Single and Double Charge-Exchange Reactions to Study Nuclear Matrix Elements (NMEs) for Neutrinoless Double Beta Decays (DBDs).

RCNP DBD 2022

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RCNP Osaka

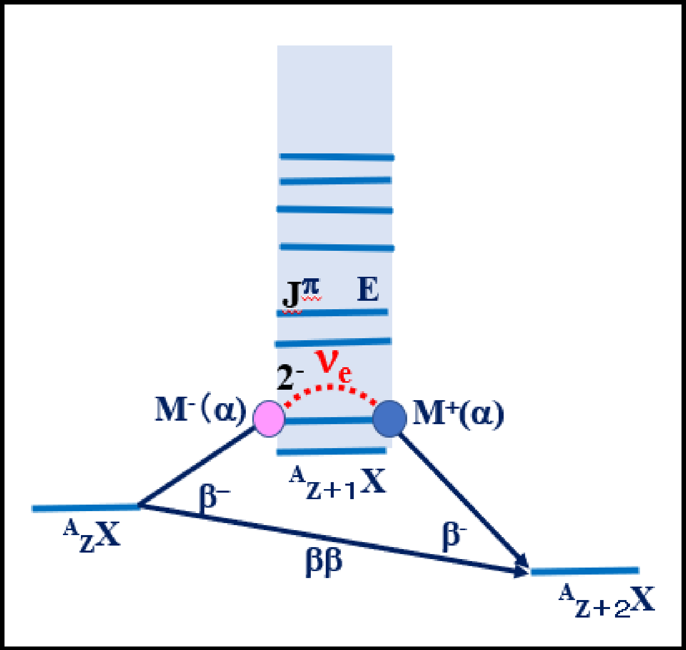
RCNP DBD Oct. 2-4, 2022. RCNP
Thanks the organizers for the invitation.

1. Nuclear matrix elements (NMEs) for DBDs and giant isospin spin (τ σ) resonances and τ σ responses.
2. Experimental spin dipole (SD) giant resonances and quenching of GT and SD single-beta NMEs.
3. SD giant resonances and pnQRPA DBD NMEs.
4. Double Charge-exchange Reactions for DBD NMEs
5. Impact on DBD experiments and on DBD NMEs.

1. H. Ejiri, J. Suhonen, K. Zuber, Phys. Rep. 797, 1 (2019).
2. H. Ejiri, Universe 6, 225 (2020); Frontiers in Physics 9, 650421 (1921).
3. L. Jokiniemi, H. Ejiri, D. Frekers, J. Suhonen, P. R. C 98, 24608 (2018).
4. H. Ejiri, L. Jokiniemi, J. Suhonen, Phys. Rev. C. Lett, 105 L022501 (2022).
5. H. Ejiri, Universe, 2022, 8, 457 (2022)

1. DBD NME and SD

$$M^{0\nu} = \left(\frac{g_A^{\rm eff}}{g_A}\right)^2 \left[M_{\rm GT}^{0\nu} + \left(g_V/g_A^{\rm eff}\right)^2 M_{\rm F}^{0\nu} + M_{\rm T}^{0\nu}\right],$$



Quenching due to effects not in model

Model NMEs

$$M_{\rm GT}^{0\nu} = \sum_k \langle t_\pm \boldsymbol{\sigma} h_{\rm GT}(r_{12}, E_k) t_\pm \boldsymbol{\sigma}\rangle$$

$$M_{\rm F}^{0\nu} = \sum_k \langle t_\pm h_{\rm F}(r_{12}, E_k) t_\pm\rangle ,$$

$$M_{\rm T}^{0\nu} = \sum_k \langle t_\pm h_{\rm T}(r_{12}, E_k) S_{12} t_\pm\rangle ,$$

$H(r_{12}) \sim 1/r_{12}$ ν potential for ν-exchange,

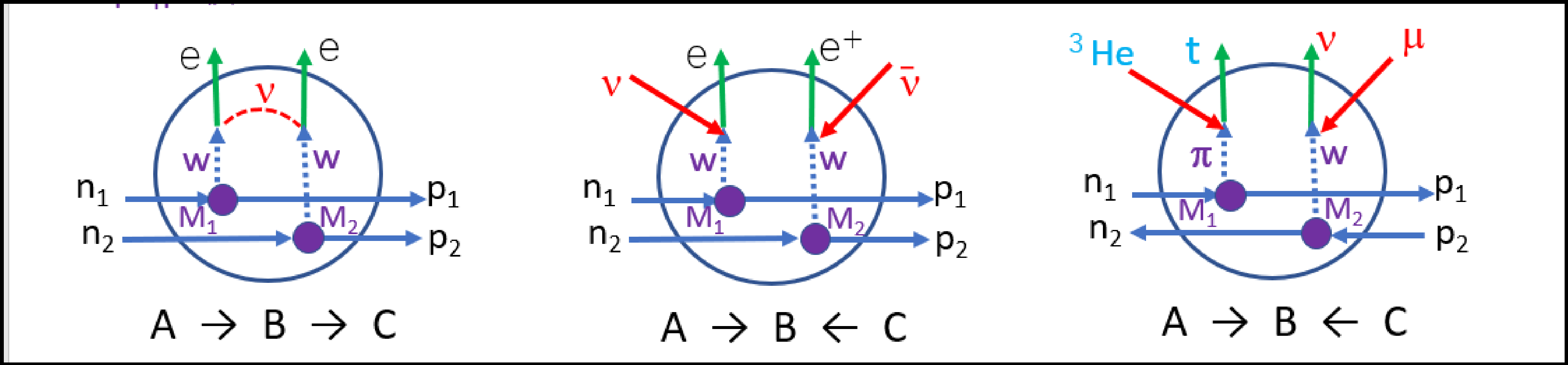
$M^{0\nu} = \Sigma_J M(J)$ J= Multipole sum

$M(J) = \Sigma_k M_k(J)$, Sum over all intermediate state k

1. Spin (σ) isospin (τ) correlation

2. Spin Dipole SD (L=1) $\tau\sigma Y_1$ to match the ν momentum

Double β decay, single β&ν and CERs



DBD M_1 , M_2 via neutrino potential by single β, ν, μ. CER NMEs

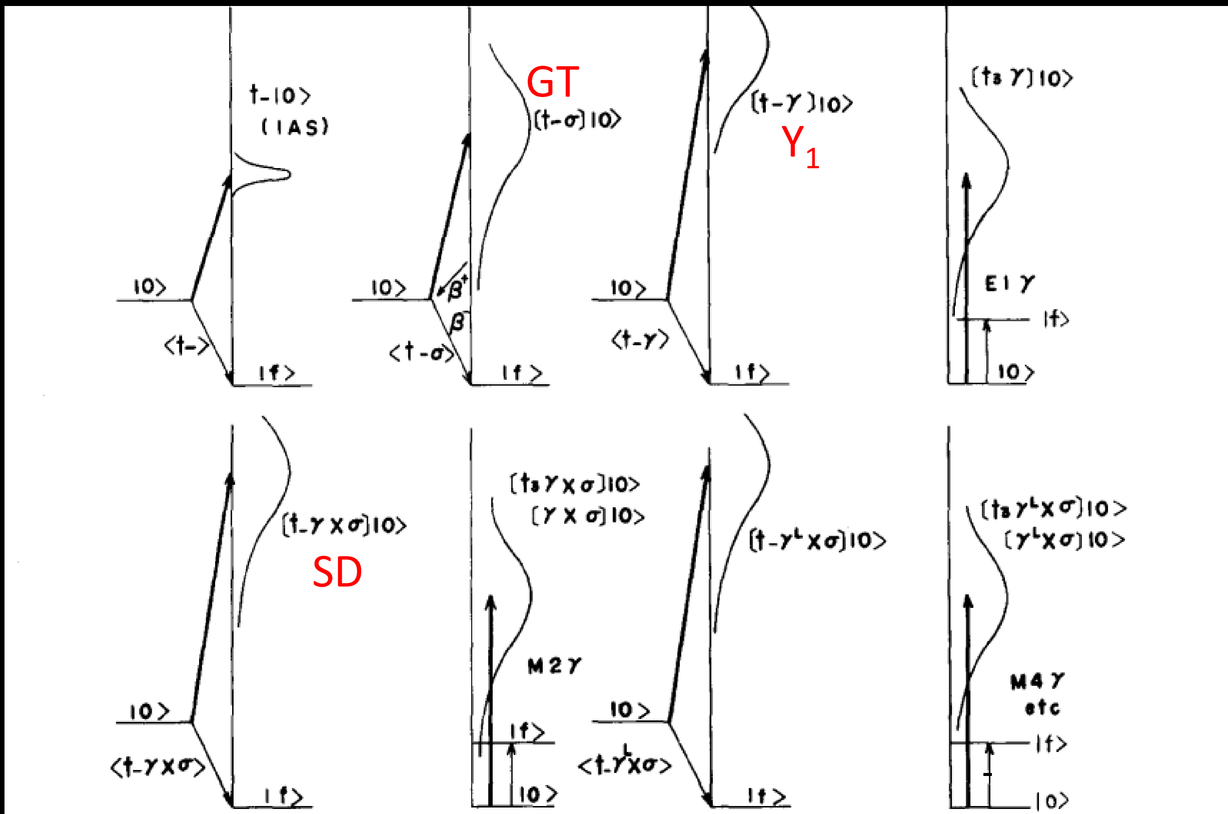
$M(\alpha, \beta^{\pm}) = (g_A^{eff})^{\pm}\, M(QRPA\ \alpha\, \beta^{\pm})$ α=GT, SD. SQ, • •

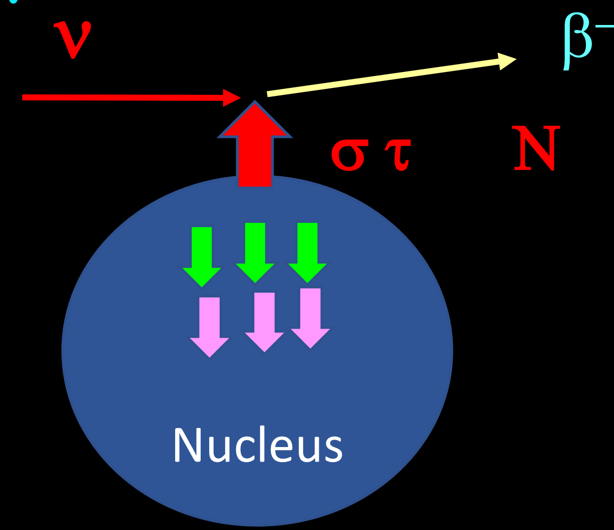
(g_A^{eff}) for renormalization effects due to non-nucleonic and nuclear medium effects which are not in pnQRPA.

