Beta decay recoil-order terms for studies of physics beyond the Standard Model

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Argonne National Laboratory
21 July 2024

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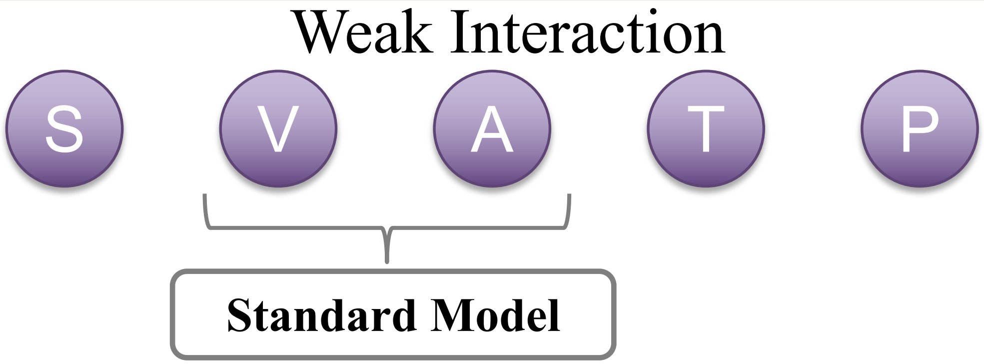
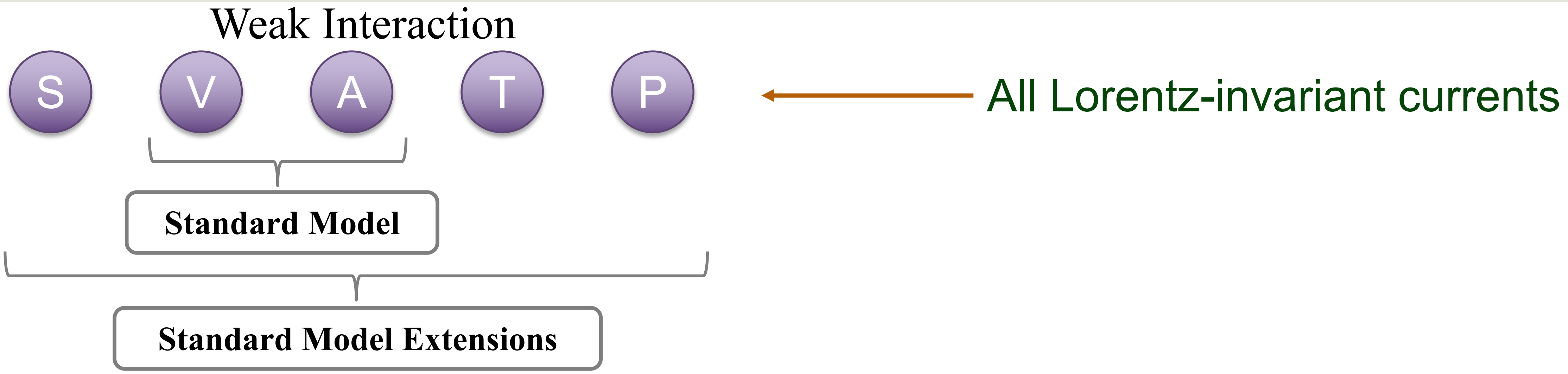
The structure of the Weak interaction



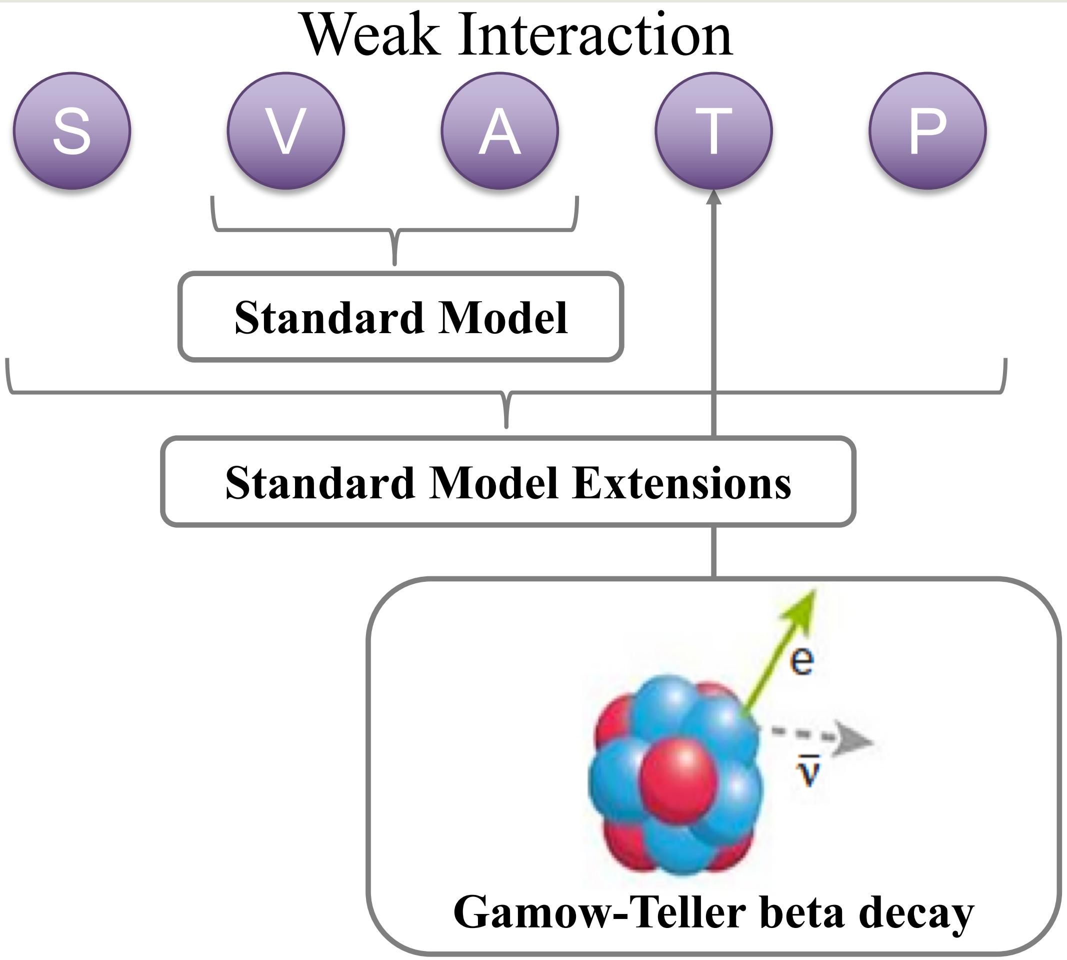
A series of β-decay experiments lead to the formulation of the V – A structure of the weak interaction:

- ❖ 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).

The structure of the Weak interaction



The structure of the Weak interaction



← All Lorentz-invariant currents

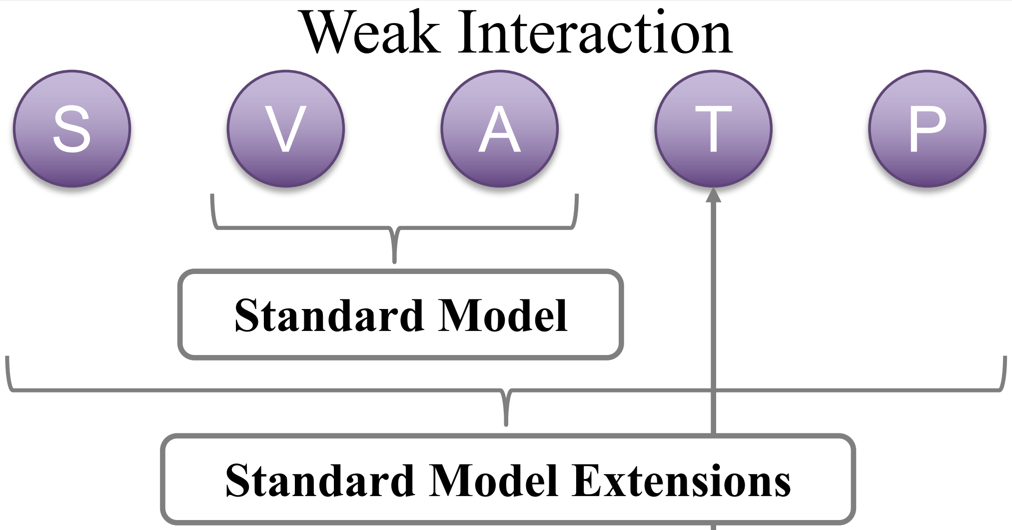
$$a_{\beta\nu} = -\frac{1}{3}\frac{|C_A|^2 - |C_T|^2}{|C_A|^2 + |C_T|^2}$$

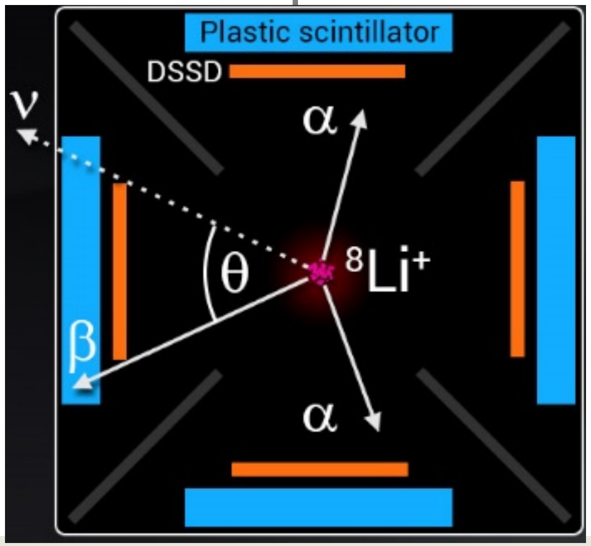
In Standard Model $a_{\beta\nu} = -\frac{1}{3}$

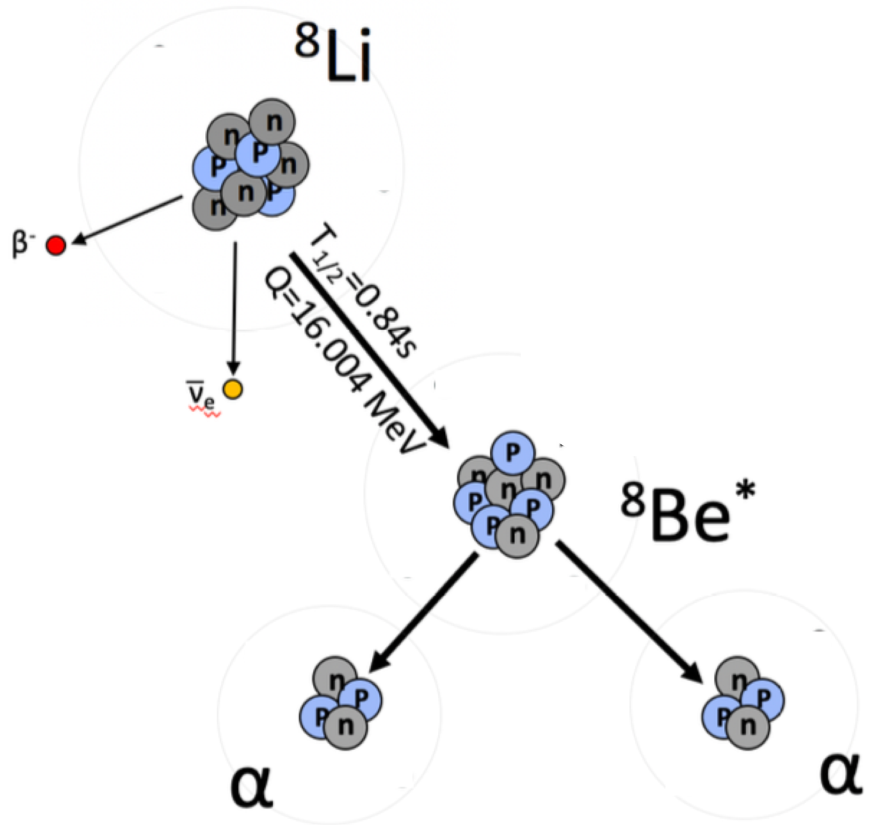
Before 2022 most precise constraint from corrected 1963 measurement of ^{6}He decay: $a_{\beta\nu} = -0.3308 \pm 0.0030$

