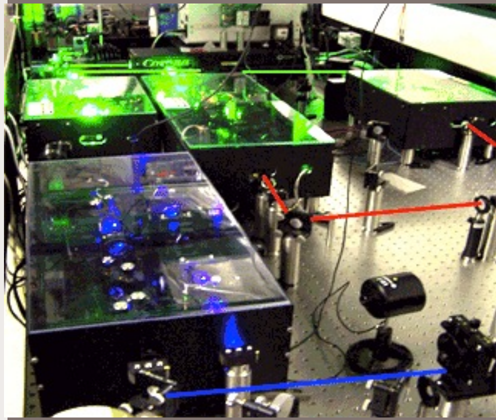
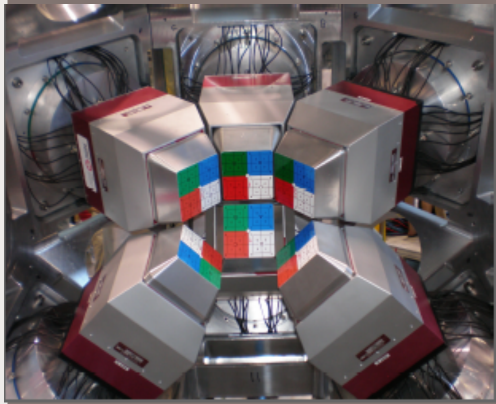
Gamma rays in light nuclei: what we have learned and can learn at TRIUMF

Nuclear Structure & Reactions: Experimental and Ab Initio Theoretical Perspectives

TRIUMF, 2014-02-20

Greg Hackman | TRIUMF





Acknowledgements and Thanks

TRIUMF

Lots of credit to go around

Thanks to the people from who've shared slides and results: Nico Orce, Elaine Kwan, Fred Sarazin, Ching-Yen Wu, Phil Voss

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Theory & Experiment Move Forward

Advances in theoretical techniques allow precise calculations for light nuclei

- No-core shell models (P. Navratil et al.)
- Green's-function Monte Carlo Phenomenological potentials
- Effective field theories
- Three-body forces

… but this isn't a theory talk (and I promise not to show any equipment either)

TRIUMF-ISAC has the tools

- World's highest ISOL power (M. Dombsky, P. Bricault) -- production
- TRILIS lasers (J. Lassen) – ionization & extraction
- ISAC (R. Laxdal, M. Marchetto) -- acceleration well above Coulomb barrier
- World-class charged-particle and gamma arrays (GH, C. E. Svensson, A.B. Garnsworthy, C.-Y. Wu)

... to test these calculations

What gamma rays can tell us

A nucleus was excited and then decayed

- Minimum 1 excited state in nucleus
- Some reaction or process excited that state
- Energy DIFFERENCE of states known
- Angular distribution depends on spins of states
- Polarization depends on parities

What we can use this for

- Reaction rates for excitation or to excited states may be measured from subsequent gamma yield
- Half-life for decays can be related to transition matrix elements
  - Which can then be related to shapes
- Selection rules, angular distributions can limit possible spins and parities of states

Excitation techniques

Inelastic scattering

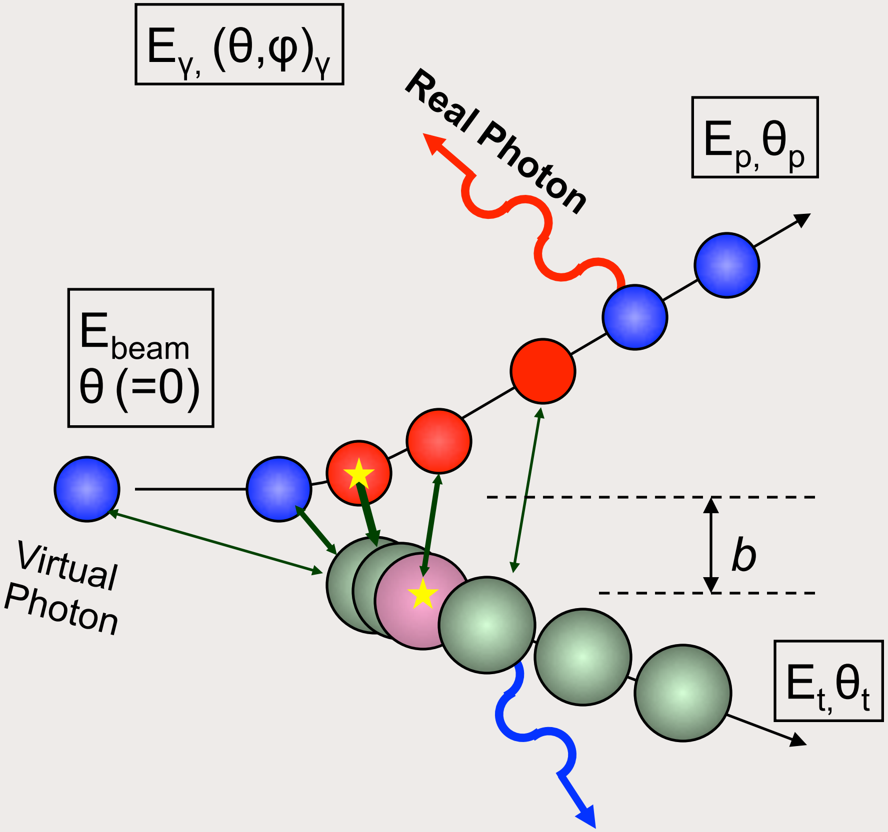
- Separation > a few fm: Coulomb excitation: excitation by mutual electric fields
- On closer contact nuclear forces can result in:
  - Radiative capture
  - Nucleon or cluster transfer
  - Fusion-evaporation

Beta decay

- Strong selection rules
- Beta particle can be a tag for “start” of lifetime measurement by electronic instrumentation
- Level scheme can be deduced from energy differences
- Primarily probes structure of daughter

Technique: Coulomb Excitation

- Near-barrier scattering
  - ~1 to 6 MeV/A, depending on Z_p, Z_t
  - Select E_{beam} for >1.5 fm closest approach for “nominal” nuclear radii
    - eliminate – or at least limit – strong-force interaction
- Excited states in projectile or target nuclei couple to Coulomb repulsion field
- Excitation probability proportional to transition matrix element, increases with decreasing impact parameter *b*
  - Typically bin γ yield by θ_p , verify distribution matches theory
- ISAC-II suitable for these experiments



- *b* evaluated from event kinematics

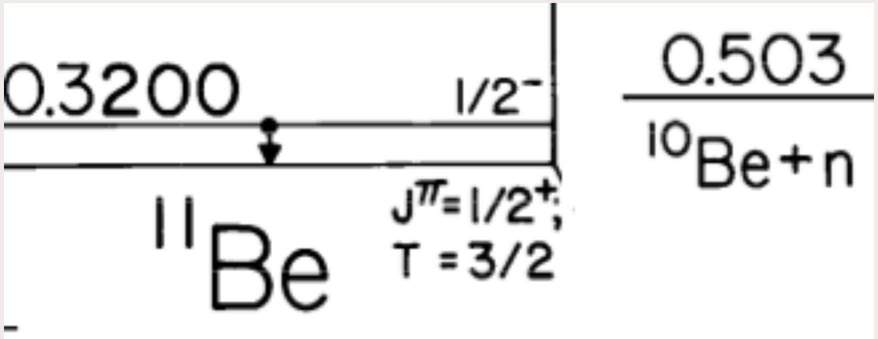
Transition Matrix Element in ^{11}Be

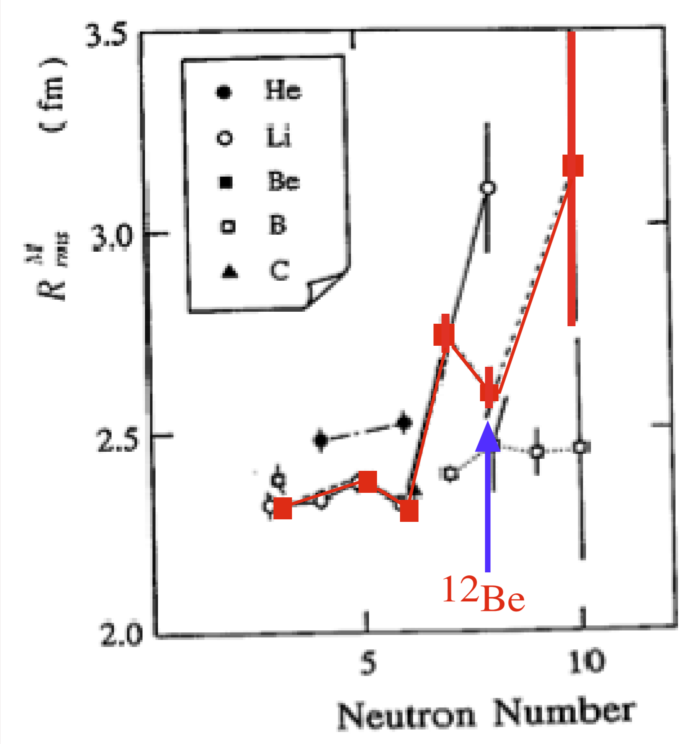
Precision measurements of B(E1) Strengths in ^{11}Be

E. Kwan, C.Y. Wu, N.S. Summers, G. Hackman, T.E Drake, C. Andreoiu, G.C. Ball, P. C. Bender, A.J. Boston, H.C. Boston, A. Chester, D. Cline, A. Close, D.S. Cross, R. Dunlop, A. Finley, A. Garnsworthy, A. B. Hayes, T. Nano, P. Narvátil, C. J. Pearson, J. Pore, K. Starosta, I.J. Thompson, P. Voss, S. J. Williams, Z.M. Wang

^{11}Be a “classic” exotic nucleus

- Weakly bound – only 1 excited state
- Inverted ground state: ½+, not ½−
- Largest known E1 -- ~ 3 W.u.
  - (115 fs)
- One-neutron halo





I. Tanihata et al, PLB 206 (1988) 592

Precision measurements of B(E1) Strengths in ^{11}Be

^{11}Be Wide range of both measurements and calculations for B(E1)

