A2: Nuclear Structure with Virtual Photons

- Electron scattering at low momentum transfers
  - → selectivity on low-multipolarity transitions → collectivity ($\lambda \leq 2$)
- High-resolution experiments
  - → fragmentation → test of complexity of the nuclear interaction
  - → weak transitions → test of “exotic” parts of the nuclear interaction
- Combination with hadronic probes
  - → decomposition of p/n degrees of freedom
  - → spin and orbital contributions to transition currents

SFB 634

Link to other projects

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- **A1**: Study of dipole response in nuclei, experimental synergies (electronics, neutron ball)
- **C2 / C5**: Strong experimental overlap (spectrometers, electronics, Si ball, data analysis tools)
- **C4**: Analysis of complex wave functions
- **D2 / D3**: Test of nuclear structure models
- **E2 / E3 / E4**: Improvement of beam properties

Physics program in the present funding period

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- Fine structure of giant resonances
  - Y. Kalmykov et al., Phys. Rev. Lett. 99, 202502 (2007) (+D3)
  - A. Shevchenko et al., Phys. Rev. C 77, 024302 (2008) (+D2)
  - A. Shevchenko et al., Phys. Rev. C 79, 044305 (2009) (+D2)
  - I. Petermann et al., Phys. Rev. C 81, 014308 (2010) (+D3)
  - I. Usman et al., Phys. Lett. B (in preparation) (+D2)
- Magnetic and GT response
  - A. Byelikov et al., Phys. Rev. Lett. 98, 082501 (2007) (+D3)
  - F. Beck et al., Phys. Lett. B 645, 128 (2007)
  - L. Popescu et al., Phys. Rev. C 75, 054312 (2007)
  - A. F. Lisetzkiy et al., Nucl. Phys. A 789, 114 (2007) (+D3)
  - F. Hofmann et al., Phys. Rev. C 76, 014314 (2007) (+D2)
  - P. von Neumann-Cosel et al., Phys. Rev. C 79, 059801 (2009)
  - K. Heyde et al., Rev. Mod. Phys. (submitted)
- Monopole transitions as a signature of symmetries
  - J. Bonnet et al., Phys. Rev. C 79, 034307 (2009)
  - N. Y. Shirikova et al., Eur. Phys. J. A 41, 393 (2009)
- Structure of the Hoyle state √
  - M. Chernykh et al., Phys. Rev. Lett. 98, 032501 (2007)
  - M. Chernykh et al., Phys. Rev. Lett. (in preparation)
- Complete dipole response from polarized proton scattering at 0° √
  - A. Tamii et al, Phys. Rev. Lett. (in preparation) (+D2)
- Mixed-symmetry states √
  - O. Burda et al., Phys. Rev. Lett. 99, 092503 (2007) (+D2)
  - J. D. Holt et al., Phys. Rev. C 76, 034325 (2007)
  - N. Pietralla et al., Prog. Part. Nucl. Phys. 60, 225 (2008)
  - C.E. Alonso et al., Phys. Rev. C 78, 017301 (2008)
  - V.Werner et al., Phys. Rev. C 78, 031301 (2008)
  - T. R. Saito et al., Phys. Lett. B 669, 19 (2008)
  - L.Bettermann et al., Phys. Rev. C 79, 034315 (2009)
  - T. Ahn et al., Phys. Lett. B 679, 19 (2009)
  - N. Lo Iudice et al., Phys. Rev. C 80, 024311 (2009)
  - C. Walz et al., Phys. Rev. Lett. (in preparation) (+D2)

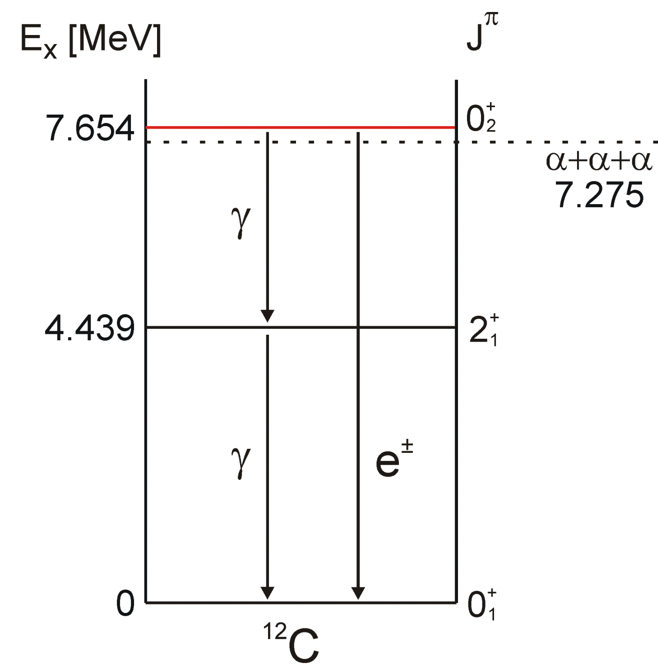
Structure of the Hoyle state in ^{12}C

- The Hoyle state is a prototype of α -cluster states in light nuclei

- Cannot be described within the shell model but within α -cluster models

- Some α -cluster models predict the Hoyle state to consist of a dilute gas of weakly interacting α particles with properties of a Bose-Einstein Condensate (BEC)
  A. Tohsaki et al., Phys. Rev. Lett. 87,192501 (2001)

- High-precision electron scattering data as a test of FMD and α -cluster models: generally good agreement but M(E0) systematically overpredicted
  M. Chernykh et al. Phys. Rev. Lett. 98, 032501 (2007)



Triple alpha process

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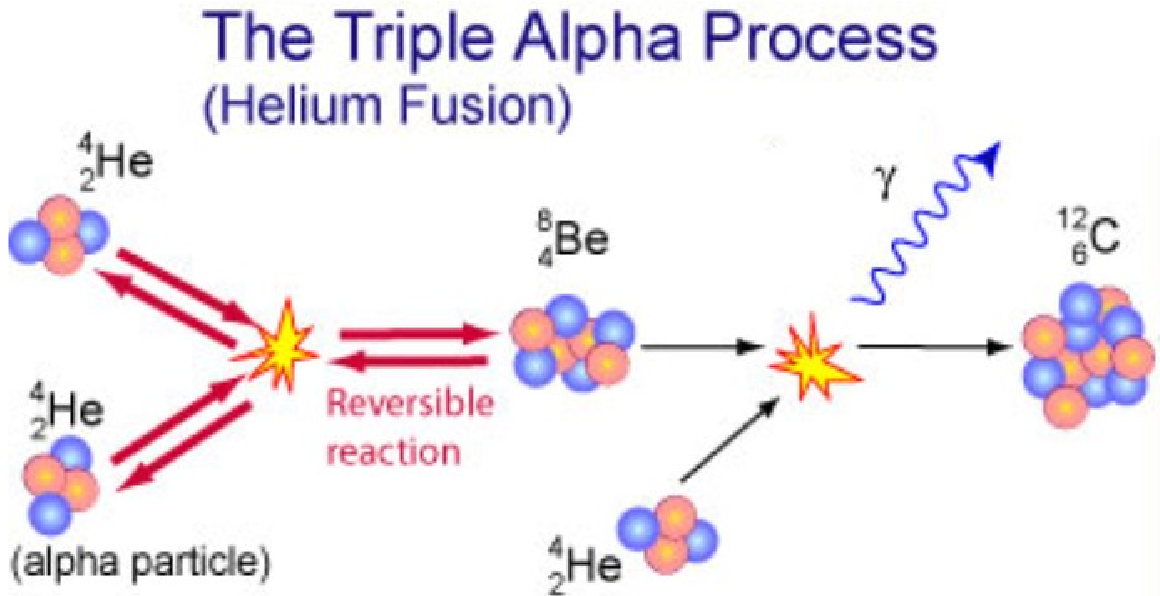


http://outreach.atnf.csiro.au

- Triple alpha reaction rate

$$r_{3\alpha} \propto \Gamma_{rad} \exp\left(-\frac{Q_{3\alpha}}{kT}\right)$$

$$\Gamma_{rad} = \Gamma_\gamma + \Gamma_\pi = \frac{\Gamma_\gamma + \Gamma_\pi}{\Gamma} \cdot \frac{\Gamma}{\Gamma_\pi} \cdot \Gamma_\pi$$

(α ,α ’) (p,p’) → Γ

(p,p’) → Γ_π

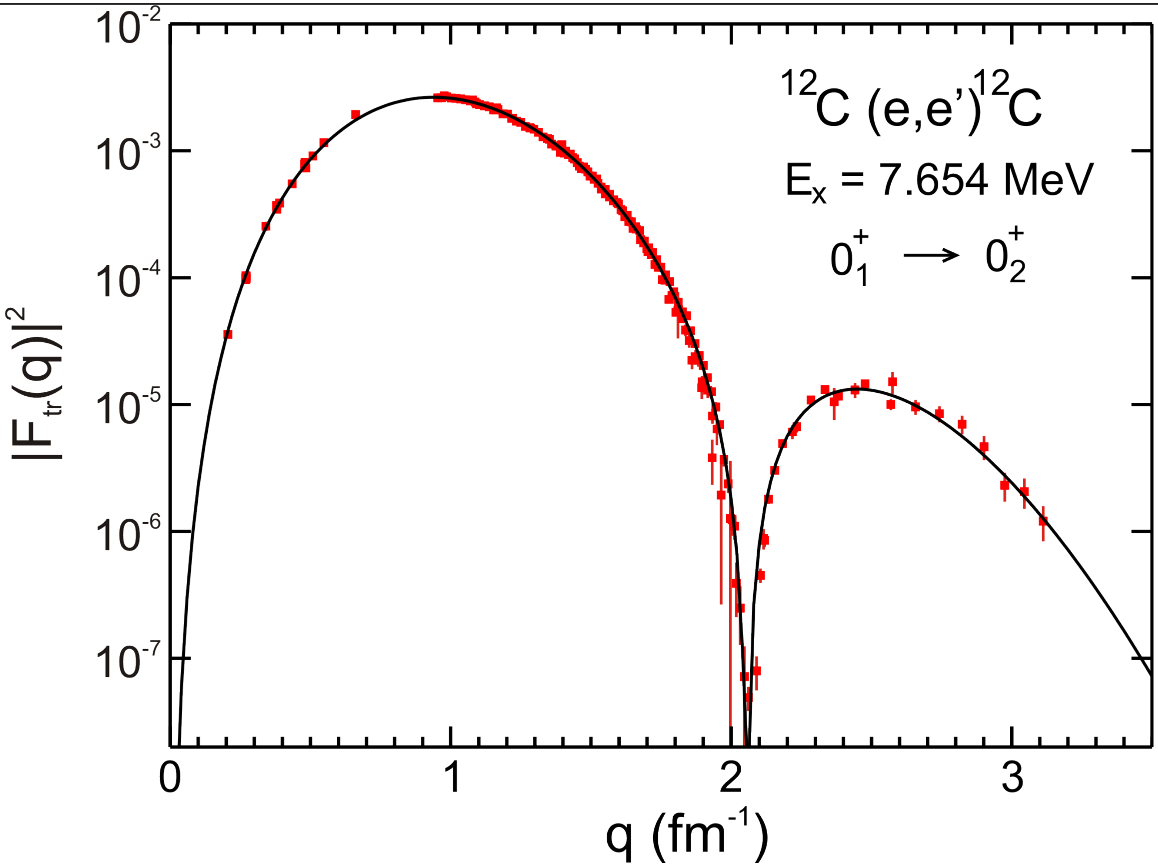
(e,e’) → Γ_π

Triple alpha reaction rate

- Reaction rate needed with accuracy ~ 5%
  S.M. Austin, Nucl. Phys. A 758, 375c (2005)

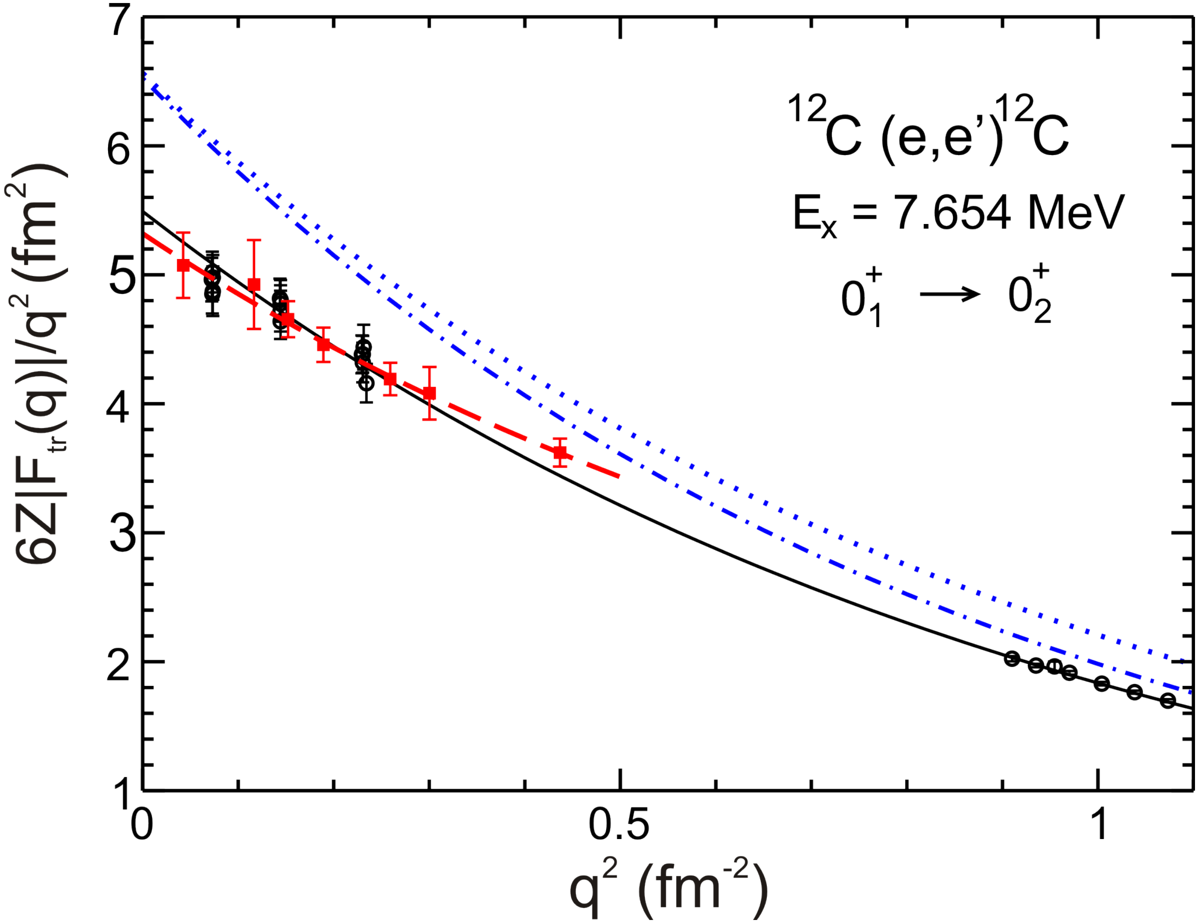
Quantity	Value	Error (%)	
$Q_{3\alpha}$	379.38 ± 0.20 keV	1.2 (T$_9$=0.2)	
Γ_{rad}/Γ	$(4.12 \pm 0.11)\times 10^{-4}$	2.7	
Γ_{π}/Γ	$(6.74 \pm 0.62)\times 10^{-6}$	9.2	
Γ_{π}	$(62.0 \pm 6.0)\times 10^{-6}$ eV	9.7	Crannell *et al.* (1967)
Γ_{π}	? $(59.4 \pm 5.1)\times 10^{-6}$ eV	8.6	Strehl (1970)
Γ_{π}	$(52.0 \pm 1.4)\times 10^{-6}$ eV	2.7	Crannell *et al.* (2005)

