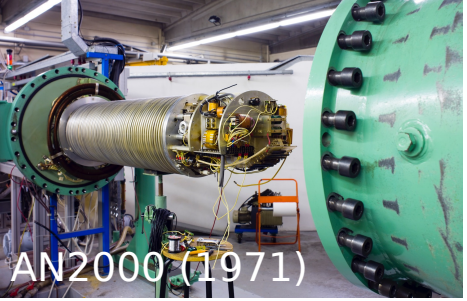
High-resolution γ-ray spectroscopy at the Legnaro National Laboratories

Daniele Mengoni
Università di Padova e INFN

for the GALILEO collaboration

Istituto Nazionale di Fisica Nucleare

source: http://home.infn.it/it/approfondimenti/

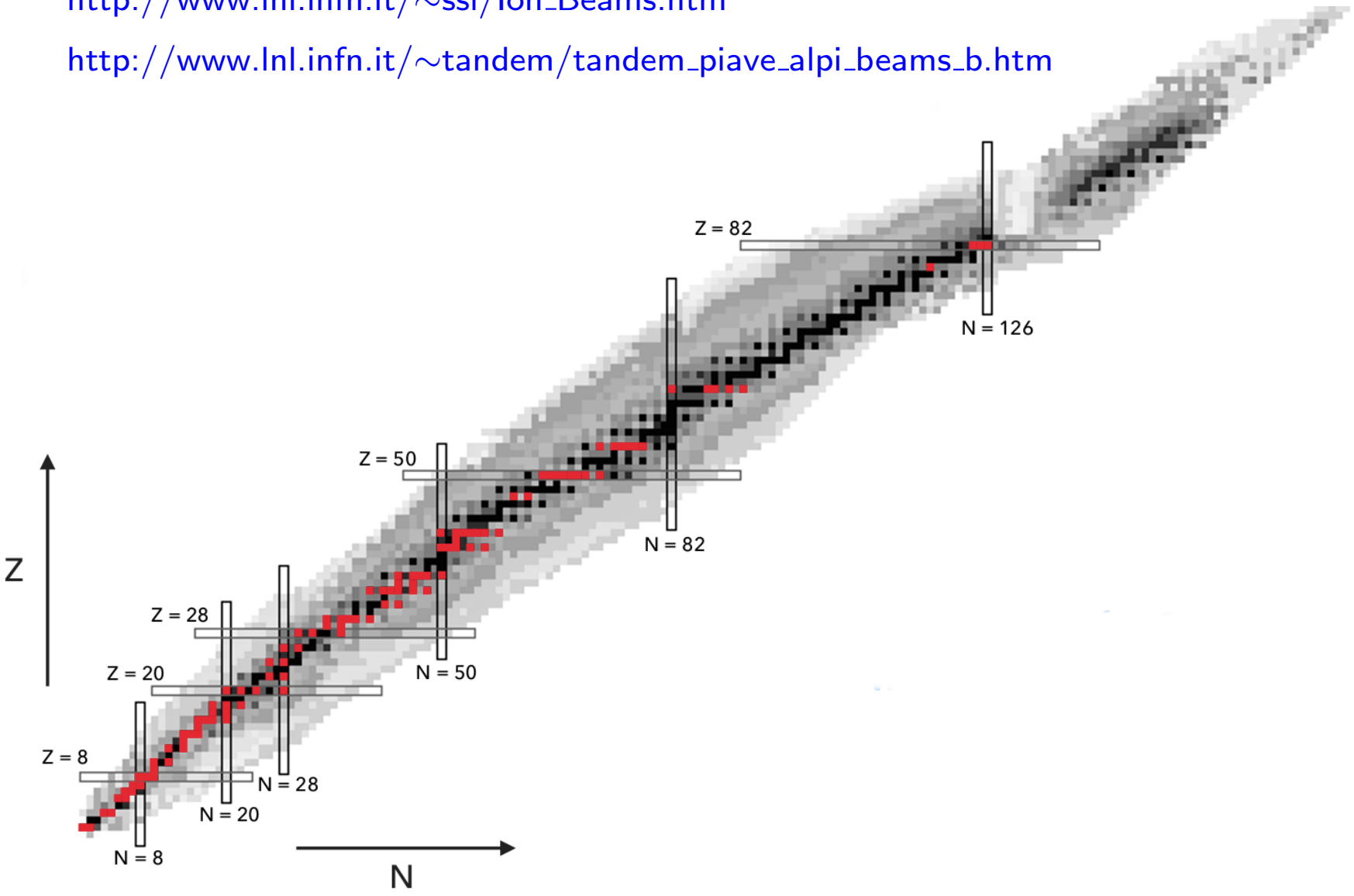


LNL Accelerators INFN

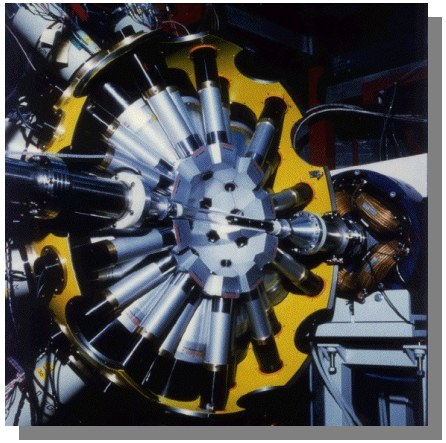
Stable Beams at LNL Legnaro:

http://www.lnl.infn.it/~ssi/Ion_Beams.htm

http://www.lnl.infn.it/~tandem/tandem_piave_alpi_beams_b.htm

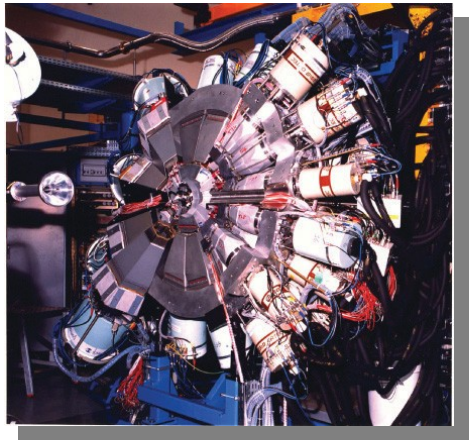


Large GammaRay Arrays at LNL



GASP 1992

ε_{ph} ~ 3% (@ 27 cm)
~ 6% (@ 22 cm)
P/T ~ 60%

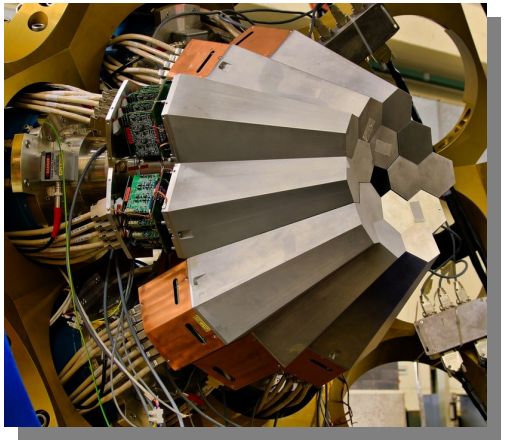


EUROBALL 1998

ε_{ph} ~ 9%
P/T ~ 50%

CLARA 2004

ε_{ph} ~ 3%
P/T ~ 50%

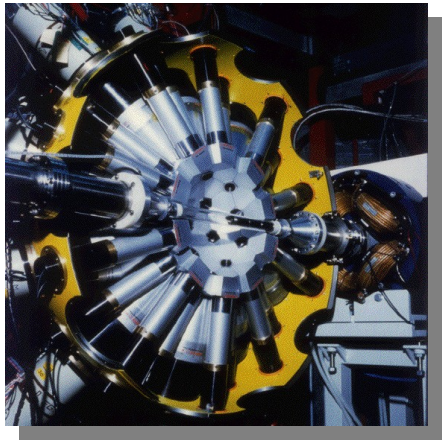


AGATA 2010

ε_{ph} ~ 6%
P/T ~ 50%

- How does the nuclear force depend on varying proton-to-neutron ratios?
- How are complex nuclei built from their basic constituents?
- What is the effective nucleon-nucleon interaction
- Provide nuclear structure input to other fields like nuclear astrophysics
- Collectivity and shell model
- Isospin symmetries
- Isospin mixing in N=Z nuclei
- How does shell structure change far away from stability ... ...

Large GammaRay Arrays at LNL



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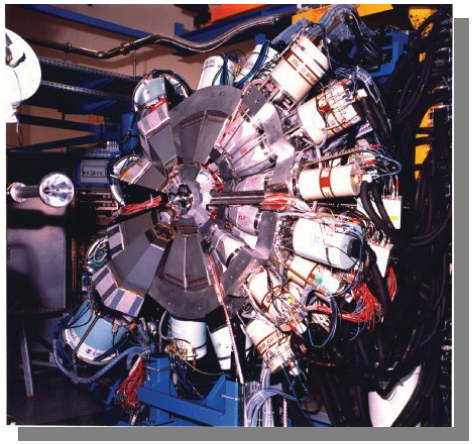

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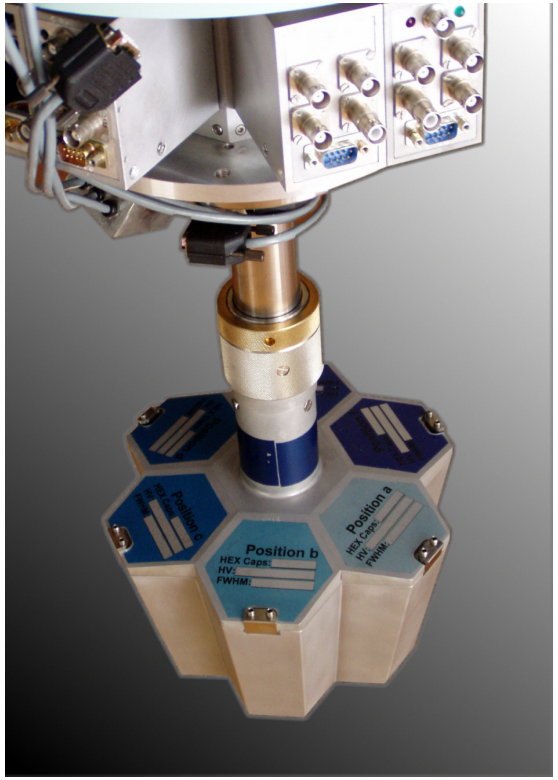
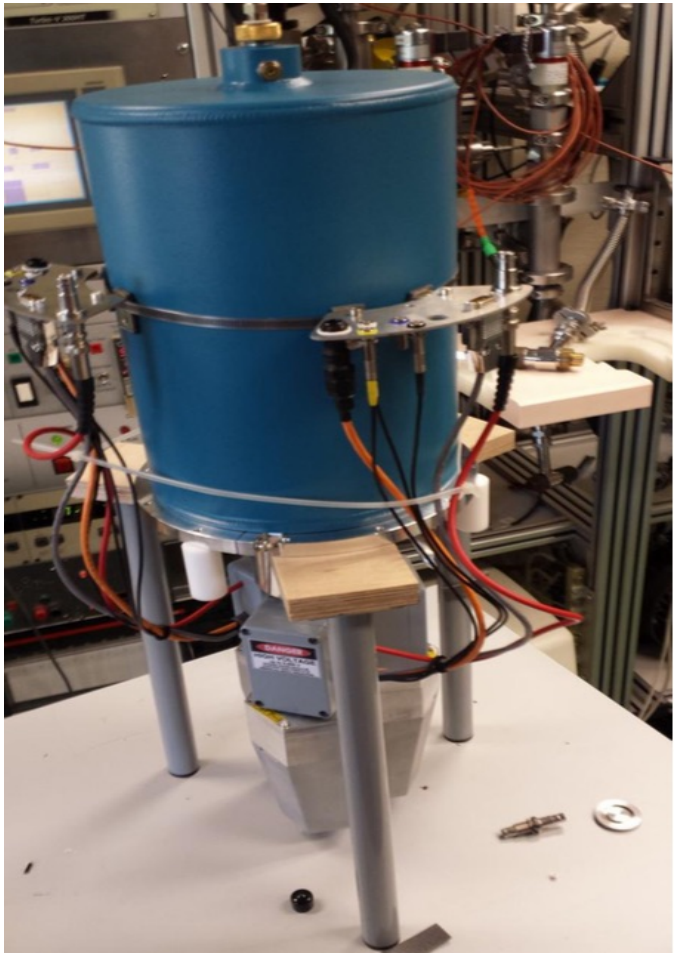
Current array: GALILEO

- 25 HPGe CS detectors
- Angles: $90^\circ/60^\circ$, 152°, 129°, 119°
- at 22.5cm; $\epsilon \sim$2.4% at 1332.5 keV
- FWHM at 1332.5 keV $<$ 2.4 keV
- Trigger-less mode
- Typical operational rate $\sim$20 kHz/det
- Common clock synchronization
- Local data processing

10 GALILEO triples



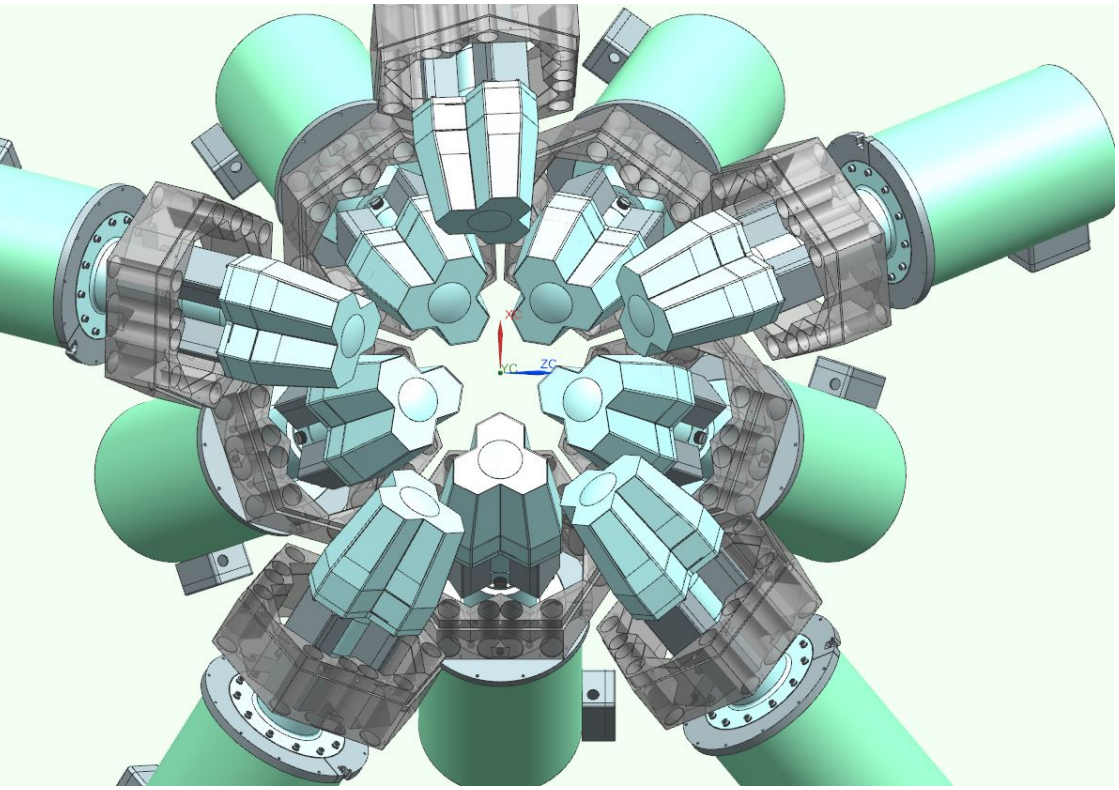


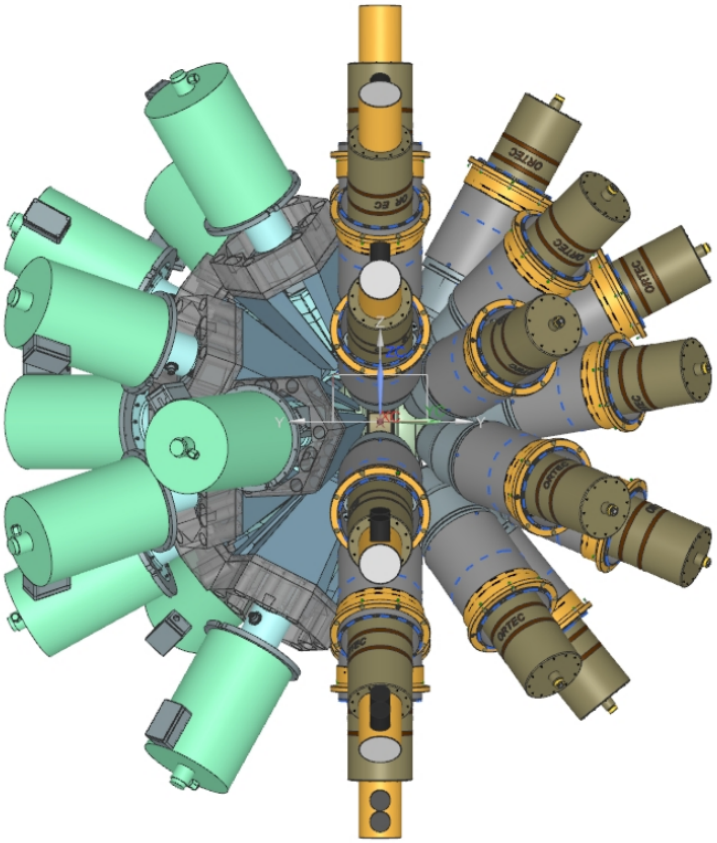
- New triple cluster out of the EUROBALL capsules.

GSI FAIR
GSI Helmholtzzentrum für Schwerionenforschung

Decay-spectroscopy campaign

Galileo Phase 2 (very soon), Tripple Clusters

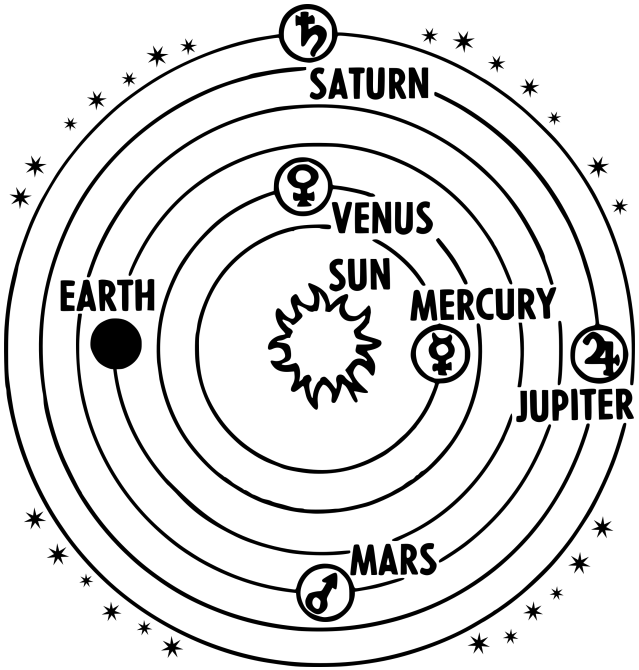


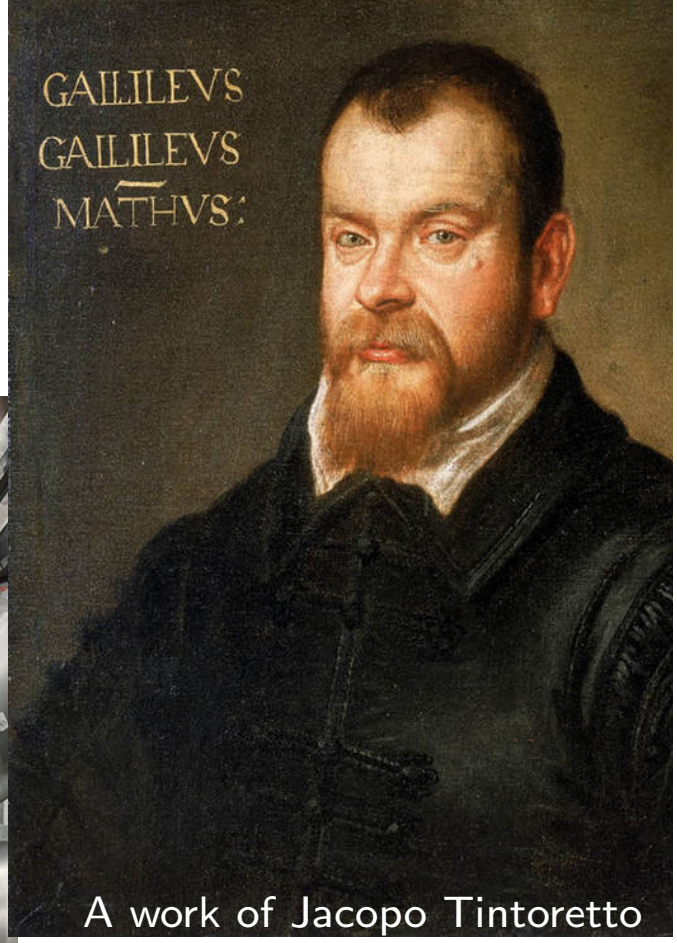


- Physics program driven configuration: 10 GTC backward angles
- Efficiency ∼7.5%, PT∼60%