$(g_A^{eff})^- \sim (g_A^{eff})^+$ for β^- , β^+ and $(g_A^{eff})^2$ for ββ

$M(\alpha, \beta\beta) = (g_A^{eff})^2\, M(QRPA\ \beta\beta)$

Spin isospin giant resonances and spin isospin core polarization in β–γ and CERs





Nucleons and quark τσ polarizations reduce nucleon σ τ for a nucleon at surface

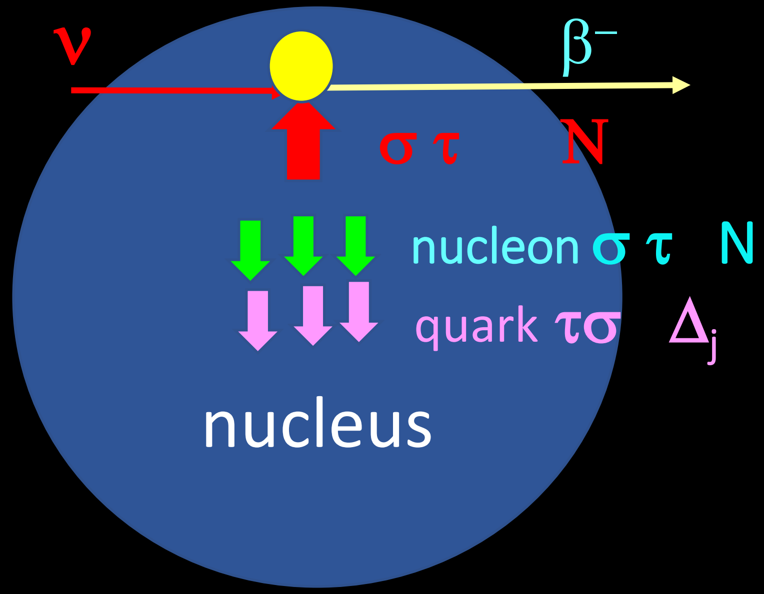
Nucleon τ σ giant resonances at 10-30 MeV region, Quark τ σ Δ-isobar nucleon-hole at 250 MV region.

H. Ejiri, J.I. Fujita Phys. Rep. 38 1978

Spin isospin polarizations and quenching

Spin isospin (στ) repulsive interactions push up most strengths into the τ στ GRs (IAS, GT, SD), Leaving little τ στ strengths at the low-states.

Nuclear medium τσ polarization



$|I> = |QP> - \varepsilon\,|GRn> - \delta\,|GR\,\Delta>$

$M^{\beta} \sim k^{eff} M_0 \quad M_0 = QP$

$k^{eff} \sim 1/(1+\chi) = 1/4$ χ: susceptibility ~ 3

1^+ 2^-

due to nuclear and isobar polarizations. Ejiri Fujita 1968-1978

Nuclear τσ symmetry, τσ GR , τσ polarization

1. T= β,γ,CER operators : vector T= τY_l, Axial-vector T=$\tau\sigma\ Y_l$

2. [H, T] ~ E_GT

   T|i> ; T GR, giant resonance: most T strengths, and little <f|T|i>

   T phonon = Coherent sum of all (N) ph excitations

   GR NME=M_{GR}= $N^{1/2}$ Ms , E_{GR}=Es+χN

   T=τ T|i> = IAS No τ Fermi strength

   T=τσ, T|i> = GT GR , little (~ 10^{-1}) GT strength to low states

   T=τσrY, T|i> = SD GR , little 2^- strength to low states

3. T isospin and spin isospin polarization

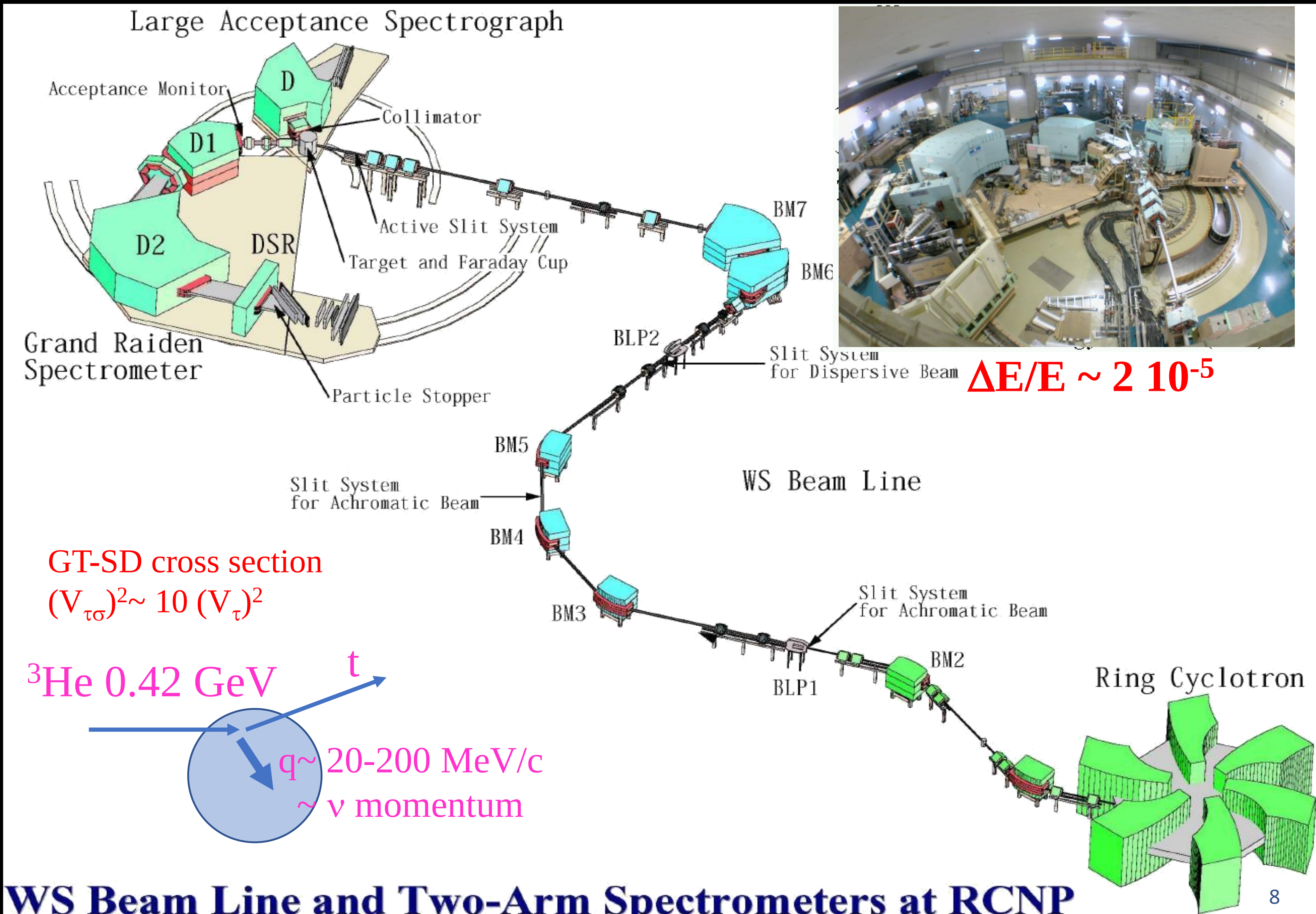
   |f> = $|f\rangle_0$ - ε|GR>

   $M \sim M_0 [1 - \varepsilon M_{GR}/M_0]$

   $= k^{eff} M_0$ $k^{eff} = 1/[1+\chi]$ χ=τ/τσ susceptivility

   ε~ 0.07 admixture of GR M_{GR}= 6 makes k^{eff} =0.6 as exps.

