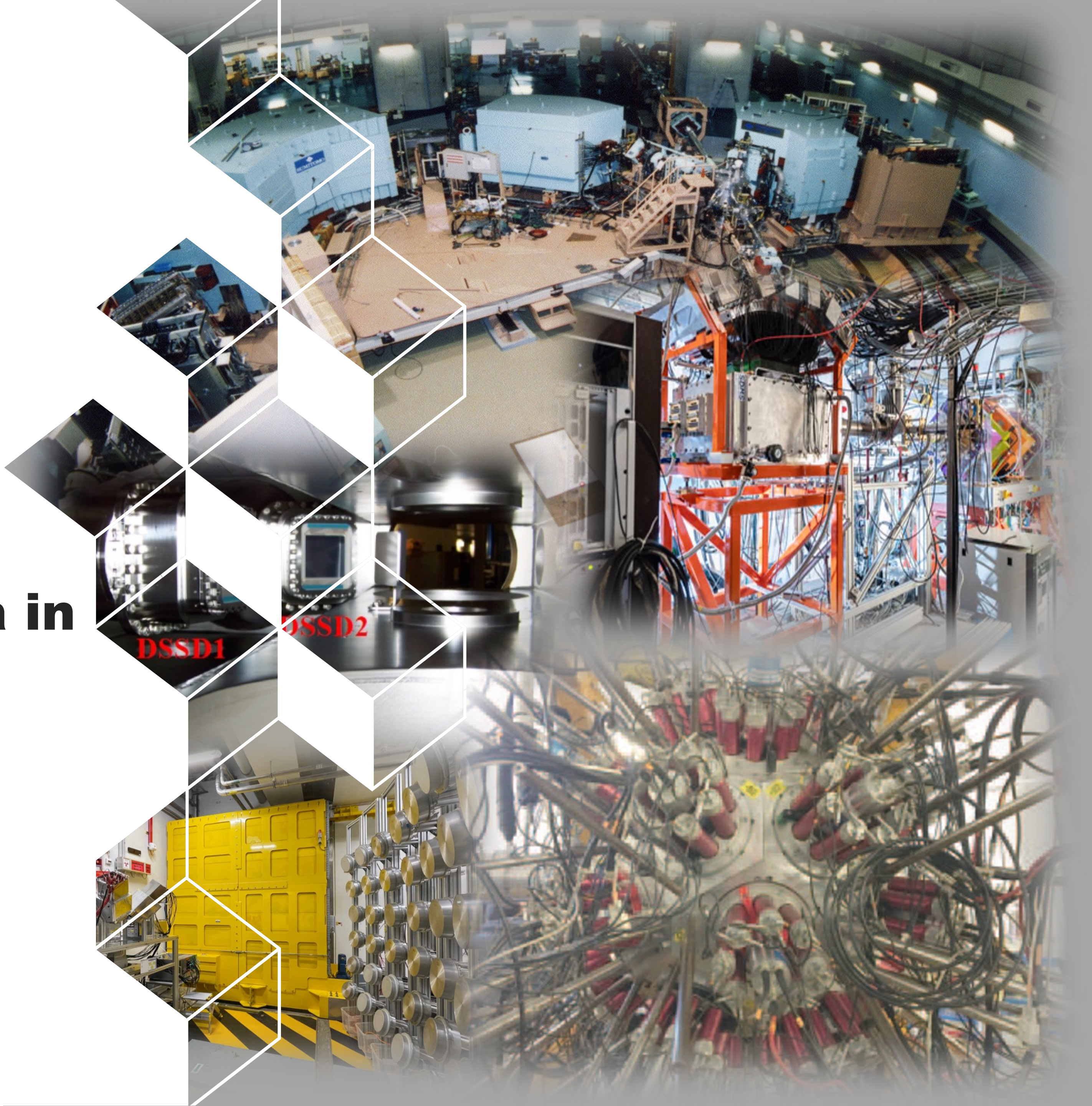
Probing Giant Resonances today: precision in stable nuclei and new phenomena in unstable ones



ESNT November 18 - 22 2024

Marine VANDEBROUCK

Outline

1. Precision in stable nuclei

Investigations of the Isoscalar Giant Monopole Resonance ((IS)GMR)

2. New phenomena in neutron-rich nuclei

Investigations of the Pygmy Dipole Resonance (PDR)

3. New phenomena in unstable nuclei

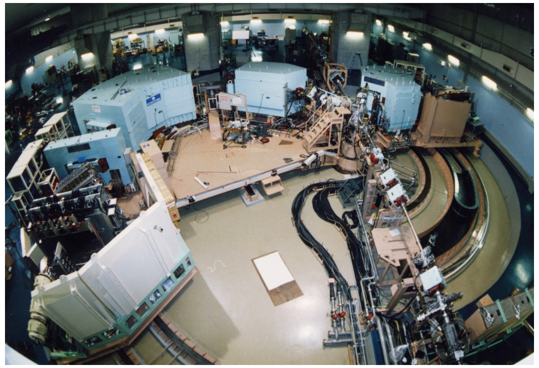
Investigations of monopole force in unstable nuclei

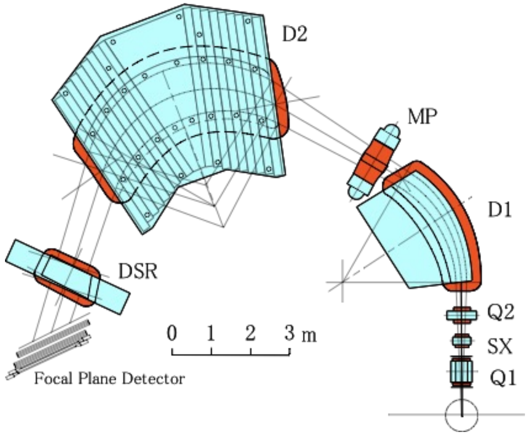
1. Precision in stable nuclei

Investigations of the Isoscalar Giant Monopole Resonance ((IS)GMR)

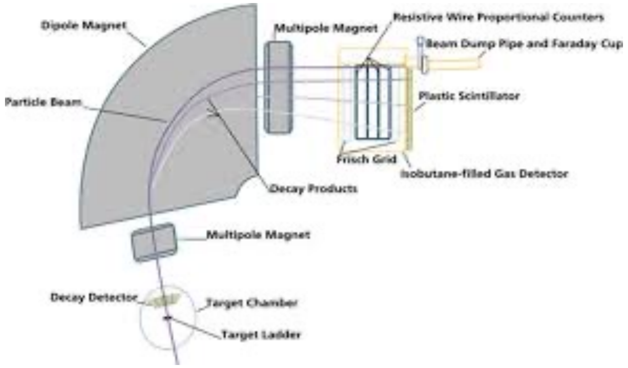
GMR measurement in stable nuclei

➢ **The state-of-the art method: (α,α’) at 35–100 MeV/nucleon**

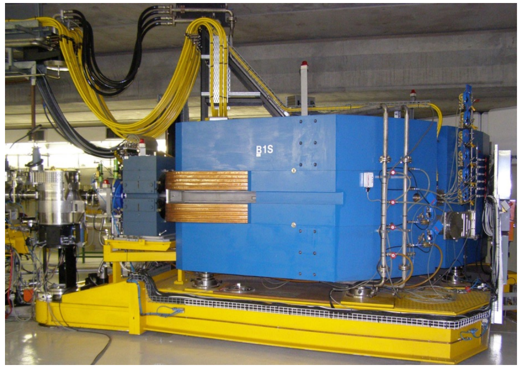


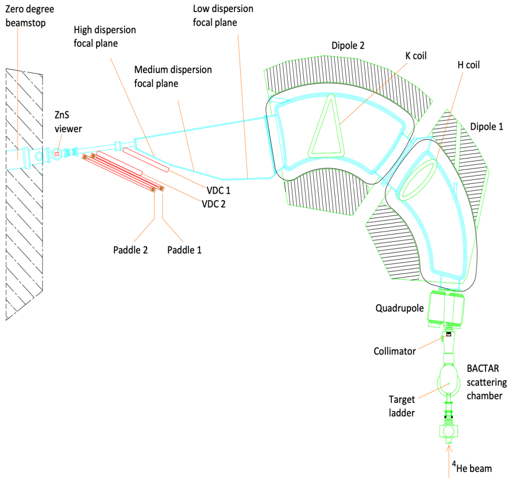


Spectrometer Grand Raiden @RCNP



M2M spectrometer @TAMU





K600 spectrometer @iThemba LABS

The background problem in excitation energy spectra

Origin of the background

➢ Physics origin
- Excitation of nuclear continuum
- Contributions from 3-body channels such as knock-out reactions
- …

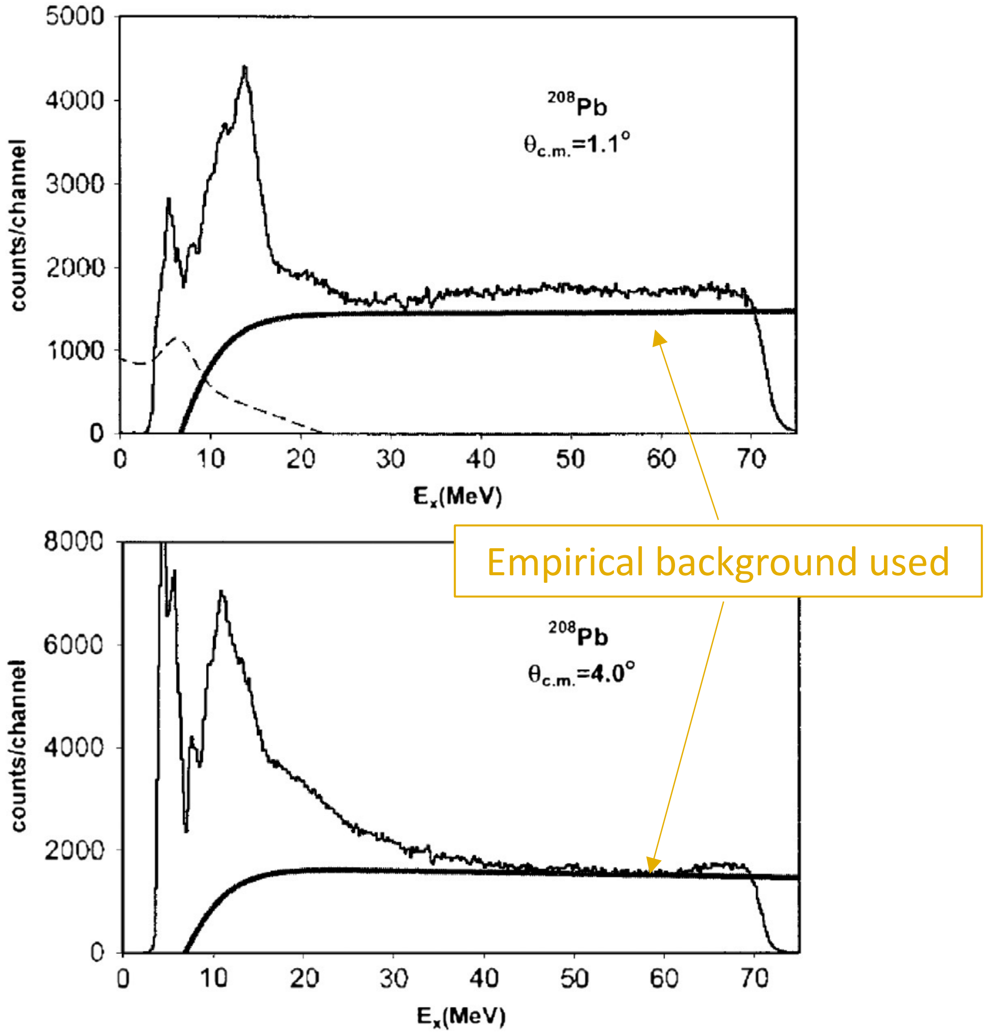
➢ Instrumental origin
- Scattering on some elements of the spectrograph
- Other possible origins that depend of the experimental setup

No direct way to estimate it
A bane of all giant resonances measurements

See discussion in the review paper
U. Garg, G. Colò, Prog. in Part. and Nucl. Phys. 101 (2018)

➢ How is this background usually dealt with ?
Background subtraction process with a background estimated "reasonably"

^{208}Pb(α,α') at Texas A&M University (TAMU)



D. H. Youngblood *et al.* Phys. Rev. C 69 (2004)

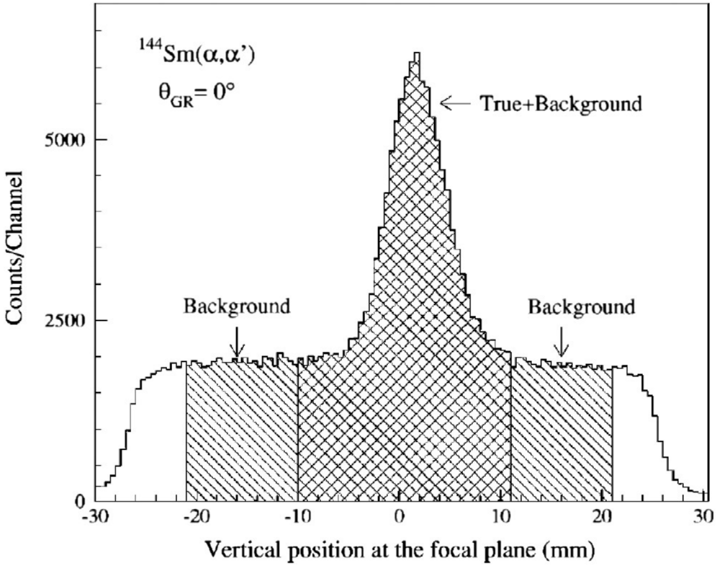
Experimental effort at Research Center for Nuclear Physics (RCNP), Osaka University