Galileo γ-ray spectrometer

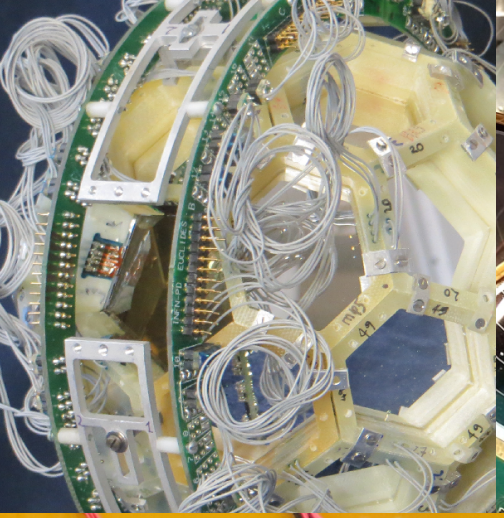
Galileo Galilei lived and worked in Padova 1592-1610

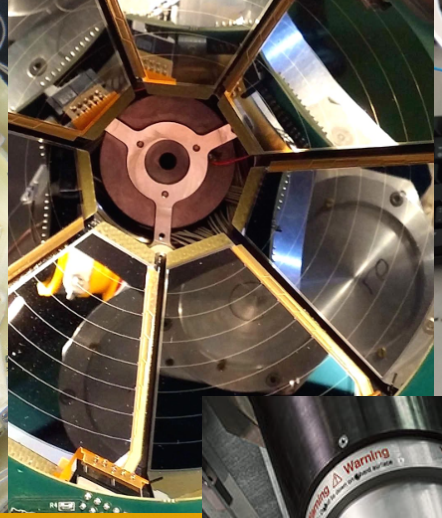


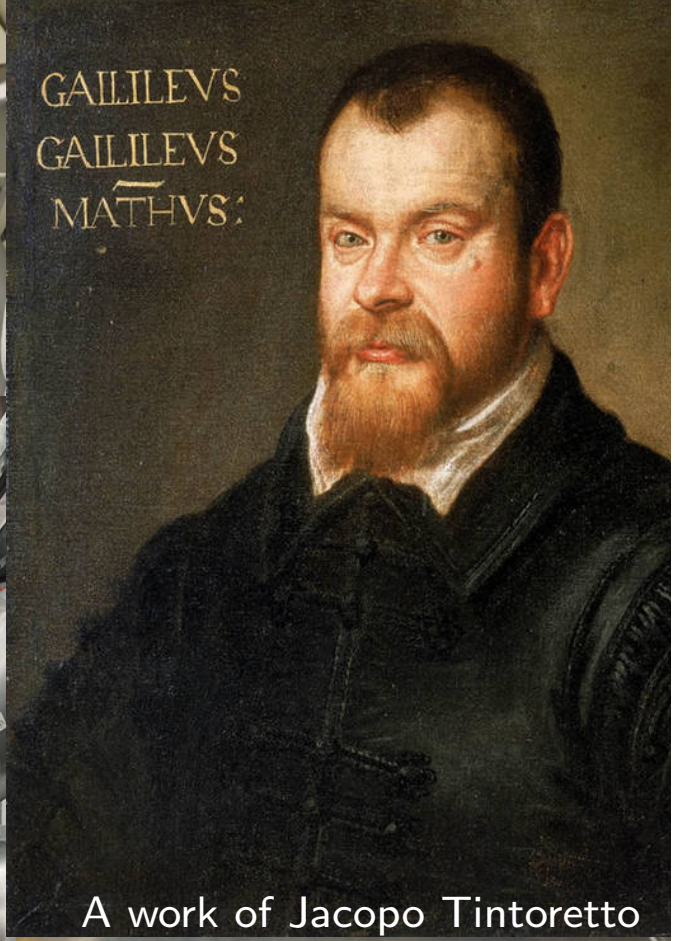


A work of Jacopo Tintoretto

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro







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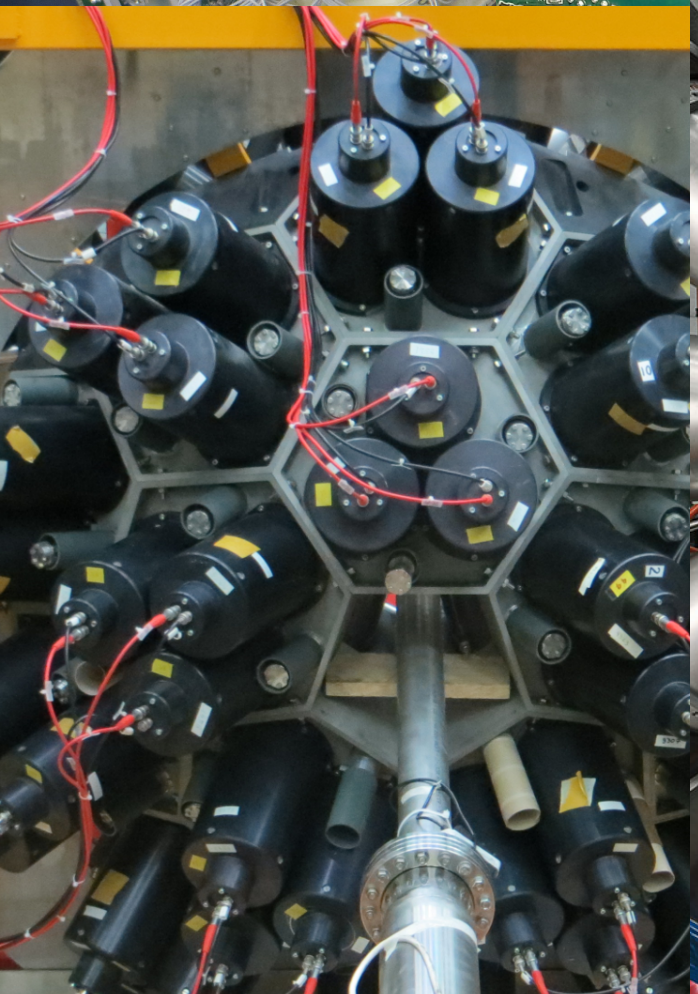
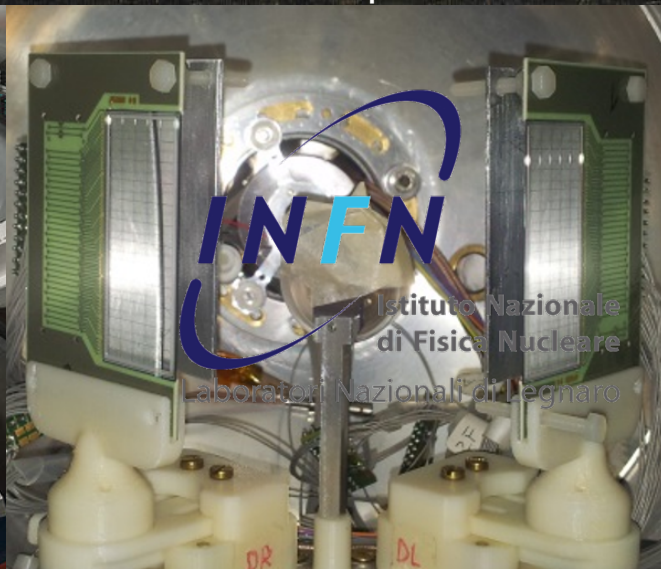
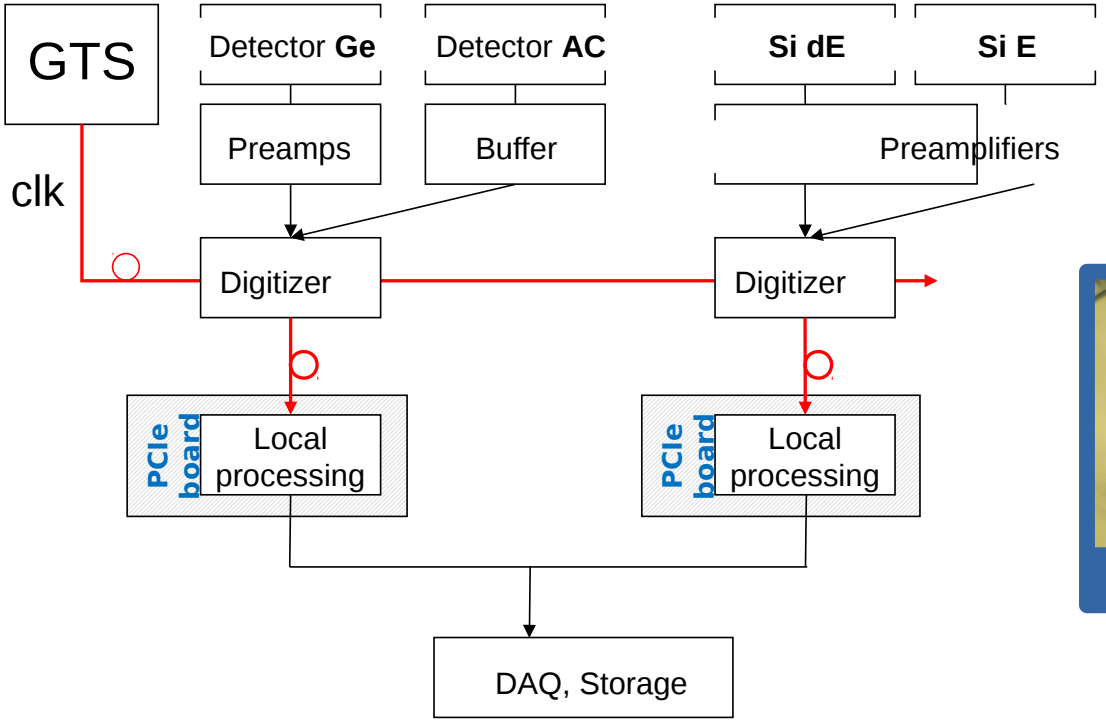


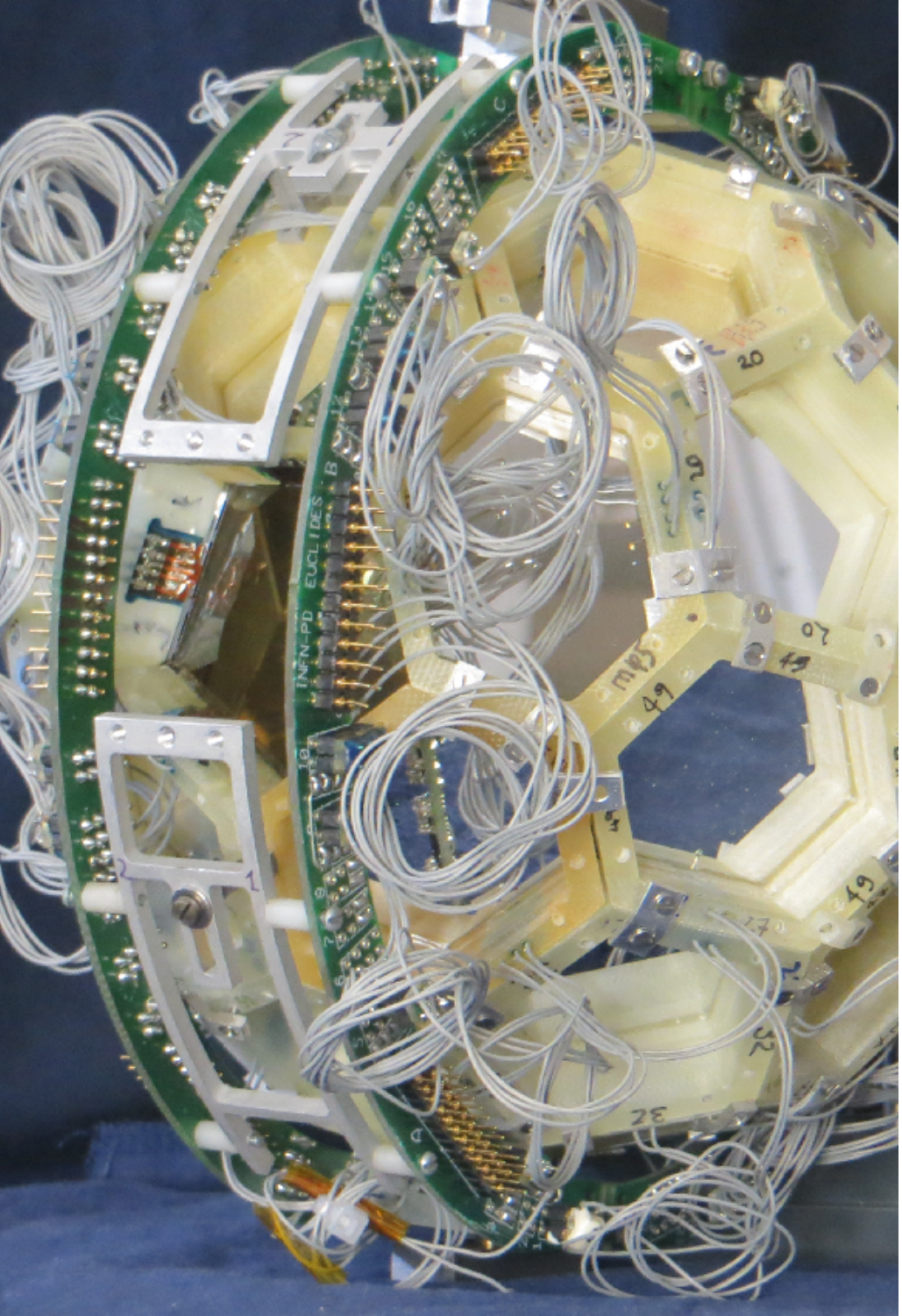


GALILEO digital electronics



- → **HPGe, AC, Ancillary digitized**
- → **Branches are sync by GTS**
- → **Trigger-less operation**
- → **240 channels available (112 for EUCLIDES)**
- → **Typical rate ~ 20 kHz/det**
- → **Max rate ~ 50 kHz/det**

SPIDER/TRACE use the same infrastructure



EUCLIDES

Light Charger particle Si-ball array

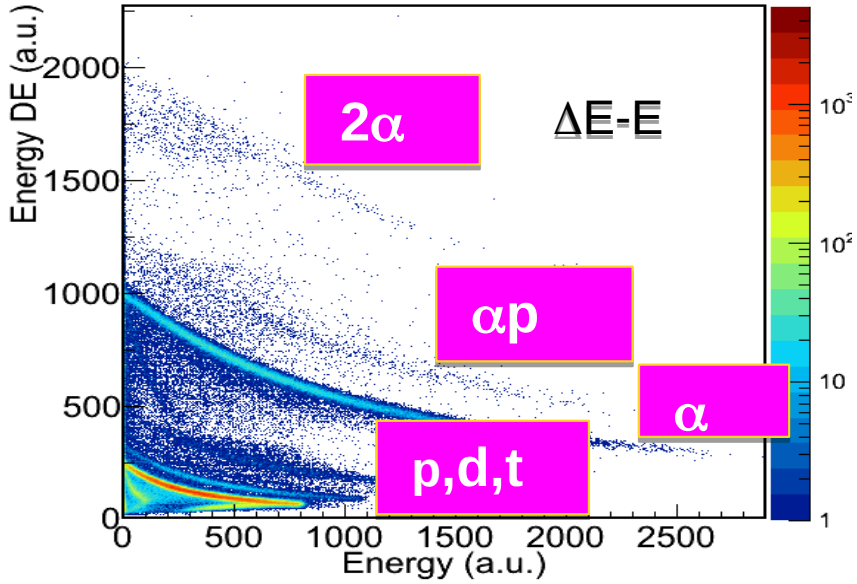
- Channel selection
- Enhanced resolving power of GALILEO
- Correction for Doppler Effect
- 80% of angular coverage
- $\epsilon(\alpha)\sim$40%*; ϵ(p)$\sim$60%*
- Plunger configuration
- 3 out of 4 experimet rely on EUCLIDES

* reaction-dependent

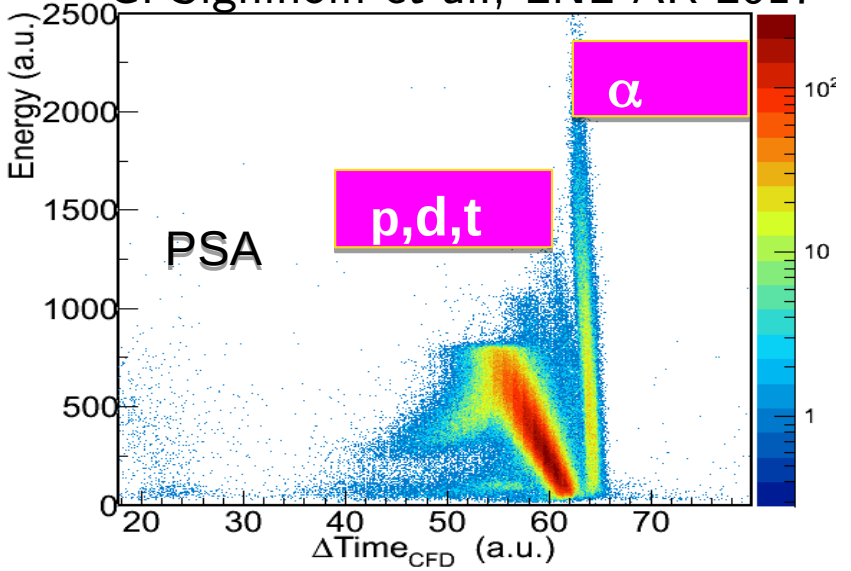
D. Testov, D. Mengoni, A. Goasduff et al.,
Eur. Phys. J. A (2019) 55 47

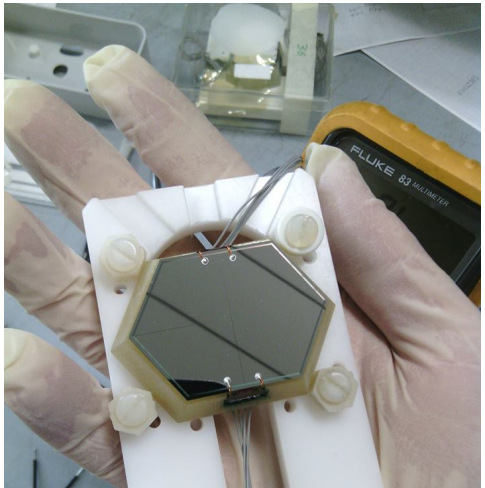
EUCLIDES Si-ball detector

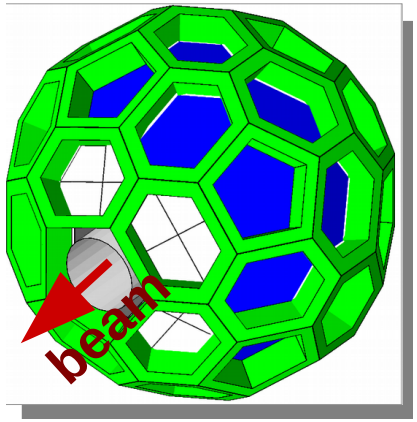
- Telescope technique (ΔE-E and ...PSA)
- 40 ΔE-E telescopes pent and hex shape
- Thickness 150 μm (ΔE) 1000 μm (E) area $\sim$10 cm^2
- Lab resolution 50 keV (ΔE) 25 keV (E)
- Trigger less operation
- New compact electronics
- 5 the most forward positioned telescopes are segmented in 4 sectors each: higher count rate, better correction for Doppler Effects



G. Sighinolfi et al., LNL AR 2017

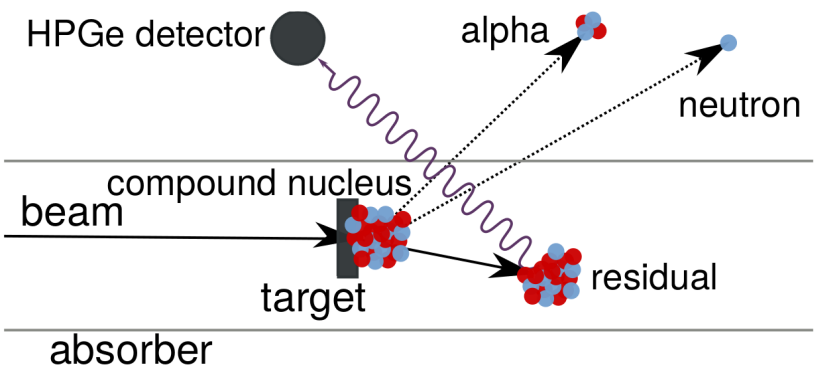






Full kinematic reconstruction

^{12}C(at 45 MeV)+^{24}Mg→^{36}Ag* →^{31}P [1α1p]