High E resolution (^{3}He,t) CERs at RCNP Osaka



$\Delta E/E \sim 2\ 10^{-5}$

GT-SD cross section

$(V_{\tau\sigma})^2 \sim 10\ (V_{\tau})^2$

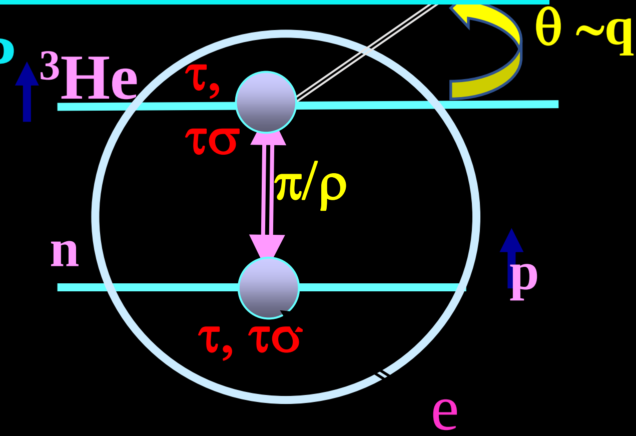
^{3}He 0.42 GeV

q~ 20-200 MeV/c

~ ν momentum

2. Exp. GT & SD GRs and quenching for single- β

$(V_{\tau\sigma}/V_{\tau})^2$~10 at E~0.42 GeV CERs at RCNP

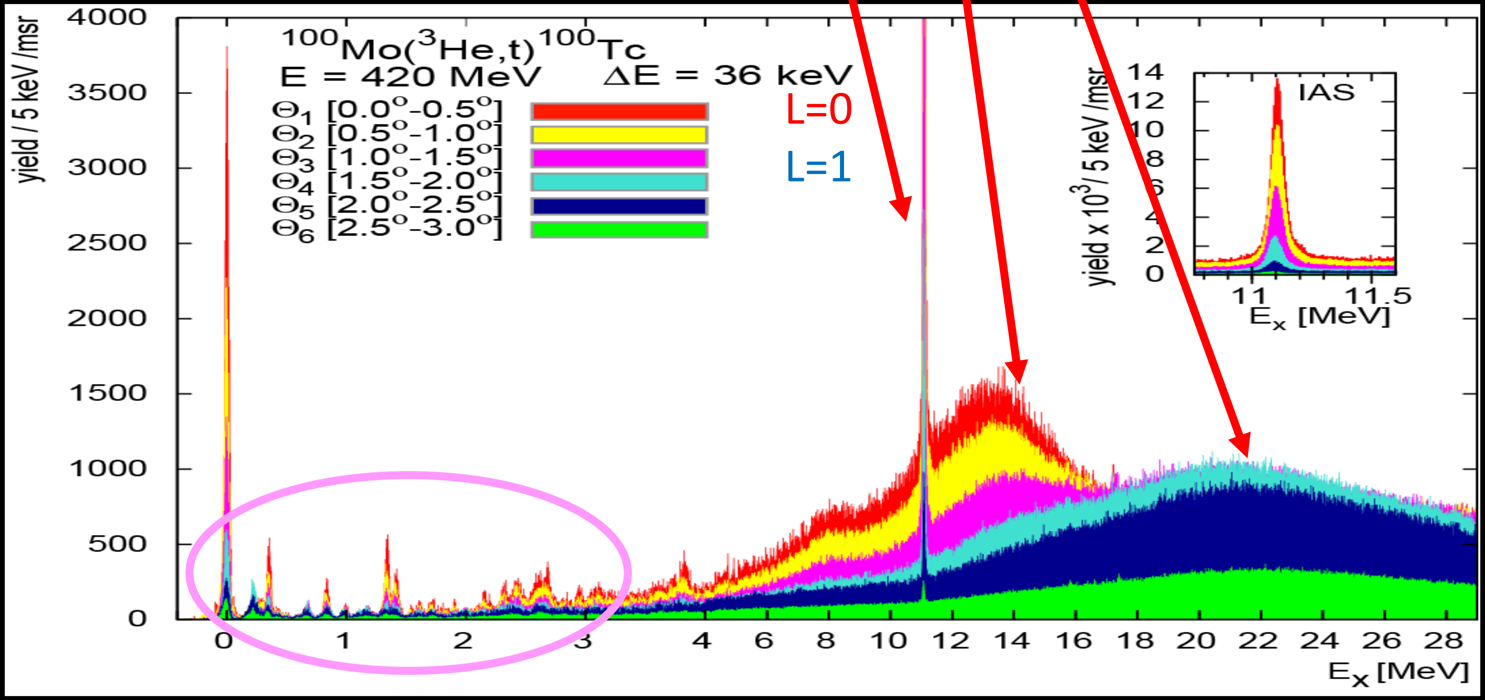


Most τσ strengths are pushed up into GRs (Giant resonances)

Fermi No at low states, all in F-GR: IAS

GT A few % at low states, 50% GT-GR

SD A few % at low states, main SD-GR

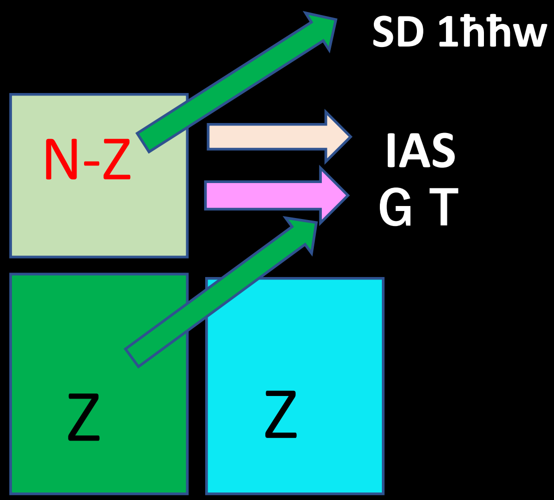


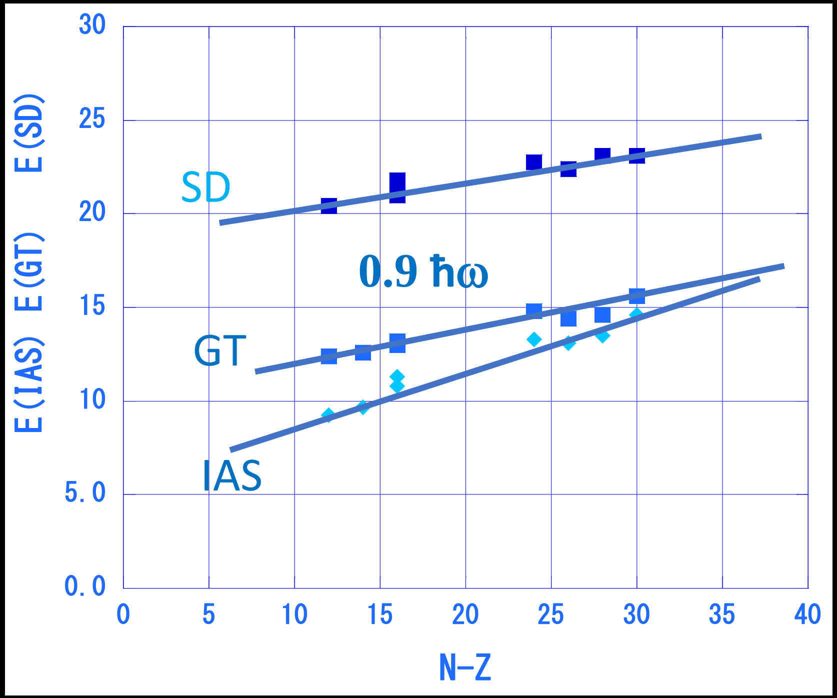
Ejiri, Suhonen, Zuber PR 797 1 2019

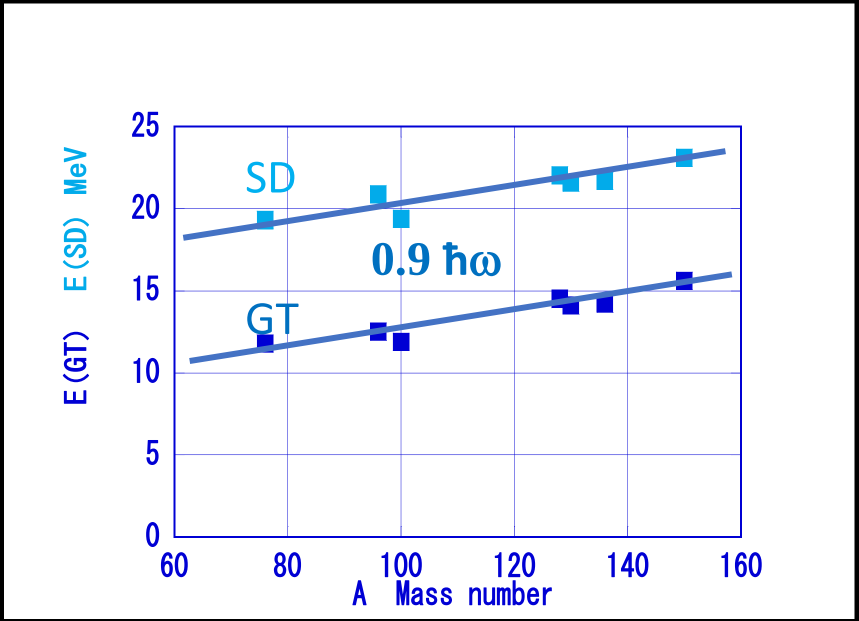
IAS, GT and SD GRs

E_G (IAS) = 5+0.3(N-Z)
E_G (GT) = 0.2 (N-Z)+9=0.06A + 6.5
E_G (SD) = 0.2 (N-Z)+16.5=0.06A+ 14

GT and SD same A dependence
E(SD)~E(GT)+0.9 ħω L=I excitation







E_G GR –Energies increase smoothly as N-Z and A, reflecting nuclear core property

Summed strengths of GRs and low-QP states

B_S(IAS) = N-Z,

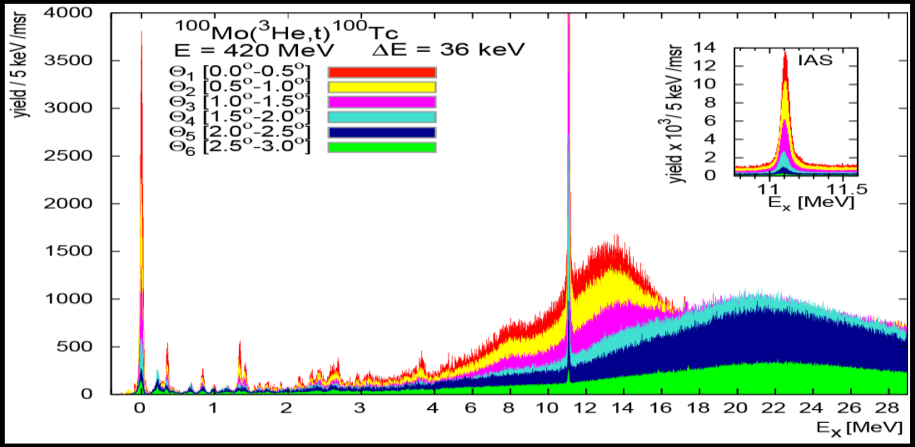
B_S(GT) =3 (N-Z)
Nucleon sum*

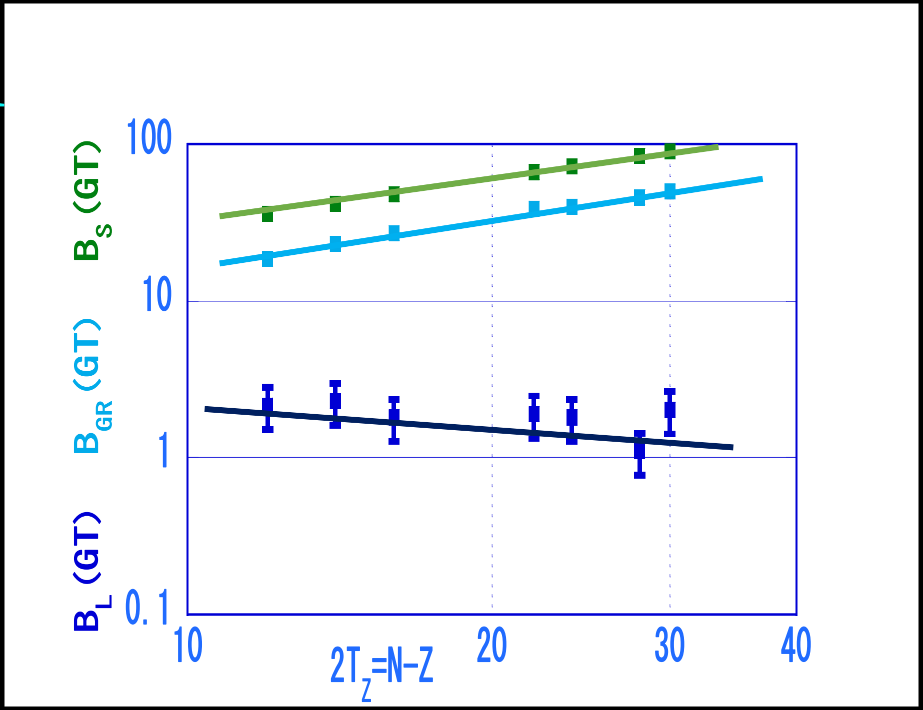
B_{GR}(GT)~ B_A(GT) = 0.55

B_L(GT) for E= 0-6MeV ~0.2- 0.1
not increase as N-Z

B_{GR}(SD)~ B_A(GT)

