Ab initio calculations of beta decay recoil-order form factors for precision measurements

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Seattle, WA

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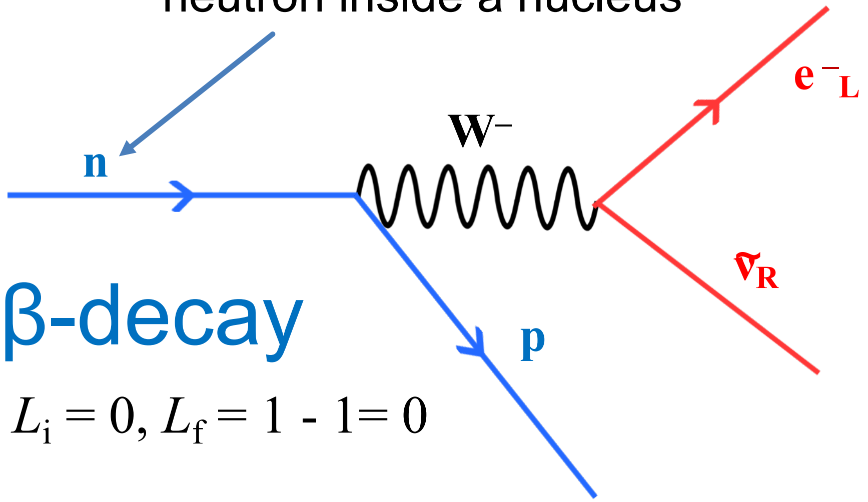
Beta decay as a probe for BSM studies

A free neutron or a neutron inside a nucleus

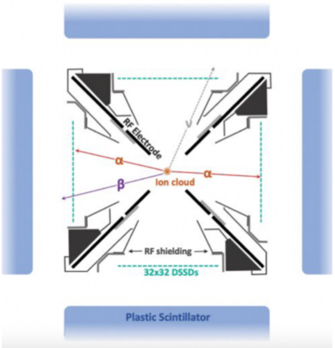


β-decay

$L_i = 0, L_f = 1 - 1 = 0$

Precision measurements need input from nuclear theory

- Beyond Standard Model (BSM) terms in weak interaction

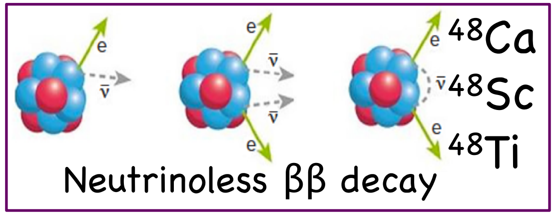


- Unitarity of the CKM quark mixing matrix

$$\begin{pmatrix} d_w \\ s_w \\ b_w \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

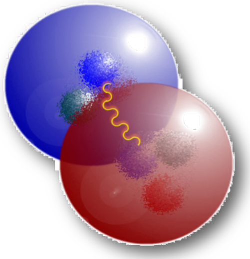
Weak states — **CKM mixing matrix** — Mass eigenstates

- Neutrinoless double beta decay



From first principles to nuclear properties

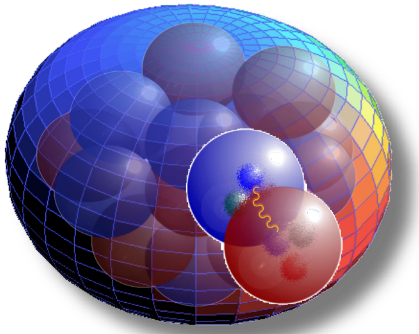
First Principles



Realistic
Interactions

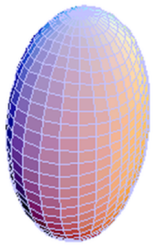
E.g., from chiral effective field theory

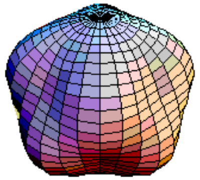
Many-body Dynamics



E.g., Symmetry-Adapted No-Core Shell Model (SA-NCSM)

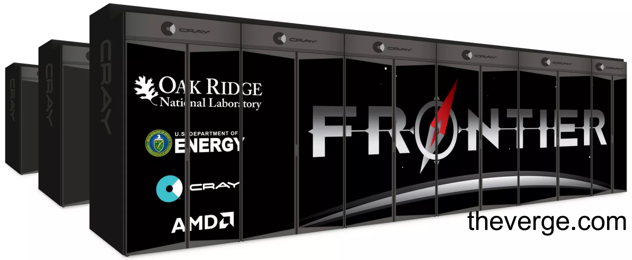
Properties of Nuclei





E.g., deformation, excitation spectrum, clustering, etc.

