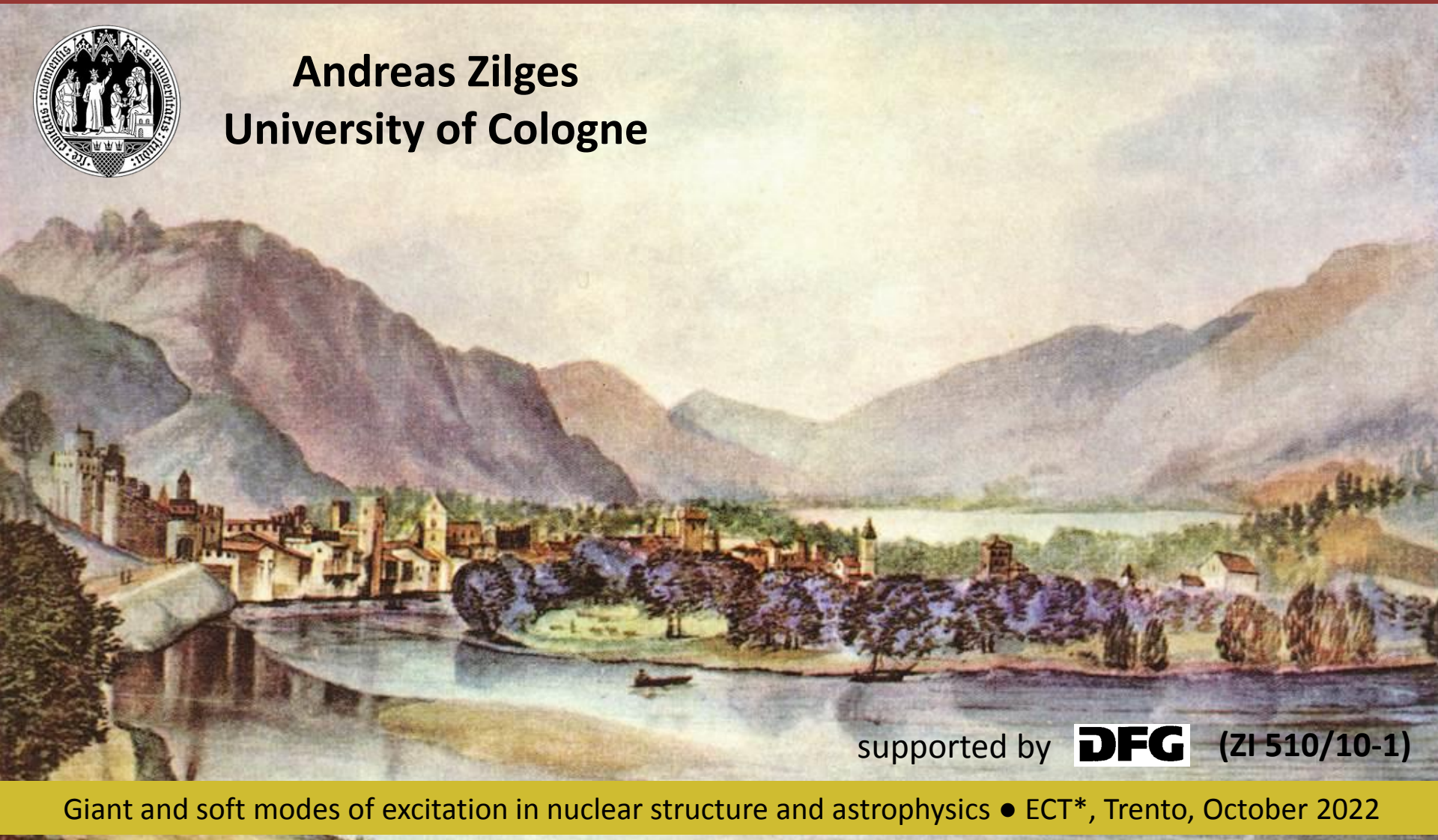
Pygmy or not Pygmy – an experimentalist's point of view

Andreas Zilges
University of Cologne



supported by DFG (ZI 510/10-1)

Giant and soft modes of excitation in nuclear structure and astrophysics ● ECT*, Trento, October 2022

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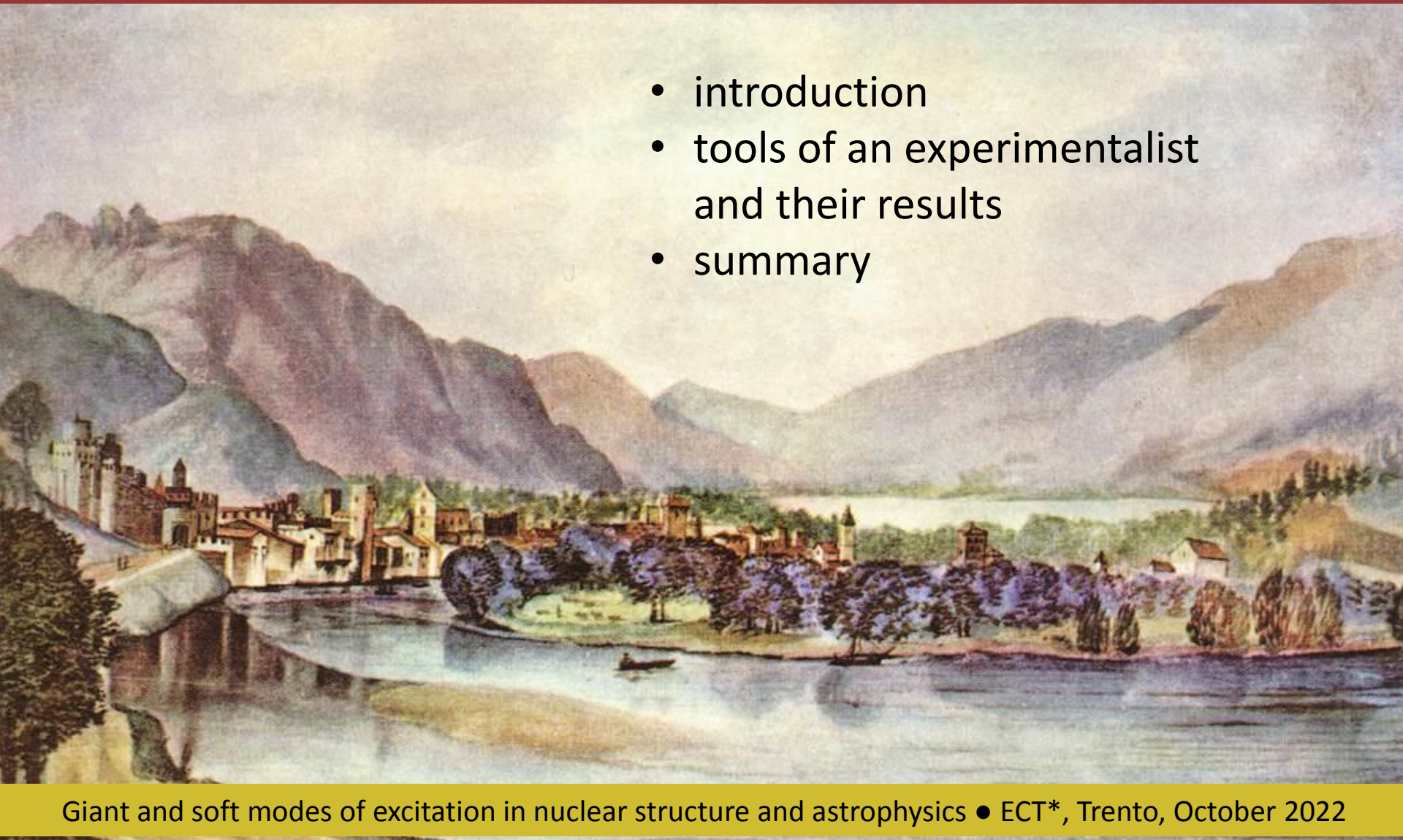
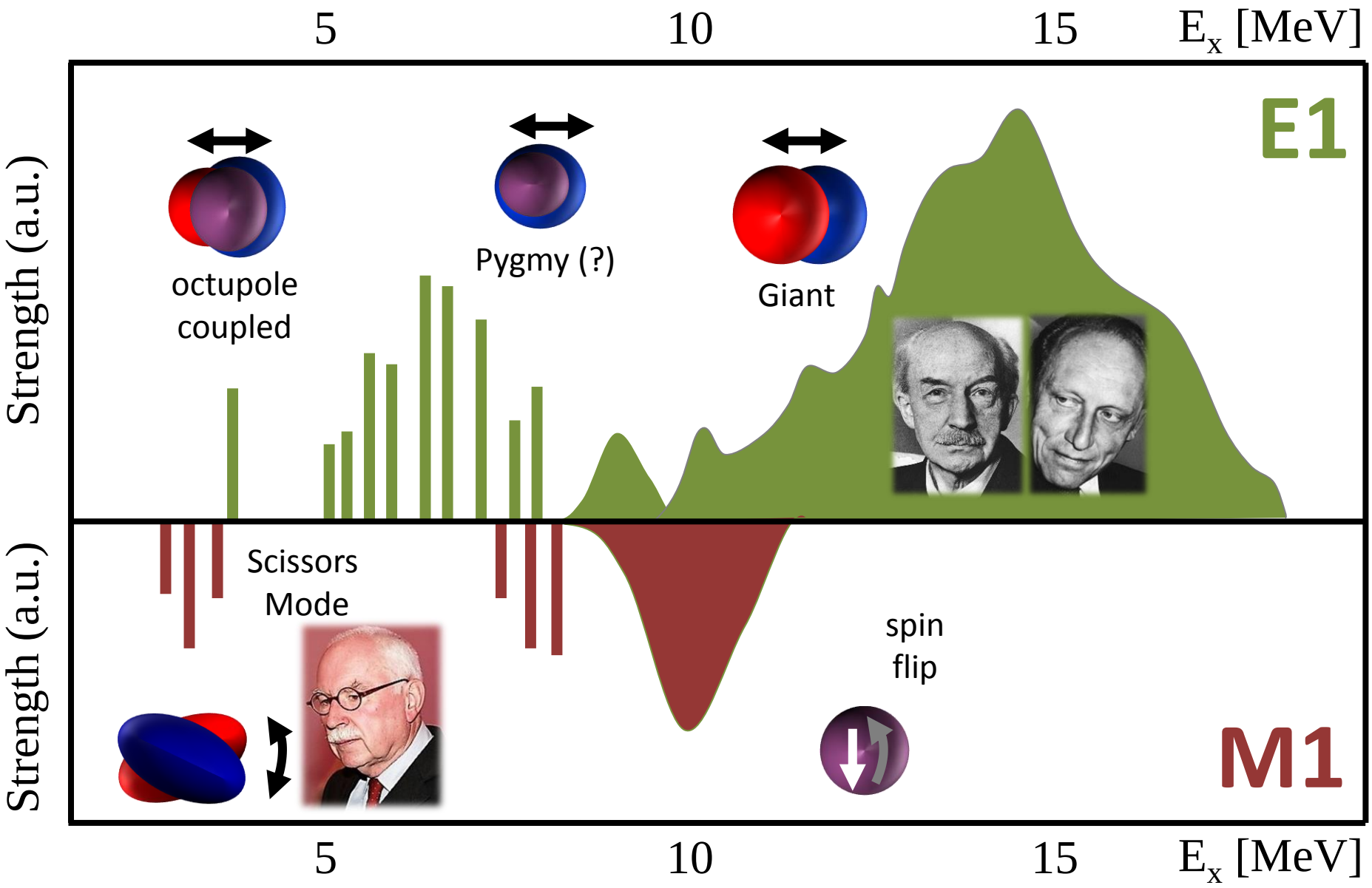
Pygmy or not Pygmy – an experimentalist's point of view