Form factor analysis



- Novel ansatz: $F_{tr}(q) = \frac{1}{Z} e^{-\frac{1}{2}(bq)^2} \sum_{n=1}^{n_{max}} c_n (bq)^{2n}$ ➡ $\Gamma_\pi = 66.3(2.0)\,\mu\text{eV}$

Low-q expansion

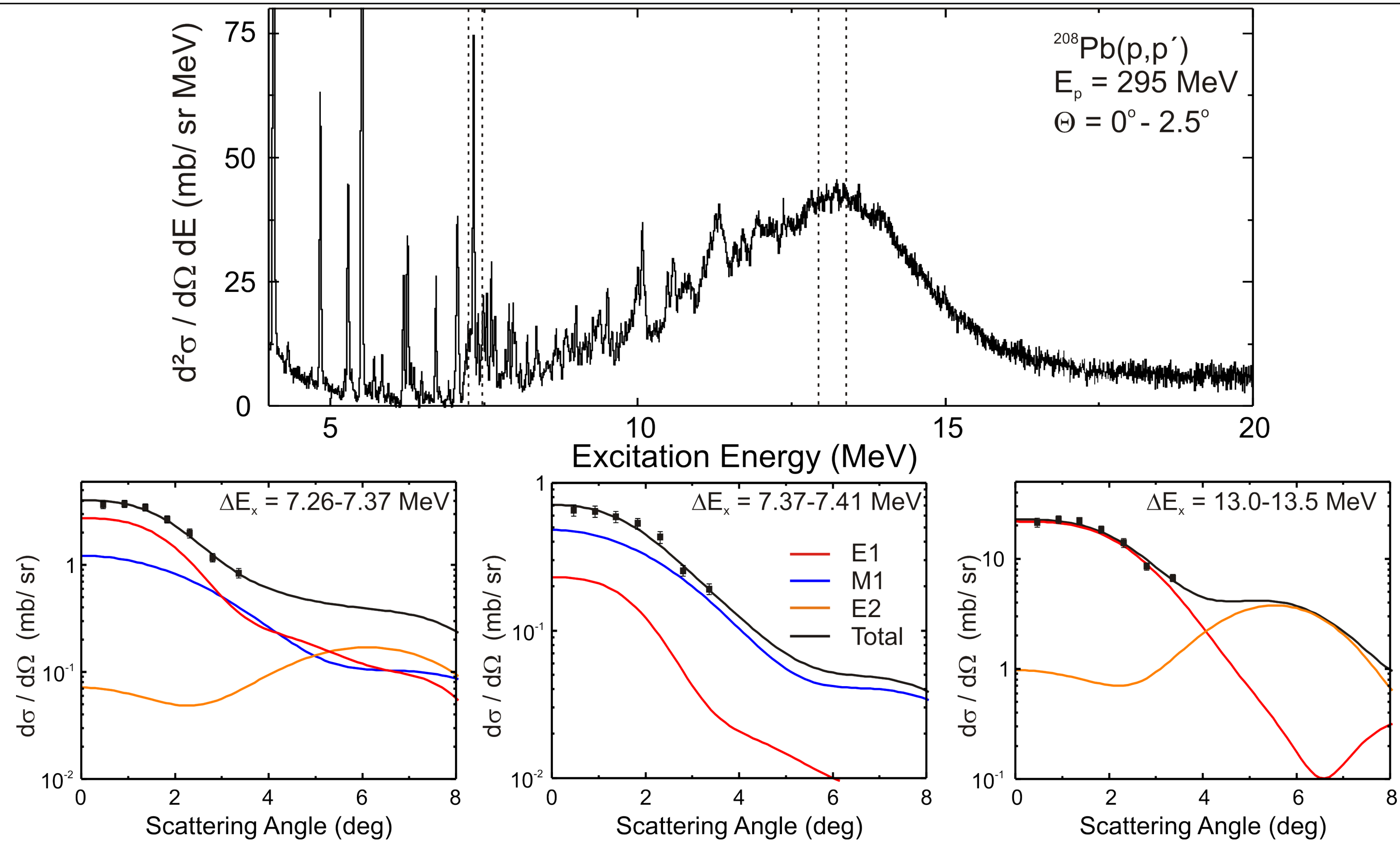


$$-\frac{6ZF_{tr}(q)}{q^2}=\left\langle r^2\right\rangle_{tr}^{low\,q}-\frac{q^2}{20}\left\langle r^4\right\rangle_{tr}^{low\,q}+\frac{q^4}{840}x^3\left(\left\langle r^2\right\rangle_{tr}^{low\,q}\right)^3-\frac{q^6}{60480}x^4\left(\left\langle r^2\right\rangle_{tr}^{low\,q}\right)^4$$

Complete E1 and M1 Strength Distributions

- Method: polarized proton scattering at 0°
- Experiments at RCNP, Osaka
  - intermediate energy: 300 MeV optimal
  - high resolution: ΔE = 25 keV (FWHM)
  - angular distributions: E1 / M1 separation
  - polarization observables: spinflip / non-spinflip separation
- ^{208}Pb: a reference case
- ^{120}Sn: resonance character of the PDR
- ^{154}Sm: double-hump structure of the spin M1 resonance
  PDR in a heavy deformed nucleus (approved proposal)

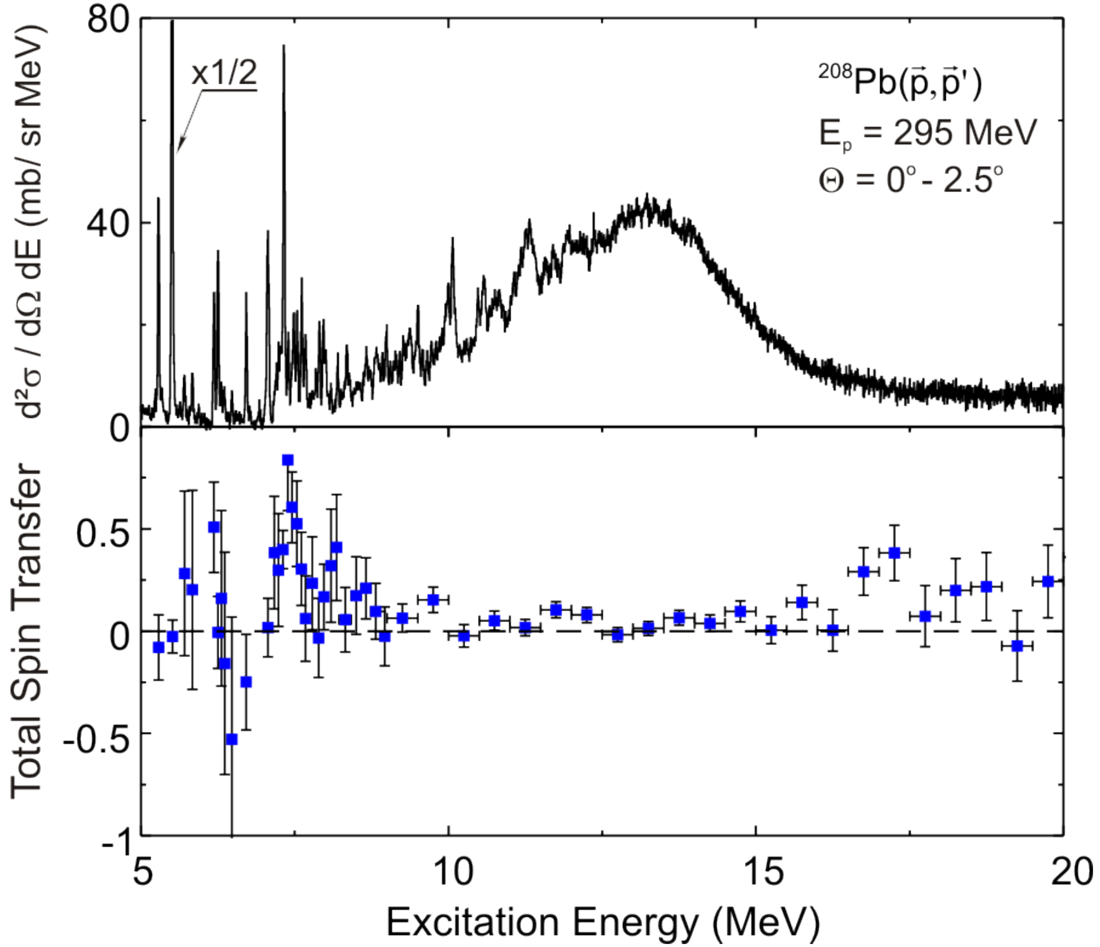
Multipole decomposition of angular distributions



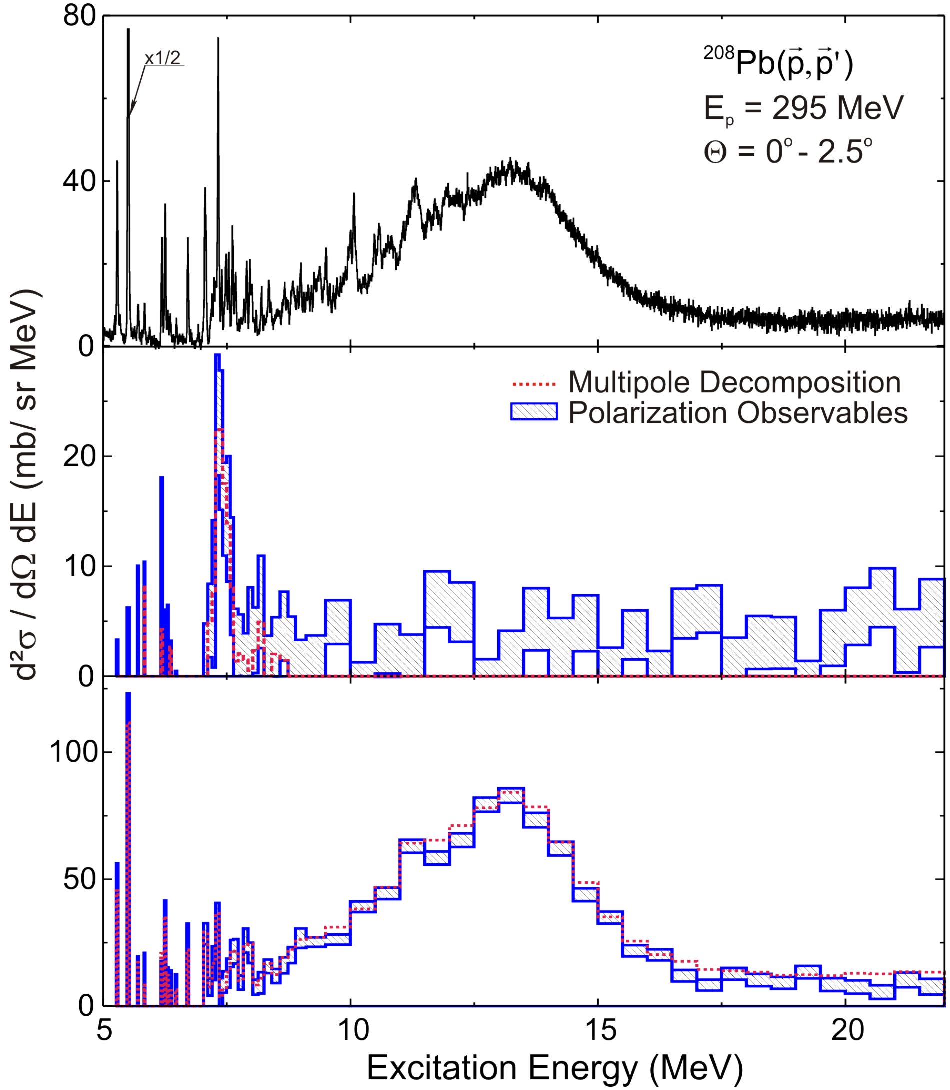
- Neglect of data for Θ > 4°: (p,p´) response too complex
- Included E1 / M1 / E2 or E1 / M1 / E3 (little difference)

Spin transfer

$$\text{Total Spin Transfer } \Sigma \equiv \frac{3-(2D_{SS}+D_{LL})}{4} = \begin{cases} 1 \text{ for } \Delta S = 1 \\ 0 \text{ for } \Delta S = 0 \end{cases}$$



