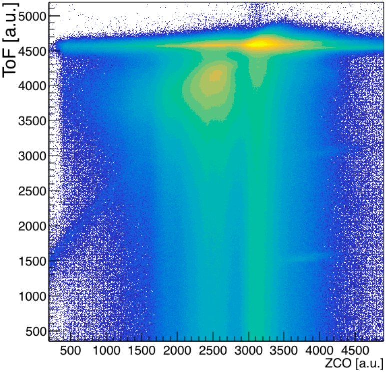

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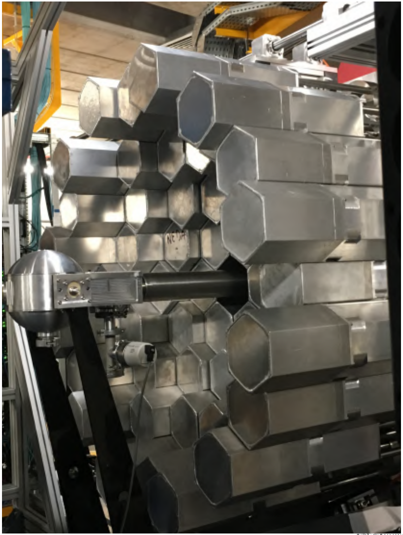
Coupling NEDA with GALILEO?



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J.J Valiente-Dobón et al., Nucl. Inst. Meth. A **927** (2019) 81.

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Coupling NEDA with GALILEO?

- NUMEXO2 readout
- GTS compatibility
- DAQ modification

Ö. Skeppstedt et al., Nucl. Inst. Meth. A **421** (1999) 531.
J.J Valiente-Dobón et al., Nucl. Inst. Meth. A **927** (2019) 81.

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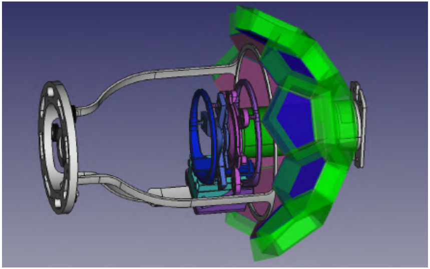
Lifetime measurements with the plunger techniques

LNL plunger developed in collaboration with IKP Cologne.
Constrains:

- Reaction chamber geometry
- Coupling to other ancillaries (Euclides, ...)
- Shadowing of the motor

⇒ Compact design



C. Müller-Gatermann et al., Nucl. Inst. Meth. A **920** (2019) 95
D. Testov et al, submitted to Nucl. Inst. Meth. A

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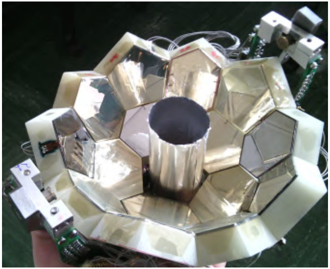

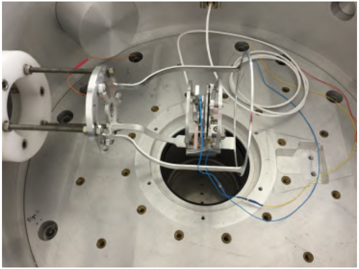

C. Müller-Gatermann et al., Nucl. Inst. Meth. A **920** (2019) 95

D. Testov et al, submitted to Nucl. Inst. Meth. A

GALTRACE:
segmented E-ΔE telescopes for direct reaction studies

- Versatile array to be coupled with:
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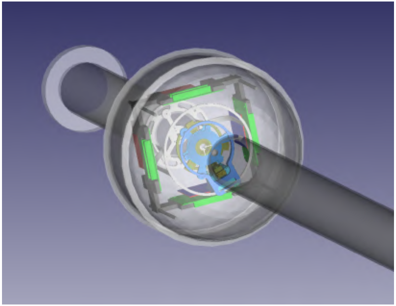
  - SPIDER
  - ...