C. Johnson, *et al.*, Phys. Rev. 132, 1149 (1963).
F. Gluck, Nucl. Phys. A 628, 493 (1998)

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



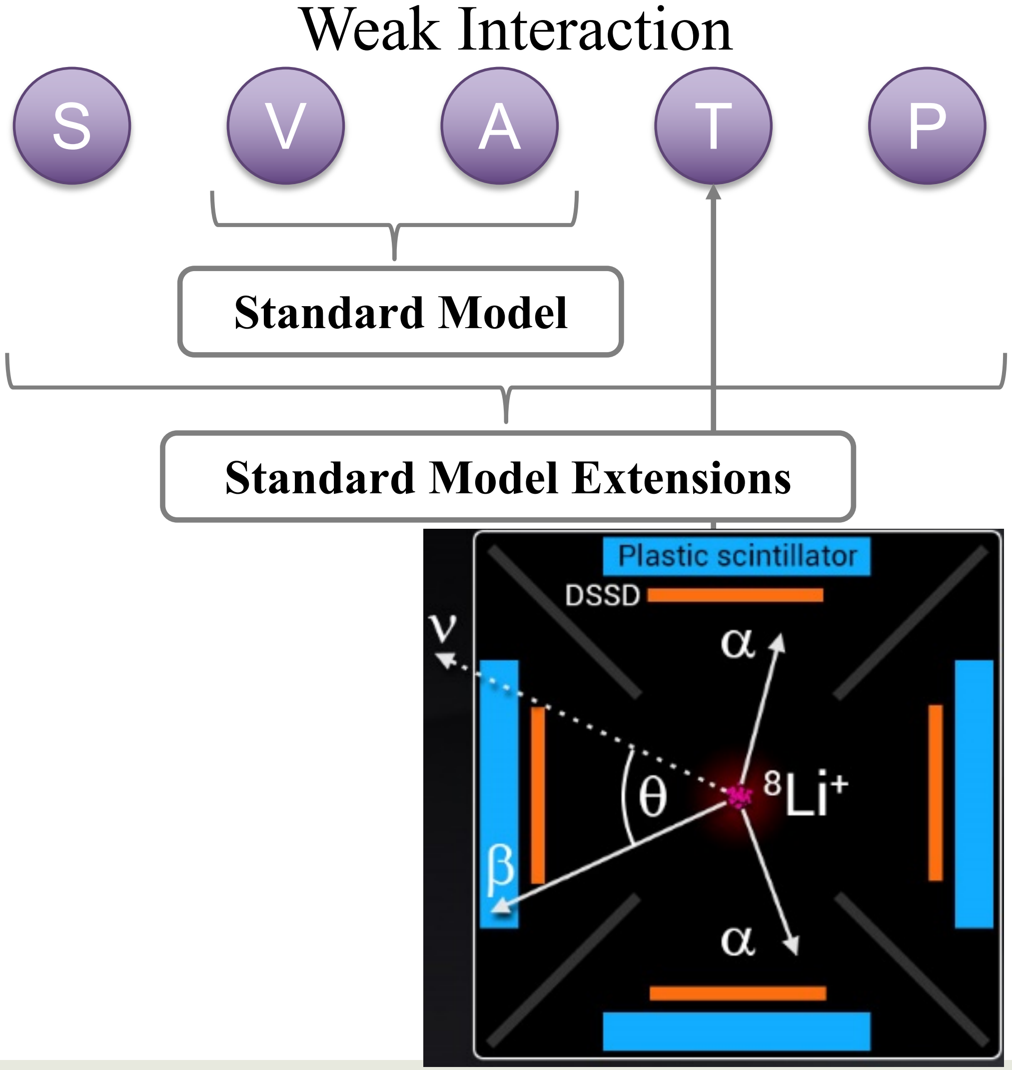


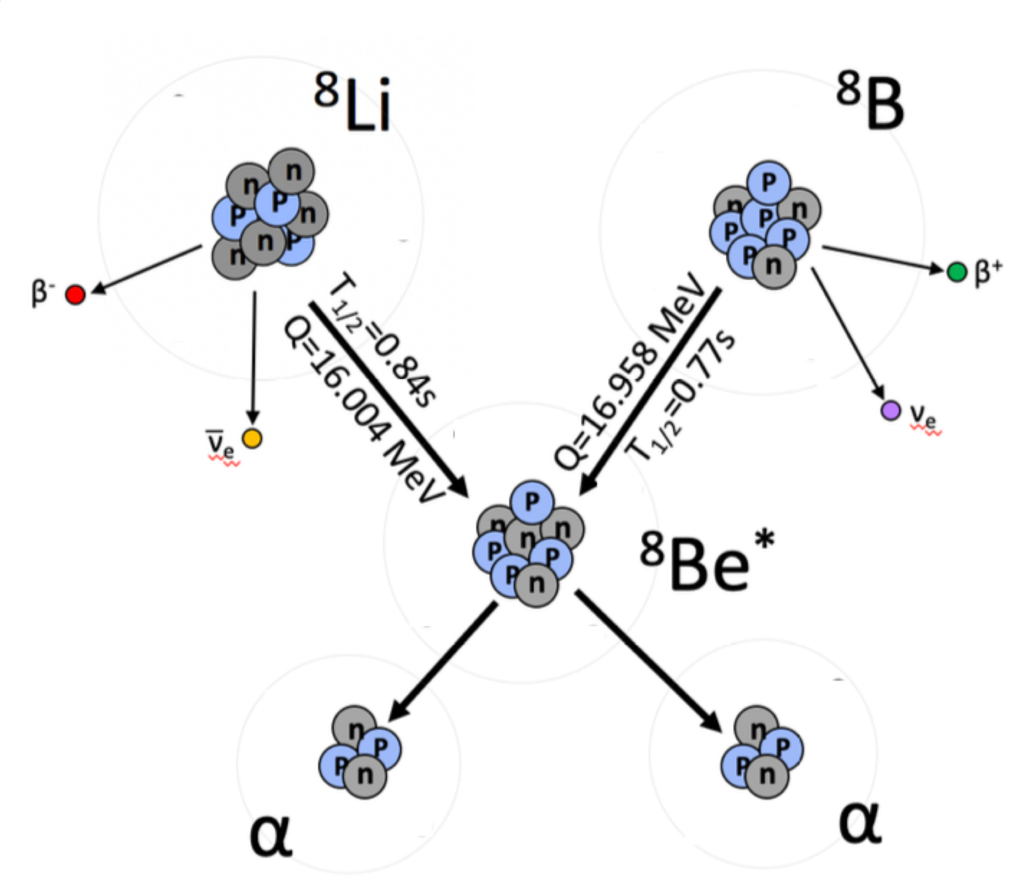


$|C_T/C_A|^2 < 0.011$(95.5 C.L) with a statistical error of 0.0038 and systematic error of 0.0043,
Which corresponds to $a_{\beta\nu} = -0.3342 \pm 0.0039$

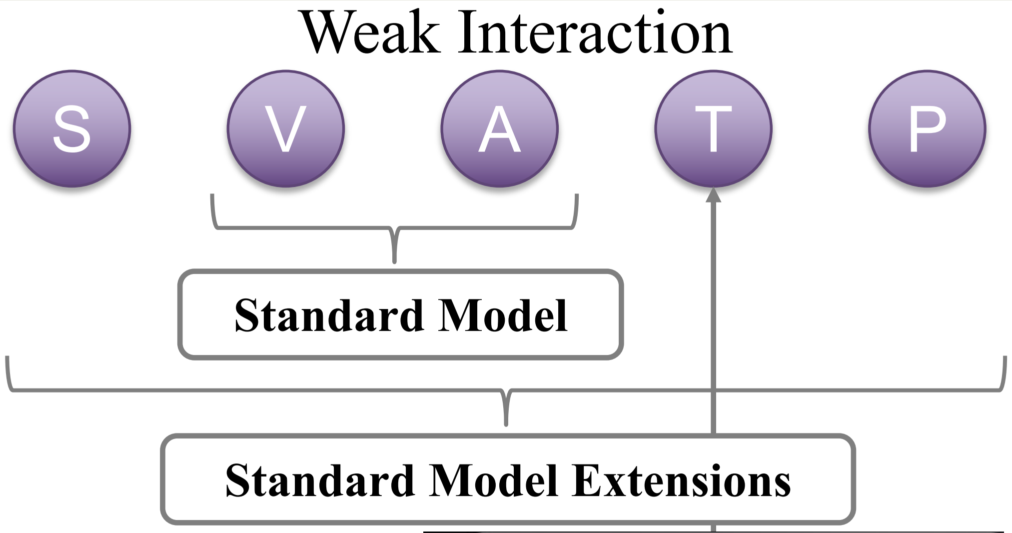
M. G. Sternberg, R. Segel, N. D. Scielzo, *et al.*, PRL **115**, 182501 (2015).

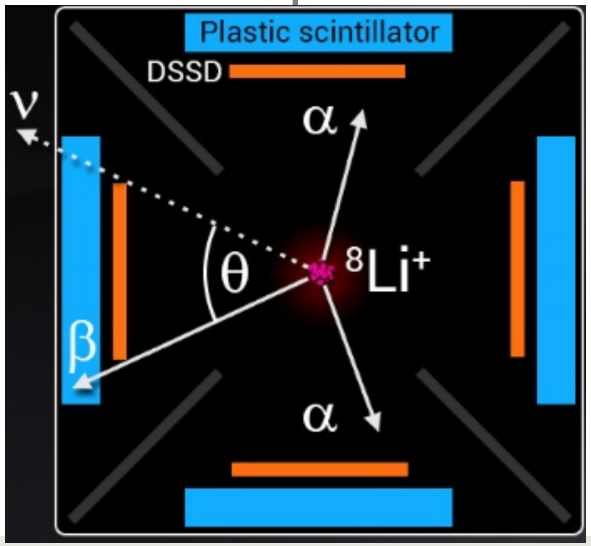
Precision measurements of ^{8}Li and ^{8}B beta decay to probe BSM physics





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





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)

$$\langle A \rangle = a \times 1 + b \times \frac{q}{M} + c \times \frac{q^2}{M^2} + \ldots$$

Leading order (Gamow-Teller)

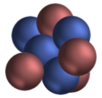
Recoil-order

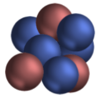
For ^{8}Li and 8B beta decays q/M ~ 0.002

Experiment needs reliable β-decay recoil-order terms

Largest recoil term matrix elements in impulse approximation

^{8}Be* ← β^--decay ← ^{8}Li





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

Nuclear recoil form-factor

$$c_0 \sim \; < \Psi_f || \sum_i^A \tau_i^{\pm} \sigma_i \; ||\Psi_0 >$$

Gamow-Teller matrix element

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

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

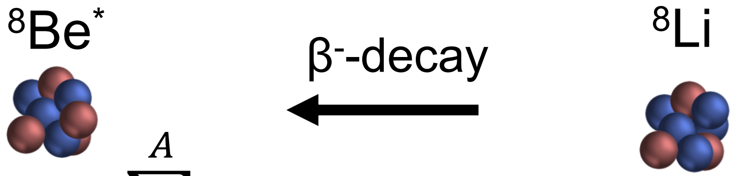
Previous values from Sumikama *et al.* measurements [PRC 83, 065501 (2011)]:

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

Heroic measurements, but low statistics → "the obtained [recoil] terms were considered as the value averaged over the analyzed energy region"

Experiment needs reliable β-decay recoil-order terms

Largest recoil term matrix elements in impulse approximation



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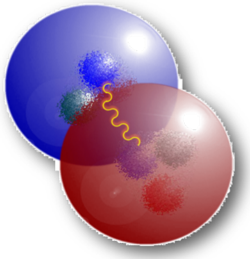
From Mary Burkey's PhD Thesis (U. Chicago/ANL/LLNL, 2019)

- Need to decrease uncertainty on $j_{2,3}/A^2 c_0$ (and other recoil-order terms)
- *Ab initio* methods to rescue

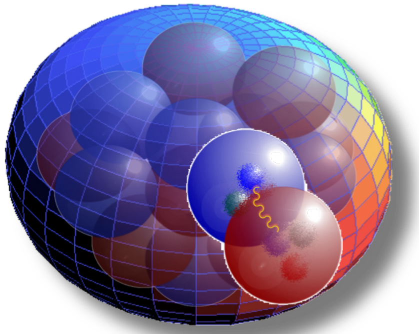
Ab initio methods in nuclear physics

First Principles



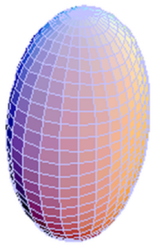
Realistic
Interactions

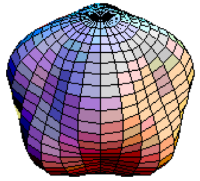
Many-body Dynamics



Symmetry-Adapted
No-Core Shell Model
(SA-NCSM)

