End

Light-Ion Induced Nuclear Physics at iThemba LABS – is There a Future? *

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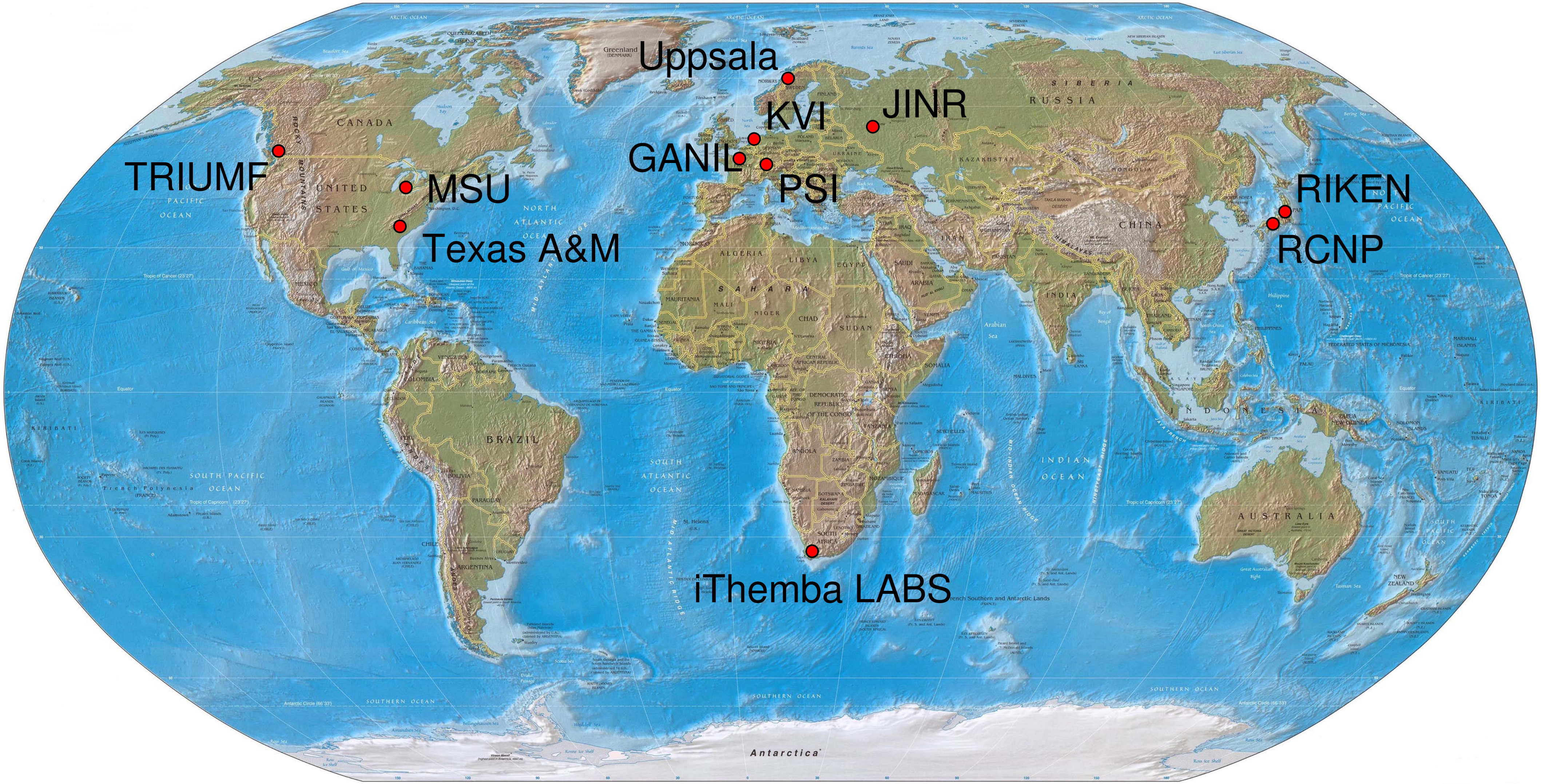
- Setting the frame
- Progress in physics through
  - → resolution
  - → selectivity
  - → new observables
- Closing remarks

* Supported by DFG under contracts SFB 634, Ne 679/2-2, and by the NRF

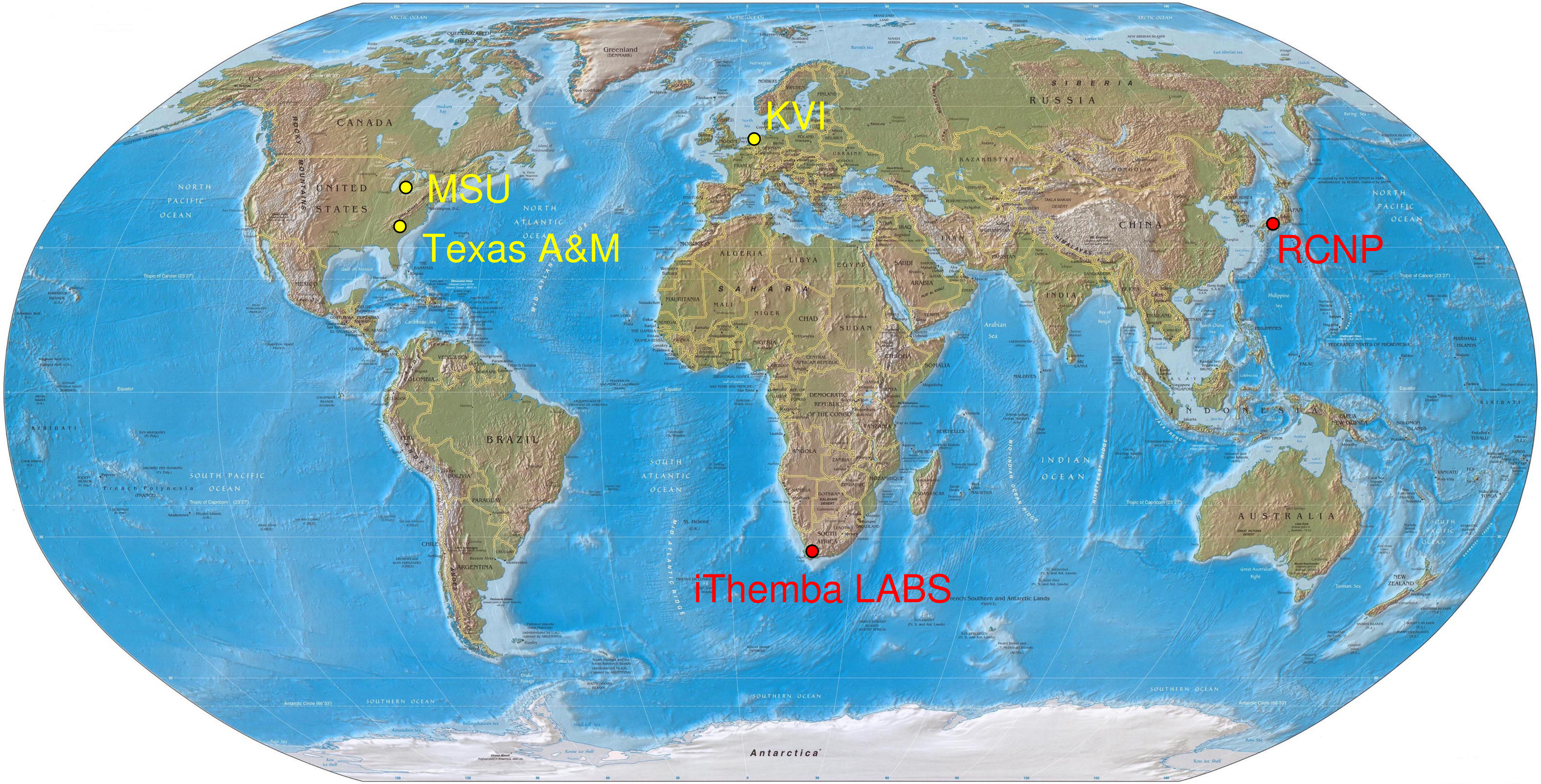
Comparable Research Centers Worldwide



Some Options I Will not Discuss

- Radioactive beams $\longrightarrow$ Second accelerator
- Intermediate energy physics (meson production, structure of the nucleon) $\longrightarrow$ energy upgrade
- Precision tests of the standard model
  $\longrightarrow$ production of selected isotopes, slowing and capturing, traps

Comparable Research Centers Worldwide



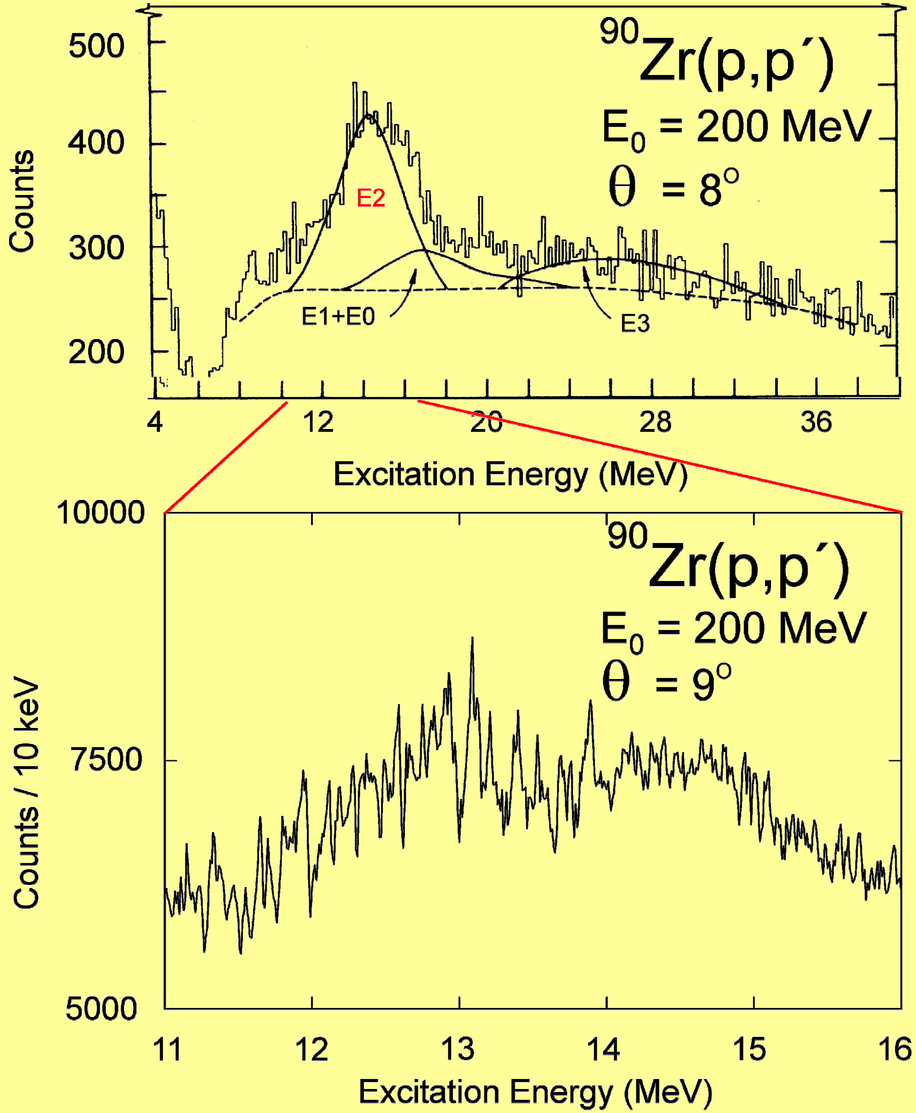
Possible Routes

- Progress in physics is closely linked to progress in experimental techniques
  - → resolution
  - → selectivity
  - → new observables - a polarimeter

  examples

- Use of complementary reactions amplifies the physics insight
  - → combine hadronic and electromagnetic probes

First Example: Fine Structure of Giant Resonances



$\Delta E \approx 1$ MeV

TRIUMF (1981)

broad bump

Lorentzian centroid and width

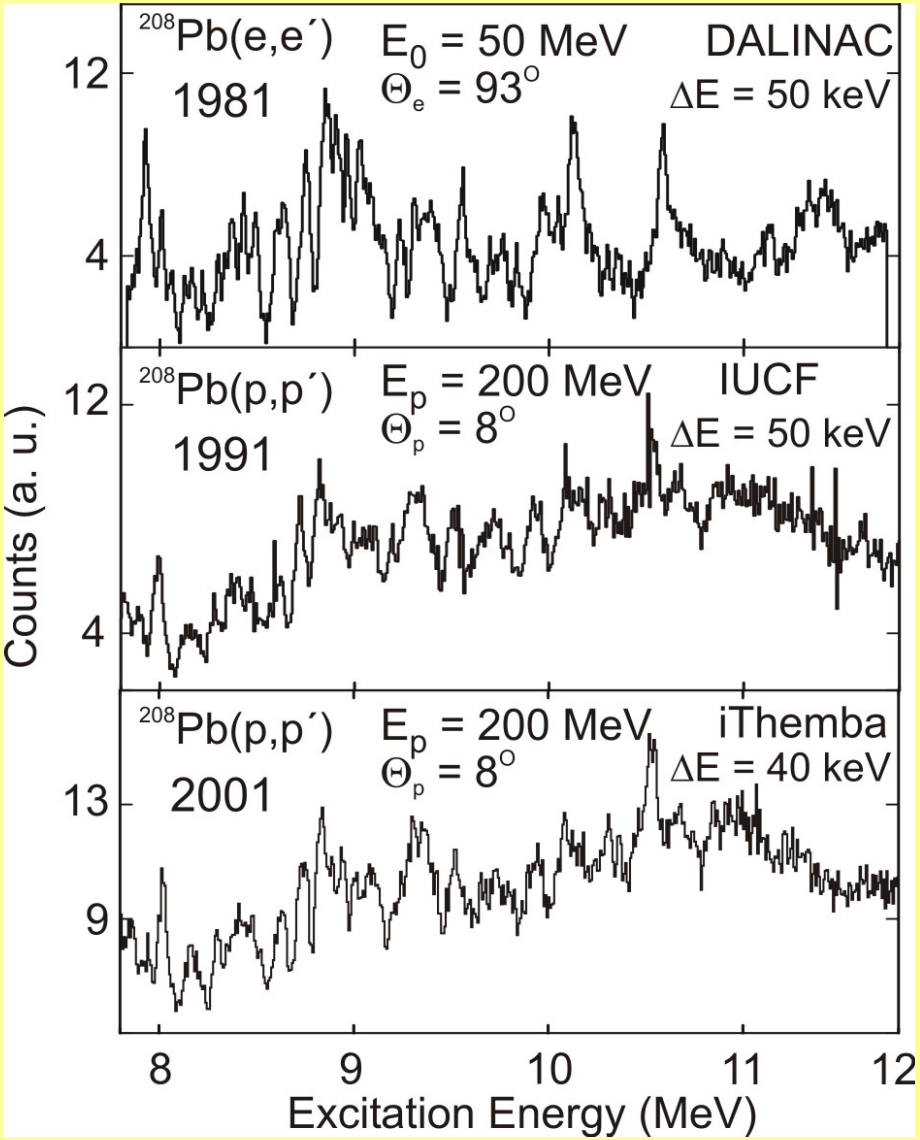
$\Delta E \approx 40$ keV

iThemba LABS (2001)

fine structure

not a Lorentzian!