UNIWERSYTET WARSZAWSKI

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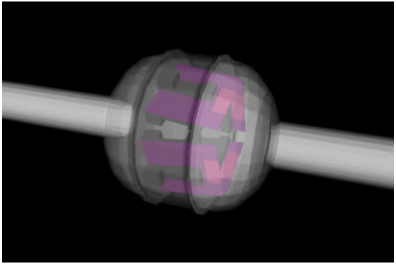
  - ASIC Pre-amps (Uni. Milano / INFN Milano)



S. Capra et al., Nucl Inst. Meth. A **935** (2019) 178.

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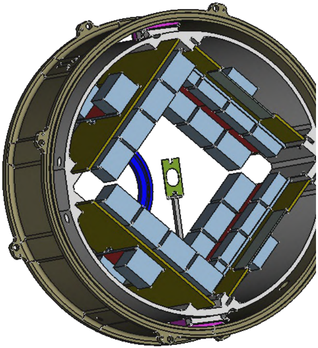

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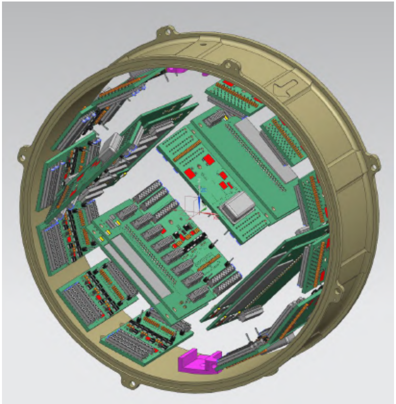

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S. Capra et al., Nucl Inst. Meth. A **935** (2019) 178.

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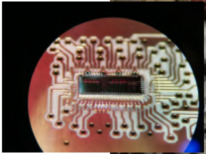
- First in-beam test: July 2019



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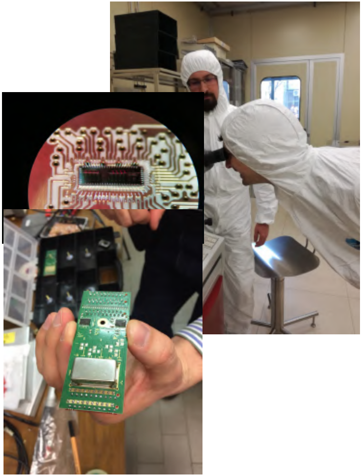
  - Now in production
- First in-beam test: July 2019
- 4 exp. submitted to the next LNL PAC



S. Capra et al., Nucl Inst. Meth. A **935** (2019) 178.

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GALTRACE:
First in-beam test

Up to 4 12×2 cm^2 E-ΔE pads telescopes

- ΔE layer:
  - 200 μm
  - 60 Pads (4×4 mm^2)
  - 61 signals (back + pads)
- E layer:
  - 1000 - 1500 μm
  - 60 Pads grouped in 4
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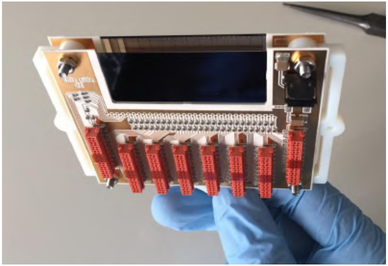

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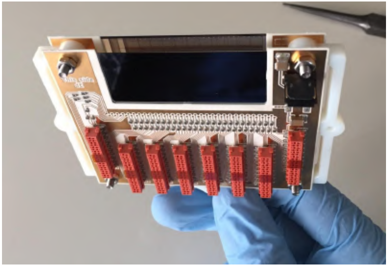

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- Commissioning experiment:
  - ^{13}C+^{nat}LiF (back. ^{nat}C)
  - Beam at 23 MeV
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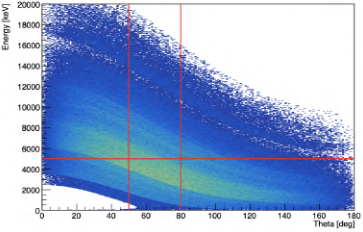

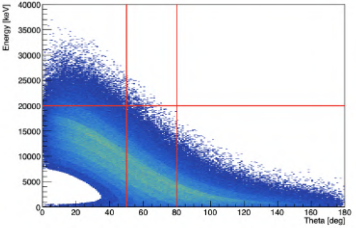

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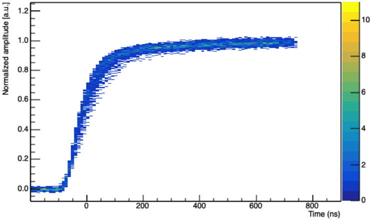