Properties of Nuclei

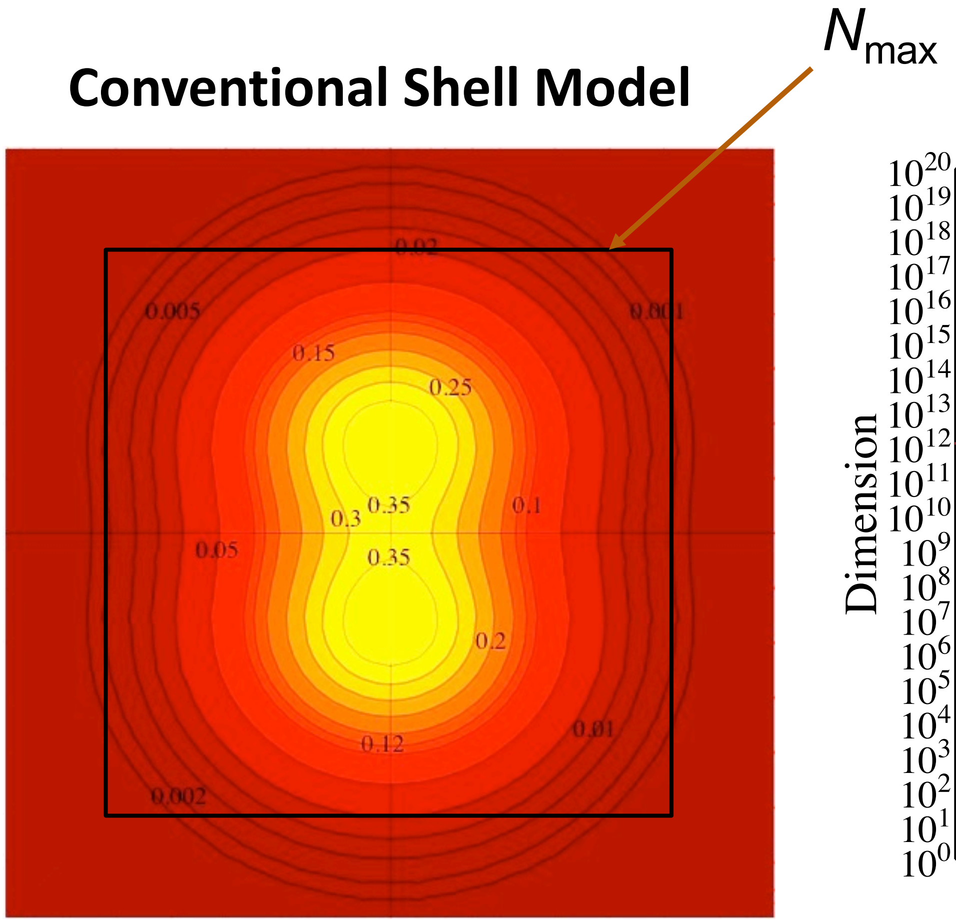


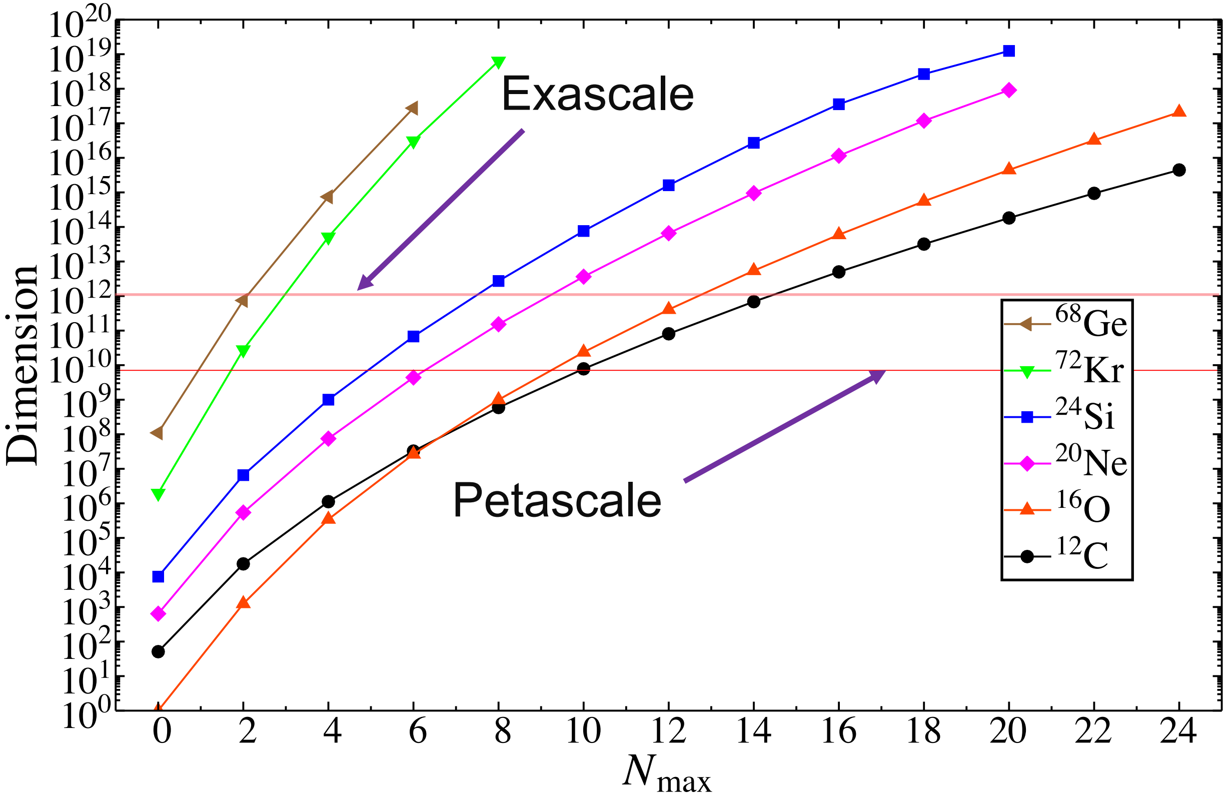


Explosive growth of the model space

Nucleus in model space

Conventional Shell Model



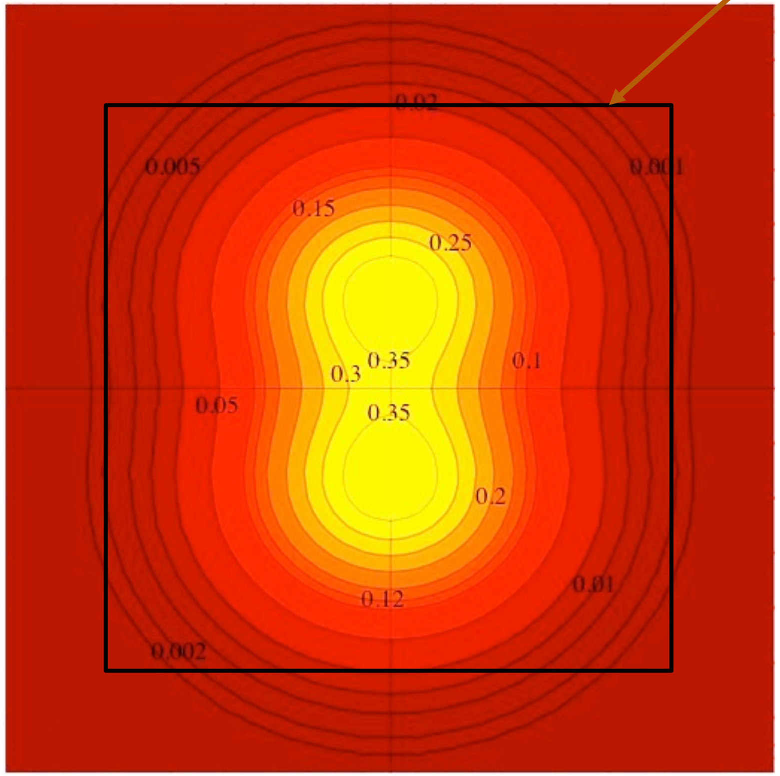


Symmetry-adapted basis helps dramatically reduce the models space size

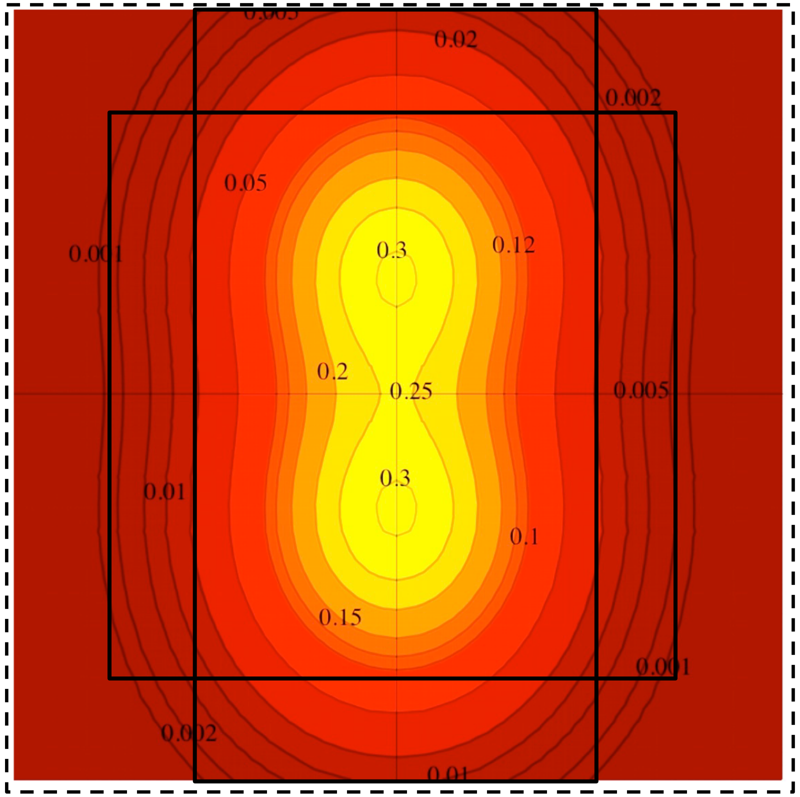
Nucleus in model space

Conventional Shell Model

N_{max}

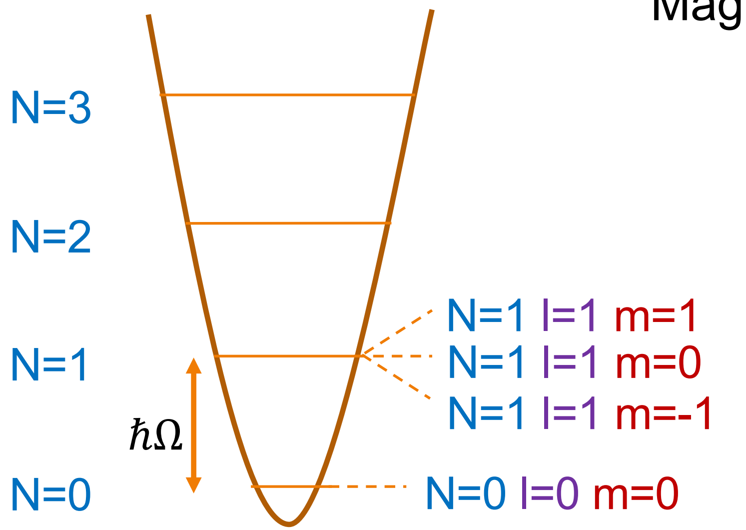


***Ab initio* Symmetry-adapted No-core Shell Model (SA-NCSM)**



SU(3) and symplectic symmetry

Quantum Harmonic Oscillator Basis



“Magic” numbers

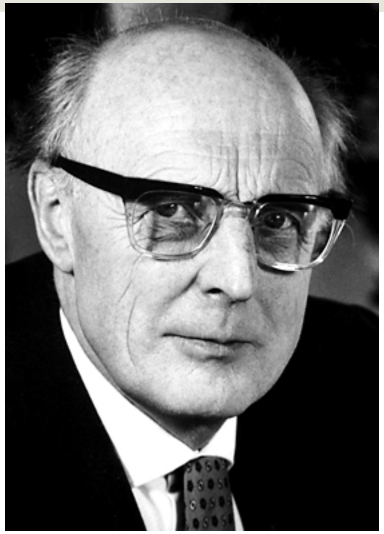
40

20

8

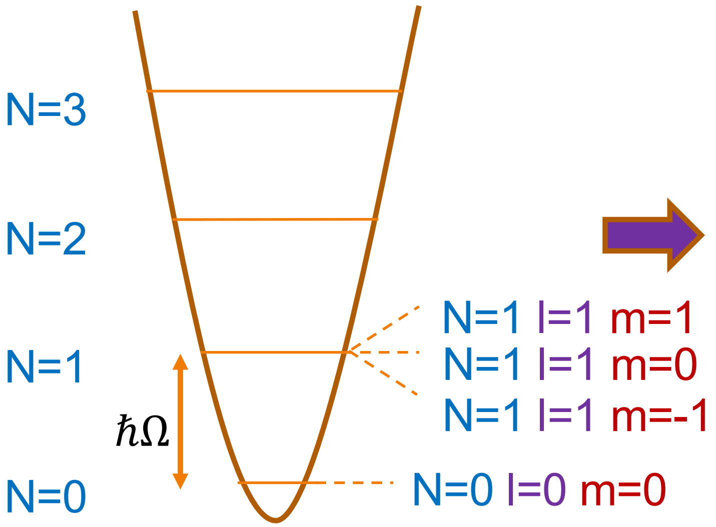
2

Filling of a harmonic oscillator (HO) shell corresponds to a “magic” number

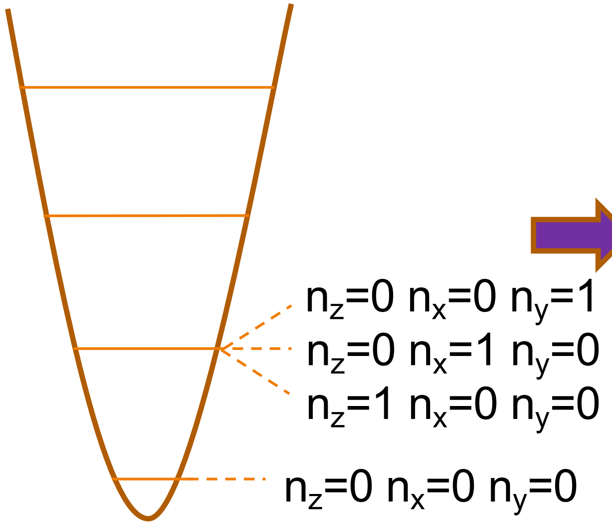


Maria Goeppert Mayer and Hans Jansen
Nobel Prize in Physics (1963)
“...for their discoveries concerning nuclear shell structure”

