Investigating the deformation of the intruder isomeric $1/2^+$ state in ^{79}Zn (N=49) via Coulomb excitation

Filippo Angelini

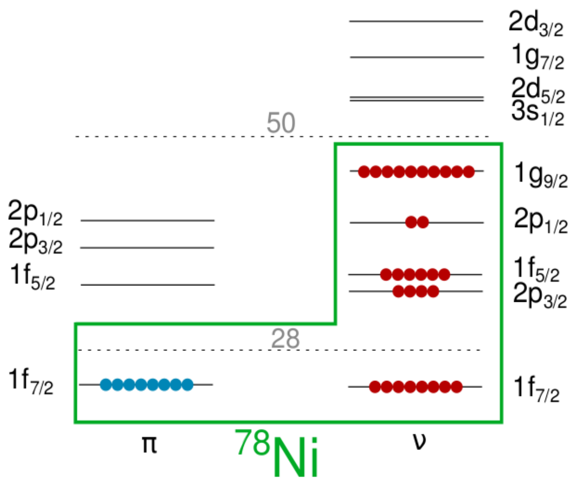
Università degli Studi di Padova, Italy

INFN – LNL, Legnaro (PD), Italy

INPC 2025

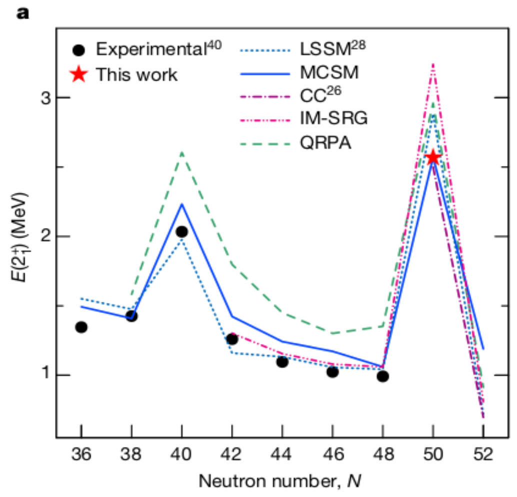
Daejeon, Korea

Nuclear shell evolution in the region of ^{78}Ni

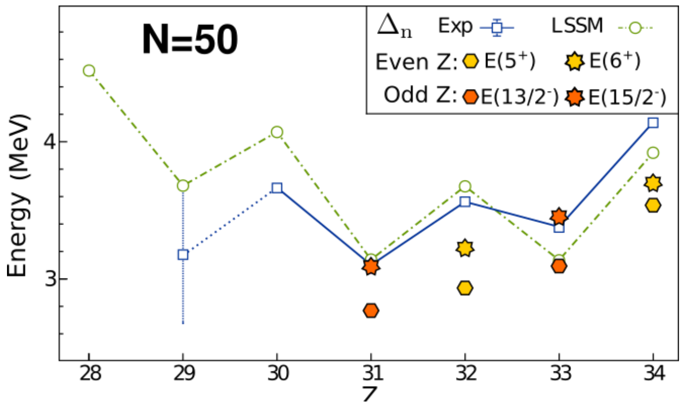


^{78}Ni is the **most exotic neutron-rich doubly-magic** nucleus that can be approached experimentally

Magicity has been confirmed from spectroscopy
But there are some questions:



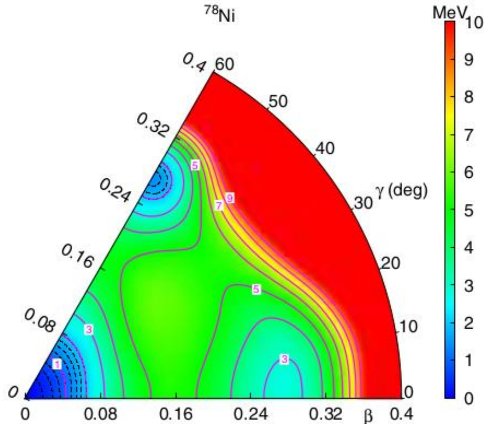
R. Taniuchi et al., Nature 569, 53–58 (2019)

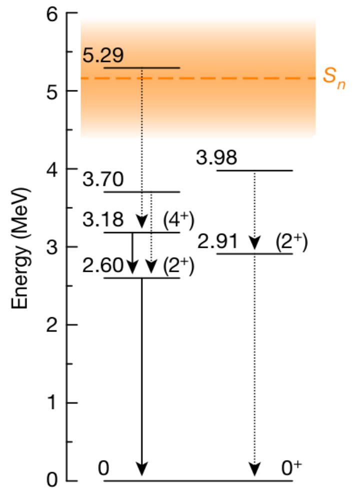


J. Dudouet et al, Phys. Rev. C 100, 011301(R) (2019)

1. The **N = 50 shell gap** follows a **parabolic behaviour** along the isotonic line

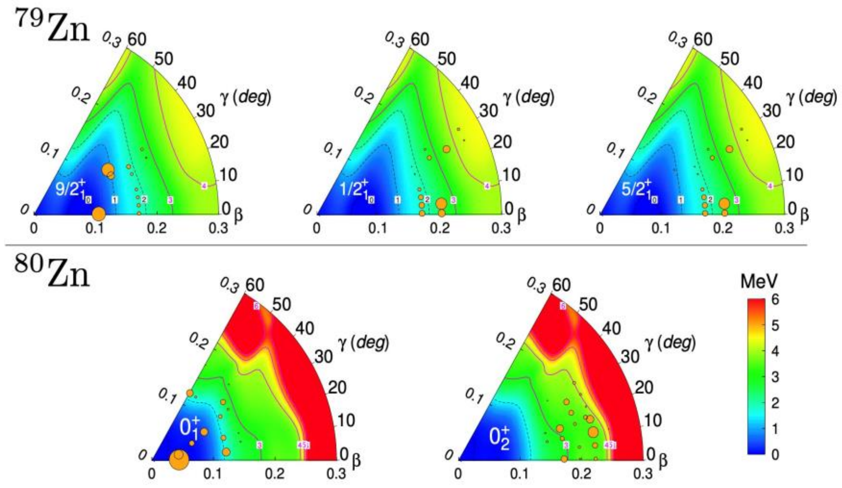
2. **Shape coexistence** has emerged in ^{78}Ni from shell model calculations: **Intruder deformed** configurations are found at low excitation energy





F. Nowacki et al., Phys. Rev. Lett. 117, 272501 (2016)   R. Taniuchi et al., Nature 569, 53–58 (2019)

Shape coexistence in the region



From L. Nies et al., Phys. Rev. Lett. 131, 222503 (2023)

Studies have shown **shape coexistence** in other two nuclei in the region:

- ^{80}Ge intruder 0^+_2
(later not confirmed)

From A. Gottardo et al., Phys. Rev. Lett. 116, 182502 (2016)

From F. H. Garcia et al., Phys. Rev. Lett. 125, 172501 (2020)

- ^{79}Zn intruder isomer $1/2^+$

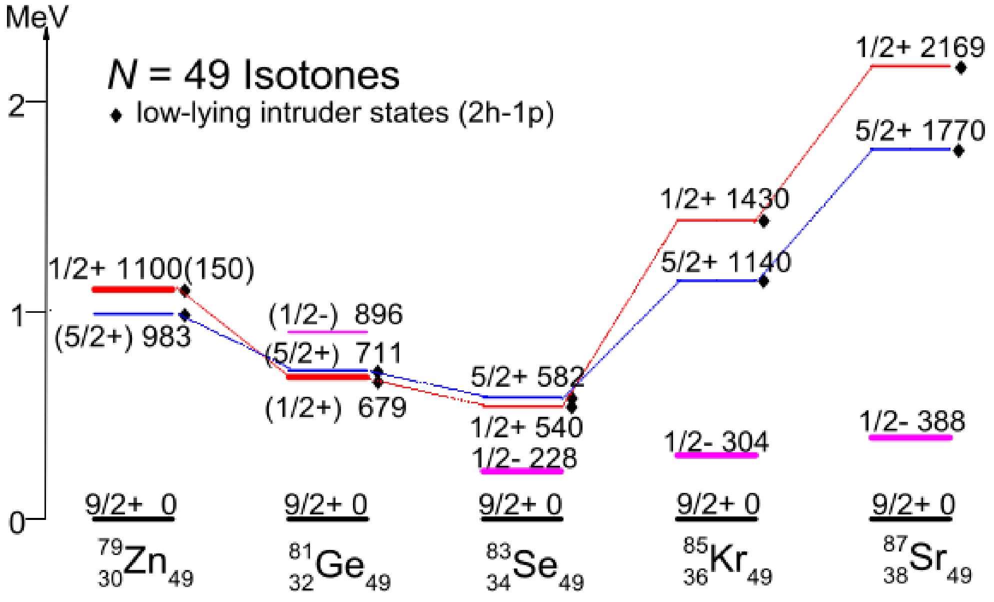
From X. Yang et al., Phys. Rev. Lett. 116, 182502 (2016)

^{79}Zn interesting case along **N=49 isotonic chain:**

- **$9/2^+$** ground states (n-hole in **$g_{9/2}$**)

- $1/2^+$ and $5/2^+$ intruder states from **neutron 2h-1p** excitations to the **$s_{1/2}$, $d_{5/2}$** shells beyond N=50

- **Deformation** in intruder band (e.g. ^{83}Se)



From X. Yang et al., Phys. Rev. Lett. 116, 182502 (2016)

^{79}Zn: previous studies

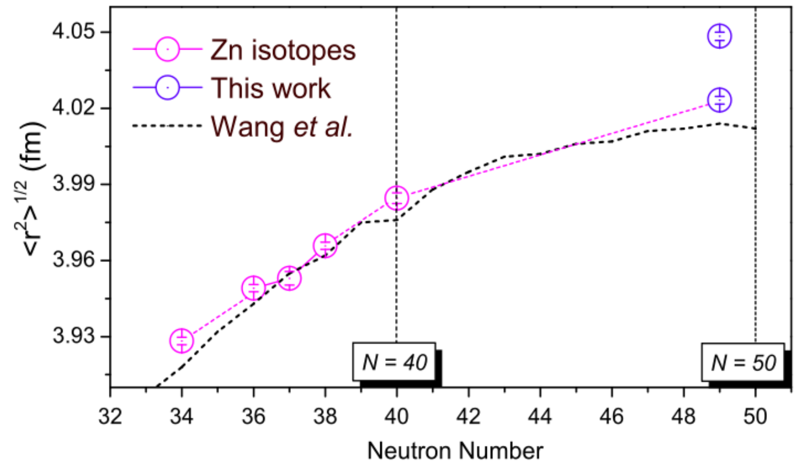
^{79}Zn studied with **radioactive beams**:

- **^{78}Zn(d,p) at ISOLDE** From R. Orlandi et al., Phys. Lett. B 740, 298-302 (2015)

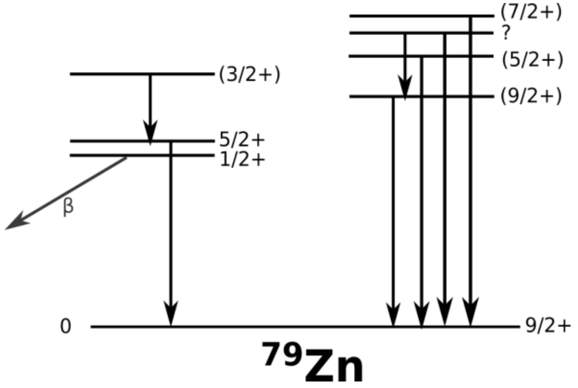
First spectroscopy, single particle character of **$5/2^+$ state**

- **Laser spectroscopy at ISOLDE**

Spin assignments for **9/2+ g.s.** (β ~ 0.14) and **$1/2^+$ isomer**
Large $\langle r^2 \rangle$ for isomer, β ~ 0.22



From X. Yang et al., Phys. Rev. Lett. 116, 182502 (2016)



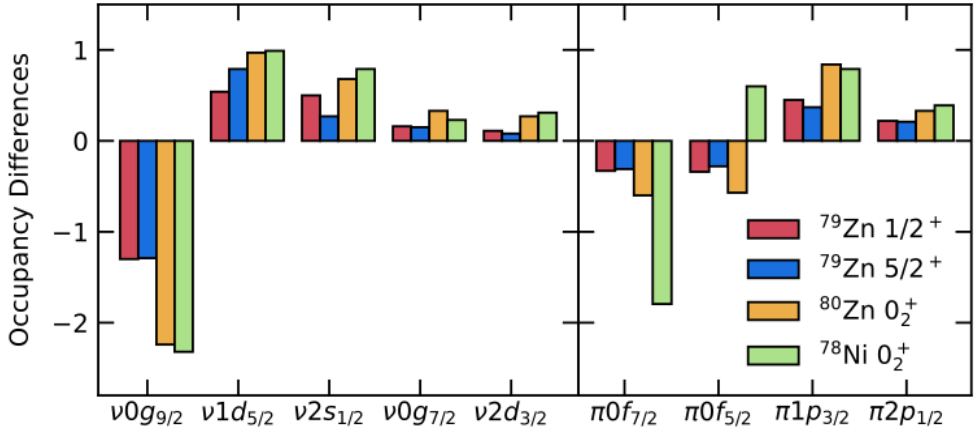
- **Beta decay at RIKEN** From M.C. Delattre's PhD thesis, Université Paris-Sud (2016)

Wide **exploration of level scheme** and spin assignments

- **Mass spectroscopy at ISOLDE, JYFL + PFSDG-U shell model calculations**

Ordering of intruder states $1/2^+$ and $5/2^+$,
Intruder band of ^{79}Zn **matches the occupancy** of ^{78}Ni 0^+_2

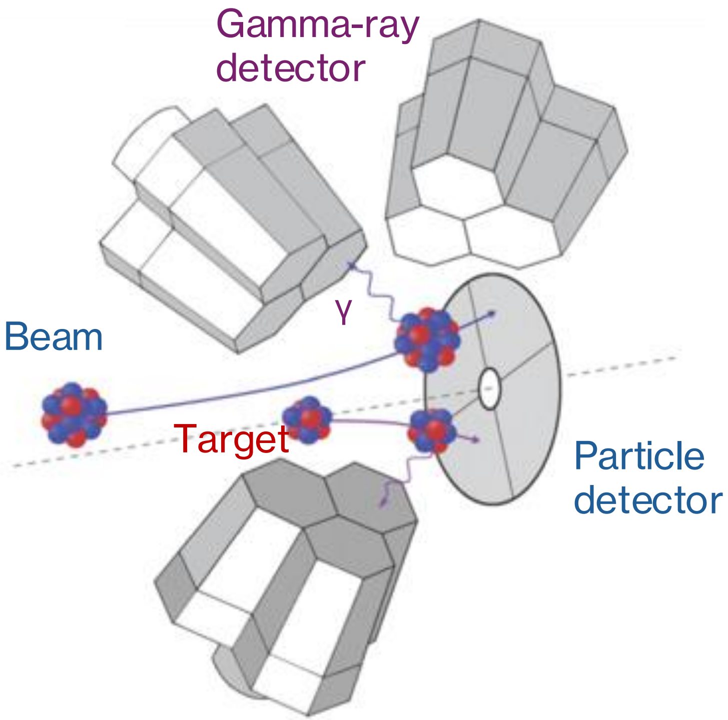
How to probe **deformation** of intruder band?
Coulomb excitation measurement



From L. Nies et al., Phys. Rev. Lett. 131, 222503 (2023)

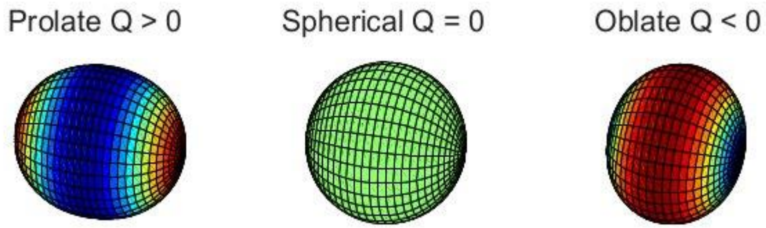
Coulomb excitation

Population of excited levels via purely **electromagnetic interaction** in a quasi-elastic scattering (**safe energy** criterion)



Measurement of **gamma-ray decay** of Coulomb-excited states **in coincidence with beam or target recoils**

Gamma-ray decay intensities, as a function of particle **scattering angle**, are related to **reduced transition probabilities** (e.g. **B(E2)**) and **spectroscopic quadrupole moments**.



For details about the method: M. Zielińska, Lecture Notes in Physics 1005 (2022), chap. 2

Determination of these observables with a **multi-dimensional fit** performed using dedicated analysis codes (e.g. **GOSIA**)

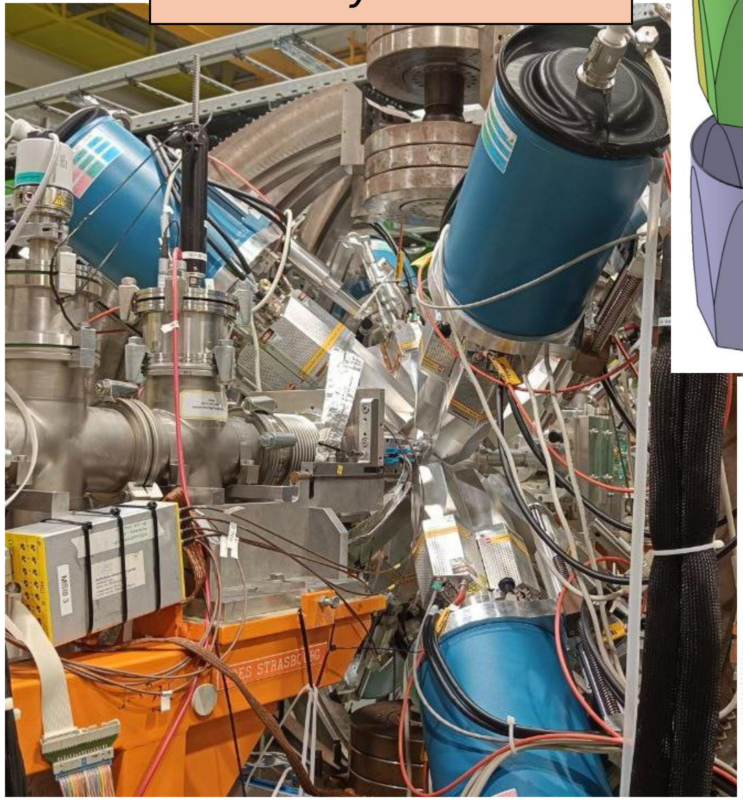
^{79}Zn Coulomb excitation at HIE-ISOLDE

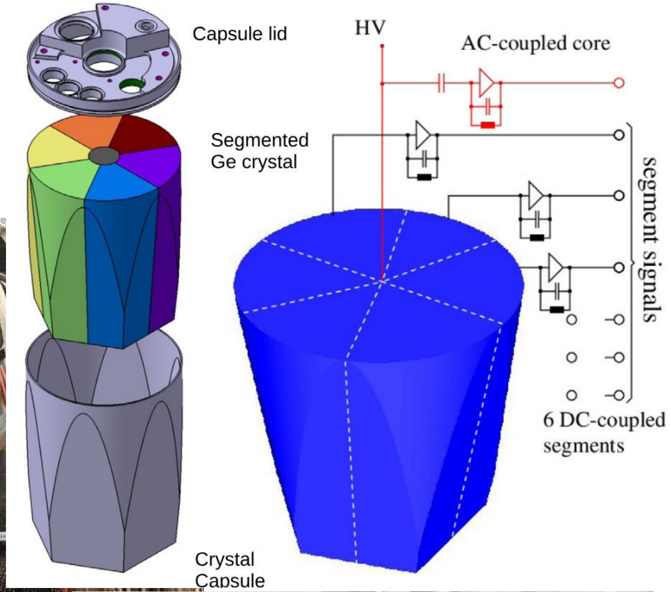
- 8 Miniball HPGe triple clusters
- Forward DSSSD detector (CD), θ range [20°,59°]

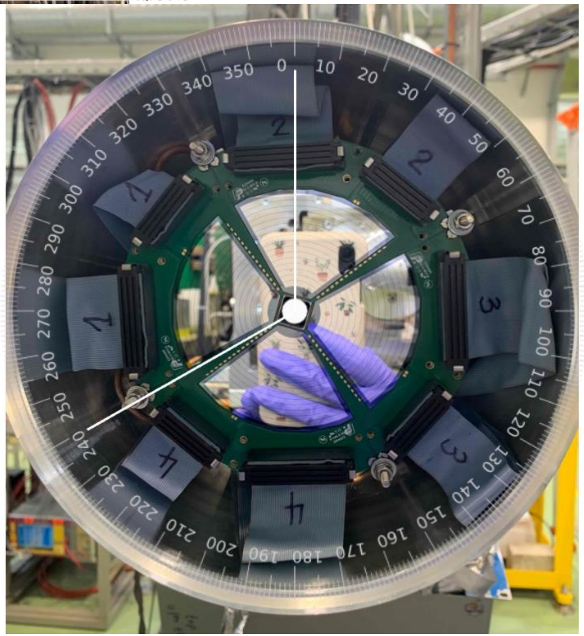
ISOL secondary beam from **UC_X** primary target
^{79}Zn @ 4.0 MeV/u, ~8x10^4 pps

