Nuclear Structure Input for Nuclear Reactions

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UNEDF

Plan of the Talk

- Nuclear Structure Tools and Effective Interactions
- Spectroscopic factors
- Charge-Exchange Reactions
- Nuclear Level Densities

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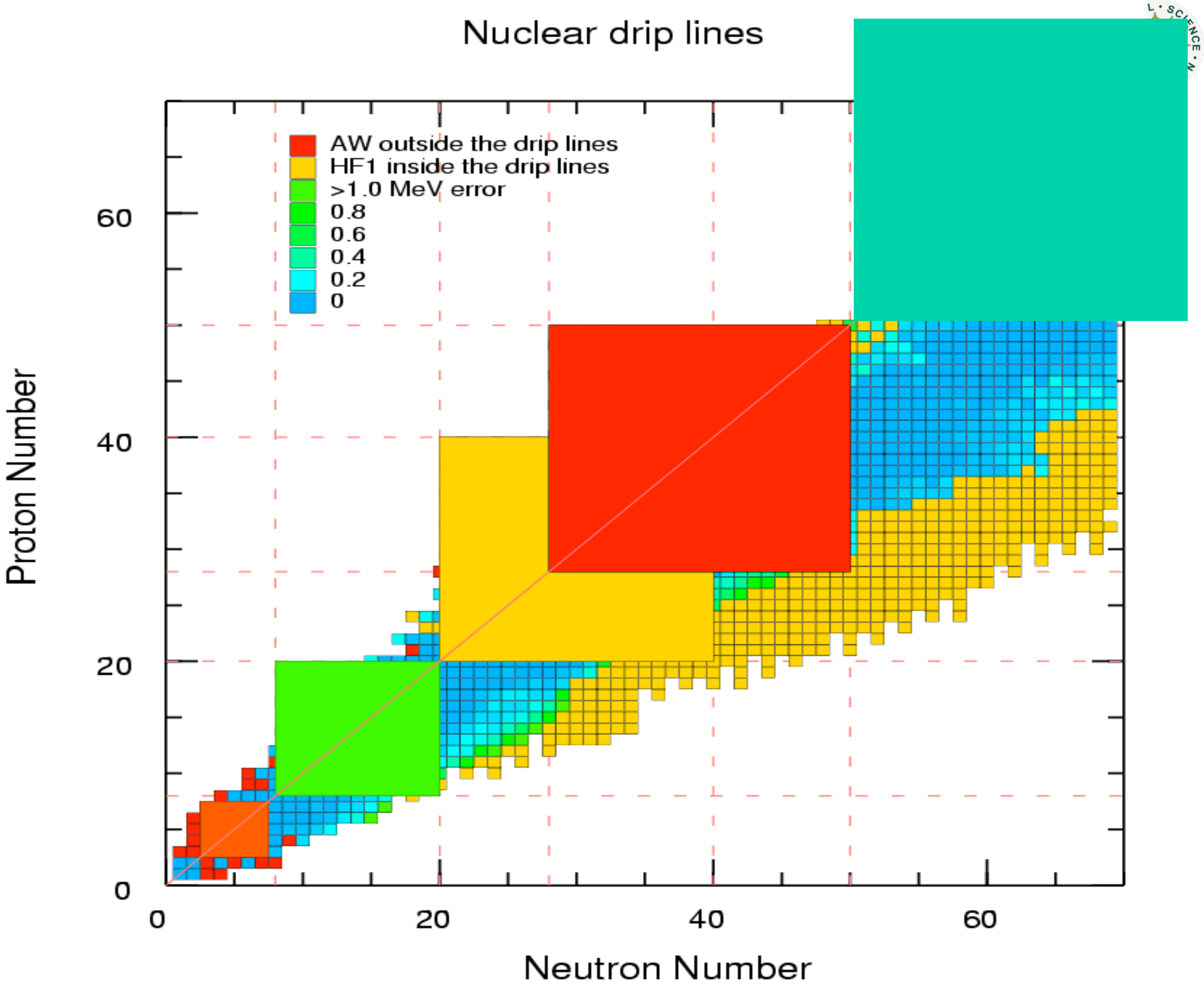
Configuration Interaction (CI)
(a.k.a. shell-model) dimensions

p - 10^2 -1960's
sd - 10^5 - 1980's
pf - 10^9 - 1990's
$pf_{5/2}g_{9/2}$ - 10^{10} - 2006
$g_{7/2}sdh_{11/2}$ - $5x10^{10}$ - '08



Example: ^{76}Sr

$pf_{5/2}g_{9/2}$ dimension

11 090 052 440

Current limit: 10^{10} - 10^{11} –> 46-48 np valence s.p. states

Extensions: Truncations, Exponential Convergence Method,

Coupled Clusters, Projected Configuration Interaction (CI), …

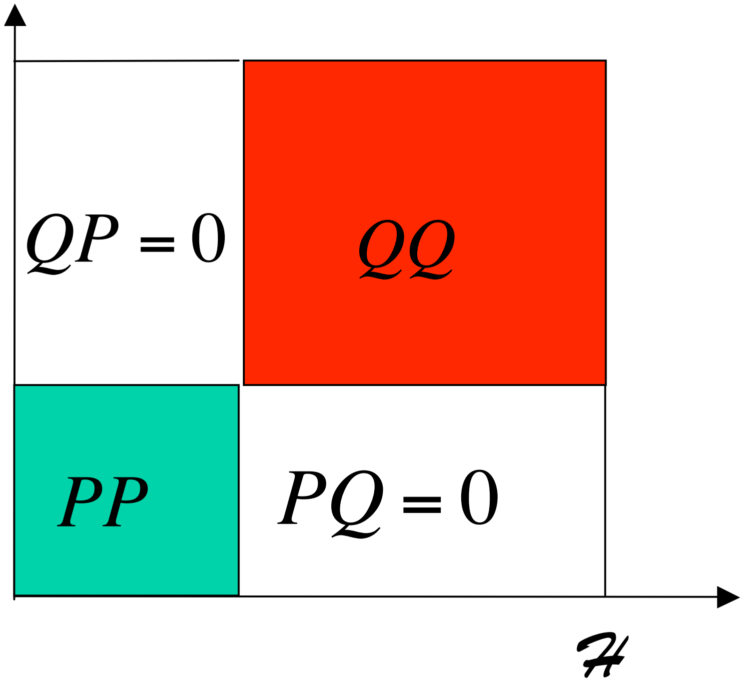
Effective Hamiltonians for Large N $\hbar\omega$ Excitations Model Spaces

Renormalization methods:

- G-matrix: Physics Reports **261**, 125 (1995)
- Lee-Suzuki (NCSM): PRC **61**, 044001 (2000)
- $V_{\text{low k}}$: PRC **65**, 051301(R) (2002)
- Unitary Correlation Operator: PRC **72**, 034002 (2004)

"Bare" Nucleon-Nucleon Potentials:

- Argonne V18: PRC **56**, 1720 (1997)
- CD-Bonn 2000: PRC **63**, 024001 (2000)
- N^3LO: PRC **68**, 041001 (2003)
- INOY: PRC **69**, 054001 (2004)



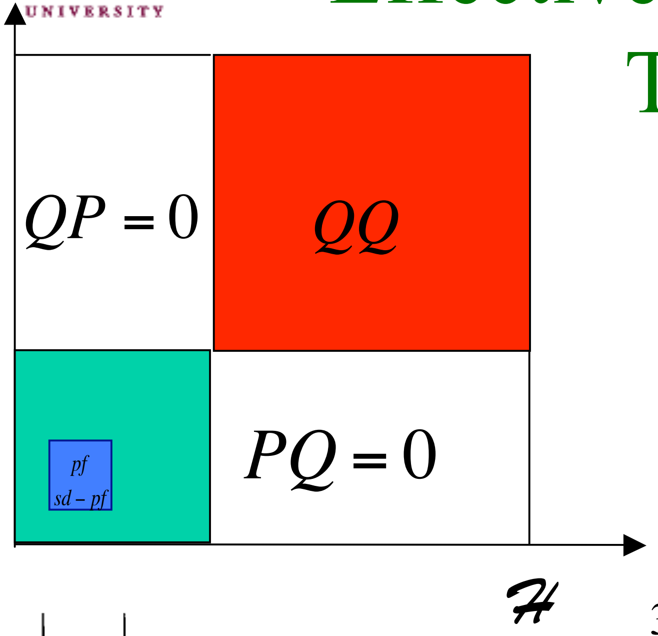
$$H = T + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk} + \cdots$$

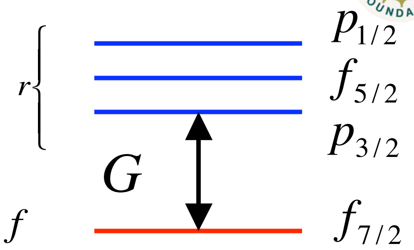
$$\Psi_{\mathcal{H}} \rightarrow \Psi_P = P\Psi_{\mathcal{H}}$$

$$\mathcal{H} = e^{-S} H e^{S} = \mathcal{H}_2 + \mathcal{H}_3 + \mathcal{H}_4 + \dots$$

$$O \rightarrow e^{-S} O e^{S}$$

Effective Hamiltonians for One or Two Major Shells

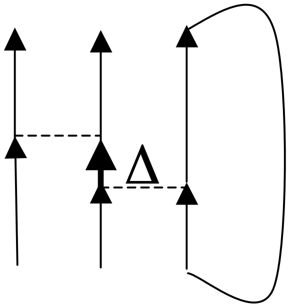




$$V_{ij}^{T} = \left\langle V_{ij\,ij}^{T} \right\rangle_{J}$$

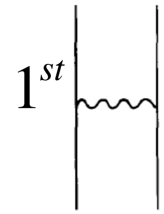
$$E_{CS}(^{56}Ni) = 16\varepsilon_f + 30\left(3V_{ff}^{1} + V_{ff}^{0}\right) - 6\left(V_{ff}^{1} - V_{ff}^{0}\right)$$

$$e_r(^{56}Ni) = \varepsilon_r + 4\left(3V_{fr}^{1} + V_{fr}^{0}\right) - \frac{3}{8}\left(V_{rr}^{1} - V_{rr}^{0}\right)$$

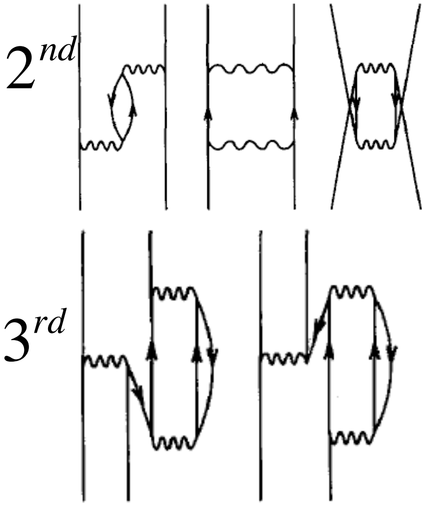


3-body –> two-body

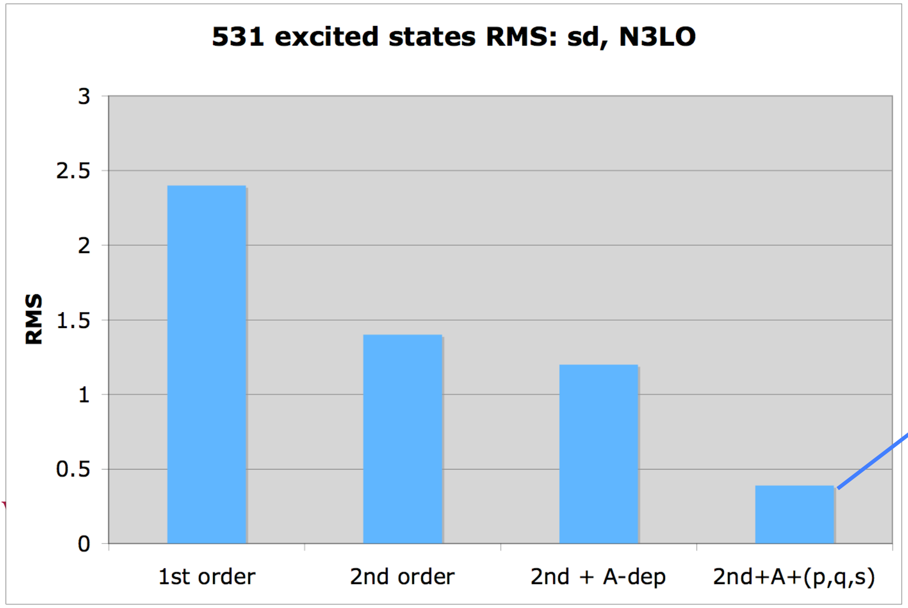
$$H = \sum_i p_i \varepsilon_i + \sum_m q_m H_m(mono) + s\sum_{\lambda>0} H_\lambda(multi)$$