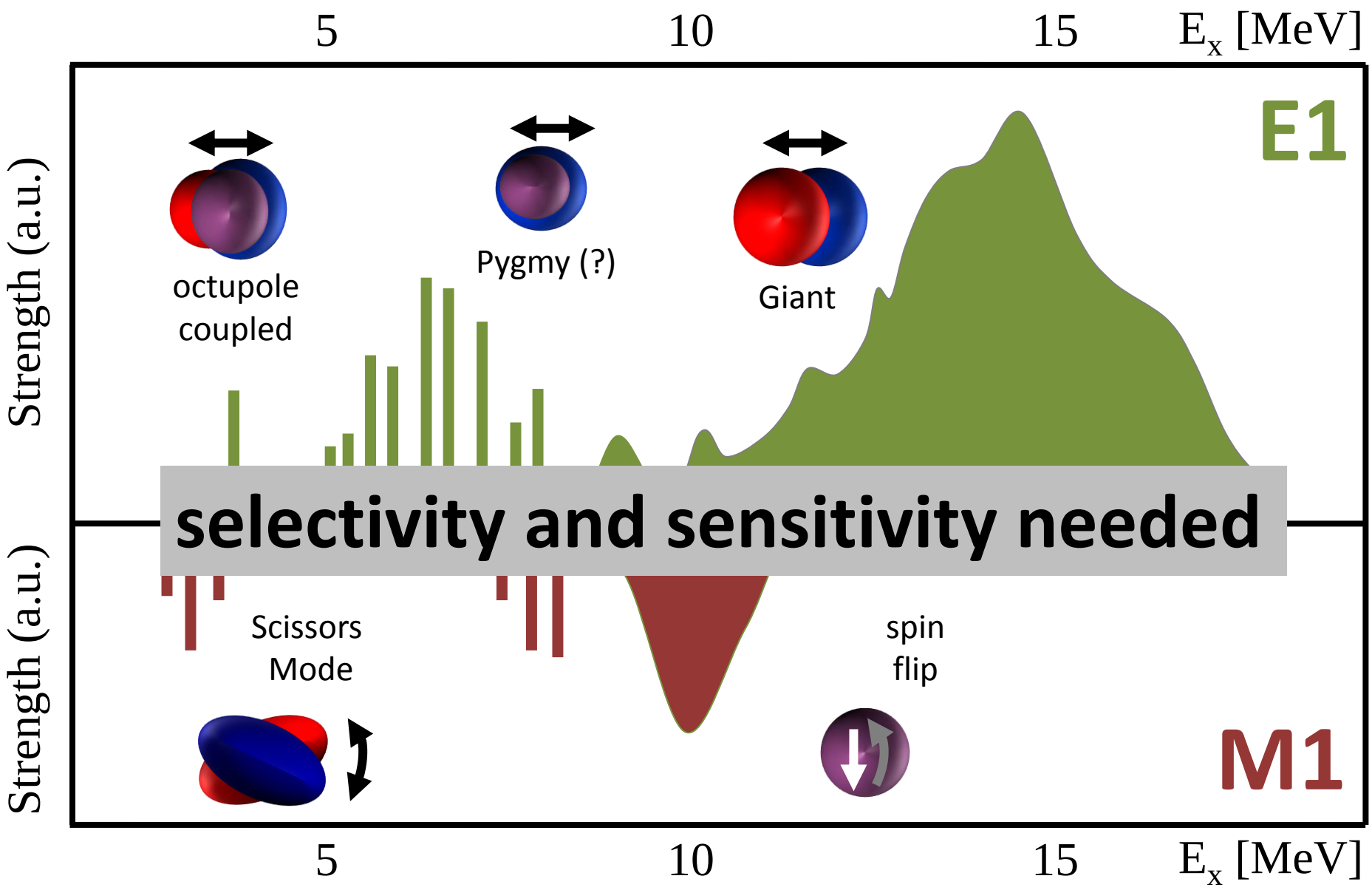


- introduction
- tools of an experimentalist and their results
- summary

Dipole response of atomic nuclei



Dipole response of atomic nuclei



Low lying E1 strength below GDR: First observation about 60 years ago

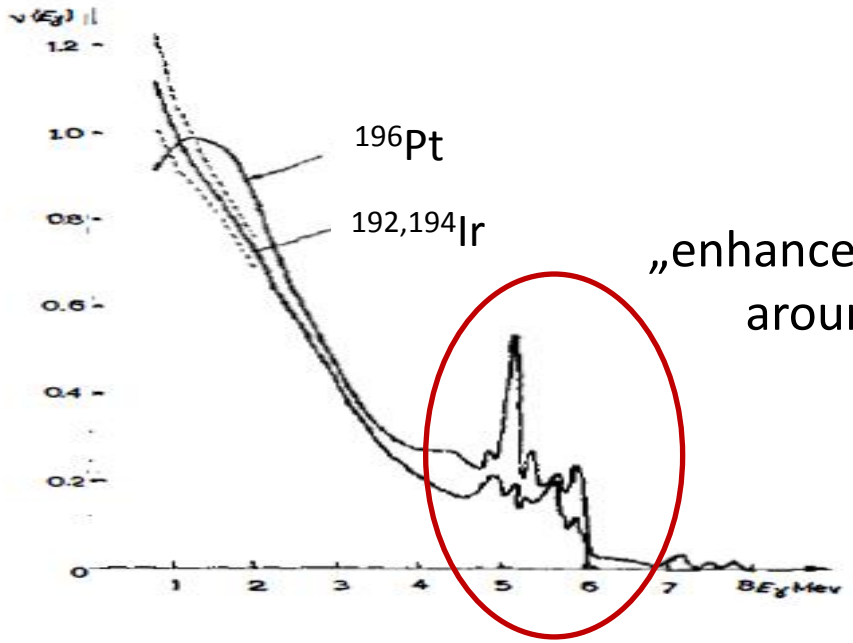
1961:

NEUTRON CAPTURE GAMMA RAYS[1]

By G. A. Bartholomew

Neutron Physics Branch, Chalk River Project, Atomic Energy of Canada Limited

Ann. Rev. Nucl. Sci. ***11*** *(1961) 259*



^{196}Pt

^{192,194}Ir

„enhanced γ transitions around 6 MeV“

First use of denotation „pygmy“ for low lying electric dipole strength

1969:

Effect of the pigmy resonance on the calculations of the neutron capture cross section

J. S. Brzosko, E. Gierlik, A. Soltan, Jr., and Z. Wilhelmi

Institute of Experimental Physics, Warsaw University, Warsaw, Poland, and Institute of Nuclear Research, Warsaw, Poland

Received November 12, 1968[1]

A comparison of the experimental cross sections of the (n, γ) reaction for several nuclei (^{103}Rh, ^{127}I, ^{181}Ta, ^{197}Au) with the compound nucleus model calculations has been made. In the formula used for the probability of gamma-ray emission from the compound nucleus, the presence of the well-known giant resonance was accounted for, as well as the presence of the "pigmy resonance" appearing at the energy $E_\gamma \approx 6$ MeV. The agreement with the experimental values is better in this case than when the "pigmy resonance" is neglected. The same conclusions can be obtained from the calculations of the shape of the spectrum of neutron capture and from the $\bar{\Gamma}_\gamma/D$ ratio.

Canadian Journal of Physics, 47, 2849 (1969)

…before it had already been used to denote E2/M1 strength below the GDR

1957:

PHYSICAL REVIEW VOLUME 106, NUMBER 2 APRIL 15, 1957

Photodisintegration of C^{13}†*‡

BARNETT C. COOK§
The Enrico Fermi Institute for Nuclear Studies, The University of Chicago, Chicago, Illinois
(Received November 9, 1956)

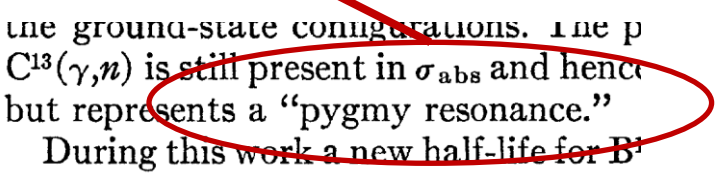
The neutron yield functions of C^{12} and C^{13} from bremsstrahlung up to 41 Mev have been measured by using direct neutron detection. The photoproton yield function for C^{13} has also been measured by detecting the B^{12} activity. These yield functions were converted into cross sections (σ) by a slightly modified standard method.

σ for $C^{13}(\gamma,xn)$ exhibits a peak of ~3.7 mb at ~13.5 Mev and the "giant resonance" peak of ~10 mb at ~24 Mev. This latter peak is broad [$\Gamma_{\frac{1}{2}} \approx 10$ Mev] in contrast to C^{12} with $\Gamma_{\frac{1}{2}} \approx 3$ Mev.

σ for $C^{13}(\gamma,p)B^{12}$ exhibits a broad ($\Gamma_{\frac{1}{2}} \approx 6$ Mev) giant resonance peak of 8.8 mb at 25.5 Mev. This large p/n emission ratio cannot be accounted for by statistical considerations.

After a reasonable allowance is made for multiple processes, these two measurements are combined to give the total γ-absorption cross section, σ_{abs}. σ_{abs} of C^{12} is also discussed. Both show a giant resonance peak but $\Gamma_{\frac{1}{2}}(C^{13}) \gg \Gamma_{\frac{1}{2}}(C^{12})$ whereas the integrals of σ_{abs} over the resonance are approximately equal. The idea that core excitation is responsible for the giant resonance is supported by the approximate equality of the resonance energies of C^{12} and C^{13}, but the remarkable difference in the width of these resonance peaks suggests a strong dependence of the absorption process on the ground-state configurations. The peak at 13.5 Mev found in $C^{13}(\gamma,n)$ is still present in σ_{abs} and hence is not due to competition, but represents a "pygmy resonance."

During this work a new half-life for B^{12} was obtained: $(18_{-1.3}^{+1.5})$ msec.



PDR: First model description

1971:

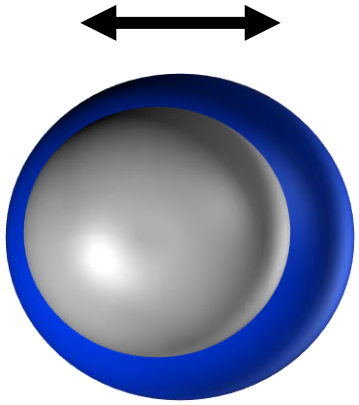
Three-Fluid Hydrodynamical Model of Nuclei*

R. Mohan, M. Danos, and L.C. Biedenharn,
*Phys. Rev. C **3** (1971) 1740*

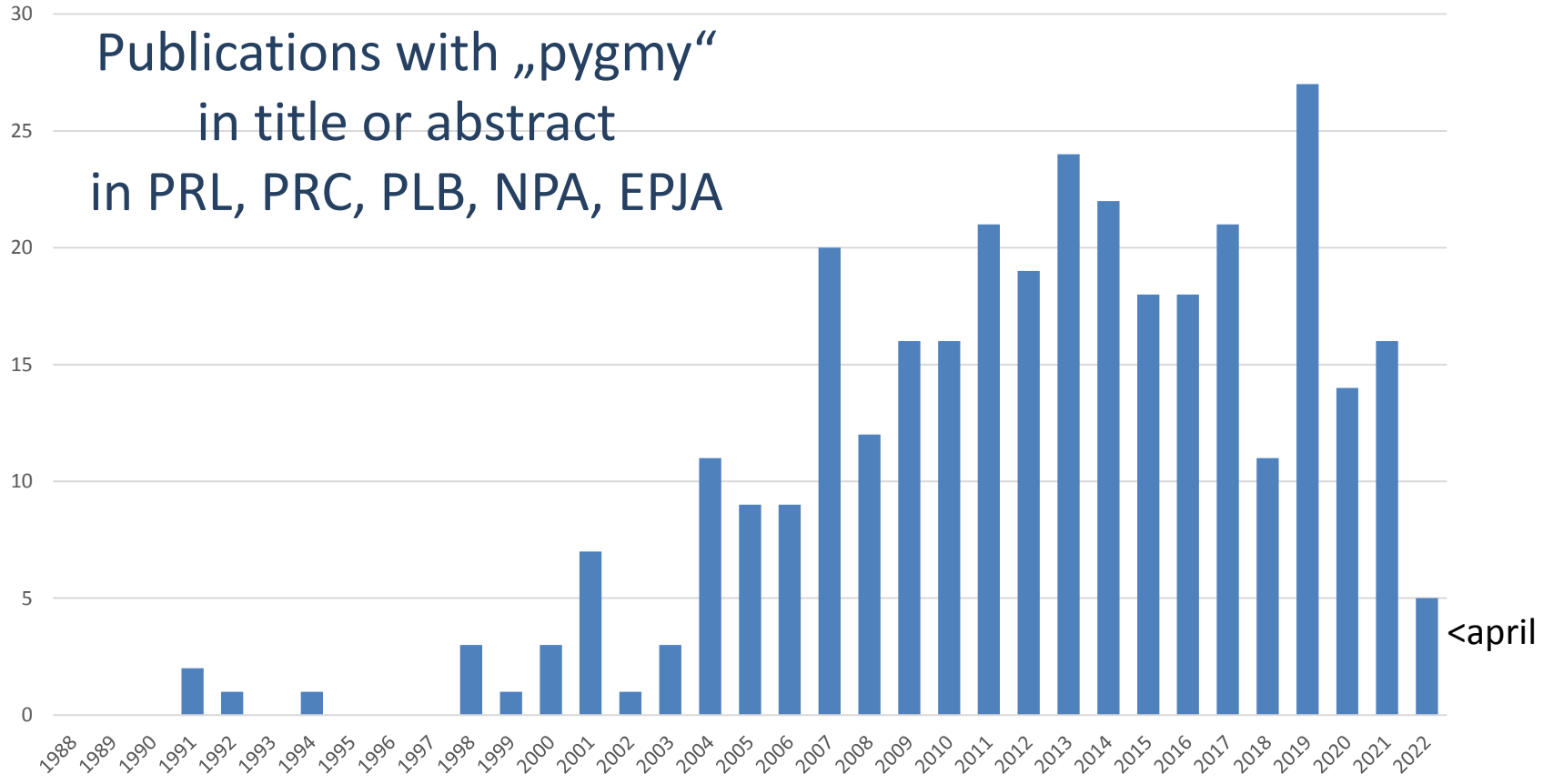
A three-fluid model of nuclei is introduced, the three fluids being the protons, the neutrons of the same orbitals as protons, and the excess neutrons, to account for the fact that the excess neutrons interact less strongly with the protons than do the neutrons which occupy the same space-spin states as the protons. Calculations of proton and neutron density distributions, of isotope shifts, and of isospin impurities have been carried out. The giant-dipole phenomenon is also studied in the present model. It is found that considerable improvement is achieved in the results for the proton density distribution and for the isospin impurities as compared with the two-fluid model. The other results are found to be consistent with previous calculations.

core: Z protons, Z neutrons

skin: N-Z excess neutrons



From past to present: Interest in PDR



D. Savran, T. Aumann, and A. Zilges:
„Experimental Studies of the Pygmy Dipole Resonance“
Prog. Part. Nucl. Phys. ***70*** *(2013) 210*

(scissors mode paper from 1984: 713 citations)