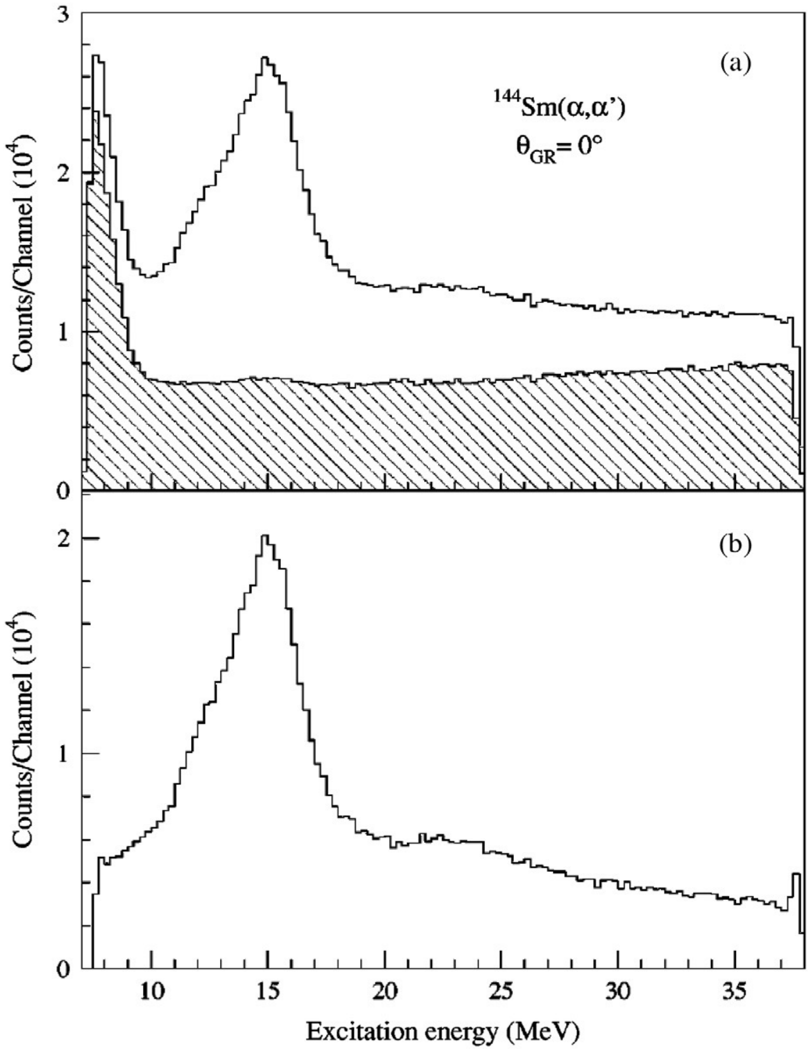
Goal: remove the instrumental background

➢ The ion optics of high resolution spectrometer Grand Raiden

- Particles scattered from the target position (i.e. our good events from (α,α') reaction) are focused vertically at the focal plane
- Background events from scattering on some elements of the spectrograph show a flat distribution vertically at the focal plane

Excitation energy spectra from RCNP experiment are almost free of all instrumental background



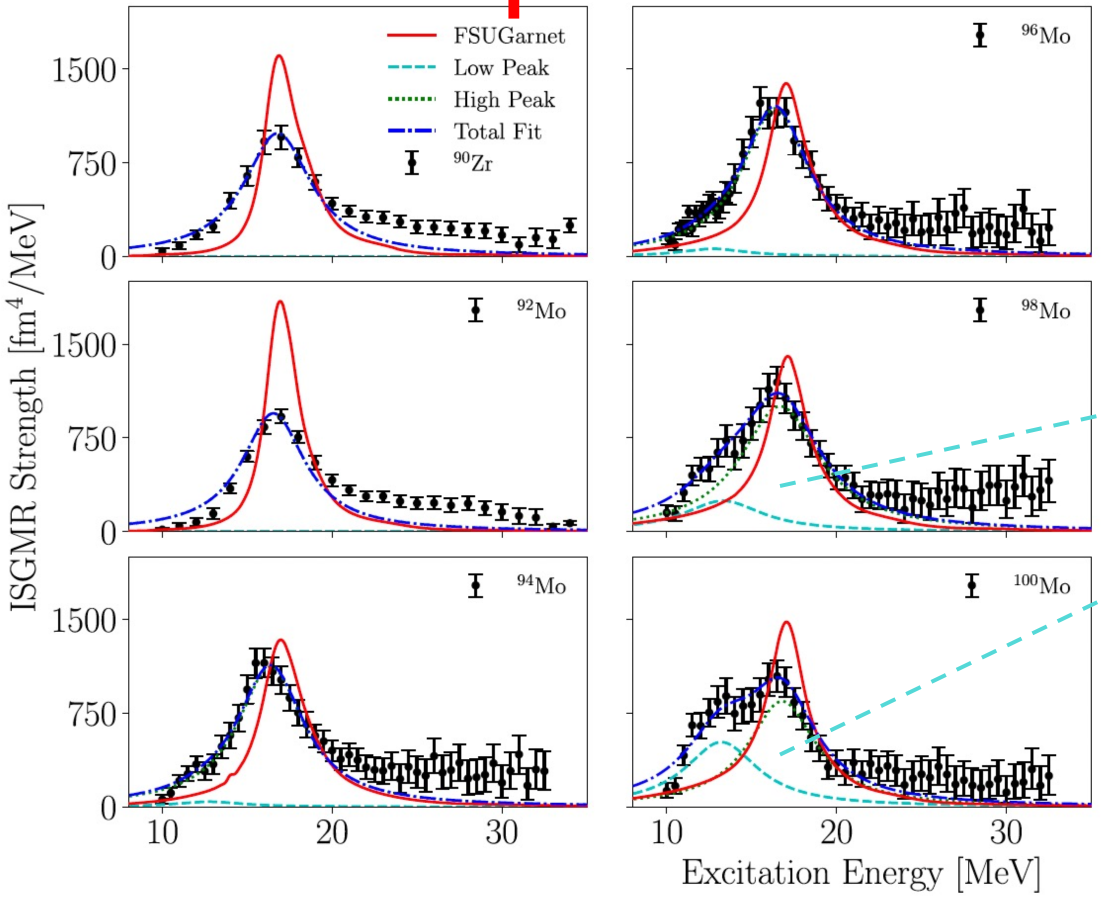


M. Itoh *et al.* Phys. Rev. C 68 (2003)

Recent results in Mo (Z = 42) isotopes

- Extraction of the monopole strength in ^{94,96,98,100}Mo using (α,α') reaction at E_α = 386 MeV

From previous measurement @RCNP
Y. K. Gupta *et al.* Phys. Lett. B 760 (2016)

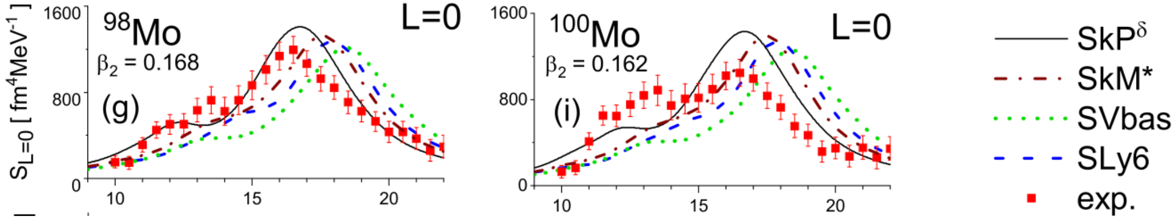


K. B. Howard *et al.* Phys. Lett. B 807 (2020)

Theoretical prediction
RPA calculations using relativistic FSUGarnet interaction (covariant energy density functional).

Effect of deformation
Coupling between the K = 0 component of the ISGQR and the main ISGMR. Not taken into account in calculations.

More advanced theoretical prediction
QRPA calculations using different Skyrme interactions taking into account pairing and axial deformations



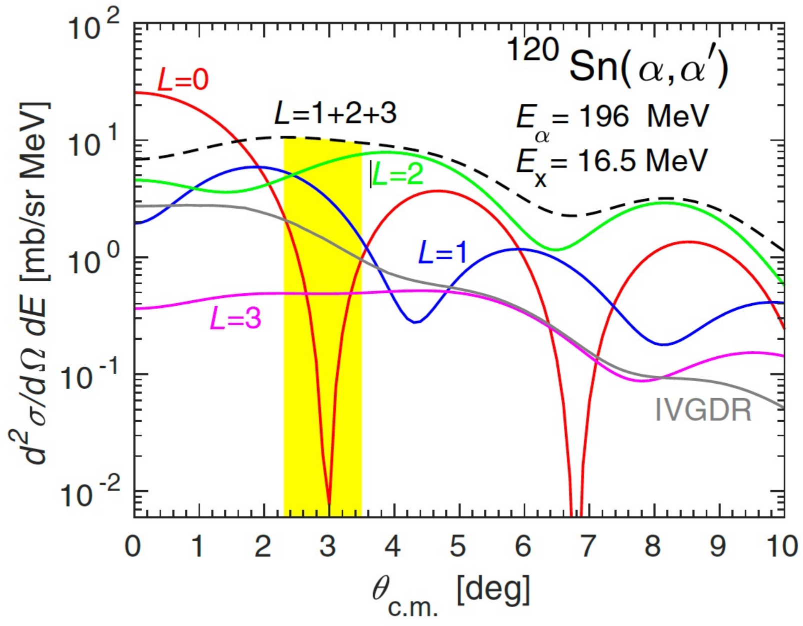
G. Colò *et al.* Phys. Lett. B 811 (2020)

New analysis approach at RCNP and iThemba Laboratory for Accelerated Based Sciences (iThemba LABS)

Goal: optimize the background subtraction analysis

➢ Extraction of the monopole strength deduced from the difference-of-spectra (DoS) technique

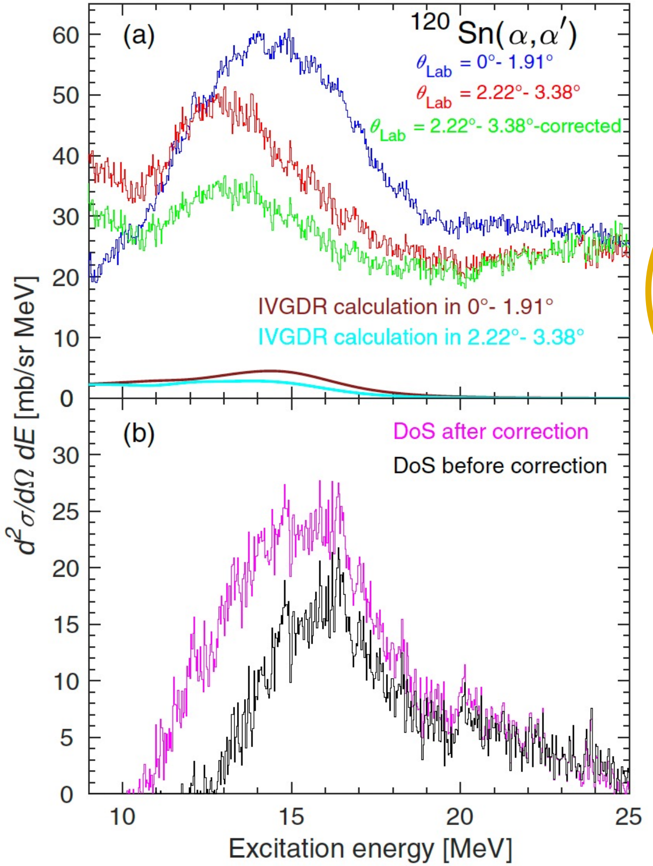
Assumption: sum of all multipolarity contributions L > 0 is essentially the same around 0° as at the first minimum of the L = 0 angular distribution



A. Bahini *et al.* Phys. Rev. C 107 (2023)

➢ Comments on the DoS technique

- Not new ! (S. Brandenburg et al. Phys. Lett. B 130 (1983))
- Need a prior subtraction of the contribution of Coulomb excitation of the IVGDR (experimental photonuclear cross sections + DWBA calculations)
- Need a correction factor to take into account the excitation-energy-dependence of the DoS (at least at iThemba)



A. Bahini *et al.* Phys. Rev. C 107 (2023)

⚠ Rely on the availability of information on the strengths of the L > 0 multipoles from previous measurements on the same nucleus ⚠

