GOSIA Results as ENSDF Data

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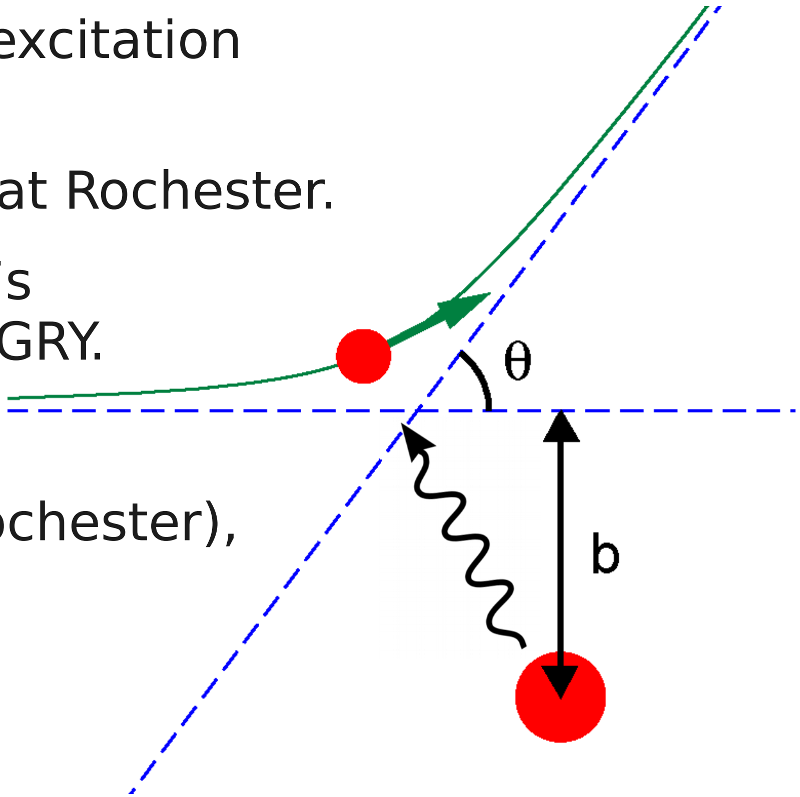
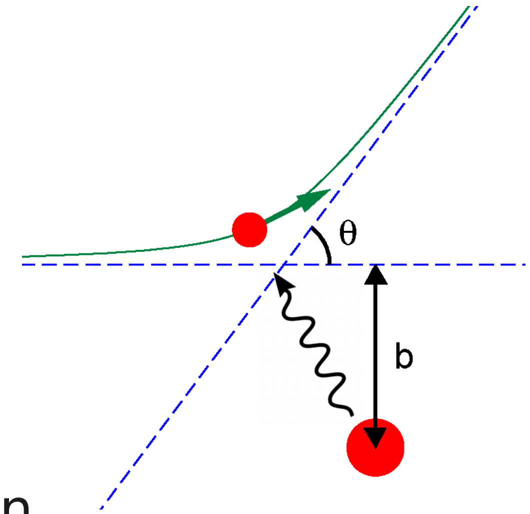
Nuclear Data Week
2019

What is Gosia?

- Semi-classical, coupled-channels Coulomb excitation simulation and analysis code.
- Developed in 1980 by Czosnyka, Cline, Wu at Rochester.
- Some concepts from 1978 Winther, deBoer's COULEX & Rochester de-excitation code CEGRY.
- Maintained by Czosnyka 1980–2006.
- Gosia Steering Committee (2008): Cline (Rochester), Gaffney (CERN), Hayes (BNL), Napiorkowski (Warsaw), Warr (Cologne), Zielińska (Warsaw)
- Contributions: Hasselgren (Uppsala), Hayes, Ibbotson (Rochester), Kavka (Uppsala/Rochester), Kotlinski (Warsaw/Rochester), Srebrny (Warsaw), Vogt (Munchen/Rochester)
- http://www.pas.rochester.edu/~cline/Gosia/index.html



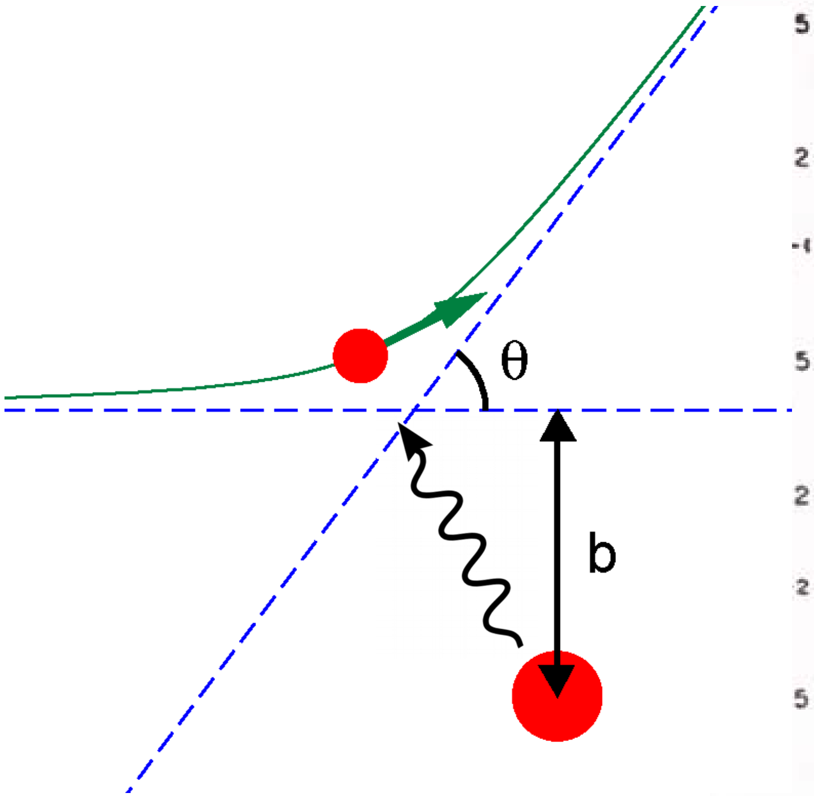
Semi-classical

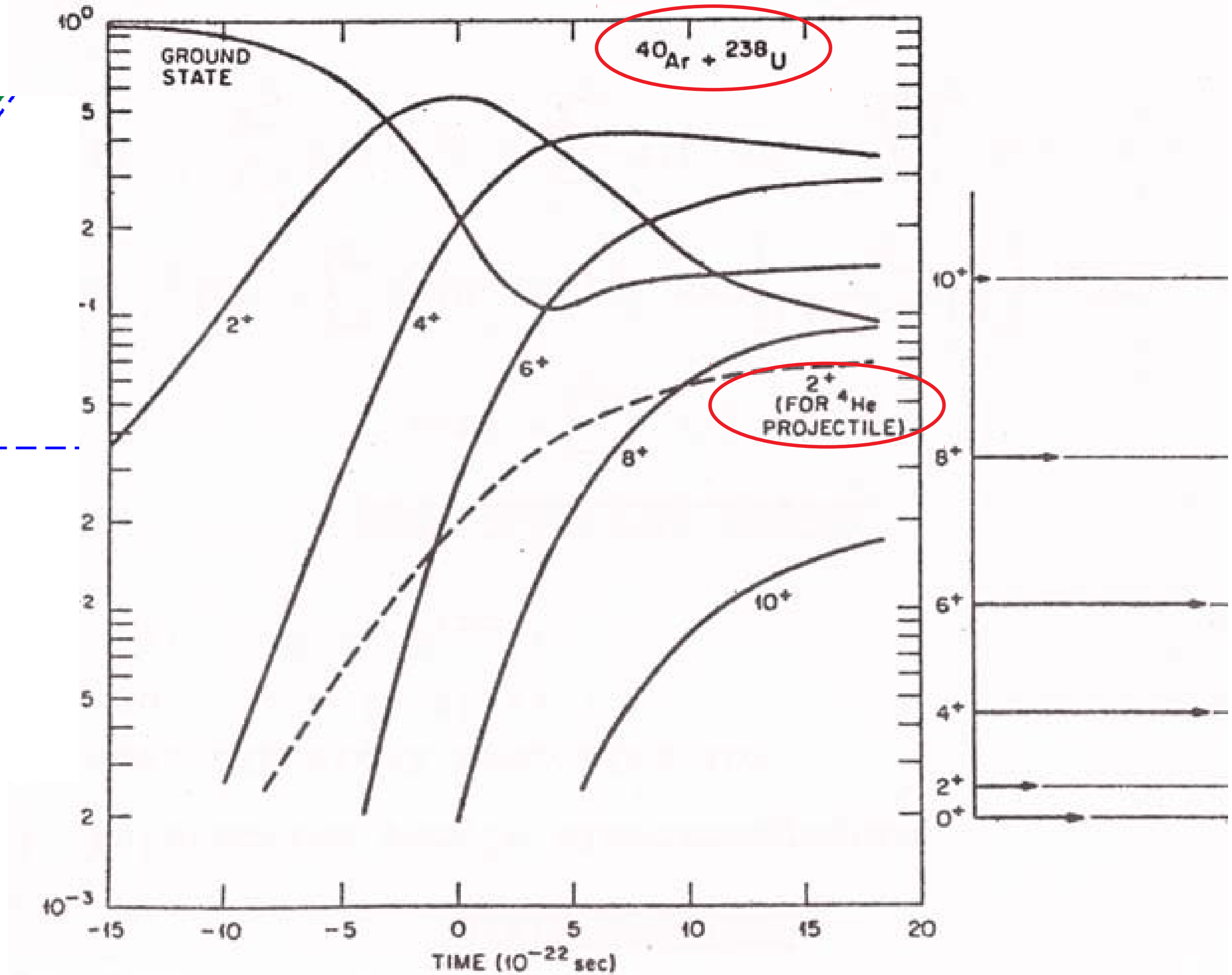


- Classical collision trajectory.
- Quantum-mechanical excitation & decay.
- Fully-quantal perturbation calculation not feasible for multi-step Coulex—calculated population of high-lying states sensitive to ~30th order perturbation.
- Appropriate for “safe” Coulex—about <80% Coulomb barrier.
- Somewhat higher for heavy ions if small impact parameter scattering excluded.
- Sommerfeld parameter: $$\eta = \frac{a2\pi}{2\lambda}$$

  η»1 → wave packet much smaller than interaction region of trajectory.