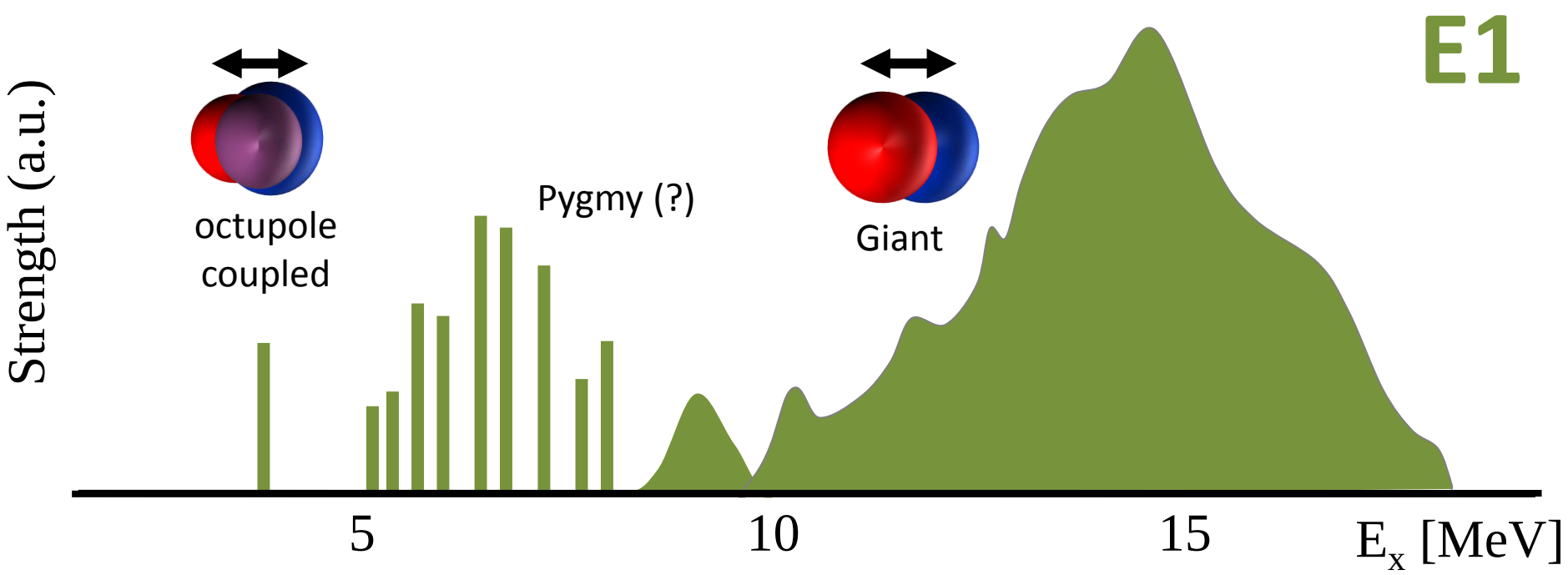
In Web of Science Core Collection

321
Citations

Highly Cited Paper

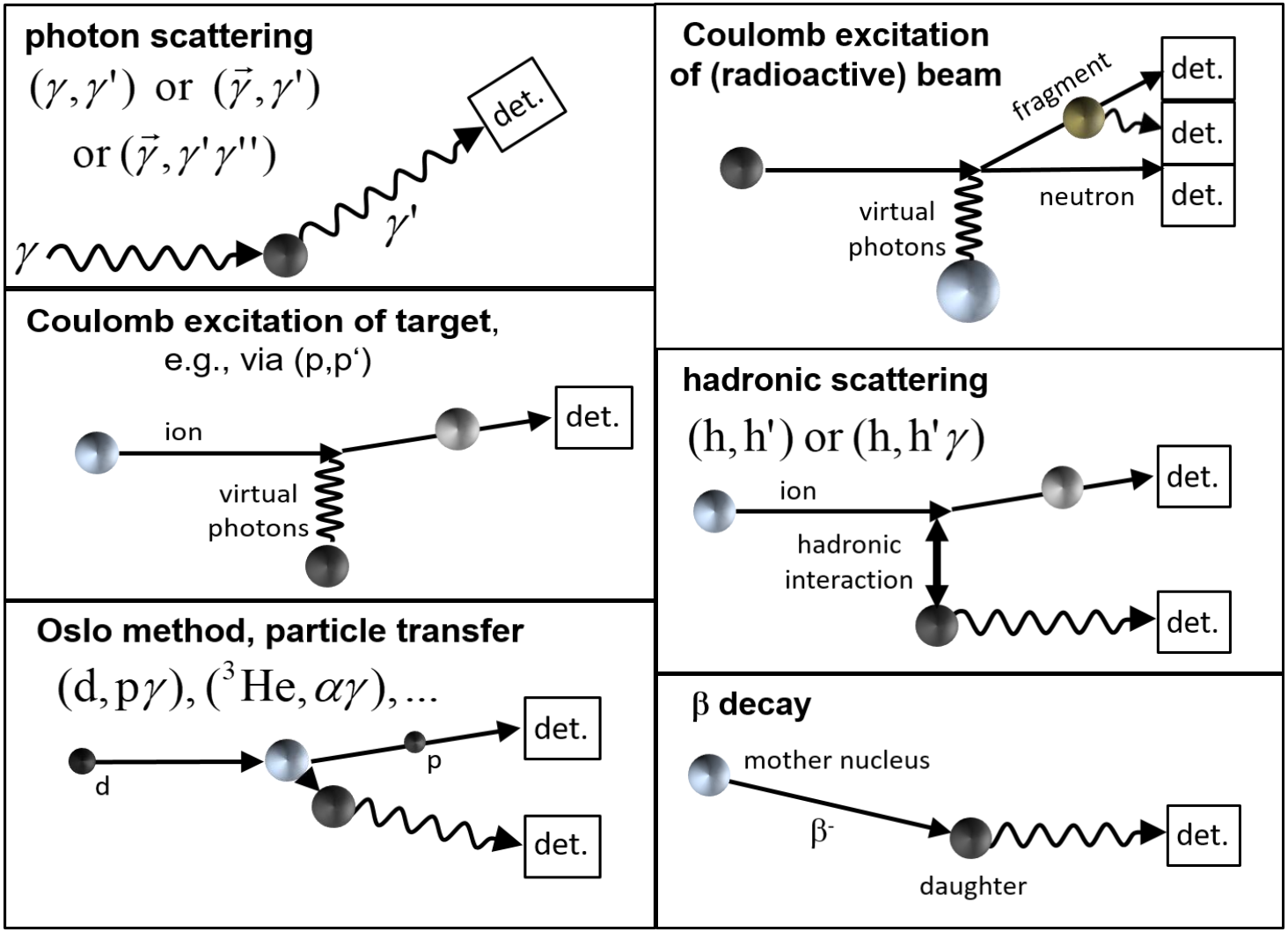
source: Web of Science

My definition of Pygmy Dipole Resonance



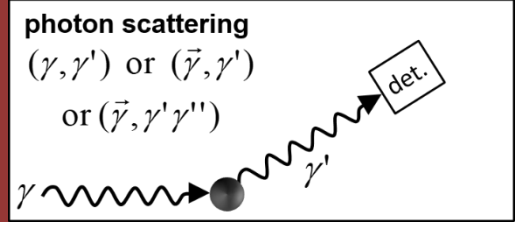
PDR ≡ electric dipole excitations with **energies between the octupole coupled mode(s) and the GDR** which have a **different structure** compared to those

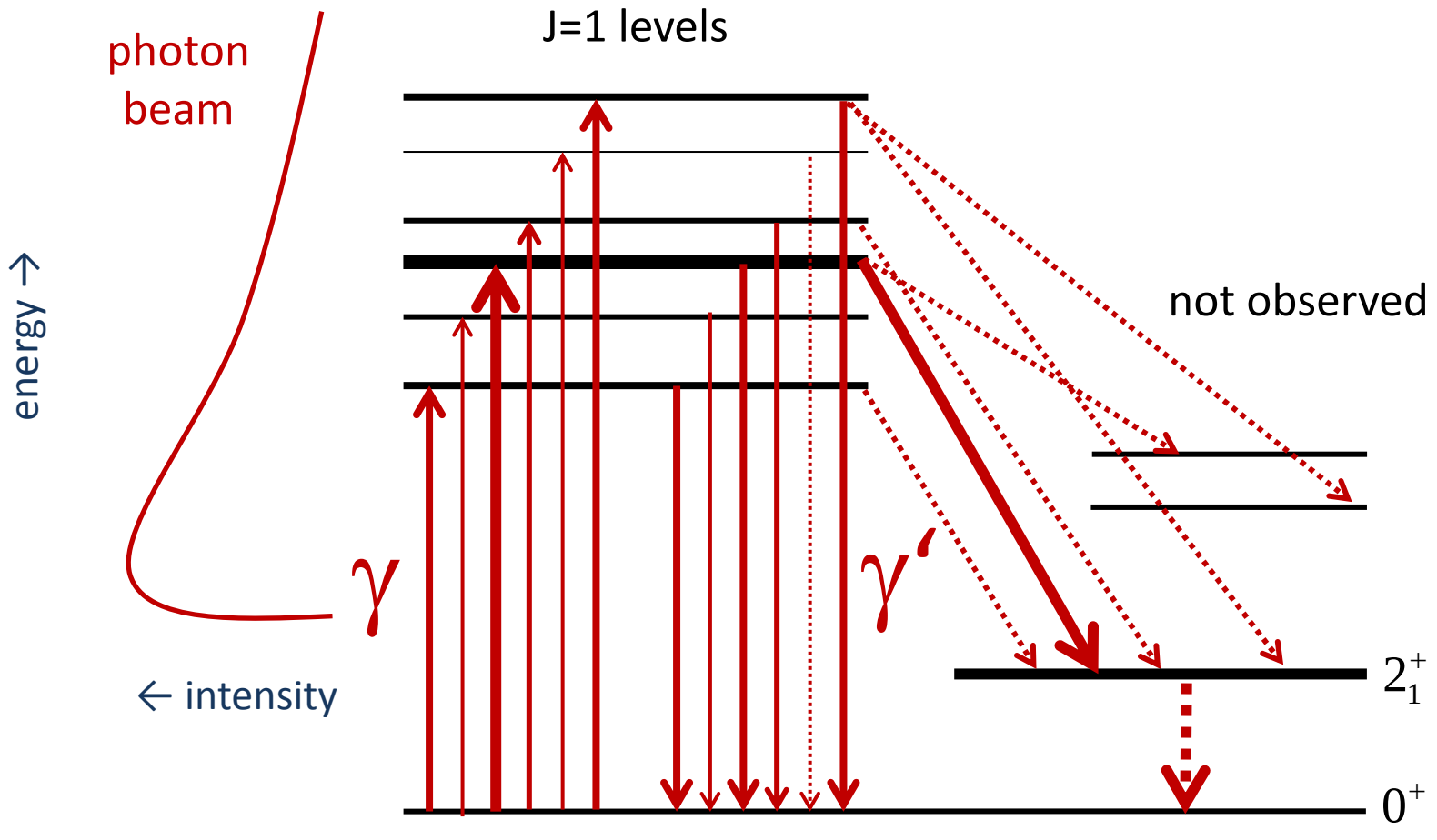
Tools of an experimentalist (selection)



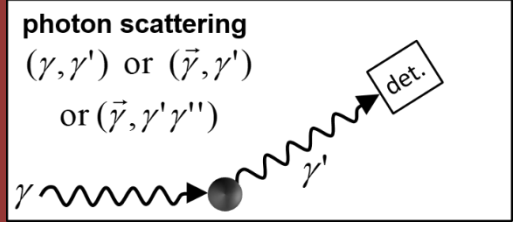
D. Savran and A. Zilges: „Handbook of Nuclear Physics“;
edited by I. Tanihata, H. Toki, T. Kajino; Springer Singapore, in press

Photon scattering (γ,γ') with bremsstrahlung beams

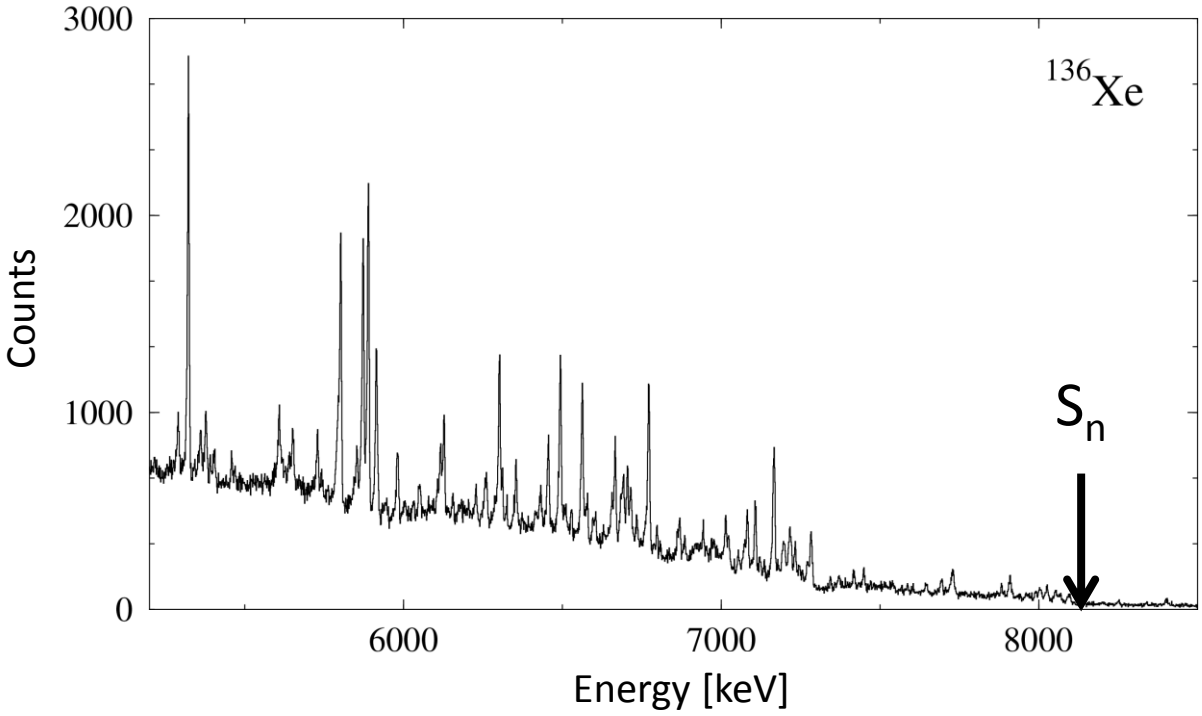




Photon scattering (γ,γ') with bremsstrahlung beams



Raw spectrum of photons scattered off ^{136}Xe:

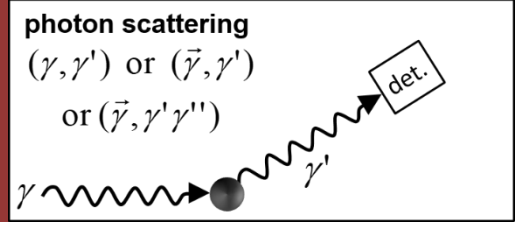


+ well understood
+ ideal overview
+ high resolution

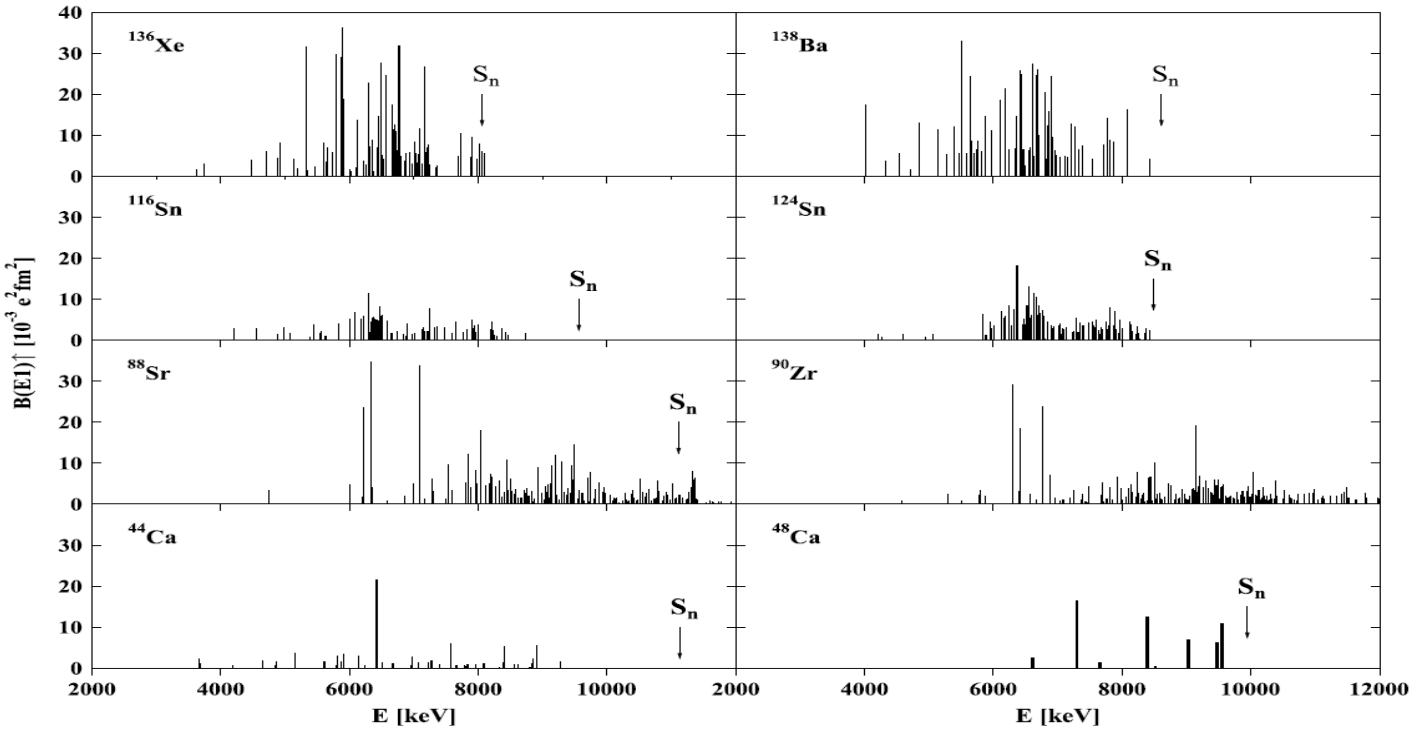
- hidden strength
- missing weak decays
- only below S_n

D. Savran et al., PRC ***84*** *(2011) 024326*

Photon scattering (γ,γ') with bremsstrahlung beams

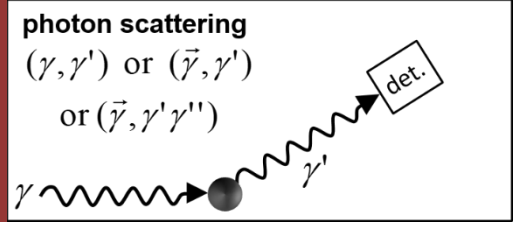


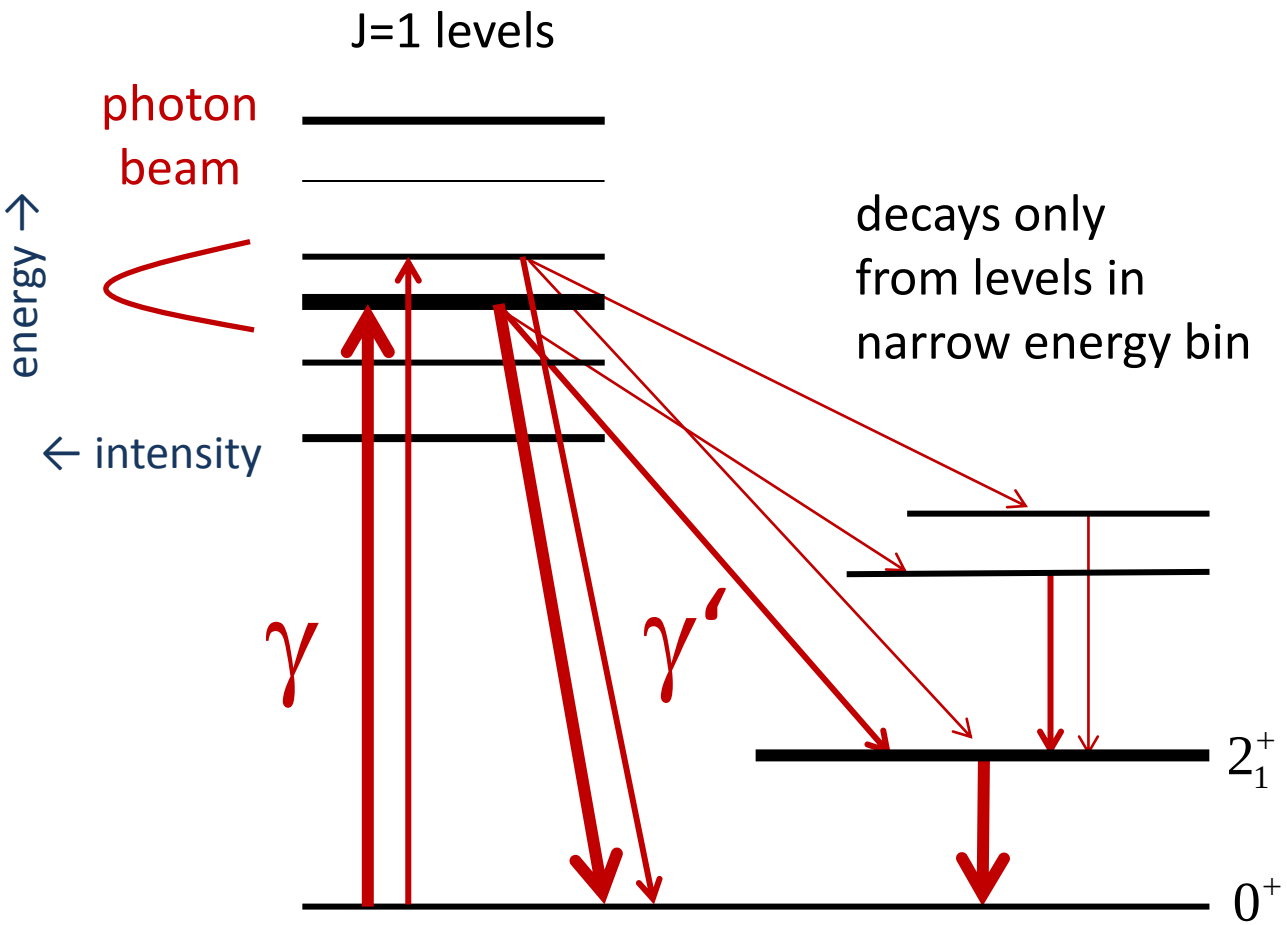
- enhancement of E1 strength between about 5 and 8 MeV
- strong fragmentation in non neutron-magic nuclei
- approaching S_n: B(E1)↑ strength is underestimated due to strength hidden in the background and unobserved γ-decay branchings



*D. Savran et al., PPNP **70** (2013) 210*

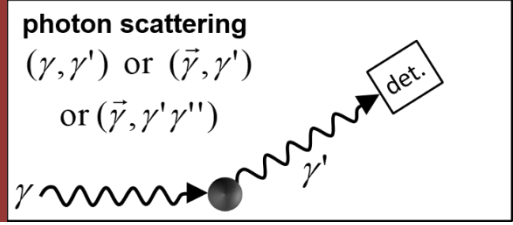
Photon scattering ($\vec{\gamma}$,γ') with polarized mono-energetic beams

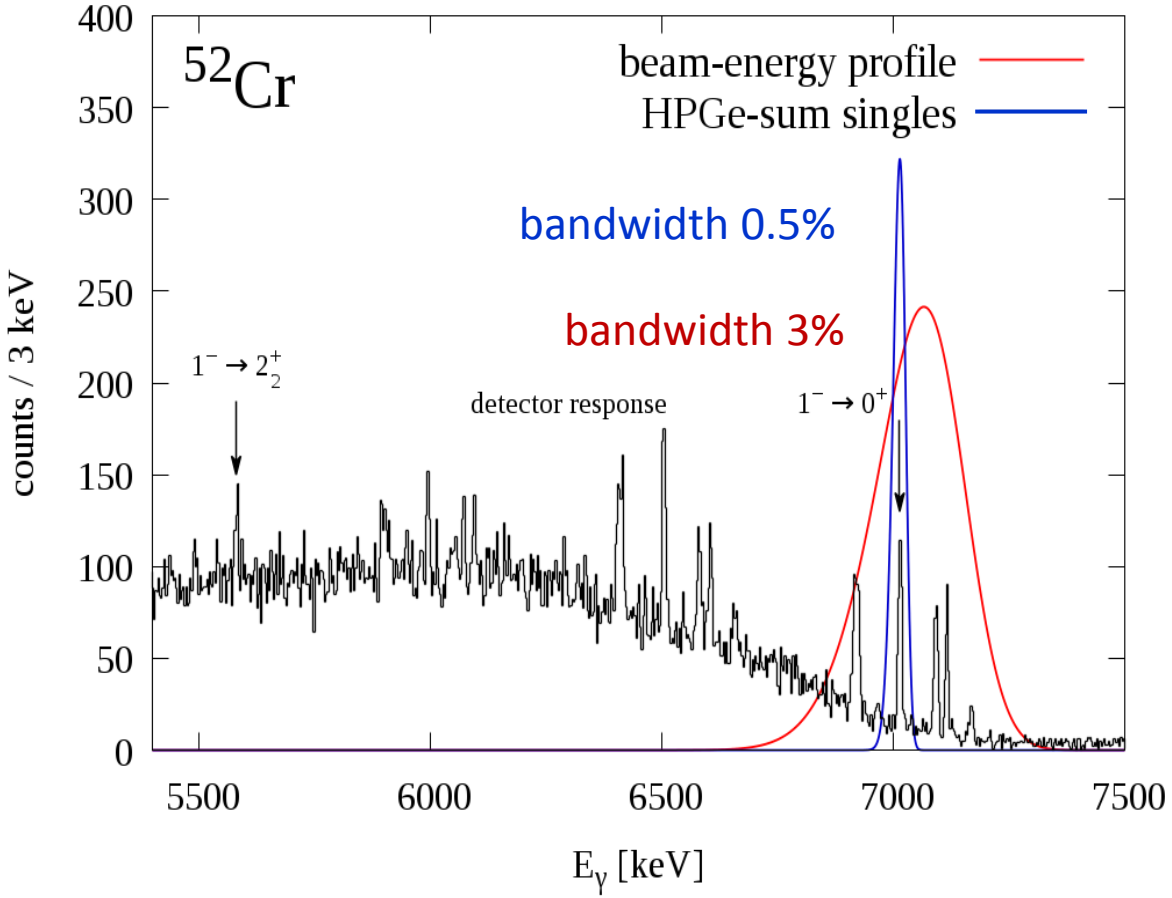




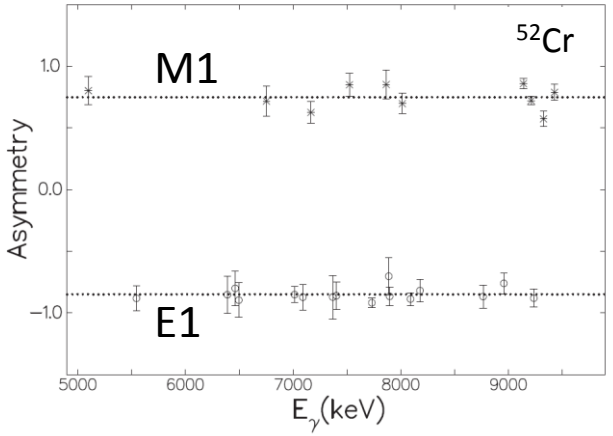
funnel effect

Photon scattering ($\vec{\gamma}$,γ') with polarized mono-energetic beams



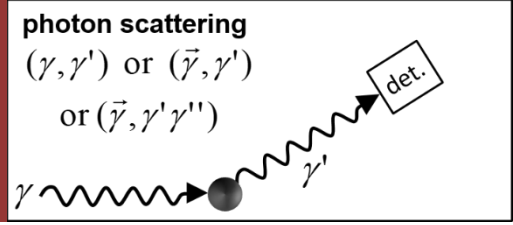


+ selection of excitation energy
+ parity determination
+ detection of unresolved strength
+ (γ,γ'γ'') possible
- difficult flux calibration
- time consuming
- only below S_n