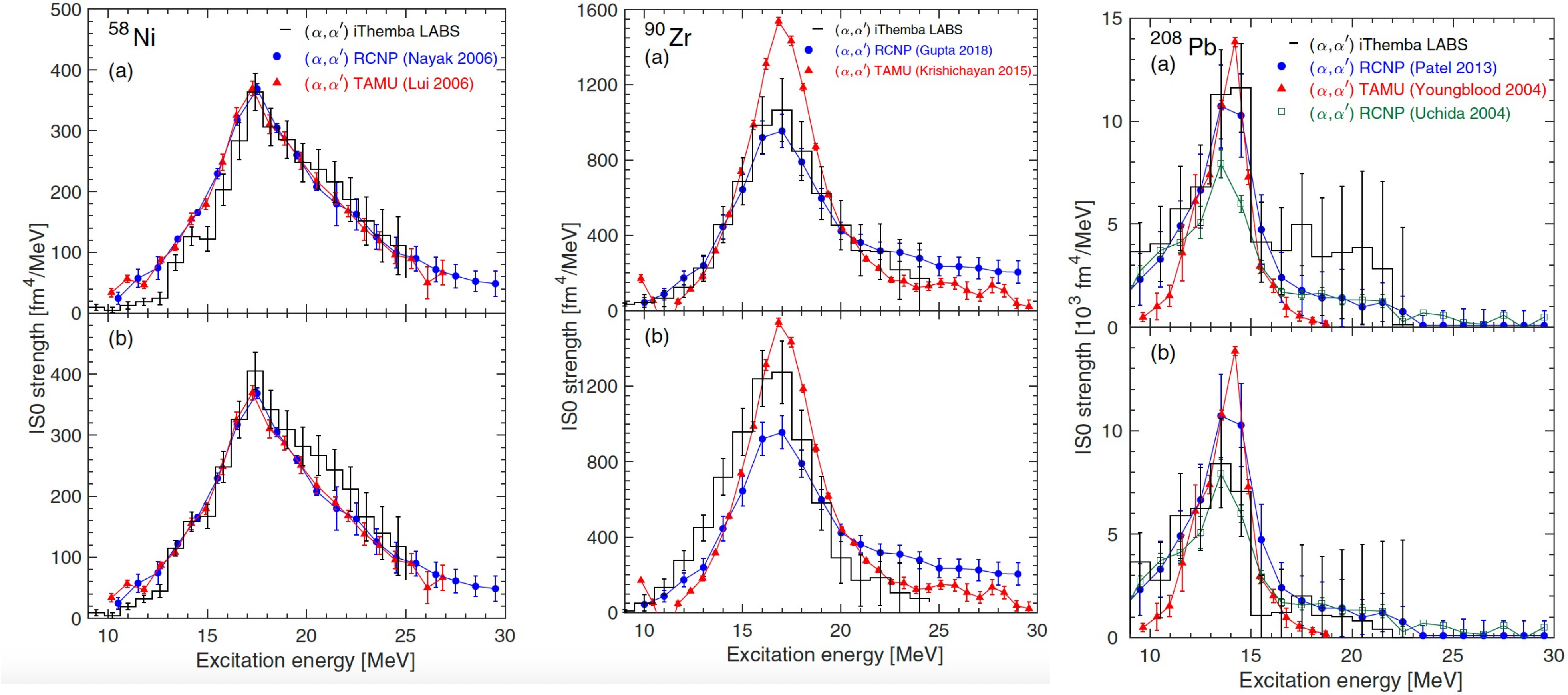
Recent results from iThemba LABS

➢ **Extraction of the monopole strength in ^{58}Ni, ^{90}Zr, ^{120}Sn and ^{208}Pb using (α,α') reaction at E_α = 196 MeV**

- Compatible results from the 3 experiments for ^{58}Ni
- Effect of the excitation-energy-dependent corrections on DoS not negligible for ^{90}Zr and ^{208}Pb

Using RCNP data for excitation-energy-dependence correction

Using TAMU data for excitation-energy-dependence correction



A. Bahini *et al.* Phys. Rev. C 107 (2023)

2. New phenomena in neutron-rich nuclei

Investigations of the Pygmy Dipole Resonance (PDR)

The Pygmy Dipole Resonance (PDR)

Pygmy Dipole Resonance (PDR)

PDR
(Pygmy Dipole Resonance)

- oscillation of a neutron skin against a symmetric proton/neutron core
- additionnal E1 strength at lower energy

GDR
(Giant Dipole Resonance)

- oscillation of neutrons against protons
- exhausts ~ 100% E1 strength

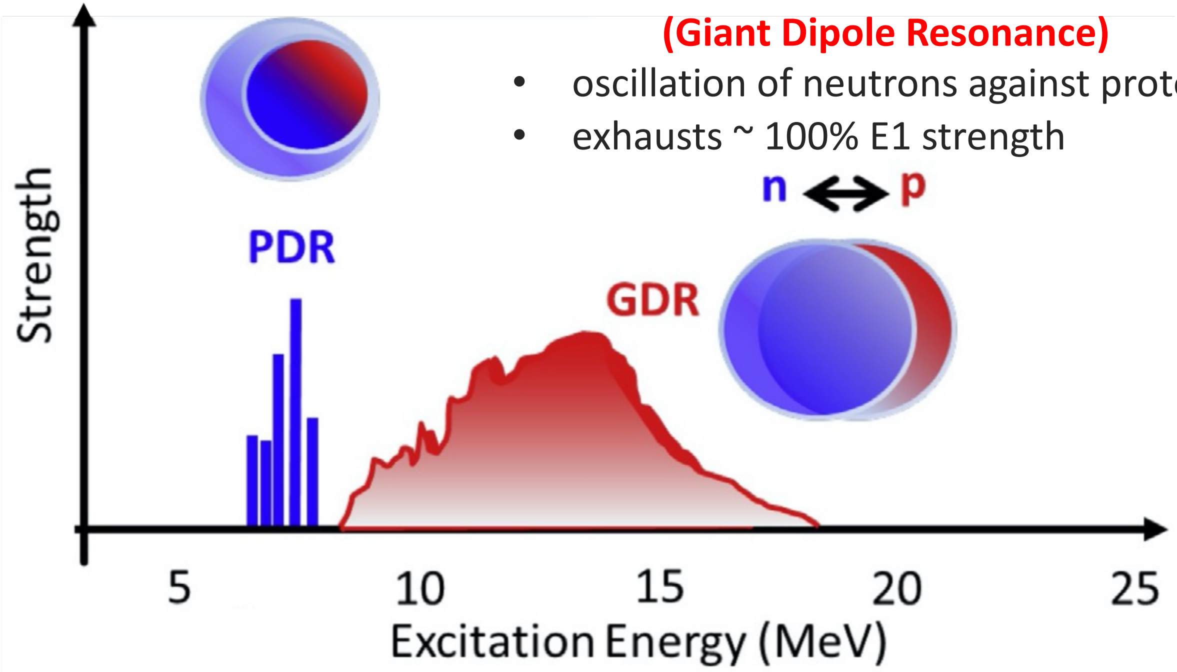


Figure extracted from A. Bracco *et al.* Prog. Part. Nucl. Phys. 106 (2019)

- ➢ Nuclear structure: study of the nature of dipole strength

- ➢ Astrophysical interest: PDR plays important role

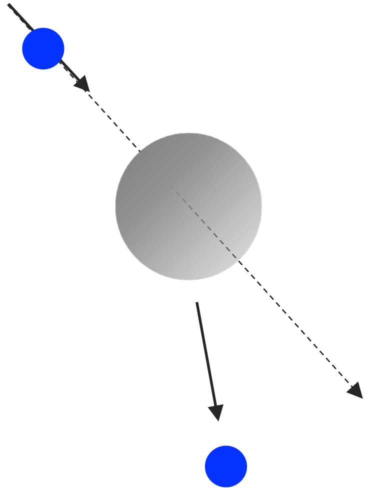
- as a constraint of the Equation of State
- for the nucleosynthesis r process

The isospin splitting of the PDR

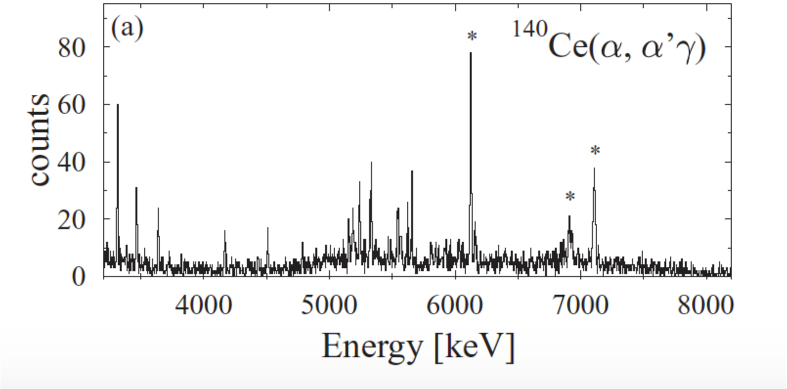
What is the nature of a nuclear excitation ?

In other words :
How protons and neutrons contribute to
the excitation strength ?

Tool
scattering reaction



Observables
Excitation energy, E_γ and cross section



D. Savran *et al.* Phys. Lett. B 786 (2018)

Interpretation
Comparison to microscopic calculations

ρ
Transition density

$$M_{\mathrm{p(n)}} = \int \rho_{fi}^{\mathrm{p}(n)}(\mathrm{r})\,\mathrm{r}^{L+2}\,\mathrm{dr}$$

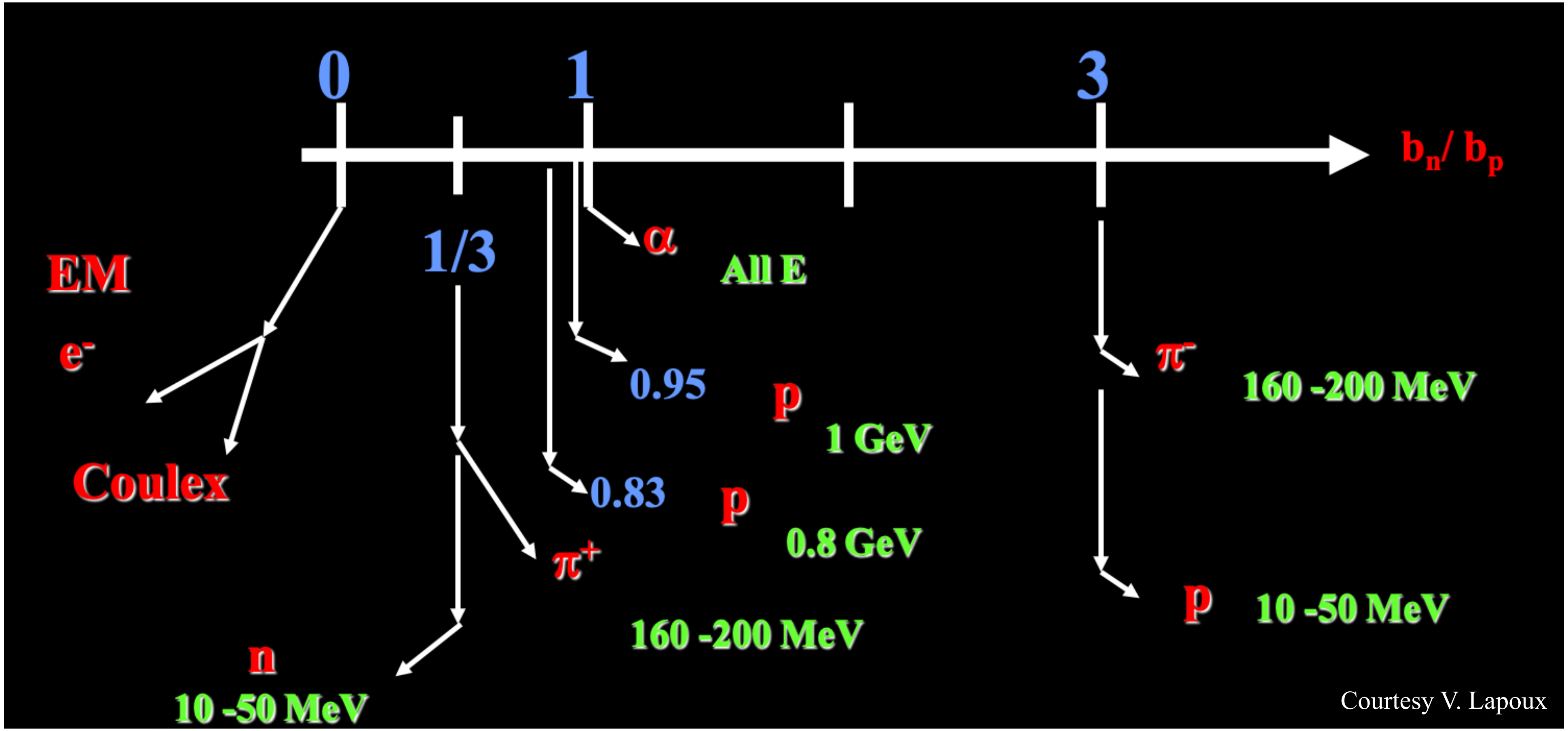
M
Multipole moment

L
Multipolarity of the transition

Complementarity of the scattering experiments

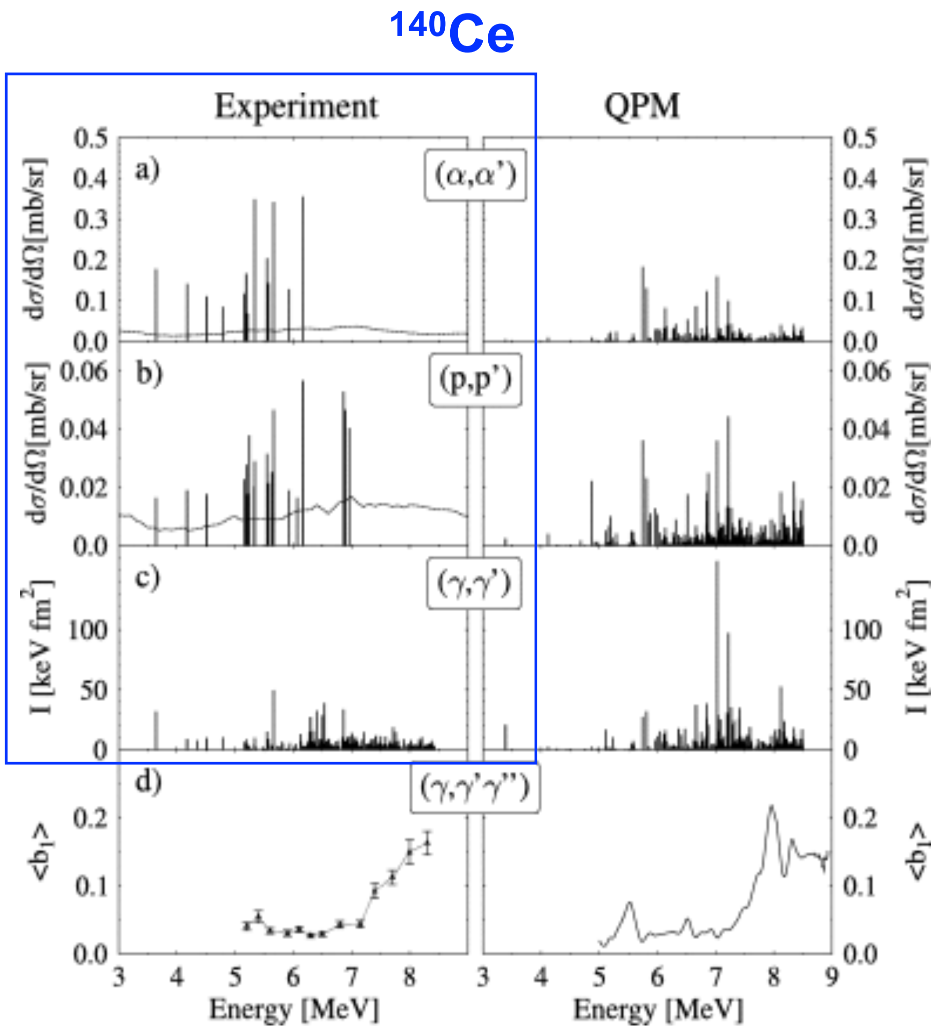
During a scattering experiment, a linear combination of M_n and M_p is probed : $M = b_n M_n + b_p M_p$

$b_{n,p}$ are the interaction strengths between the external field and n,p of the nucleus



A. Berstein *et al.* Phys. Lett. B 103, 255 (1981)
E. Khan, Phys. Rev. C 105, 014306 (2022)

Complex microscopic structure of the PDR



D. Savran *et al.* Phys. Lett. B 786 (2018)

Isoscalar probes ➡ 4-6 MeV

Proton probe ➡ selected states

Electromagnetic probe ➡ 4-8 MeV

If several models are able to reproduce E1 strength at lower energy than the GDR, they do not agree on the fine structure

New probes are necessary to resolve the complexity of the isospin character of the PDR

Study of the PDR using (n,n’) reaction SPIRAL2/NFS

Spokespersons: M. V. (CEA Saclay) and I. Matea (IJCLab).