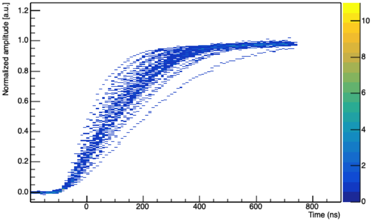

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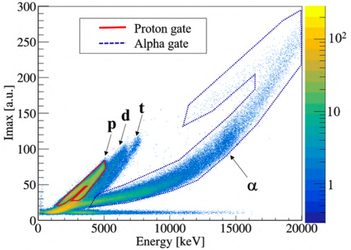

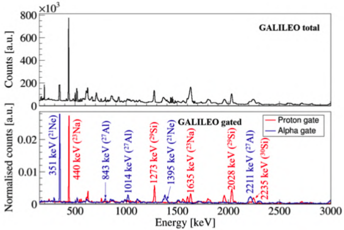

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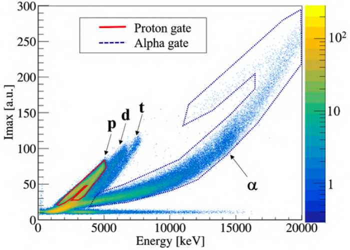

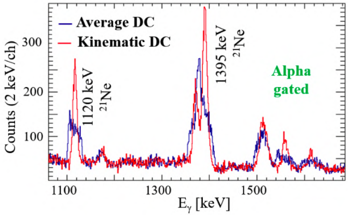

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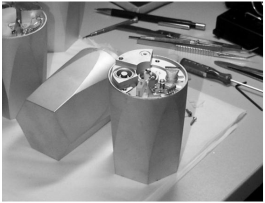
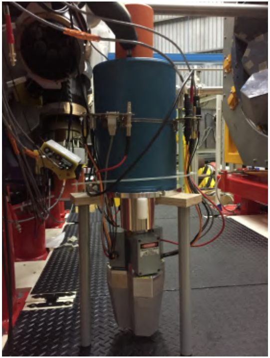
The GALILEO project - Phase 2



EUROBALL TC + AGATA electronics

- preamplifiers
- digital sampling
- preprocessing
- DAQ



Combination of GASP and EUROBALL detectors

- 25 GASP detectors @ 23.5 cm
- 10 TC detectors @ 23.5 cm

$\epsilon_{ph} \sim$ 6.3% @ 1.3 MeV

P/T $\sim$ 50%

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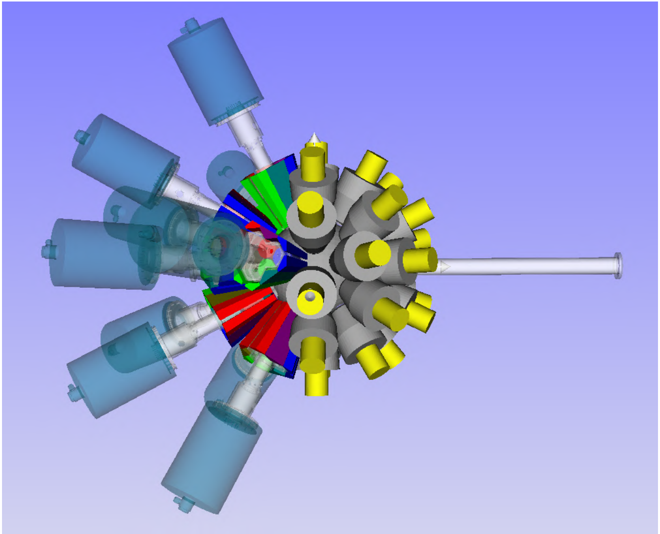
The GALILEO Phase II upgrade



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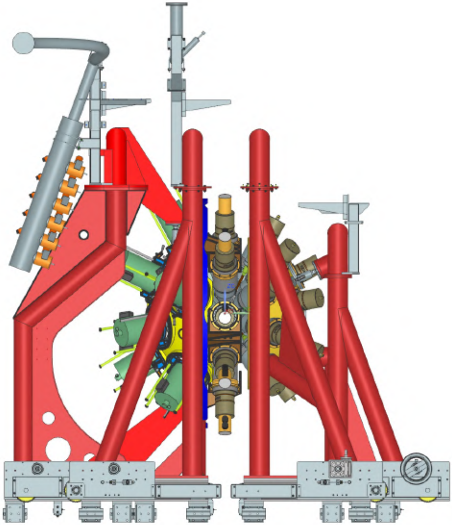

