

6th International Conference on Collective Motion in Nuclei under Extreme Conditions

October 29 – November 2, 2018, Cape Town, South Africa

Gamma decay of pygmy states in $^{90,94}\text{Zr}$ from inelastic scattering of light ions

Fabio Crespi

Università degli Studi di Milano - INFN

□ Motivation

E1 strength at particle threshold: the Pygmy Dipole Resonance

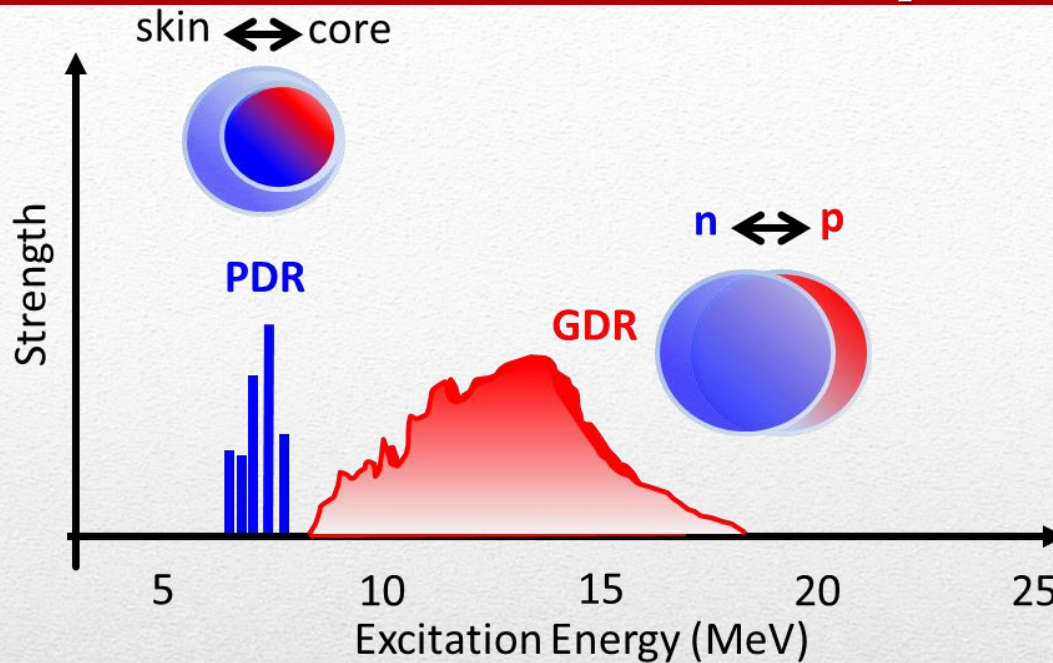
□ Heavy Ion Inelastic Scattering

□ Light Ion (α , p) Inelastic Scattering

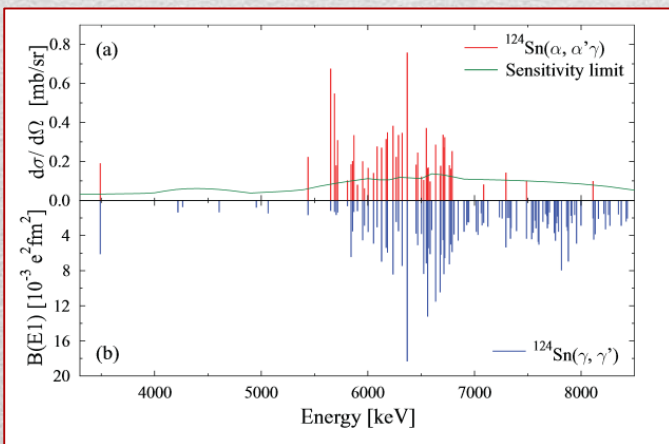
- *Experimental setup at RCNP (Osaka Univ.) with CAGRA + HECTOR+(LaBr:Ce) and Grand Raiden*
- *Results (preliminary) from experiments with $^{90,94}\text{Zr}$ targets*

□ Conclusions and Future Work

Nuclear Structure information from the E1 response in Nuclei



The splitting in the population of the states reveals a different underlying structure



- low energy part \rightarrow **isoscalar character** (*neutron-skin oscillations*)
- high-energy states \rightarrow **isovector nature** (*transition towards the GDR*)

(*) figure from J. Endres et al., Phys. Rev. Lett. 105, 212503 (2010)
 See also e.g. "Experimental studies of the Pygmy Dipole Resonance"
 D. Savran, T. Aumann, A. Zilges – Prog. Part. Nucl. Phys., 70(2013)210

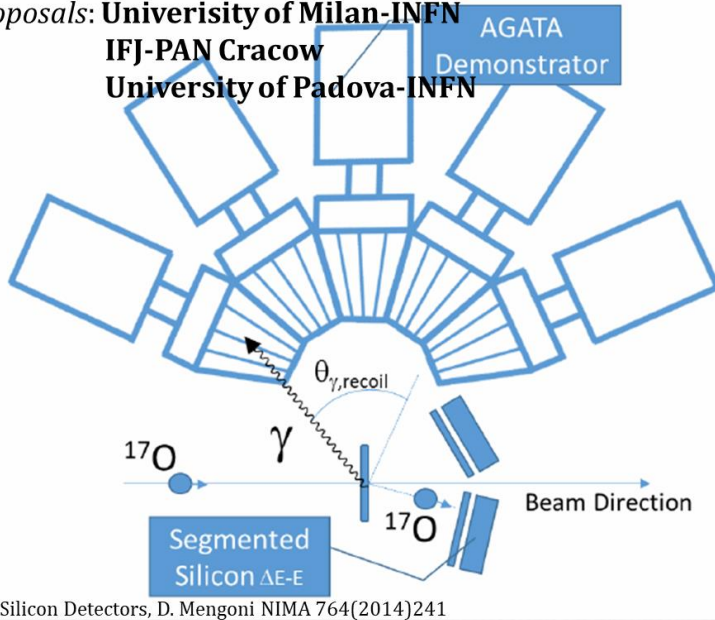
Heavy Ion Inelastic Scattering

Key issues for the interpretation of the nature of the PDR states are the determination of their characteristic transition density and the isospin character

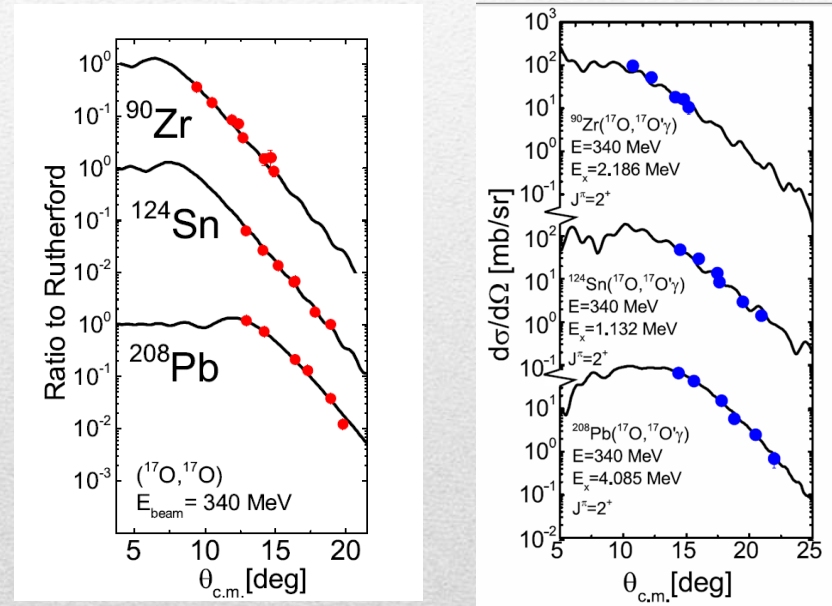
Inelastic scattering of ^{17}O @ 20 MeV/u on different targets + γ -rays in coincidence

Experiments at Legnaro, (2011)

Proposals: University of Milan-INFN
IFJ-PAN Cracow
University of Padova-INFN



Differential cross sections for Elastic and the 2^+ states in ^{90}Zr , ^{124}Sn , ^{208}Pb

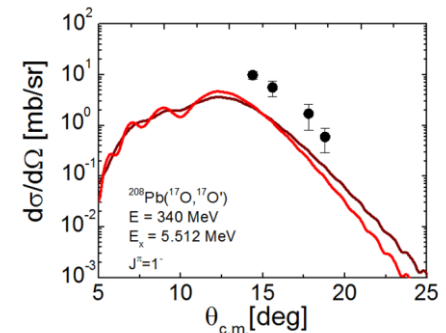


1- states:

The calculation accounts only for a fraction of the measured yield

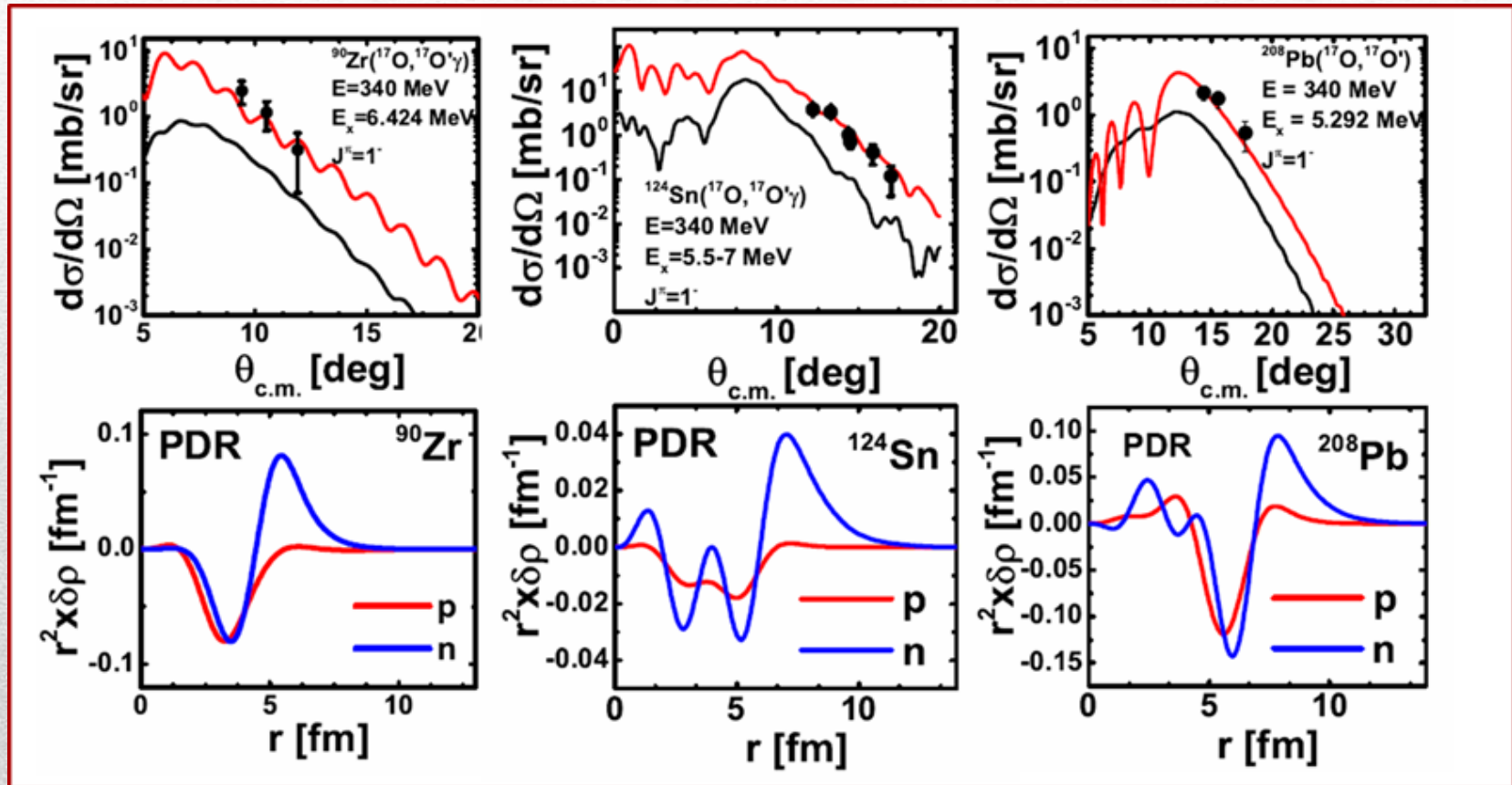
Why?

Calculations obtained using a standard form factor are found to be very similar to the Coulomb excitation alone

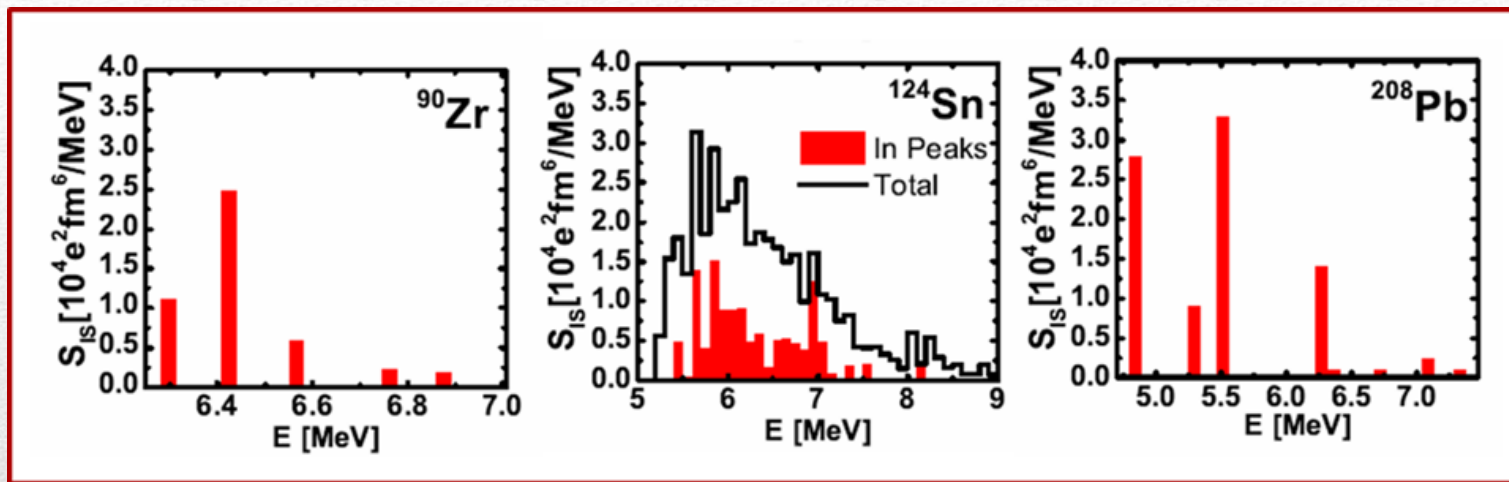


Heavy Ion Inelastic Scattering

- DWBA calculation were performed (red solid lines) using microscopic form factors* based on the transition density associated to the E1 PDR states



- The main objective of the data analysis was the extraction of the values of the **isoscalar strength** from the measured cross section



$(^{17}\text{O}, ^{17}\text{O}'\gamma)$ reaction is a good tool to investigate the isospin properties of the pygmy states

F.C.L. Crespi, et al., PRL113 (2014) 012501
L. Pellegrini, et al., PLB738 (2014)519

*E. G. Lanza et al.,
Phys. Rev. C 84 (2011) 064602

F.C.L. Crespi et al, PRC 91 (2015) 024323
A. Bracco, F.C.L. Crespi and E.G. Lanza, EPJA(2015)51:99

- «**multi-messenger**» investigation of the **PDR****:

$(\alpha, \alpha'\gamma)$ reaction (isoscalar character, surface-sensitive),

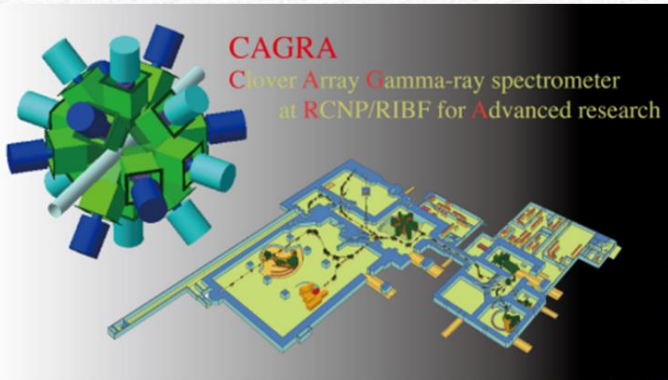
$(p, p'\gamma)$ reaction (mainly isoscalar character, better sensitivity to the inner transition density)

(γ, γ') (mainly isovector character).

** D. Savran et al. Physics Letters B 786 (2018) 16–20

Experimental campaign at RCNP Osaka (October-December 2016)

