Benchmarking aspects of weak interaction physics using beta decay and two-nucleon transfer experiments

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Symmetries of the weak interaction

$$\mathcal{L}^q_{\rm EW} = -eJ^\mu_{\rm em} - \frac{g}{2\sqrt{2}}\left\{W^+_\mu J^\mu_W + W^-_\mu J^{\mu\dagger}_W\right\} - \frac{g}{2\cos\theta_W} Z_\mu J^\mu_Z$$

Key assumption

- Only left-handed chiral fields in both the charged and neutral current sectors

- Left-right symmetric extensions to the Standard Model
  - Pati and Salam (1974)
  - Senjanović and Mohapatra (1975)
  - Shaban and Stirling (1992)
  - Herczeg (2001)

  } Right-handed weak Interactions

- There exists a direct connection between right-handed weak currents, the see-saw mechanism and $0\nu\beta\beta$ decays
  - Bilenky, Faessler, Potzel and Šimkovic (2011)
  - Rodejohaan (2011)
  - Štefánik, Dvornický, Šimkovic, and Vogel (2015)
  - Deppisch, Hati, Patra, Pritimita and Sarkar (2018)

Probing RHCs with atomic nuclei

$$d\Gamma \propto (E_0 - E)^2 pE \left\{ f_1(E) + f_4(E) \frac{\langle \boldsymbol{J} \rangle}{J} \cdot \frac{\boldsymbol{p}}{E} + \cdots \right\} dE\, d\Omega_e$$

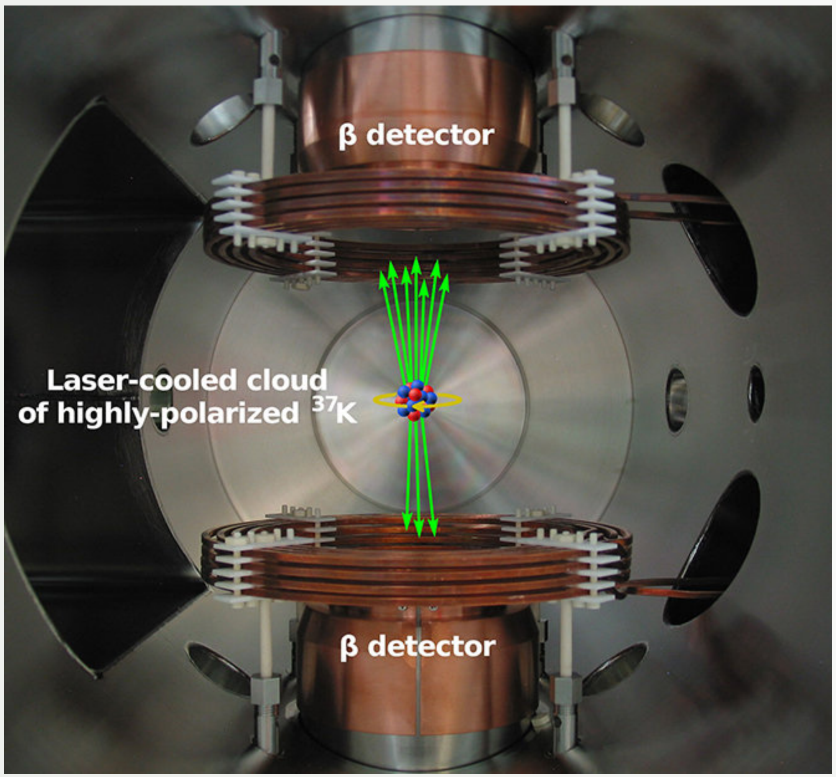
Holstein and Treiman, Phys. Rev. C 3, 1921 (1971)

$$f_1 \to f_1 + x^2 a^2 + y^2 c^2,$$

$$f_4 \to f_4 - \frac{y^2 c^2}{J+1} - 2\sqrt{\frac{J}{J+1}}\, xyac$$

RHC physics ⇒ $x \simeq \delta - \zeta;\; y \simeq \delta + \zeta$

Bég, Budny, Mohapatra, and Sirlin, Phys. Rev. Lett. 38, 1252 (1977)



TRINAT at TRIUMF
(picture from phys.org)

Isotope	$j = j'$	$f_V t$ (s)	Y_0	A_0	$\varepsilon_{\zeta\zeta}$
^{3}H	1/2	1141.3(21)	0.4778(6)	−0.9919(1)	−1.095
^{11}C	3/2	3972.0(141)	1.3532(69)	−0.5992(2)	0.472
^{13}N	1/2	4694.5(193)	1.801(16)	−0.3330(2)	0.943
^{15}O	1/2	4407.4(80)	−1.5944(53)	0.7080(17)	−0.532
^{17}F	5/2	2314.0(69)	−0.7776(19)	0.9972(2)	−0.357
^{19}Ne	1/2	1725.1(44)	0.6250(11)	−0.0396(9)	24.23
^{21}Na	3/2	4106.4(116)	−1.4206(62)	0.8617(18)	−0.308
^{23}Mg	3/2	4754.7(179)	1.852(16)	−0.5574(18)	0.324
^{25}Al	5/2	3743.1(76)	−1.2493(34)	0.9362(8)	−0.238
^{27}Si	5/2	4172.2(131)	1.4557(72)	−0.6973(8)	0.263
^{29}P	1/2	4869.1(181)	−1.956(18)	0.6060(45)	−0.456
^{31}S	1/2	4860.9(274)	1.949(27)	−0.3301(7)	0.842
^{33}Cl	3/2	5668.6(127)	3.463(52)	−0.3821(44)	0.161
^{35}Ar	3/2	5717.7(142)	−3.674(68)	0.4201(72)	−0.131
^{37}K	3/2	4591.3(302)	1.721(23)	−0.5720(24)	0.353
^{39}Ca	3/2	4347.3(111)	−1.5567(69)	0.8213(20)	−0.285
^{41}Sc	7/2	2873.4(84)	−0.9377(26)	0.9983(2)	−0.237

B. Fenker et al, Phys. Rev. Lett 120 062502 (2018)

Naviliat-Cuncic, Girard, Deutsch and Severijns, J. Phys. G: Nucl. Part. Phys. 17 919 (1991)

Probing RHCs with ^{19}Ne β decay

$$d\Gamma \propto (E_0 - E)^2 pE \left\{ f_1(E) + f_4(E)\frac{\langle \boldsymbol{J} \rangle}{J} \cdot \frac{\boldsymbol{p}}{E} + \cdots \right\} dE\, d\Omega_e$$

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$$A_\beta(E) = \left[\frac{f_4(E)}{f_1(E)} \right]$$

Beta asymmetry

RHC physics → $x \simeq \delta - \zeta;\ y \simeq \delta + \zeta$

Year	Reference	$A_\beta(0)$	A_β
1963	Commins and Dobson	...	−5.7(5)
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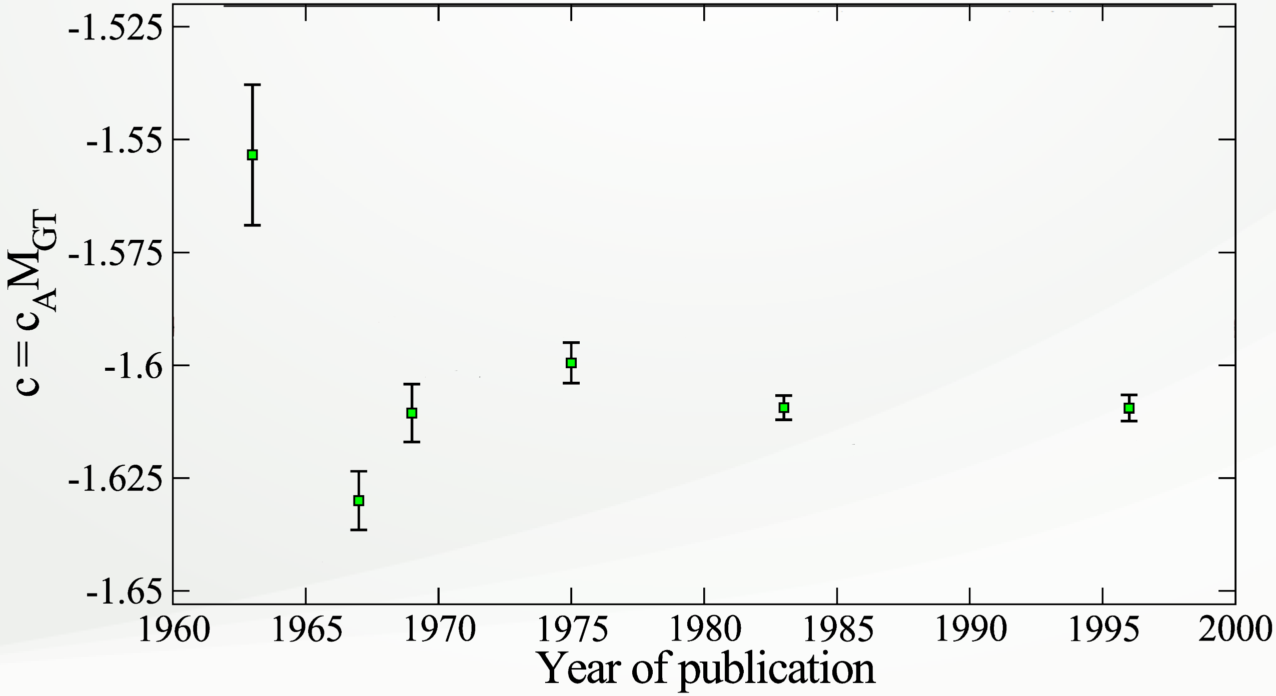

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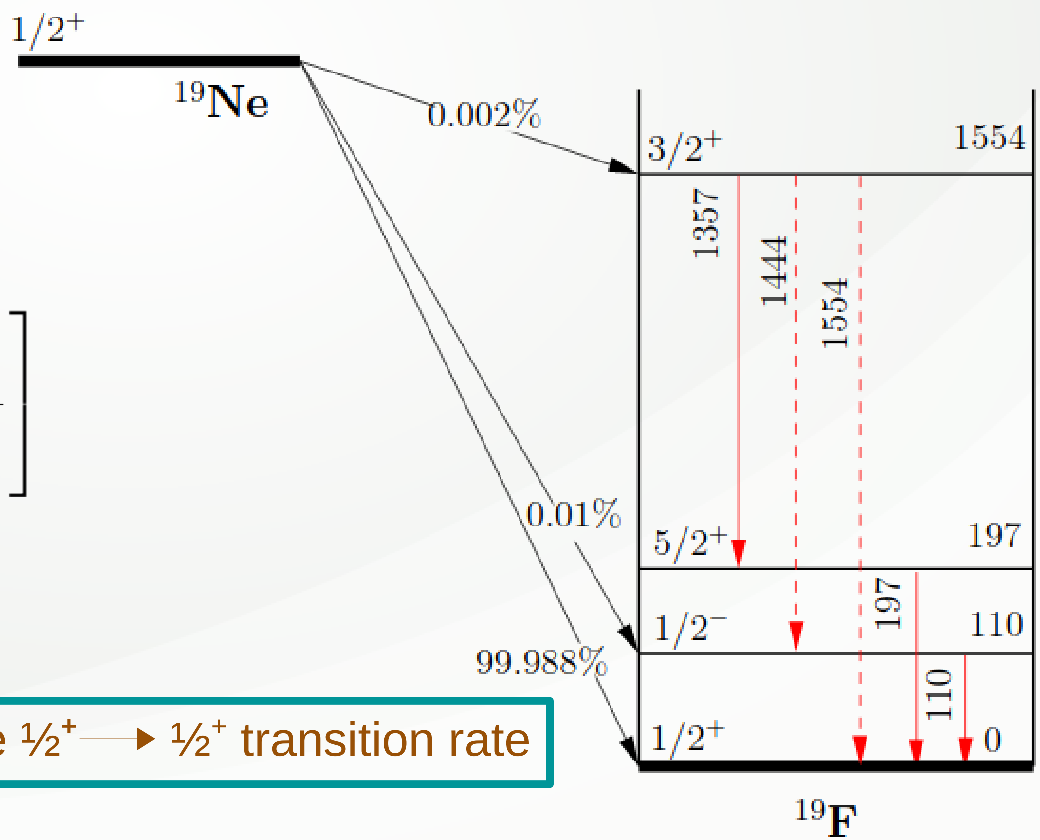
RHC physics $\Rightarrow$ $x \simeq \delta - \zeta;\ y \simeq \delta + \zeta$

$$R = \left(\frac{\mathcal{F}t^{0^+ \to 0^+}}{\mathcal{F}t^{^{19}\mathrm{Ne}}} \right)$$

$$\simeq \left[\frac{a^2(1+x^2) + \left(\frac{f_A}{f_V}\right) c^2 (1+y^2) + r_i}{2a^2(1+x^2)} \right]$$



Motivation I

Need a high precision determination of the ½⁺ → ½⁺ transition rate

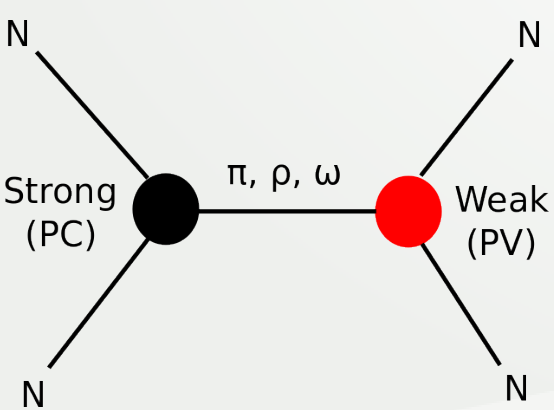
Symmetries of the weak interaction

$$\mathcal{L}_{\mathrm{EW}}^{q} = -eJ^{\mu}_{\mathrm{em}} - \frac{g}{2\sqrt{2}}\left\{W^{+}_{\mu}J^{\mu}_{W} + W^{-}_{\mu}J^{\mu\dagger}_{W}\right\} - \frac{g}{2\cos\theta_W}Z_{\mu}J^{\mu}_{Z}$$

Key assumption

- Only left-handed chiral fields in both the charged and neutral current sectors
- Flavor-conserving quark-quark weak interactions least understood
- Parity violation → filter to isolate weak interaction effects

Theory



Desplanques, Donoghue and Holstein (DDH) meson exchange model for the NN potential

Ann. Phys. **124**, 449 (1980)

Experiment

- $A_L(\vec{p}, p)$: Bonn, Los Alamos, PSI, TRIUMF
- $A_L(\vec{p}, \alpha)$: PSI
- $P_\gamma(n, p)$: Gatchina
- $A_\gamma(\vec{n}, p)$: Los Alamos, Grenoble

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- χPT : Chiral perturbation theory
- EFT ($\not\pi$): Pionless EFT
- 1/Nc Expansion
- Lattice QCD