B_L(SD) for E= 0-10 MeV
~ 0.1 of B(SD sum
not increase as N-Z





* Ikeda Fujita Fujii Sum -rule

Renormalization of β & γ for low QP states

$M^{\beta} \sim k\, M_0$ M_0=QP

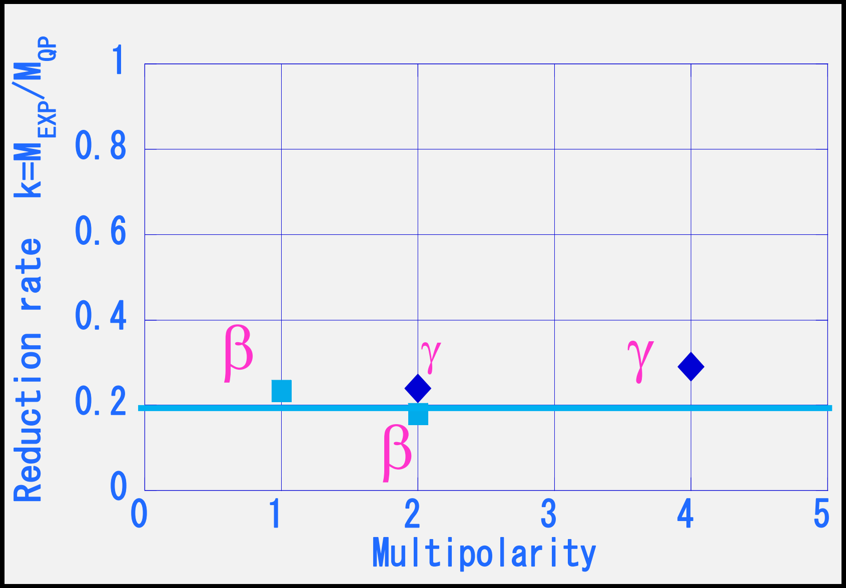
k~0.2-0.25

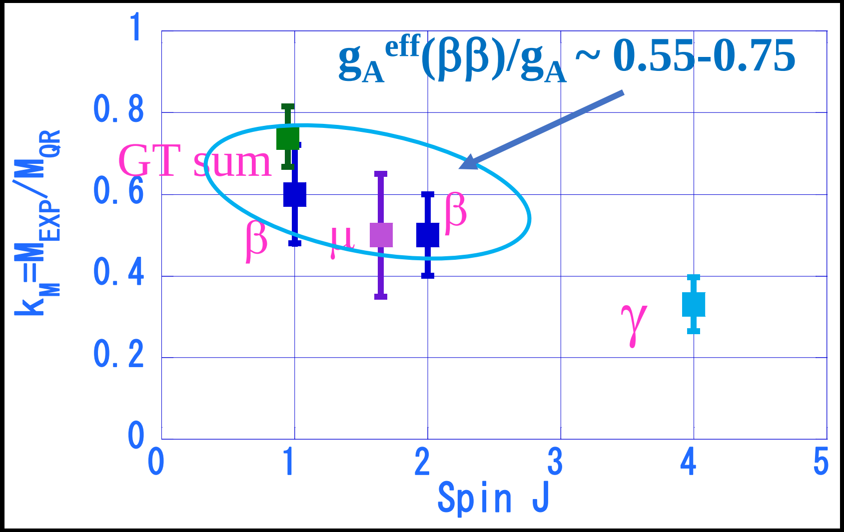
due to such nucl. and non-nucl. τσ correlations and nucl. medium that are not in QP model.

$M^{\beta} \sim k_M\, M_{QR}$ M_{QR}=pnQRPA

$k_M = g_A^{eff}/g_A \sim 0.65 \pm 0.1$

due to such non-nucl. τσ correlations and nucl. medium that are not in QRPA





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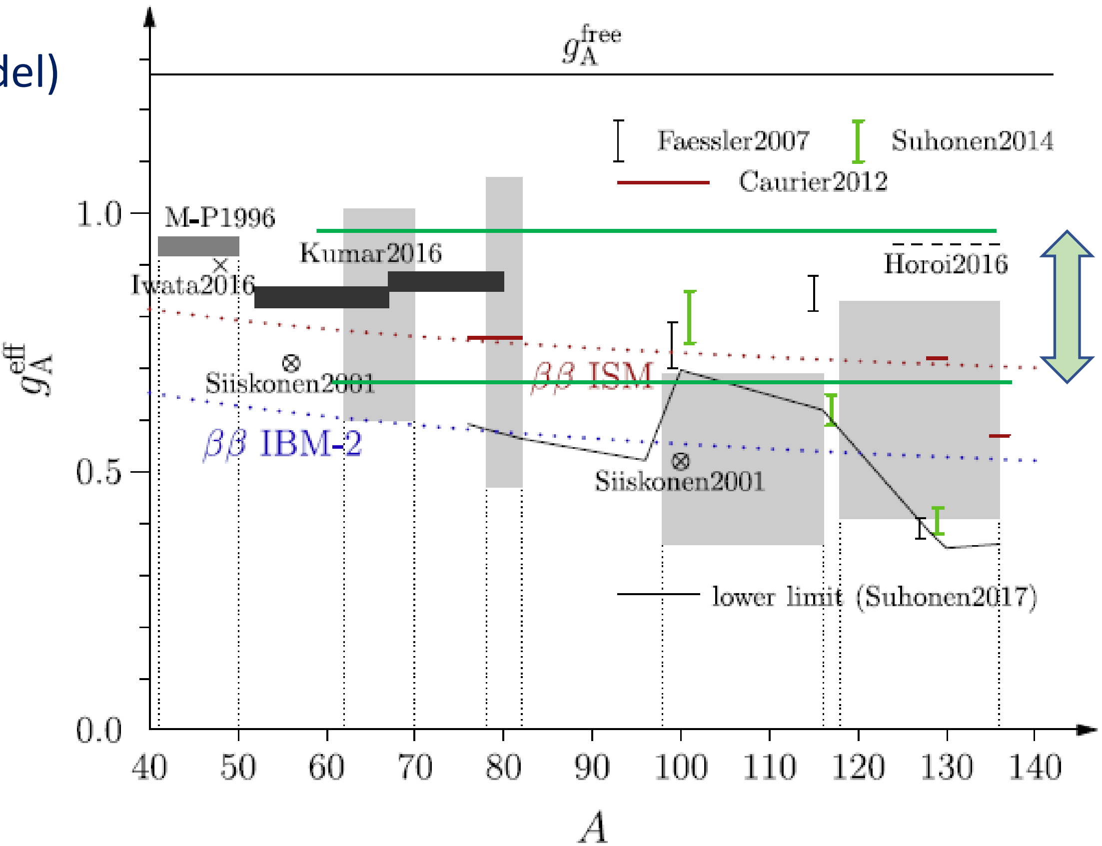
L. Jokiniemi J. Suhonen H. Ejiri AHEP2016 ID8417598

L. Jokiniemi J. Suhonen. H. Ejiri and I. Hashim PL B 794 143 (2019)

34 *H. Ejiri, J. Suhonen and K. Zuber / Physics Reports 797 (2019) 1–102*

g^{eff} from $2\nu\beta\beta$
M(EXP)/M(Model)



Present
0.74x1.27

0.55x1.27

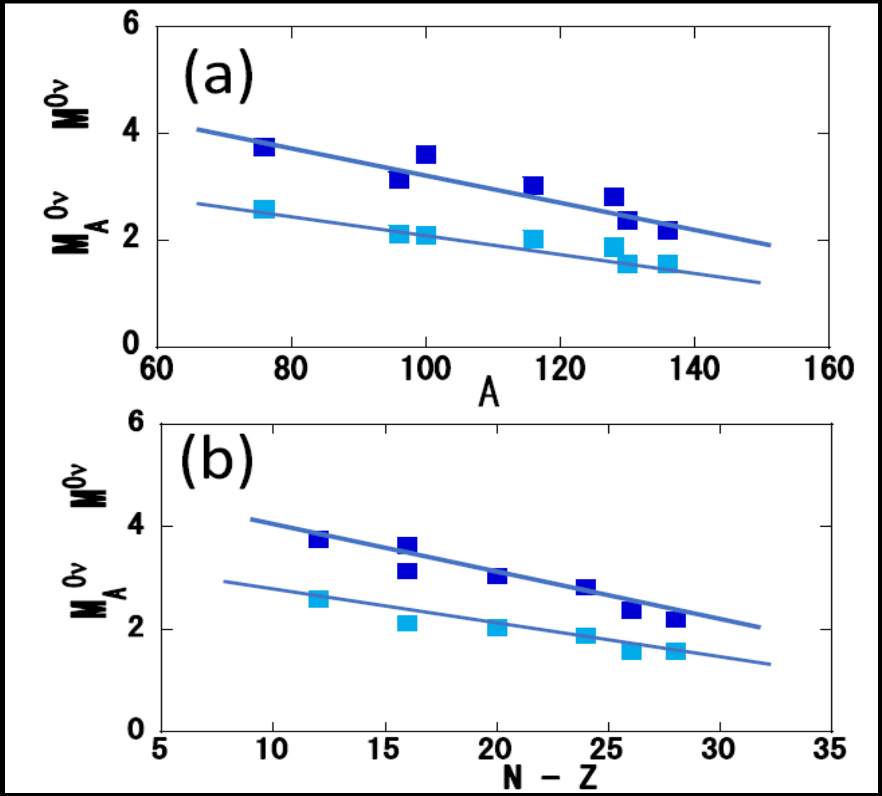
Fig. 29. Effective values of g_A in different theoretical β and $2\nu\beta\beta$ analyses for the nuclear mass range $A = 41 - 136$. The quoted references are *Suhonen2017* [216], *Caurier2012* [233], *Faessler2007* [242], *Suhonen2014* [243] and *Horoi2016* [235]. These studies are contrasted with the ISM β-decay studies of *M-P1996* [229], *Iwata2016* [230], *Kumar2016* [231] and *Siiskonen2001* [228]. For more information see the text and Table 3 in Section 3.1.2 and the text in Section 3.1.3.

. Ejiri H, Suhonen J and Zuber Z 2019 Phys. Rep. 797 1

3. SD giant resonances and pnQRPA DBD NMEs.

DBD pnQRPA NMES with

g_{ph} from exp. E(SD)
$g_A^{eff}/g_A = 0.75$ from GT sum



$M^{0\nu}$ and $M^{0\nu}_A$ decrease as A and N-Z, in contrast to F, GT, SD GR energies and strengths which increase as A and N-Z.