Semi-classical Time-Evolution





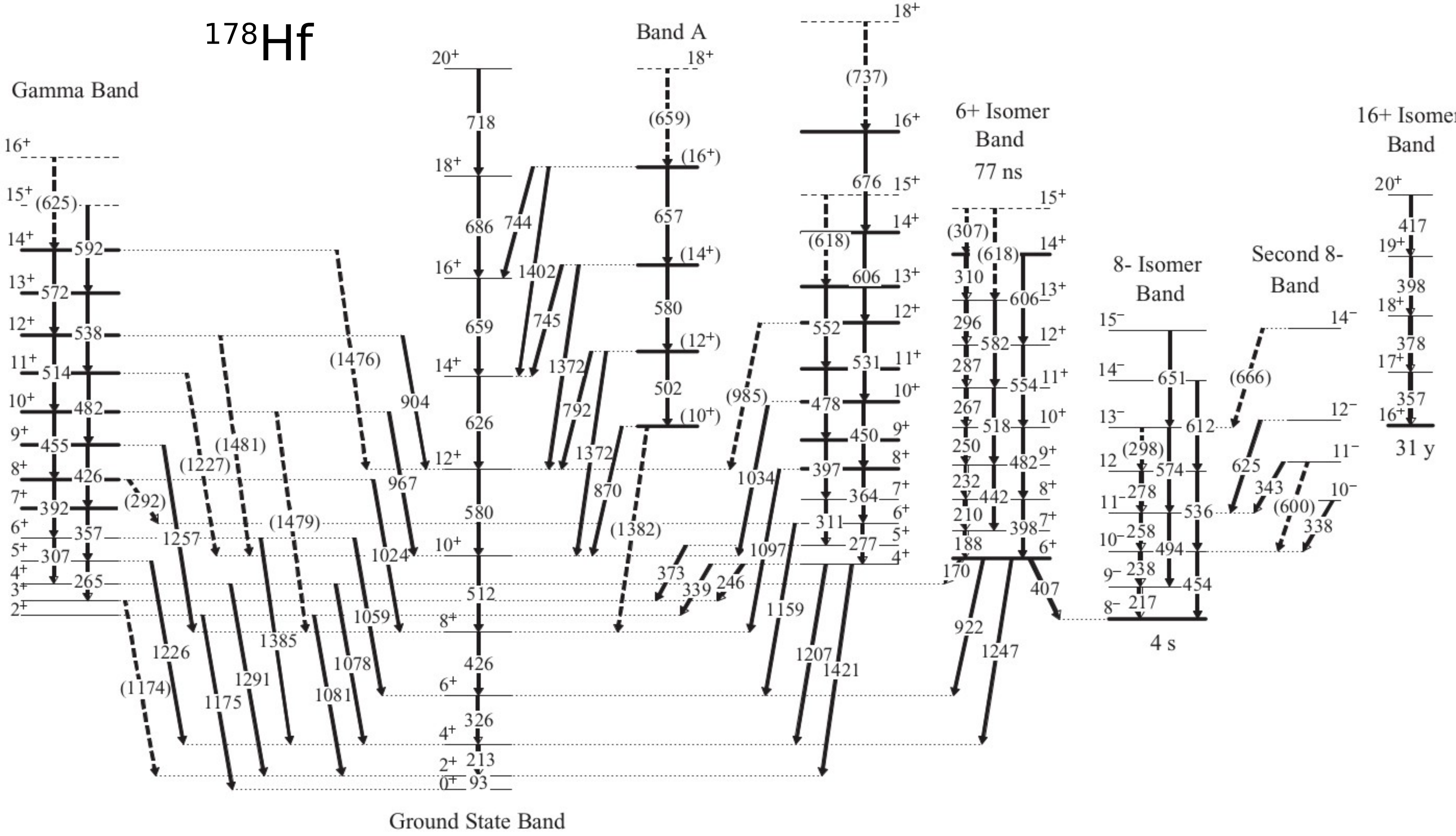
Typical Applications

- Predominantly E2 & E3 matrix elements from excitation
- M1, E1... from decay
- Measure B(E2) and/or Q_s in ~two-state system
- Many electric and magnetic matrix elements in strongly-collective system

Typical Applications

Strongly-deformed systems

Collective Rotor: Intrinsic vs. Individual M.E.



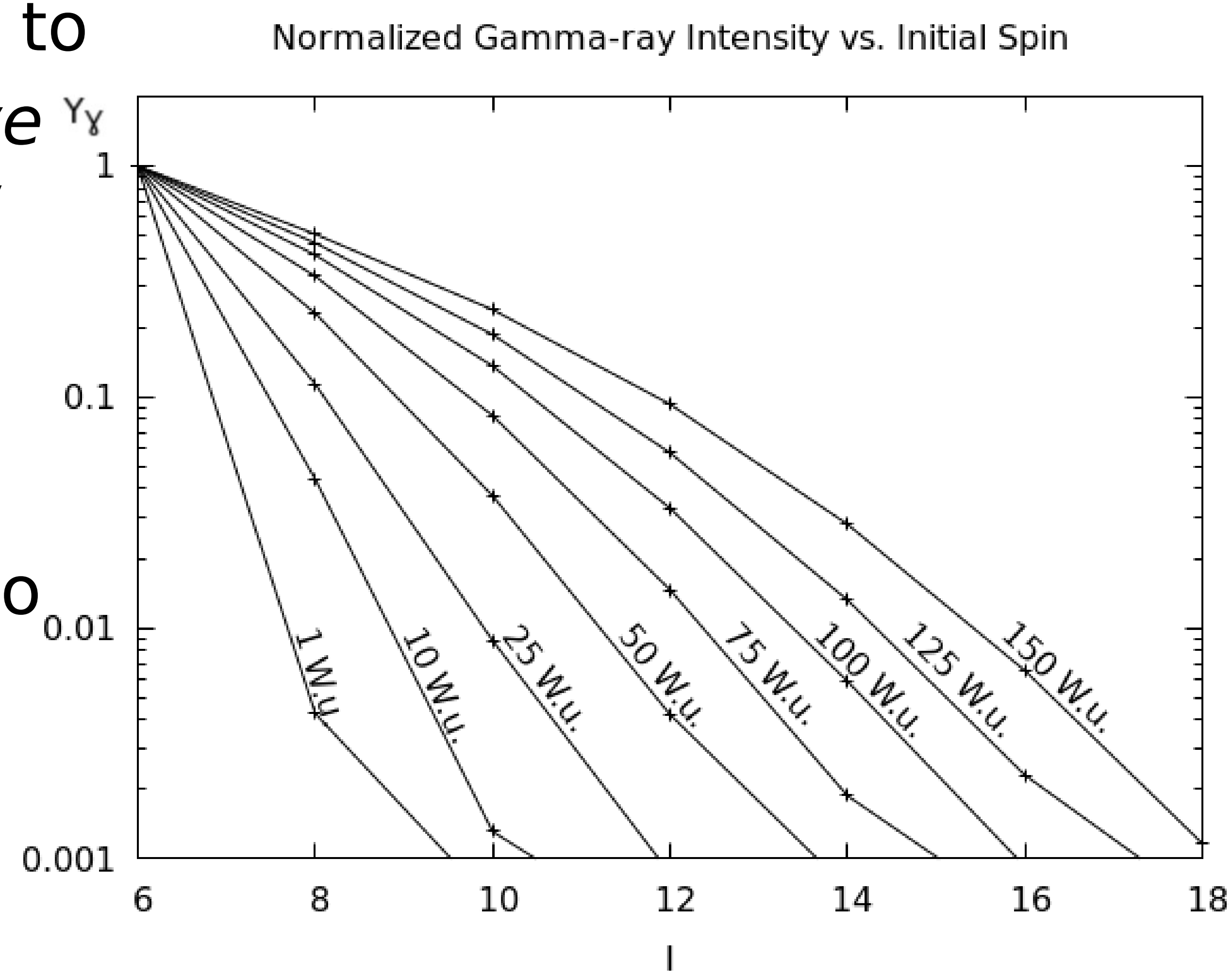
E2 Matrix Elements of Collective Bands

- Requires relative yield only.
- GSB is rigid rotor to good approximation.

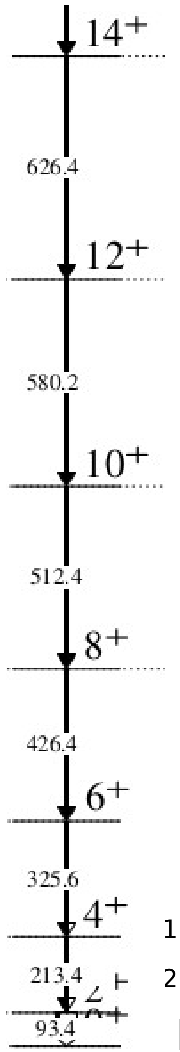
1) Measure Q_o assuming rigid rotor.
2) Fit $<I_i+2||E2||I_i>$ for $I^{\pi}>6^{+}$ where observed yield is sensitive to Q_o.
3) In reality, some iteration with fits to $K^{\pi}=2^{+},4^{+}$ required.

Gamma Yield Sensitivity to Quadrupole Moment

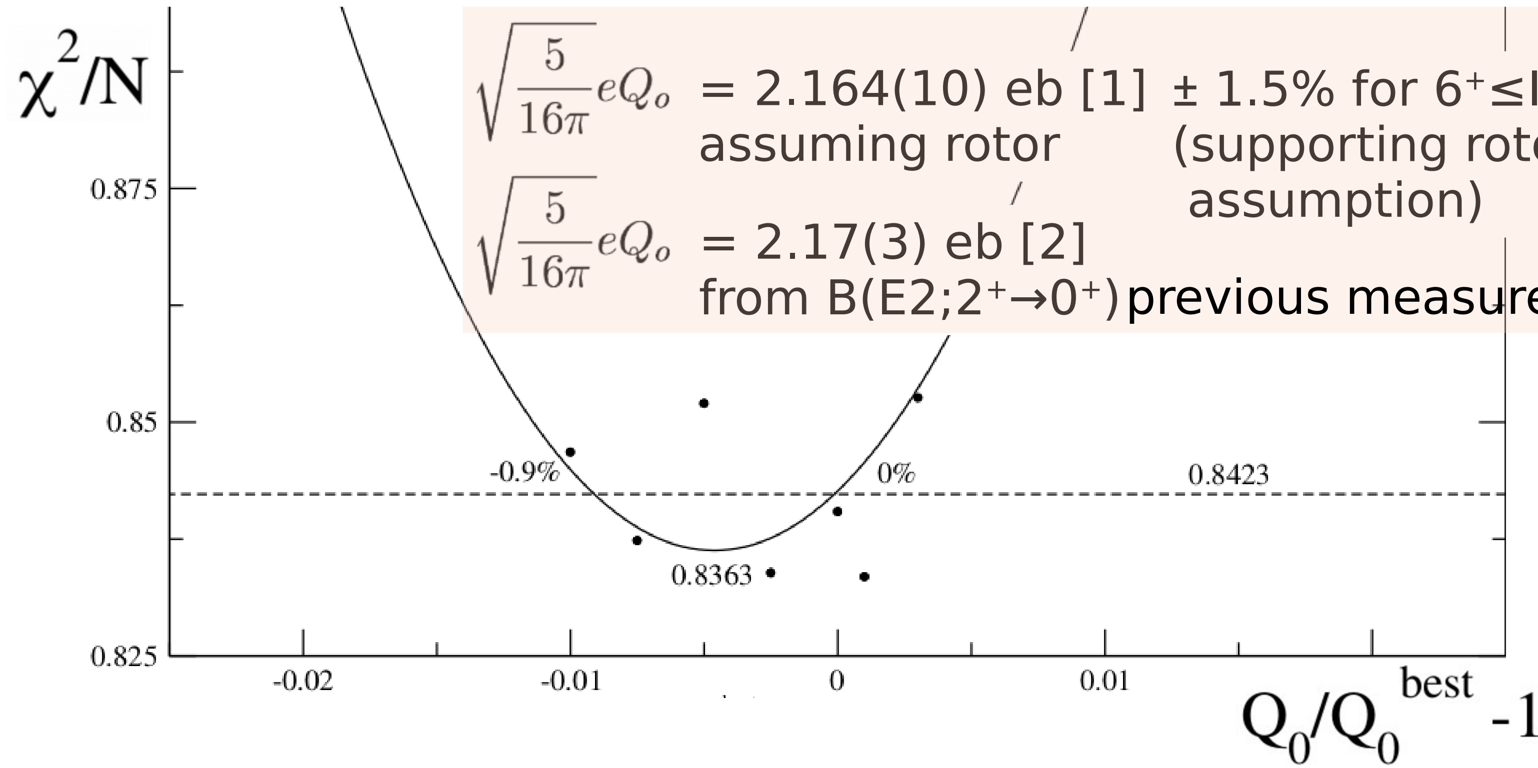
- Measured Q_o sensitive to rotational band *relative* gamma yield intensity
- No external normalization
- Q_o typically sensitive to ≤5% level



