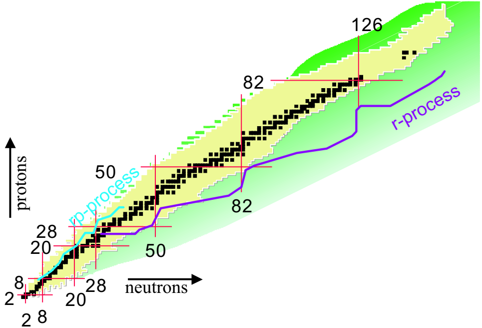
Global Calculations of β Decay for the r Process

J. Engel

July 27, 2018

Nuclear Landscape

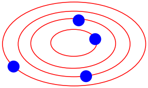
To locate the site(s) of the *r* process, need reaction rates and properties in very neutron-rich nuclei.



β decay particularly important. Increases *Z* throughout the *r* process, and competition with neutron capture during freeze-out can have large effect on abundances.

Generic Framework: Skyrme Density-Functional Theory

Zero-range density-dependent effective potential, treated in mean-field theory.



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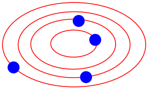

Can be represented as density functional:

$$\mathcal{E} = \int d^3r \left(\underbrace{\mathcal{H}_{\text{even}} + \mathcal{H}_{\text{odd}}}_{\mathcal{H}_{\text{Skyrme}}} + \mathcal{H}_{\text{kin.}} + \mathcal{H}_{\text{em}} \right)$$

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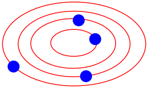

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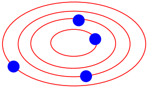

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QRPA: time-dependent mean-field theory with small harmonic perturbation by β-decay transition operator.

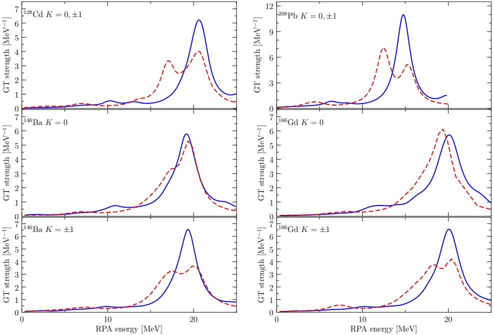
Matrix elements of operator between the initial state and final excited states at $E = \hbar\omega$ obtained from response of nucleus oscillating with frequency ω.

I. What We've Done

Fast Skyrme QRPA in Deformed Nuclei

Finite-Amplitude Method (Nakatsukasa et al.)

Strength functions computed directly, in orders of magnitude less time than with usual QRPA.



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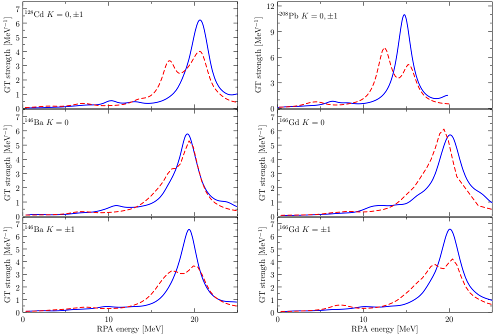
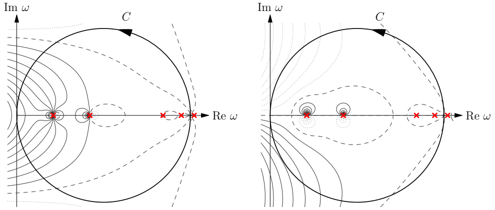
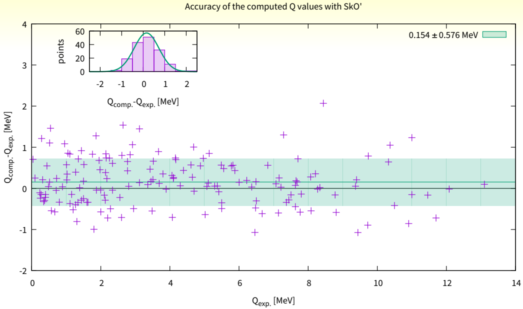


Beta-decay rates obtained by integrating strength with phase-space weighting function in contour around excited states below threshold.