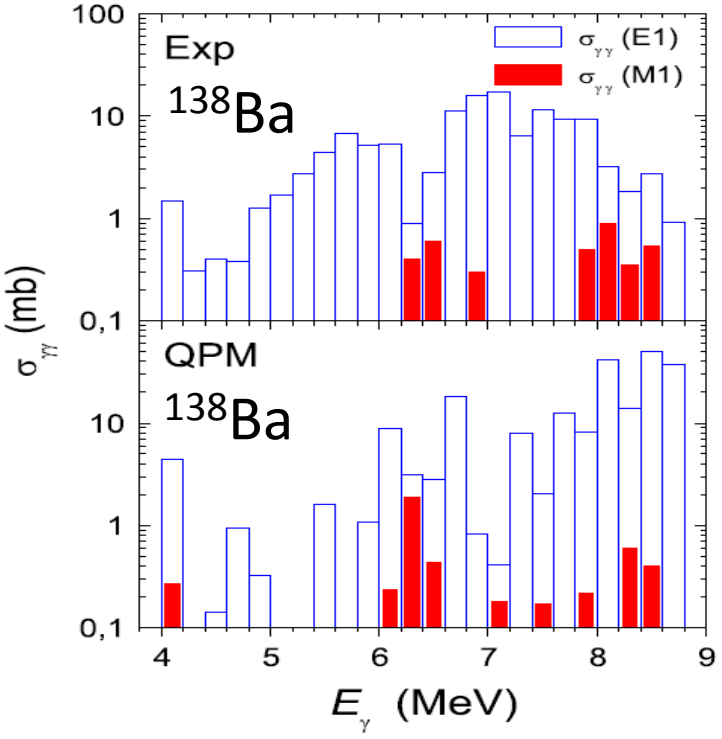


*J. Wilhelmy et al., PRC **97** (2018) 054319*
*Krishichayan et al., PRC **91** (2015) 044328*

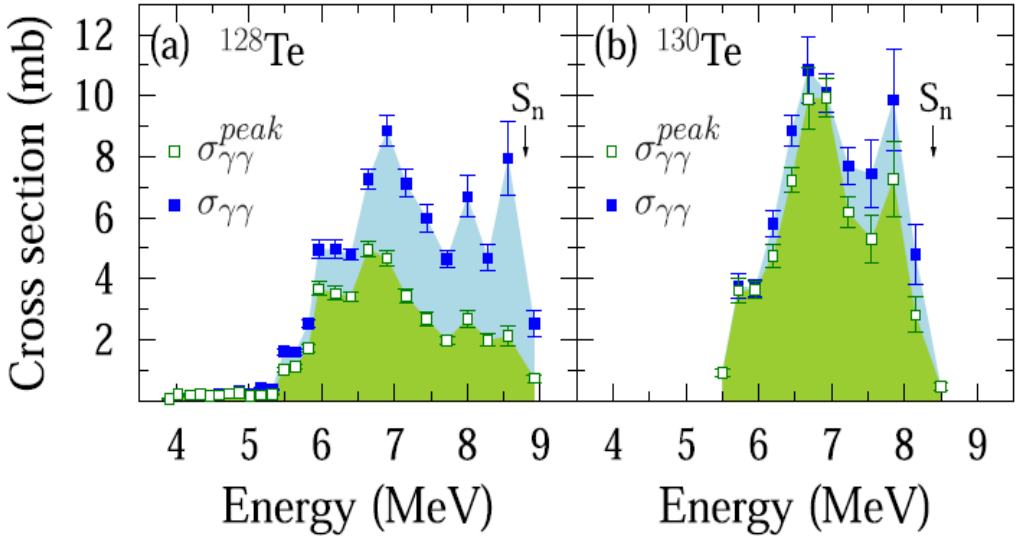
Photon scattering ($\vec{\gamma}$,γ') with polarized mono-energetic beams



- parity determination and nearly complete detection of decays allow more robust comparison to theory
- for certain isotopes: deviations from statistical model assumptions



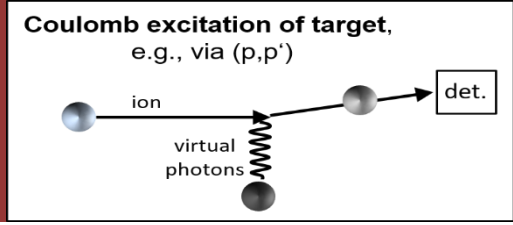
*A.P. Tonchev et al., PRL **104** (2010) 072501*

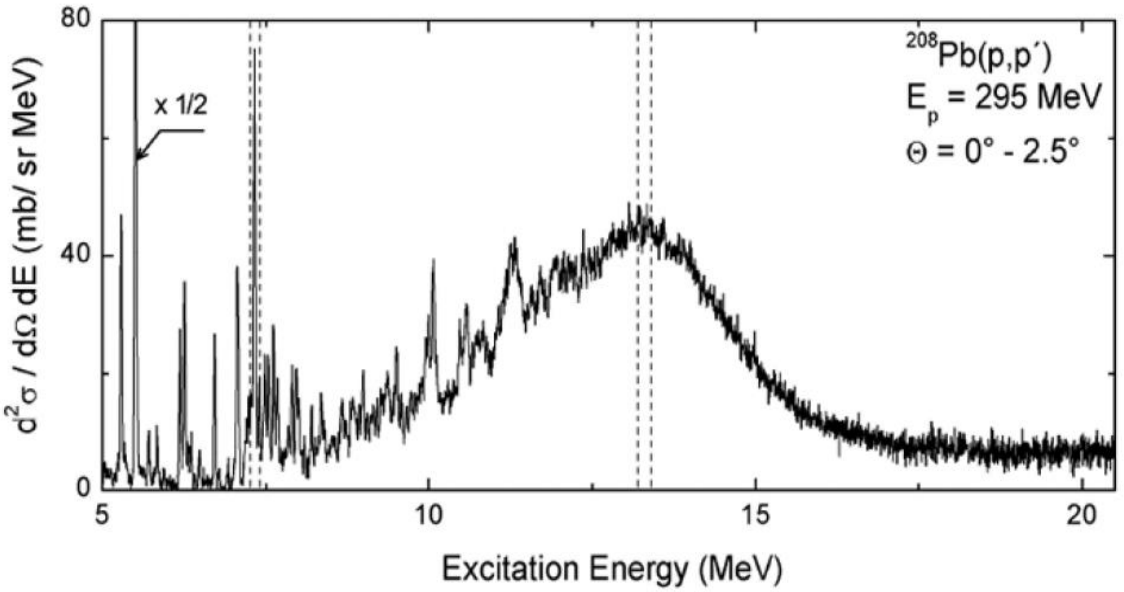


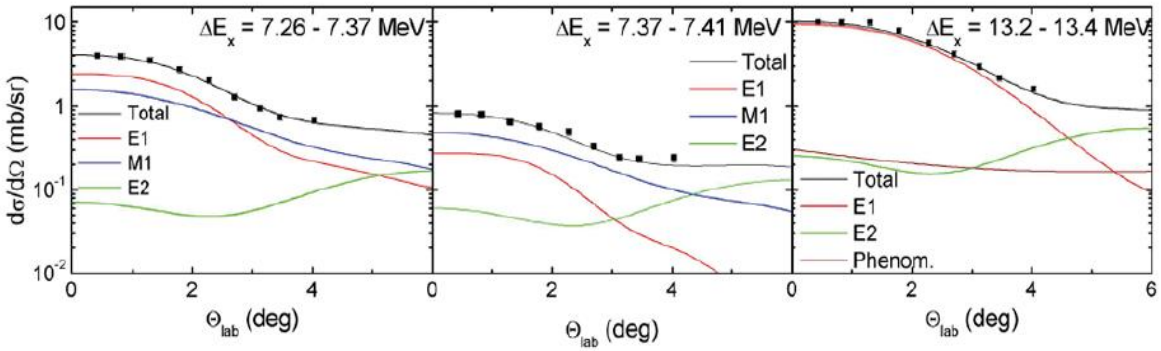
*J. Isaak et al., PRC **103** (2021) 044317*

→ talk by MIRIAM MÜSCHER

Coulomb excitation with virtual photons on stable nuclei





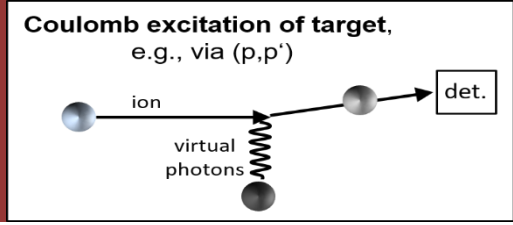


*P. von Neumann-Cosel and A. Tamii, EJPA **55** (2019) 110*

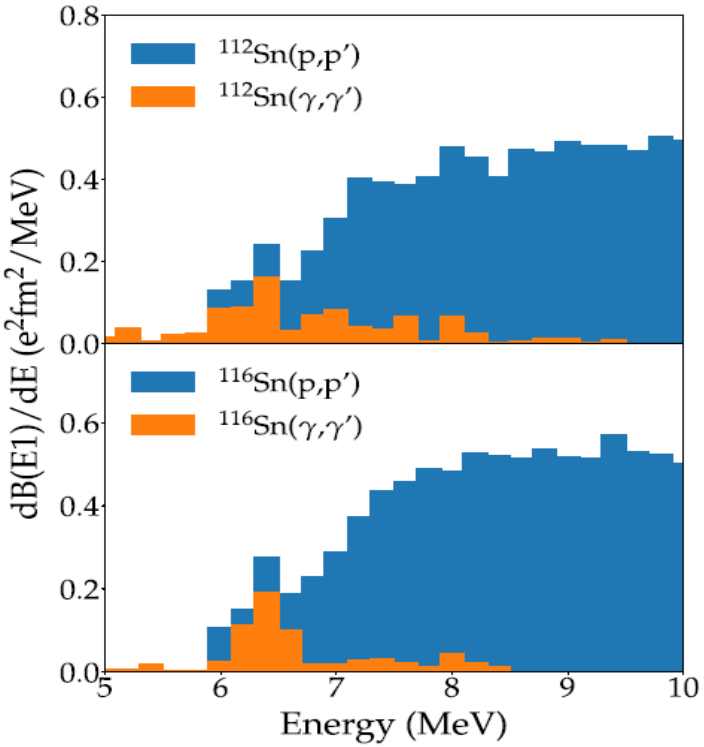
+ excitation is measured: strength below and above S_n,
+ detection of „unresolved“ strength

- multipole decomposition
- no information about decay branching

Coulomb excitation with virtual photons on stable nuclei

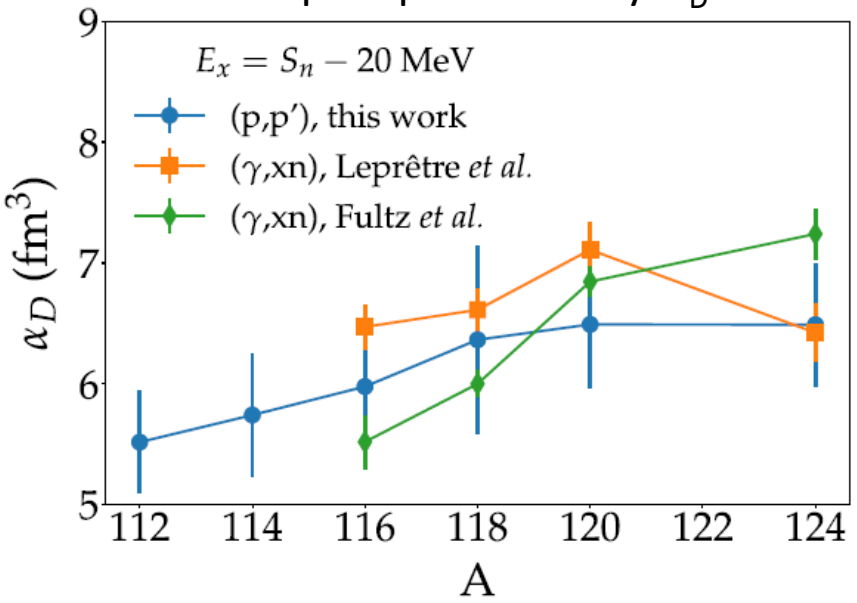


- B(E1) strength distributions independent of γ-decay branchings and level density
- direct access to dipole polarizability below about 20 MeV



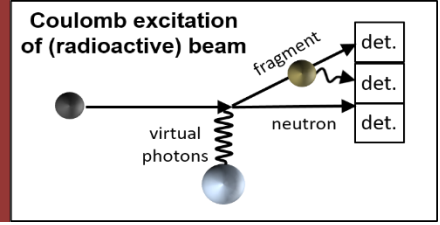
*S. Bassauer et al., PRC **102** (2020) 034327*