Example: Quadrupole moment of collective nucleus ^{178}Hf



Rotor model fit of Q_o to measured γ-ray yield of GSB



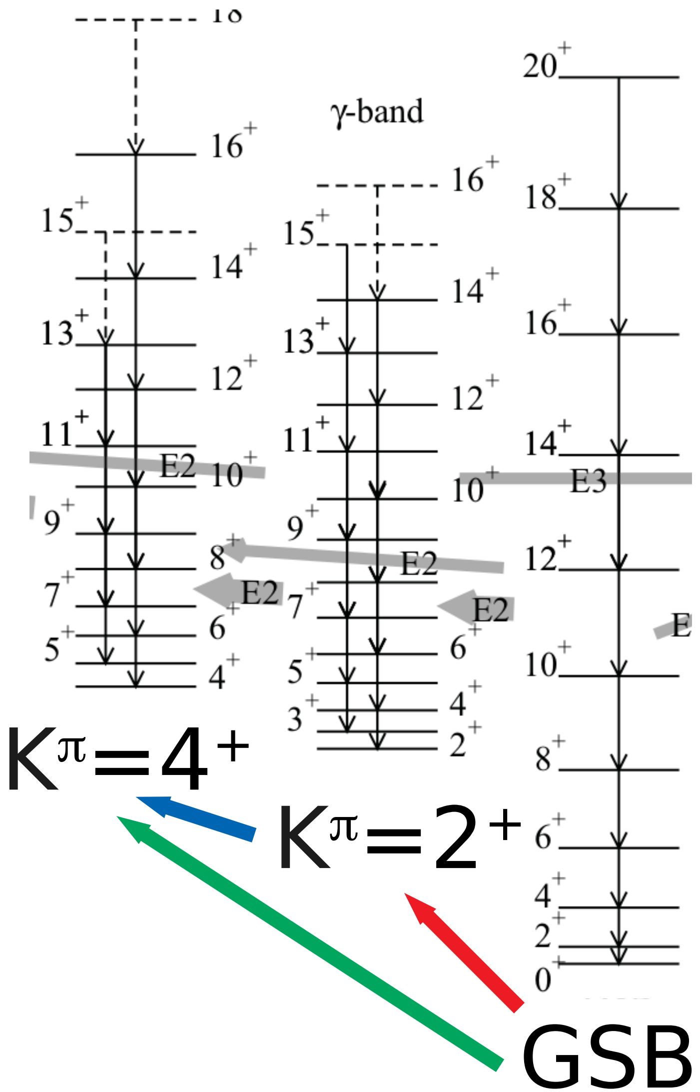
$\sqrt{\frac{5}{16\pi}} eQ_o$ = 2.164(10) eb [1] assuming rotor ± 1.5% for $6^+ \leq I^\pi \leq 16^+$ (supporting rotor assumption)

$\sqrt{\frac{5}{16\pi}} eQ_o$ = 2.17(3) eb [2] from $B(E2;2^+ \rightarrow 0^+)$ previous measurement

[1]Hayes et al., Phys. Rev. C **75**, 034308 (2007), Thesis (2005, unpublished)

[2]From $B(E2;2^+ \rightarrow 0^+)$ = 159(5) W.u.
E. Brown, Nuclear Data Sheet **54**, 199 (1988)
Citing R.M. Ronningen et al., Phys. Rev. C 15, 1671 (1977)

Collective Rotor: Intrinsic vs. Individual M.E.



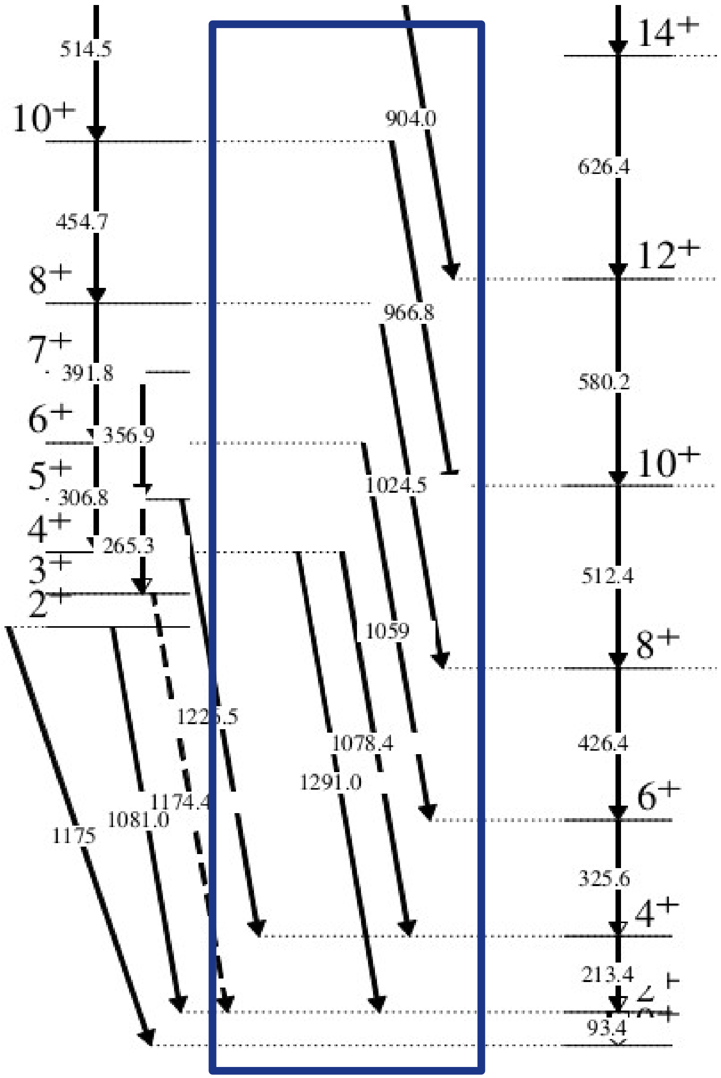
The intrinsic matrix elements $\langle K_f \mid \mathcal{M}\lambda \mid K_i \rangle = m_0 + \Delta \vec{I}^2 m_1$

~5% error

m	ν	m_0	m_1	Comment
$\langle 2^+ \mid E2 \mid 0^+ \rangle$	0	0.266(12) eb	-0.00347(15) eb	[a] $m = 0.252(11)$
$\langle 4^+ \mid E2 \mid 2^+ \rangle$	0	0.447(19) eb		
$\langle 4^+ \mid E2 \mid 0^+ \rangle$	2	9.1×10^{-4} eb	-1.47×10^{-5} eb	±6%
$\langle 4^+ \mid M1 \mid 0^+ \rangle$	3	6.3×10^{-5} μ_N	-9.5×10^{-7} μ_N	±30%
$\langle 6^+ \mid E2 \mid 4^+ \rangle$	0	0.094(3) eb		
$\langle 6^+ \mid E2 \mid 2^+ \rangle$	2	0.00116(10) eb		
$\langle 6^+ \mid E2 \mid 0^+ \rangle$	4	1.57×10^{-6} eb	$-2.10 \times^{-8}$ eb	±3.5%
$\langle 6^+ \mid M2 \mid 8^- \rangle$	0	0.102(9) $\mu_N b^{1/2}$		
$\langle 8^- \mid E3 \mid 2^+ \rangle$	3	$0.36\ ^{+0}_{-0.07}$ $eb^{3/2}$		[b] Alaga rule
$\langle 8^- \mid E3 \mid 0^+ \rangle$	5	$0.37\ ^{+0.07}_{-0.01}$ $eb^{3/2}$		[b] Alaga rule

Hayes et al., Phys. Rev. C 75, 034308 (2007)

Collective Rotor:
Intrinsic vs. Individual M.E.



Quotable

GSB→ γ-band

K-allowed $\langle \gamma \mid E2 \mid \mathrm{GSB} \rangle = 0.266(12)$

$-3.47(15) \times 10^{-3}\{I_\gamma(I_\gamma+1) - I_0(I_0+1)\}$ (eb)

Informational

I_i	I_f	m (eb)	$B(E2) \times 10^3$ (e^2b^2)	I_i	I_f	m (eb)	$B(E2) \times 10^3$ (e^2b^2)
0	2	0.347	120.	[illegible]	[illegible]	[illegible]	11.1
2	2	0.449	40.3	[illegible]	[illegible]	[illegible]	42.8
2	3	-0.548	60.1	10	10	1.05	52.4
2	4	0.318	20.2	10	11	-0.683	22.2
4	2	0.119	1.57	10	12	0.212	2.14
4	3	-0.415	19.1	12	10	0.595	14.2
4	4	0.668	49.6	12	11	-1.10	48.8

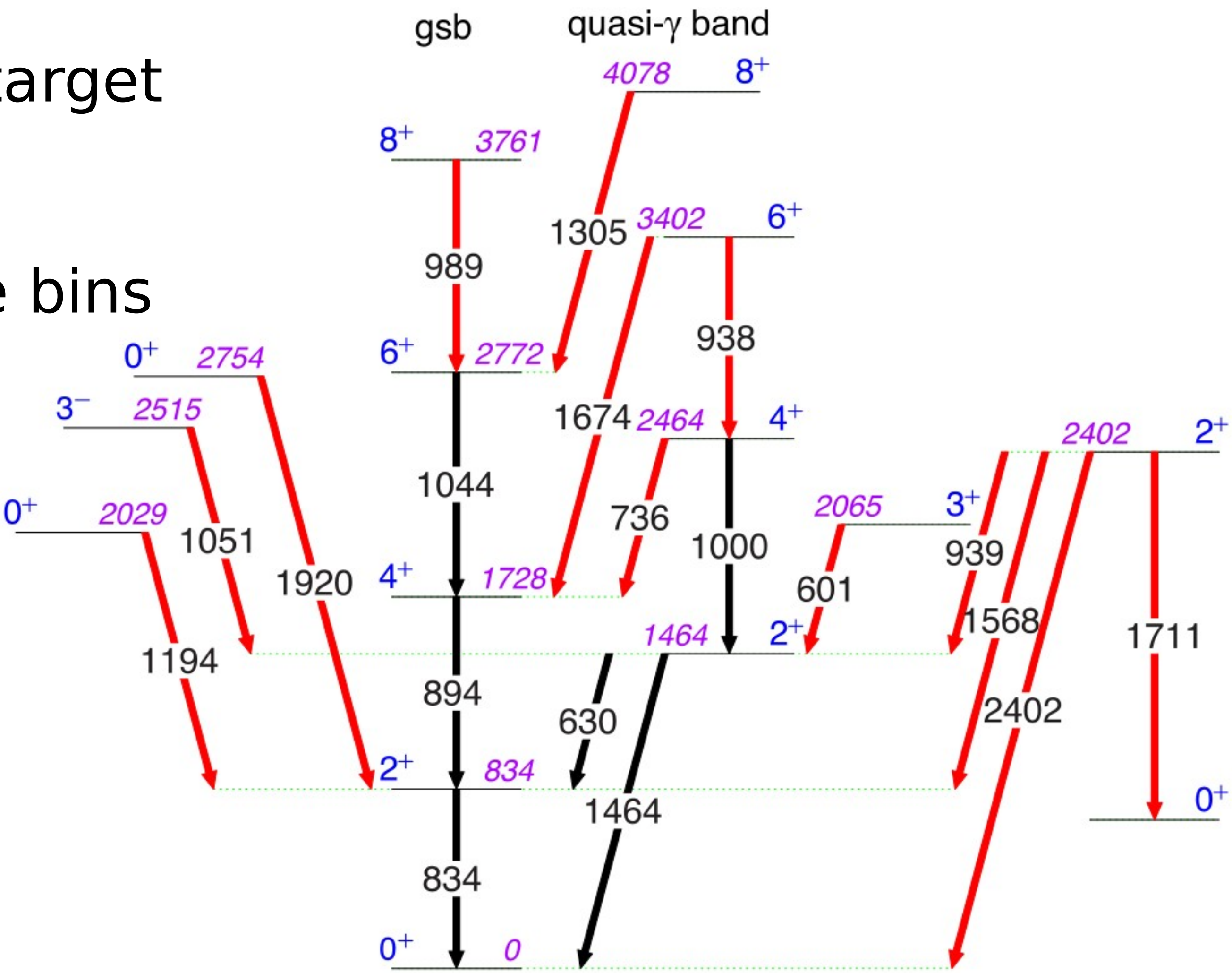
Table 9.5: Reduced matrix elements $m = \langle I_f, K = 2^+ \| E2 \| I_i, K = 0^+ \rangle$ and $B(E2) = B(E2; \mathrm{GSB} \to \gamma)$ values for the K-allowed E2 transitions. $\langle \gamma \mid E2 \mid \mathrm{GSB} \rangle = 0.252(11)$ eb to first order in ΔI^2.

Typical Applications

Weaker B(E2), several-state problems

^{72}Ge Coulex

- ^{72}Ge on ^{208}Pb 0.5 mg target at 301 MeV
- 7 10° scattering angle bins from 30° to 165°
- E2 couplings of primary interest



Ayangeakaa et al., PLB **754**, 254 (2016)

^{72}Ge Coulex

- Results very similar to previous measurements
- What is a reasonable expectation of the errors?