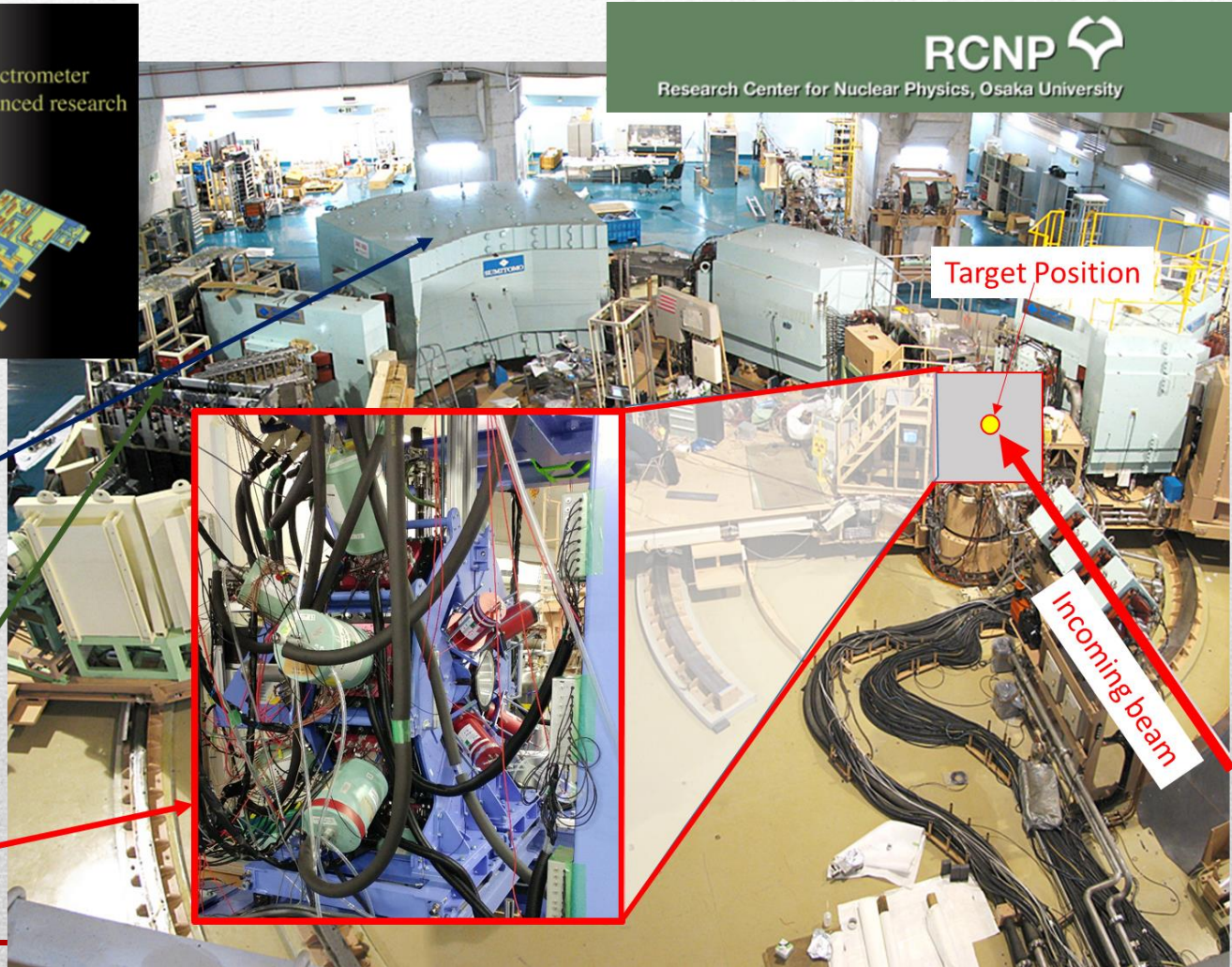
- Study of the Structure of the Pygmy Dipole Resonance States via the $(p, p' \gamma)$ and $(\alpha, \alpha' \gamma)$ Reactions in [in $^{90,94}\text{Zr}$] $E_{\text{proton}} = 80 \text{ MeV}$, $E_{\text{alpha}} = 130 \text{ MeV}$
- - Spokespersons A. Bracco, F. Crespi and N. Pietralla



Grand Raiden Spectrometer
Resolution: 37,000
Momentum Byte: 1.05
Acceptance: 5.6 msr

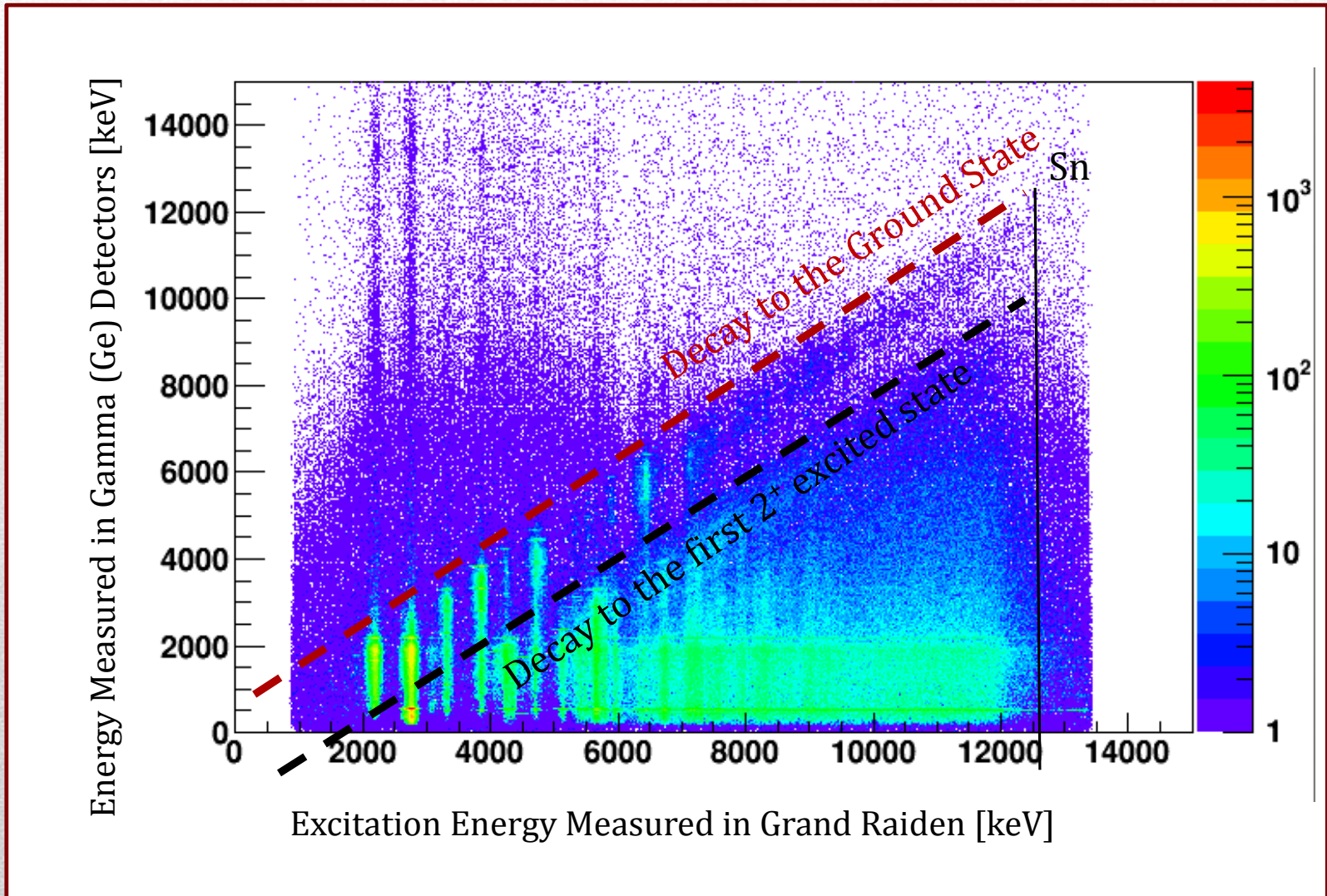
Focal Plane Detector
2 VDC Systems
2 Trigger Scintillators

Gamma Detection System
CAGRA
- 12 CLOVERS
- 4 LaBr3:Ce 3,5''x8''



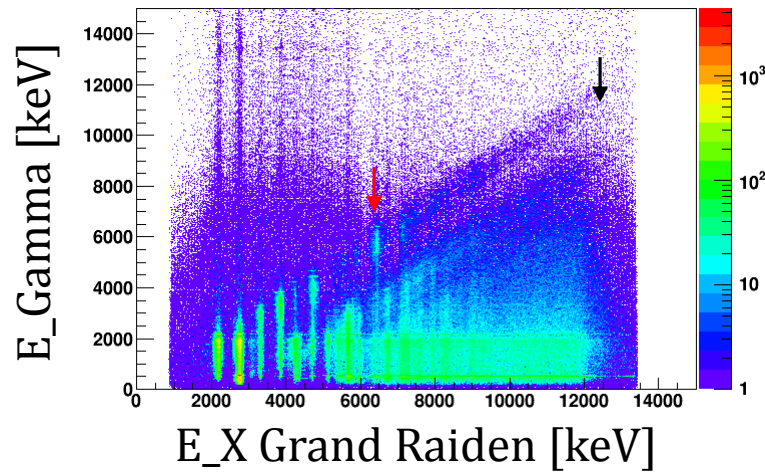
$(\alpha, \alpha'\gamma)$ Reaction in ^{90}Zr , $E_{\alpha} = 130\text{MeV}$

- light-ion inelastic scattering with the high-resolution spectrometer Grand-Raiden in coincidence with gamma-ray detection (background subtracted)

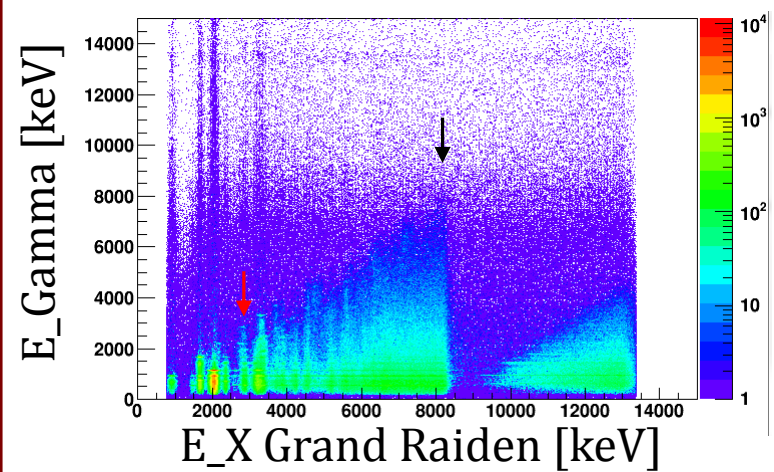


PDR States via the $(p, p'\gamma)$ and $(\alpha, \alpha'\gamma)$ Reactions in $[\text{in } ^{90,94}\text{Zr}]$