^{116}Cd

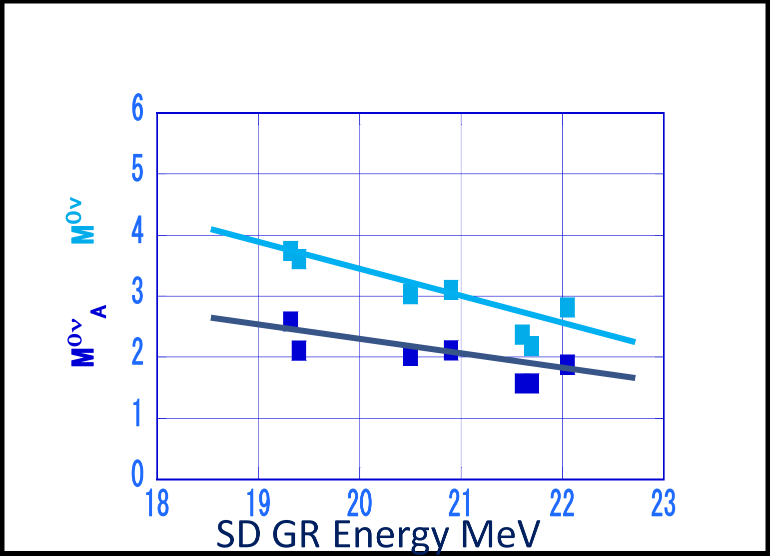
The model NMEs smoothly decrease as A and N-Z, reflecting the nuclear core effects, depending little on the valence nucleons.

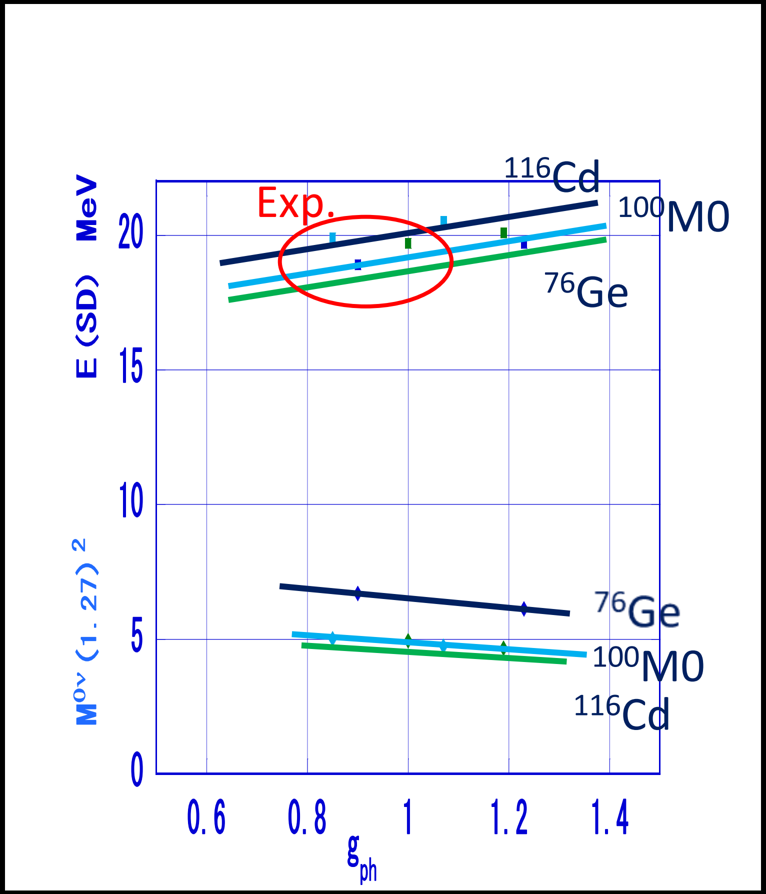
E(SD GR) MeV

L. Jokiniemi, H. Ejiri, D. Frekers, and J. Suhonen, P. R. C 98, 24608 (2018).

NMEs decrease as E-GR and g_{ph}

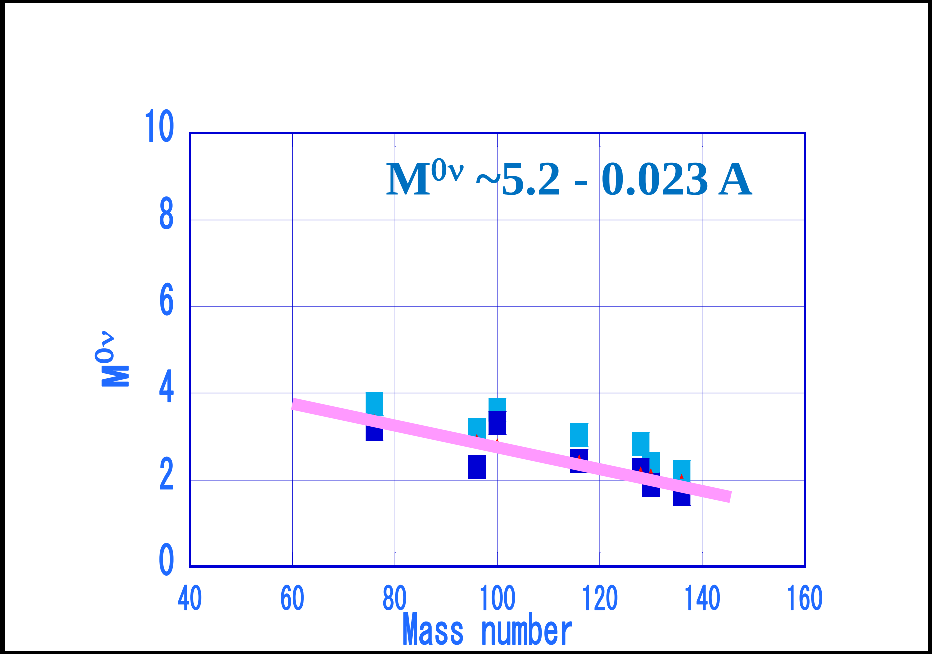
^{116}Cd

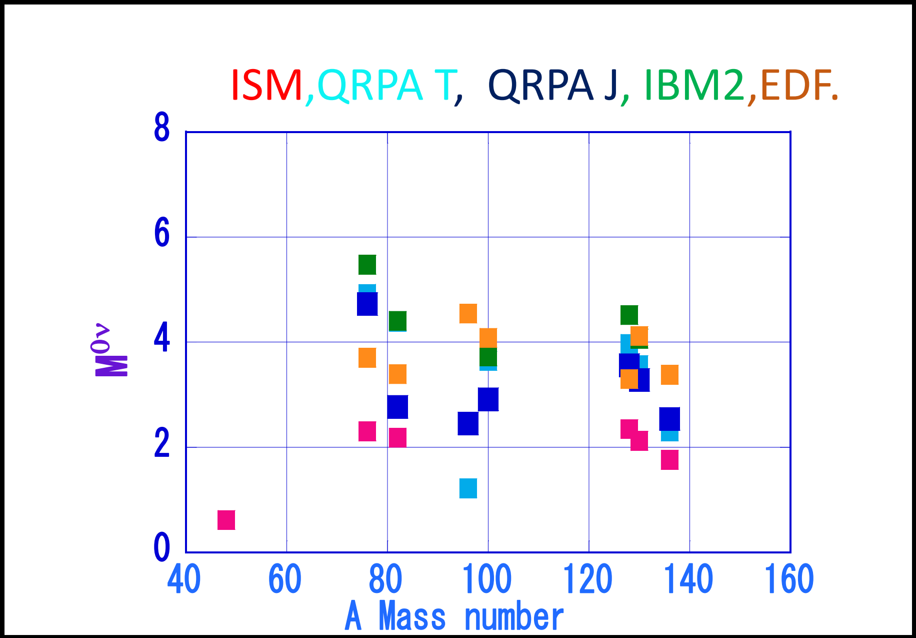




1. L. Jokiniemi, H. Ejiri, D. Frekers, and J. Suhonen, P. R. C 98, 24608 (2018).

$M^{0\nu}$ (pnQRPA) with experimental parameters





$M^{0\nu}$~ pnQRPA with experimental

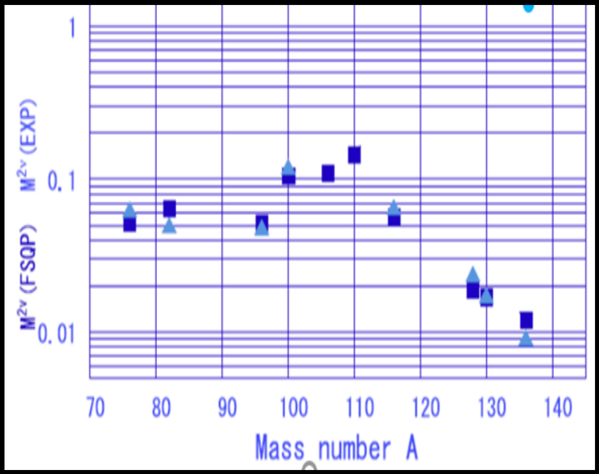
ROPP 2014 Vergados Ejiri Simkovic

g_A^{eff}/g_A 0.65 ± 0.1,

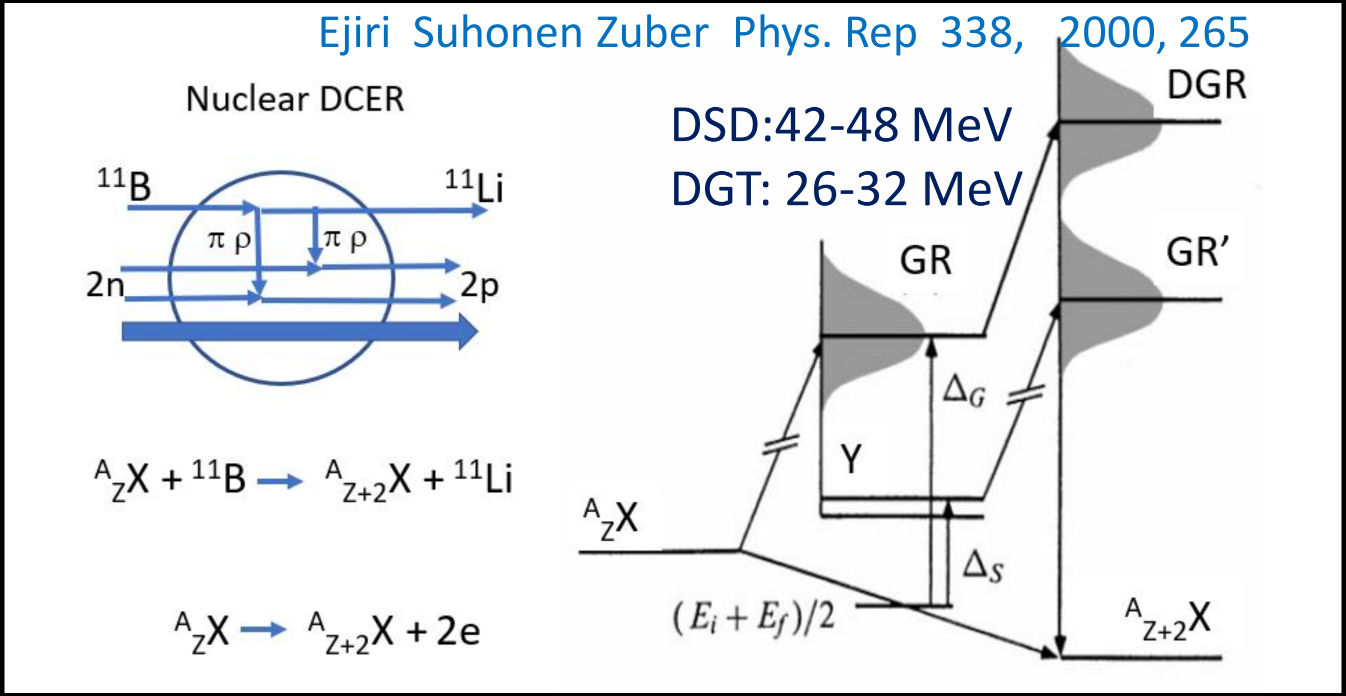
g_{ph} from SD GR –E and g_{pp} from 2νββ exps.