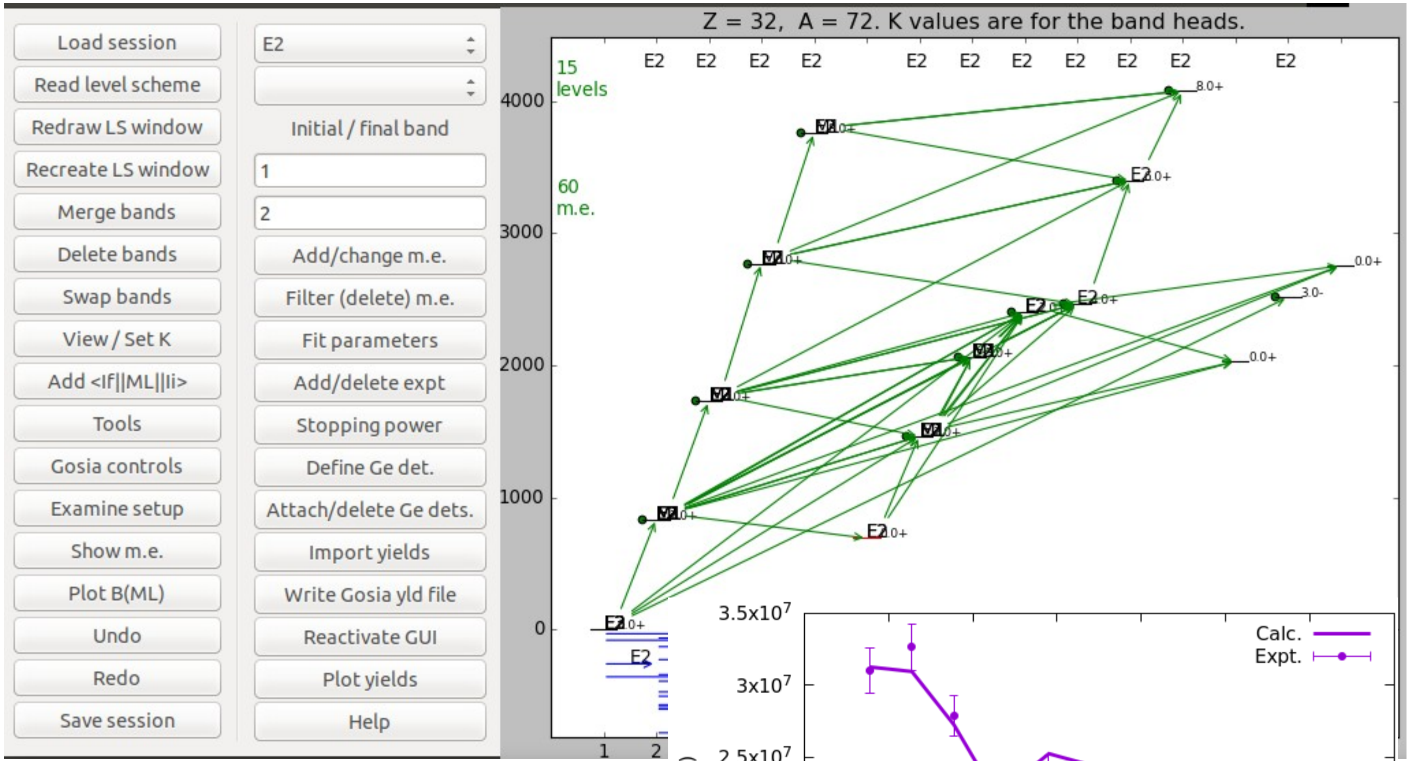
Reduced $E2$ matrix elements for transitions of ^{72}Ge, deduced from the present work, in comparison with previous measurements.

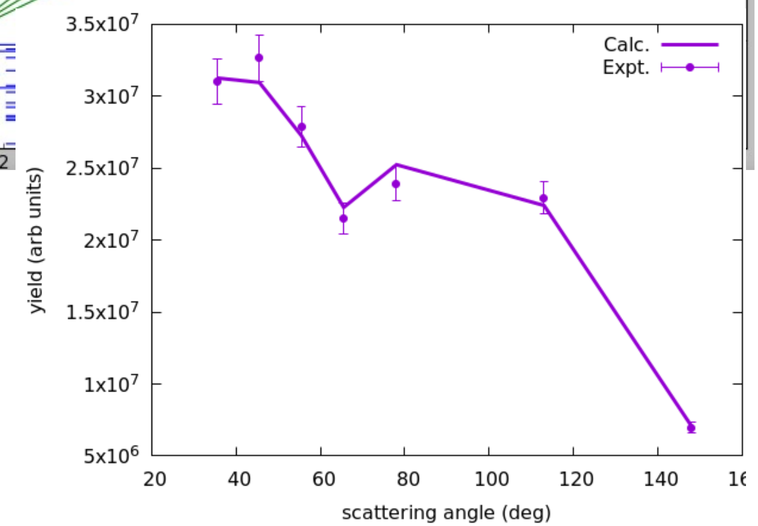
$I_i^\pi \to I_f^\pi$	$\langle I_i \| \|\mathcal{M}(E2)\| \| I_f \rangle$ (eb)		
	This work	Ref. [34]	Refs. [40,41]
$0_1^+ \to 2_1^+$	0.457(4)	0.46(1)	0.457(7)
$2_1^+ \to 4_1^+$	0.90(2)	0.89(4)	0.76(4)
$4_1^+ \to 6_1^+$	$1.11^{+0.04}_{-0.05}$	1.2(3)	
$6_1^+ \to 8_1^+$	$1.1^{+0.2}_{-1.6}$		
$2_1^+ \to 2_1^+$	$-0.16^{+0.07}_{-0.02}$	$-0.16^{+0.10}_{-0.07}$	−0.17(8)
$4_1^+ \to 4_1^+$	$-0.14^{+0.09}_{-0.04}$	−0.01(1)	
$6_1^+ \to 6_1^+$	$-0.20^{+0.08}_{-0.25}$	−0.1(5)	
$2_1^+ \to 0_2^+$	$0.35^{+0.01}_{-0.02}$	0.36(4)	$\|0.45(2)\|$
$4_1^+ \to 2_2^+$	$-0.06^{+0.03}_{-0.04}$	−0.08(5)	
$6_1^+ \to 4_2^+$	$0.28^{+0.10}_{-0.05}$	$< \|0.4\|$	

Ayangeakaa et al., PLB **754**, 254 (2016)

Aside: RACHEL UI for Gosia

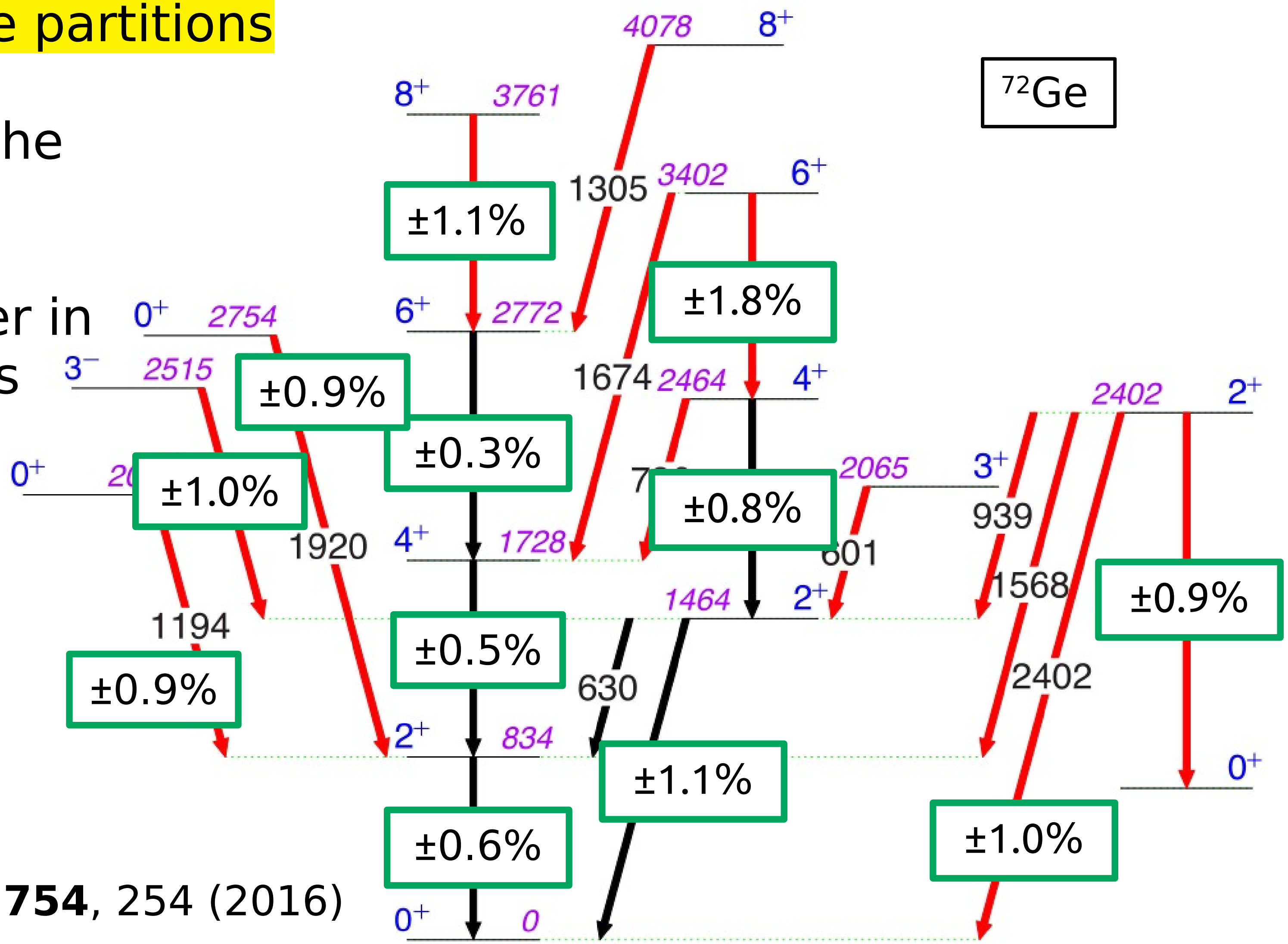
- "Semi-GUI"
- Developed in 2005, updates in progress for Python3, Qt...
- Simulation
- Experiment planning
- **Design experiments for analysis**
- Data analysis
- Plots of results
- Run in RACHEL / generate input files for GOSIA





Simulation: Statistical (only) Error with ~5% Error in Yields

- 7 scattering angle partitions
- 5% error bars in the simulated data
- No random scatter in data→ no conflicts



Ayangeakaa et al., PLB **754**, 254 (2016)

Simulation: Statistical (only) Error with ~5% Error in Yields

- 1 scattering angle partition→ no sensitivity to cross section vs. impact parameter