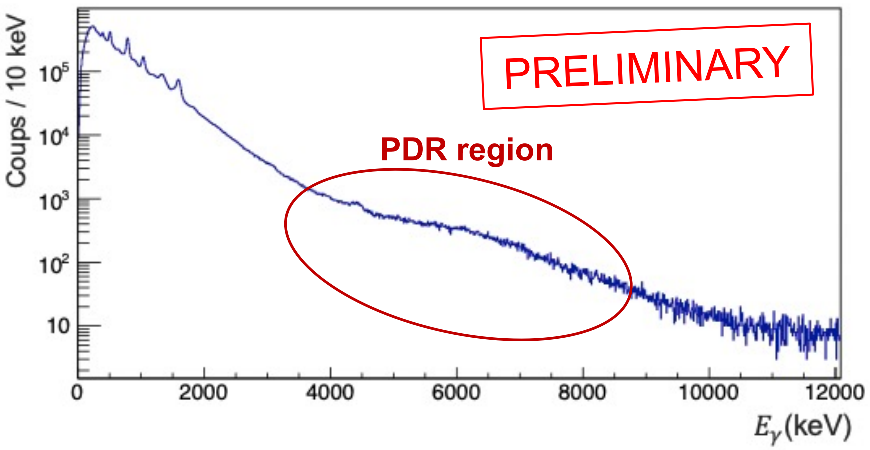
➢ Motivation

- First study of the PDR using (n,n’) reaction
- Why is it interesting ?

(n,n’) is an elementary probe:

- which does not require Coulomb correction
- complementary to (p,p’) and to other reactions

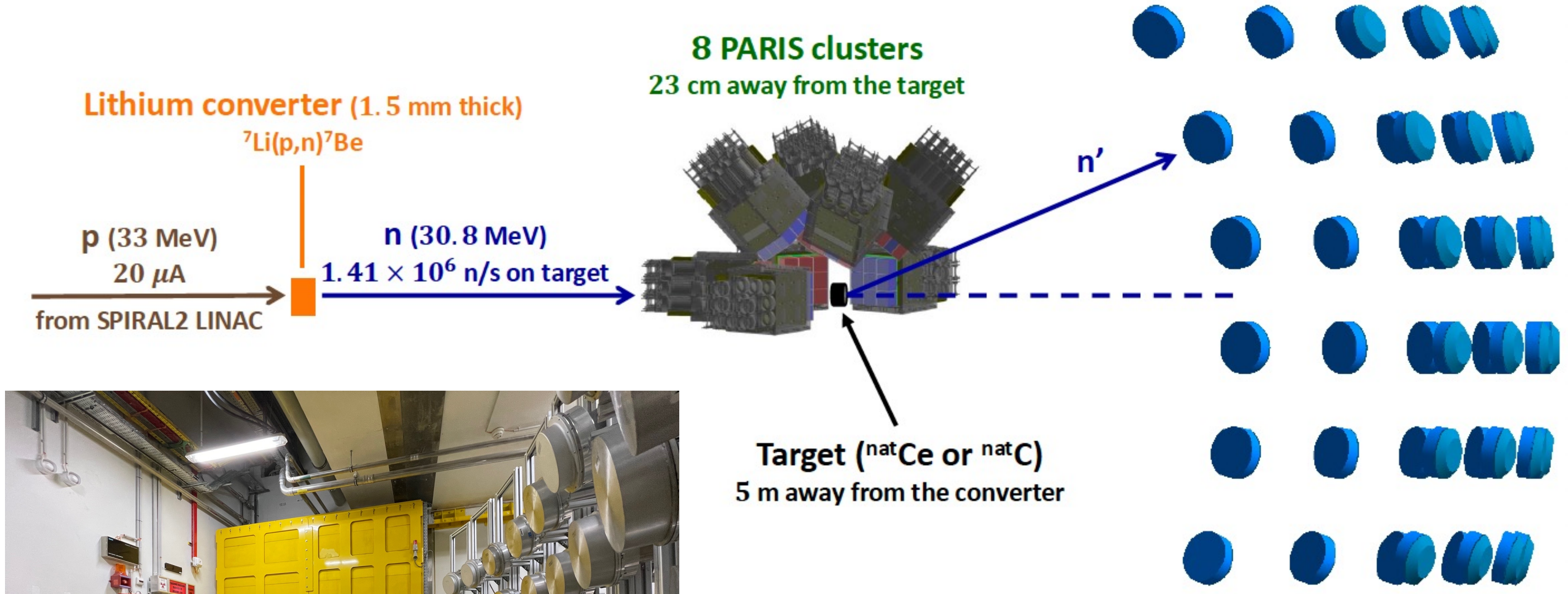
➢ Promising preliminary results

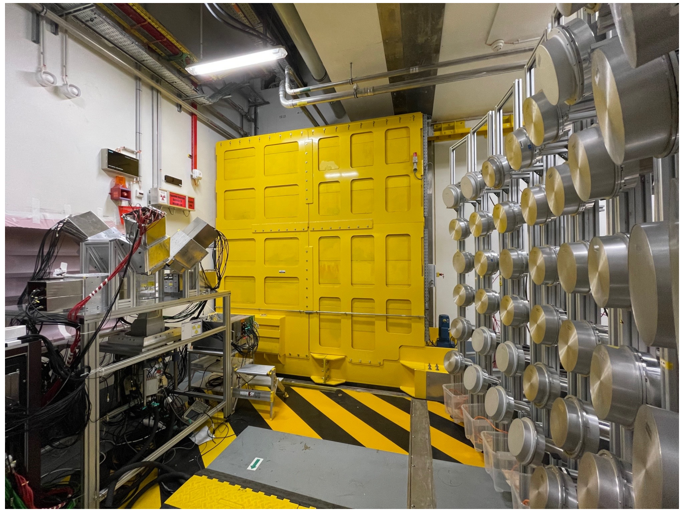


Experiment in September 2022

$^{140}Ce(n,n')^{140}Ce^*(\gamma)^{140}Ce$ @NFS

48 MONSTER modules
3 m away from the target





Ongoing analysis by Périne Miriot-Jaubert
(PhD student CEA Saclay Irfu/DPhN)

Study of the PDR using (p,p’) reaction at CCB

Spokespersons: O. Wieland (INFN, Milano) and M. Kmiecik (IFJ PAN, Krakow)c

➢ Motivation

- Study the predicted dependence of the PDR on N/Z ratio
- Nickel isotopic chain : large variety of N/Z ratio experimentally accessible

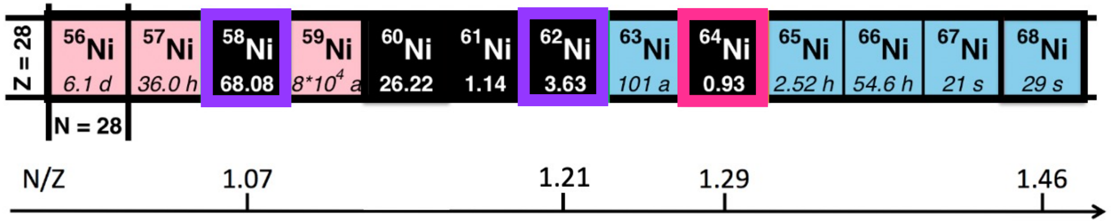
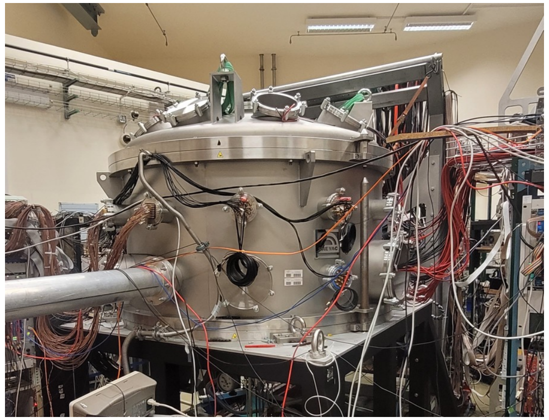
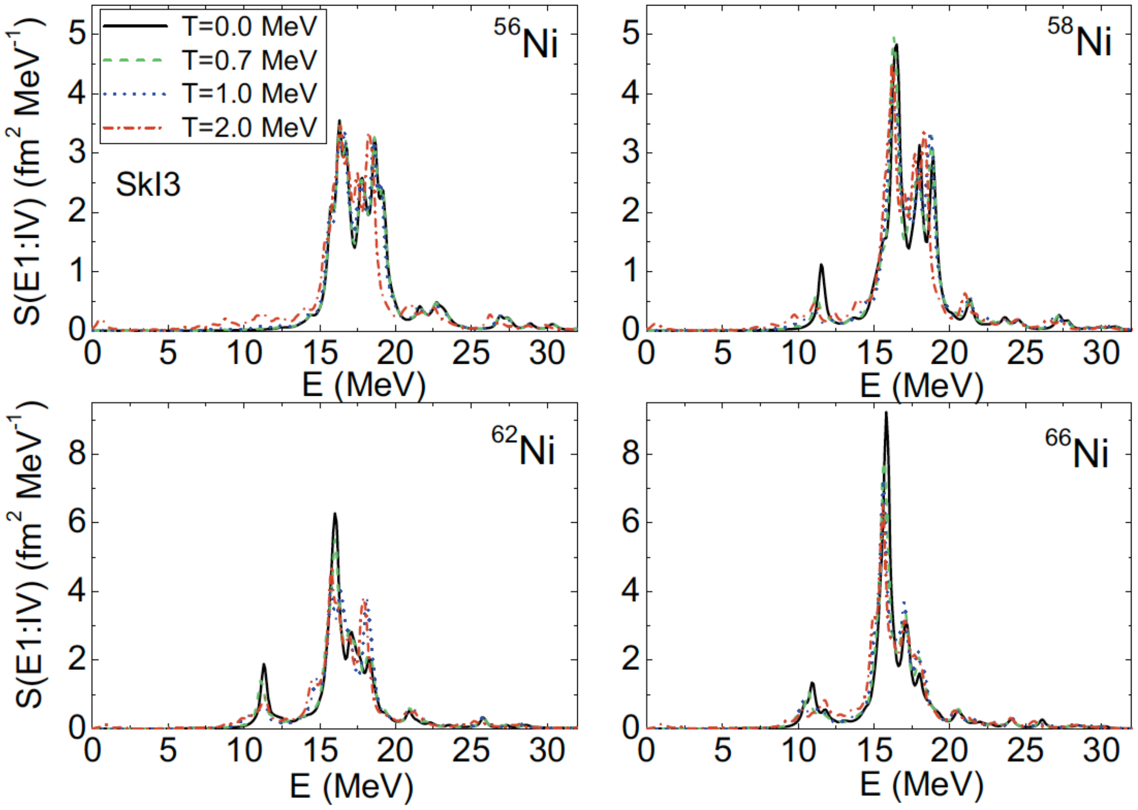


Figure extracted from the proposal of the experiment (2022)



Study at CCB (Krakow) using (p,p’) reaction at $E_p = 180$ MeV



E. Yüksel et al. EPJA 55, 230 (2019)

➢ An experimental program launched in 2024

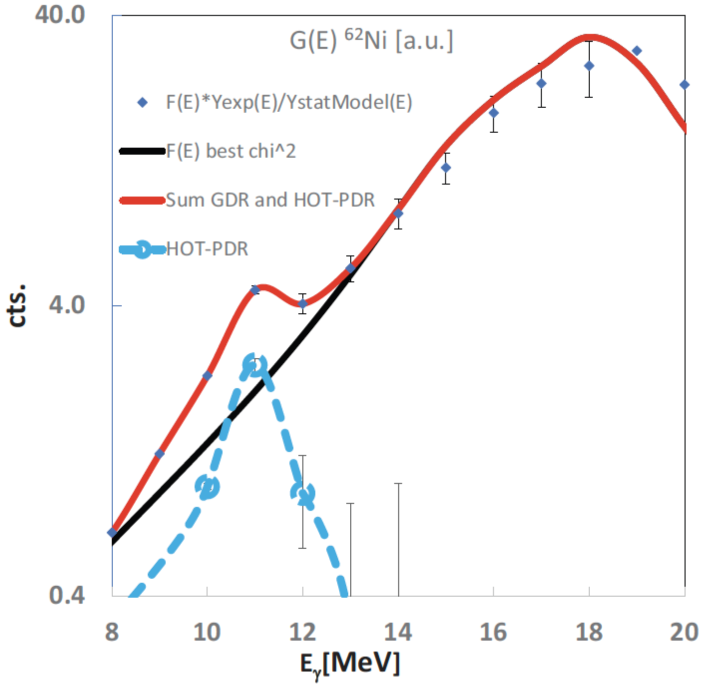
- Data taken for ^{58,62}Ni isotopes in March 2024 – ongoing analysis (A. Giaz, INFN Milano)
- Proposal to continue the study in ^{64}Ni : next year ?