Gardner, Haxton and Holstein, Ann. Rev. Nucl. Part. Sci. **67**, 69 (2017),

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↳ NPDGamma Expt

D. Blyth et al., PRL **121**, 242002 (2018)

Symmetries of the weak interaction

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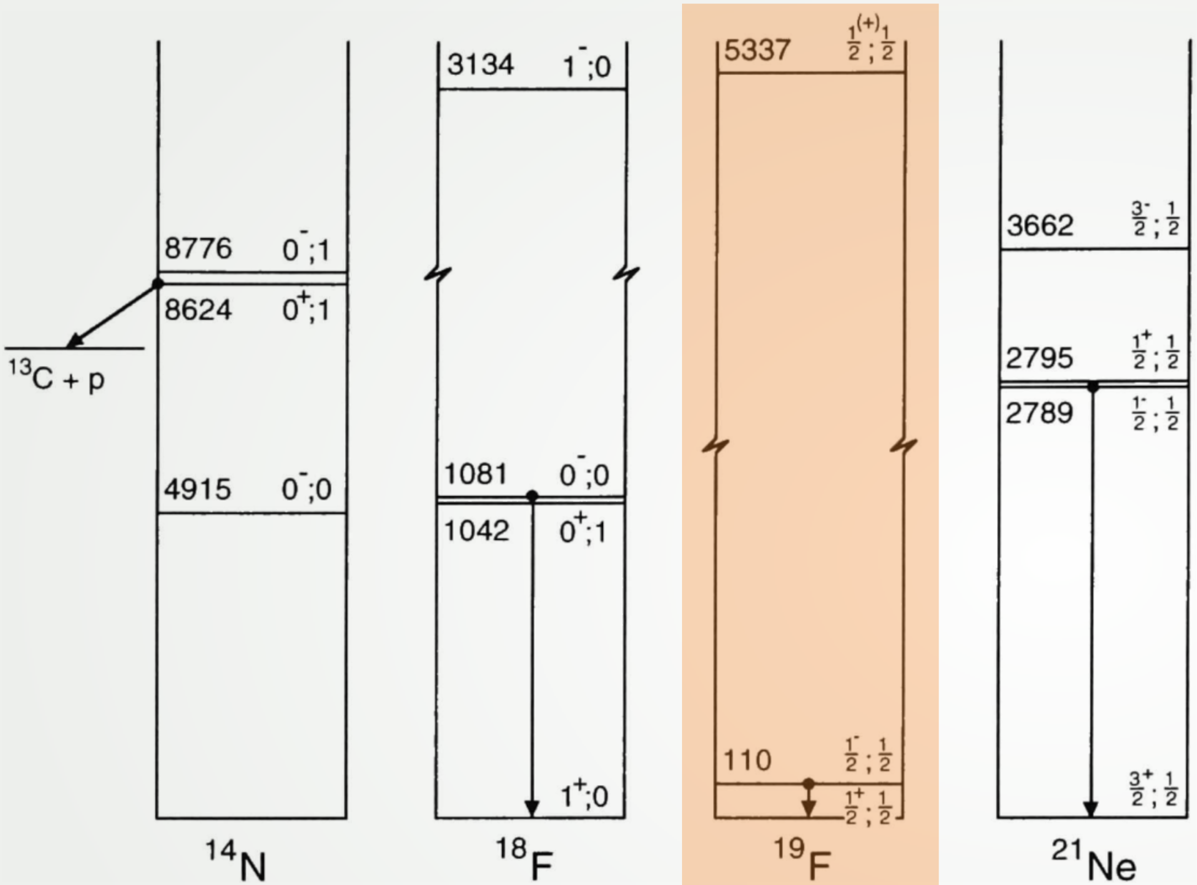
→ NPDGamma Expt

D. Blyth et al., PRL **121**, 242002 (2018)

Challenge

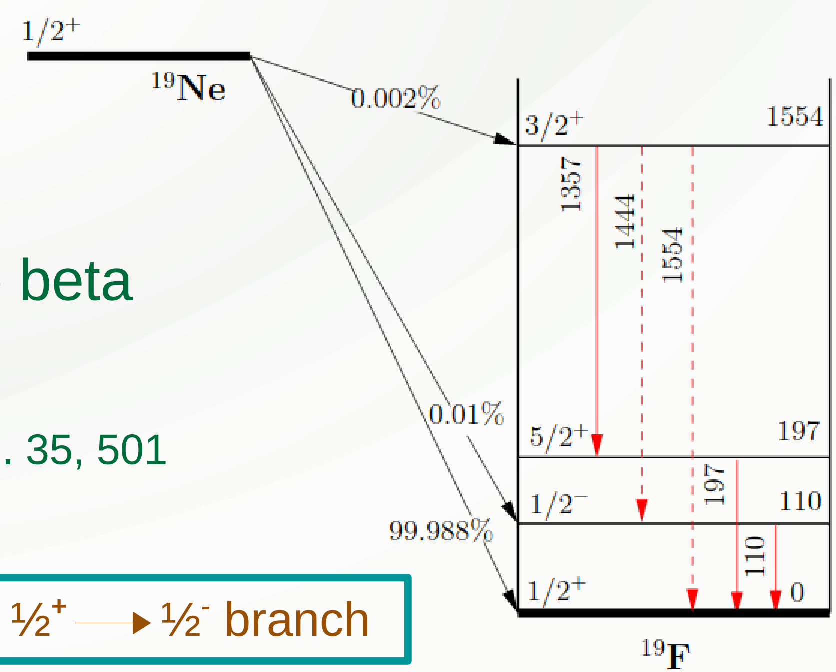
$H_{weak}/H_{strong} \sim 10^{-7}$

Parity doublets in light nuclei as amplifiers



$$|\psi_{J+}\rangle \simeq |\phi_{J+}\rangle + \frac{|\phi_{J-}\rangle\langle\phi_{J-}|H_{wk}|\phi_{J+}\rangle}{E_+ - E_-}$$
$$= |\phi_{J+}\rangle + \epsilon|\phi_{J-}\rangle,$$
$$|\psi_{J-}\rangle \simeq |\phi_{J-}\rangle + \frac{|\phi_{J+}\rangle\langle\phi_{J+}|H_{wk}|\phi_{J-}\rangle}{E_- - E_+}$$
$$= |\phi_{J-}\rangle - \epsilon|\phi_{J+}\rangle.$$

$$A_\gamma(^{19}\mathrm{F}) = \begin{cases} (-8.5 \pm 2.6) \times 10^{-5} & \text{Seattle} \\ (-6.8 \pm 1.8) \times 10^{-5} & \text{Zurich} \end{cases}$$



Matrix element calibrated using axial-charge beta decay

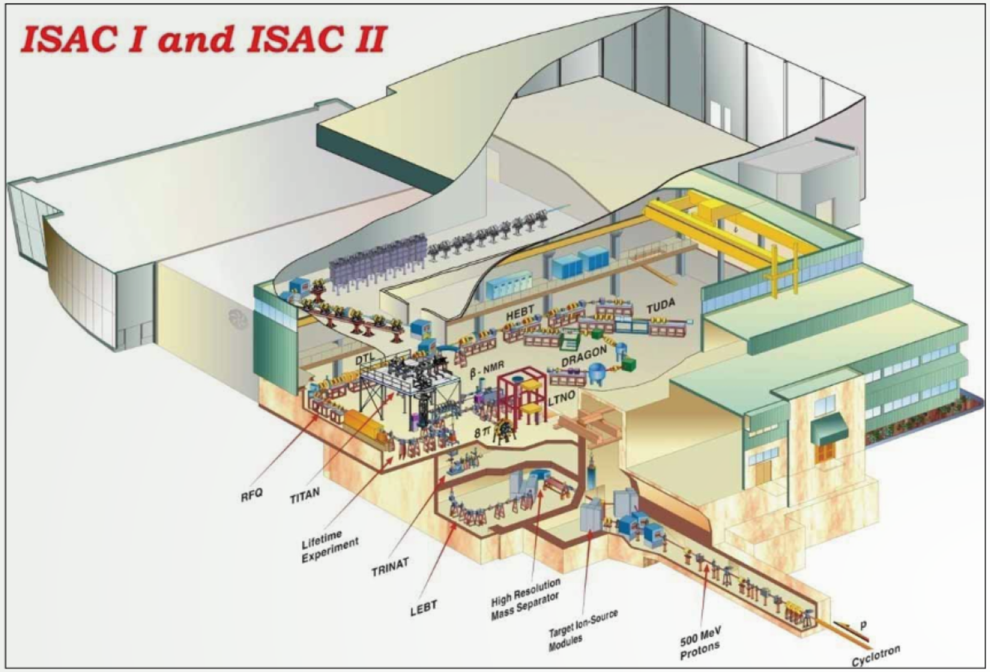
W. C. Haxton, PRL **46**, 698 (1981)

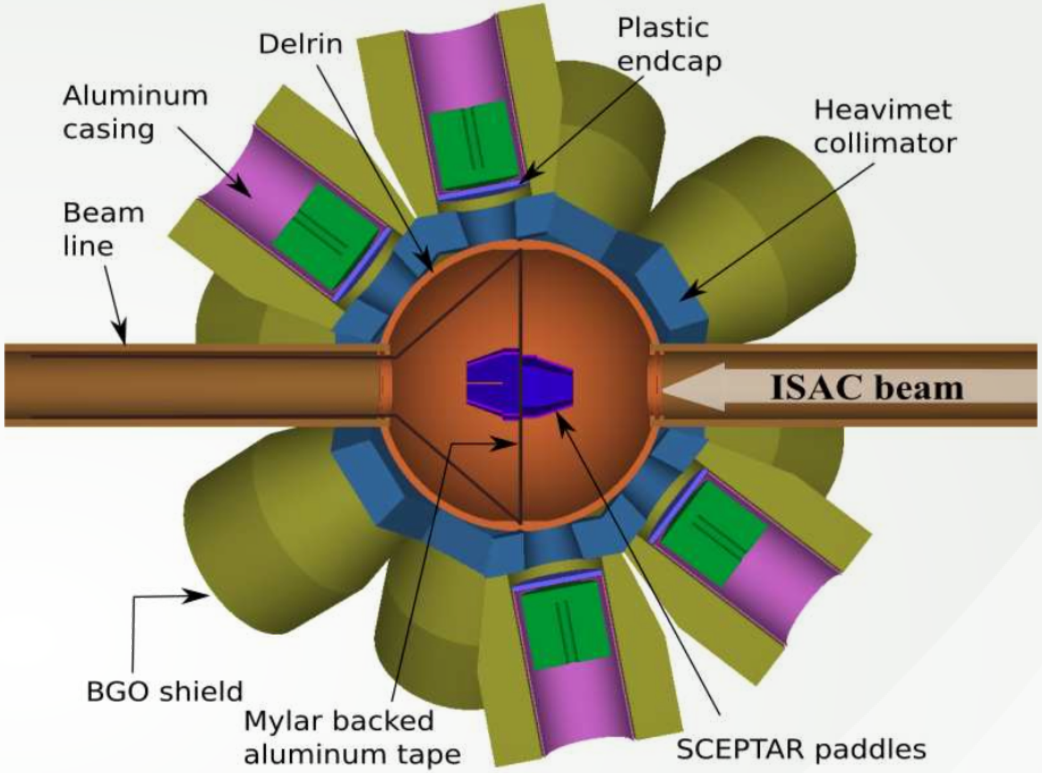
E. G. Adelberger and W. C. Haxton, Ann. Rev. Nucl. Part. Sci. 35, 501 (1985)

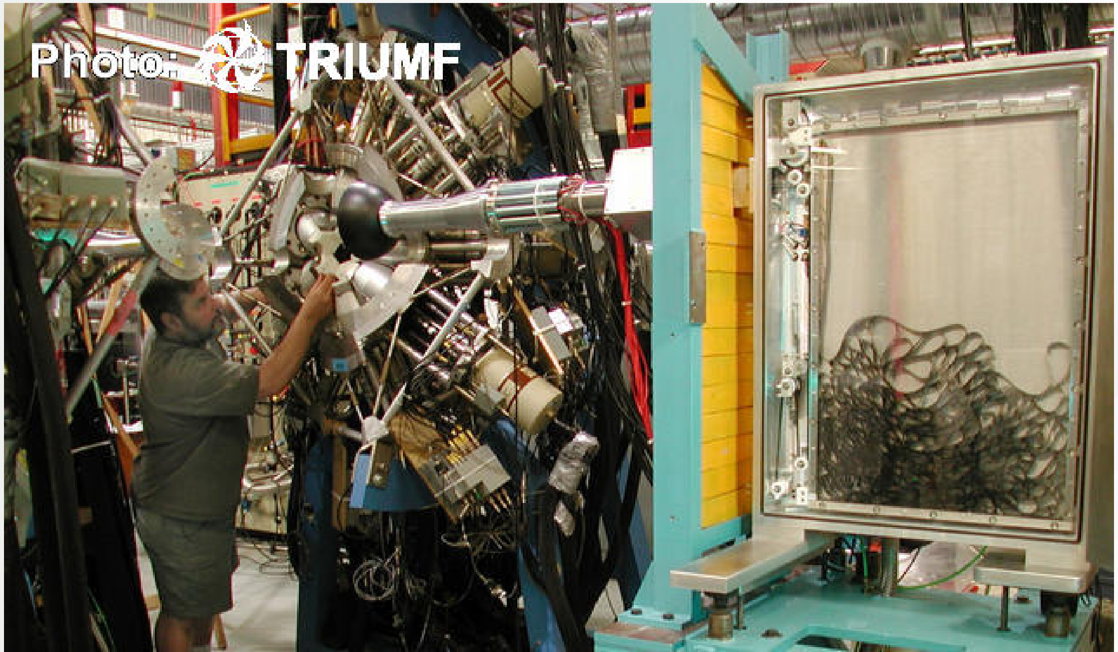
Motivation 2

Need a high precision determination of the $\frac{1}{2}^+ \rightarrow \frac{1}{2}^-$ branch

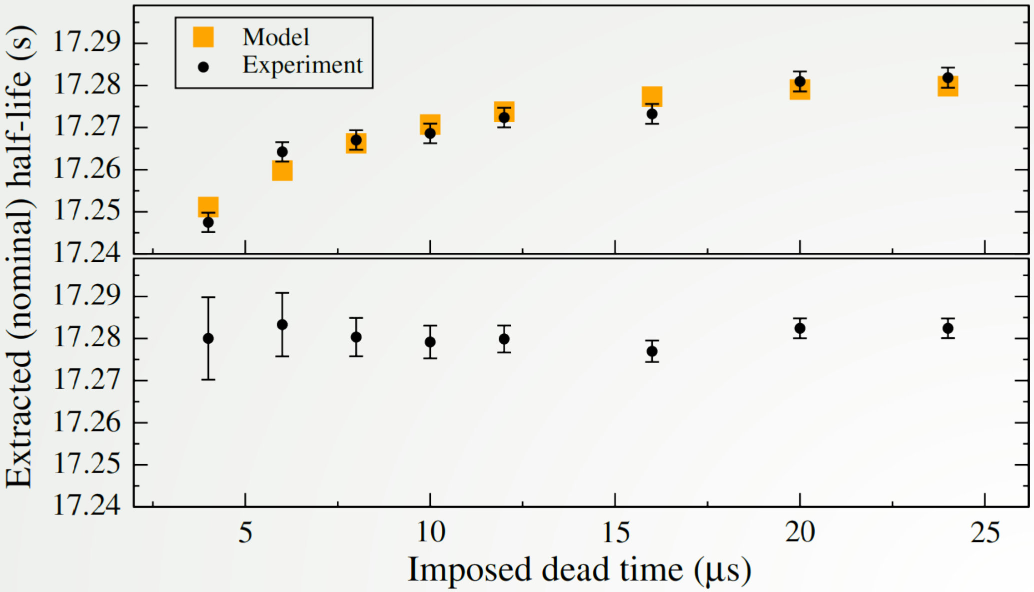
Experimental details (8π at TRIUMF)