Collaboration with N. Bez, M. Rampazzo

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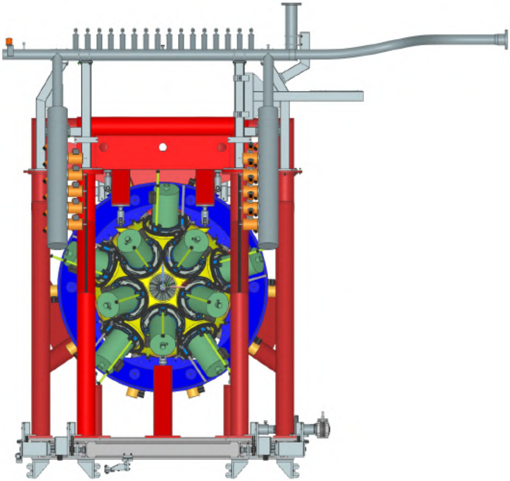

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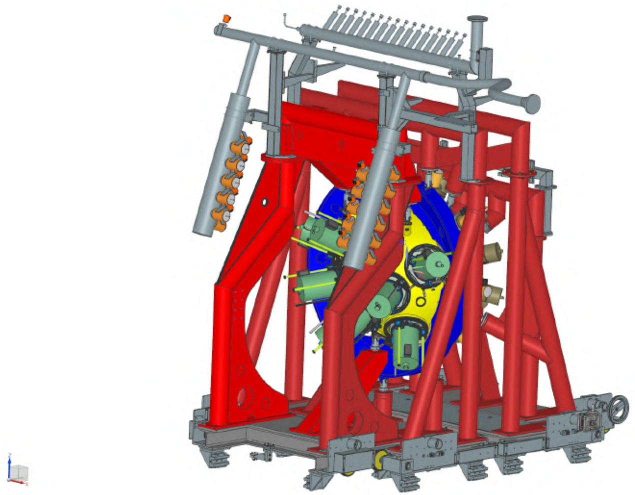

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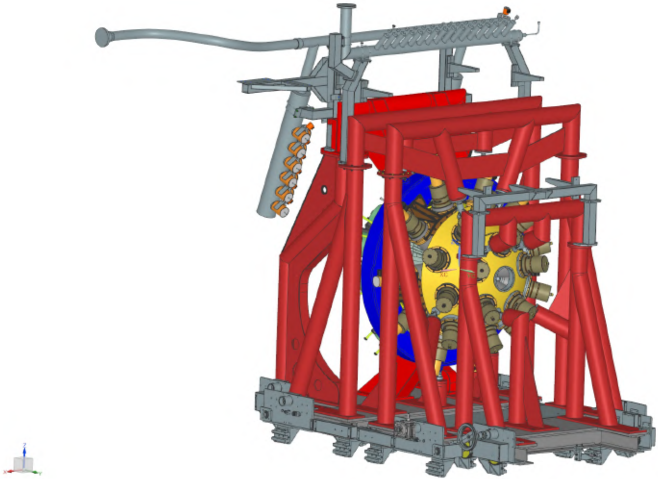

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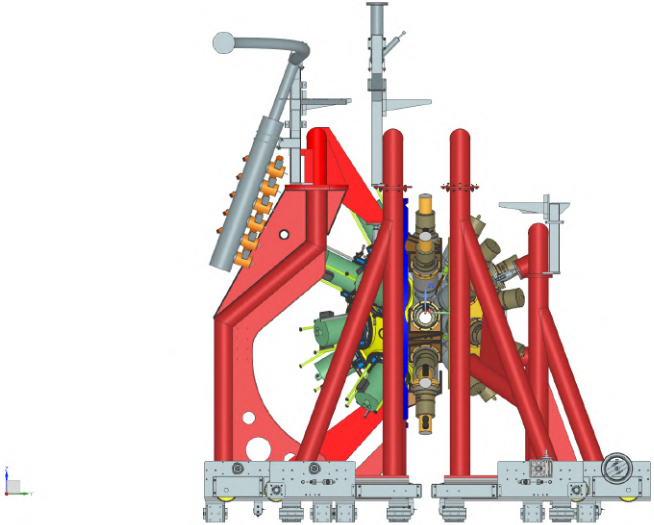
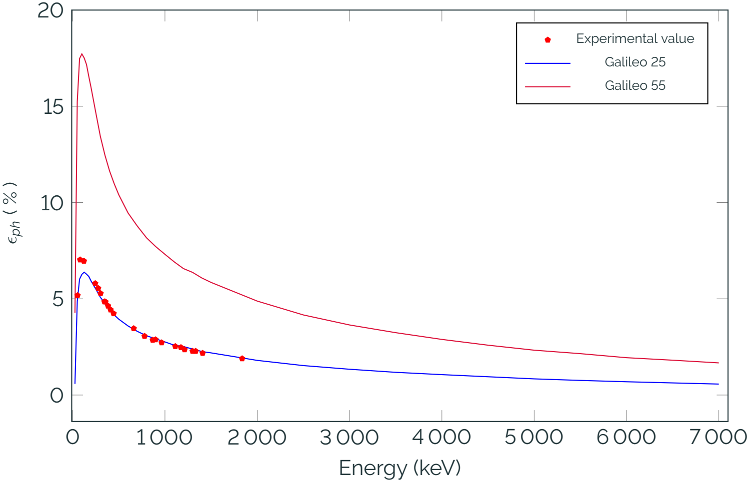
The GALILEO Phase II upgrade



