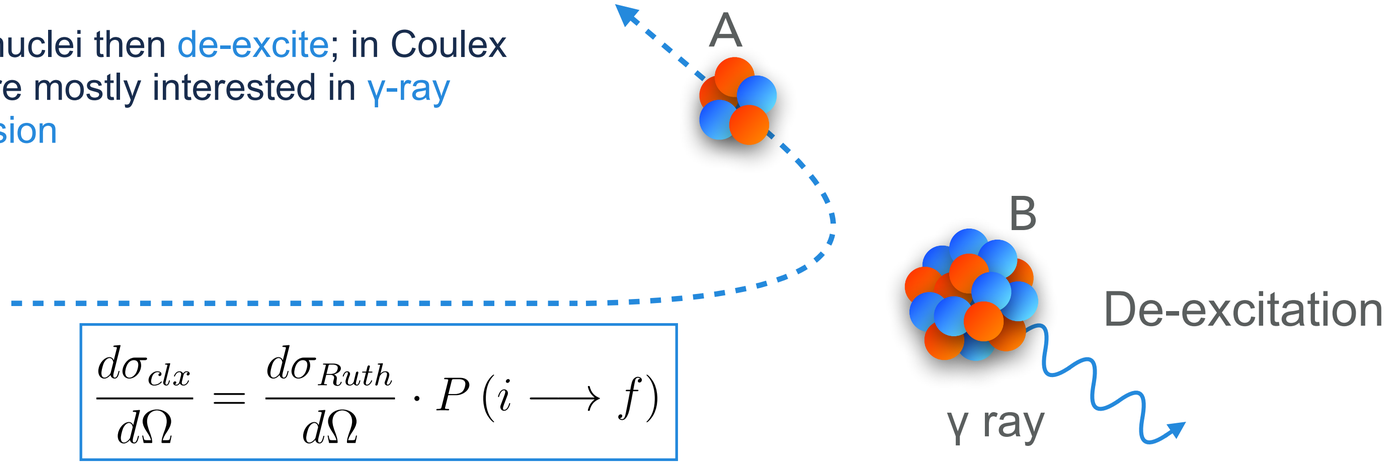
Marco Rocchini
INFN - Istituto Nazionale di Fisica Nucleare
FIRENZE DIVISION

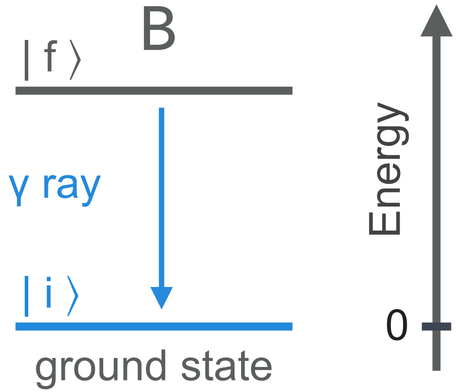
Two Complementary Probes for Nuclear Structure at FRIB:
Coulomb Excitation and Internal Conversion Electron Studies

Low-Energy Coulomb Excitation (aka Coulex)

- Inelastic scattering between two interacting nuclei, in the “purely” electromagnetic regime
- The time-dependent electromagnetic field between the two nuclei can induce excitations
- The nuclei then de-excite; in Coulex we are mostly interested in γ-ray emission



$$\frac{d\sigma_{clx}}{d\Omega} = \frac{d\sigma_{Ruth}}{d\Omega} \cdot P\left(i \longrightarrow f\right)$$



Low-Energy Coulomb Excitation (aka Coulex)

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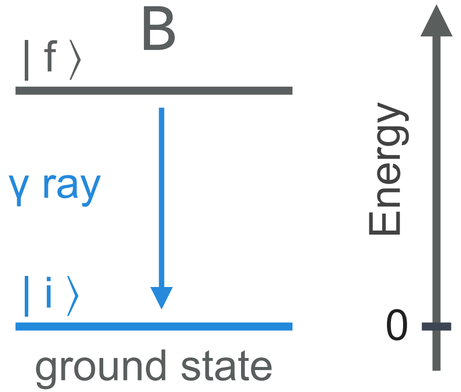
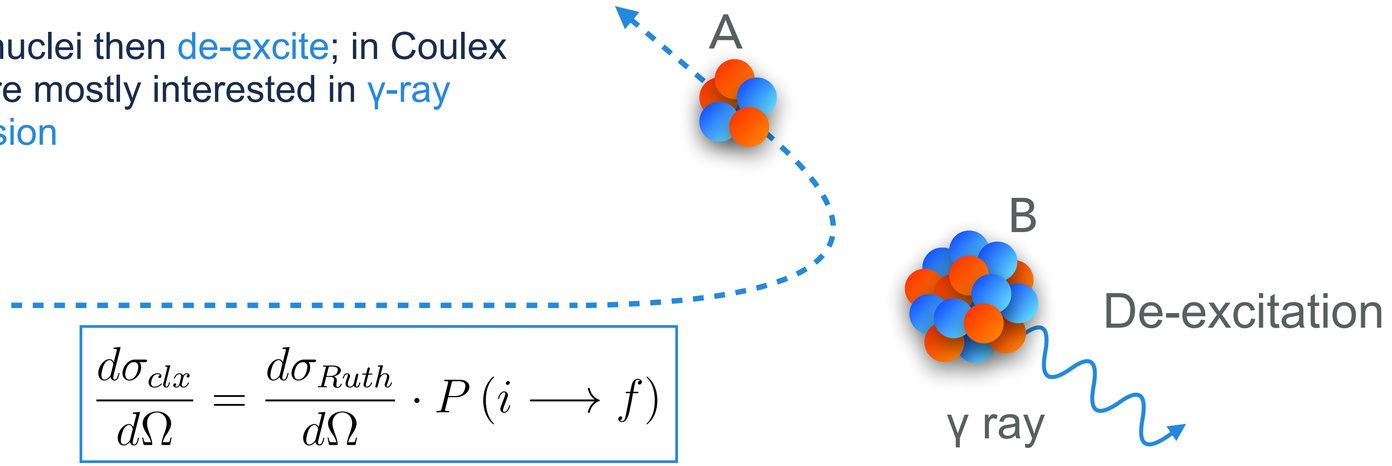




$$\frac{d\sigma_{clx}}{d\Omega} = \frac{d\sigma_{Ruth}}{d\Omega} \cdot P\left(i \longrightarrow f\right)$$

- Example: first 2+ state in an even-even target nucleus

$$P\left(0_1^+ \longrightarrow 2_1^+\right) = F\left(\theta, E_P\right) \underbrace{B(E2)}_{\sim|\langle 2^+||E2||0^+\rangle|^2} \left[1 + 1.32 \frac{A_P}{Z_T} \frac{\Delta E}{\left(1 + \frac{A_P}{A_T}\right)} \underbrace{Q_s\left(2^+\right)}_{\sim\langle 2^+||E2||2^+\rangle} K\left(\theta, E_P\right)\right]$$

Access to: transition probabilities, spectroscopic quadrupole moments

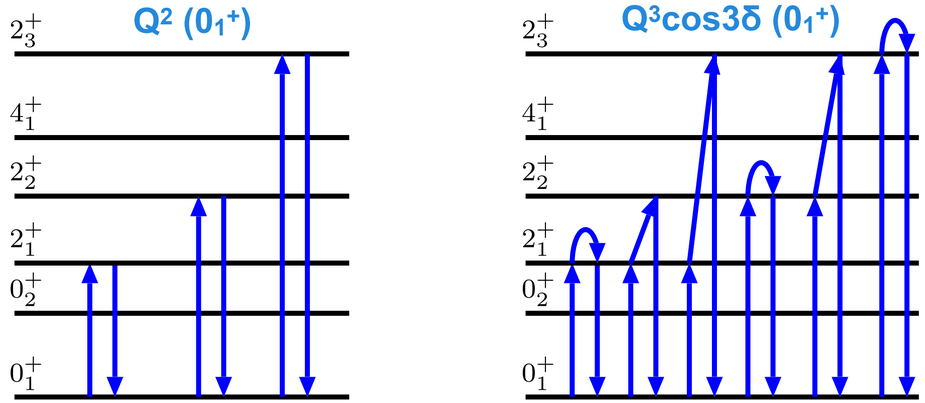
Quadrupole Sum Rules & Rotational Invariants

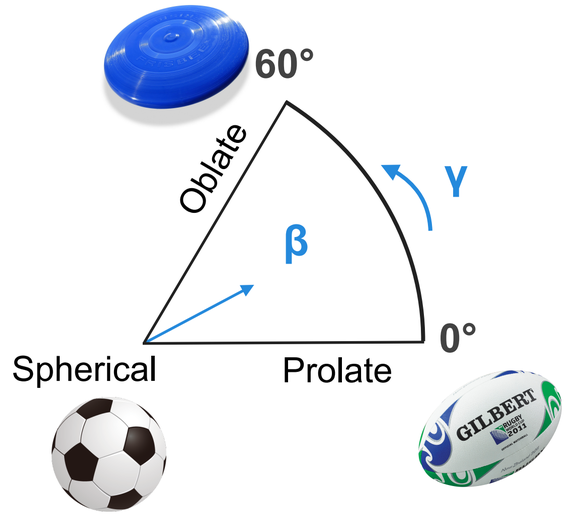
- Unique feature of Coulex ⟹ Possible to get relative signs of transitional matrix elements, and spectroscopic quadrupole moments of excited states with their sign
- Quadrupole Sum Rules ⟹ (β, γ) deformation parameters for g.s. and excited states in a model-independent way

$$\langle i \left| Q^2 \right| i \rangle = \frac{\sqrt{5}}{\sqrt{2I_i+1}} \sum_t \langle i \,||E2||\, t \rangle \langle t \,||E2||\, i \rangle \begin{Bmatrix} 2 & 2 & 0 \\ I_i & I_i & I_t \end{Bmatrix}$$

$$\langle i \left| Q^3 \cos(3\delta) \right| i \rangle = -\frac{\sqrt{35}}{\sqrt{2}} \frac{1}{2I_i+1} \sum_{tu} \langle i \,||E2||\, t \rangle \langle t \,||E2||\, u \rangle \langle u \,||E2||\, i \rangle \begin{Bmatrix} 2 & 2 & 2 \\ I_i & I_t & I_u \end{Bmatrix}$$

(Q², δ) equivalent to (β, γ)



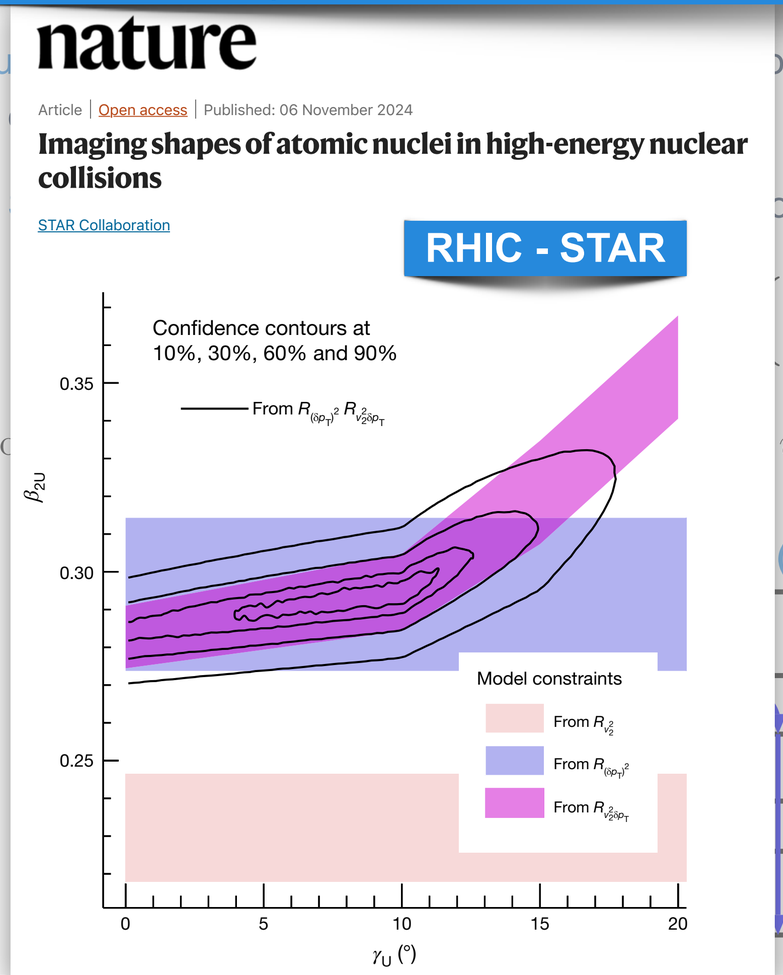


K. Kumar, Phys. Rev. Lett. 28 (1972) 249 & D. Cline, Annu. Rev. Nucl. Part. Sci. 36 (1986) 683

Hot topic not only in nuclear physics ⇒ New studies at high-energy physics facilities (and also intermediate energies from yesterday's talk?)

- Unique featu… moments of …
- Quadrupole …

$\langle i | Q^3 \, co$



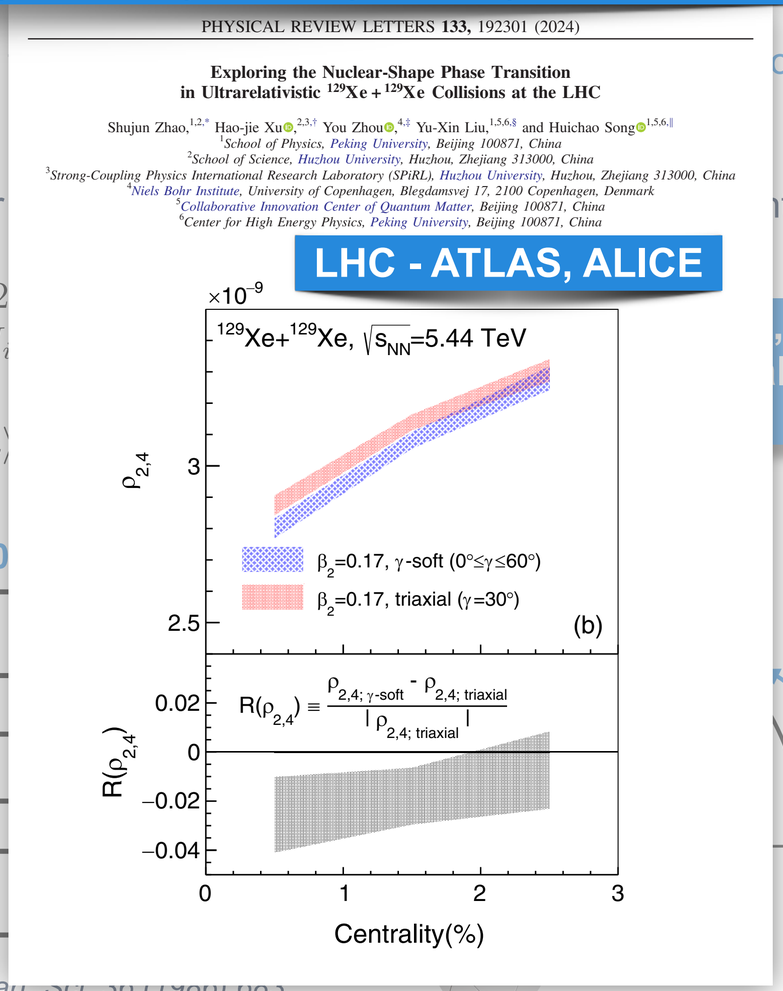
nature

Article | Open access | Published: 06 November 2024

Imaging shapes of atomic nuclei in high-energy nuclear collisions

STAR Collaboration

RHIC - STAR



PHYSICAL REVIEW LETTERS 133, 192301 (2024)

Exploring the Nuclear-Shape Phase Transition in Ultrarelativistic ^{129}Xe + ^{129}Xe Collisions at the LHC

Shujun Zhao,[1,2,*] Hao-jie Xu,[2,3,†] You Zhou,[4,‡] Yu-Xin Liu,[1,5,6,§] and Huichao Song[1,5,6,‖]

[1]School of Physics, Peking University, Beijing 100871, China
[2]School of Science, Huzhou University, Huzhou, Zhejiang 313000, China
[3]Strong-Coupling Physics International Research Laboratory (SPiRL), Huzhou University, Huzhou, Zhejiang 313000, China
[4]Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, 2100 Copenhagen, Denmark
[5]Collaborative Innovation Center of Quantum Matter, Beijing 100871, China
[6]Center for High Energy Physics, Peking University, Beijing 100871, China