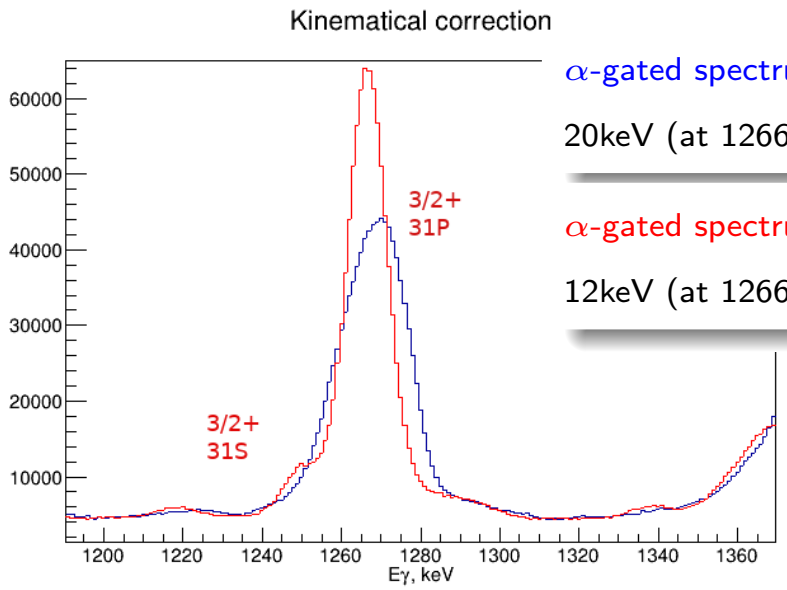
$$p_{residual} = p_{compound} + \sum_{particles} p_{particle}$$

Mean velocity

Euclides Energy Calibration

Energy-loss for each particle in the absorber

Angles of Euclides telescopes

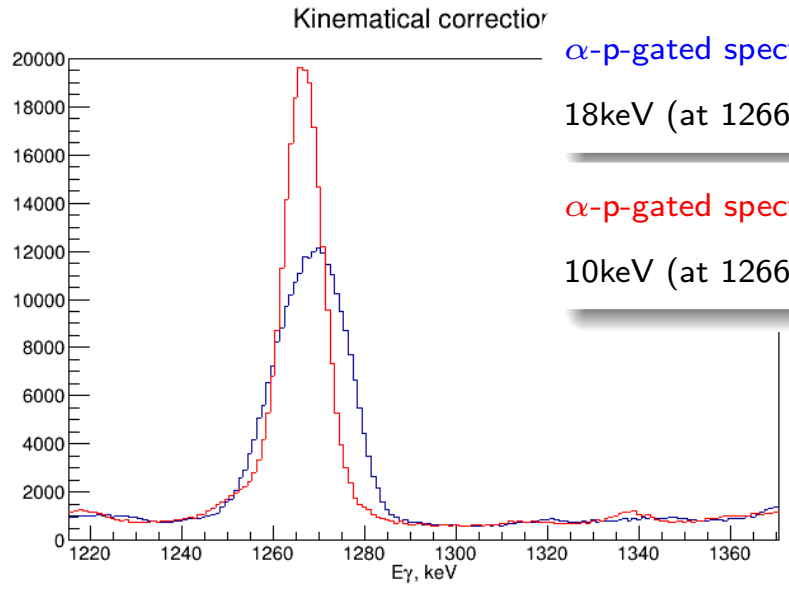


α-gated spectrum

20keV (at 1266 keV)

α-gated spectrum

12keV (at 1266 keV)

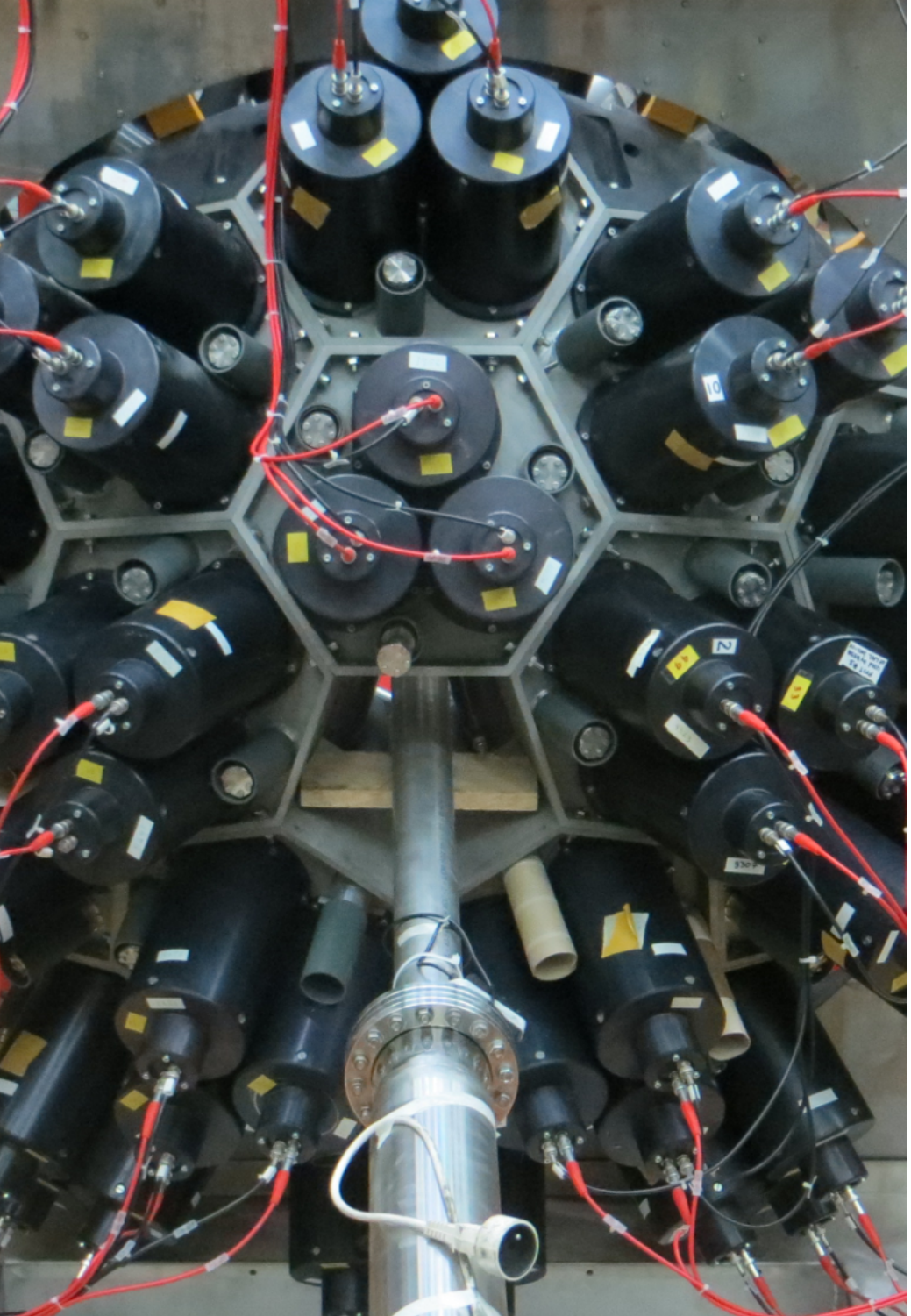


α-p-gated spectrum

18keV (at 1266 keV)

α-p-gated spectrum

10keV (at 1266 keV)



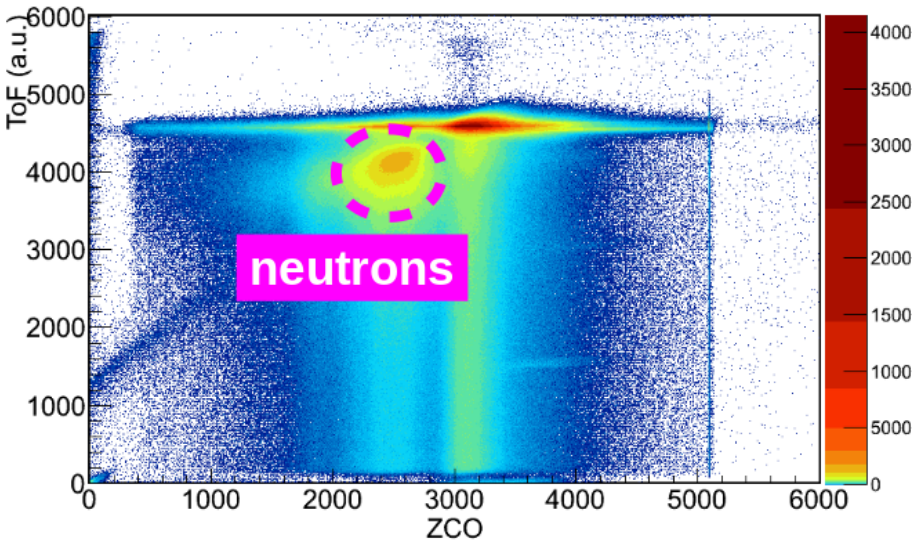
Neutron Wall

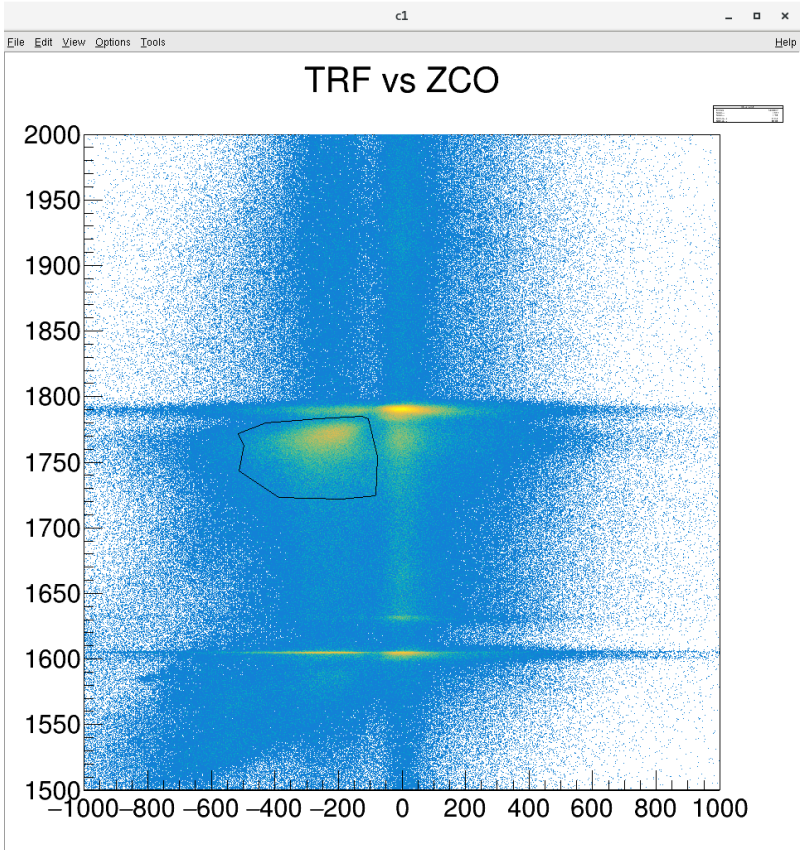
- Enhanced resolving power of GALILEO
- liquid scintillator (BC501A) ~150 liters
- Number of detectors: 45
- Mounted at 0° (forward hemisphere)
- Target to detector face distance: 51 cm.
- 25% of angular coverage
- ϵ(1n)~25(2)%; ϵ(2n)~2(1)%
- Probability to miss-interpret γ-ray as a neutron: $\leq 10^{-3}$

Credits: Grzegorz Jaworski

A. Lonardi, Master thesis (2015)

Neutron Wall



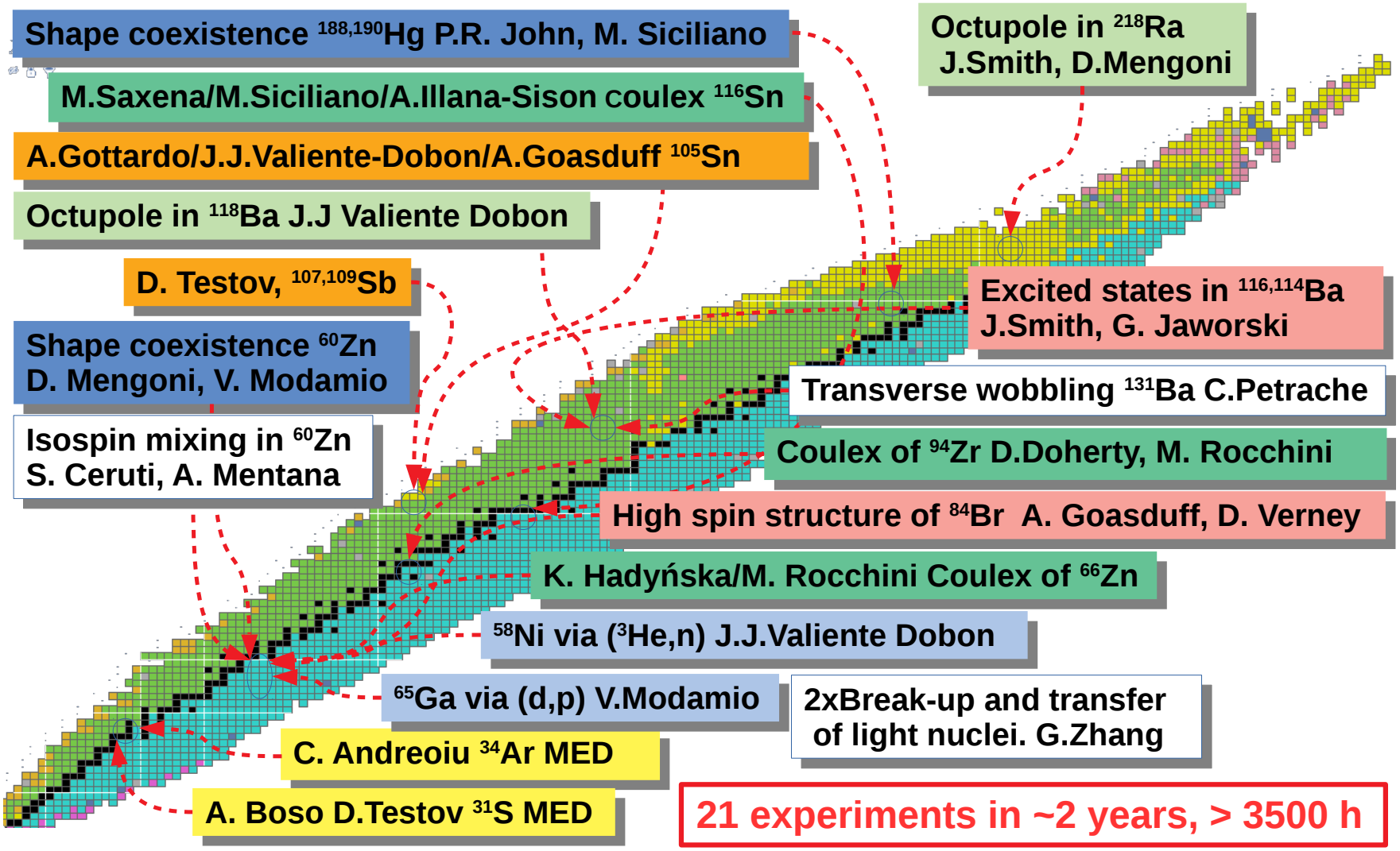


- Three types of signals for each of them: QVC, TOF, ZCO
- Preselected neutron condition provided to the trigger
- VME/Digital electronics, depending on the channel availability

Credits: Grzegorz Jaworski

A. Lonardi, Master thesis (2015)

Science campaign

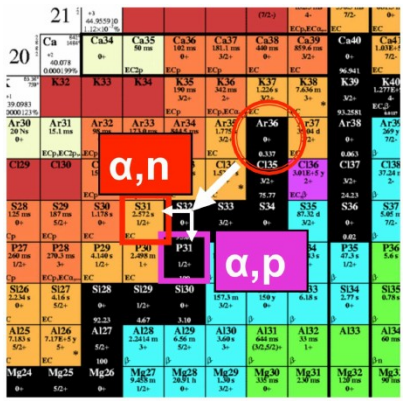


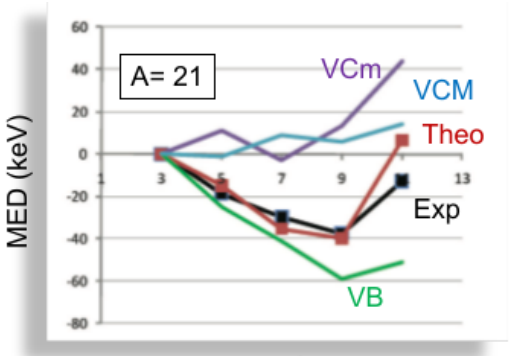
21 experiments in ~2 years, > 3500 h

^{12}C(45 MeV) + ^{24}Mg
Boso, Testov, Lenzi, Recchia et al

Presentation on Tuesday – D.Testov

MED in mirror nuclei A=31

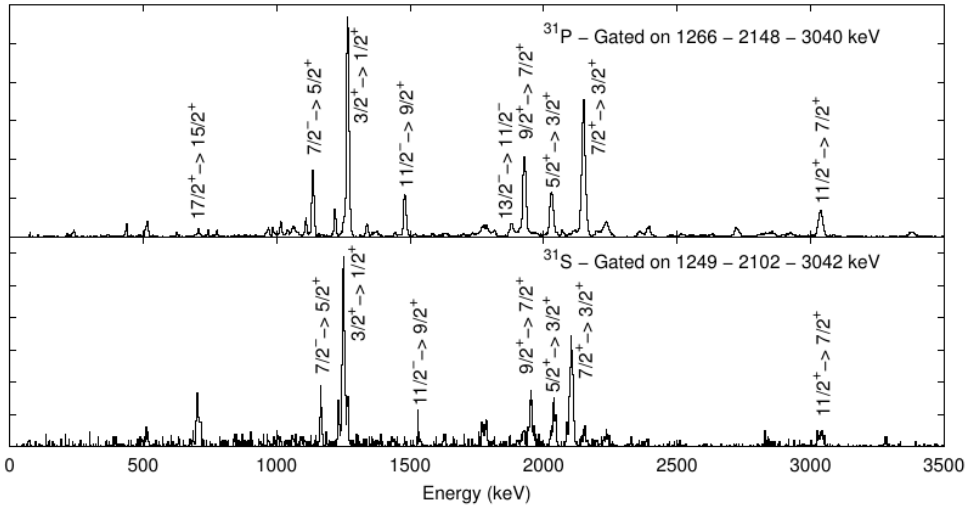




The **same type** of V_B term as in the $f_{7/2}$ shell is needed in the lower sd shell to reproduce MED

- Large nuclear V_B contribution in the *fp* shell nuclei. In the *sd*?
- High-spin states in mirror 31P and 31S
- B(E1) strength via lifetime
- J>13/2 states not yet observed in 31S

Under analysis, but higher spins already visible.



... On mass A=23, A.Boso et al., PRL 121 (2018) 032502

MA Bentley and SM Lenzi, Progr.Part. and Nuc.Phys. 59 (2007) 497

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Boso, Testov, Lenzi, Recchia et al

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MED in mirror nuclei A=31

- Large nuclear V_B contribution in the *fp* shell nuclei. In the *sd*?