Collaboration with N. Bez, M. Rampazzo

The GALILEO Phase II upgrade: Performances



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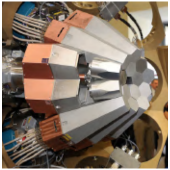
AGATA coming back

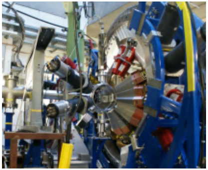
The AGATA time line

2009



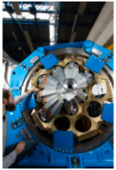
AGATA@LNL

2011



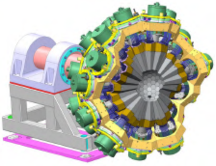
AGATA@GSI

2014



AGATA@GANIL

2021



AGATA@LNL

AGATA back to LNL:

- From 1π up to 2π HPGe array
- One year shut-down before the installation
- Six months from 2022 of stable beams
- When available RIB from SPES 6 months RIB and 6 months stable beams

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Local Project Manager: J.J. Valiente-Dobón

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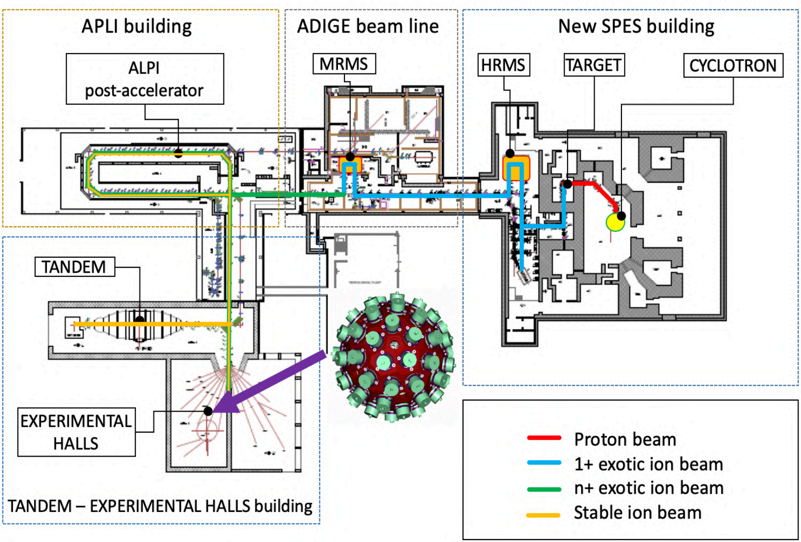
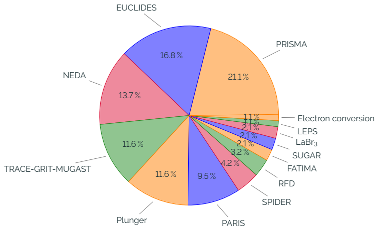
AGATA location @ LNL



Stable beam experimental campaigns

First physics workshop for AGATA@LNL with stable beams in March 2019
$\Longrightarrow$ **60 LoIs** distributed in:

- Light Exotic Nuclei and astrophysics
- Nuclear Resonances
- Nuclear Shapes
- Nuclear Shell Structure
- High-spin Physics
- $N = Z$ nuclei
- Nuclear Reactions