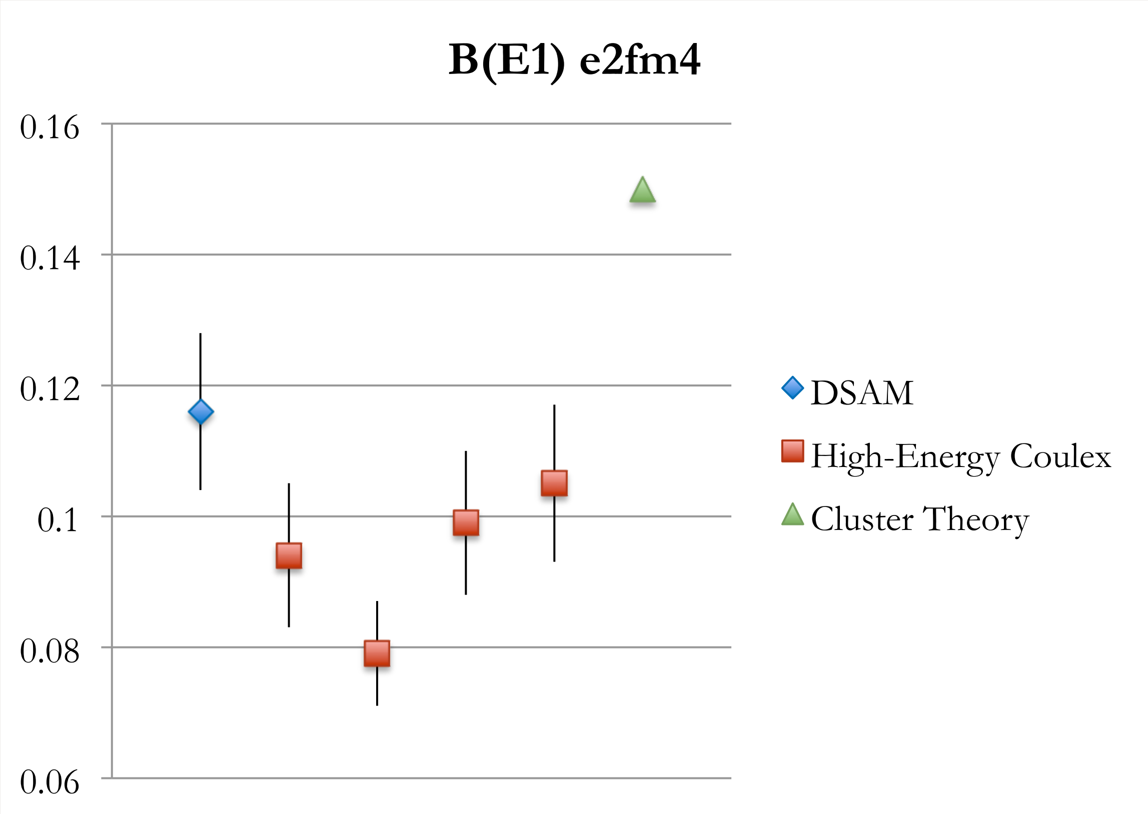
- Prior, only lifetimes and high-energy inelastic scattering data existed
- Low-energy Coulomb excitation affords high precision, limits non-electromagnetic systematic errors

B(E1) (e^2fm^4)	Source	Ref.
0.116(12)	DSAM lifetime measurement	PRC 28, 497 (1983)
0.094(11) 0.079(8) 0.099(11) 0.105(12)	Intermediate-energy Coulomb excitation	PRC 56,R1 (1997) Ibid PLB 394, 11 (1997) PLB 650, 124 (2007)
0.15	Phenomenological cluster	NPA 596, 171 (1886)
0.006	Ab Initio No-core shell (wrong g.s.)	PRC 71, 044312 (2005)
0.018	No-core shell with resonating groups	PRL 101, 092501 (2008)

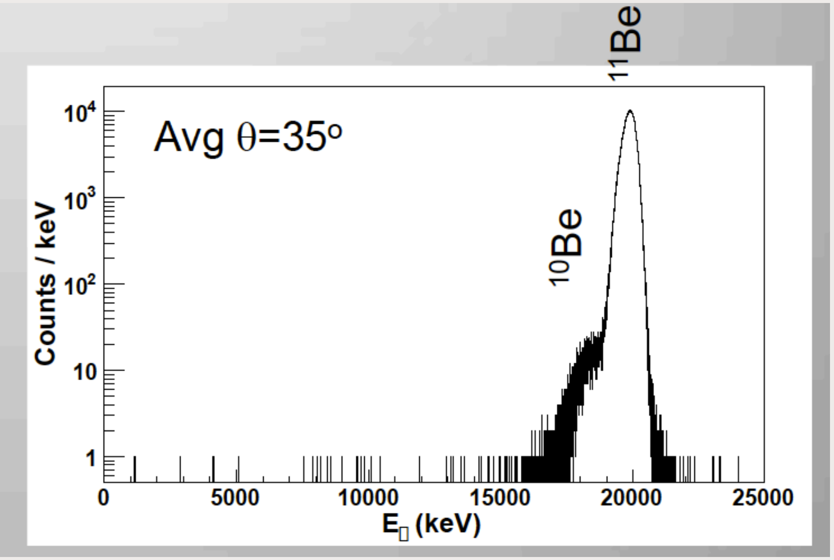
Precision measurements of B(E1) Strengths in ^{11}Be

^{11}Be Wide range of both measurements and calculations for B(E1)

- Prior, only lifetimes and high-energy inelastic scattering data existed
- Some calculations couldn't even get ground state correct
- Low-energy Coulomb excitation affords high precision, limits non-electromatgneitc systematic errors



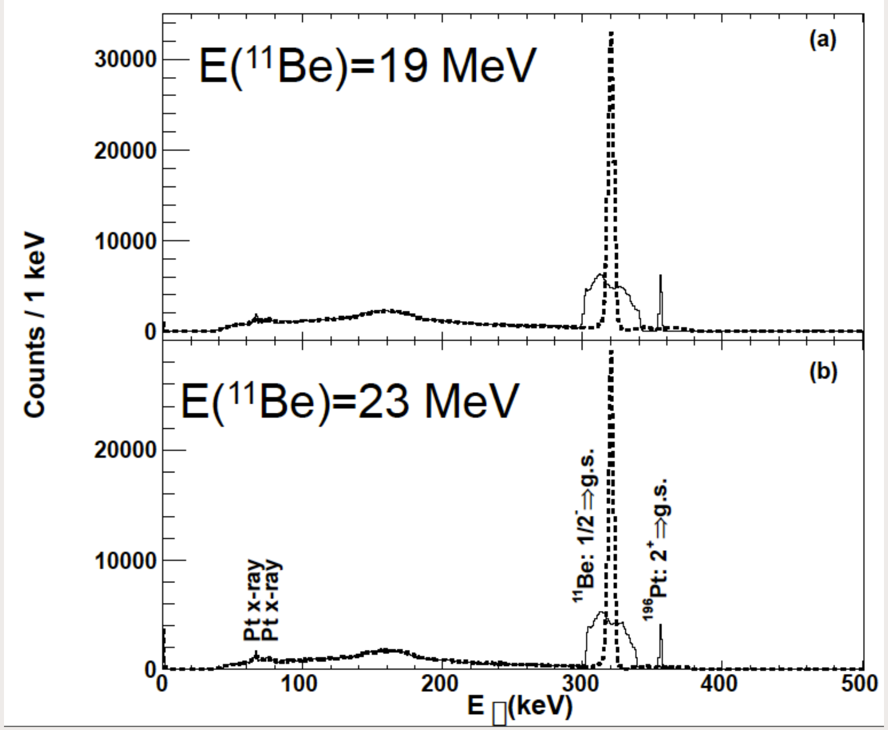
Precision measurements of B(E1) Strengths in ^{11}Be



^{11}Be Coulomb excitation at 19, 23, 42 MeV on ^{196}Pt as a "standard candle"

- 300,000 particles per second – world's most intense ^{11}Be beams
- Detect ^{11}Be in Si "CD"-style detectors
- Plotted here: Spectrum of measured scattered nucleus energies
- In principle this is enough
  - Kinematics (energy & direction of recoil) are enough to determine a reaction Q value to discriminate ^{11}Be, ^{11}Be*, ^{10}Be
- In practice, cannot resolve 320 keV separation