$M^{0\nu}$ =3-2 ~ 5.2 - 0.023 A ± 10%

A smooth function of A, reflecting the nuclear core effect, in contrast to the 2νββ NMEs, which depend on the valence nucleons.

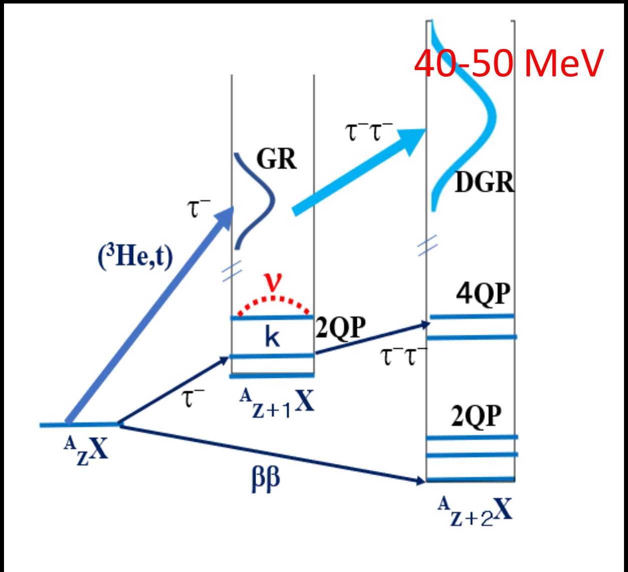


4. Double charge exchange reactions (DCERs)
Mainly double GRs (GT, SD).
Little strengths at low-states of the DBD interest



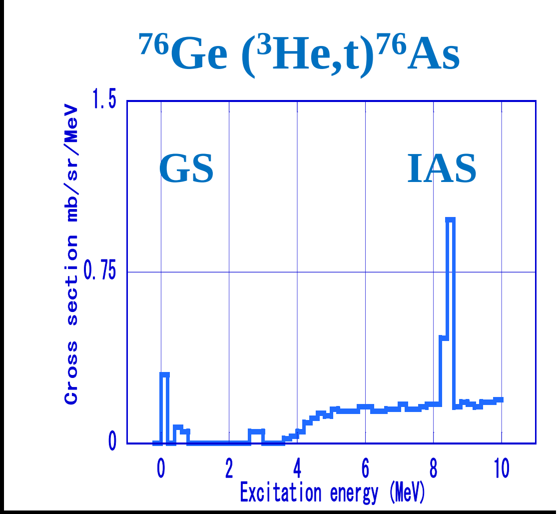
NEWS: Cappuzzello, Agodi, Menendez, Lenske
F. Cappuzzello et al Eur. Phys. J. A 51 2015 145. NEUMEN
C. Agodi et al., NEWS , Catania HI CER Project
N. Shimizu, J. Menendez, K. Yako Phys. Rev. Lett. 120 142502 2018
H. Lenske et al, Universe 7() 98 2021.

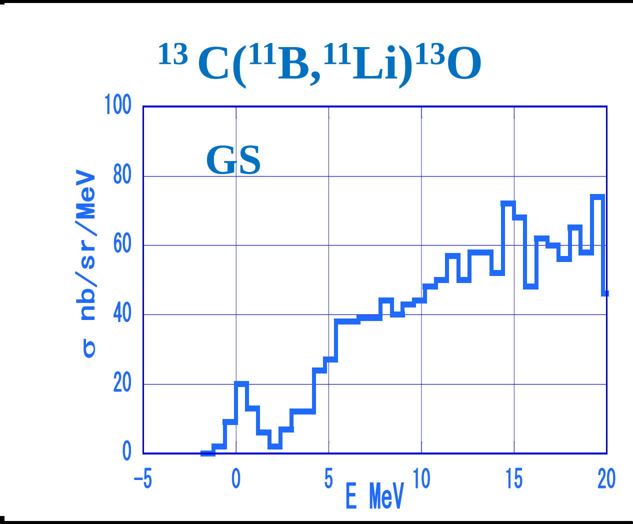
3. Double Charge Exchange Reaction

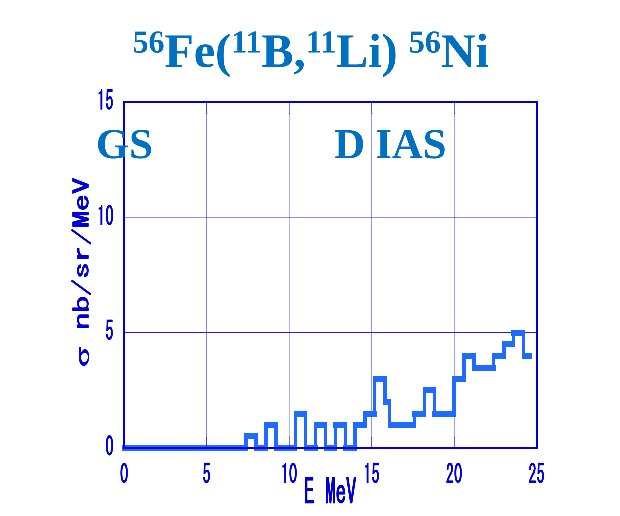


RCNP $^{56}Fe(^{11}B,^{11}Li)\,^{56}Ni$ at E=0.88 GeV.

1. $(V_{\tau\sigma}/V_{\tau})^4 \sim 12$ enhances τσ GT SD excitation
2. Q value = - 50 MeV, p-transfer 100 MEV/c same as DBD, and L=1 (SD)







SCER $^{76}Ge(^{3}He,t)^{76}As$ at p=70 MeV/c SD strength 0.1 of QP with $k_{\tau\sigma} \sim 0.3$.

$^{13}C(^{11}B,^{11}Li)^{13}O$ excites well the ground state and other low states

DCER $^{56}Fe(^{11}B,^{11}Li)\,^{56}Ni$ excites little low-QP GT-SD states with $(k_{\tau\sigma})^2 \sim 0.1$

SCER and DCER NMEs

The SD cross-section is expressed in terms of the SD strength $B(\mathrm{SD,QP}_i)$ as

$$d\sigma(\mathrm{SD},\mathrm{QP}_i)/d\Omega = (2L+1)K(\mathrm{SD},\mathrm{QP}_i)N(\mathrm{SD},\mathrm{QP}_i)|j_1(q_iR)|^2|J_{\tau\sigma}|^2B(\mathrm{SD},\mathrm{QP}_i),$$

$$\frac{d\sigma(\mathrm{SD},\mathrm{QP}_i)/d\Omega}{d\sigma(\mathrm{F},\mathrm{IA})/d\Omega} = 3\frac{|j_1(q_iR)|^2}{|j_0(q_{\mathrm{IA}}R)|^2}\frac{|J_{\tau\sigma}|^2}{|J_\tau|^2}\frac{B(\mathrm{SD},\mathrm{QP}_i)}{B(\mathrm{F},\mathrm{IA})},$$

$$\frac{d\sigma(\mathrm{GTSD},\mathrm{QP}_k)/d\Omega}{d\sigma(\mathrm{FF},\mathrm{DIA})/d\Omega} = \frac{3|j_1(q_kR)|^2}{|j_0(q_{DI}R)|^2}\frac{|J_{\tau\sigma}|^4}{|J_\tau|^4}\frac{B(\mathrm{GTSD},\mathrm{QP}_k)}{B(\mathrm{FF},\mathrm{DIA})},$$

Reduction coefficients for SD and GT・SD　NMES

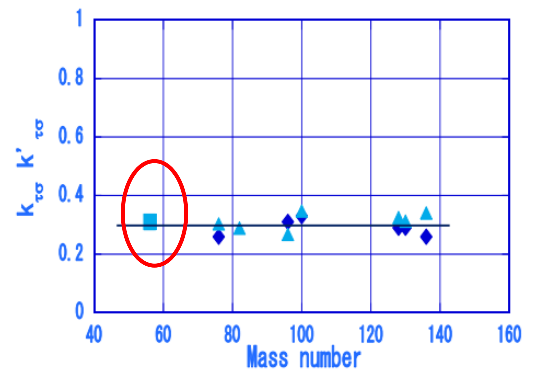
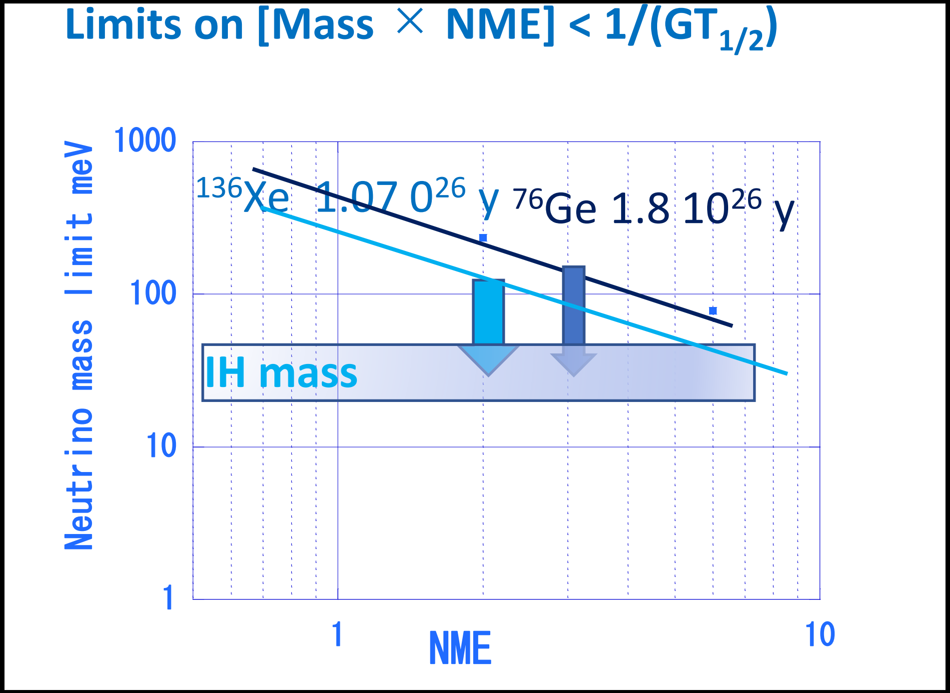