All (local) GALILEO ancillaries will be available + possible others

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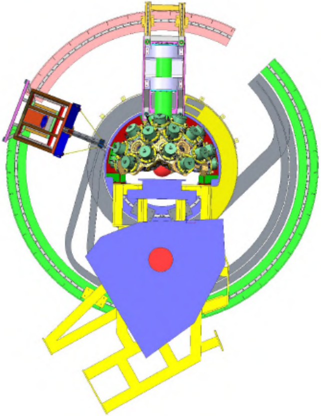
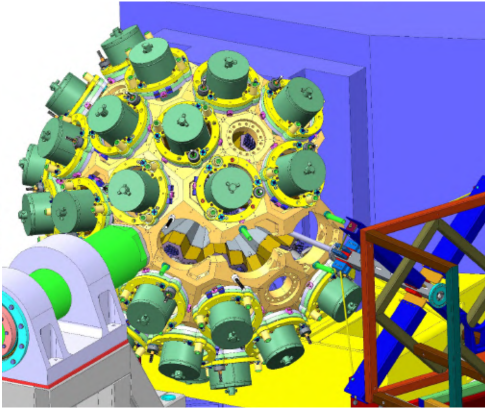
Setup AGATA+PRISMA





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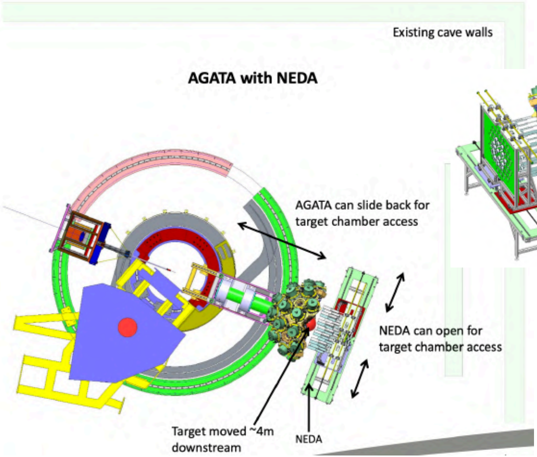
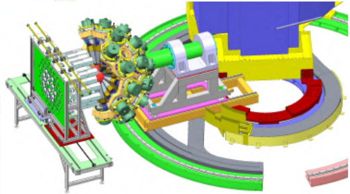
Setup "Zero-degrees"

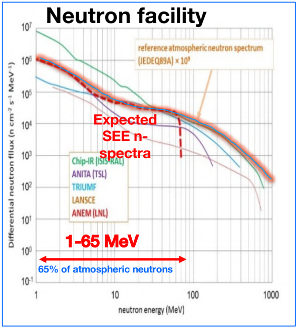


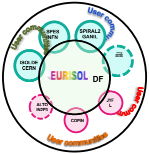


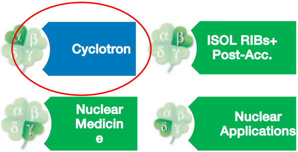
SPES
Exotic beams for science

The SPES Project goals

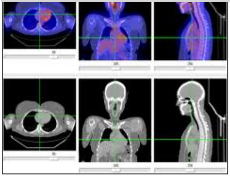
- 2^{nd} generation ISOL facility for nuclear physics as part of the EURISOL_DF initiative (ESFRI_2020):
- Production & re-acceleration of exotic beams (neutron rich nuclei $\rightarrow$ 10^{13} f/s)
- Research and Production of Radio-Isotopes for Nuclear Medicine
- Accelerator-based neutron source (Proton and Neutron Facility for Applied physics)







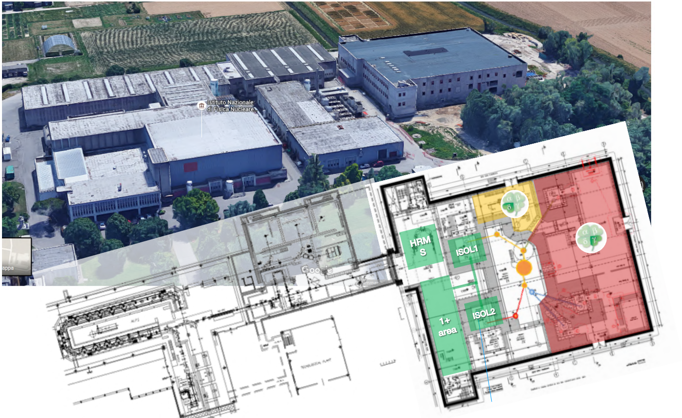
Radioisotpes for medicine



SPES infrastructure layout

SPES @ LNL: Facility for the production of RIB

- New High power compact CYCLOTRON 70 MeV 750 mA
- New configuration of High power ISOL System (8 kW Target ion source)
- ALPI superconductive LINAC (up-graded) for RIB's reacceleration