Mixture of g.s. and isomer: **r(^{79}Zn^m) = 7.1(4)%**
Ratio measured from mass spectroscopy

First run in 09/2023
Recovery in 08/2024







<u>Targets:</u>
- ^{208}Pb 4 mg/cm^2 for low target bg
- ^{196}Pt 3 mg/cm^2 for target normalization

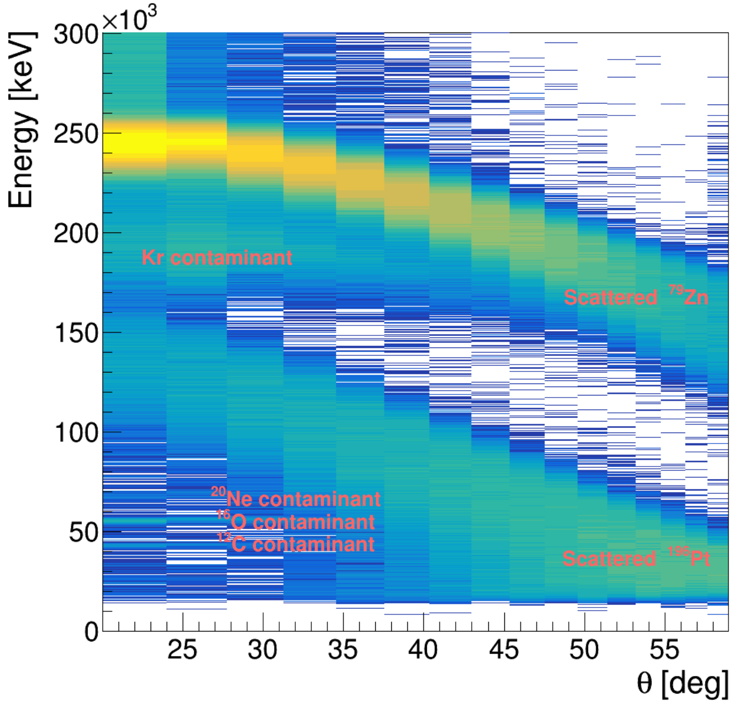
Scattering of **either partners** can be detected in the CD -> **Different θ_{CM}**

Gamma rays detected with Miniball
In flight emission: **Doppler correction needed**

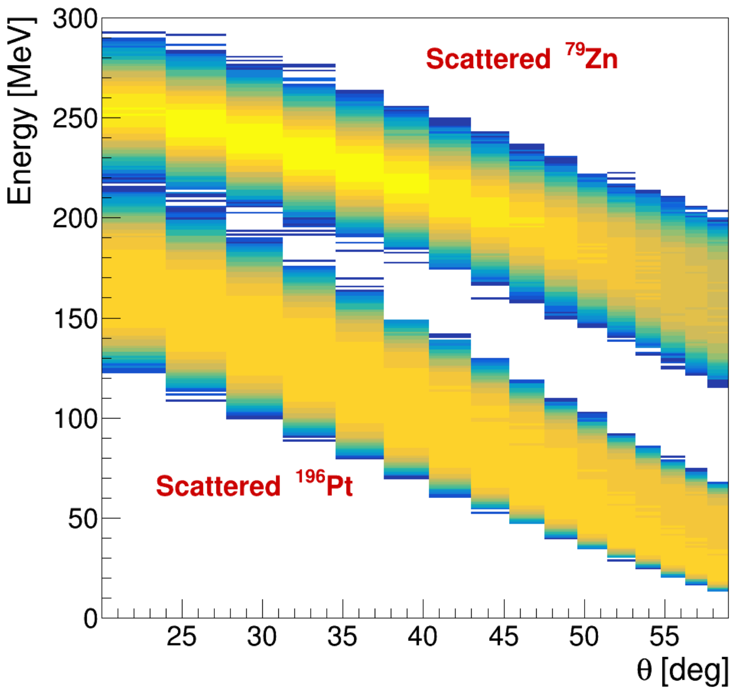
$$E_\gamma^{CM} = E_\gamma \frac{1-\beta\cos(\theta)}{\sqrt{1-\beta^2}}$$

Calibration of the CD detector

Experiment



Simulation

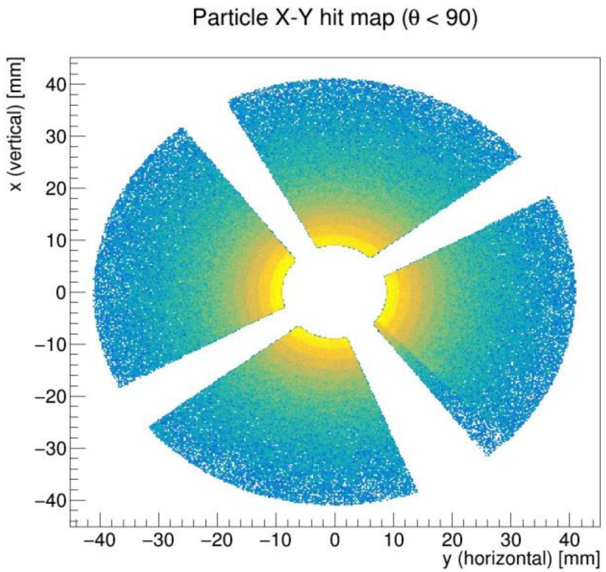


^{79}Zn on ^{196}Pt

Stable **beam contaminants** from EBIS charge breeder (A/Q=4):
$^{12}C^{3+}$, $^{16}O^{4+}$, $^{20}Ne^{5+}$, $^{40}Ar^{10+}$,
$^{84}Kr^{21+}$/ $^{80}Kr^{20+}$

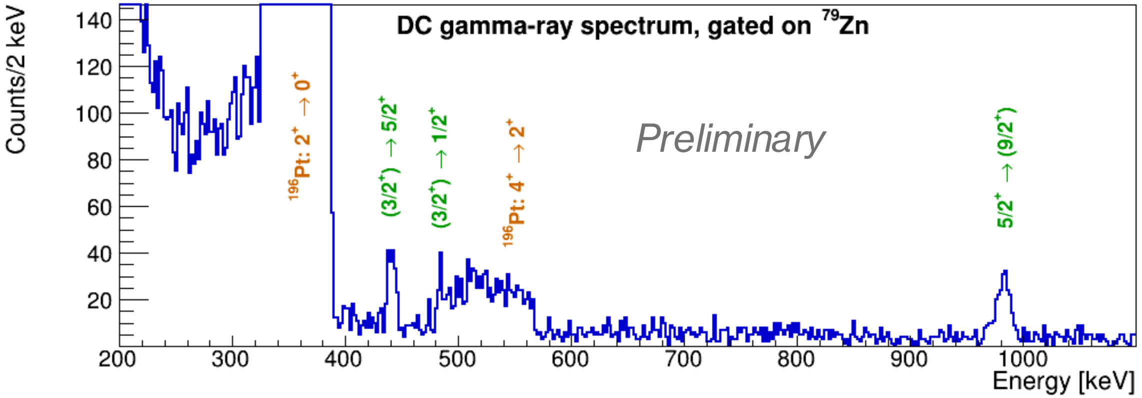
Kinsim simulation used to estimate the energy released in each ring

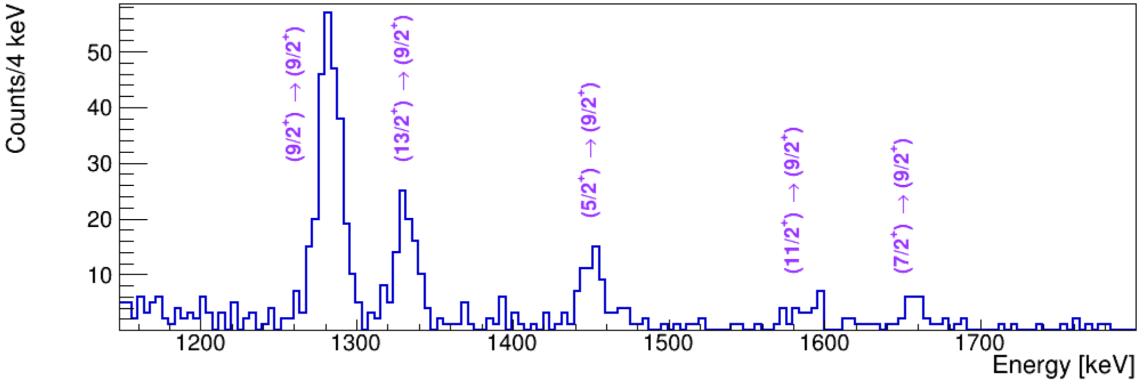
Calibration of segments:
P-side vs N-side