LHC - ATLAS, ALICE

K. Kumar, Phys. Rev. Lett. 28 (1972) 249 & D. Cline, Annu. Rev. Nucl. Part. Sci. 36 (1986) 683

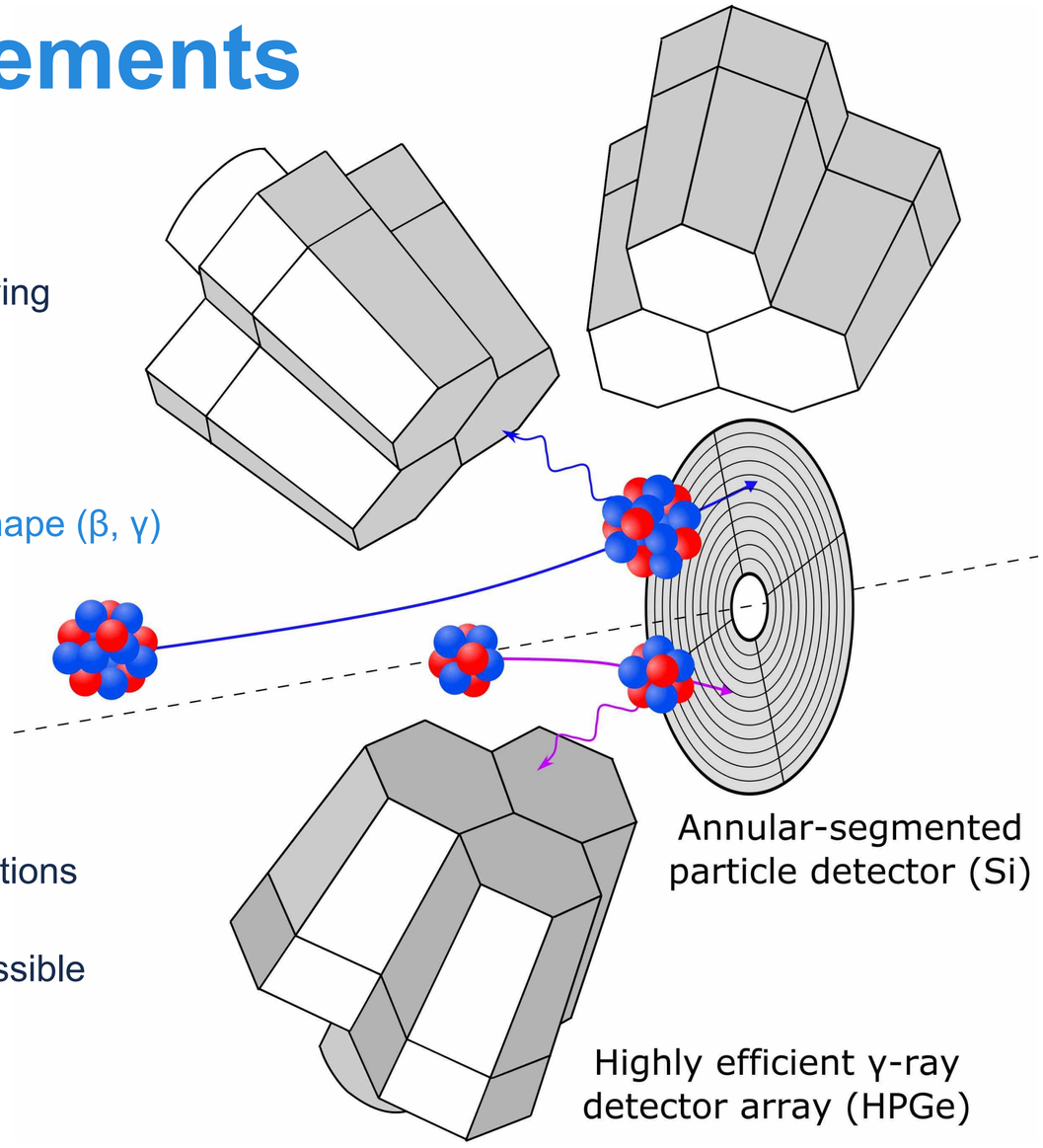
Experimental Requirements

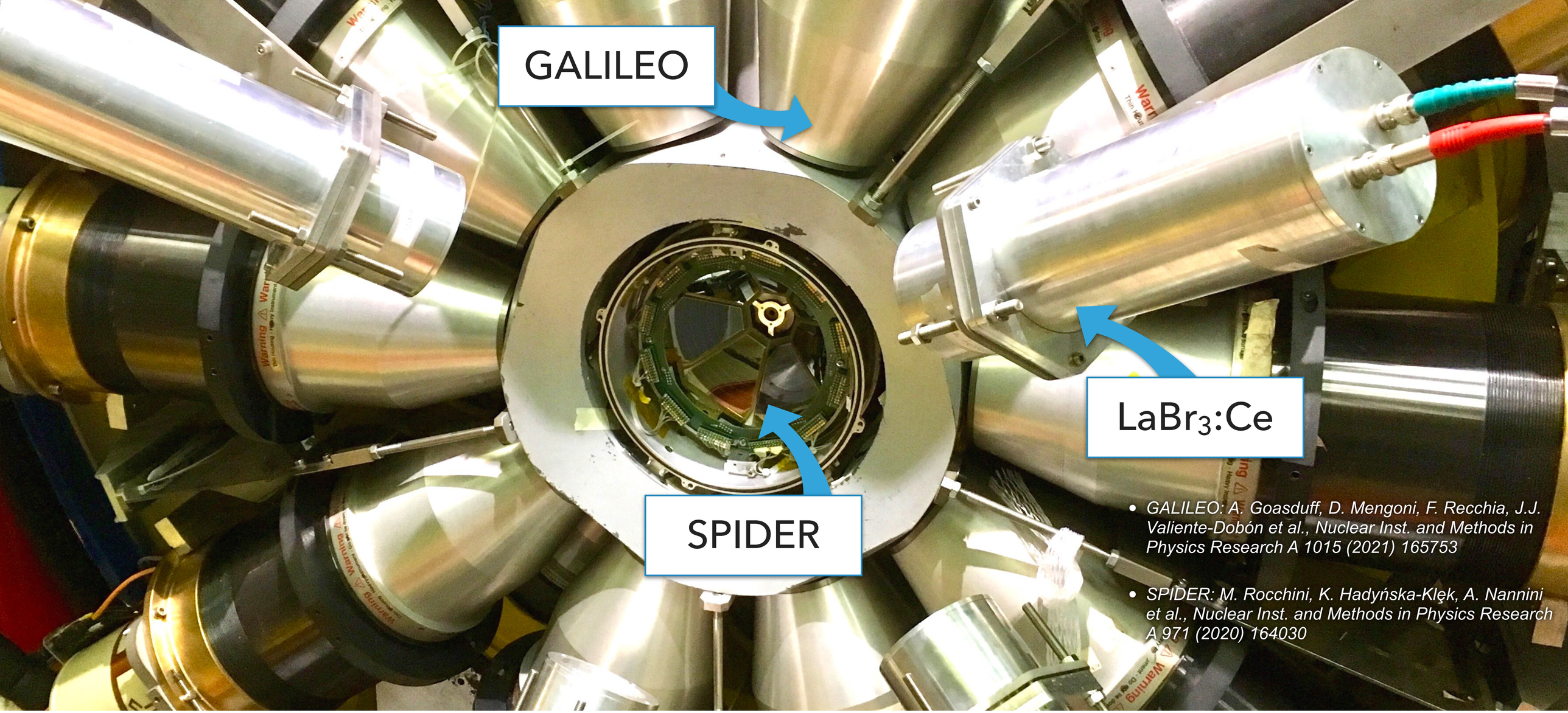
What can we get?

- Reduced transition probabilities for transitions between low-lying states, mainly *E2* and *E3* multipolarity
- Spectroscopic quadrupole moments for excited states
- Rotational invariants (Q, δ) ⟹ Direct access to the nuclear shape (β, γ)

What do we need?

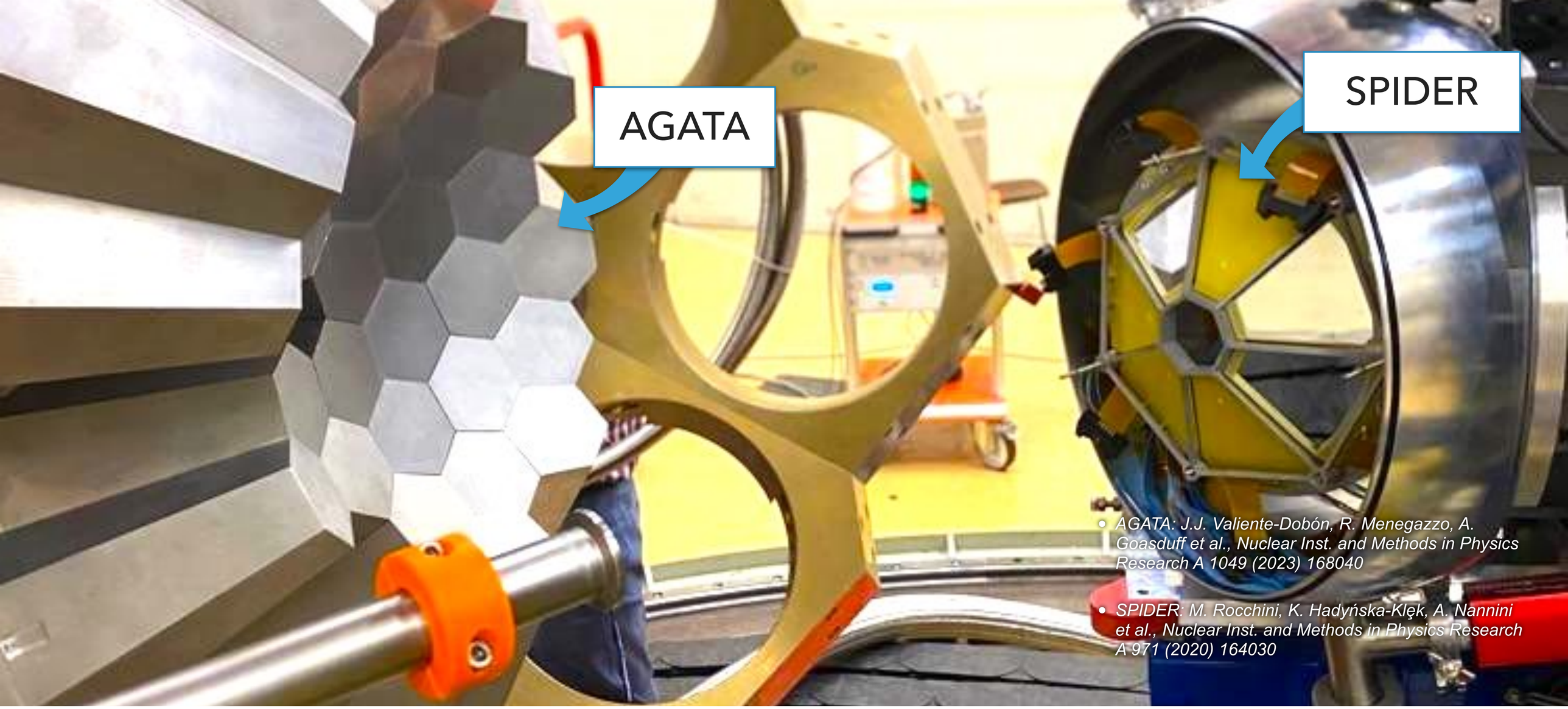
- Beam energies around 3-6 MeV/A
- Good technique for weak-intensity beams ⟹ Large cross sections
- Gamma-ray array and heavy ion detector with as good as possible efficiency, energy or time resolutions, and segmentations





- *GALILEO: A. Goasduff, D. Mengoni, F. Recchia, J.J. Valiente-Dobón et al., Nuclear Inst. and Methods in Physics Research A 1015 (2021) 165753*
- *SPIDER: M. Rocchini, K. Hadyńska-Klęk, A. Nannini et al., Nuclear Inst. and Methods in Physics Research A 971 (2020) 164030*

GALILEO with SPIDER (2016 - 2019)



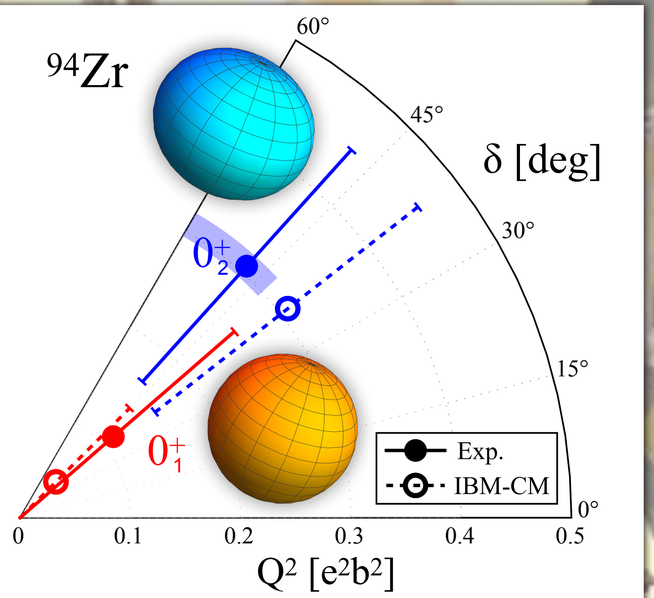
- *AGATA: J.J. Valiente-Dobón, R. Menegazzo, A. Goasduff et al., Nuclear Inst. and Methods in Physics Research A 1049 (2023) 168040*
- *SPIDER: M. Rocchini, K. Hadyńska-Klęk, A. Nannini et al., Nuclear Inst. and Methods in Physics Research A 971 (2020) 164030*

AGATA with SPIDER (2022 - ongoing)

AGATA with SPIDER (2022 - ongoing)

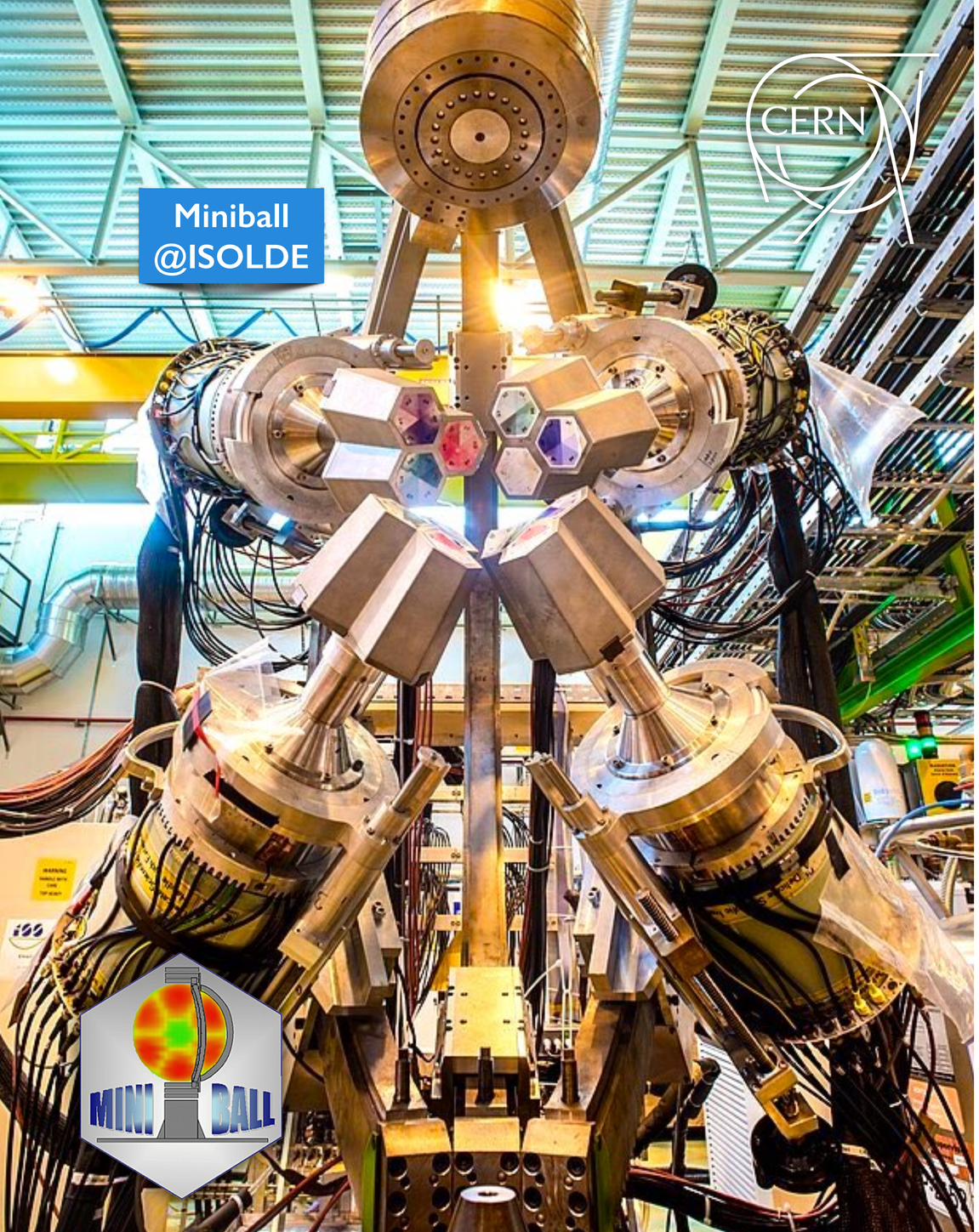
More than 20 experiments performed with GALILEO and AGATA coupled to SPIDER from A ~ 40 to A ~ 160, with SPs from 3 different continents (other 3 accepted)

- Our newest completed analysis: low-energy Coulomb excitation performed with a ^{94}Zr beam on a ^{208}Pb target (*SPs: D.T. Doherty, M. Rocchini, M. Zielinska*)
- First determination in the entire Zr isotopic chain of the 2_1^+ and 2_2^+ spectroscopic quadrupole moments and the 0_1^+ and 0_2^+ rotational invariants
- *N. Marchini, M. Rocchini, M. Zielinska, A. Nannini et al., submitted to Physics Letters B (advanced review phase)*