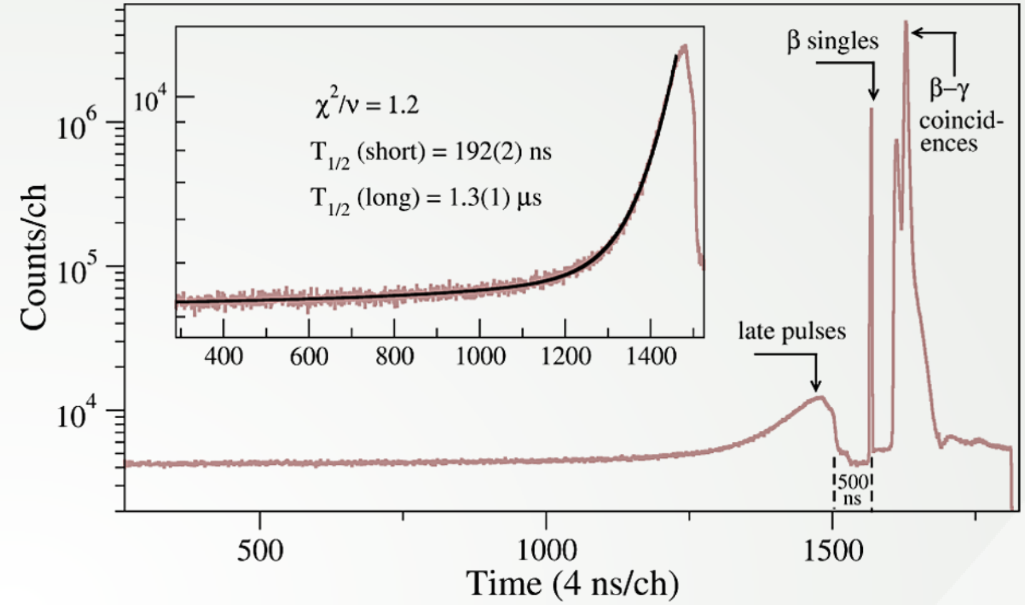


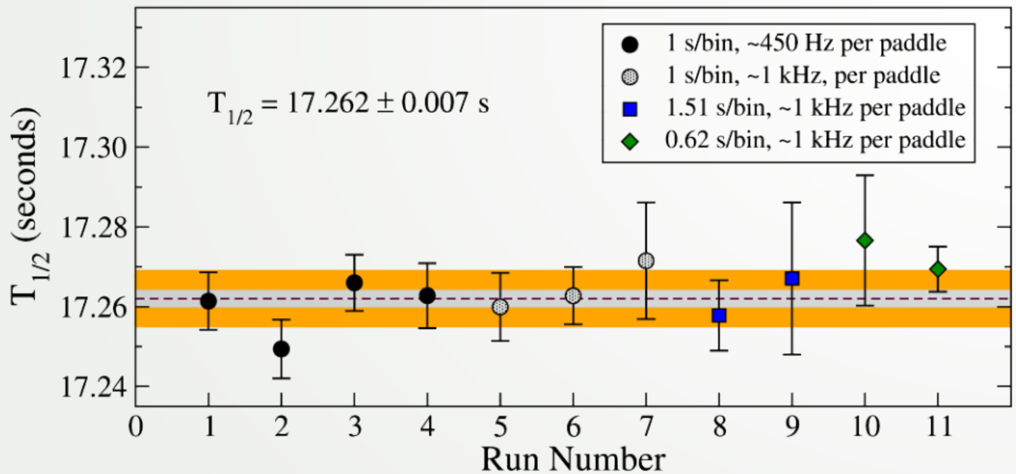


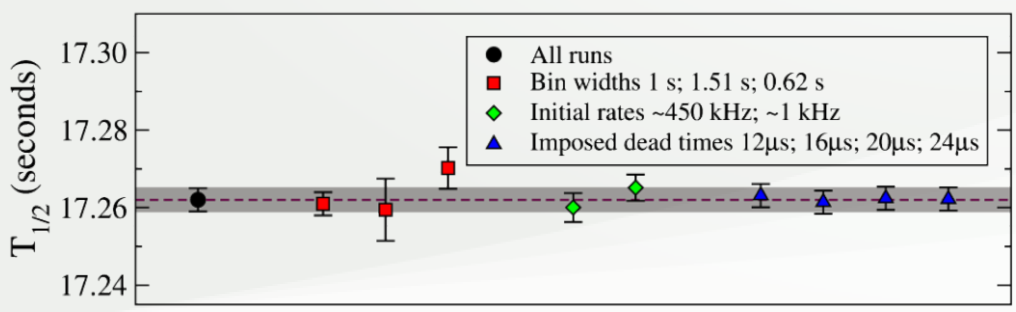


Half-life determination





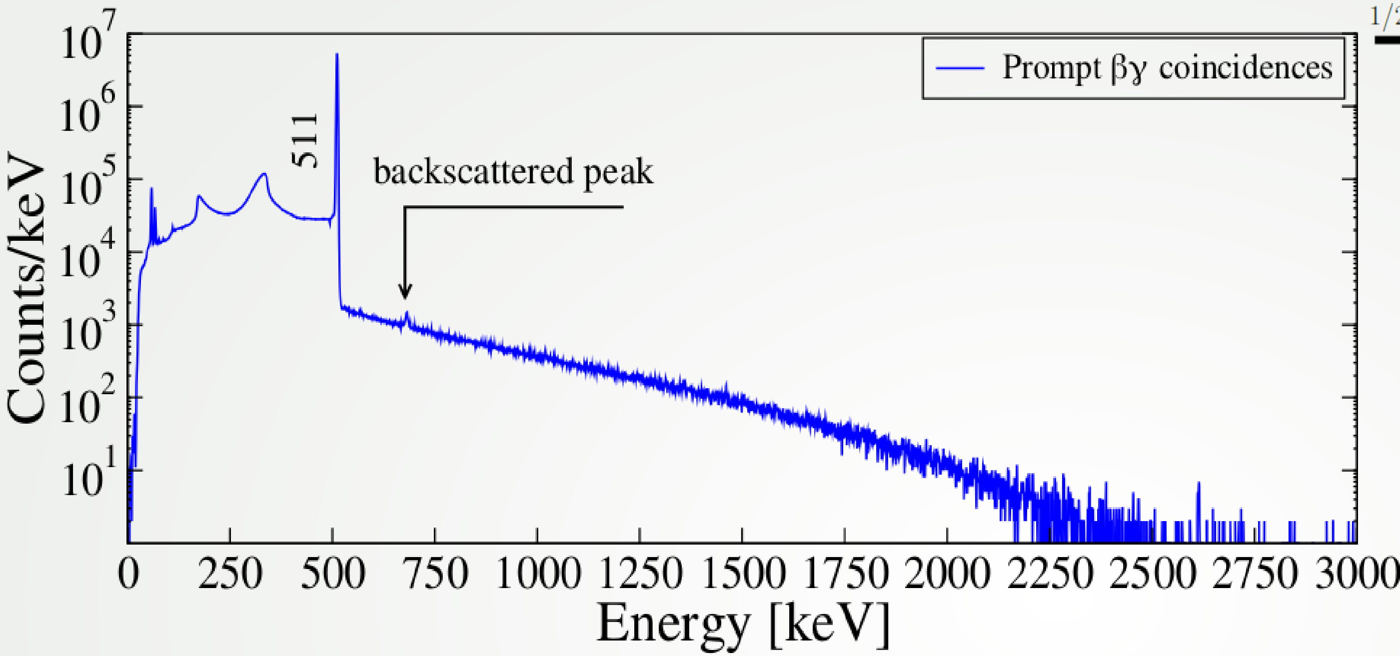


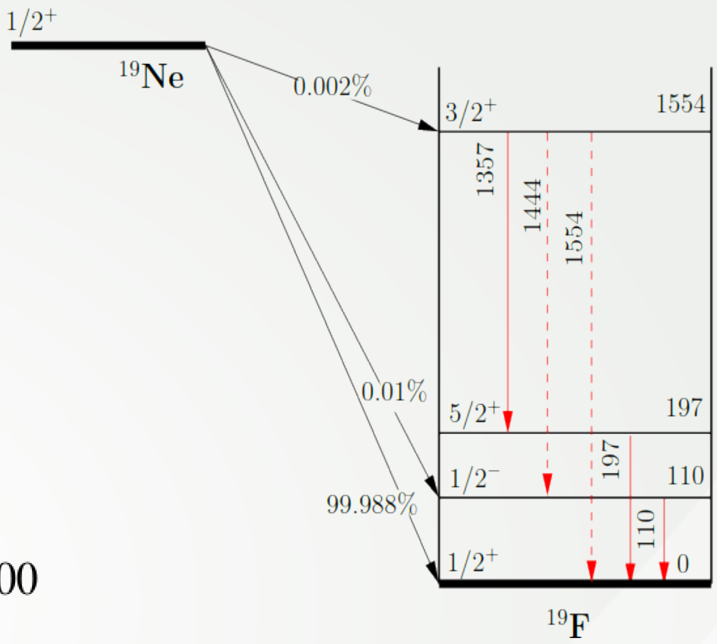


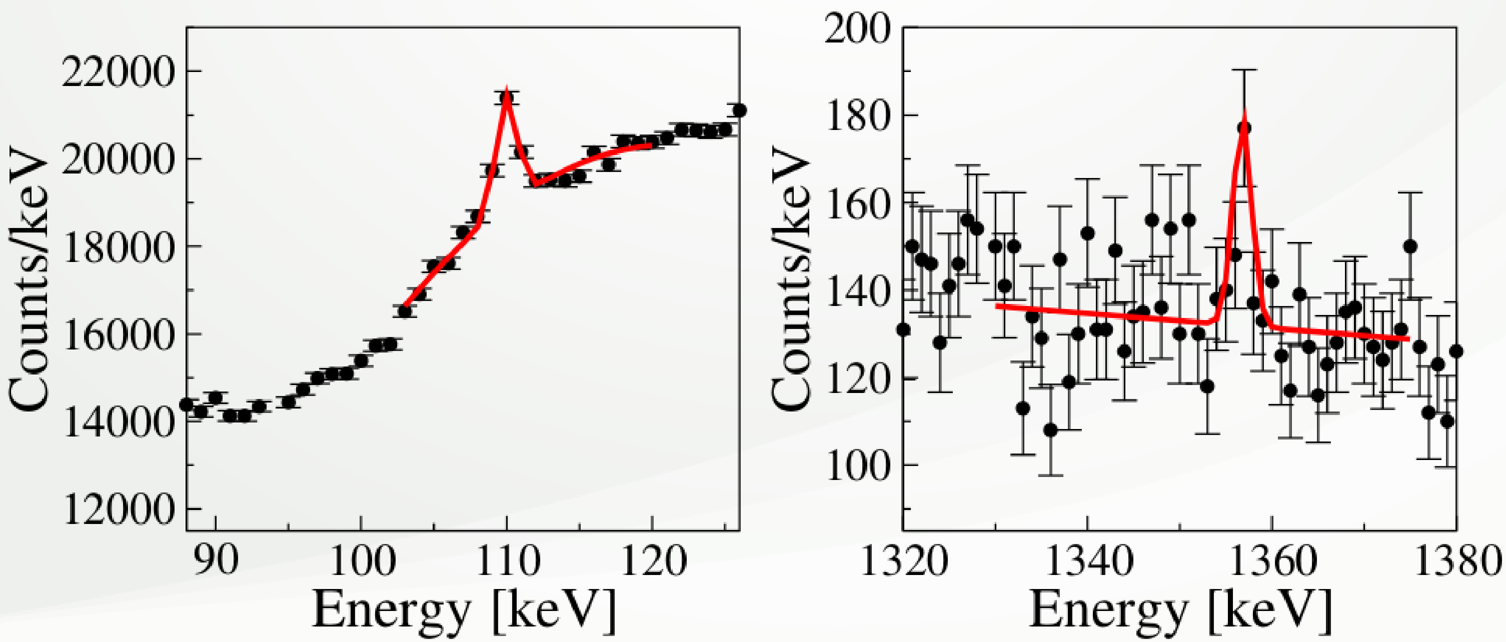
Half life now known to 0.01% relative uncertainty (TRIUMF, GANIL, KVI)

$T_{1/2}$ = 17.257(2) s

Branching ratio determination







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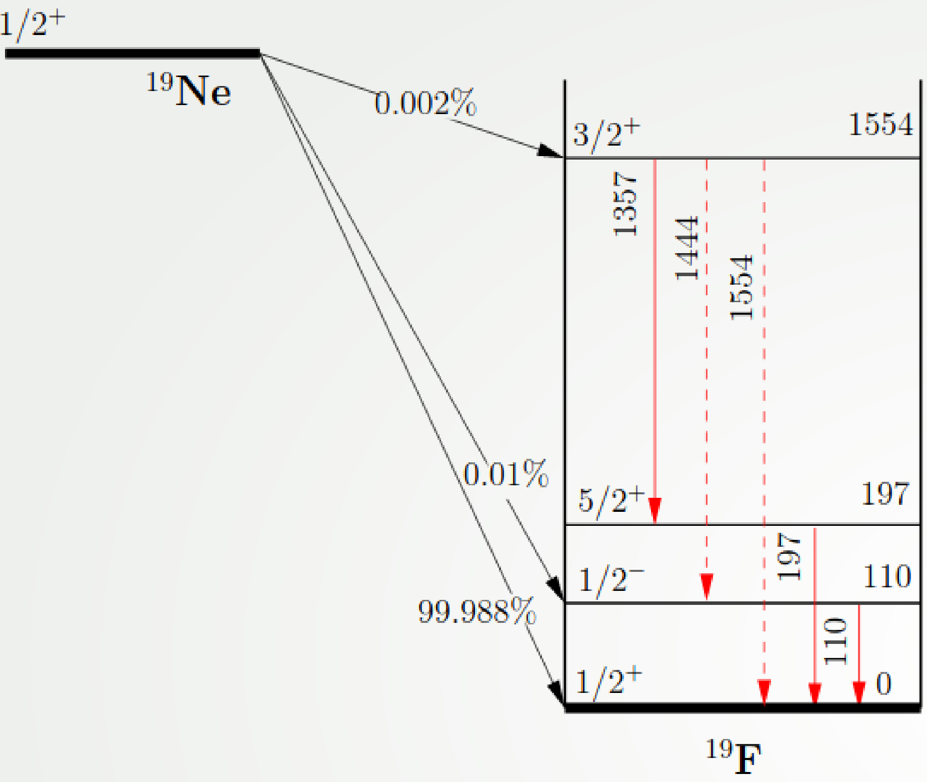


$$\frac{N_{ij}^{\beta\gamma}}{N_\beta} = \frac{1}{\sum_m B_m \eta_m}\left[B_i\eta_i + \sum_{k>i} B_k \eta_k \gamma_{ki}\right]\gamma_{ij}\epsilon_{ij}$$

$$B_1 \simeq k_1 \left(\frac{N_{10}^{\beta\gamma}}{N_\beta \cdot \epsilon_{10}}\right)$$

