Study of the Nuclear Dipole Response using the Monoenergetic and Polarized Photon Beams at HIGS

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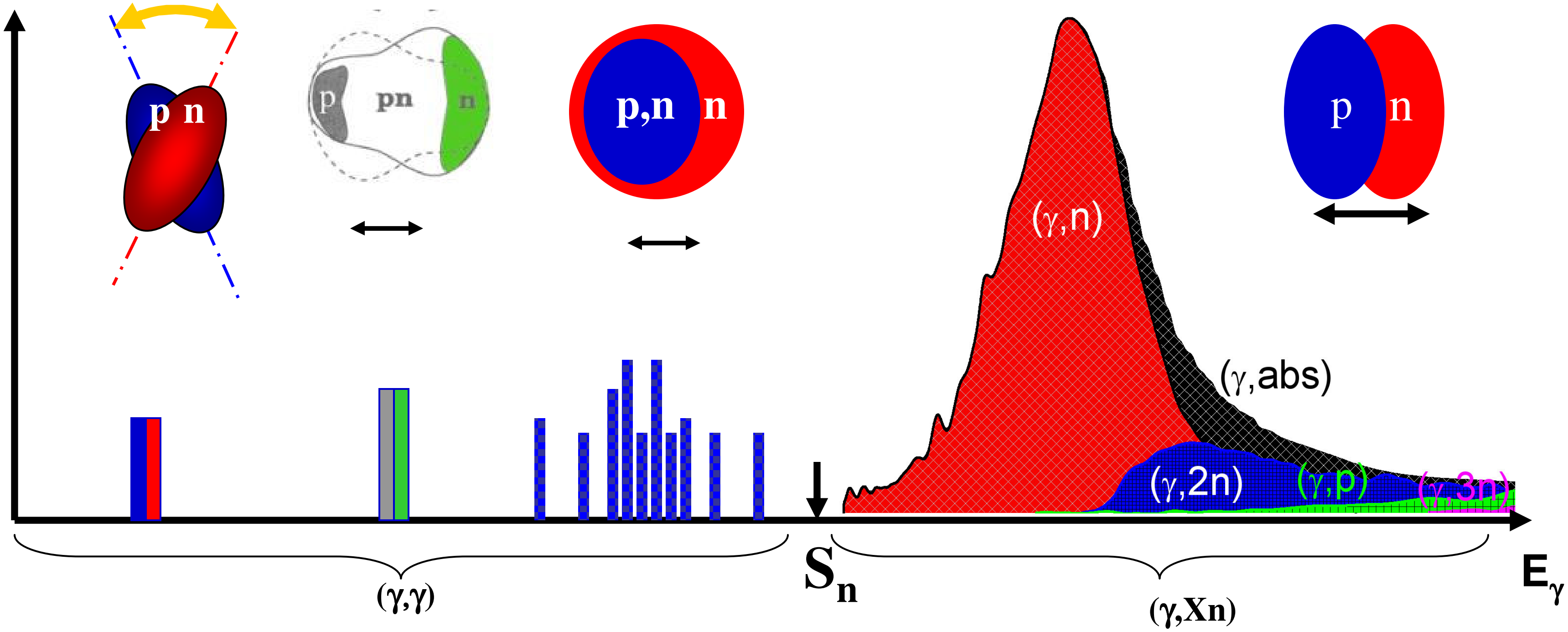
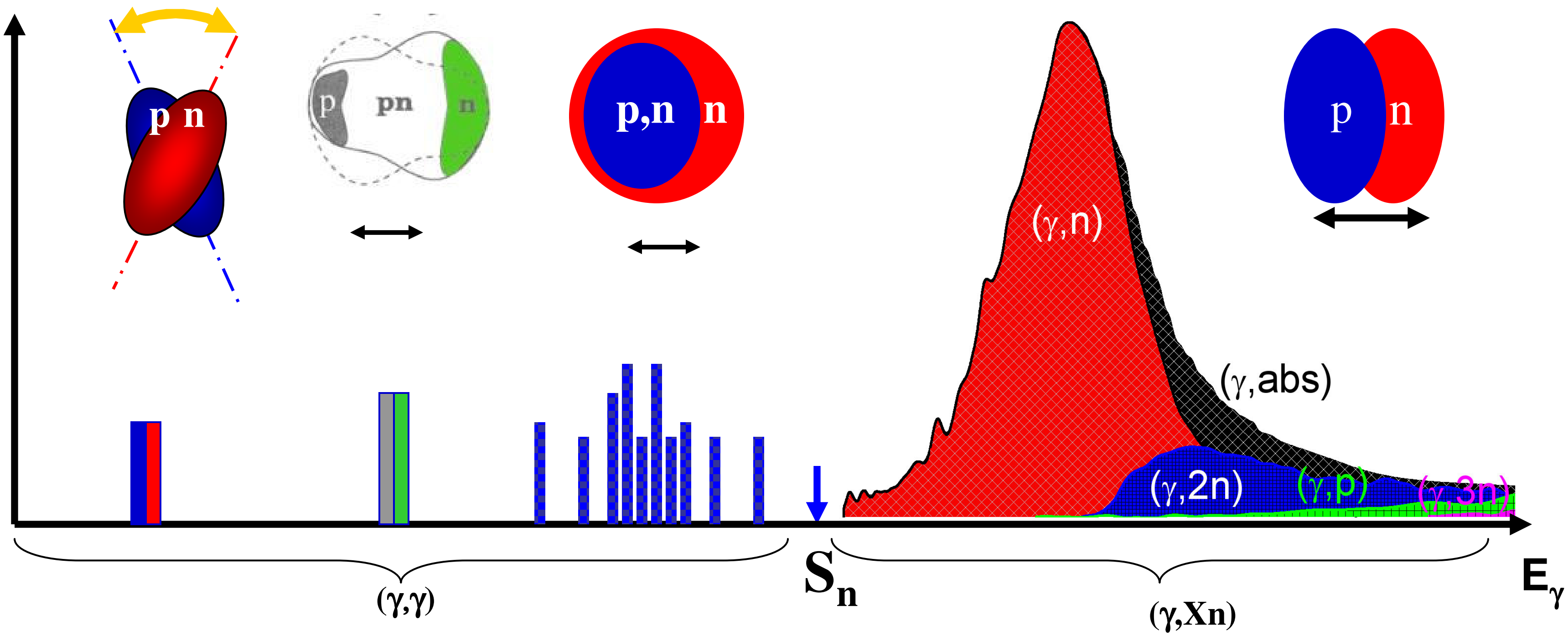
Characteristic Response of an Atomic Nucleus to EM Radiation



- **Giant Dipole Resonance: E_x ~16 MeV, B(E1) ~ W.u.**
- **Orbital "Scissors" mode: E_x ~ 3 MeV, B(M1) ~ $3\mu_N^2$**
- **Two Phonon Excitation: E_x ~ 4 MeV, B(E1) ~ 10^{-3} W.u.**
- **Pygmy Dipole Resonance ?**

Importance of Dipole Excitations Around the Particle Threshold



Nuclear structure phenomenon

- New and fundamental mode of excitation below the GDR

Impact on nucleosynthesis

- Gamow window for photo-induced reactions in explosive steller events

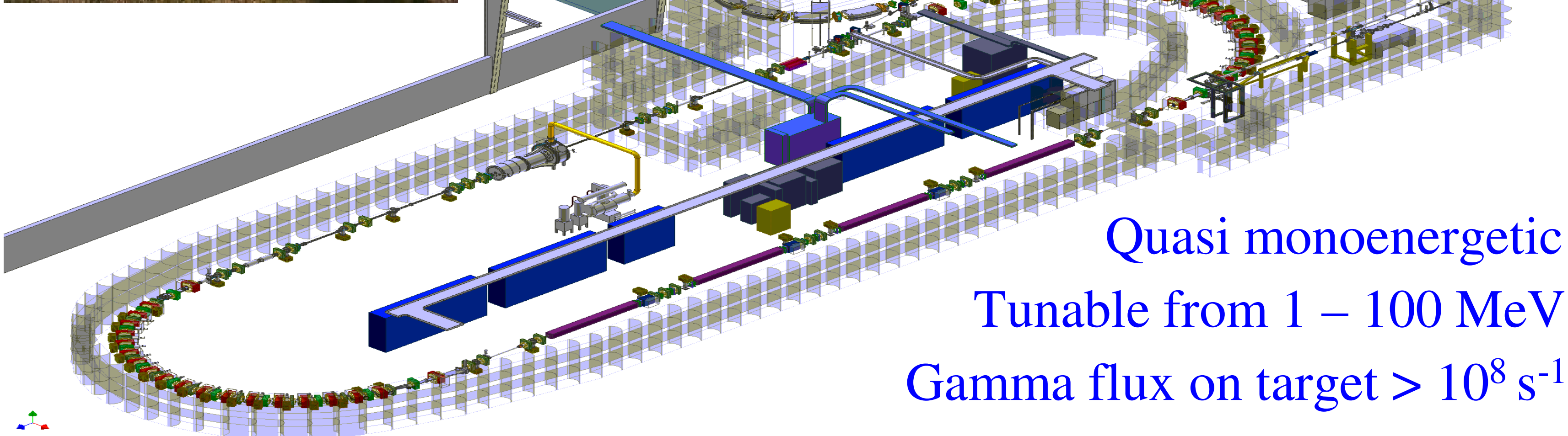
Importance for understanding of exotic nuclei