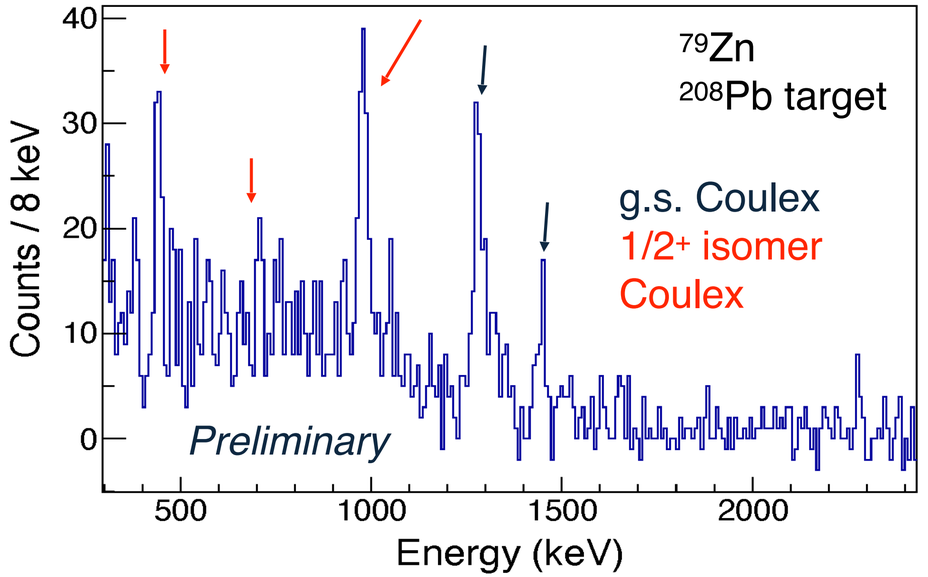
SPIDER

- *AGATA: J.J. Valiente-Dobón, R. Menegazzo, A. Goasduff et al., Nuclear Inst. and Methods in Physics Research A 1049 (2023) 168040*
- *SPIDER: M. Rocchini, K. Hadyńska-Klęk, A. Nannini et al., Nuclear Inst. and Methods in Physics Research A 971 (2020) 164030*

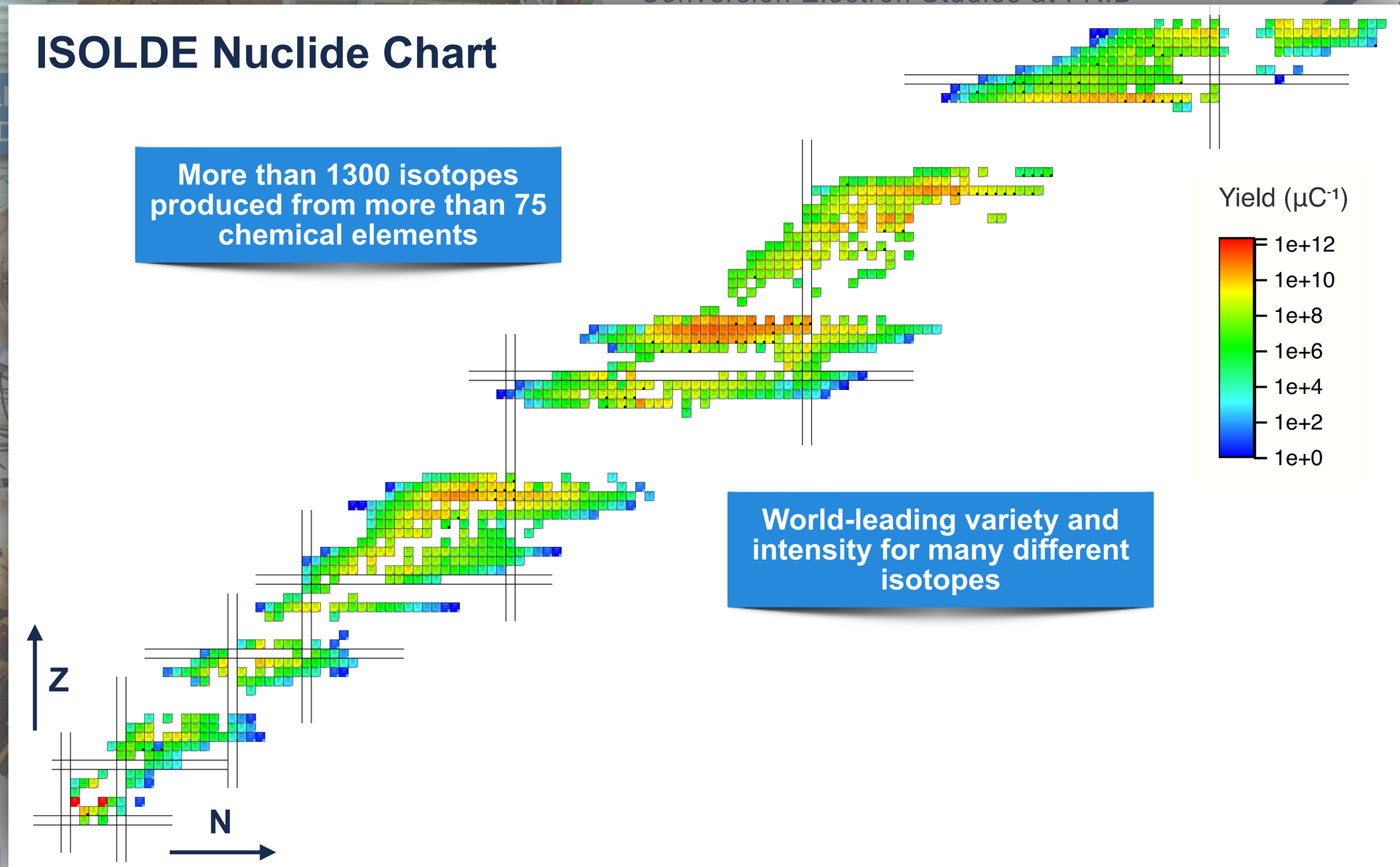


GAMMA@Miniball

- Low-energy Coulomb excitation: an ideal technique to investigate the deformation of post-accelerated radioactive ions
- Long campaign at ISOLDE with the Miniball HPGe array for the detection of the γ-rays and a segmented silicon detector for the scattered beam
- Recent example from GAMMA (*SP: A. Gottardo, M. Zielinska*): Coulomb excitation of both the ground and the lowest-lying isomeric state of ^{79}Zn

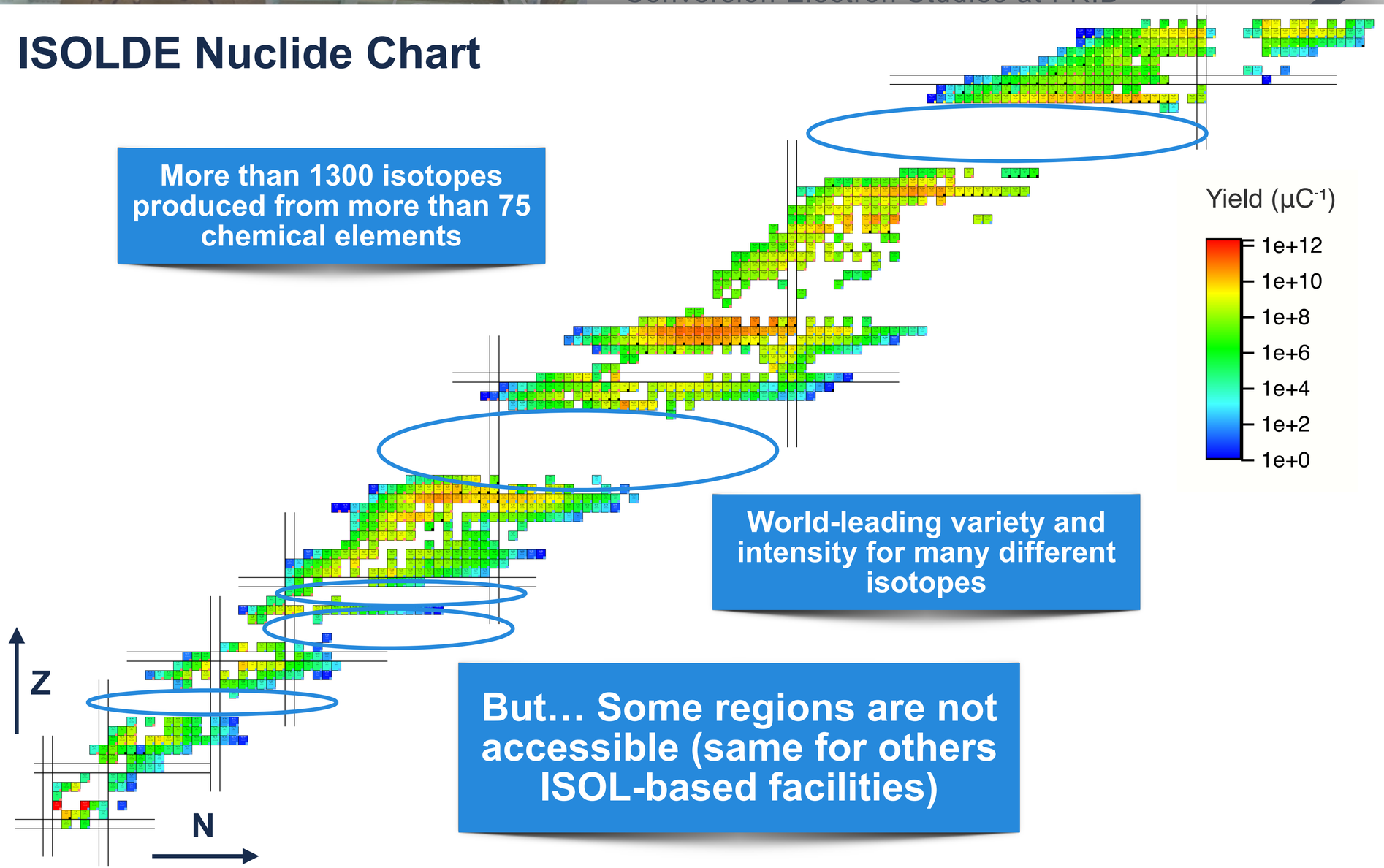


ISOLDE Nuclide Chart



ISOLDE Nuclide Chart

More than 1300 isotopes produced from more than 75 chemical elements

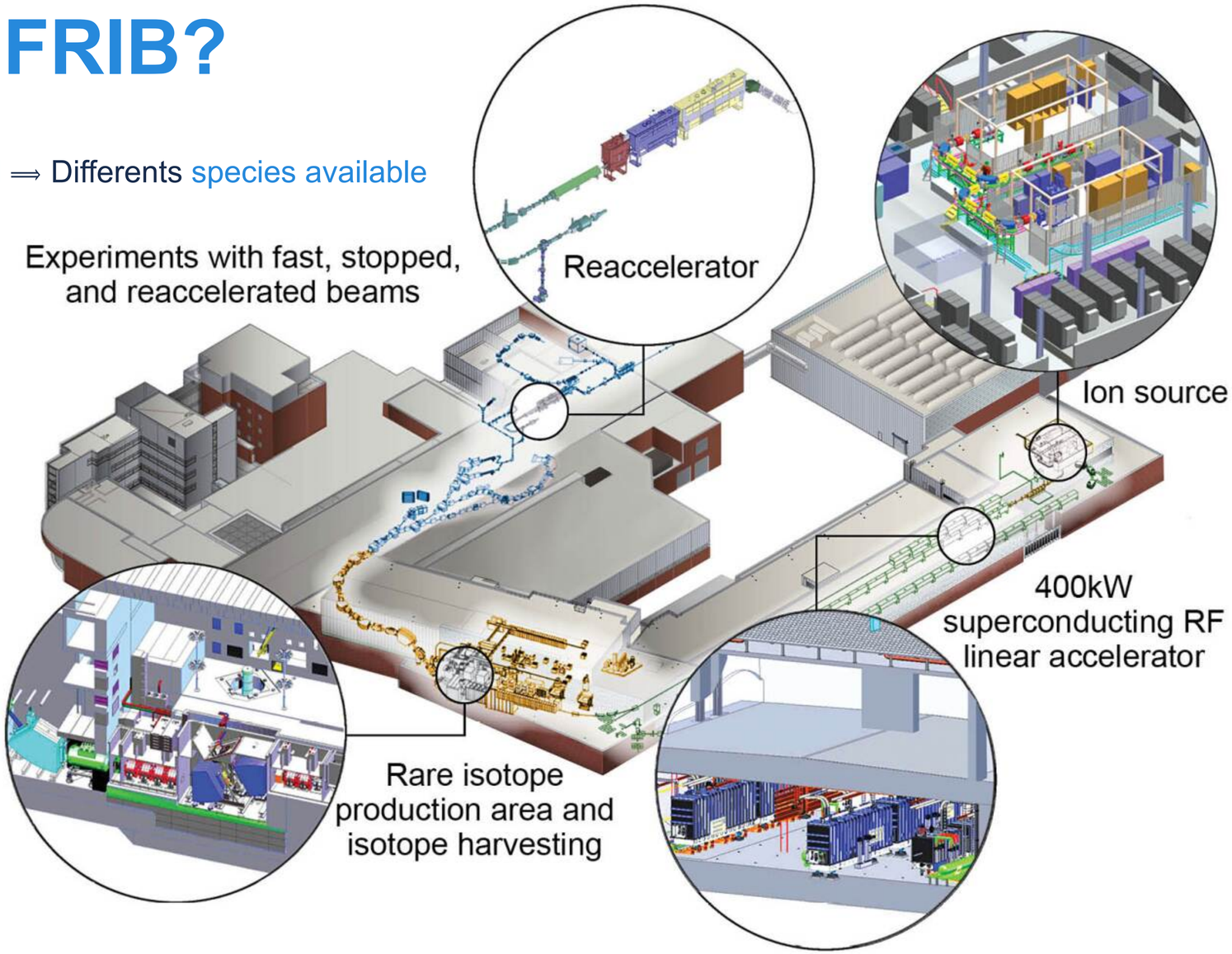


World-leading variety and intensity for many different isotopes

But… Some regions are not accessible (same for others ISOL-based facilities)

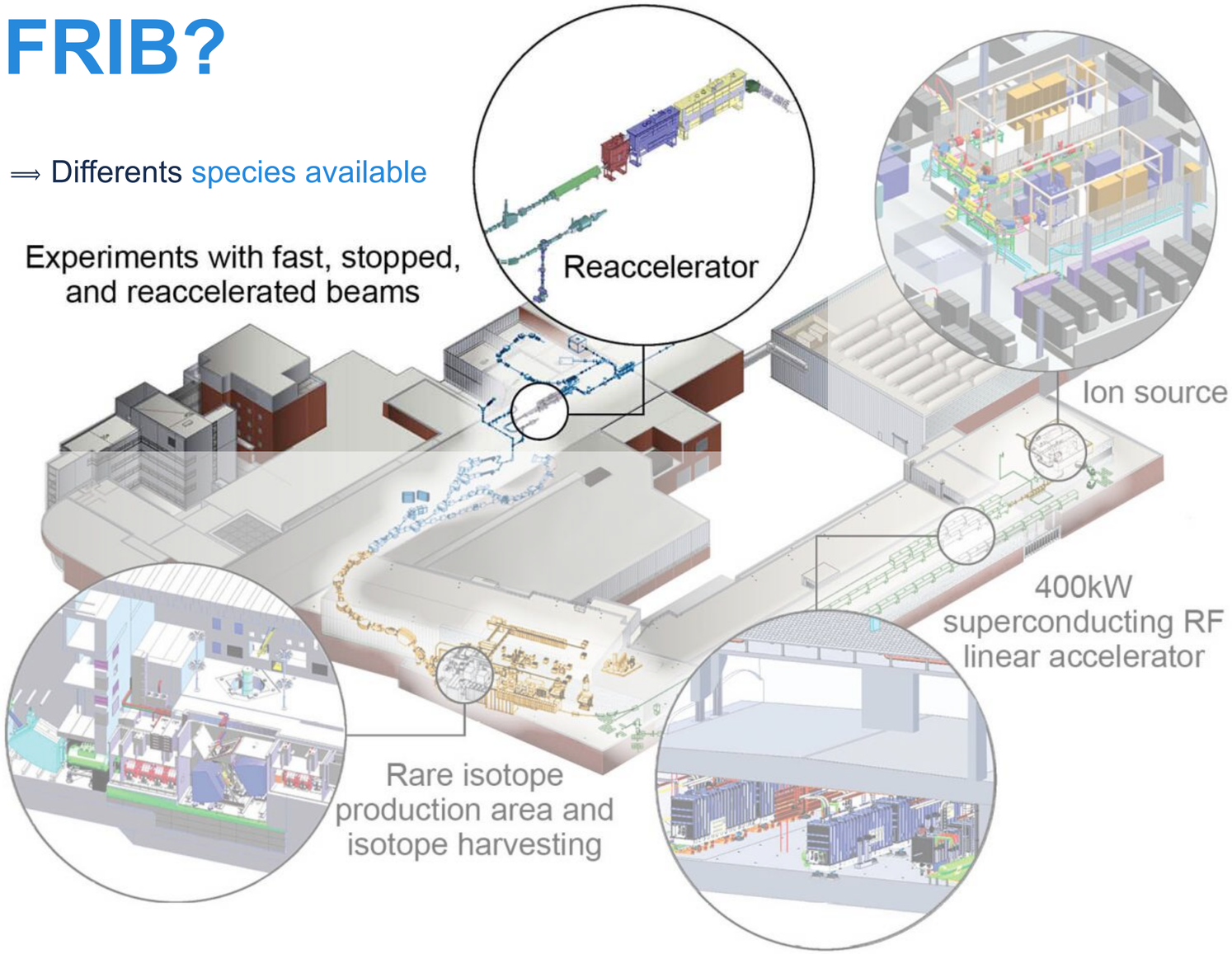
Coulex at FRIB?

- Different RIBs production method ⟹ Differents species available



Coulex at FRIB?

- Different RIBs production method ⟹ Differents species available
- Availability of ReA beams: proper beam energy for Coulex



Coulex at FRIB?