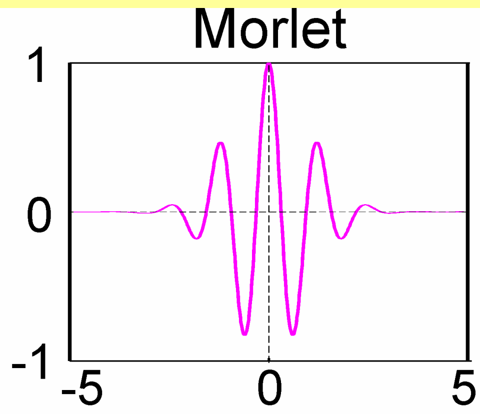
Fine Structure of Giant Resonances



- Different probes but similar structures
- Reproducable → fine structure are physics not statistical fluctuations

Wavelet Analysis

$$\int_{-\infty}^{\infty} \Psi^*(x)\, dx = 0 \quad \text{and} \quad \int_{-\infty}^{\infty} \left|\Psi^*(x)\right|^2 dx < \infty$$



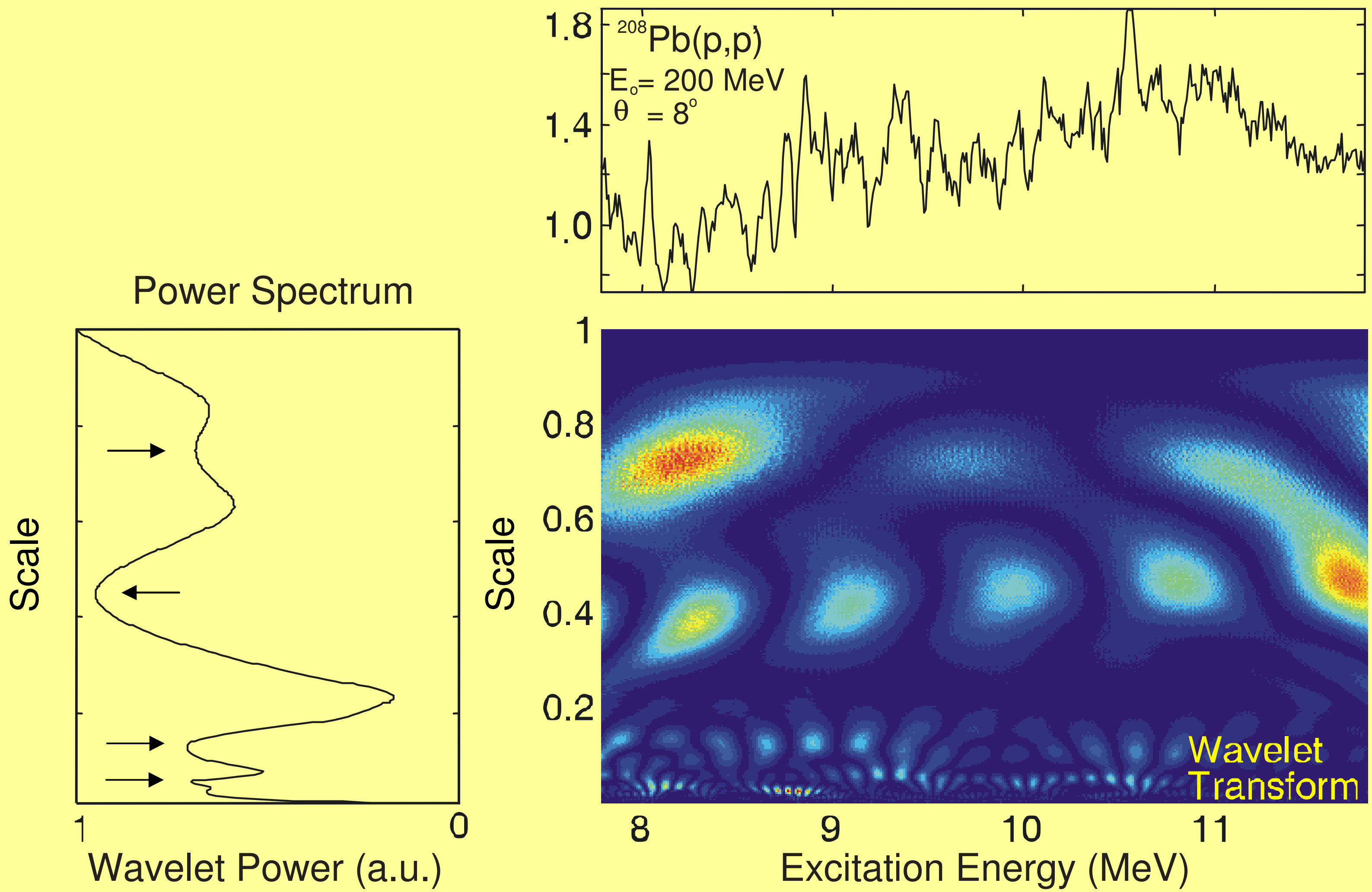
$$\Psi(x) = \cos(2\pi\omega x)\, e^{-x^2/2}$$

Wavelet coefficients:

$$C(\underset{\text{scale}}{\underset{\uparrow}{\delta E}}, \underset{\text{position}}{\underset{\uparrow}{E_x}}) = \frac{1}{\sqrt{\delta E}} \int \underset{\text{spectrum}}{\underset{\uparrow}{\sigma(E)}}\ \underset{\text{wavelet}}{\underset{\uparrow}{\Psi^*}}\left(\frac{E_x - E}{\delta E}\right) dE$$

Continuous: δE, E_x are varied continuously

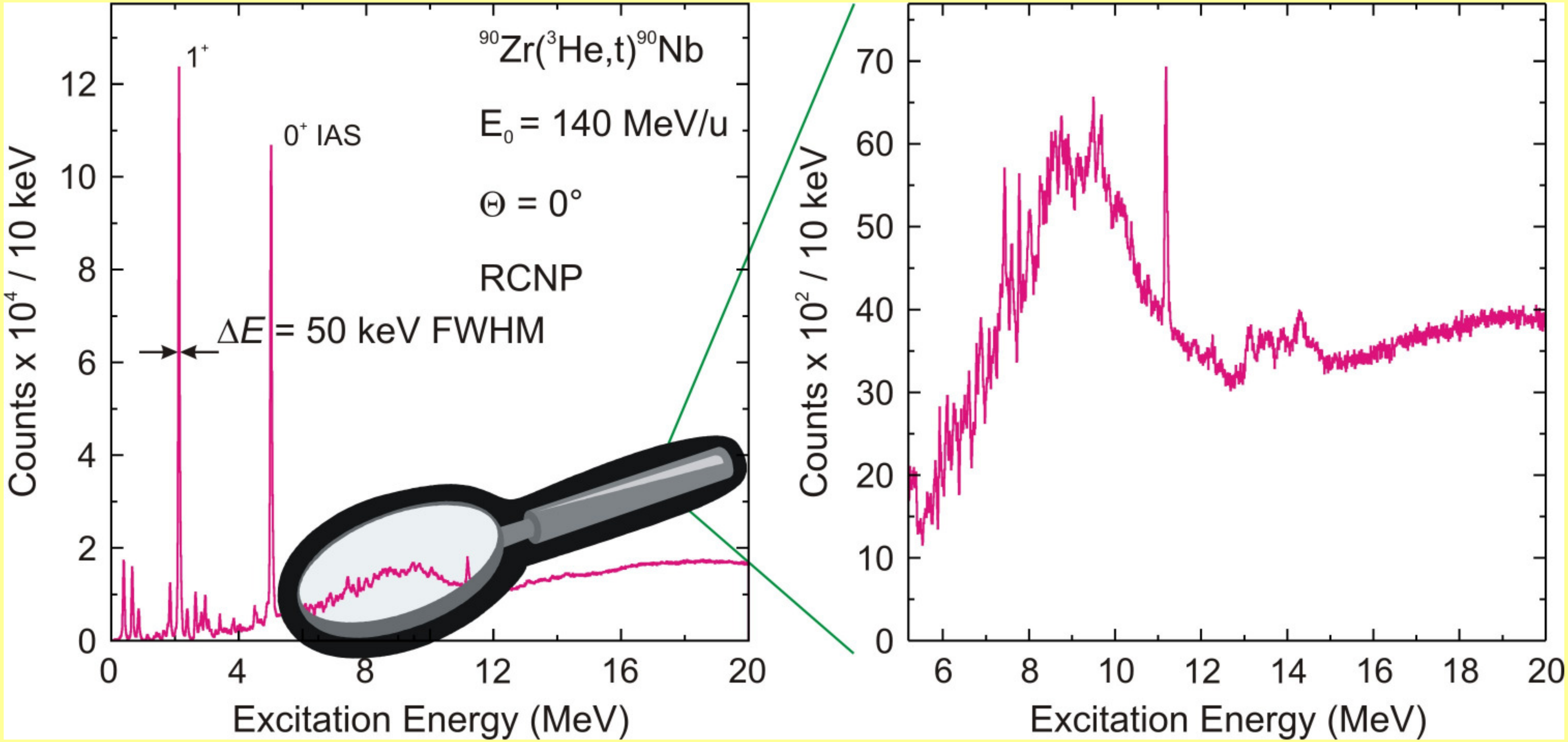
Wavelet Analysis of ^{208}Pb



- Scales characterize the fine structure

  A. Shevchenko et al., Phys. Rev. Lett. 93, 122501 (2004)

Fine Structure of the Spin-Flip GT Resonance



- Fine structure of giant resonances is a global phenomenon, e.g. observed also in the GT resonance (a spin-isospin flip mode)

Y. Kalmykov et al., Phys. Rev. Lett. 96, 012502 (2006)

Second Example: Mixed-Symmetry States in ^{94}Mo

- IBM $\rightarrow$ pairing of nucleons to s- / d-bosons
- IBM-2 $\rightarrow$ F-spin: π boson: $F_0 = 1/2$
  ν boson: $F_0 = -1/2$

$$\frac{|N_\pi - N_\nu|}{2} \leq F \leq F_{max} = \frac{N_\pi + N_\nu}{2}$$

$\longrightarrow$ $F = F_{max}$: symmetric states

$\longrightarrow$ $F < F_{max}$: mixed-symmetry states (ms)

- Q-phonon scheme:

$$Q_s = Q_\pi + Q_\nu \qquad |2_1^+\rangle \propto Q_s |0_1^+\rangle$$

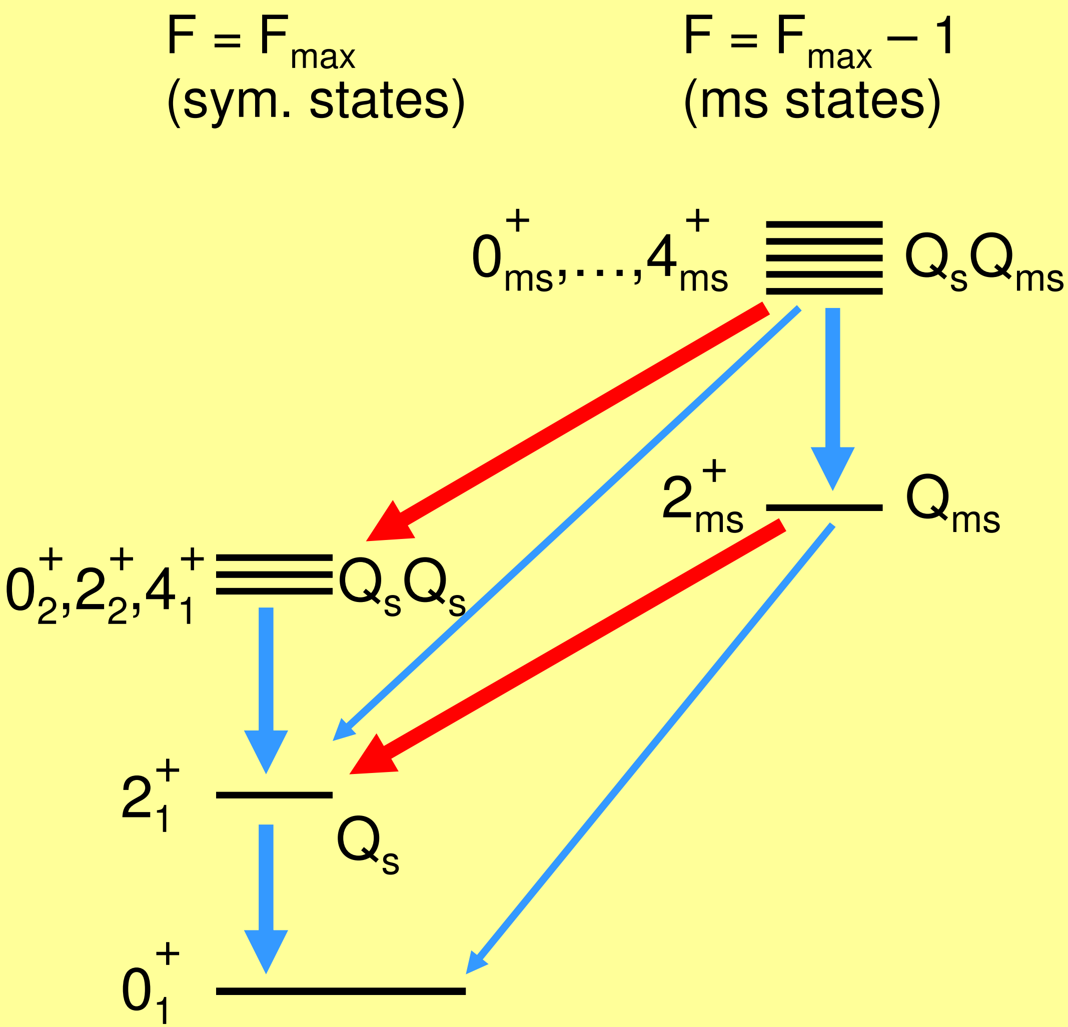
$$Q_{ms} = \frac{N}{2}\left(\frac{Q_\pi}{N_\pi} - \frac{Q_\nu}{N_\nu}\right) \qquad |2_{ms}^+\rangle \propto Q_{ms} |0_1^+\rangle$$

- Are ms states elementary excitations like low-energy surface vibrations (phonons)?
- Coupling to multiphonon states

$\longrightarrow$ harmonic?

$\longrightarrow$ pure?

Signatures of MS States



- Strong **E2** transitions for decay of symmetric Q-phonon
- Weak E2 transitions for decay of ms Q-phonon
- Strong **M1** transitions for decay of ms states to symmetric states

- Test case ^{94}Mo

N.Pietralla et al., Phys. Rev. Lett. 83, 1303 (1999); Phys. Rev. Lett. 84, 3775 (2000)
C.Fransen et al., Phys. Lett. B 508, 219 (2001); Phys. Rev. C 67, 024307 (2003)

Combined Study of ^{94}Mo(e,e´) and ^{94}Mo(p,p´)

- Complete observation of all 2^+ states up to 4 MeV required

  $\longrightarrow$ high resolution

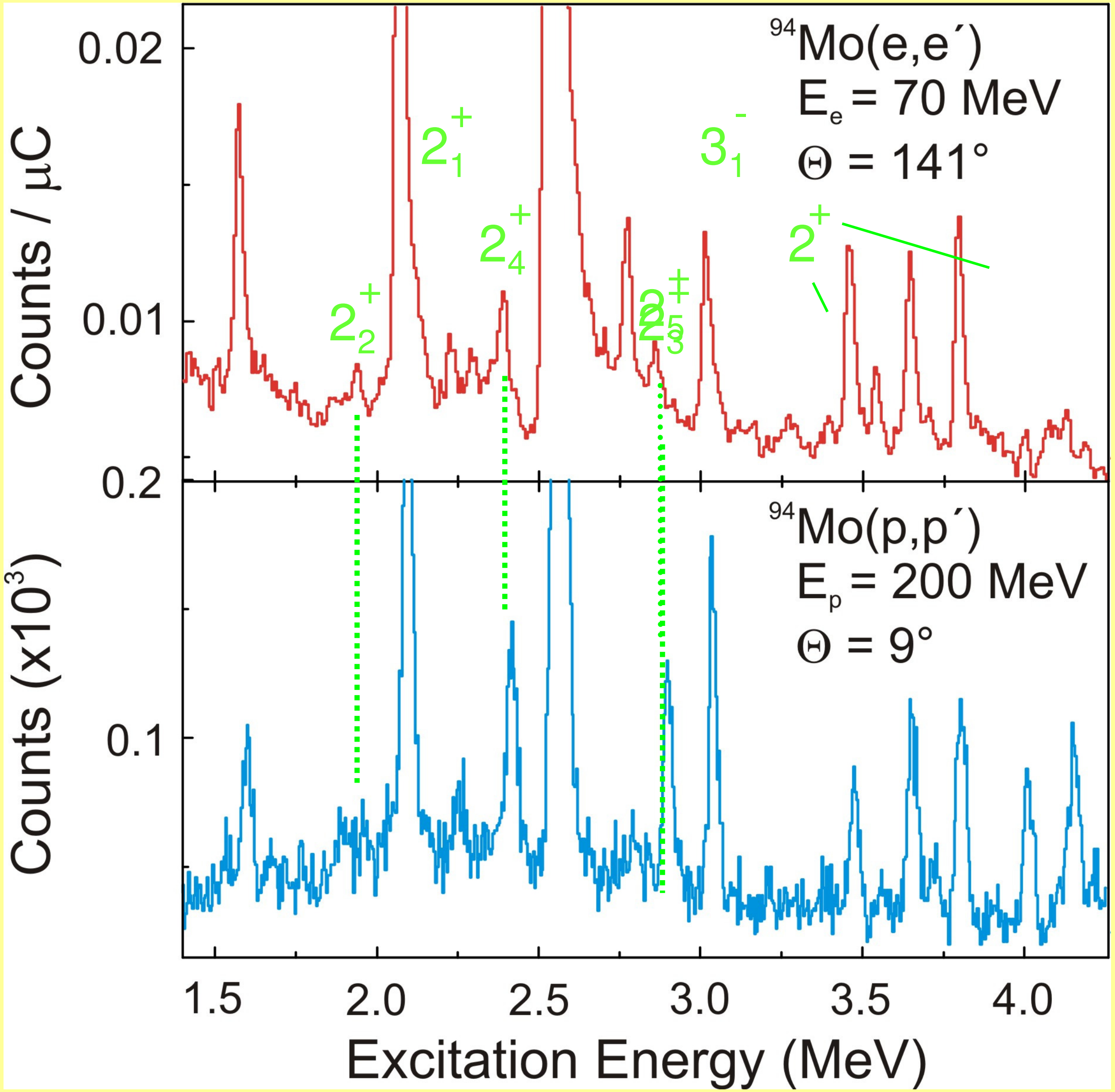
- Sensitive to one-phonon components of the wave functions