Comparison of both methods

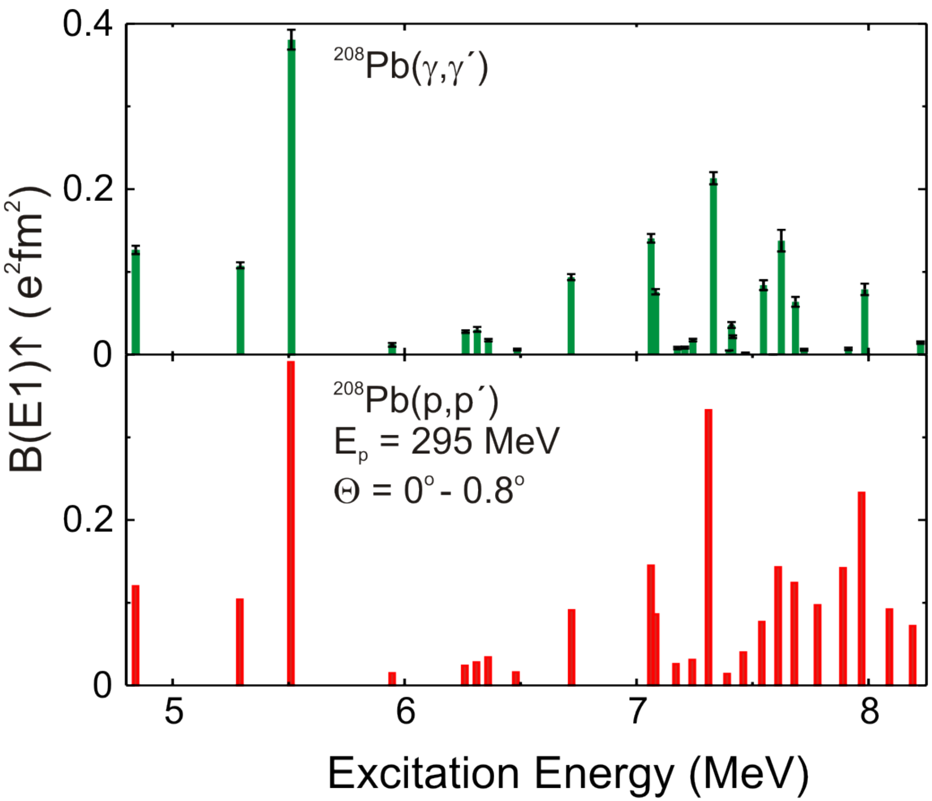


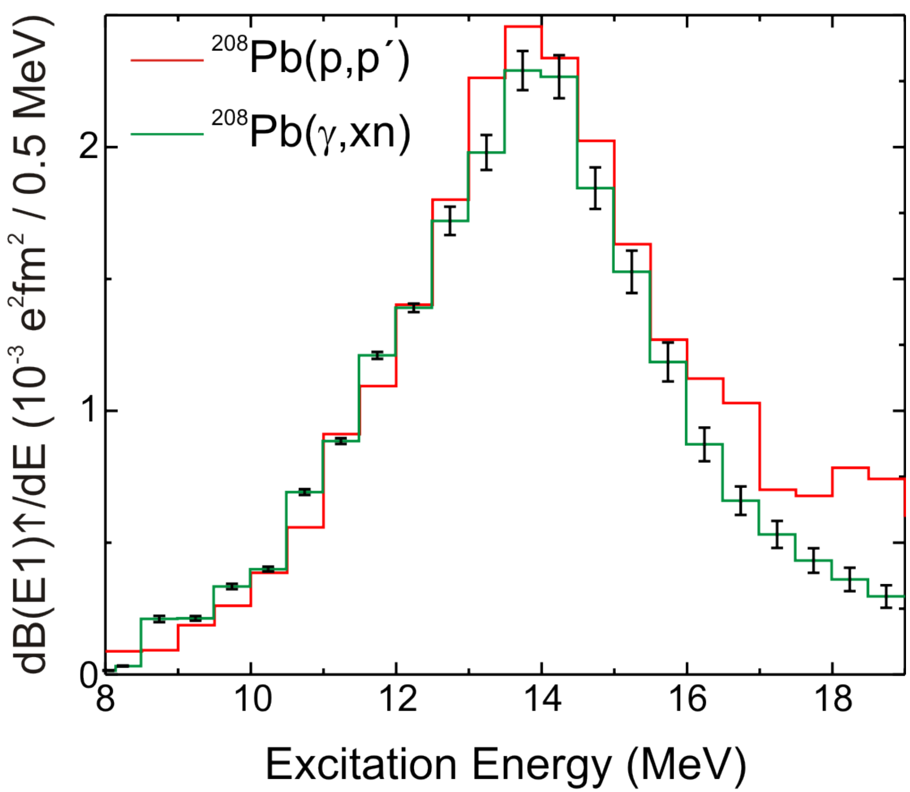
Total

Δ S = 1

Δ S = 0

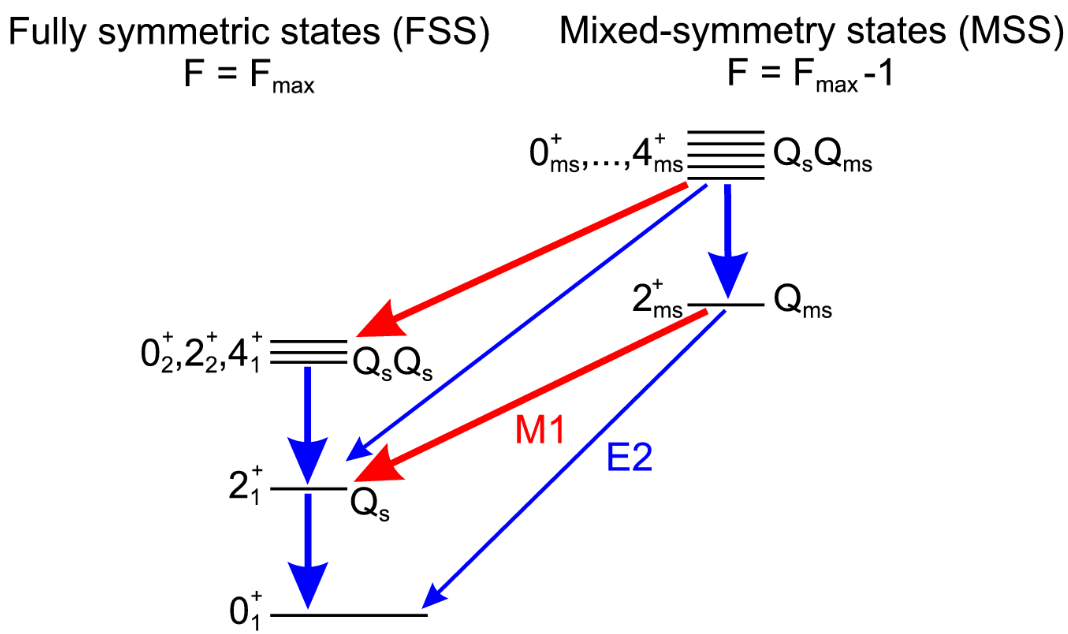
B(E1) Strength

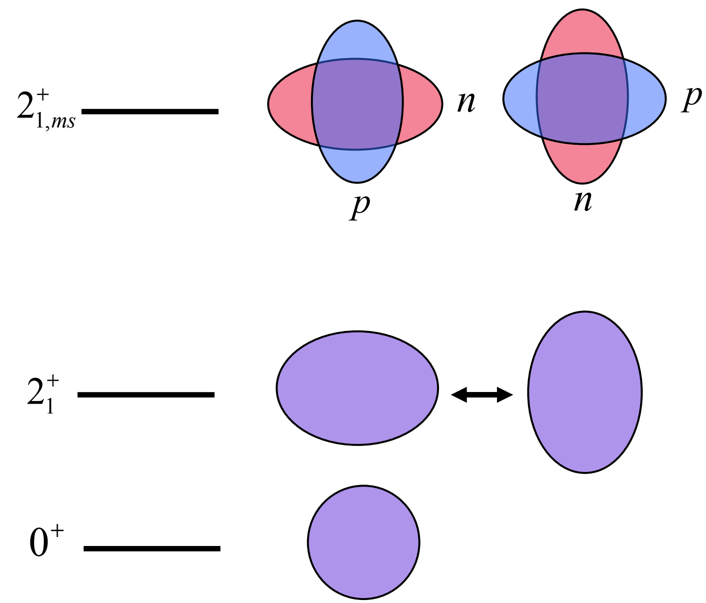




- extracted assuming semiclassical Coulomb excitation

Mixed-symmetry states as low-energy building blocks





- Strong E2 transitions for decay of Q_s-phonon
- Weakly collective E2 transitions for decay of Q_{ms}-phonon
- Strong M1 transitions for decay of MSS to FSS

Study of MS 2^+ states with (e,e´) and (p,p´) reactions

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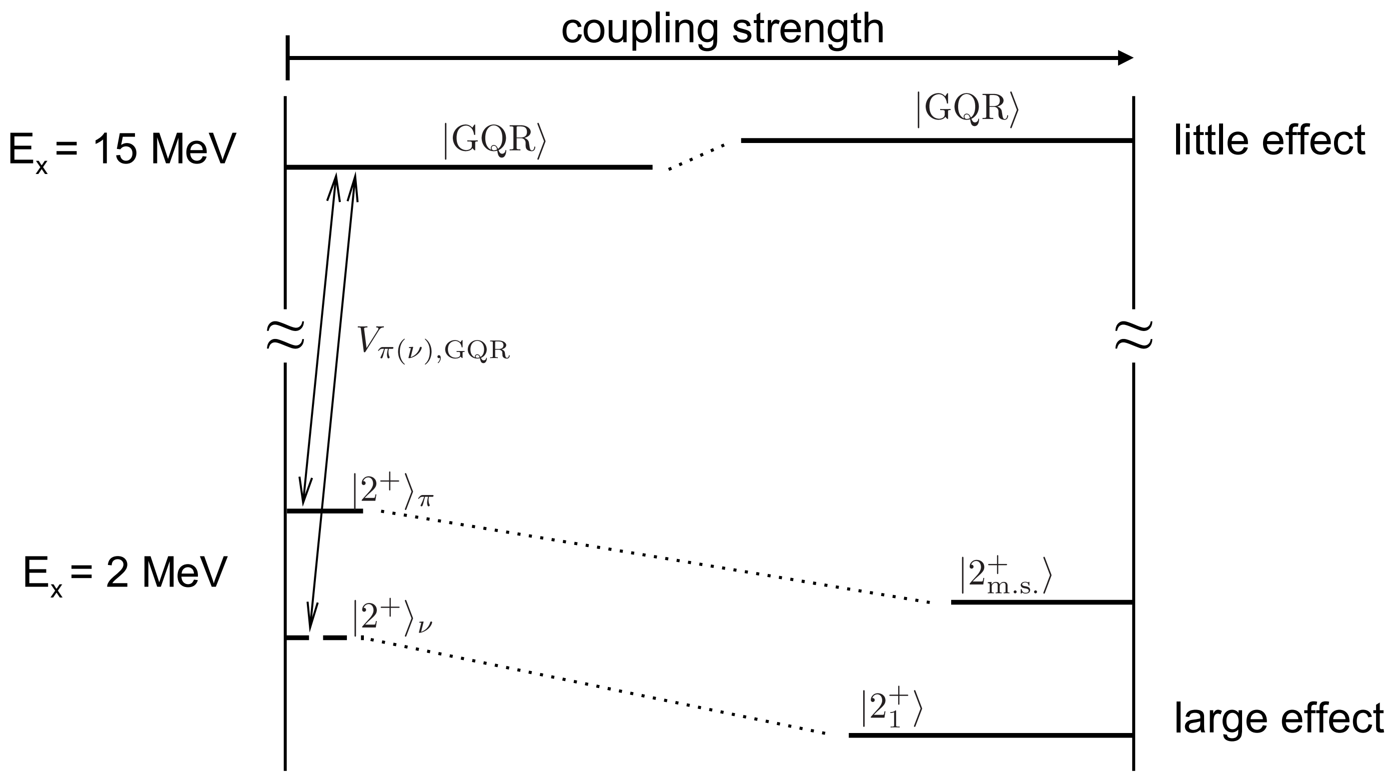
- (e,e´) and (p,p´) test collectivity
- Comparison of (e,e´) and (p,p´) allows proton/neutron decomposition of the wave function
- Isovector Character (in the valence shell) of MS 2^+ states experimentally confirmed in ^{92}Zr, ^{94}Mo
- Current questions:
  - What determines collectivity of transition to 2^+ MS states?
  - What regulates transition from initial p / n to IS / IV structure?

$\longrightarrow$ coupling to GQR

Coupling to GQR: a 3-state model



$$|2_1^+\rangle = \beta\left(\alpha|2^+\rangle_\nu + \sqrt{1-\alpha^2}|2^+\rangle_\pi\right) + \sqrt{1-\beta^2}|\mathrm{GQR}\rangle$$

$$|2^+_{\mathrm{m.s.}}\rangle = \tilde{\beta}\left(\tilde{\alpha}|2^+\rangle_\pi - \sqrt{1-\tilde{\alpha}^2}|2^+\rangle_\nu\right) + \sqrt{1-\tilde{\beta}^2}|\mathrm{GQR}\rangle$$

- reminiscent of EFT: high-energy sector can be integrated out → effective charges

New experimental test of MS character of 2⁺ states

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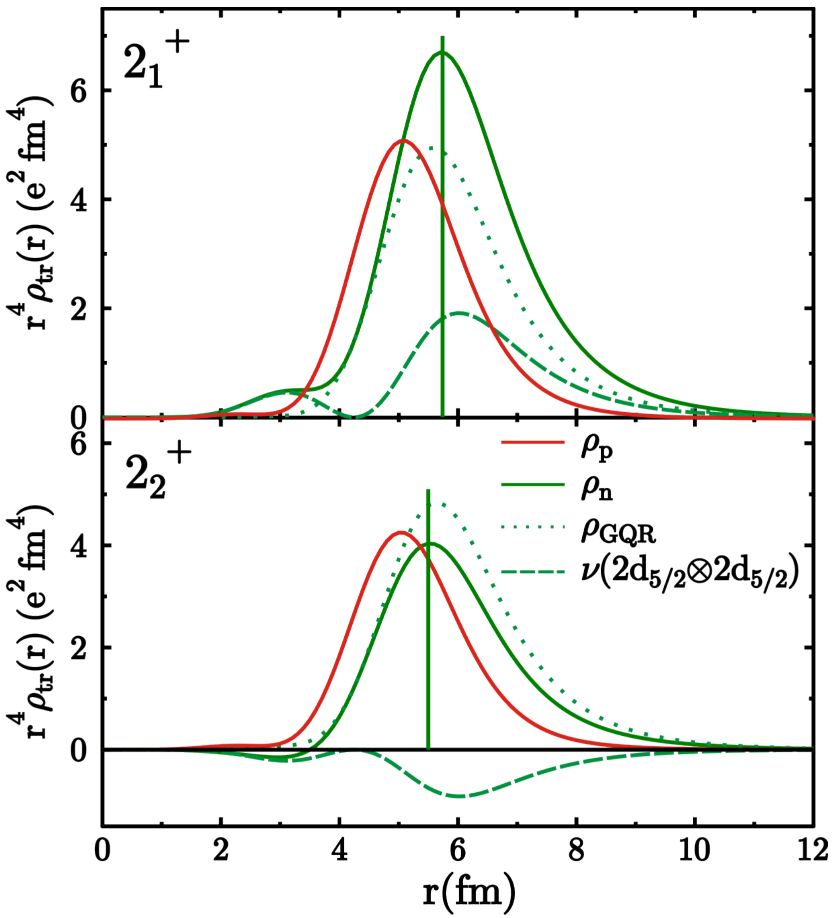
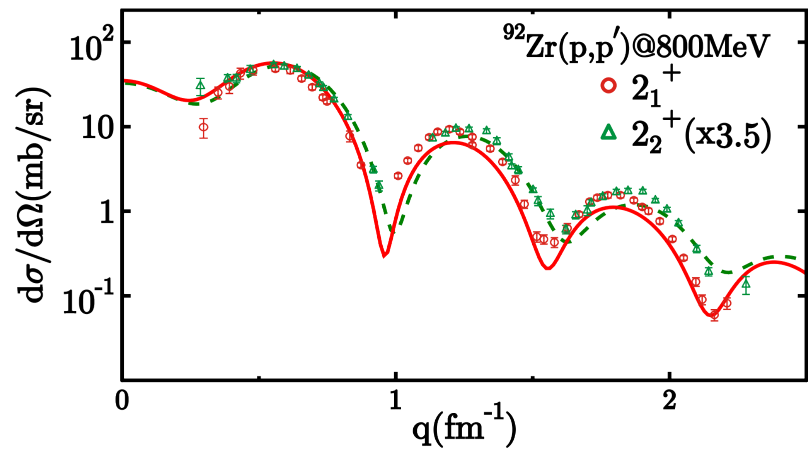
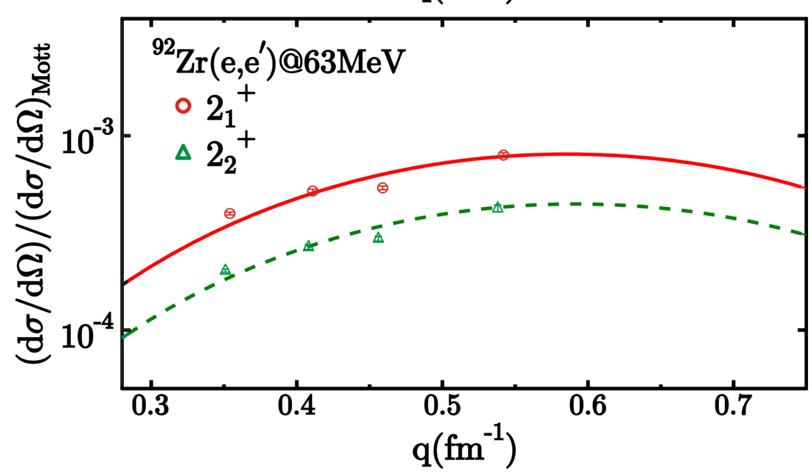




shift



no shift

- shift of neutron transition density
- direct signature for MS state!