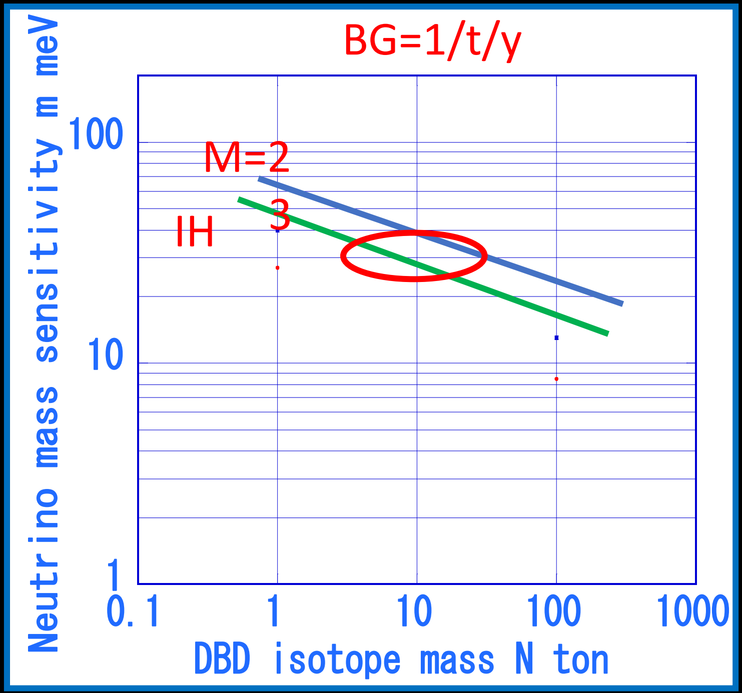
Figure 3. Reduction coefficients for axial-vector NMEs. Light blue triangles: $k_{\tau\sigma}$(SD) for the QP SD states by SCERs on DBD nuclei. Blue diamonds: $k'_{\tau\sigma}$(SD) for low-ling SD states by SCERs on DBD nuclei. Light blue square: $(k_{\tau\sigma}(\mathrm{GTSD}))^{1/2}$ for the QP GT-SD states by DCER on ^{56}Fe. Solid line: the reduction coefficient of 0.3 to guide eye.

Nuclide	B(SD, QP)	B(F, IA)	$k_{\tau\sigma}$(SD)	$k'_{\tau\sigma}$(SD)
^{76}Ge	0.080 ± 0.016	12	0.30 ± 0.05	0.26 ± 0.05
^{82}Se	0.091 ± 0.018	14	0.29 ± 0.04	-
^{96}Zr	0.024 ± 0.005	16	0.27 ± 0.04	0.31 ± 0.06
^{100}Mo	0.053 ± 0.011	16	0.35 ± 0.05	0.33 ± 0.06
^{128}Te	0.452 ± 0.090	24	0.32 ± 0.05	0.29 ± 0.05
^{130}Te	0.456 ± 0.090	26	0.31 ± 0.05	0.29 ± 0.05
^{136}Xe	0.457 ± 0.091	28	0.34 ± 0.05	0.26 ± 0.05
Nuclide	B(GTSD, QP)	B(FF, DIA)	$k_{\tau\sigma}$(GTSD)	-
^{56}Fe	0.61 ± 0.12	8	0.092 ± 0.014	-

4. Impacts

1. DBD EXPs : $M^{0\nu}$ =2~3 smooth function of A, depends little on individual nuclei. DBD isotopes should be selected by detector requirements, ton scale isotopes **N** and low-BG **B**





2. Current limits (GERDA,KamLAND) may reach IH mass, by a factor ~ 5 in ν-mass and $>10^3$ in NT/B

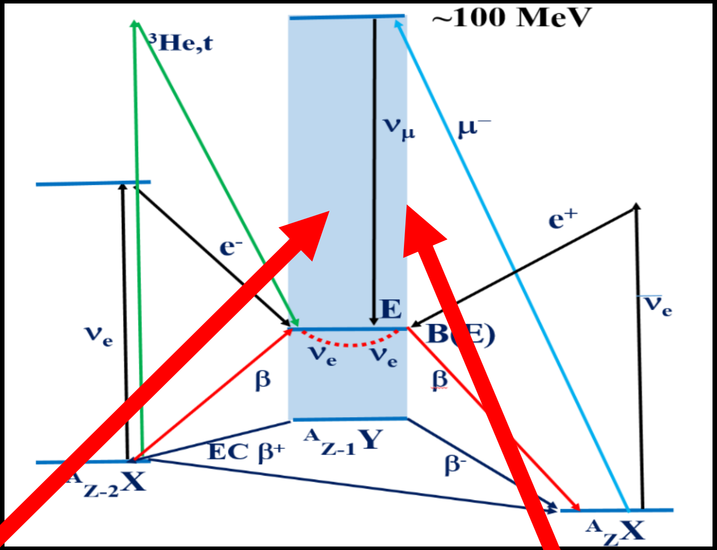
$m_\nu = 2\, m_0\ [B/NT]^{1/4}$

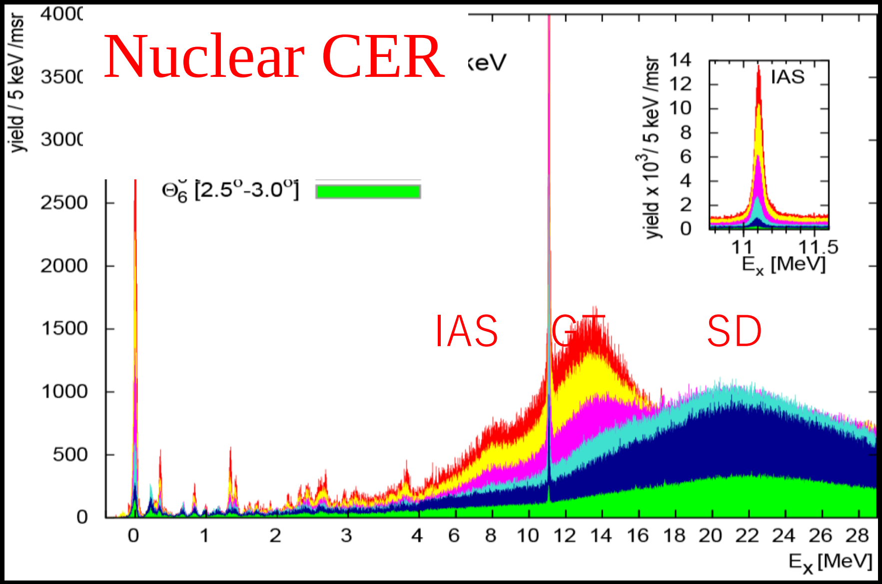
m_0 ~ 40 meV $/M^{0\nu}$ with ε=0.5

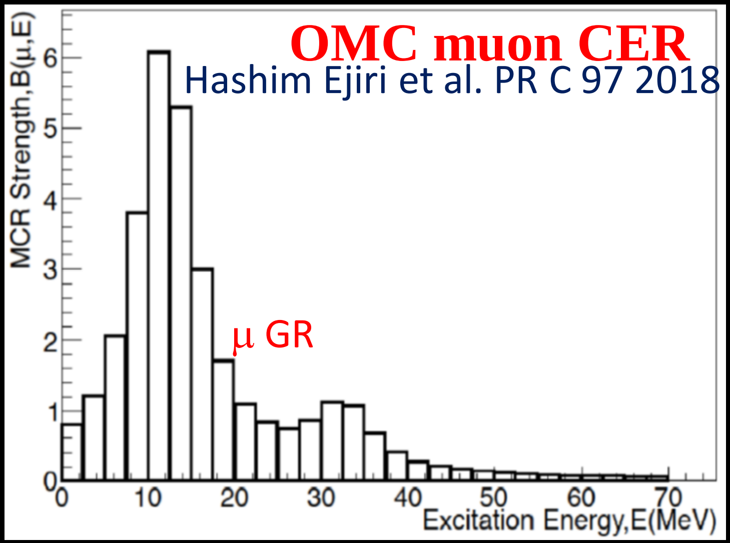
for Ge, Se. Mo. Cd. Te. Xe

2. DBD Models.

DBD model |i> and |f> are such that have realistic τ –τσ correlations and/or effective weak coupling to reproduce the quenched and enhanced τ –τσ at low-states and giant resonances in intermediate nucleus .







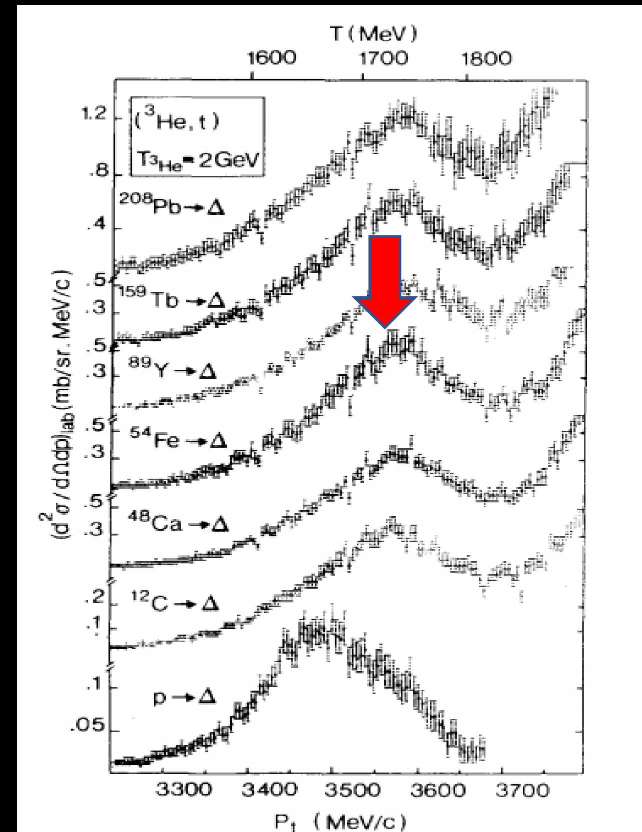
5. Quark στ)flip GR=Delta Δ and quenching of στ -g_A

Bohr Mottelson PL B 100 1981
Rho NP A 231 1974
H. Ejiri PRC 26 '82 2628

$|I> \sim |QP> - \varepsilon\,|GR\ N> - \delta\,|GR\ \Delta>$

$M \sim k^{eff} M_0 \quad k^{eff}(\Delta) \sim 1/[1+\chi_\Delta]$

GT sum $\chi_\Delta \sim 0.4$, $k^{eff}(\Delta) \sim 0.7$



Kirchuk et al., Phys. Scripta 59 1999

$$V = g'_{NN} C\delta^3(\boldsymbol{r}_{12})\sigma_1 \cdot \sigma_2 \tau_1 \cdot \tau_2 + g'_{\Delta N} \frac{f_\pi N\Delta}{f_\pi NN} C\delta^3(\boldsymbol{r}_{12})\boldsymbol{S}_1 \cdot \sigma_2 \boldsymbol{T}_1 \cdot \tau_2$$

(^{3}He,t) with E=2 GeV
150 MeV/c SQ 3^+ S0=4^-
Quark τσ excit to Δ
D. Contard et al. PL B 168

$g_{\Delta N}'/g_{NN}'=0.6$ B(GT) quench 0.5
$g^{eff}_A/g_A=0.7$ at A=209

Delta Δ quenching effect

Delta giant resonance reduces $M^{0\nu}$ $k=g_A^{eff}/g_A=(1+\chi_\Delta)^{-1}$

$\chi_\Delta = k\, h_\Delta\, A$ since all nucleons are involved in the Δ excitation.