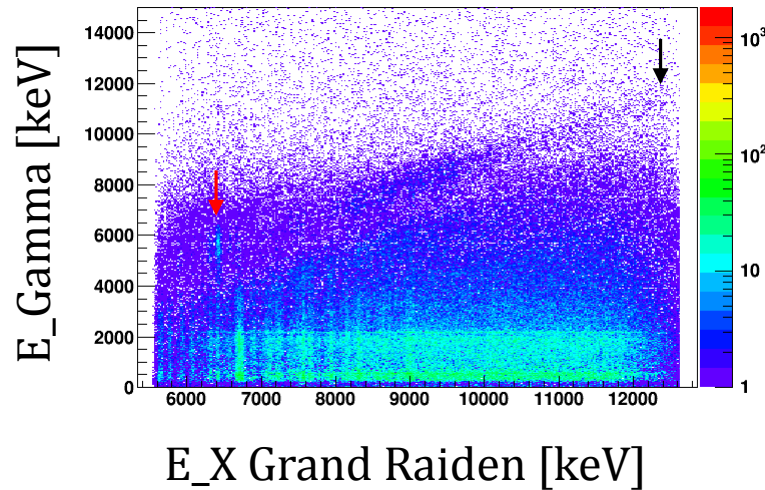
$(\alpha, \alpha'\gamma)$ $E_\alpha = 130\text{MeV}$ [^{90}Zr]



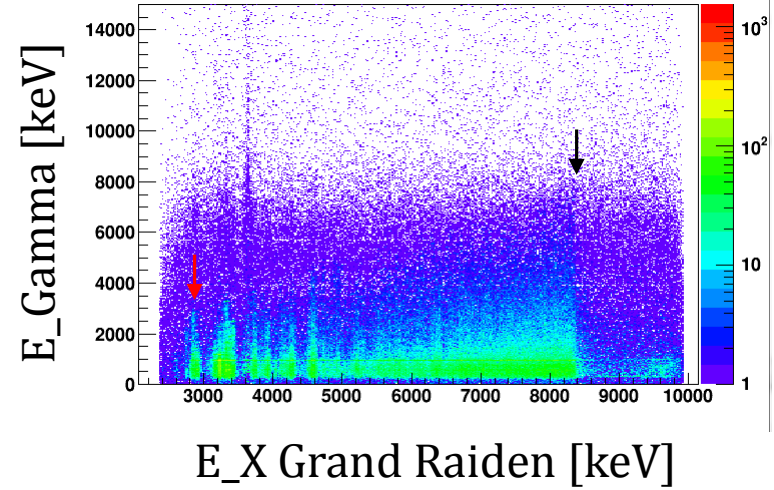
$(\alpha, \alpha'\gamma)$ $E_\alpha = 130\text{MeV}$ [^{94}Zr]



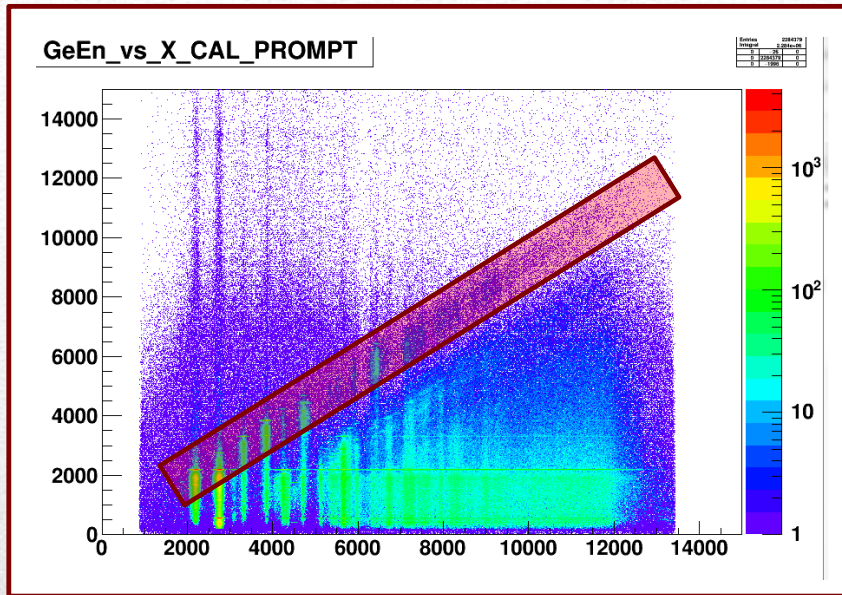
$(p, p'\gamma)$ $E_p = 80\text{MeV}$ [^{90}Zr]



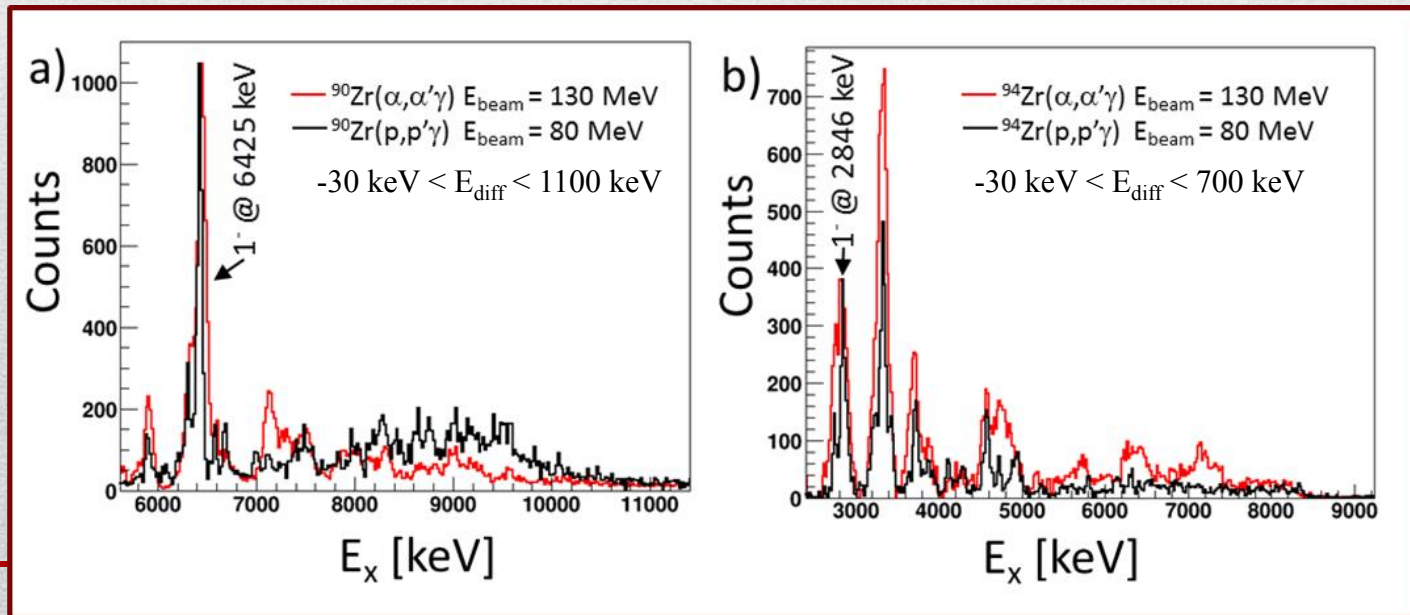
$(p, p'\gamma)$ $E_p = 80\text{MeV}$ [^{94}Zr]