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- Coulex setup available: JANUS

Experiments with
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Rare
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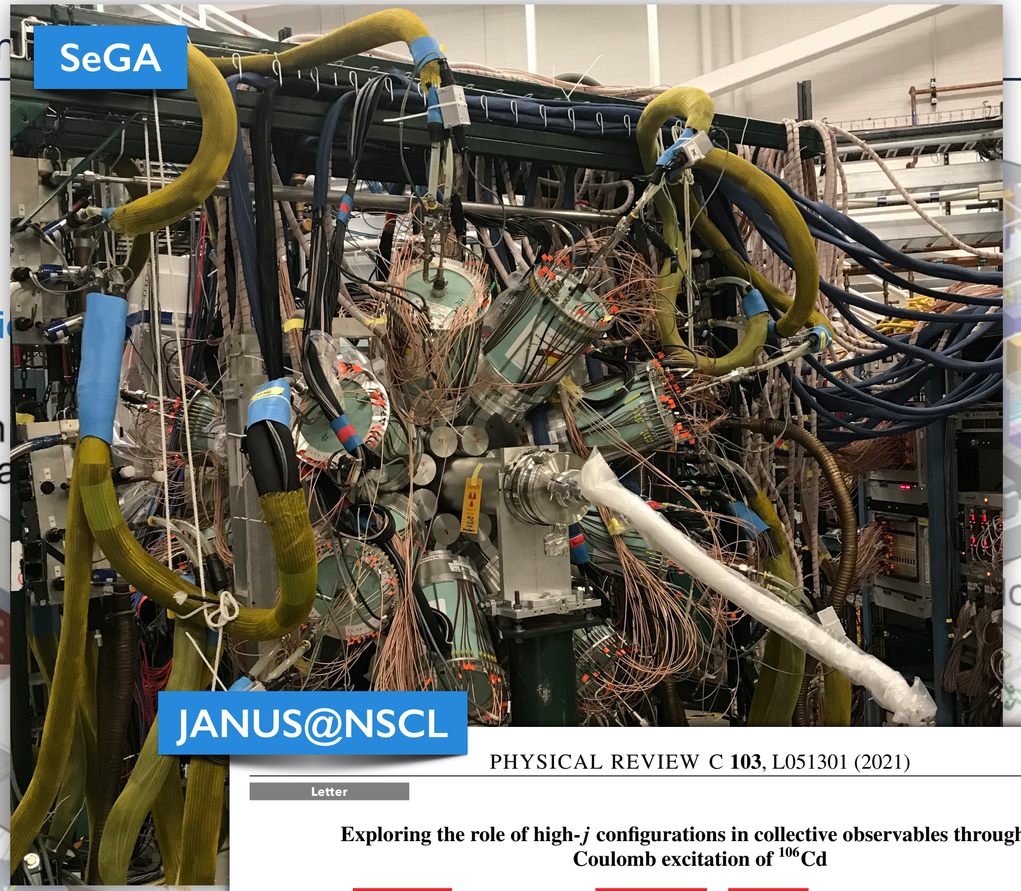
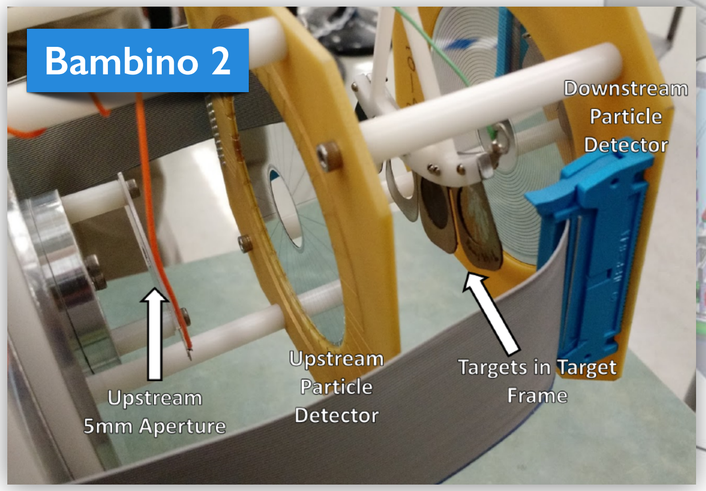
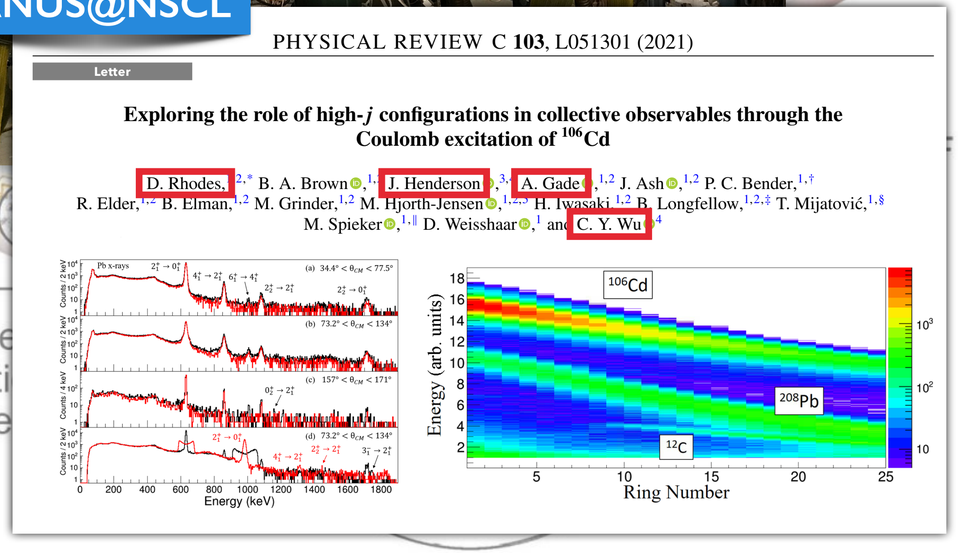
isotope







PHYSICAL REVIEW C **103**, L051301 (2021)

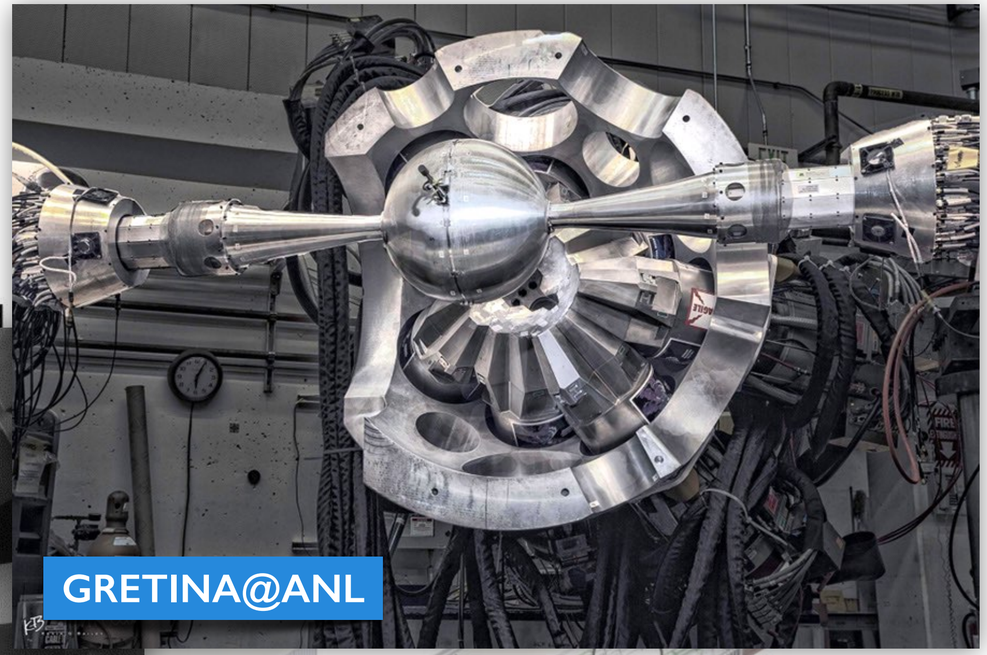
Letter

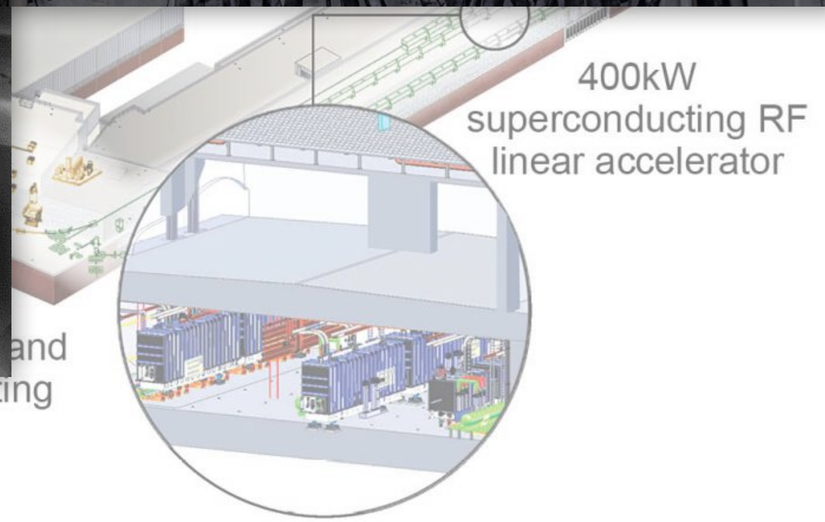
Exploring the role of high-j configurations in collective observables through the Coulomb excitation of ^{106}Cd

D. Rhodes,[1,2,*] B. A. Brown,[1,2] J. Henderson,[3,†] A. Gade,[1,2] J. Ash,[1,2] P. C. Bender,[1,†] R. Elder,[1,2] B. Elman,[1,2] M. Grinder,[1,2] M. Hjorth-Jensen,[1,2,‡] H. Iwasaki,[1,2] B. Longfellow,[1,2,§] T. Mijatović,[1,§] M. Spieker,[1,‖] D. Weisshaar,[1] and C. Y. Wu[3,4]

Coulex at FRIB?

- Different RIBs production method ⟹ Differents species available
- Availability of ReA beams: proper beam energy for Coulex
- Coulex setup available: JANUS
- Possible future with GRETA and CHICOX?





Coulex at FRIB?

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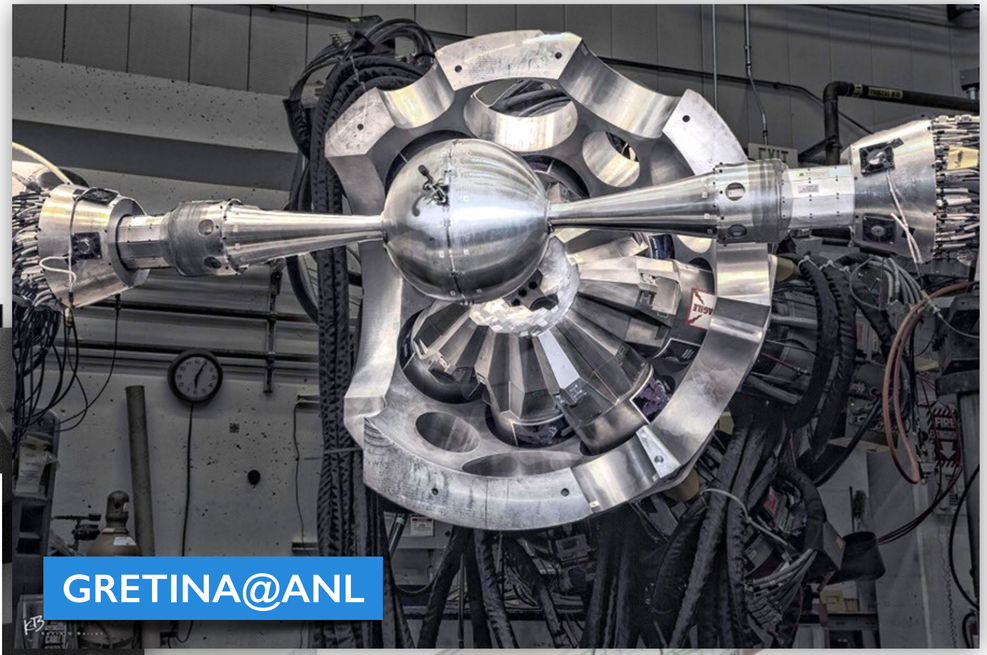
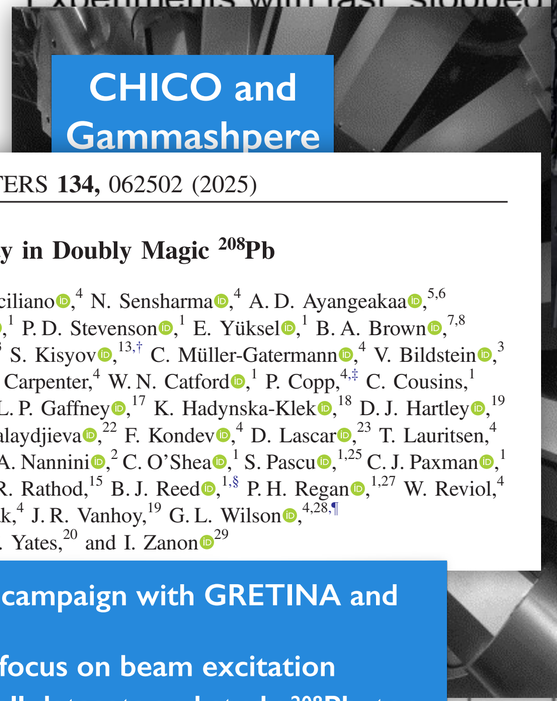


Experiments with fast, stopped

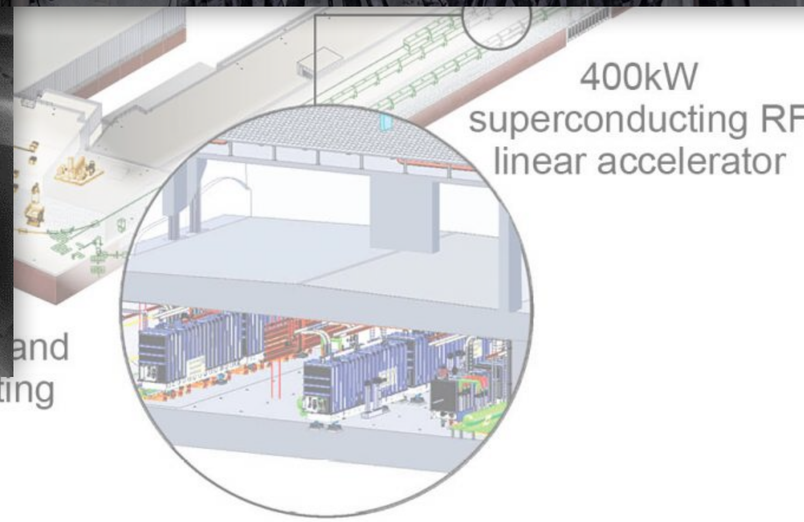


PHYSICAL REVIEW LETTERS **134,** 062502 (2025)

Deformation and Collectivity in Doubly Magic ^{208}Pb

J. Henderson,[*] J. Heery,[1] M. Rocchini,[2,3] M. Siciliano,[4] N. Sensharma,[4] A. D. Ayangeakaa,[5,6] R. V. F. Janssens,[5,6] T. M. Kowalewski,[5,6] Abhishek,[1] P. D. Stevenson,[1] E. Yüksel,[1] B. A. Brown,[7,8] T. R. Rodriguez,[9,10,11] L. M. Robledo,[10,11,12] C. Y. Wu,[13] S. Kisyov,[13,†] C. Müller-Gatermann,[4] V. Bildstein,[3] L. Canete,[1] C. M. Campbell,[14] S. Carmichael,[15] M. P. Carpenter,[4] W. N. Catford,[1] P. Copp,[4,‡] C. Cousins,[1] M. Devlin,[16] D. T. Doherty,[1] P. E. Garrett,[3] U. Garg,[15] L. P. Gaffney,[17] K. Hadynska-Klek,[18] D. J. Hartley,[19] S. F. Hicks,[20,21] H. Jayatissa,[4,‡] S. R. Johnson,[5,6] D. Kalaydjieva,[22] F. Kondev,[4] D. Lascar,[23] T. Lauritsen,[4] G. Lotay,[1] N. Marchini,[2] M. Matejska-Minda,[24] S. Nandi,[4] A. Nannini,[2] C. O'Shea,[1] S. Pascu,[1,25] C. J. Paxman,[1] A. Perkoff,[26] E. E. Peters,[20] Zs. Podolyák,[1] A. Radich,[3] R. Rathod,[15] B. J. Reed,[1,§] P. H. Regan,[1,27] W. Reviol,[4] E. Rubino,[7,‖] R. Russell,[1] D. Seweryniak,[4] J. R. Vanhoy,[19] G. L. Wilson,[4,28,¶] K. Wrzosek-Lipska,[18] S. W. Yates,[20] and I. Zanon[29]