Precision measurements of B(E1) Strengths in ^{11}Be

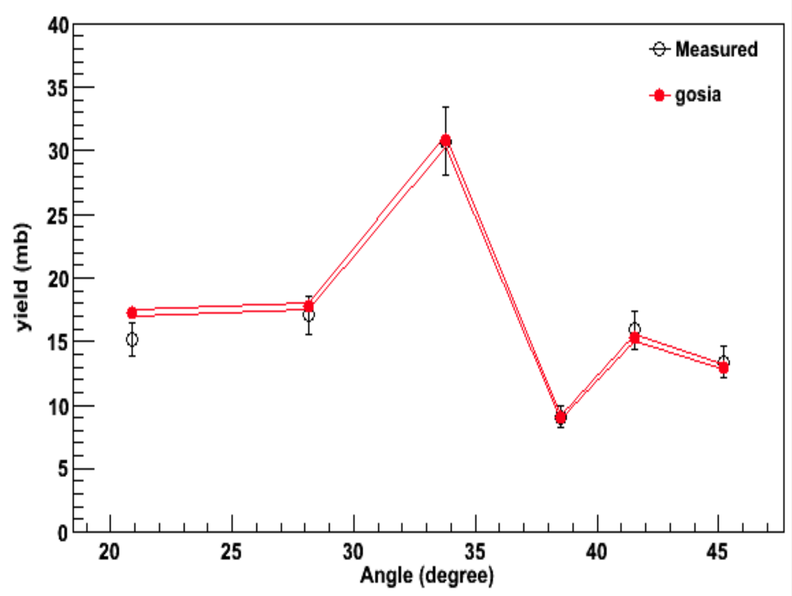


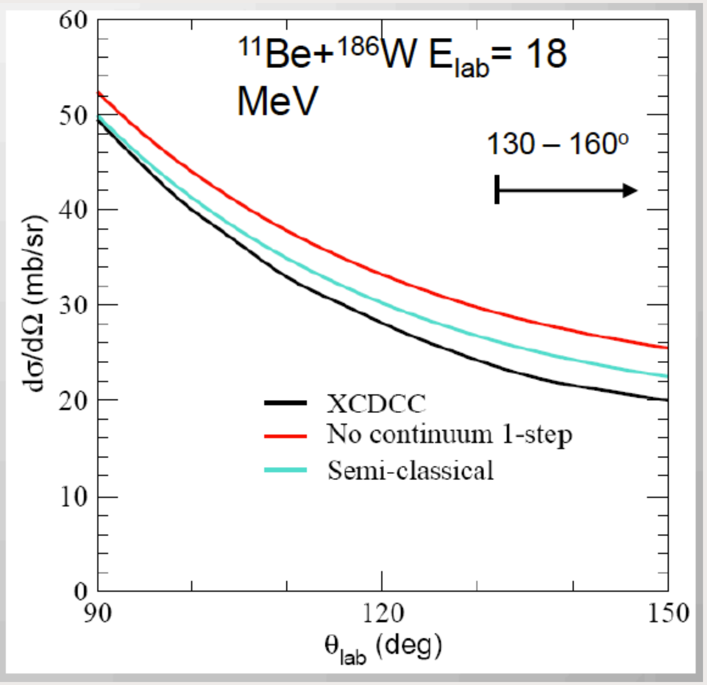
- Measure cross-section from gamma yield
  - ^{196}Pt excitation probability well known, de-excitation gamma ray has similar energy
  - Use ^{196}Pt target excitation
- Plotted here: Gamma ray energy spectrum observed at same time as a scattered Be
- Solid lines: Laboratory frame gamma spectrum
  - Lines emitted from scatterd Be are Doppler broadened
- Dashed lines are corrected for Doppler shift of recoiling ^{11}Be

B(E1) Strengths in ^{11}Be: 0.105(2) e^2fm^4

^{11}Be B(E1; ½⁻ ➔ ½⁺): 0.105(2) e^2fm^4

- Semi-classical calculation at low scattering angles where continuum excitations are minimal
  - Angular distributions well reproduced
- Large-angle data will be used to disentangle continuum effects of 30%

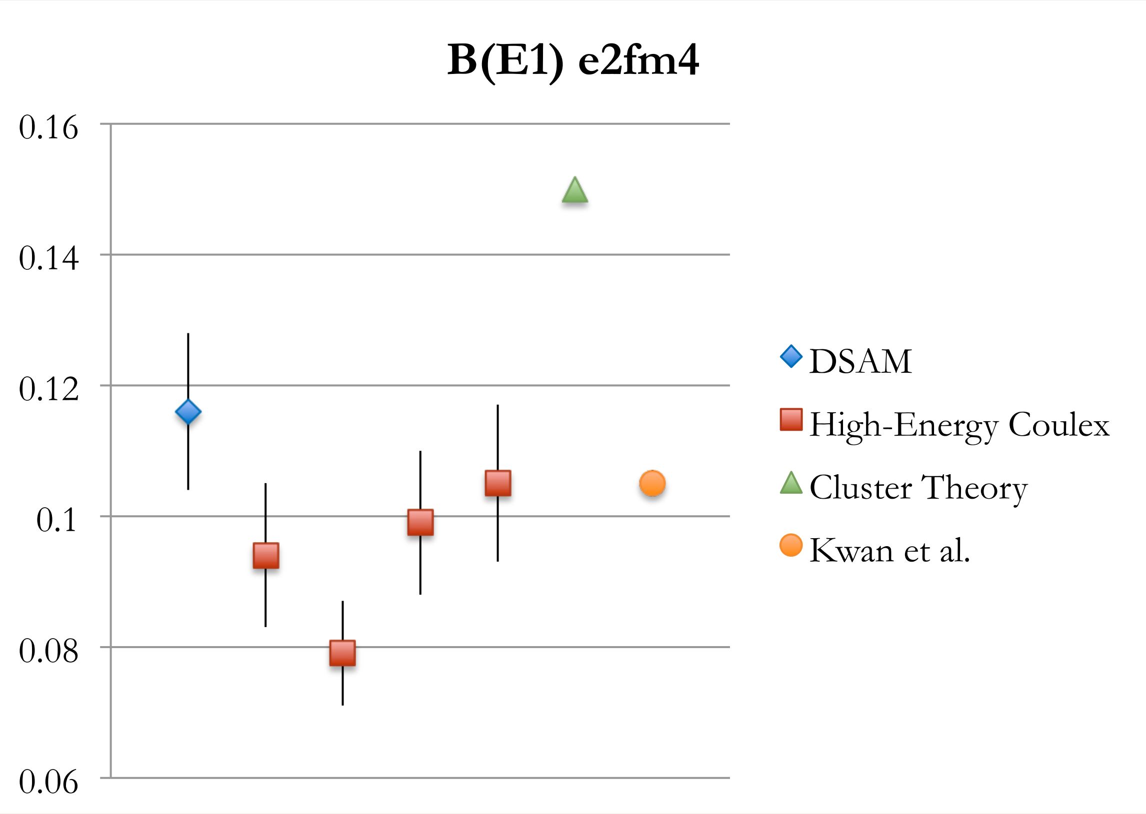




B(E1) Strengths in ^{11}Be: 0.105(2) $e^2 fm^4$

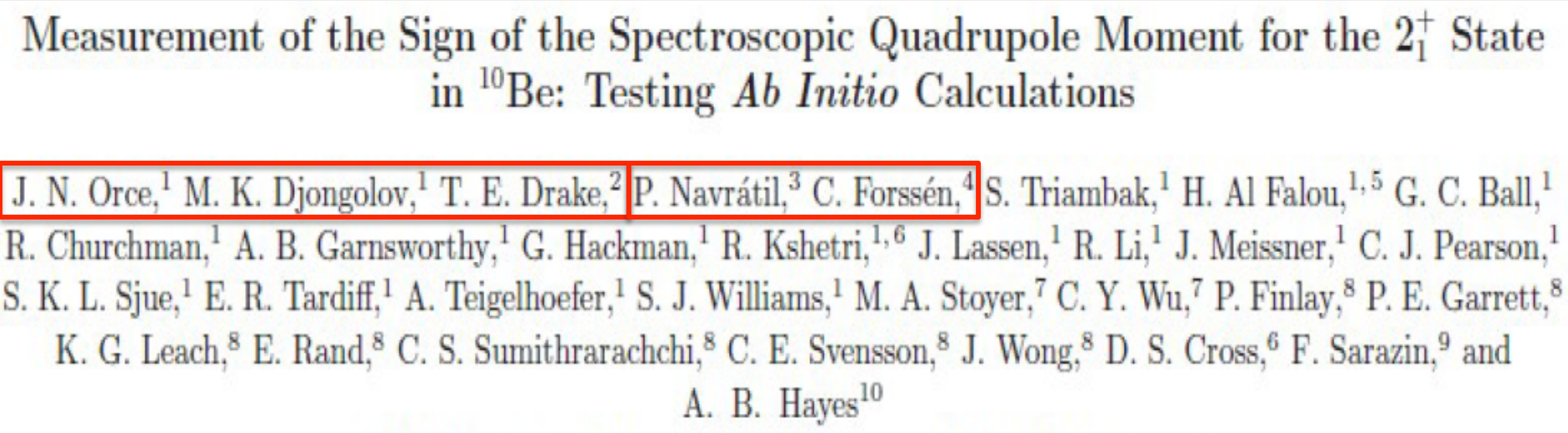
^{11}Be B(E1; ½⁻ ➔ ½⁺): 0.105(2) $e^2 fm^4$

- Measured in low-energy (near-barrier) Coulomb excitation
- Uncertainty 2%
- Compare to 10% in DSAM, high-energy Coulex



Shape of ^{10}Be

Structure of light nuclei: ^{10}Be

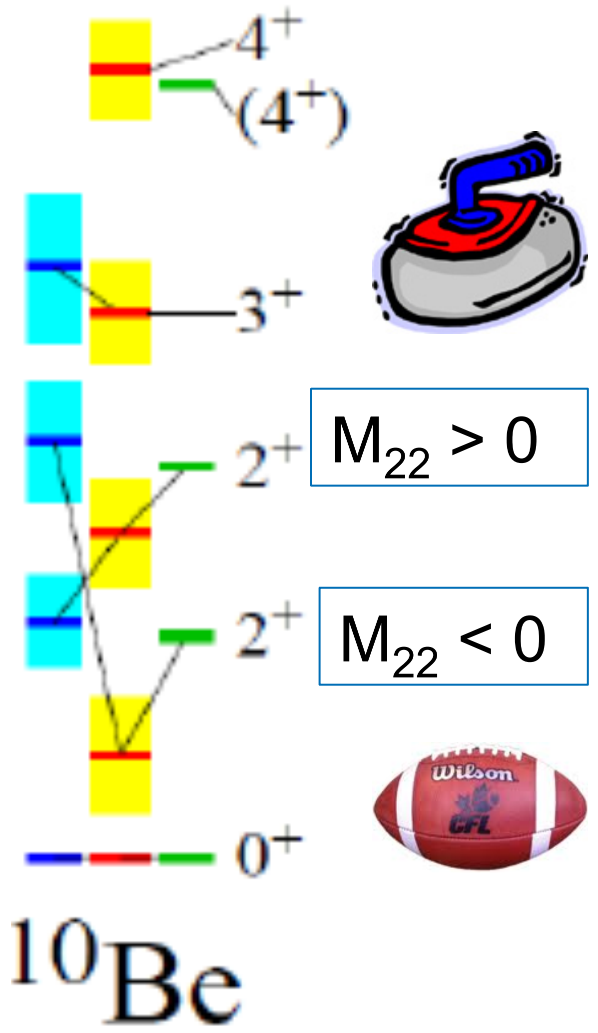


Measurement of the Sign of the Spectroscopic Quadrupole Moment for the 2_1^+ State in ^{10}Be: Testing *Ab Initio* Calculations