Plans for the new funding period

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▪ Study of α cluster states in coincidence experiments	J. Birkhan
▪ Structure of the PDR	I. Poltoratska
▪ Isoscalar giant dipole resonance in (e,e´n) coincidence experiments	A.M. Heilmann
▪ Mixed-symmetry states	A. Scheikh-Obeid C. Walz
▪ Test of IBM symmetries	A. Krugmann

Search for 2^+ state built on the Hoyle state

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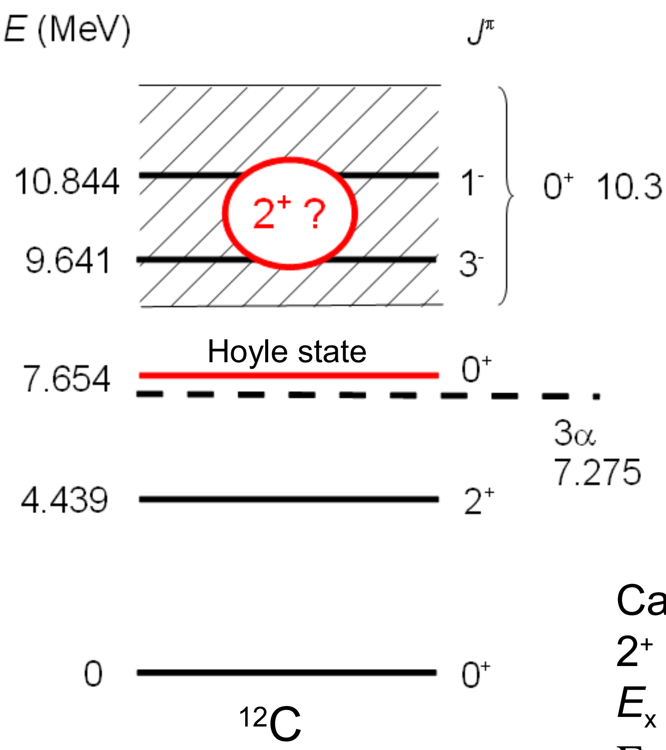
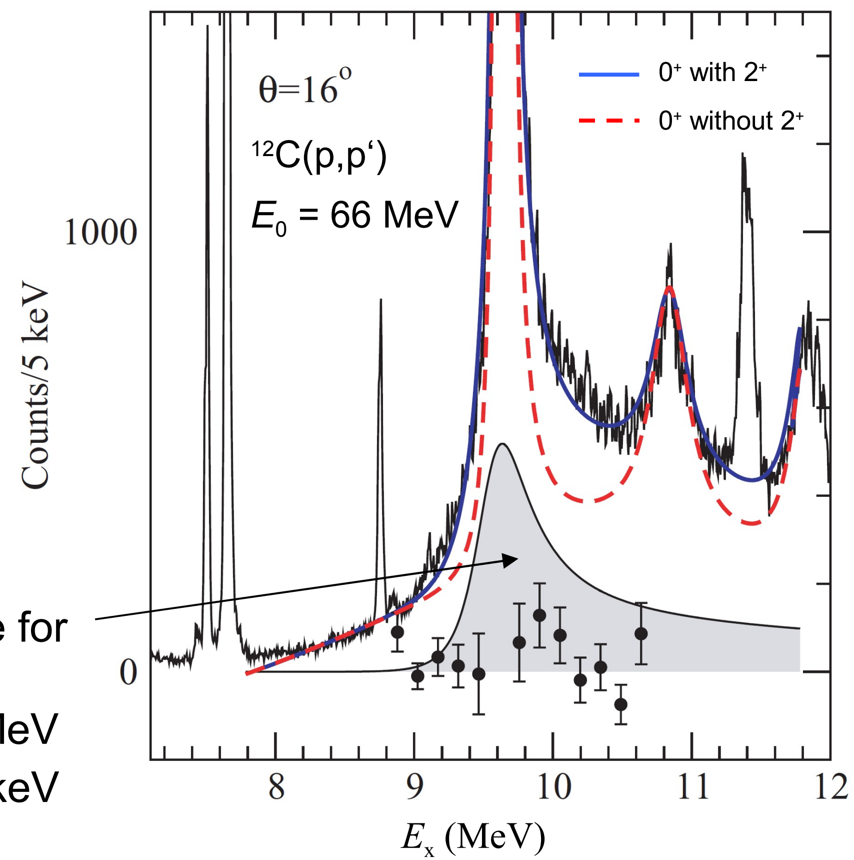


iThemba LABS



Candidate for 2^+ state

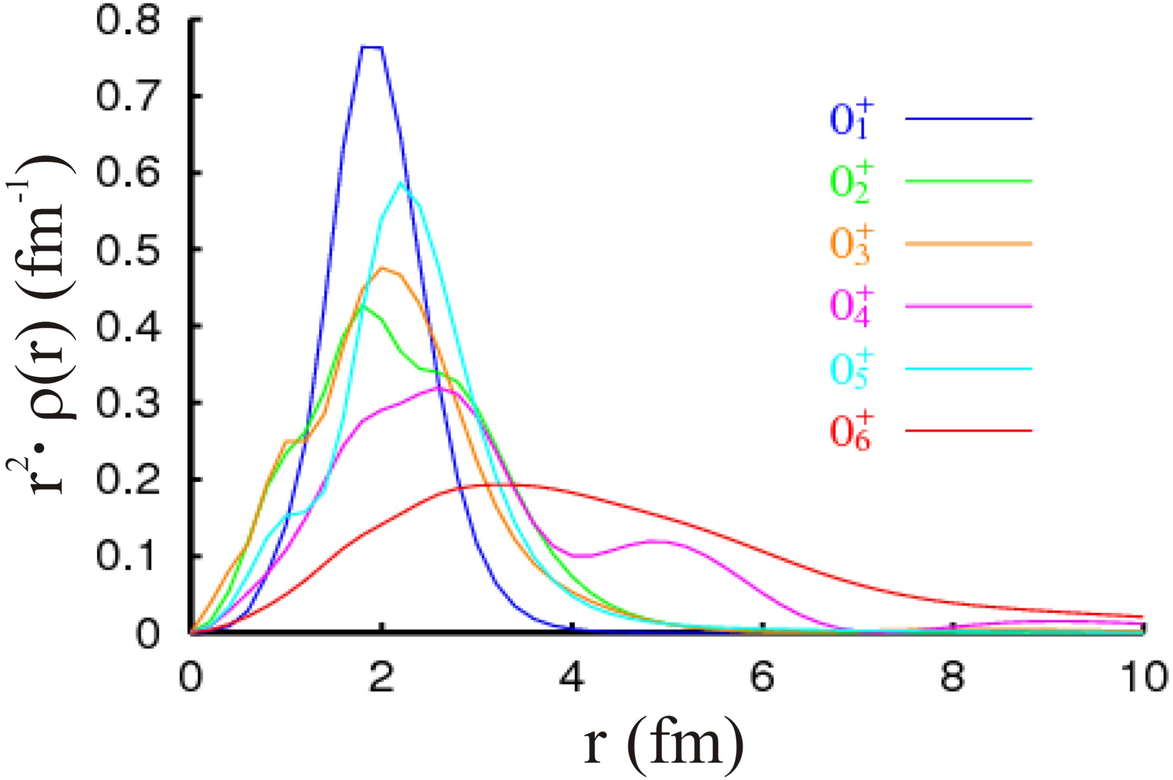
E_x = 9.6 MeV

Γ = 600 keV

M. Freer et al., Phys. Rev. C **80**, 041303(R) (2009)

Analog of the Hoyle state in ^{16}O

Y. Funaki, talk at COMEX3 (2009)



0_6^+ : dilute α gas

Analog of the Hoyle state in ^{16}O

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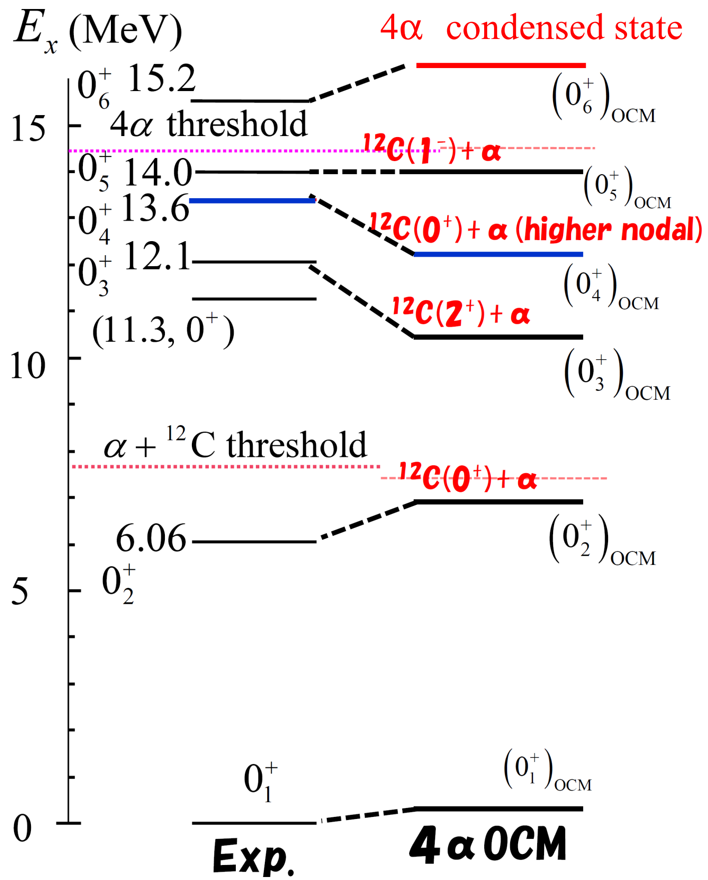
Level scheme of ^{16}O



0_4^+ state: T. Wakasa, Y. F. et al., PLB 653, 173 (2007).

	R_{rms} (fm)	M(E0) (fm²)	M(E0) (fm²) Exp.
$(0_1^+)_{OCM}$	2.7		
$(0_2^+)_{OCM}$	3.0	3.9	0_2^+: 3.55
$(0_3^+)_{OCM}$	3.1	2.4	0_3^+: 4.03
$(0_4^+)_{OCM}$	4.0	2.4	0_4^+: no data
$(0_5^+)_{OCM}$	3.1	2.6	0_5^+: 3.3
$(0_6^+)_{OCM}$	5.6	1.0	0_6^+: no data

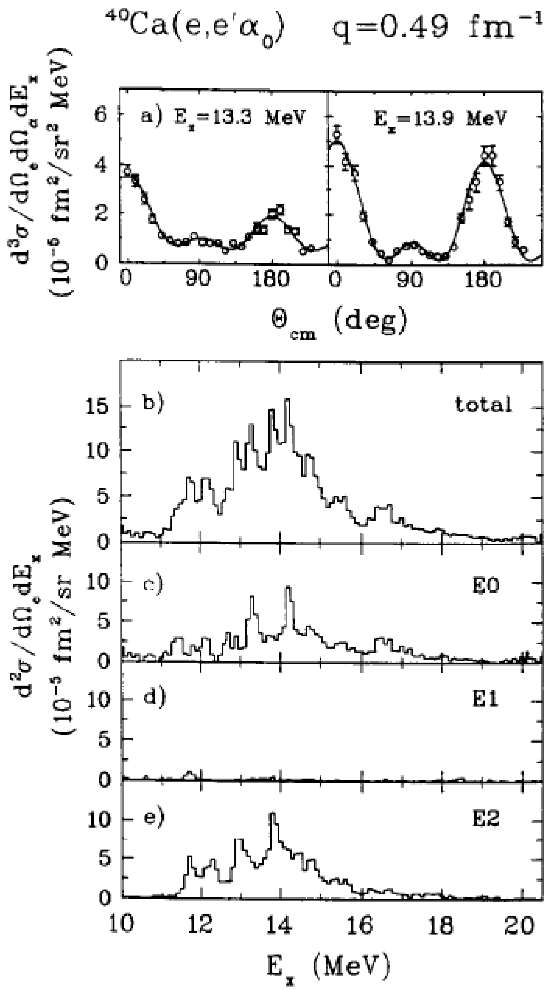
Prediction: $\Gamma\ (0_6^+)$ = 50 keV (R-matrix theory)

Experiment: $\Gamma\ (0_6^+)$ = 166(30) keV

Y. Funaki et al., Phys. Rev. Lett. 101, 082502 (2008)

Y. Funaki et al., Phys. Rev. C 80, 064326 (2009)

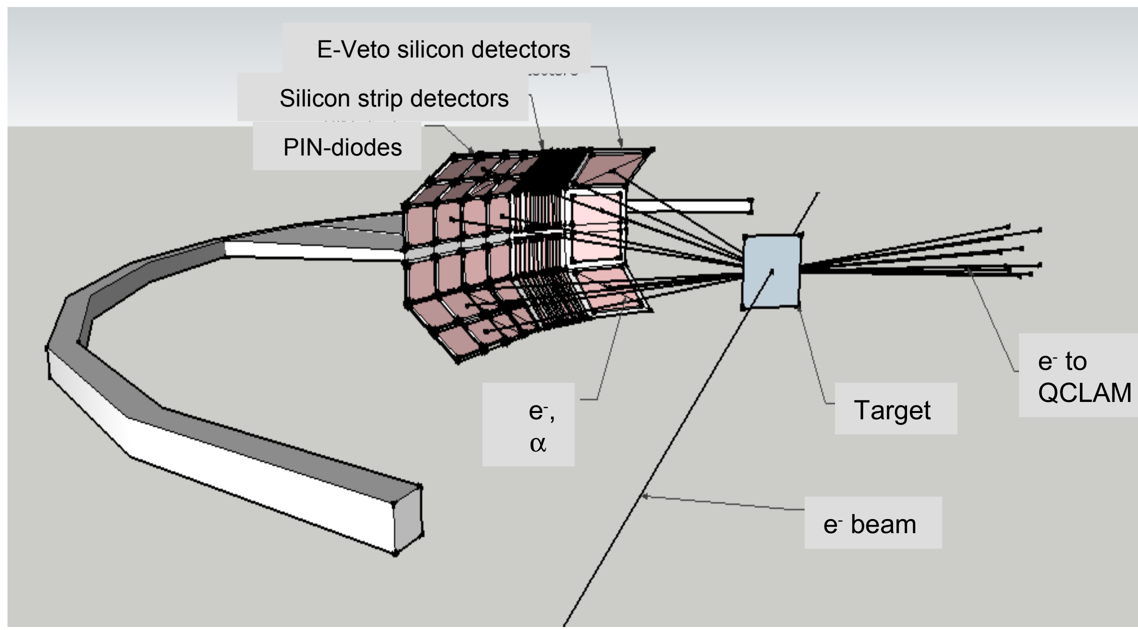
Multipole decomposition via (e,e‘α) – coincidence experiment



$$W(\theta,E_x,q)=\left|\sum_{\lambda=0}^{2}\sqrt{2\lambda+1}\cdot C_\lambda(E_x,q)\cdot e^{i\delta_\lambda(E_x,q)}\cdot P_\lambda(\cos\theta)\right|^2=\sum_{n=0}^{4}a_n\cos^n\theta$$