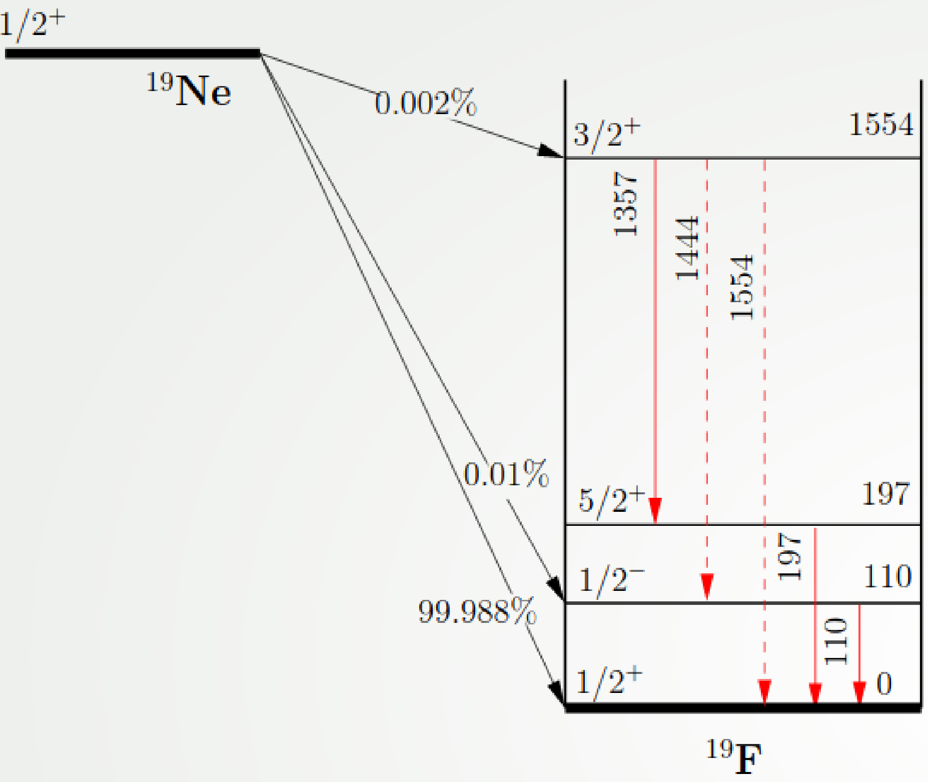
Source	Correction	$\frac{\Delta B_1}{B_1}$ (%)
Coincidence summing	1.0089(6)	0.06
Random coincidences	0.961(9)	0.94
Pile up	1.00324(1)	0.001
Dead time	1.00577(6)	0.006
Q_β value dependence on β efficiency	1.000(2)	0.20
$N_{10}^{\beta\gamma}/N_\beta$ ratio		6.4
HPGe efficiency (ϵ_{10})		2.4

	Measured β branch (%)		
Transition	Previous work		This work
$1/2^+ \to 3/2^+$	0.0021(3)[a]	0.0023(3)[b]	0.0017(5)
$1/2^+ \to 1/2^-$	0.012(2)[c]	0.011(9)[d]	0.0099(7)

[a] D. E. Alburger
[b] E. G. Adelberger *et al.*
[c] E. G. Adelberger *et al.*
[d] E. R. J. Saettler *et al.*

- First-forbidden β decay branch now known with three times better precision
- Superallowed ½ → ½ branch is now 99.9878(7)%

Branching ratio determination



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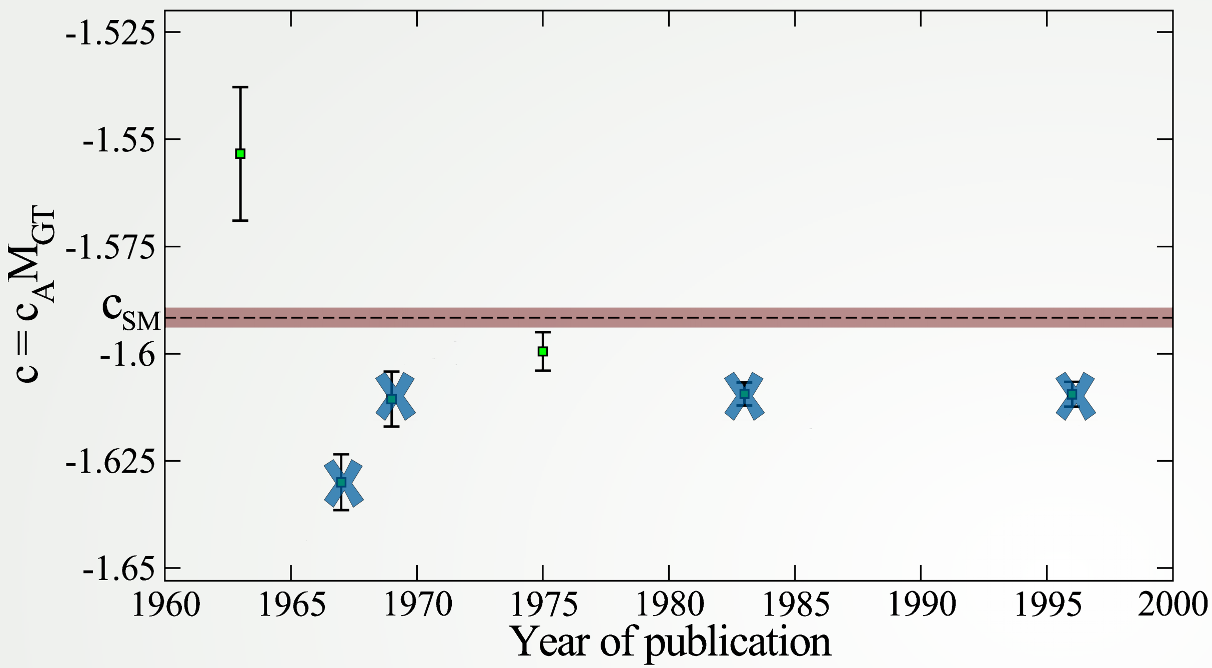
- Precision in $\mathcal{F}t$ value improved by a factor of ~3.5

Results



Year	Reference	$A_\beta(0)$	A_β
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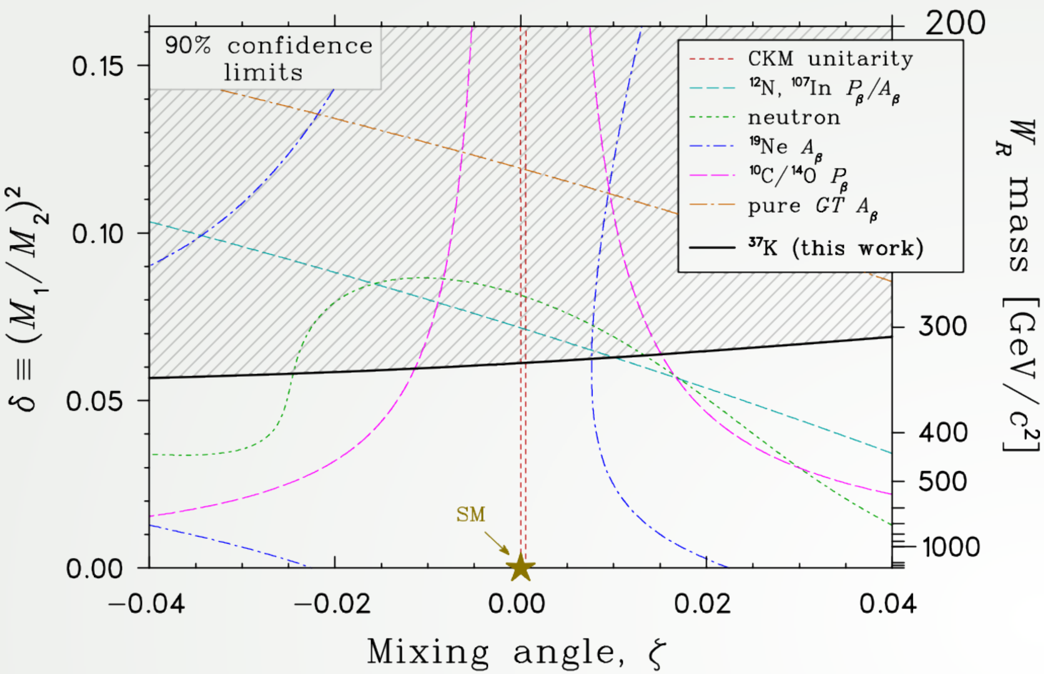
1983	~~Schreiber~~	~~$-3.603(83)$~~	~~...~~
1996	~~Jones~~	~~$3.52(11)$~~	~~...~~

- Violates CKM unitarity by more than 5σ
- Violates CKM unitarity at the 99.6% CL

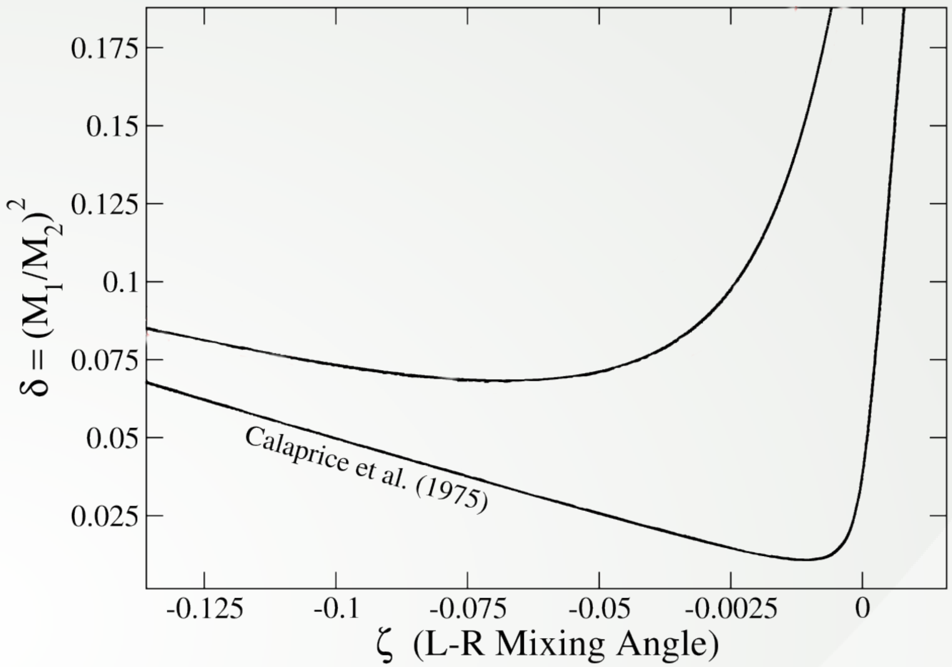
$$A_\beta^{\text{expt}} = -0.0391 \pm 0.0014$$

$$A_\beta^{\text{SM}} = -0.0415 \pm 0.0006$$

Results and conclusions



B. Fenker et al, Phys. Rev. Lett **120,** 062502 (2018)



This work + 1975 measurement of A_β
(Best fit disagrees with the SM by only 1.7σ)

- One of the most precisely measured $\mathcal{F}t$ values for T = ½ mirror β decays is from ^{19}Ne: $\mathcal{F}t = 1721.44(92)$ s
- First-forbidden decay rate is found to be ~ 10 times lower than shell model calculations that used PNC nucleon-meson couplings recommended by Desplanques, Donoghue and Holstein

B. M. Rebeiro et al, Phys. Rev. C **99**, 065502 (2019)

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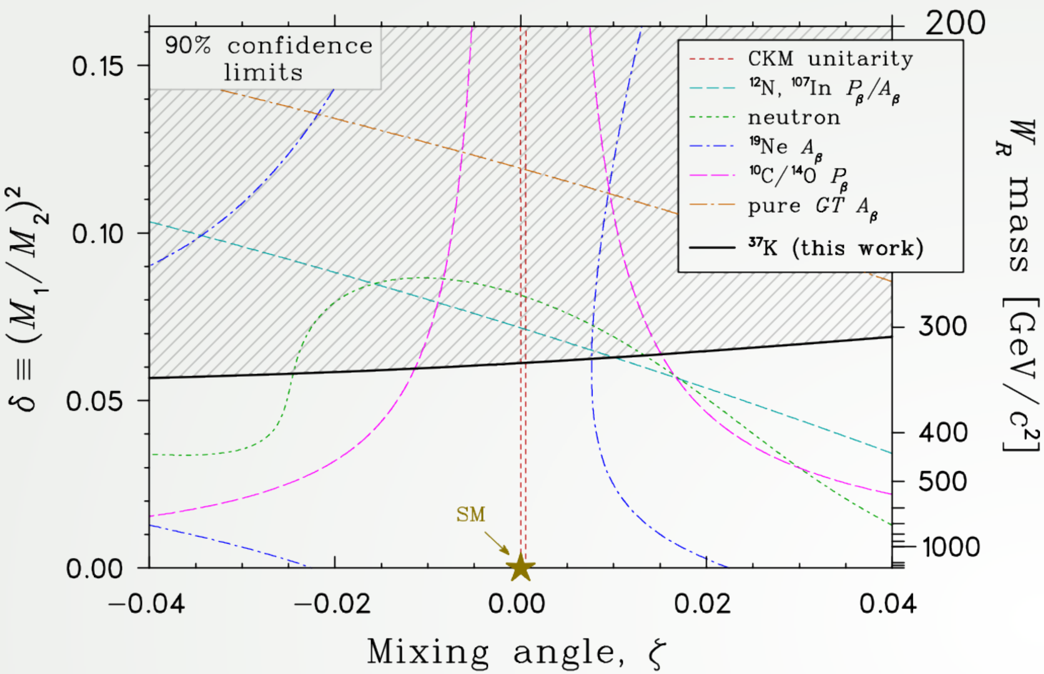

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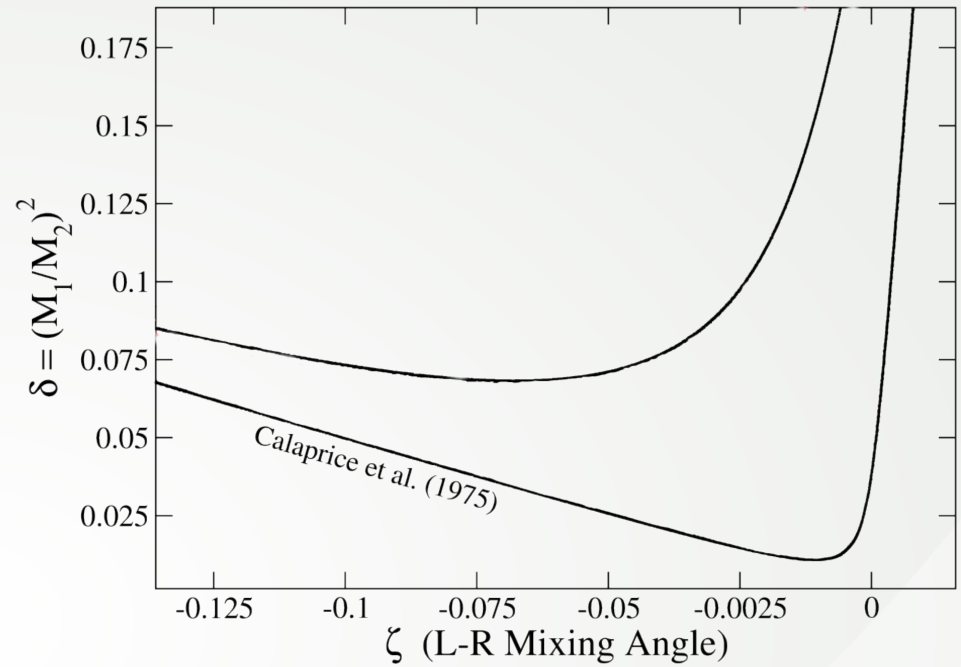

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Remeasurements of the asymmetry measurements are welcome!