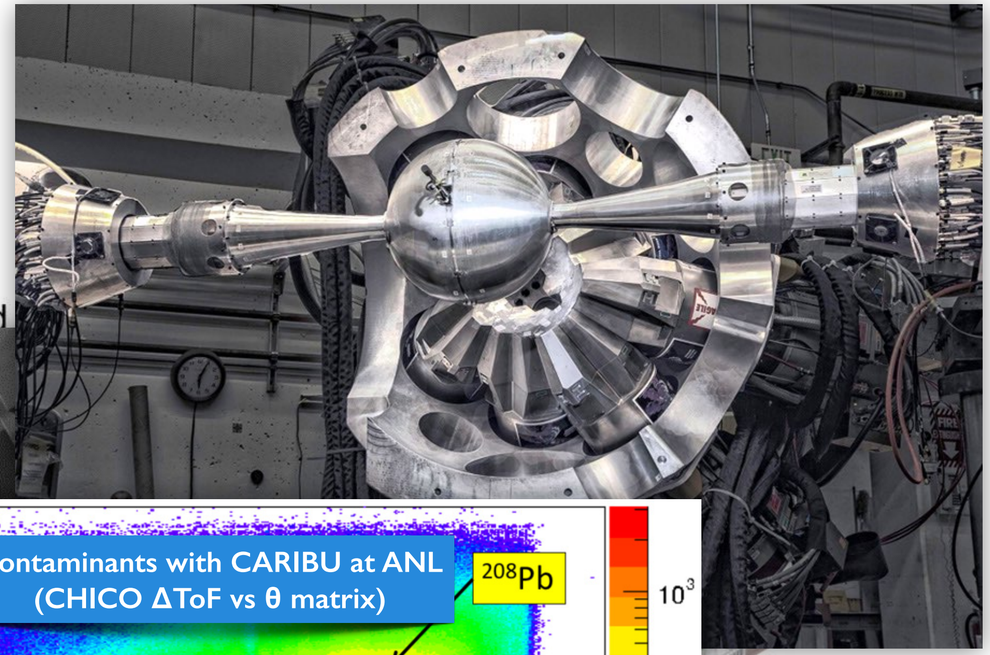
- Low-energy Coulomb excitation campaign with GRETINA and CHICO2 at ANL
- Several beams on a ^{208}Pb target, focus on beam excitation
- Jack's (great) idea: let's combine all datasets and study ^{208}Pb, too



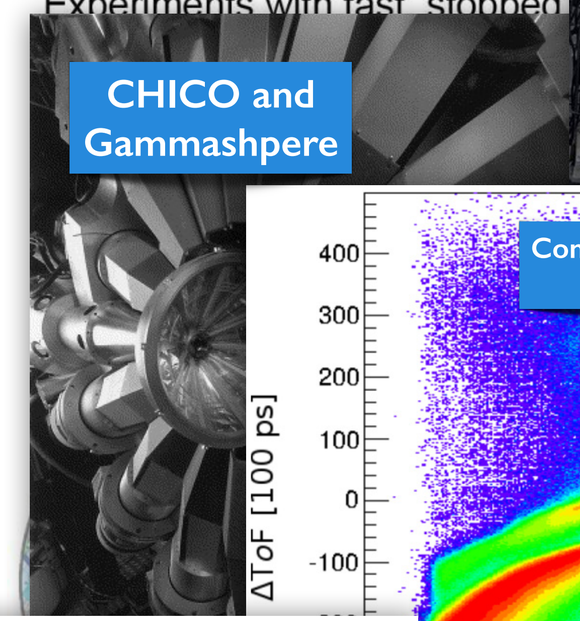
and
otope harvesting

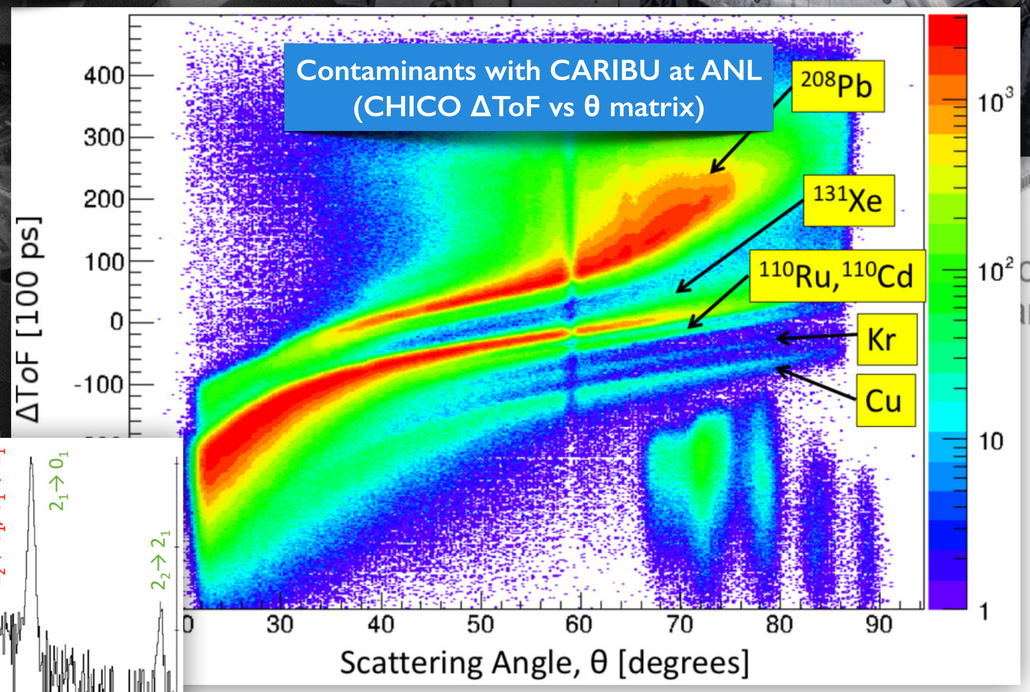
Coulex at FRIB?

- Different RIBs production method ⟹ Differents species available
- Availability of ReA beams: proper beam energy for Coulex
- Coulex setup available: JANUS
- Possible future with GRETA and CHICOX?
- Level of purity of the beams?



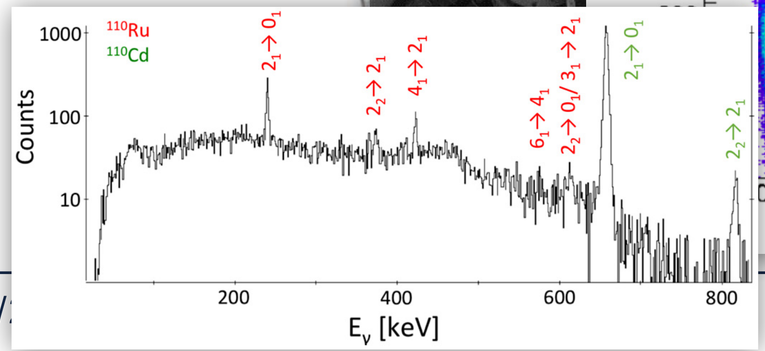
Experiments with fast, stopped





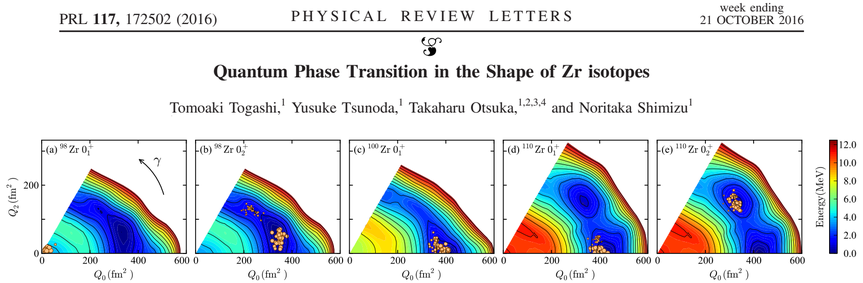
400kW
conducting RF
r accelerator

D.T. Doherty, J.M. Allmond, R.V.F. Janssens et al., Phys. Lett. B 766 (2017) 334



QPT in Zirconium Isotopes

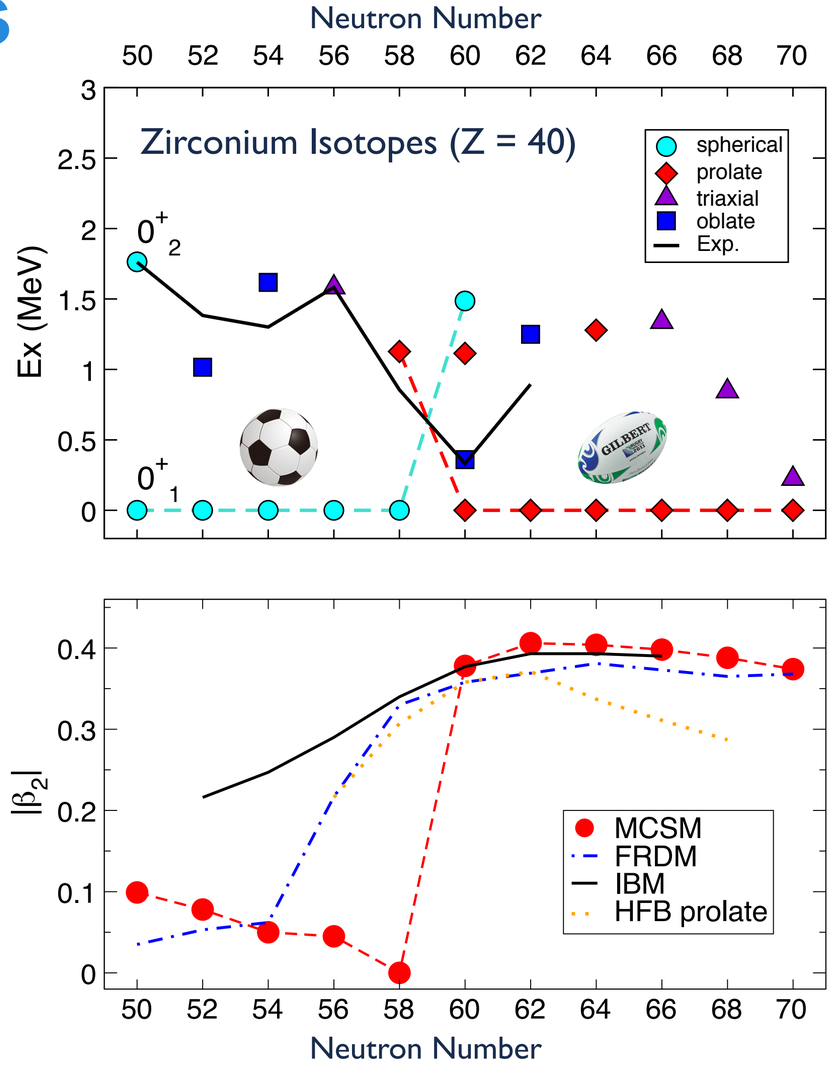
- The Zr isotopes undergo a dramatic change in nuclear properties at N = 60, for a long time not been reproduced by any theoretical model
- Monte Carlo Shell Model ⟹ Excellent reproduction of experimental data, for the first time also around N = 60


PRL 117, 172502 (2016) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2016

Quantum Phase Transition in the Shape of Zr isotopes

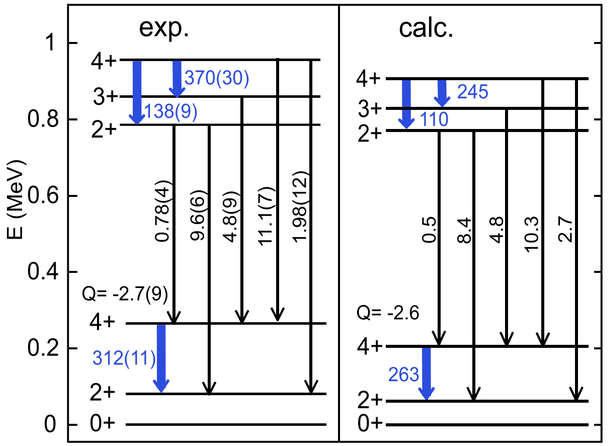
Tomoaki Togashi,[1] Yusuke Tsunoda,[1] Takaharu Otsuka,[1,2,3,4] and Noritaka Shimizu[1]

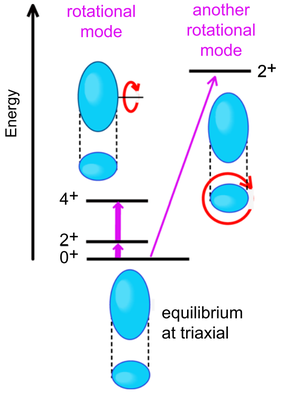
- Combination of type-I and type-II shell evolution, which induces a Quantum Phase Transition (QPT) in these isotopes
- We are studying several of these isotopes (^{94}Zr, ^{96}Zr, ^{98}Zr, ^{100}Zr) with multiple techniques at LNL, TRIUMF, ANL and MLL ⟹ Key missing experiments: Coulex of radioactive Zr
- Not possible with ISOL ⟹ beam intensities for ReA beams at FRIB [pps]:
  - ^{98}Zr - $3.3 \cdot 10^5$ 👍, ^{100}Zr - $2.6 \cdot 10^5$ 👍, ^{102}Zr - $1.6 \cdot 10^5$ 👍, ^{104}Zr - $1.4 \cdot 10^4$ 👍

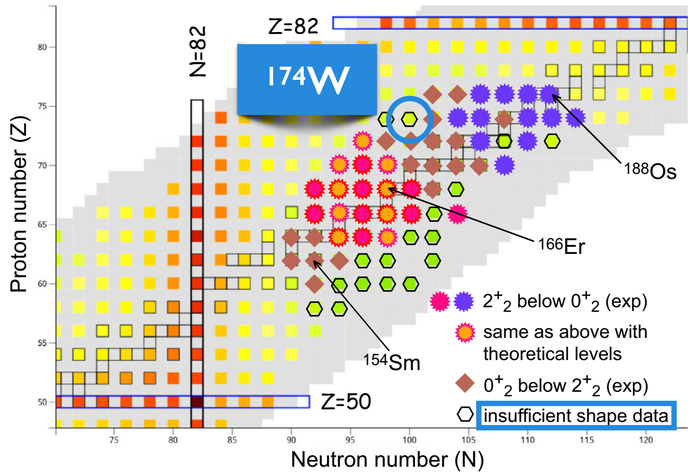


Triaxiality in Bohr-Mottelson's Ideal Rotors

- Collective models, traditional picture: rotors, vibrators, γ-soft nuclei and γ-rigid nuclei ⟹ Only for the first two, there has been "strong" experimental evidence
- Nuclear vibrations at low energy were doubted first for β bands in rotational nuclei (e.g., *P.E. Garrett, J. Phys. G 27 (2001) R1*) and then for g.s. in supposed vibrators (e.g., *P.E. Garrett, T.R. Rodríguez et al., Phys. Rev. Lett. 123 (2019) 142502*)
- What about γ-vibrations? ⟹ Recent Monte Carlo Shell Model (*T. Otsuka et al., Eur. Phys. J. A 61 (2025) 126*): the 2_2^+ state is not a vibration, instead, it originates from a (different kind of) rotation
- Recent unexpectedly small g-factor in the K = 12^+ isomer of ^{174}W (*M. Rocchini, A. Nannini, G. Benzoni, E. Vigezzi et al., Eur. Phys. J. A 56 (2020) 289*), a supposed simple, ideally prolate-deformed, nucleus ⟹ Triaxiality could explain the observation
- Not possible with ISOL ⟹ beam intensities for ReA beams at FRIB [pps]: ^{174}W - $2.2 \cdot 10^5$ 👍 (other isotopes in this region of mass possible)

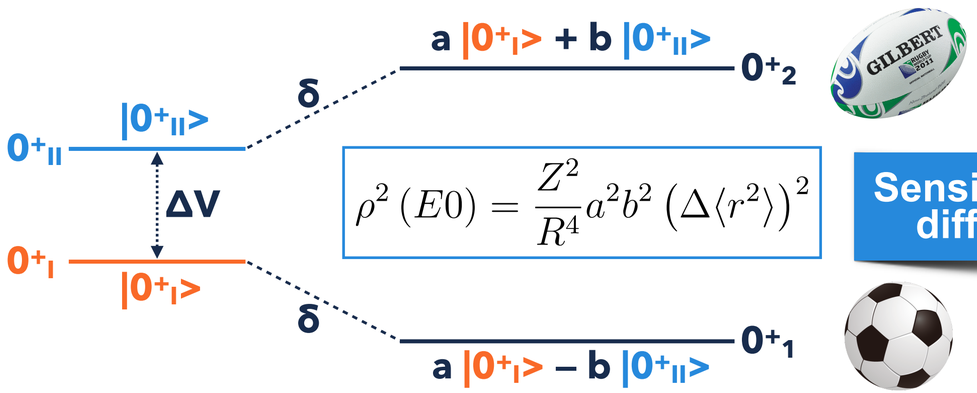






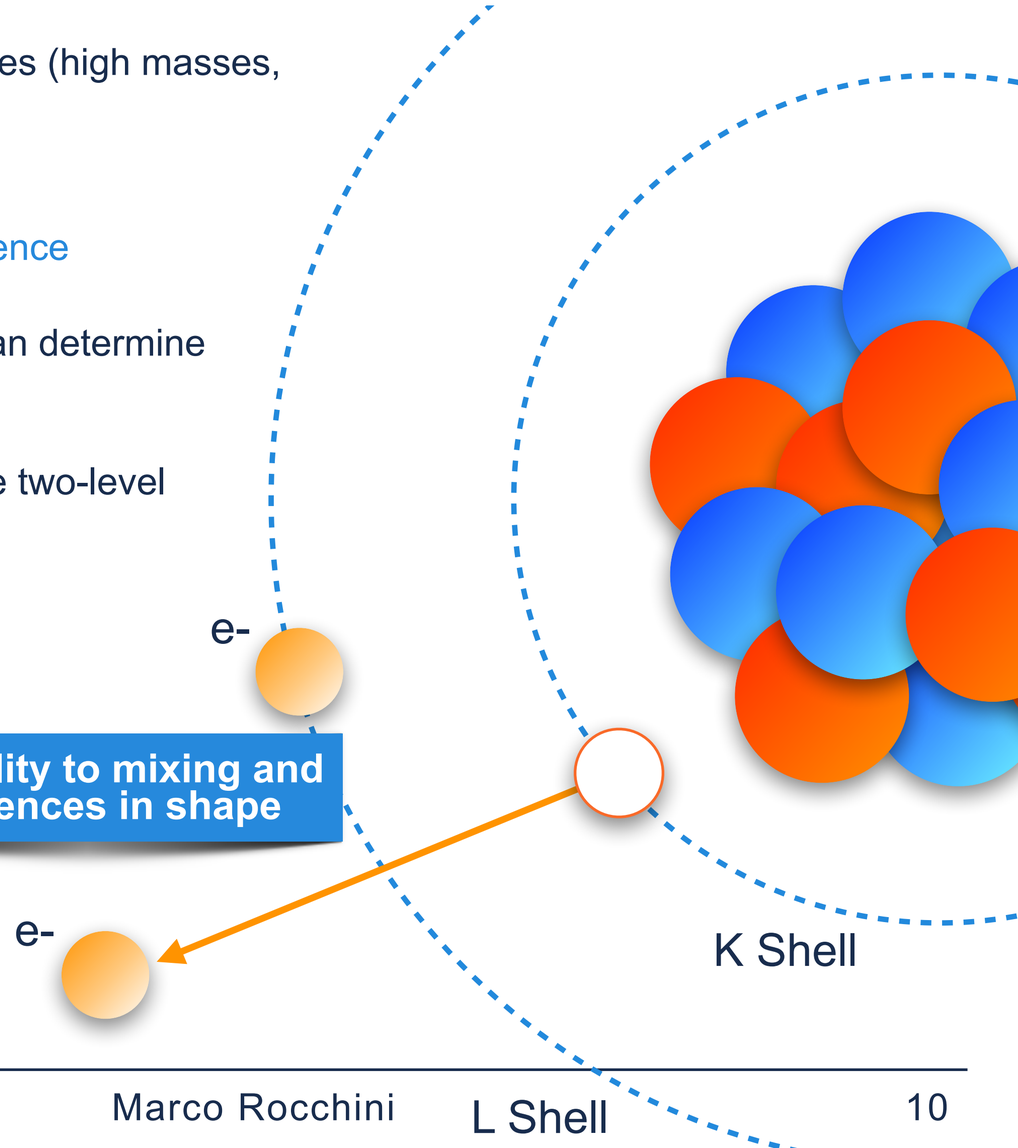
Internal Conversion Electrons (aka ICEs)