Spectroscopy ^{31}S and ^{31}P

- Corrections of spin-parity assignment from previous works
- Systematics of transitions and levels known previously

Shell model calculations

- MED description A=31 for high spin states $\pi+$ and π-
- USD interaction for $\pi+$
- First description of MED in the cross-shell excitation, A=31, 35
- Breaking the ^{28}Si core allows reliable description of A=31, 35 MED values π- (a few particles in sdfp)
- V_b terms includes all the orbitals from the valence space $(s_{1/2}d_{3/2}f_{7/2}p_{3/2})$

reproduce MED

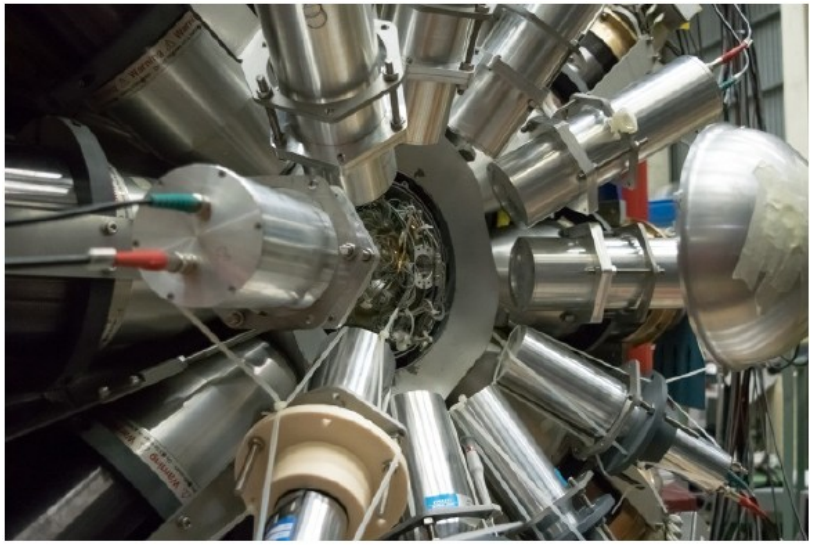
... on mass A=23, A.Boso et al., PRL 121 (2018) 032502

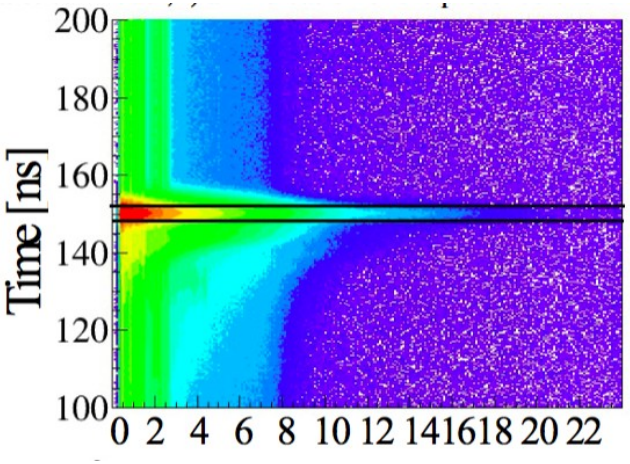
MA Bentley and SM Lenzi, Progr.Part. and Nuc.Phys. 59 (2007) 497

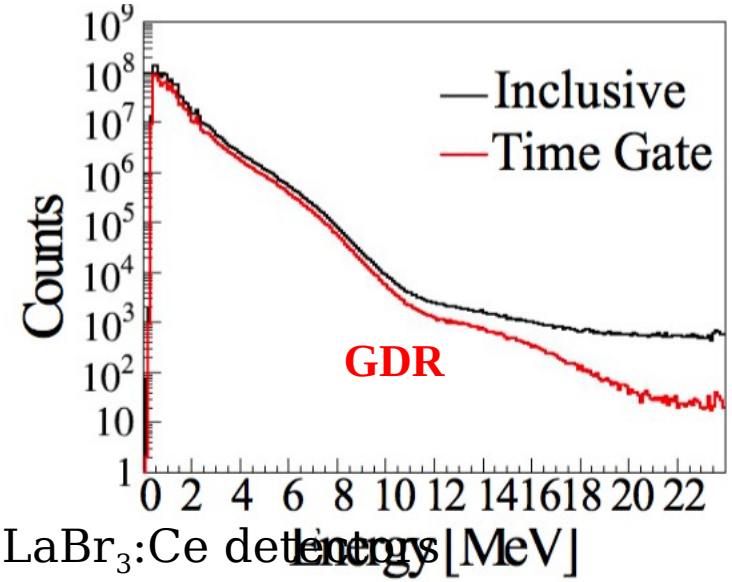
$^{32}S + ^{28}Si \rightarrow$ GDR in ^{60}Zn
S.Ceruti, G.Gosta, F.Camera et al

ISOSPIN mixing

- Coulomb interaction breaks the isospin symmetry⇒ Isospin Mixing
- E1 transitions (as Giant Dipole Resonance decay) in N=Z nuclei are sensitive to the degree of mixing
- Isospin mixing decreases as the excitation energy increases
- Comparison of yield of GDR in a N=Z nucleus to the one of N>Z allow to extract the isospin-mixing probability

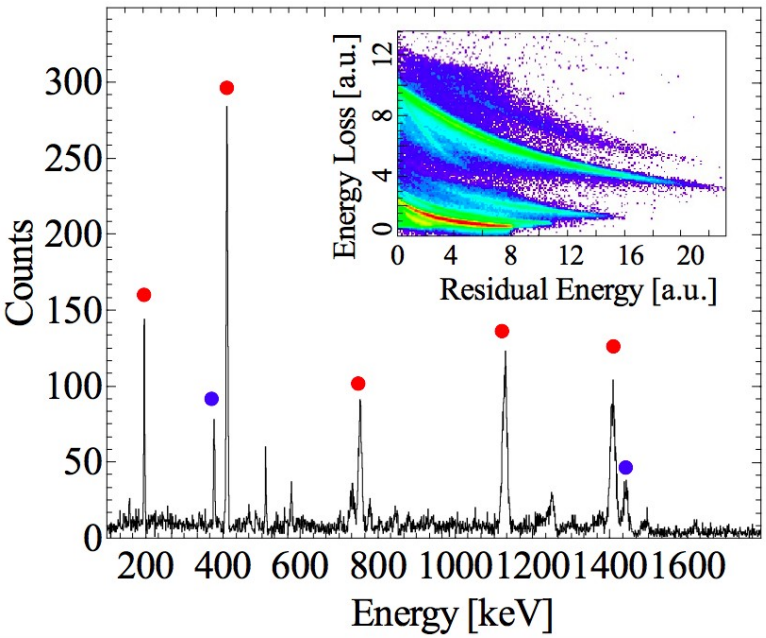


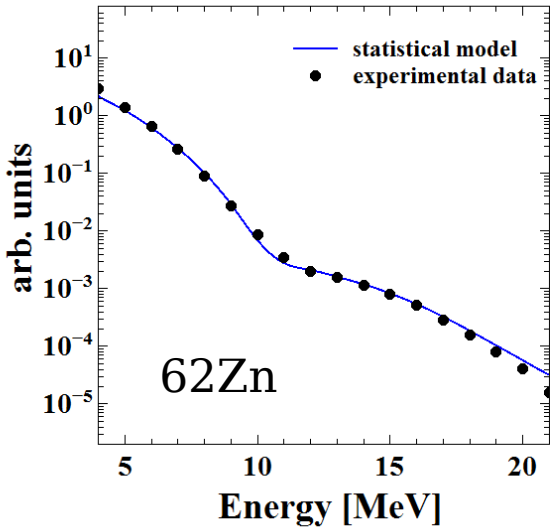


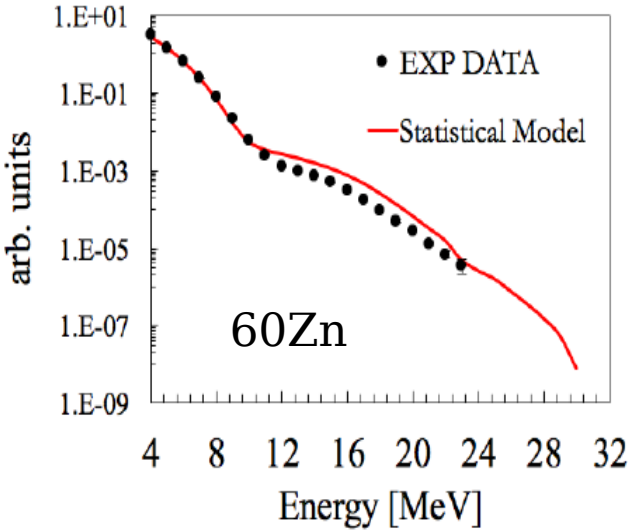


Time selection to reject random coincidences in $LaBr_3$:Ce detectors

The experiment





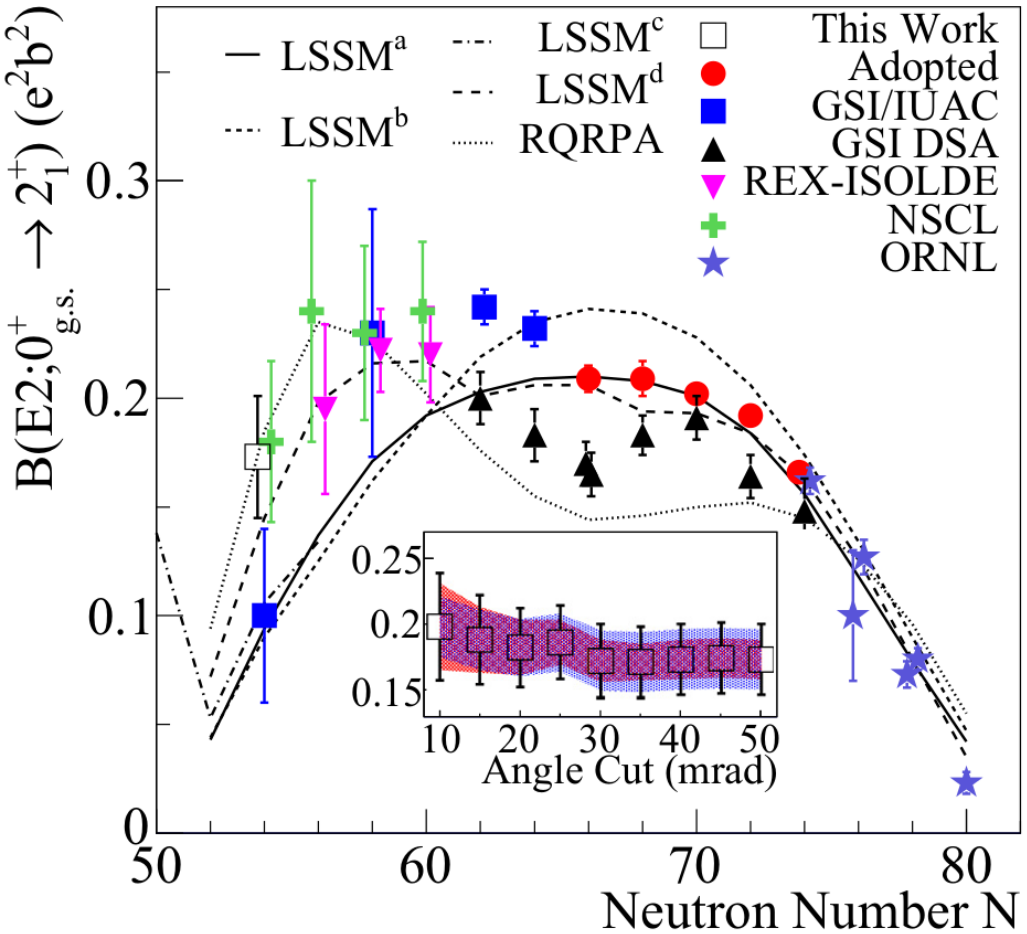


- Tuning of the statistical model: Study of residual nuclei (GALILEO+EUCLIDES)
- Zn-60 data are reproduced by using a standard statistical model
- GDR strength in 60Zn, clearly **inhibited** Evidence of **E1 selection rule** How much?? **Isospin Mixing**

BE2 strengths around Sn-100

Many-body quantal systems

Systematics of 2+ states in Sn

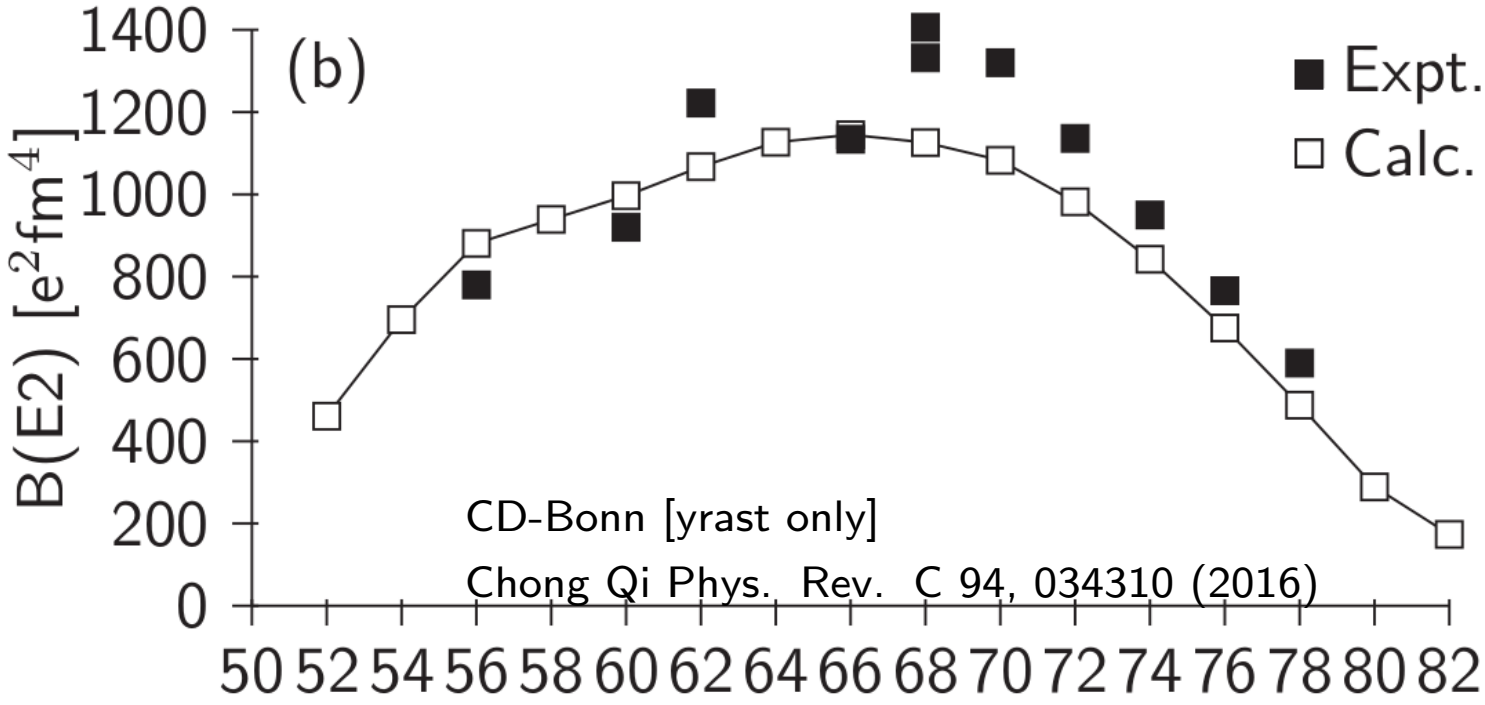


P. Doornenbal et al.
Phys. Rev. C 90, 061302(R) (2014)

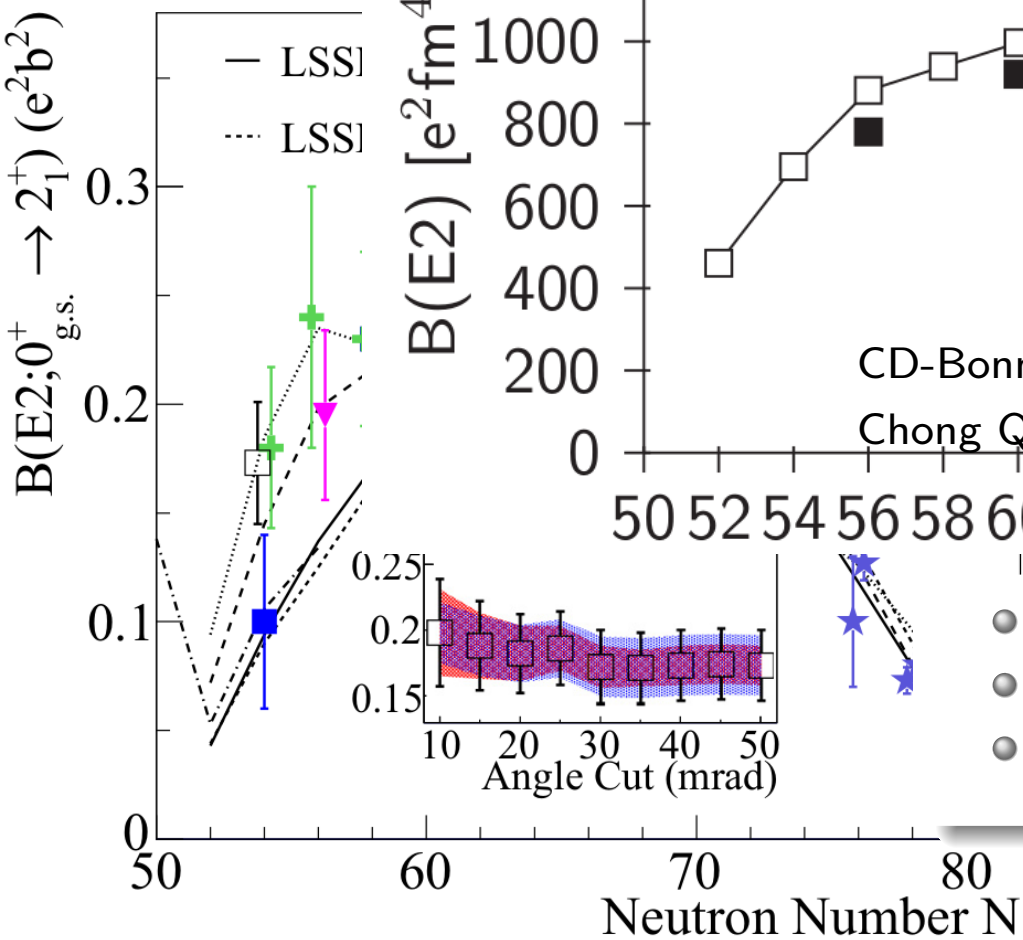
high interest in this context is the robustness of the proton Z = 50 shell closure when the N = 50,82 magic numbers are approached.

stems

Systematics of 2+ states in Te



Syster

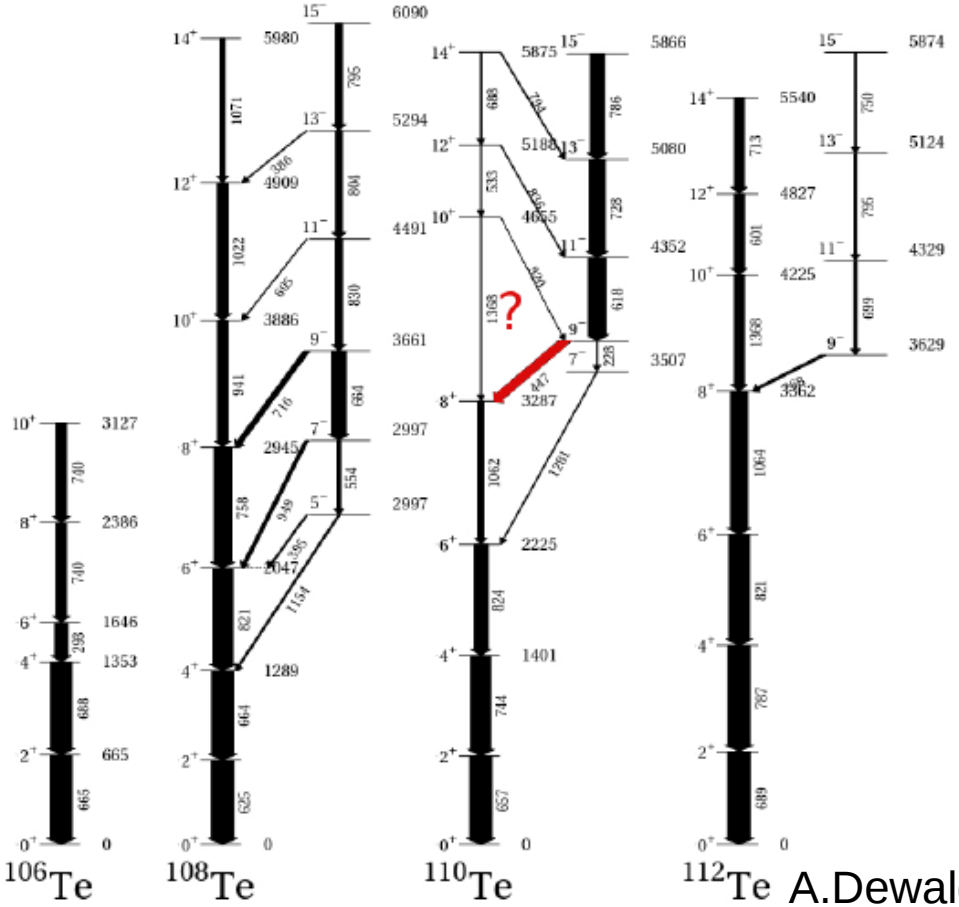


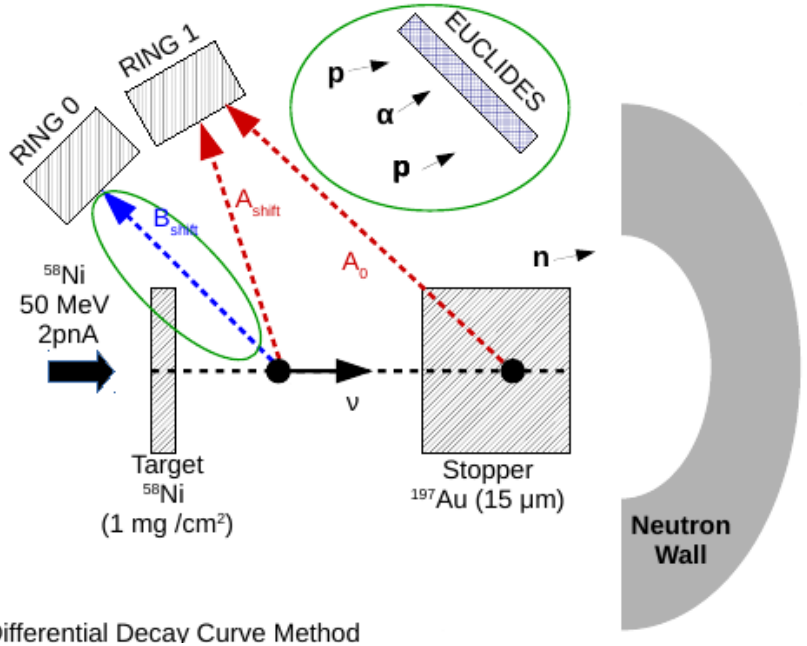
- Broken seniority scheme
- inadequate model space/interactions
- Systematic and statistical uncertainties

P. Doornenbal et al.
Phys. Rev. C 90, 061302(R) (2014)

58Ni@250MeV+58Ni → (116Ba)* D.Testov, S.Bakes et al.