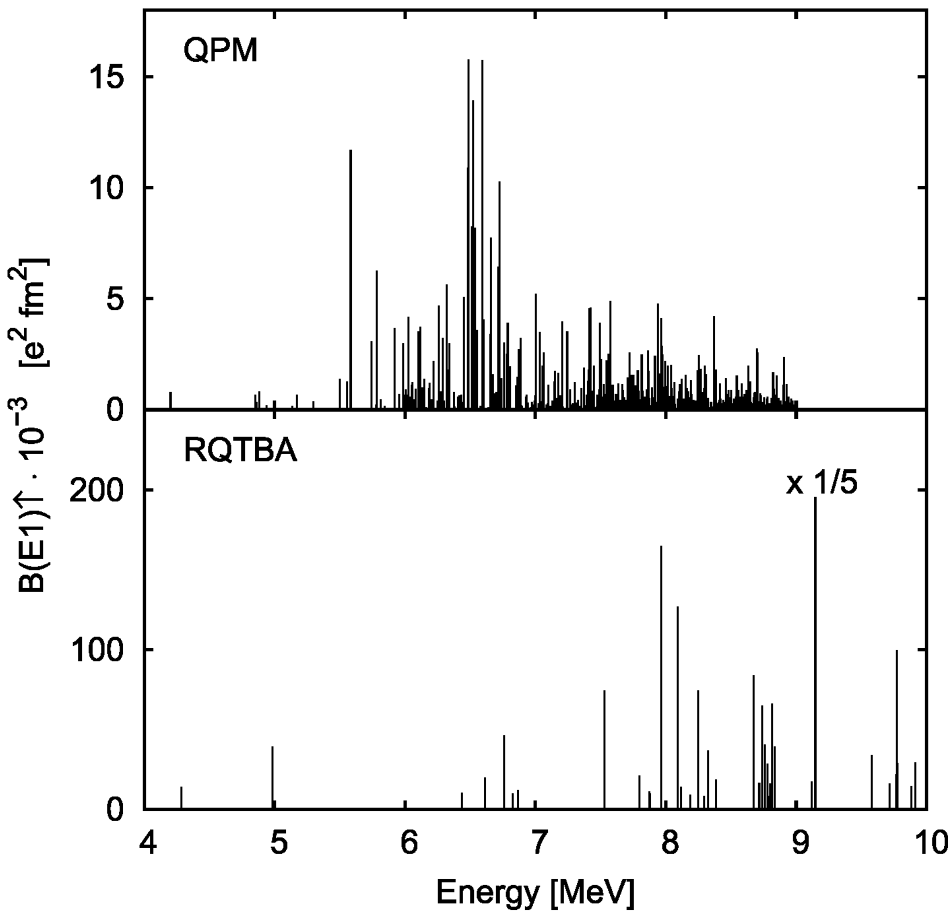
→ multipole decomposition

Large solid angle detector → test setup



H. Diesener et al., Phys. Lett. B 352, 201 (1995)

Complete E1 response: example ^{120}Sn

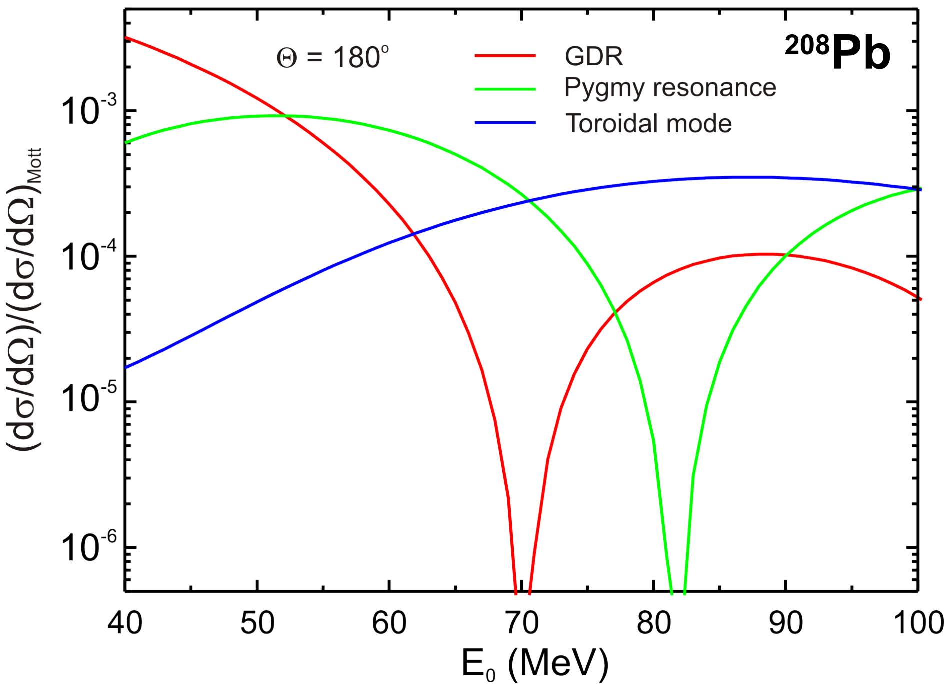


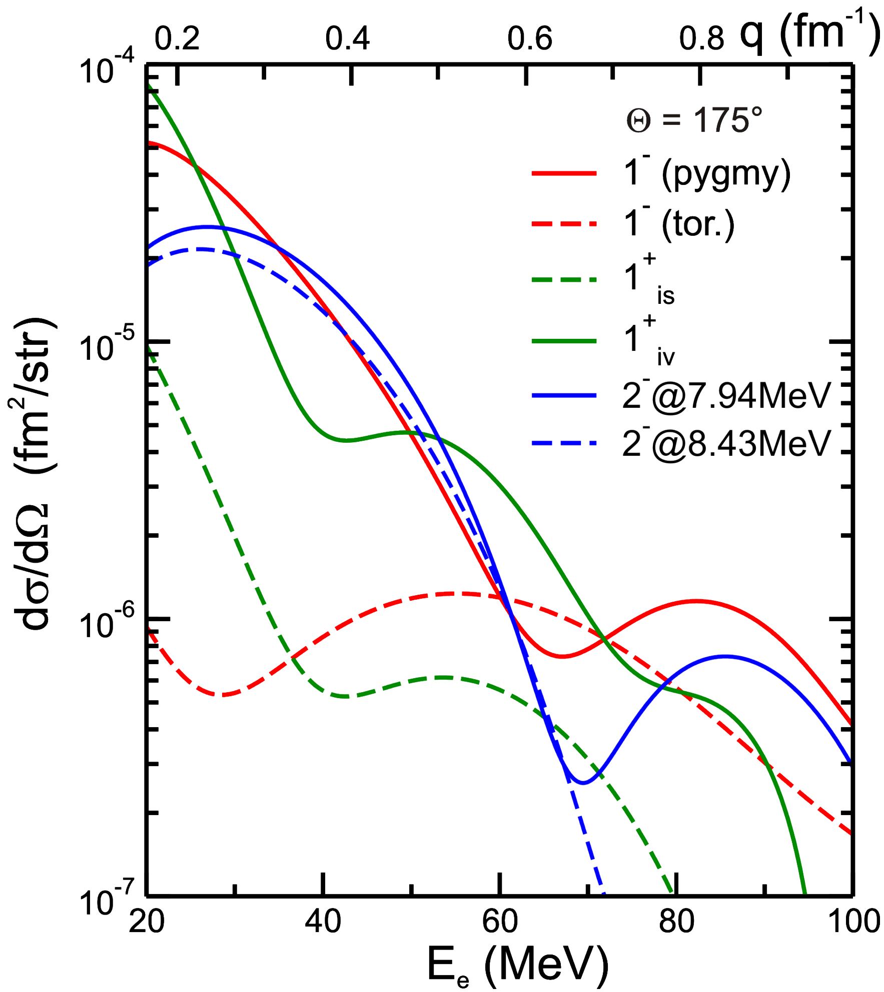
V.Yu. Ponomarev

E. Litvinova

- Very different predictions for centroid and strength of the PDR
  → distinction from measurements of the complete E1 response

Structure of the PDR from transverse electron scattering





- Clear signature, but can one distinguish from other J^π ?

Neutron Ball for (e,e'n) experiments

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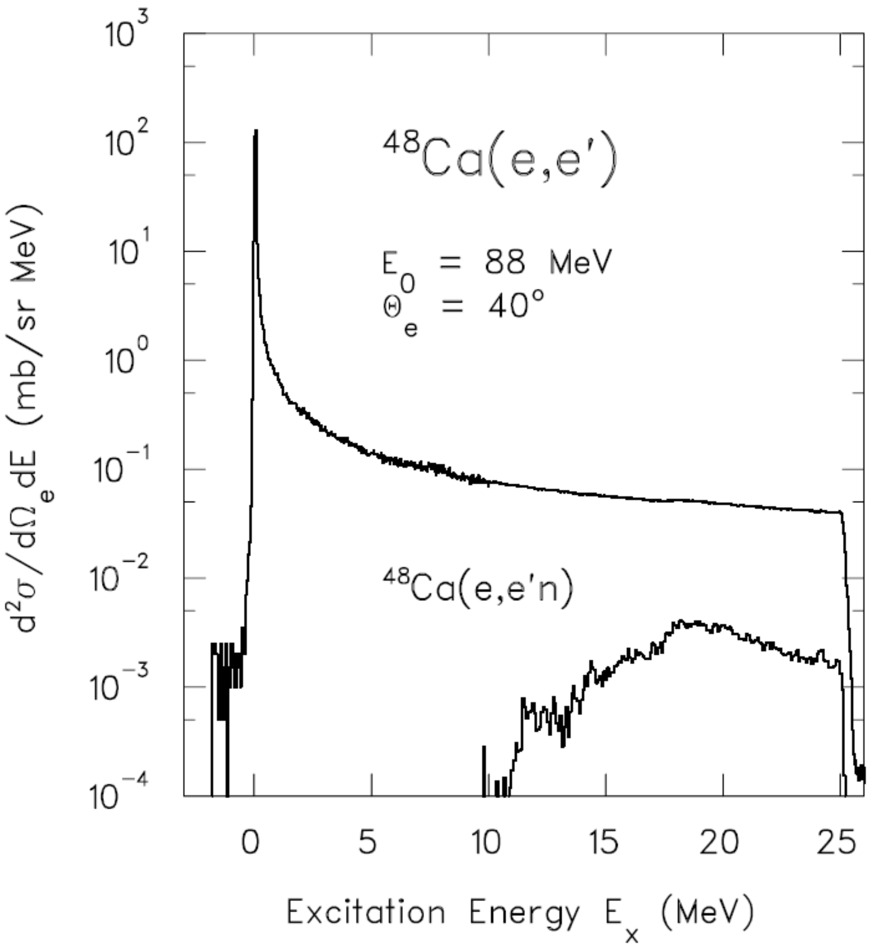


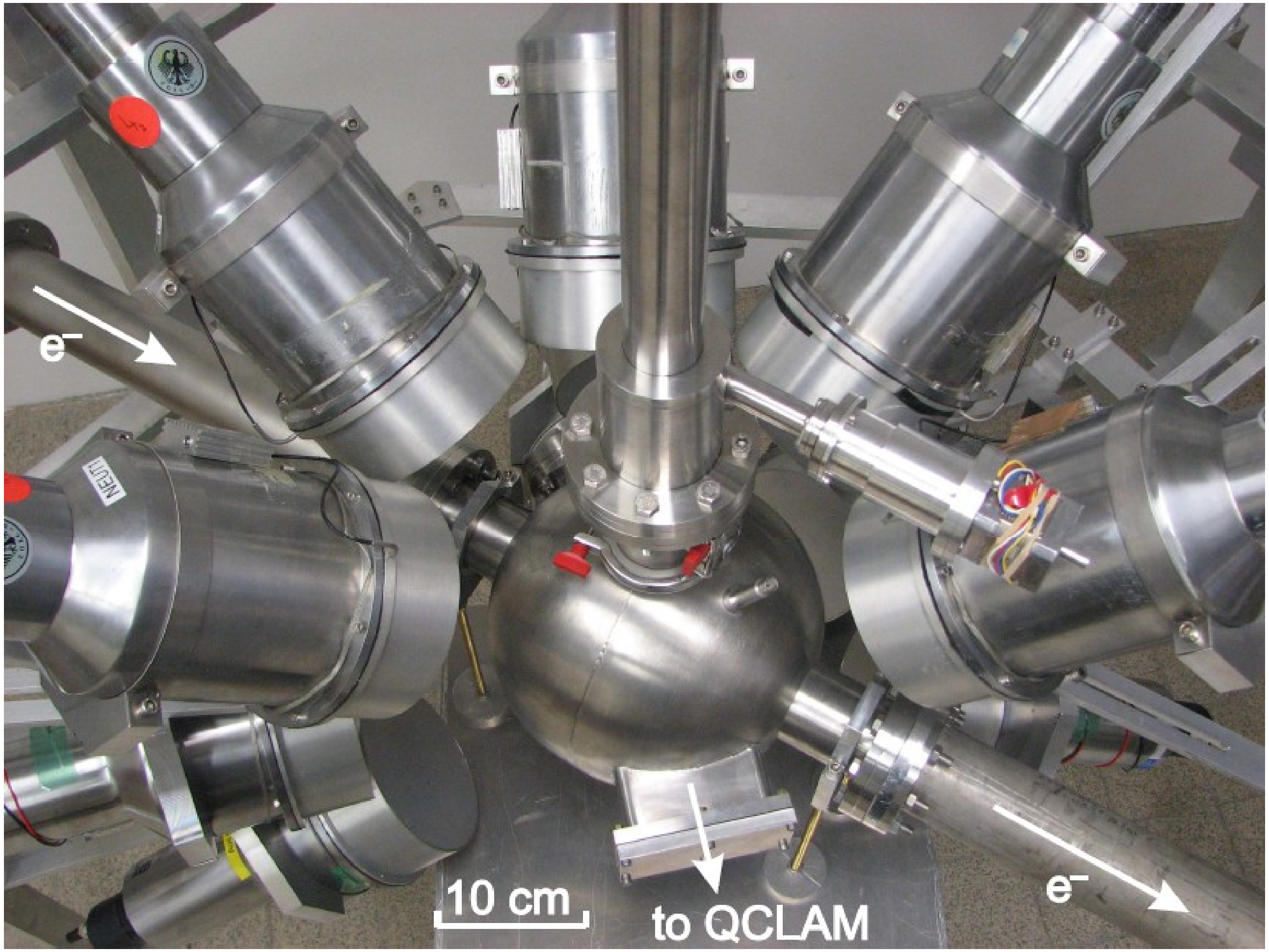
S.Strauch et al, Phys. Rev. Lett. (1998)

exclusive experiments almost background-free but very small coincidence cross sections

→ large solid angle ball

works as trigger
(no angular correlations)