Re $[S(\omega)f(\omega)]$ Im $[S(\omega)f(\omega)]$



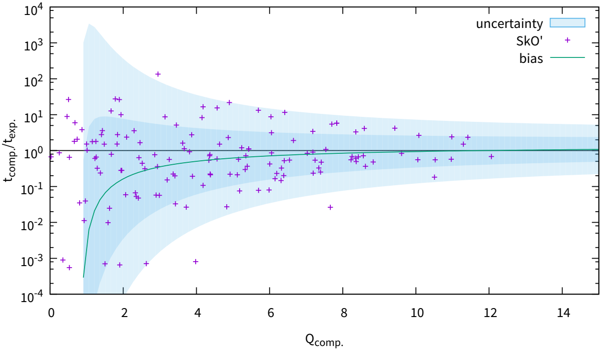
Fit of $\mathcal{H}_{odd}$ and Results



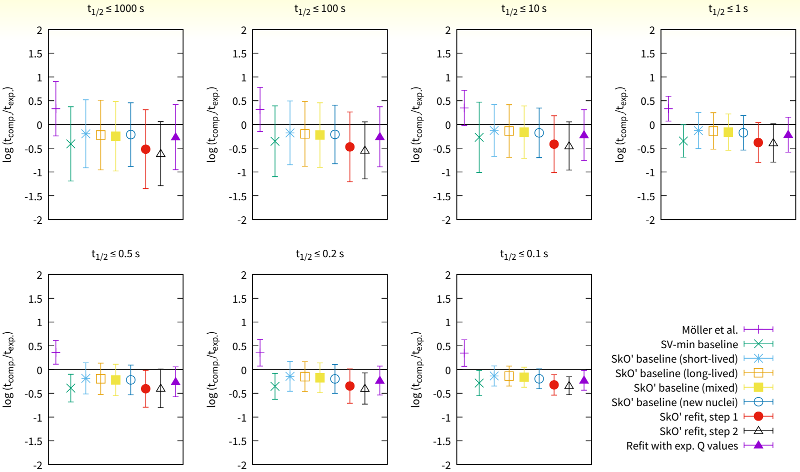
Q values not given perfectly, and β rate roughly $\propto Q^5$.

Adjusted only spin-isospin interaction and isoscalar pairing.

Uncertainty decreases with increasing Q.



Lots of Other Fitting Attempts



Meh…. Not doing as well as we had hoped.

Is the QRPA near its limits? We think so.

But We Really Care About High-Q/Fast Decays

- These are the most important for the *r* process.

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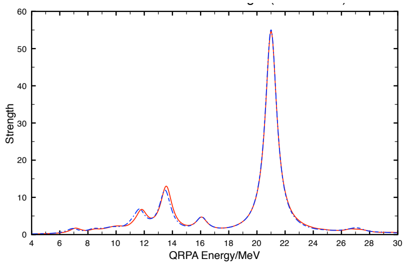
- These are the most important for the *r* process.
- And they are easier to predict. Phase space weights contribution of each state by $(\Delta E)^5$:

$$\frac{(\Delta E + \delta)^5}{(\Delta E)^5} = 1 + 4\frac{\delta}{\Delta E} + \ldots$$

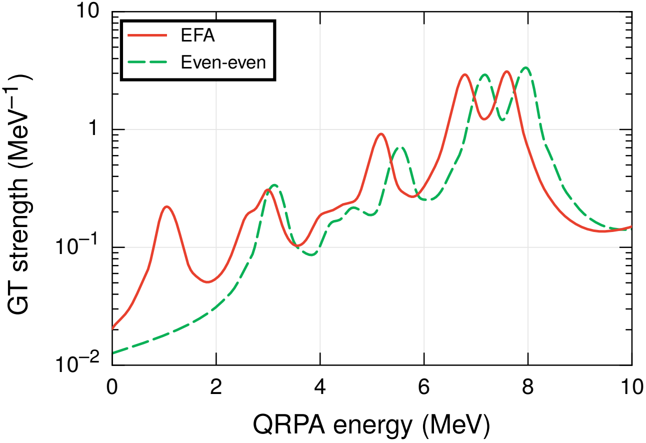


A small error of δ in the energy of a state with low excitation energy (large ΔE) will make little difference in the rate.