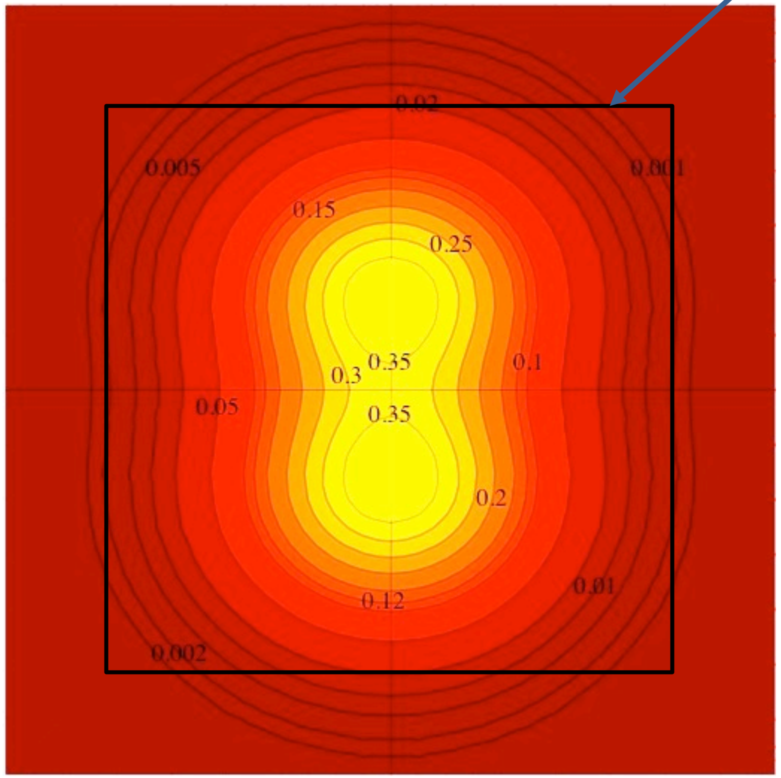
Explosive growth of the model space



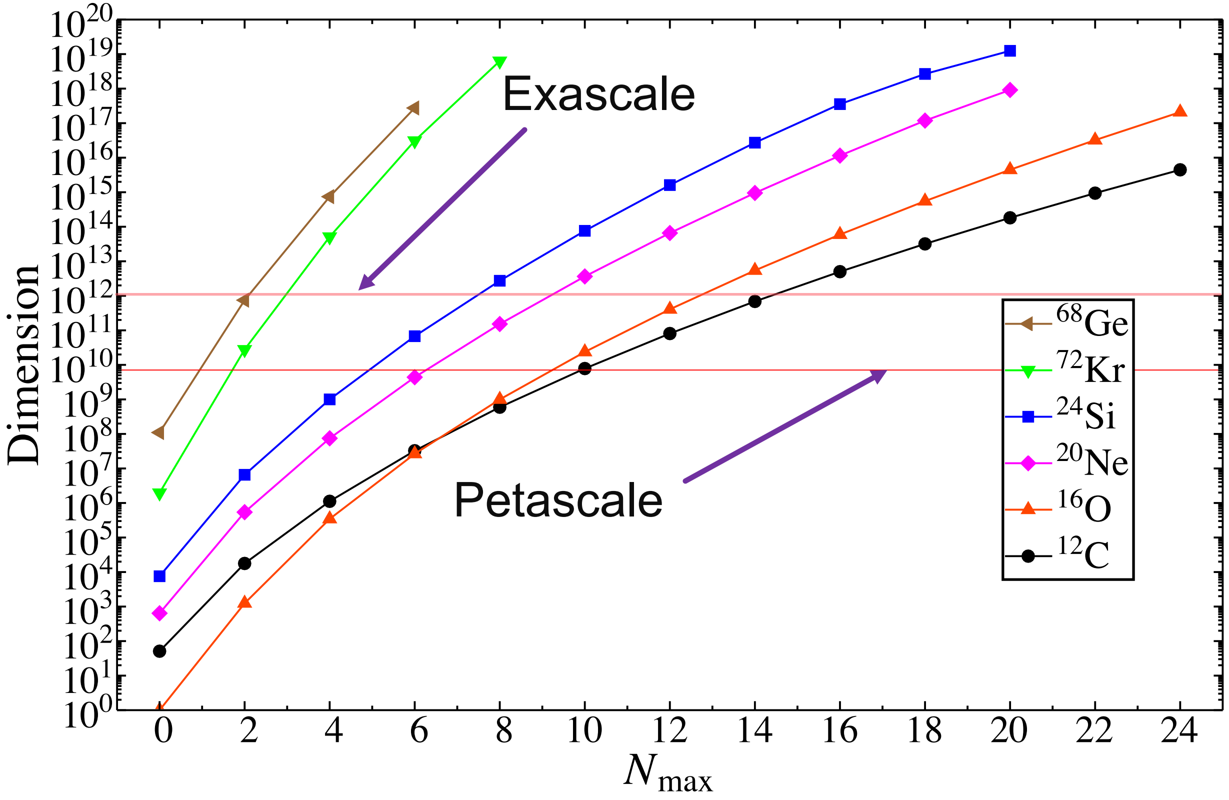
First exascale computer

Conventional Shell Model

N_{max}



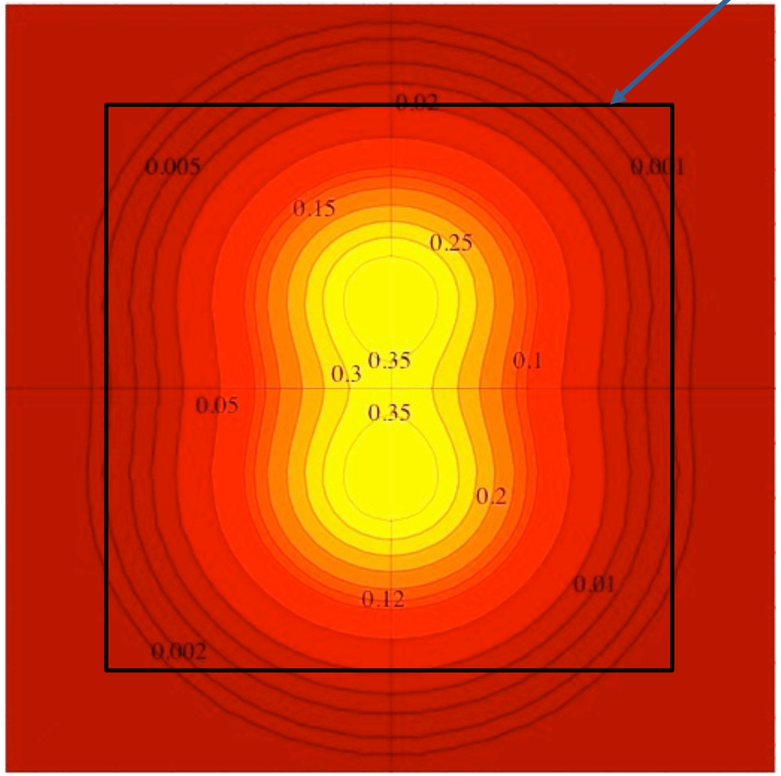
Nucleus in model space



Symmetry-adapted basis helps dramatically reduce the models space size

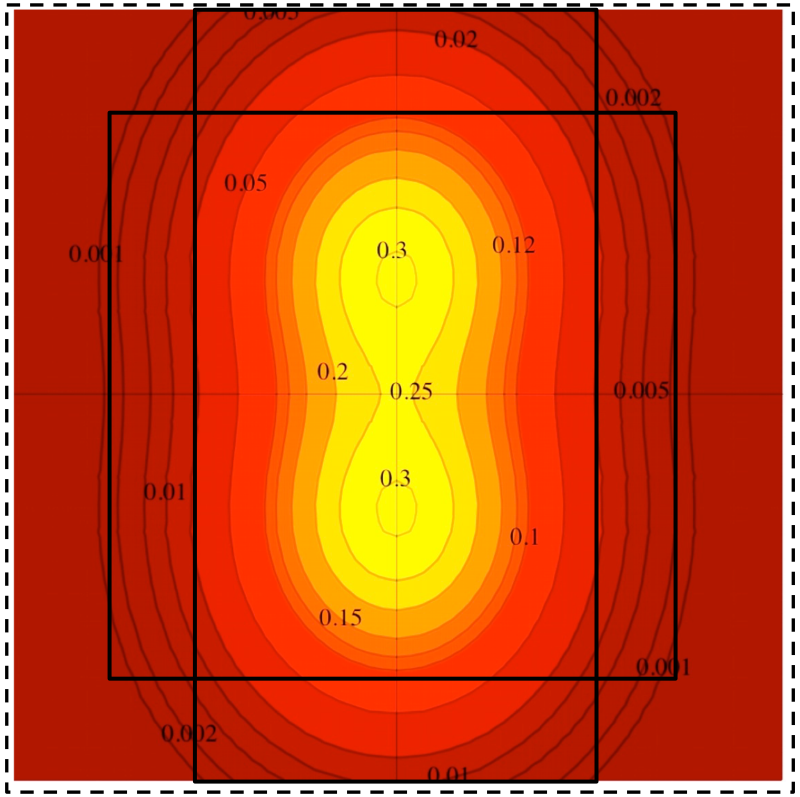
Conventional Shell Model

N_{max}



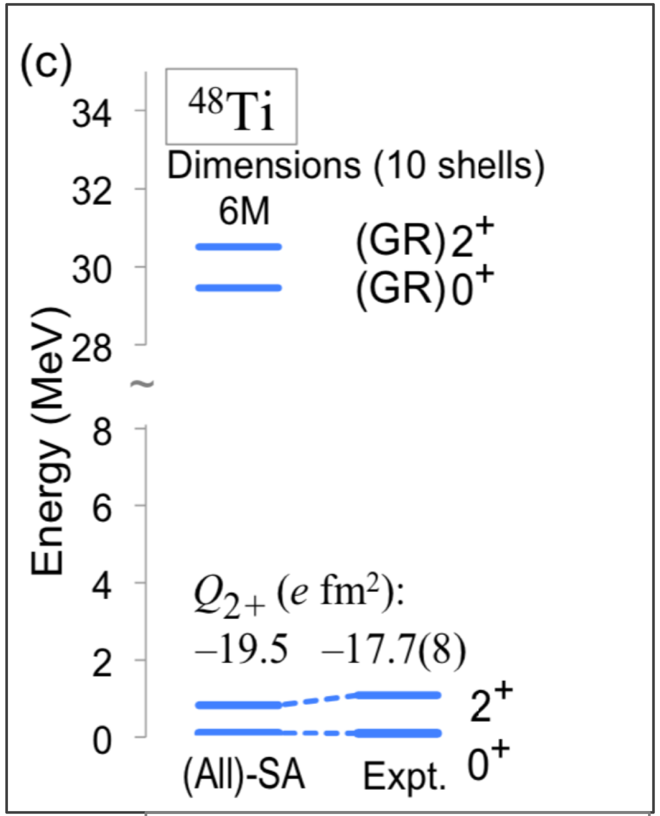
Nucleus in model space

Ab initio Symmetry-adapted No-core Shell Model (SA-NCSM)



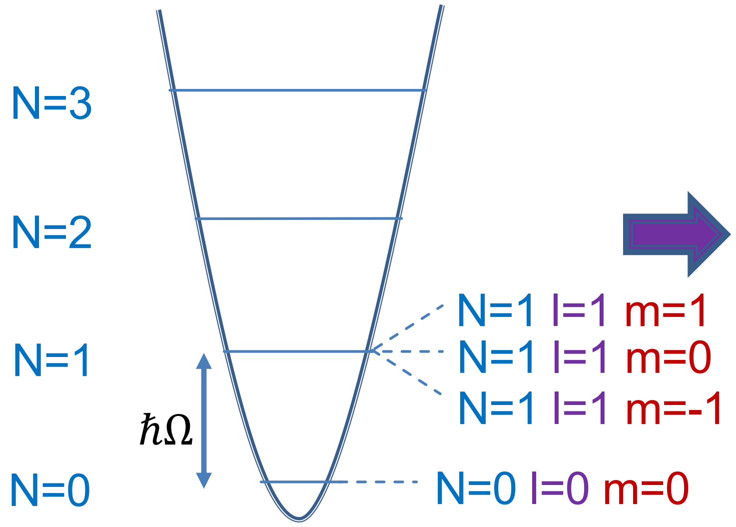
SU(3) and symplectic symmetry

Reaching medium-mass nuclei

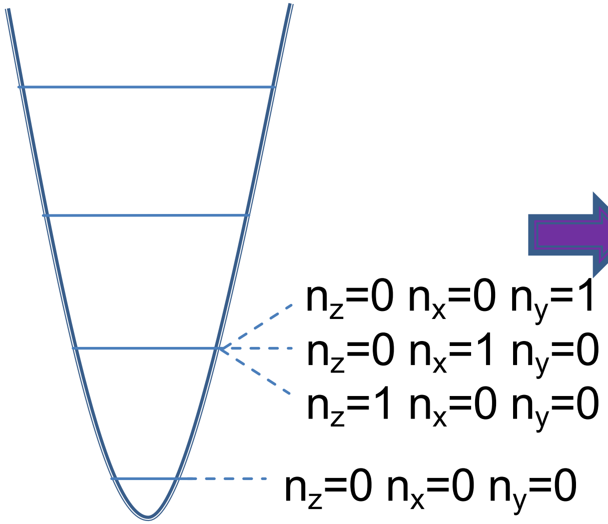


NNLO$_{opt}$ $\hbar\Omega = 15$ MeV

Symmetry-adapted Basis: SU(3)-coupled



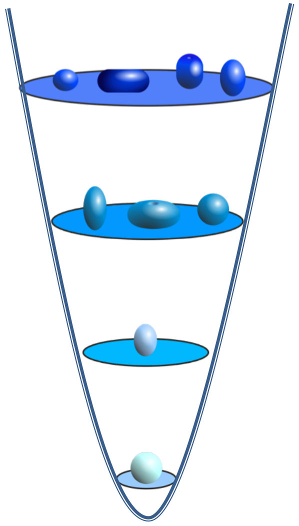
Spherical harmonic oscillator (HO): basis states given by {N l m}



$N = n_z + n_x + n_y$

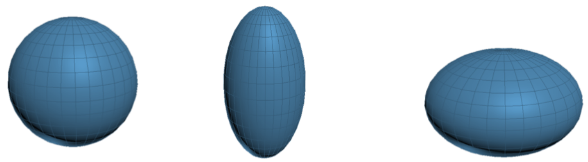
Basis states given by $\{n_x\ n_y\ n_z\}$

$$a^+_{Nlm} \equiv a^+_{(N\ 0)lm}$$



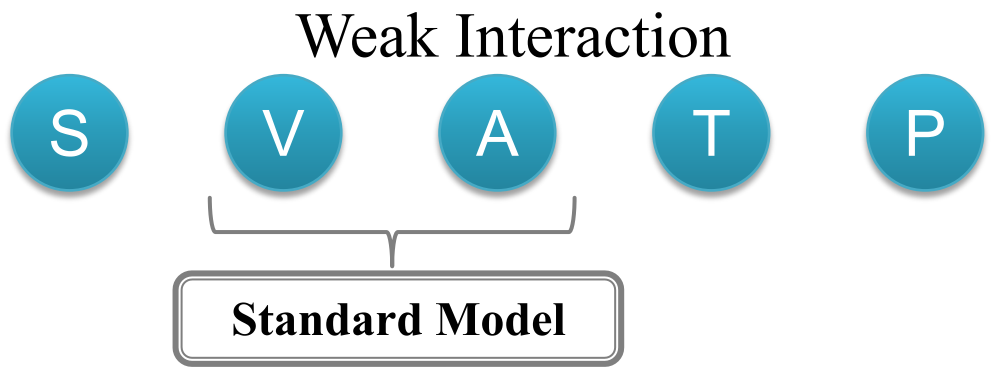
$\lambda = n_z - n_x$, $\mu = n_x - n_y$ (single particle)

Basis states given by $(\lambda\ \mu)$ quantum numbers



Sphere (0 0) Prolate (λ 0) Oblate (0 μ)

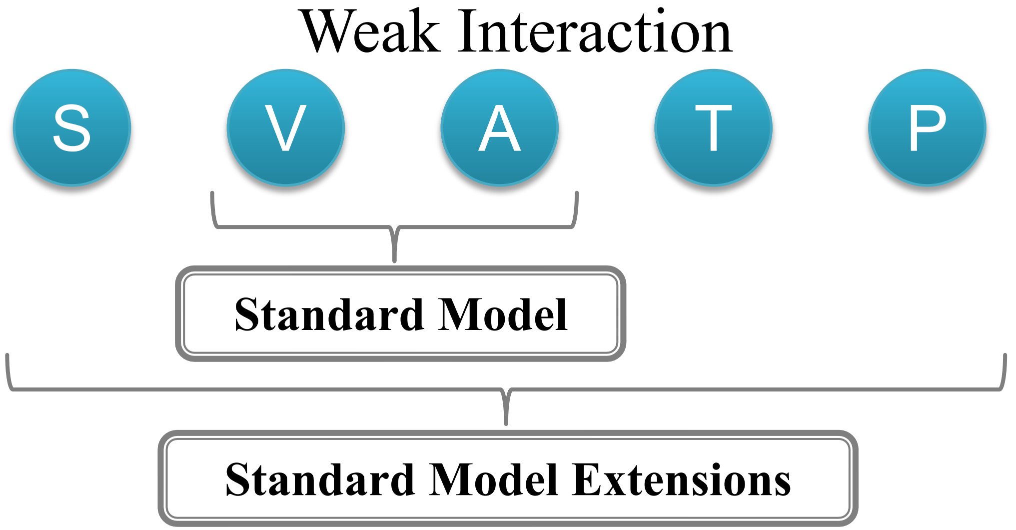
Weak interaction in Standard Model



A series of β-decay experiments lead to the formulation of the V – A structure of the weak interaction:

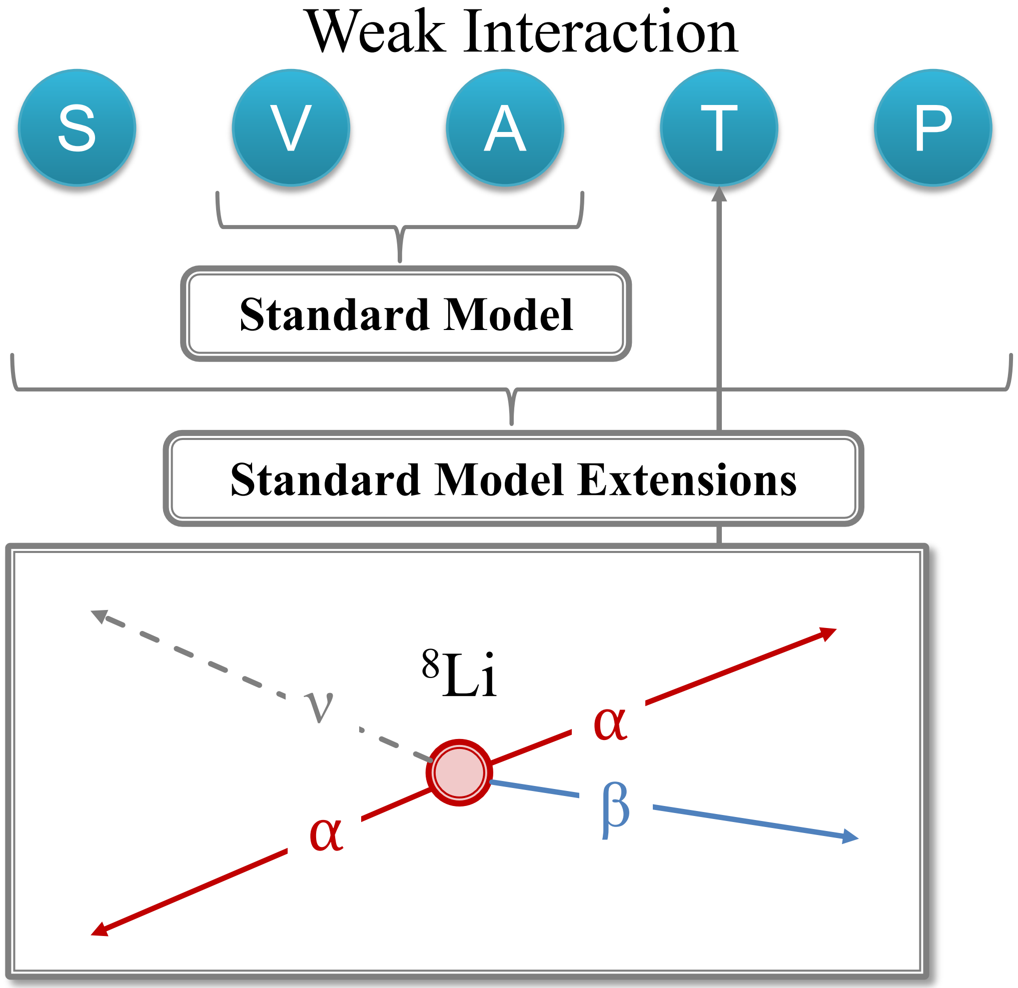
C. S. Wu, *et al*., Phys. Rev. 105, 1413 (1957).
W. B. Herrmannsfeldt, *et al*., Phys. Rev. 107, 641 (1957).
C. Johnson, *et al*., Phys. Rev. 132, 1149 (1963).