Neutron Ball



Performance

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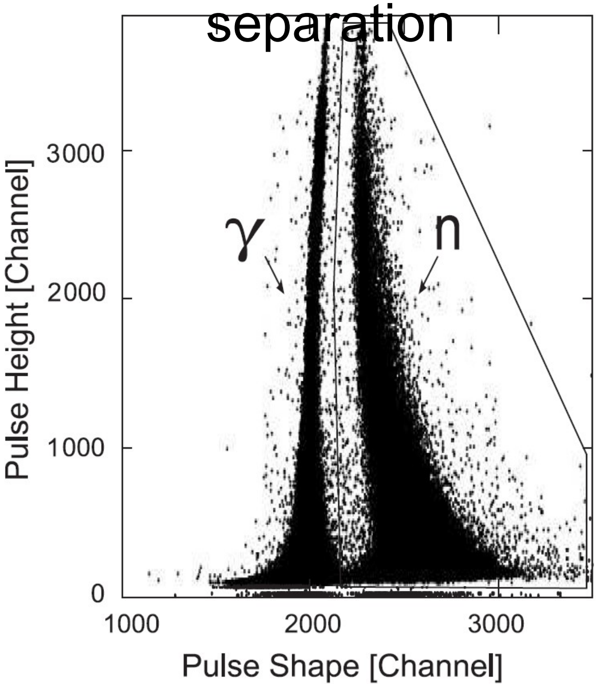
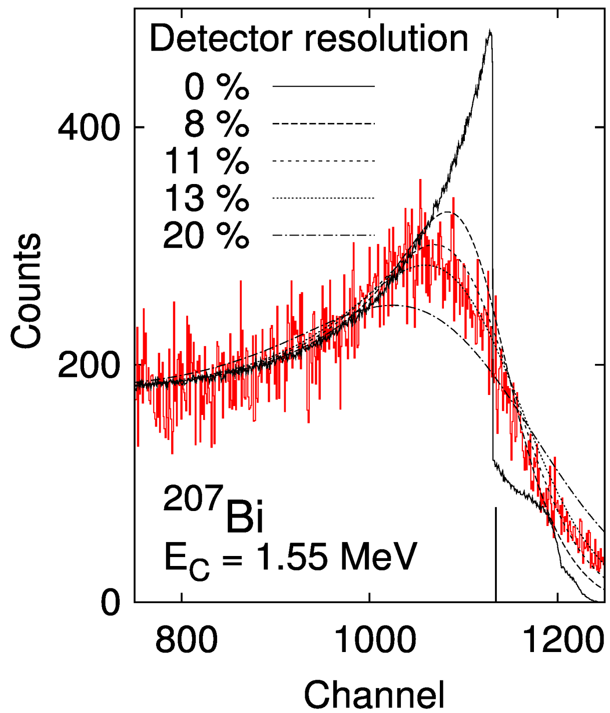
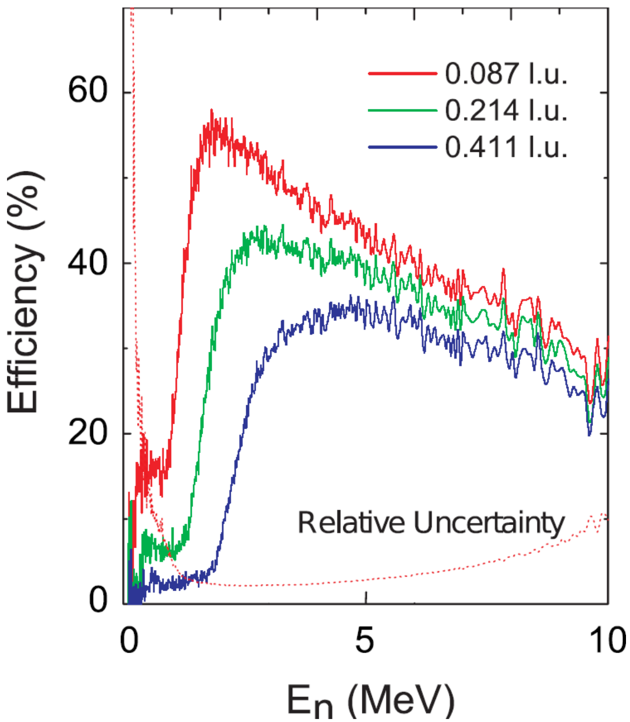
n/γ separation



detector response

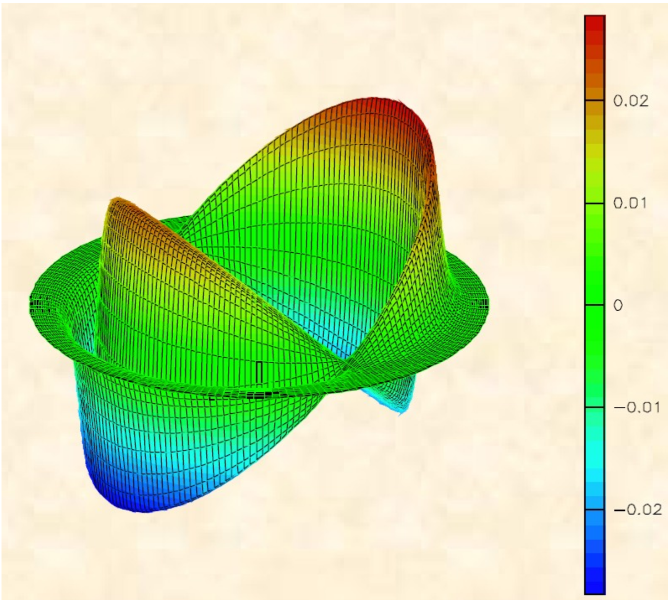


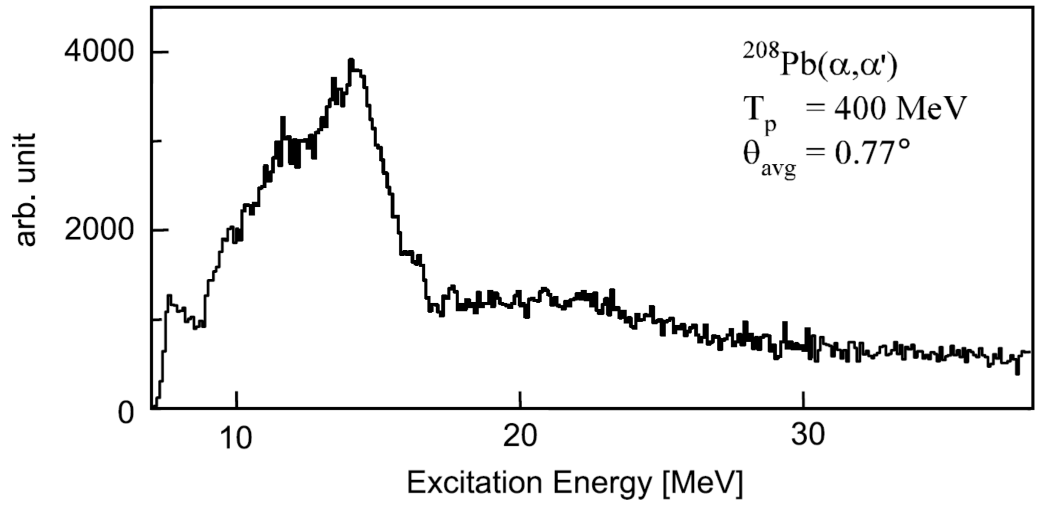
efficiency



- needs commissioning run

Physics: The isoscalar giant dipole resonance





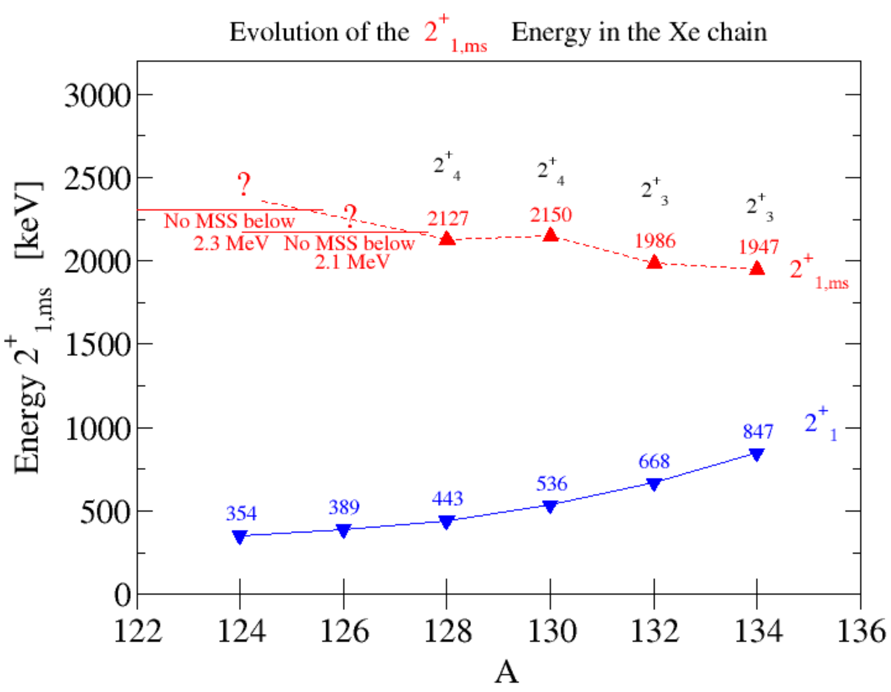
$$E_{ISGDR} = \hbar\sqrt{\frac{7}{3}\frac{K_A + \frac{27}{25}\epsilon_F}{m\langle r^2\rangle}}$$

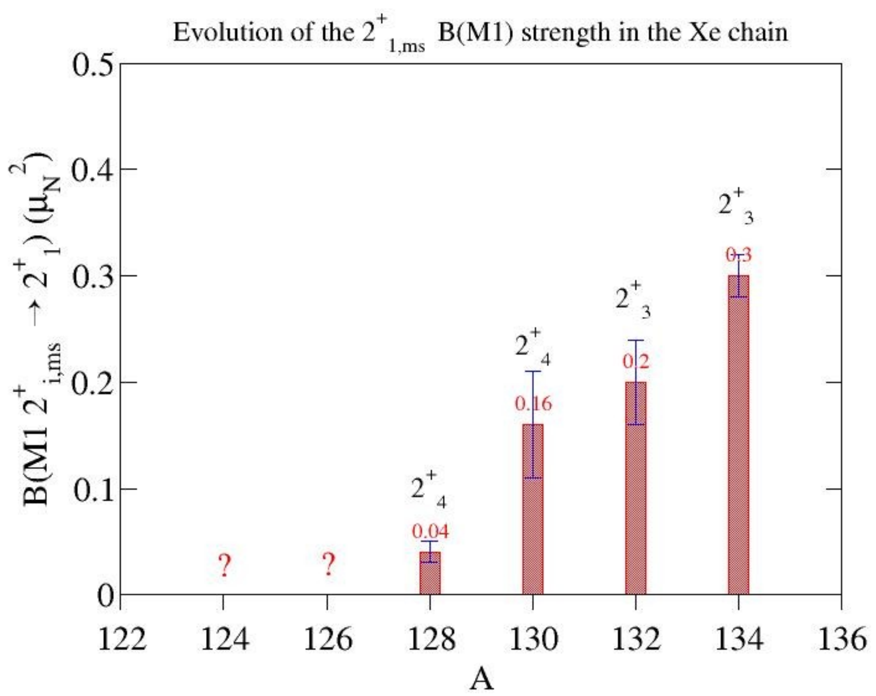
- multipole decomposition
- large quasi-free background

→ large uncertainties

→ no reliable values for EWSR

Mixed symmetry states: the Xe isotope chain

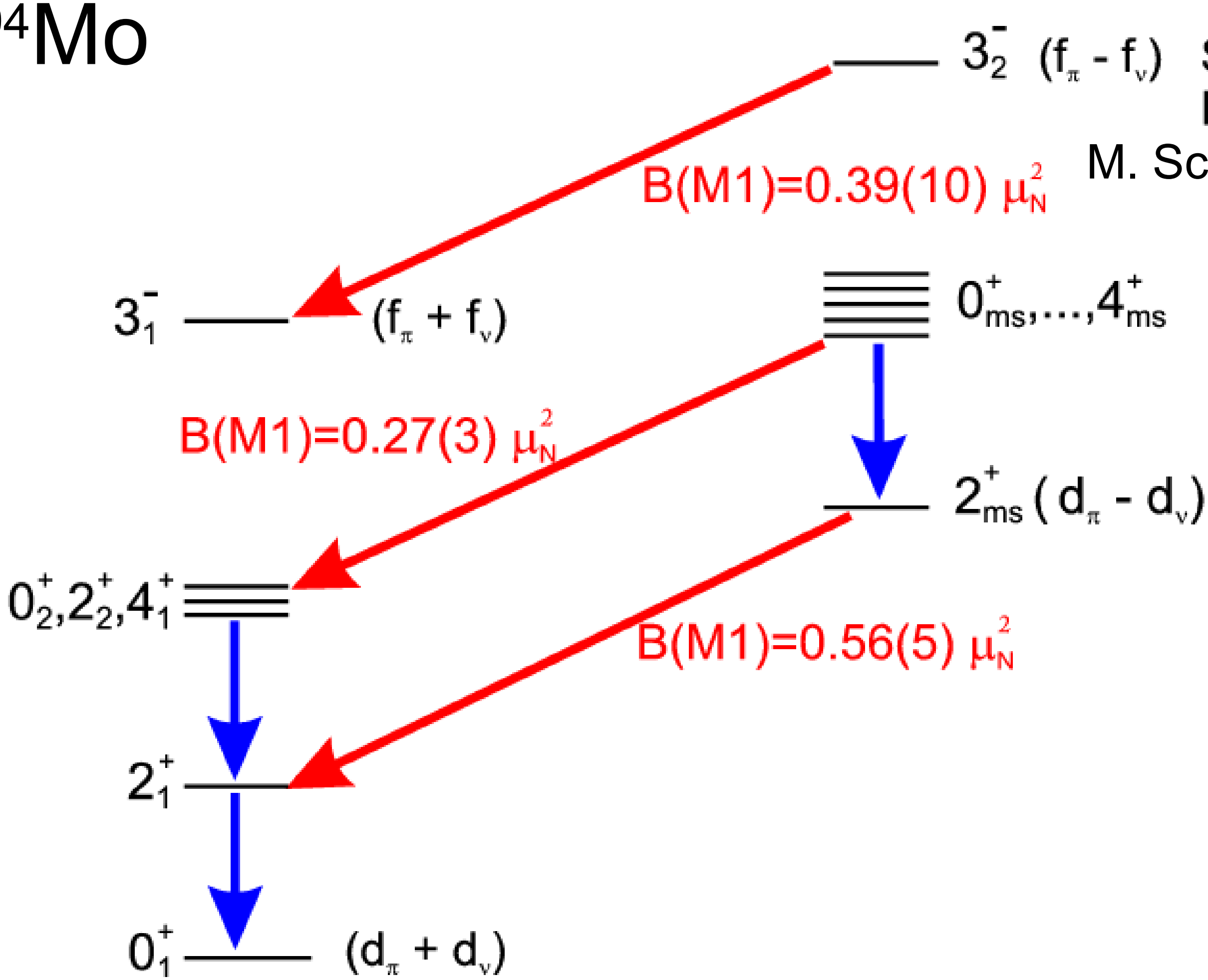




- Test GQR coupling scheme in transition towards deformation

Mixed symmetry 3⁻ states?