- E1 strength will be shifted to lower energies in neutron rich system

Motivation

- Low-energy dipole modes of excitation below the neutron threshold
  - What is the character of the PDR? Electric or Magnetic?
  - What is the strength of the PDR?
  - What is the decay pattern below the particle separation energy which is governed by the photon strength function?
  - What is the impact of PDR on the astrophysical reaction rates at the Gamow peak in stellar burning scenarios, especially the *p*-process?
- Experimental probe: photons (monoenergetic and 100% linearly polarized)
- Experimental technique: Nuclear Resonance Fluorescence

High Intensity Gamma Ray Source (HIGS)



Quasi monoenergetic

Tunable from 1 – 100 MeV

Gamma flux on target > 10^8 s^{-1}

100% linearly and circular polarization of γ rays

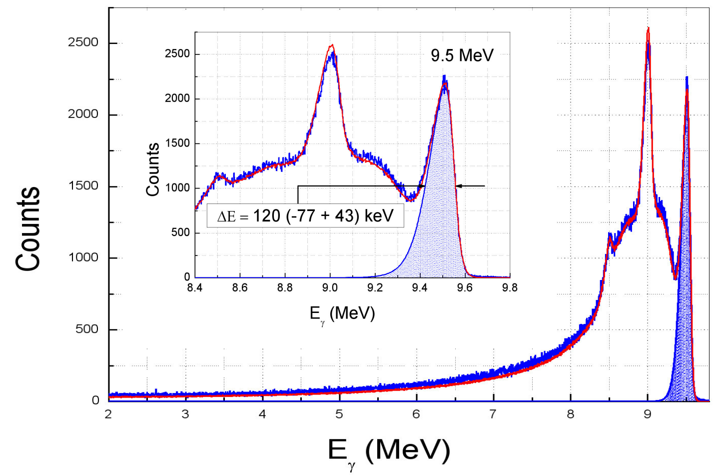
Energy selection: collimation, no need for tagging

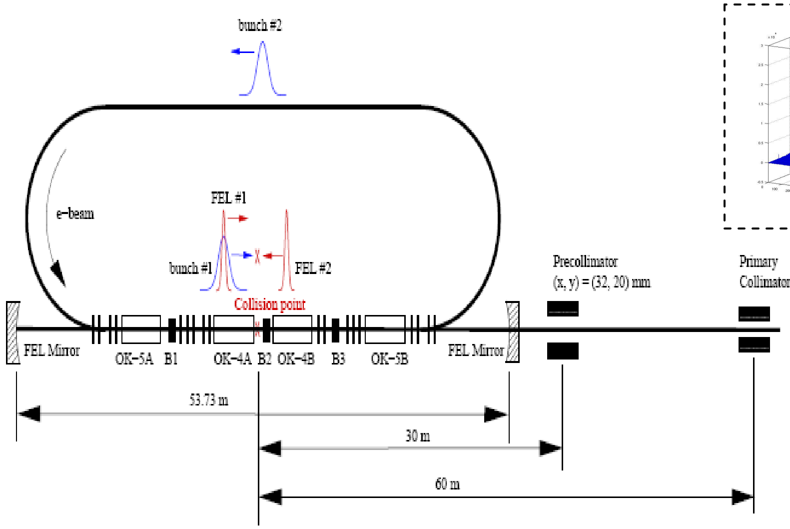
Experimental Setup at HIGS

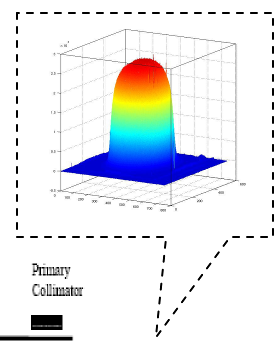
Gamma beam: $\Phi_\gamma > 10^8$ γ/s (>1000 γ/s/eV), ΔE/E = 3%, pulsed and 100% horizontally polarized

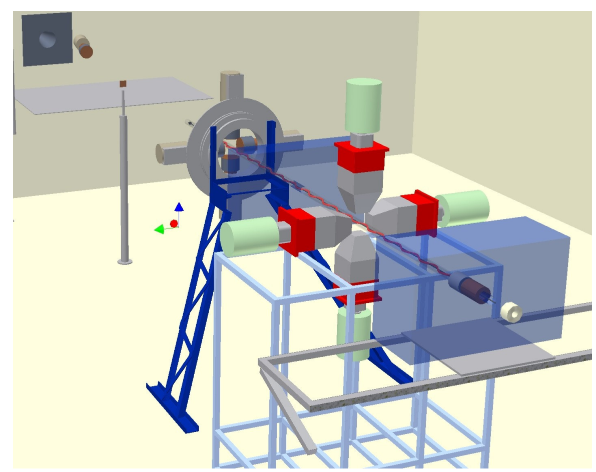
Detector systems:

- 4 Clovers + BGO; $\varepsilon_{array} = 1.4\%$ @ $E_\gamma = 1.33$ MeV
- Quartet of 60 % detectors with Pb and Cu passive shields
- Beam monitor detector: 123% HPGe









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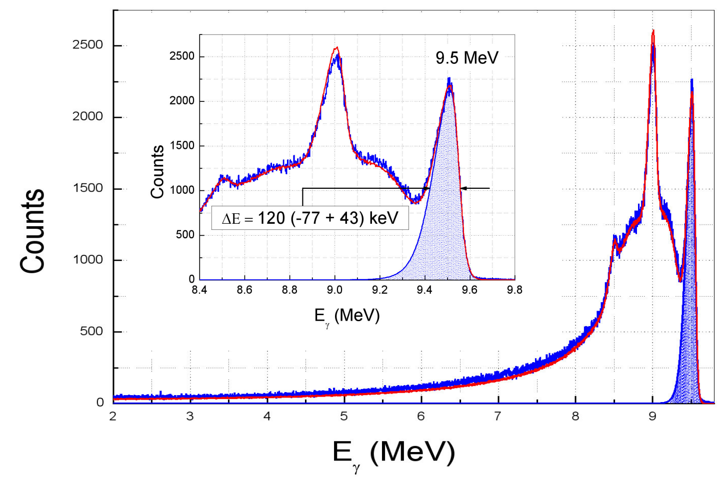
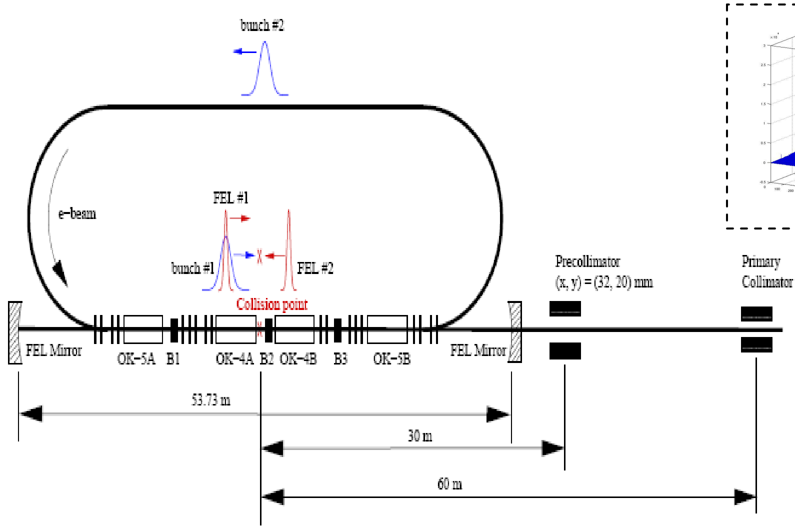
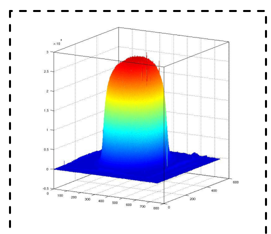
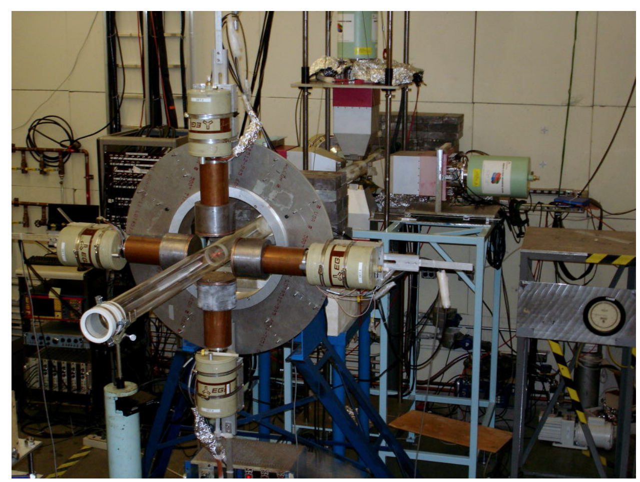
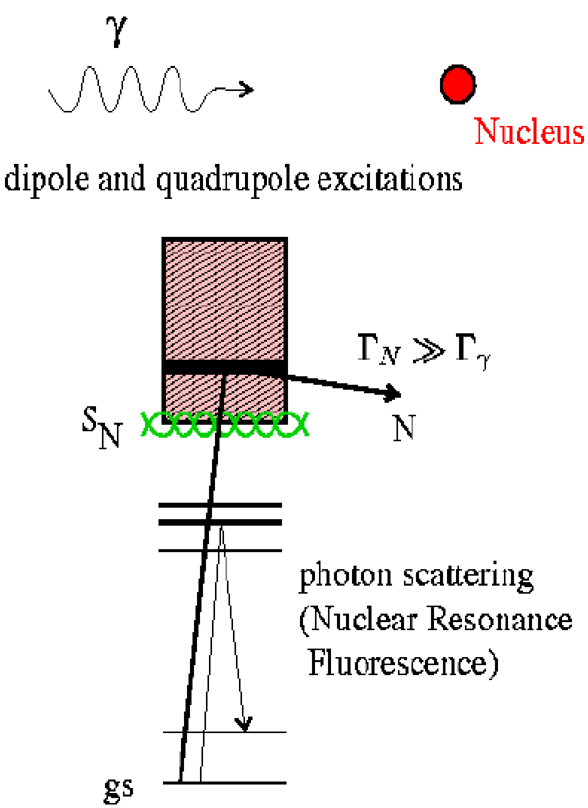