J. N. Orce,[1] M. K. Djongolov,[1] T. E. Drake,[2] P. Navrátil,[3] C. Forssén,[4] S. Triambak,[1] H. Al Falou,[1,5] G. C. Ball,[1] R. Churchman,[1] A. B. Garnsworthy,[1] G. Hackman,[1] R. Kshetri,[1,6] J. Lassen,[1] R. Li,[1] J. Meissner,[1] C. J. Pearson,[1] S. K. L. Sjue,[1] E. R. Tardiff,[1] A. Teigelhoefer,[1] S. J. Williams,[1] M. A. Stoyer,[7] C. Y. Wu,[7] P. Finlay,[8] P. E. Garrett,[8] K. G. Leach,[8] E. Rand,[8] C. S. Sumithrarachchi,[8] C. E. Svensson,[8] J. Wong,[8] D. S. Cross,[6] F. Sarazin,[9] and A. B. Hayes[10]

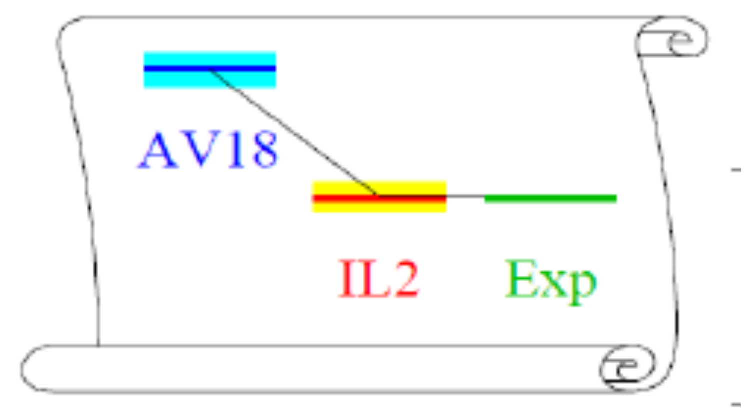
GFMC AV18 + IL2 (3 body)

- Conventional wisdom: ^{10}Be 0^+_{gs}, 2^+_1 prolate ($M_{22}>0$)
- GFMC AV18 alone: 2^+_1 oblate, 2^+_2 prolate
- Include IL2 3-body forces: 2^+_1 prolate, 2^+_2 oblate

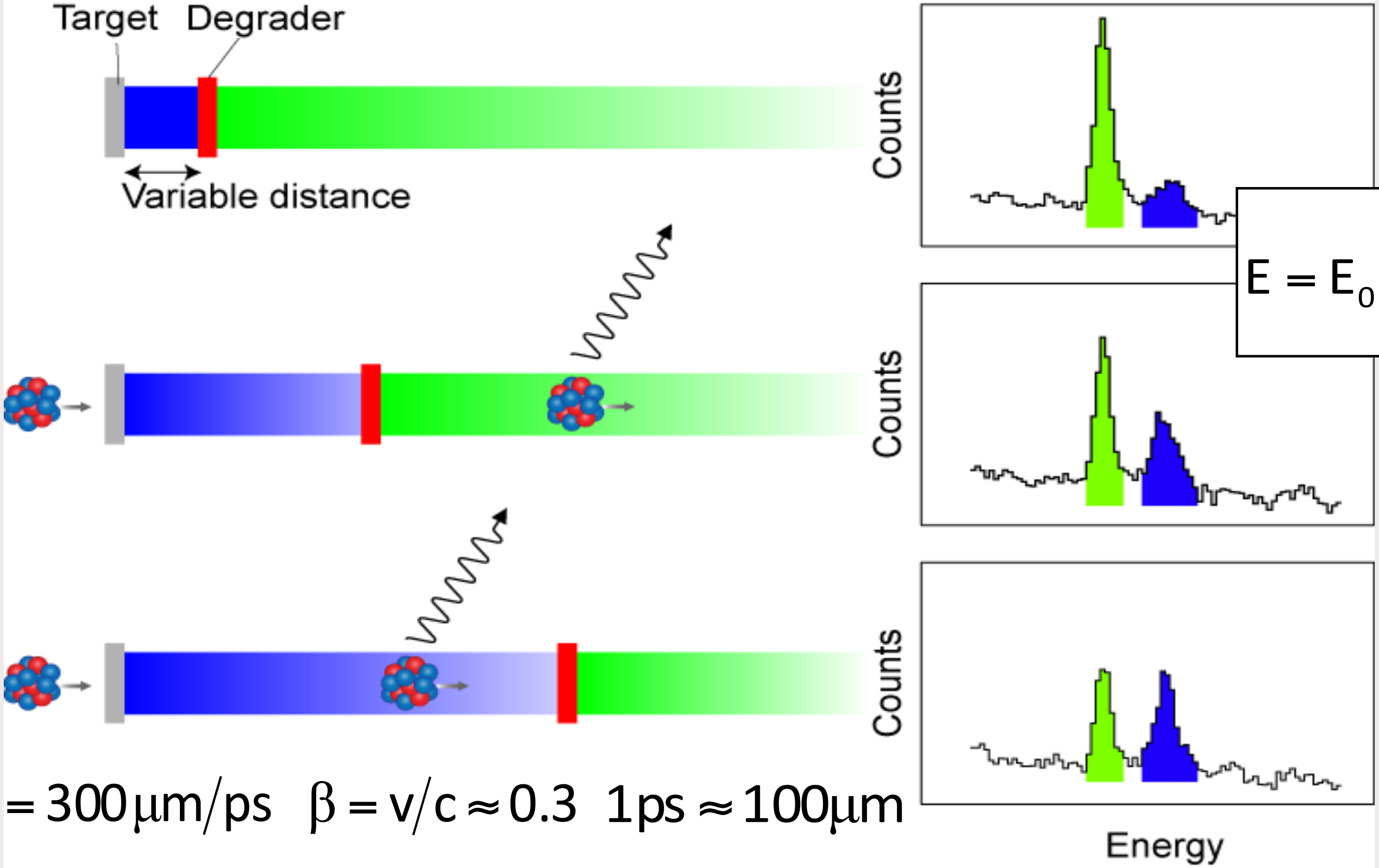


$M_{22} > 0$

$M_{22} < 0$



The Recoil Distance Method



$$E = E_0 \frac{\sqrt{1-\beta^2}}{1-\beta\cos\theta}$$

$$c = 300\mu m/ps \quad \beta = v/c \approx 0.3 \quad 1ps \approx 100\mu m$$

Doppler Shift methods for lifetime measurement

- Plunger method suitable down to picoseconds
- Could use thick degrader -> stopper
- A thick backing on a thin target – or a thick excitation target – would give a continuum of Doppler shifts, rather than two distinct peaks
- This can be modeled and lifetimes measured from lineshape