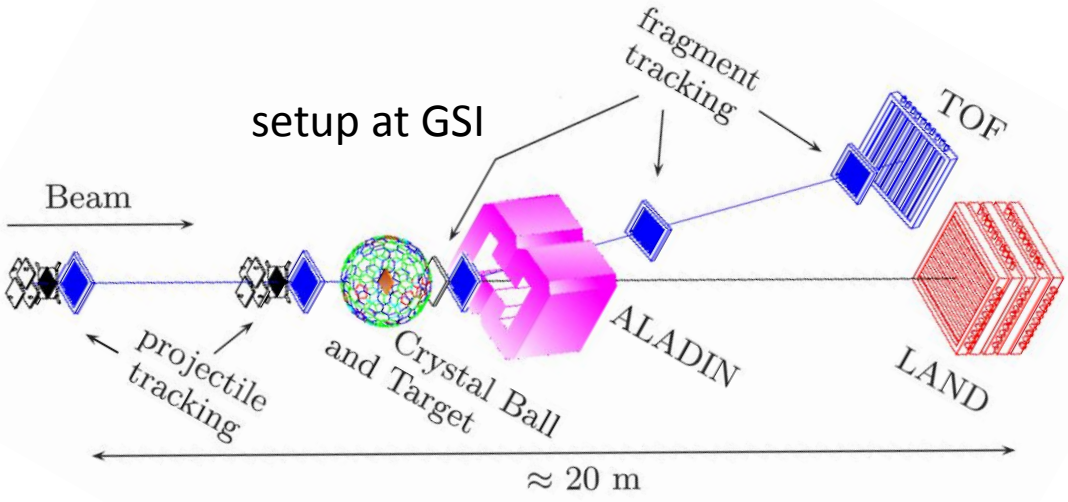
dipole polarizability α_D

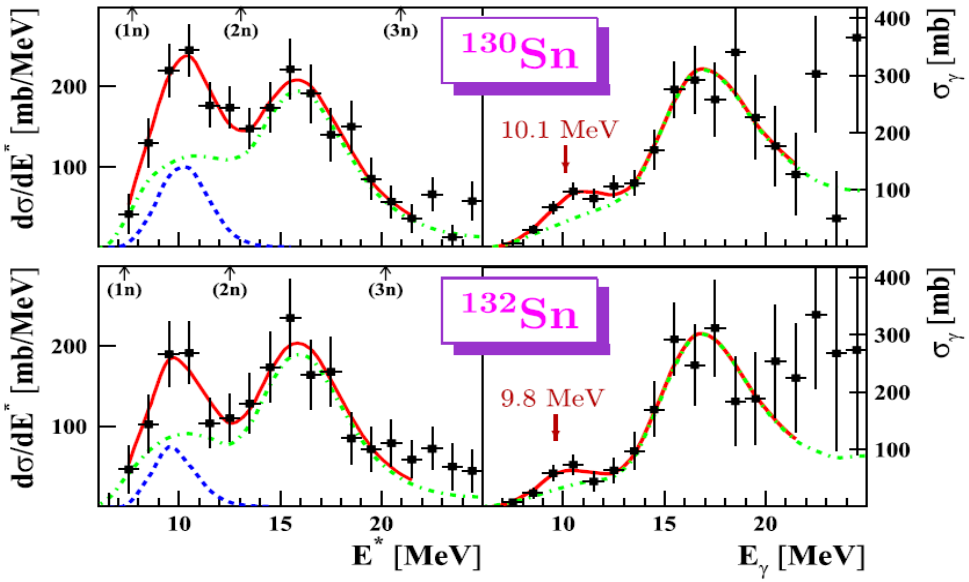


→ talks by ATSUSHI TAMII, ISABELLE BRANDHERM, and PETER VON NEUMANN-COSEL

Coulomb excitation of relativistic (radioactive) ion beam





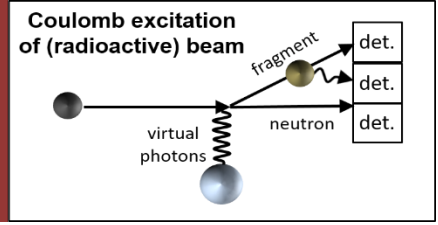


*P. Adrich et al., PRL **95** (2005) 132501*

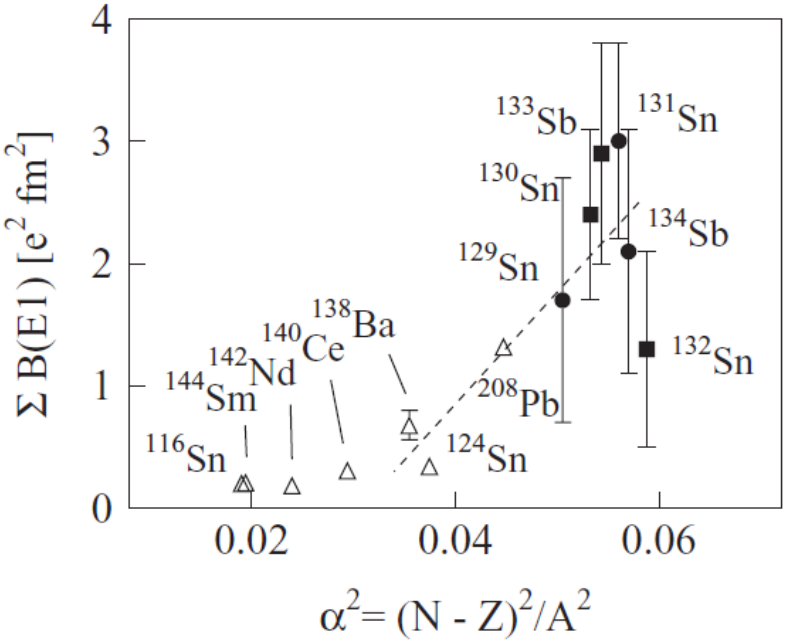
+ study of exotic nuclei possible
+ complete kinematics

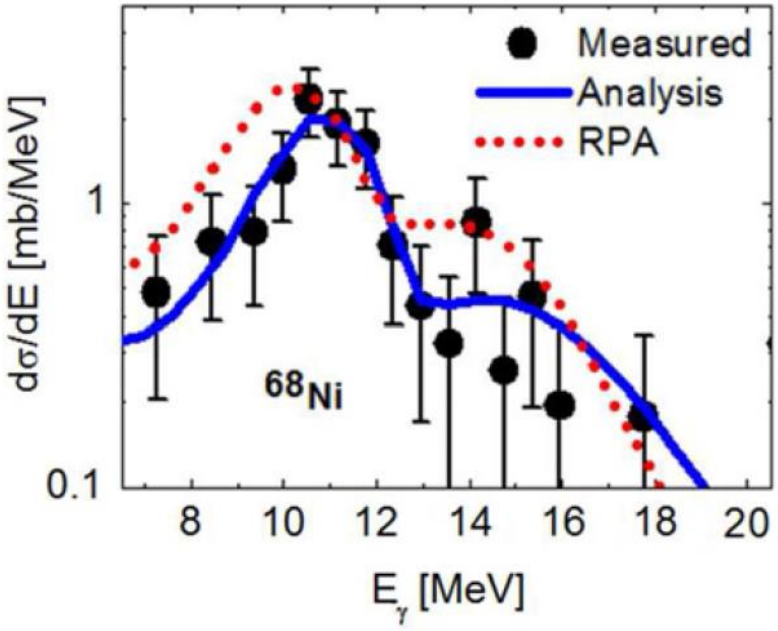
- complex data evaluation
- limited energy resolution
- only EM response

Coulomb excitation of relativistic (radioactive) ion beam



- E1 strength below GDR seems to increase with N/Z ratio (better: Coulomb corrected Fermi energy: $\Delta_{CCF} = (S_{2p} - S_{2n})/2 + E_C$)
- model description of E1 strength in exotic nuclei is tested, important for r process and nuclear equation of state

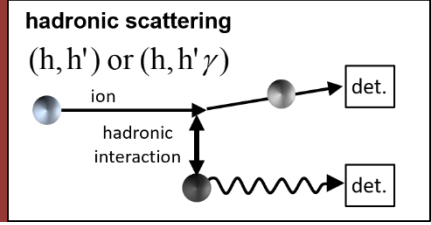


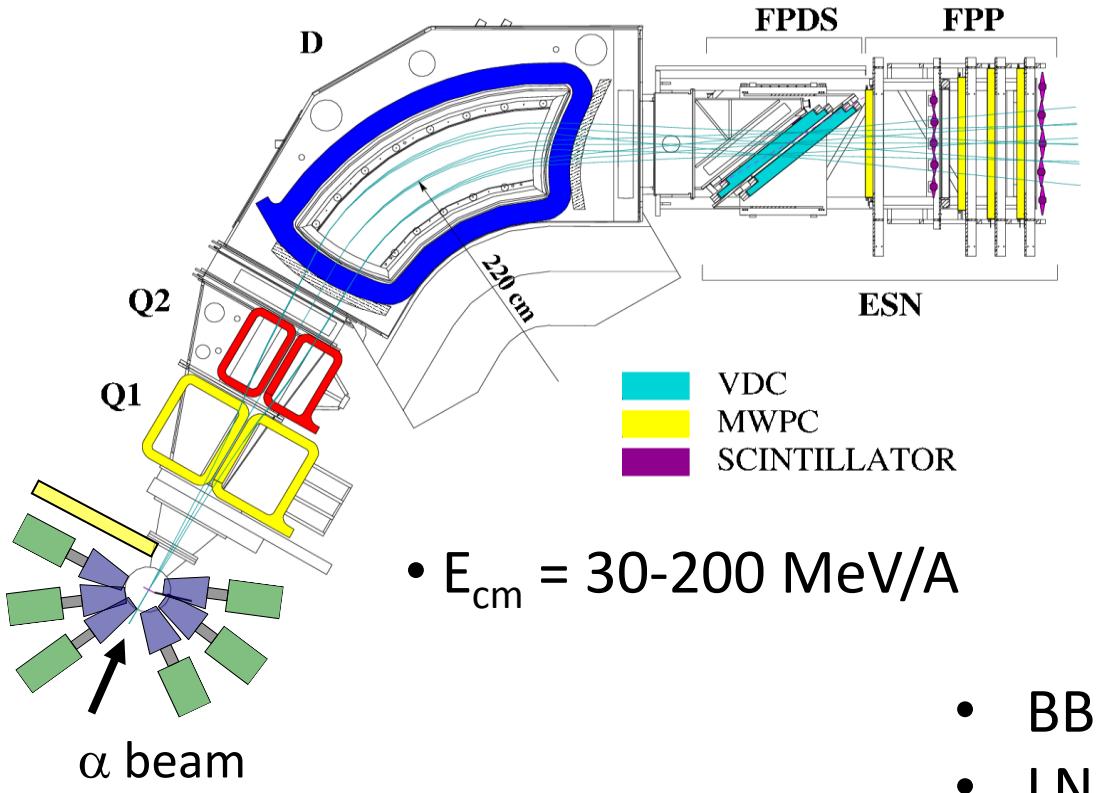


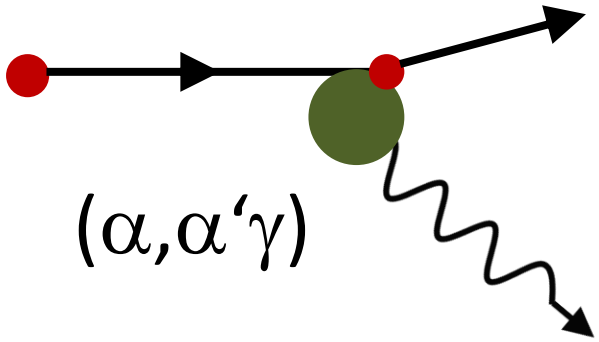
*A. Klimkiewicz et al., PRC **76** (2003) 051603(R)*