- Competitive process to γ-ray emission ⟹ Favourable in certain cases (high masses, low transition energies, high multipolarities)
- Particularly suited to study, for instance, breathing modes (nuclear compressibility), clustering, octupole collectivity, and shape coexistence
- By measuring the ratio of emission between γ-rays and ICEs, we can determine the parity of excited states
- *E0* transitions (γ-ray forbidden) and their strength $\rho^2(E0)$, the simple two-level mixing model:



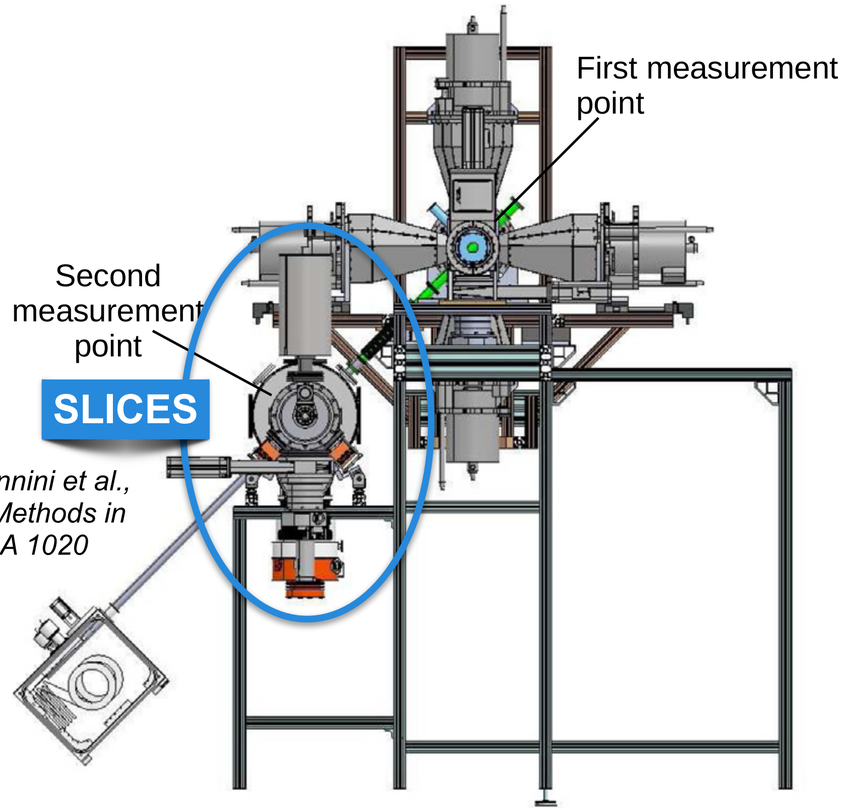
$$\rho^2(E0) = \frac{Z^2}{R^4} a^2 b^2 \left(\Delta\langle r^2\rangle\right)^2$$

Sensibility to mixing and differences in shape



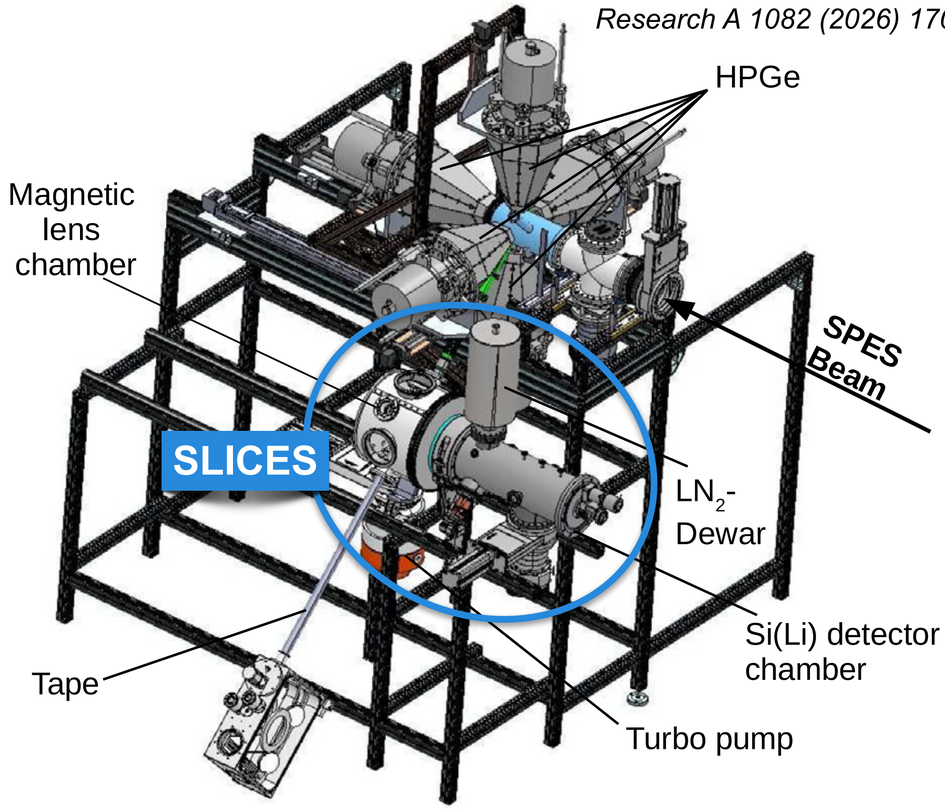
Our ICE Spectrometer: SLICES

- SLICES stands for Spes Low-energy Internal Conversion Electron Spectrometer
- Designed for the Beta Decay Station (BDS) of SPES



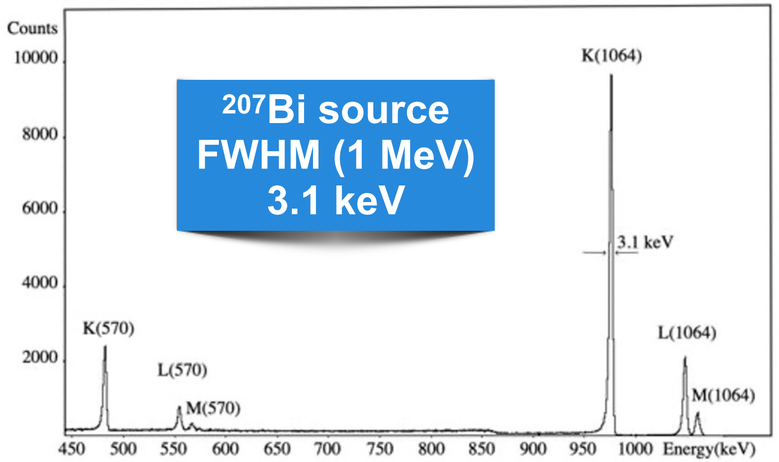
N. Marchini, A. Nannini et al., Nuclear Inst. and Methods in Physics Research A 1020 (2021) 165860

A. Saltarelli, G. Benzoni et al., Nuclear Inst. and Methods in Physics Research A 1082 (2026) 170927



The Si(Li) Detector

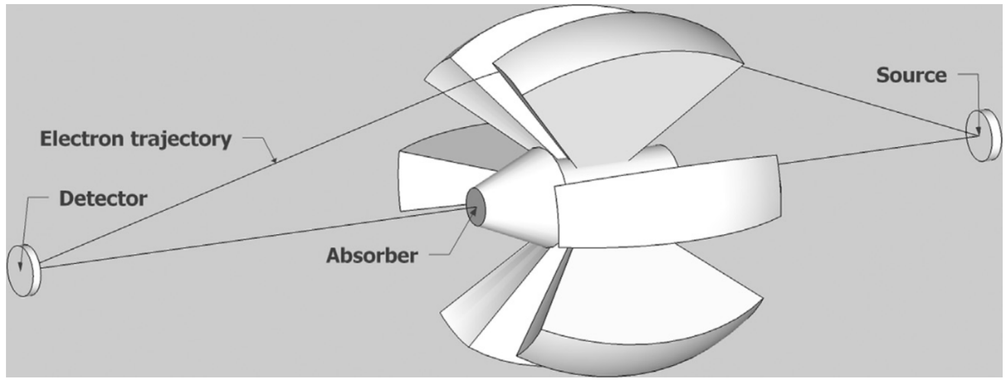
- Developed in collaboration with the Jülich research center (Germany)
- Diameter = 76.2 mm (active area ≈ 3900 mm^2)
- Thickness = 6.8 mm (for electrons up to ≈ 2 MeV)
- Segmented in 32 independent sectors to obtain small junction capacitances (thus low-noise)
- Mylar-foil (17 μm) in front of the detector surface to protect from impurities when cooled, not affecting electrons above ≈ 35 keV

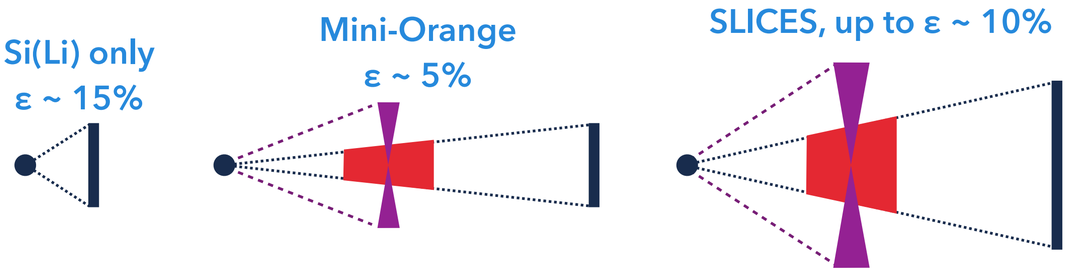


N. Marchini, A. Nannini et al., Nuclear Inst. and Methods in Physics Research A 1020 (2021) 165860

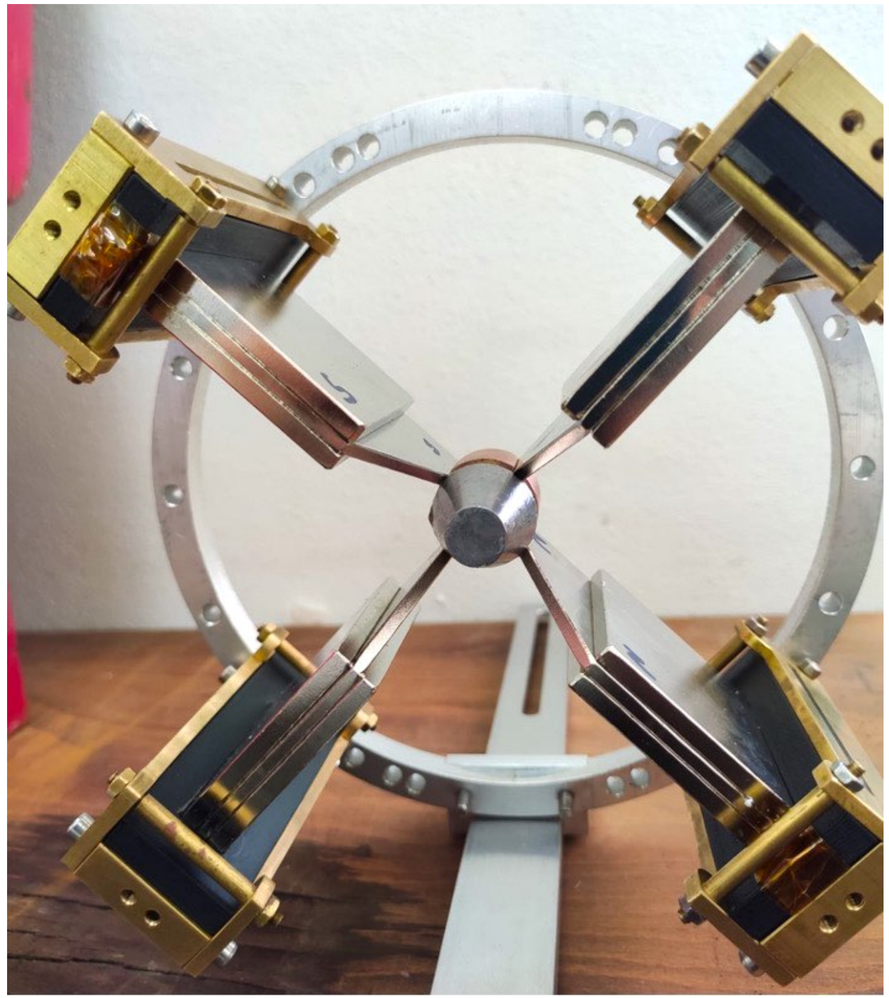
The Magnetic Transport System

- SLICES employs a magnetic transport system composed of a magnetic lens and a central absorber
- Large efficiency and good reduction of γ-ray background





(drawings not to scale)



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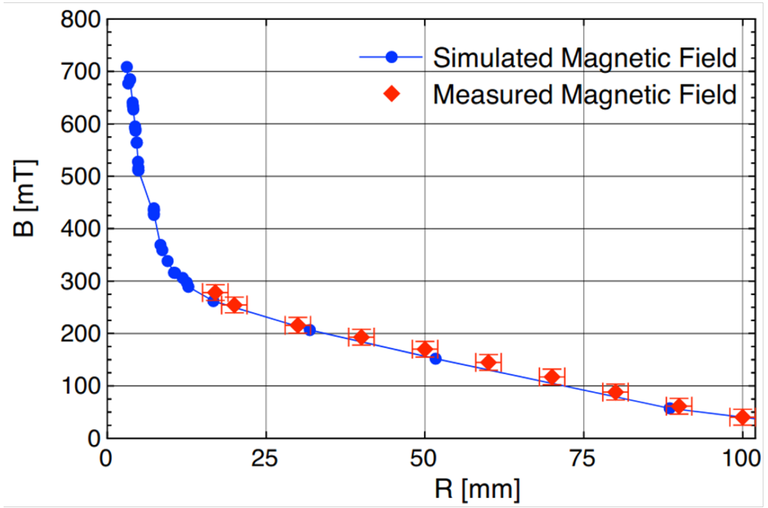
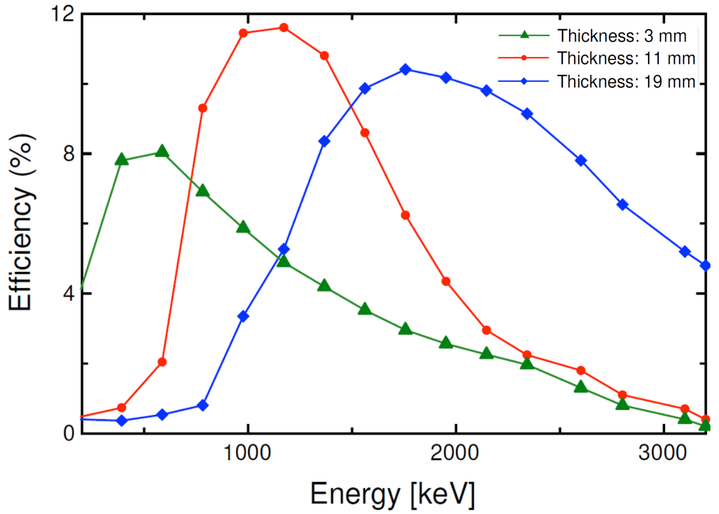
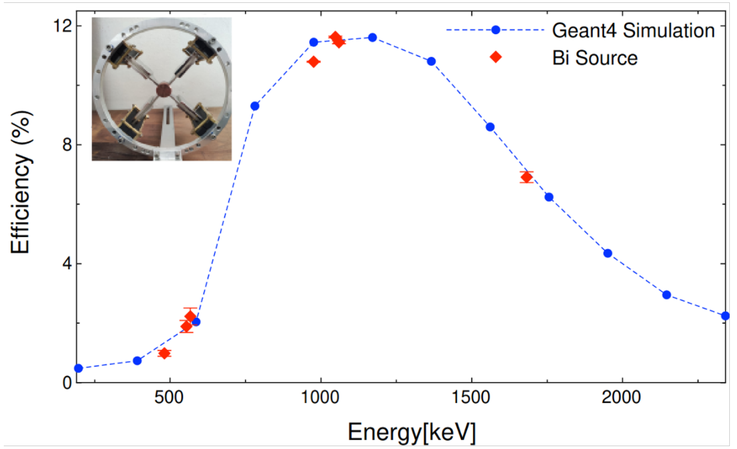
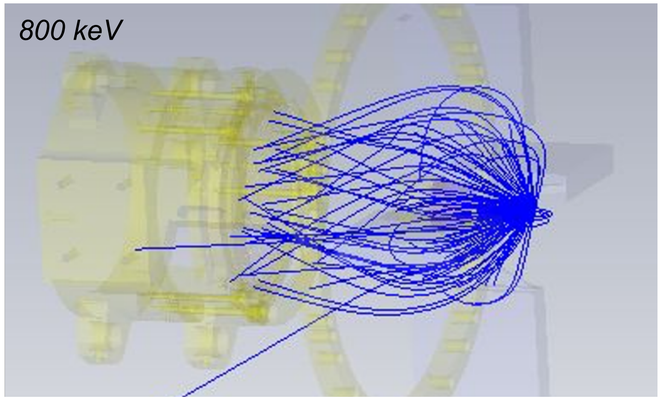
The Magnetic Transport System