Traditional DSAM results

McCutchan, Lister et al., arXiv:0907.3688v1

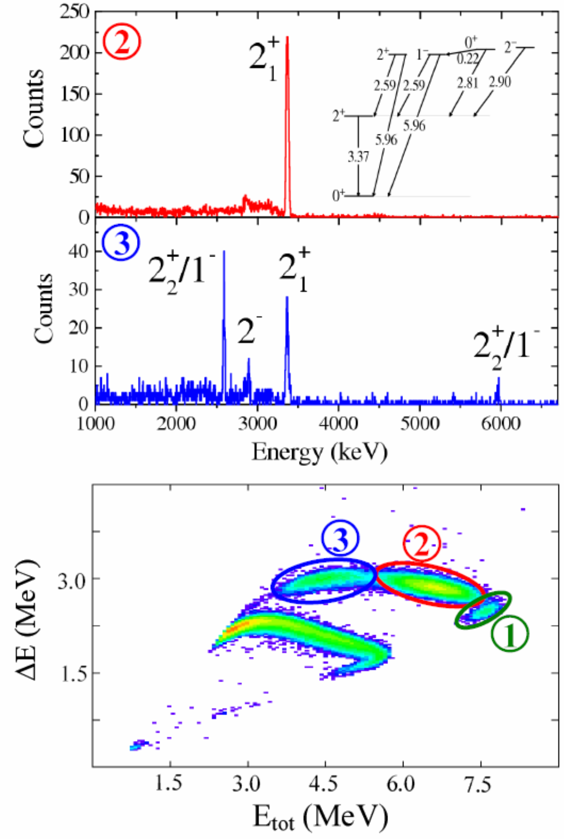
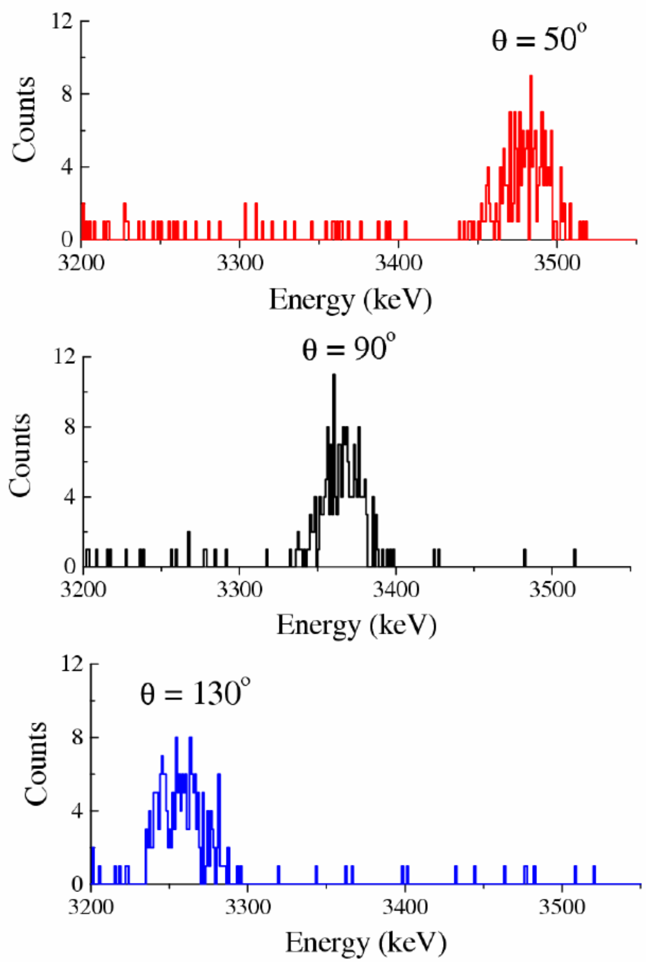
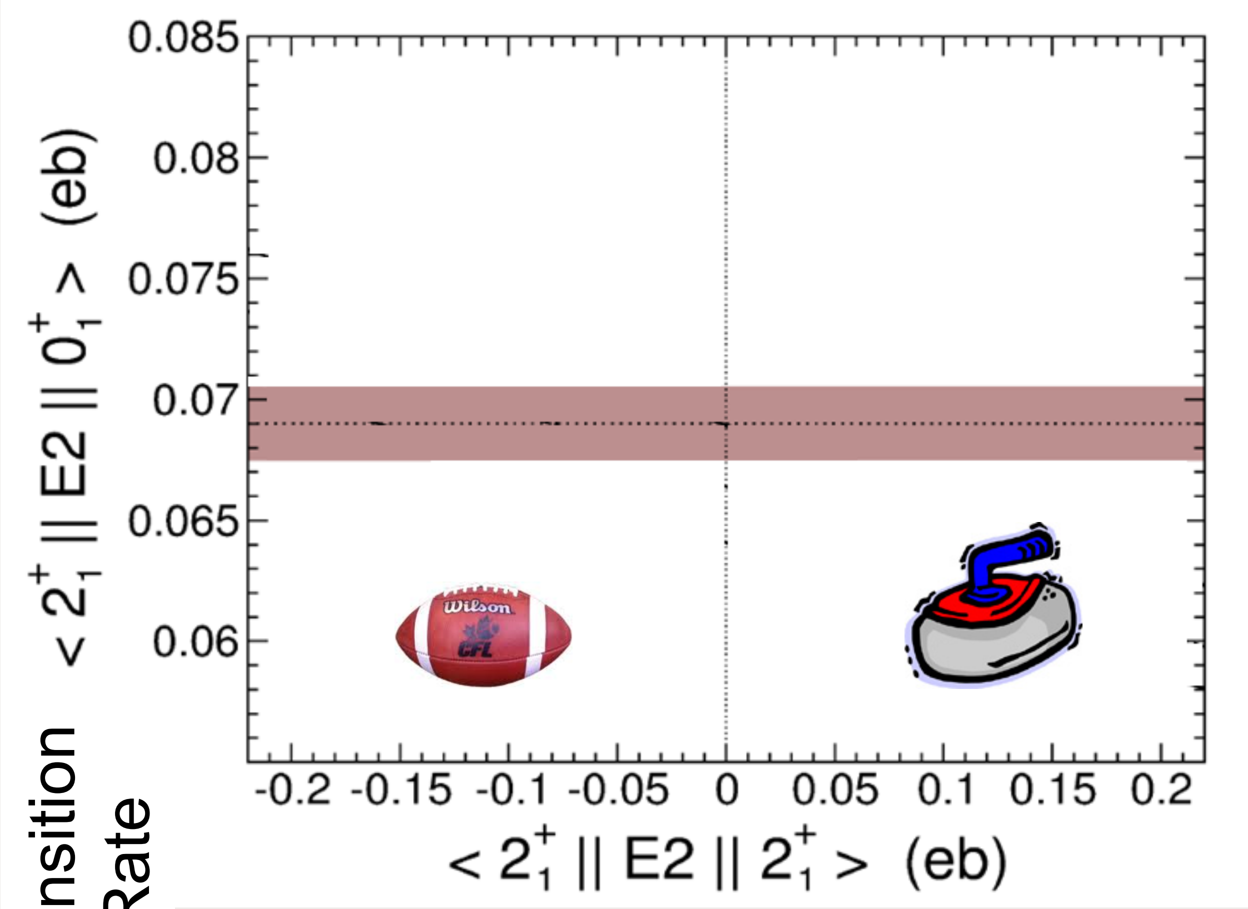


FIG. 1: (Color online) (Top and middle) Spectra gated on ^{10}Be recoil groups with the γ-ray transitions labeled by the decaying state. (Bottom) Energy loss versus total energy from the ion chamber behind the focal plane of the FMA. The circled regions correspond to direct population of distinct ^{10}Be levels. The inset of the top panel shows a level scheme for the five bound excited states in ^{10}Be with γ-ray energies in MeV.

- ^{10}Be Doppler shift attenuation method measurement
- $T_{1/2}(2^+_1)=142\pm 3(\text{stat.})\pm 7(\text{syst.})$fs
- Measured LIFETIME (<0||E2||2>)



The results



Transition Rate

Shape

- Brown band: transitional matrix element, 3 previous lifetime measurements
- Most recent and most important: E. A. McCutchan et al., Phys. Rev. Lett. 103, 192501 (2009).
- Lifetime alone doesn't indicate sign of M_{22}

Measuring Quadrupole Moments –Reorientation Effect

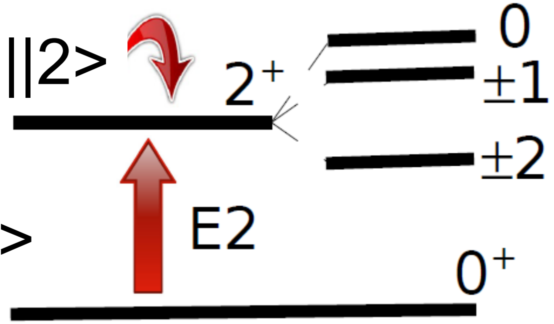
(2nd order effect in Coulomb excitation)

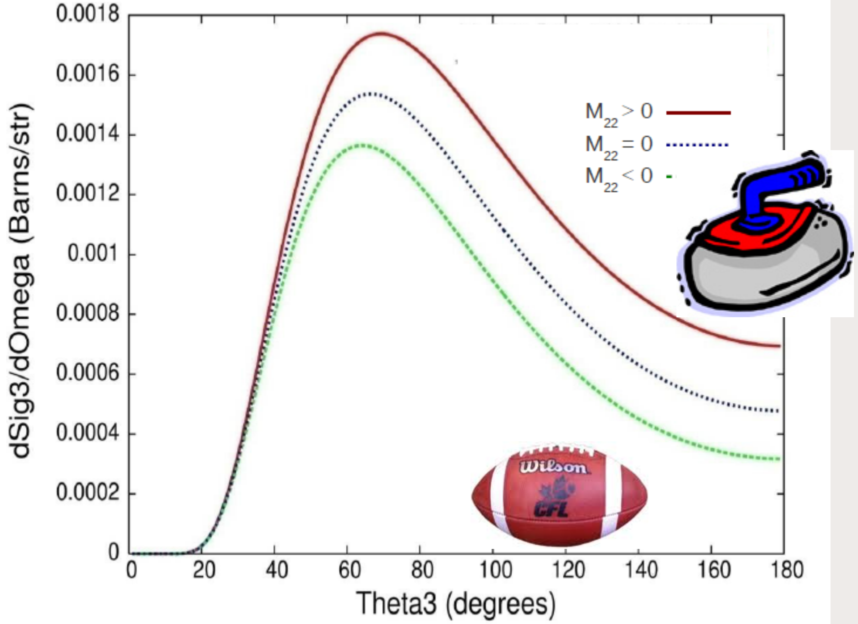
$$\boxed{\sigma_{E2} = \sigma_R[k_1(\theta_{CM},\xi)B(E2)\,(\,1 + k_2(\theta_{CM},\xi)\;Q_S(2_1^+)\,)]}$$