- Mixed-symmetry $\leftrightarrow$ isovector excitation in the valence shell

  $\longrightarrow$ isoscalar / isovector decomposition

- UCT / U Cologne / TU Darmstadt / iThemba LABS / Wits collaboration

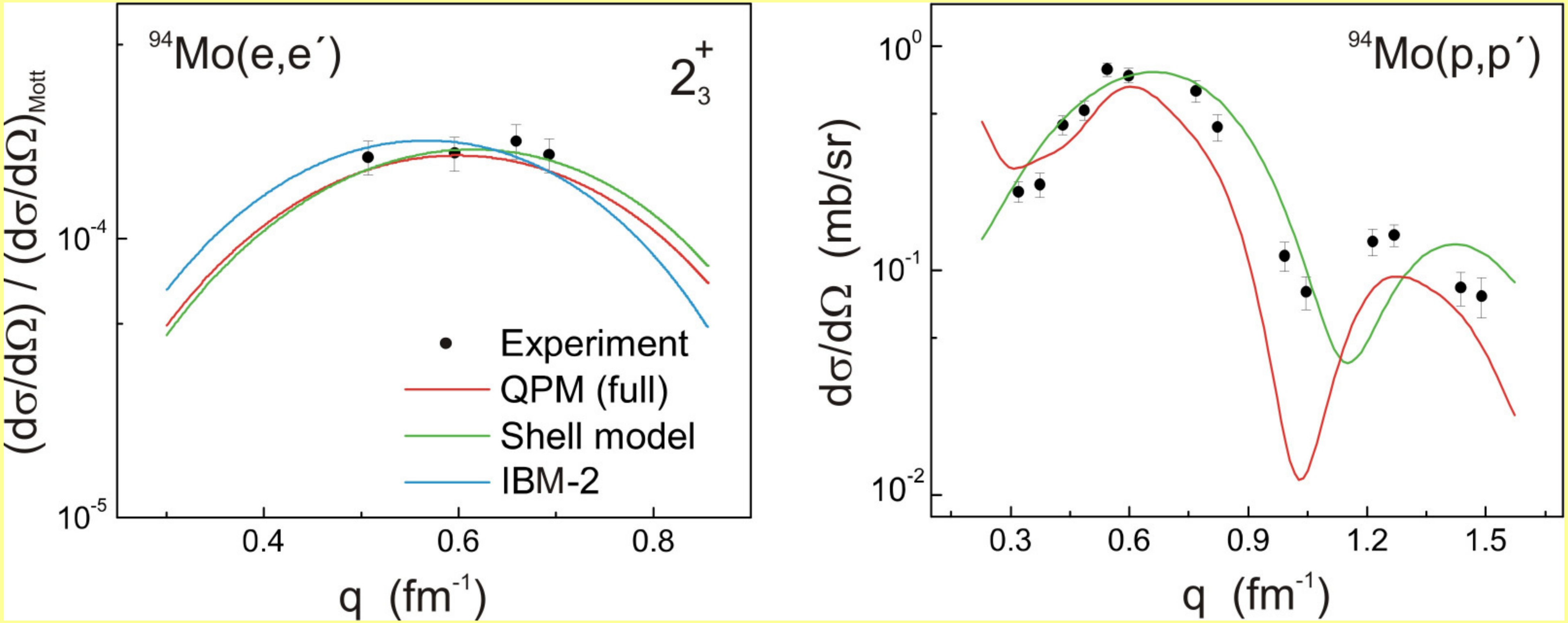
Data



S-DALINAC

iThemba LABS

One-Phonon MS State



- Phonon character confirmed

O. Burda et al., Phys. Rev. Lett. (to be published)

Selectivity

Selectivity can be achieved by

- Kinematics

  $\longrightarrow$ example: 0° inelastic proton scattering

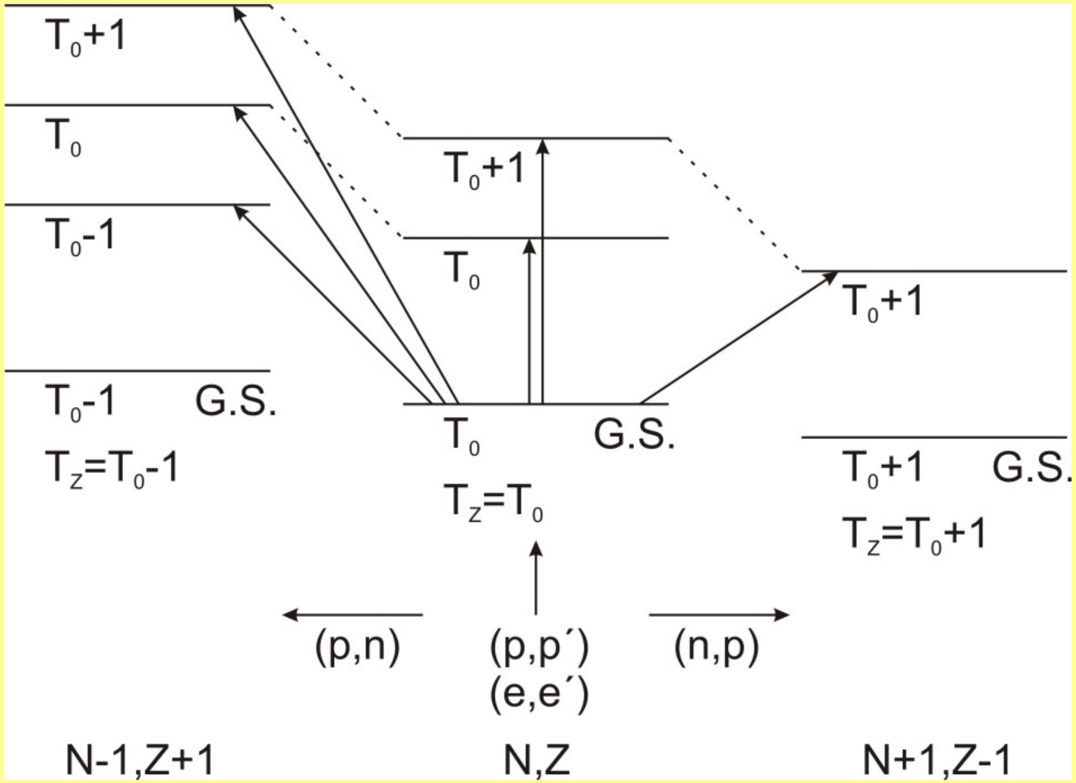
- Coincidence experiments

  $\longrightarrow$ example: isospin structure of the pygmy dipole resonance from $(\alpha,\alpha'\gamma)$

3rd Example: Inelastic Proton Scattering under 0°

- At 0° and intermediate energies (100 - 400 MeV/u)
  GT mode selectively excited
- Gamow-Teller: $\Delta L = 0$, $\Delta S = 1$, $\Delta T = 1$

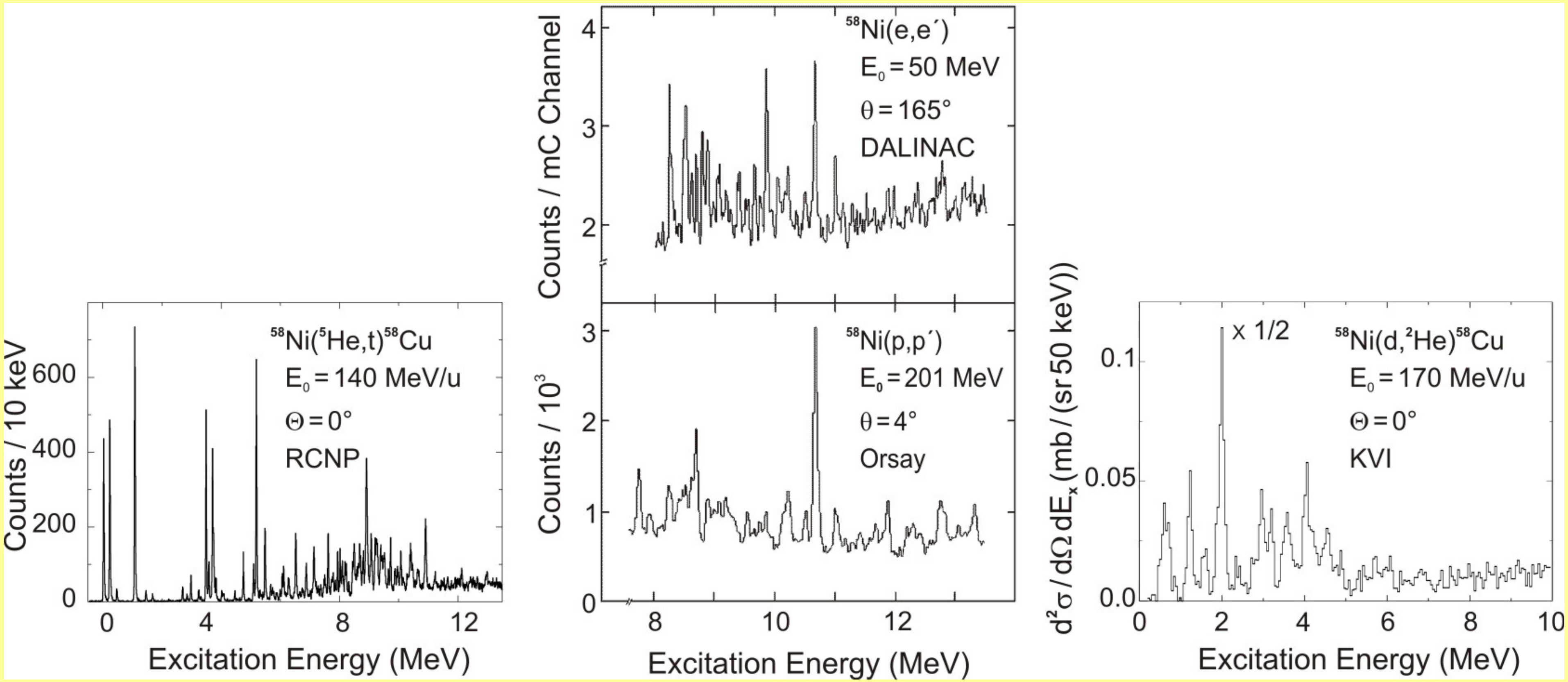
Isospin Symmetry



β^- decay β^+ decay

A = 58

GT$_-$ GT$_0$ GT$_+$



H.Fujita et al., EPJ (2002) W.Mettner et al., NPA (1987) M.Hagemann et al., PLB (2005)

- Benchmark tests of modern microscopic nuclear theory

GT Strengths in Nuclei and Supernova Physics

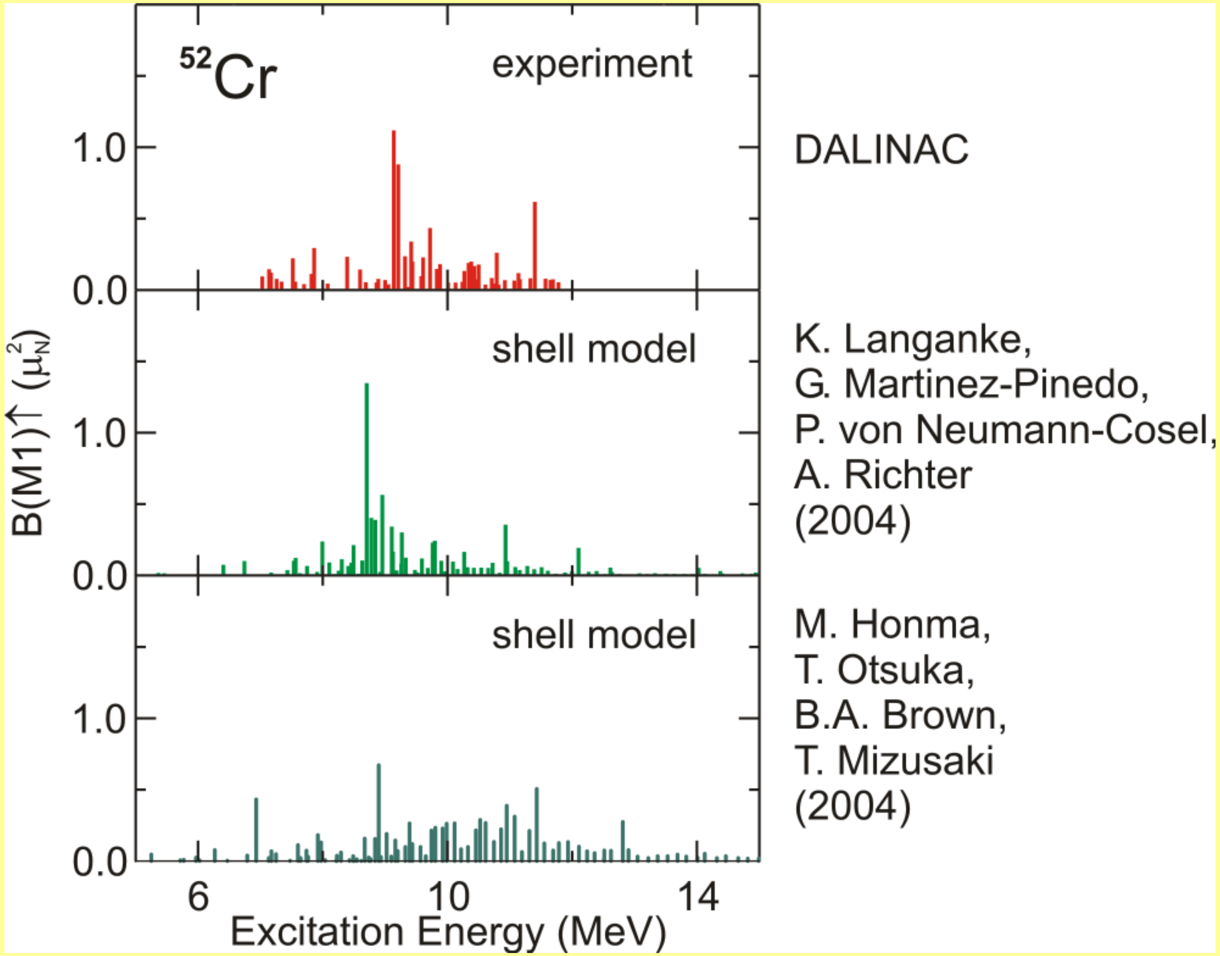
- Determine late precollapse stages of massive stars

  $\longrightarrow$ properties of "iron" core

- Explosive nucleosynthesis during the supernova shock wave

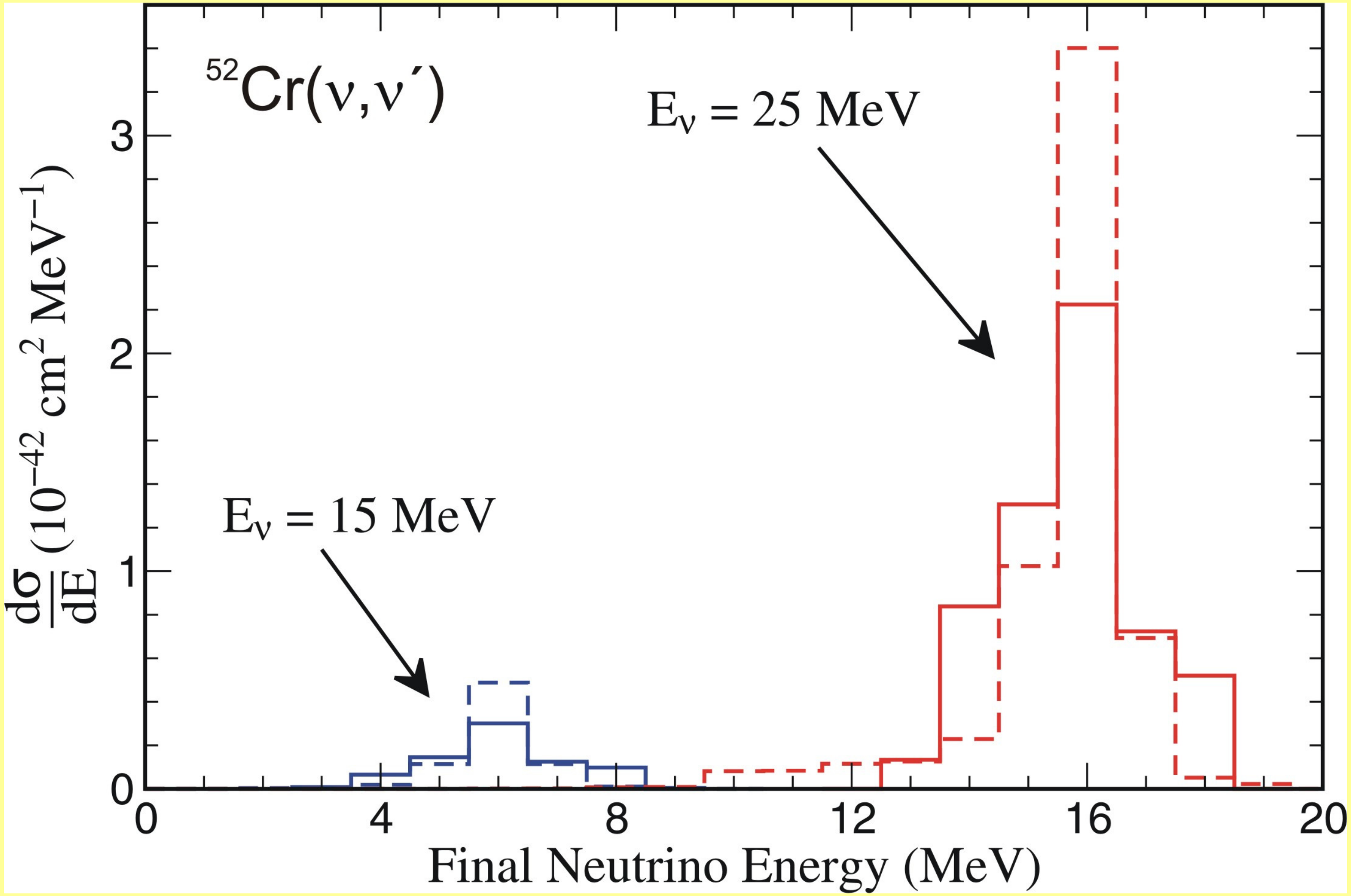
- Example: neutral current neutrino scattering on nuclei

Can State-of-the-Art Shell-Model Be Used to Predict the GT_0 Strength?