- Detailed study of the magnetic transport system with GEANT4 and CST Studio
- Simulations validated with source and in-beam measurements
- Different choices of magnets for different energies of the electrons
- Shape of magnets optimised to minimise the backscattering
- Broad high-efficiency energy ranges for electrons of ≈ 500 - 2000 keV range

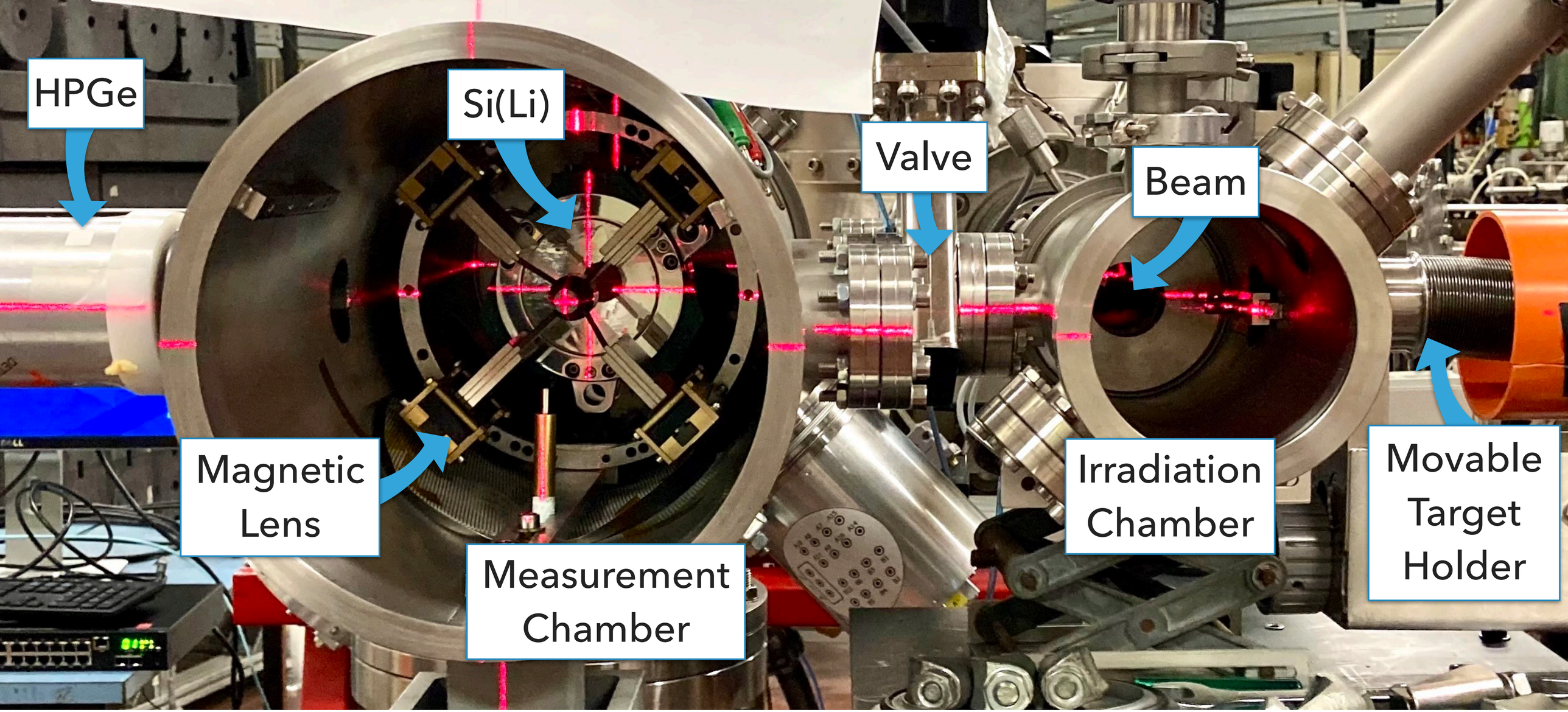








N. Marchini, A. Nannini et al., Nuclear Inst. and Methods in Physics Research A 1020 (2021) 165860

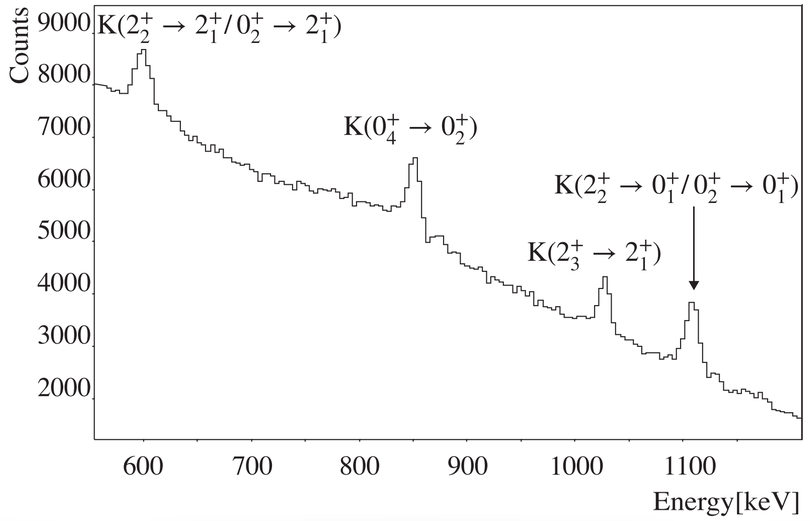


SLICES with Proton Beams @LNL

PHYSICAL REVIEW C **105**, 054304 (2022)

Electric monopole transitions and structure of low-spin states in ^{106}Pd

N. Marchini,[1,2] A. Nannini,[2] M. Ottanelli,[2] A. Saltarelli,[1,3] G. Benzoni,[4] E. R. Gamba,[5,*] A. Goasduff,[6] A. Gottardo,[6] J. Ha,[7] T. Krings,[8] M. Perri,[1,3] M. Polettini,[4,9] M. Rocchini,[10] and P. Sona[2]



Waiting for SPES, we used SLICES for beta-decay studies following (p,n) reactions: 3 experiments performed (1 published) another one accepted at the last LNL PAC meeting

Valve

Beam

Irradiation Chamber

Movable Target Holder

nt Chamber

SLICES with Proton Beams @LNL

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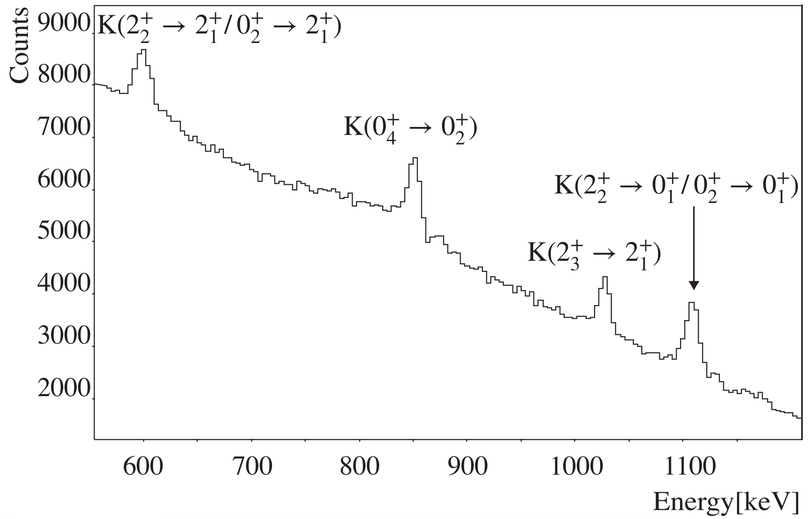

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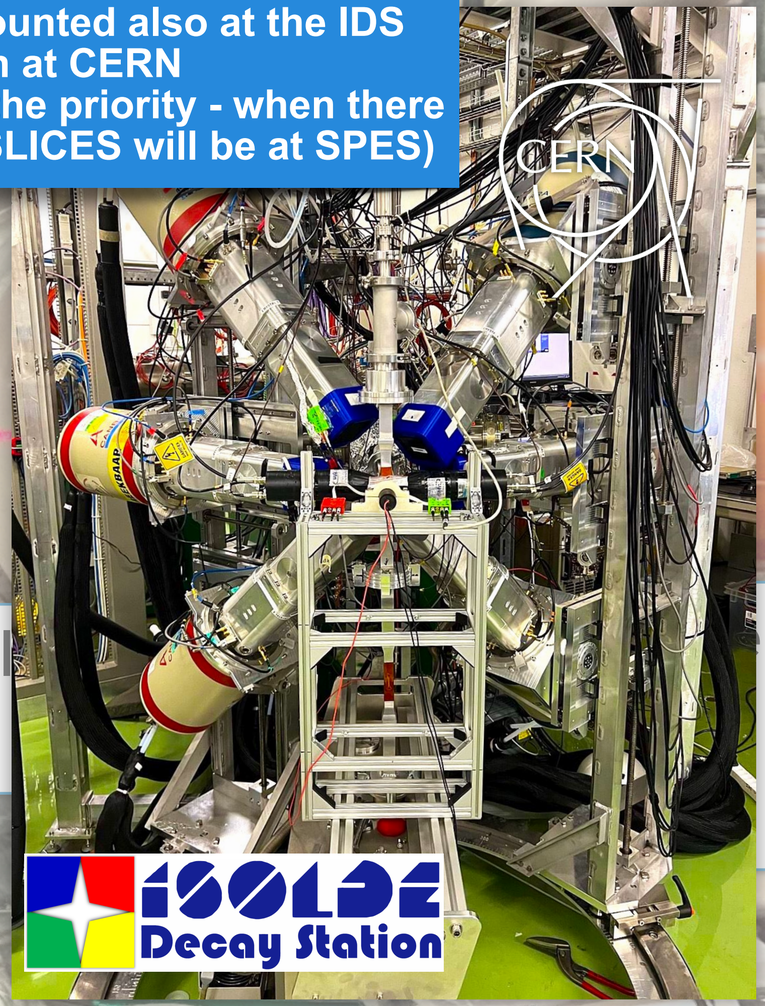
SLICES will be mounted also at the IDS station at CERN (but SPES remains the priority - when there are useful beams, SLICES will be at SPES)



SLICES with Proton Beams @LNL

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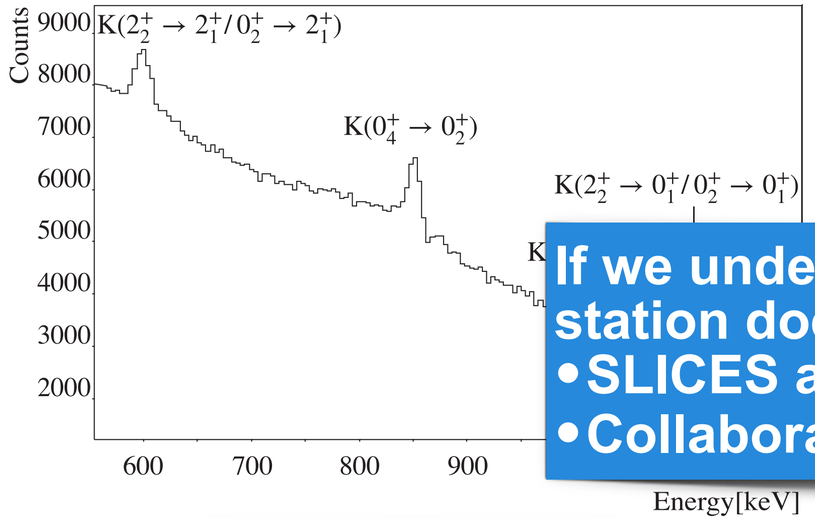

Waiting for SPES, we used SLICES for beta-decay studies following (p,n) reactions: 3 experiments performed (1 published) another one accepted at the last LNL PAC meeting

Chamber

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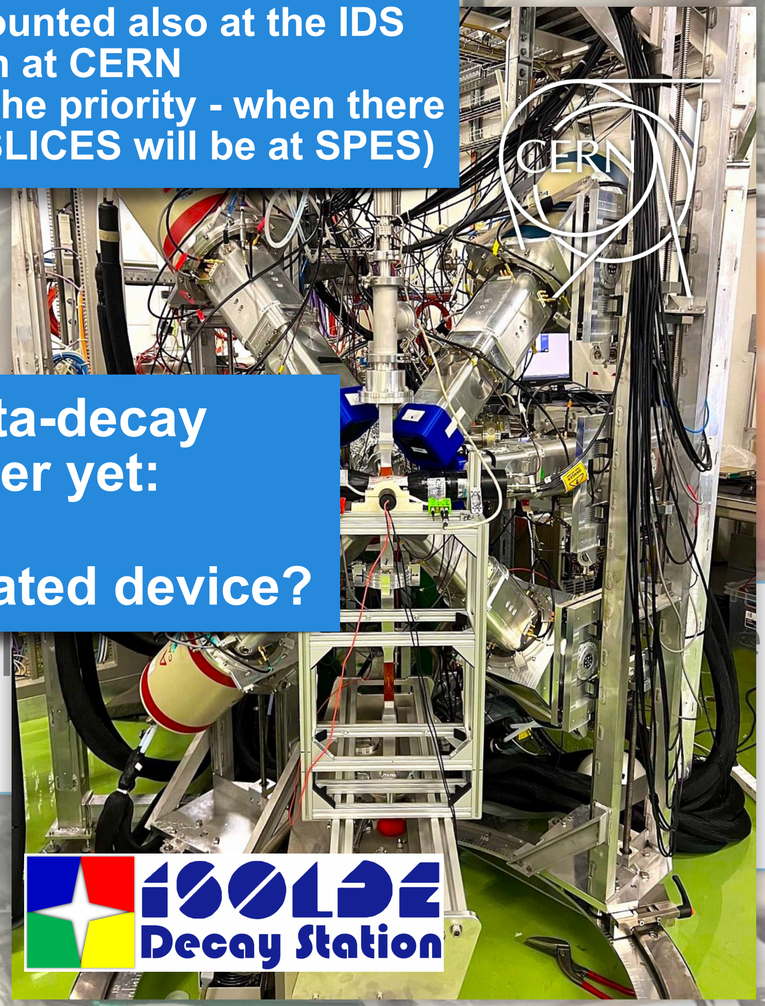


If we understood correctly, the FRIB beta-decay station doesn't have an ICE spectrometer yet:

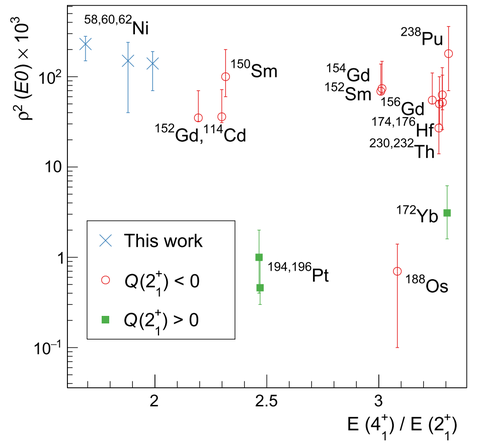
- **SLICES at FRIB?**
- **Collaboration to develop a new, dedicated device?**

SLICES with Proton Beams @LNL

The Puzzle of Strong $\rho^2(E0; 2_2^+ \longrightarrow 2_1^+)$ Values

- The $\rho^2(E0; 2_2^+ \longrightarrow 2_1^+)$ value should be small in all collective paradigms (rotors, vibrators, γ-soft nuclei and γ-rigid) ⟹ Always an excitation of the ground state, meaning the same intrinsic deformation and no mixing
- Even microscopic models (Shell Model and Beyond-Mean-Field approaches) predict small $\rho^2(E0; 2_2^+ \longrightarrow 2_1^+)$ values
- Study in the stable Ni Isotopes ⟹ Largest $\rho^2(E0; 2_2^+ \longrightarrow 2_1^+)$ values observed in the entire nuclide chart (2_2^+ below 0_2^+, shape coexistence not possible)
- Our study on ^{74}Se ⟹ Very large $\rho^2(E0; 2_2^+ \longrightarrow 2_1^+)$ also in this case and hints of unexpected triaxiality
- It would be interesting to extend to the neutron-rich Ni isotopes, where multiple shape coexistence has been observed (and $0_2^+ \longrightarrow 0_1^+$ also interesting)
- Not possible with ISOL ⟹ beam intensities for stopped beams at FRIB [pps]: ^{68}Co (for beta decay to ^{68}Ni) - $1.4 \cdot 10^5$ 👍