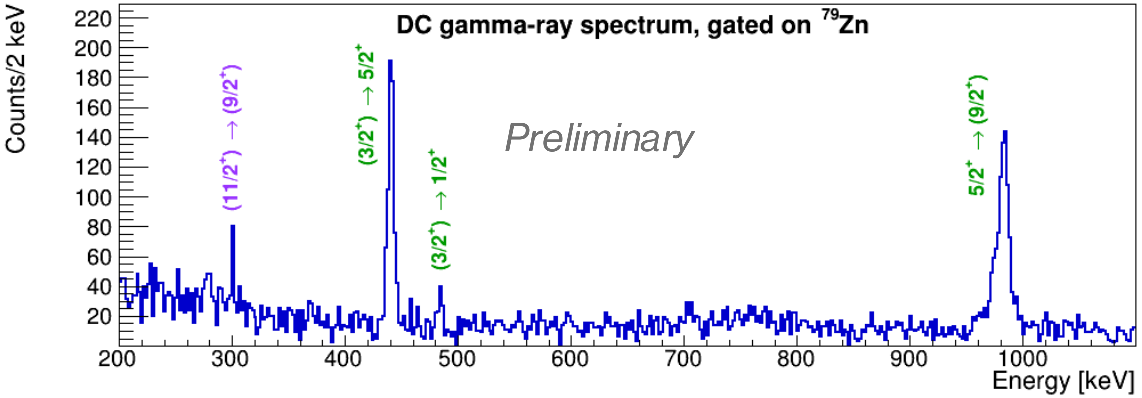
DC addback spectra: target comparison

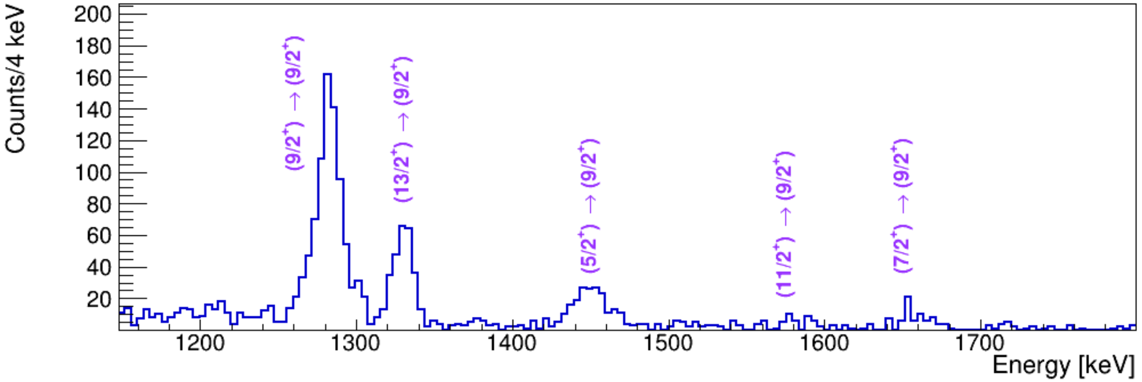
^{196}Pt target



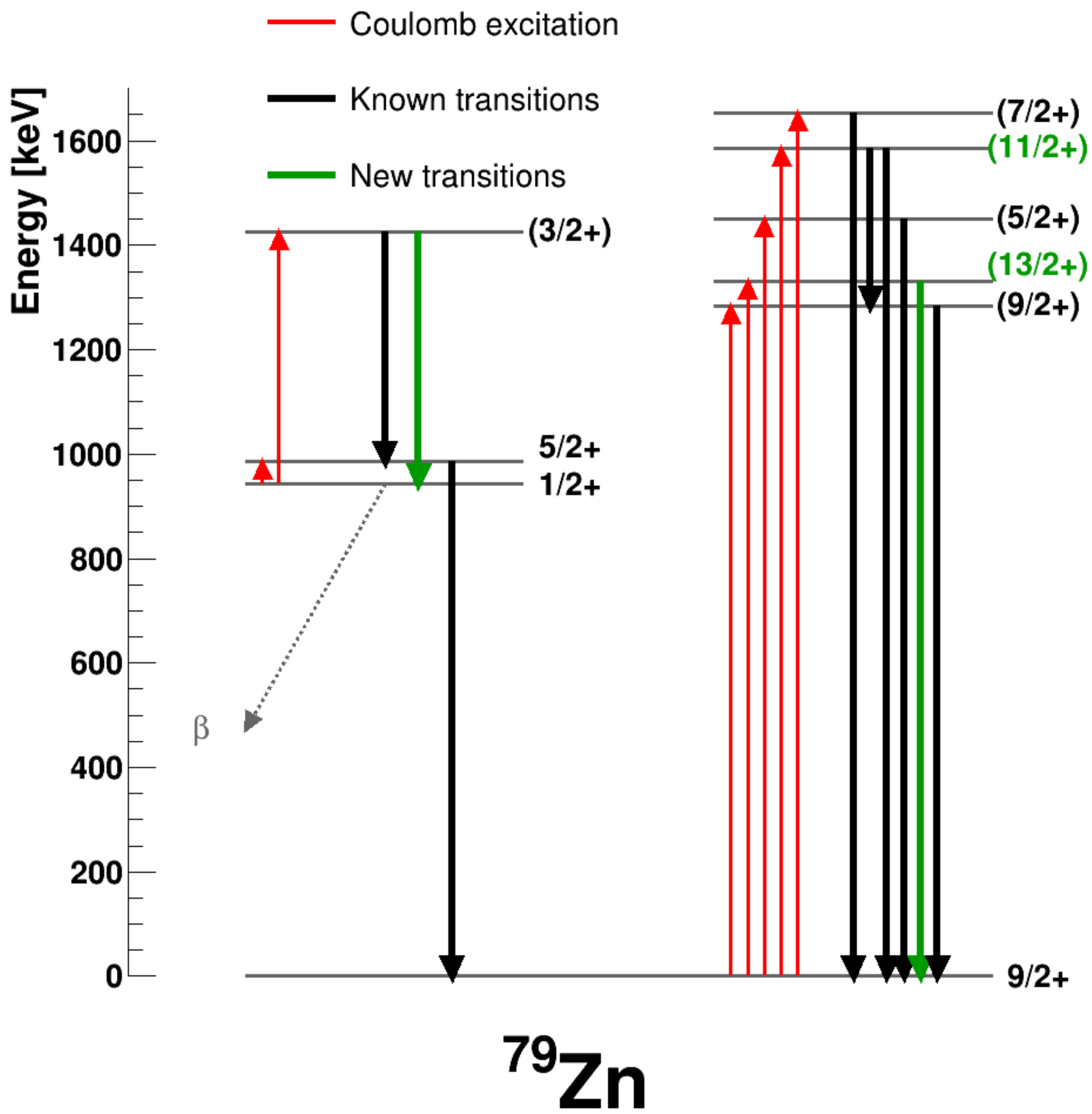


^{208}Pb target





Identified transitions

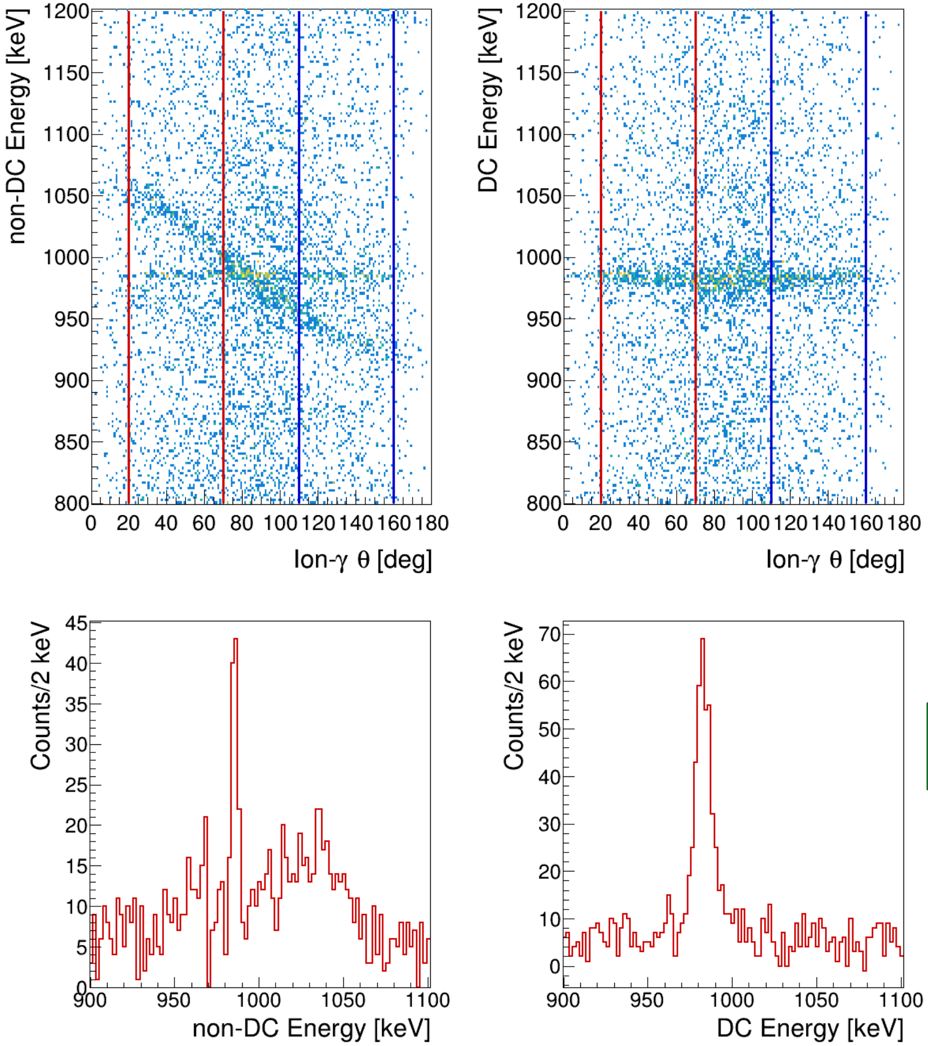


- New transition measured at ~480 keV: It completes the **intruder band** scheme as a **(3/2$^+$) -> 1/2$^+$** decay.

- Whole multiplet of **$g_{9/2}$ n-hole coupled with 2$^+$ of ^{80}Zn** was observed: 5 states lying around **E(2$^+$;^{80}Zn) = 1492(1) keV**.

- Assignment of **(11/2$^+$)** and **(13/2$^+$)** spins: their population in beta decay was hindered due to **low spin** of mother nucleus (5/2$^-$)

State at 985 keV: lifetime



Inspired from R. Clews's Master thesis, University of Liverpool (2021)

Transition at **985 keV: 5/2⁺->9/2⁺$_{g.s.}$**

Components are visible both **with and without DC**

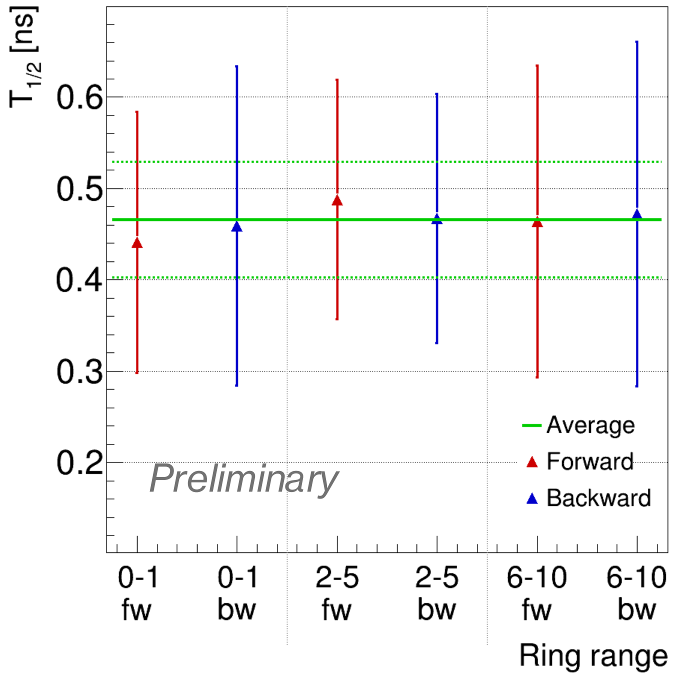
A part of the decays happens **after implantation** in the CD

Sort of **Recoil Distance Doppler Shift** method with different CD rings to estimate lifetime

$$< T_{1/2} >= 0.466 \pm 0.063 \text{ ns}$$

$$B(E2; 5/2^+ \rightarrow 9/2^+) = 0.065 \pm 0.009 \text{ W.u.}$$

Strongly **hindered** transition!