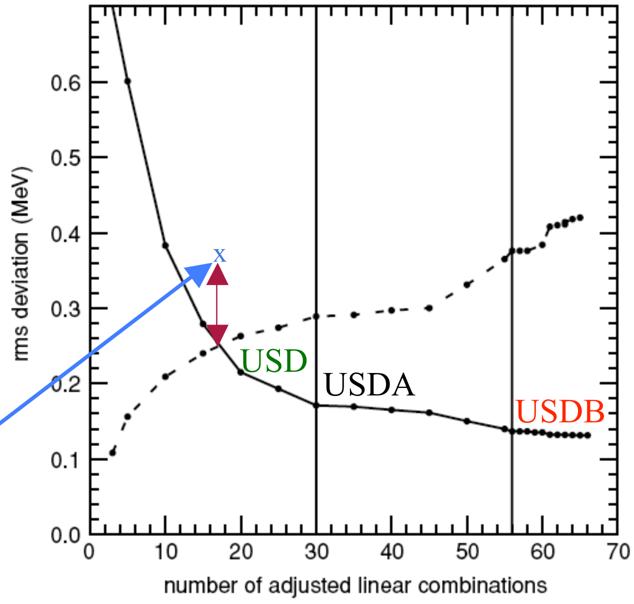
core polarization:
Phys. Rep. **261**, 125 (195)



$$RMS = \sqrt{\frac{1}{N_s}\sum_{i=1}^{N_s}\left(E_i^{th} - E_i^{\exp}\right)^2}$$



Brown & Richter, PRC **74**, 34315 (2006)



Kernz08 - Queensto
December 1, 2008

GXPF1A Effective Interaction: $f_{7/2}p_{3/2}p_{1/2}f_{5/2}$

Renormalized G-matrix ➔ GXPF1

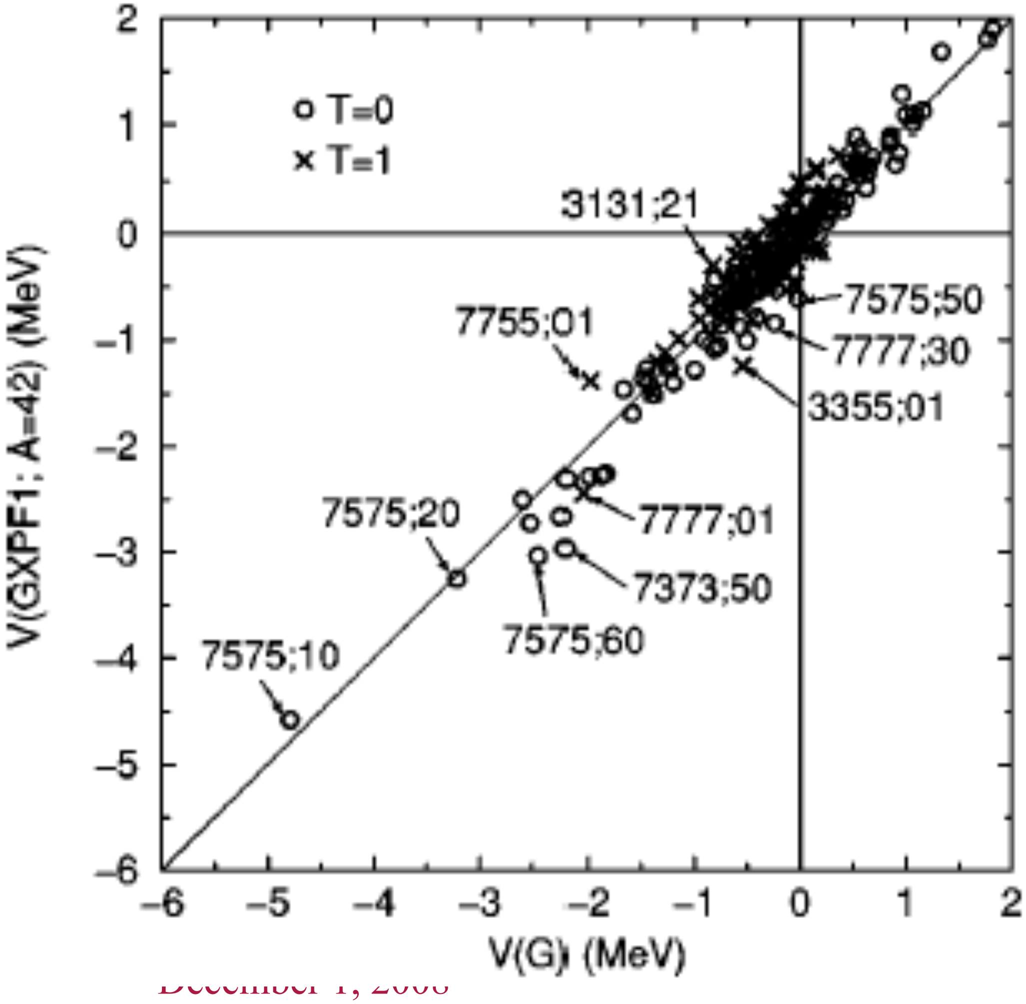
Phys. Rev. C **69**, 34355 (2004)

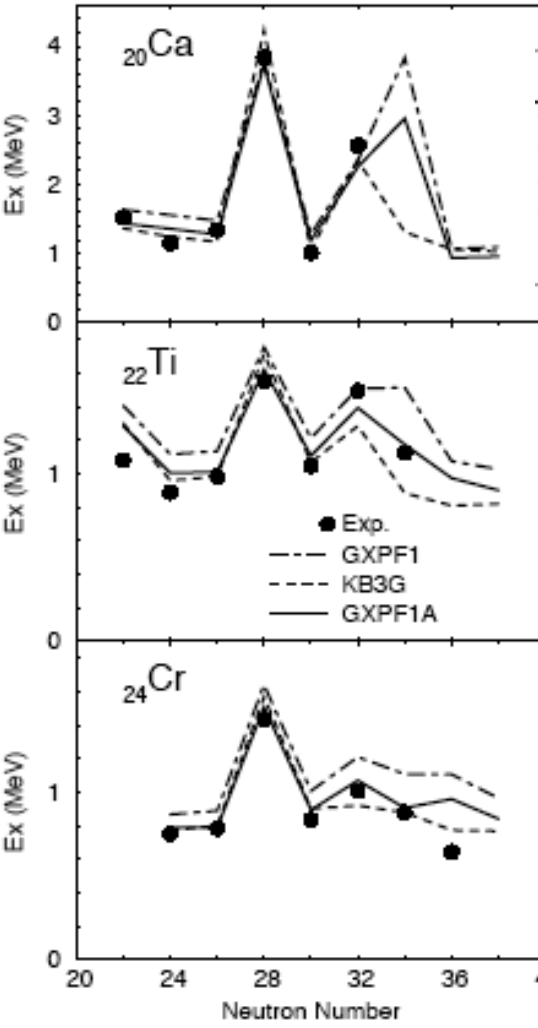
699 energies, 87 nuclei, A=47-66
rms=168 keV

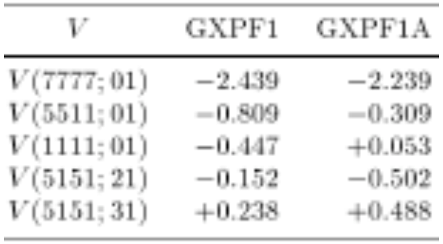
GXPF1 ➔ GXPF1A

M. Honma et al, ENAM04

5 matrix elements adjusted for N=34







V	GXPF1	GXPF1A
$V(7777;01)$	−2.439	−2.239
$V(5511;01)$	−0.809	−0.309
$V(1111;01)$	−0.447	+0.053
$V(5151;21)$	−0.152	−0.502
$V(5151;31)$	+0.238	+0.488

^{56}Ni states

J	#
0	1
2	1
4	1
0	2
0	3
6	1
2	2
4	2
4	3
8	1
10	1

Spectroscopic Factors

$$S = \frac{|< \Psi^{A} \omega J || a_k^{+} || \Psi^{A-1} \omega' J' >|^2}{(2J+1)} = \frac{|< \Psi^{A-1} \omega' J' || \tilde{a}_k || \Psi^{A} \omega J >|^2}{(2J+1)}$$

$$\sigma^{-} = S \, \sigma_{sp}$$

One particle removal cross section

$$\sigma^{+} = \frac{(2J_f + 1)}{(2J_i + 1)} S \, \sigma_{sp}$$

$$S(t_z) = |< T T_z \mid T' T'_z t t_z >|^2 \, \frac{|< \Psi^{A+1} \omega J T ||| a_k^{+} ||| \Psi^{A} \omega' J' T' >|^2}{(2J+1)(2T+1)}$$