Symmetry-adapted Basis: SU(3)-coupled

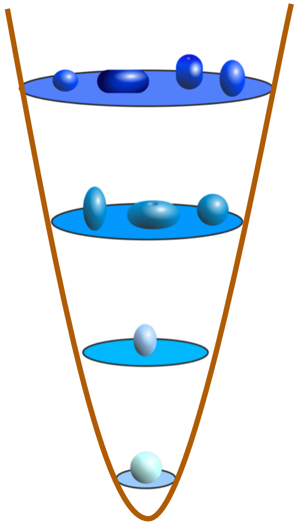


Spherical harmonic oscillator (HO): basis states given by {N l m}



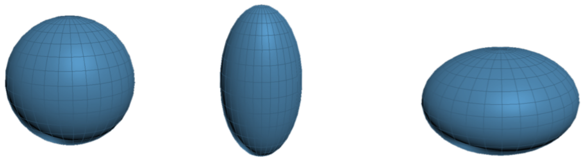
$N = n_z + n_x + n_y$

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

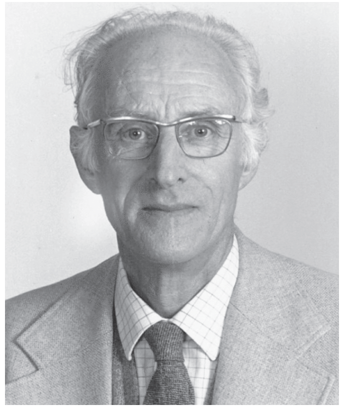


$\lambda = n_z - n_x$, $\mu = n_x - n_y$
(single particle)

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

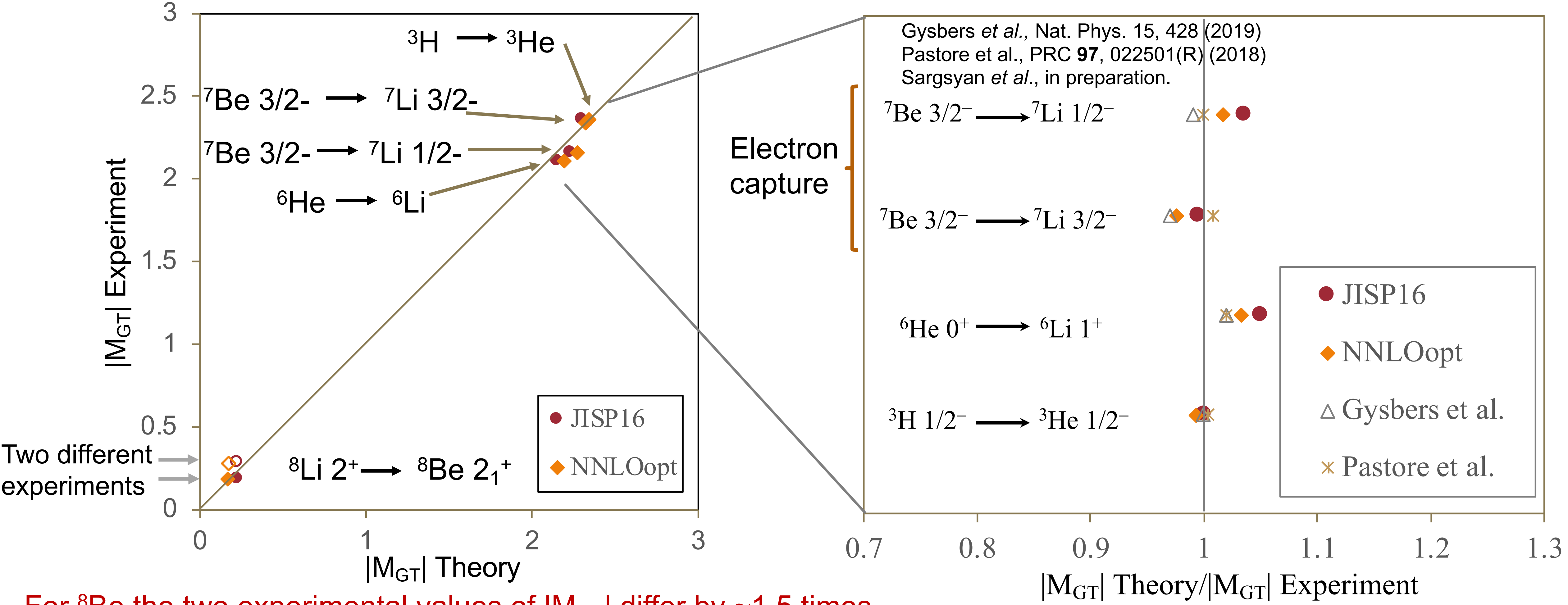


Sphere (0 0) Prolate (λ 0) Oblate (0 μ)



James Philip Elliott

Beta decays with SA-NCSM

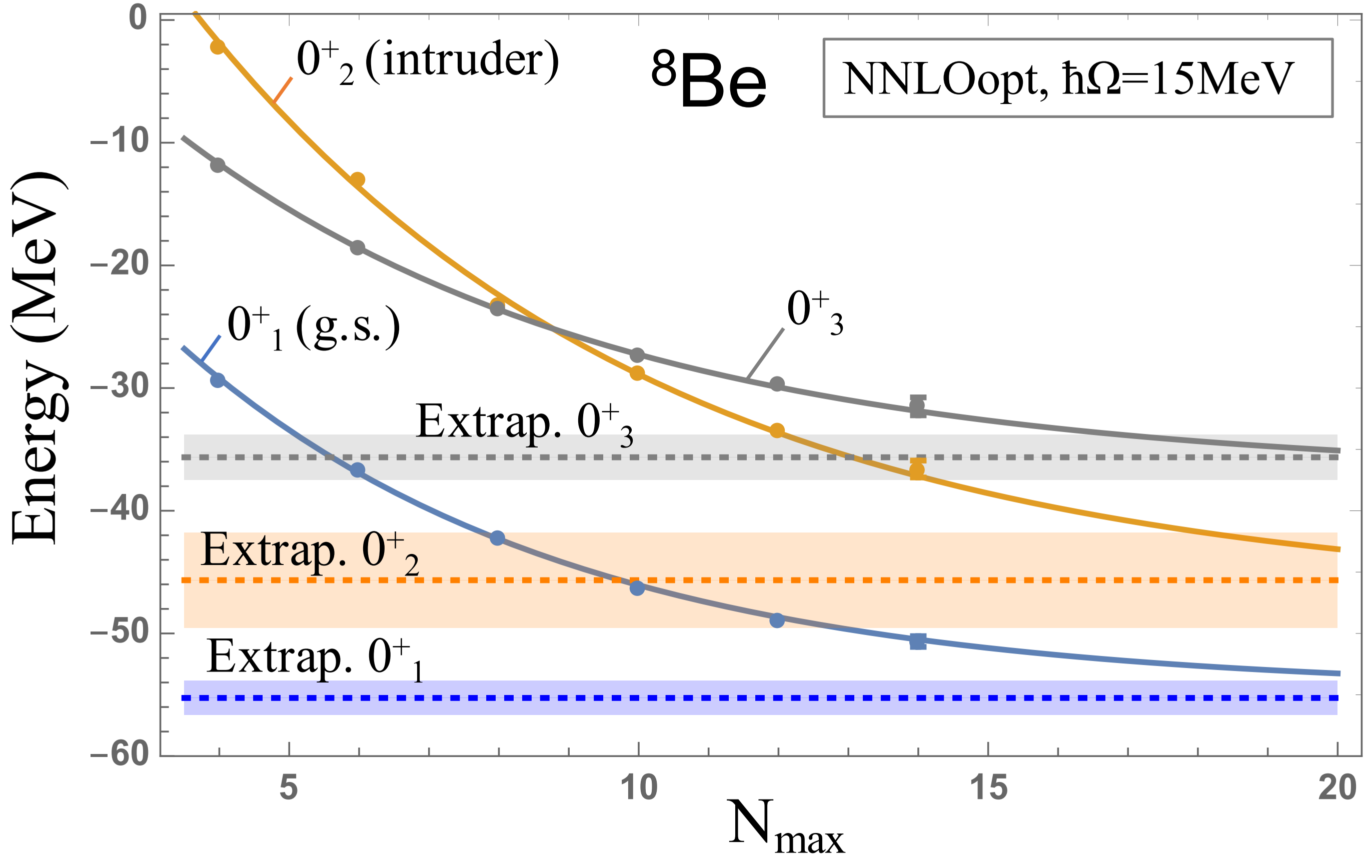


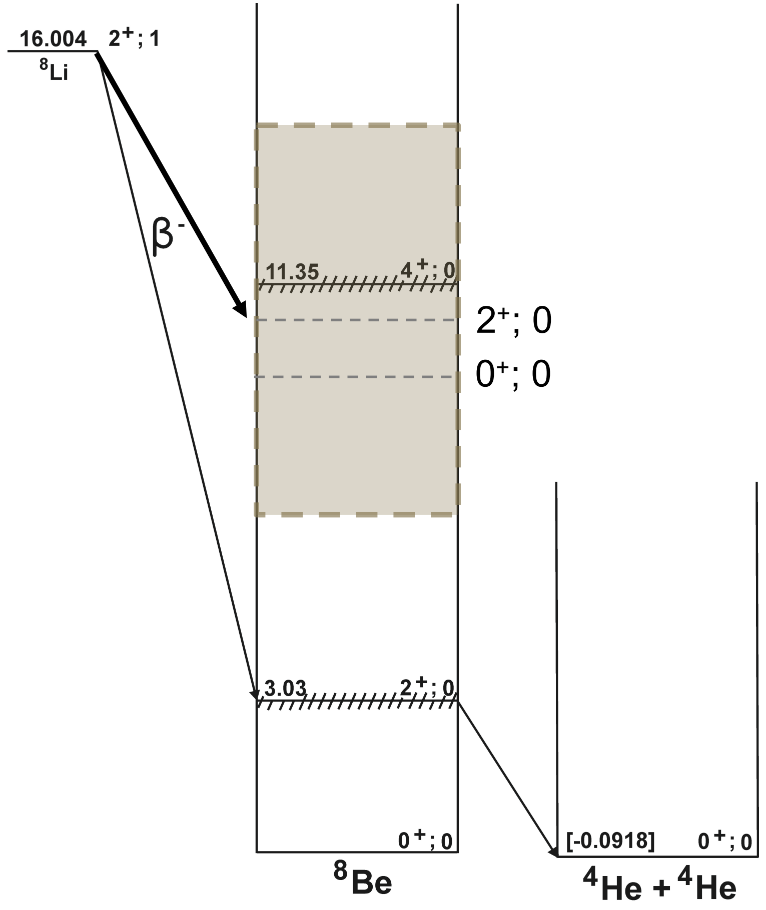
For ^{8}Be the two experimental values of $|M_{GT}|$ differ by ~1.5 times