- 5% error bars in the simulated data

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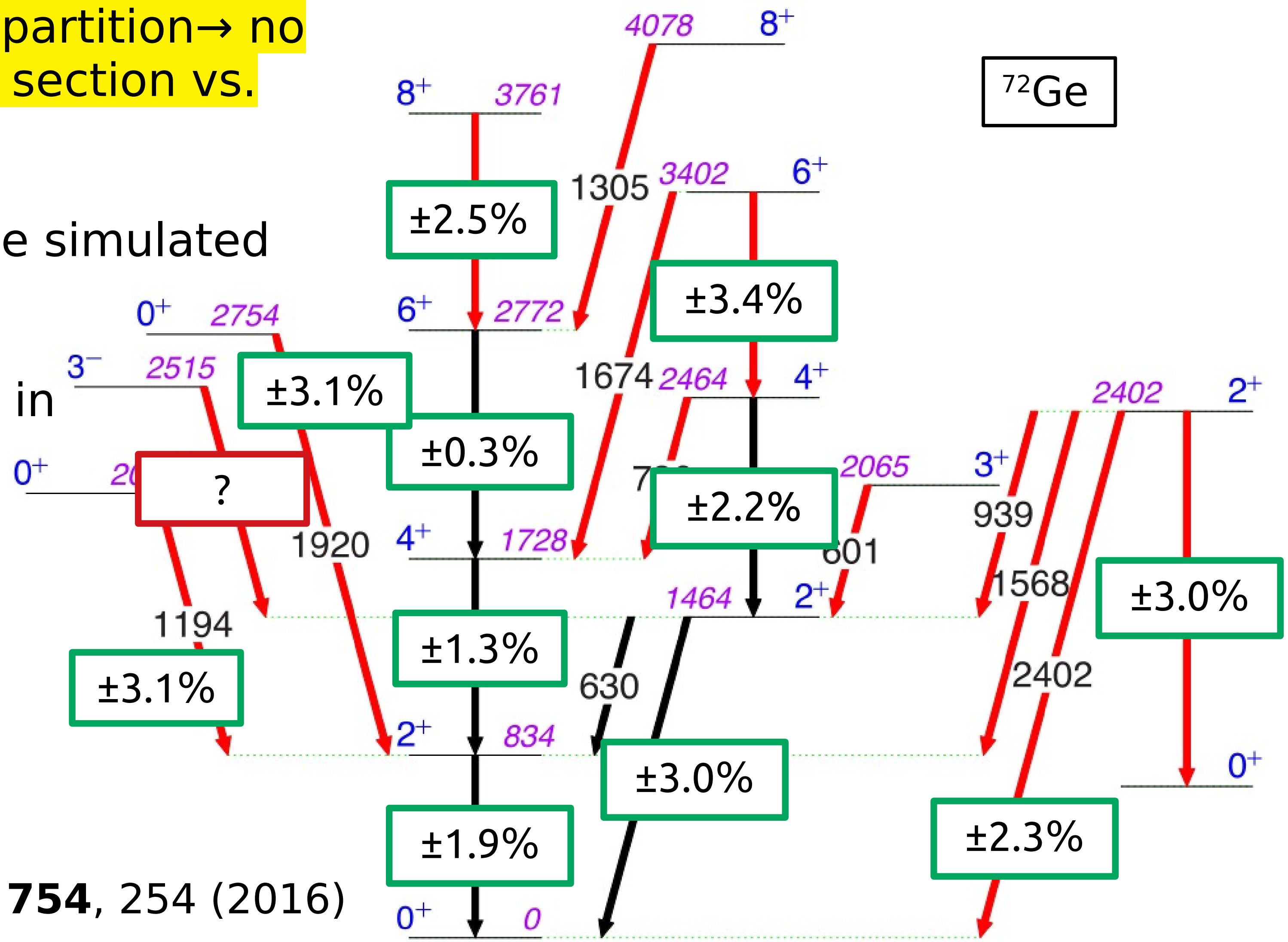
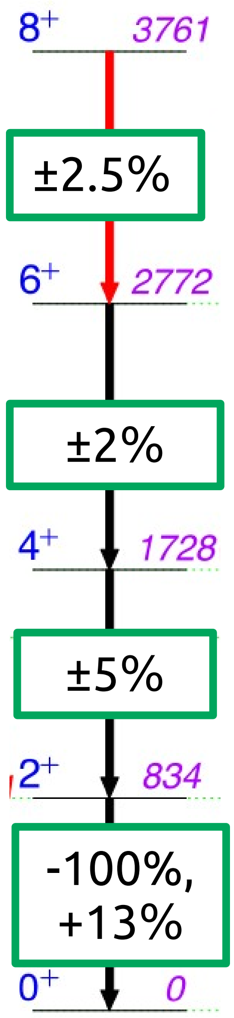


Ayangeakaa et al., PLB **754**, 254 (2016)

Simulation: Statistical (only) Error with ~5% Error in Yields

- 1 scattering angle partition → no sensitivity to cross section vs. impact parameter
- Ground sequence only
- 5% error bars in the simulated data
- No random scatter in data→ no conflicts
- NOTE: strongly deformed case would have no sensitivity to 2→ 0

^{72}Ge



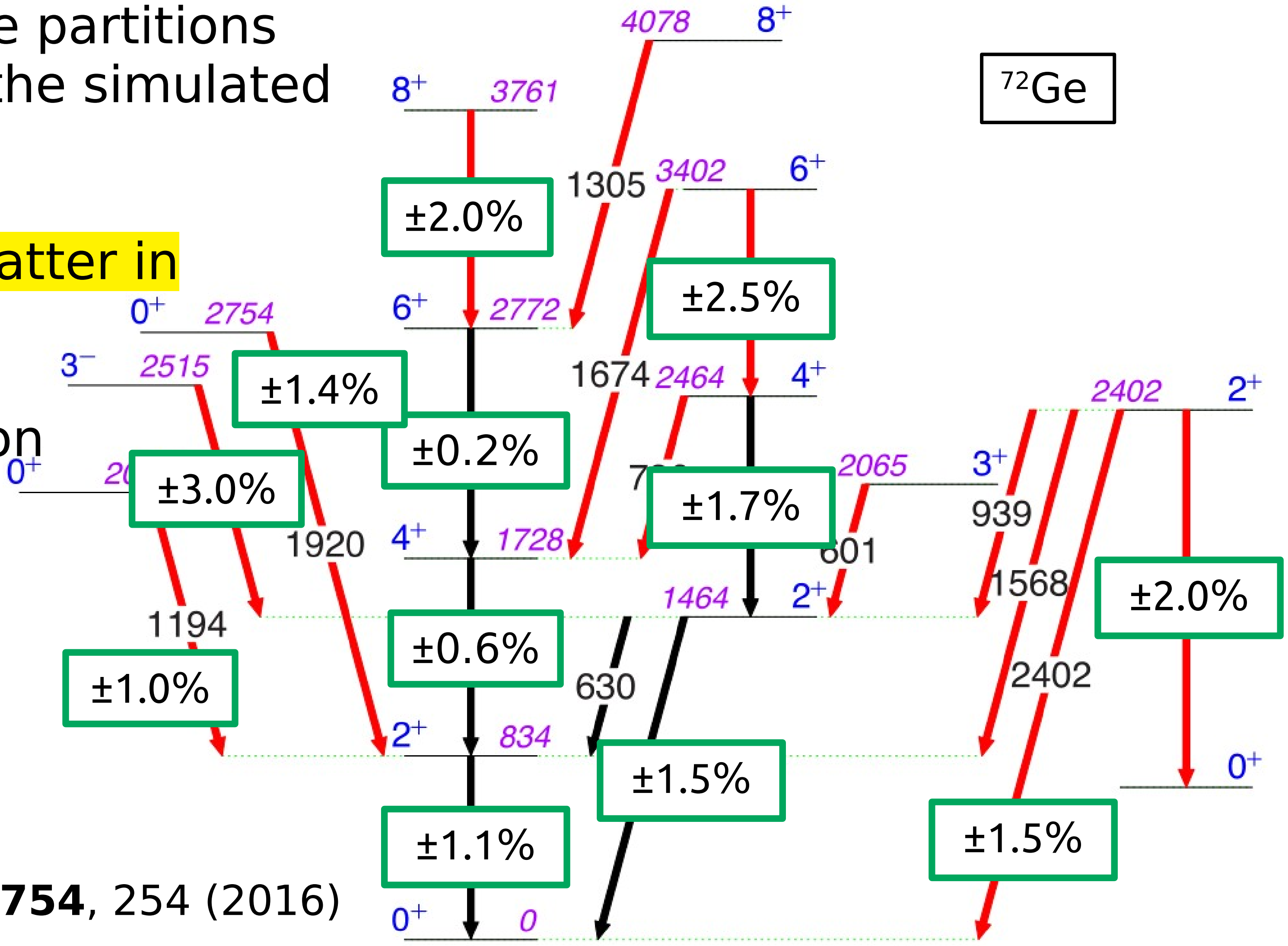
Ayangeakaa et al., PLB **754**, 254 (2016)

Simulation: Statistical (only) Error with ~5% Error in Yields

- 7 scattering angle partitions
  5% error bars in the simulated data

- **WITH** random scatter in data→ conflicts

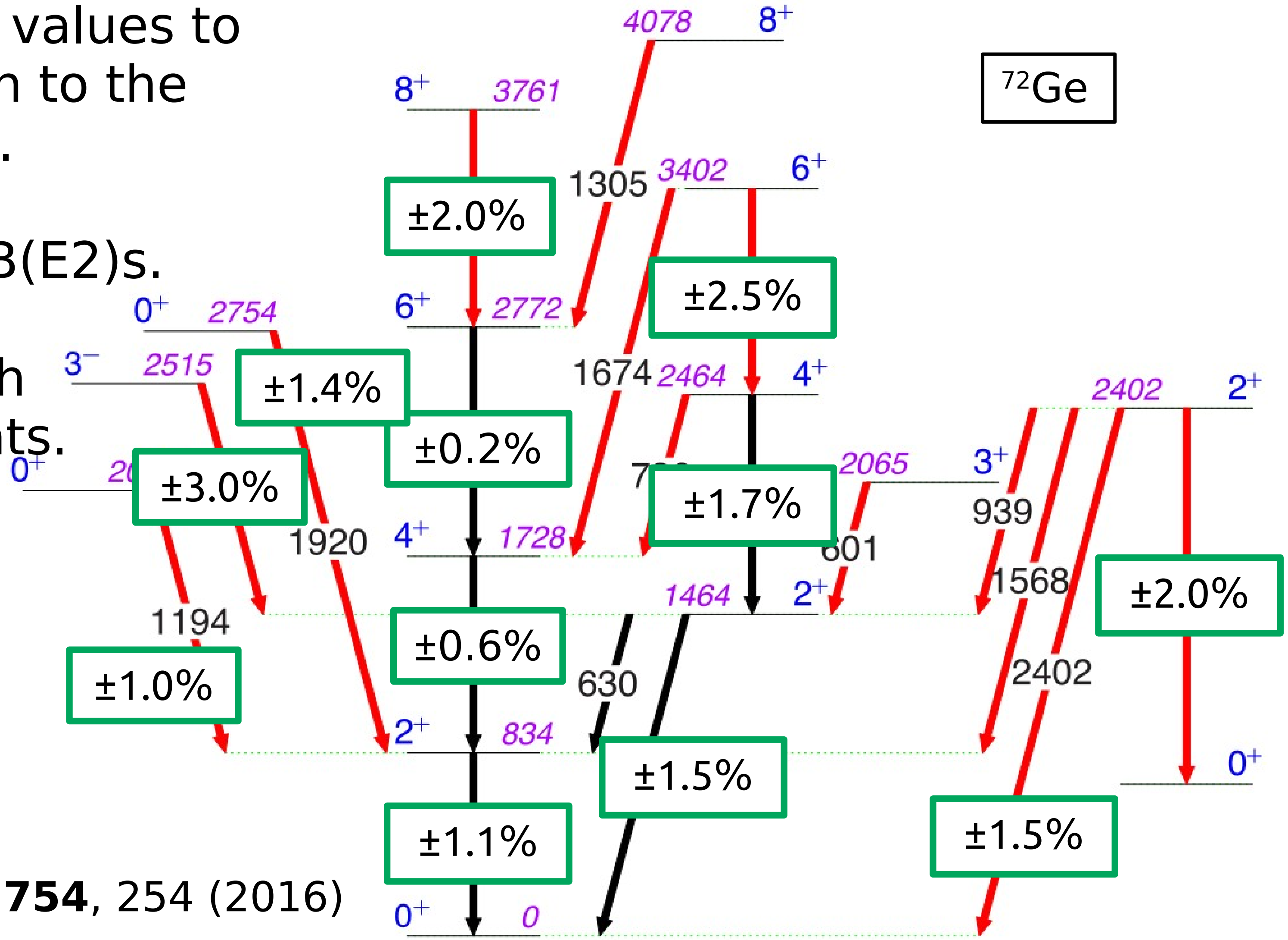
- Gives an indication of the best-case sensitivity in the measurement



Ayangeakaa et al., PLB **754**, 254 (2016)

Simulation: Statistical (only) Error with ~5% Error in Yields

- Use known B(E2) values to narrow the search to the correct minimum.
- Remove known B(E2)s.
- Repeat the search without constraints.