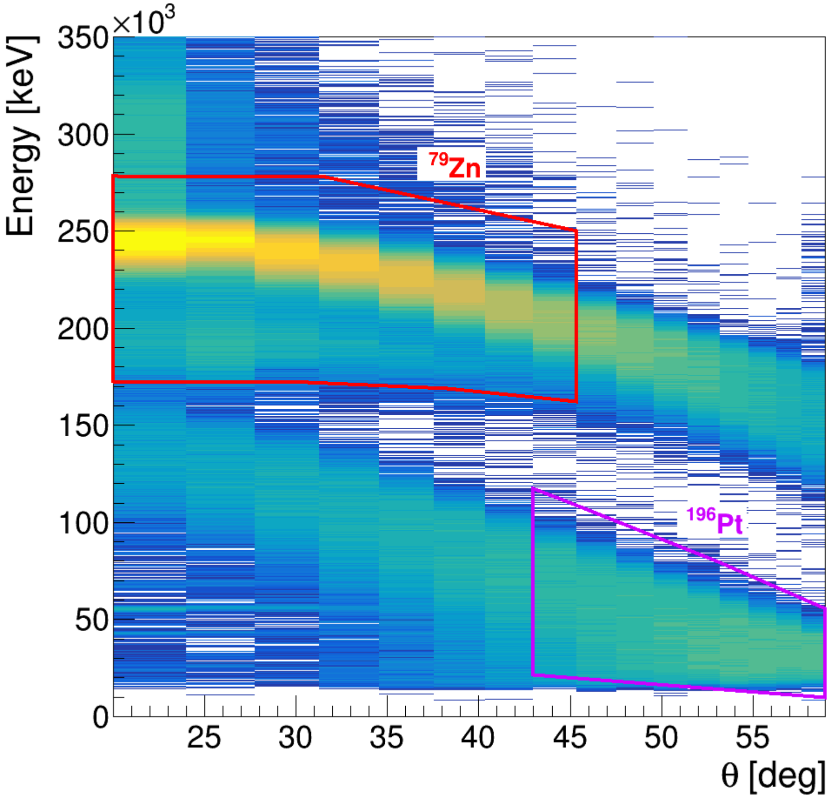


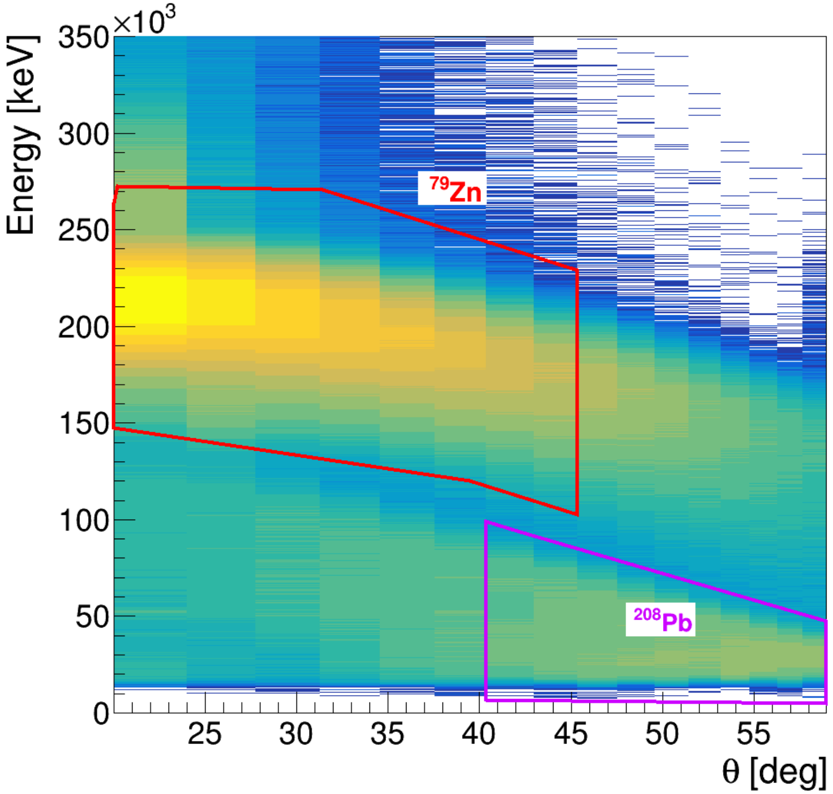
GOSIA analysis: safe energy cuts

GOSIA is a standard code used to extract **electromagnetic matrix elements** via a multi-dimensional fit of **gamma-ray intensities** measured in Coulomb excitation experiments

GOSIA2 used for normalization to **target excitations (^{196}Pt)**

Extraction of **EM matrix elements** and uncertainty estimation

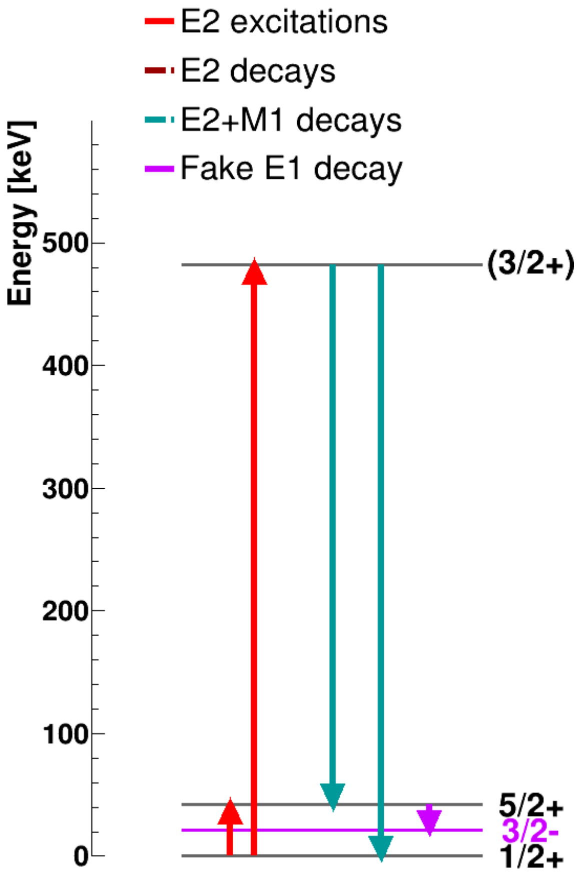




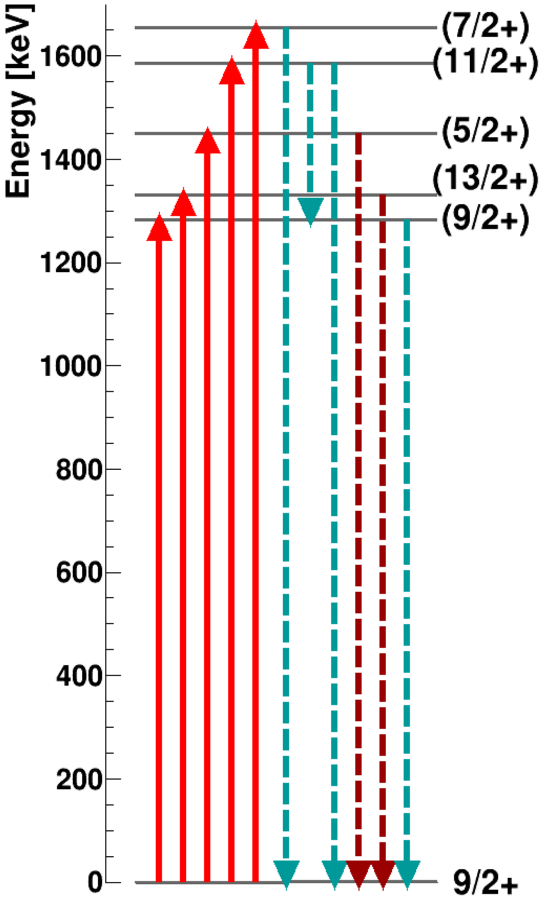
Selections for ensuring:

- **Safe energy criterion.**
- **No double counting of the θ_{CM} range where both scattered partners can be detected.**

GOSIA analysis: excitation schemes



Isomer scheme



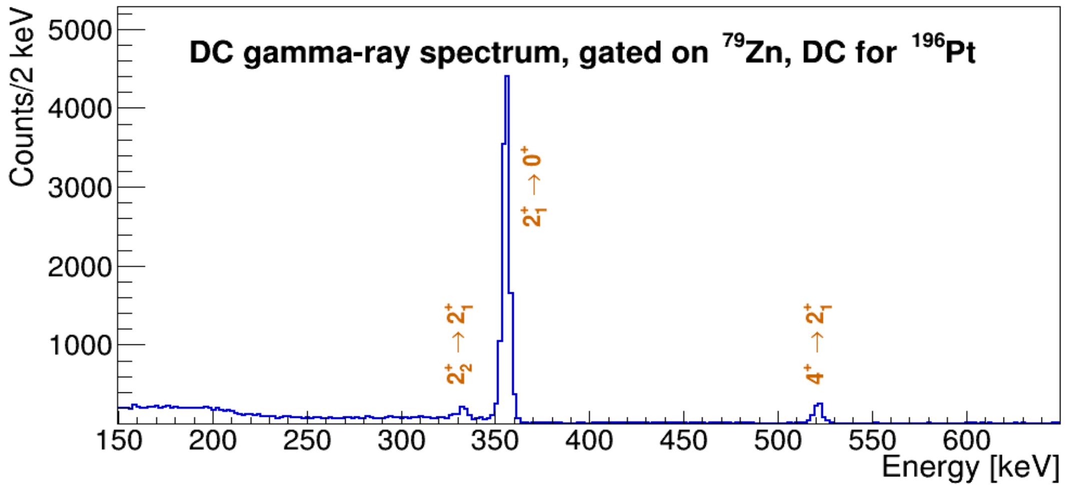
Ground state scheme

From the (5/2$^+$) lifetime estimation, the excitation of this state from g.s. is **negligible (~1%)**

It is possible to use a simpler treatment with **2 separate schemes** for **isomer** and **g.s.** excitations.