Non-renormalized interactions, unquenched g_A

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

E. Caurier,[1] P. Navrátil,[2] W. E. Ormand,[2] and J. P. Vary[3]
[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

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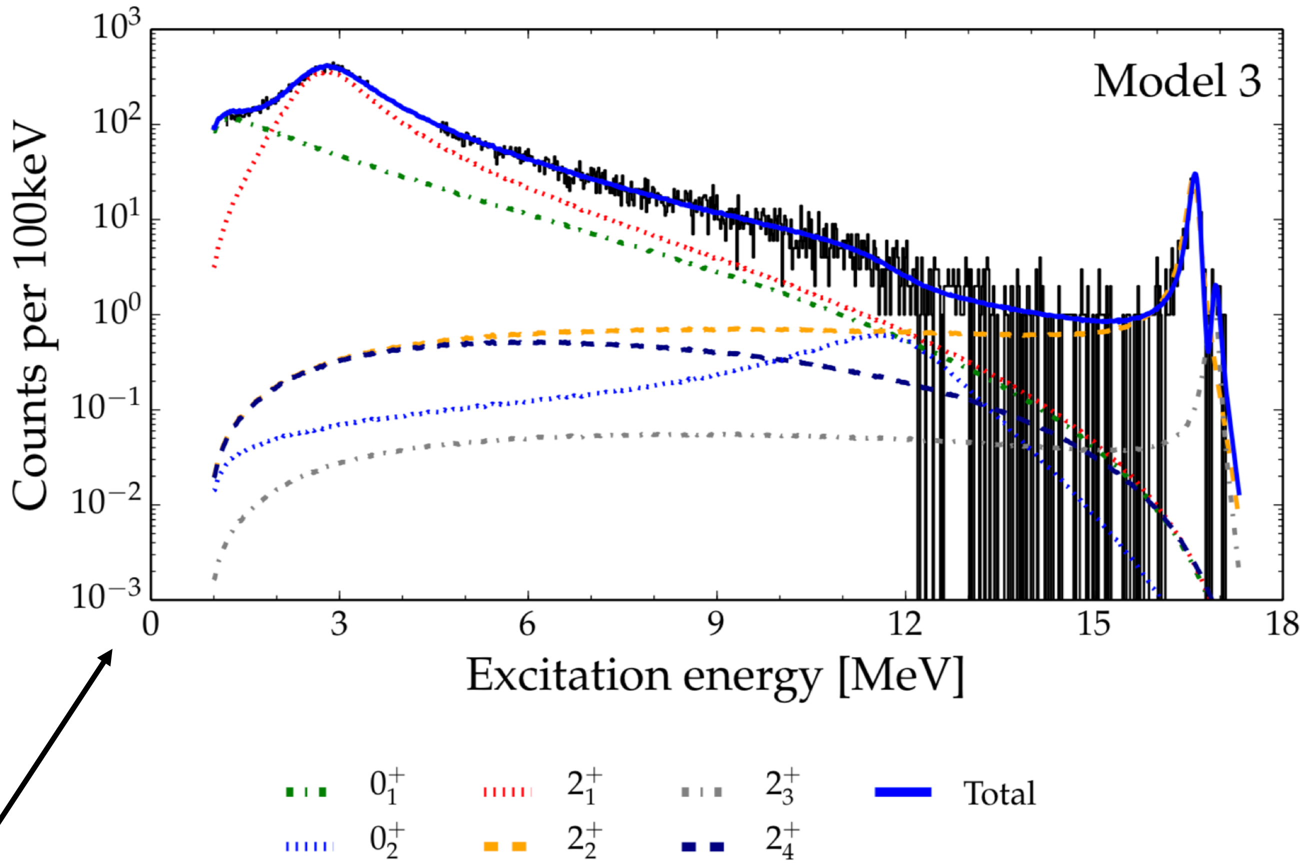
Light nuclei

ABSTRACT

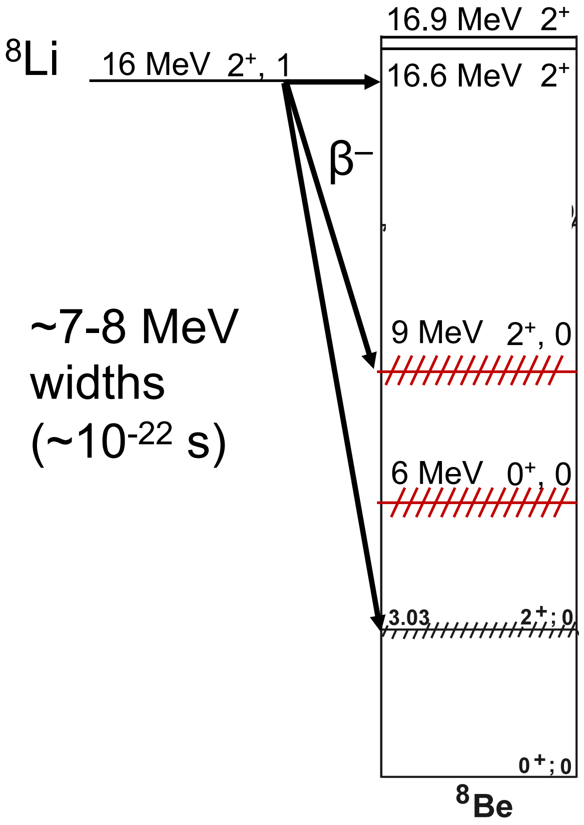
A current challenge for ab initio calculations is systems that contain large continuum contributions such as ^{8}Be. We report on new measurements of radiative decay widths in this nucleus that test recent Green's function Monte Carlo calculations.
Traditionally, γ ray detectors have been utilized to 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.

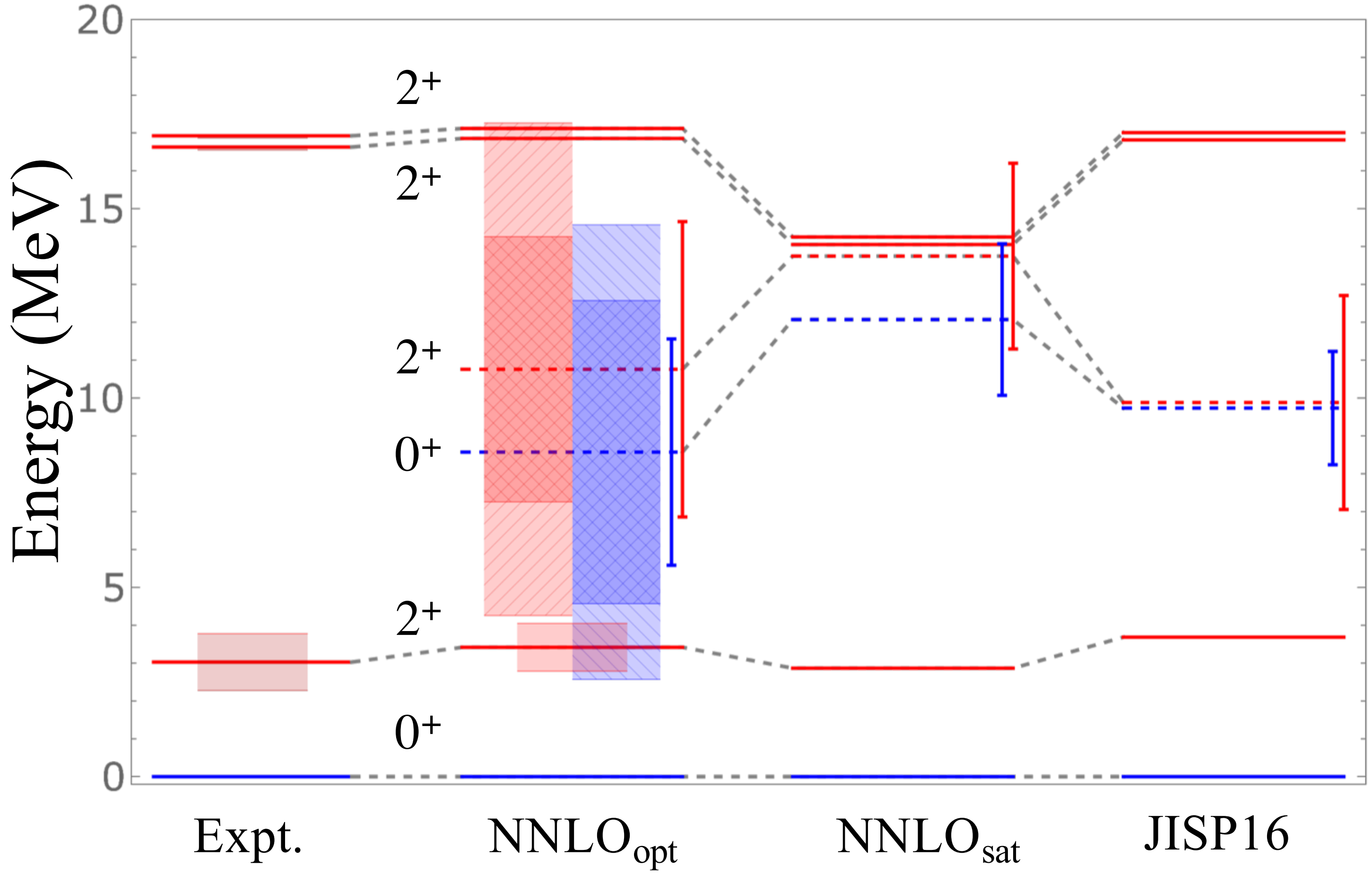


Munch et al., Phys. Lett. B 782 (2018) 779–784

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

- First proposed by Barker in 1968-69



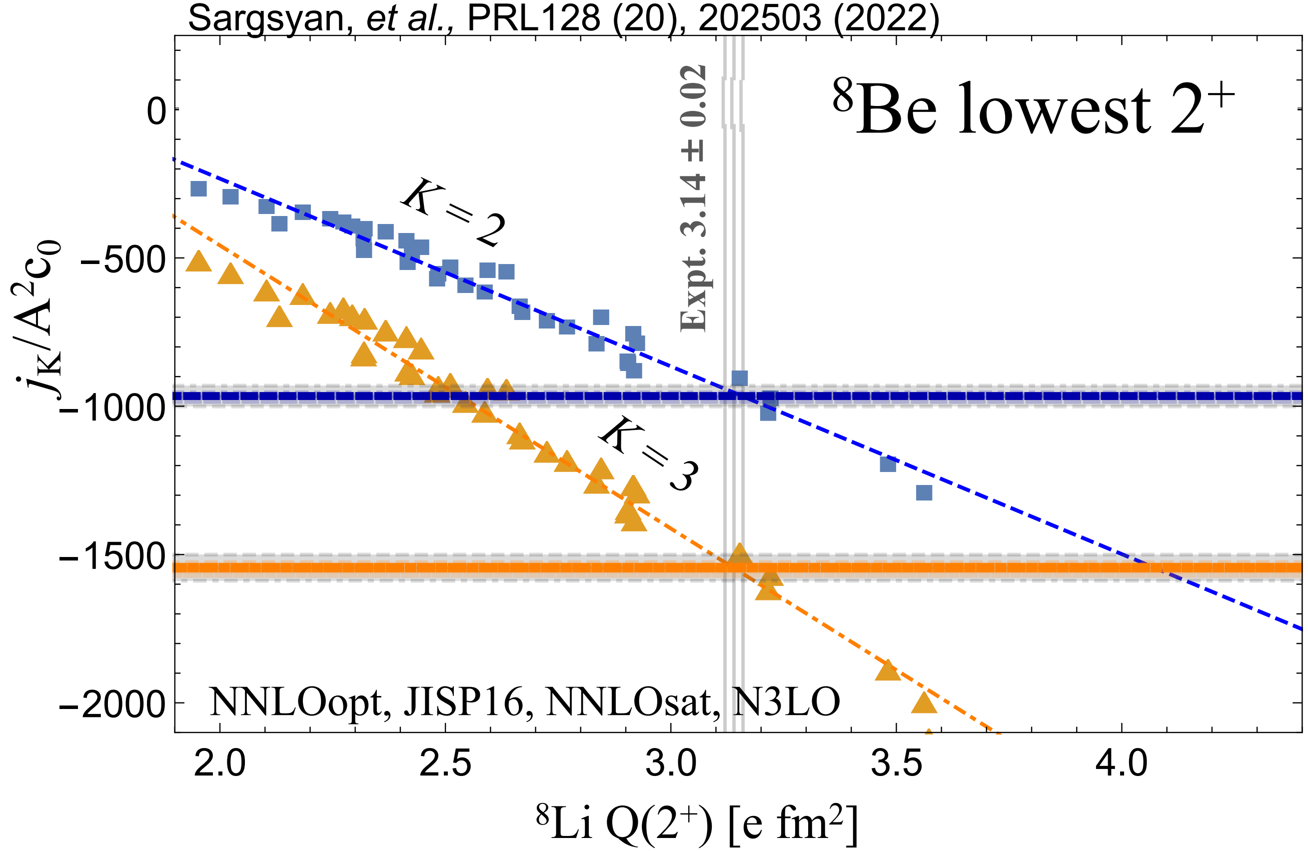


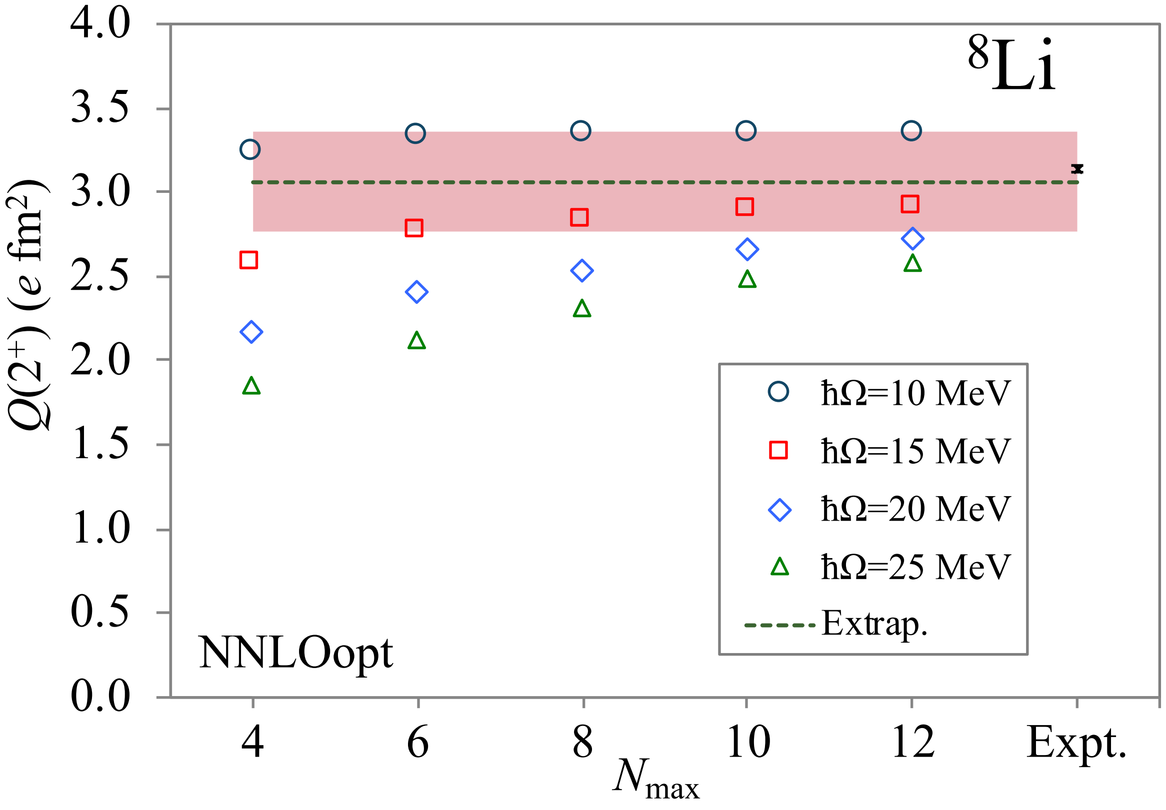
F. C. Barker. Australian Journal of Physics, vol. 21, 239–257, 1968.
F. C. Barker. Australian Journal of Physics, vol. 22, 293–316, 1969.