Ayangeakaa et al., PLB **754**, 254 (2016)

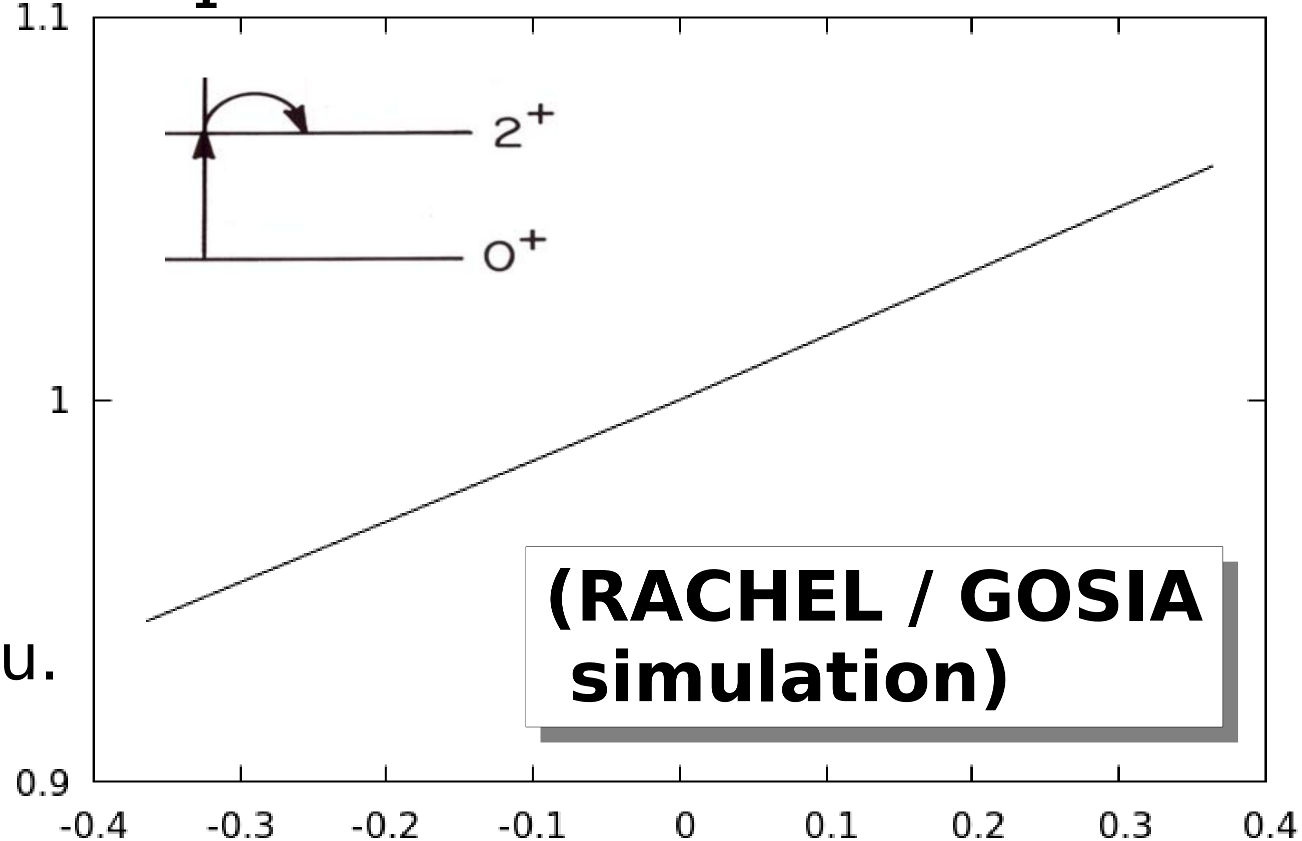
National Nuclear Data Center
A.B. Hayes

(Approximately) Two-state Problems

Reorientation Effects

- Coulomb excitation of ^{60}Ni beam by ^{16}O beam at safe energy of 30MeV
- Predicted population of 2^+_1 excited state
- Known $B(E2;2^+_1 \rightarrow 0^+_1) = 13$ W.u.
- Constructive / destructive interference

2^+_1 Level population (norm)

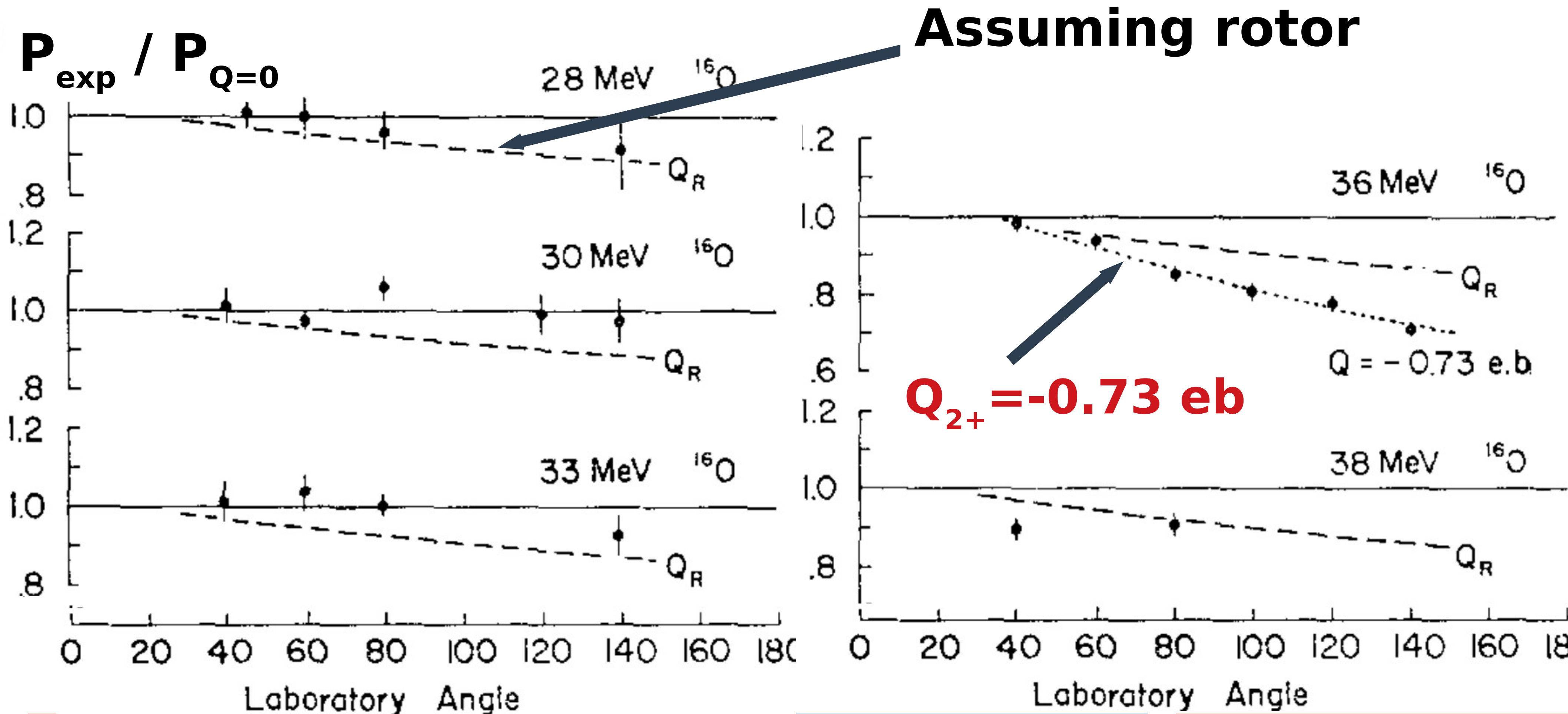


$Q_{2+} = <2^+_1||E2||2^+_1>$

Reorientation Effects: Coulomb-Nuclear Interference

Population $P_{exp}/P_{Q=0}$ of 2^+ state vs. scattering angle (spectrograph)

Cline et al., Nucl Phys A 133, 445 (1969)

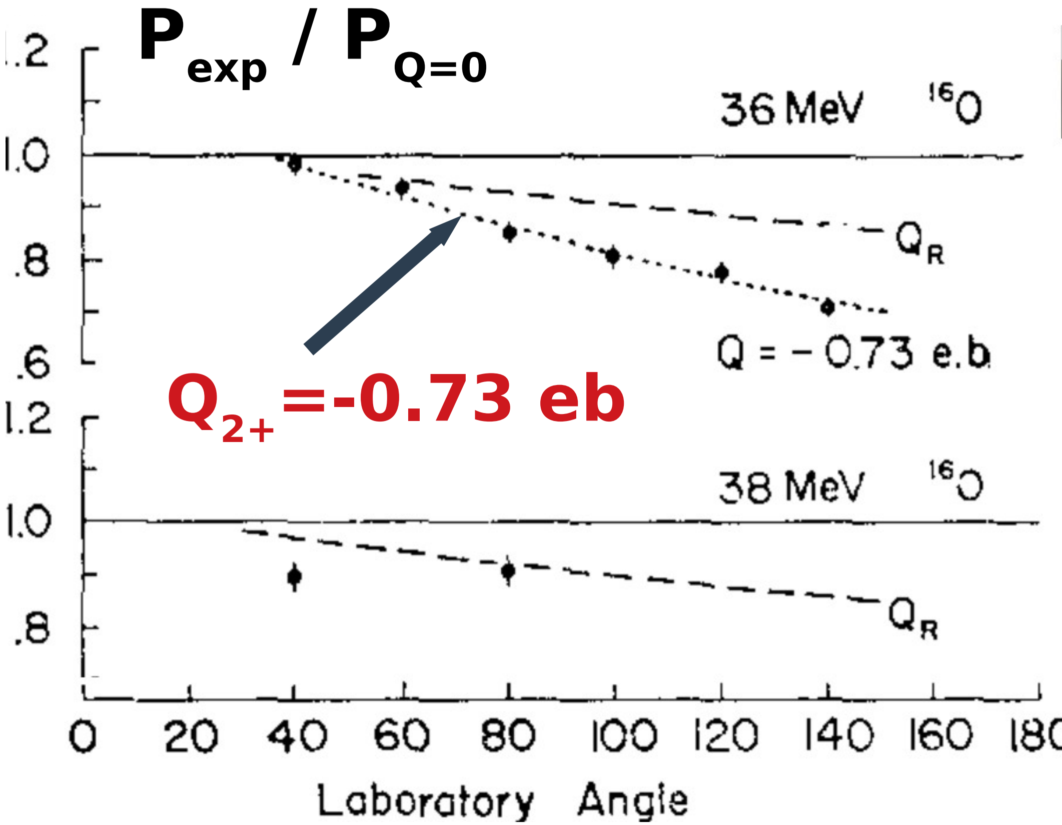


Reorientation Effects: Systematic Error

Population $P_{exp}/P_{Q=0}$ of 2^+ state vs. scattering angle (spectrograph)

Cline et al., Nucl Phys A 133, 445 (1969)

- Requires $E_{beam} \leq 30$ MeV
- Equivalently, surface separation of r=1.25fm $(A_t^{1/3} + A_p^{1/3})$ **≥ 5 fm**
- Coulex is not "safe" for high energy by limiting scattering angle!
- Static moment is the first thing to go.