PDR in hot nuclei

Experimental program to study the hot PDR in Ni isotopic chain at IFIN

➢ Motivation

- Does PDR survive in hot nuclei ?
- First measurement of the PDR at finite temperature



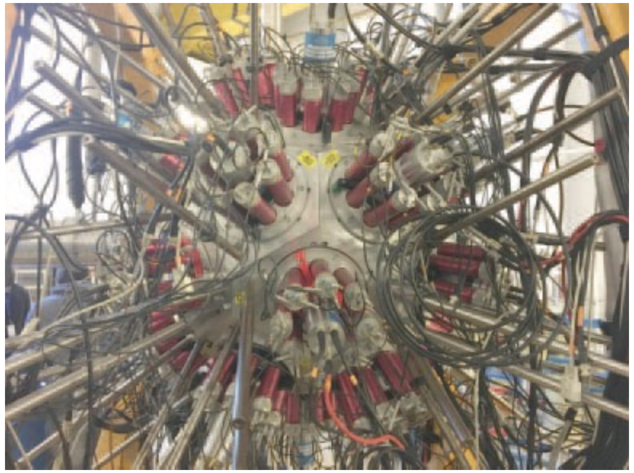
O. Wieland *et al.*, IL NUOVO CIMENTO 47 C, 24 (2024)

➢ Results

- No low-lying strength observed in ^{56}Ni as expected
- Extra yield below GDR at around 10 MeV for $^{60, 62}$Ni isotopes
- For ^{62}Ni, value of around 4% of the EWSR extracted
- GDR tail simulated with statistical model (Gemini++)

Experiment at IFIN (Romania) in 2022

Study in hot ^{56,60,62}Ni (<T_{PDR}> = 1.6 MeV)



The ELIGANT setup

In 2024: following experiment with **^{56,66}Ni** isotopes, ongoing analysis

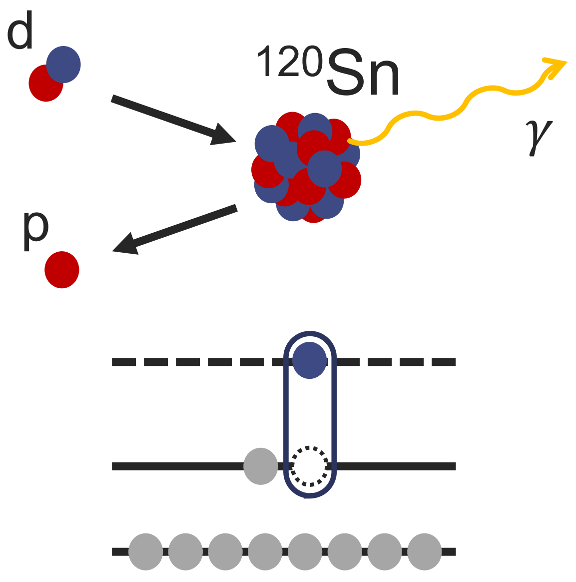
Collectivity of the PDR

Collective vs single-particle character of the PDR

➤ Probing the single-particle character of the PDR

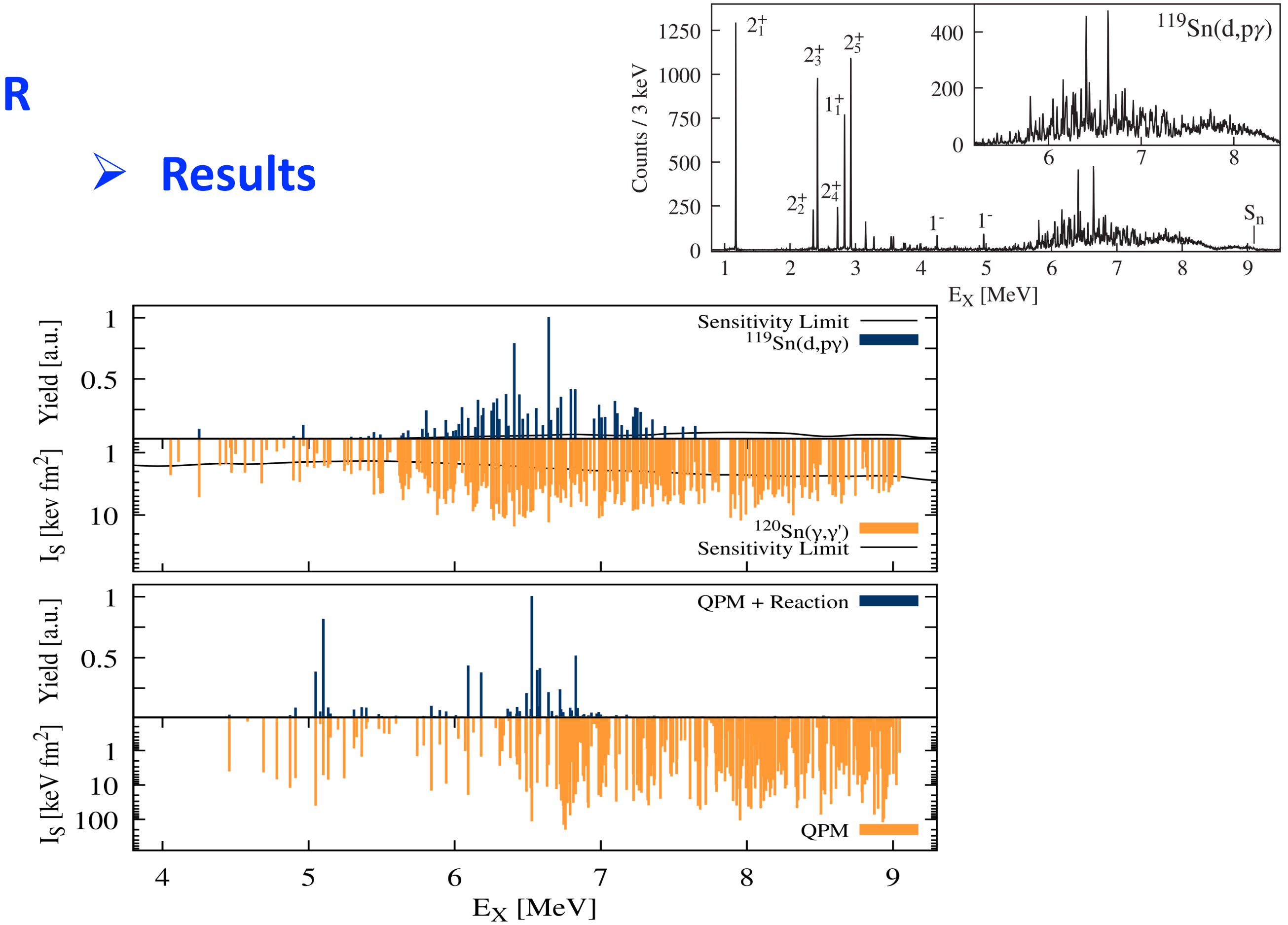
Method:

- Study of the PDR populated in neutron-transfer experiment using (d,p) reaction in ^{120}Sn at the University of Cologne



- Selective to specific 1p-1h content within PDR states

➤ Results



M. Weinert *et al.*, Phys. Rev. Lett. 127 (2021) 242501

- Strong population in lower PDR region
- Comparison calculations in the quasiparticle-phonon model (QPM) and QPM combined with reaction theory shows a qualitative agreement ➡ insights details of the microscopic structure

3. New phenomena in unstable nuclei

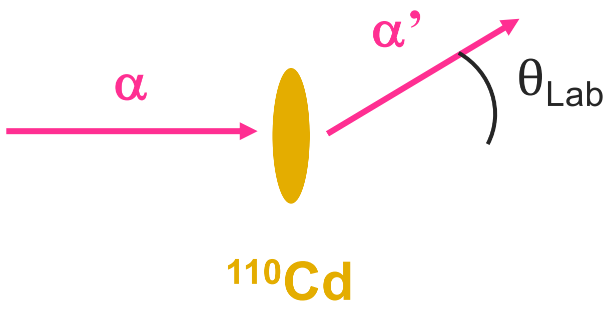
Investigations of monopole force in unstable nuclei

An experimental challenge

Method in stable nuclei

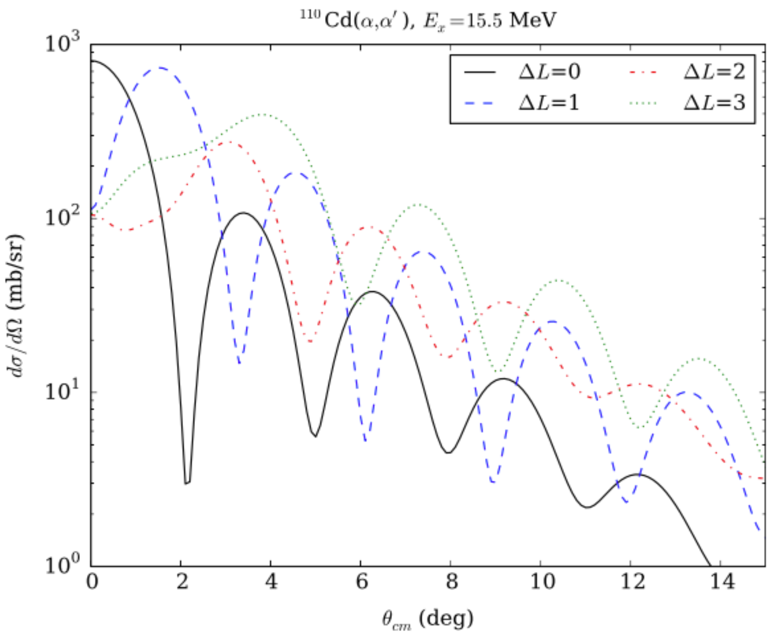
➢ **Which reaction ?**

Inelastic scattering of isoscalar particles, typically α, at 35–100 MeV/nucleon



➢ **Which analysis method ?**

Missing mass method. $E^*(^{110}Cd)$ is deduced from $E_{\alpha'}$ and θ_{Lab} using 2 body kinematics laws

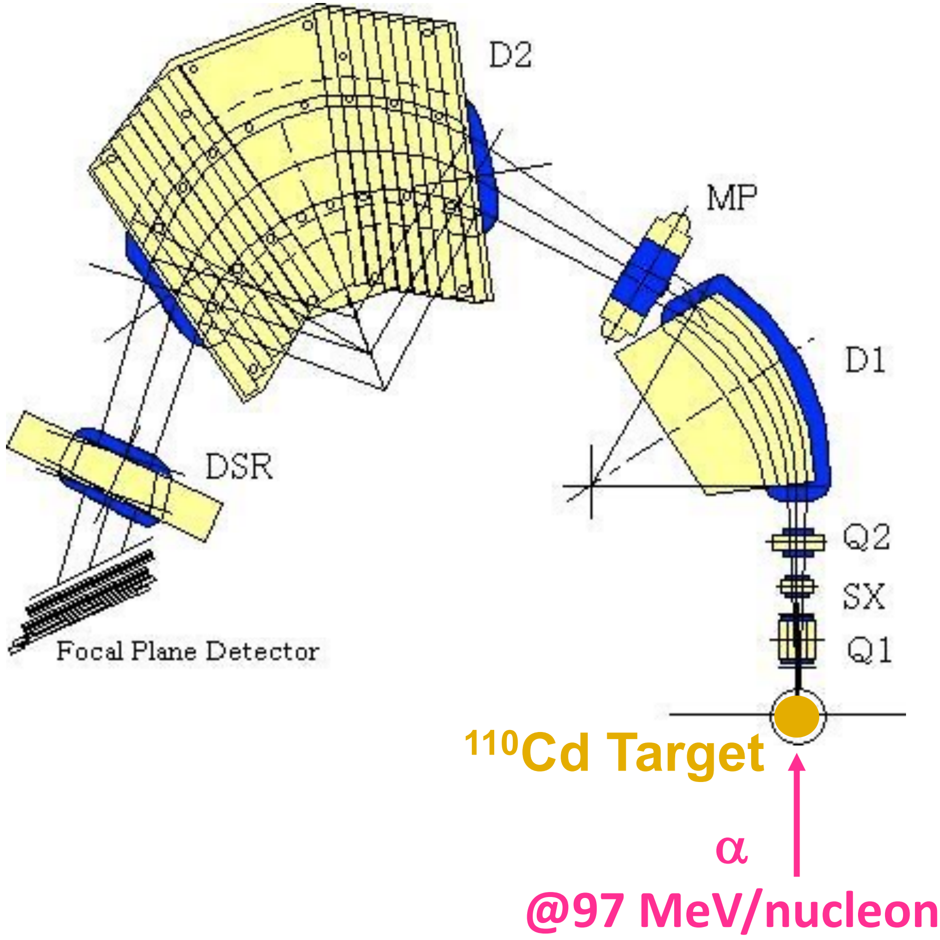


U. Garg and G. Colò, Part. And Nucl. Phys. 101 (2018)

➢ **How to identify the ISGMR, i.e. L = 0 strength ?**

Angular distribution at small angles in the center-of-mass

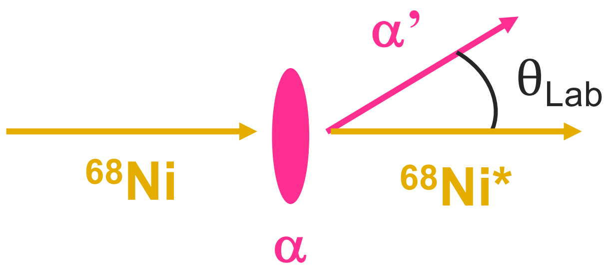
Magnetic spectrometer "Grand Raiden"
@RCNP, Osaka University



In unstable nuclei, what is the difficulty?