^{94}Mo



Mixed symmetry 3⁻ and 4⁺ states?

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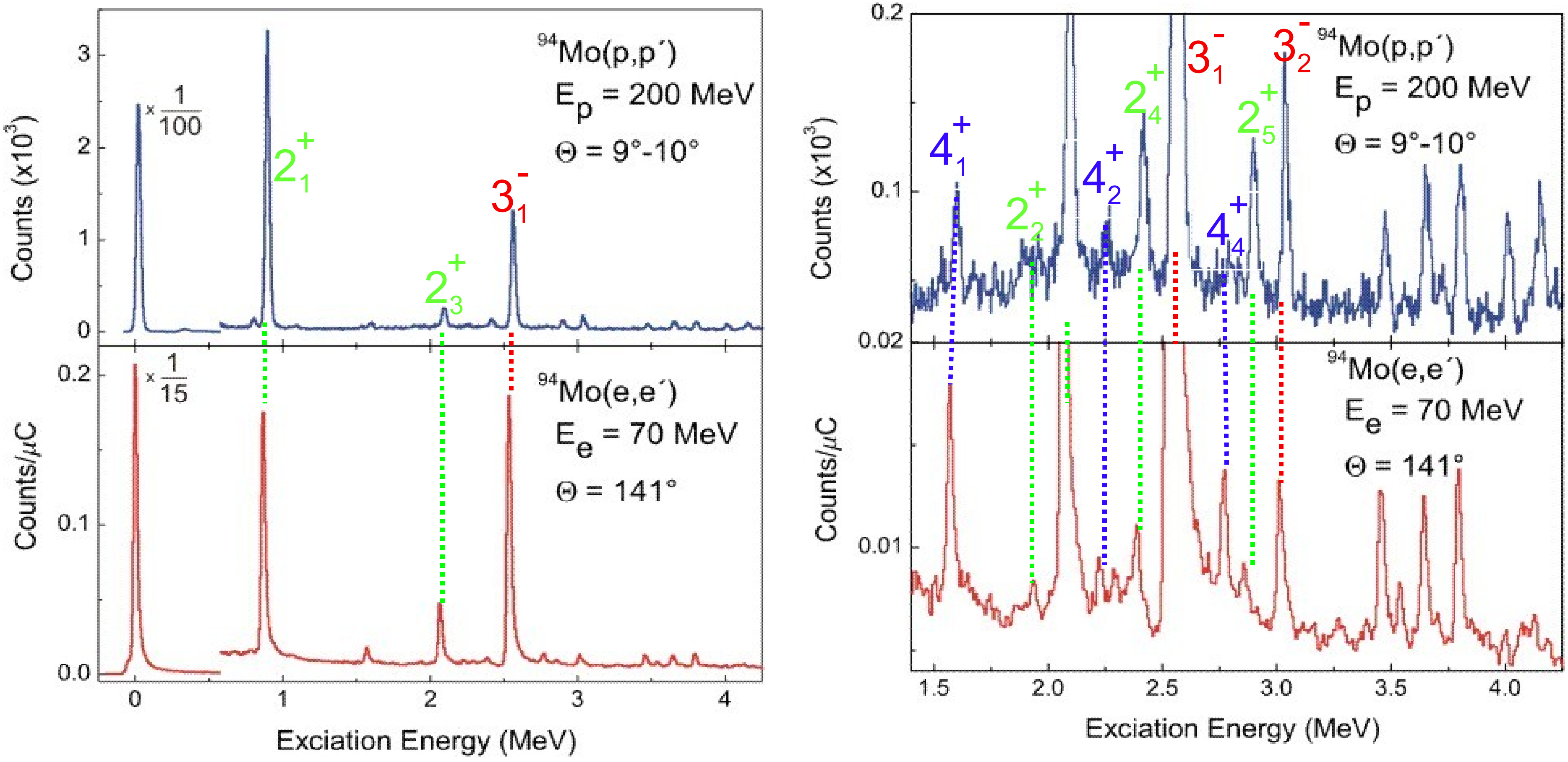
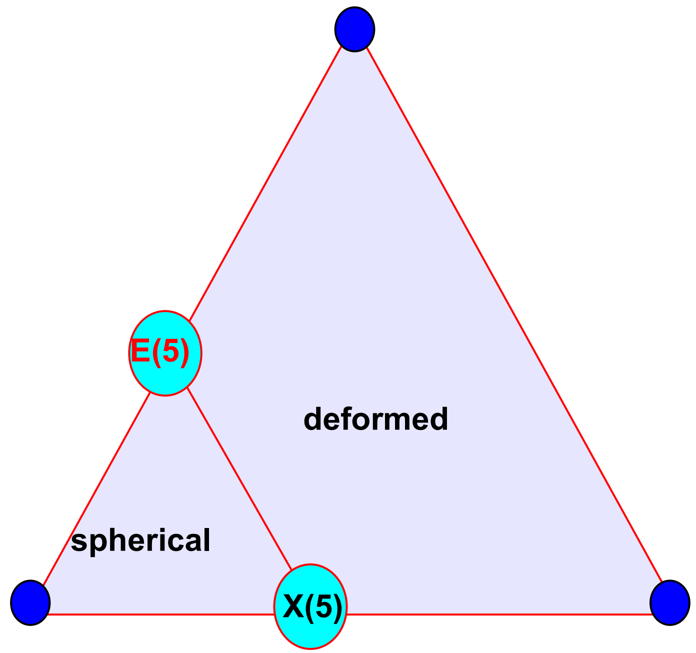


IBM symmetries

U(6) ⊃ O(6) ⊃ O(5) ⊃ O(3)

γ -soft



U(6) ⊃ U(5) ⊃ O(5) ⊃ O(3)

vibrator

U(6) ⊃ SU(3) ⊃ O(3)

rotor

Testing the X(5) symmetry

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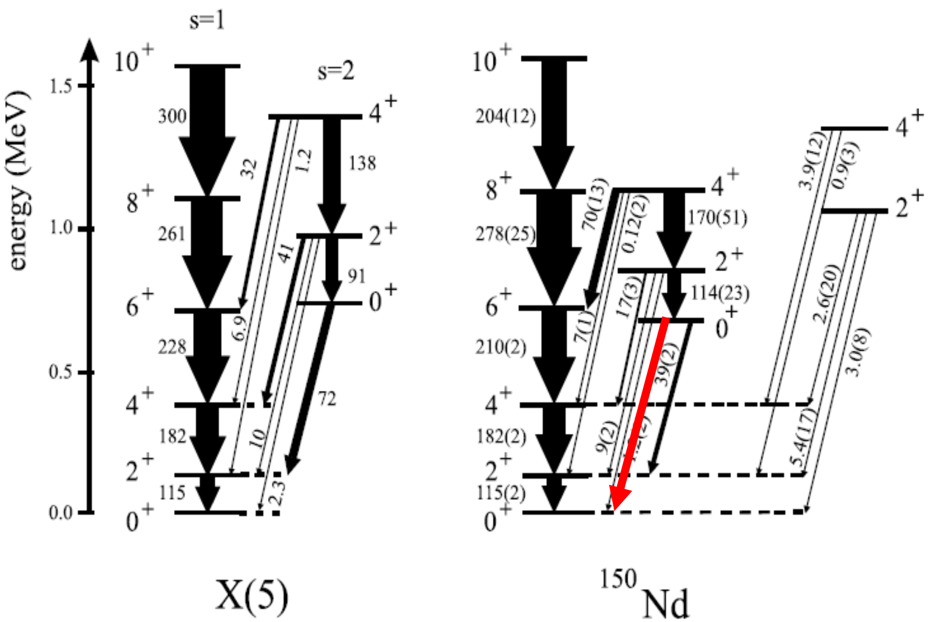
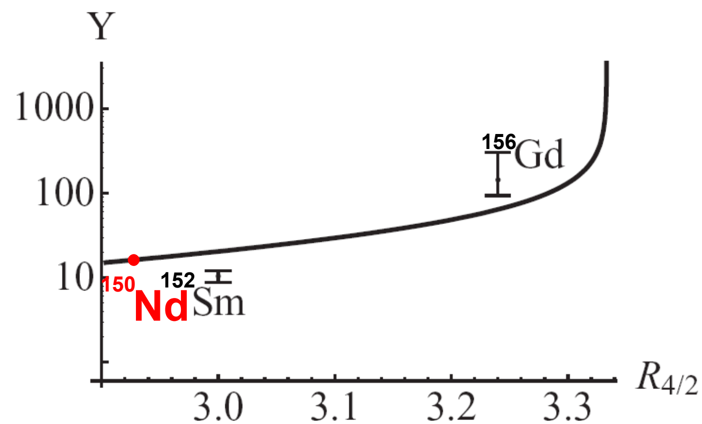
B(E2) transition strengths



R. Krücken et al., Phys. Rev. Lett. 88, 232501 (2002)

CBS model

$$Y = \frac{\rho^2(0_2^+ \rightarrow 0_1^+)\,(e^2 R^4 Z)^2 \left(\frac{3}{4\pi}\right)^2}{B(E2, 0_2^+ \rightarrow 2_1^+)^2}$$



- absolute value of $\rho^2(E0)$ needed to test X(5) character of ^{150}Nd

J. Bonnet et al., Phys. Rev. C 79, 034307 (2009)

E0 transition strengths at the S-DALINAC

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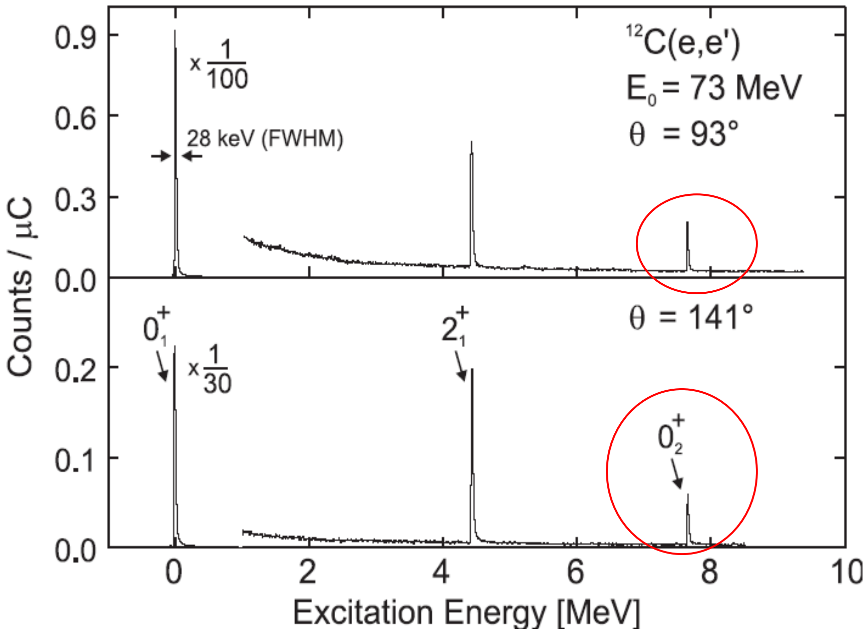
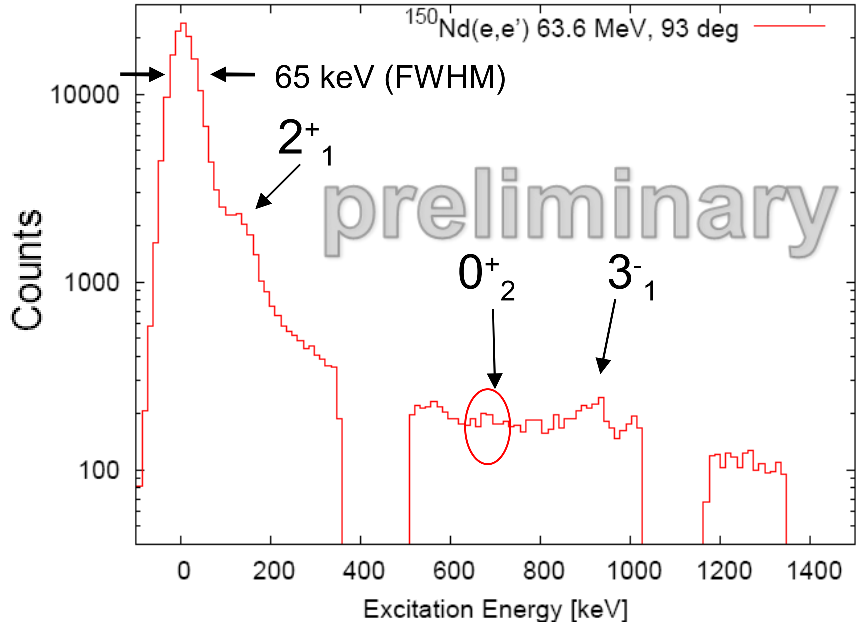
0^+_2 (Hoyle) state in ^{12}C



0^+_2 state in ^{150}Nd

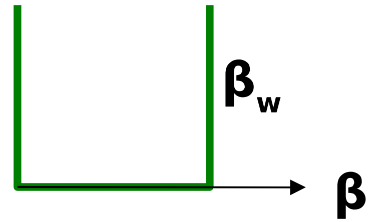


- Short test run in December 2009
- $\rho^2(E0)$= 560·10^{-3} measured
- CBS predicts $\rho^2(E0) \approx 100 \cdot 10^{-3}$