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

Correlation between j_K and Q helps constrain recoil order terms

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

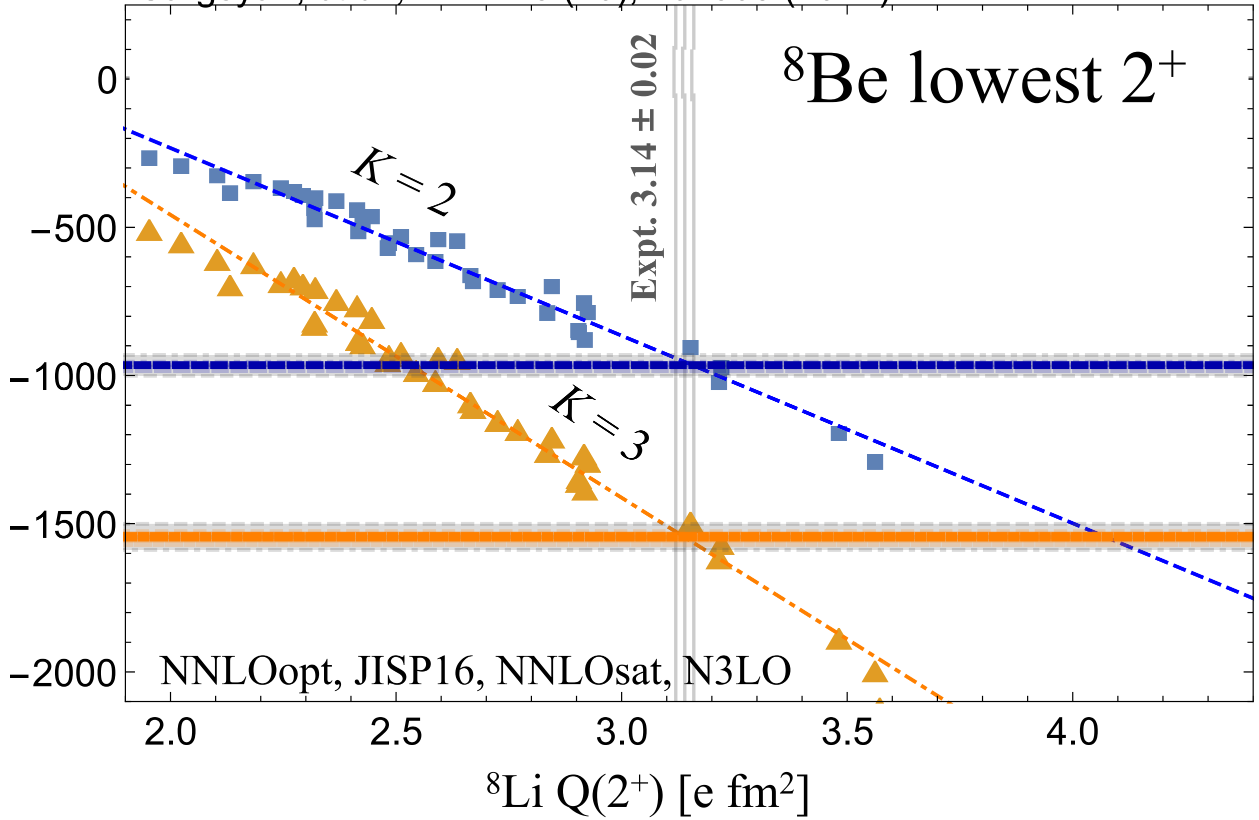




$$j_K \propto <\Psi_f|| \sum_i^A \tau_i^\pm [\sigma_i \times \hat{Q}_2(\hat{r}_i)]^K ||\Psi_0>$$ ⟵ Nuclear recoil term

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

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



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

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Total	$\mathbf{3.62 \times 10^{-3}}$

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
Theory	Recoil-Order Terms & Radiative Corrections	0.0015
Experiment	α-Energy Calibration	0.0007
Experiment	Detector Lineshape	0.0009
Experiment	Data Cuts	0.0009
Experiment	β Scattering	0.0010
Total		0.0028

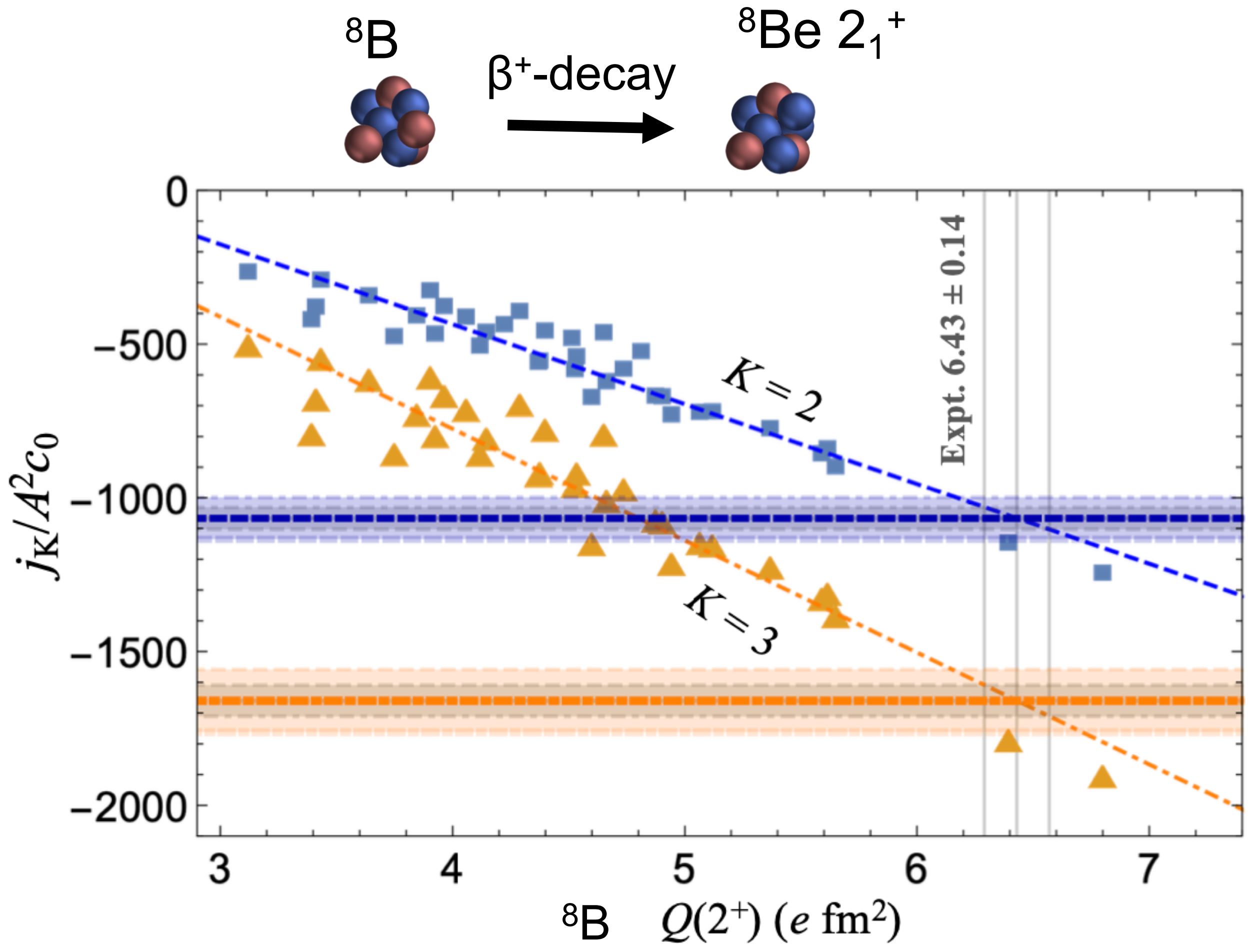
MT Burkey, *et al.* (incl. Sargsyan), PRL 128 (20), 202502 (2022).

The most precise constraint now →

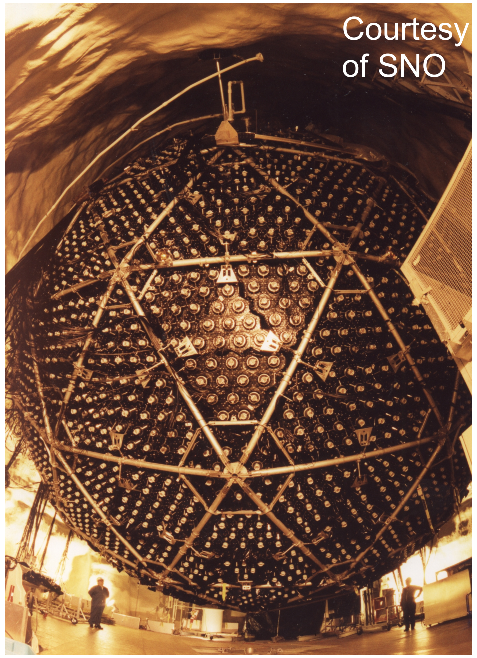
$|C_T/C_A|2 = -0.0012 \pm 0.0019\text{stat} \pm 0.0028\text{syst}$

$a_{\beta\nu} = -0.3325 \pm 0.0023$

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



Also important for precision measurements of solar neutrinos!



$|C_T/C_A|^2 = -0.0017 \pm 0.0029\text{stat} \pm 0.0031\text{syst}$

$a_{\beta\nu} = -0.3345 \pm 0.0028$

Longfellow, Gallant, Sargsyan, *et al.* PRL **132,** 142502 (2024).

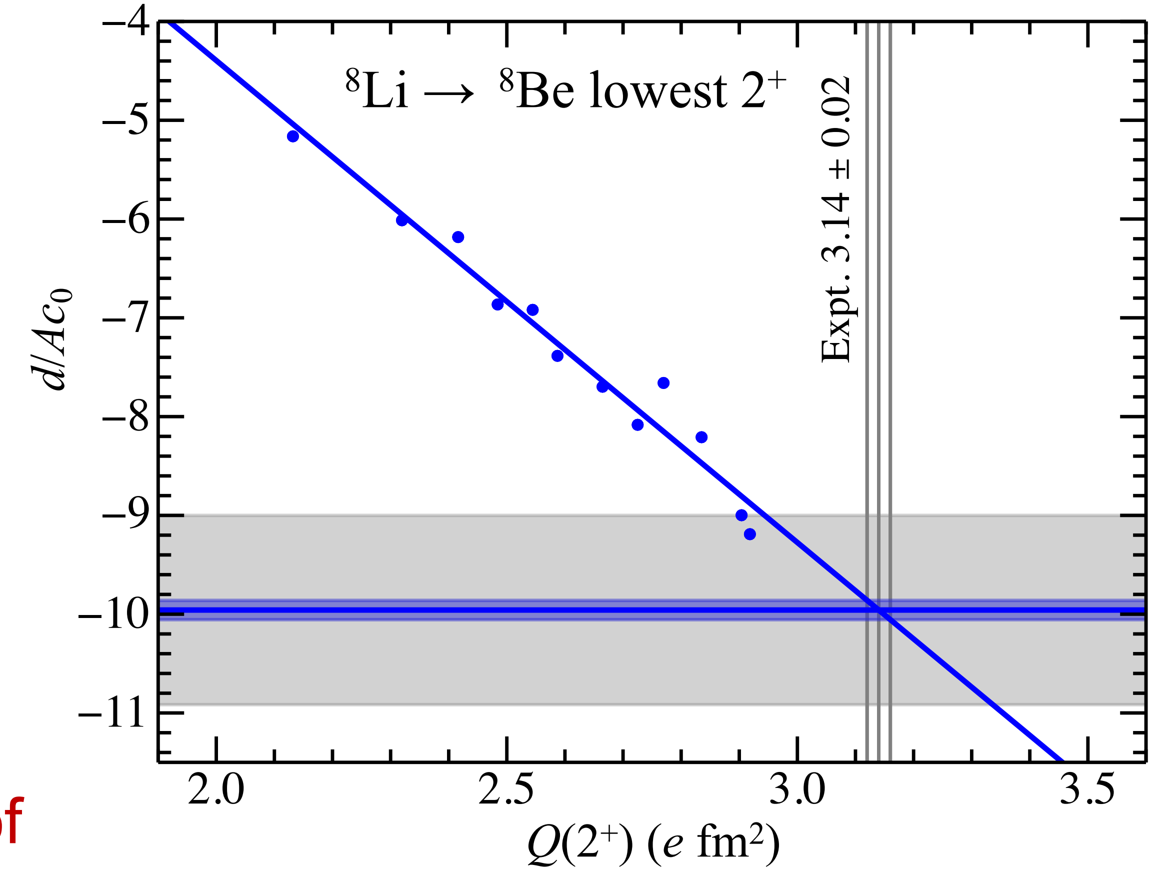
Weak magnetism and induced tensor recoil-order terms