^{110}Te





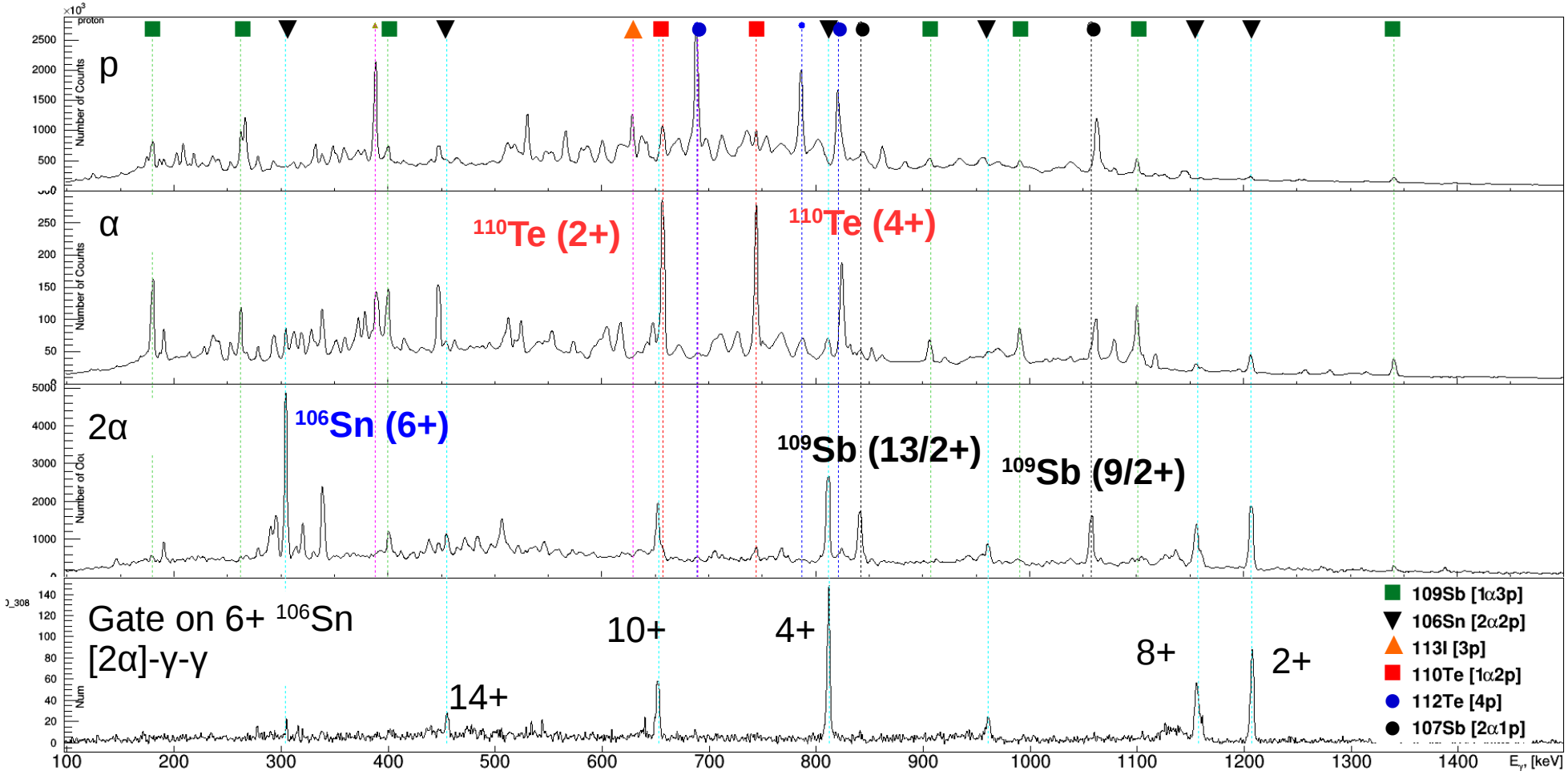
A.Dewald et al., Prog. Part. & Nucl. Phys. 67 (2012) 786

- Tracking the change in deformation of Sn by looking at Sb (9/2+ states)
- Known lifetime in 109Sb and 112Te as reference measurement
- Analysis on the state of interest in 109Sb and 110Te. New states in 110Te already measured.

C. Müller-Gatermann at al., NIMA 920, (2019) 95.

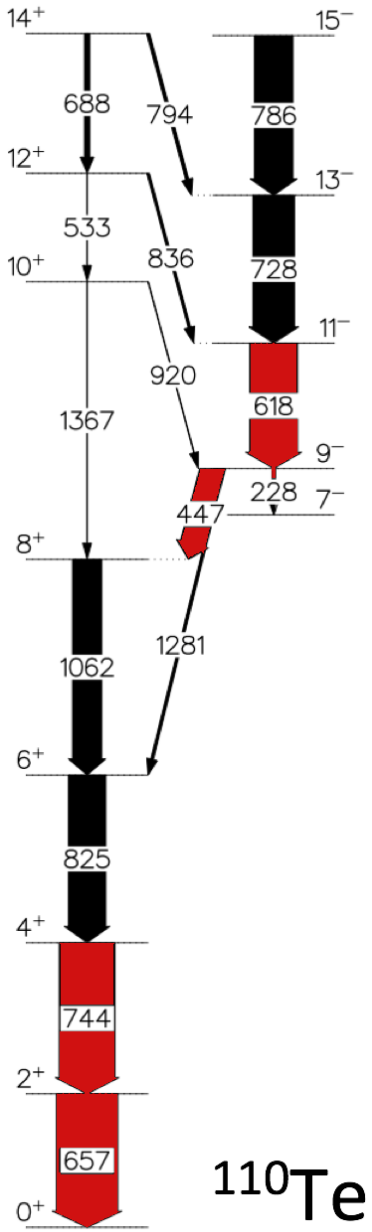
D. Testov et al., EPJA 55, (2019) 47

Resolving power

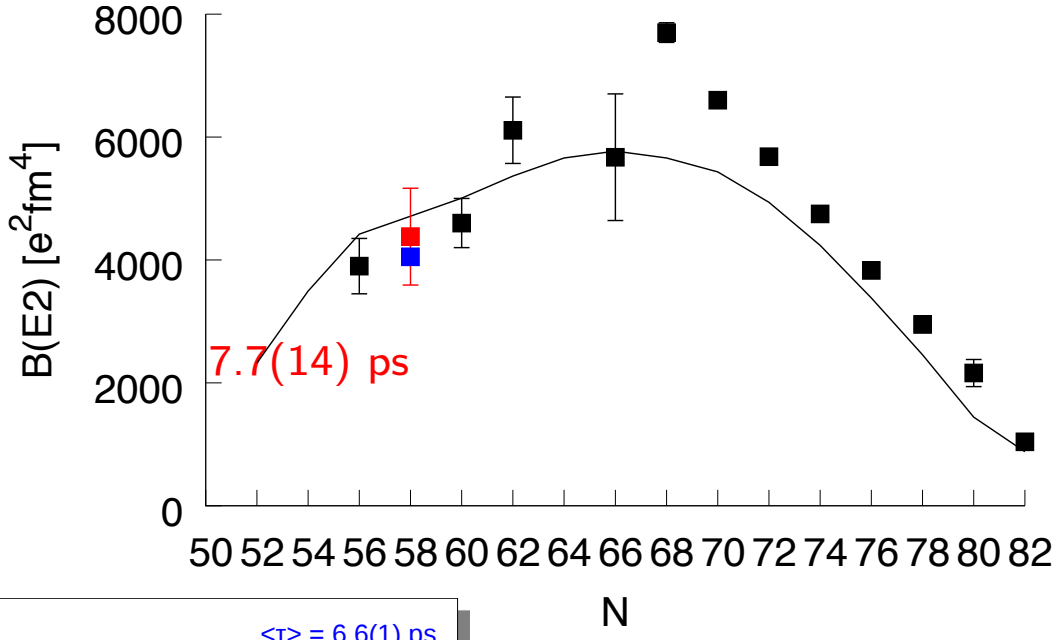


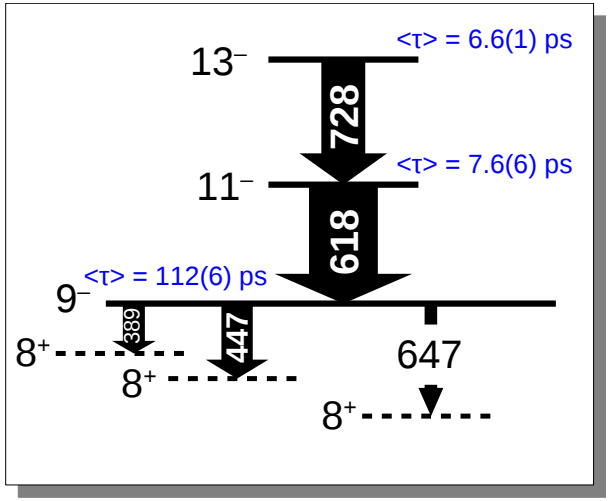
γ-γ (90deg vs 90deg) full projection

A closer look to tellurium

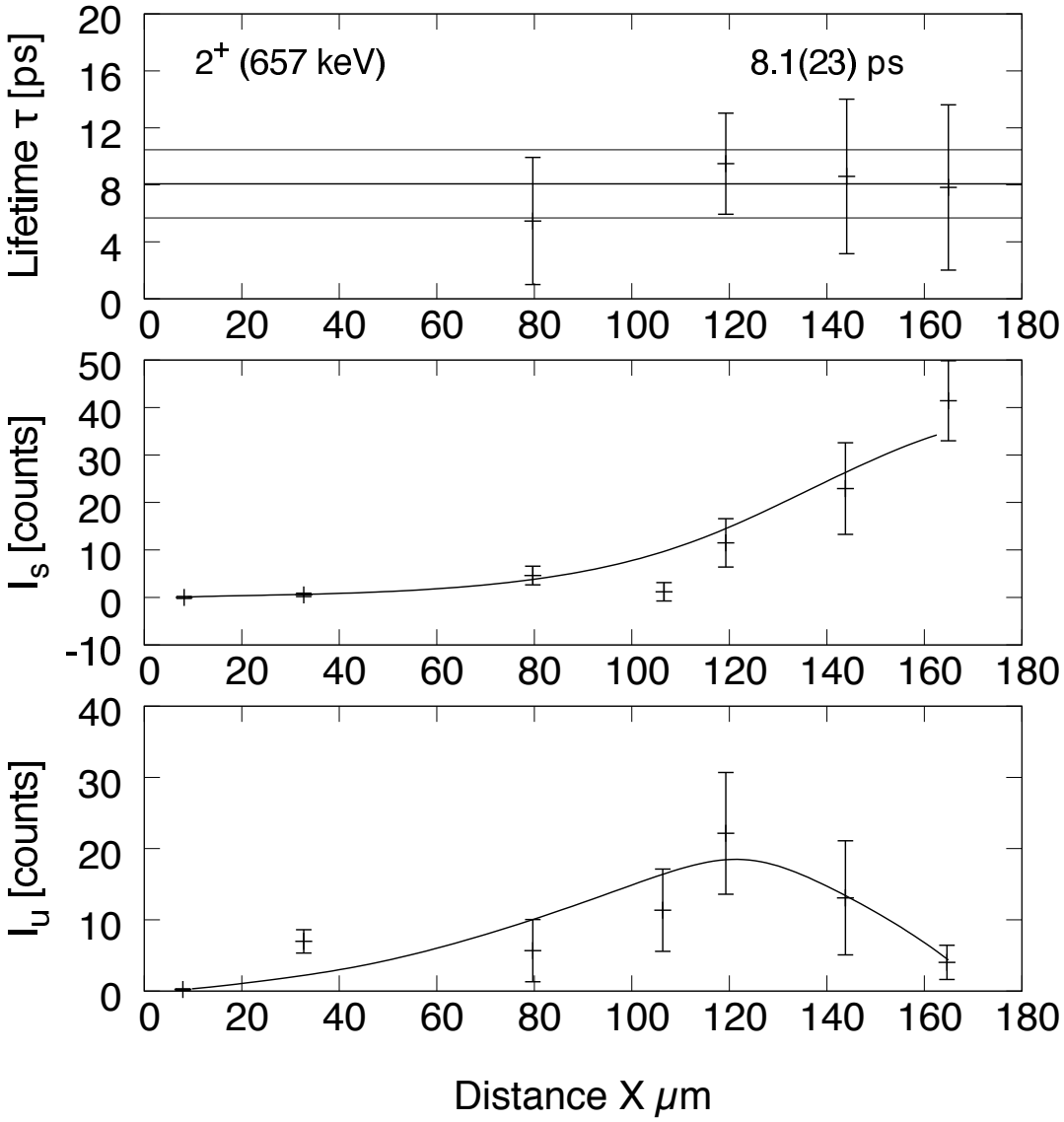


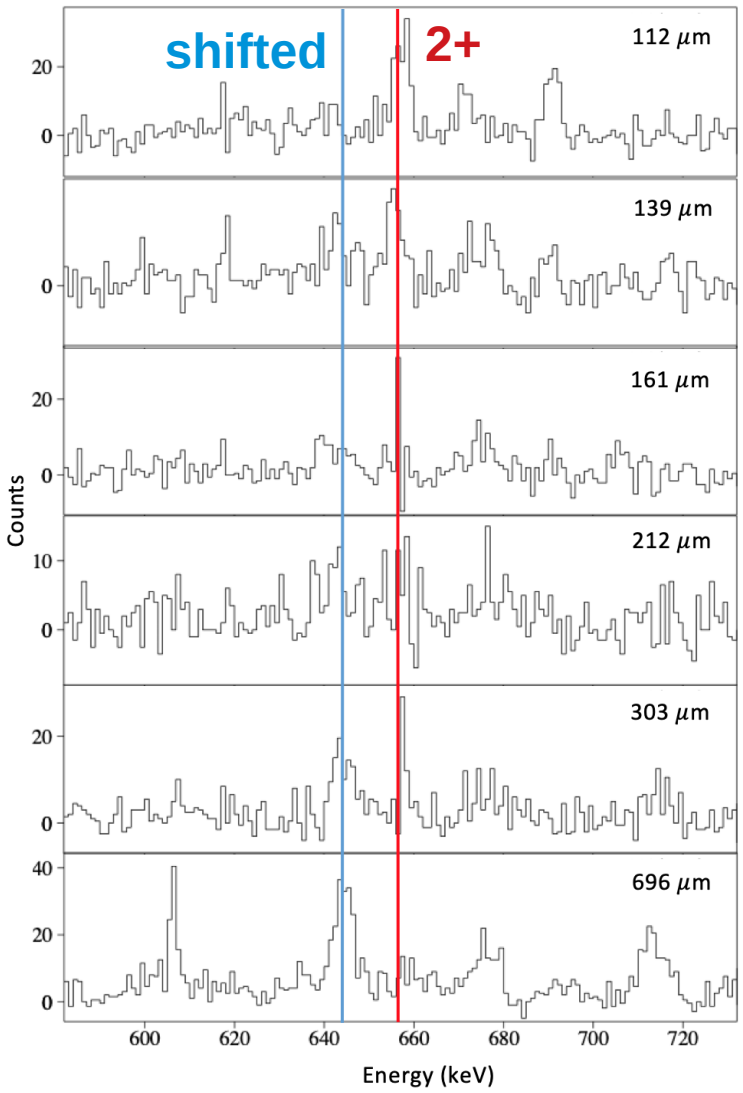
Systematics of 2+ states in Te



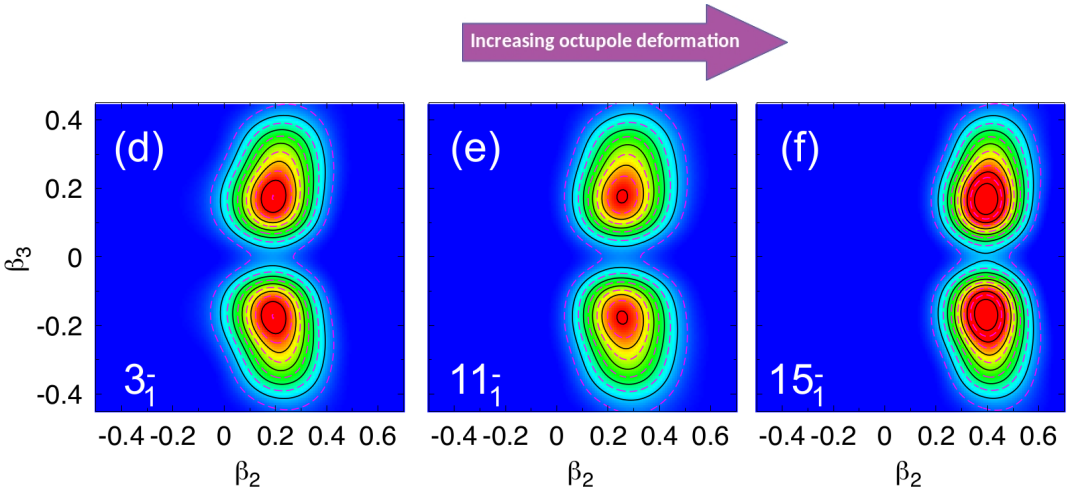


lifetime of 2+ state

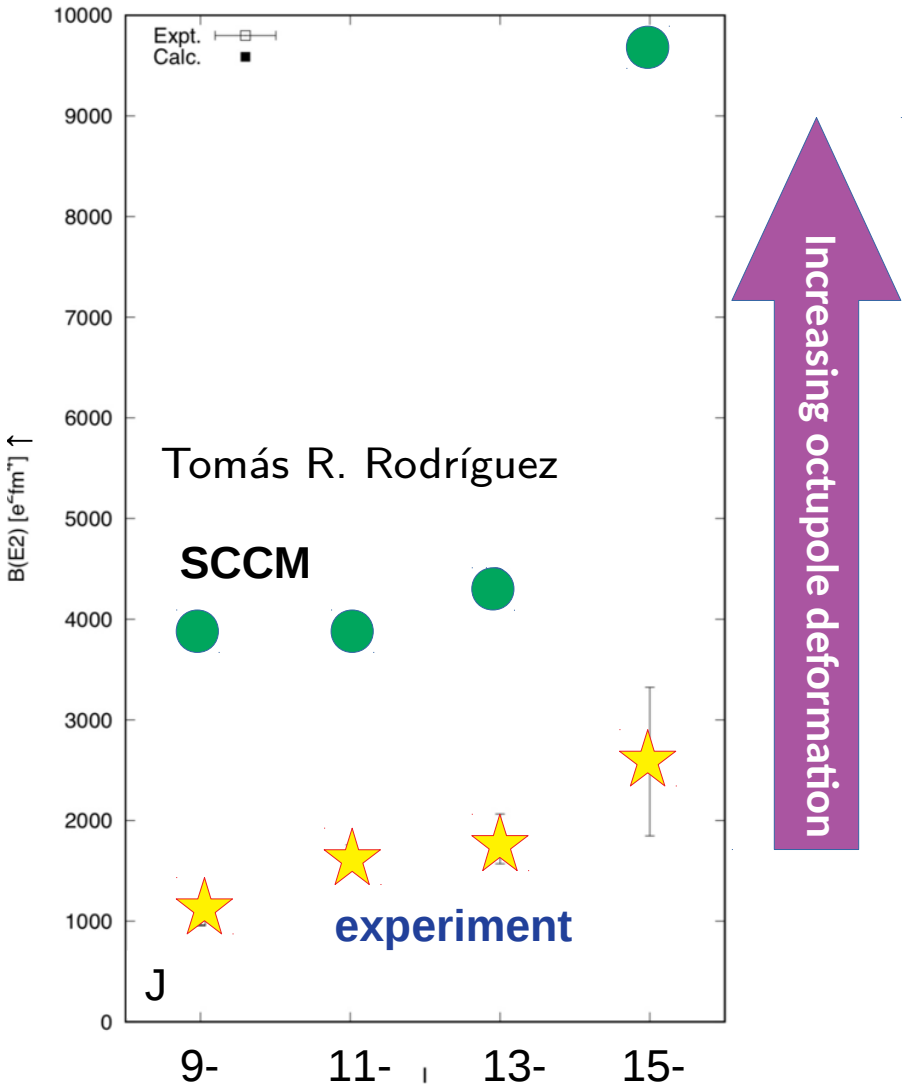




SCCM calculations



Collective wave functions in the (β_2, β_3)-plane for the yrast negative parity states calculated using axial SCCM method including parity symmetry breaking



Restrition to axial symmetry and lack of symmetry breaking that does not allow spin allignement

qualitative agrement of the data

Symmetry conserving configuration mixing calculations (SCCM) based on the Gogny D1S energy density functional axial quadrupole and octupole degrees of freedom

Future

SPES


Istituto Nazionale
di Fisica Nucleare...
Google
2D
Immagini ©2016 Google,Dati cartografici ©2016 Google
Termini
Privacy
Invia feedback
20 m