Weak interaction in Standard Model



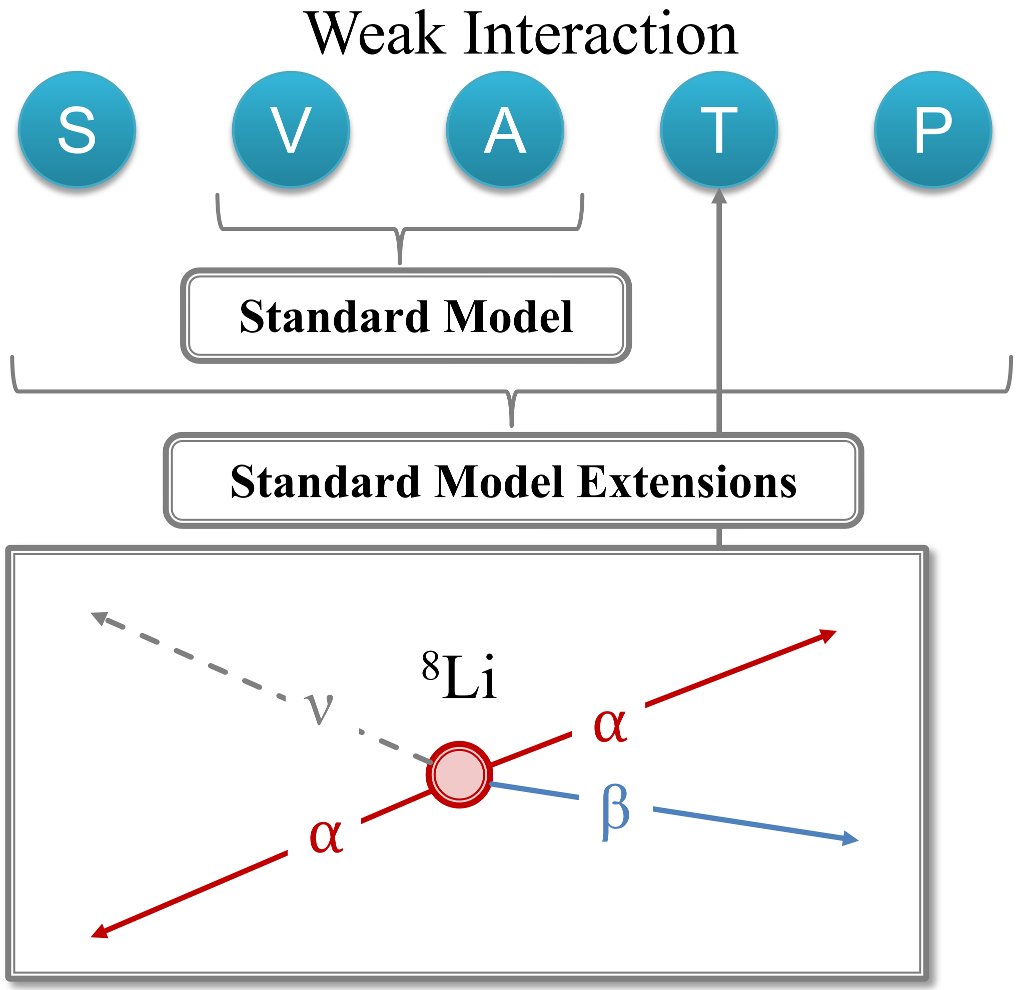
← All Lorentz-invariant currents

Precision measurements of ^{8}Li beta decay to probe BSM physics



M. G. Sternberg, R. Segel, N. D. Scielzo, *et al.*, PRL **115**, 182501 (2015).
MT Burkey, G Savard, AT Gallant, *et al.*, PRL 128 (20), 202502 (2022).

Precision measurements of ^{8}Li beta decay to probe BSM physics



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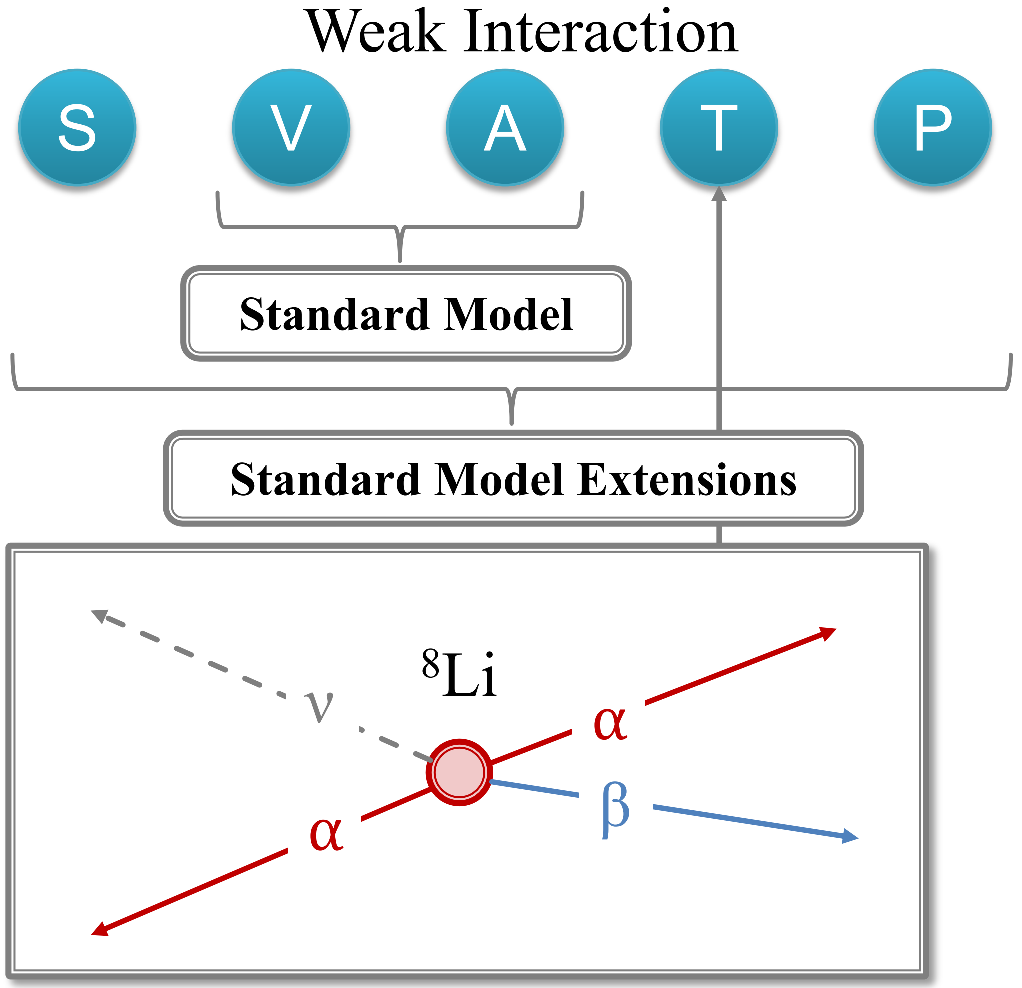
Systematic Uncertainty	$\Delta\lvert C_T/C_A\rvert^2$
Calibration	1.4×10^{-4}
α energy corrections	1.17×10^{-3}
Cuts to the data	1.25×10^{-3}
Radiative and recoil order terms	3.36×10^{-3}
α Si detector lineshape	6.3×10^{-4}
β Scattering	5.0×10^{-4}
Total	$\mathbf{3.62 \times 10^{-3}}$

From Mary Burkey's PhD Thesis (U. Chicago/ANL/LLNL, 2019)

Precision measurements of ^{8}Li beta decay to probe BSM physics



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$$\langle A \rangle = \underbrace{a\times 1}_{\text{Leading order (Gamow-Teller)}} + \underbrace{b\times\frac{q}{M} + c\times\frac{q^2}{M^2} + \ldots}_{\text{Recoil-order}}$$

Leading order (Gamow-Teller)

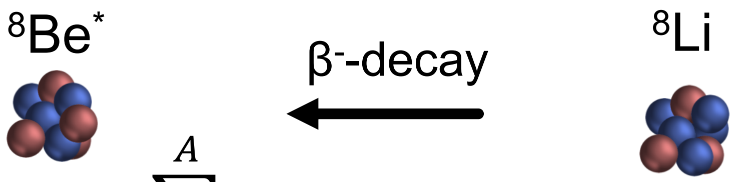
Recoil-order

For ^{8}Li beta decay $q/M \sim 0.002$

M. G. Sternberg, R. Segel, N. D. Scielzo, *et al.*, PRL **115**, 182501 (2015).
MT Burkey, G Savard, AT Gallant, *et al.*, PRL 128 (20), 202502 (2022).

Experiment needs reliable β-decay recoil-order terms

Matrix elements in impulse approximation



$$j_K \propto < \Psi_f || \sum_{i}^{A} \tau_i^{\pm}[\sigma_i \times \hat{Q}_2(\hat{r}_i)]^K \; ||\Psi_0 >$$

Nuclear recoil form-factor

$$c_0 \propto < \Psi_f || \sum_{i}^{A} \tau_i^{\pm}\sigma_i \; ||\Psi_0 >$$

Gamow-Teller matrix element

B. R. Holstein, Rev. Mod. Phys. 46, 789 (1974)

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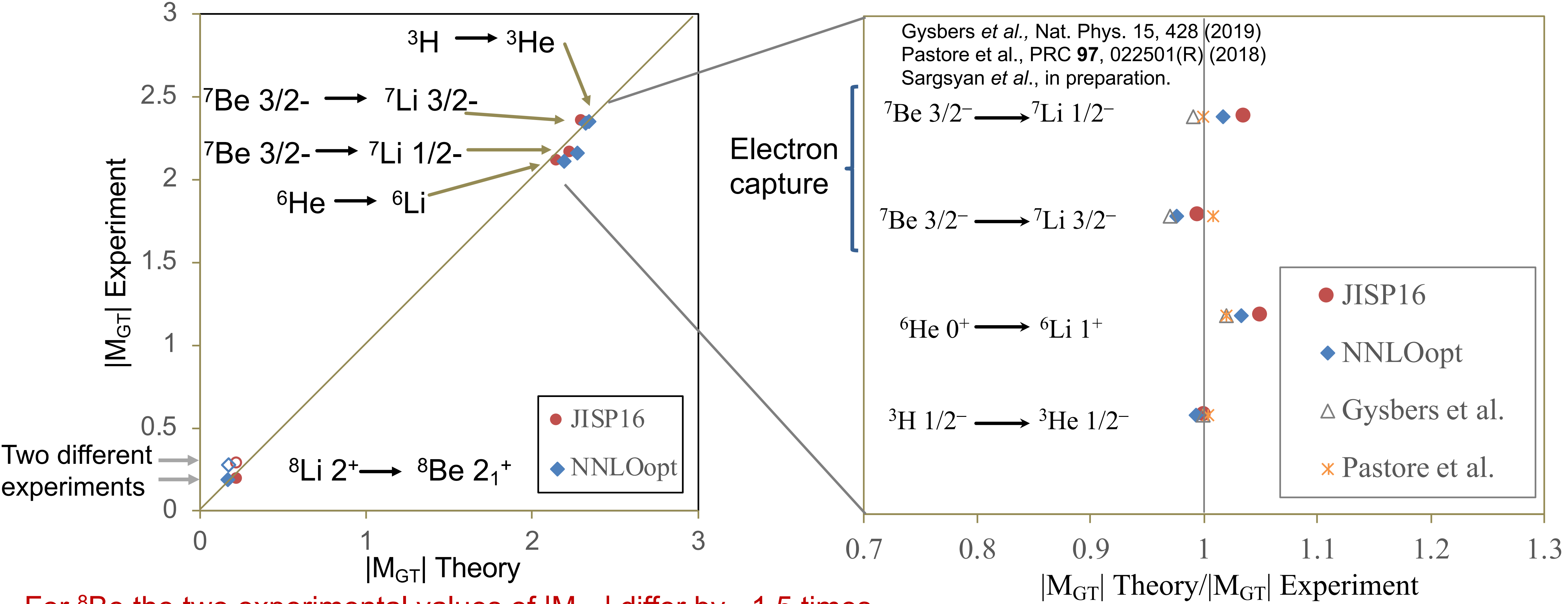
Need more accurate and precise $j_{2,3}/A^2c_0$ and other recoil-order terms