Both projectile and target experience strong time-dependent field gradients

M_{22}=<2||E2||2>

<2||E2||0>



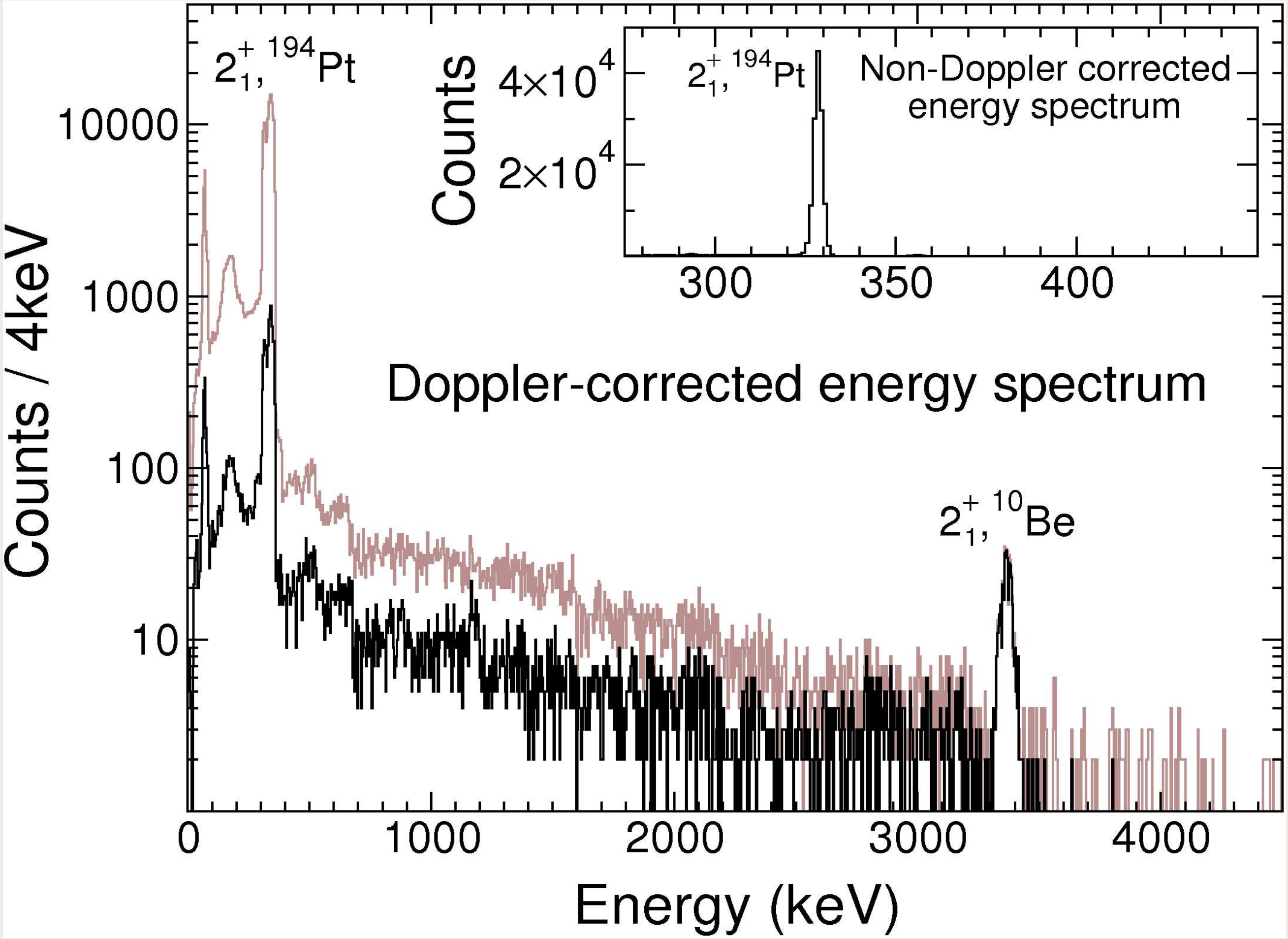


Q_S = (const) x M_{22}

Integrated cross section depends on both B(E2) and M_{22}

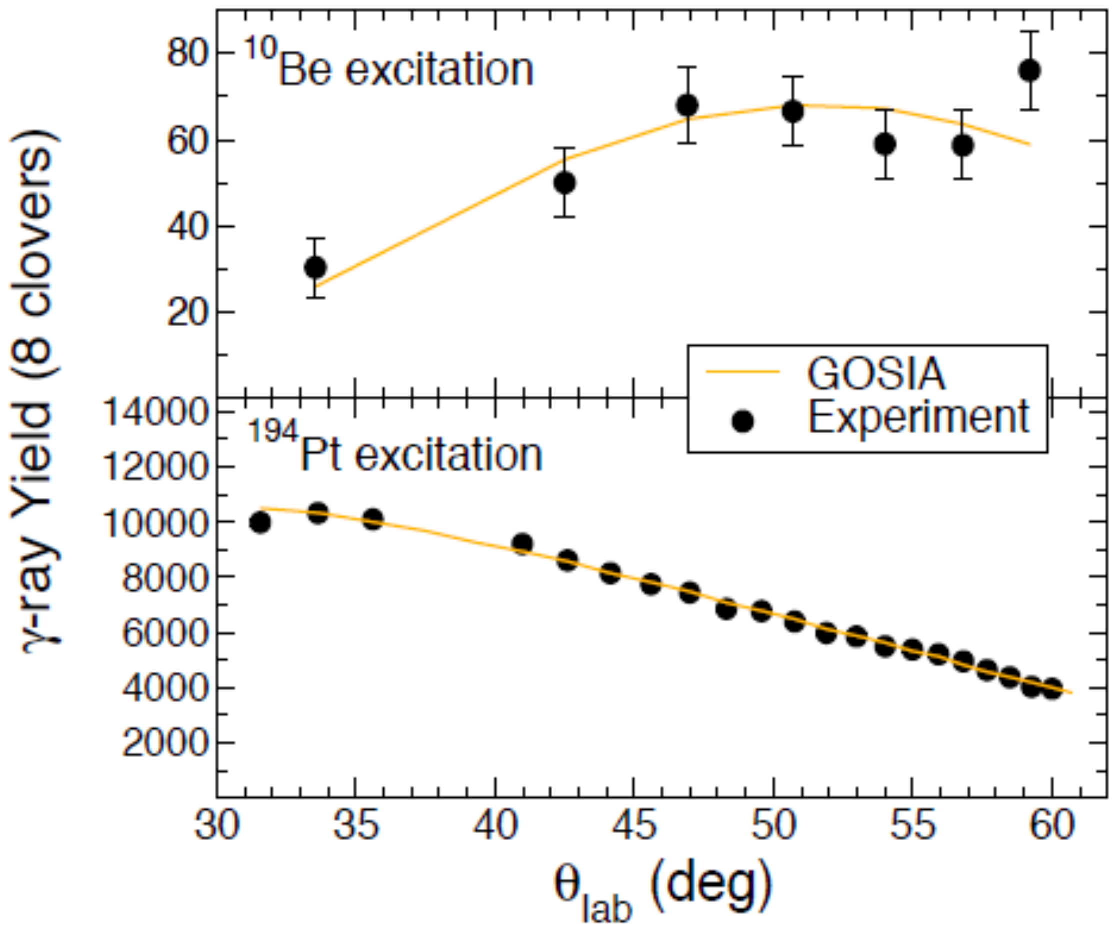
^{194}Pt(^{10}Be,^{10}Be*)^{194}Pt , 41 MeV

- laser ionized ^{11}Be accelerated to 41MeV
- beam intensity ~ 10^7/s ^{10}Be^{2+}
- experiment ran for ~ 100 hr
- 3 mg/cm^2 ^{194}Pt target
- 8 TIGRESS clover detectors
- Same setup as 11Be measurement from before



Doppler-corrected energy spectra with (black) and without(brown) a ^{10}Be inelastic particle-coincidence condition

Yields as a function of scattering angle θ_{lab}

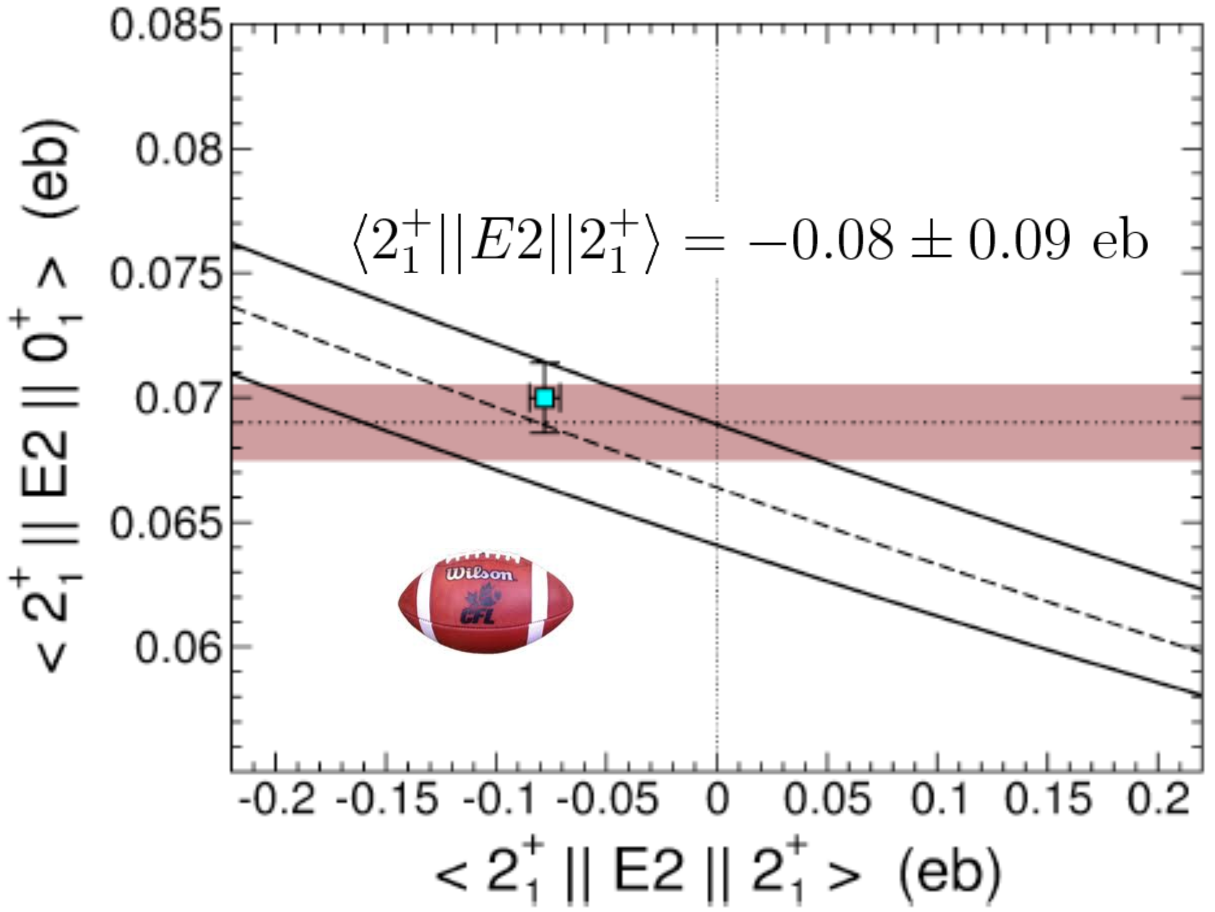


- Angular distribution shape matches GOSIA (EM-only) predictions
- From this we infer (claim?) no nuclear interference
- Use known B(E2) in ^{194}Pt as "standard candle"
- Differential & integrated cross-sections for 10Be normalized against GOSIA calculations for ^{194}Pt

$$\frac{\sigma_{E2}^{T}\, W(\theta)^{T}}{\sigma_{E2}^{P}\, W(\theta)^{P}} = \frac{N_{\gamma}^{T}}{N_{\gamma}^{P}} \frac{\varepsilon_{\gamma}^{P}}{\varepsilon_{\gamma}^{T}} = \frac{I_{\gamma}^{T}}{I_{\gamma}^{P}}$$

The results

$$P_{0_1^+\to 2_1^+} \propto B(E2;0_1^+ \to 2_2^+)[1+\alpha Q(2_1^+)]$$



- Brown band: transitional matrix element
- Diagonal band: 1 σ limits of the ratio of the integrated experimental yields from 30-60 degrees
- **Data point: NCSM with the CD Bonn 2000 two body potential**
- The first excited 2+ state of ^{10}Be is prolate.