*O. Wieland and A. Bracco, PPNP **66** (2011) 374*

Hadronic interaction with protons, α particles, ^{17}O ions





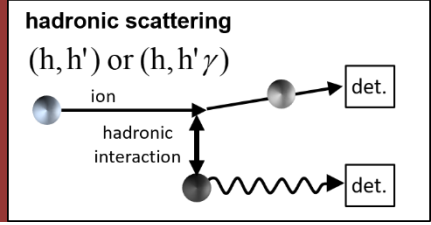


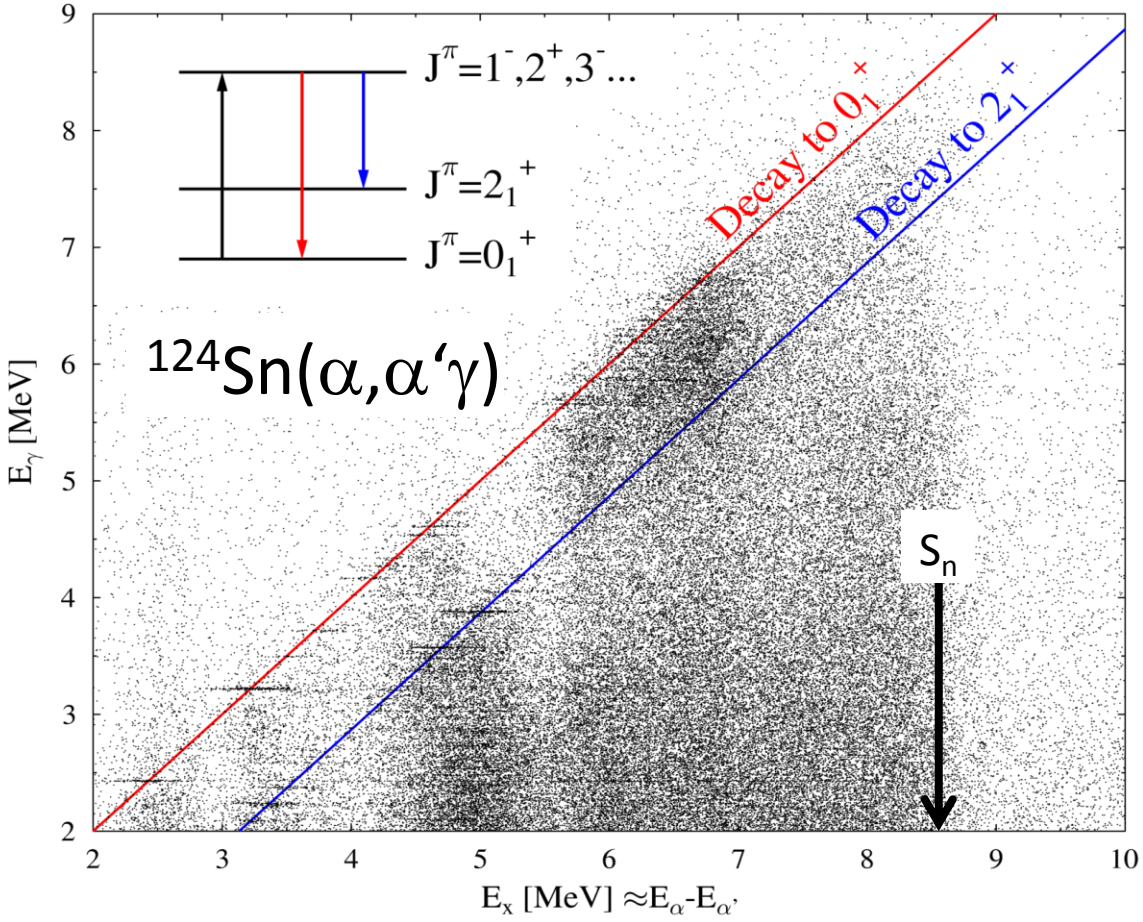
- E_{cm} = 30-200 MeV/A

D. Savran, M.N. Harakeh, A.Z.

- BBS@KVI (deceased 2012)
- LNL-INFN (^{17}O beam)
- K600 @ iThemba LABS
- CAGRA campaign @ RCNP
- BigRIPS@RIKEN

Hadronic interaction with protons, α particles, ^{17}O ions





+ distinguishes between isoscalar and isovector character
+ good selectivity and resolution with coincidence condition
- only sensitive at nuclear surface
- time consuming experiments

*J. Endres, E. Litvinova et al., PRL **105** (2010) 212503*

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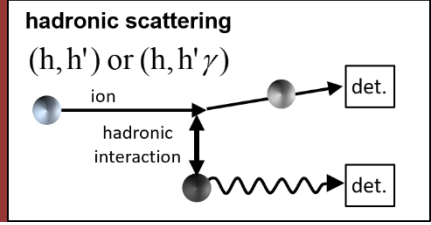

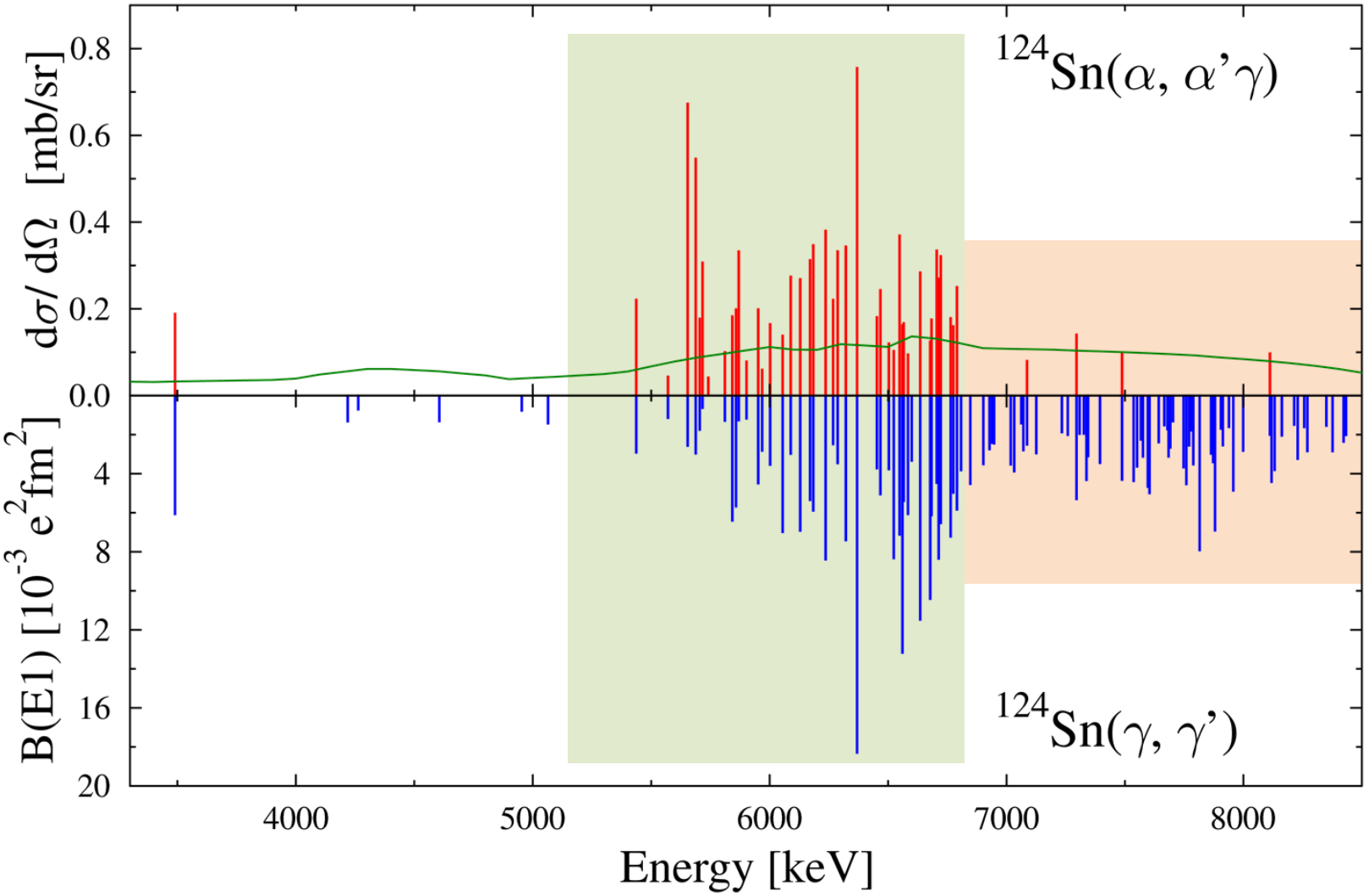

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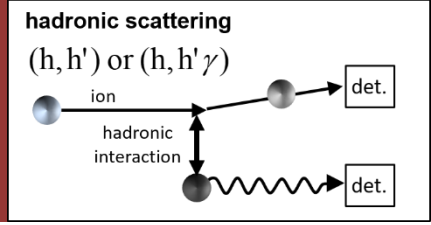
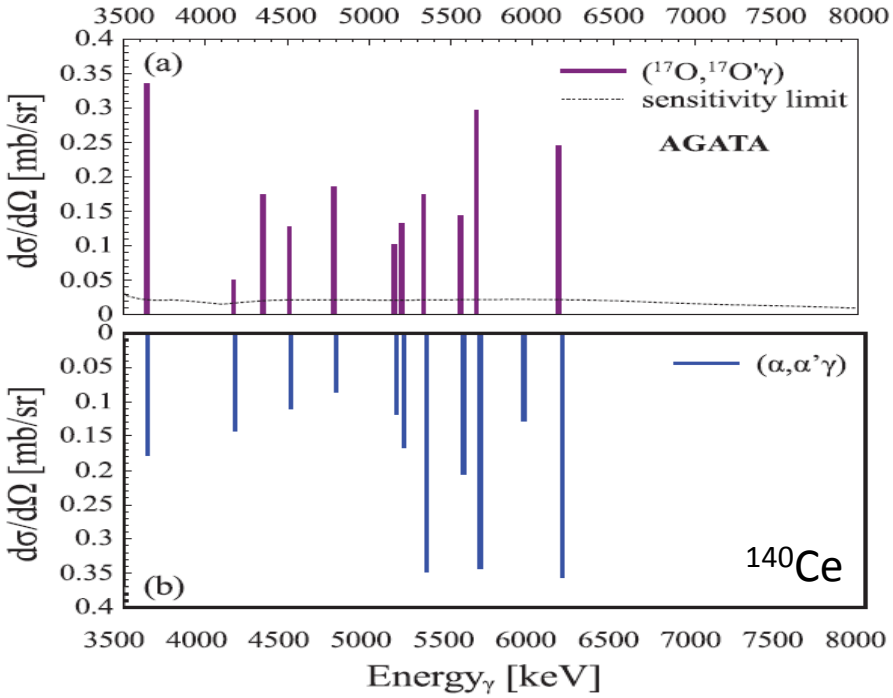
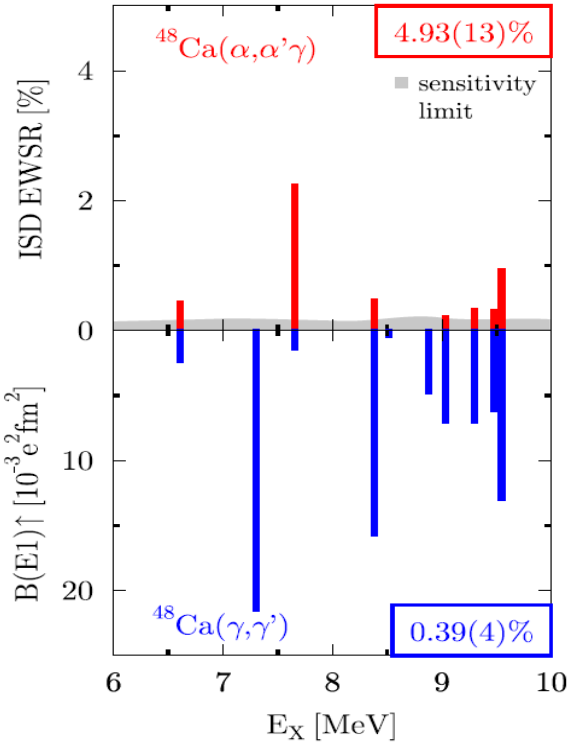


- heavy nuclei: E1 strength below GDR seems to split into dominantly isoscalar and dominantly isovector part
- medium mass nuclei: state-by-state variation of the isospin character

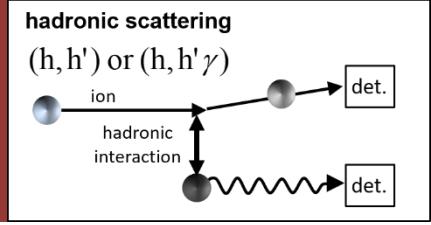


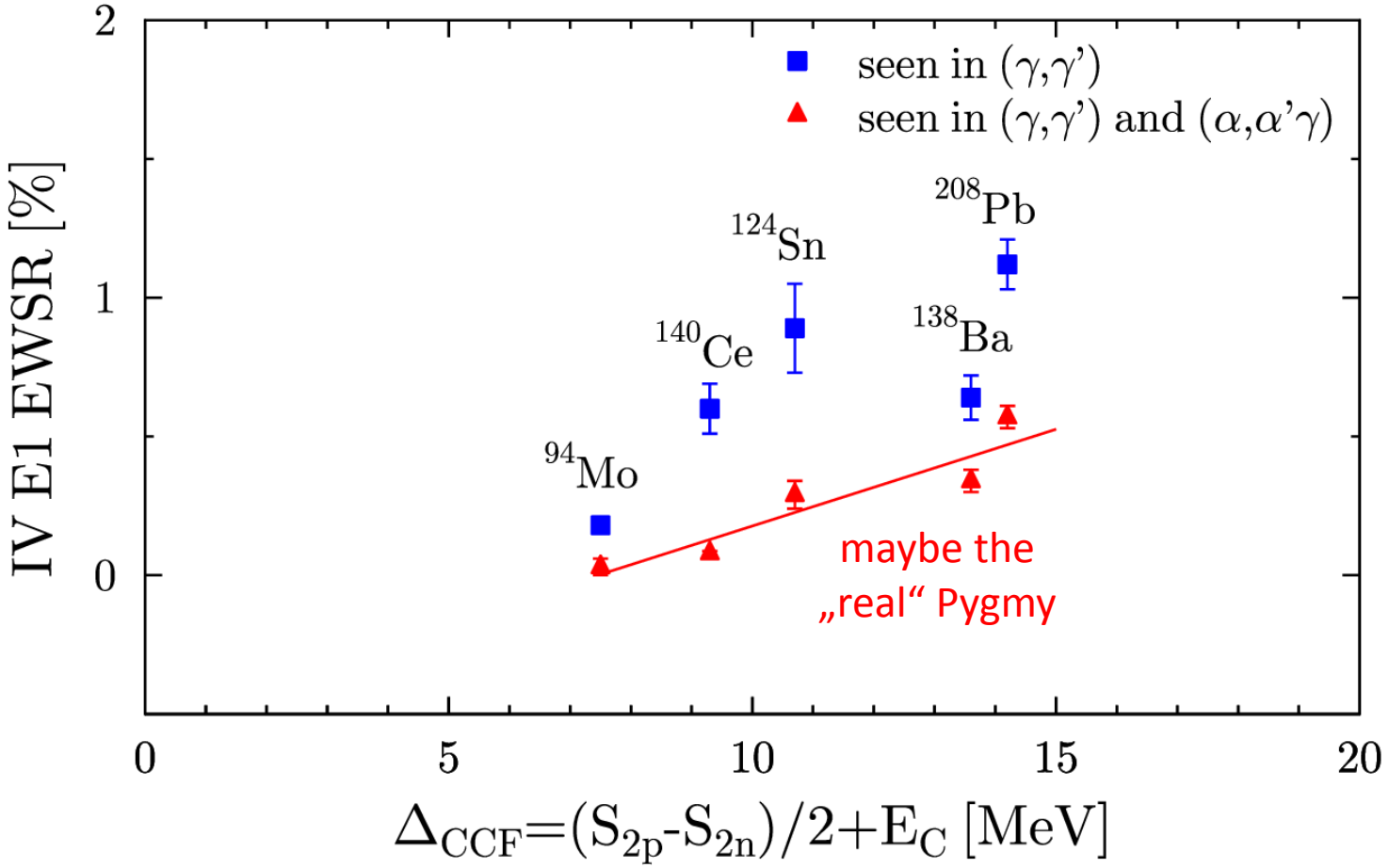
*M. Krzysiek, A. Bracco et al., PRC **93** (2016) 044330*