Use ab initio methods to calculate them

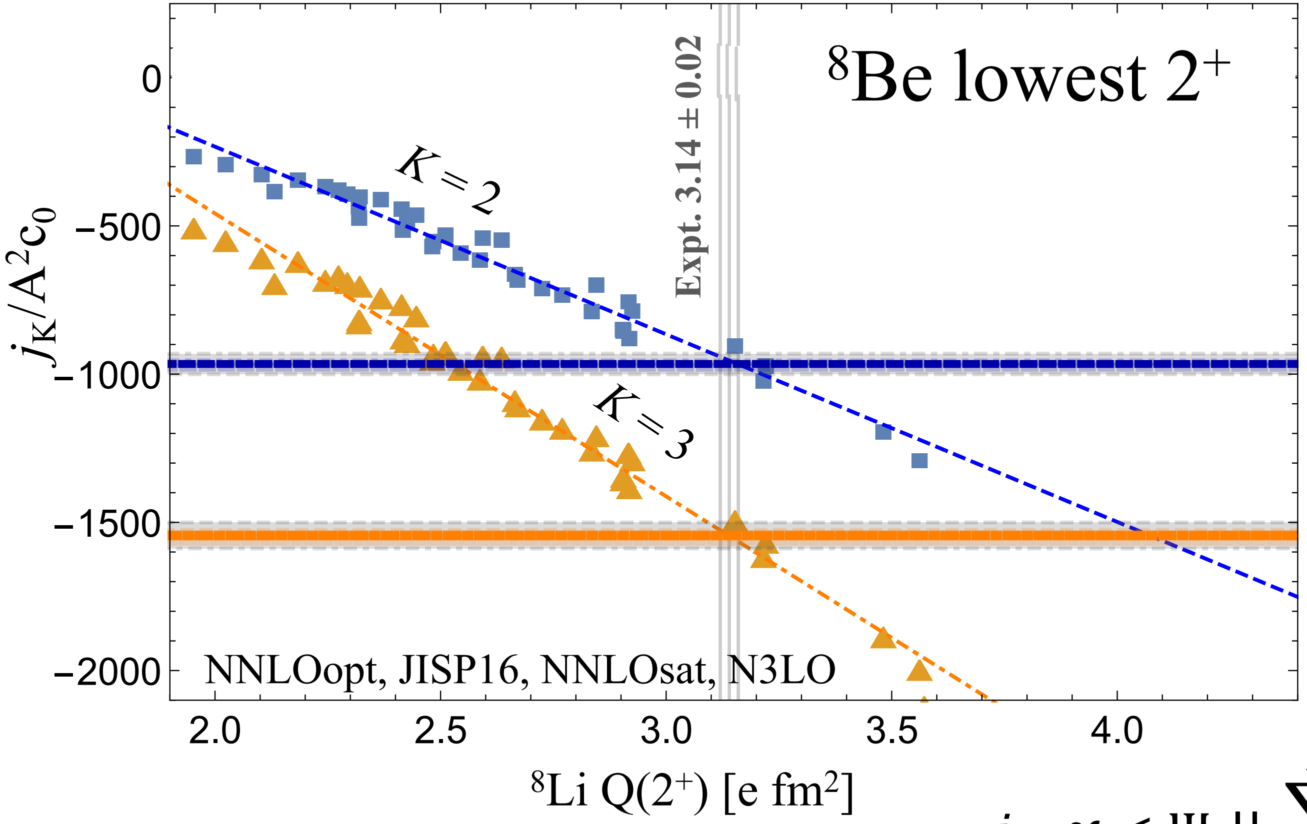
Beta decays with SA-NCSM

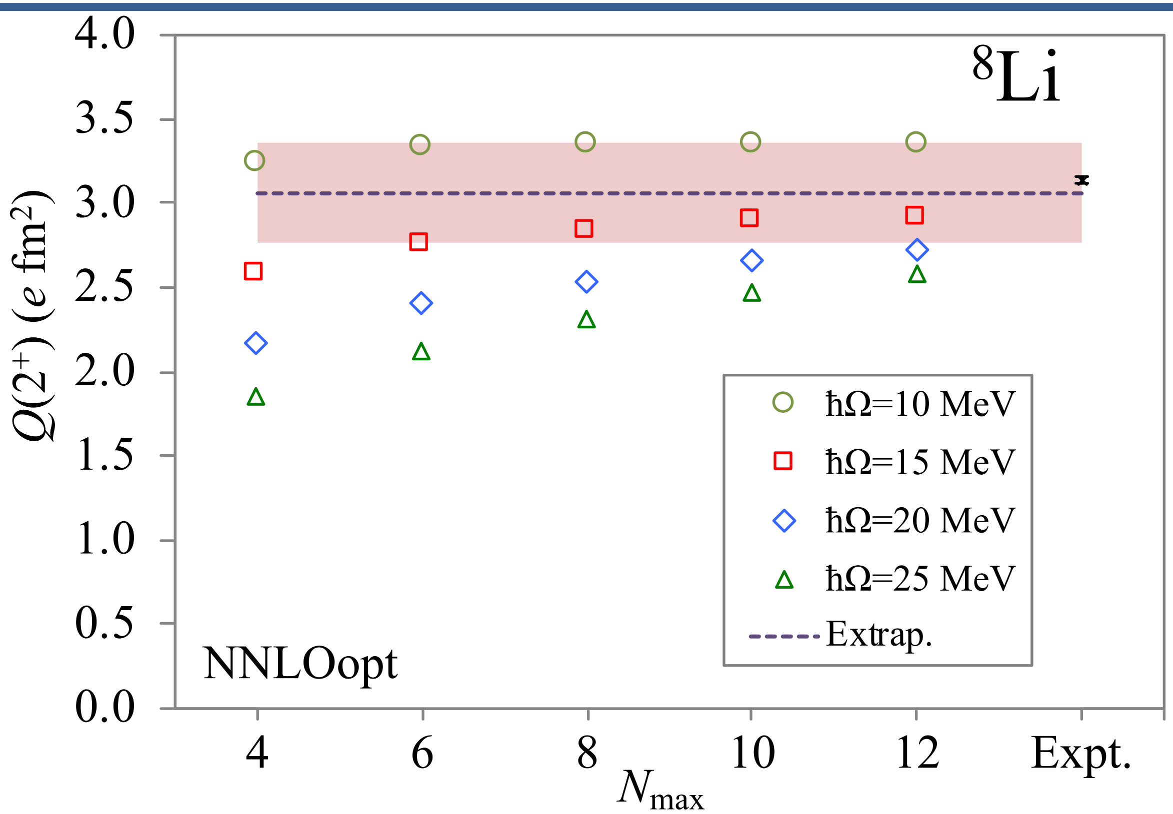


For ^{8}Be the two experimental values of $|M_{GT}|$ differ by ~1.5 times

Non-renormalized interactions, unquenched g_A

Correlation between j_K and Q helps constrain recoil order terms



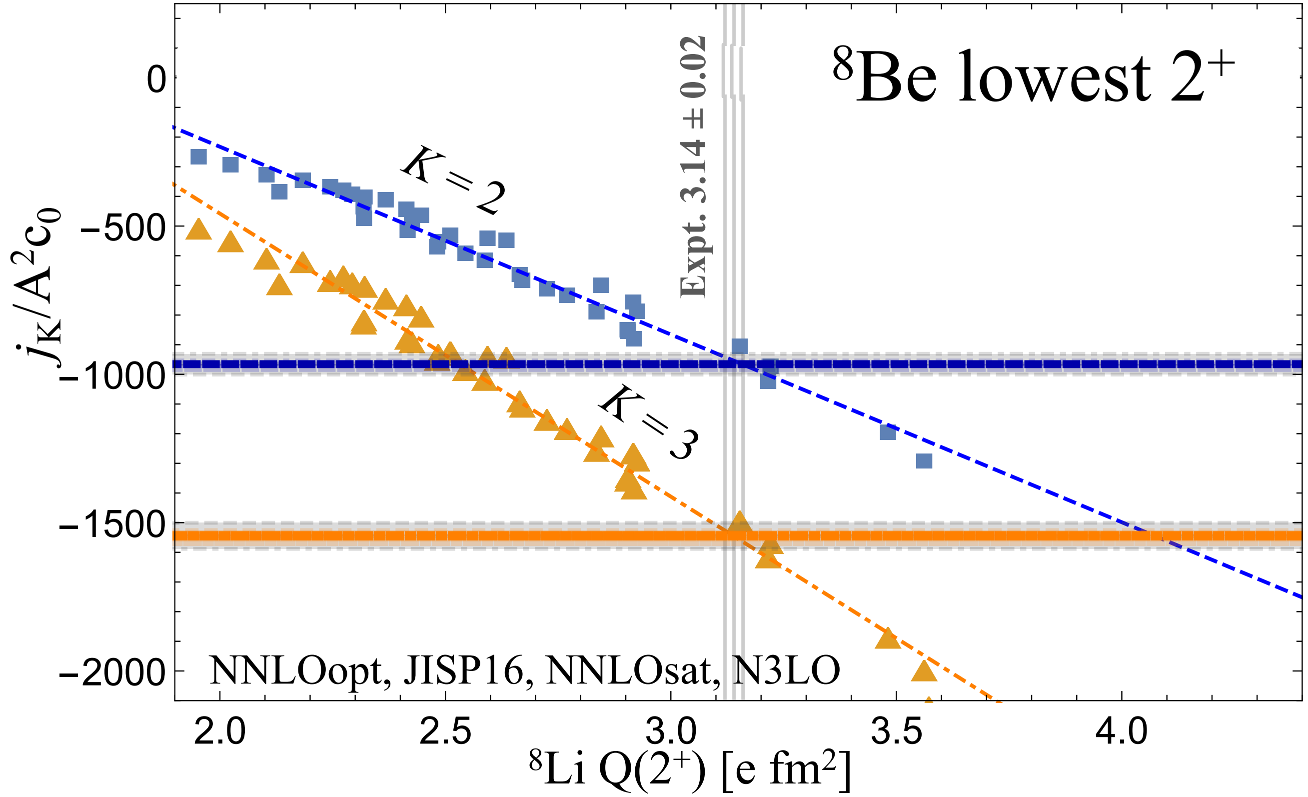


$$j_K \propto < \Psi_f || \sum_i^A \tau_i^{\pm}[\sigma_i \times \hat{Q}_2(\hat{r}_i)]^K \; ||\Psi_0 >$$ ⟵ Recoil-order term

$$c_0 \propto < \Psi_f || \sum_i^A \tau_i^{\pm}\sigma_i \; ||\Psi_0 >$$ ⟵ Gamow-Teller matrix element

Sargsyan, Launey, Burkey, *et al.*, PRL128 (20), 202503 (2022)

Most precise beta-decay measurement of its type in 50 years!



Mary Burkey's PhD Thesis (U. Chicago/ANL/LLNL, 2019)

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Improved by nearly 50%!

TABLE I. Summary of dominant systematic uncertainties, listed at 1σ.

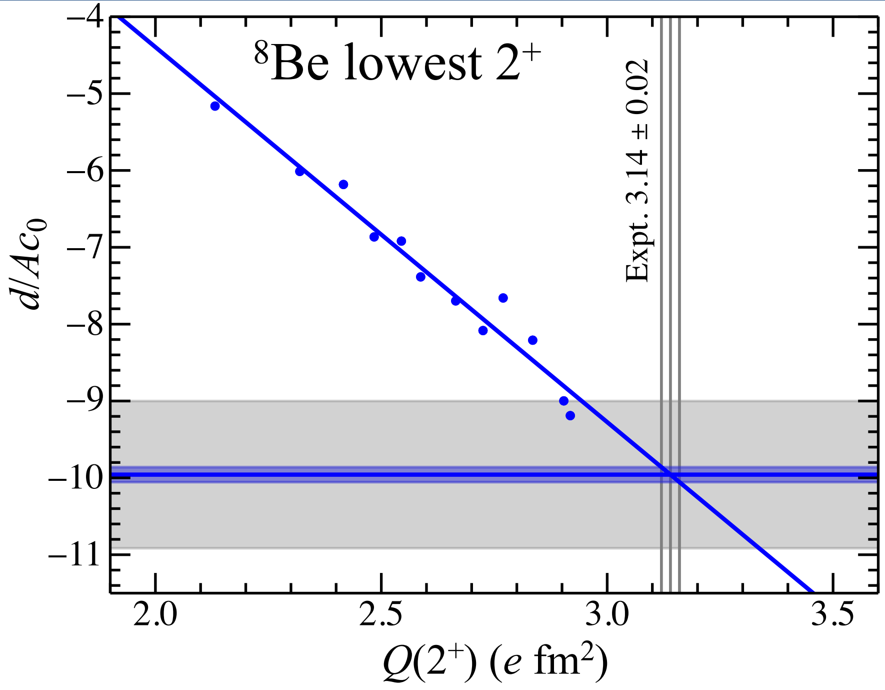
	Systematic Uncertainty	$\Delta\|C_T/C_A\|^2$
Theory	Intruder State (added linearly)	0.0005
	Recoil-Order Terms & Radiative Corrections	0.0015
Experiment	α-Energy Calibration	0.0007
	Detector Lineshape	0.0009
	Data Cuts	0.0009
	β Scattering	0.0010
Total		0.0028

Most precise beta-decay measurement of its type in 50 years!

MT Burkey, G Savard, AT Gallant, *et al.*, PRL 128 (20), 202502 (2022).