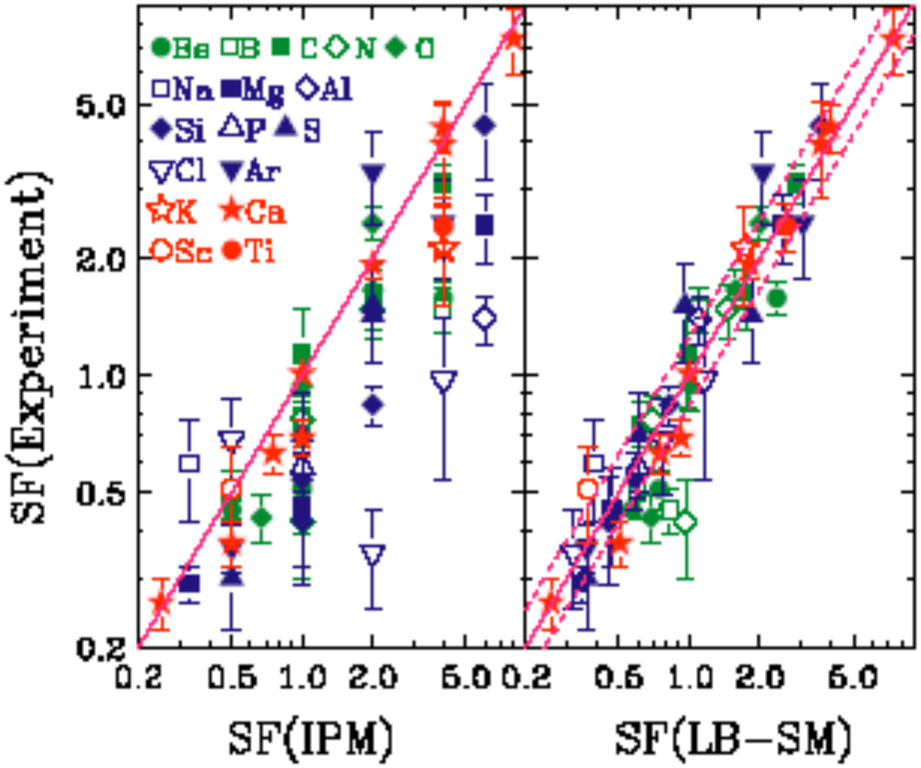
$$S(t_z) \equiv C^2 \, S(T)$$

$$\Gamma = (C^2 S) \, \Gamma_{sp}$$

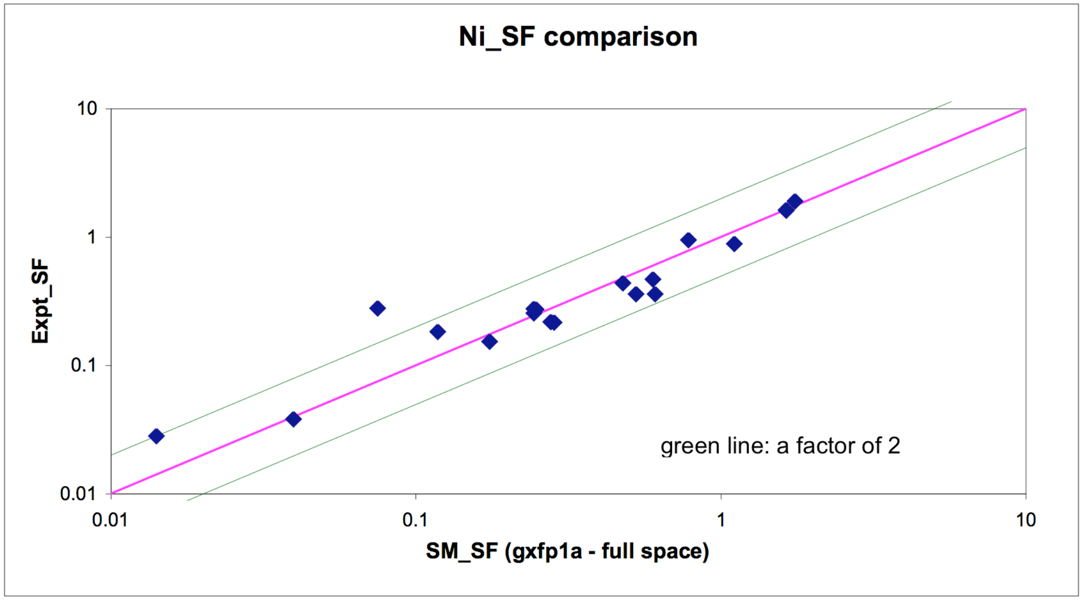
Spectroscopic factors: Shell Model vs Independent Particle Model (IPM)

$$\mathrm{SF} = n \quad \text{for } n = \text{even};$$

$$\mathrm{SF} = 1 - \frac{n-1}{2j+1} \quad \text{for } n = \text{odd}$$

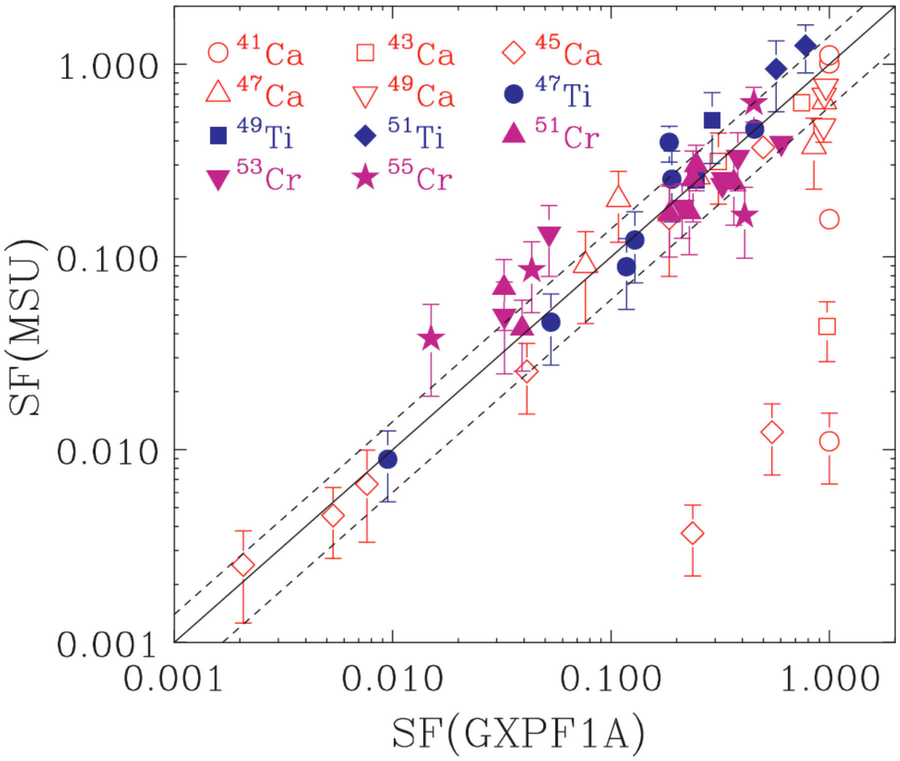


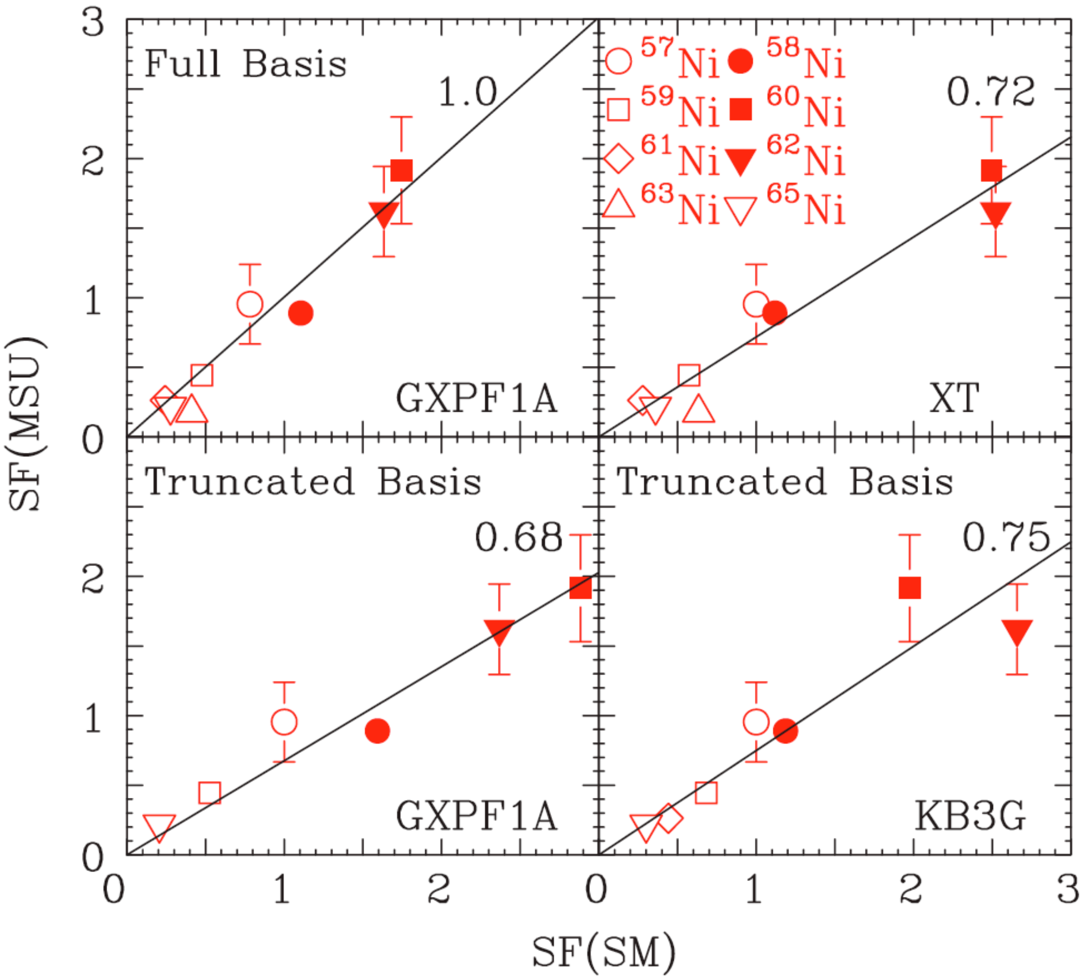
B. Tsang et al. Phys. Rev. Lett. 95 (2005)



Ni isotopes, GXPF1A interaction

Spectroscopic factors in the pf-shell





One neutron removal reaction ^{12}C(^{22}F, ^{21}F)^{13}C

E. SAUVAN *et al.* PHYSICAL REVIEW C **69**, 044603 (2004)

TABLE II. Summary of the results obtained with the carbon target. Where available the results of other experiments are also listed.

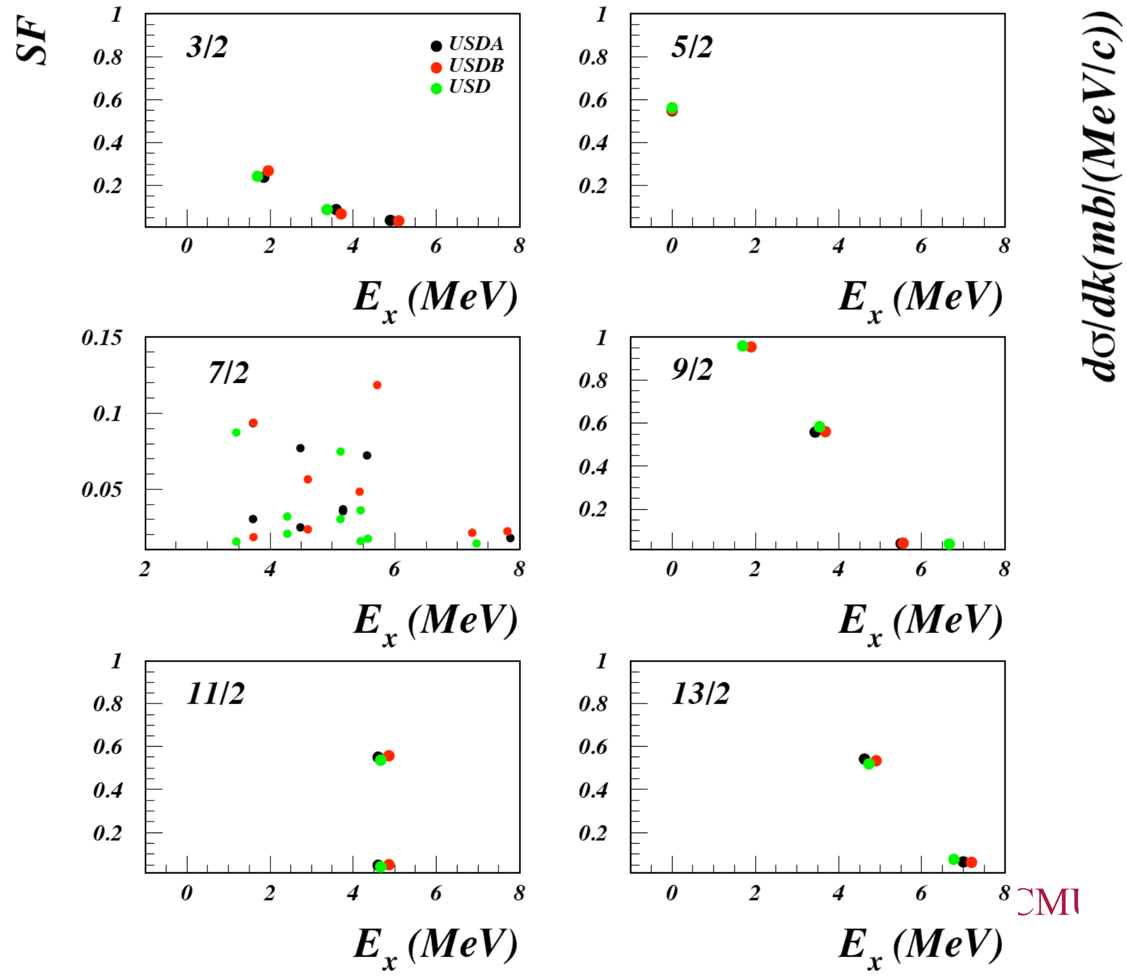
^AZ	Energy (MeV/nucleon)	$FWHM_{pz}^{lab}$ (MeV/c)	$FWHM_{pz}^{cm}$ (MeV/c)	$FWHM_{px}^{lab}$ (MeV/c)	$FWHM_{px}^{cm}$ (MeV/c)	σ_{-1n} (mb)	$\sigma_{-1n}^{Glauber}$ (mb)	J^π
^{22}F	64	212±14	185±14	278±28	274±28	121±16	87	4^+
^{23}F	59	267±4	235±4	236±10	232±10	114±12	106	$5/2^{+c,r,s}$