Odd Nuclei

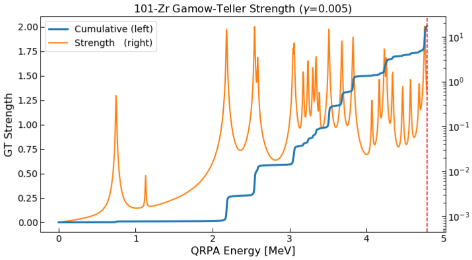
$J \neq 0$,   degenerate ground state

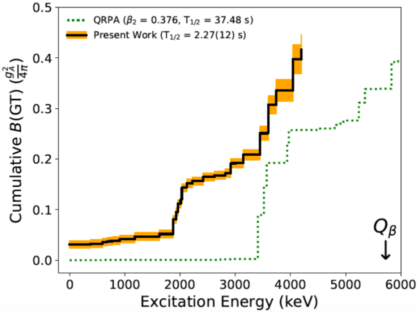
Treat degeneracy as ensemble of state and angular-momentum-flipped partner (equal filling approximation).



Comparison with Recent Data in ^{101}Zr

Evan Ney just computed this last night.





II. What We'll Do

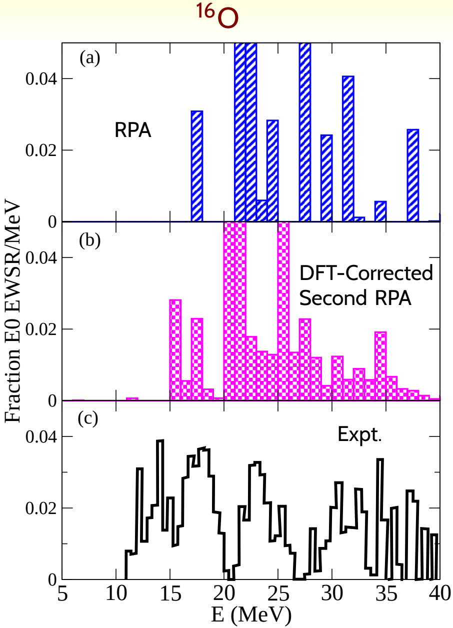
(after computing new rate table)

Improving RPA/QRPA

RPA produces states in intermediate nucleus, but form is restricted to 1p-1h excitations of ground state.

Resonances come out in right place, but there's very little fragmentation.

Second RPA adds 2p-2h states that mix with 1p-1h states, increase fragmentation.



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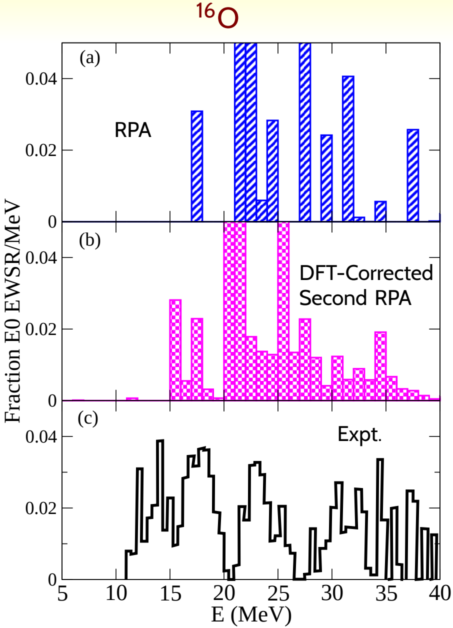
Also see talks by Elena and Caroline.



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We need to find a way to extend something like the FAM to second QRPA.

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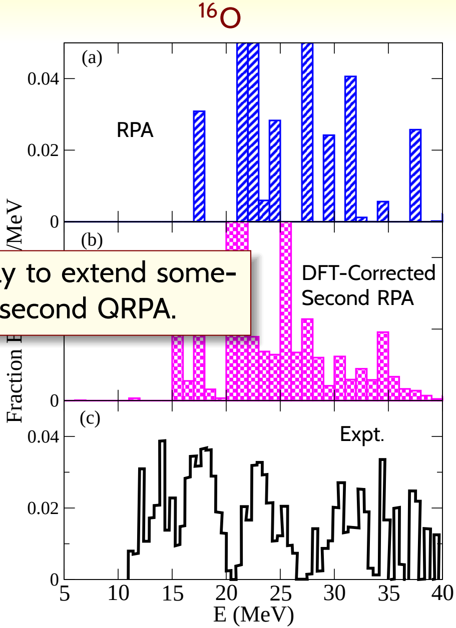
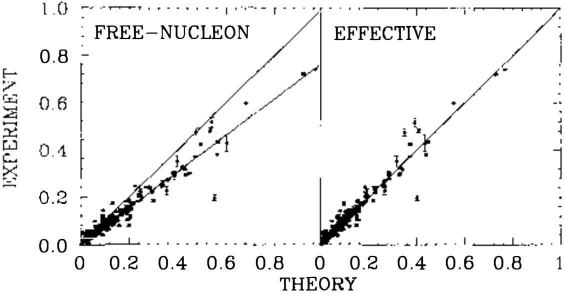