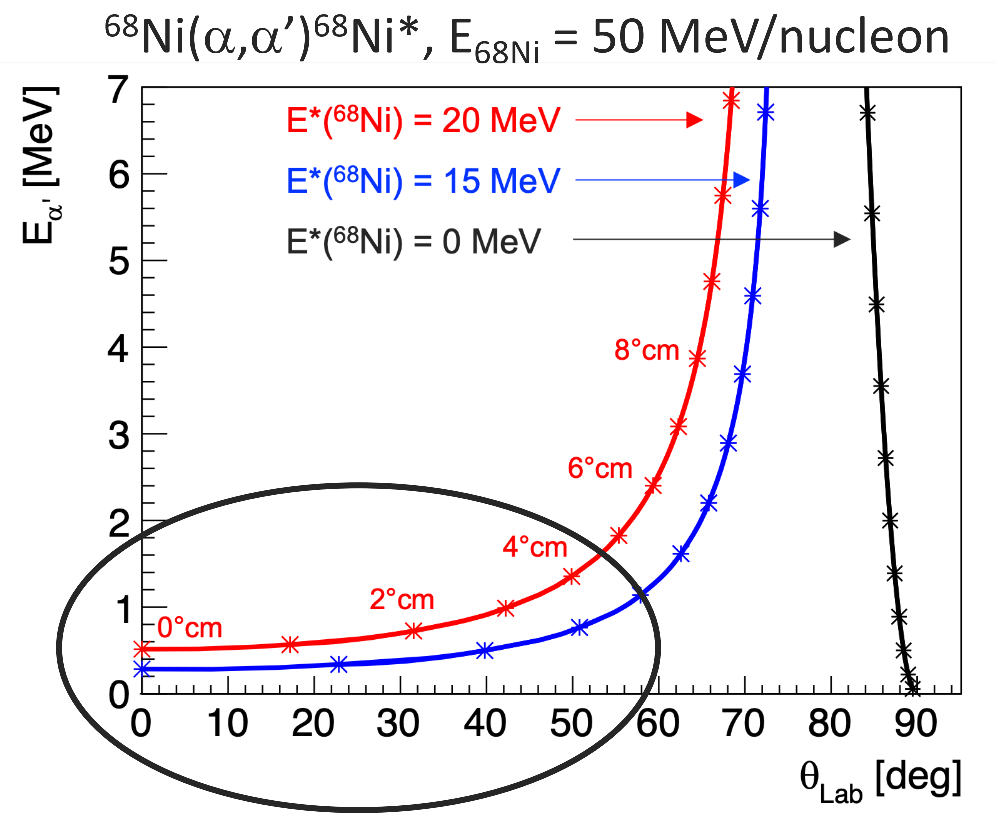
➢ Which reaction ?

Inelastic scattering of isoscalar particles, typically α, at 35–100 MeV/nucleon **but in inverse kinematics**



➢ Which analysis method ?

Missing mass method. $E^*(^{68}Ni)$ is deduced from $E_{\alpha'}$ and θ_{Lab} using 2 body kinematics laws



➢ How to identify the ISGMR, i.e. L = 0 strength ?

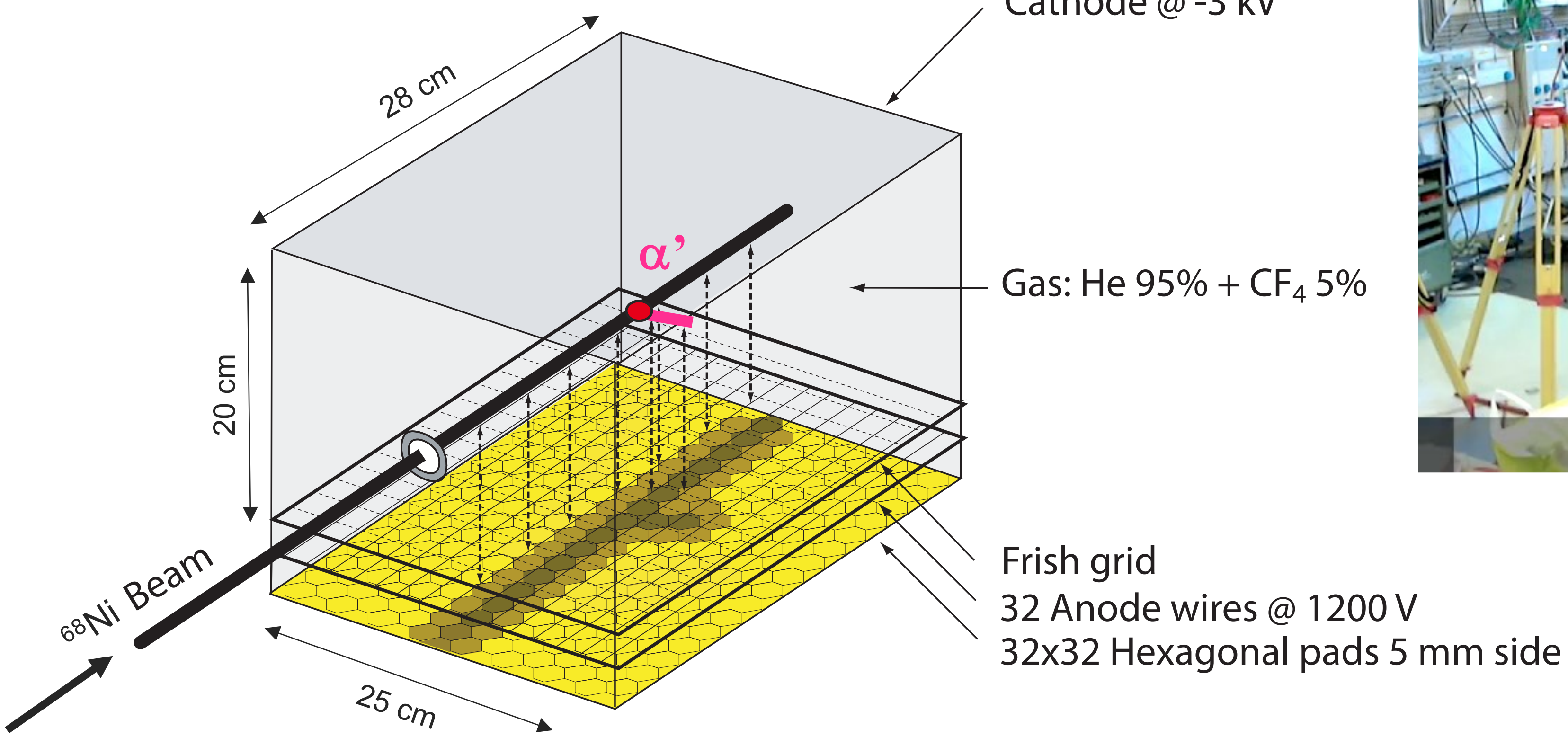
Angular distribution at small angles in the center-of-mass