Takeaway message

- Precision gamma-ray measurements using Coulex techniques can be used to measure transition matrix elements to 2% or better, determine sign of diagonal matrix elements

Spins, Parities and States in ^{32}Na

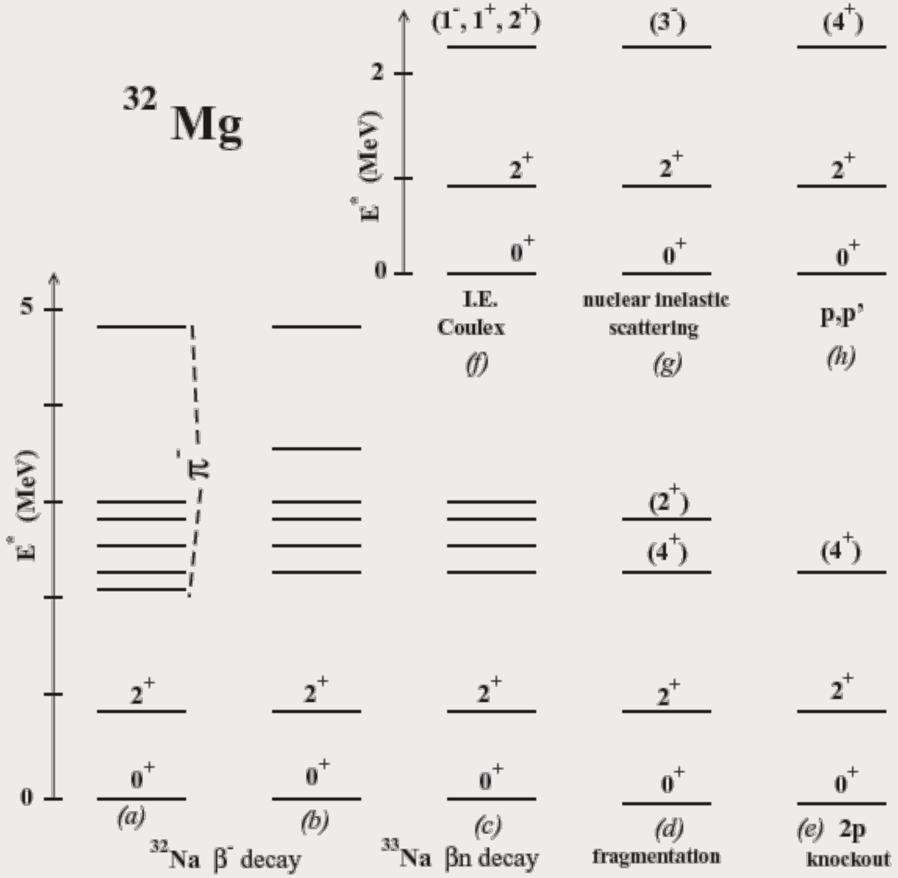
Motivation

- The “Island of inversion” – (fp) orbitals intruding in (sd) shell due to the weakening of the N=20 shell closure → Deformation.

- ^{32}Mg, the archetypical “Island of Inversion” nucleus
    - First indicator – low E(2^+) at 885keV [D.Guillemaud-Mueller et al., NPA 426 (1984) 37]
    - large B(E2) in ^{32}Mg, remeasured many times since [T.Motobayashi et al., PLB 346 (1995) 9]
    - (fp) intruders – one-neutron knockout reaction populating (fp) orbitals in ^{31}Mg [J.R.Terry et al., PRC 77 (2008) 014316]
    - 0^+_2 (likely isomeric) state at 1058(2)keV observed in ^{30}Mg(t,p) [K.Wimmer et al., PRL 105 (2010) 252501]
    - Additional levels (negative parity states) through β-decay of ^{32}Na [G.Klotz et al., PRC 47 (1993) 2502, C.M.Mattoon et al., PRC 75 (2007) 017302, V.Tripathi et al., PRC 77 (2008) 034310]
    - State at 2321keV observed in many experiments with only tentative spin assignment, widely believed to be the 4^+ state [see next slide]

Where is the 4^+ state? Is it the 2321keV state?

Figure from V. Tripathi et al., PRC 77 (2008) 034310



- (a) G.Klotz et al., PRC 47 (1993) 2502
- (b) C.M.Mattoon et al., PRC 75 (2007) 017302
- (c) S.Nummela et al., PRC 64 (2001) 054313
- (d) F.Azaiez et al., Eur. Phys. J. A15 (2002) 93
- (e) D.Bazin et al., PRL 91 (2003) 012501
- (f) B.V.Pritychenko et al., PLB 461 (1999) 322
- (g) W.Mittig et al., Eur. Phys. J A15 (2002) 157
- (h) S.Takeuchi et al., J. Phys. Conf. Ser. 49 (2006) 153

$$E((4^+),2321\text{keV}) / E(2^+,885\text{keV}) = 2.62$$

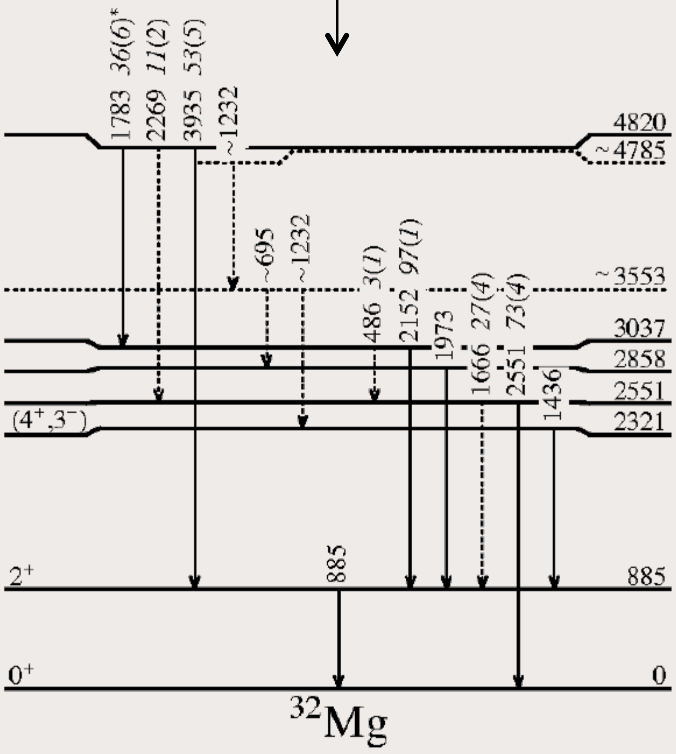
Inconsistency

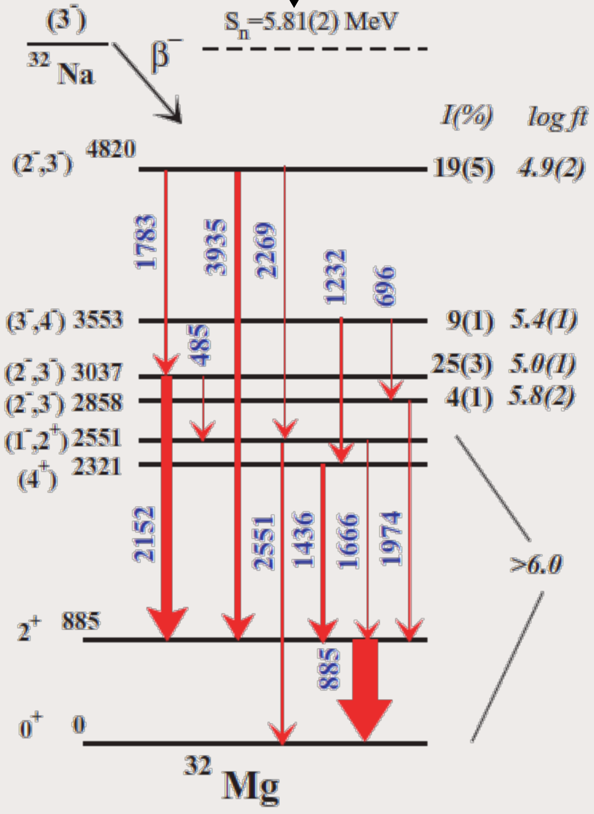
- Beta-decay measurements implied all ^{32}Mg states above 2+ were directly fed, therefore common negative parity
- Coulex and reactions proposed positive parities and range of spins
- At least one of them must be wrong …

- Motivated 8pi experiment to study ^{32}Na decay to ^{32}Mg

Level scheme from recent β-decay studies

C.M.Mattoon et al., PRC 60 (2007) 017302 – TRIUMF / 8pi
V. Tripathi et al., PRC 77 (2008) 034310 – NSCL / SEGA