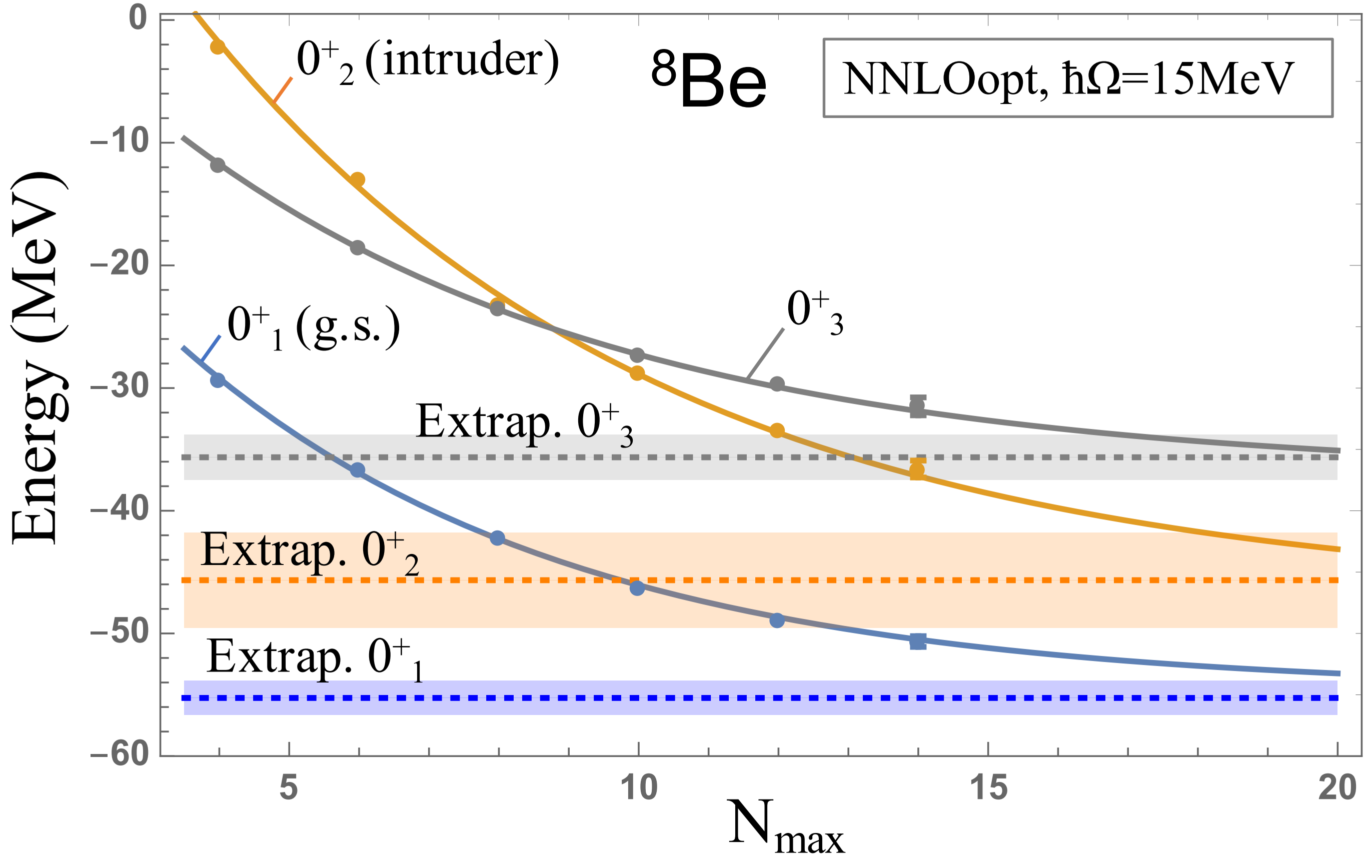
Weak magnetism and induced tensor recoil-order terms

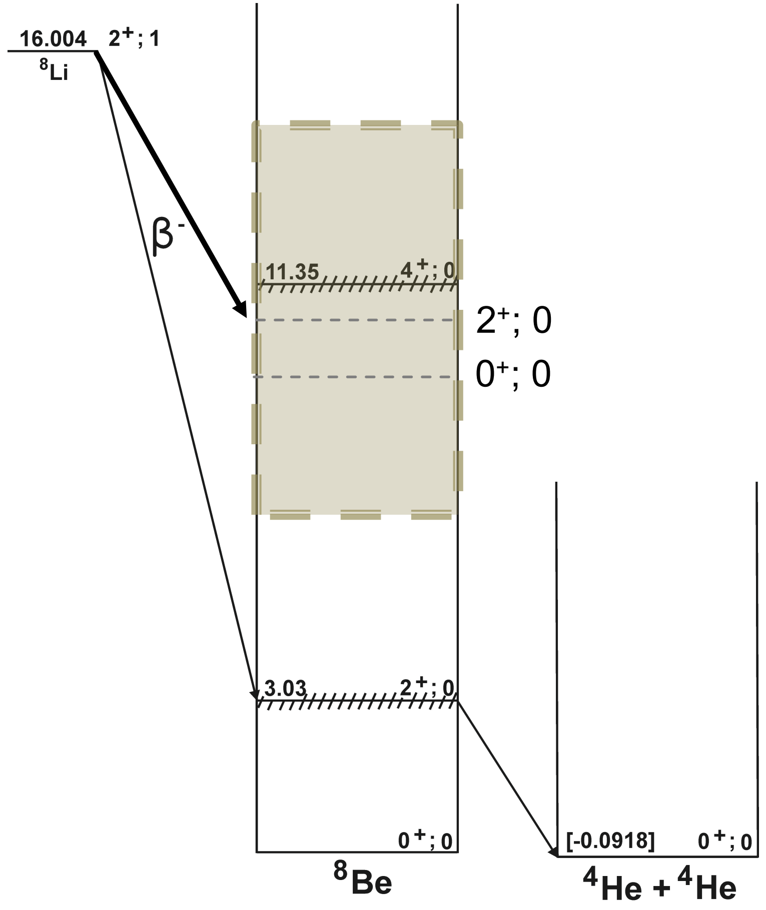
- Weak magnetism (b) and induced tensor (d) recoil terms: next significant after j_2 and j_3
- Important for the tests of conserved vector current (CVC) hypothesis and existence of second class currents
- With SA-NCSM we can calculate these beta decay recoil-order terms for up to intermediate mass nuclei



Possible intruder states in ^{8}Be can explain the discrepancy in ^{8}Li beta decay

Sargsyan, *et al.*, PRL128 (20), 202503 (2022)





Adapted from https://nucldata.tunl.duke.edu

0^+ and 2^+ intruder states in ^{8}Be

PHYSICAL REVIEW C, VOLUME 64, 051301(R)

Intruder states in ^{8}Be

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[1]*Institut de Recherches Subatomiques, IN2P3-CNRS-Université Louis Pasteur, Batiment 27/1, F-67037 Strasbourg Cedex 2, France*
[2]*Lawrence Livermore National Laboratory, L-414, P. O. Box 808, Livermore, California 94551*
[3]*Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011*
(Received 11 July 2001; published 4 October 2001)

Low-lying intruder $T=0$ states in ^{8}Be have been posited and challenged. To address this issue, we performed *ab initio* shell model calculations in model spaces consisting of up to $10\hbar\Omega$ excitations above the unperturbed ground state with the basis state dimensions reaching 1.87×10^8. To gain predictive power we derive and use effective interactions from realistic nucleon-nucleon (NN) potentials in a way that guarantees convergence to the exact solution with increasing model space. Our $0\hbar\Omega$ dominated states show good stability when the model space size increases. At the same time, we observe a rapid drop in excitation energy of the $2\hbar\Omega$ dominated $T=0$ states. In the $10\hbar\Omega$ space the intruder 0^+0 state falls below 18 MeV of excitation and, also, below the lowest 0^+1 state. Our extrapolations suggest that this state may stabilize around 12 MeV. We hypothesize that these states might be the broad resonance intruder states needed in R-matrix analysis of $\alpha-\alpha$ elastic scattering. In addition, we present our predictions for the $A=8$ binding energies with the CD-Bonn NN potential.

Measurement of the full excitation spectrum of the ^{7}Li$(p,\gamma)\alpha\alpha$ reaction at 441 keV

Check for updates

Michael Munch *, Oliver Sølund Kirsebom, Jacobus Andreas Swartz, Karsten Riisager, Hans Otto Uldall Fynbo

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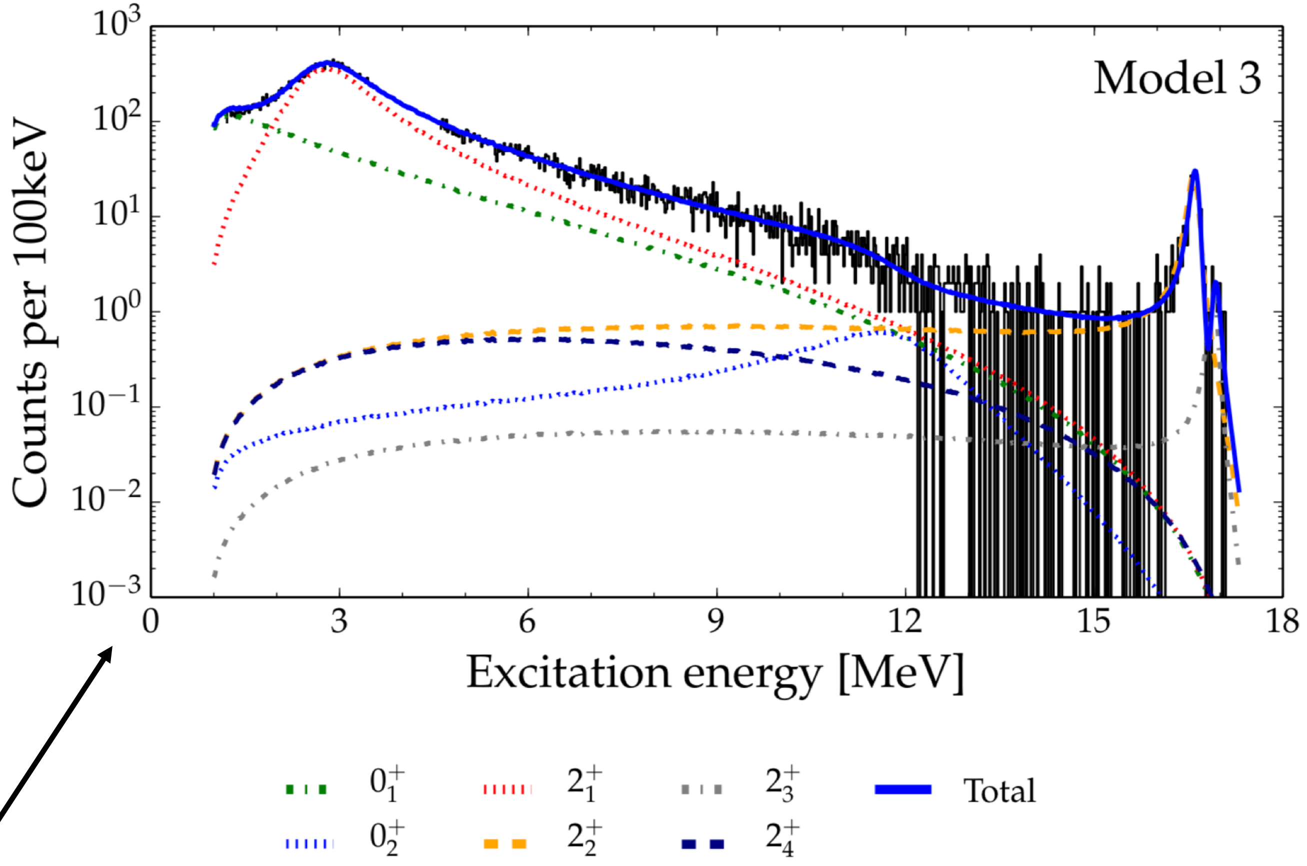
Radiative decay width
Light nuclei

ABSTRACT

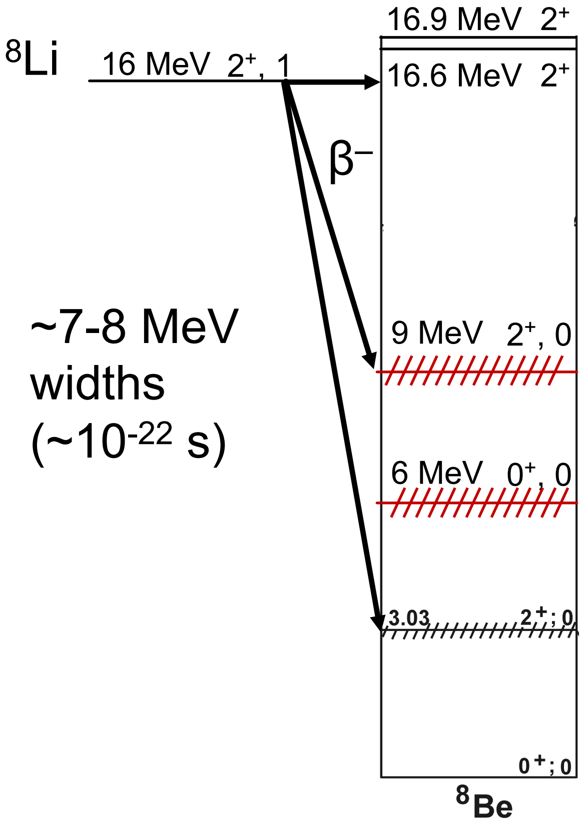
A current challenge for ab initio calculations is systems that contain large continuum contributions such as ^{8}Be. We report on new measurements of radiative decay widths in this nucleus that test recent Green's function Monte Carlo calculations.
Traditionally, γ ray detectors have been utilized to measure the high energy photons from the ^{7}Li$(p,\gamma)\alpha\alpha$ reaction. However, due to the complicated response function of these detectors it has not yet been possible to extract the full γ ray spectrum from this reaction. Here we present an alternative measurement using large area Silicon detectors to detect the two α particles, which provides a practically background free spectrum and retains good energy resolution.
The resulting spectrum is analyzed using a many-level multi channel R-matrix parametrization. Improved values for the radiative widths are extracted from the R-matrix fit. We find evidence for significant non-resonant continuum contributions and tentative evidence for a broad 0^+ resonance at 12 MeV.