- Weak magnetism (b) and induced tensor (d) recoil terms: next significant after j_2 and j_3

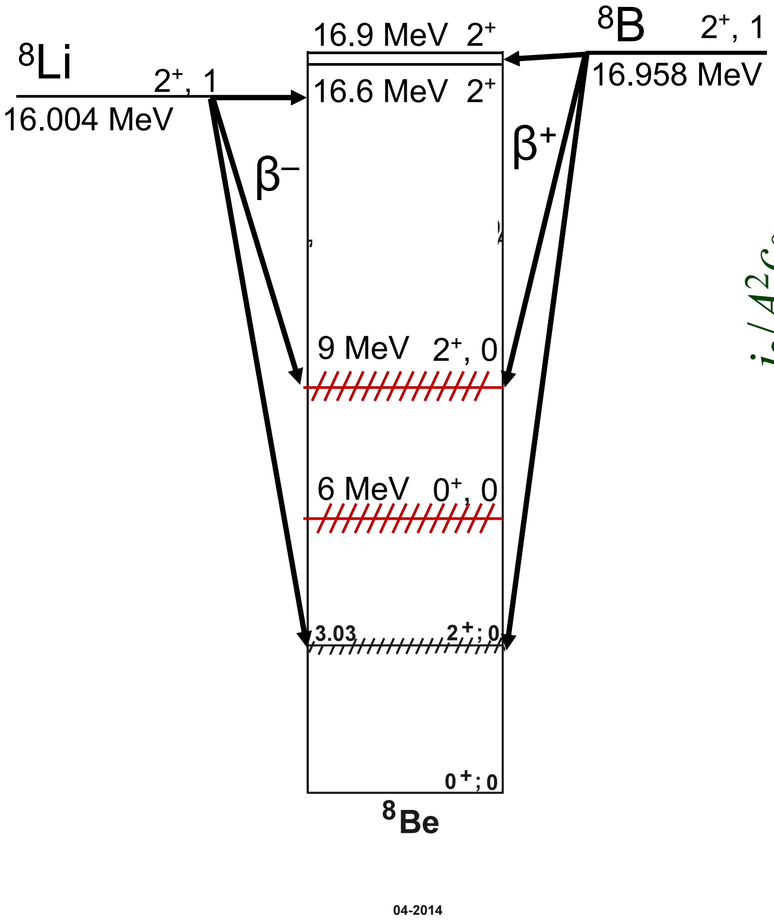
- Important for the tests of conserved vector current (CVC) hypothesis and existence of second class currents

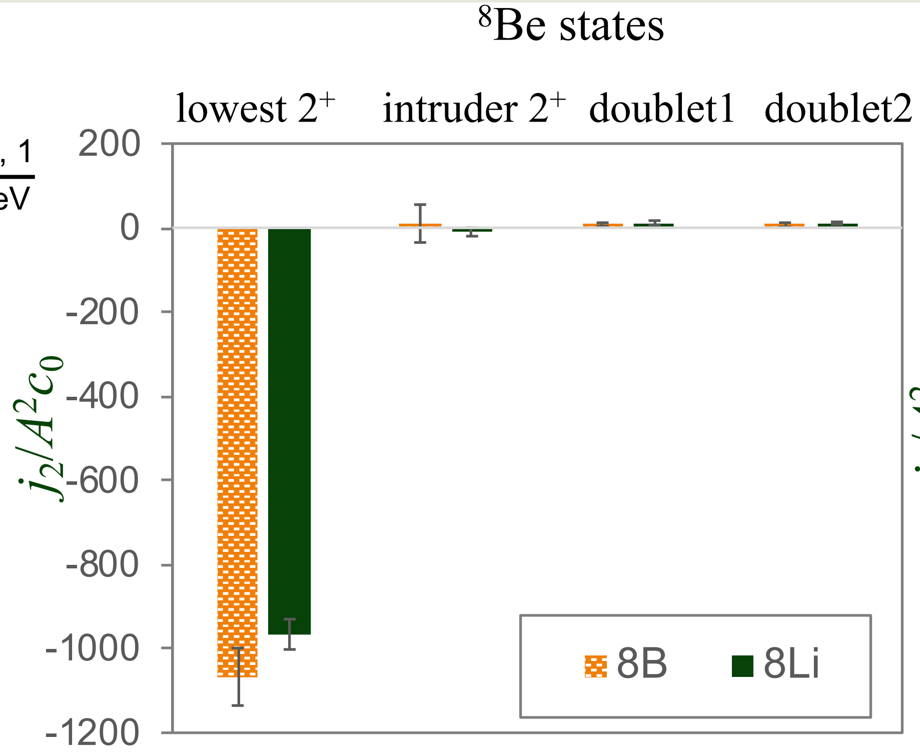
- With SA-NCSM we can calculate these beta decay recoil-order terms for up to intermediate mass nuclei

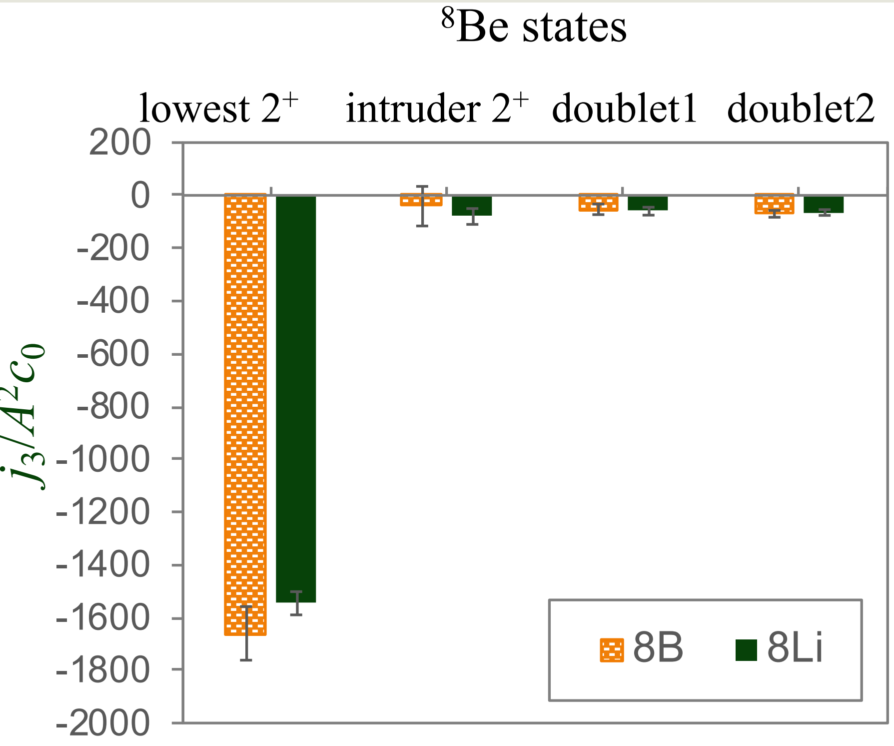
- We are currently working on calculations of b and d for $^{22}Na \Longrightarrow {}^{22}Ne$ beta decay



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







➢ j_2/A^2c_0 and j_3/A^2c_0 values for the lowest 2^+ are much larger than for other states!

Strong correlation between 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

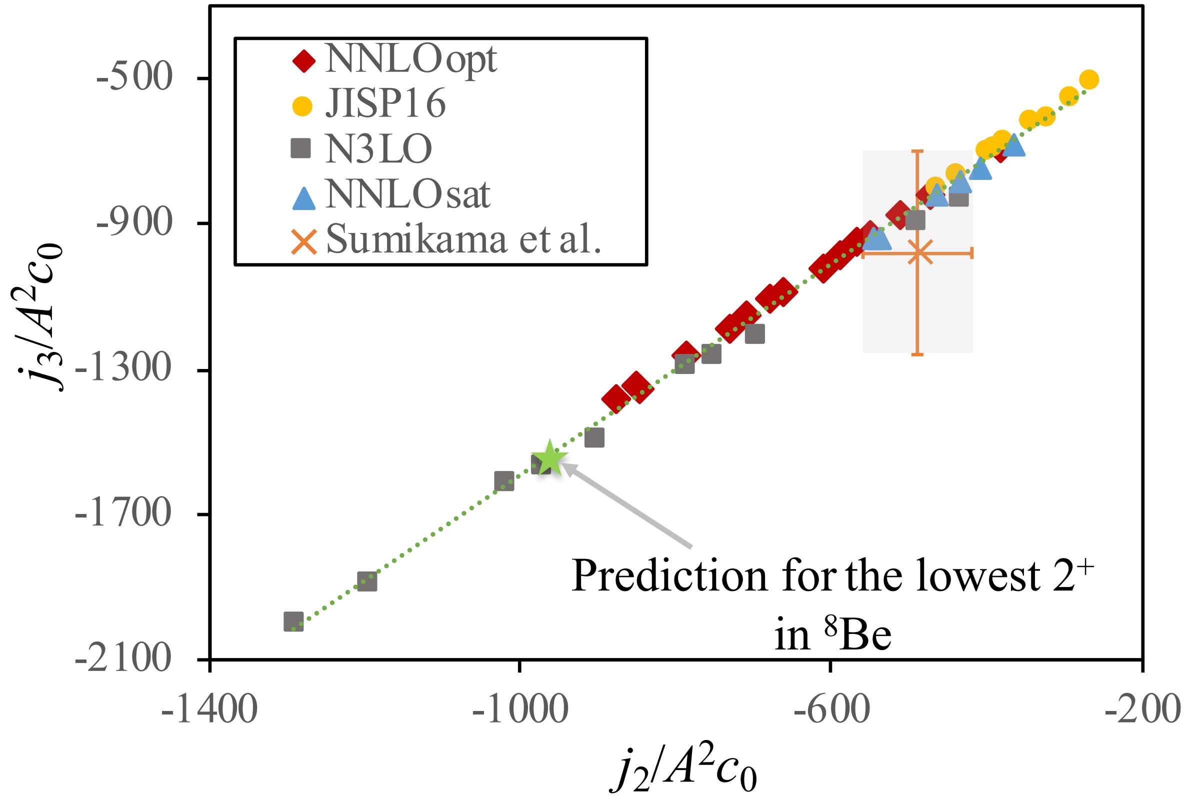
T. Sumikama,[1,2] K. Matsuta,[1] T. Nagatomo,[3] M. Ogura,[1] T. Iwakoshi,[1] Y. Nakashima,[1] H. Fujiwara,[1] M. Fu M. Mihara,[1] K. Minamisono,[4] T. Yamaguchi,[5] and T. Minamisono[6]

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

Extremely difficult measurements, hence "the obtained [recoil] terms were considered as the value averaged over the analyzed energy region"

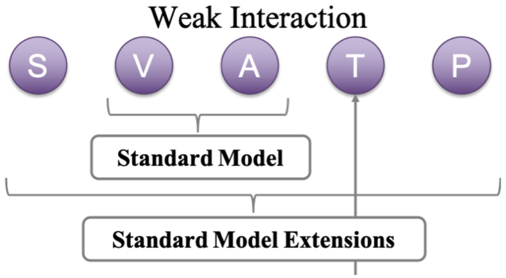
But energy dependence is important!!