Ground state gamma decay, Ex spectra



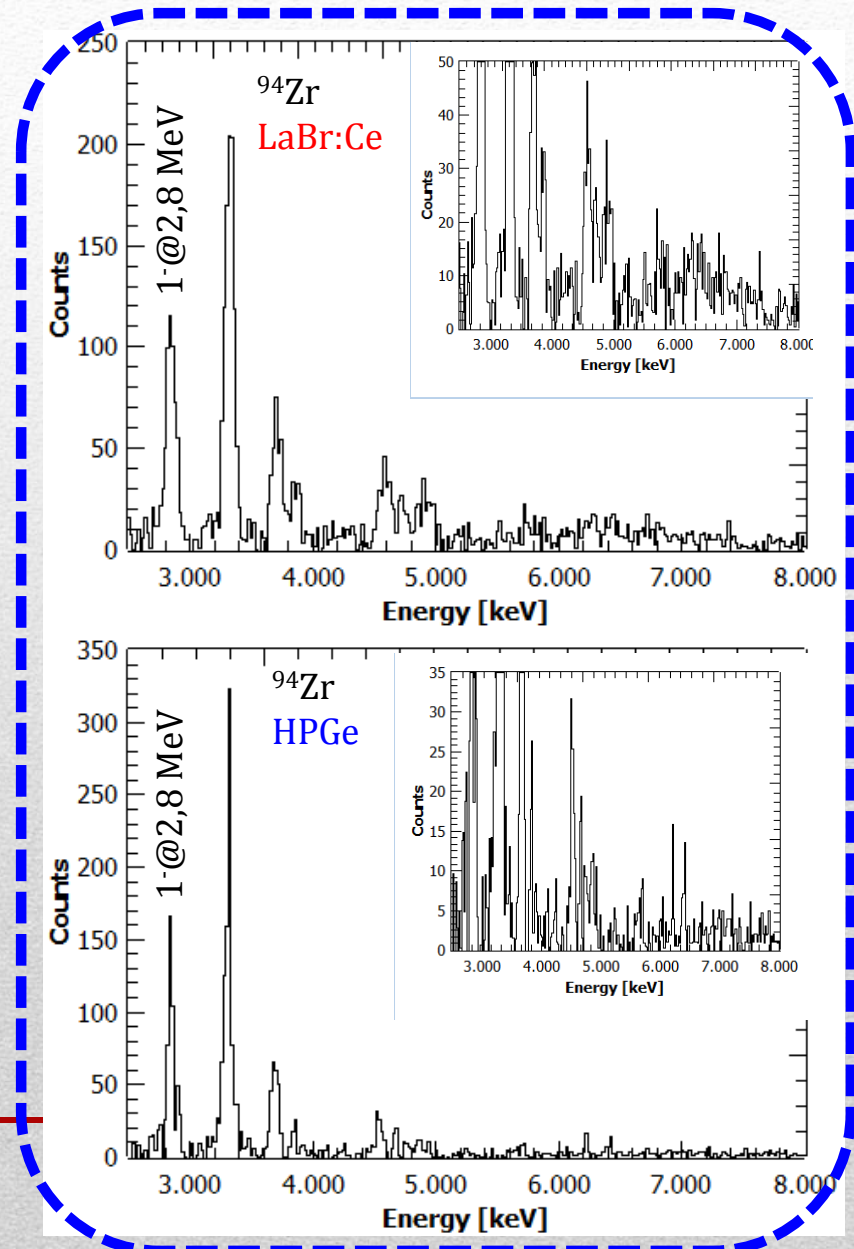
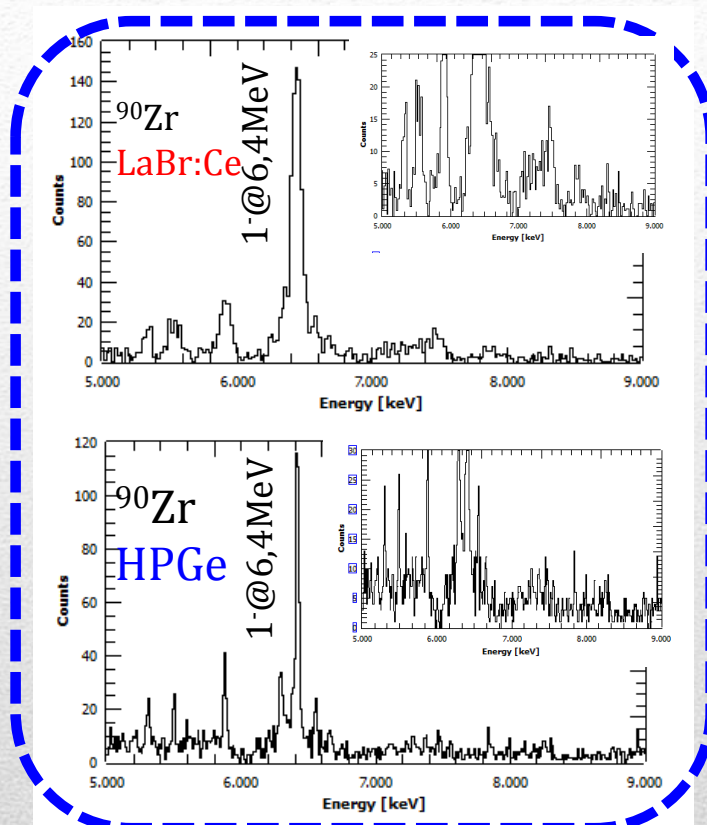
- histograms showing the **excitation energy (measured with Grand Raiden)** of the $^{90,94}\text{Zr}$ target nuclei for the alpha inelastic reaction at $E_{beam} = 130$ MeV (red line histogram) and the proton inelastic scattering reaction at $E_{beam} = 80$ MeV (black line histogram).
- For both ^{90}Zr and ^{94}Zr there is **clear similarity** between the levels excited by protons and those excited by alpha particles **in the lower energy part**. In contrast, in the higher energy part the spectra appear to be significantly different.



Ground state gamma decay, Egamma spectra

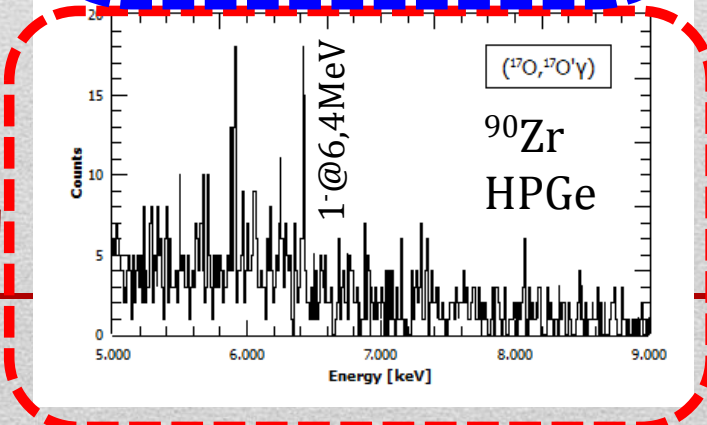
Gamma-ray spectra (from HPGe and LaBr:Ce) for $^{90,94}\text{Zr}$ ($\alpha, \alpha'\gamma$)

$$-30 \text{ keV} < E_{\text{diff}} < 150 \text{ keV}$$



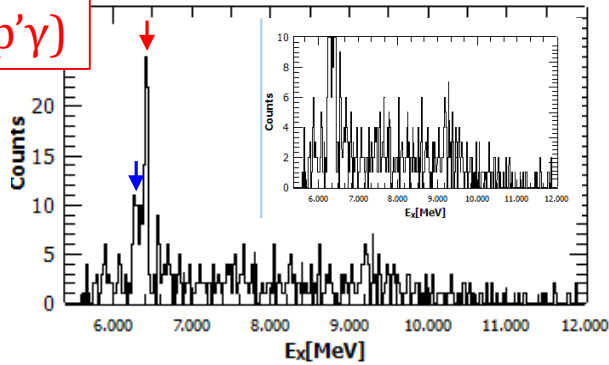
F.C.L. Crespi
et al, PRC 91
(2015)
024323

($^{170}, ^{170'}\gamma$)
Measurement in
2010 LNL-INFN

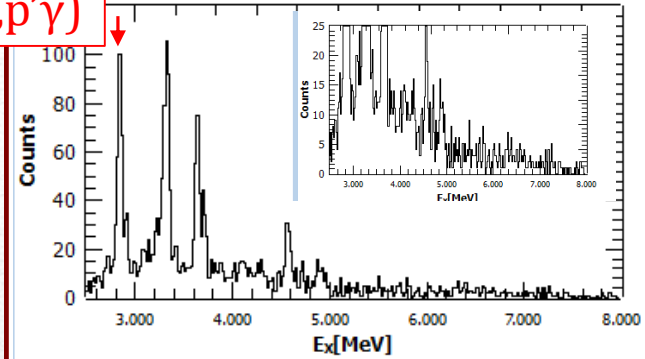


Comparison of E_x spectra for $(p,p'\gamma)$ and $(\alpha,\alpha'\gamma)$ with (γ,γ')