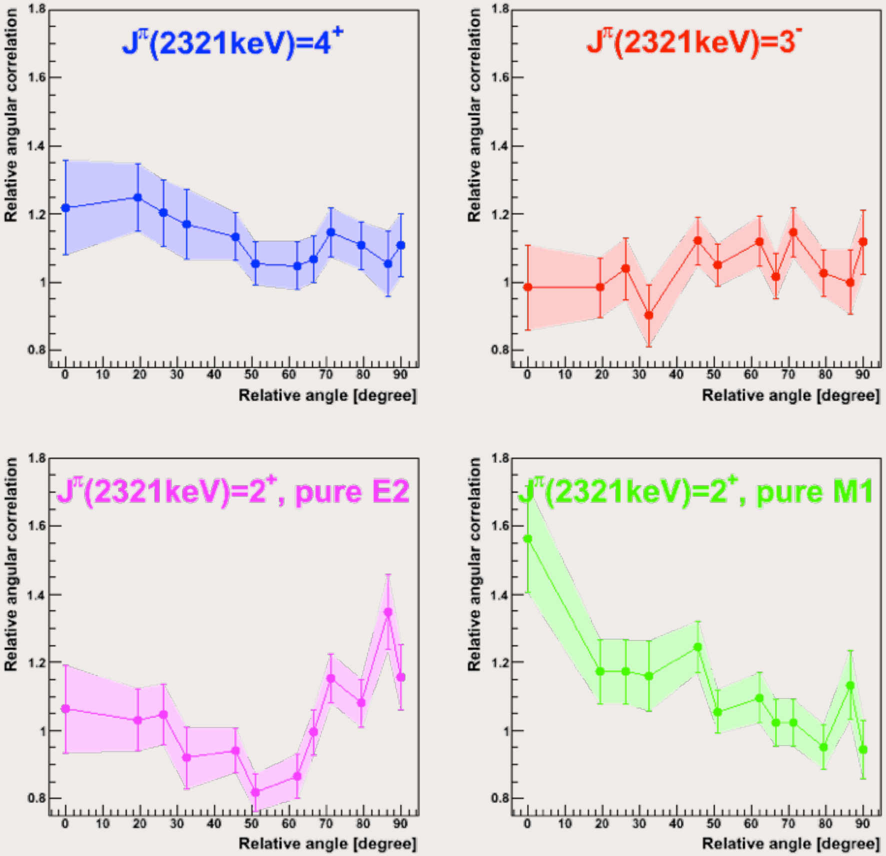
Tentative spin assignment based on MCSM calculations

Main result:

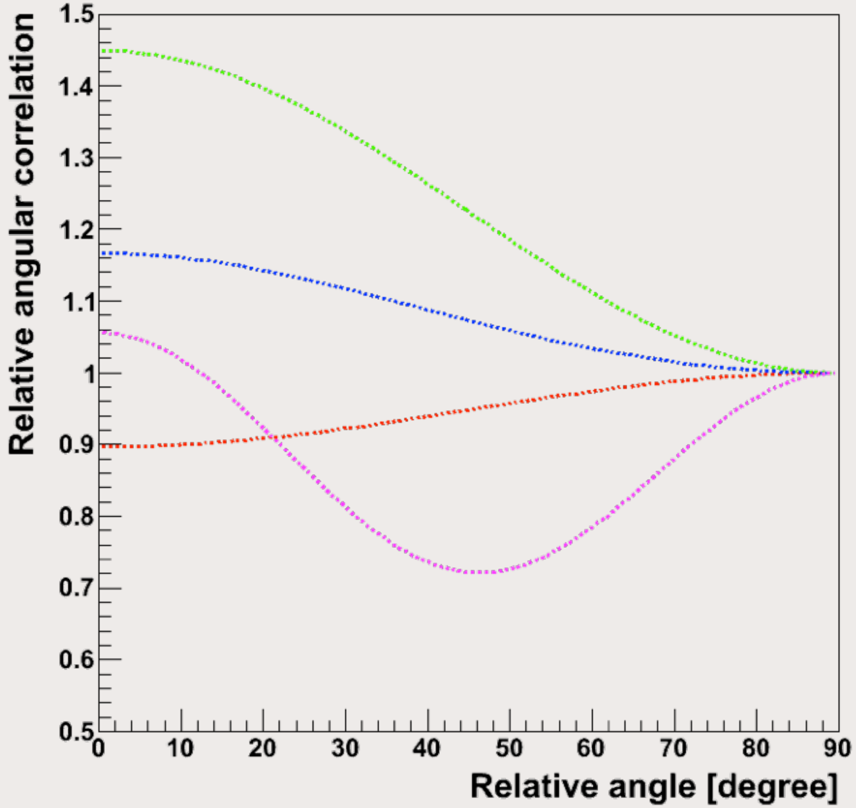
removed parity constraint for possible 4+ candidate states

- Initial beta-decay measurements implied all ^{32}Mg states above 2+ were directly fed, therefore common negative parity
- New gamma branches allow indirect feeding of e.g. 2321 keV state
- Still don’t know spins
  - 8pi, SEGA weren’t sensitive enough
- GRIFFIN will allow us to determine spins from angular distributions

Angular correlation – J^{π}(2321keV) → 2^{+}(885keV) → 0^{+} (gs)



Geant4 simulations by E.Rand, University of Guelph

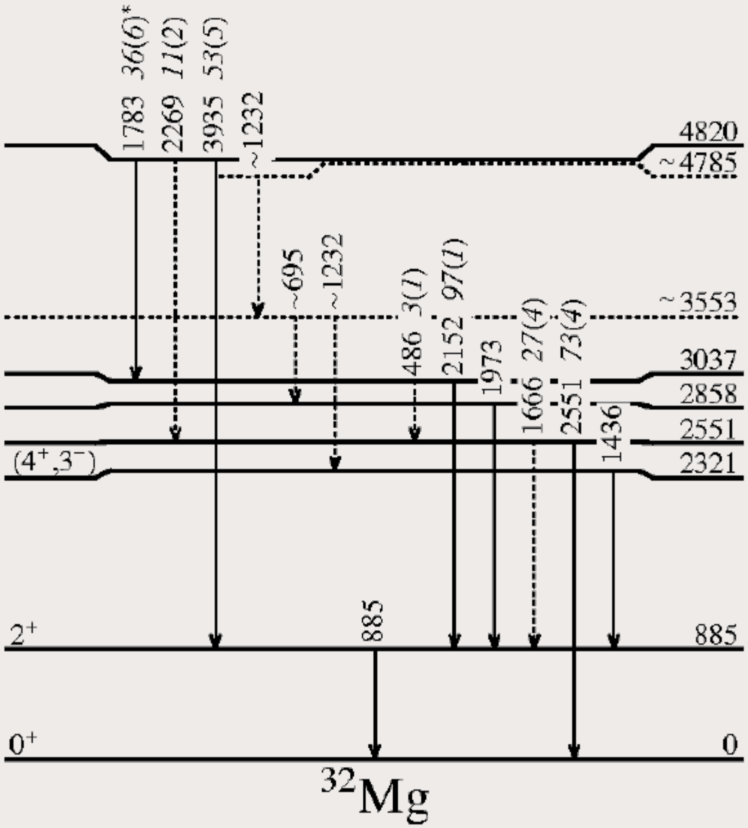


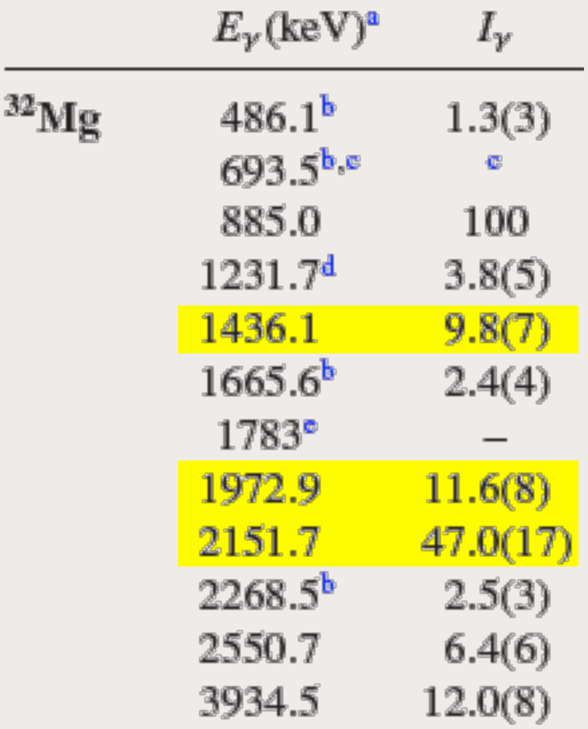
Simulations based on 16 clovers and a realistic number of β-γ-γ coincidences to be collected during the proposed experiment (1.4x10^5 β-γ, ~2% γ-γ efficiency, 10% feeding)

→ A few thousands β-γ-γ coincidences → A few hundreds events per data point (<10% error)

Other candidates for γ–γ angular correlations

C.M.Mattoon et al., PRC 60 (2007) 017302





	E_γ (keV)[a]	I_γ
^{32}Mg	486.1[b]	1.3(3)
	693.5[b,c]	[c]
	885.0	100
	1231.7[d]	3.8(5)
	1436.1	9.8(7)
	1665.6[b]	2.4(4)
	1783[e]	–
	1972.9	11.6(8)
	2151.7	47.0(17)
	2268.5[b]	2.5(3)
	2550.7	6.4(6)
	3934.5	12.0(8)

No direct feeding to gs, 2⁺ states → Comparison of intensity to 885keV (intensity: 100)

Takeaway message

- Gamma ray measurements add to body of knowledge required to constrain (or remove constraints on) possible spins of observed states

Items I didn’t discuss

- Gamma rays are key to controlling the “Pandemonium Effect” that was expected to confound high-precision branching ratio measurements with increasing mass
- Gamma tagging of excited states in transfer reactions resolves particle angular distributions where charged-particle detection cannot
- Multi-crystal detector arrays like the ones at TRIUMF are also sensitive to gamma ray polarization – hence can give insight into parities as well as spins

Acknowledgements

- Results, slides, discussion taken from Fred Sarazin, Colorado School of Mines; Elaine Kwan, LLNL now NSCL; Ching-Yen Wu, LLNL; Nico Orce, TRIUMF now iThemba; Phil Voss, SFU

Thank you!

Merci!

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NSERC
CRSNG

Western Economic Diversification Canada
Diversification de l'économie de l'Ouest Canada

Natural Resources Canada
Ressources naturelles Canada

BC Cancer Agency
CARE + RESEARCH

D-Pace

CINP
ICPN

Institute of Particle Physics

imagination at work
Canada

nordion

Selkirk College

cpdc
Centre for Probe Development and Commercialization

AAPS
Advanced Applied Physics Solutions

LAWSON
HEALTH RESEARCH INSTITUTE

Positron Emission Tomography Imaging
at
THE UNIVERSITY OF BRITISH COLUMBIA

Pacific Parkinson's Research Institute