- Shell model works reasonably
- Probe: B(M1) from (e,e´) $\propto |M_S \pm M_L|^2$ $\rightarrow$ Spin dominant

ν – Nucleus Scattering Cross Sections

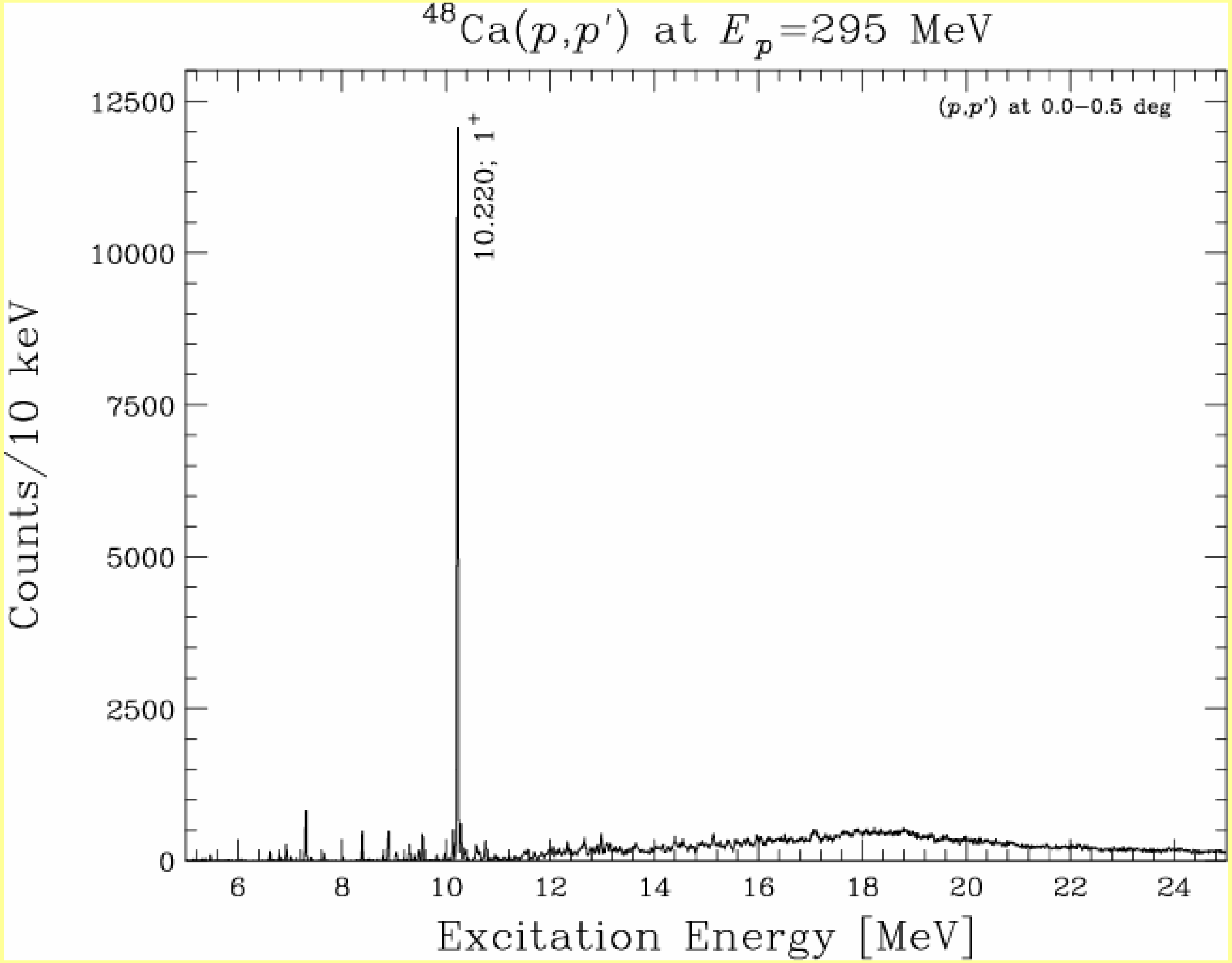


K.Langanke, G.Martinez-Pinedo, PvNC, A.Richter, Phys. Rev. Lett. 93, 202501 (2004)

Inelastic Proton Scattering under 0°

- Goal: extract GT_0 from $(p,p') \propto |M_s|^2$
- Very difficult: beam scattering, suppression of elastic scattering
- But very rewarding if combined with high resolution
- Initiative at iThemba LABS by UCT / TU Darmstadt / U Gent / iTL / Wits collaboration (with support from experts from RCNP and U Notre Dame)

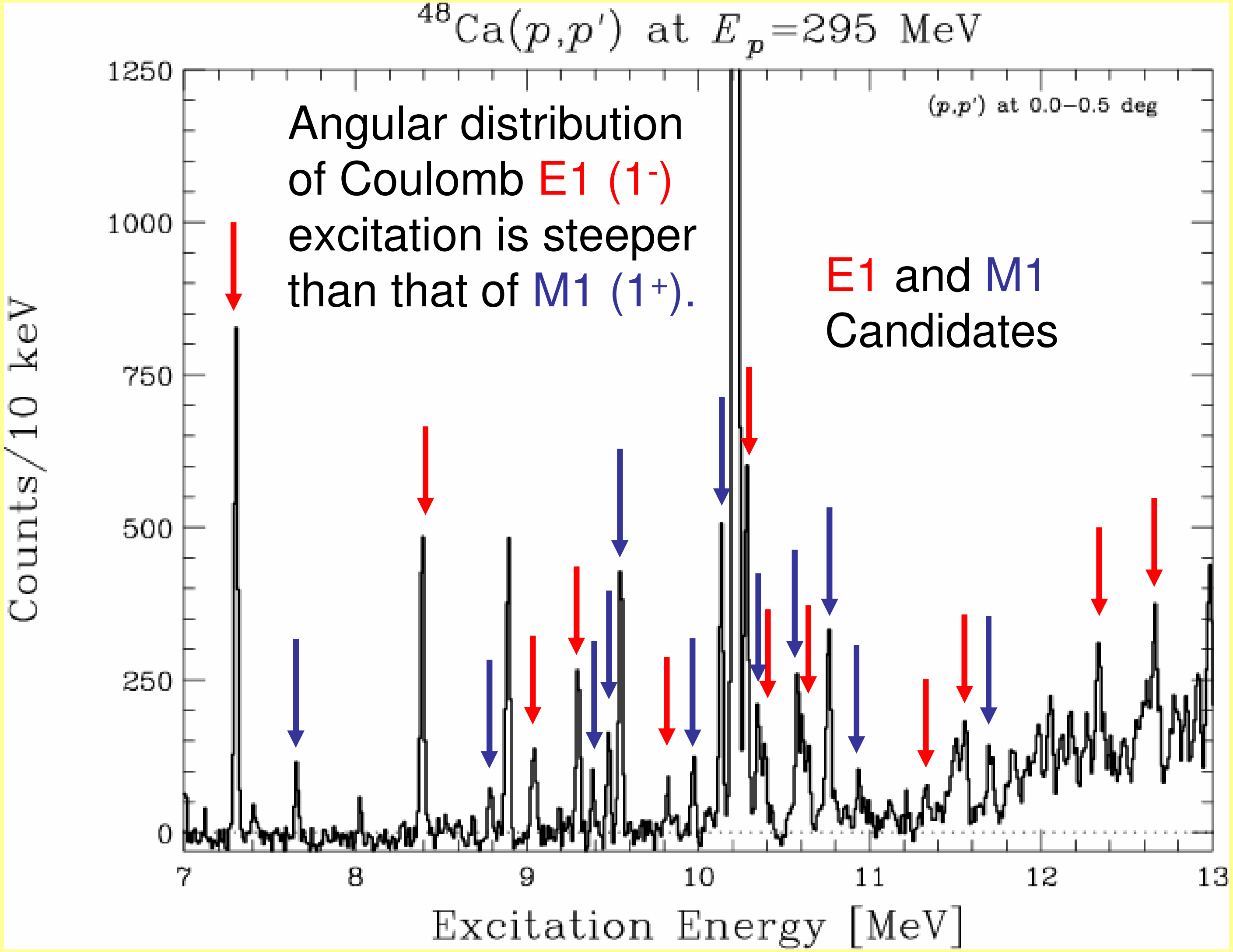
Very Recent Results from RCNP: ^{48}Ca



- Pure neutron $f_{7/2} \rightarrow f_{5/2}$ spinflip M1 excitation

  $\longrightarrow$ prime test case of spin quenching in nuclei

Very Recent Results from RCNP: ^{48}Ca

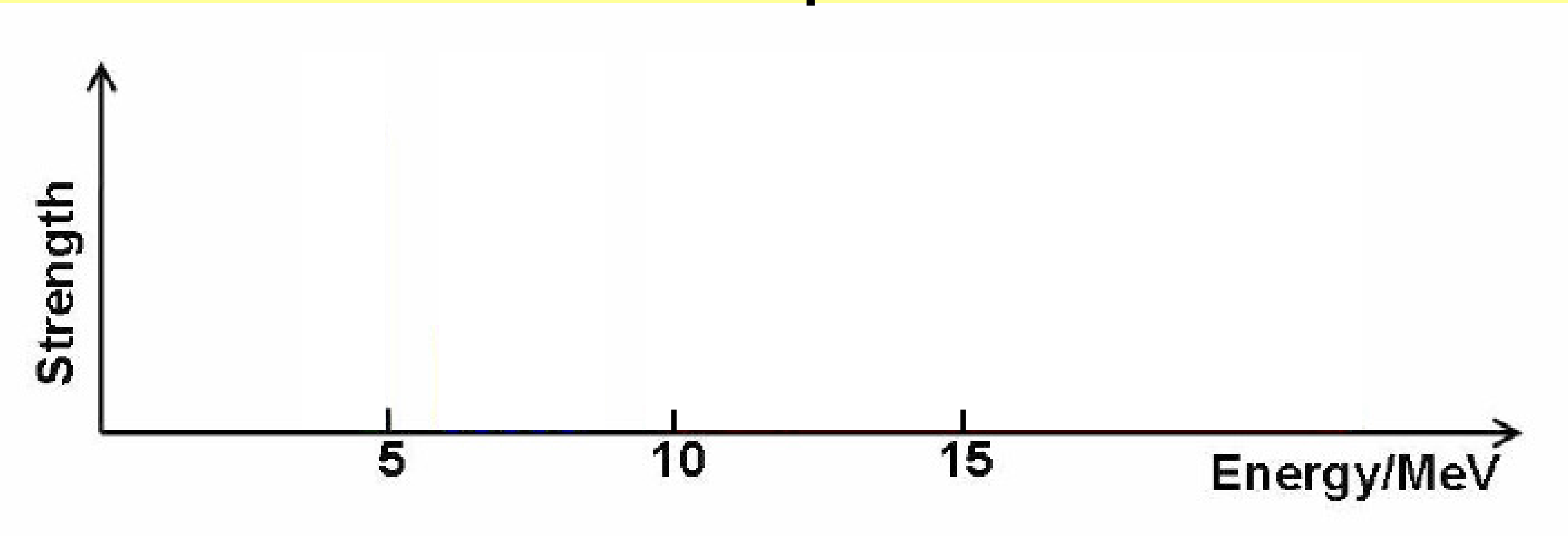


- Weak components of the M1 strength

A. Tamii et al., to be published

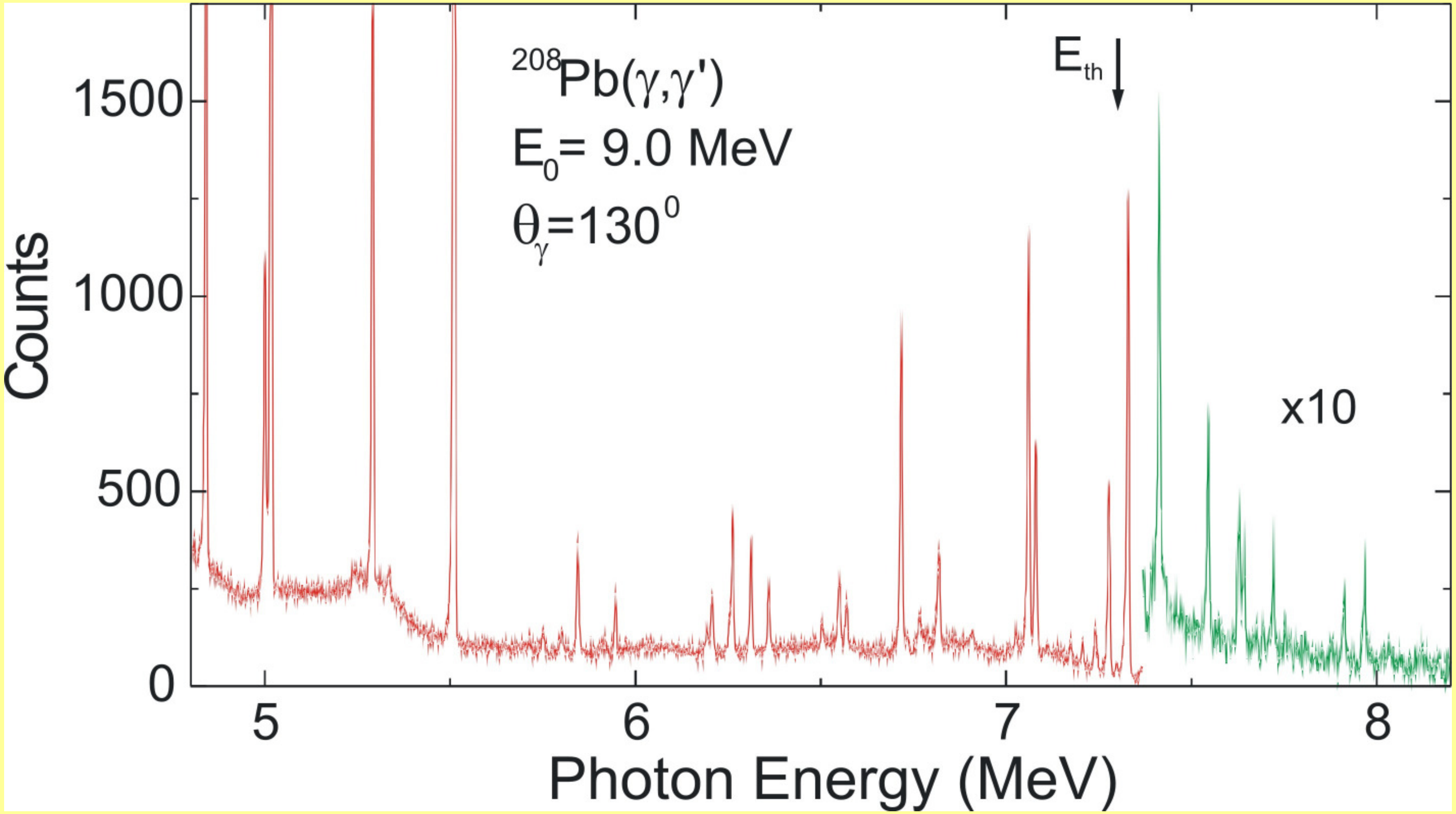
4th Example: Isospin Structure of the PDR from (α,$\alpha'\gamma$) Coincidence Experiments

E1 Response



- Two-phonon state ($2^+ \otimes 3^-$)
- Pygmy dipole resonance (PDR)
- Giant dipole resonance (GDR)

