Neutrino nuclear responses for medium momentum virtual neutrinos in DBDs and μ τ supernova neutrinos

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Neutrino nuclear responses (square of nuclear matrix elements NMEs) for medium momentum (30-200 MeV/c) virtual neutrinos in double beta decays (DBDs) and μ–τ supernova neutrinos are of current interest. Theoretical calculation for them are hard since they are very sensitive to nucleonic and non-nucleonic (meson & Delta isobar) correlations and nuclear medium effects. Thus experimental inputs are valuable to help evaluate them. So far experimental studies are limited to low-momentum (a few MeV/c , L=0 s-wave) GT (Gamow Teller) NMEs.

The spin dipole (SD, L=1 p wave) responses f or medium p virtual DBD and m t supernova neutrinos were studied for the first time by using medium energy CERs (charge exchange reactions) at RCNP. The measured SD NME is quite quenched with respect to pnQRPA. It gives the neutrino-less DBD NME ~1.9. Impact on DBD and supernova neutrino NMEs are discussed.

1. Ejiri H, Suhonen J and Zuber Z 2019 Phys. Rep. 797 1
2. Ejiri H 2019 Frontiers in Physics 10.3389/fphys. 00030
3. Ejiri H, 2019 J. Phys. G. Nucl. Part. Phys. 46 125202
4. Ejiri H , C.A. 2020 J. Phys. 47 LT 01.

Neutrino nuclear responses for medium-momentum virtual neutrinos in DBD and μτ supernova neutrinos.

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RCNP Osaka

1. **Neutrino nuclear responses in nuclear physics.**
2. **Experimental studies for ν nuclear responses for low and medium momentum transfers**
3. **Medium momentum responses for DBD and SN.**
4. **Impact on DEDs and neutrino nucleosynthesis.**
5. **Concluding remarks**

1. Ejiri H, Suhonen J and Zuber K 2019 Phys. Rep. 797 1
2. Ejiri H 2019 Frontiers in Physics 10.3389/fphys. 00030
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1. Neutrino nuclear responses in nuclear physics.

1. Neutrino properties of particle and astrophysics interests beyond and within standard model are studied in nuclei as micro-laboratories.

2. $T = G\,B(\alpha)\,X$
   T: Rate, Cross section, G: phase space, kinematic
   $B(\alpha) = |M(\alpha)|^2$ Response/NME is crucial for X
   X: astro-particle physics quantities,
   ν-mass , ν-phase in $\beta\beta$, ν production/flux, synthesis

3. Nuclei: many body hadron/nucleon system is used for selective pick-up signals , reject BGs, but need $B(\alpha)$

4. $B(\alpha) = |M(\alpha)|^2$ $M(\alpha)$: (hardly calculated)$= g^{eff} M_K(\alpha)$
   g^{eff} effective coupling $M_K(\alpha)$ nuclear model NME

Momentum dependence of the weak couplings

A. Quark level to nucleon level

$$g_V(q^2) = \frac{g_V}{\left(1 + q^2/M_V^2\right)^2} \ ; \ g_A(q^2) = \frac{g_A}{\left(1 + q^2/M_A^2\right)^2} \ ,$$

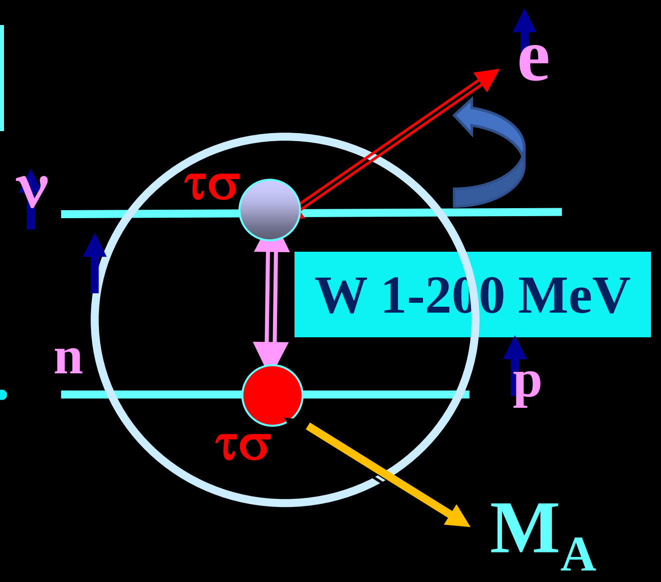
Mv~ 0.84 GeV, and M_A~1 GeV from accelerator exp.
Thus q= 1-150 MeV/c present region , the weak couplings are constant within a few % for nucleons.