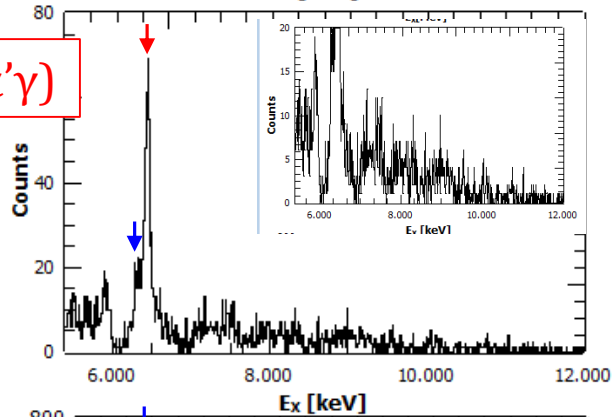
$^{90}\text{Zr}(p,p'\gamma)$



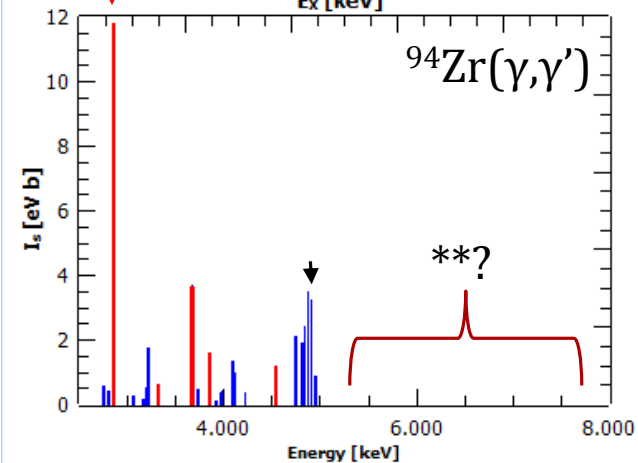
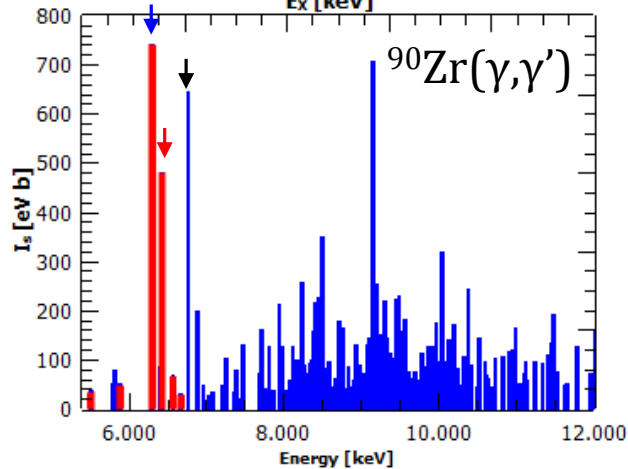
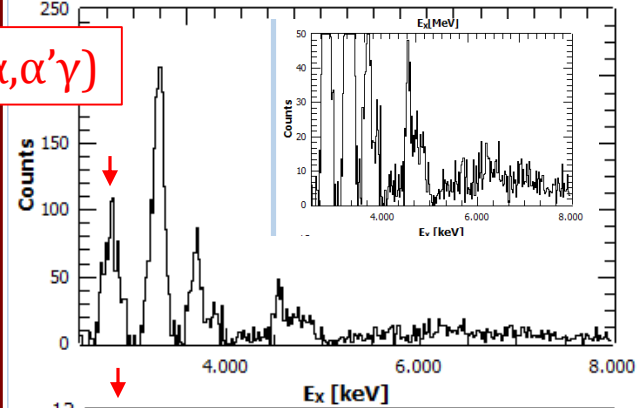
$^{94}\text{Zr}(p,p'\gamma)$



$^{90}\text{Zr}(\alpha,\alpha'\gamma)$



$^{94}\text{Zr}(\alpha,\alpha'\gamma)$



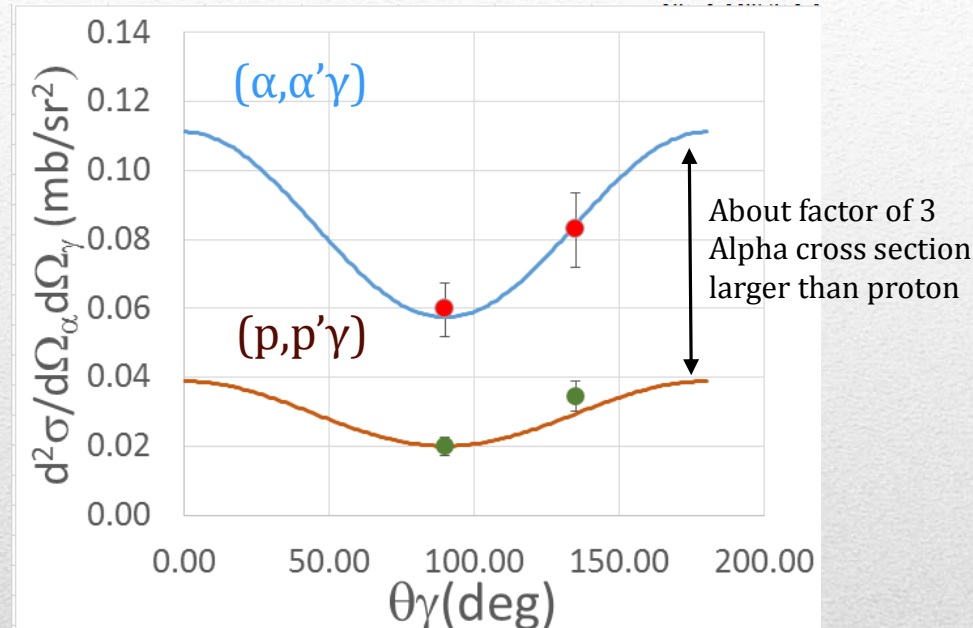
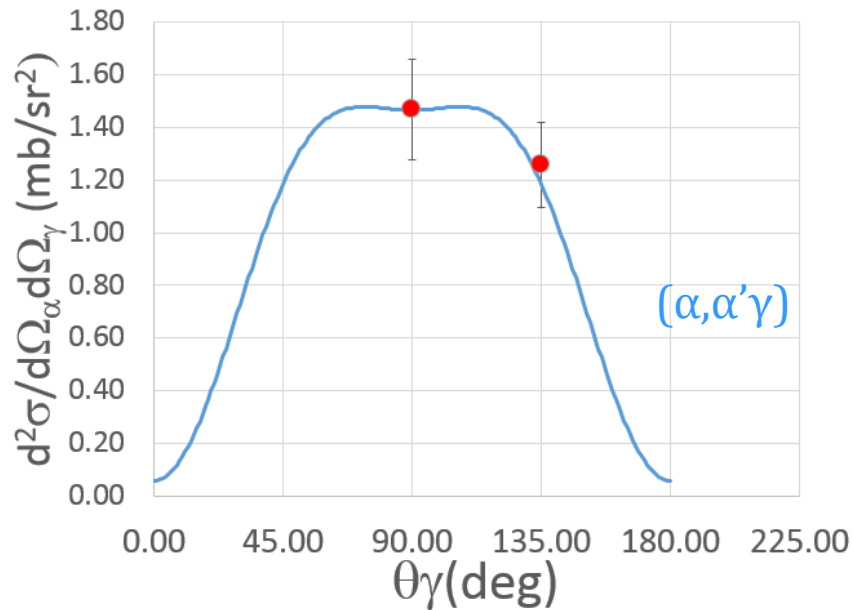
α - γ angular correlations

□ Double differential cross sections

➤ Calculations done with Chuck3*,** and AngCor codes***

^{90}Zr : first 2^+ state at 2186keV

^{90}Zr : 1^- state at 6425 keV



$(p, p'\gamma)$ threshold at $\sim 5,5$ MeV

□ Differential cross sections:

2^+ state at 2186 keV $(\alpha, \alpha'\gamma)$: **15.4 mb/sr**

1^- state at 6425 keV $(\alpha, \alpha'\gamma)$: **0.95 mb/sr**

1^- state at 6425 keV $(p, p'\gamma)$: **0.33 mb/sr**

✓ Consistency between cross section extracted with the singles of grand raiden and those extracted with the gamma peaks

*P. D. Kunz, program CHUCK, University of Colorado (unpublished) ***M. N. Harakeh and L. W. Put, program ANGCOR, KVI internal report 67i, 1979 (unpublished).

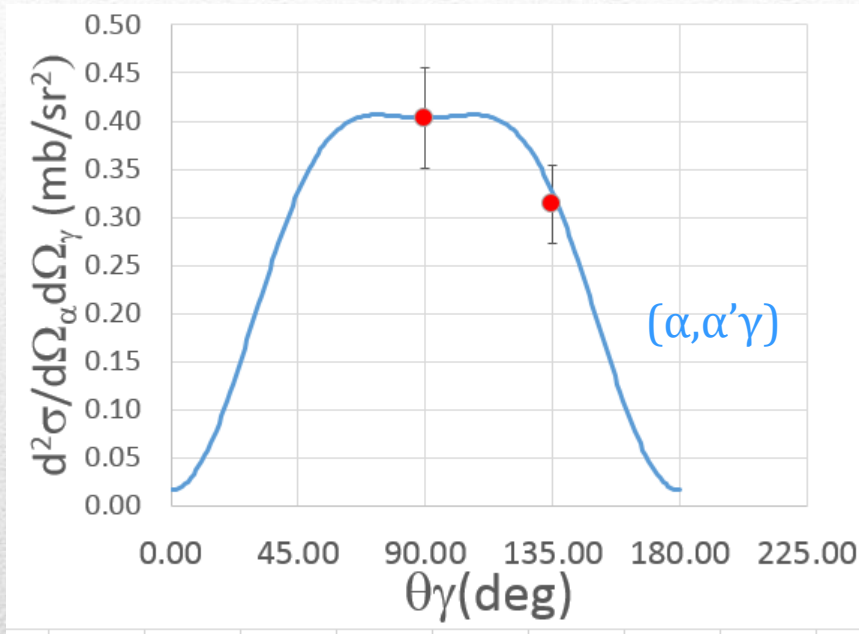
**J. R. Comfort and M. N. Harakeh, program CHUCK3, modified version of CHUCK, 1979 (unpublished).