PDR in ^{208}Pb



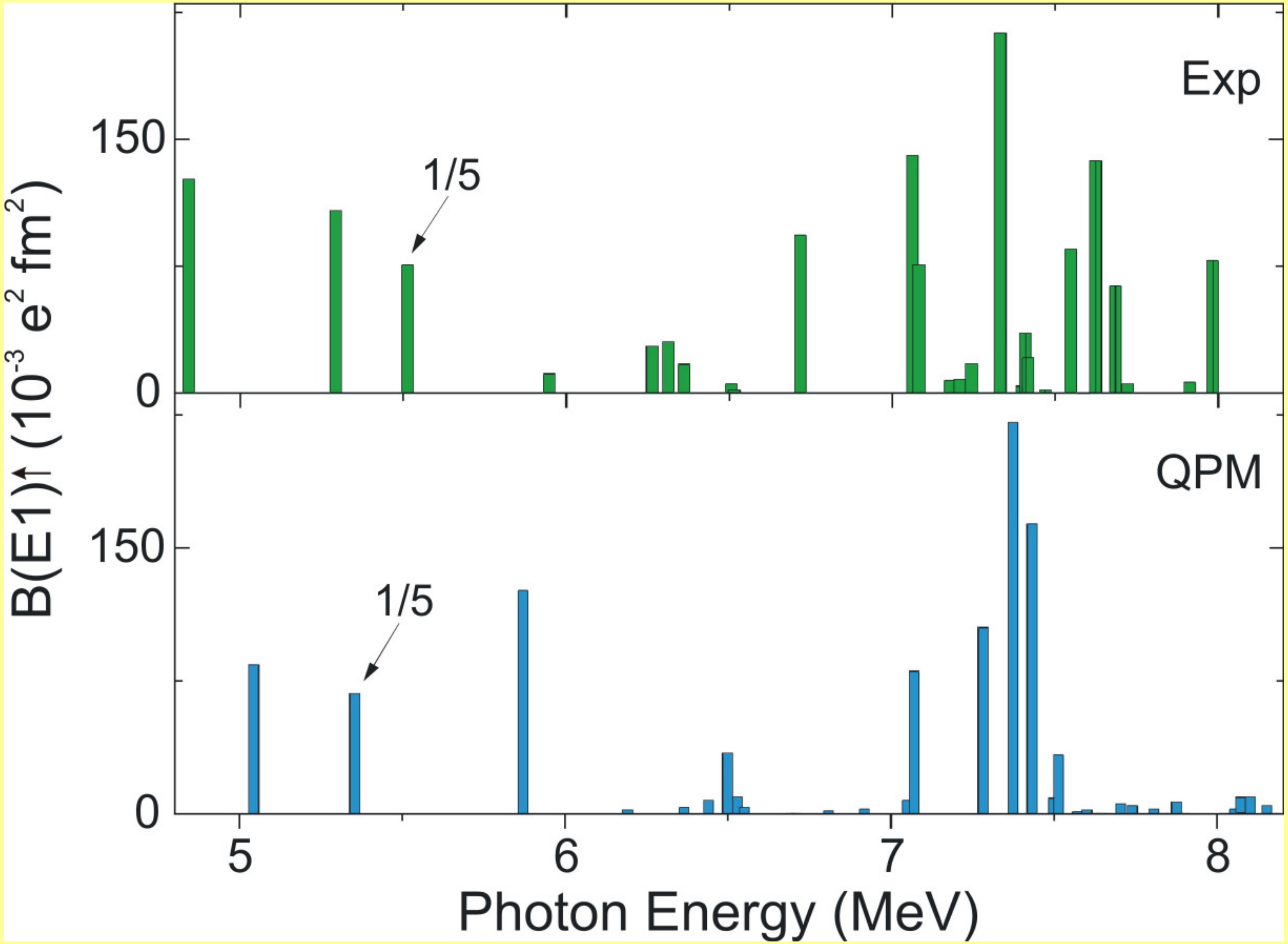
- Experimental evidence for PDR in ^{208}Pb

  N. Ryezayeva et al., Phys. Rev. Lett. 89, 272502 (2002)

- Also established at other shell closures (^{48}Ca, N=82)

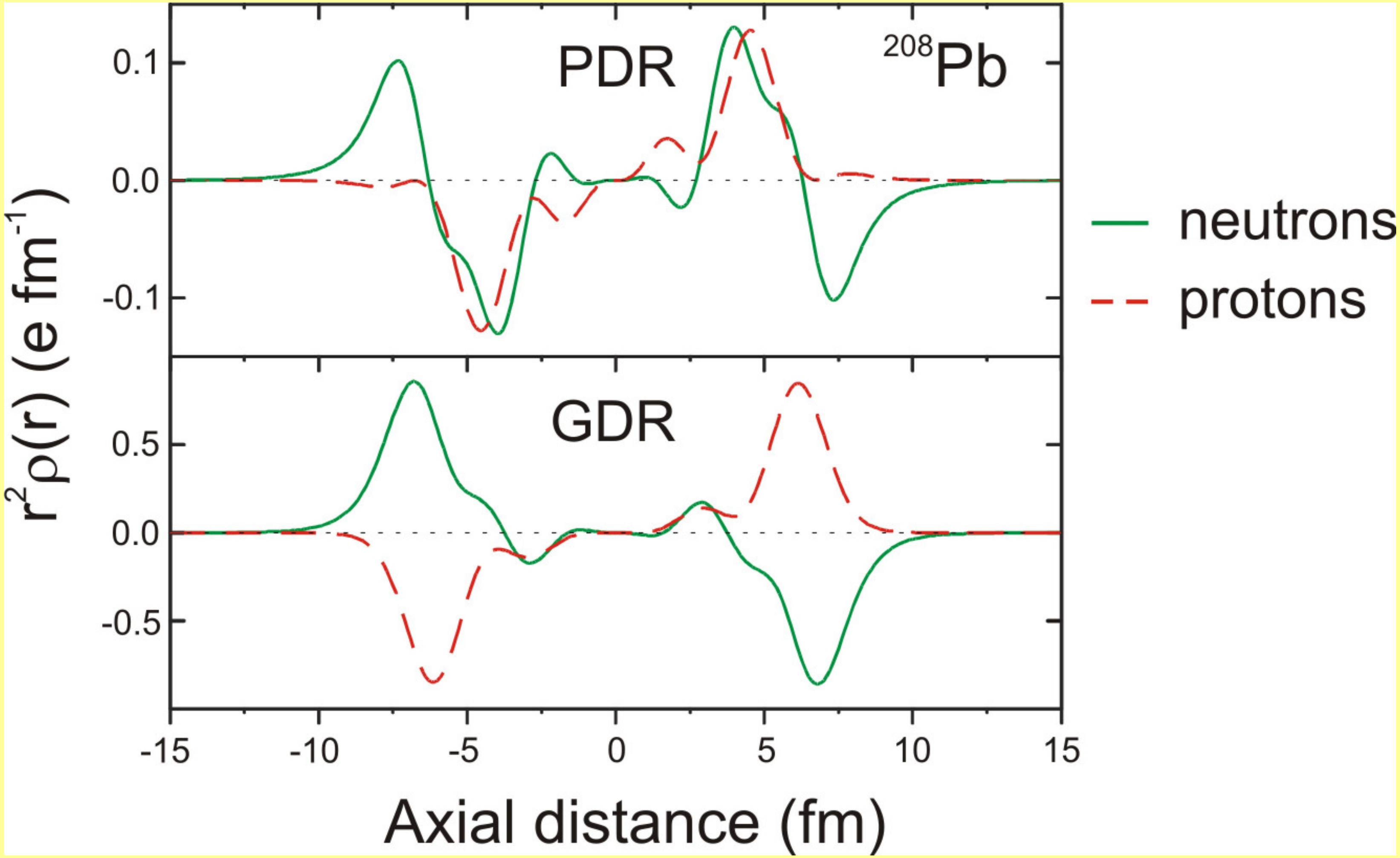
  A. Zilges et al., Phys. Lett. 542B, 43 (2002)
  T. Hartmann et al., Phys. Rev. Lett. 93, 192501 (2004)

Theoretical Interpretation of the PDR in ^{208}Pb



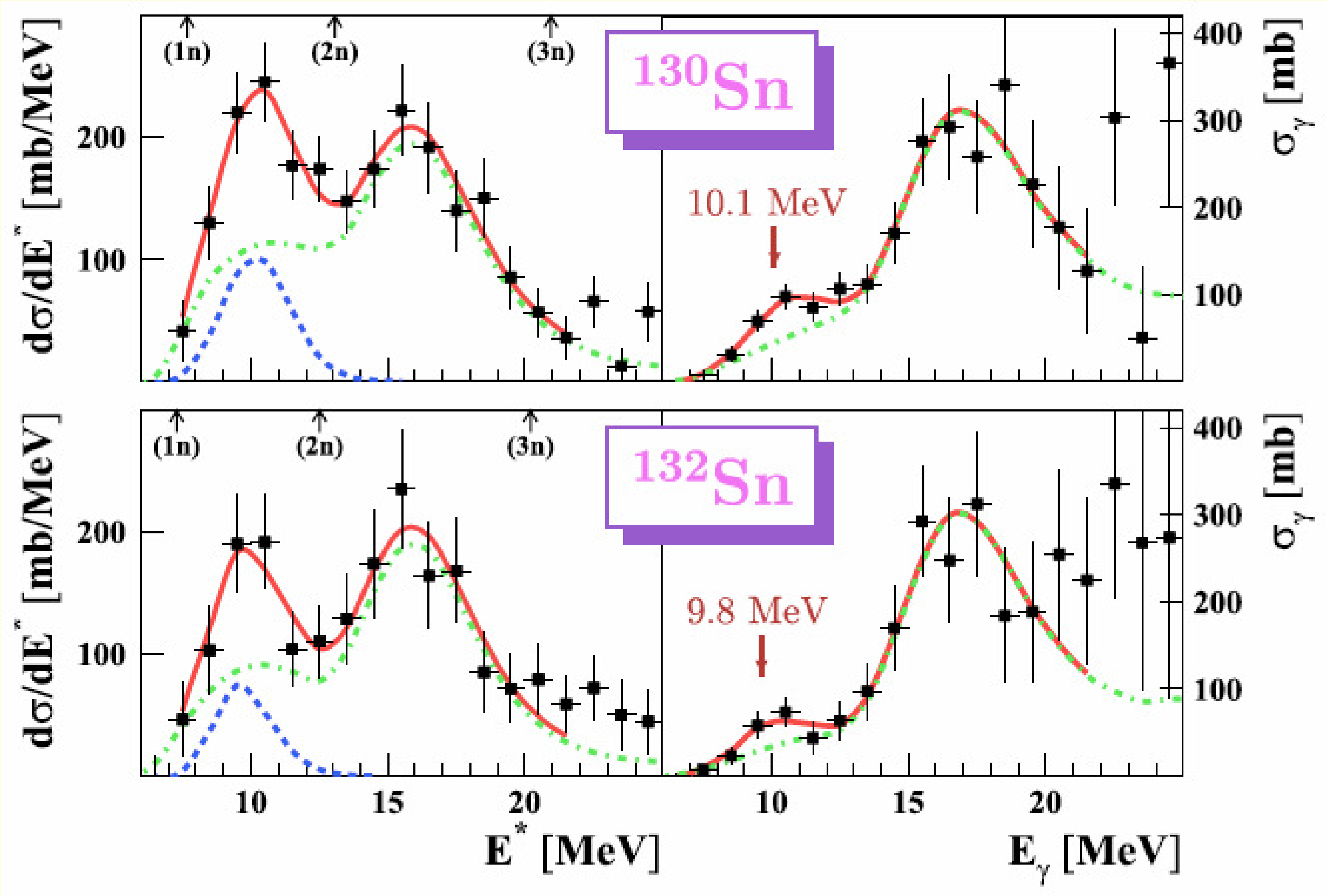
- Very good description by Quasiparticle Phonon Model including complex configurations

Isospin Nature of the Mode



- PDR charge transition density largely isoscalar
- But surface neutron density oscillations

PDR from Coulomb Breakup in Exotic Nuclei



GSI

- Relation to E1 strength at threshold in stable nuclei?

P. Adrich et al., Phys. Rev. Lett. 95, 132501 (2005)

Experimental Test of the Isospin Character of the PDR

Isospin character of PDR

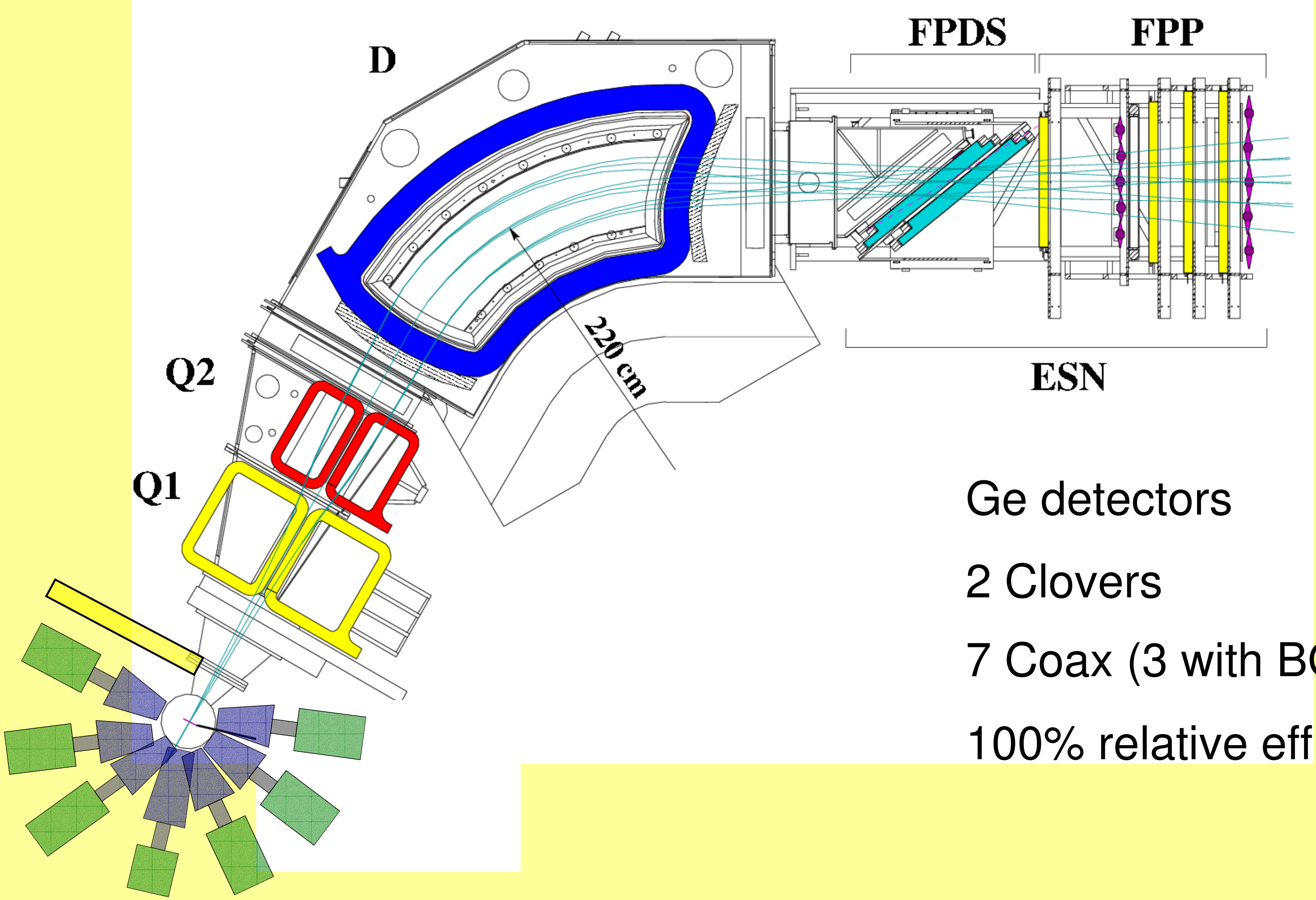
→ use (α,α'): pure isoscalar response but resolution insufficient in heavy nuclei

→ (α,$\alpha'\gamma$) with Ge detectors challenging because of background

→ feasibility study at KVI

TU Darmstadt / KVI collaboration

Setup at KVI



Ge detectors

2 Clovers

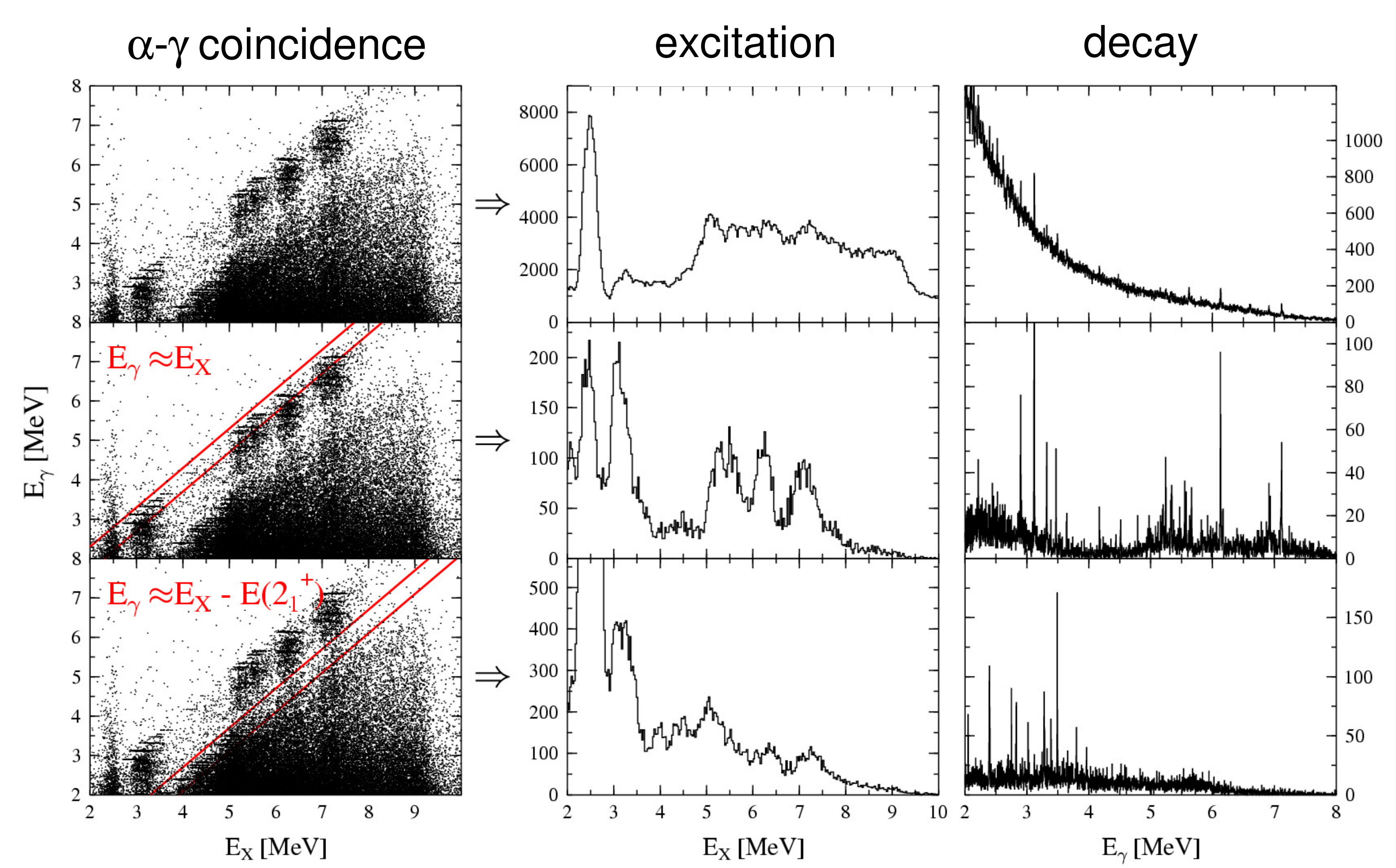
7 Coax (3 with BGO)