L.J. Evitts, A.B. Garnsworthy, T. Kibédi et al., Phys. Lett. B 779 (2018) 396
"Identification of significant E0 strength in the $2_2^+ \rightarrow 2_1^+$ transitions of ^{58,60,62}Ni"



Physics Letters B 844 (2023) 138067

Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/physletb

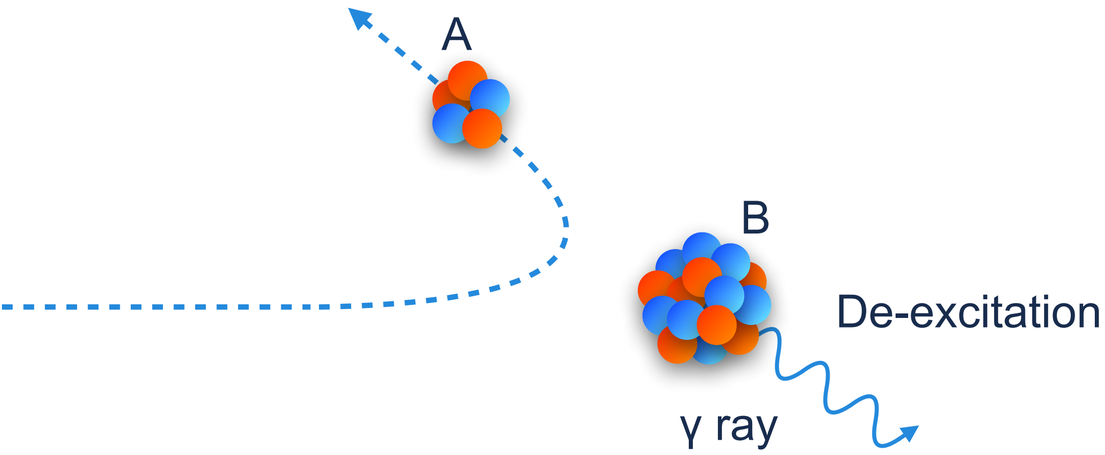
Emergence of triaxiality in ^{74}Se from electric monopole transition strengths

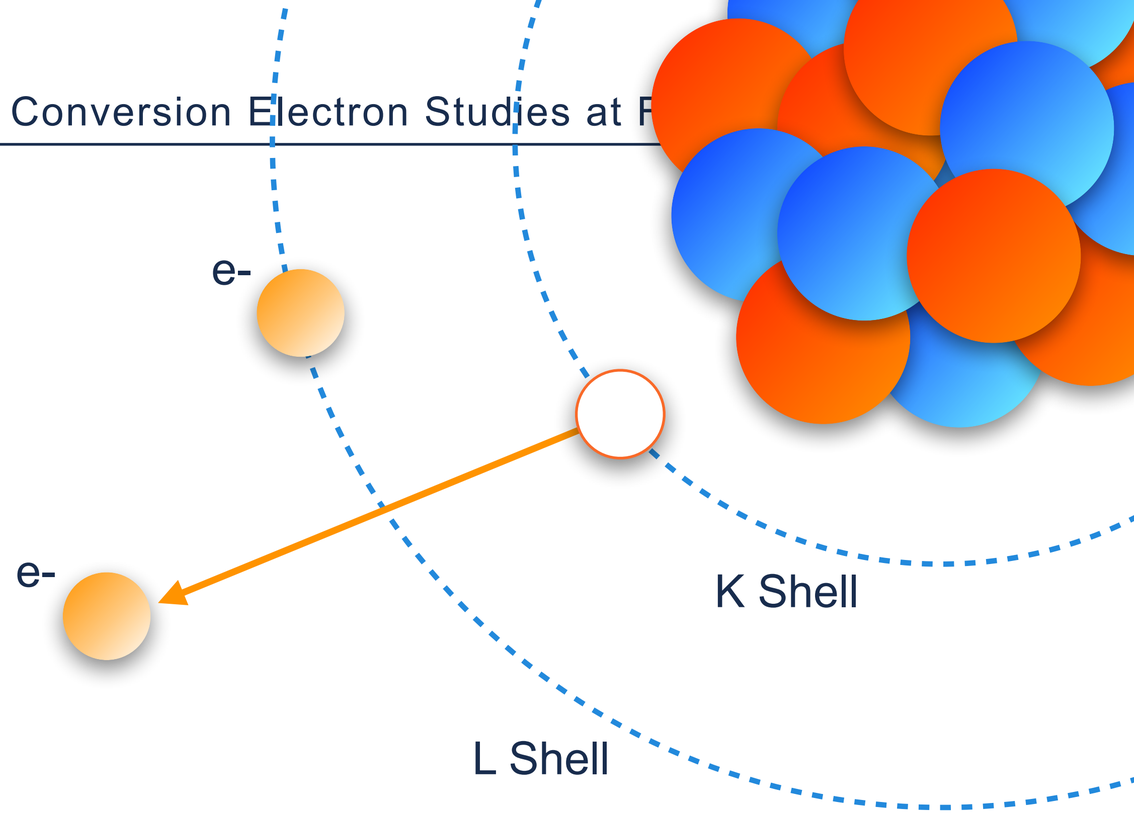
N. Marchini[a,b,c,*], A. Nannini[a], M. Rocchini[a], T.R. Rodríguez[d], M. Ottanelli[a], N. Gelli[a], A. Perego[a,b], G. Benzoni[e], N. Blasi[e], G. Bocchi[e], D. Brugnara[f], A. Buccola[a,b], G. Carozzi[f,g], A. Goasduff[f], E.T. Gregor[f,1], P.R. John[g,h], M. Komorowska[i], D. Mengoni[g,h], F. Recchia[g,h], S. Riccetto[j,k,2], D. Rosso[f], A. Saltarelli[c,j], M. Siciliano[f,g,3], J.J. Valiente-Dobón[f], I. Zanon[f,g]

Summary

Low-energy Coulomb excitation

- FRIB will offer many new opportunities for Coulex with ReA beams
- We are excited to jump in and collaborate
- Setup ready, no need for developements
- Virtually, possibilities for the next few decades





Spectroscopy of Internal Conversion Electrons

- Internal Conversion Electron spectroscopy could nicely complement the instruments at the FRIB beta-decay station
- SLICES is small and portable ⟹ It can be transported to FRIB, but we need to carefully plan the timeline with SPES and ISOLDE
- Alternatively, we could collaborate with FRIB on a new instrument

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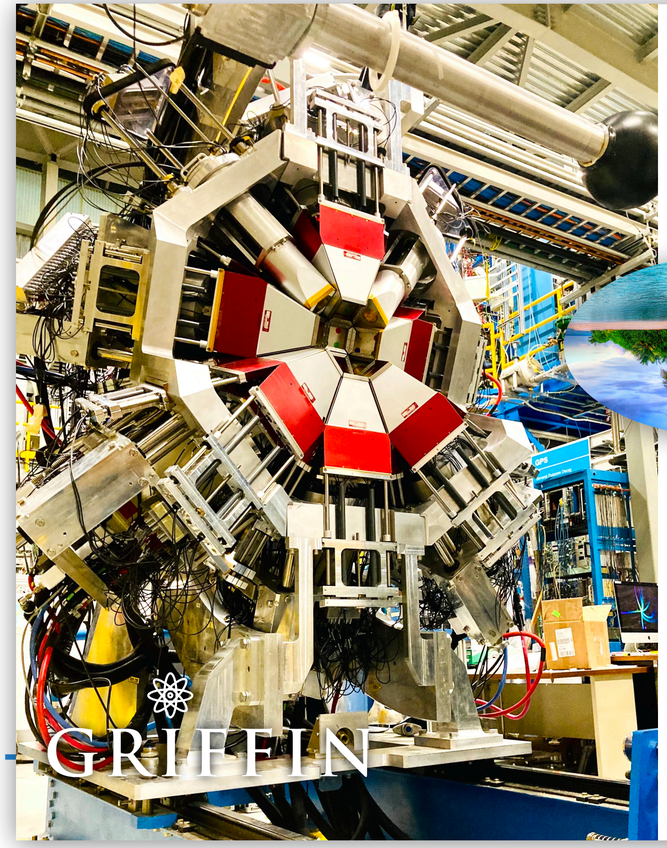

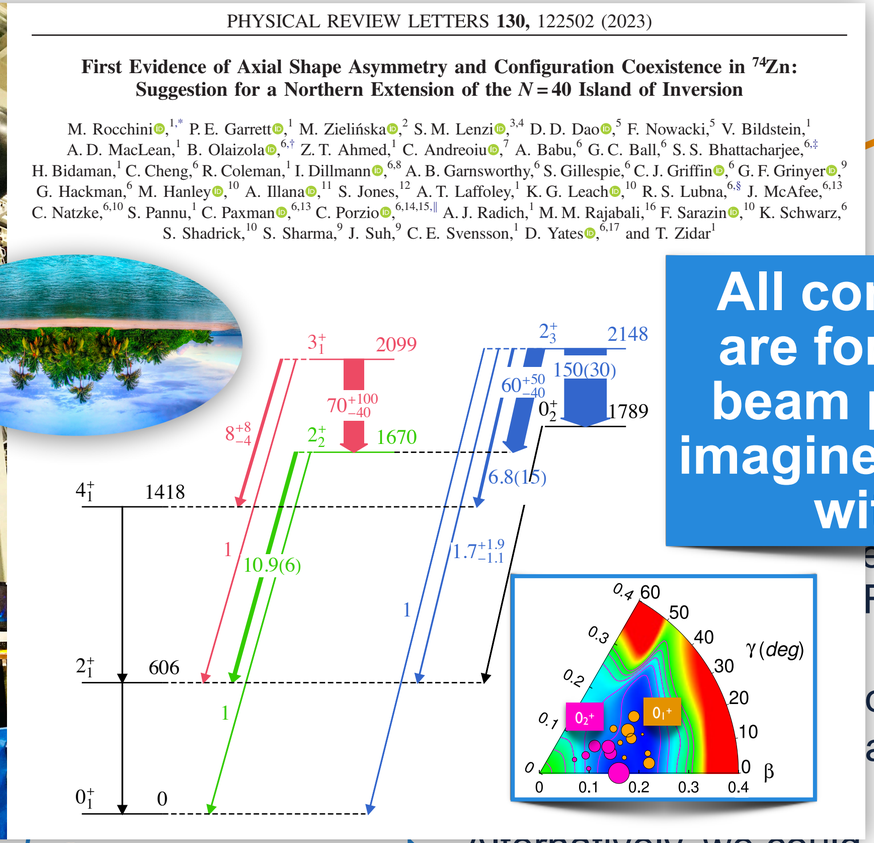

PHYSICAL REVIEW LETTERS **130,** 122502 (2023)

First Evidence of Axial Shape Asymmetry and Configuration Coexistence in ^{74}Zn: Suggestion for a Northern Extension of the $N = 40$ Island of Inversion

M. Rocchini,[1,*] P. E. Garrett,[1] M. Zielińska,[2] S. M. Lenzi,[3,4] D. D. Dao,[5] F. Nowacki,[5] V. Bildstein,[1] A. D. MacLean,[1] B. Olaizola,[6,†] Z. T. Ahmed,[1] C. Andreoiu,[7] A. Babu,[6] G. C. Ball,[6] S. S. Bhattacharjee,[6,‡] H. Bidaman,[1] C. Cheng,[6] R. Coleman,[1] I. Dillmann,[6,8] A. B. Garnsworthy,[6] S. Gillespie,[6] C. J. Griffin,[6] G. F. Grinyer,[9] G. Hackman,[6] M. Hanley,[10] A. Illana,[11] S. Jones,[12] A. T. Laffoley,[1] K. G. Leach,[10] R. S. Lubna,[6,§] J. McAfee,[6,13] C. Natzke,[6,10] S. Pannu,[1] C. Paxman,[6,13] C. Porzio,[6,14,15,‖] A. J. Radich,[1] M. M. Rajabali,[16] F. Sarazin,[10] K. Schwarz,[6] S. Shadrick,[10] S. Sharma,[9] J. Suh,[9] C. E. Svensson,[1] D. Yates,[6,17] and T. Zidar[1]

γ ray

All considered yields are for 15kW primary beam power: can you imagine what we can do with 400kW?!

- ns
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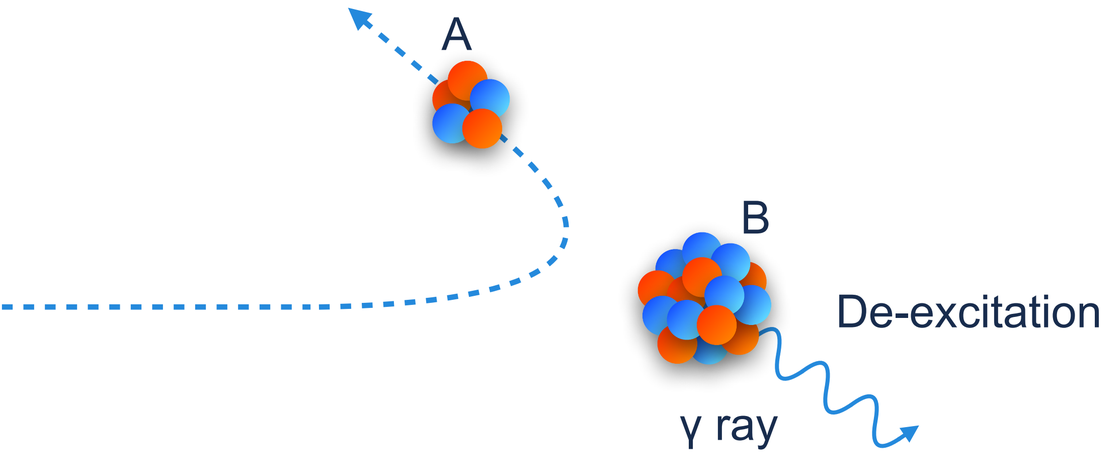

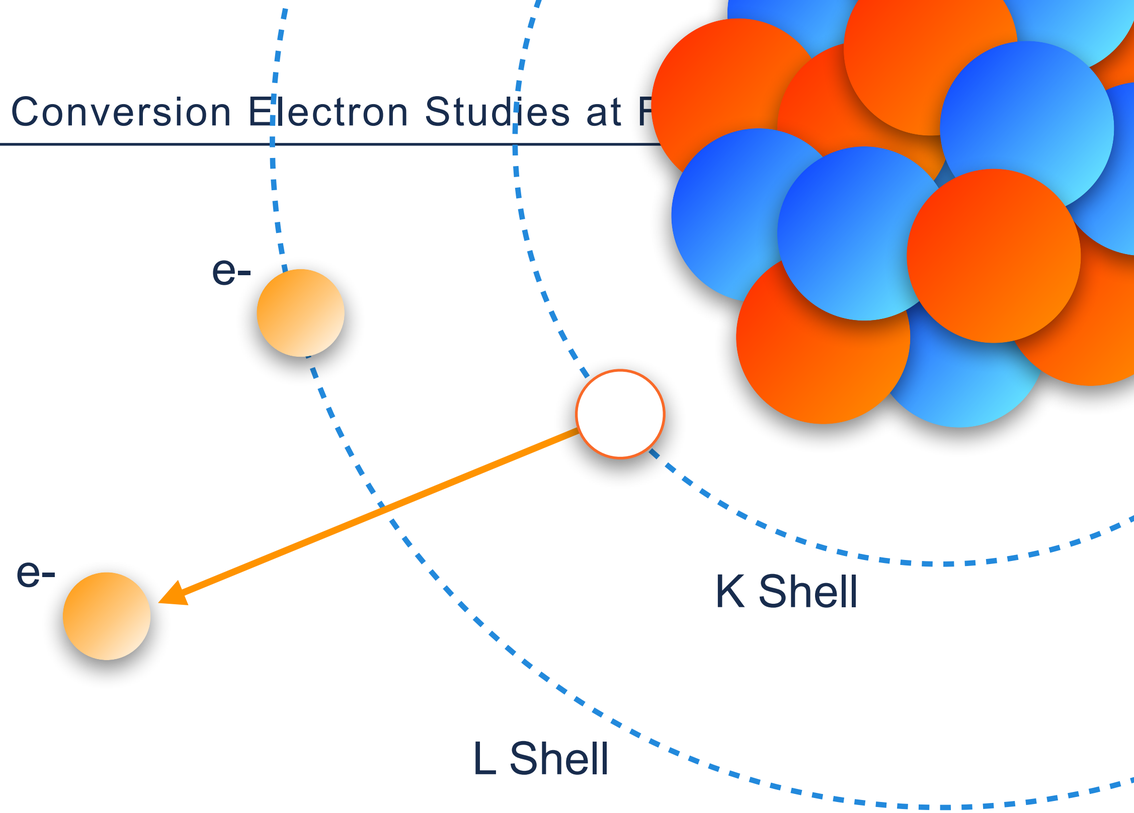

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Marco Rocchini
INFN - Istituto Nazionale di Fisica Nucleare
FIRENZE DIVISION

THANK YOU FOR THE ATTENTION