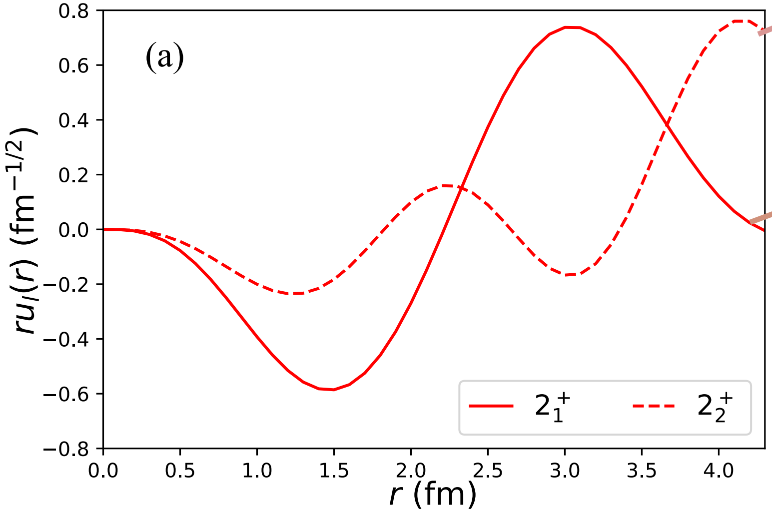
Munch et al., Phys. Lett. B 782 (2018) 779–784

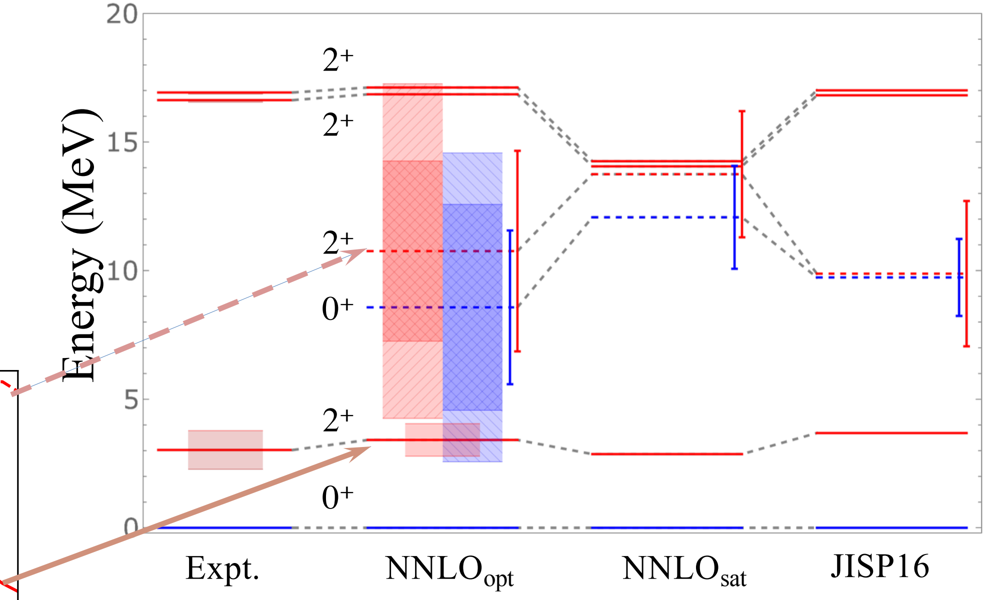
^{8}Be low-lying 0^+ and 2^+ states not confirmed in experiments

- First proposed by Barker in 1968-69



~7-8 MeV widths (~10^{-22} s)

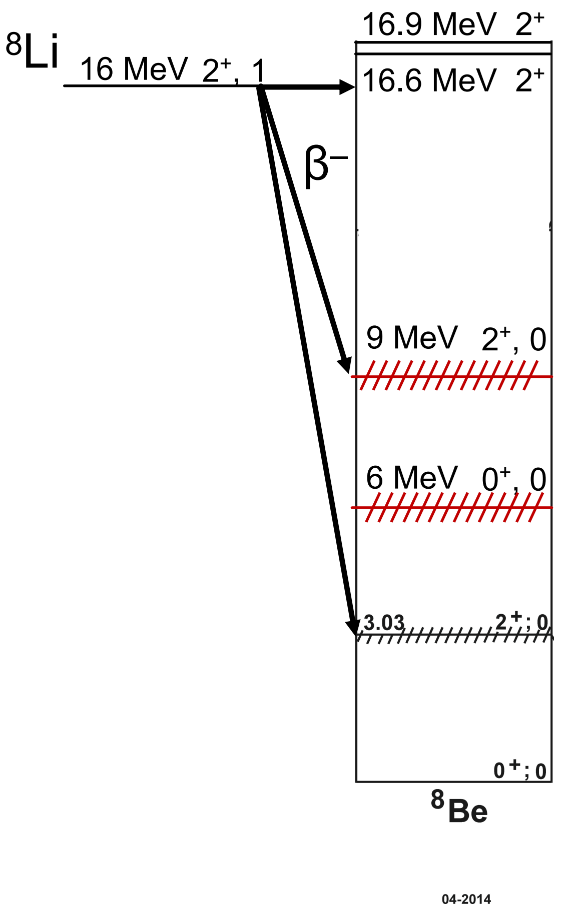




Sargsyan, Launey, Burkey, *et al.*, PRL128 (20), 202503 (2022)

F. C. Barker. Australian Journal of Physics, vol. 21, 239–257, 1968.
F. C. Barker. Australian Journal of Physics, vol. 22, 293–316, 1969.

Recoil terms for all ^{8}Li β-decay accessible states



^{8}Be states	j_2/A^2c_0	j_3/A^2c_0	d/Ac_0	b/Ac_0
2_1^+	-966 ± 36	-1546 ± 44	10.0 ± 1.0	6.0 ± 0.4
2_2^+(new)	-10 ± 10	-80 ± 30	-0.5 ± 0.5	3.7 ± 0.4
2_3^+(doublet 1)	12 ± 5	-60 ± 15	0.3 ± 0.2	3.8 ± 0.2
2_4^+(doublet 2)	11 ± 3	-65 ± 11	0.2 ± 0.2	3.8 ± 0.2

- j_2/A^2c_0 and j_3/A^2c_0 values for the lowest 2^+ are much larger than for other states
- b/Ac_0 and d/Ac_0 values are also important for tests of conserved vector current hypothesis

Previous state-of-the-art values for j_2 and j_3

PHYSICAL REVIEW C **83**, 065501 (2011)

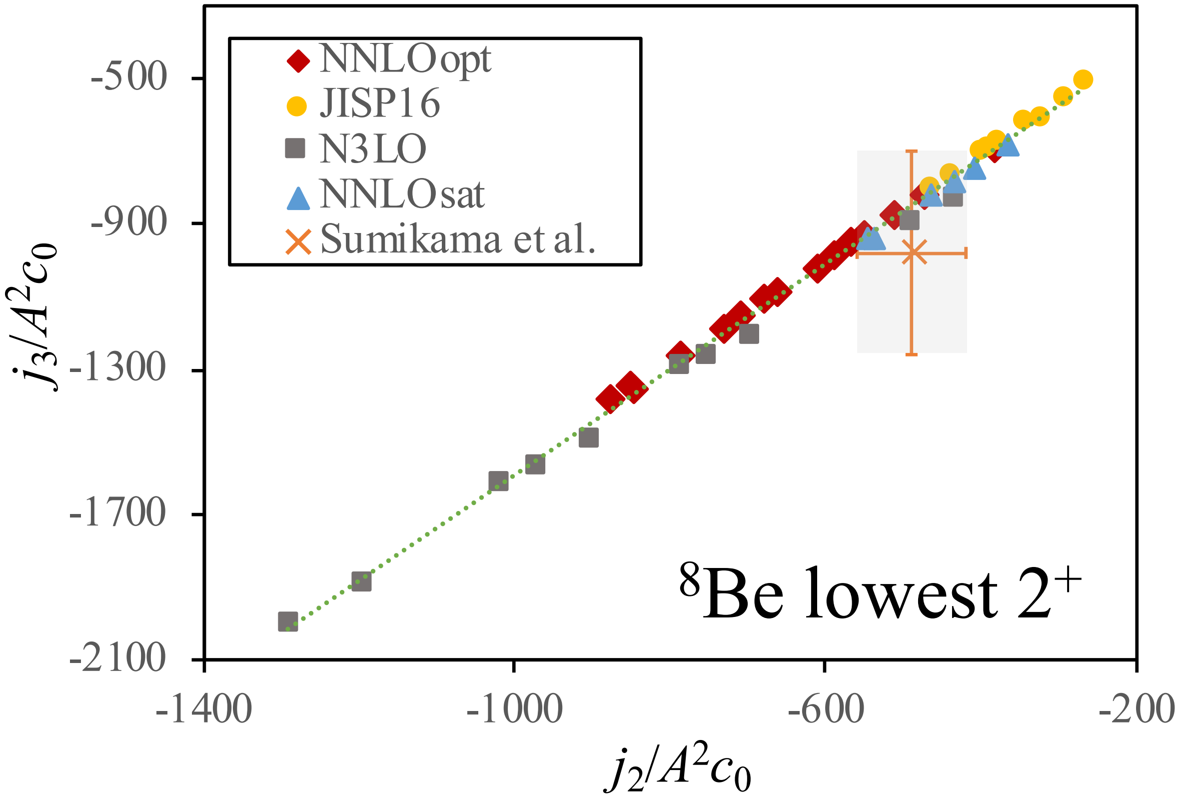
Test of the conserved vector current hypothesis by a β-ray angular distribution measurement in the mass-8 system

T. Sumikama,[1,2] K. Matsuta,[1] T. Nagatomo,[3] M. Ogura,[1] T. Iwakoshi,[1] Y. Nakashima,[1] H. Fujiwara,[1] M. Fu
M. Mihara,[1] K. Minamisono,[4] T. Yamaguchi,[5] and T. Minamisono[6]

$$j_2/A^2c_0 = -490 \pm 70$$
$$j_3/A^2c_0 = -980 \pm 280$$

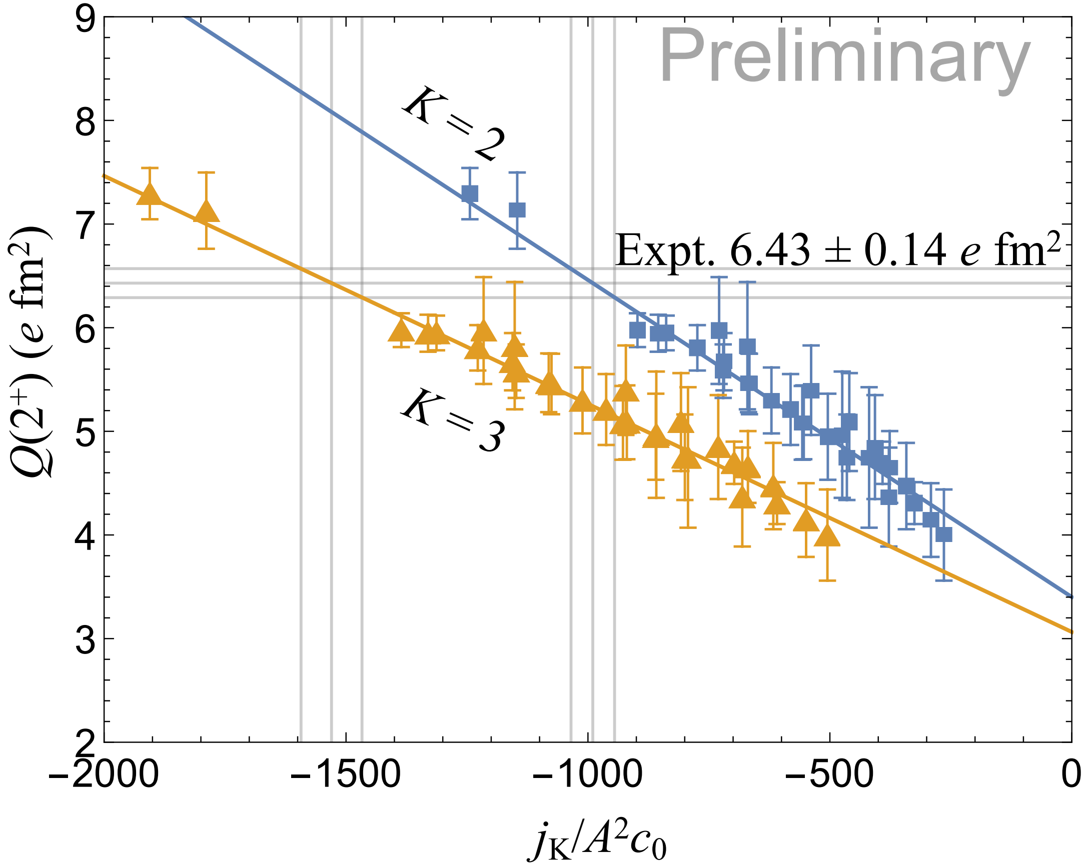
- Extremely difficult measurements ⇨ Large uncertainties
- j_2 and j_3 values were considered constant over the entire beta decay energy range