B. Nucleon to nuclear level. Nucleon dressed in nucleus

Nuclear Response = M : M=NMEs

$T = G\,[\,M\,(m_\nu)/A_\nu\,]^2$

Nuclear phys   Particle/astro phys.



A. DBD Neutrino-less ββ M

$M=g^2_A M_A - g^2_V M_V + g^2_A M_T$ with bare $g_{A,V}$ for free N.

$M_A=k_A^2\, M_A(\text{model})$, $M_V=k_V^2\, M_V(\text{model})$,

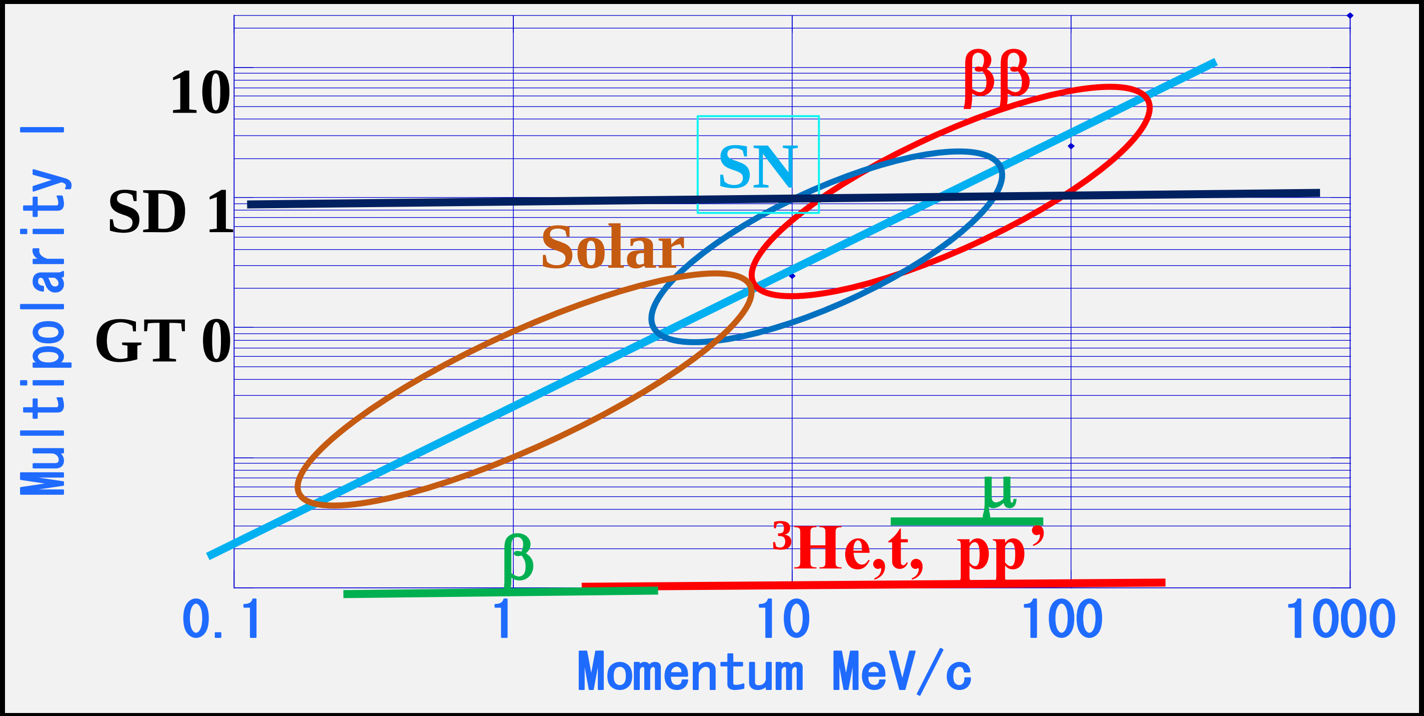
$k_A = g_A^{eff}/g_A$: Effects which are not in M_A(model)

B. Astro ν and anti-ν response

$M_A=k_A\, M_A(\text{model})$, $k_A = g_A^{eff}/g_A$:

DBD ν and Astro ν are q=5-150 MeV/c, $J^{\pm}$ with J=0-5

Momentum p MeV/c and multipolarity l



Momentum involved in nuclei

$p = 1/r_{12} \sim 1/\text{(fm)} = 1\text{-}200$ MeV/c

$L \sim pr = 0\text{-}5$

Momentum involved in 0νββ NME

$M = g^2_A M_{DA} + g^2_F M_{DF}$ $M_A = <h\sigma\sigma\tau\tau>$ $M_F = -<h\tau\tau>$ $h \sim a/(r_1 - r_2)$

Virtual Majorana neutrino exchange between r_1 and r_2

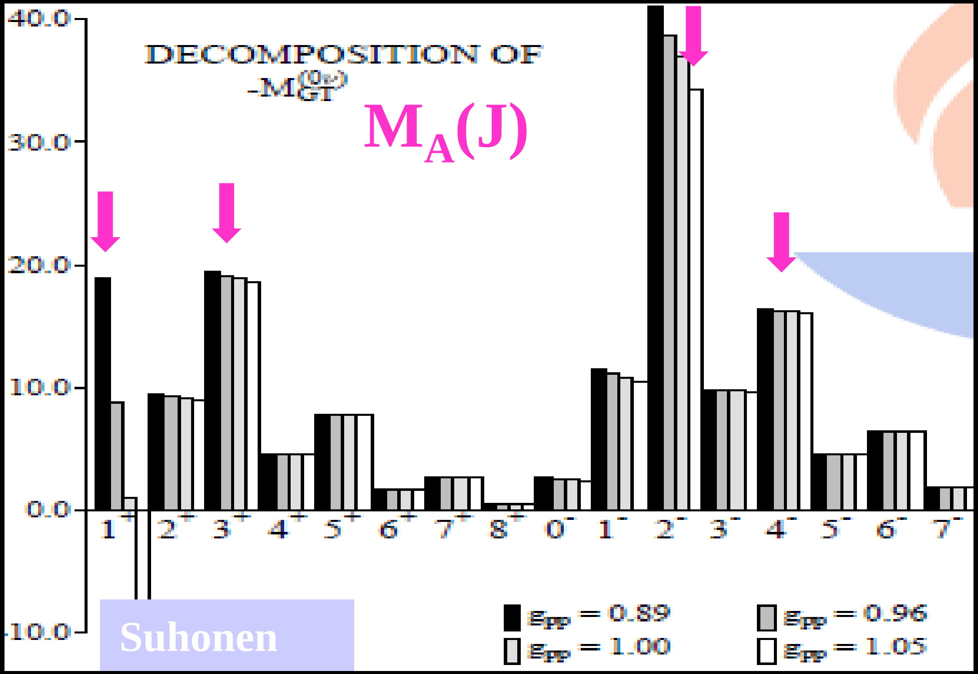
$p = 1/(1\text{-}5 \text{ fm}) = 40 – 200$ MeV/c $L = pr = 1 – 5$