α - γ angular correlations

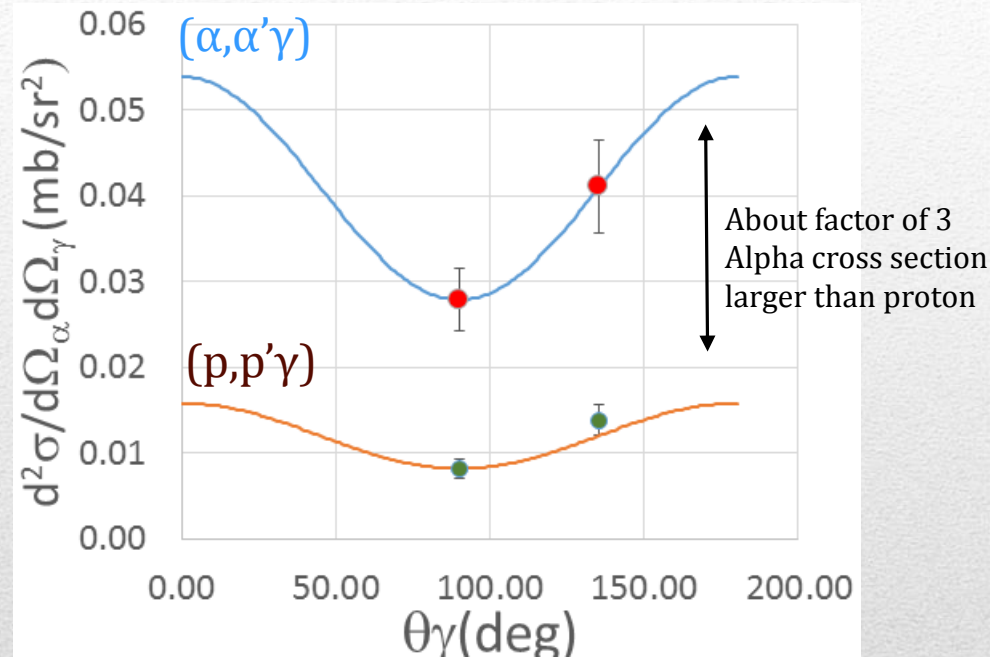
□ Double differential cross sections

➤ Calculations done with Chuck3*,** and AngCor codes***

^{94}Zr : first 2^+ state at 919 keV



^{94}Zr : 1^- state at 2846 keV



$(p, p'\gamma)$ threshold at $\sim 2,4$ MeV

□ Differential cross sections:

2^+ state at 919 keV $(\alpha, \alpha'\gamma)$: **4,22 mb/sr**

1^- state at 2846 keV $(\alpha, \alpha'\gamma)$: **0.46 mb/sr**

1^- state at 2846 keV $(p, p'\gamma)$: **0.13 mb/sr**

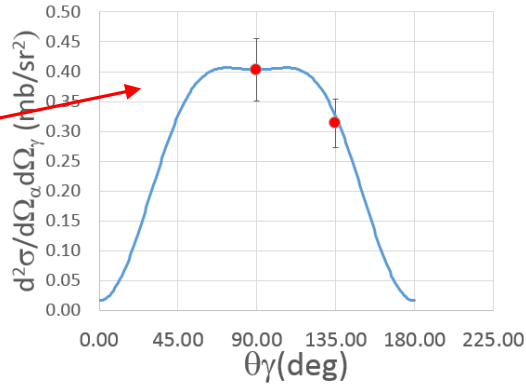
*P. D. Kunz, program CHUCK, University of Colorado (unpublished) ***M. N. Harakeh and L. W. Put, program ANGCOR, KVI internal report 67i, 1979 (unpublished).

**J. R. Comfort and M. N. Harakeh, program CHUCK3, modified version of CHUCK, 1979 (unpublished).

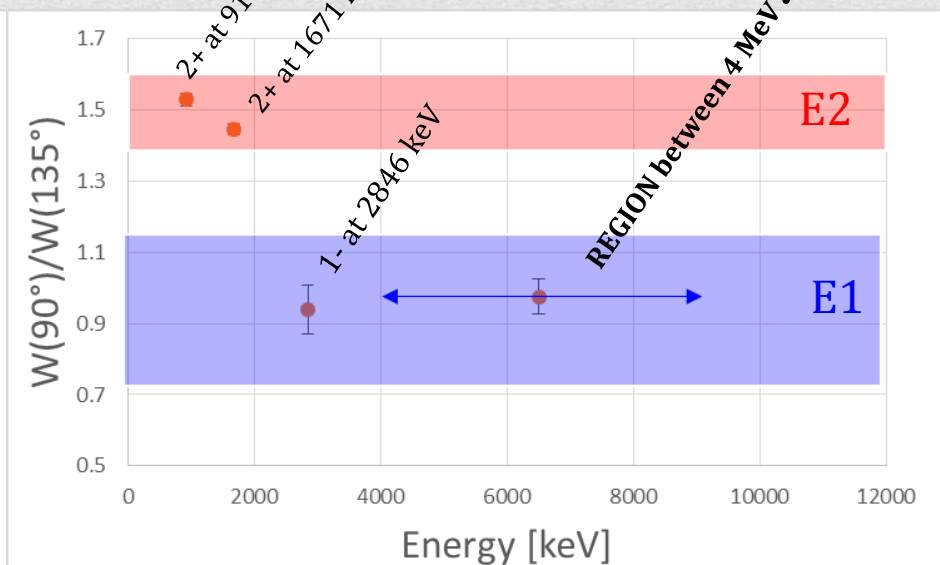
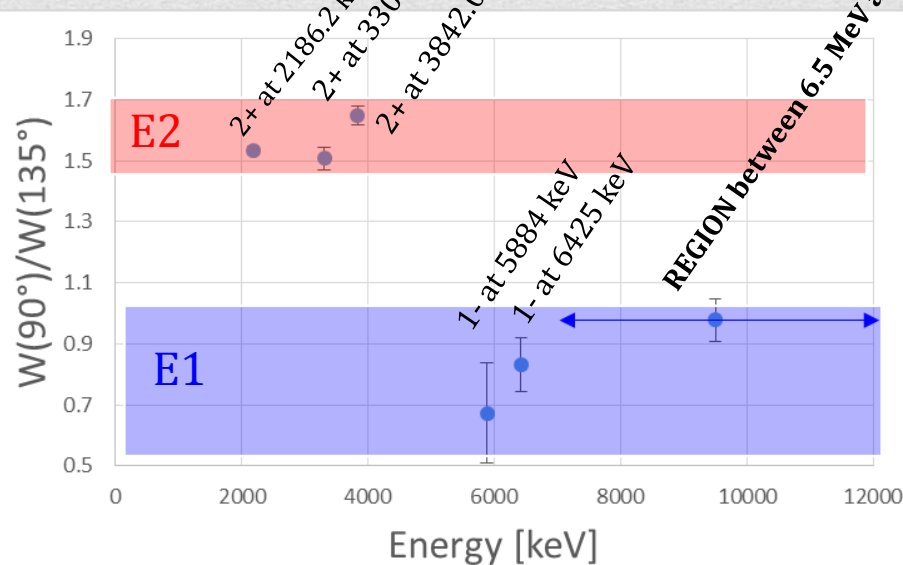
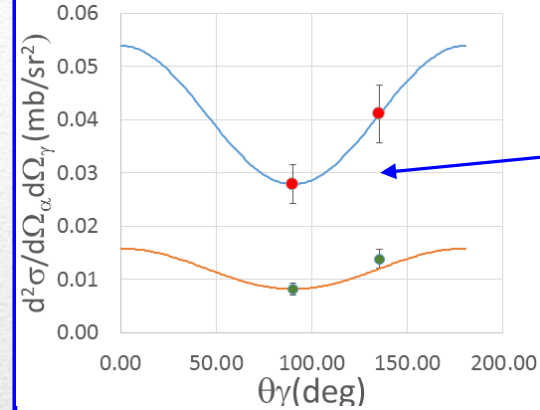
Angular distribution of gamma rays in the PDR region

Asymmetry of the yield at 90 deg in respect to 135 deg used to check the multipolarity of the transitions observed in the gamma spectra and the PDR region

E2
 $W(90^\circ) > W(135^\circ)$



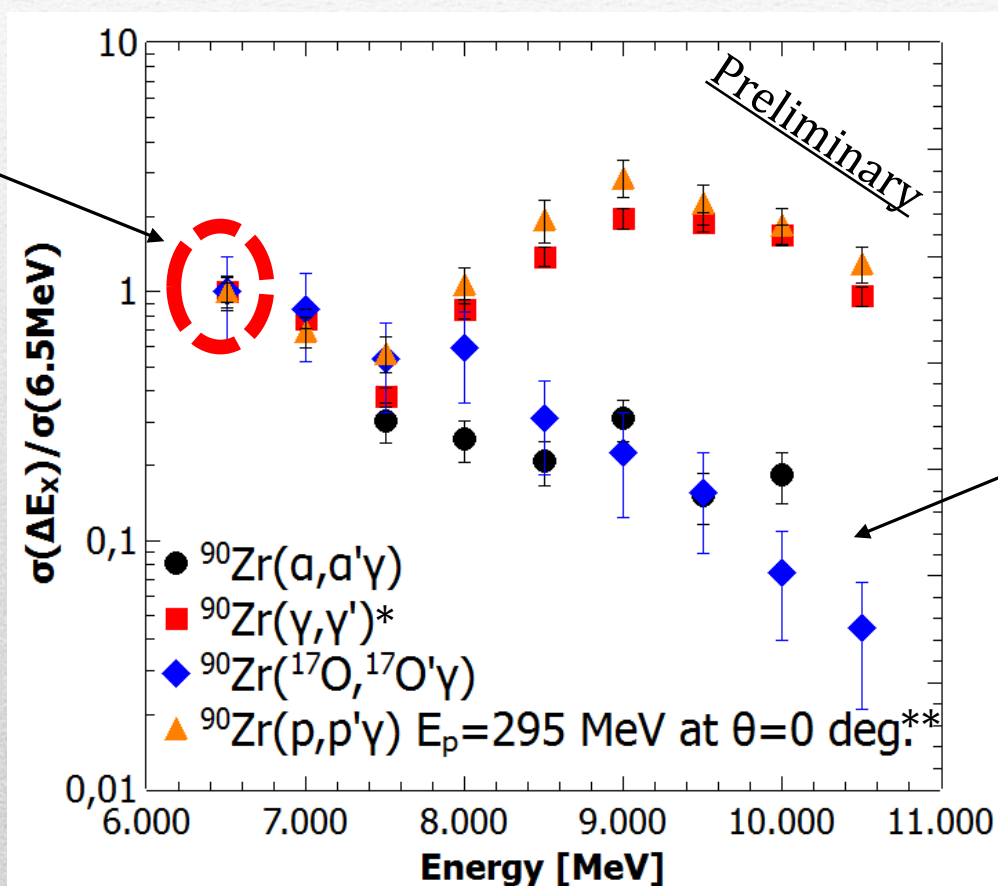
E1
 $W(90^\circ) < W(135^\circ)$



Comparison of the relative cross sections (@6.5 MeV) for IS and IV probes

- It is interesting to compare for ^{90}Zr the relative behavior of the cross sections measured at $E_x > 6.5$ MeV with the $(\alpha, \alpha'\gamma)$, and other probes. For this purpose, the quantity $\sigma R = \sigma(E_x) / \sigma(6.5 \text{ MeV})$, where $\sigma(E_x)$ is the cross section at excitation energy E_x , has been evaluated for these reactions.