Nuclear Resonance Fluorescence Technique



Experimental observables in NRF

- Excitation energy E_x
- Spin and parity J, π
- Decay width Γ_0
- Branching ratio Γ_i/Γ

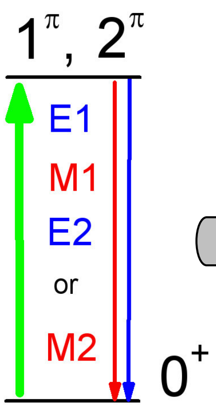
In a completely model independent way !

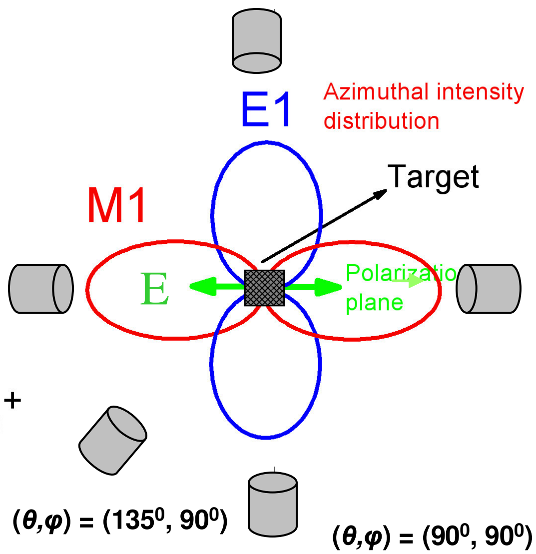
HIGS Advantages

- Excitation of a narrow energy window
- Selective E1, M1, and E2 excitation
- High resolution (γ spectroscopy)

Parity Measurements with a Linearly Polarized Photon Beam

Azimuthal distribution



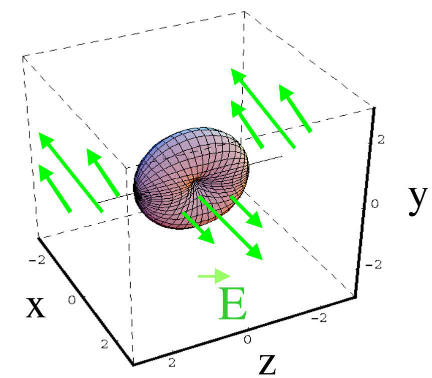


$$\Sigma = \frac{W(90^0,0^0) - W(90^0,90^0)}{W(90^0,0^0) + W(90^0,90^0)} = \pi_1 = \begin{cases} +1 & for \quad J^\pi = 1^+, 2^+ \\ -1 & \quad\quad\;\; J^\pi = 1^-, 2^- \end{cases}$$

Experimental Asymmetry of 0.96

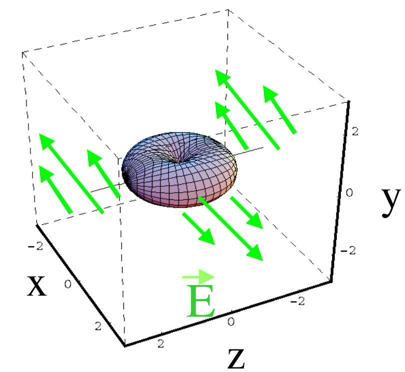
Electric (E1)

$0^+ \rightarrow 1^- \rightarrow 0^+$



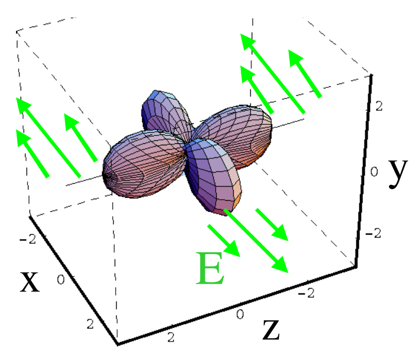
Magnetic (M1)

$0^+ \rightarrow 1^+ \rightarrow 0^+$



Quadruple (E2)

$0^+ \rightarrow 2^- \rightarrow 0^+$



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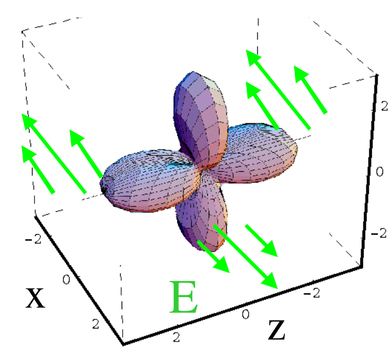
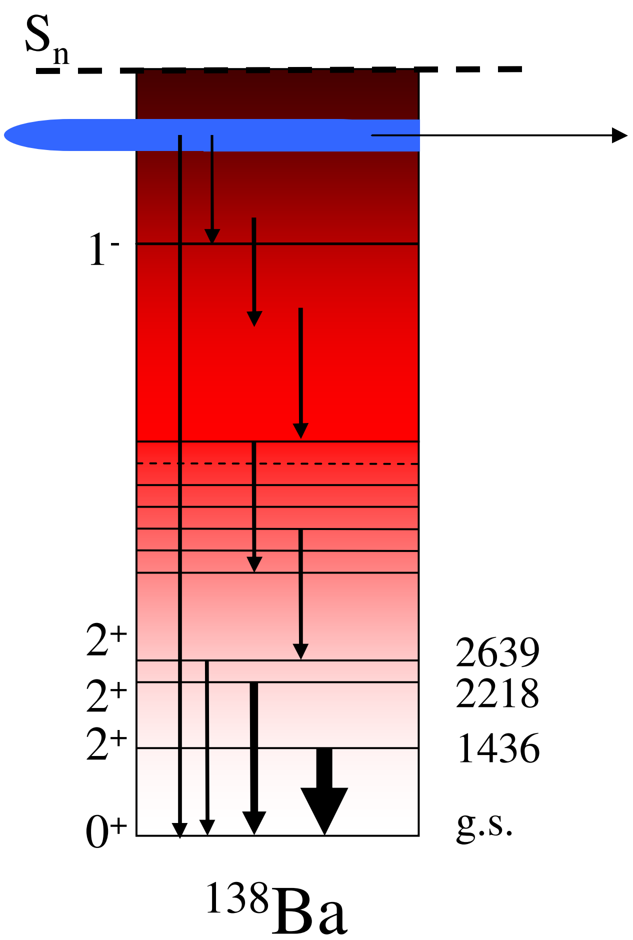


A. Tonchev, NIM **B 241** (2005) 51474

What we are measuring?