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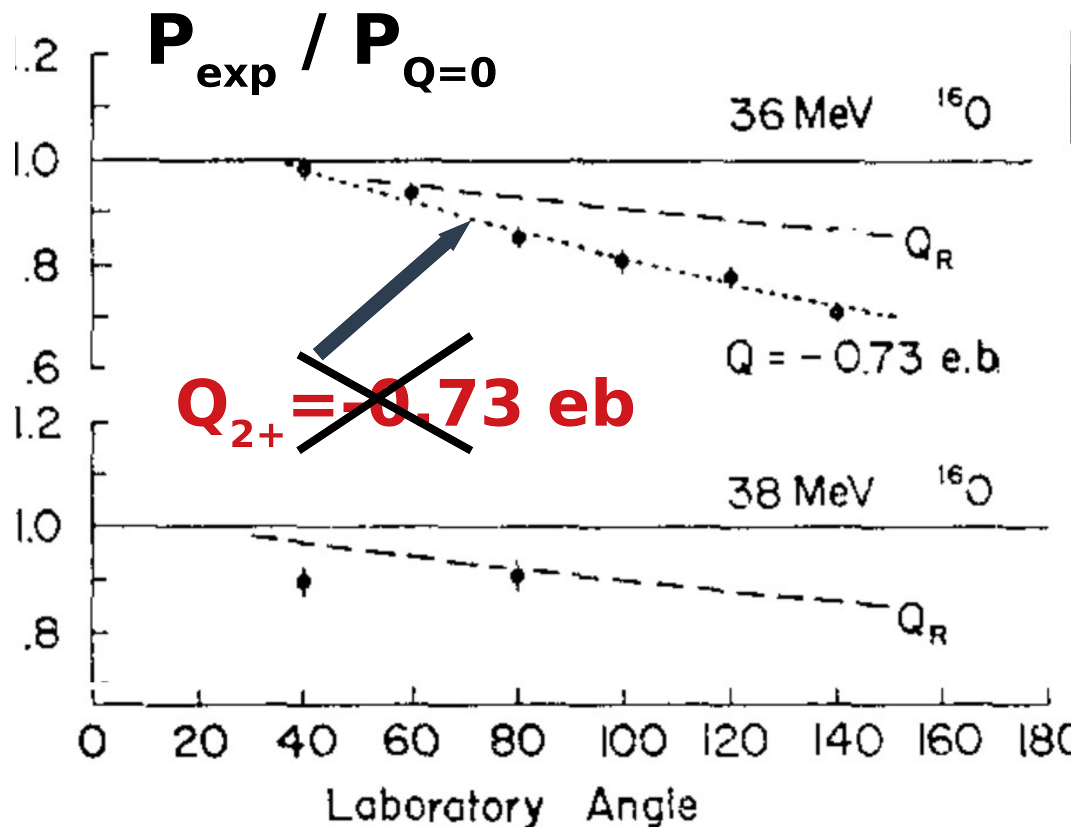
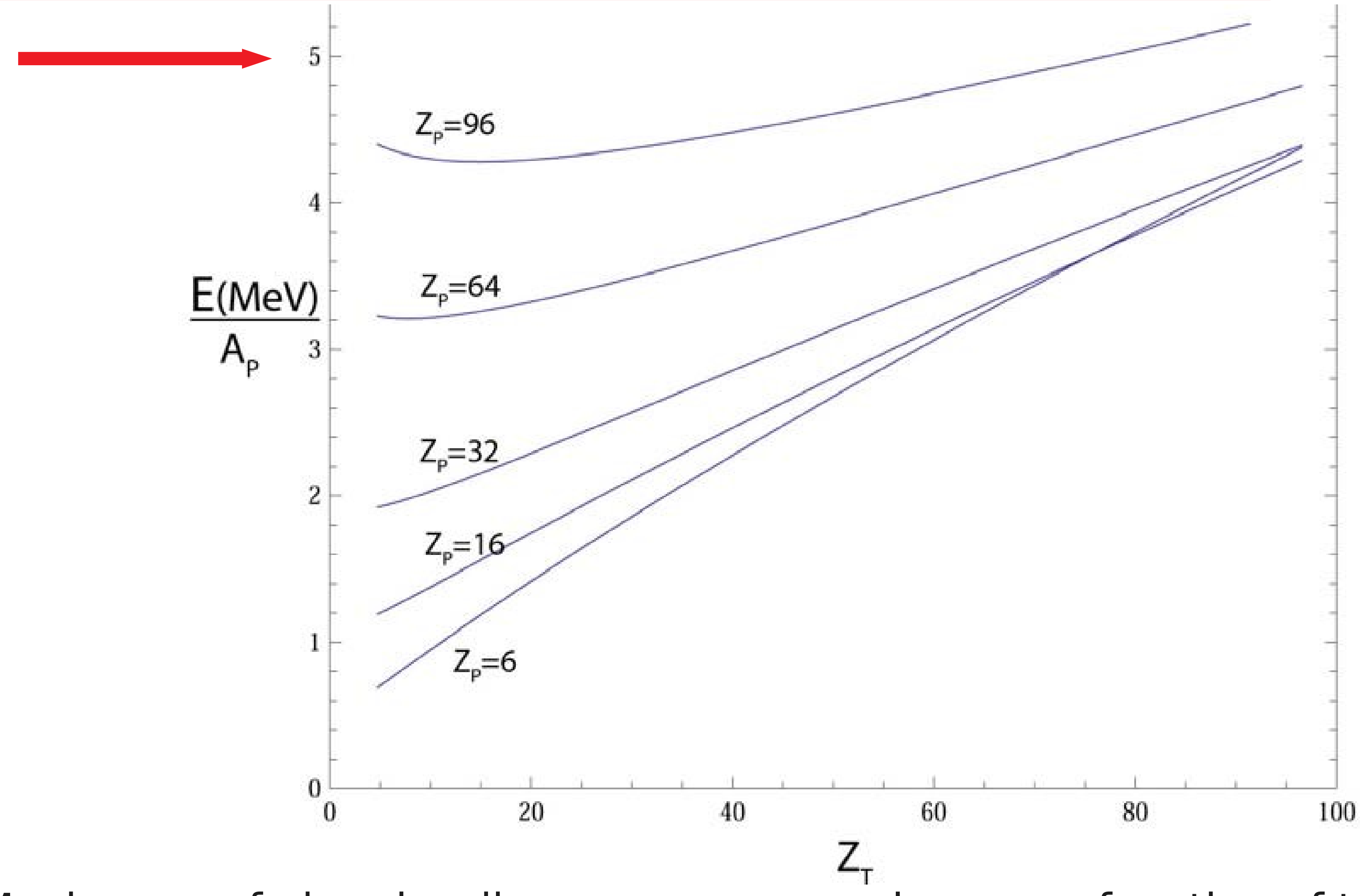
- $E_{beam} \leq 30$ MeV
- $B(E2;0^+ \rightarrow 2^+) = 0.0917(18)\ e^2b^2$
- $Q_{2+} = 0.00(8)$ eb



Semi-classical



Maximum safe bombarding energy per nucleon as a function of target Z.
(Gosia manual)

Gosia2

- ~1 strongly populated state; can't self-normalize
- Normalization to Rutherford is difficult experimentally (as opposed to older spectrograph data).
- Make use of mutual target / projectile excitation.

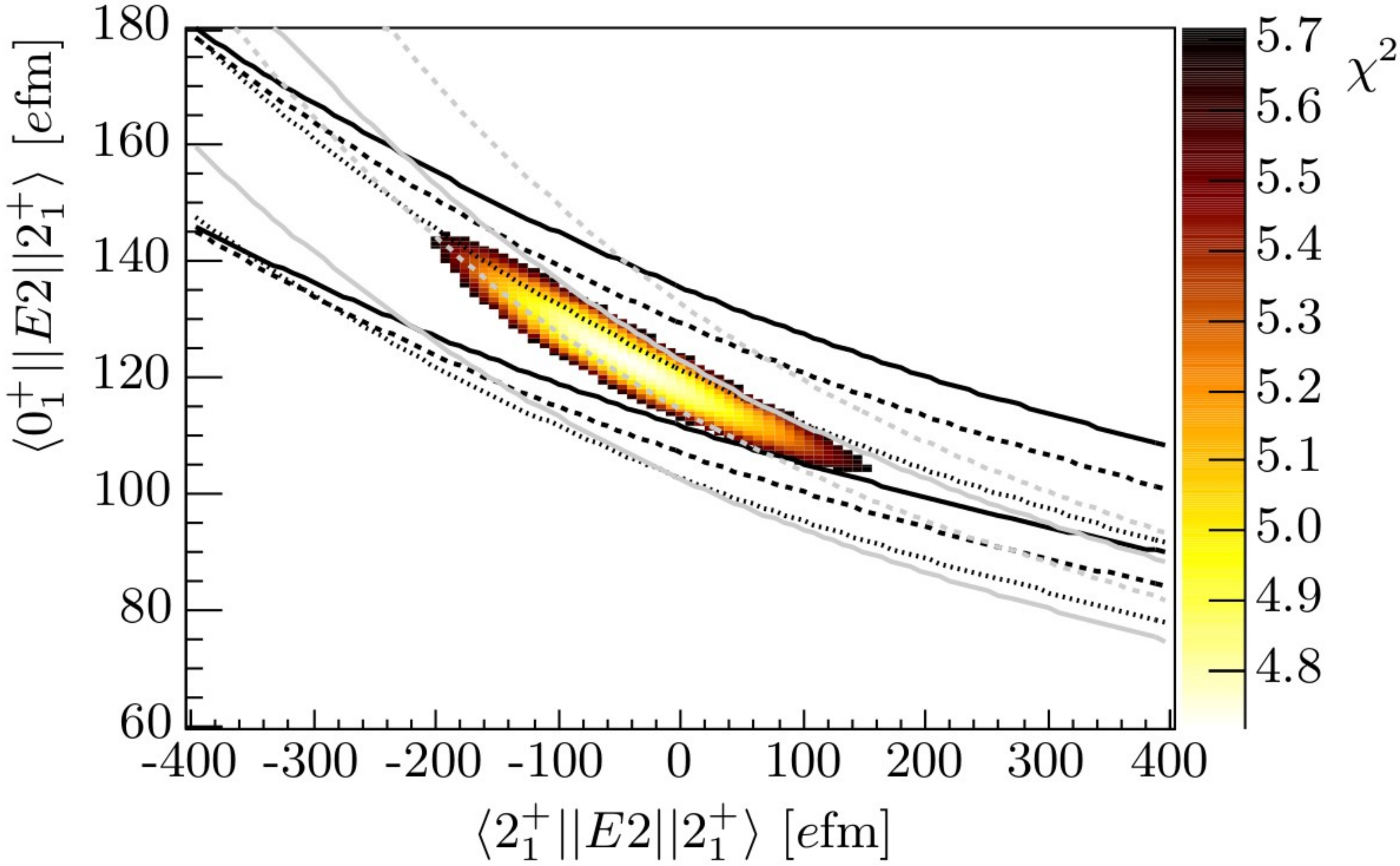
$$\frac{N_p}{N_t} = \frac{b_p \epsilon_\gamma (E_p) \sigma_p}{b_t \epsilon_\gamma (E_t) \sigma_t}$$

- Deduce transition probability (usually B[E2]) from known transition probability in collision partner.

  → Independent measurement of **quantity of interest**, but does require input of **previous measurements for collision partner**.

- **The static moment and B(E2) both affect population. Accuracy and realistic uncertainty require correlated error calculation.**

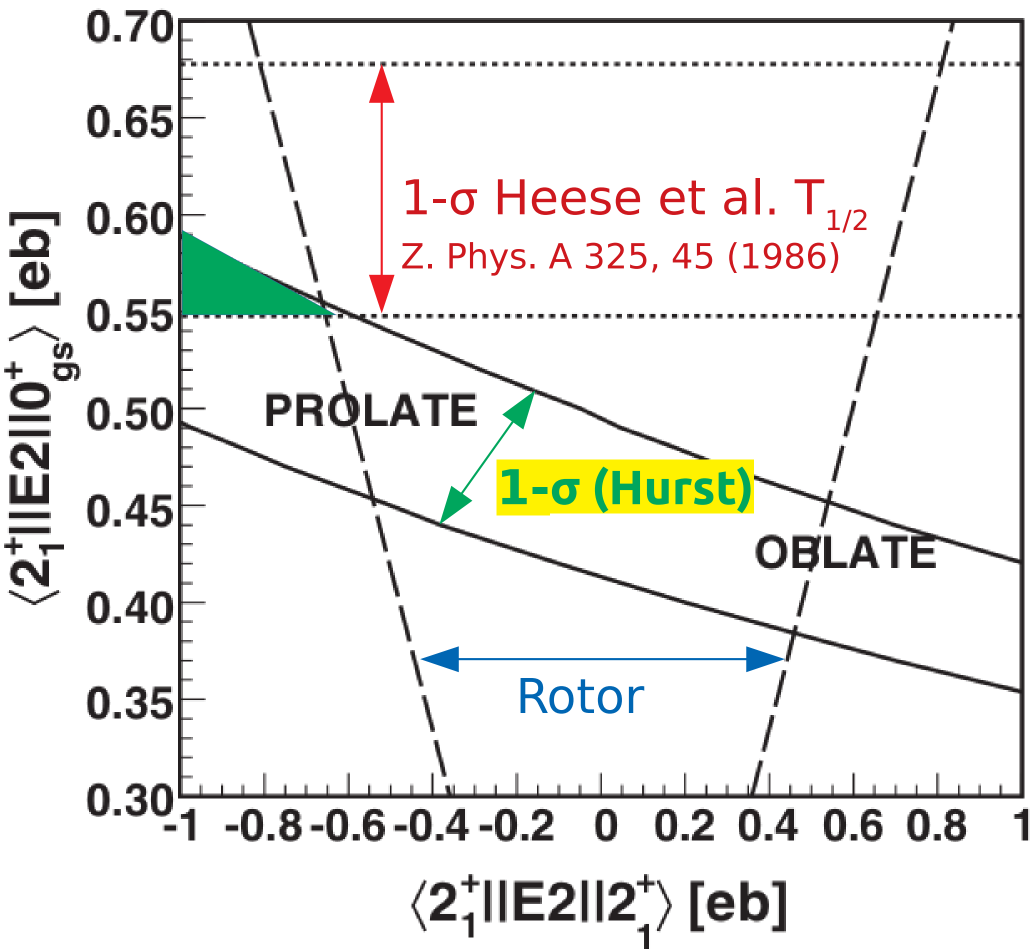
Gosia2



M. Zielińska et al.: Eur. Phys. J. A (2016) 52: 99

^{70}Se: Oblate or Prolate?