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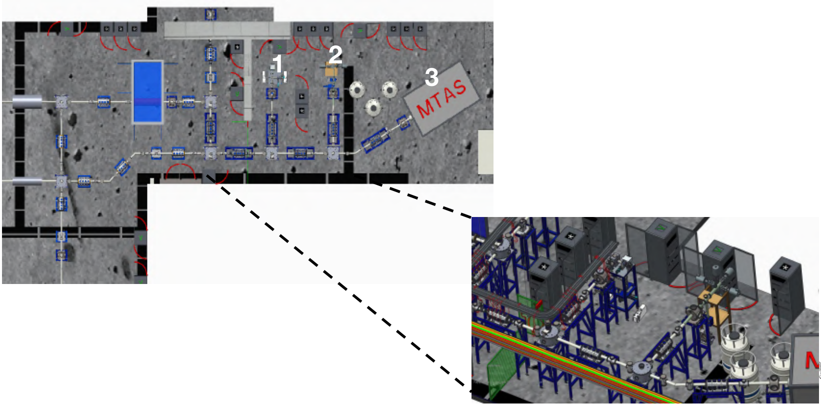
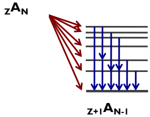
Low energy experimental area

Room for 3 separate set-ups:

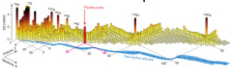
1. Beam monitoring station equipped with moving tape system
2. In-house set-up for β-decay exp and conversion electron spectrometer:
   $\Longrightarrow$ b-DS and SLICES
3. Space for bulky equipment for TAS measurement andor β-delayed neutron emission studies



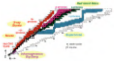
Project b-DS + SLICES: Nuclear structure via β decay



- Study of nuclear structure:
  $\Longrightarrow$ selective tool (selection rules peculiar highlight decay paths)
  $\Longrightarrow$ study of evolution of shapes and exotic shapes
  $\Longrightarrow$ evolution of magic number



- Study of β decay properties ($T_{1/2}$, P_n, BR, S_β, ...)
  $\Longrightarrow$ strong link to stellar nucleo-synthesis (inputs for r- and s- process)
- Exotic decay modes: PDR via β decay



- Fundamental questions: CKM unitarity via study of super-allowed decays
- Complementary with other approaches
- Simple equipment: a β-decay station (b-DS) @ SPES
- A number of everyday applications of β-decaying sources can be found, for instance, in nuclear medicine, nuclear safety ...

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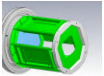
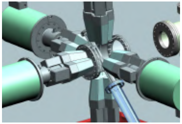
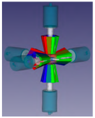
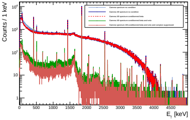
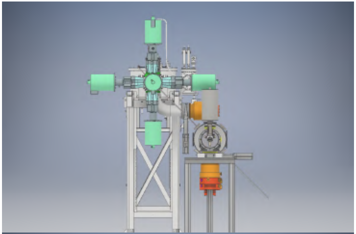
The b-DS β-decay station @ SPES

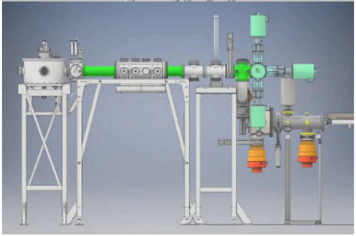
2 positions served by the same moving tape:

- Large coverage of decay times
- Measurement of $\beta - \gamma$ and E0
- Flexibility to add detectors for fast-timing high-energy γ-rays
- EJ212 with SiPM readout 
- 
- Simulation and dedicated data analysis tools