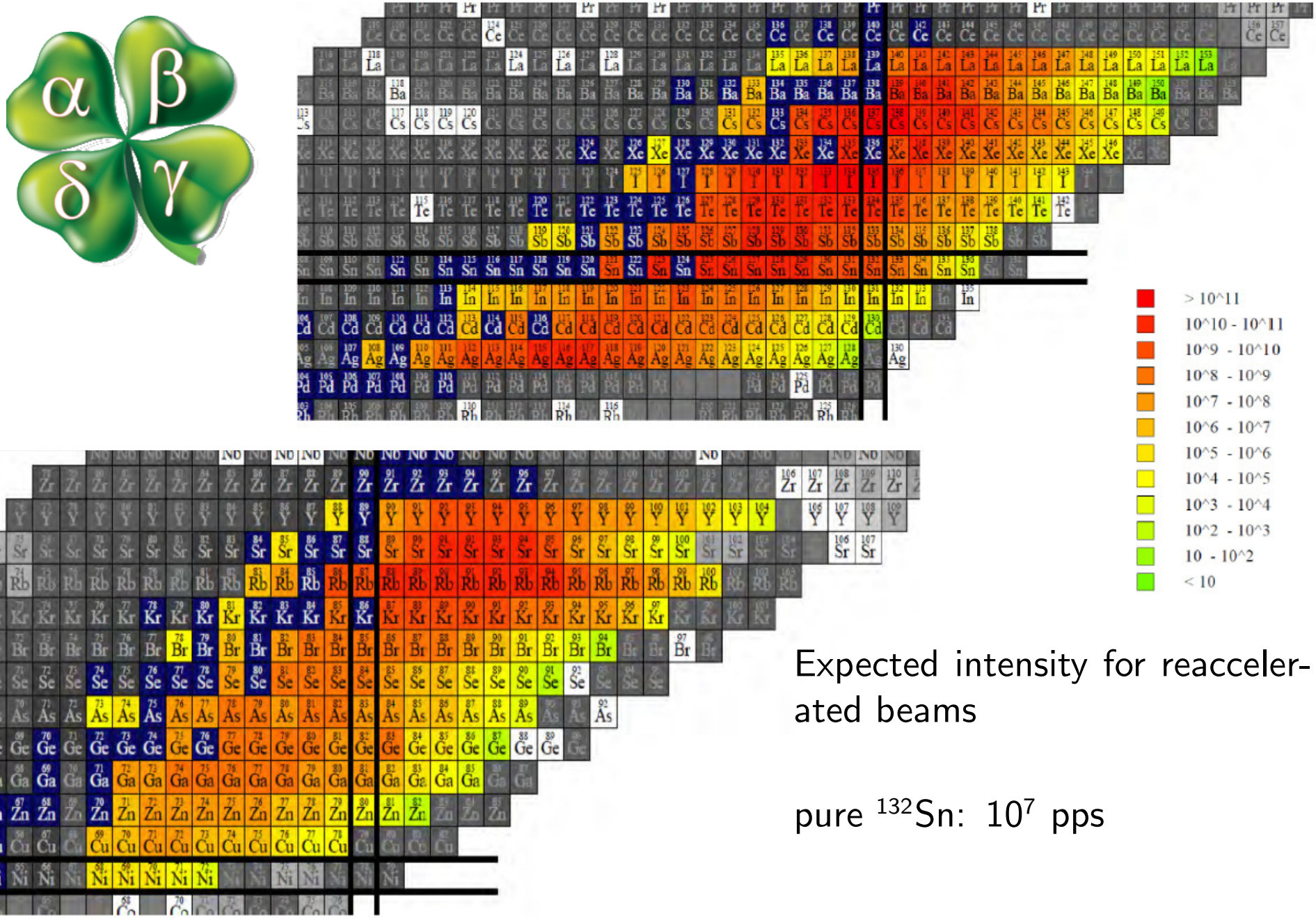
SPES facility

Second generation ISOL facility: pure and intense beams

10^{13} fissions/s

UCx Target (... + not fissile also foreseen)

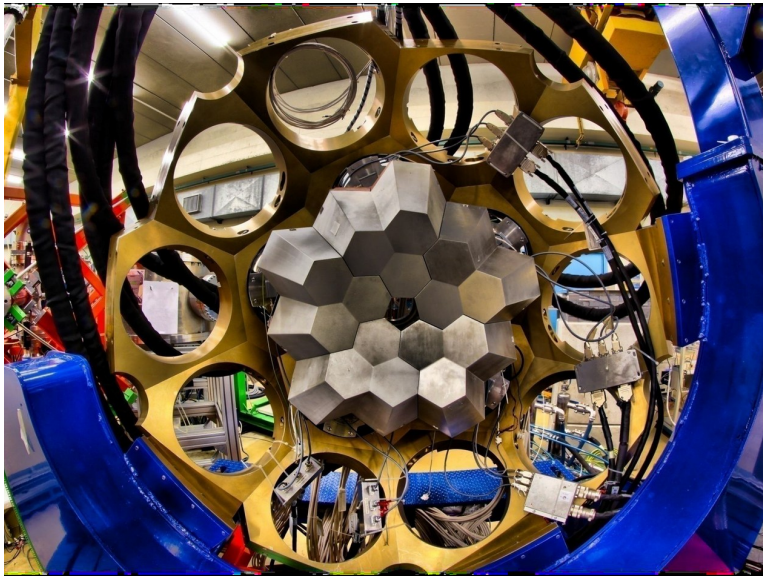
SPES facility

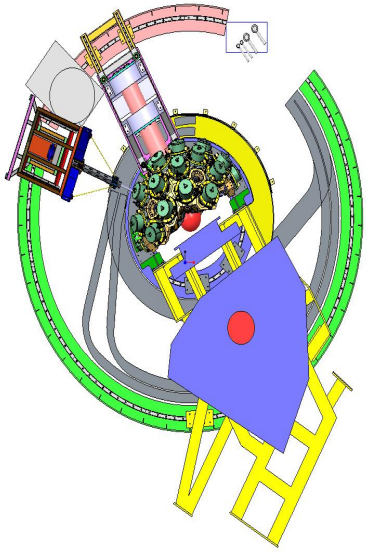


Expected intensity for reaccelerated beams

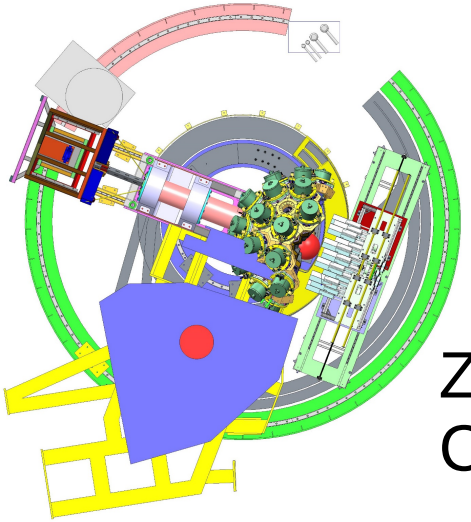
pure ^{132}Sn: 10^7 pps

Cutting-edge detection system





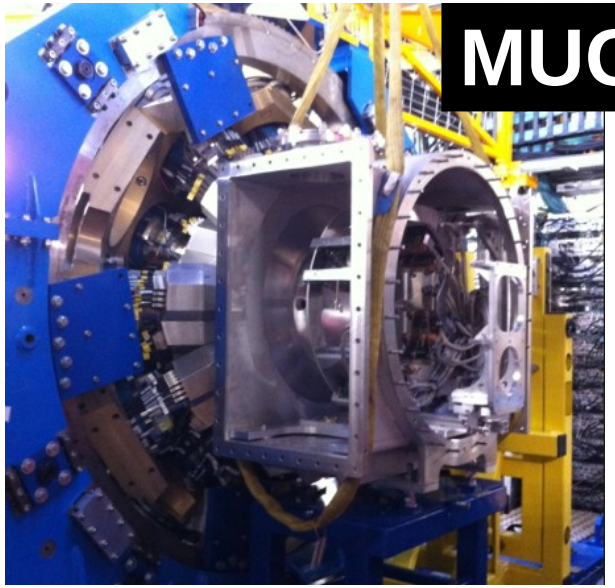
AGATA+PRISMA Configuration

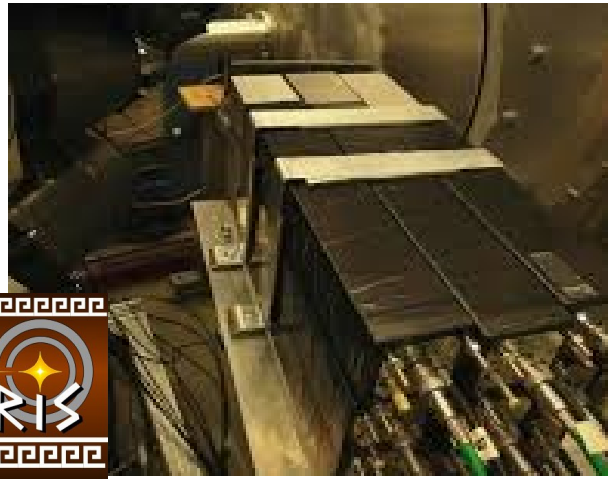


Zero degree Configuration

Expected more than 1π → more than 10% eff in singles

Cutting-edge detection system





To take home

- Intensive stable beams provided by LNL Legnaro accelerators have triggered intensive research of nuclear structure using GASP, EUROBALL, CLARA, AGATA and GALILEO arrays
- GALILEO (Phase I) consists of 25 HPGe Compton suppressed detectors $\epsilon \sim$2.4% FWHM at $<$ 2.4 keV at 1332.5 keV
- Number of different ancillary detectors (EUCLIDES, [Neutron Wall], TRACE, SPIDER, plunger, RFD) leads to variety of nuclear studies studies: $>$20 experiments
- Photon efficiency of GALILEO will be enhanced after an update with Tripple clusters (very soon)
- SPES RIBs will further enriched the physics cases at LNL
- In the near future, even more performing setup will be available (AGATA, NEDA, MUGAST, etc)
- Galileo Galilei worked at Padova University from 1592 - 1610

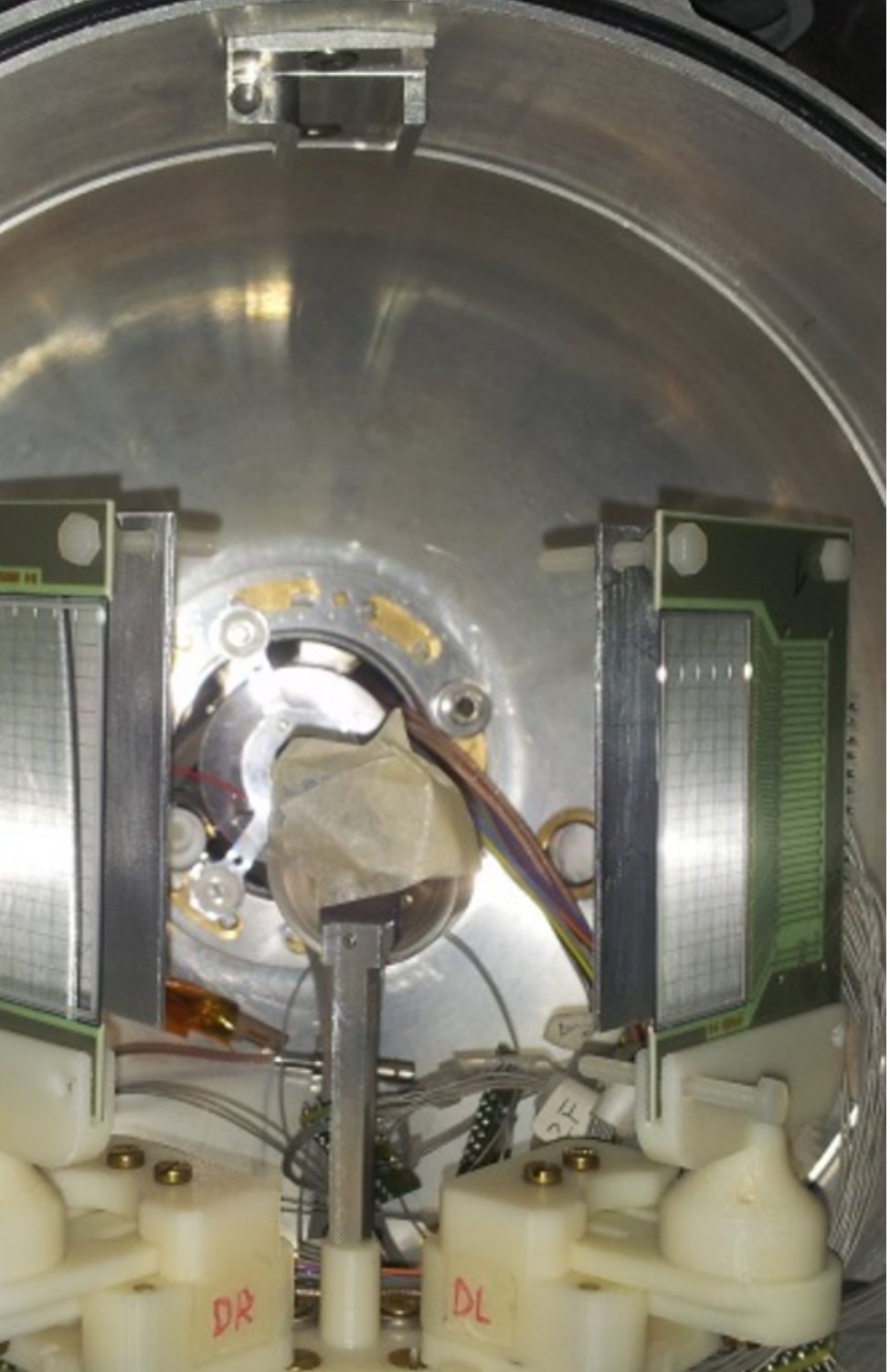
Credits to GALILEO collaboration:

D. Testov[1], J.J. Valiente-Dobón[2], D. Mengoni[1], F. Recchia[1],
A. Goasduff[1], S. Bakes[17], A. Boso[1,4], S. Lenzi[1], G. de Angelis[2], S. Lenzi[1],
S. Bakes[1,2,b], C. Boiano[3], B. Cederwall[5], G. Colucci[2], M. Cicerchia[3],
P. Čolović[6], F. Didierjean[7], M. Doncel[8], J.A. Dueñas[9], F. Galtarossa[2],
A. Gozzelino[2], K. Hadyńska-Klęk[4], R. Isocrate[2], G. Jaworski[2],
P.R. John[10], H. Liu[5], S. Lunardi[1], R. Menegazzo[1], A. Mentana[3],
V. Modamio[11], A. Nannini[12], D.R. Napoli[2], M. Palacz[13], G. Pasqualato[1],
M. Rocchini[12], S. Riccetto[3], B. Saygi[14], E. Sahin[15], M. Siciliano[3],
Yu. Sobolev[16], S. Szilner[6], ..., ..., ..., ..., ..., ..., ..., ..., ..., ..., ..., ..., ...,
..., ..., ..., ..., ..., ..., ..., ..., ..., ..., ..., ...

Credits to GALILEO collaboration:

[1] Dipartimento di Fisica e Astronomia and INFN, Sezione di Padova, Padova, Italy.
[2] INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy.
[3] Dipartimento di Fisica dellUniversità di Milano e Sezione INFN, Milano, Italy.
[4] National Physical Laboratory, Teddington, Middlesex, TW11 0LW, UK
[5] KTH Royal Institute of Technology, Stockholm, Sweden
[6] Ruder Boskovic Institute, Zagreb, Croatia.
[7] Institut Pluridisciplinaire Hubert CURIEN (IPHC), Strasbourg, France.
[8] The University of Liverpool, UK
[9] Departamento de Ingeniería Elctrica, Escuela Técnica Superior de Ingeniería, Universidad de Huelva, Spain.
[10] Institut für Kernphysik, Technische Universität Darmstadt, Germany.
[11] University of Oslo
[12] Università degli Studi and INFN Sezione di Firenze, Florence, Italy.
[13] HIL, Poland.
[14] Ege University, Faculty of Science, Department of Physics, Izmir, Turkey.
[15] University of Surrey
[16] Joint Institute for Nuclear Research, Dubna, Moscow region, Russia
[17] also at University of Surrey, Department of Physics, UK

..., ...



TRACE

TRACE: a highly-segmented Silicon detector for light charged particles emitted in fusion evaporation and direct nuclear reactions

Identification of A$\sim$10 mass ions at low kinetic energy, by PSA analysis

Experimental setup - TRACE

Eur. Phys. J. A 54 209 (2018)

credits: N. Cieplicka-Oryńczak

Reaction and detection

- To produce low energy Li, Be, B, C .... fragments we used:

^{37}Cl beam (186 MeV, 1pnA) + ^{12}C target (200 µm)

- The nuclei of interest, target-like products (Li, Be, B, C ...) of mass A~10, are scattered at ~40º-60º. The kinetic energy of these products varies from a few MeV to a few tens of MeV.

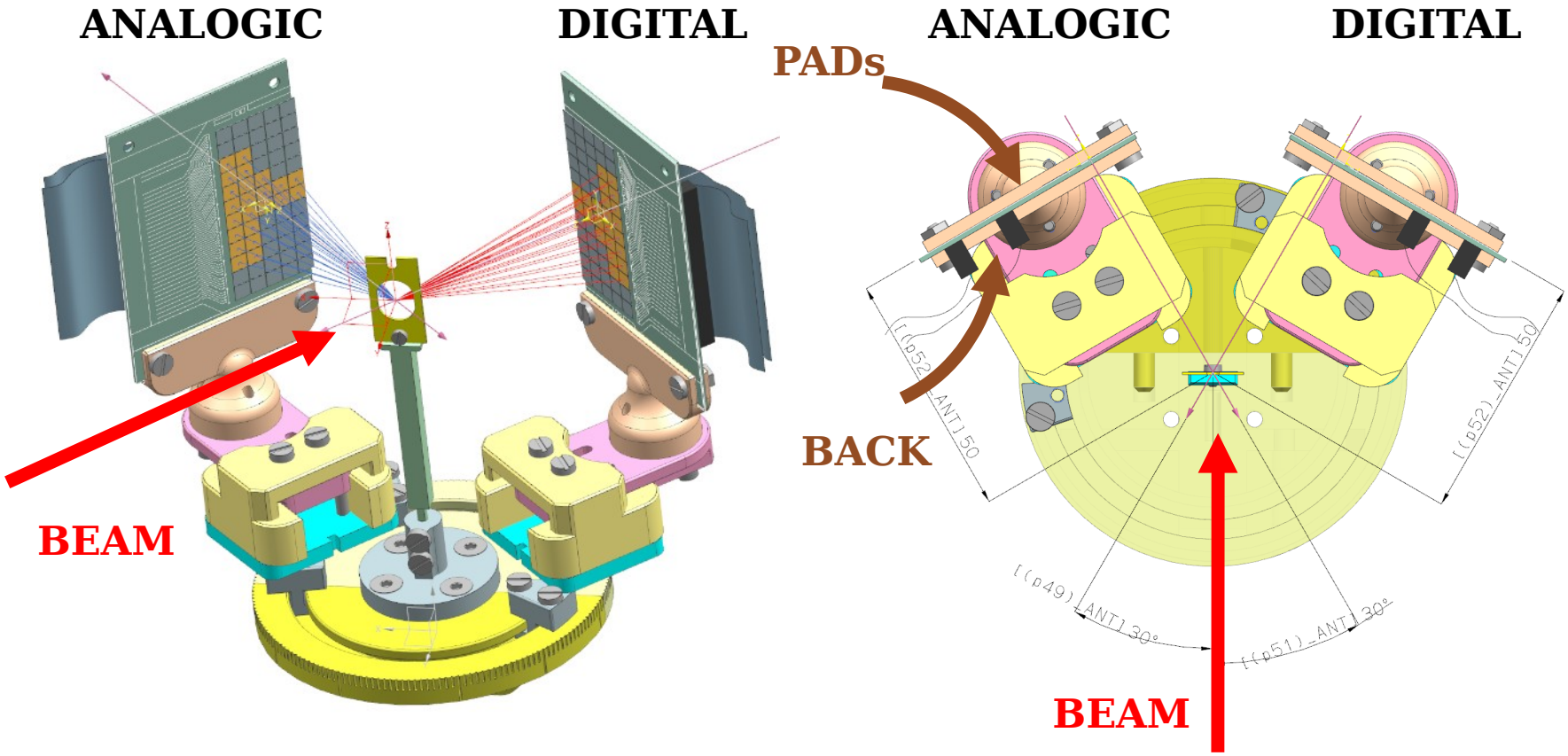
- Measurements of the energy, position, mass and charge: Pulse Shape Analysis of the signals from the TRACE detector

Experimental setup - TRACE

Eur. Phys. J. A 54 209 (2018)

credits: N. Cieplicka-Oryńczak

Experimental setup – TRACE



Experimental setup - TRACE

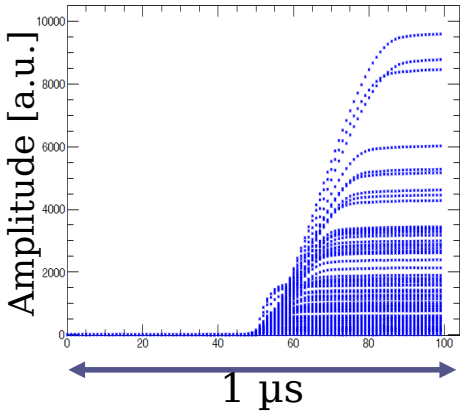
Eur. Phys. J. A 54 209 (2018)