Beame energy: ($\Delta E/E = 3\%$)

From the beam energy:

$E_i, J, \pi, \Gamma_0, \Gamma_i / \Gamma,$

$\sigma_{el} = f(E_\gamma)$

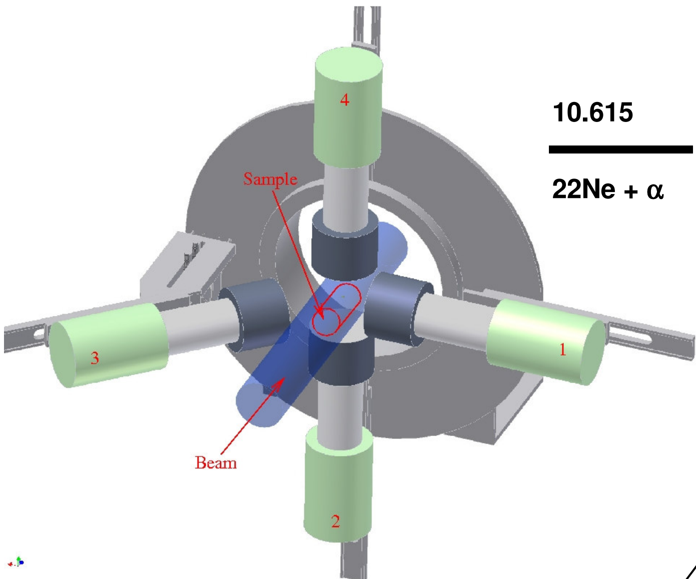
From the 100% linearly polarized HIGS beam allows to distinguish among different transition types

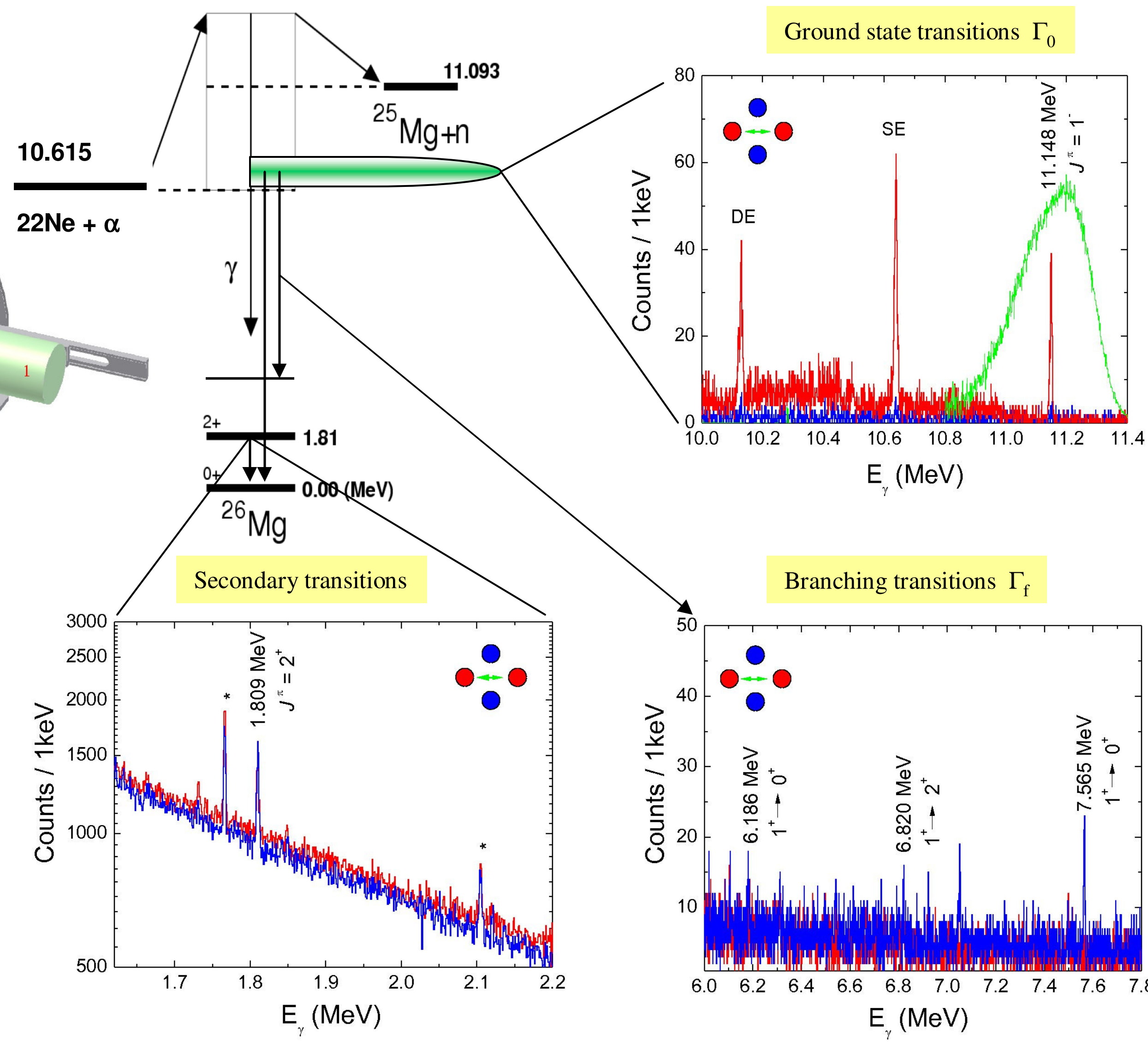
From the first excited states to g.s.:

$\sigma_{inel} = f(E_\gamma)$

$\sigma_{tot} = \sigma_{el} + \sigma_{inel} = \sigma_{abs}$

HIGS: Pushing the Limit of Sensitivity



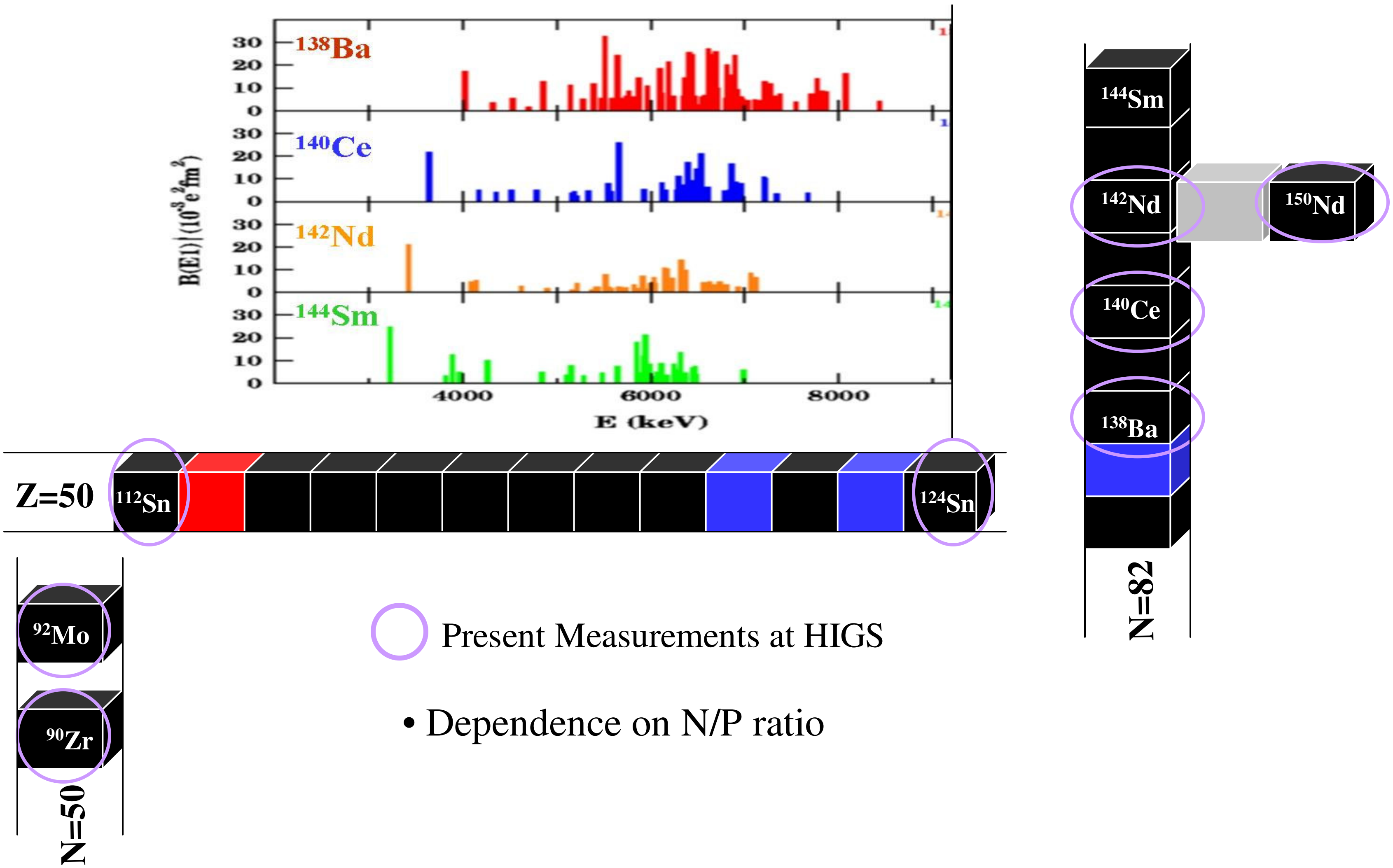


HIGS detection sensitivities:

resonance states with $\Gamma_{tot} \geq 1\text{meV}$

Present Experimental Activities at HIGS

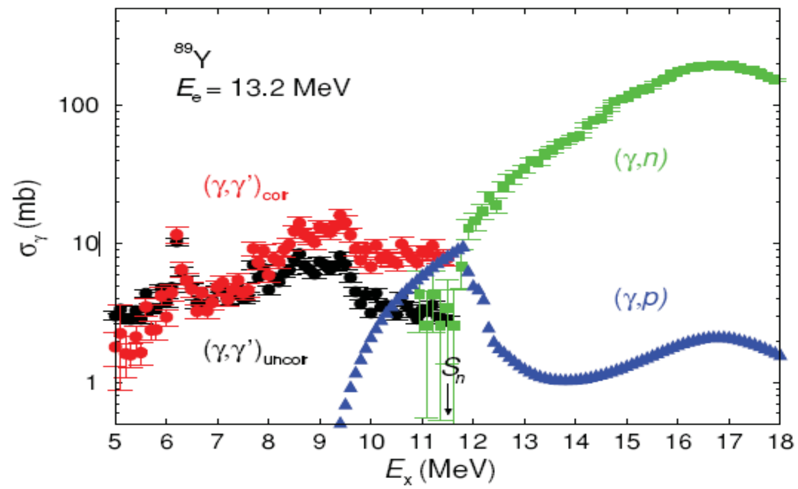
S. Volz et al., Nucl. Phys. **A** 779 (2006) 1.

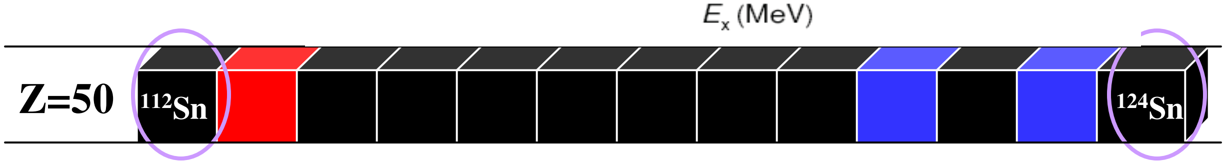


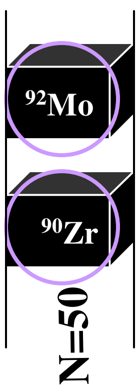
• Dependence on N/P ratio

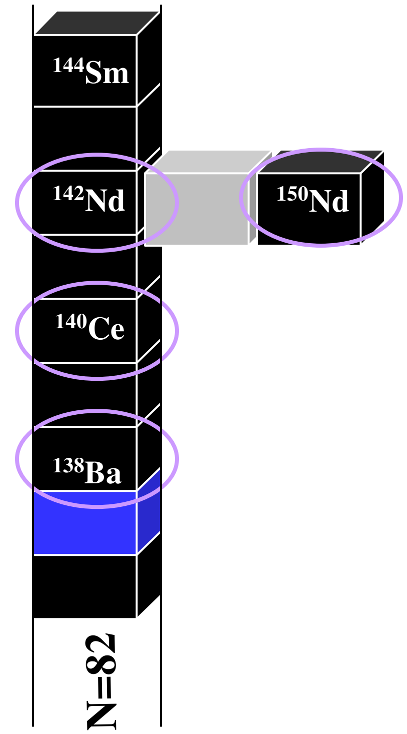
Present Experimental Activities at HIGS

N. Benouaret et al., Phys. Rev. **C** 79   014303 (2009)





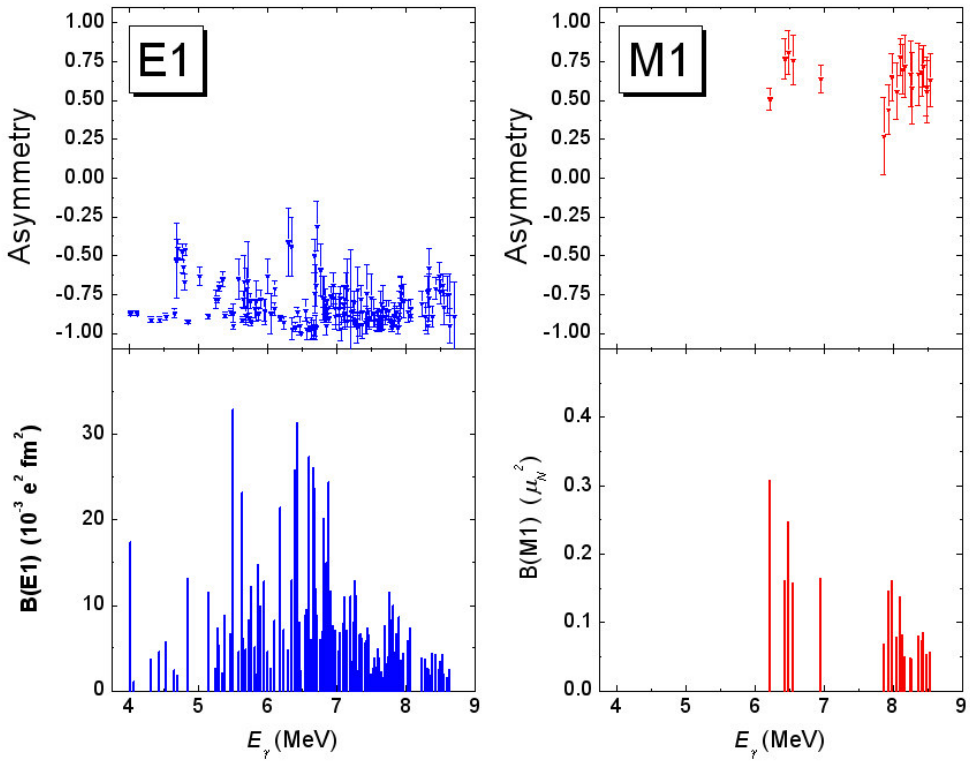




Present Measurements at HIGS

- Dependence on N/P ratio
- Dependence on deformation

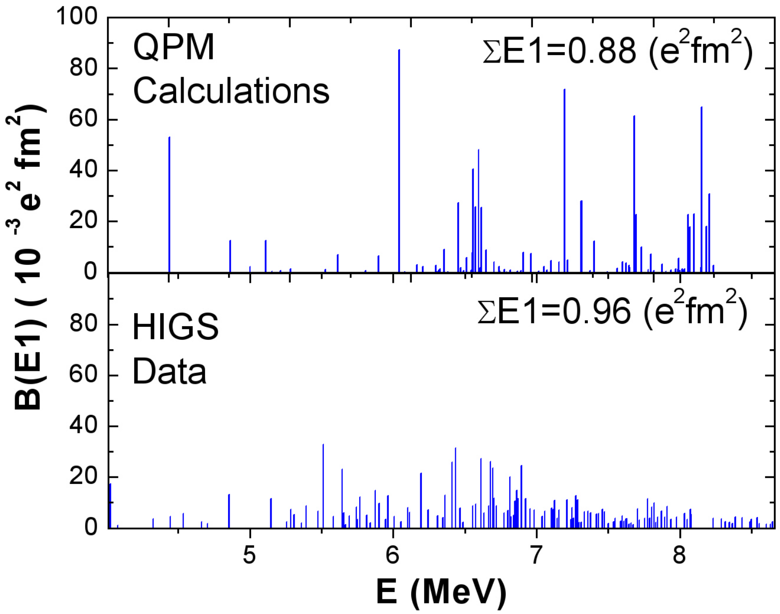
Experimental Asymmetry from $^{138}Ba(\gamma,\gamma)$