Incorporating Quenching of g_A

Leading order decay operator in Gamow-Teller decay is $g_A \vec{\sigma} \tau_+$.

50-Year-Old Problem: Effective g_A needed in all calculations of shell-model or QRPA type.

Brown & Wildenthal



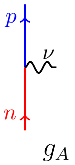
Quenching increases with *A*.

Many suggestions about the cause but, until recently, no consensus.

Axial Weak Current in Chiral Effective Field Theory

β Decay (simplified) with electron lines omitted

Leading order:



Usual β-decay current.

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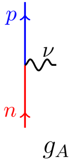
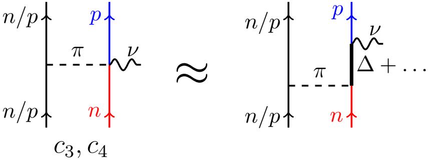
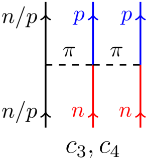


Usual β-decay current.

Higher order:

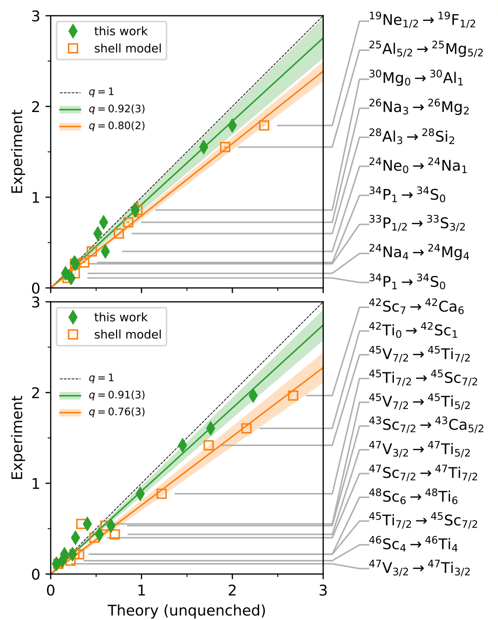


Coefficients same as in three-body interaction:



These are usually neglected.

Quenching in the *sd* and *pf* Shells



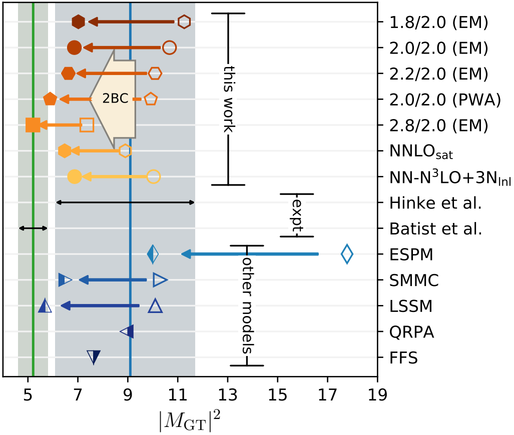
IMSRG calculation, Holt et al, preliminary

Shell model seems to include most correlations. Bulk of quenching comes from two-body current.

…And in ^{100}Sn

Coupled-Cluster Calculation of β Decay

Hagen et al, unpublished



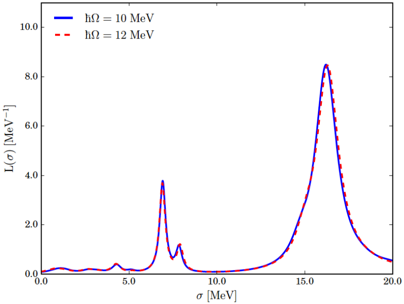
Again, good part of the quenching accounted for by two-body current.