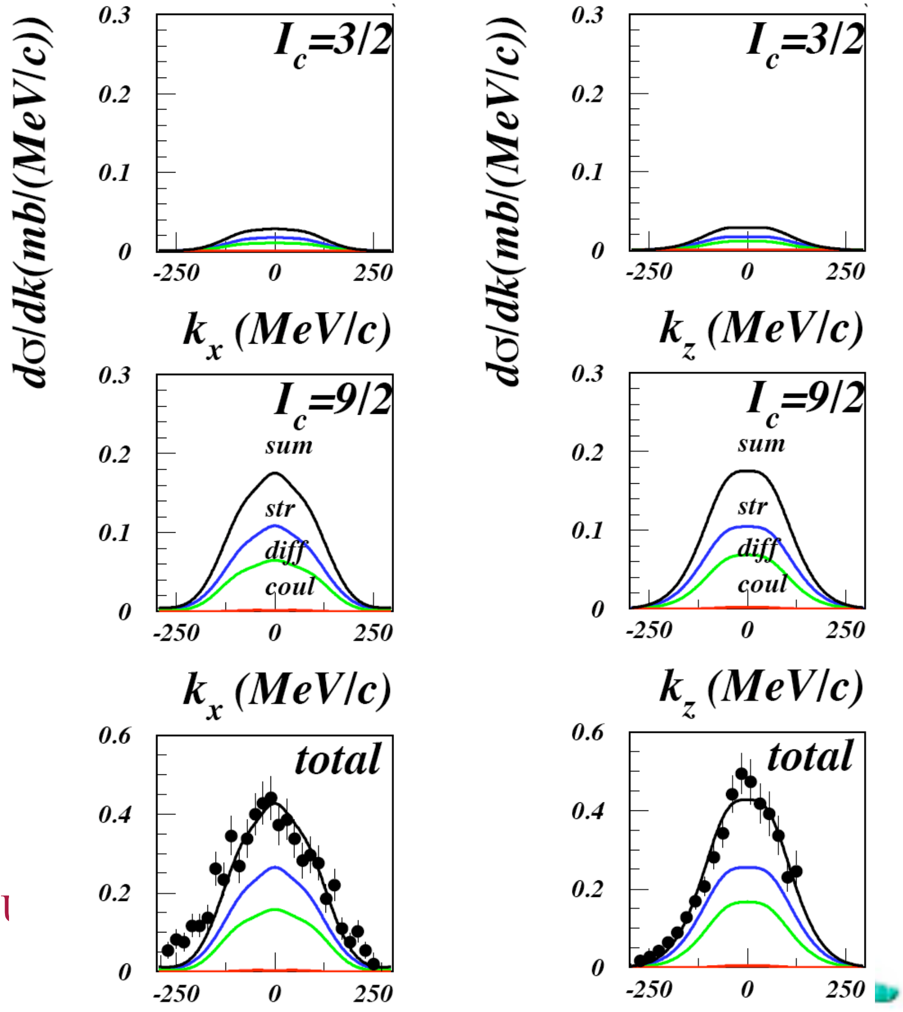
USD

USDB

σ=109.24 mb

σ_{exp} =121+/-16 mb

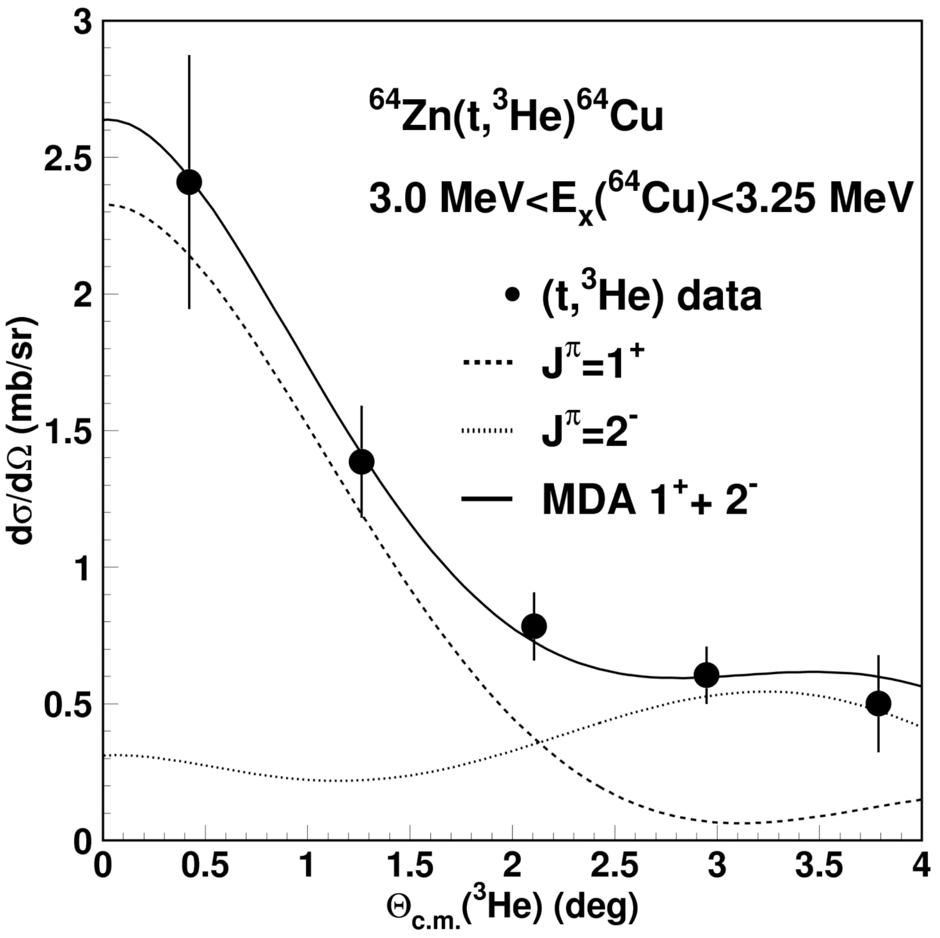


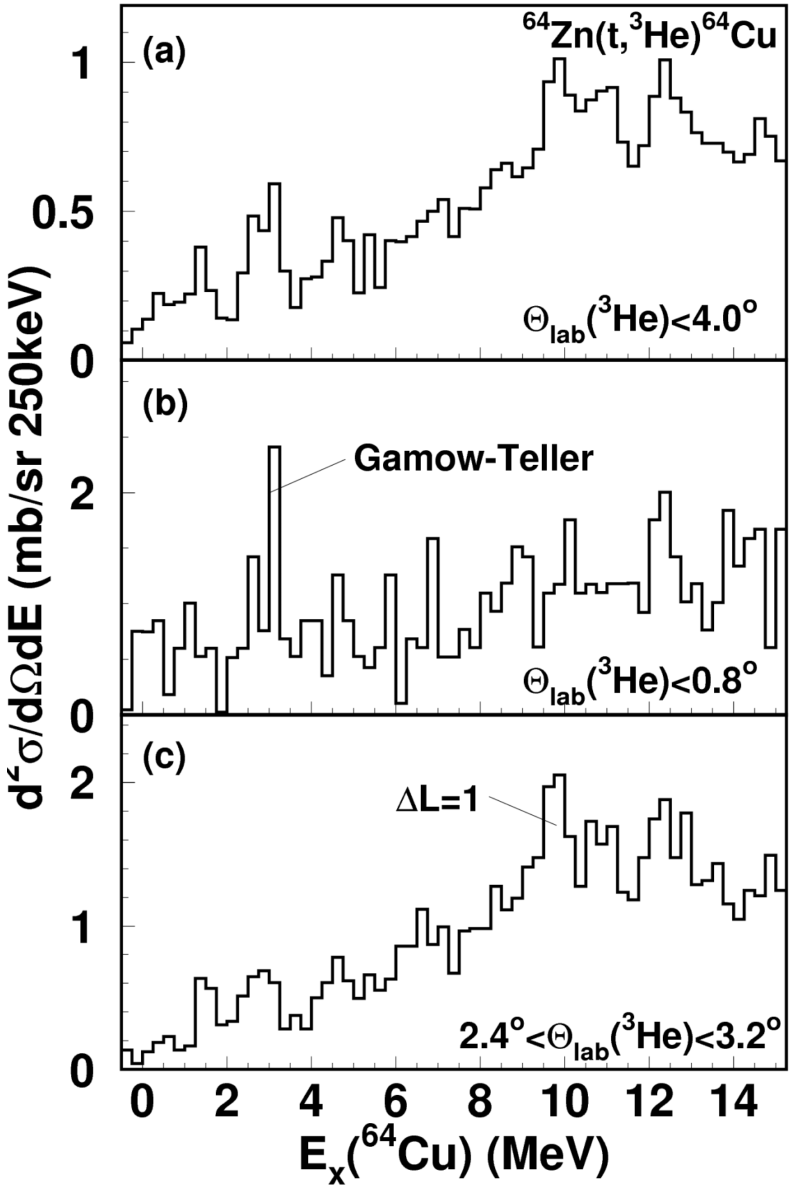


^{64}Zn(t,^{3}He): test of e-capture rates in stellar evolution

Thesis: Wes Hitt
Also ^{58}Ni(t,^{3}He) Cole et al. Phys. Rev. C 74, 034333 (2006)

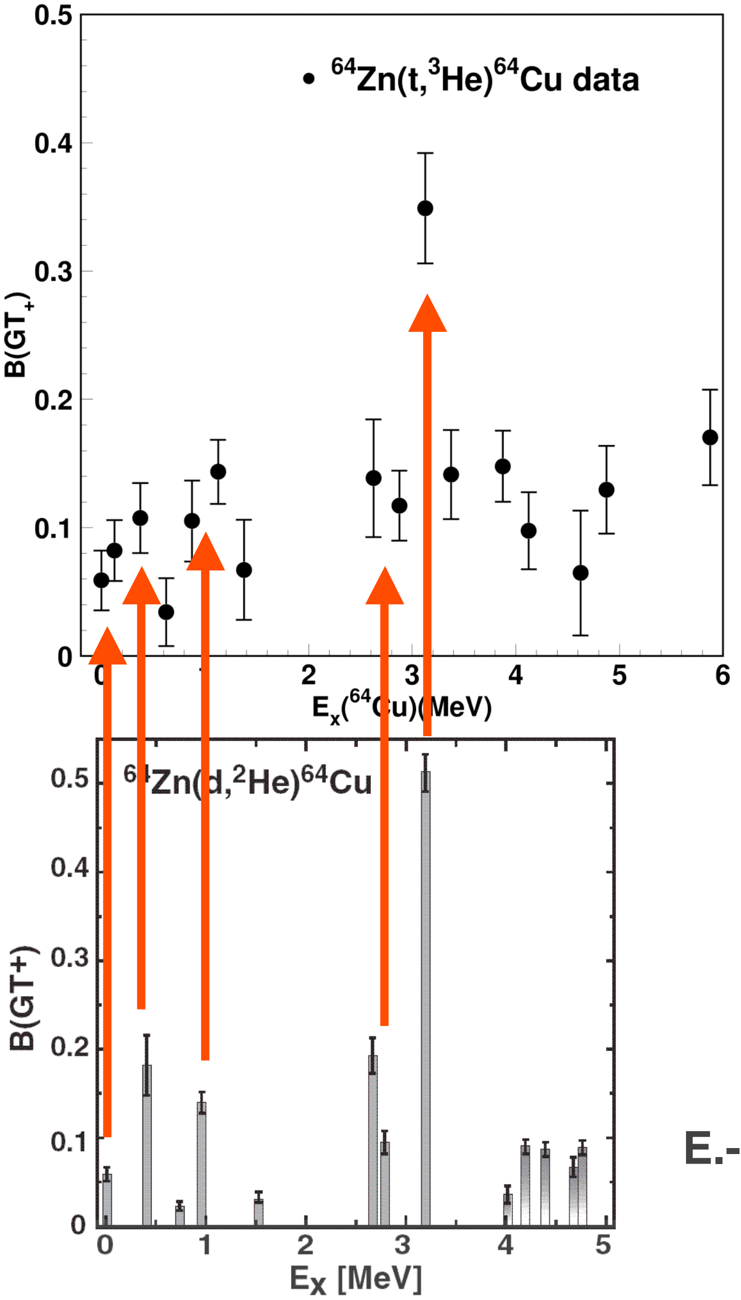
$$\left.\frac{d\sigma(\Delta L=0)}{d\Omega}\right|_{q\to 0} = \hat{\sigma}_{\mathrm{GT}} B(\mathrm{GT}_{+})$$