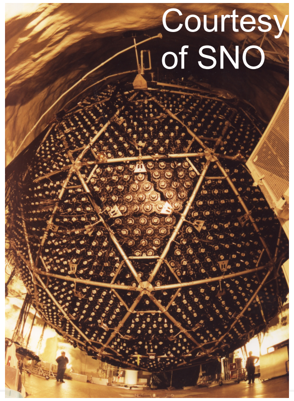
Strong correlation between j_2 and j_3 recoil-order terms

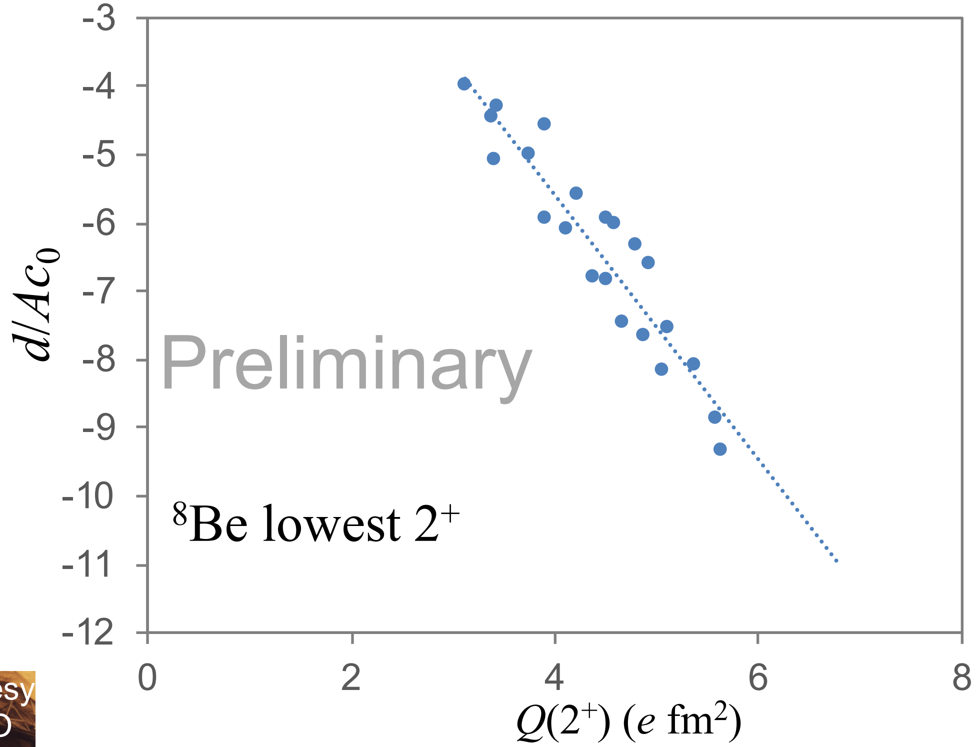


Sargsyan, *et al.*, PRL128 (20), 202503 (2022)

Recoil terms for ^{8}B to inform precision beta decay experiments

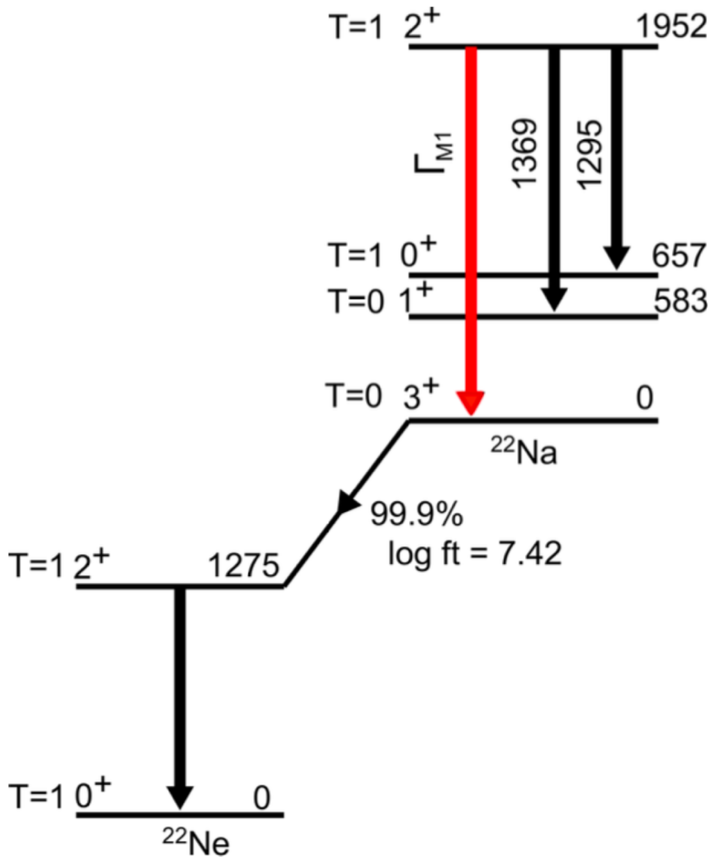






Also important for precision measurements of solar neutrinos!
See talk by B. Longfellow

Weak magnetism and induced tensor terms in ^{22}Na



S. Triambak, *et al.*, Phys. Rev. C 95, 035501 (2017)

Using CVC they determined

$$|b/Ac| = 8.9 \pm 1.2$$

$$|d/Ac| = 21 \pm 6$$

Which disagree with shell model calculations

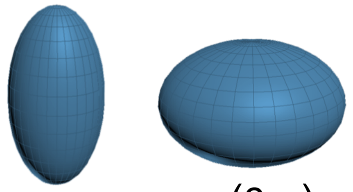
Form factor	Calculated value
Weak magnetism b/Ac_1	-19
Second-order axial vector $c_2/c_1 R^2$	-0.37
First-class induced tensor d/Ac_1	-3.2

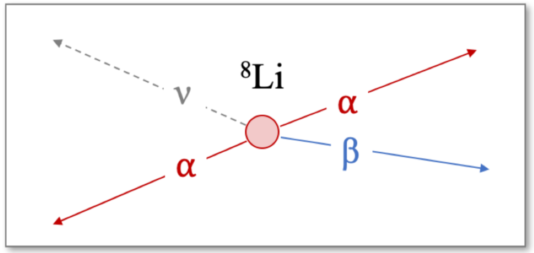
R. B. Firestone, W. C. McHarris, and B. R. Holstein, Phys. Rev. C **18**, 2719 (1978)

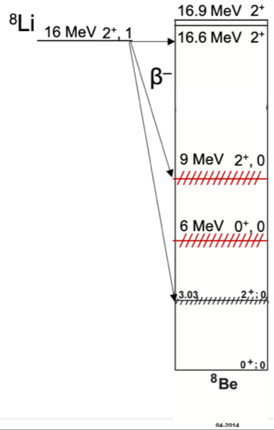
- If the sign of b/Ac is different from shell model prediction, then $|d/Ac| = 3 \pm 6$
- Our preliminary calculations favor this scenario

Summary

- The SA-NCSM employs emergent symmetries in nuclei to decrease the dimensionality of the model space, thus allowing us to reach heavier nuclei and large model spaces
- Our calculations of ^{8}Li beta decay recoil-order terms helped experiment to constrain BSM tensor currents in the weak interaction
- The calculated b/Ac_0 and d/Ac_0 values are important for tests of conserved vector current hypothesis
- Low-lying intruder states in ^{8}Be can have important implications for A=8 beta decays and related precision measurements







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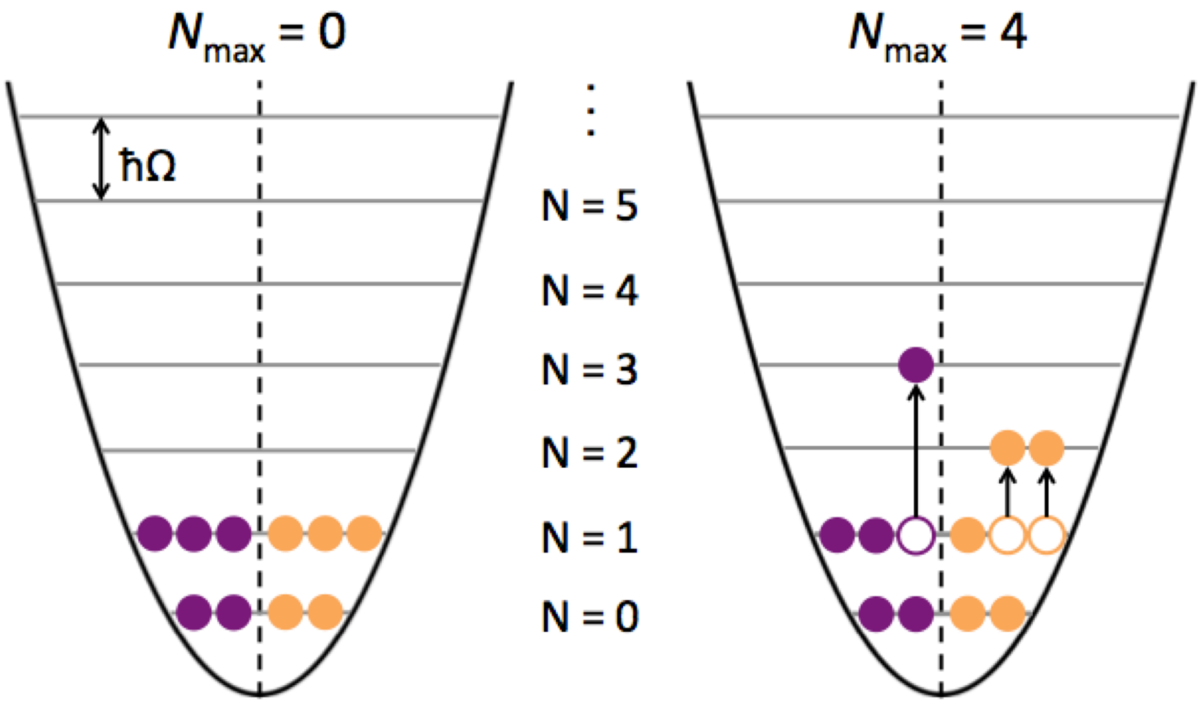
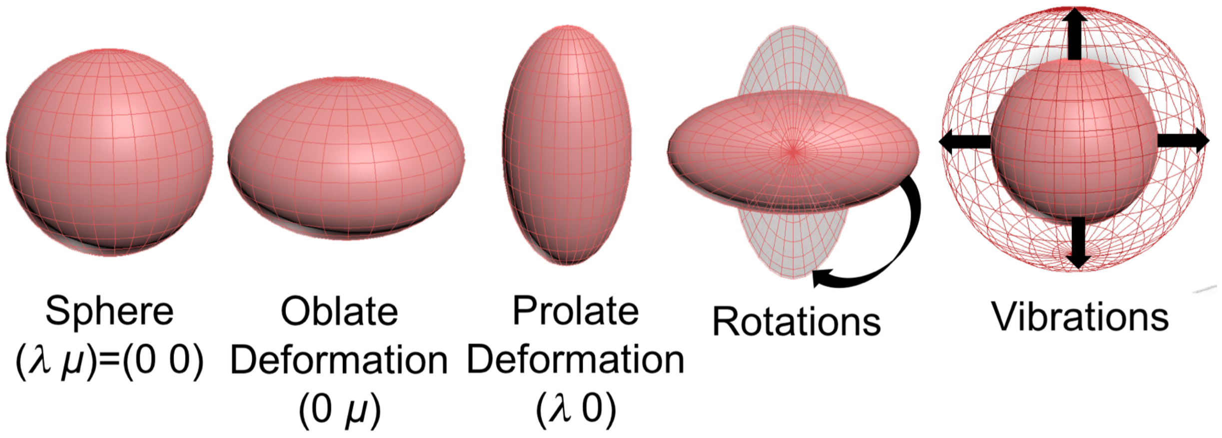
Thank you!