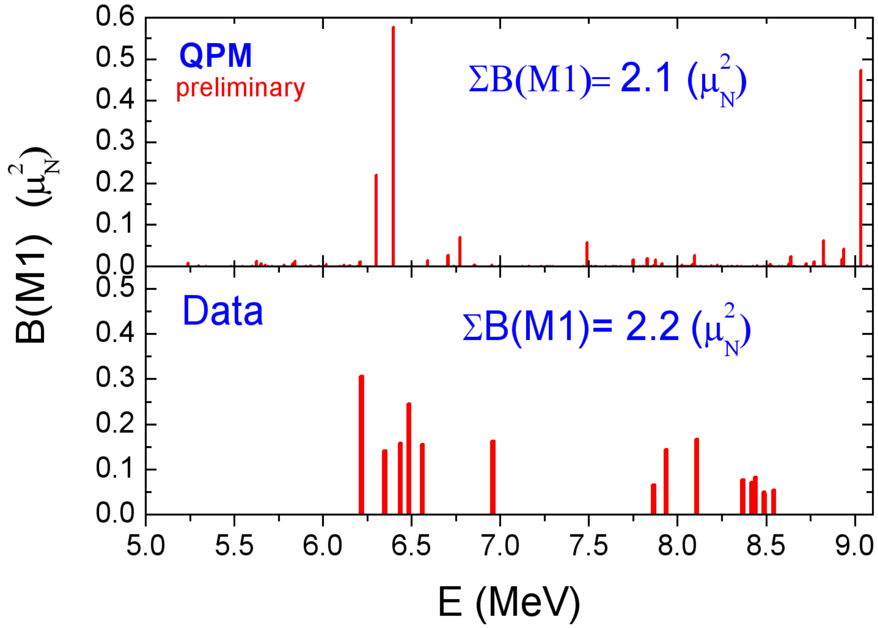


Asymmetry = $(N_h-N_v)/(N_h+N_v)$

- Total of 172 measured states
- 103 states identified for the first time
- Spin and parity assignment for 172 states (20 previously known)
- $\sum B(E1) = 0.96\ (18)\ e^2\ fm^2$ (1.3% TRK)
- 18 new M1 states identified
- M1 strength highly fragmented
- $\sum B(M1) = 2.2\ (8)\ \mu_N^2$
- M1 center of gravity ~ 35 $A^{-1/3}$
- Completely disentangling the E1 from the M1 distribution
- Direct measurement of the E1/M1 strengths

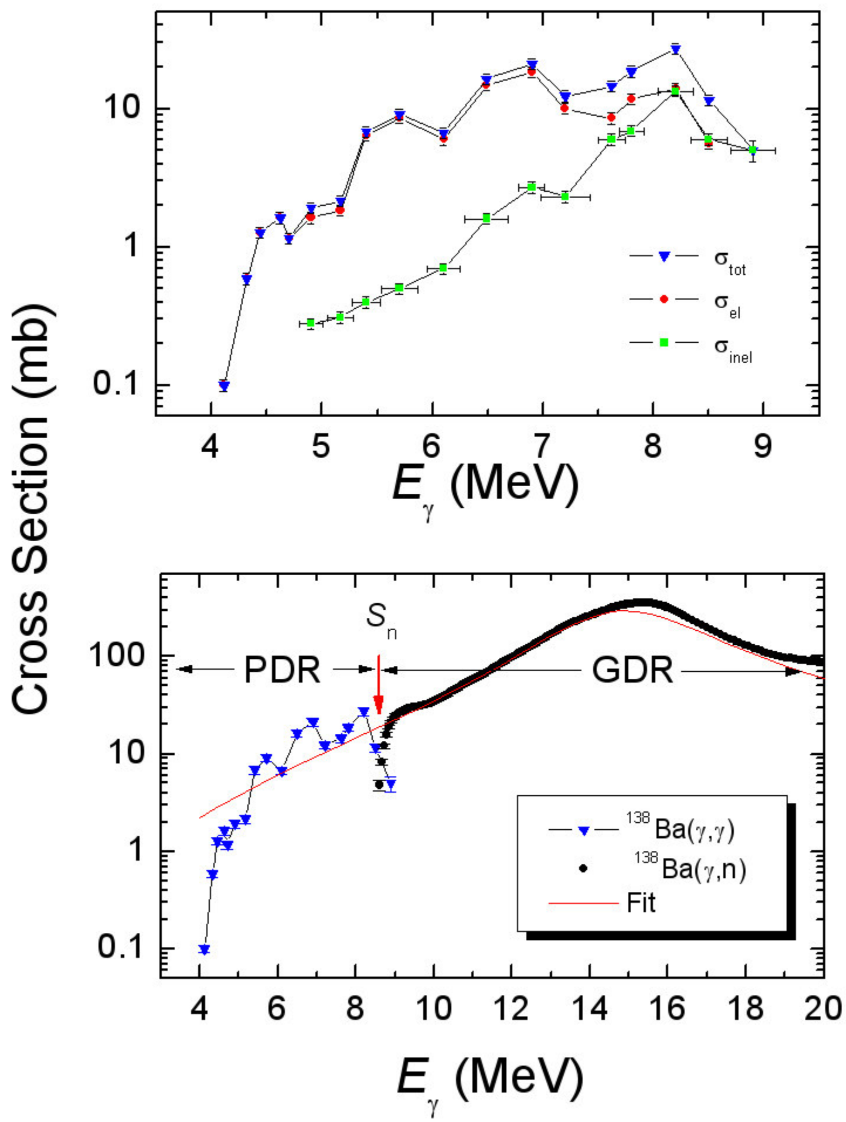
QPM Calculation of the E1 and M1 Strength in ^{138}Ba





Preliminary calculations by N. Tsoneva

Cross Section Composition in ^{138}Ba



- Elastic-scattering cross section dominates in the low-energy region ($E_\gamma \leq 7.5$ MeV)
- Inelastic-scattering cross section takes over at energies close to the neutron separation energy
- σ_{el} are only 30(5) % of σ_{tot} at $E_\gamma \leq B_{th}$
- ➔ The reaction rate will be govern by the inelastic part.

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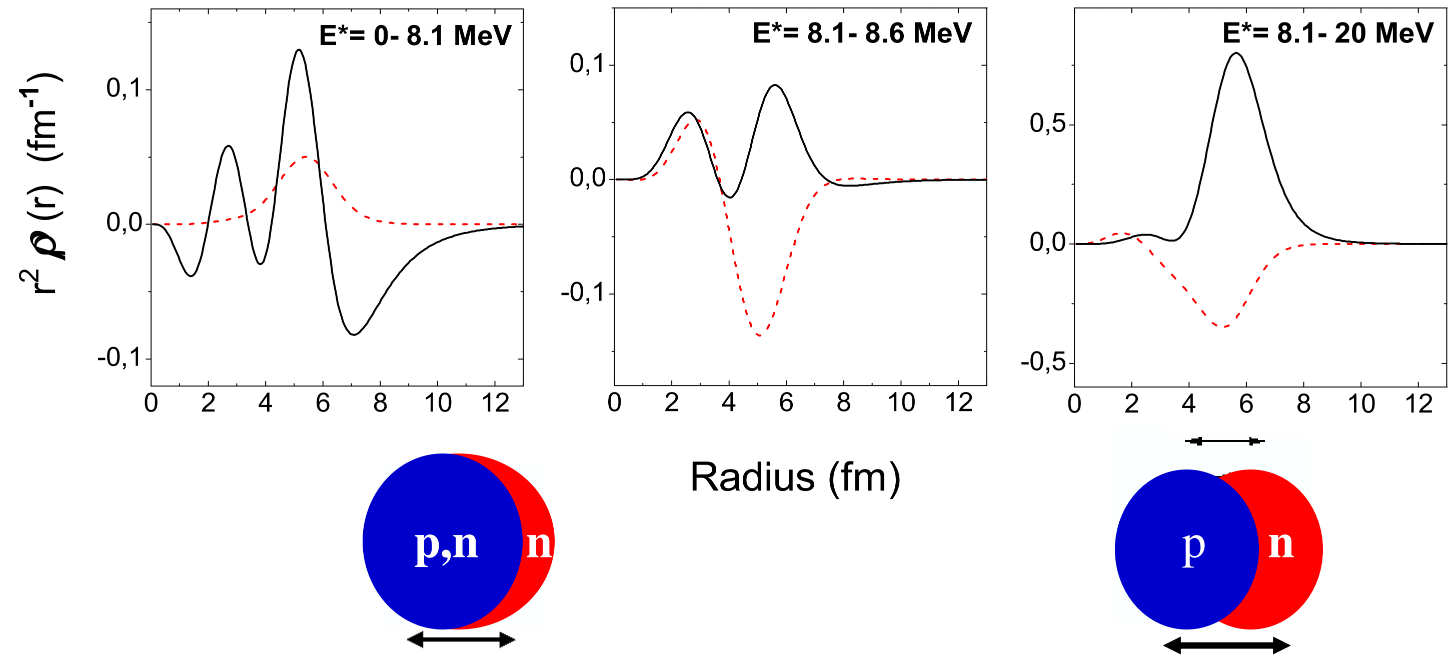
Interpretation of the Pygmy Resonance in QPM calculations