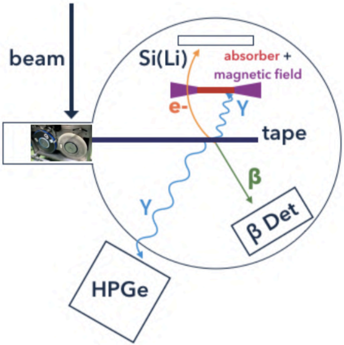






Contact person: G. Benzoni - INFN Milan

SLICES:
SPES Low-Energy Internal Conversion Electron Spectrometer

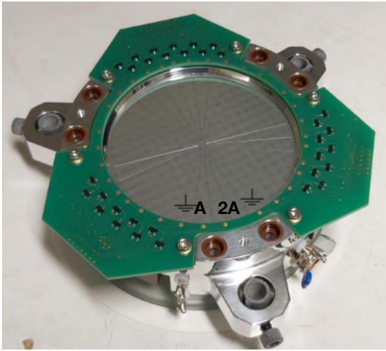


- Using b-DS tape system
- Si(Li) detector for e^-:
  - Diameter = 70 mm (3900 mm^2)
  - Thickness = 6.8 mm
  - Segmented in 32 independent sectors
- Magnetic transport system
- Plastic scintillator for β-tagging
- HPGe detector for γ rays

Contact person: A. Nannini - INFN Florence

SLICES
Si(Li) detector system

Test of the resolution at the Jülich Forschungszentrum with a ^{207}Bi source (analog acquisition)



Segment	ACQ time (s)	Shaping (μs)	FWHM (keV)
2A	1500	6	3.4
A	1500	6	3.7
A	1500	3	2.4

Measurement performed at 975 keV.

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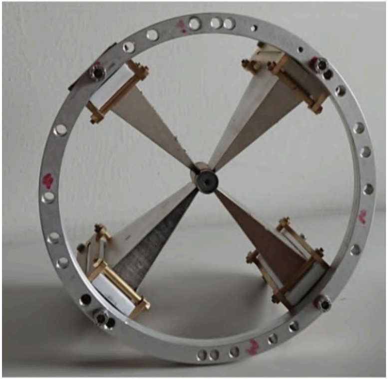
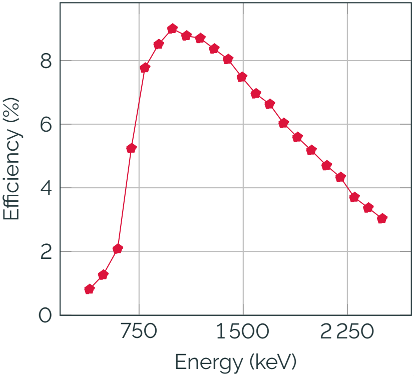
SLICES:
Magnetic transport system

Four permanent magnets (NdFeB) assembled around a photon shield.

Simulated efficiency (source-magnets-detector 0-60-125)
(CST Particle Studio simulation)





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Summary and perspectives

Conclusions

- High resolution γ-ray spectroscopy shed light on new phenomenons
- Strong collaborations between experimental and theoretical nuclear physicists allow to deepen our understanding of the nuclear interaction:
  - Tensor force
  - Key role of the 3N force
  - Importance of the continuum for the description of weakly bound nuclei
- The *terra incognita* is now getting closer and closer:
  - Pushing back the technical limits of the detection setup (counting rate, efficiency, ...)
  - Radioactive ion beams facility like SPES
- But we should not forget the stable beams:
  - High precision measurements which are important to really constrains the theoretical models
  - Exploring the high energy structure of stable nuclei to look for exotic structures

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Conclusions on LNL γ-spectroscopy infrastructure

- GALILEO is the permanent γ-ray spectrometer at LNL
  - Its first implementation, Phase-1, is operational with 25 HPGEs.
  - GALILEO makes use of various ancillary detectors managed at national and international collaborations.
  - First campaign GALILEO Phase-1 since 2015
    NW + Euclides + Plunger + $LaBr_3$ + SPIDER + ...
  - Other campaigns will follow: GALTRACE, RFD, ...
  - It is expected to represent the resident γ-ray spectrometer with the advent of RIBs at SPES.
- Working on the installation of AGATA@LNL:
  - Mechanical infrastructure
  - DAQ and computing farm installation
  - ...
- Development of dedicated setups for the 1^+ beam lines at SPES:
  - Test of the tape system are promising,
  - First mechanical parts of the b-DS and SLICES chambers are under construction,
  - Test of the detection setups are ongoing.

THANK YOU FOR YOUR ATTENTION!

Special thanks to the GALILEO and GAMMA group and in particular G. Benzoni, A. Nannini, and J.J. Valiente-Dobòn

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