Backup slide zone





Recoil-order terms in β-decay

Beta decay rate: $d\Gamma \propto |T|^2$

T matrix in SM (V–A): $T \propto l^{\mu}\langle\beta\,|V_\mu - A_\mu|\alpha\rangle$

$$l^\mu \langle \beta, J'M'|\, A_\mu \,|\alpha, JM\rangle = C^{JM}_{J'M'1k}\epsilon_{ijk}\epsilon_{ij\lambda\eta}\frac{1}{4M}\left[c(q^2)l^\lambda P^\eta - d(q^2)l^\lambda q^\eta + \frac{1}{(2M)^2}h(q^2)q^\lambda P^\eta \mathbf{q}\cdot\mathbf{l}\right] + C^{JM}_{J'M'2k}C^{2k}_{1n2n'}l_n(4\pi/5)^{1/2}Y_{2n'}(\hat{q})\frac{q^2}{(2M)^2}j_2(q^2) + C^{JM}_{J'M'3k}C^{3k}_{1n2n'}l_n(4\pi/5)^{1/2}Y_{2n'}(\hat{q})\frac{q^2}{(2M)^2}j_3(q^2) + \ldots$$

Systematic Uncertainty	$\Delta\|C_T/C_A\|^2$
Calibration	1.4×10^{-4}
α energy corrections	1.17×10^{-3}
Cuts to the data	1.25×10^{-3}
Radiative and recoil order terms	3.36×10^{-3}
α Si detector lineshape	6.3×10^{-4}
β Scattering	5.0×10^{-4}
Total	$\mathbf{3.62 \times 10^{-3}}$

From Mary Burkey's PhD Thesis (U. Chicago/ANL/LLNL, 2019)

B. R. Holstein, Rev. Mod. Phys. 46, 789 (1974)

Recoil-order terms in β-decay

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T matrix in SM (V–A): $T \propto l^{\mu}\langle\beta\,|V_{\mu} - A_{\mu}|\alpha\rangle$

Axial current matrix element

Leading order (Gamow-Teller)

Recoil-order q/M

$$l^{\mu}\langle\beta, J'M'|\,A_{\mu}\,|\alpha, JM\rangle = C^{JM}_{J'M'1k}\epsilon_{ijk}\epsilon_{ij\lambda\eta}\frac{1}{4M}\left[c(q^2)l^{\lambda}P^{\eta} - d(q^2)l^{\lambda}q^{\eta}\right.$$
$$\left. + \frac{1}{(2M)^2}h(q^2)q^{\lambda}P^{\eta}\mathbf{q}\cdot\mathbf{l}\right]$$
$$+ C^{JM}_{J'M'2k}C^{2k}_{1n2n'}l_n(4\pi/5)^{1/2}Y_{2n'}(\hat{q})\frac{q^2}{(2M)^2}j_2(q^2)$$
$$+ C^{JM}_{J'M'3k}C^{3k}_{1n2n'}l_n(4\pi/5)^{1/2}Y_{2n'}(\hat{q})\frac{q^2}{(2M)^2}j_3(q^2) + \ldots$$

Lepton current matrix element

Recoil-order $(q/M)^2$

Systematic Uncertainty	$\Delta\|C_T/C_A\|^2$
Calibration	1.4×10^{-4}
α energy corrections	1.17×10^{-3}
Cuts to the data	1.25×10^{-3}
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For ^{8}Li and ^{8}B beta decay q/M ~ 0.002

B. R. Holstein, Rev. Mod. Phys. 46, 789 (1974)

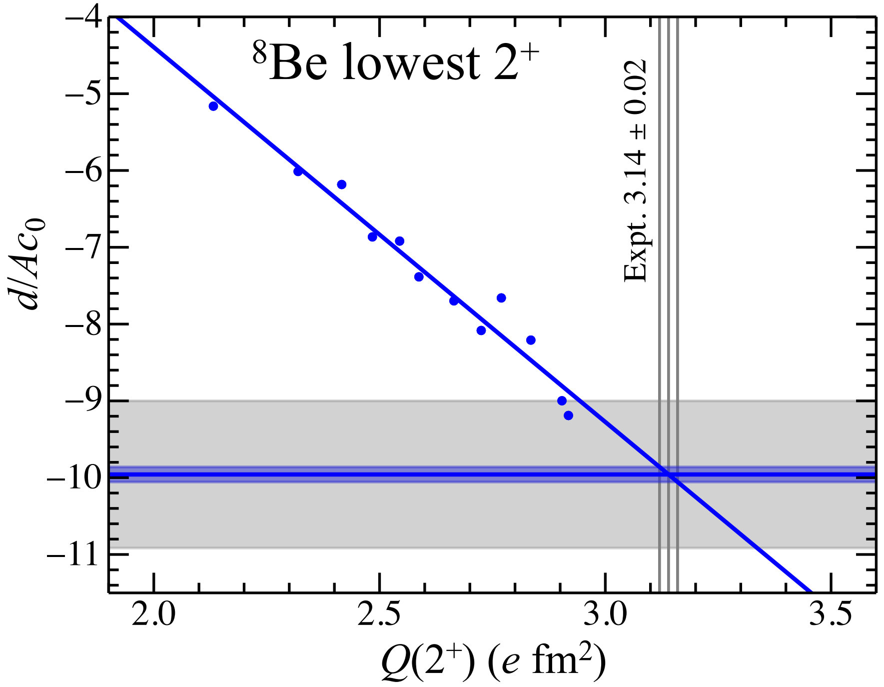
Recoil-order terms b/Ac_0 and d/Ac_0

- Weak magnetism (b) and induced tensor (d) recoil terms become the next significant sources of uncertainty with more precise j_2 and j_3.

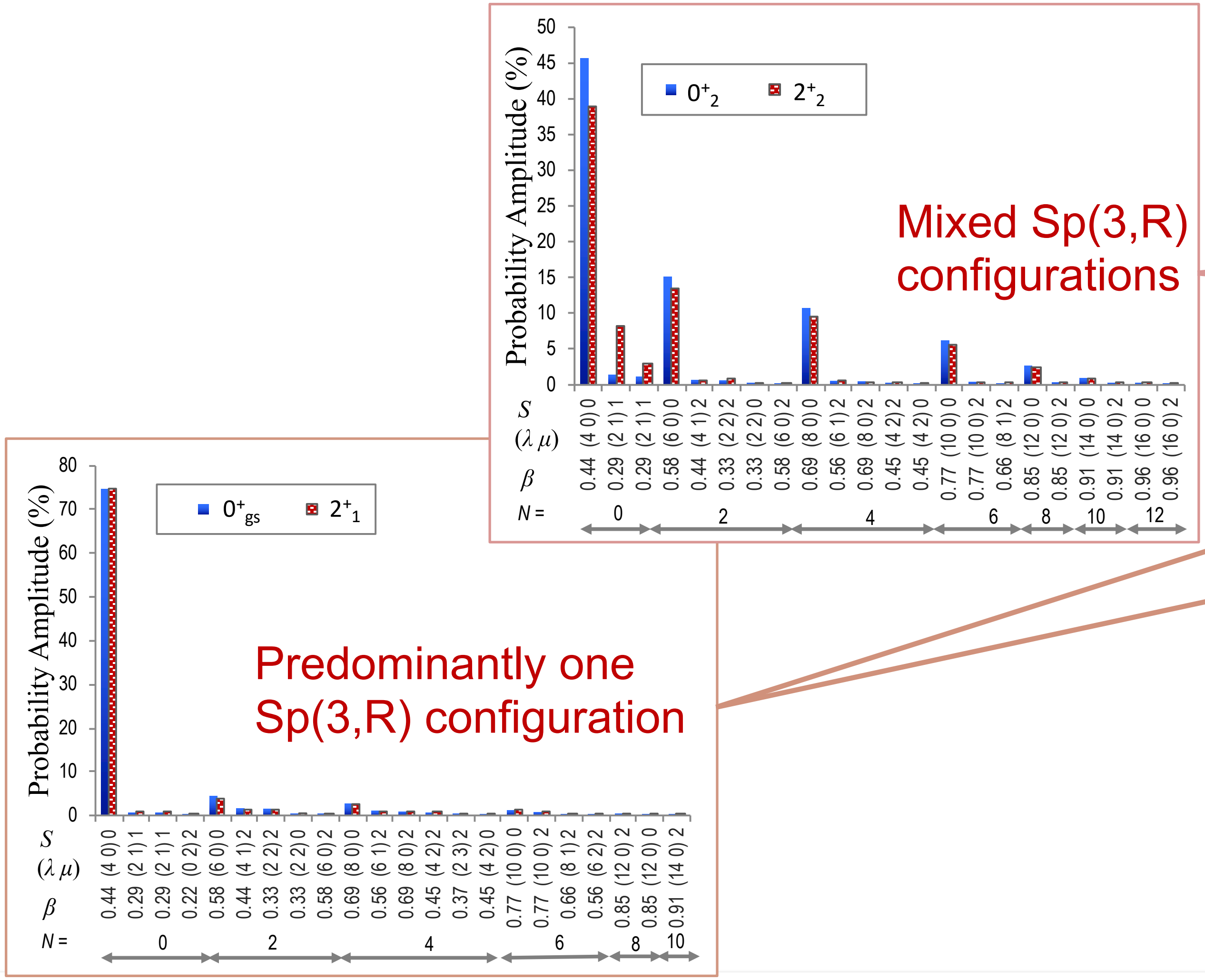
$$b \propto g_M \langle \Psi_f || \sum_i^A \tau_i^{\pm} \sigma_i \; || \Psi_0 \rangle + g_V \langle \Psi_f || \sum_i^A \tau_i^{\pm} L_i \; || \Psi_0 \rangle$$

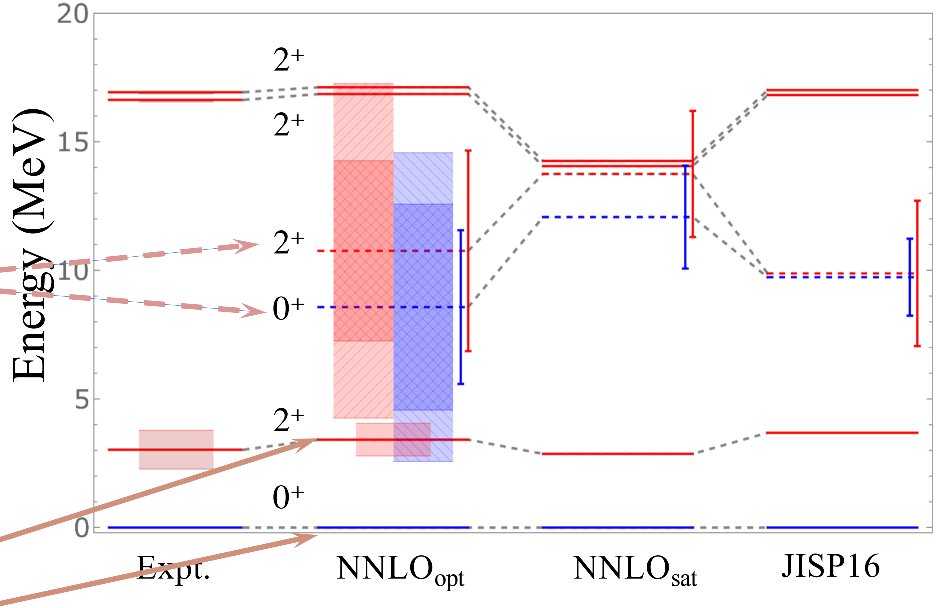
$$d \propto < \Psi_f || \sum_i^A \tau_i^{\pm} \sqrt{2} [L_i \times \sigma_i]^1 \; || \Psi_0 >$$

$g_M(0) = 4.7$ Weak magnetism coupling
$g_V(0) = 1.0$ Vector coupling



^{8}Be low-lying 0^+ and 2^+ states not confirmed in experiments





Sargsyan, Launey, Burkey, *et al.*, PRL128 (20), 202503 (2022)

$$
\begin{aligned}
j_K(q^2) &= -(-)^{J'-J}\frac{2}{3}\frac{g_A(q^2)}{\sqrt{2J+1}}\frac{M^2c^4}{(\hbar c)^2}\langle J'||\sqrt{\frac{16\pi}{5}}\sum_i^A \tau_i^{\pm} r_i^2[Y_2(\hat{r}_i)]^K \times \sigma_i||J\rangle \\
&= -(-)^{J'-J}\frac{2}{3}\frac{g_A(q^2)}{\sqrt{2J+1}}\frac{(Am_N)^2c^4}{(\hbar c)^2}b^2\langle J'||\sum_i^A \tau_i^{\pm}[\hat{Q}_2(\hat{r}_i)\times\sigma_i]^K||J\rangle \\
&= -(-)^{J'-J}\frac{2}{3}\frac{g_A(q^2)}{\sqrt{2J+1}}\frac{A^2m_Nc^2}{\hbar\Omega}\langle J'||\sum_i^A \tau_i^{\pm}[\hat{Q}_2(\hat{r}_i)\times\sigma_i]^K||J\rangle\,,
\end{aligned}
$$