- Hurst et al.: ^{70}Se on ^{104}Pd @ 206MeV (>7fm separation)
  → <2% population of states other than 2^+_1
- Gosia2: norm proj to targ γ-yield
- Fit $B(E2; 0^+ \rightarrow 2^+_1)$, $\langle 2^+_1||E2||2^+_1\rangle$
- Requires accurate data for collision partner ^{104}Pd
  - Luontama et al. ^{104}Pd (p,2n), (p,p'), Coulex (1986)
- Consistency with $T_{1/2}$ meas requires $\langle 2^+_1||E2||2^+_1\rangle$ less than -0.5eb
  → consistent with **prolate** deformation



- Note: Common mistake is to fit B(E2) *without including* correlations with $\langle 2^+_1||E2||2^+_1\rangle$ in error calculation.

A.M. Hurst *et al.*, PRL 98, 072501 (2007).

Validation of the Method in ^{70}Se Experiment Using ^{74}Se

- Measured gamma yields for Coulex of ^{74}Se on ^{104}Pd
- Combined with <2^+||E2||2^+> = -0.36(7) eb (19% error) from Lecomte PRC 18, 2801 (1978).
- Adopted B(E2) = 0.387(8) e^2b^2 (2% err)
- Hurst et al. obtained B(E2;$0^+ \rightarrow 2^+$) = 0.36(2)e^2b^2 (5.5% err)

A.M. Hurst *et al.*, PRL 98, 072501 (2007).

Conclusions

- Very precise measurements are possible using Coulex and GOSIA
- Partitioning of data is very important (i.e. scattering angle)
- Collective strength / many populated states → relative gamma yields give absolute measurements
- Two-state problems require
  - Normalization to collision partner yields
  - Known B(E2), <2+||E2||2+> of collision partner
- Other problems lie somewhere in the middle
- Safe Coulex usually better than high statistics
- Inverse kinematics—don't get me started...
- Include all matrix elements in correlated error calculations
- Plan and simulate analysis before submitting proposals!

END

END

END

END

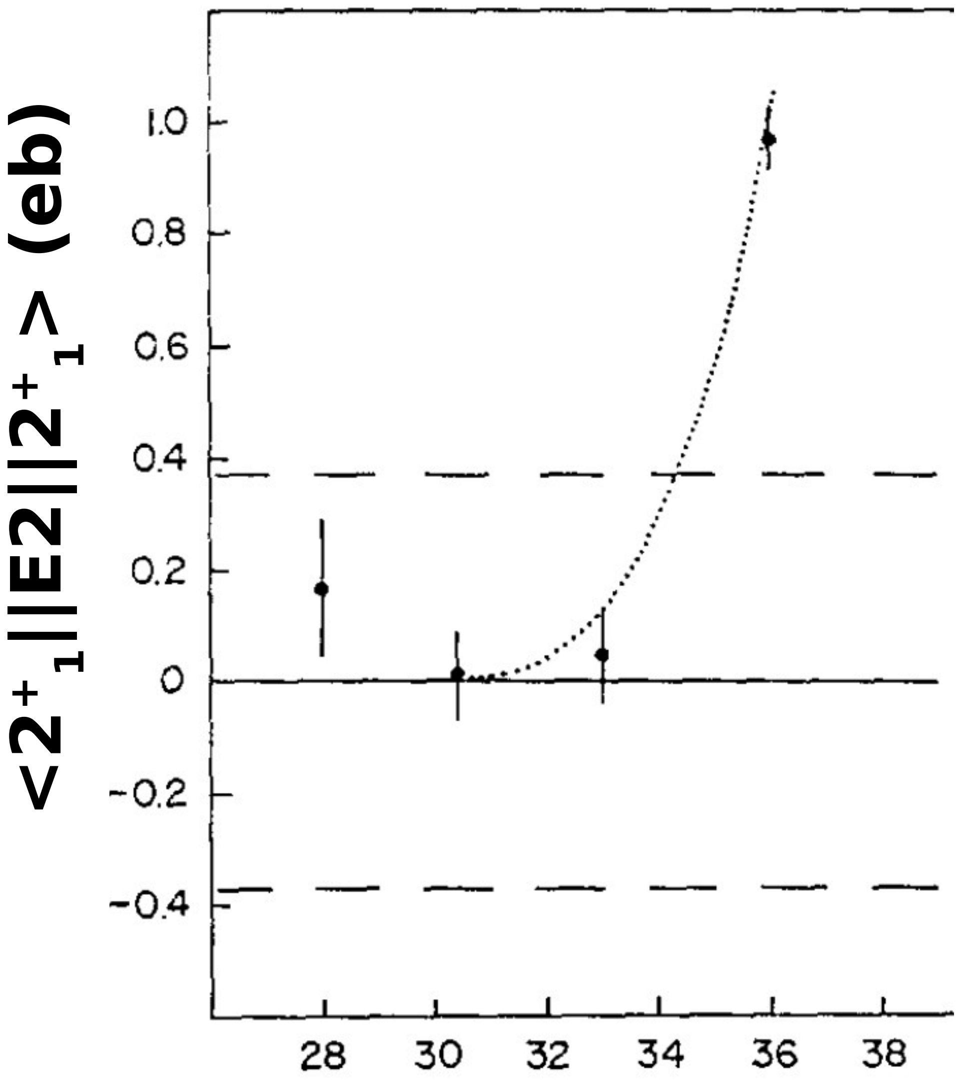
Terminology

Yield	Gamma-ray intensity following Coulex
EM multipole operator matrix element	$< I_s M_s \lvert M(\lambda,\mu) \rvert I_f M_f > = (-1)^{I_s - M_s} \begin{pmatrix} I_s & \lambda & I_f \\ -M_s & \mu & M_f \end{pmatrix} < I_s \lvert\lvert M(\lambda) \rvert\rvert I_f >$
Reduced matrix element	$< I_s \lvert\lvert M(\lambda) \rvert\rvert I_f >$
Quadrupole moment (in-band transitions)	$\langle I_f K \mid\mid E2 \mid\mid I_i K \rangle = (2I_i+1)^{1/2} \langle I_i K 20 \mid I_f K \rangle \sqrt{\frac{5}{16\pi}} eQ_o$
	$\langle K_f I_f \lVert \mathcal{M}(\lambda) \rVert K_i I_i \rangle = \sqrt{2I_i+1} \langle I_i 0 \lambda K_f \mid I_f K_f \rangle$
"Intrinsic" matrix element (inter-band transitions)	$\times \langle K_f \mid \mathcal{M}(\lambda, \mu = K_f) \mid K_i = 0 \rangle \begin{cases} \sqrt{2} & K_f \neq 0 \\ 1 & K_f = 0 \end{cases}$
Reduced transition probability	$B(E(M)\lambda; I_i K_i \to I_f K_f) \equiv \frac{\mid \langle I_f K_f \lVert E(M)(\lambda,\mu) \rVert I_i K_i \rangle \mid^2}{2I_i + 1}$

Terminology

GSB	Ground-state rotational Band
Static moment	$< I \,\|\|M(\lambda)\|\| I \;>$
“Safe” Coulex	Collision energy low enough that Coulomb-nuclear interference is negligible. Rule of thumb: $E_{beam} \leq 80\%\ E_{barrier}$
Sommerfeld parameter?	
Adiabaticity?	
Eccentricity?	

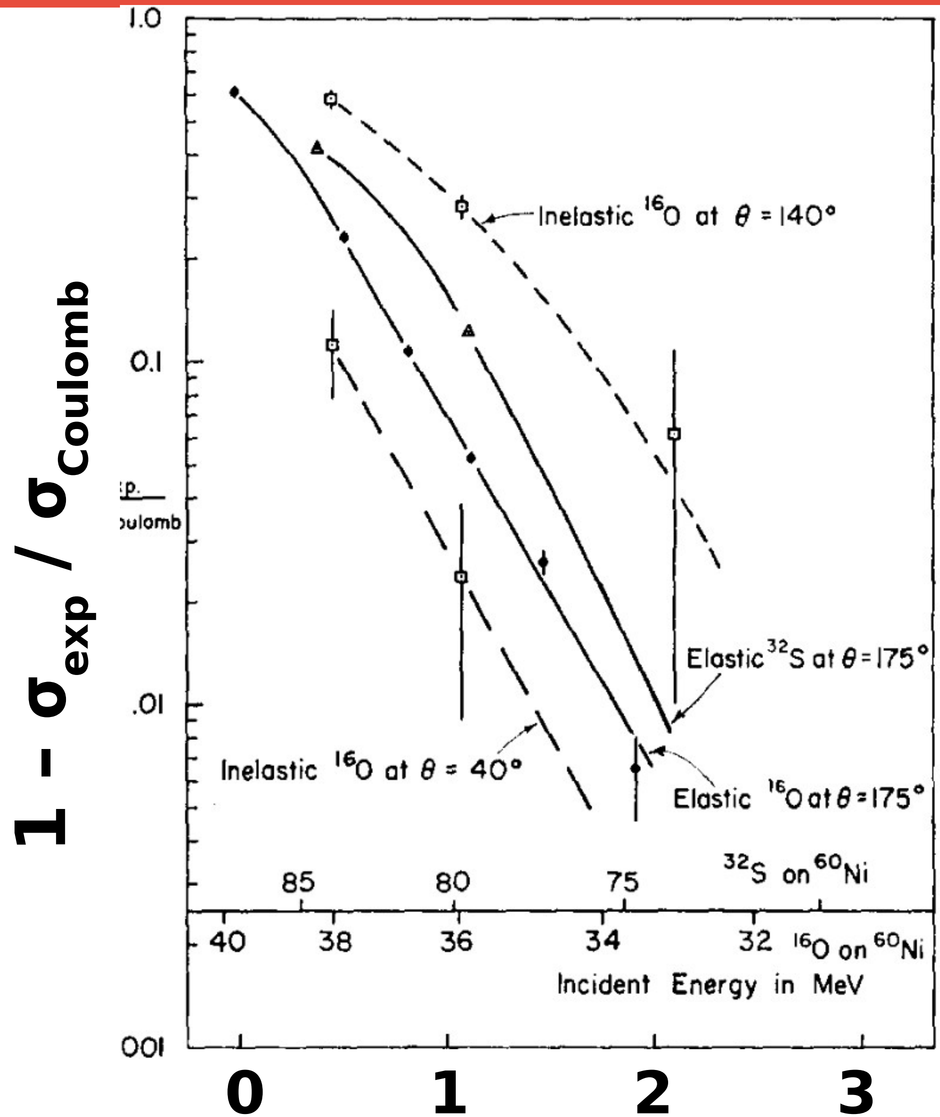
Reorientation Effects: Systematic Error



- Requires E_{beam} ≤30 MeV
- Equivalently, surface separation of $r=1.25fm\ (A_t^{1/3} + A_p^{1/3})$ **≥ 5 fm**
- Coulex is not “safe” for high energy by limiting scattering angle!
- Static moment is the first thing to go.

^{16}O Incident Energy (MeV)

Reorientation Effect



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Surface separation (fm)