Normalization point



Similar behaviour for the case of $(\alpha, \alpha'\gamma)$ and $(^{17}\text{O}, ^{17}\text{O}'\gamma)$

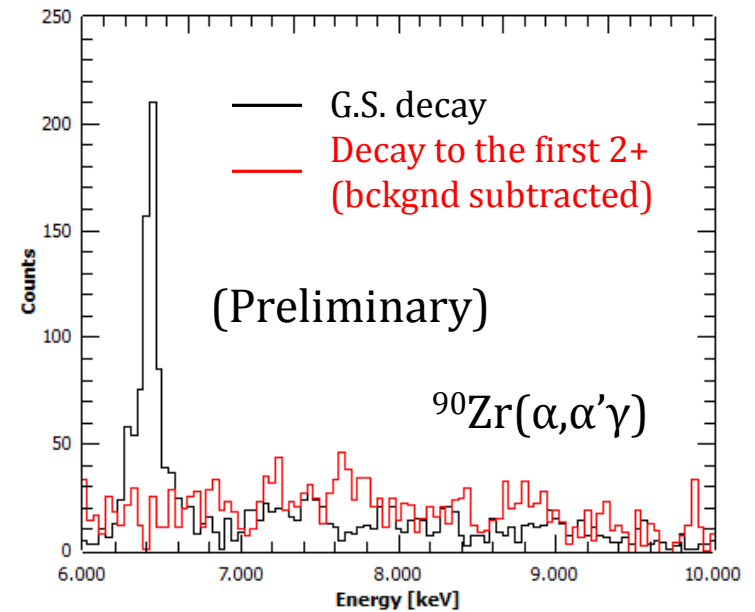
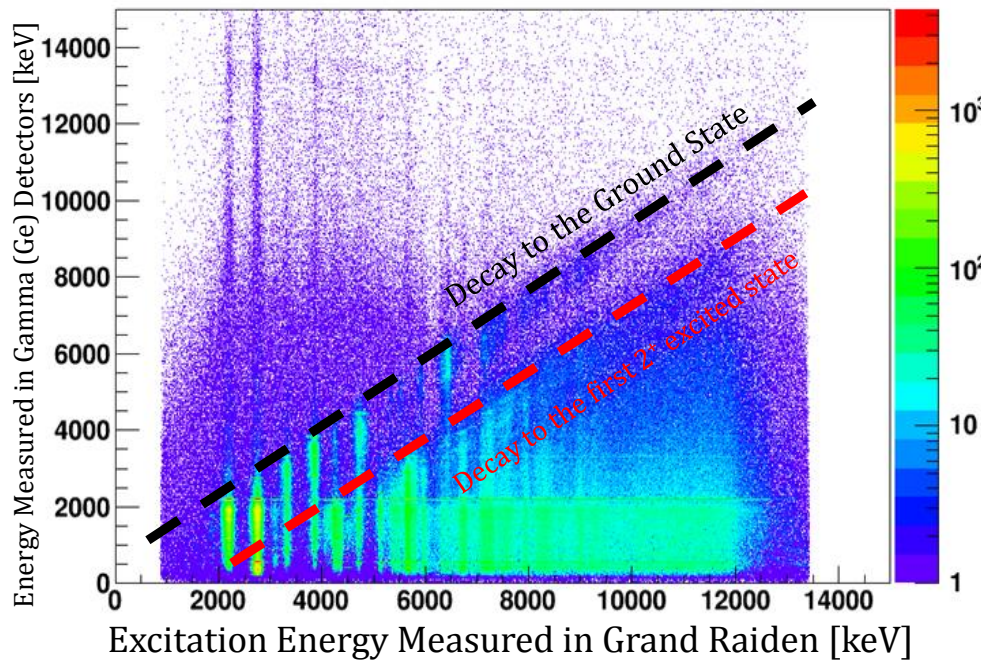
F.C.L. Crespi et al, PRC 91 (2015) 024323

*R. Schwengner et al. PRC 78 064314 (2008)

C. Iwamoto et al. PRL **108, 262501 (2012)

Branching Ratio

- ❑ Black line histogram: E_x , ground state decay
- ❑ Red line histogram: E_x , decay to the first 2+
- ❑ Upper limit extracted for the branching ratio of the 6424 keV 1⁻ state to the first 2⁺ state at 2186 keV of ^{90}Zr : **< 13%**



Conclusions and Future Work

❑ **Results (preliminary) from light-ion inelastic scattering experiments at RCNP**

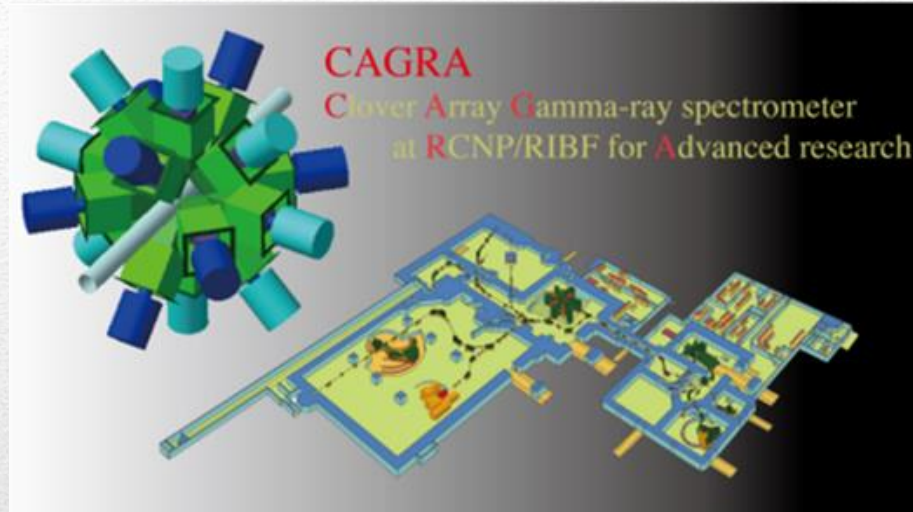
- *Population of the PDR states in $^{90,94}\text{Zr}$ with $(\alpha, \alpha'\gamma)$ and $(p, p'\gamma)$ reactions*
- *Comparison of E_x spectra for $(\alpha, \alpha'\gamma)$, $(p, p'\gamma)$ (g.s. decay) with (γ, γ')*
- *α - γ angular correlations and differential cross sections*
- *$W(90^\circ) / W(135^\circ)$ asymmetry and multipolarity of γ radiation*
- *Relative cross section compared for IS and IV probes*
- *Branching ratio (upper limit) for 6.4 MeV 1^- state in ^{90}Zr*

❑ **Future work**

- *Comparison of experimental cross sections for PDR states in $^{90,94}\text{Zr}$ with calculations*
-

Collaboration

Experiments at RCNP (Osaka University) – CAGRA Collaboration



Gamma decay of pygmy states in $^{90,94}\text{Zr}$ from inelastic scattering of light ions

F.C.L. Crespi¹, A. Bracco¹, A. Tamii², N. Blasi³, F. Camera¹, O. Wieland³, N. Aoi², D. Balabanski⁴, S. Bassauer⁵, A. S. Brown⁶, M. P. Carpenter⁷, J. J. Carroll⁸, M. Ciemala⁹, A. Czeszumska², P. J. Davies⁶, L. Donaldson¹⁰, Y. Fang², H. Fujita², G. Gey², M.N. Harakeh¹¹, T. H. Hoang², N. Ichige¹², E. Ideguchi², A. Inoue², J. Isaak², C. Iwamoto¹³, D. G. Jenkins⁶, O. H. Jin², T. Klaus⁵, N. Kobayashi², T. Koike¹², M. Krzysiek^{4,9}, M. Kumar Raju², M. Liu¹⁴, A. Maj⁹, D. Montanari¹⁵, L. Morris⁶, S. Noji¹⁶, S. G. Pickstone¹⁷, D. Savran¹⁸, M. Spieker^{17,*}, G. Steinhilber⁵, C. Sullivan^{19,20,22}, B. Wasilewska⁹, V. Werner⁵, T. Yamamoto², Y. Yamamoto², X. Zhou¹⁴, S. Zhu⁷

$(\alpha, \alpha'\gamma)$ Reaction in ^{90}Zr , $E_{\alpha} = 130\text{MeV}$

- light-ion inelastic scattering with the high-resolution spectrometer Grand-Raiden in coincidence with gamma-ray detection (background subtracted)