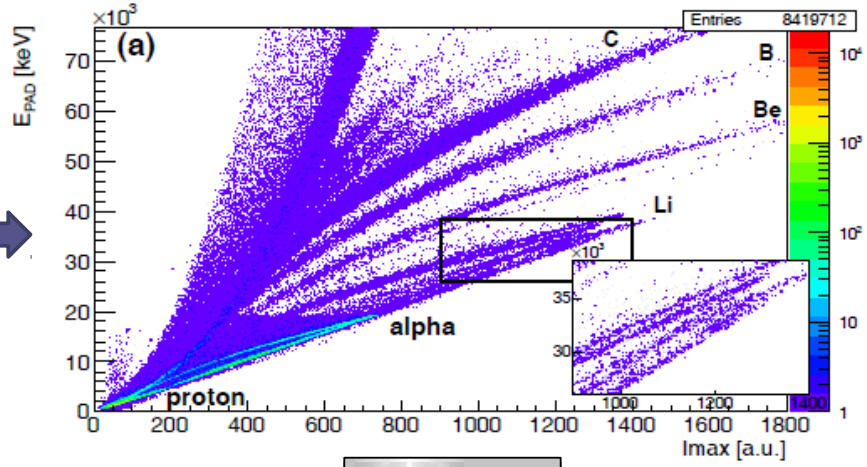
credits: N. Cieplicka-Oryńczak

Identification matrices

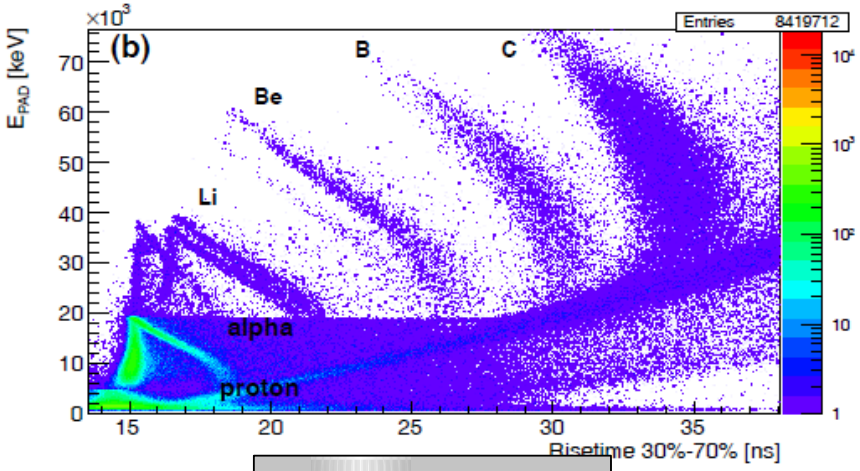
TRACE signals

- Signal measurement at every 10 ns
- Energy „BACK" and „PAD"
- Imax from the derivative
- Rise time

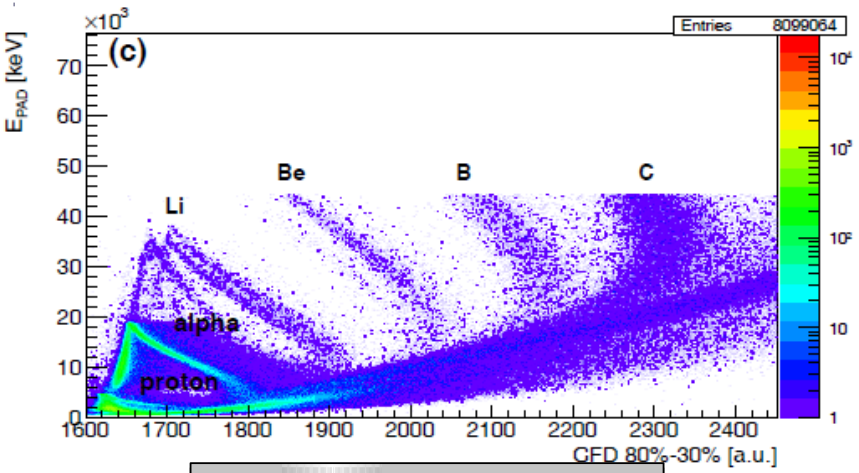




E vs I_{max}



E vs Rise time



E vs CFD 80%-30%

Experimental setup - TRACE

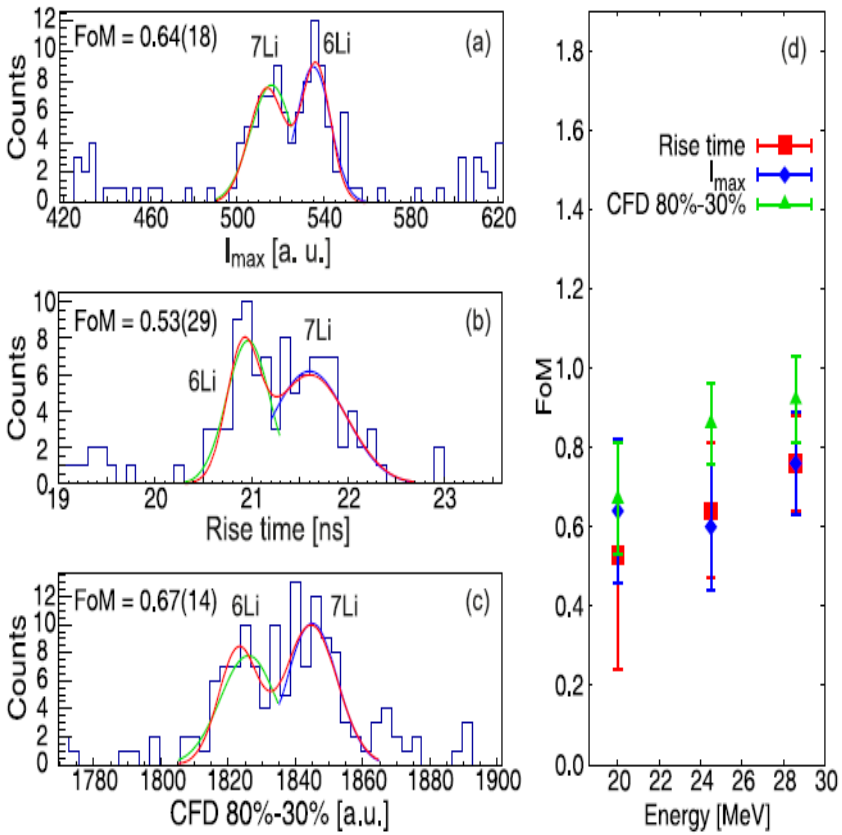
Eur. Phys. J. A 54 209 (2018)

credits: N. Cieplicka-Oryńczak

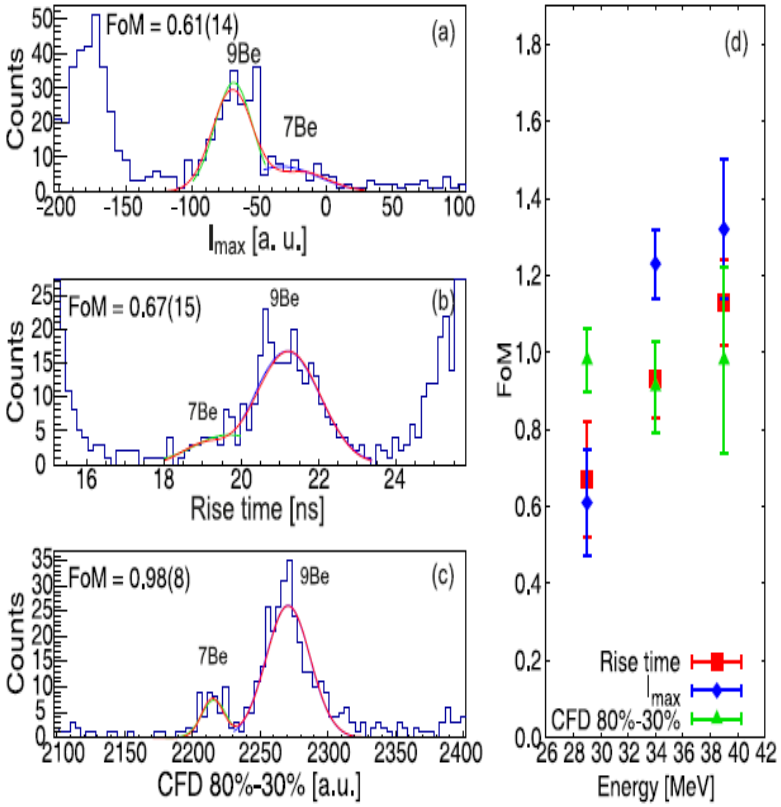
Figure of merit

$$FoM = \frac{C_2 - C_1}{FWHM_1 + FWHM_2}$$

Li isotopes: identification possible down to 20 MeV

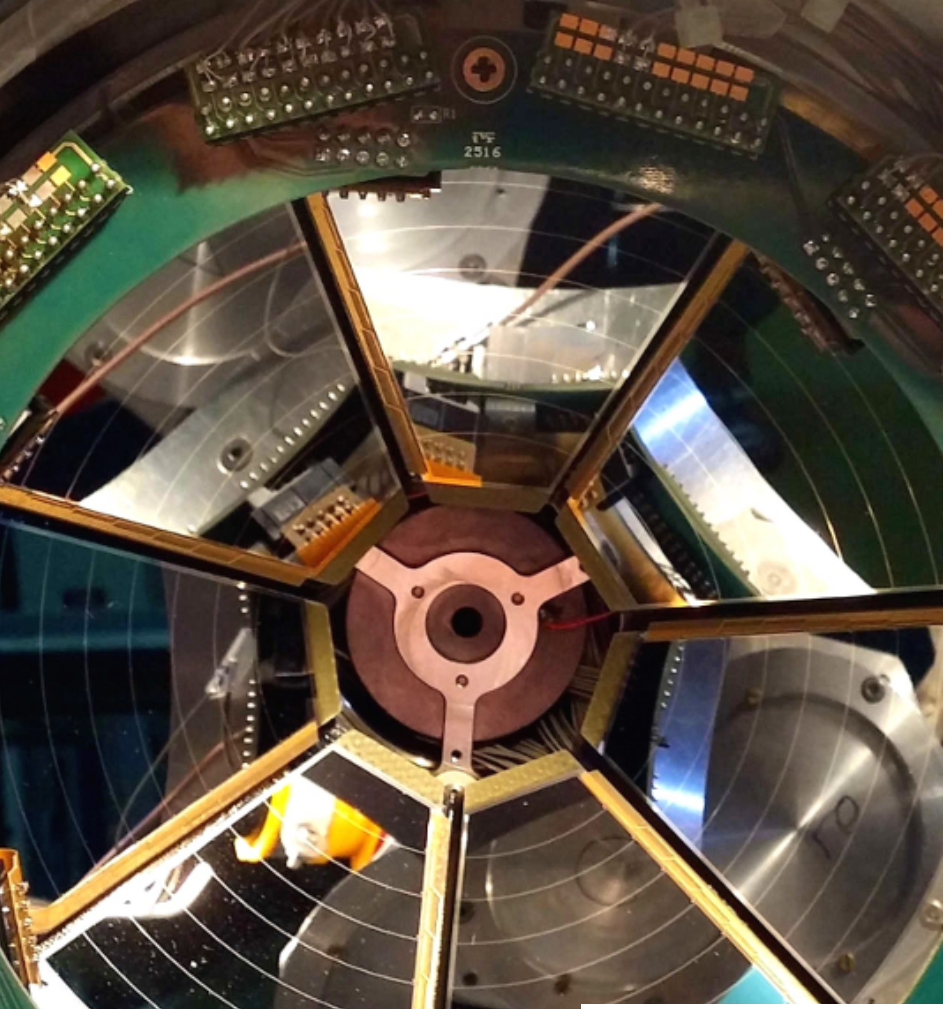


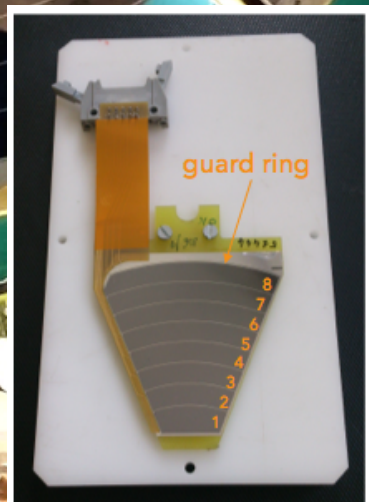
Be isotopes: identification possible down to 29 MeV



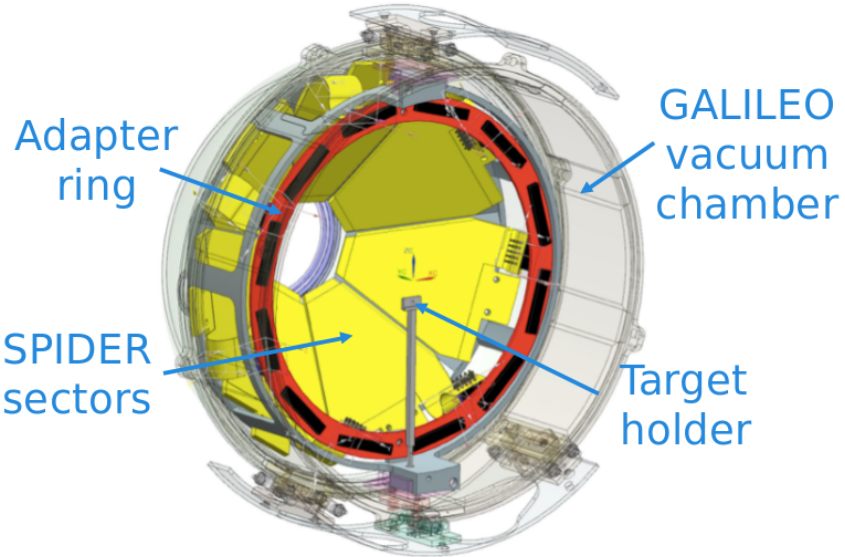
Silicon PIe DEtectoR

M. Rocchini Phys.Scr. 92, 074001 (2017)

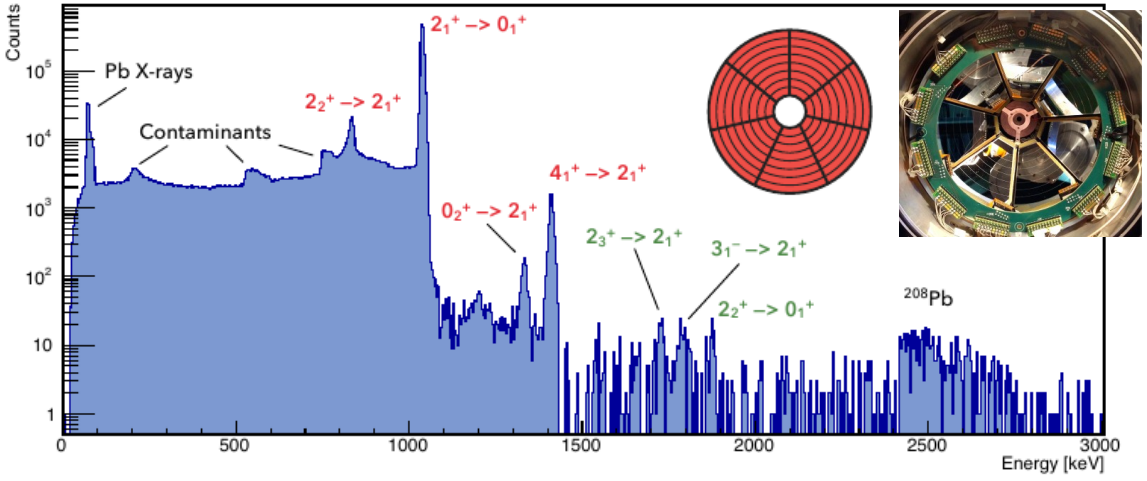


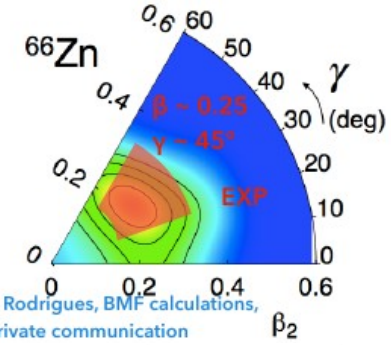


- Independent sectors, 8 strips + guard ring
- Detector thickness ~300 μm, dead layers ~50 nm in the junction (front) side and ~350 nm in the ohmic (rear) side
- Cone configuration (7 sectors) at backward angles: 8.5 cm from the target $\Omega/4\pi = 17.3\%$



Coulomb excitation



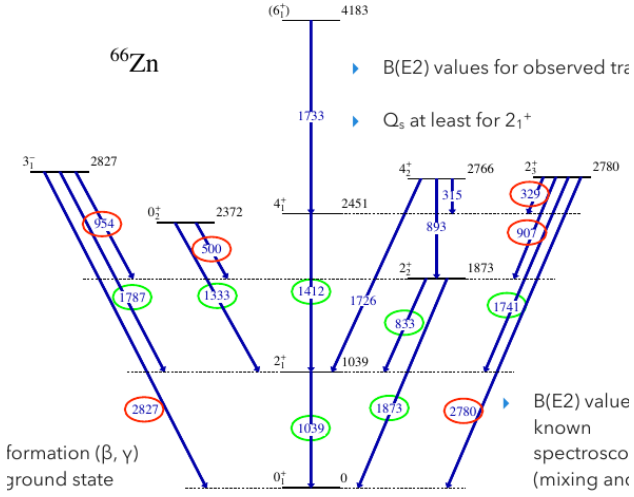


B(E2; $2_1 \to 0_1$)	278(3) efm^2	$Q_s(2_1)$	25(12) efm^2

Known values (NNDC database):

B(E2; $2_1 \to 0_1$) = 277(6) efm^2 $Q_s(2_1)$ = 24(8) efm^2

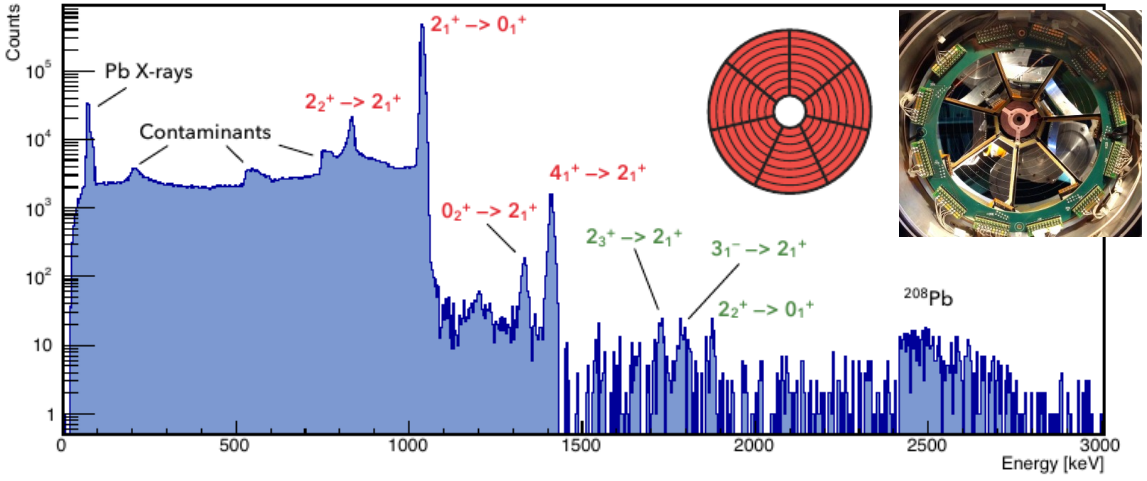
B(E2; $0_2 \to 2_1$)	36(16) efm^2

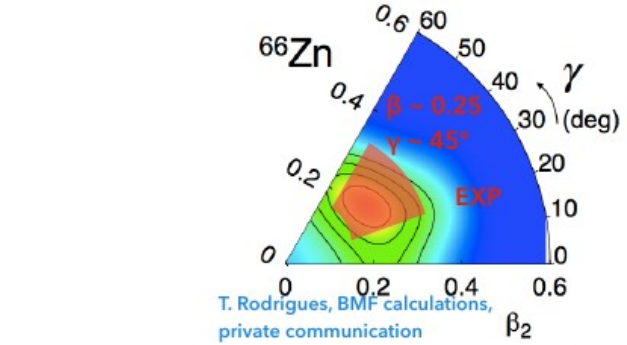


- Lamp-shaped silicon detector
- Known BE2 for calibration
- Shape of the 0^+_2 structure
- 2^+_2

^{66}Zn(70 MeV) + ^{208}Pb [M.Rocchini,K.Hadinska-Klek]