100% relative efficiency

- Total photopeak efficiency: 0.5% at 1.33 MeV

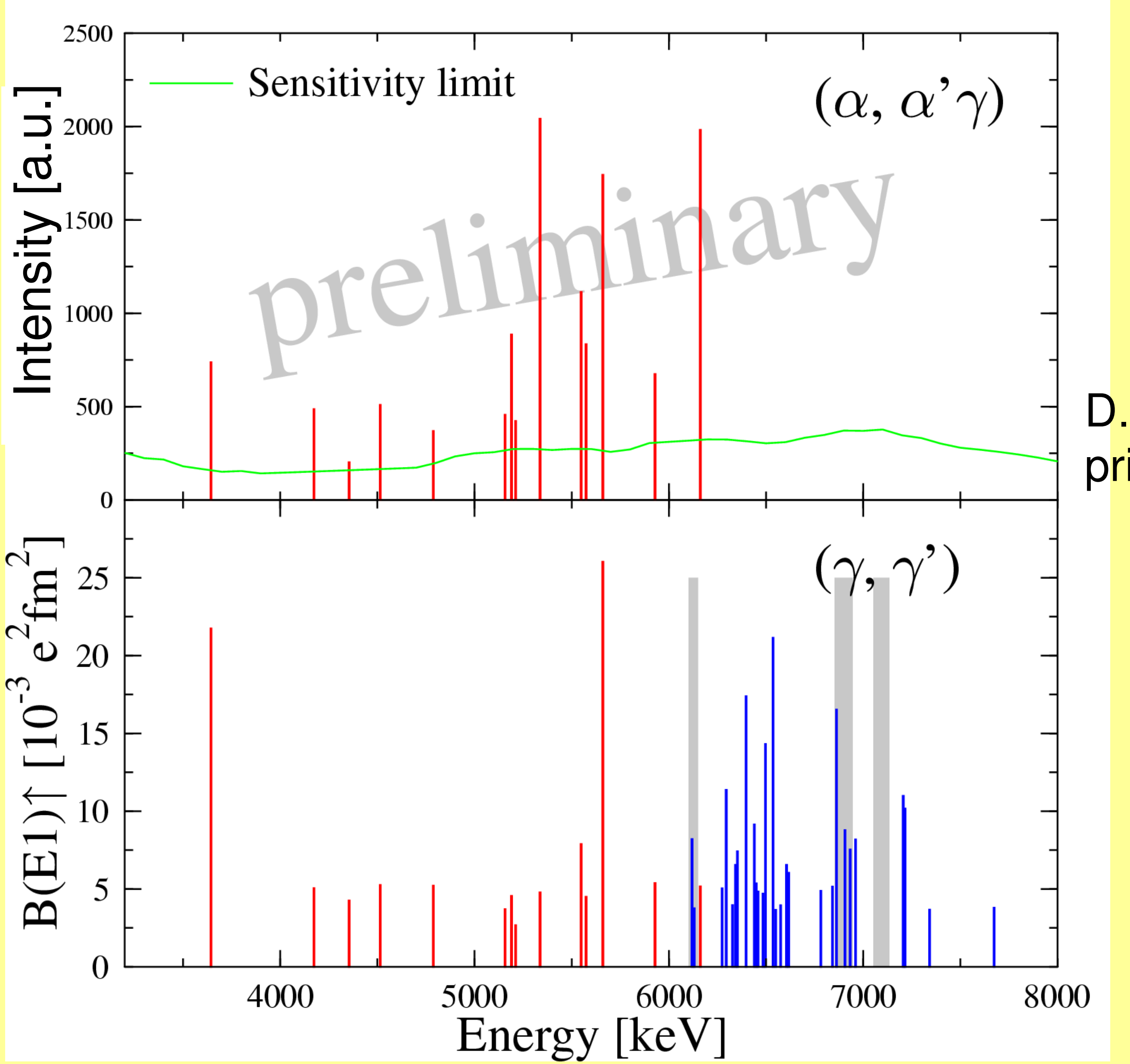
  D.Savran et al., Nucl. Inst. Meth. A (in press)

^{140}Ce(α,α´γ)



- Selectivity by gating on g.s. and 2^+ decay

^{140}Ce(α,α´γ) vs. ^{140}Ce(γ,γ´)



D. Savran, A. Zilges, private communication

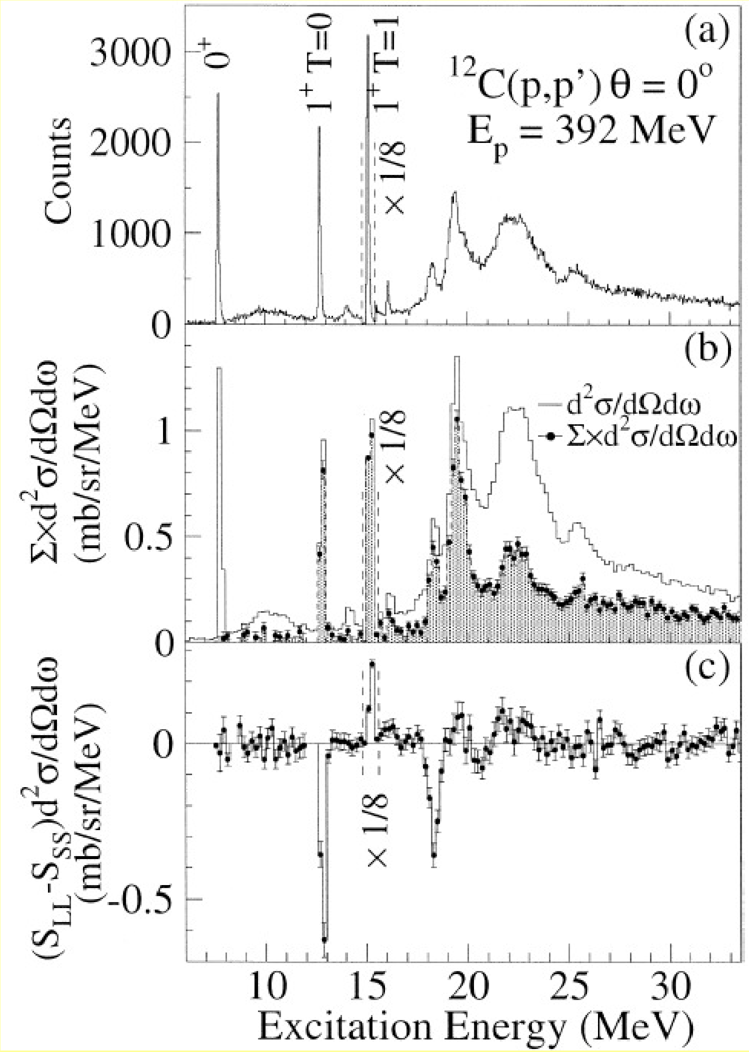
- Is the PDR a superposition of two modes?

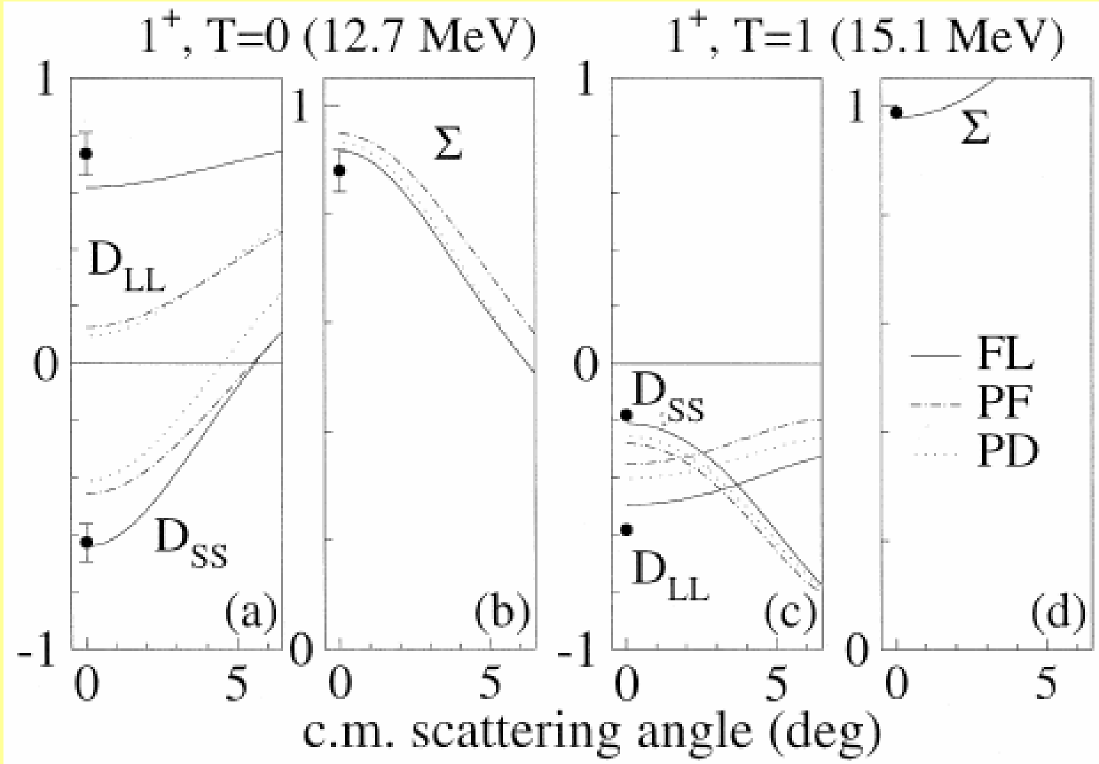
New Observables – a Polarimeter

- Polarization observables help to unravel
  - → nuclear structure
  - → properties of the effective NN interaction

- Polarization transfer
  - → longitudinal spin flip probability $S_{LL} = (1 - D_{LL}) / 2$
  - → transverse spin flip probability S_{SS}(or S_{nn}) $= (1 - D_{SS}) / 2$
  - → total spin transfer $\Sigma = [3 – (D_{LL} + D_{SS} + D_{NN})] / 4$

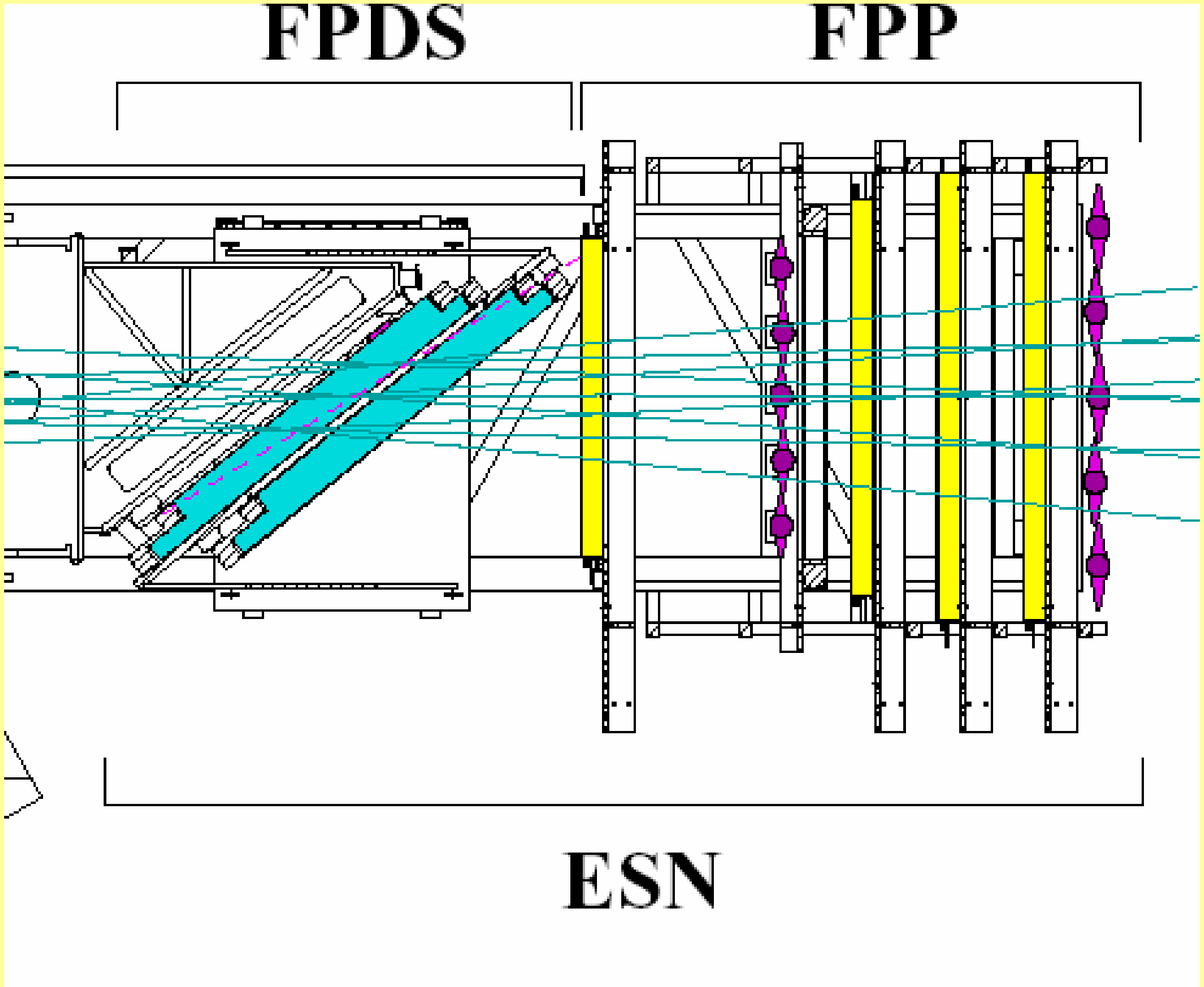
Application to $J^{\pi} = 1^{+}$ states in ^{12}C





A.Tamii et al., Phys. Lett. B 459, 61 (1999)