Strong correlation between j_2 and j_3 recoil-order terms

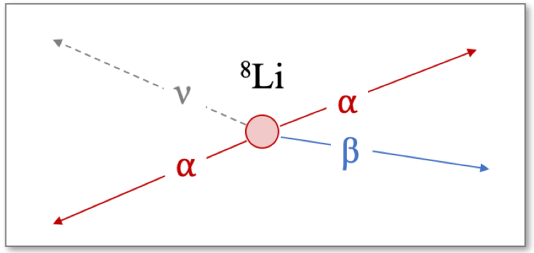


Summary

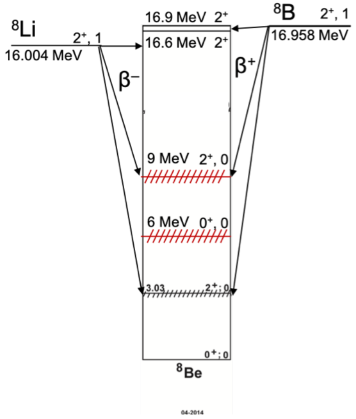
➢ Precision measurements of ^{8}Li and ^{8}B beta decays have recently set the most stringent limit on the tensor coupling in weak interactions in the low-energy regime



➢ *Ab initio* SA-NCSM calculations of ^{8}Li and ^{8}B beta decay recoil-order terms helped experiment to decrease systematic uncertainties



➢ 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

Acknowledgements

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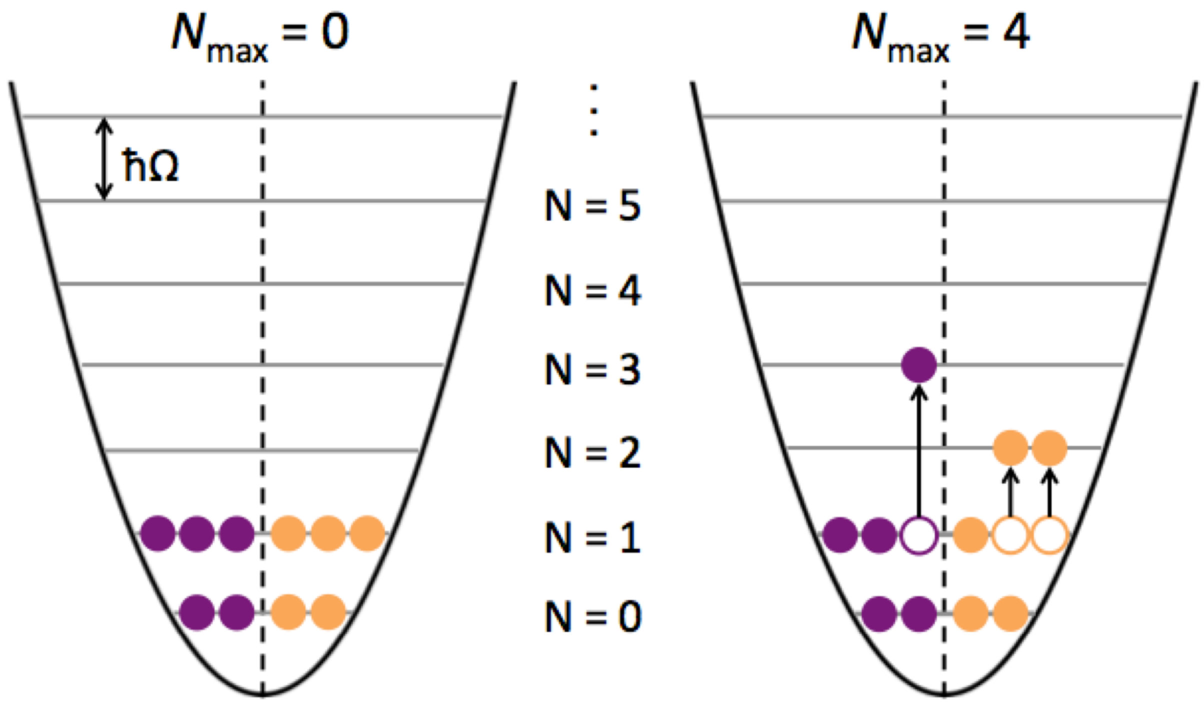
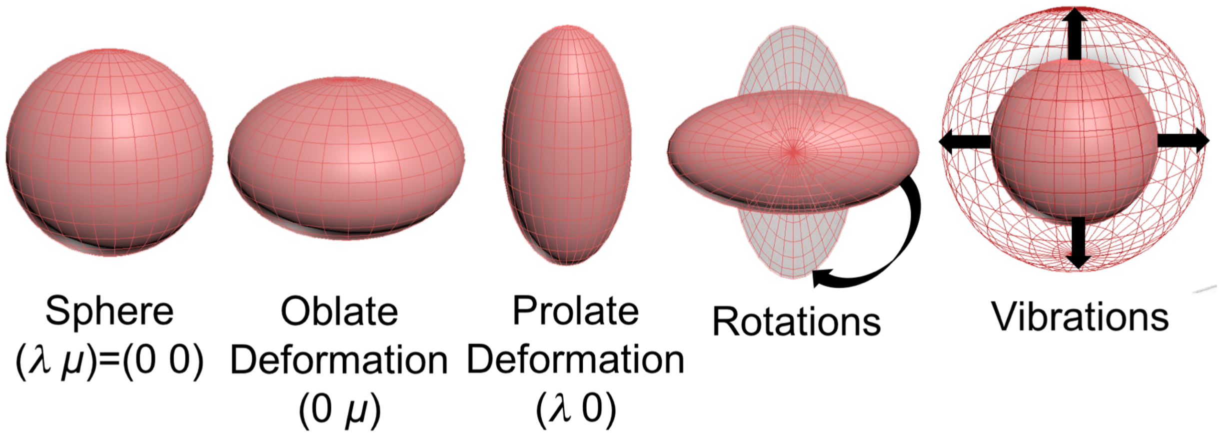
U.S. DEPARTMENT OF ENERGY

Experimental crew at the ATLAS facility at Argonne National Lab

Thank you!

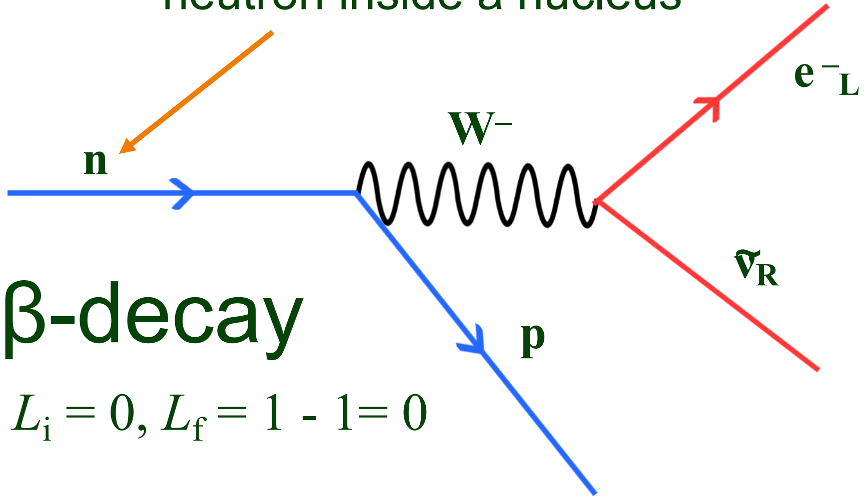
Backup slide zone





Beta decay as a probe for BSM studies

A free neutron or a
neutron inside a nucleus



β-decay

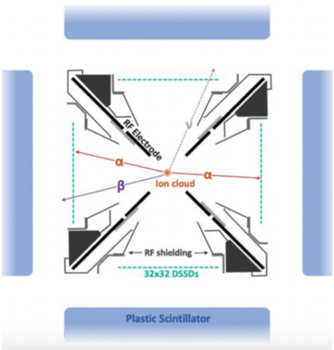
$L_i = 0, L_f = 1 - 1 = 0$

- Unitarity of the CKM quark mixing matrix

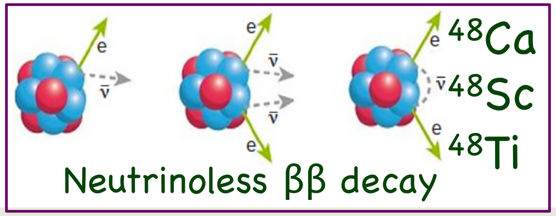
$$\begin{pmatrix} d_w \\ s_w \\ b_w \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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

- Beyond Standard Model (BSM) terms in weak interaction

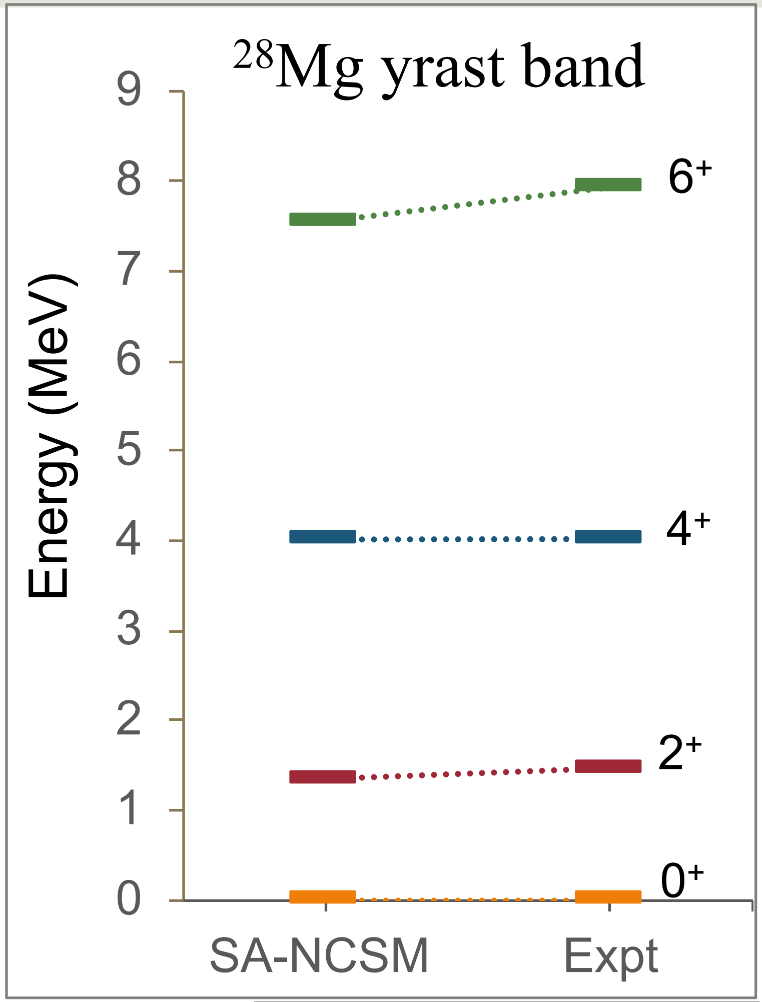


- Neutrinoless double beta decay

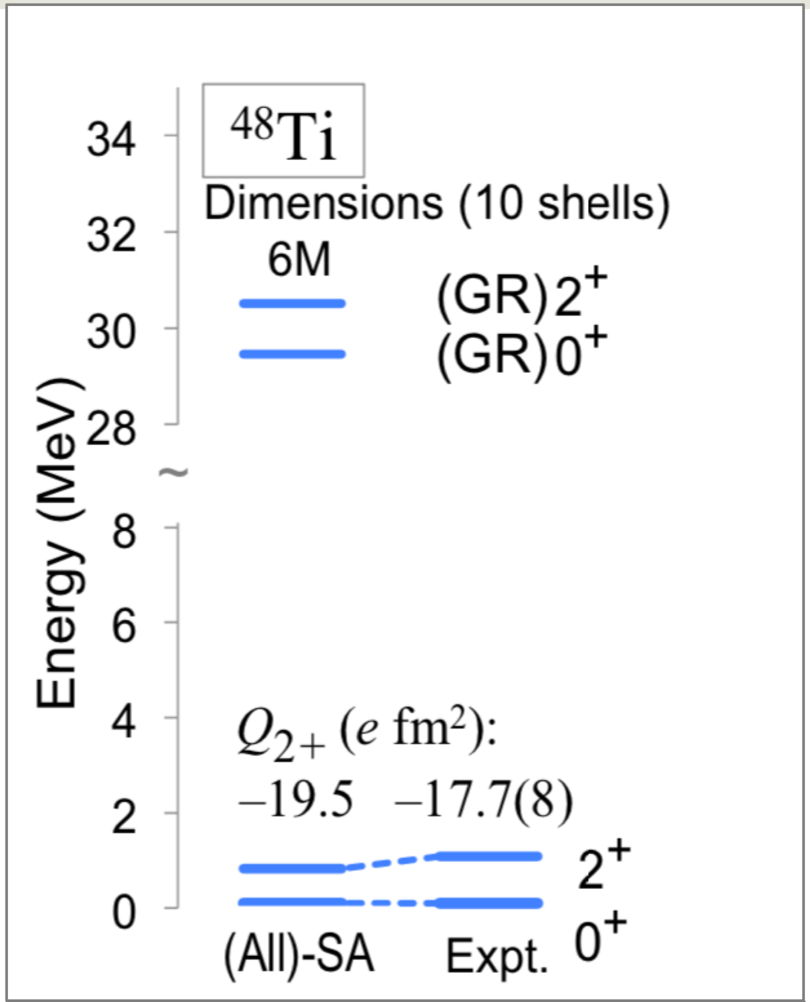


Precision measurements need input from nuclear theory

SA-NCSM can reach intermediate mass nuclei



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



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

Recoil-order terms in β-decay

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

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

Axial current matrix element

Leading order (Gamow-Teller)

Recoil-order q/M

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

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}
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)

For ^{8}Li and ^{8}B beta decay q/M ~ 0.002

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