Normalization to ^{196}Pt **2$^+$ excitation**

Analysis is ongoing



Conclusions

Up to now:

- Observed population of states built on the $9/2^+$ **ground state** and the $1/2^+$ **intruder isomeric state** in ^{79}Zn via low-energy Coulomb excitation

- Lifetime extracted for **$5/2^+$ intruder state:** very **hindered** transition

- **GOSIA analysis** ongoing

Perspectives:

- Extraction of **EM matrix elements** with uncertainties

- Comparison with predicted values from **shell model calculations**

Thank you to the collaboration!

F. Angelini [1,2], A. Gottardo[1], M. Zielińska [3], I. Anastasov [4], M. Balogh [1], F. Browne [5], D. Brugnara [1], J. Cederkall [6], G. Colombi [7], F. Didierjean [8], G. Duchene [8], M. Droste [9], Z. Eleme [10], S. Franchoo [11,12], L. Gaffney [13], B. Gongora Servin [1,14], A. Illana [15], B. Johansson [16], B. Jones [13], M. Kaci [11], D. Kalaydjieva [7], H. Kleis [9], M. Komorowska [17], T. La Marca [18], S. Lange [7], M.M.R. Majid [6], N. Marchini [19], K. Mashtakov [7], A. Nannini [19], L. Nies [20], B. Olaizola [21], E. Pilotto [2,22], C. Porzio [20], M. Rocchini [19], M. Satrazani [23], K. Stoychev [7], G. Tocabens [3], P. Van Duppen [23], N. Warr [9], K. Wrzosek-Lipska[17], L. Zago [1] + *the Miniball and ISOLDE collaborations*

1 *INFN-LNL*, Legnaro (PD), Italy
2 *University of Padova*, Padova, Italy
3 *CEA Saclay*, Gif-sur-Yvette, France
4 *University of Sofia*, Sofia, Bulgaria
5 *University of Manchester*, Manchester, UK
6 *University of Lund*, Lund, Sweden
7 *University of Guelph*, Guelph, Canada
8 *IPHC-Strasbourg*, Strasbourg, France
9 *University of Cologne*, Cologne, Germany
10 *University of Ioannina*, Ioannina, Greece
11 *IJCLab-Orsay,* Orsay, France
12 *University Paris-Saclay,* Orsay, France
13 *University of Liverpool*, Liverpool, UK
14 *University of Ferrara*, Ferrara, Italy
15 *UCM*, Madrid, Spain
16 *Chalmers University of Technology*, Gothenburg, Sweden
17 *HIL UW*, Warsaw, Poland
18 *University of Florence*, Florence, Italy
19 *INFN-Florence*, Florence, Italy
20 *CERN*, Geneva, Switzerland
21 *IEM-CSIC*, Madrid, Spain
22 *INFN-Padova*, Padova, Italy
23 *KU Leuven*, Leuven, Belgium

BACKUP SLIDES

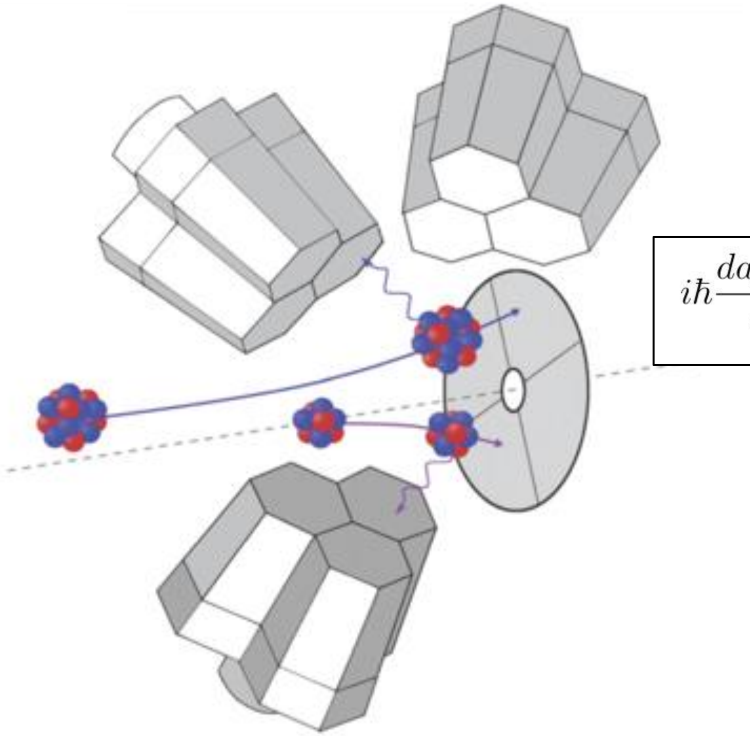
Coulomb excitation

Heavy ion **inelastic scattering** via **electromagnetic interaction**

Safe energy -> **Purely EM** interaction

Cline's "safe energy" criterion

$$E_P(\theta_{CM}) < 0.72 \cdot \frac{Z_P Z_T}{1.25\left(A_P^{1/3} + A_T^{1/3}\right) + 5} \cdot \frac{A_P + A_T}{A_T} \cdot \left(1 + \frac{1}{\sin\frac{\theta_{CM}}{2}}\right) \quad [\mathrm{MeV}]$$



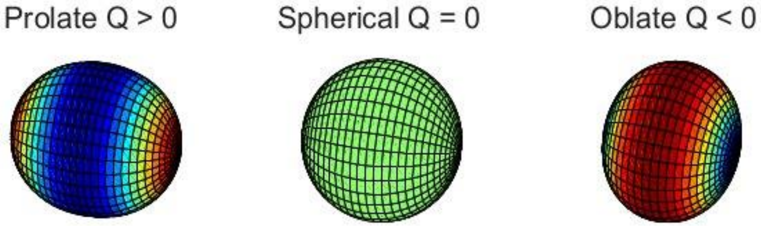
Time-dependent perturbation theory

$$i\hbar \frac{da_k(t)}{dt} = \sum_n a_n(t) \langle \varphi_k | V(t) | \varphi_n \rangle \exp \frac{it}{\hbar}(E_k - E_n)$$

$$\frac{d\sigma_{clx}}{d\Omega} = \frac{d\sigma_R}{d\Omega} \cdot P_n \qquad P_n = |a_n|^2$$

EM potential **V(t)** expanded in **multipoles**
Excitation σ is proportional to EM multipole **matrix elements** (mainly E2)

Extraction of **transitional matrix elements** and **quadrupole moments**



<u>Setup:</u> *Heavy ion particle detector + gamma array*

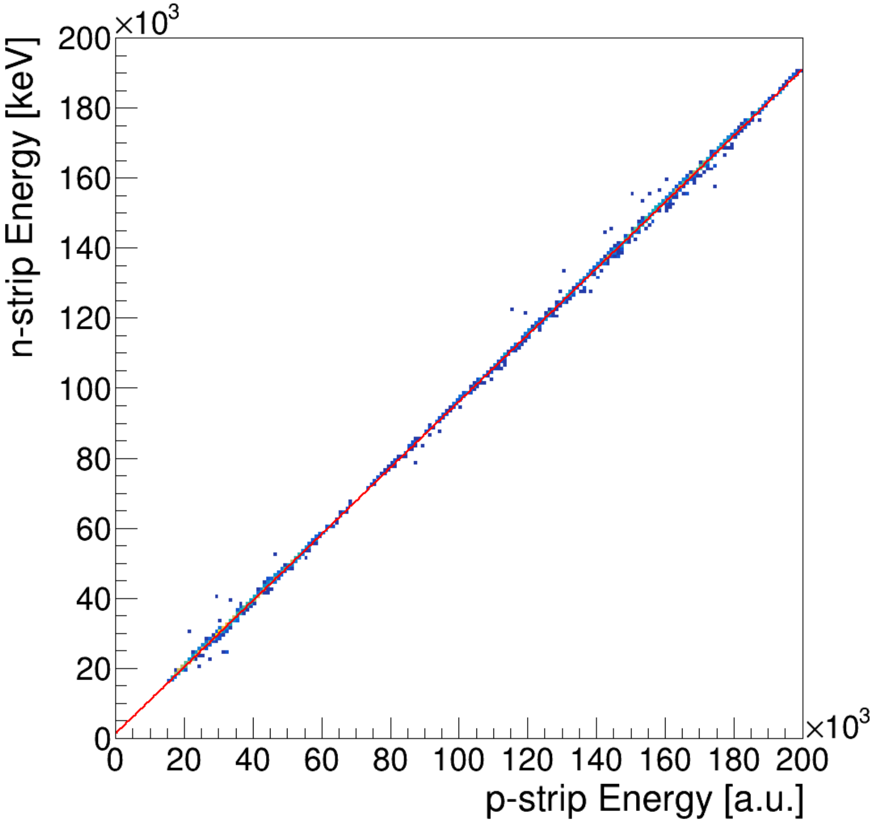
Gamma decays used to quantify the excitations of states