- Evidence for surface neutron density oscillations
- “Soft dipole mode“ at 7 MeV is mixture of isoscalar and isovectorcomponents

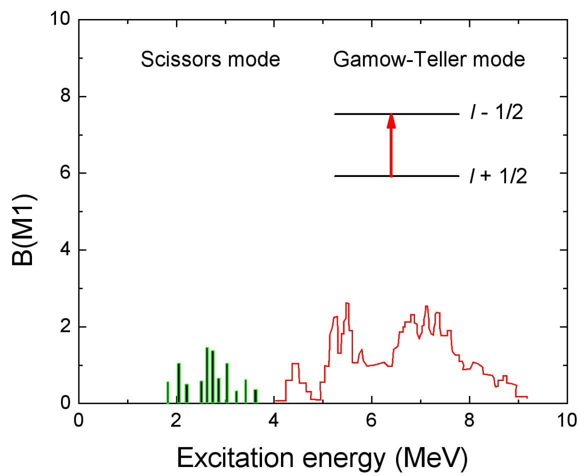
N. Tsoneva, H. Lenske, PRC 77, 024321 (2008)

N. Paar *et al.*, Rep. Prog. Phys. 70, 691 (2007)

First Important Result from HIGS

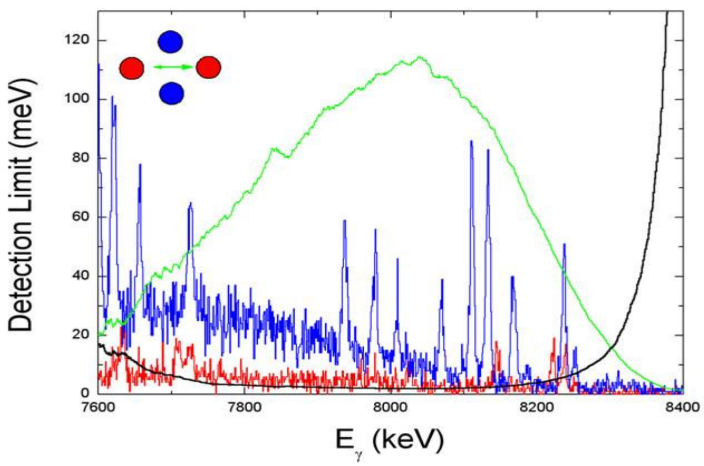
PRD is indeed predominantly E1 more of excitation !

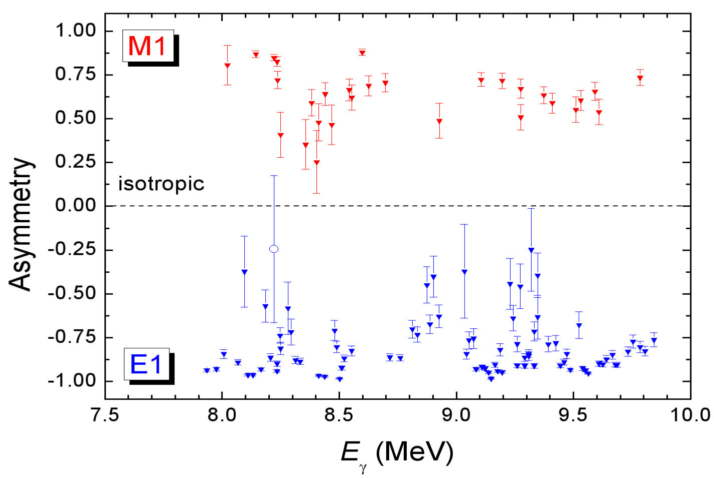
Experimental Asymmetry from $^{90}Zr(\gamma,\gamma')$



- Total of 83 E1 states analyzed so far.
- Total of 29 M1 states analyzed so far.
- Center of gravity of M1 strength at 9 MeV
- $\sum$ (M1) = 3.8(2) μ_N^2

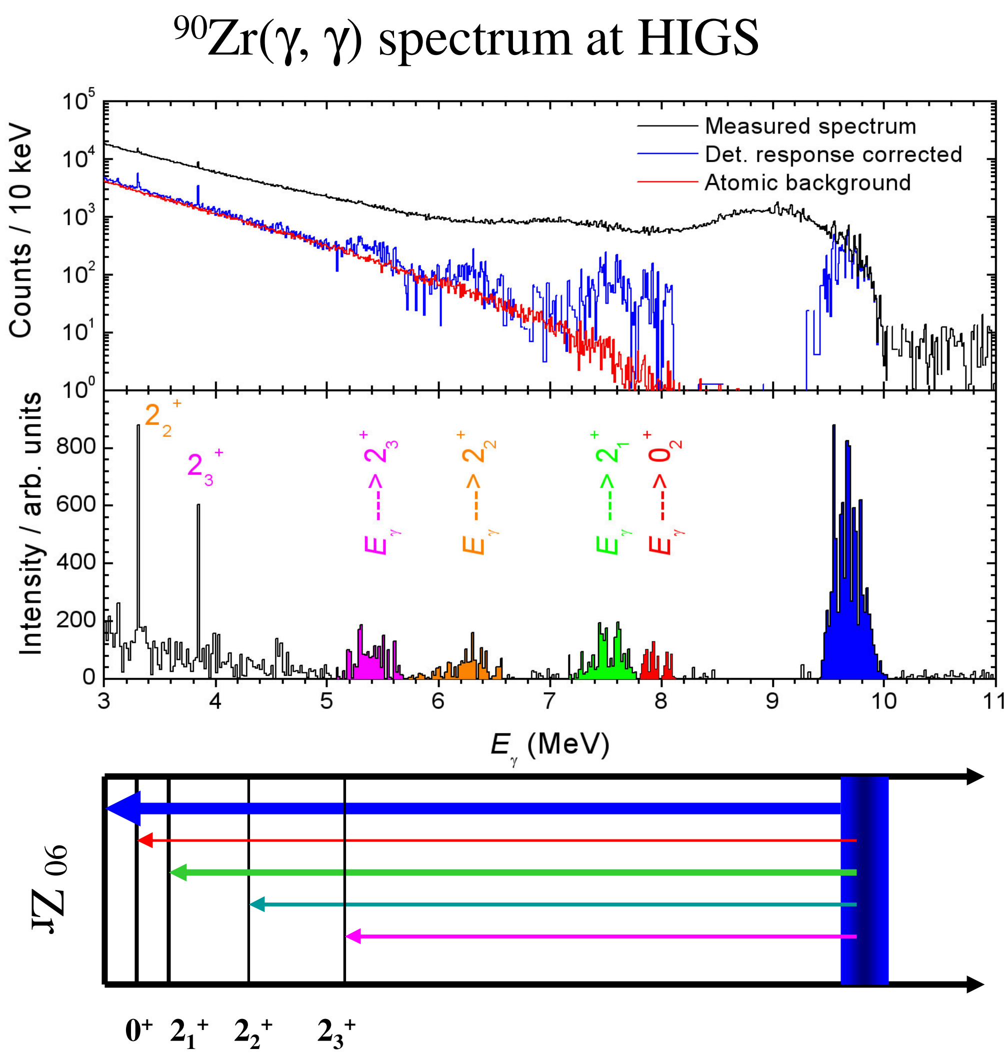
Fine structure of the Giant M1 resonance





G. Rusev: Data analysis in progress

Investigation of Photon-Strength Functions: ^{90}Zr case



G. Rusev *et al*. PRC 77, 064321 (2008)

- Photon-strength function describes energy distribution of photon emission from high-energy states.