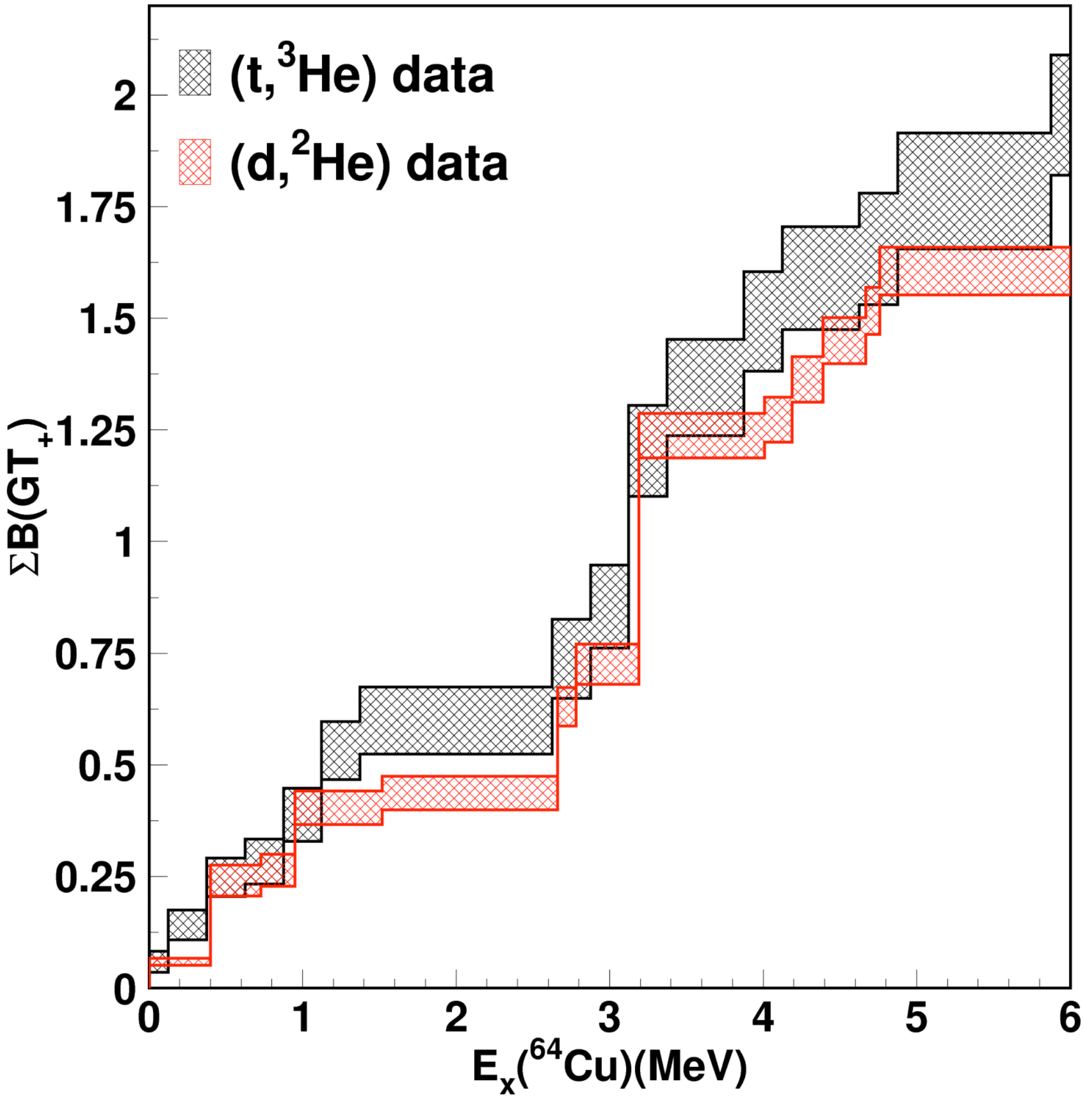




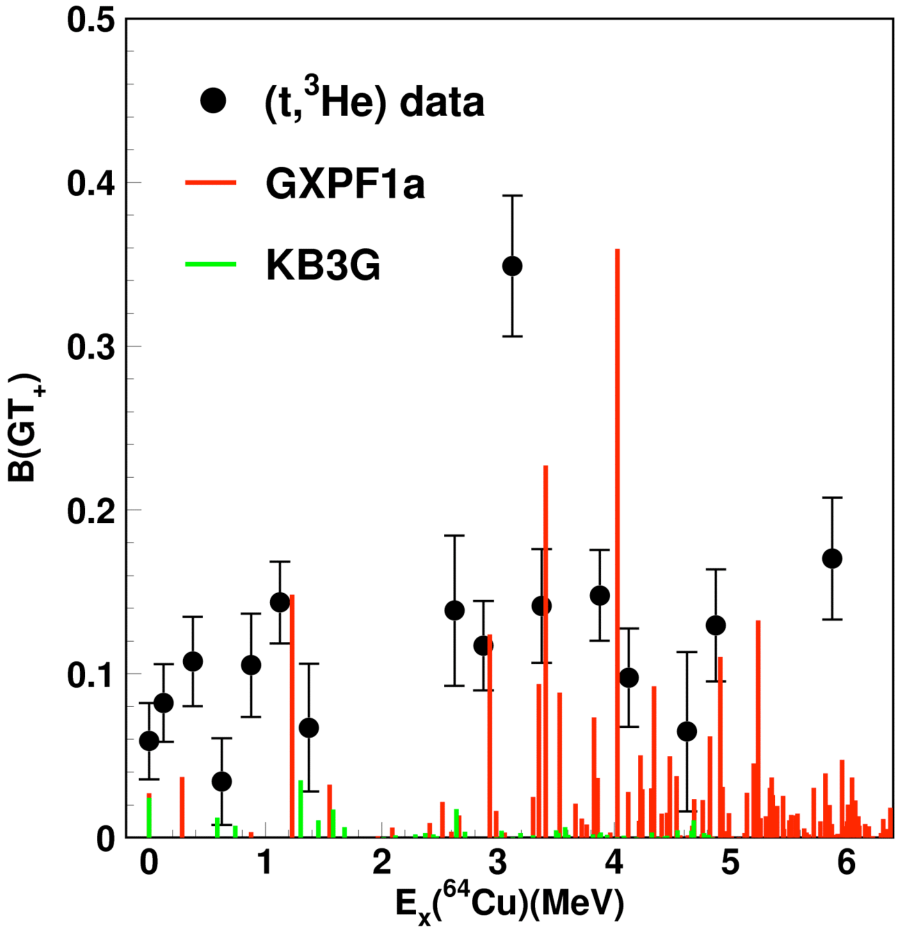
Use empirical unit cross section from (^{3}He,t)

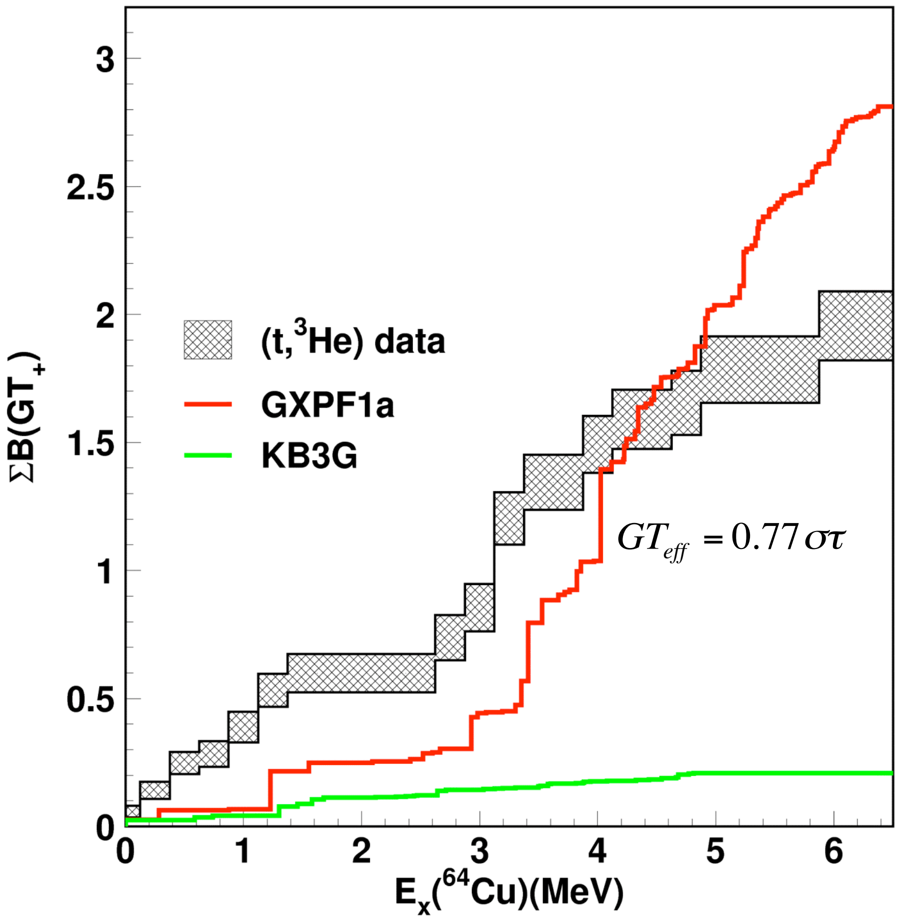
Comparison with (d,^{2}He)





E.-W. Grewe, et.al. Phys. Rev.C 77 064303 (2008).