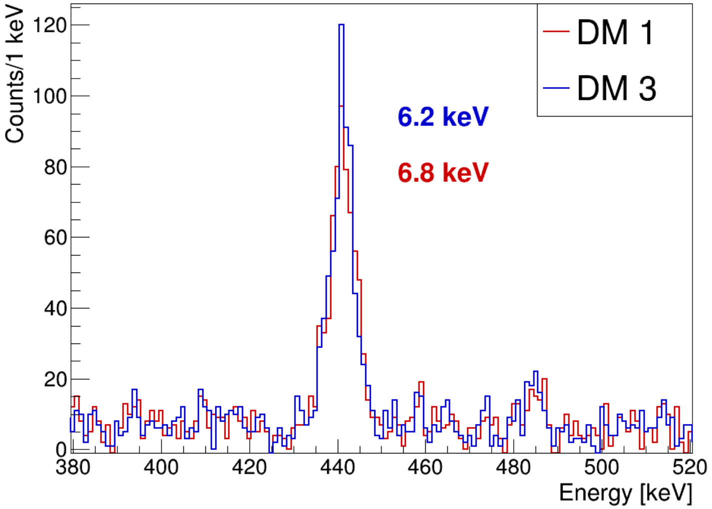
CD p-n side calibration

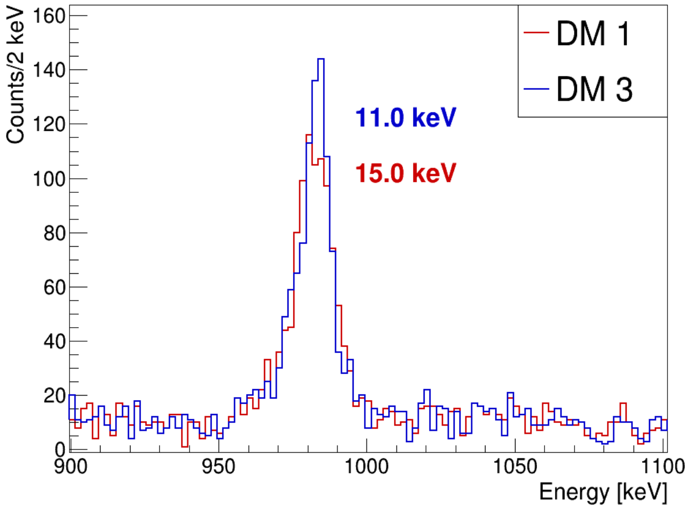
A. Ring 13 (**P-side**) is calibrated with the simulation

B. All the **N-side** strips are calibrated with coincident events with the ring 13

C. All the remaining P-side rings are calibrated with coincident events with N-side strip 5

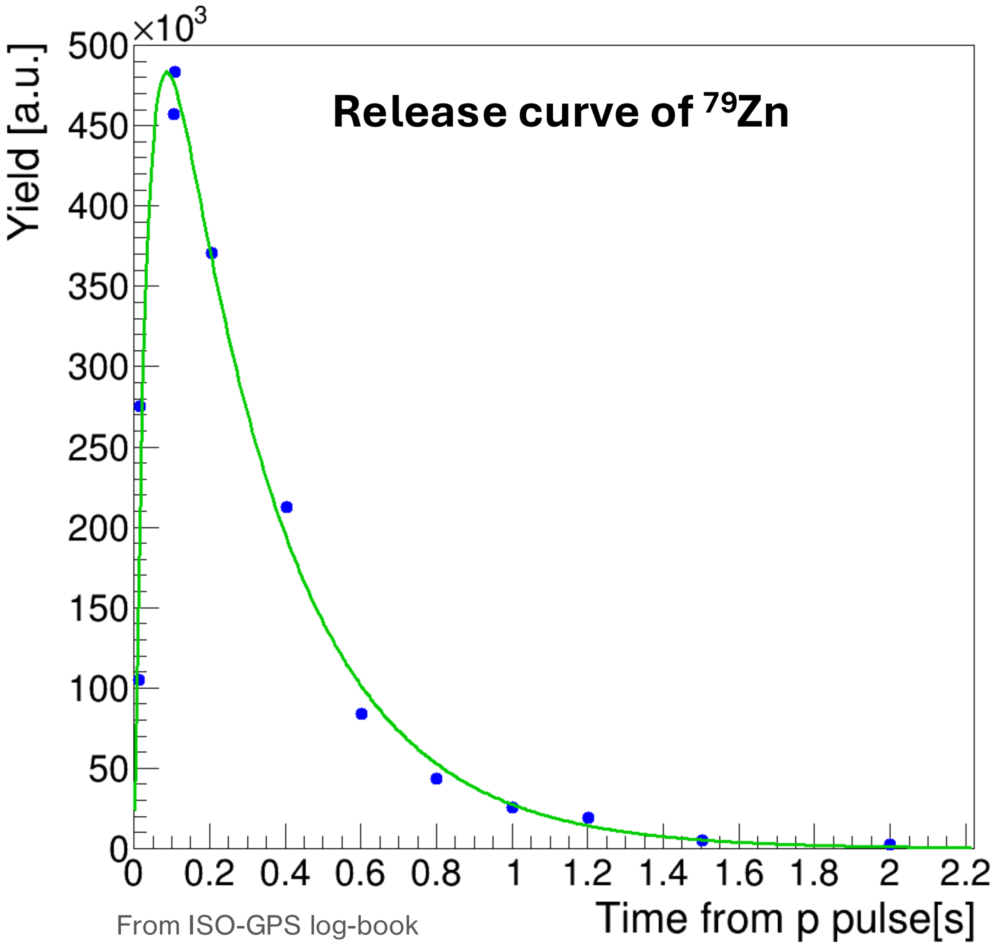




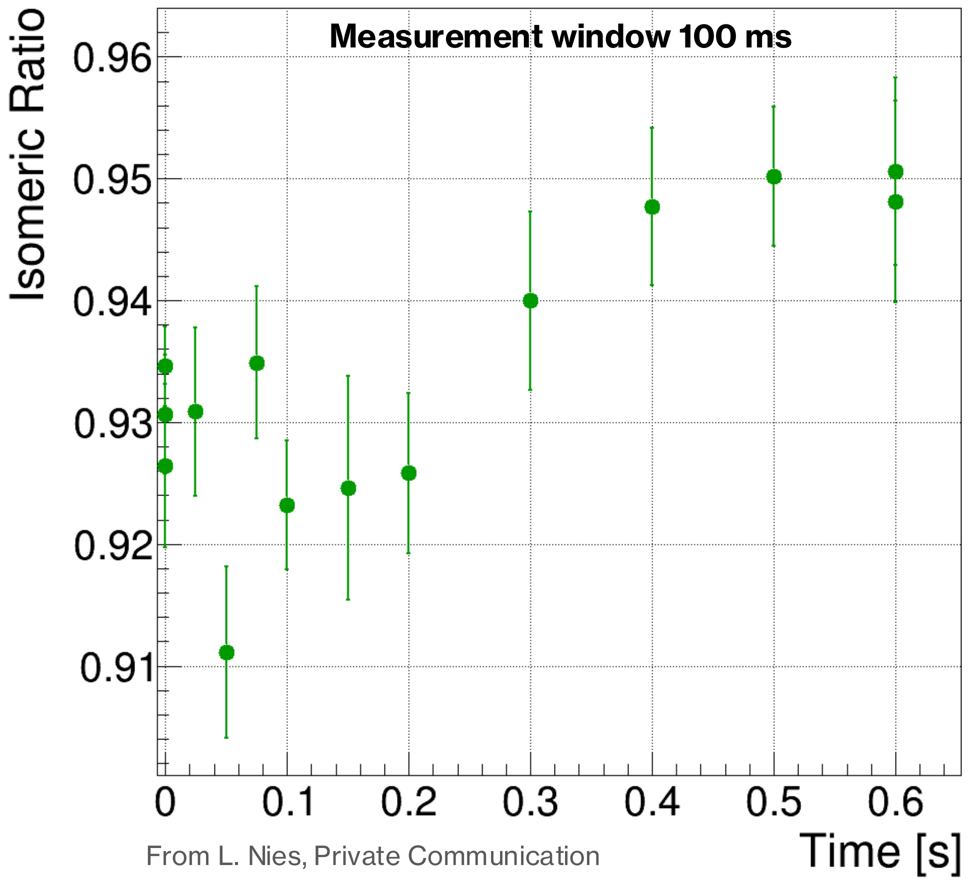


Doppler Mode 1: Average β from the CD angle
Doppler Mode 3: event-by-event β from CD energy

Isomeric ratio estimation



From ISO-GPS log-book



From L. Nies, Private Communication

$$f_i = \frac{\int_{t_i}^{t_i+100\text{ ms}} R(t)\, dt}{\int_0^{1.2\text{ s}} R(t)\, dt}$$

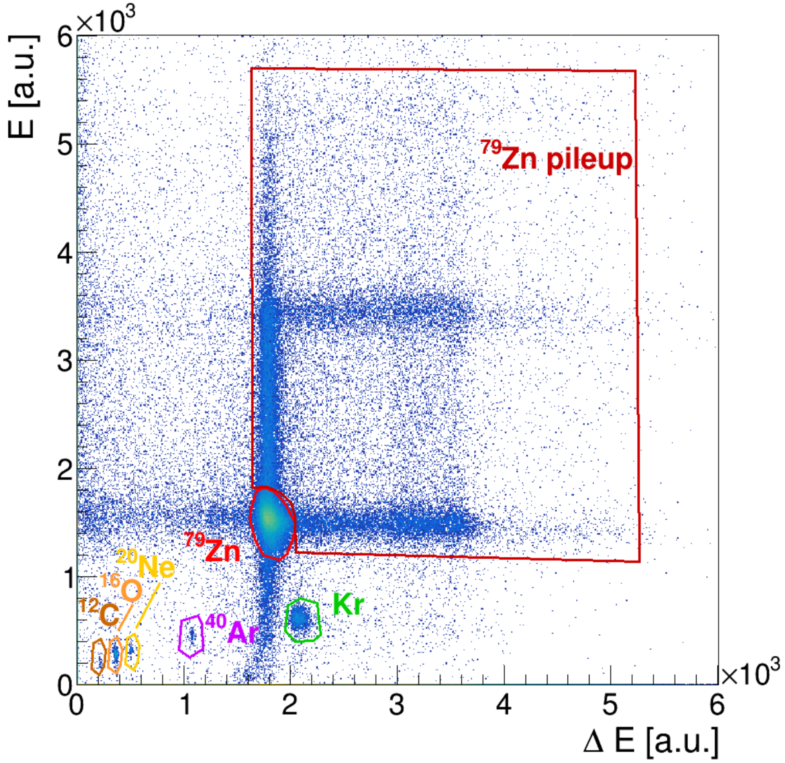
r = N(^{79}Zn in g.s.)/N(^{79}Zn total)