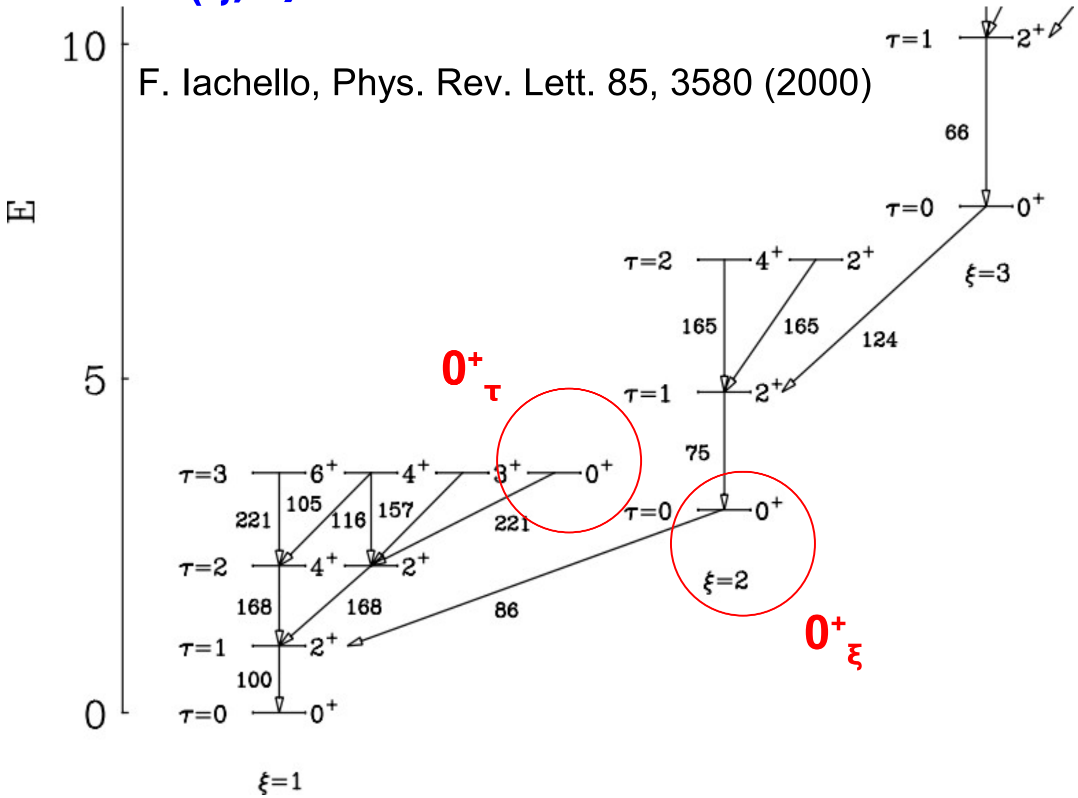
Signatures of E(5) symmetry

- Analytical solution H_{Bohr} with **$V(\beta,\gamma)=V(\beta)$**

  Solutions: zeros of Bessel functions → **$E(\xi,\tau)$**



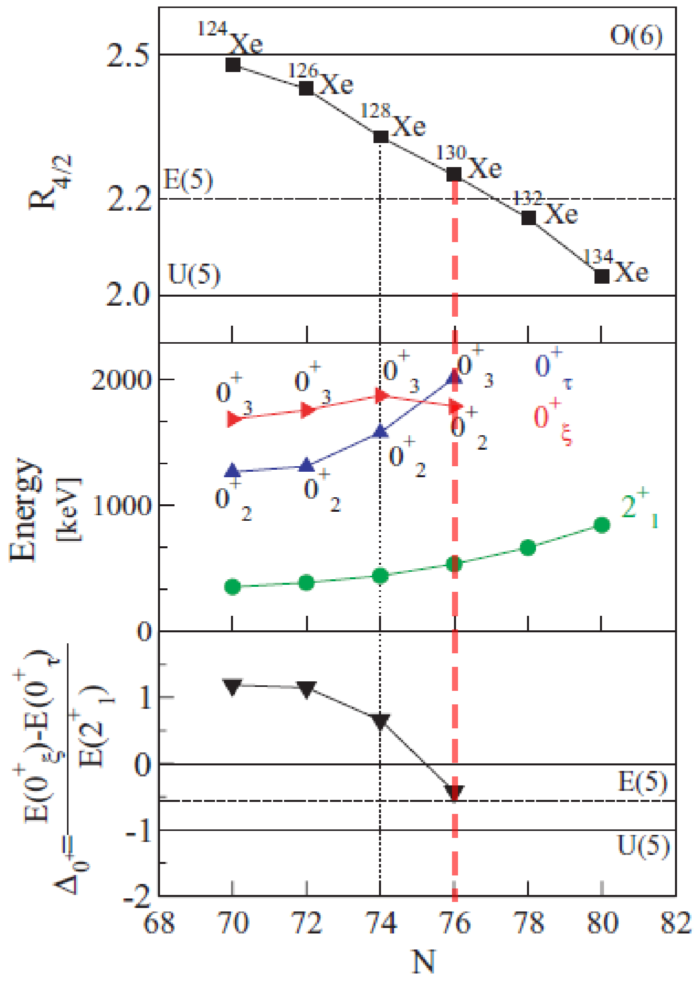
F. Iachello, Phys. Rev. Lett. 85, 3580 (2000)

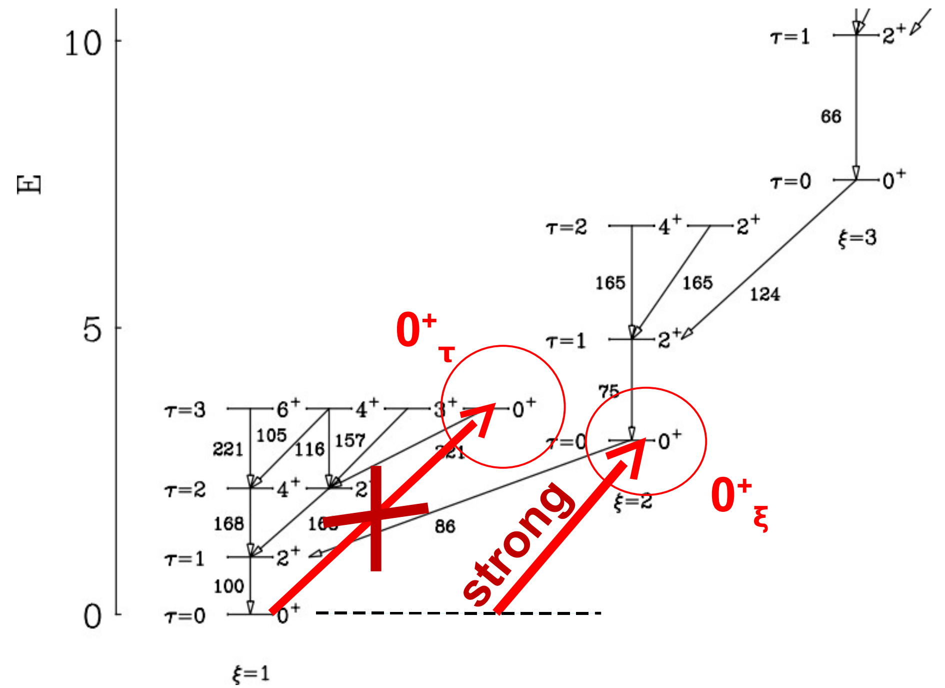


Key observables:

$R_{4/2}$, $R_{0/2}$, B(E0,E2) from 0^+ states

^{130}Xe: Best E(5) candidate

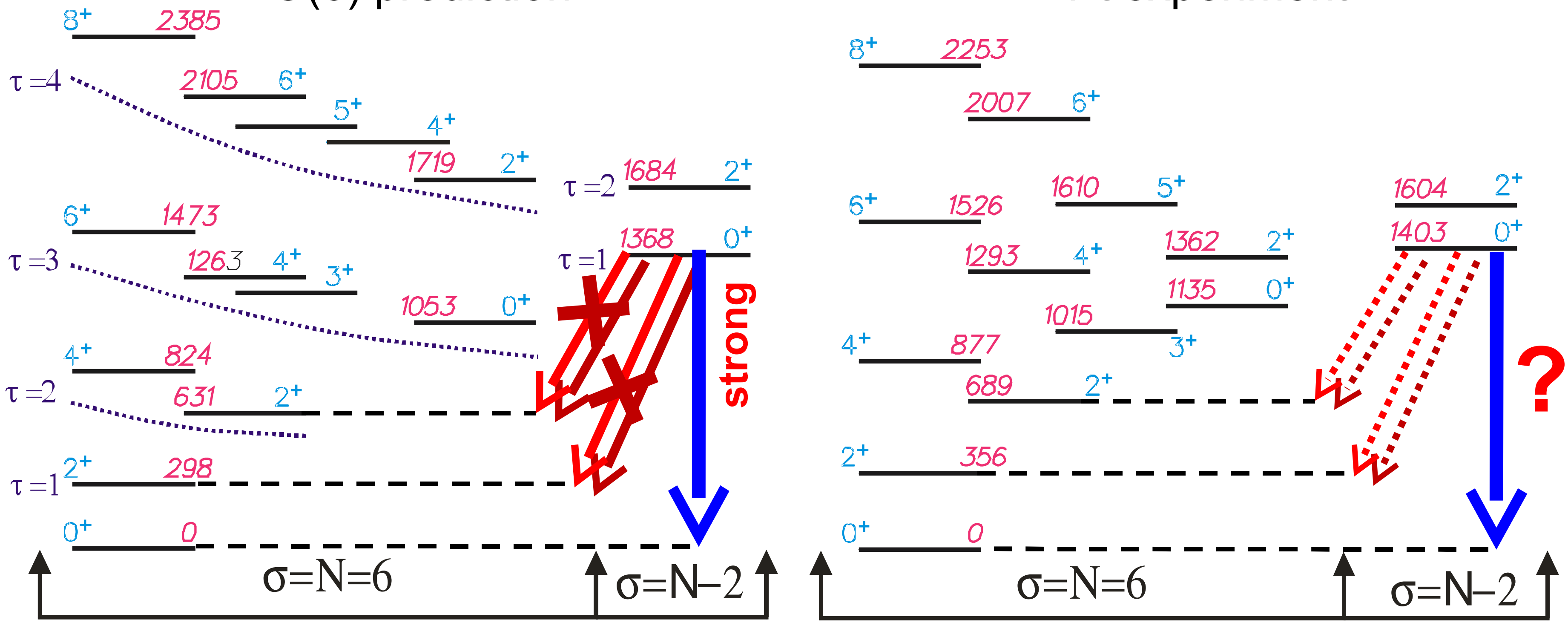




L. Coquard *et al.*, Phys. Rev. C 80, 061304(R) (2009)

O(6) symmetry in ^{196}Pt

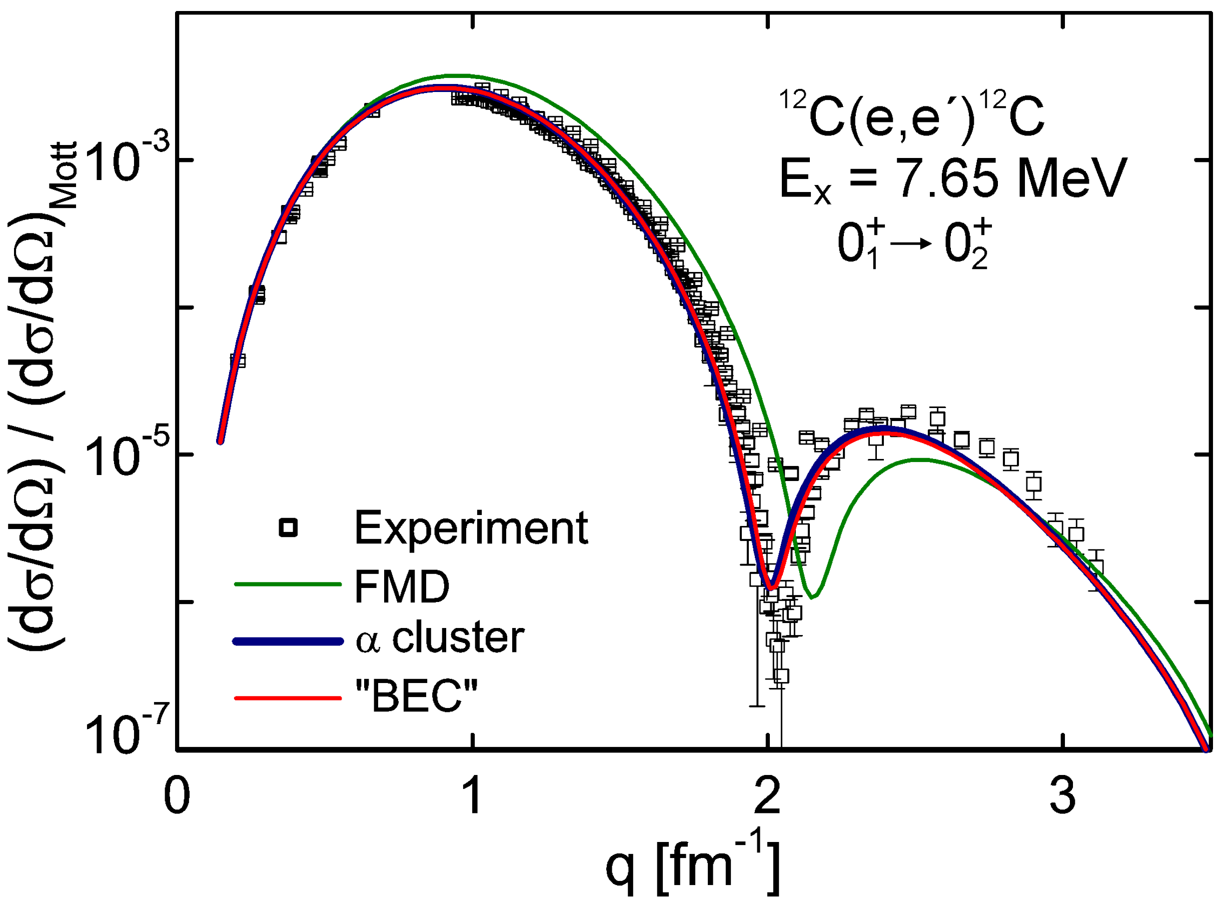
O(6) prediction | ^{196}Pt experiment



- E2 selection rules: $\Delta\sigma = 0, \Delta\tau = \pm 1$
- E0 selection rules: $\Delta\sigma = \pm 2, \Delta\tau = 0$

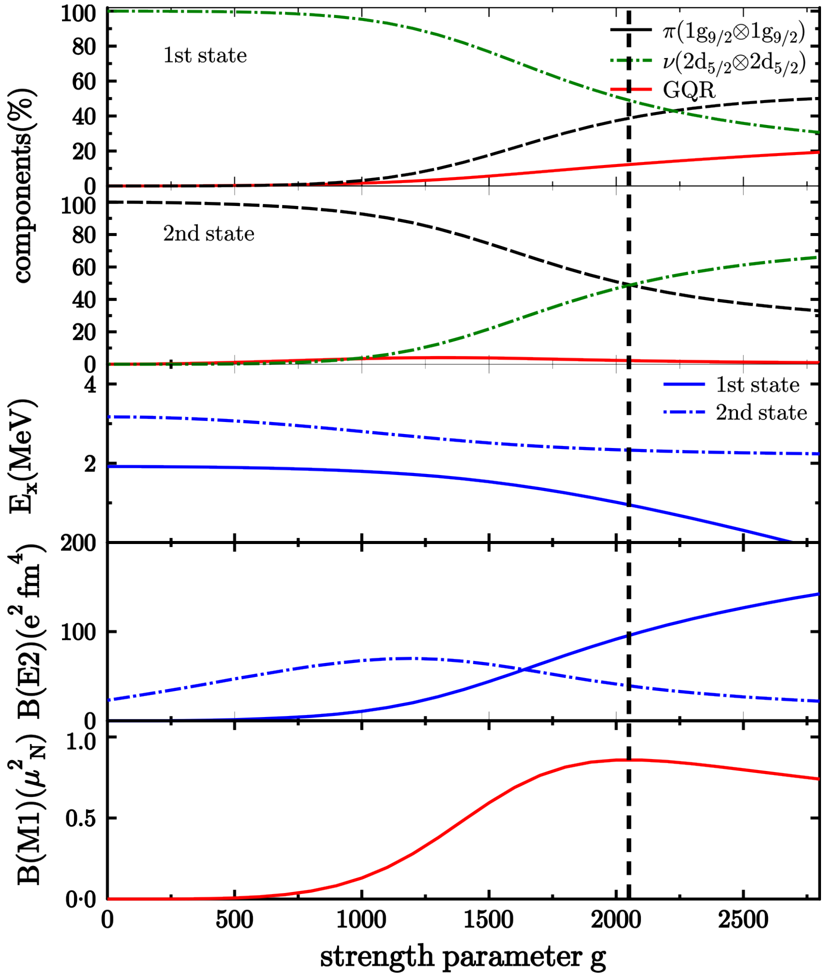
Decisive signature: $\rho^2(E0)$

Transition form factor to the Hoyle state



- generally good agreement, but E0 matrix element systematically overpredicted by all models

3-state model for ^{92}Zr



- good correspondence with full microscopic QPM result