5th Example: EURO SUPERNOVA Detector at KVI and Applications



Focal Plane Detector (FPDS):
- 2 VDCs

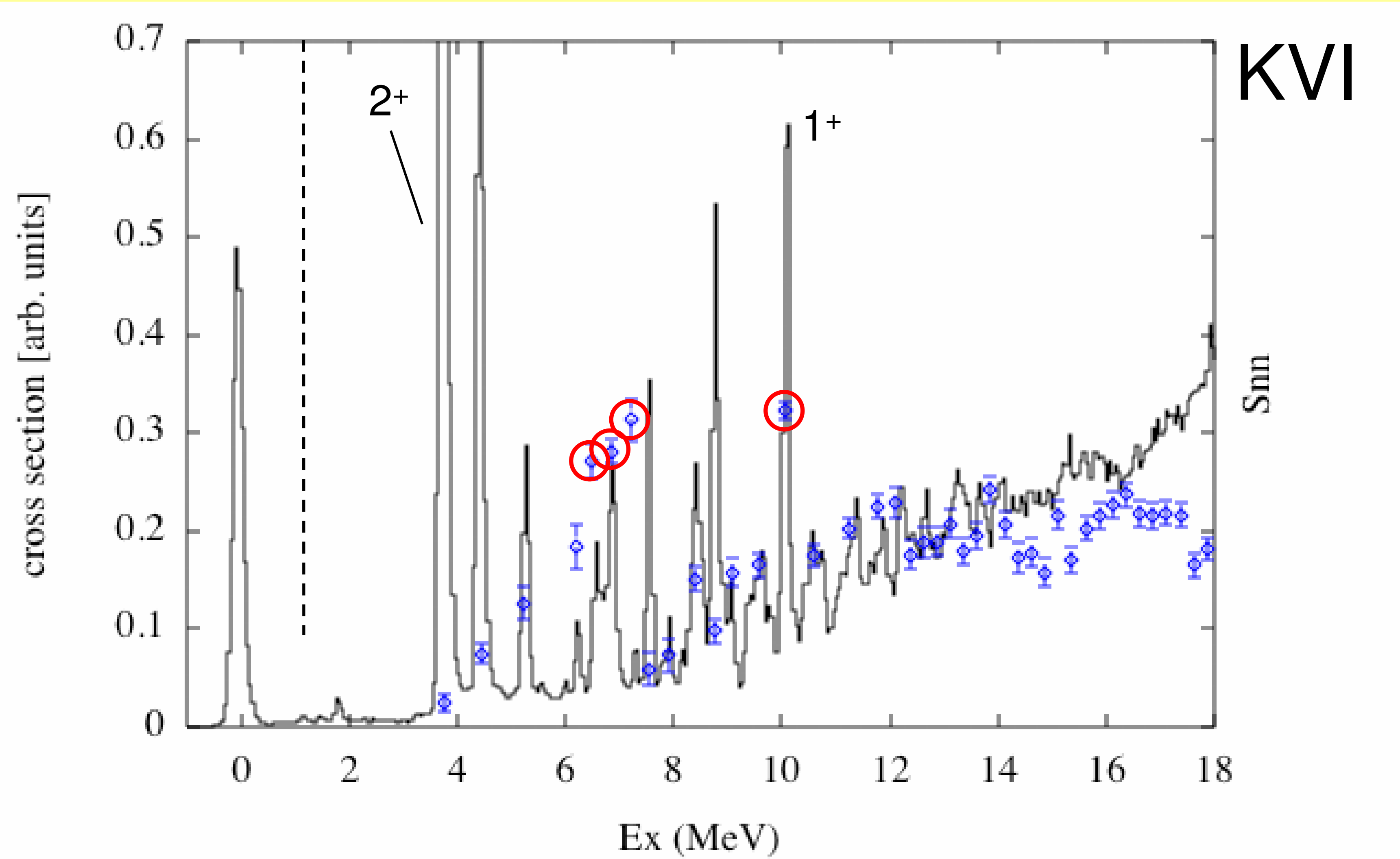
Focal Plane Polarimeter (FPP):
- 4 MWPCs
- graphite analyzer

Electronics:
- fast readout
- VDC readout by pipeline TDCs
- VDC decoding using imaging technics
- DSP based online analysis

- U Münster / U Bari / TU Darmstadt / U Gent / FHS Iserlohn / U Milano / TRIUMF / KVI collaboration

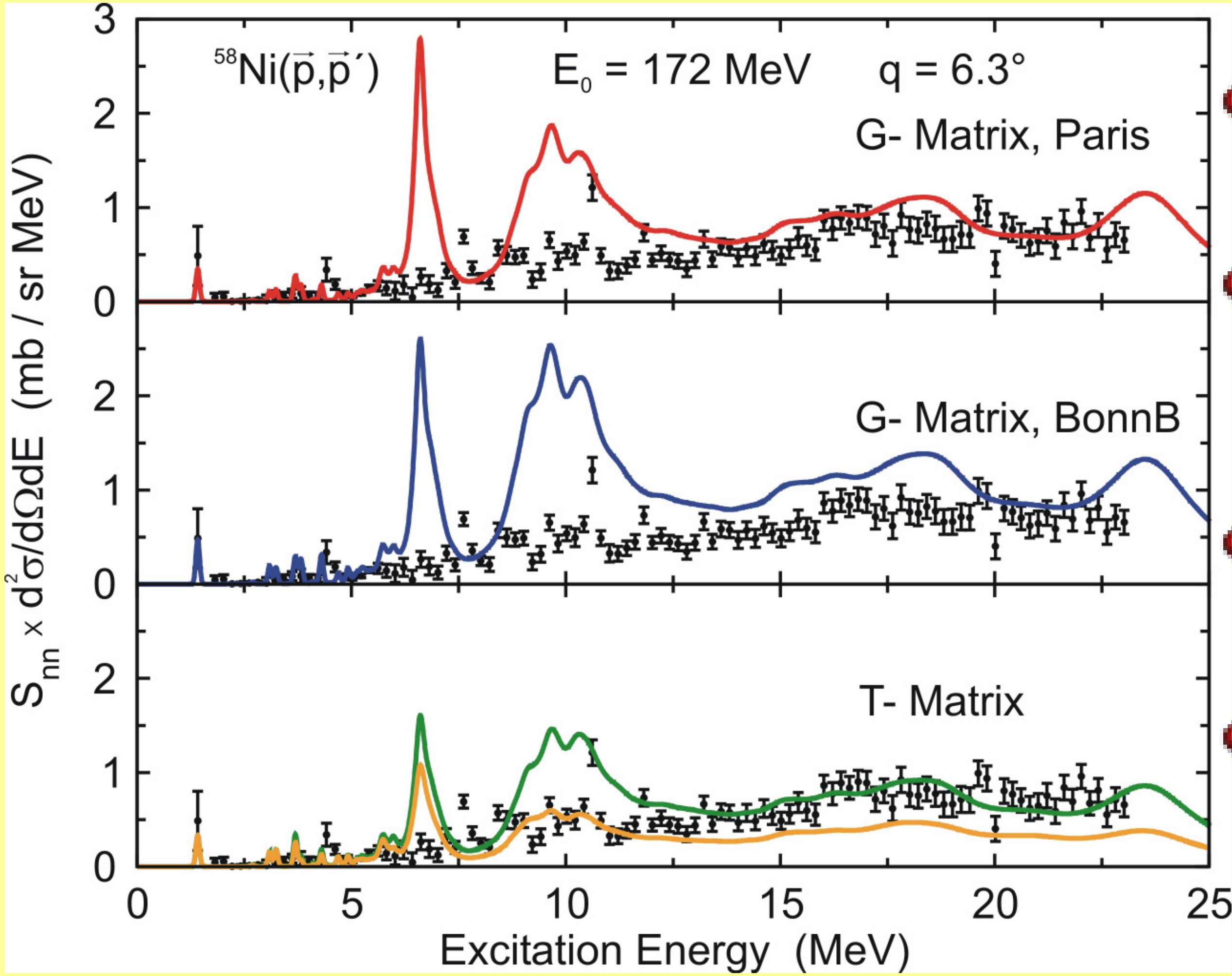
Example: Spinflip Strength in ^{48}Ca

$^{48}Ca(\vec{p},\vec{p}'), E_0 = 172$ MeV, $\Theta = 9.5°$



- Spin-flip probabilities for single excitations up to 10.5 MeV
- Unique resolution and statistics

Spinflip Cross Sections in ^{58}Ni



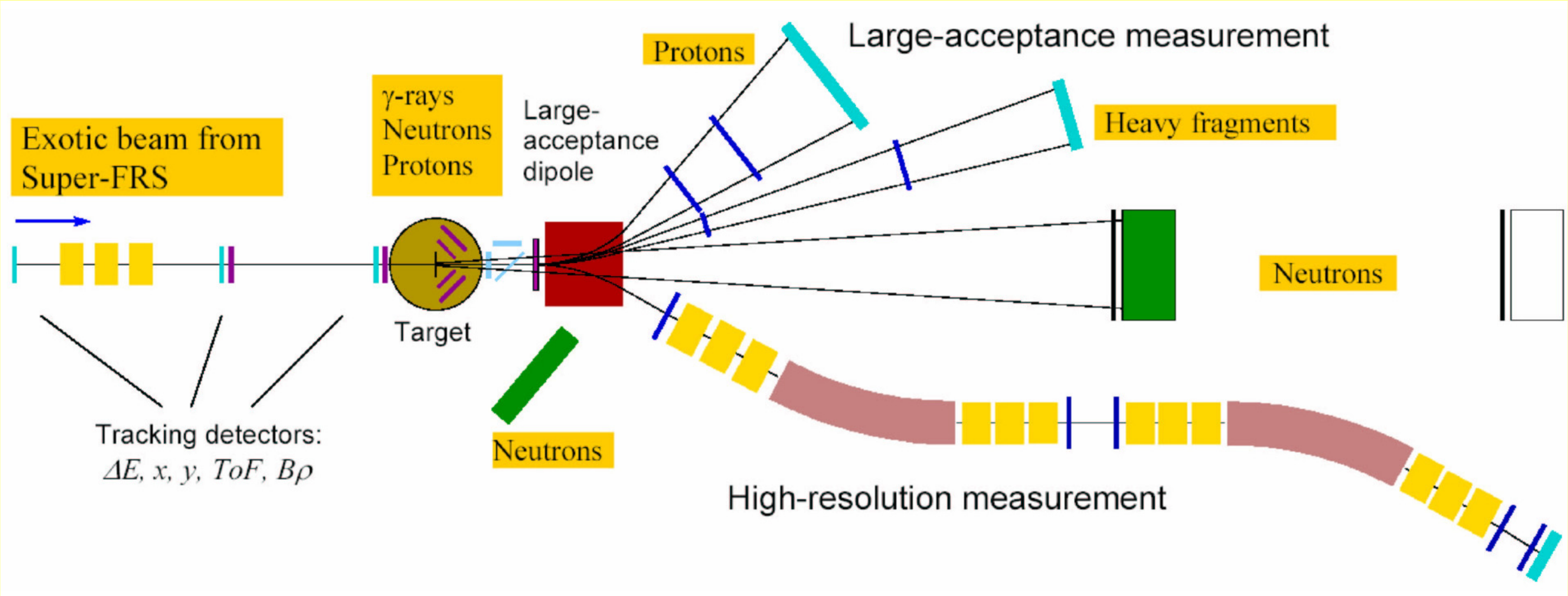
- test of effective pA interactions
- nuclear structure input: QPM including complex configurations
- description at higher E_x reasonable
- bump at $E_x \approx 7$ and 10 MeV M1 / M2 / E1

F.Hofmann et al., Phys. Lett. B 612, 165 (2005), Phys. Rev. Lett. (to be published)

Concluding Remarks: Connection to Radioactive Beam Facilities

- All major radioactive beam facilities have programs to study collective nuclear modes with light-ion reactions in inverse kinematics

Example: R^{3}B Project at FAIR (GSI Upgrade)



Concluding Remarks: Connection to Radioactive Beam Facilities

- All major radioactive beam facilities have programs to study collective nuclear modes with light-ion reactions in inverse kinematics

- Reaction mechanism becomes an issue again

- Effective NN interaction remains an issue

$\longrightarrow$ precision studies on stable targets needed

Concluding Remarks: Possible Options at iThemba LABS

- High-resolution plus 0° at the spectrometer

  $\longrightarrow$ strong physics case!

- Combine with (parts of) AFRODITE

  $\longrightarrow$ promises real physics surprises!

- A polarimeter allowing high data rates

  $\longrightarrow$ manifold use

- Some options to think about

  $\longrightarrow$ a second large solid-angle spectrometer

  $\longrightarrow$ neutron and charged particle detector arrays (but state-of-the-art)

Conclusion

- Is there a future for light-ion induced Nuclear Physics at iThemba LABS?