Coulomb excitation





T. Rodrigues, BMF calculations, private communication

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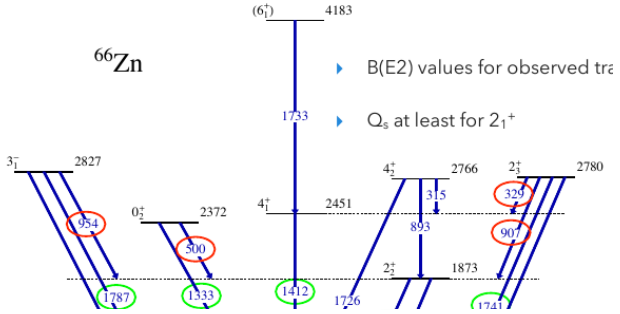
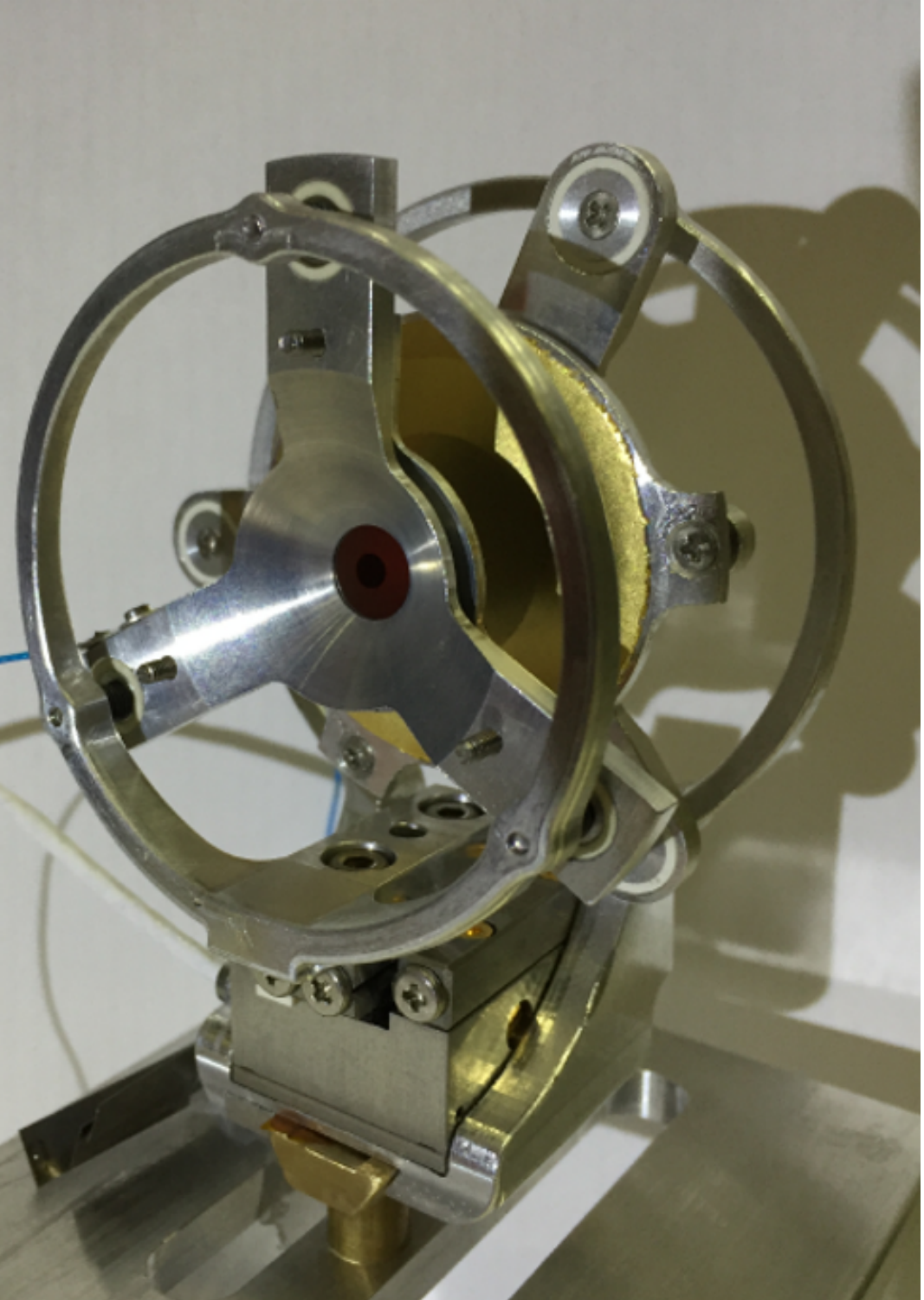


- Lamp-shaped silicon detector
- Known BE2 for calibration
- Shape of the 0^+_2 structure

Coulex of ^{94}Zr D.Doherty, M.Rocchini

Coulex of ^{116}Sn M.Saxena, M.Siciliano

70 MeV) + ^{208}Pb [M.Rocchini,K.Hadinska-Klek]

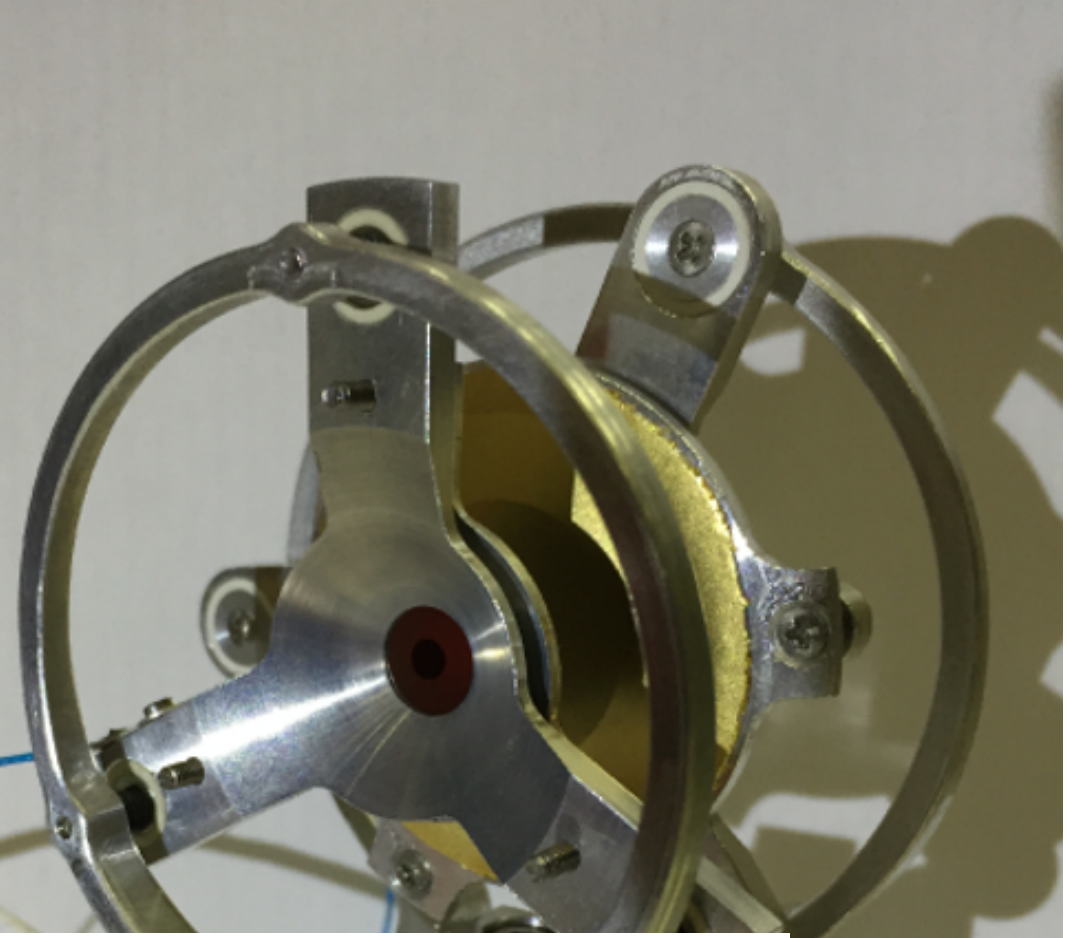


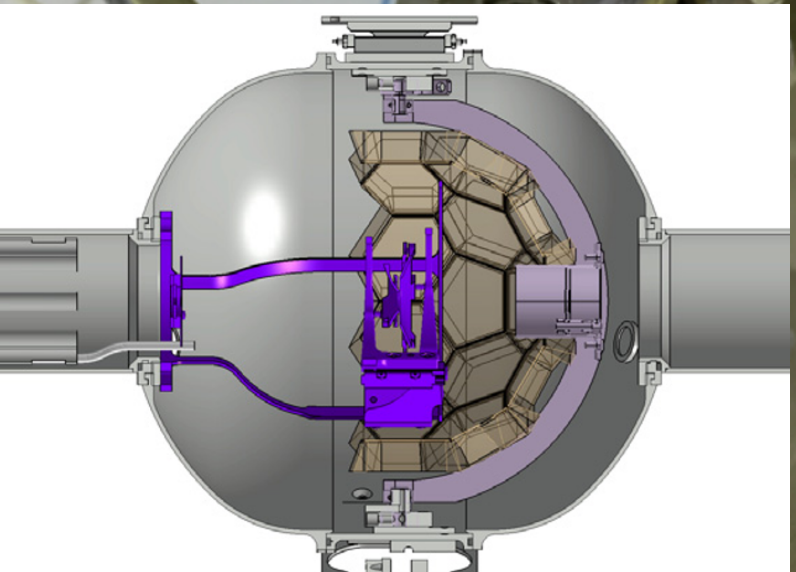
Plunger

C. Müller-Gatermann et al.,

Nucl. Inst.&Meth. A 920 95 (2019)

- Very compact design of the otor (LPS-24) 24 mm x 33 mm x 20mm
- Target is moving with respect to the fixed stopper
- active feedback system to compensate for beam induced changes of the target to degrader distance
- Motor (LPS-24) distance range 15 mm
- Resolution of the position sensor 20 nm
- Only one HPGe at 90° (below the motor) is shadowed
- guarantees the compatibility to ancillary detectors, e.g. EUCLIDES





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C. Müller-Gatermann et al.,
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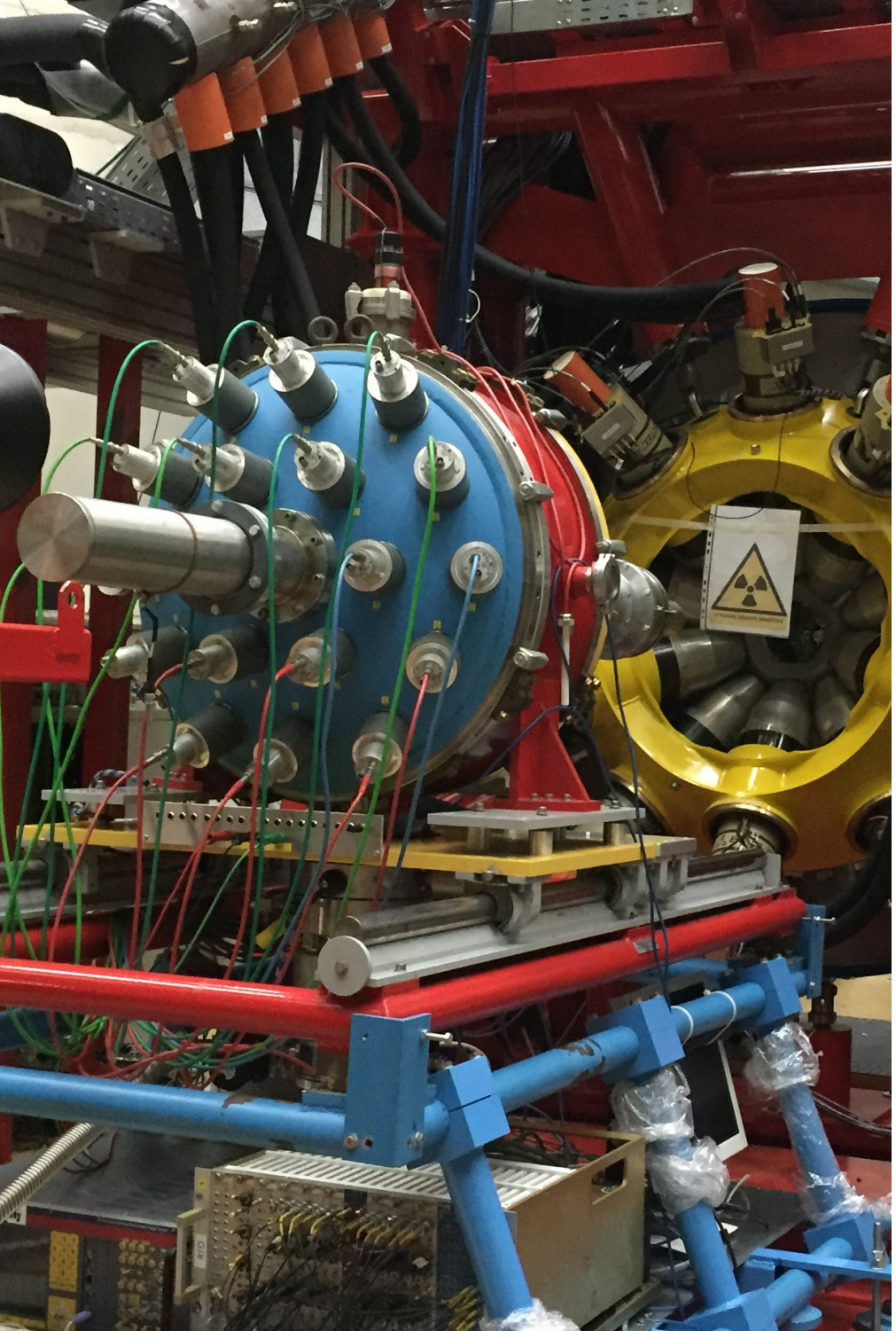
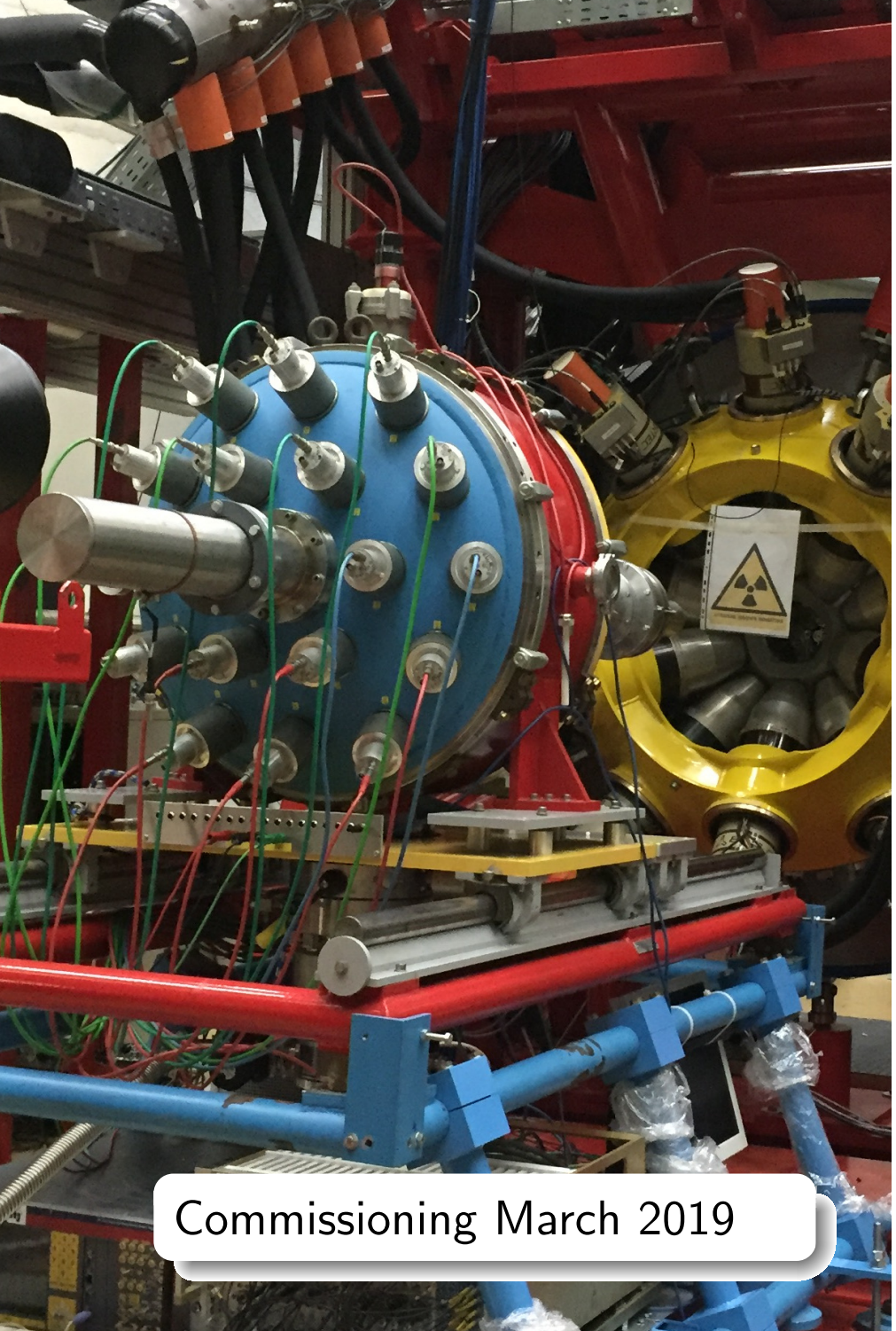


Recoil Filter Detector

- measures evaporation residues in coincidence with γ-rays
- Angular coverage 1.5°-8.9° at the distance
- 0.5 - 2 μm aluminised Mylar foil; ions hitting the foil knock out electrons, which are then accelerated by the tension of 20 kV nd focus onto a thin, fast plastic scintillator mounted on a photomultiplier.
- γ-recoil efficiency is 20-50%
- Correction for Doppler Effects for recoils $\beta \sim$5%
- estimation of a lifetime of highly excited states in the fs range
- possibility of a coupling to other ancillary devices: EUCLIDES/plunger.



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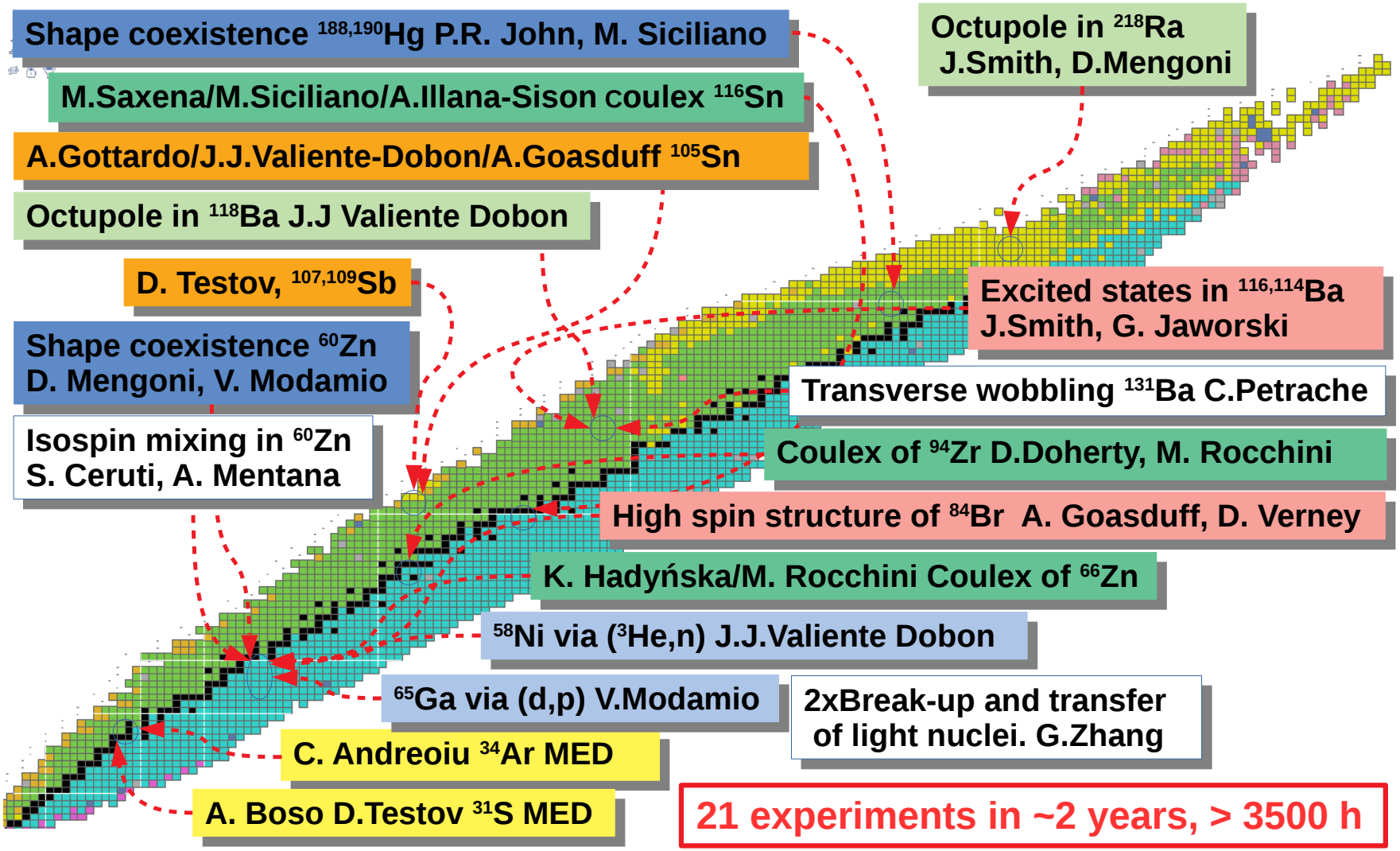
Science campaign



21 experiments in ~2 years, > 3500 h