➡ **Low detection energy threshold**

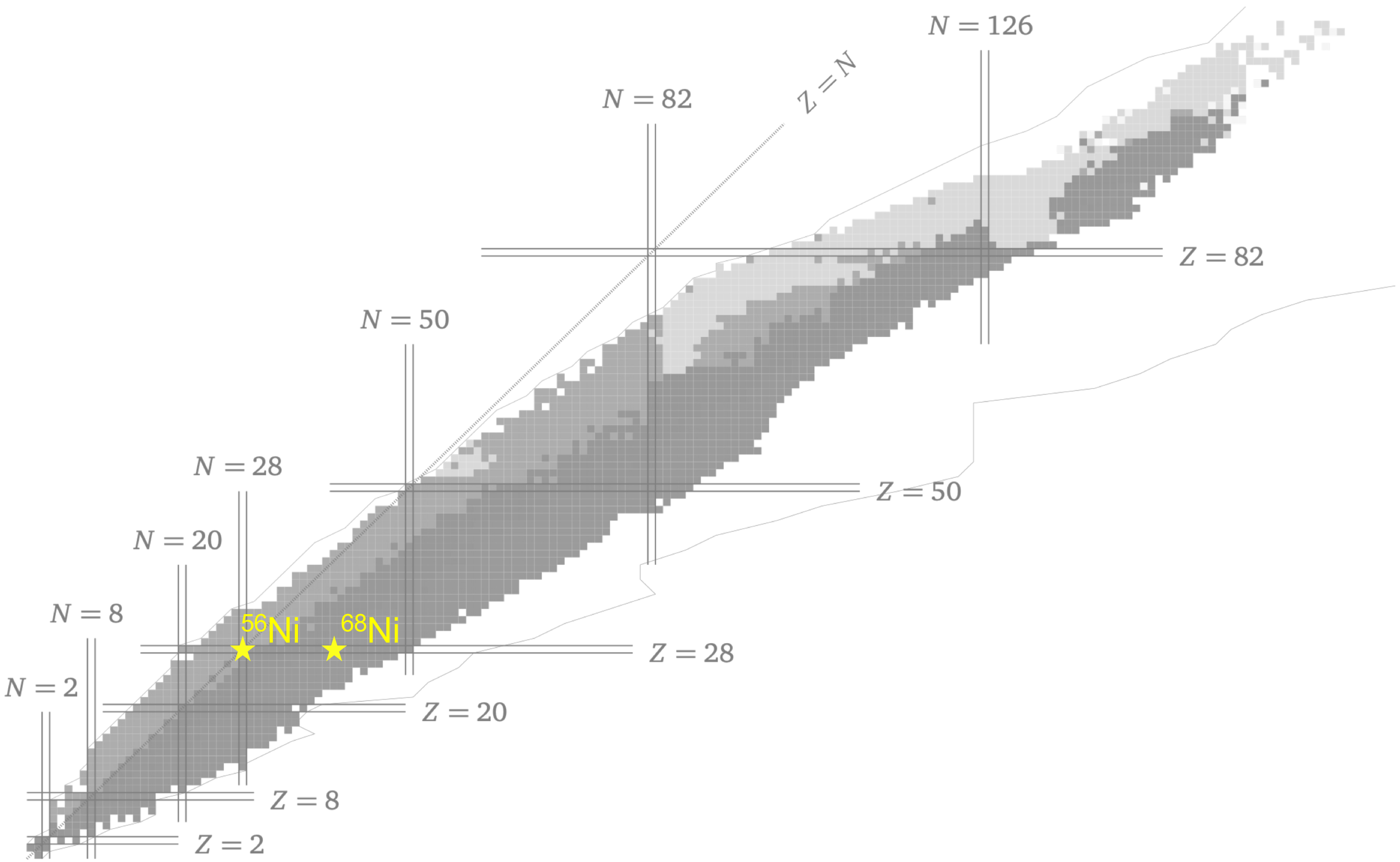
MAYA

Pioneering work with detector MAYA at GANIL

The active target MAYA at GANIL



GMR results in unstable nuclei using MAYA

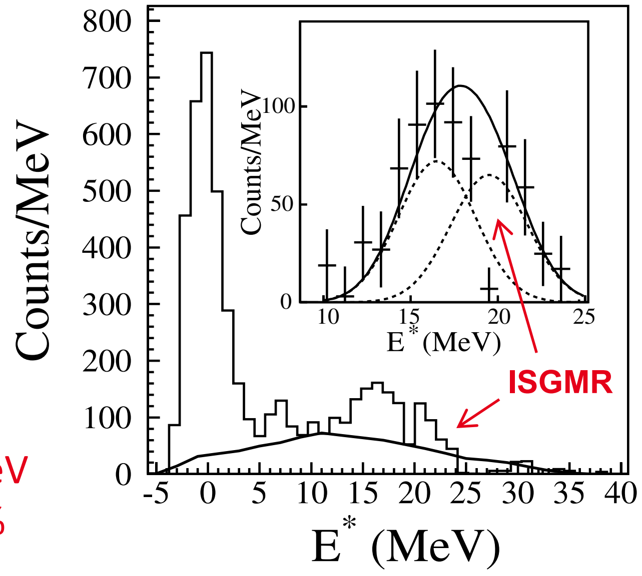


GMR results in unstable nuclei using MAYA

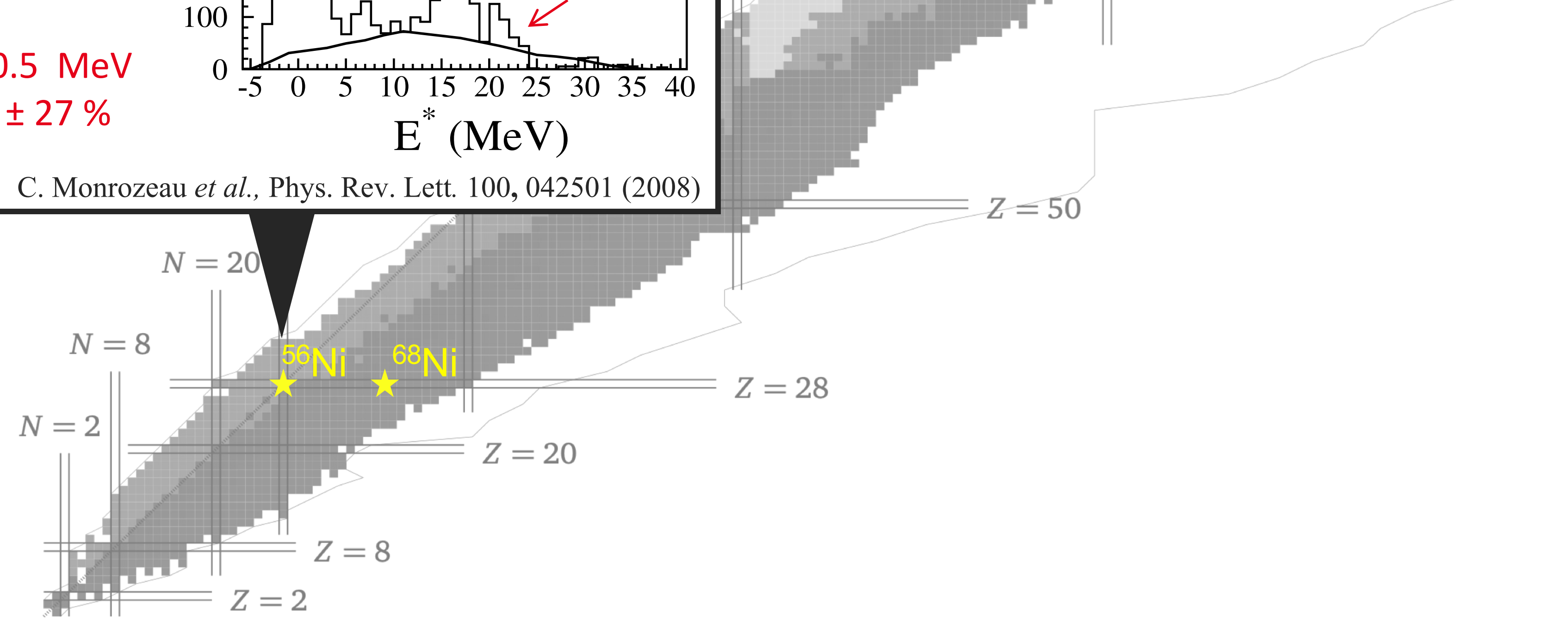
2005 ^{56}Ni

^{56}Ni + d → d' + ^{56}Ni*
50 MeV/nucleon
SPEG + MAYA @GANIL

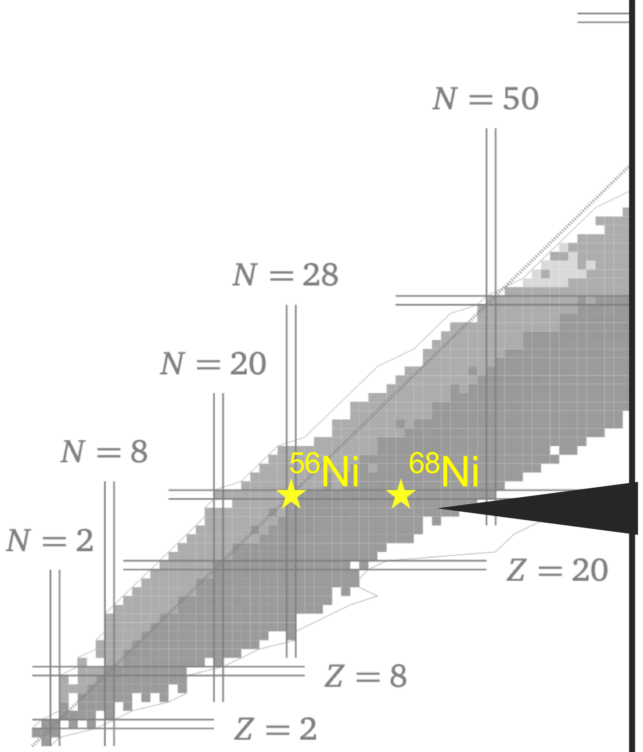
E*(^{56}Ni)$_{ISGMR}$ = 19.3 ± 0.5 MeV
EWSR(^{56}Ni)$_{ISGMR}$ = 136 ± 27 %



C. Monrozeau *et al.*, Phys. Rev. Lett. 100, 042501 (2008)



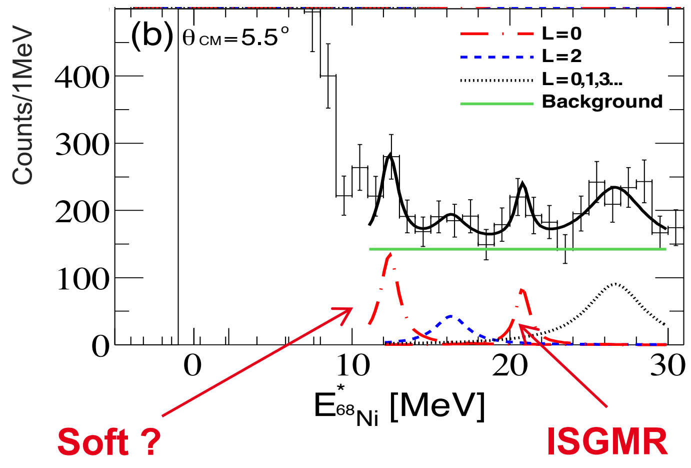
GMR results in unstable nuclei using MAYA

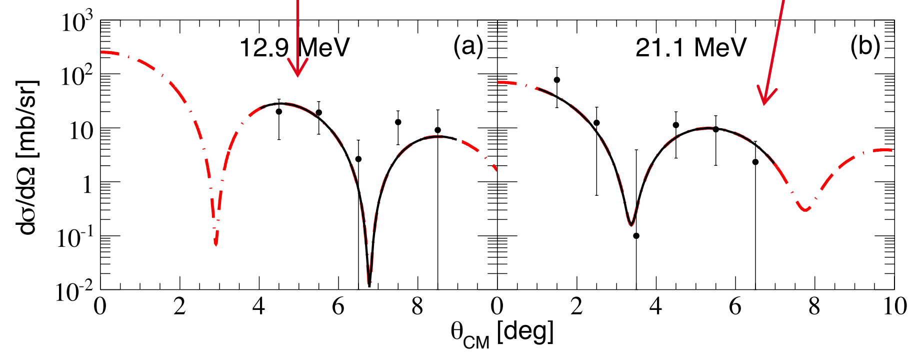


2010 | ^{68}Ni

^{68}Ni + d → d' + ^{68}Ni*
^{68}Ni + α → α' + ^{68}Ni*
50 MeV/nucleon LISE + MAYA @GANIL

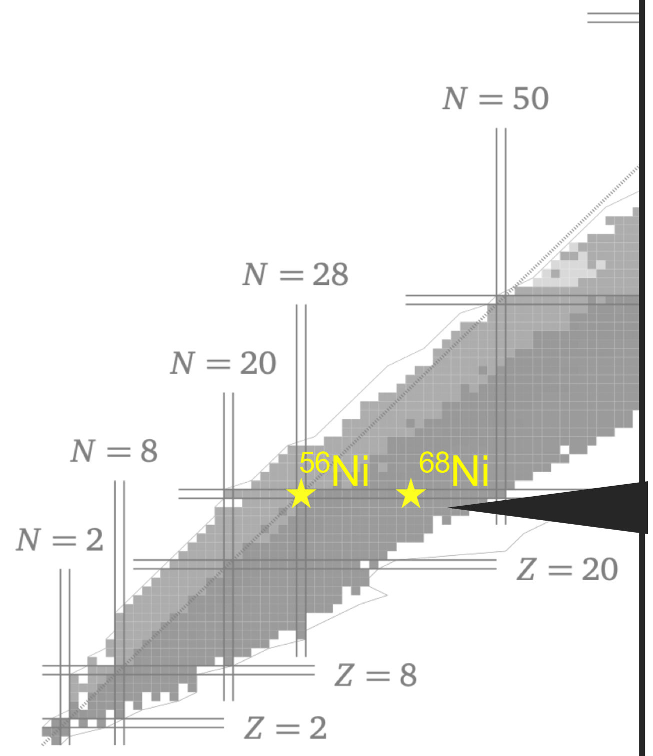
E*(^{68}Ni)$_{ISGMR}$ = 20.9 ± 1.0 MeV (d,d')
E*(^{68}Ni)$_{ISGMR}$ = 21.1 ± 1.9 MeV (α,α')
No extracted EWSR





M. Vandebrouck *et al.*, Phys. Rev. Lett. 113, 032504 (2014)
M. Vandebrouck *et al.*, Phys. Rev. C. 92, 024316 (2015)

GMR results in unstable nuclei using MAYA



2010

^{68}Ni

^{68}Ni + d → d' + ^{68}Ni*

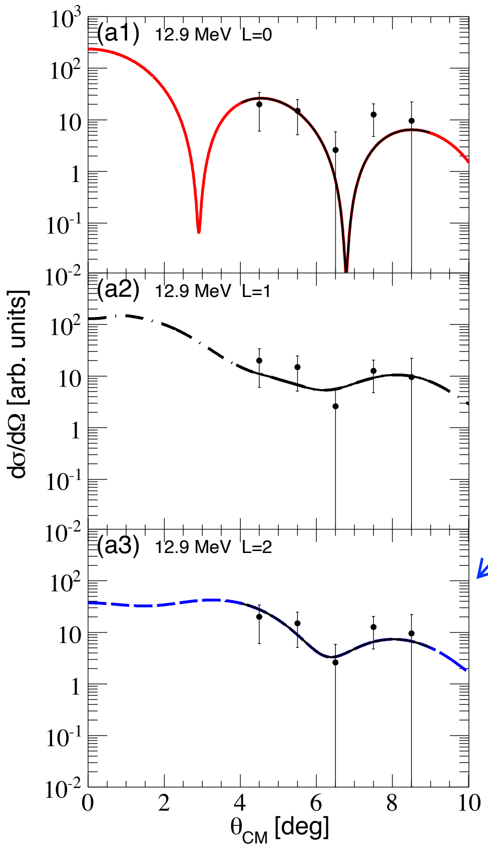
^{68}Ni + α → α' + ^{68}Ni*

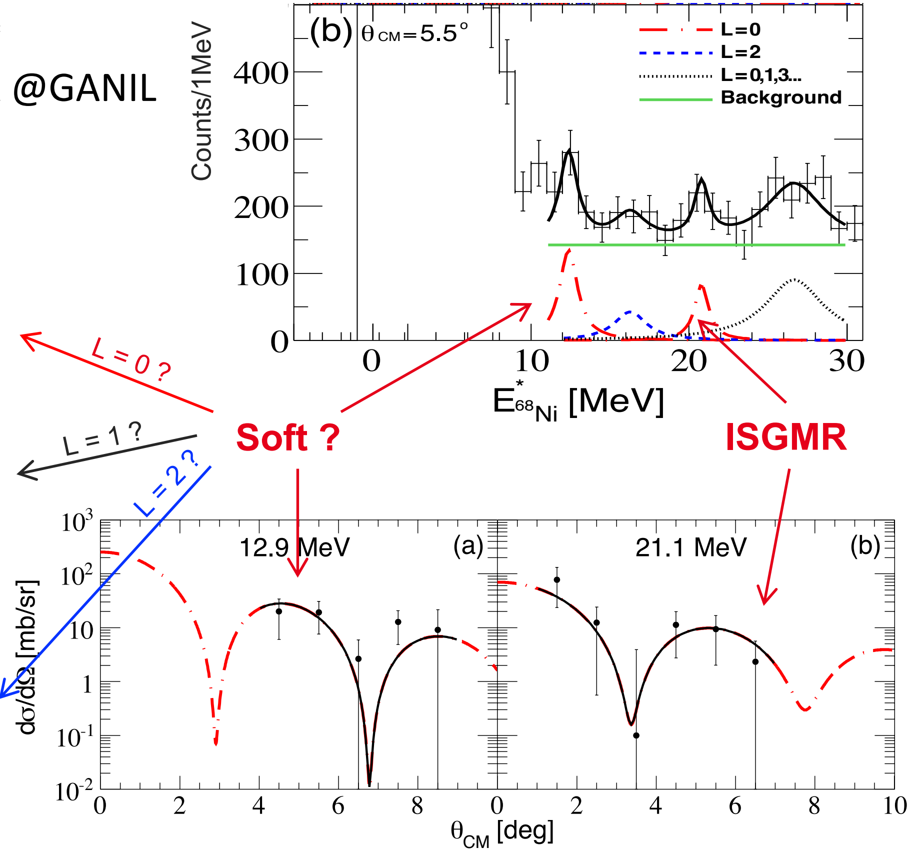
50 MeV/nucleon LISE + MAYA @GANIL

E*(^{68}Ni)$_{ISGMR}$ = 20.9 ± 1.0 MeV (d,d')

E*(^{68}Ni)$_{ISGMR}$ = 21.1 ± 1.9 MeV (α,α')

No extracted EWSR





M. Vandebrouck *et al.*, Phys. Rev. Lett. 113, 032504 (2014)

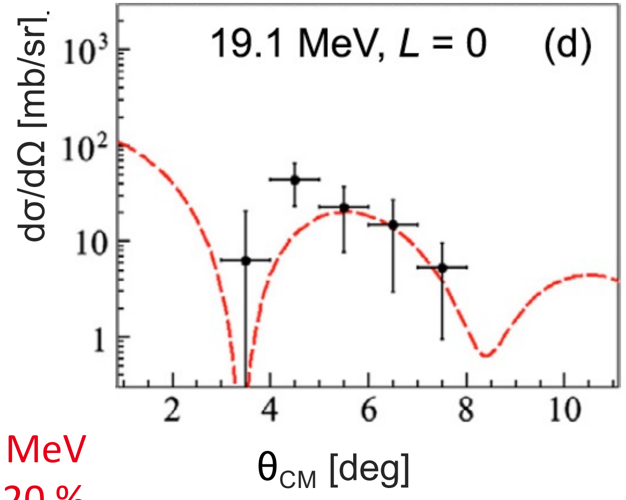
M. Vandebrouck *et al.*, Phys. Rev. C. 92, 024316 (2015)