* Assume $k_\Delta=g_A^{eff}/g_A\sim0.74$ from GT total strength/sum without Δ.

*A dependence of h_Δ

1. E(GR)-E(ph) =0.013 ħ ω 3(N–Z)

   $h_N=0.013\ \hbar\,\omega=\kappa A^{-1/3}$

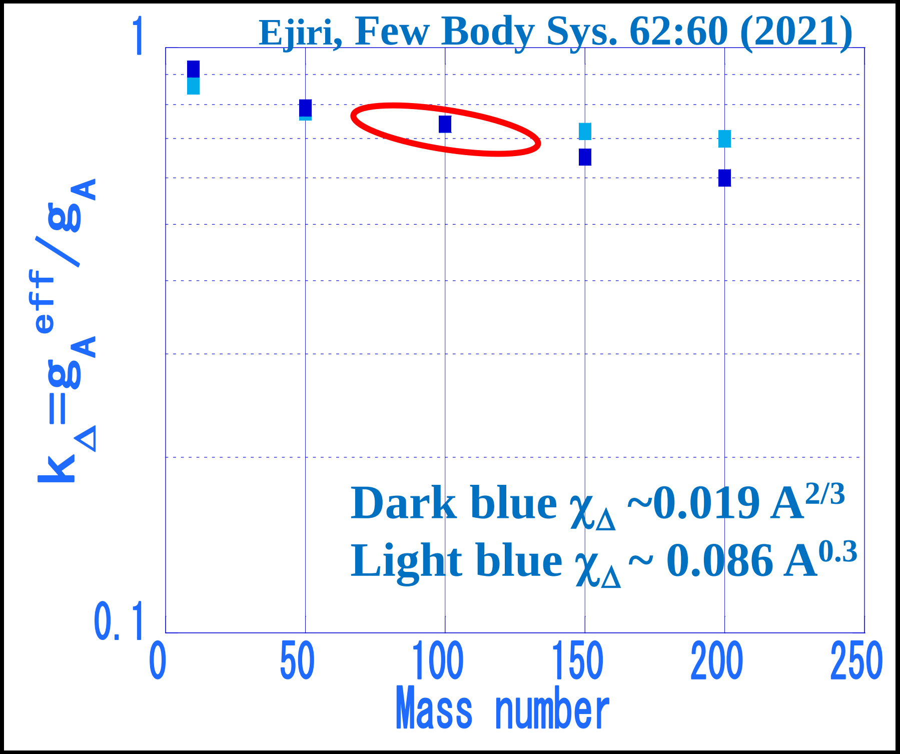
   $\chi_\Delta=0.019\ A^{2/3}$

2. Quench of B(GT) at A=50-150

   QRPA Homma et al

   $h_N=2.6\ A^{-0.7}$

   $\chi_\Delta\sim 0.086\ A^{0.3}$



Δ reduces τσ NMEs by 0.65-0.65

The effect of 5-10 % can be seen

even at A~15-10 where accurate NMEs are available from shell models.

5. Concluding remarks.

1. Most SD strengths are in the high SD GR. The GR energies and strengths increase smoothly with A, reflecting στ correlations.

2. The pnQRPA $M^{0\nu}$ with g_{ph} from the exp. GR E(SD) decreases as A , N-Z, E(SD), reflecting the negative effects of the στ repulsive interactions and στ core polarization.

3. Using the experimental $(g_A^{eff}/g_A)\sim0.65\pm0.1$ for the pnQRPA, $M^{0\nu}\sim5.2 - 0.023$ A , i.e. 3-2 for A=76-136.

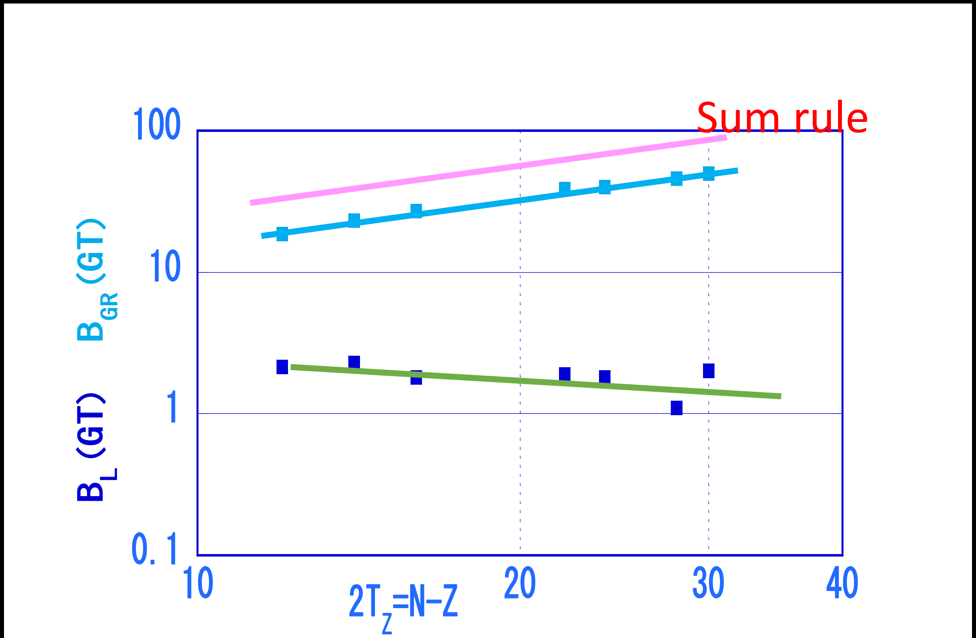
4. SCER and DCER are used to study τσ strength distributions.

5. $M^{0\nu}$ values depend little on individual nuclei. DBD exps should be as ton-scale isotopes, low-BGs and good E resolution.

6. Experimental CERs, OMC, and DCERs and theoretical calculations of the NMEs including Δ are encouraged.

Thanks for your attention.

Most GT , SD strengths are in the giant resonance regions



B_A(GT) = 0.55 × Sum=3(N-Z)＊

B_L(GT) for E= 0-6MeV

~0.2- 0.1 of B_{GR}(SD) , not increase as N-Z

＊ Ikeda Fujita Fujii Sum -rule

M4 gamma transitions

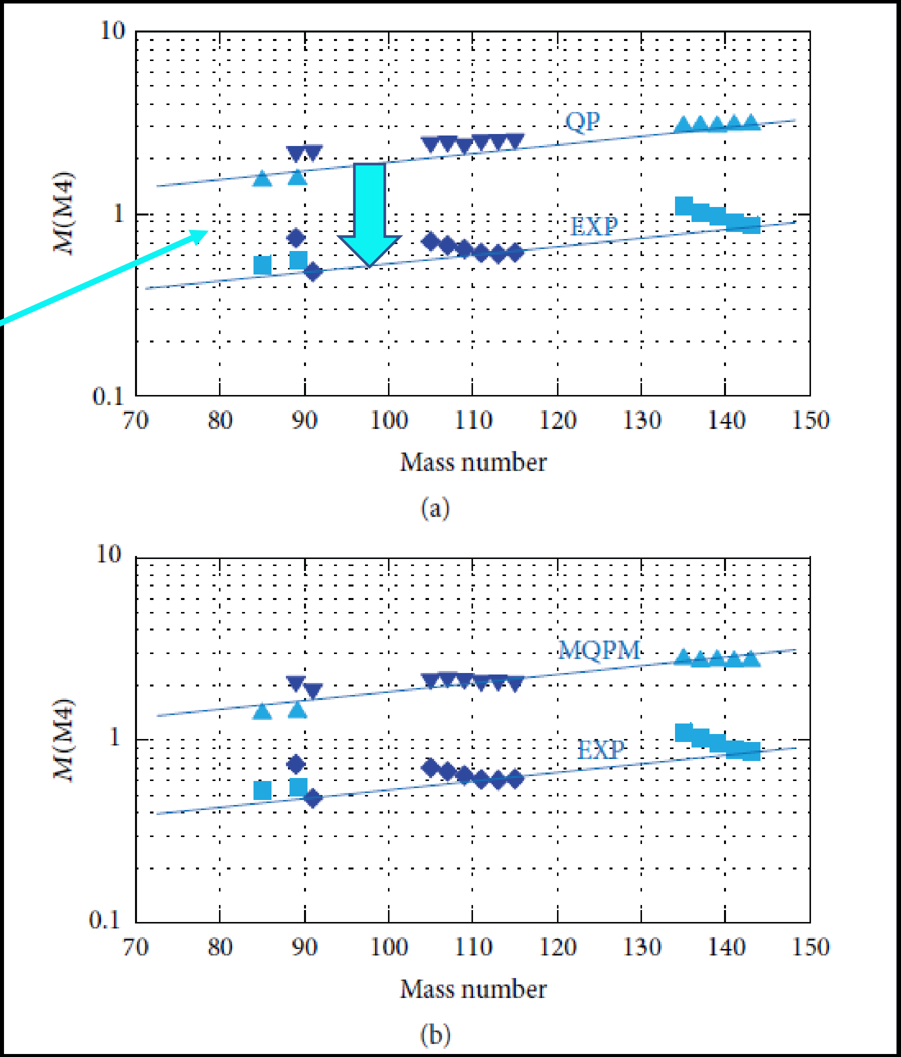
Mainly isovector

$[\tau\sigma r^3 Y_3]_4$

$M_{EXP} \sim k\ M_{QP}$

K=0.29

M increase as A ~r^3



MQPPM=

Microscopic QP phonon model

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