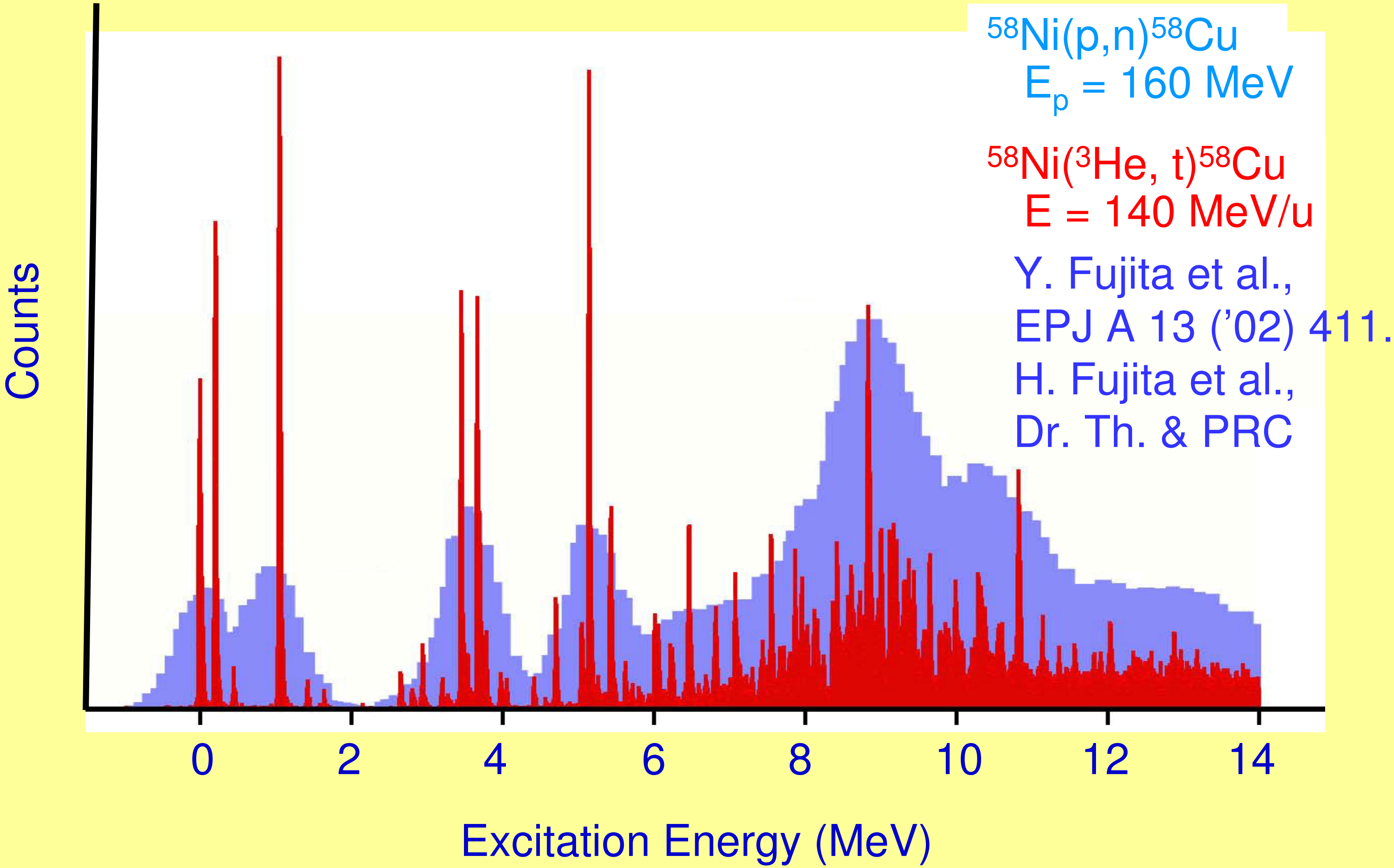
- YES, there is

  - and it could be bright

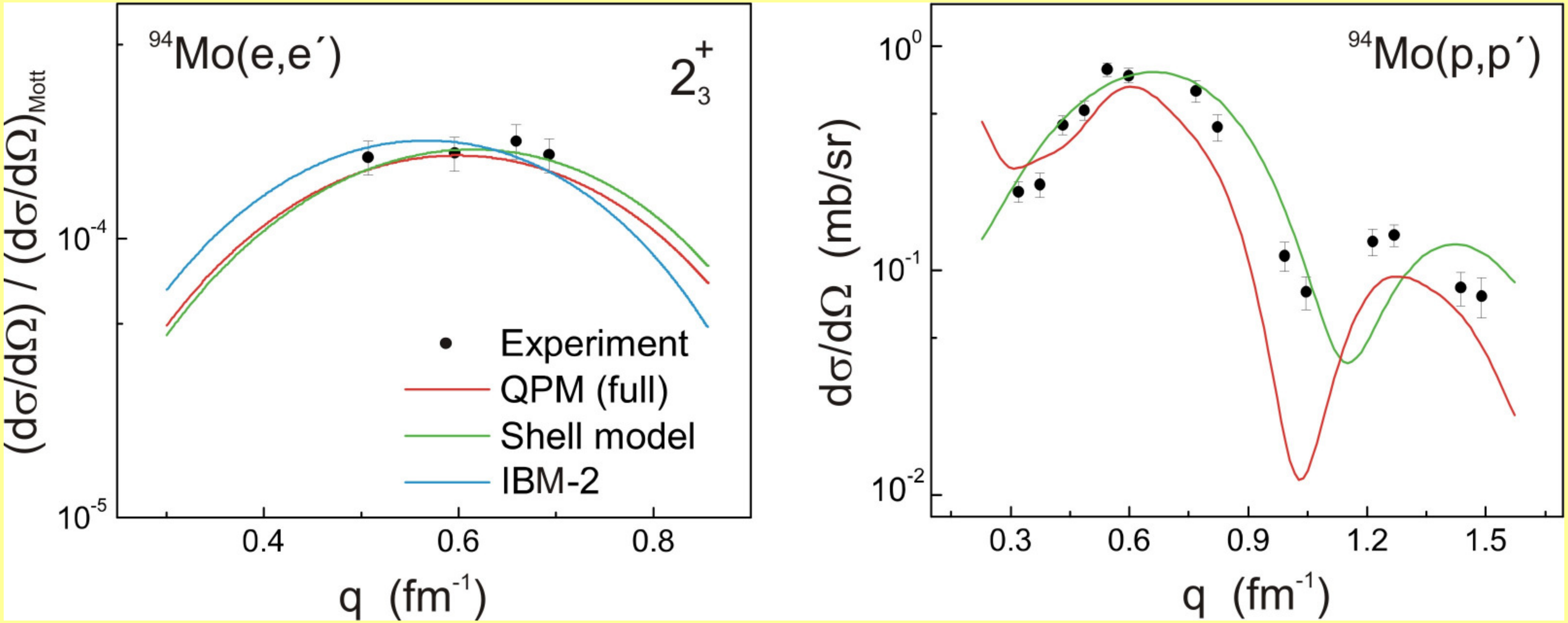
End

>

High-Resolution GT$_-$ Strength from 0° Charge-Exchange Reaction



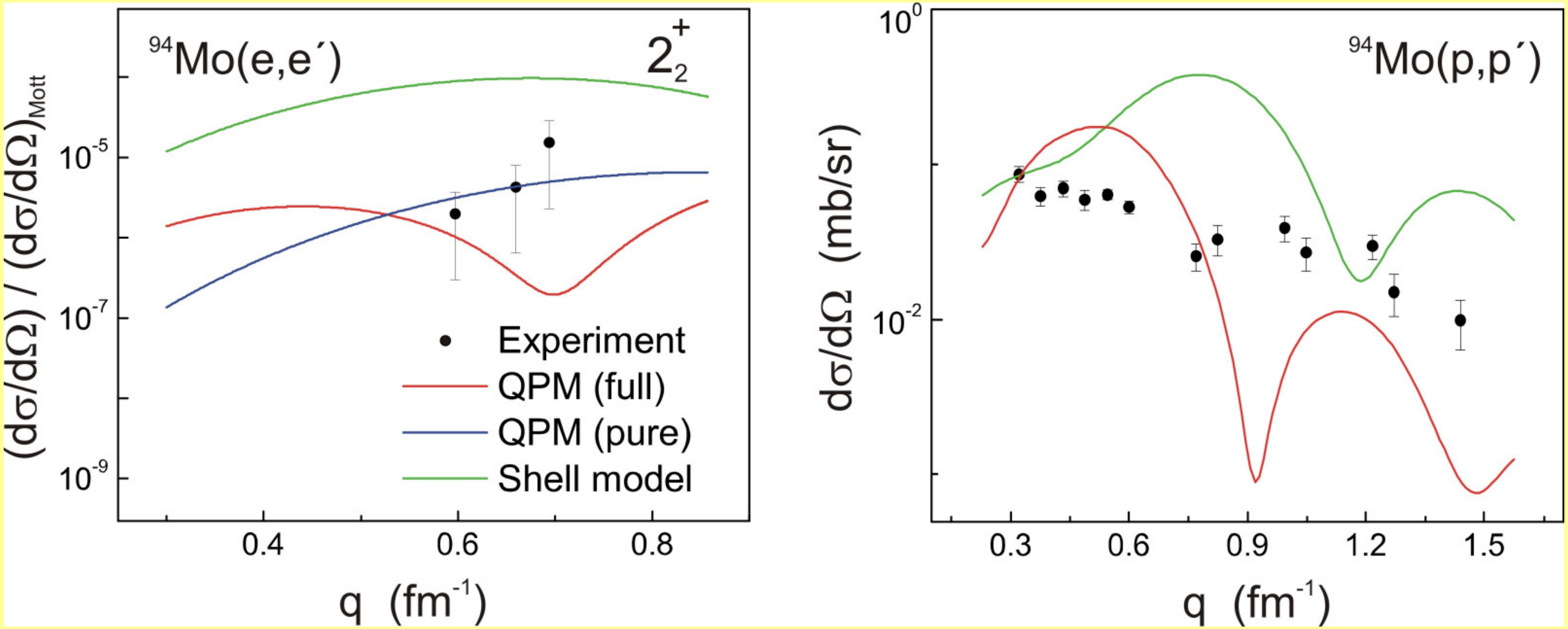
One-Phonon MS State



- Phonon character confirmed

O. Burda et al., Phys. Rev. Lett. (to be published)

Symmetric Two-Phonon State

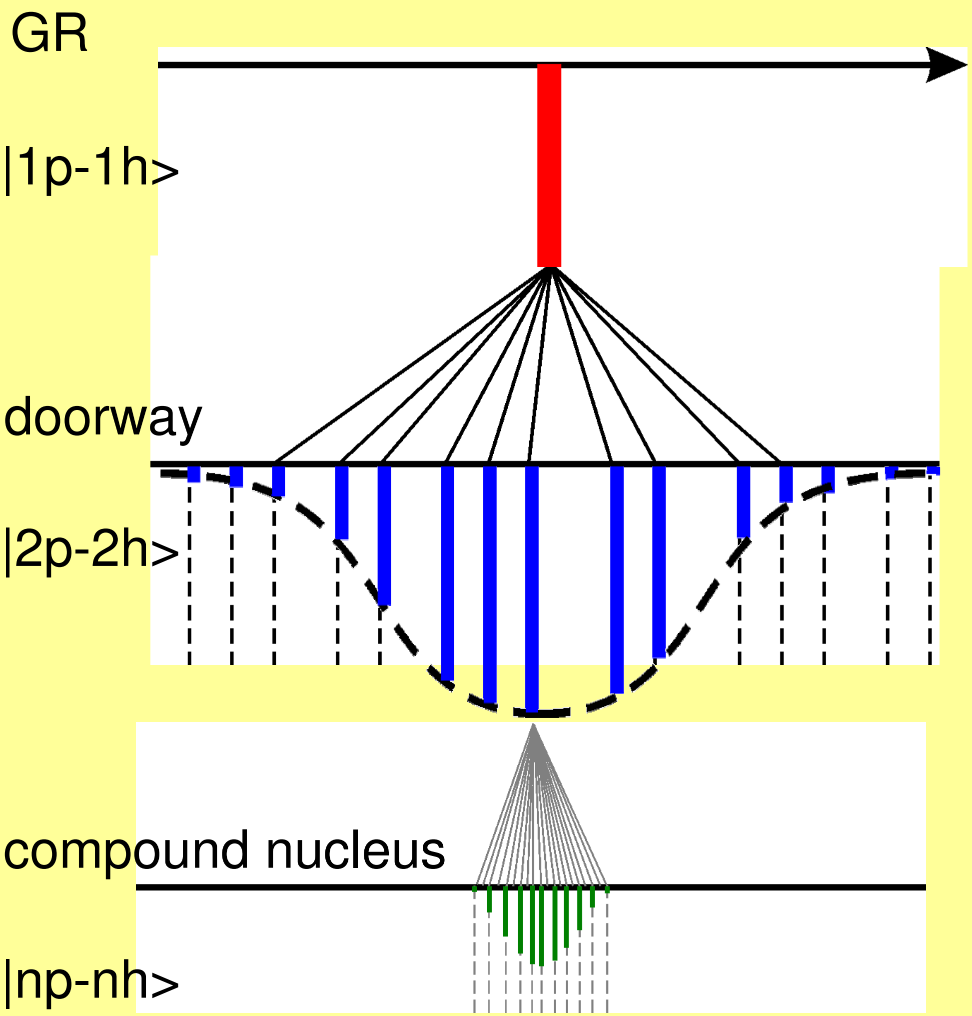


- very pure

- two-step contributions

→ coupled-channel analysis

Origin of Scales: Decay of Giant Resonances



Scales

$t \sim 10^{-22}$ s $\Gamma \sim$ MeV

$t \sim 10^{-21}$ s $\Gamma \sim$ MeV - keV

$t \sim 10^{-16}$ s $\Gamma \sim$ keV - eV

$\longrightarrow$ talk at Wednesday, 13:40

ν-p Process

PRL **96,** 142502 (2006) PHYSICAL REVIEW LETTERS week ending 14 APRIL 2006

Neutrino-Induced Nucleosynthesis of $A > 64$ Nuclei: The νp Process

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W. R. Hix,[6] K. Langanke,[3,7] and N. T. Zinner[8]

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[6]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
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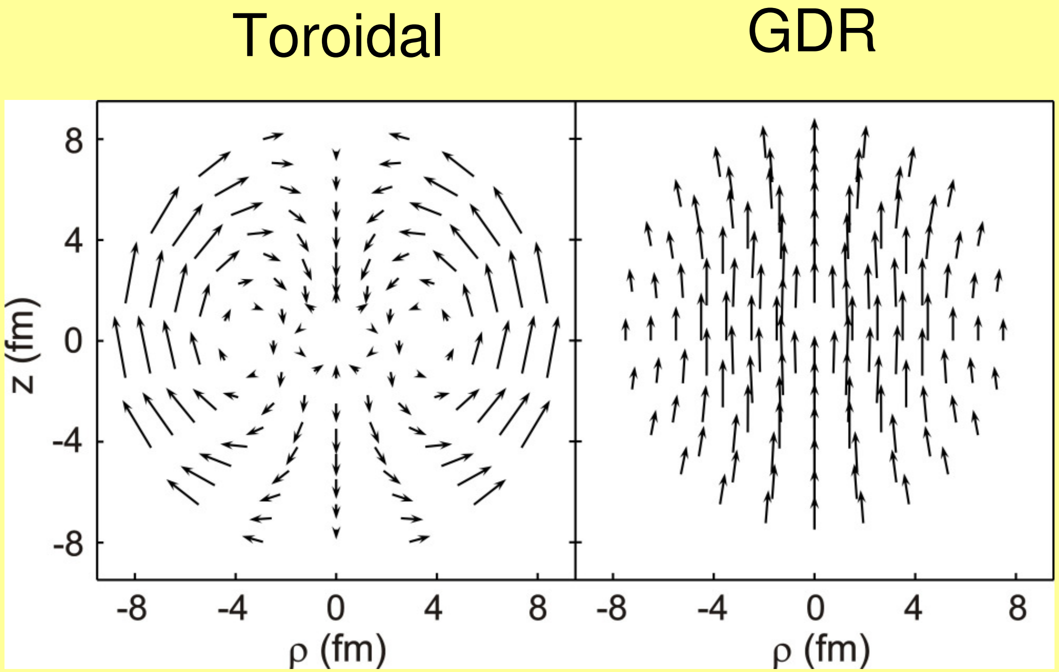
[8]*Institute for Physics and Astronomy, University of Århus, DK-8000 Århus C, Denmark*

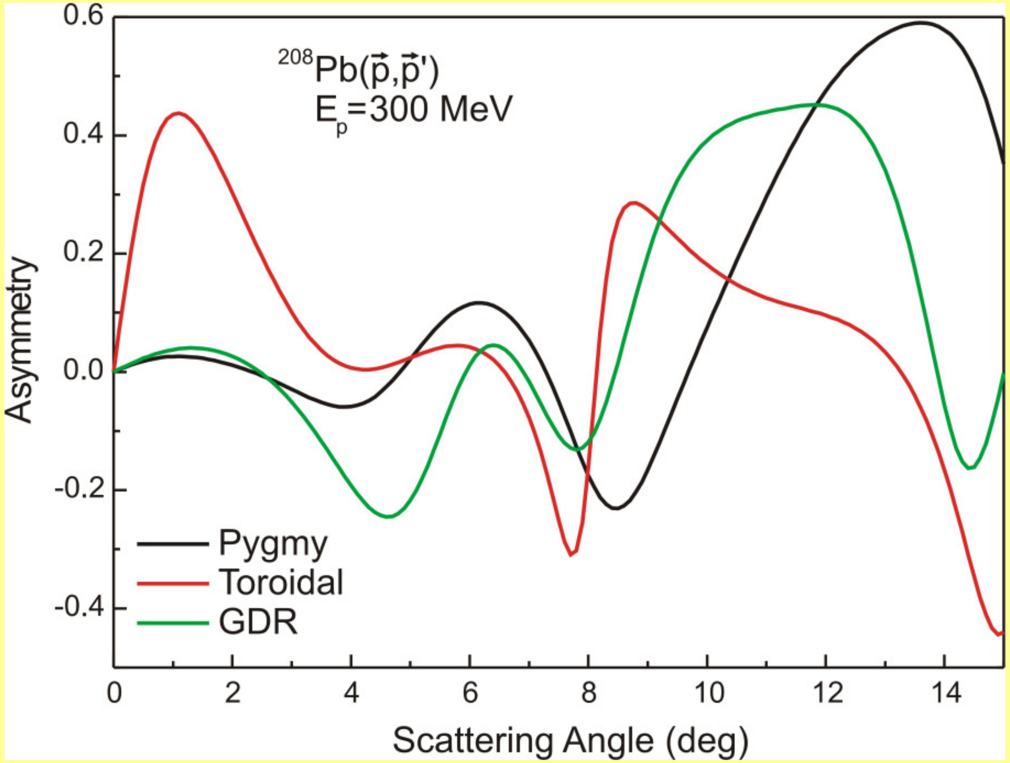
(Received 10 November 2005; published 10 April 2006)

We present a new nucleosynthesis process that we denote as the νp process, which occurs in supernovae (and possibly gamma-ray bursts) when strong neutrino fluxes create proton-rich ejecta. In this process, antineutrino absorptions in the proton-rich environment produce neutrons that are immediately captured by neutron-deficient nuclei. This allows for the nucleosynthesis of nuclei with mass numbers $A > 64$, making this process a possible candidate to explain the origin of the solar abundances of ^{92,94}Mo and ^{96,98}Ru. This process also offers a natural explanation for the large abundance of Sr seen in a hyper-metal-poor star.

DOI: 10.1103/PhysRevLett.96.142502 PACS numbers: 26.30.+k, 25.30.Pt, 97.60.Bw

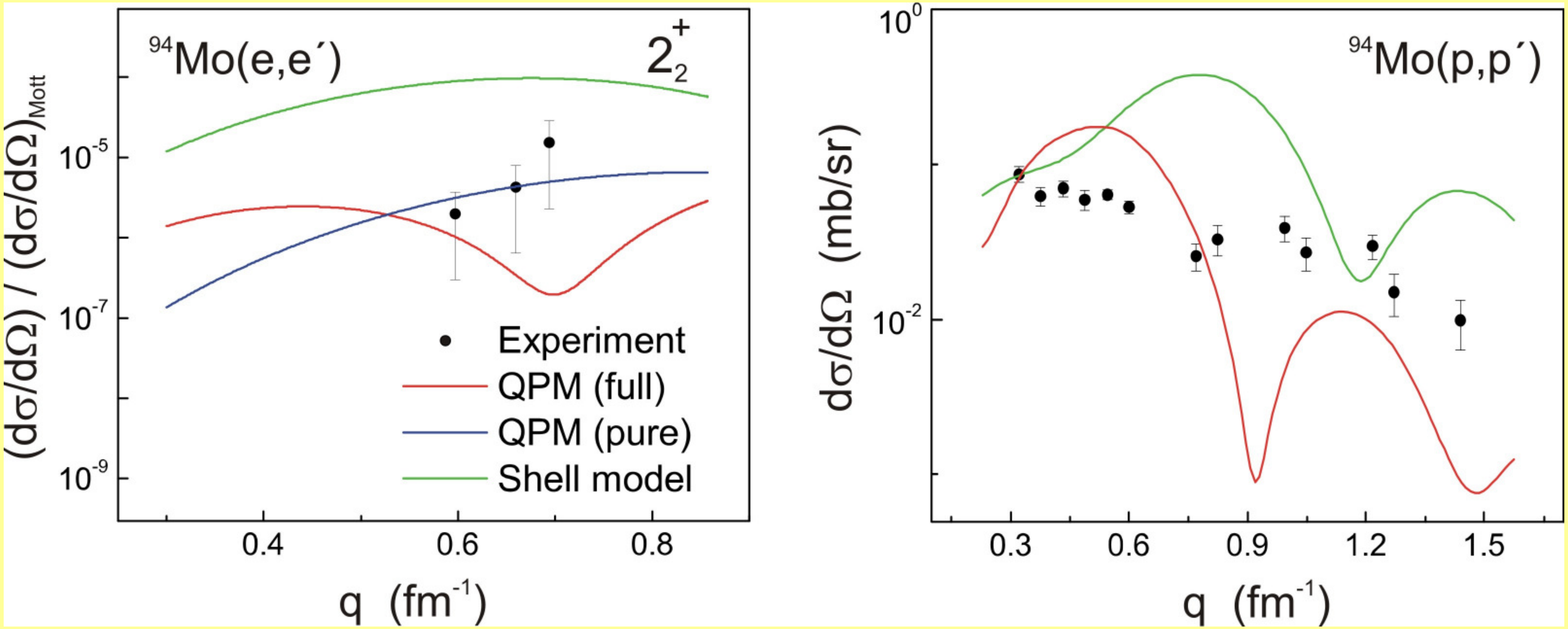
Asymmetries of E1 transitions in $(\vec{p},\vec{p}\,')$
Example ^{208}Pb





- Prediction of toroidal E1 mode with vortex current distribution
- Signature in asymmetries?

Symmetric Two-Phonon State



- very pure
- two-step contributions

→ coupled-channel analysis