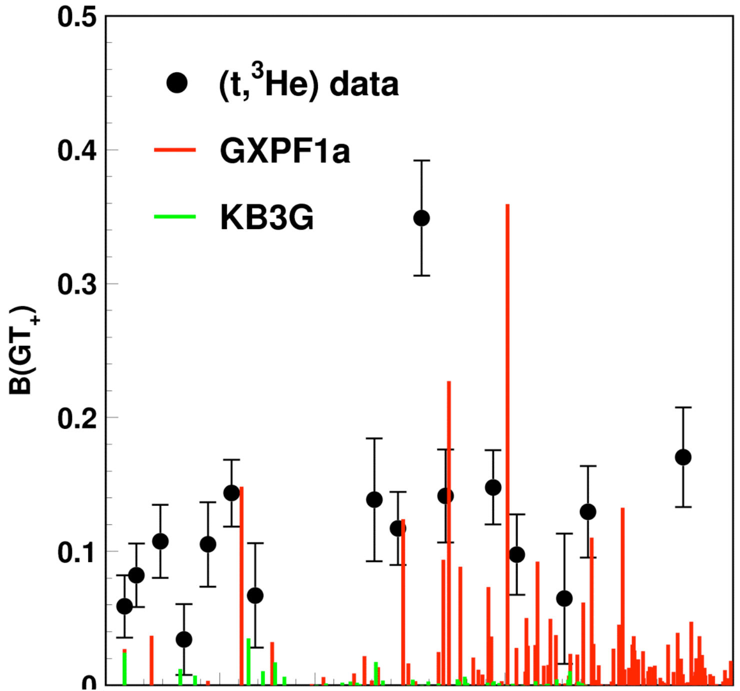


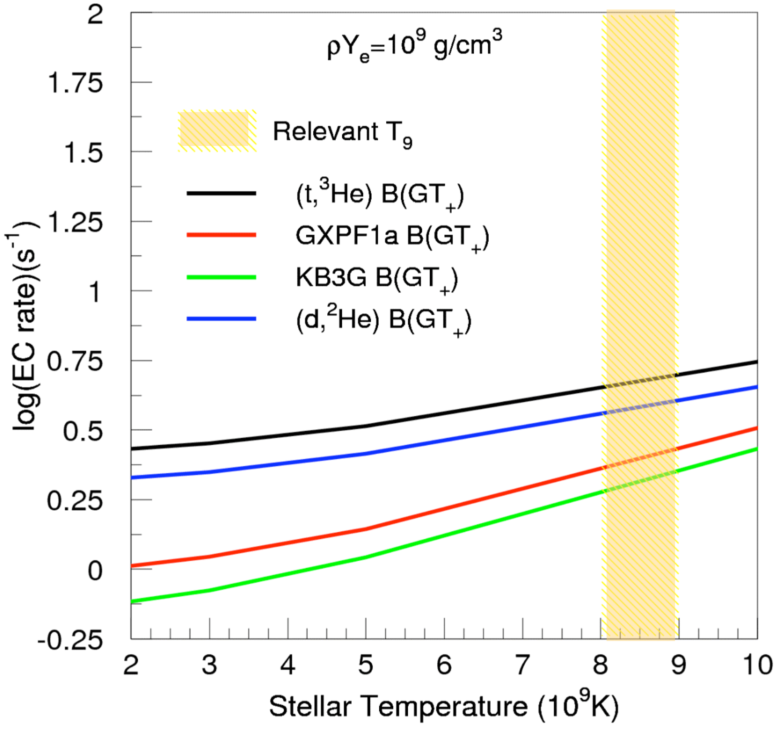
Calculations by M. Horoi with NuShellX – no truncations!!

GXPF1a M. Honma et.al. Eur. Phys. J. A 25 s01, 499-502 (2005)

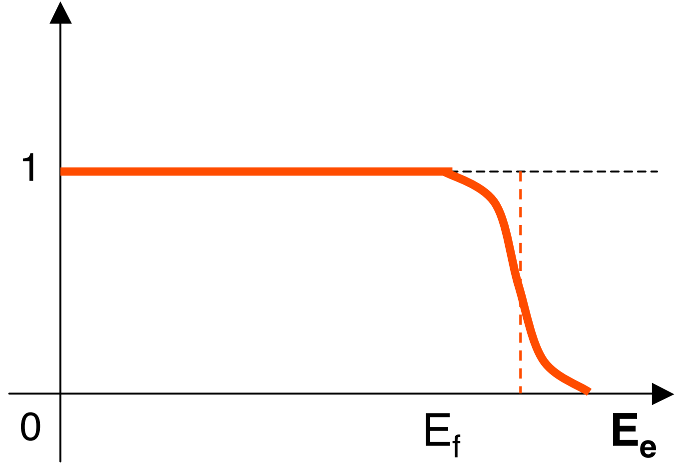
KB3G A. Poves et.al. Nucl. Phys. A694, 157(2001)

Effects on weak stellar rates





EC rate program: A.D. Becerril-Reyes, S. Gupta, K.L. Kratz, P. Moller, H. Schatz, Proc. Of NIC-IX, PoS Geneva (2006).



— ● (t,^{3}He) data

— (d,^{2}He) data

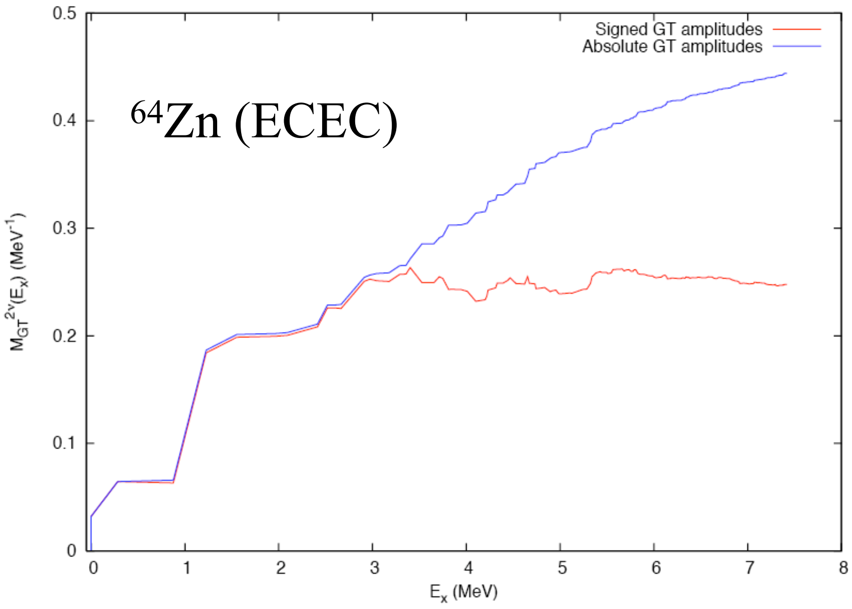
— GXPF1a interaction

— KB3G interaction

▨ relevant temperature range at specific ρY_e

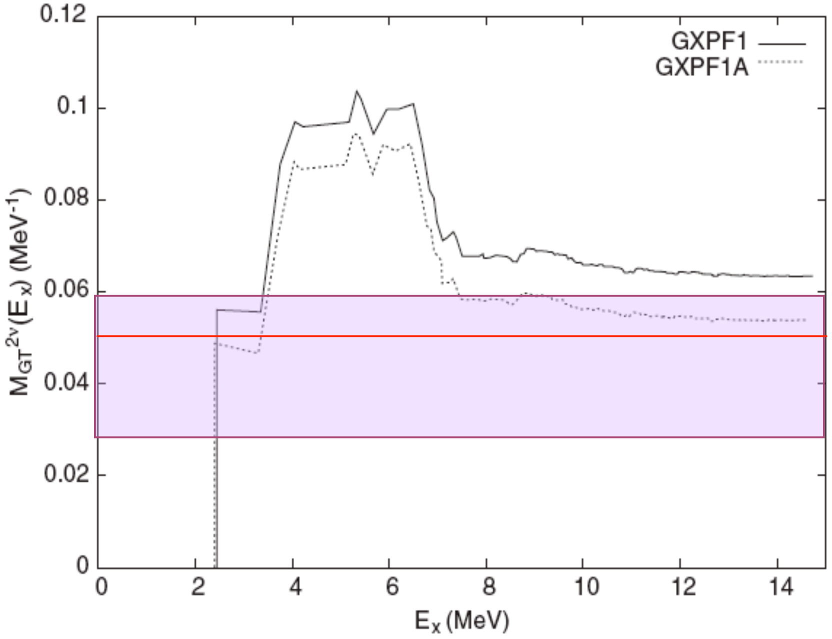
Double Beta Decay (DBD)

- 2νDBD experimental results known for 10 nuclei, including decays to excited states: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{150}Nd, ^{238}U (also ECEC of ^{130}Ba)
- 0νDBD may be a unique tool to get the neutrino masses and other physics beyond Standard Model

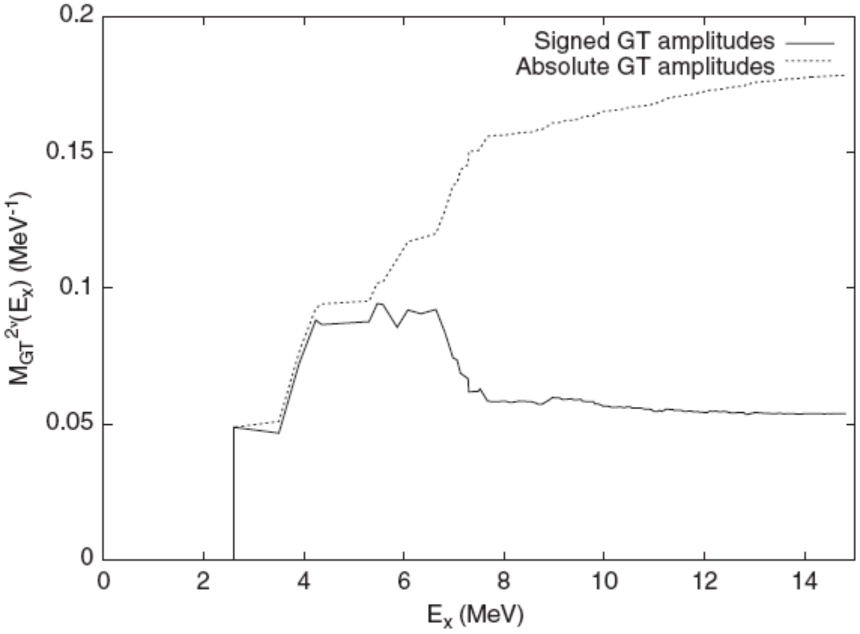


$$M_{\mathrm{GT}}^{2\nu}(0^+) = \sum_k \frac{\langle 0_f \| \sigma\tau^- \| 1_k^+ \rangle \langle 1_k^+ \| \sigma\tau^- \| 0_i \rangle}{E_k + E_0}$$

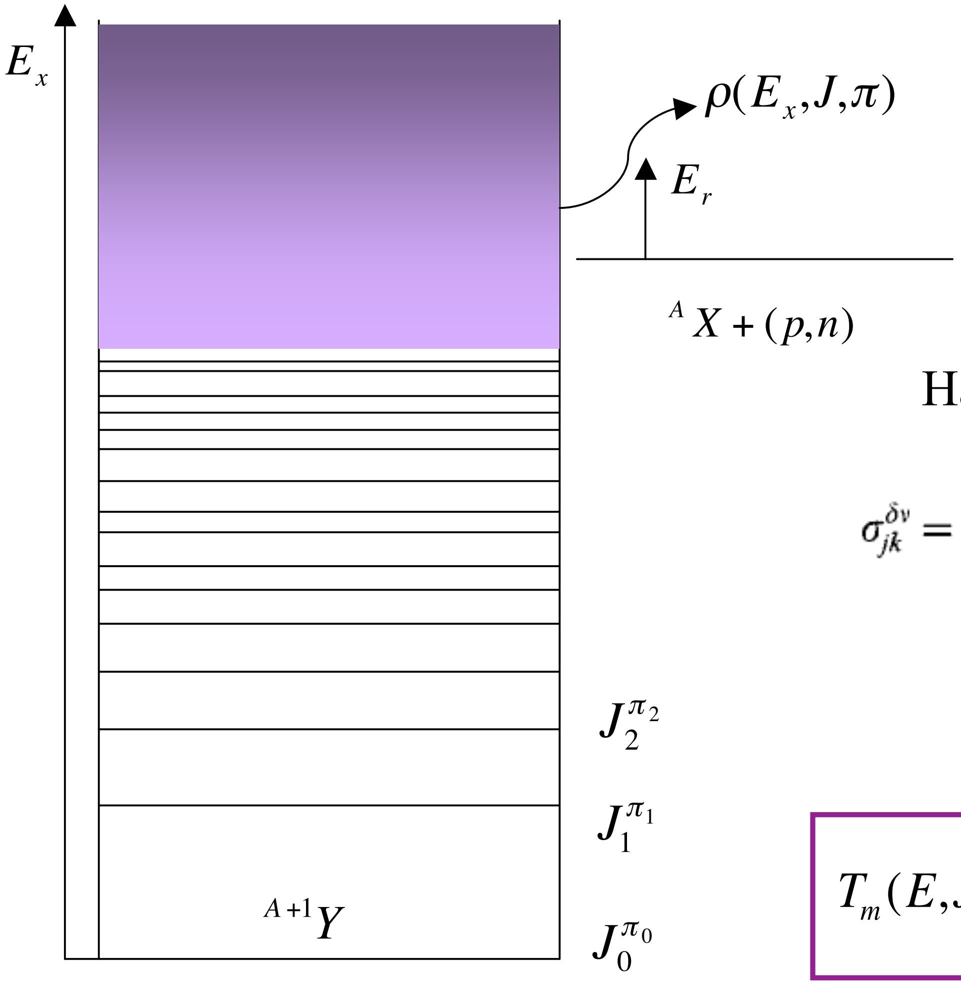
Horoi, Stoica, Bown, PRC **75**, 034303 (2007) ^{48}Ca - 250 1^+ states