Revisiting weak interaction symmetries

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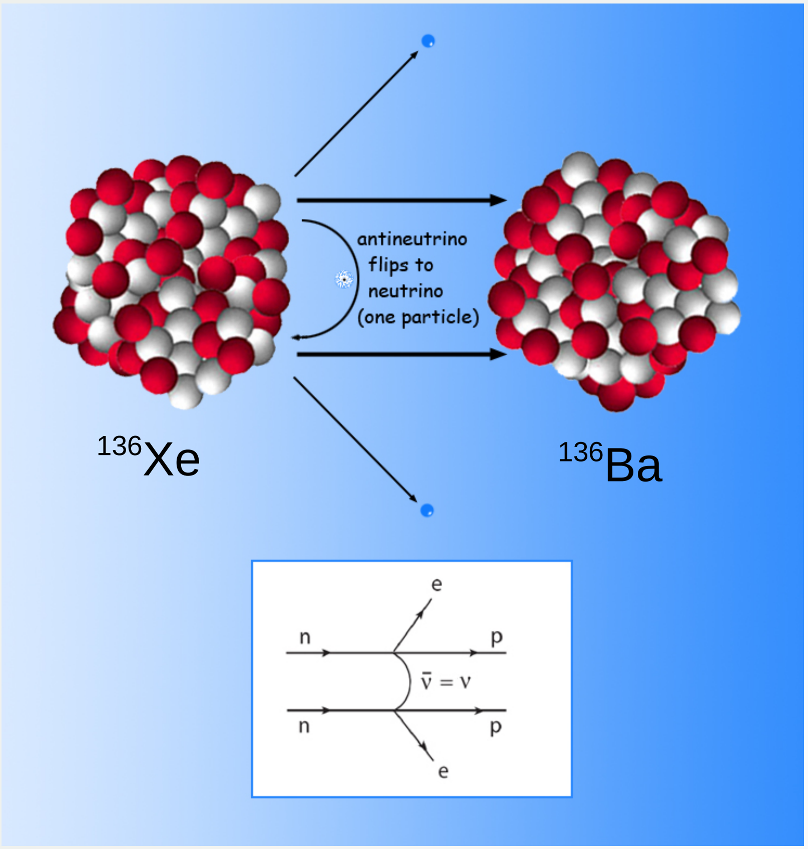
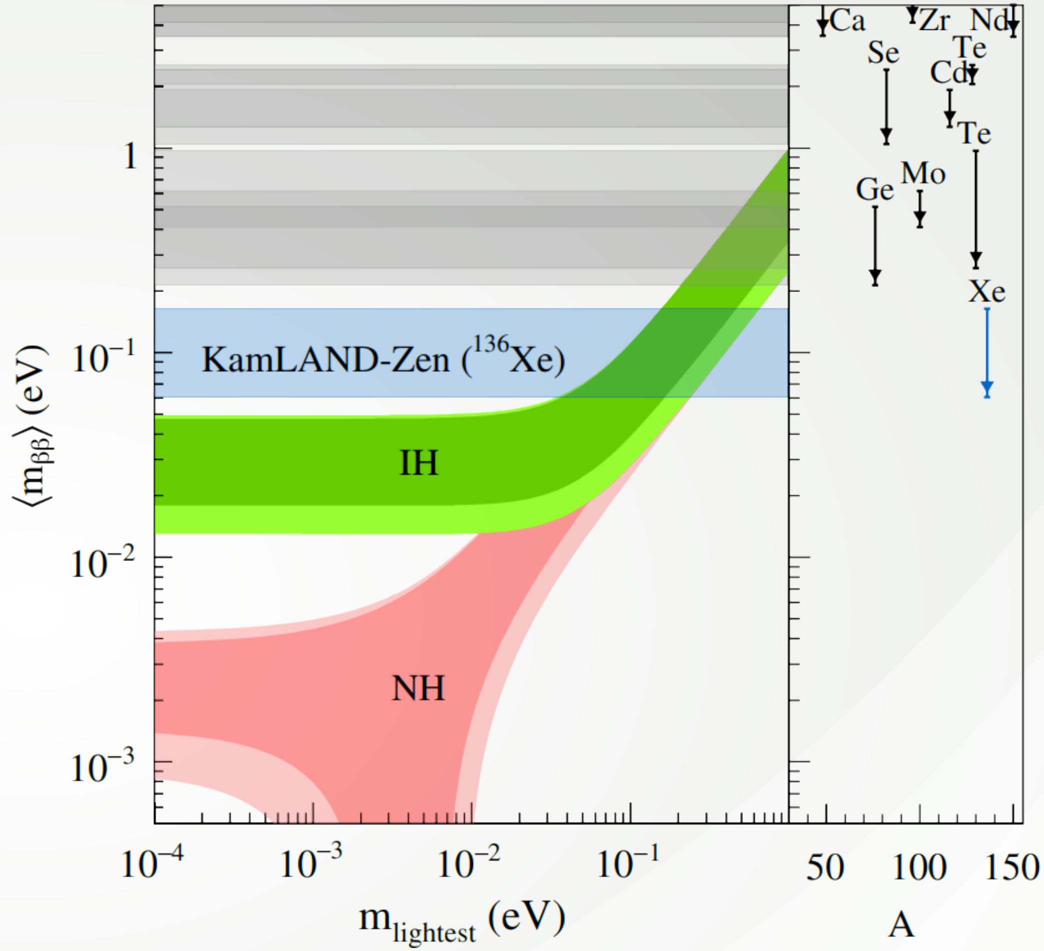
The 0νββ decay of ^{136}Xe

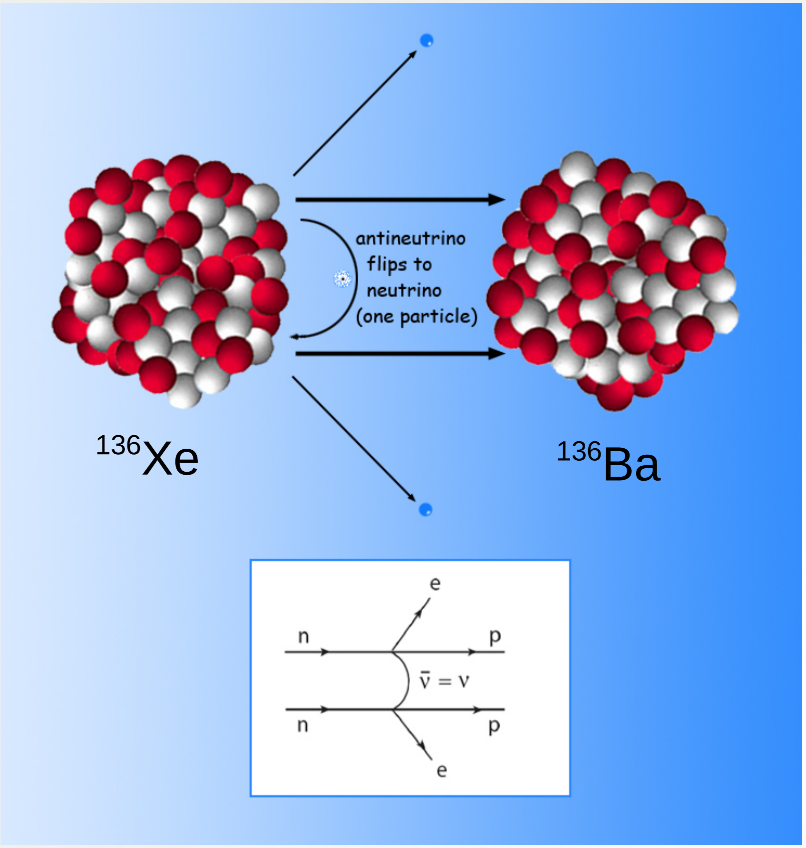


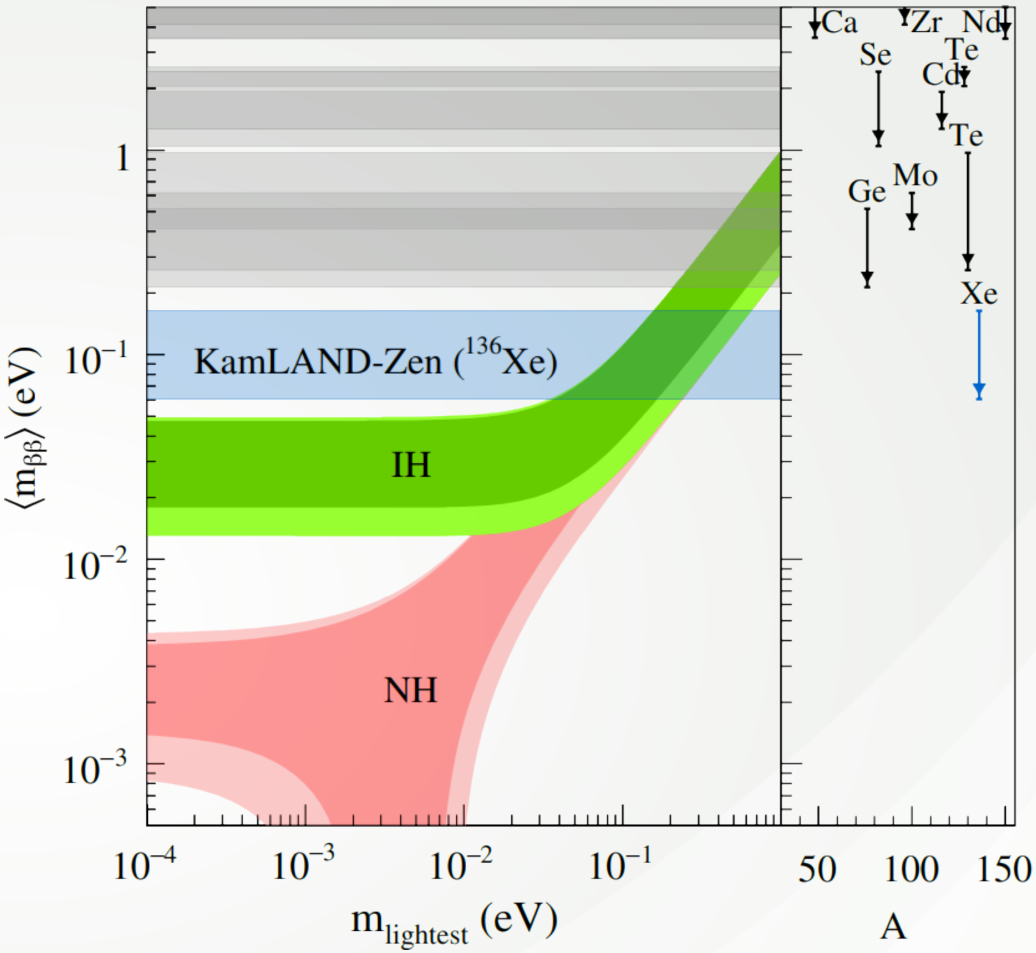


$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 \left(\frac{\langle m_{\beta\beta} \rangle}{m_e} \right)^2$$