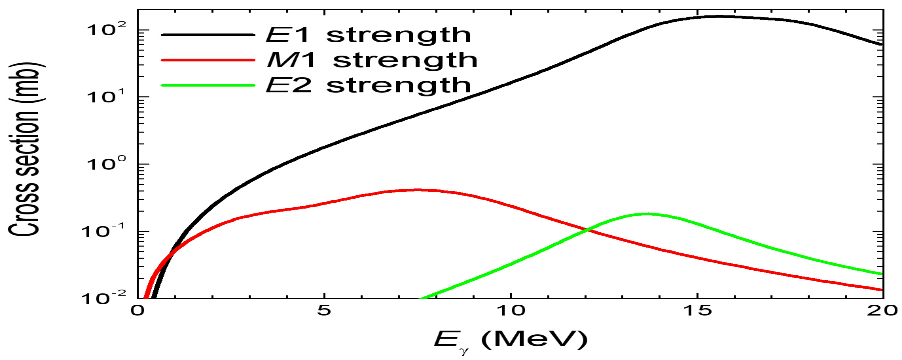
$$f(E_\gamma) = \langle \Gamma_\gamma / D E_\gamma^3 \rangle$$

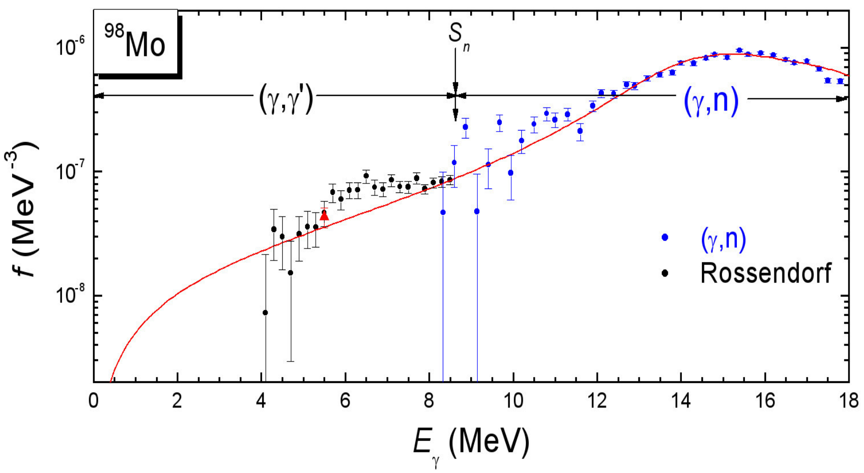
- Importance: Astrophysical network calculations; new fast nuclear reactors, statistical models.

Preliminary results

- E1 is the dominant multipolarity transition
- Primary transitions are strongly dictated by the microscopic properties of the low-lying levels.
  - PSF is not smooth curve below the B_n and $E_\gamma > 4$ MeV.
  -

Investigation of Photon-Strength Functions: ^{98}Mo case





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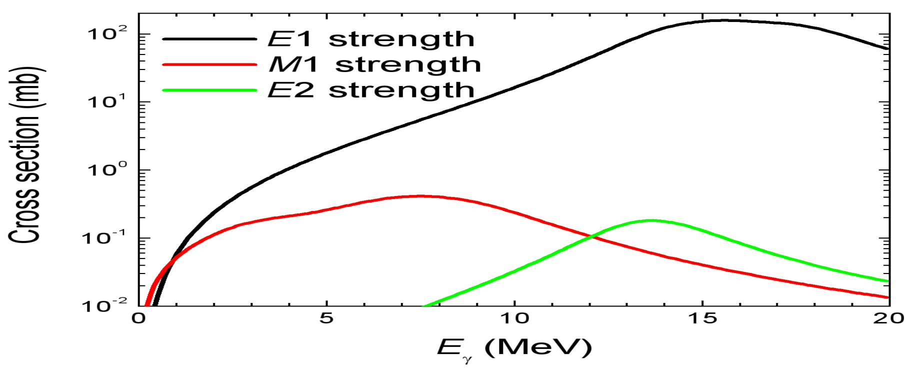

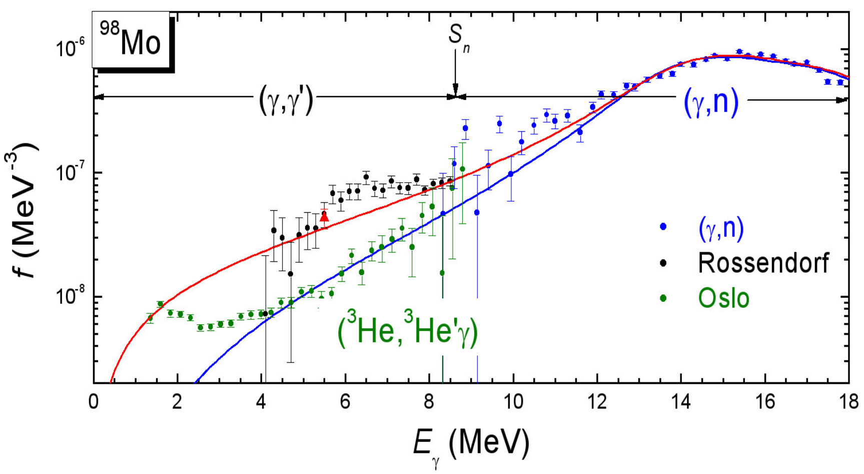

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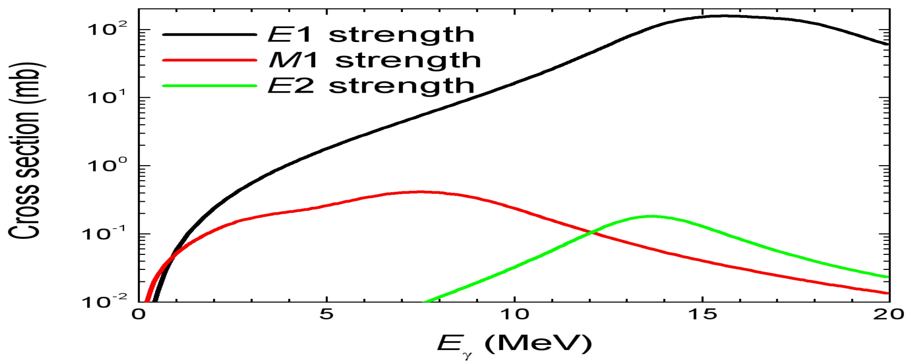

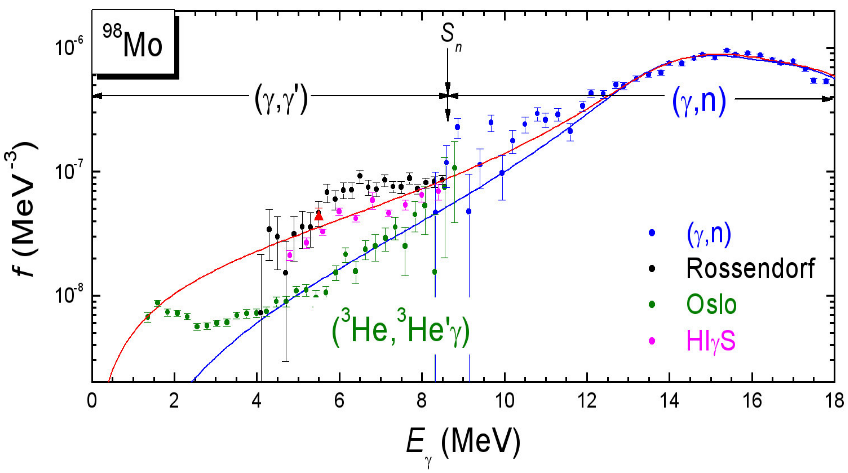

G. Rusev *et al*. PRC 77, 064321 (2008)

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$$f(E_\gamma) = <\Gamma_\gamma / D\, E_\gamma^3>$$

- Importance: Astrophysical network calculations; new fast nuclear reactors, statistical models.
- Present data from HIGS support standard Lorentzian shape down to 4MeV
- Measurements with different probes.

Proposed reactions:

HIGS: ^{98}Mo (γ,γ)

DANCE: ^{97}Mo(n,γ)

Tandem: ^{98}Mo(n,n'γ)

Techniques

NRF, neutron capture, neutron scattering

Summary

- More than 1000 new parities were assigned in: ^{90}Zr, ^{98}Mo, ^{112,124}Sn, ^{138}Ba ^{140}Ce, and ^{142}Nd.
- PDR is indeed an E1 excitation.
- PDR is an enhanced strength below the GDR

Participants

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