Quenching increases with mass, at least up to Sn.

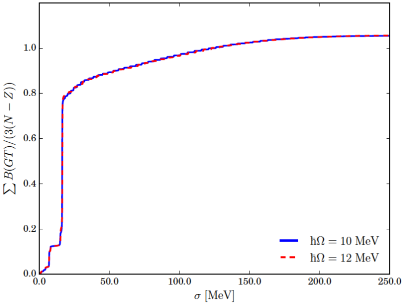
Spectator nucleons contribute coherently to two-body current.

Gamow-Teller Strength in ^{132}Sn

Coupled-clusters result from G. Hagen



Strength vs. energy



Running sum

Almost 20% of strength above 30 MeV and 10% above 50 MeV.

Adding the Two-body Currents within FAM

Response constructed from $X(\omega)$ and $Y(\omega)$, essentially the ph and hp pieces of the change $\delta\rho(\omega)$ of the density from mean-field one.

FAM Equations for one-body current operator F, from TDHF:

$$\begin{aligned}(\varepsilon_m - \varepsilon_i - \omega)\, X_{mi} + \delta h_{mi} &= -F_{mi} \\ (\varepsilon_m - \varepsilon_i + \omega)\, Y_{mi} + \delta h_{mi} &= -F^*_{mi}\,,\end{aligned}$$

where

$$\delta h = \lim_{\eta \to 0} \frac{h\left[\rho_0 + \eta\delta\rho(\omega)\right] - h_0}{\eta}\,.$$

Thus, h depends on X and Y implicitly through $\delta\rho$.

Two-body current operator G would be treated the same way as Hamiltonian H:

$$\boxed{\begin{aligned}H &\longrightarrow h = T + \mathrm{Tr}\left(V\rho_0\right) \\ G &\longrightarrow g = \mathrm{Tr}\left(G\rho_0\right)\,.\end{aligned}}$$

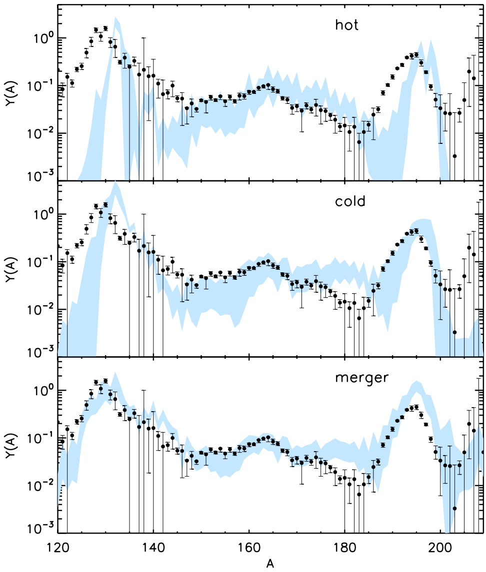
Finite Temperature

Useful for *r* process, particularly important for electron capture in supernova collapse.

We can already do even nuclei; Evan has derived equations (nontrivial) for odd nuclei.

What's at Stake for *r* Process?

Significance of Factor-of-Two Uncertainty



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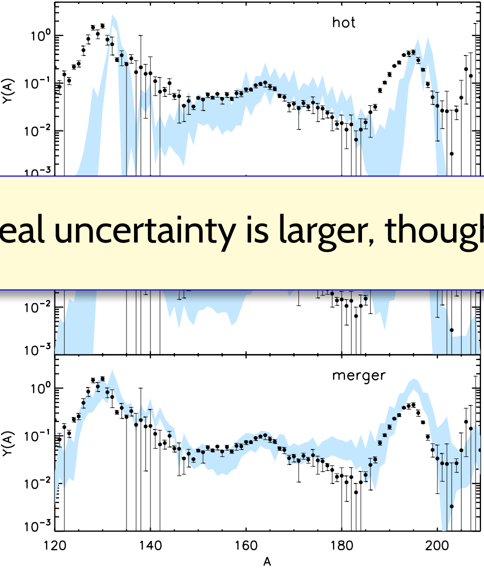

Real uncertainty is larger, though.

Finally…

\begin{Acknowledgments}

Evan, Tom, Mika, Matt, Rebecca, Gail, Carla …

Thanks!

\end{Acknowledgments}

\end{Talk}