A. Gando et al., PRL 117, 082503 (2016)

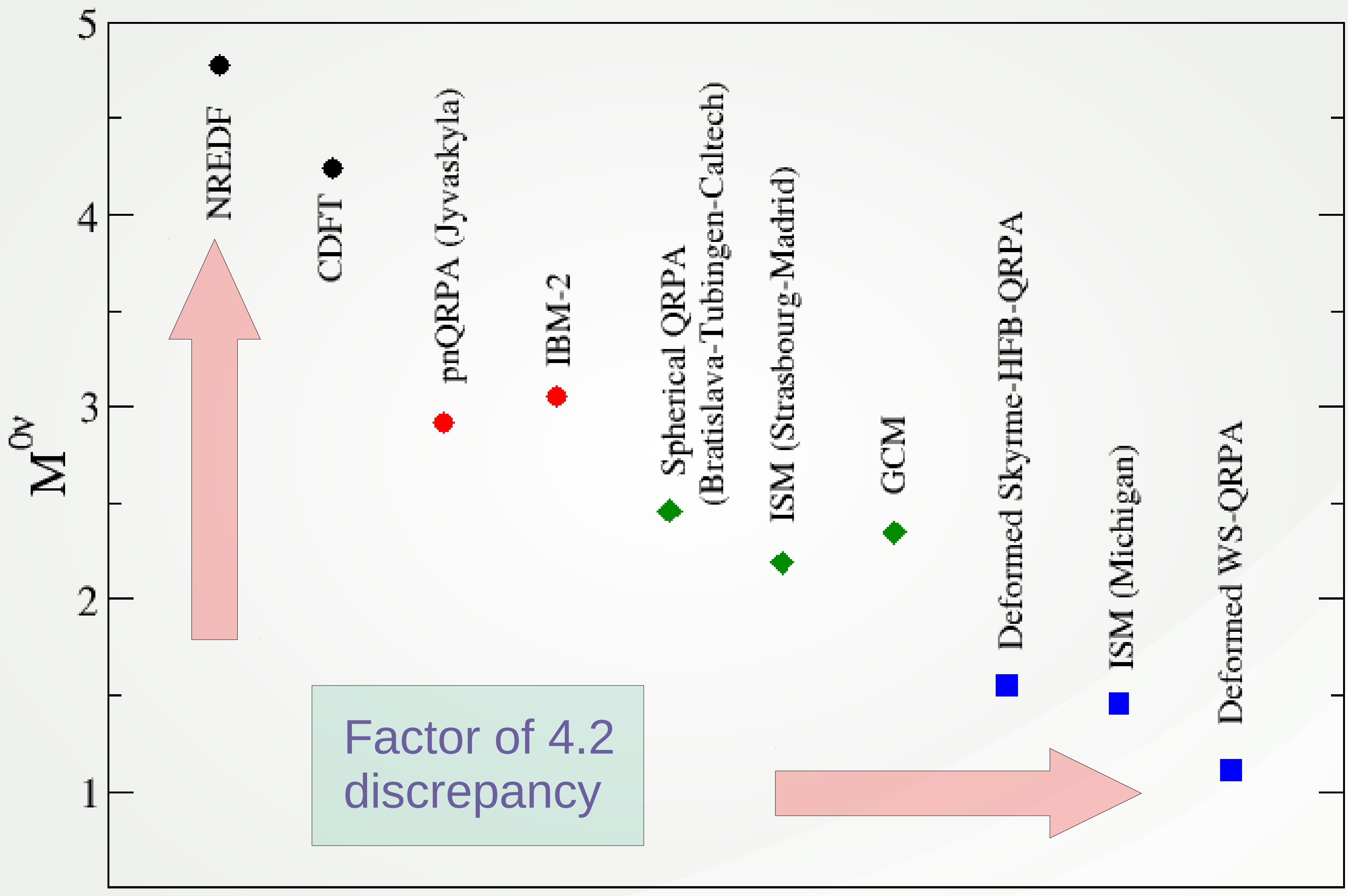
The $0\nu\beta\beta$ decay of ^{136}Xe



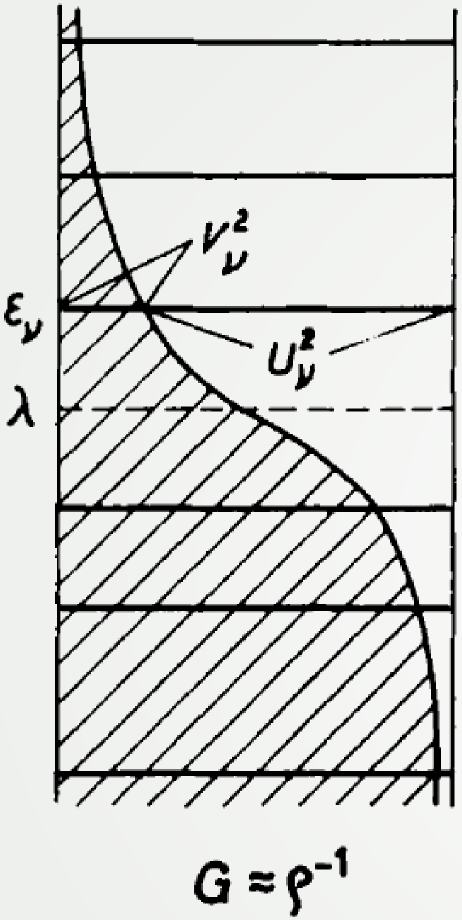


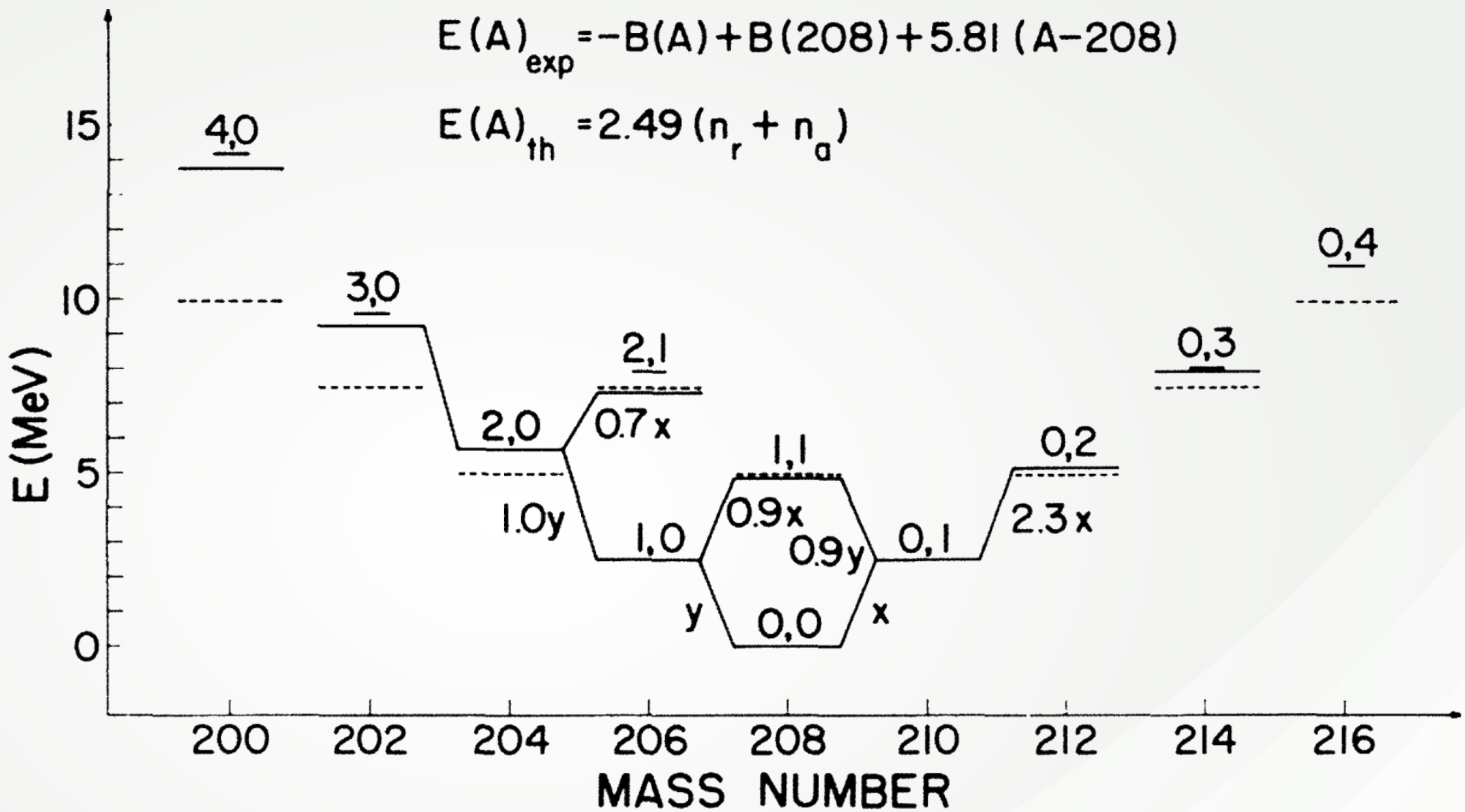
- ^{136}Xe $\beta\beta$ decay experiments have certain advantages...
- ^{136}Xe has singly closed shell (N = 82) ⇨ nearly spherical

The NME for ^{136}Xe $0\nu\beta\beta$ decay



Nucleon pairing and the BCS approximation





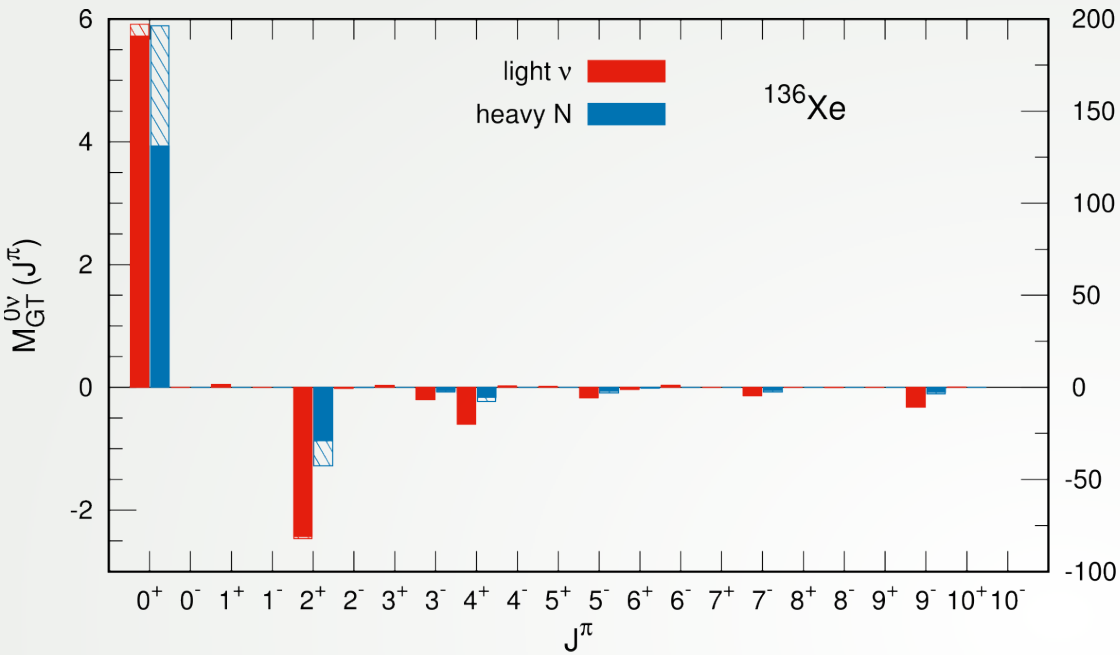
Nathan and Nilsson, Alpha, beta and gamma-ray spectroscopy (Ed. Kai Siegbahn)

Broglia, Hansen and Riedel, Advances in Nuclear Physics: Vol 6

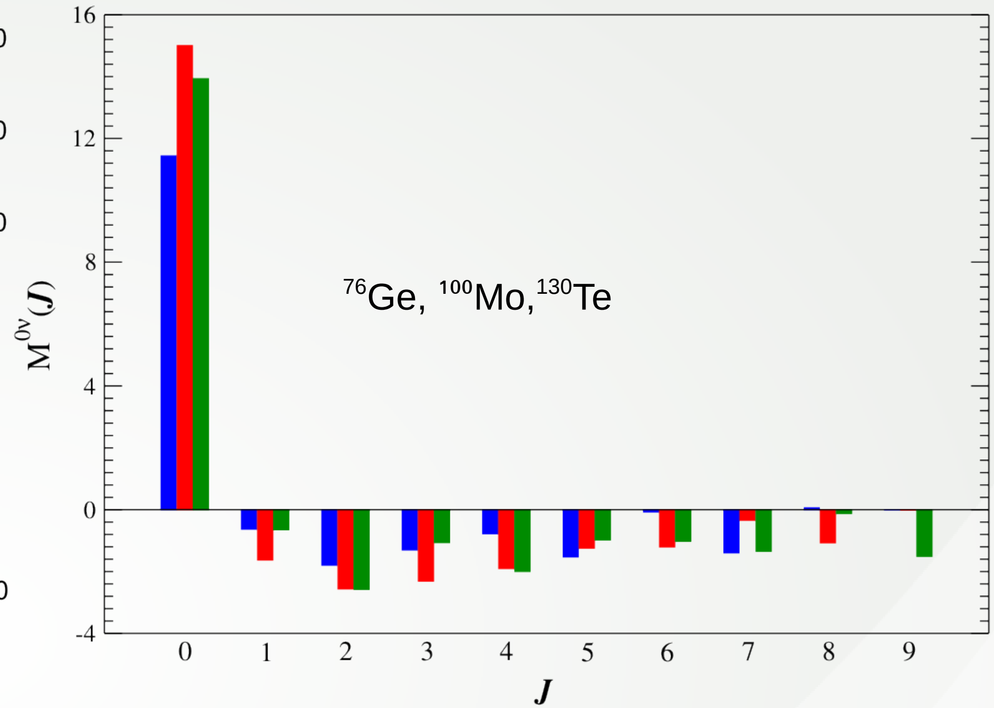
Two-nucleon transfer reactions such as (p,t), (t,p), (3He,n) are useful probes

→ Strong population of the ground states in the superfluid limit

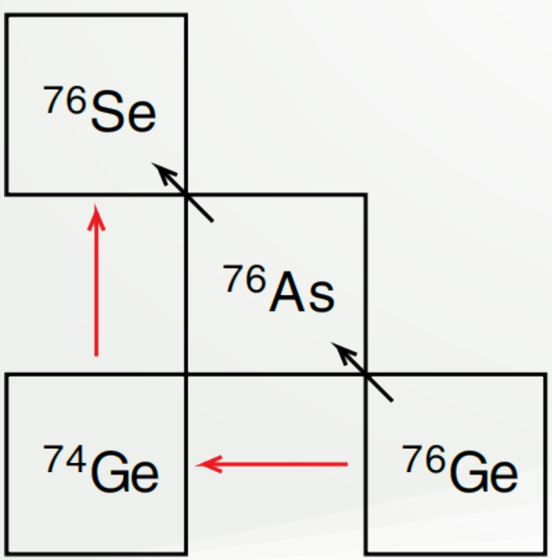
Anatomy of 0νββ decay NMEs



J. Menéndez, J. Phys. G: Nucl. Part. Phys. **45,** 014003 (2018)



P. Vogel, J. Phys. G: Nucl. Part. Phys. **39**, 124002 (2012)



$$M^{0\nu}(E_x, J_m) = \sum_{E_m < E_x, J_m} V(f, i, m)$$

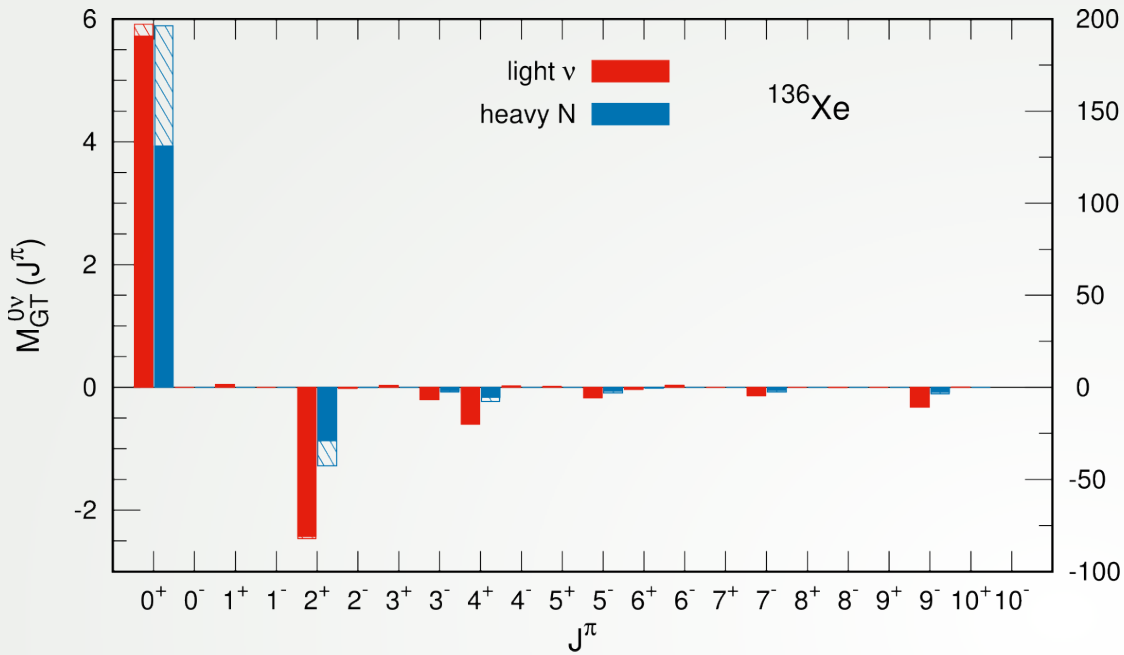
where

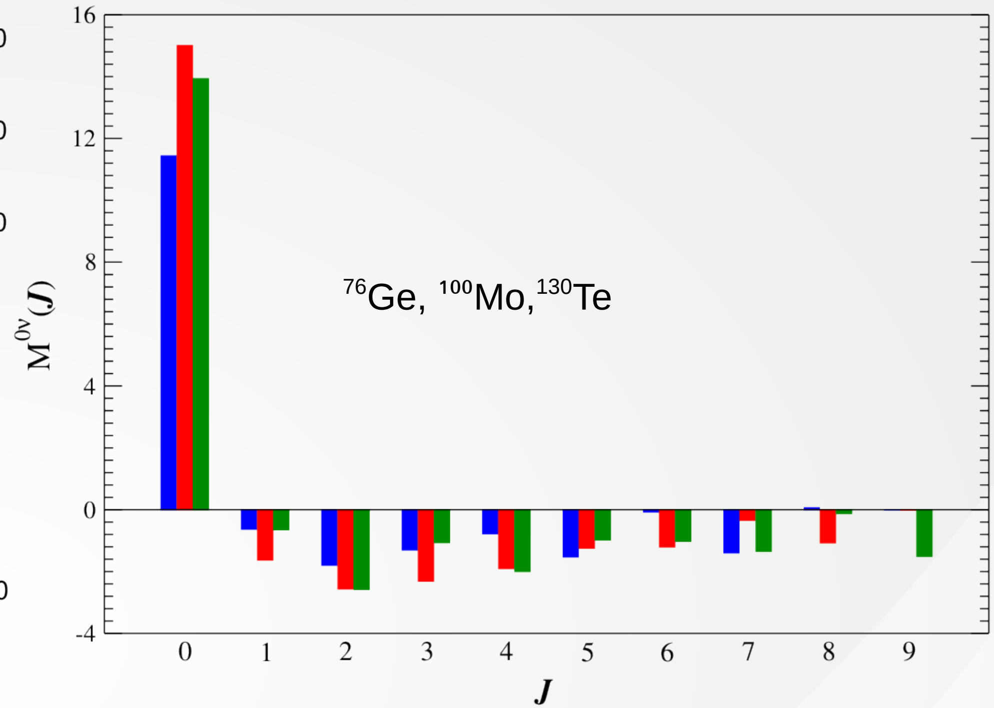
$$V(f, i, m) = \sum_{k_\alpha \le k_\beta, k_\gamma \le k_\delta} \langle k_\alpha, k_\beta, J_m | V | k_\gamma, k_\delta, J_m \rangle$$

$$\times \mathrm{TNA}(f, m, k_\alpha, k_\beta, J_0)\mathrm{TNA}(i, m, k_\gamma, k_\delta, J_0)$$