Mi



Nuclear Level Densities (NLD)



(n,γ), (n,xn), (n,n'), (n,p), (n,f), …

Hauser and Feshbach, Phys. Rev **87**, 366 (1952)

$$\sigma_{jk}^{\delta\nu} = \frac{\pi\hbar^2}{2\mu_{ij}E_{ij}}\,\frac{1}{(2J_i^\delta+1)(2J_j+1)} \times \sum_{J,\pi}(2J+1)\,\frac{T_j^\delta(E,J,\pi,E_j^\delta,J_j^\delta,\pi_j^\delta)\,T_k^\nu(E,J,\pi,E_k^\nu,J_k^\nu,\pi_k^\nu)}{\sum_m T_m(E,J,\pi)}$$

$$\boxed{T_m(E,J,\pi) = \int_{E_{\min}}^{E_{\max}} T(E,J,\pi;E_x,J_x,\pi_x)\,\rho(E_x,J_x,\pi_x)\,dE_x}$$

NLD and Statistical Spectroscopy

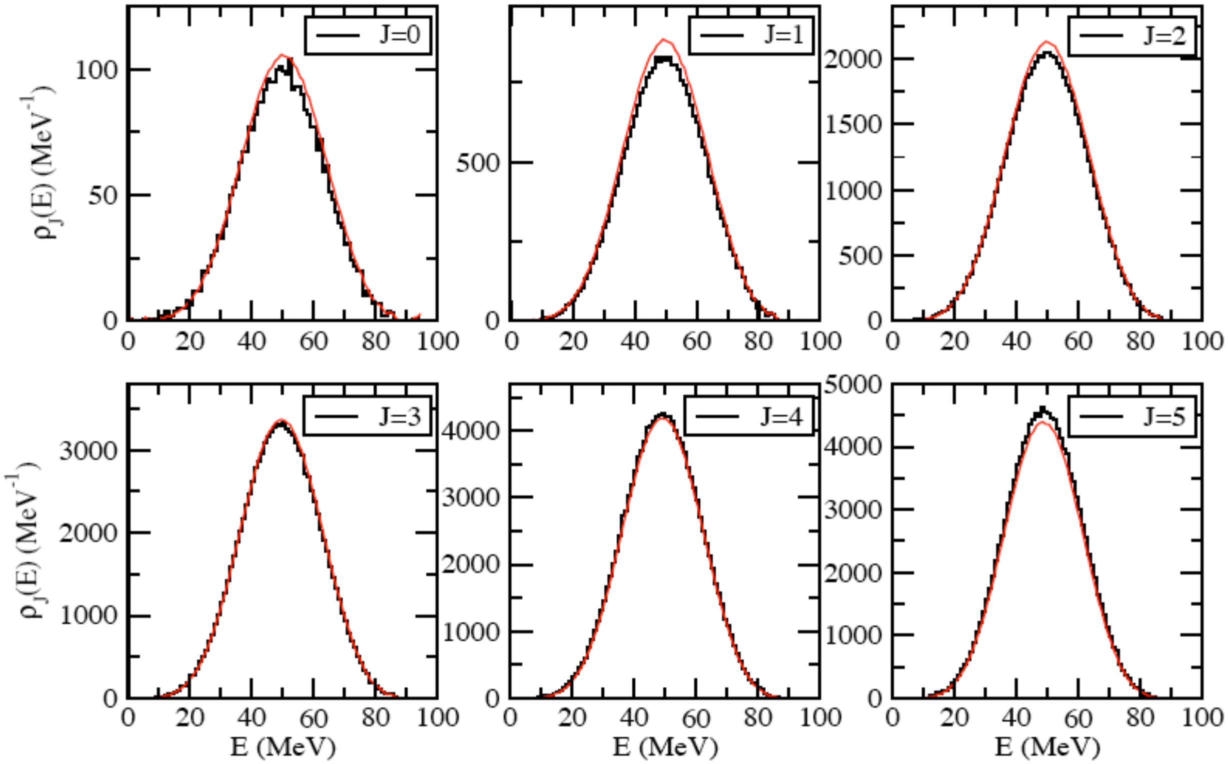
M. Horoi et al. :

PRC **67**, 054309 (2003),

PRC **69**, 041307(R) (2004),

NPA **785**, 142 (2005).

PRL **98**, 265503 (2007)



^{28}Si $\pi = +$ staircase: CI, USD

Configurations: e.g. 4 particles in sd
d3 d5 s1
4 0 0
3 1 0
3 0 1 …

preserve rotational invariance and parity

$$\rho(E_x,J,\pi) = \sum_{c\in conf} D_c(J,\pi)\, G_{FR}\left(E, E_c(J), \sigma_c(J)\right)$$

$$E_c(J), \sigma_c(J) \leftarrow Tr_{SD_c} < M \mid H^q \mid M >_{SD_c}$$

$$E_x = E - E_{g.s.}$$

$E_{g.s.}$ from CI, PCI, Exponential Convergence Method (PRL **82**, 2064 (1999)), CC, etc.

$E_c(J)$, $\sigma_c(J)$: computational intensive

Configurations can be calculated in parallel

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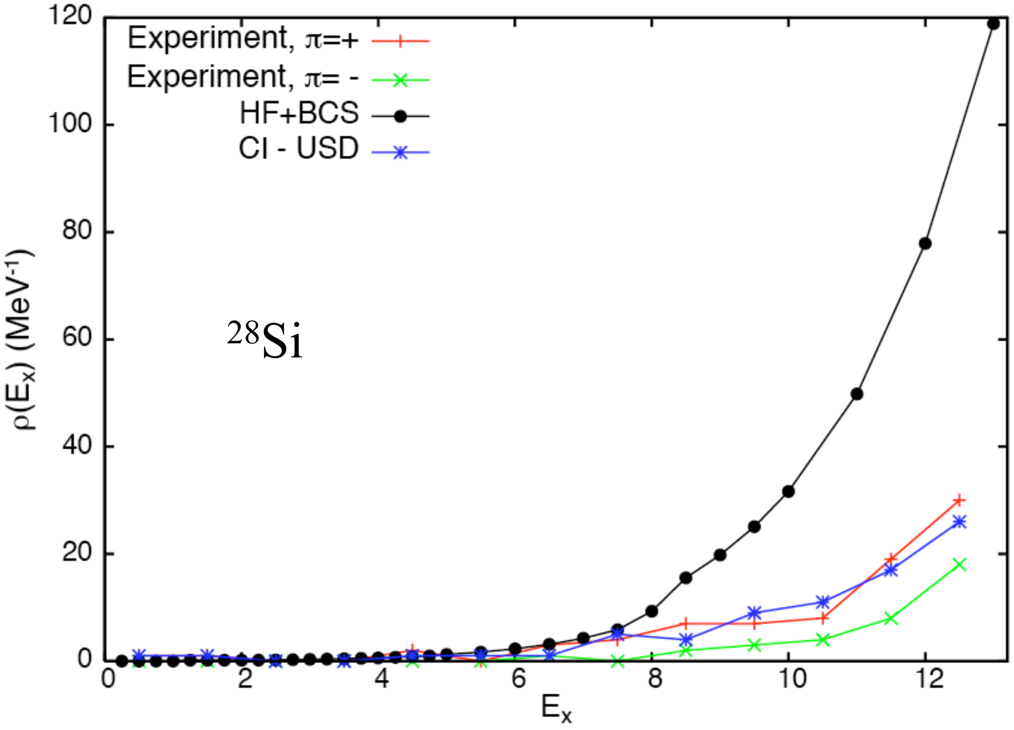
Accurate Nuclear Level Densities

Comparison of:

1. CI,
2. HF+BCS
   www-astro.ulb.ac.be/Html/nld.html
3. experimental data

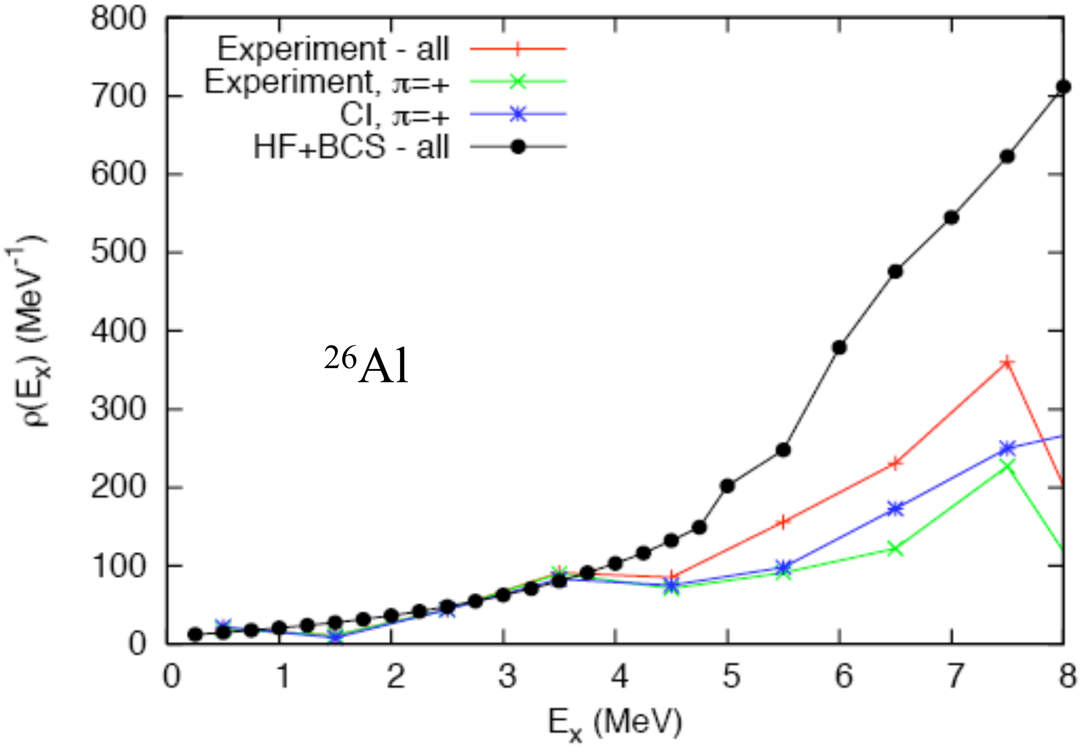


Complete spectroscopy: sd-shell nuclei

Conclusions:

- HF+BCS overestimates the data

- CI accurately describes the data



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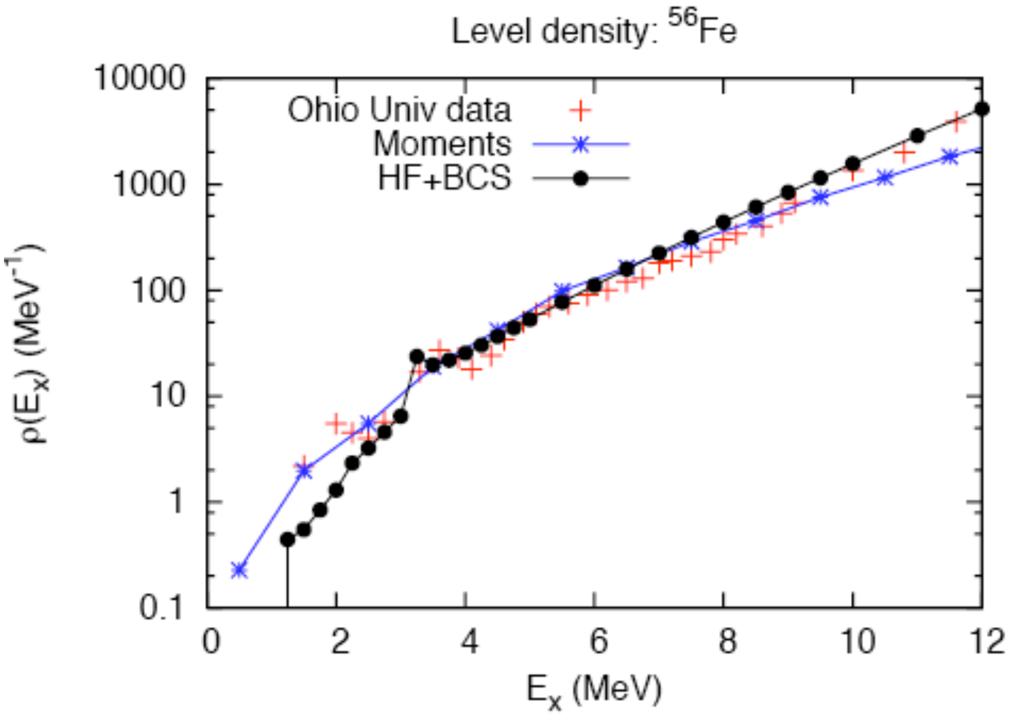
NLD of ^{56}Fe: CI, Moments, HF+BCS



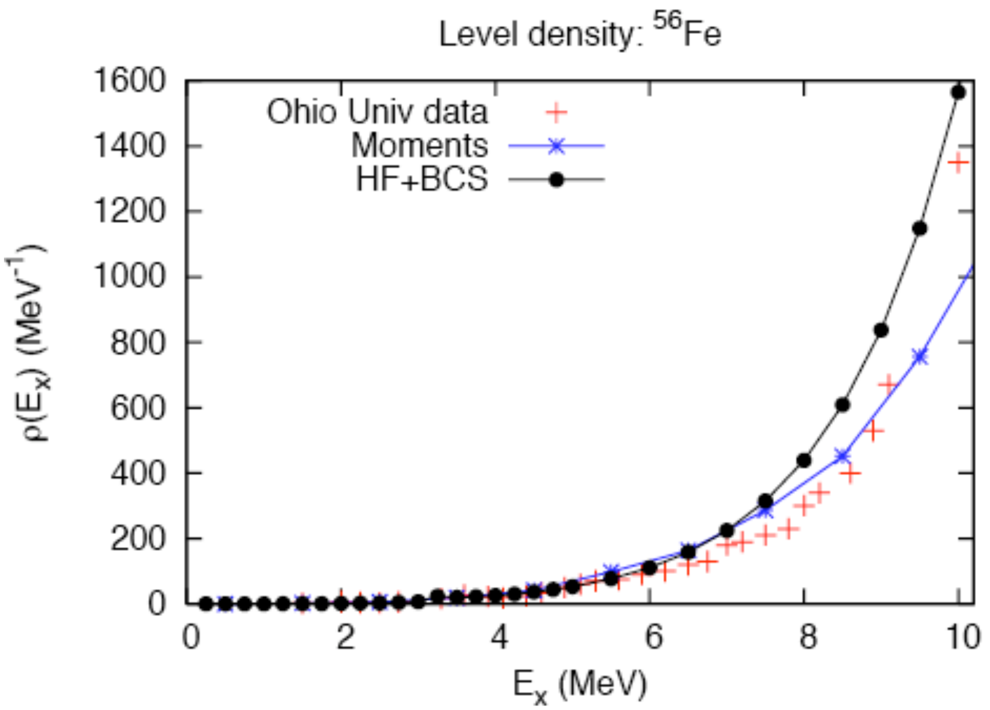
Ohio data: PRC **74**, 014314 (2006)

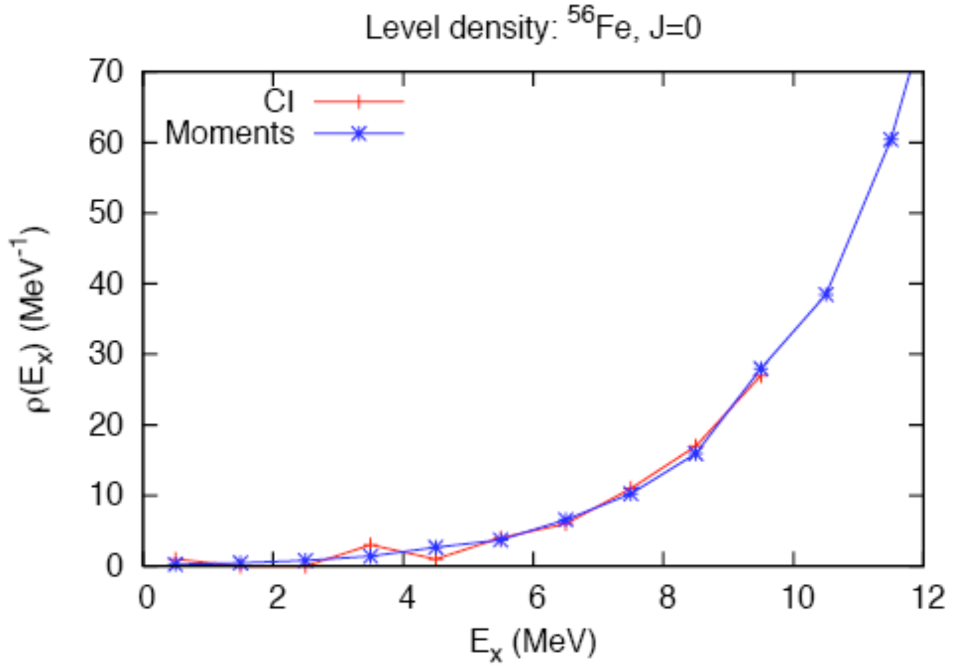
HF+BCS: $\rho_{HF+BCS}(U)$

- Demetriou and Goriely, Nucl. Phys. **A695** (2001) 95.
- http://www-astro.ulb.ac.be/Html/nld.html

HFB+Combinatorial: $\rho(E_x, J, \pi)$

- S. Hilaire and S. Goriely, Nucl. Phys. **A779** (2006) 63
- http://www-astro.ulb.ac.be/Html/nld_comb.html





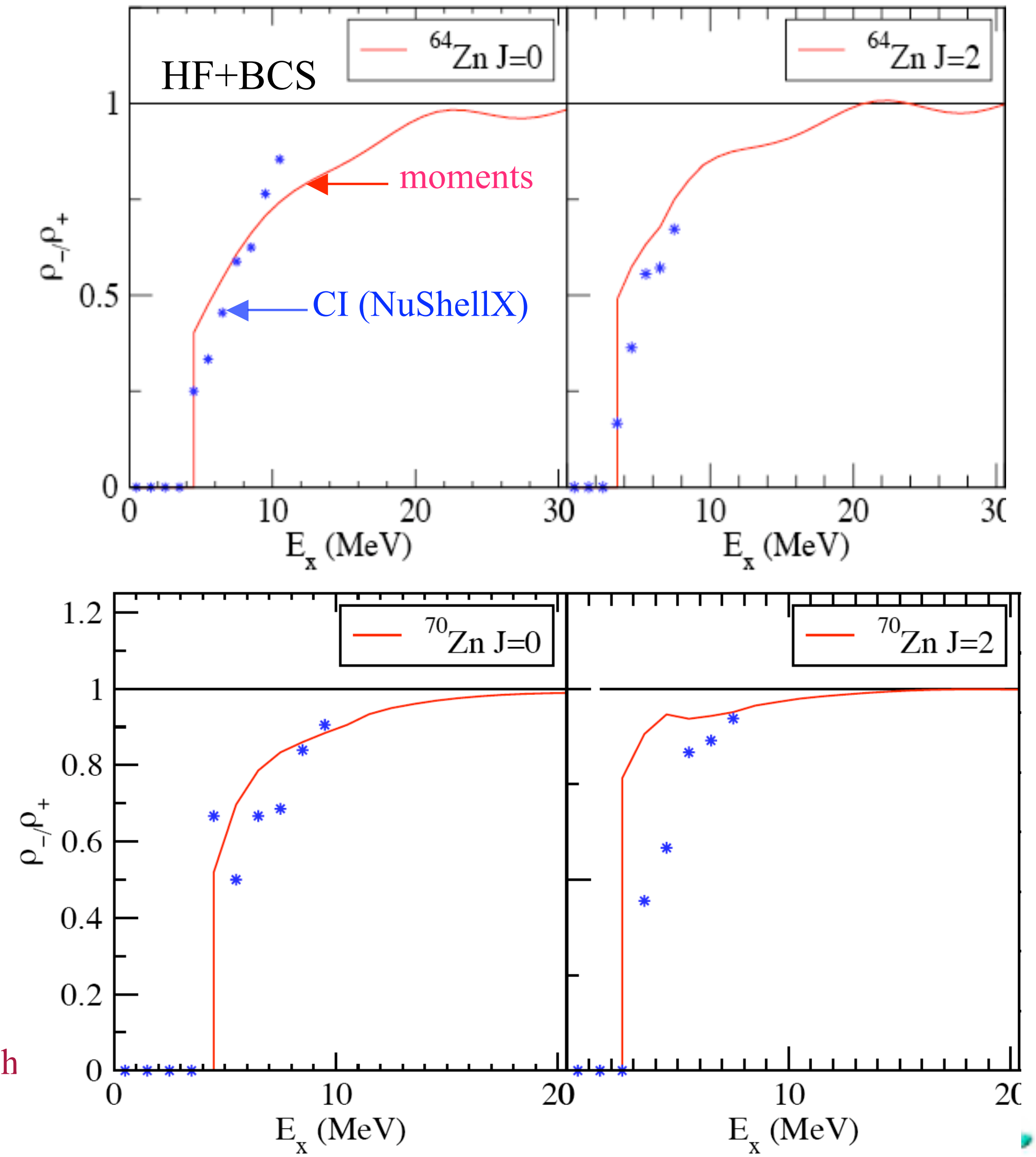
Ratio of unnatural to natural NLD of different parities at low energies

$$\rho(E_x, J, \pi) = (1/2)\, \mathcal{F}(U, J)\, \rho_{FG}(U)$$

$$U = E_x - \Delta$$

Equal contribution to both parities

Remedy by Alhassid, Bertsch, Liu, Nakada, PRL 84, 4313 (2000) + Basel group (Rauscher)



Configurations: e.g. 4 particles in fpg

f5	**p3**	**p1**	**g9**	**π**
4	**0**	**0**	**0**	**+**
3	**1**	**0**	**0**	**+**
3	**0**	**1**	**0**	**+**
3	**0**	**0**	**1**	**-**

…

preserve rotational invariance and parity

Summary and Outlook

Accurate description of correlations in nuclei is very important!

- ✓ CI can successfully describe complex many-body states, but also simple "Shell Model" configurations, collective configurations, and their coexistence.
- ✓ CI can provide for the most part accurate input to reactions models:
  - ✓ Electromaganetic transition amplitudes
  - ✓ Spectroscopic amplitudes
  - ✓ Gamow-Teller transition amplitudes
  - ✓ Nuclear level densities
- ✓ The real challenge the is to find ways of calculating consistently, i.e. using the same underlying Hamiltonian, the nuclear structure and the nuclear reaction effects. This seems to be possible for light nuclei (e.g. GFMC, or NCSM+RGM), but remains a challenge for the medium heavy nuclei.

Collaborators

- B. A. Brown - MSU/NSCL
- V. Zelevinsky - MSU/NSCL
- Z. Gao - CMU
- B. Tsang - MSU
- R. Zegers - MSU
- W. Hitt - MSU
- F. Carstoiu - Bucharest
- M. Hjorth-Jensen - Oslo
- T. Otsuka - Tokyo
- M. Honma - Aizu