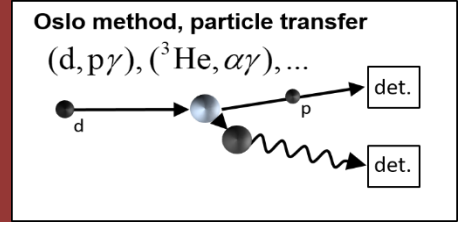
*V. Derya et al., PLB **730** (2014) 288*

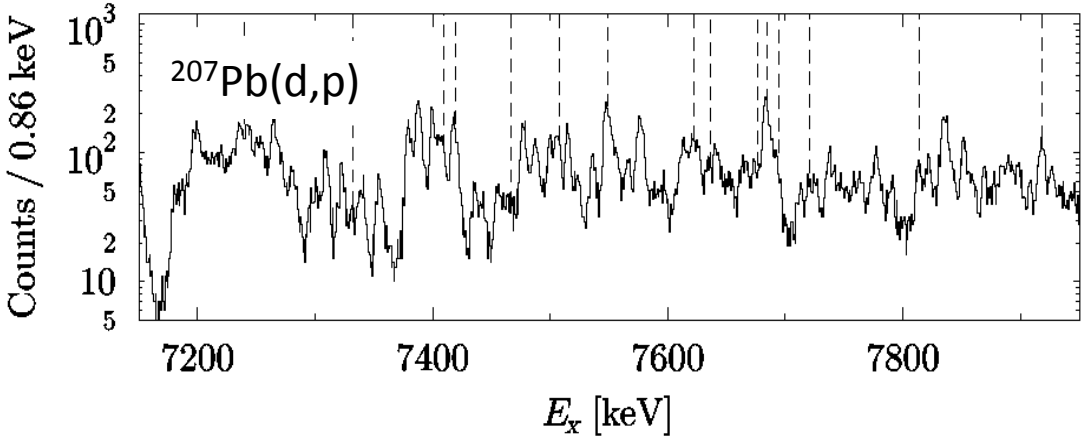
Hadronic interaction with α particles, protons, ^{17}O ions

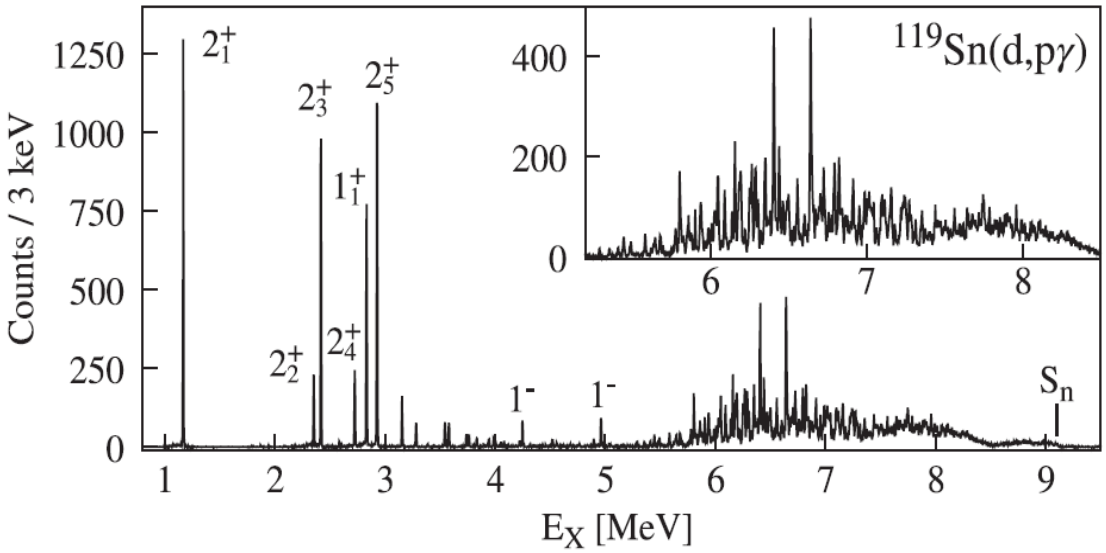




One-neutron transfer (d,p) reactions



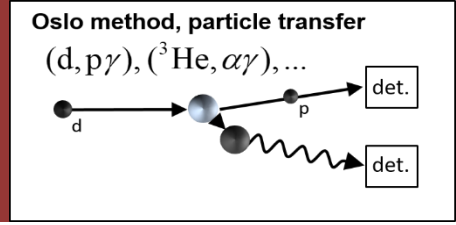




+ determines single particle character
+ good energy resolution
- studies only possible on certain nuclei
- data evaluation partly model dependent

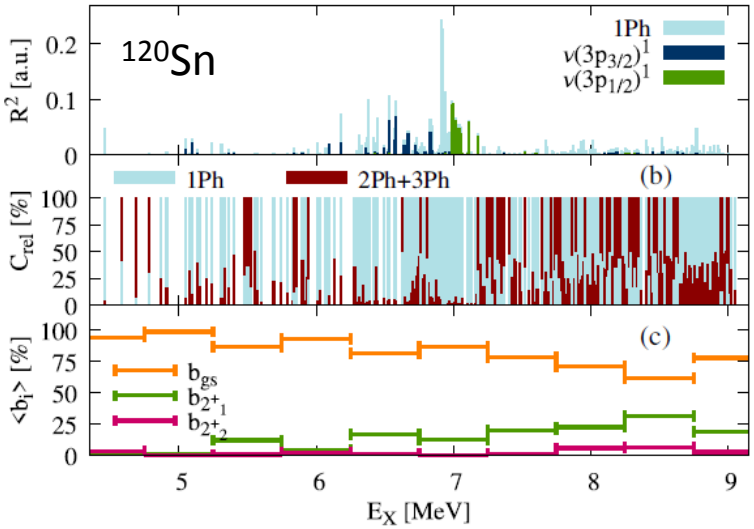
*M. Spieker et al., PRL **125** (2020) 102503*
*M. Weinert et al., PRL **127** (2021) 242501*

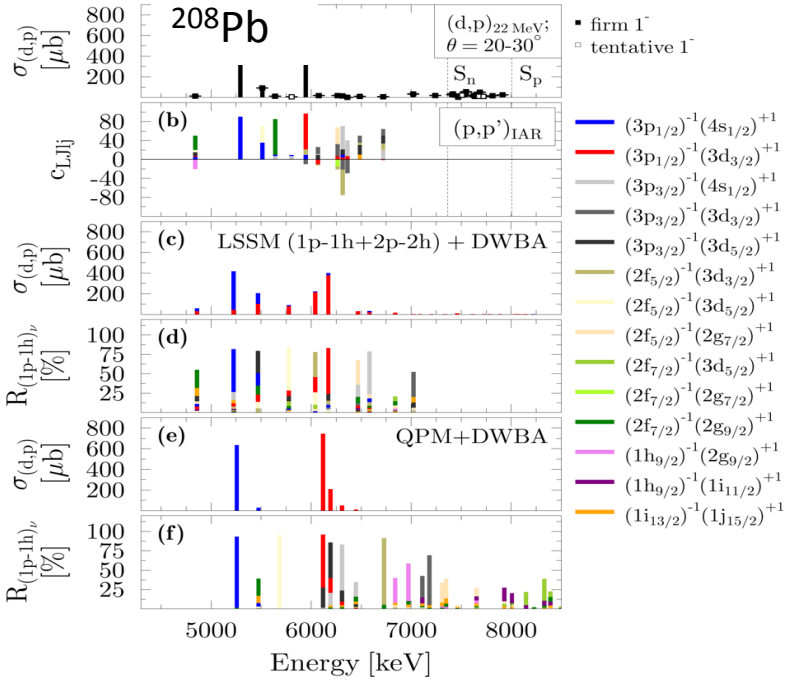
One-neutron transfer (d,p) reactions



- The low energy part of the E1 response is dominated by 1p1h configurations – at least in ^{120}Sn
- In doubly magic ^{208}Pb large scale shell model calculations and EDF+QPM do reproduce the gross features of the experiment

→ talks by MICHAEL WEINERT and MARK SPIEKER





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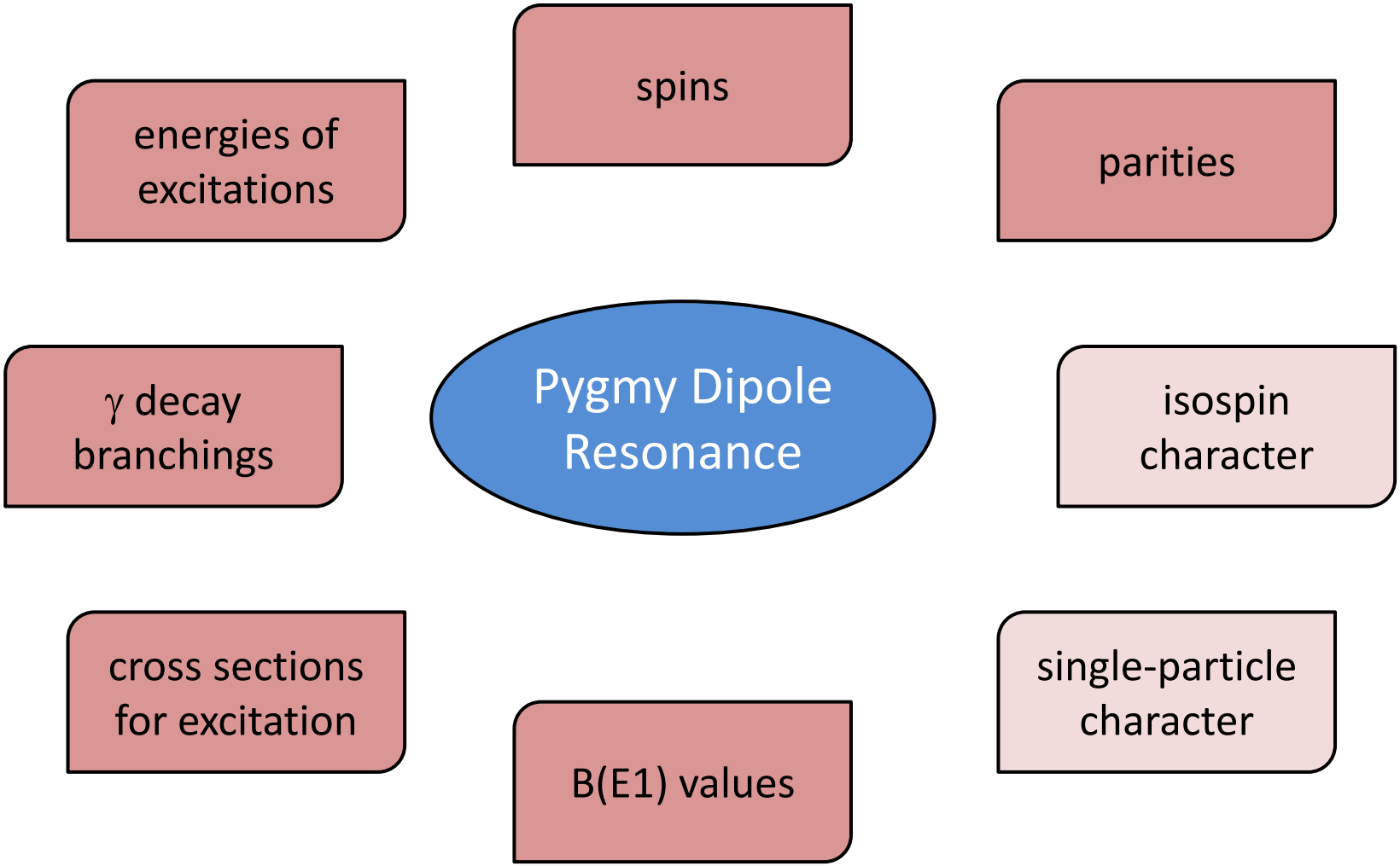
Experimental observables



Summary

- Electromagnetic response is often prerequisite for other experiments, but not sufficient to understand structure.
- Experiments and data evaluation are more complex for hadronic probes.
- Do not compare apples and pears/oranges!

- Systematics are very helpful:
  Evolution with mass, N/Z ratio, deformation…
  They are missing for hadronic probes.
- Form factors would be nice, could be feasible with (e,e‘γ).
- We need theory: Nuclear structure and reaction.

Pygmy or not Pygmy – an experimentalist's point of view

Miriam Müscher, Michael Weinert, Felix Heim, Johann Isaak[+], Florian Kluwig, Markus Müllenmeister, Deniz Savran[*], Tanja Schüttler, Basia Wasilewska, Julius Wilhelmy, and A. Z.

University of Cologne

+ TU Darmstadt

* GSI

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