B. A. Brown, M. Horoi and R. A. Senkov, Phys. Rev. Lett. **113**, 262501 (2014)

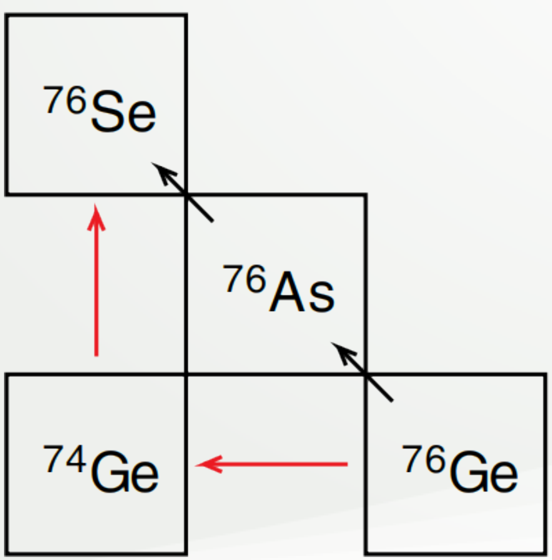
Anatomy of 0νββ decay NMEs





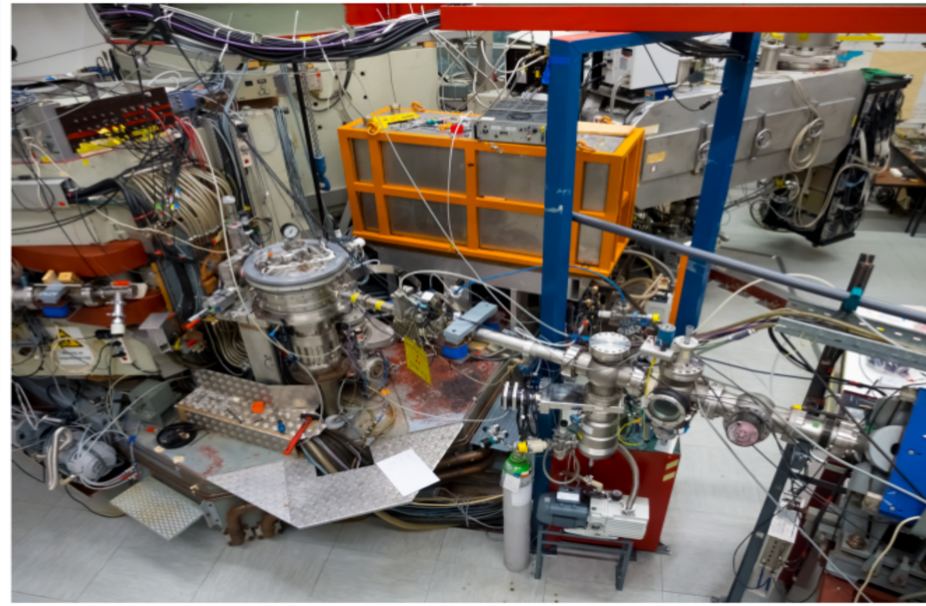
J. Menéndez, J. Phys. G: Nucl. Part. Phys. **45,** 014003 (2018)

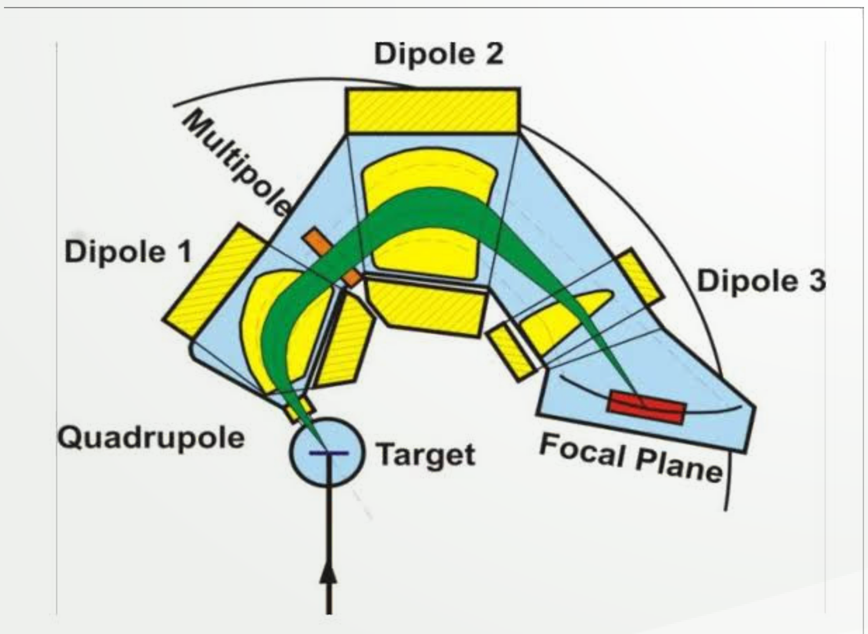
P. Vogel, J. Phys. G: Nucl. Part. Phys. **39**, 124002 (2012)

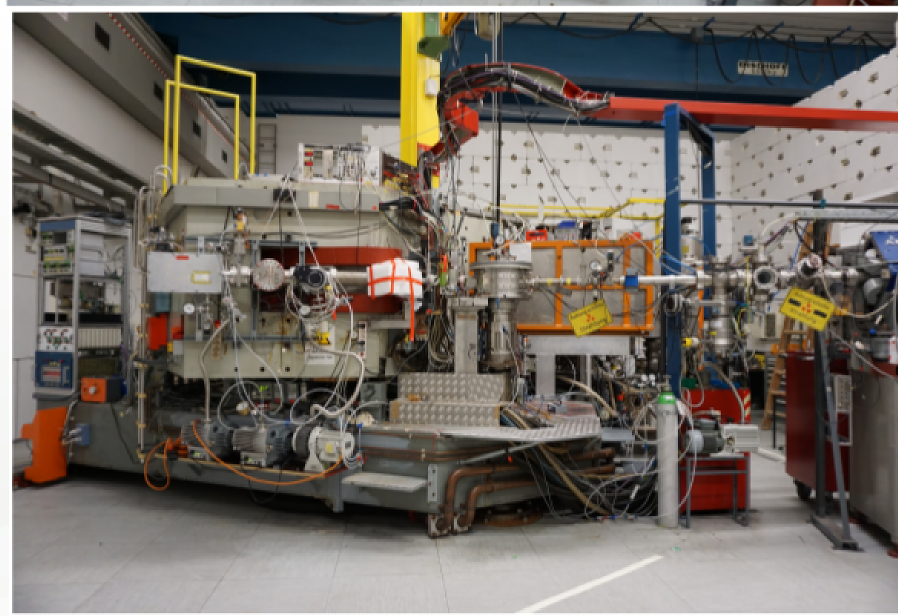


- The NME is dominated by the $J^+ = 0^+$ ground state in ^{74}Ge
- There are cancellations from intermediate states with J > 0, dominated by the 2^+ contributions
- Relates to pair-transfer properties of the ground states

Benchmarking NME calculations with ^{138}Ba(p,t)

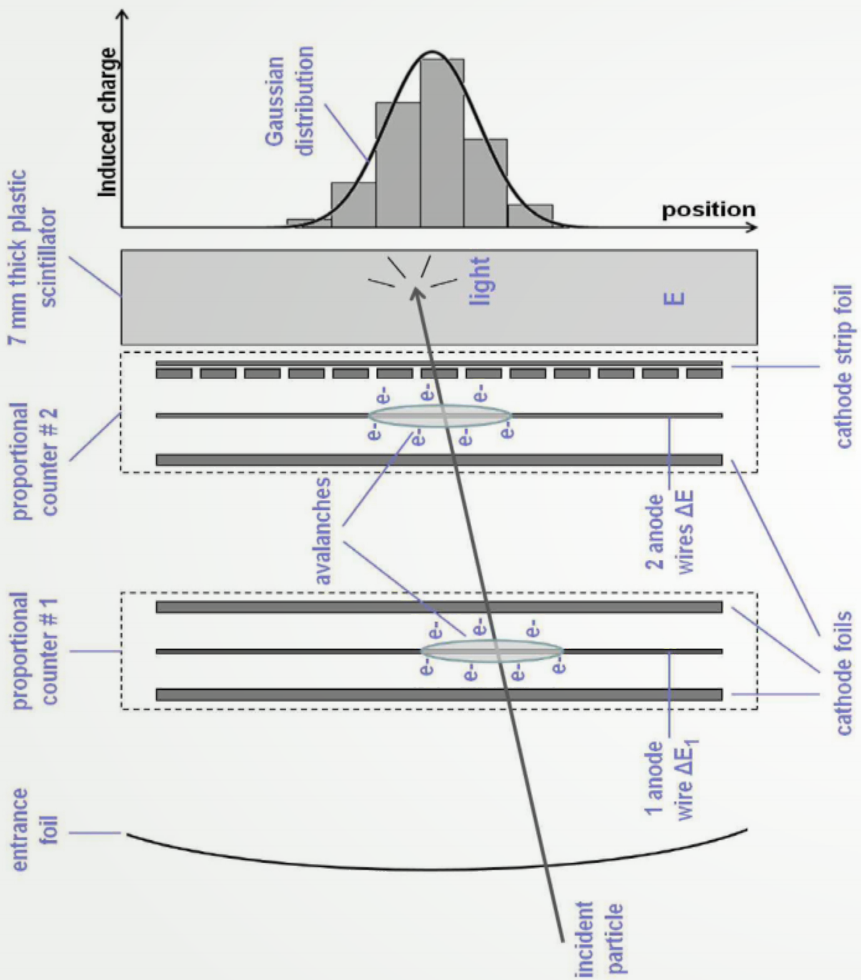


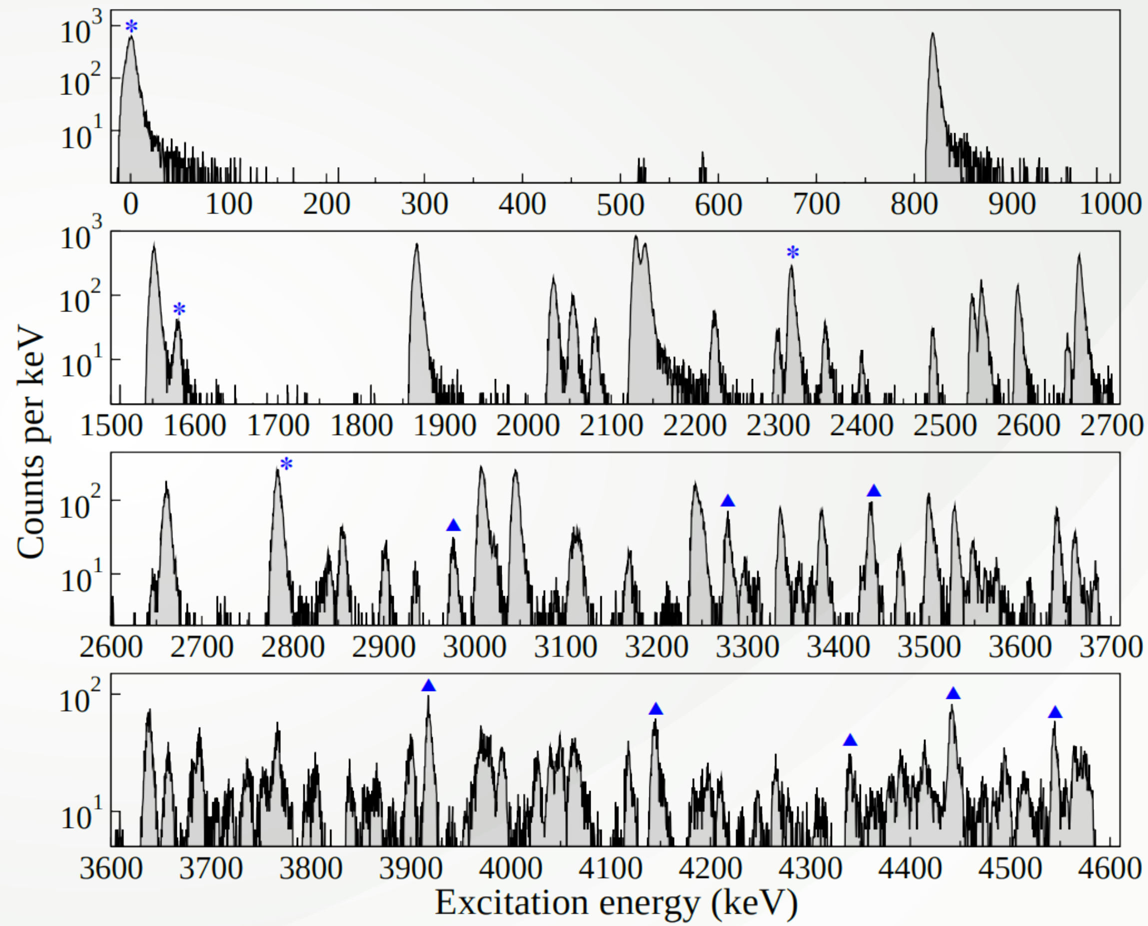




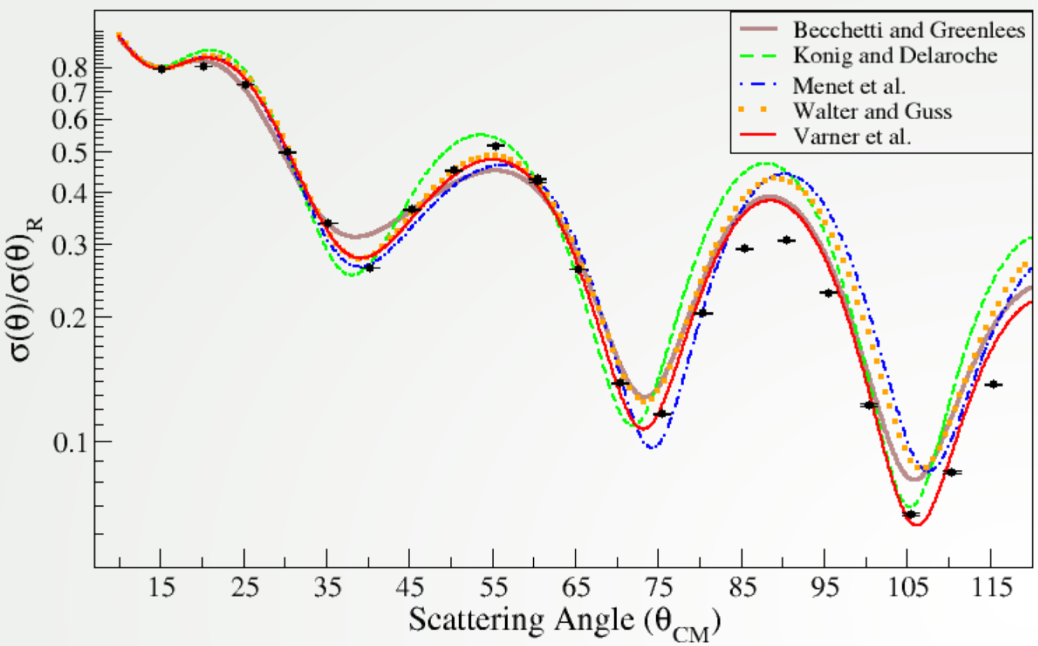
High resolution Q3D spectrograph at MLL in Garching, Germany

Benchmarking NME calculations with ^{138}Ba(p,t)