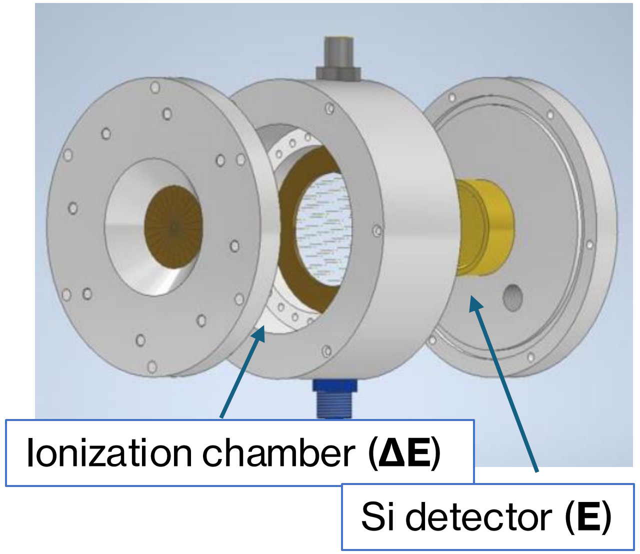
$$\bar{r} = \frac{\sum_i \frac{r_i \cdot f_i}{\sigma_i^2}}{\sum_i \frac{f_i}{\sigma_i^2}} \qquad \sigma_{\bar{r}} = \sqrt{\frac{1}{\sum_i \frac{f_i}{\sigma_i^2}}}$$

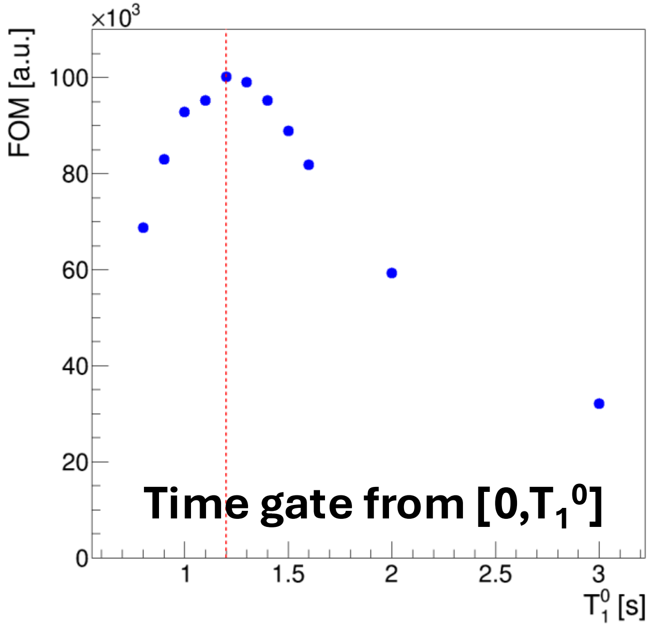
Weighted average on **uncertainty** and **integral of release curve**

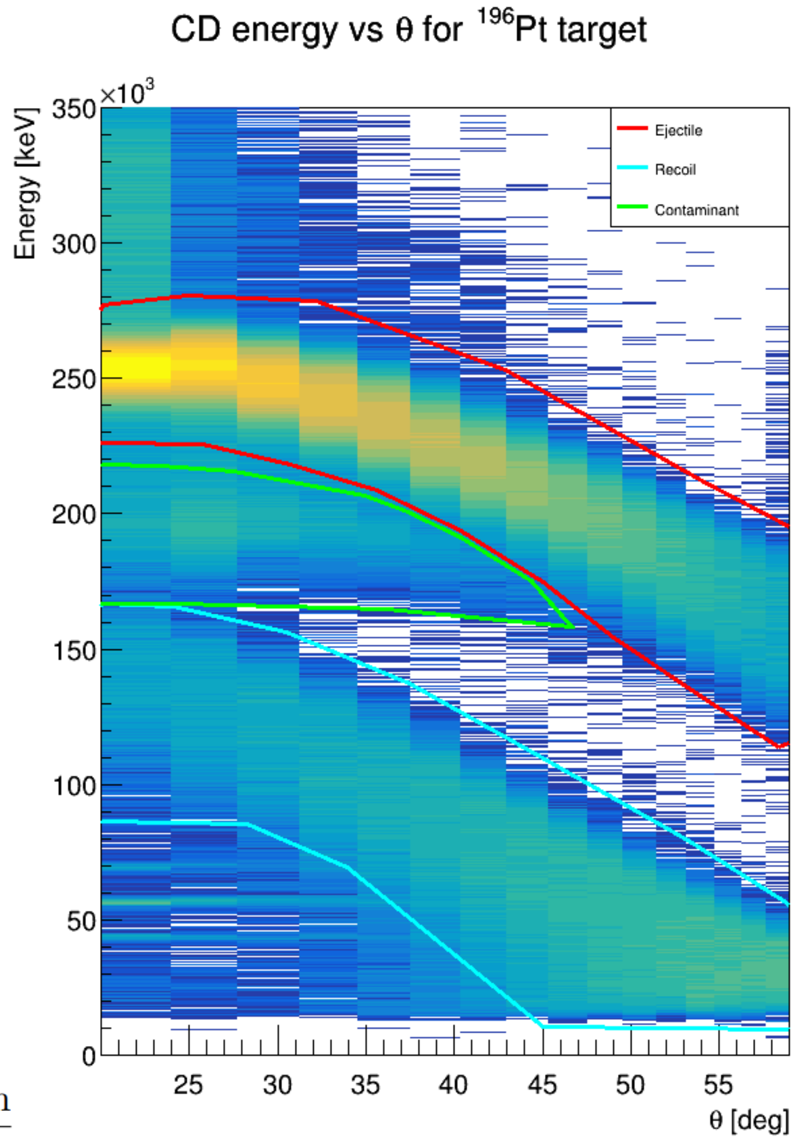
$$\bar{r} = 0.9308 \pm 0.0039$$

Beam contaminants









Beam contaminants can excite ^{196}Pt:
Their effect must be **evaluated**

No time correlation with proton pulse

^{79}Zn $T_{1/2}$~ 0.7 s
Time gate **must not cut Zn**
Optimal T_1^0 = 1.2s

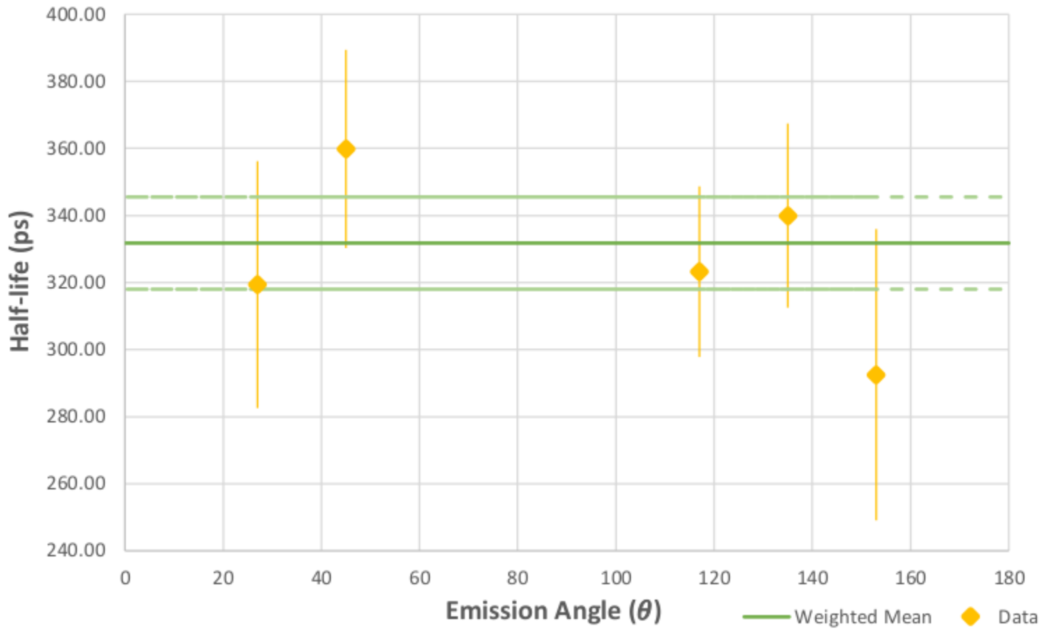
$$FOM = \frac{\text{Integral } [430, 450] \text{ keV from DC } \gamma \text{ spectrum}}{\text{Kr/Zn ratio from IC}}$$

State at 985 keV: lifetime

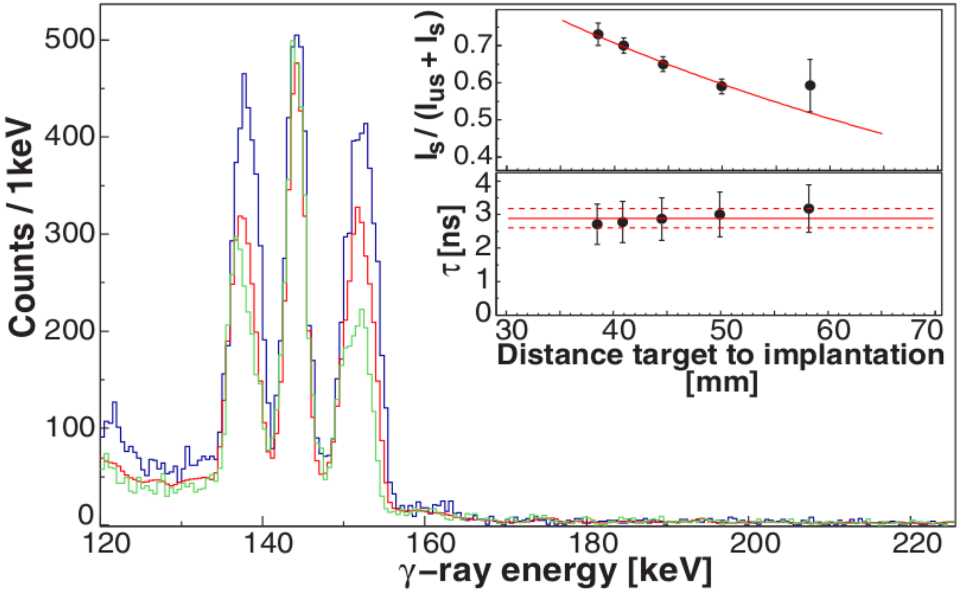
How to extract lifetime ?

Dividing into theta ranges and extracting the ratio of stopped and in-flight component (plunger-like)

Method tried before in a coulex of ^{98}Sr, but result was significantly lower than real value!



R. Clews's Master thesis, University of Liverpool (2021)



E. Clement et al., PRC 94, 054326 (2016)

^{222}Rn Coulomb excitation at Miniball. Compatible with literature.

Previously measured value:
$T_{1/2}$ (2^+)= 320 ± 20 ps