GMR results in unstable nuclei using MAYA

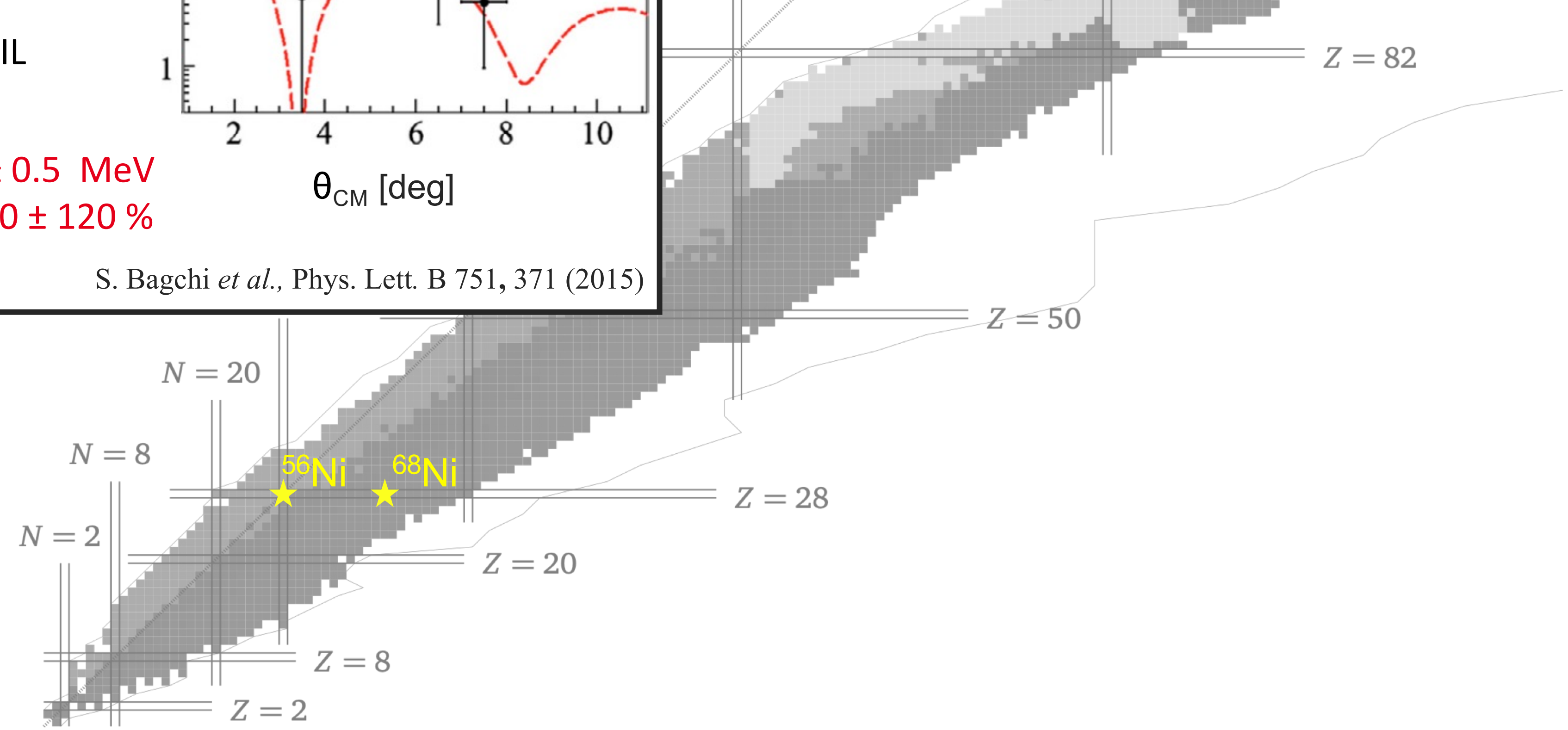
2011 ^{56}Ni

$^{56}Ni + \alpha \rightarrow \alpha' + ^{56}Ni^*$
50 MeV/nucleon
LISE + MAYA @GANIL

$E^*(^{56}Ni)_{ISGMR}$ = 19.1 ± 0.5 MeV
$EWSR(^{56}Ni)_{ISGMR}$ = 240 ± 120 %



S. Bagchi *et al.*, Phys. Lett. B 751, 371 (2015)

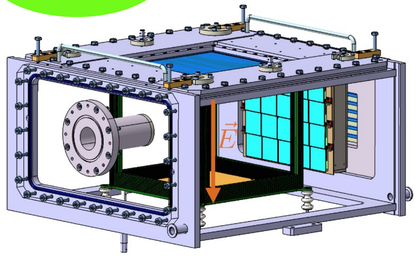


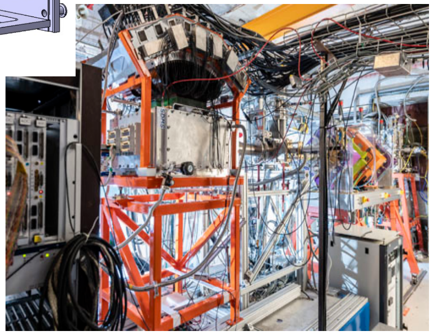
And now …

GMR results in unstable nuclei using active targets

- \+ Active targets are suited for ISGMR measurement in unstable nuclei
- \- Limitations of the MAYA detection setup (energy and angular resolutions for low-energy recoiling particles)
- ➡ Development of several active targets in the world (ACTAR at GANIL, AT-TPC in US, CAT active target in Japan…)
  Three recent experiments dedicated to the study of GMR in unstable nuclei (on going analysis)

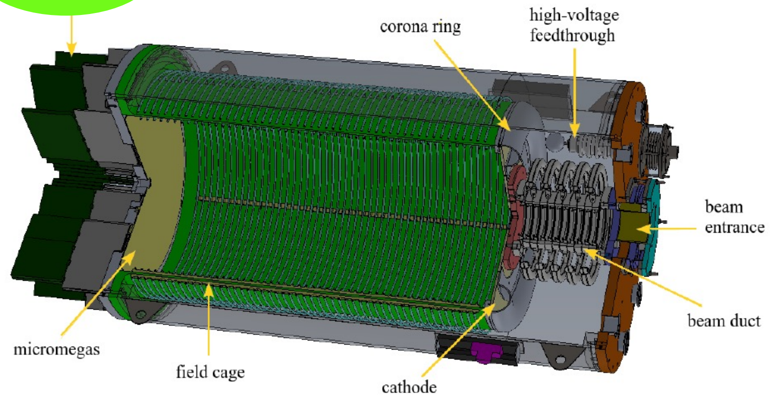
2019 $^{58,68}Ni + \alpha \rightarrow \alpha' + {}^{58,68}Ni^*$





Courtesy T. Roger

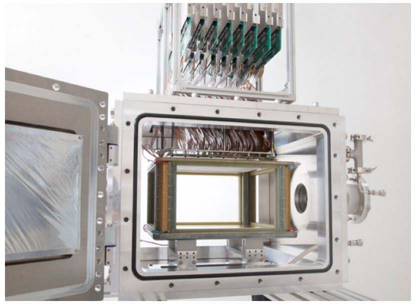
2020 $^{70}Ni + \alpha \rightarrow \alpha' + {}^{70}Ni^*$

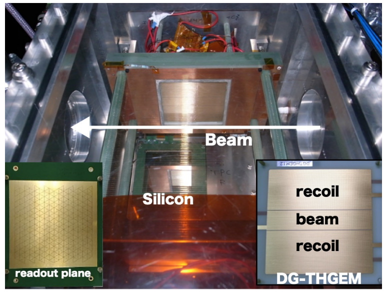


AT-TPC

See T. Ahn's talk @ECT* in 2022

2016 $^{132}Sn + d \rightarrow d' + {}^{132}Sn^*$





CAT

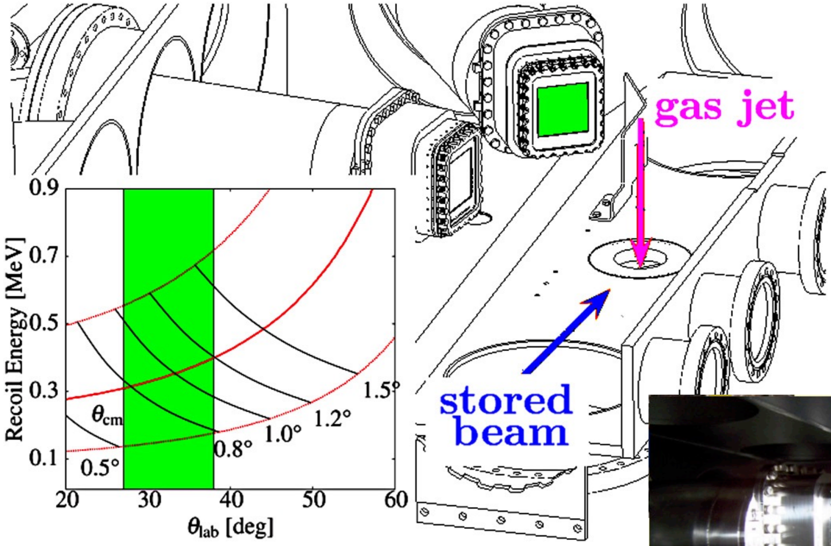
See S. Ota's talk @COMEX6

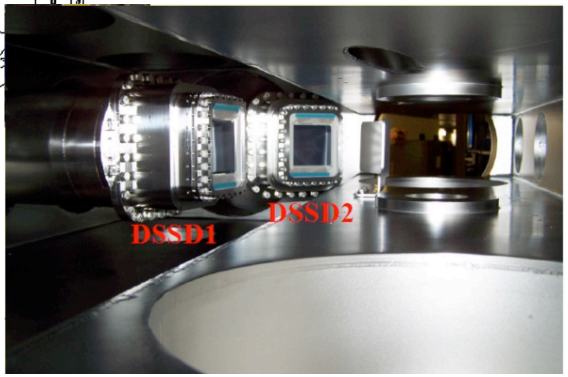
GMR results in unstable nuclei using storage rings

➢ Storage ring, an alternative to active target

The experimental method:

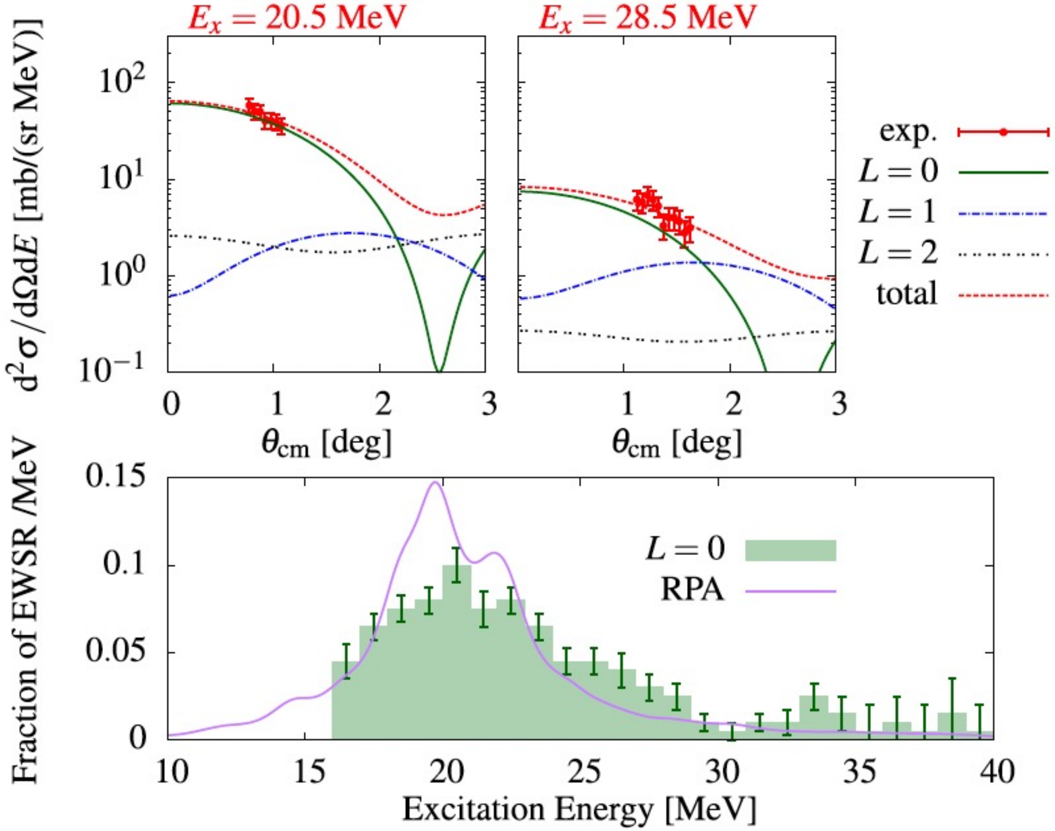
- Stored-beam technique using Experimental heavy-ion Storage Ring (ESR) at GSI ➡ high luminosity
- Gas-jet target of helium
- Windowless detector array placed inside the ring





➢ Proof of principle in stable ^{58}Ni

Showing that measurement at very low angle in the center of mass is possible



J. C. Zamora *et al.*, Phys. Lett. B 763 (2016)

Conclusion

- Giant resonances can be complicated studies due to original experimental setups used and analysis procedures

- Past 2 decades provide **pioneering results** like first GMR measurement in unstable nuclei, first attempt to understand the collectivity of the PDR ….

- Promising future opportunities thanks to the next generation facilities

- Final message: working together with theorists (structure and reaction!) is of paramount importance for these studies

Thank you !