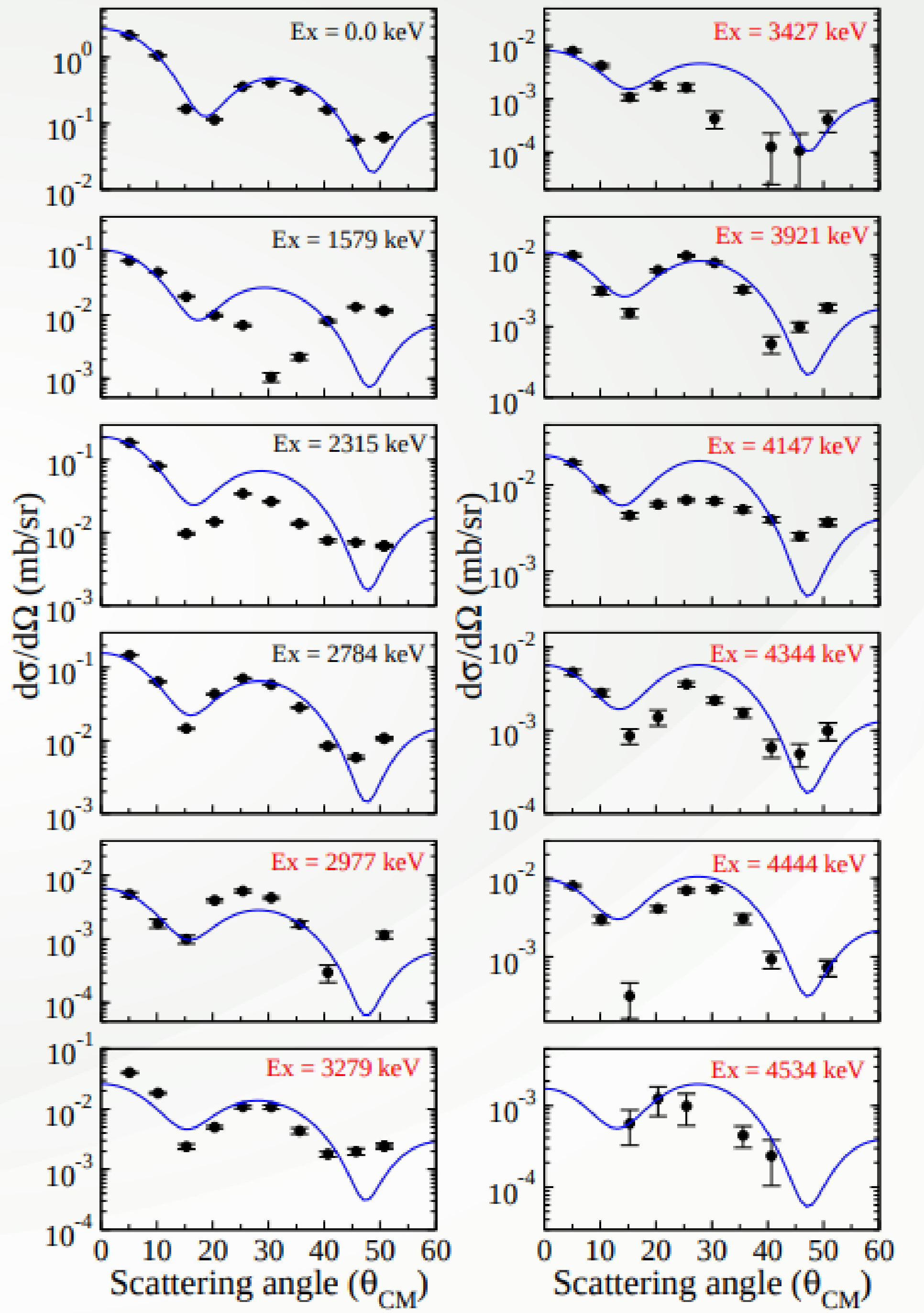




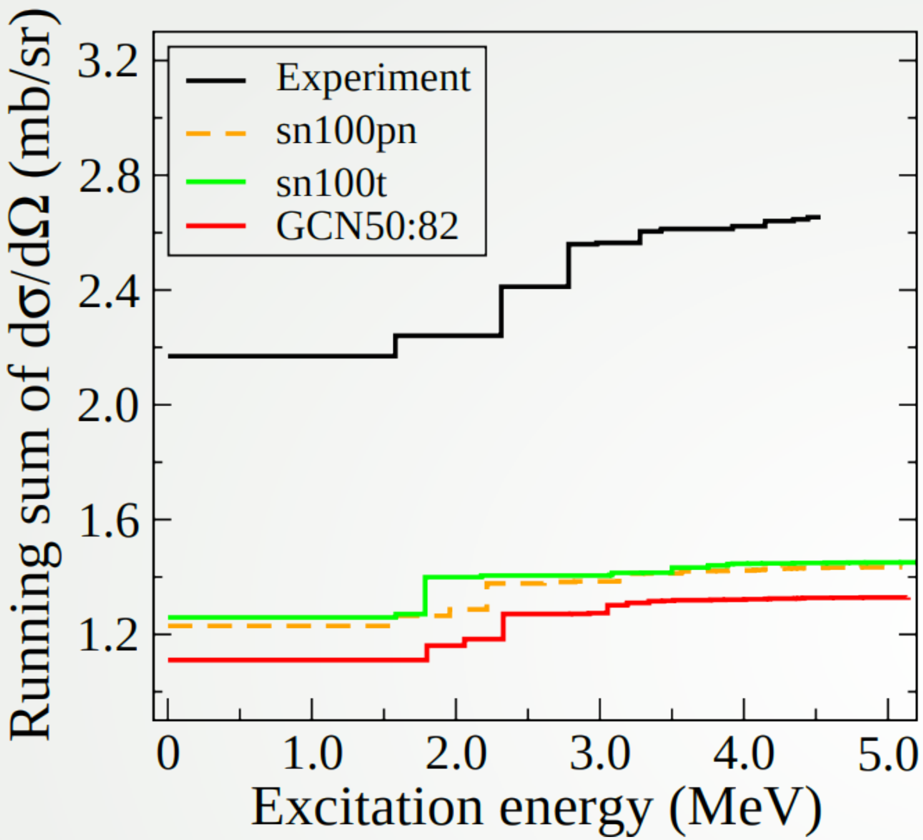
Benchmarking NME calculations with ^{138}Ba(p,t)



E_x [keV]	$(d\sigma/d\Omega)_{5^\circ}$ [mb/sr]	ϵ_i [%]
0	2.17(12)	100.0
1579	0.071(4)	5.1(7)
2315	0.17(1)	15.2(19)
2784	0.148(8)	14.6(17)
2977	0.0046(6)	0.65(9)
3279	0.041(2)	3.3(3)
3427	0.0082(8)	1.1(1)
3921	0.0096(8)	2.2(3)
4147	0.018(1)	5.4(7)
4344	0.0055(6)	1.8(3)
4444	0.0075(7)	3.2(4)
4534[a]	...	0.6(3)
Integrated $L = 0$ strength relative to the ground state		$\sum \epsilon_i = 53(3)\%$



Benchmarking NME calculations with ^{138}Ba(p,t)



- Used the NuShellX code with the five-orbital ($0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$, $0h_{11/2}$) valence space to get the wavefunctions for ^{138}Ba and first 50 0^+ states in ^{136}Ba
- NuShellX ⇒ two-neutron transfer amplitudes (TNA) ⇒ coherent sum of both direct and sequential two-step transfer

Benchmarking NME calculations with ^{138}Ba(p,t)

LEVELS OF ^{52}Fe STUDIED WITH THE (p, t) REACTION †

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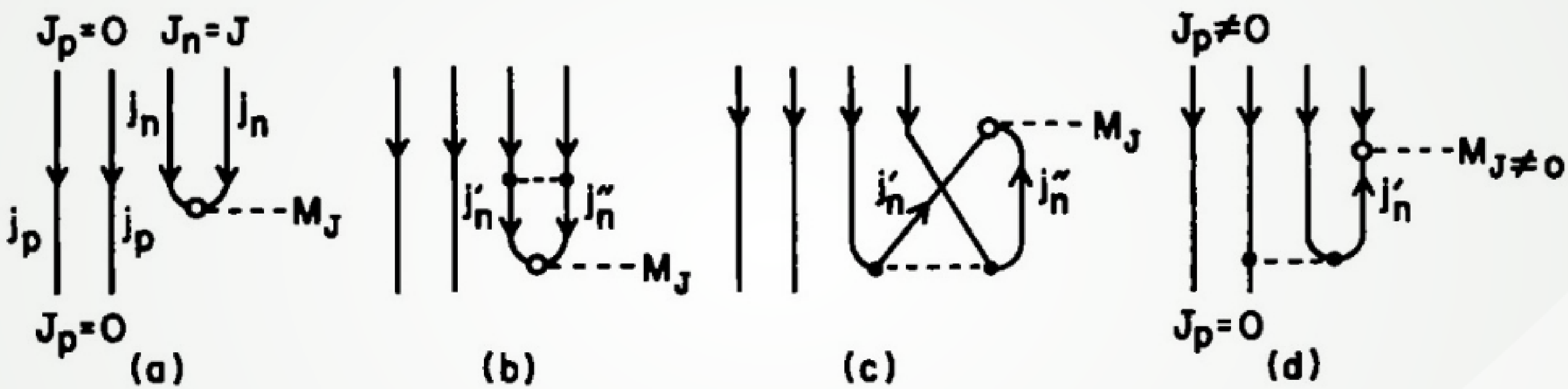
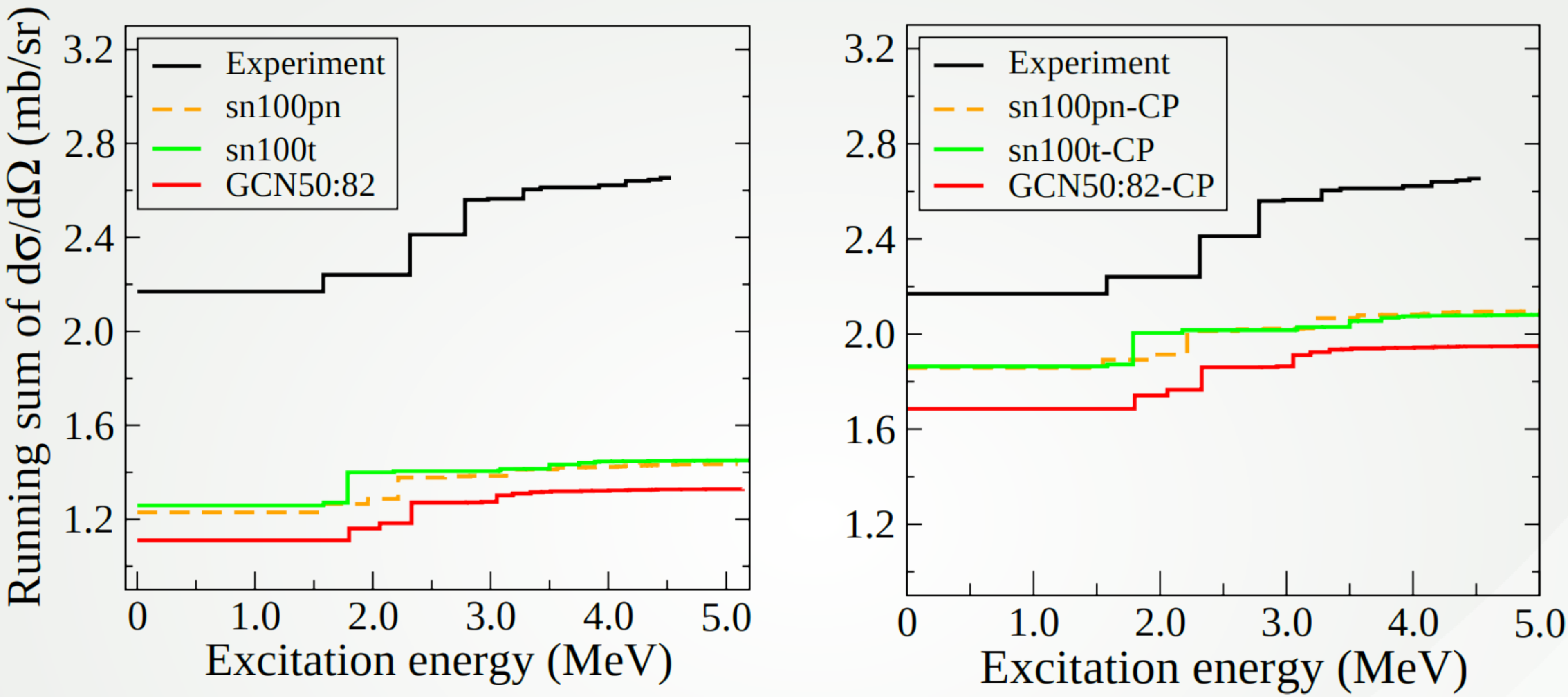


Fig. 8. Diagrams of the ^{54}Fe(p, t)^{52}Fe reaction assuming, (a) the zeroth-order process with ^{54}Fe in a pure $(j_p = 1f_{7/2})^{-2}_{J_p=0}$ configuration and ^{52}Fe in a pure $(j_p = 1f_{7/2})^{-2}_{J_p=0}(j_n = 1f_{7/2})^{-2}_{J_n=J}$ configuration, (b) a first-order process which includes two-hole admixtures in ^{52}Fe, and (c) a first-order process which includes two-particle admixtures in ^{54}Fe. Diagram (d) shows a first-order process due to three-hole one-particle admixtures with $(j_p = 1f_{7/2})^{-2}_{J_p\neq0}$ in ^{54}Fe.

Nucl. Phys. **A302**, 186 (1978)

Coherent contributions from orbitals outside the valence space enhance the L = 0 (p,t) cross section

Benchmarking NME calculations with ^{138}Ba(p,t)



- We obtain better agreement after incorporating these ladder-diagram corrections to the TNA (assumed the scattering of pairs of neutrons to twenty three orbitals beyond the model space)

- ^{136}Xe → ^{134}Xe is very similar to ^{138}Ba → ^{136}Ba (both are N = 82 → N = 80)

Results

- QRPA: Šimkovic, Rodin, Faessler and Vogel (2013) – 23 orbitals

  $M^{0\nu}(GT) = 2.18$

- QRPA: Fang (this work) – 28 orbitals

  $M^{0\nu}(GT) = M(J = 0) + M\ (J > 0) = 9.63 – 7.65 = 1.98$

- ISM: E. Caurier, J. Menéndez, F. Nowacki, and A. Poves (2008)

  $M^{0\nu}(GT) = M(J = 0) + M\ (J > 0) = 5.72 – 3.95 = 1.77$

- ISM: Horoi (this work) – sn100t + five orbitals: PRL **110**, 222502 (2013)

  $M^{0\nu}(GT) = M(J = 0) + M\ (J > 0) = 5.67 – 3.73 = 1.94$

- ISM: Brown (this work) $M_{GT}(J = 0; G.S) = 5.72$

  $M_{GT}(J = 0; G.S) = 9.04$

  Ratio = 1.58

- Using this ratio, we get a corrected ISM value $M_{GT}\ (J = 0) = 8.96$

Based on comparison with our experimental data

Conclusions

- Our ^{138}Ba(p,t) work indicates a large breakdown of the BCS pairing approximation for neutrons in ^{136}Ba

- A similar analysis of ^{136}Ba(p,t) data shows that this persists in ^{134}Ba: See Jespere Ondze's poster

- Quite likely due to dissimilar deformations in initial and final nuclei
  ⇨ shape-transitional Ba nuclei with N ≤ 82

- Our ISM analysis (after taking into account core-polarization corrections to the TNA) results in a value of M_{GT} (J = 0) that agrees with a large model-space QRPA calculation

- We recommend improved calculations of this part of NME as well as the canceling M_{GT} (J > 0) terms, taking into account physics contributions from beyond the model space.

PHYSICAL REVIEW C **87**, 064315 (2013)

Effective double-β-decay operator for ^{76}Ge and ^{82}Se

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