$g^2_A M_{DA} \sim \Sigma\ g_A M_{SB}\ g_A M_{SB}$

Axial vector $M_A(J)$

$M_A(J) = g_A\ \tau\ [\sigma \times f(r)\ Y_l]_J$

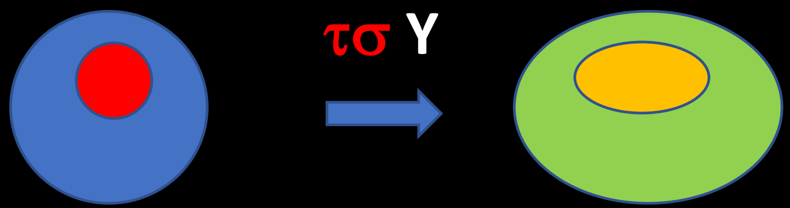
J=2- Spin dipole : SD



Effective couplings $k_A = g^{eff}/g$

$M_A = k_A\, M_A(\text{model})$ $k = g^{eff}/g$ Deviation of model NME

from Exp. = True MNE since Model is NOT perfect



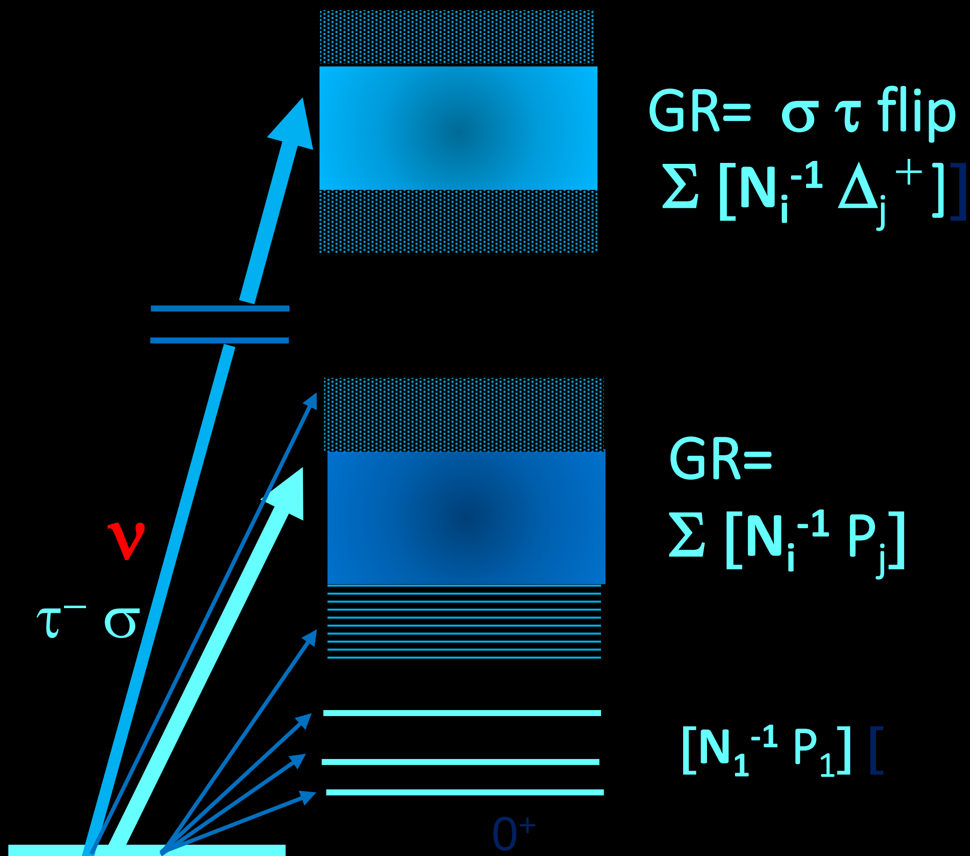
Dress / core
change i-f

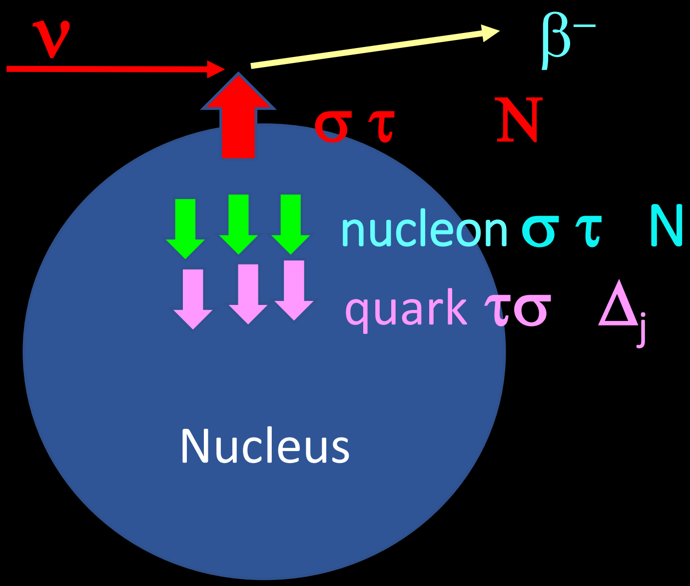
Since 1960 for μ GT as e^{eff}/e .

A : Theoretical way ab initio NME $k_A = g^{eff}/g = 1$
Cal. for g^{eff}/g for meson isobar , many body, medium

B: Experimental way : present
Exp g^{eff}/g = Exp NME/Model NME and
Use Exp. g^{eff}/g and Model QP, QRPA to get NME

Weak int.: spin isospin τσ $N^{-1}N$ GR and $N^{-1}\Delta$ GR





H. Ejiri PRC 26 '82 2628

Nuclear core change ,
Bohr Mottelson
PL B 10 '81 10 Isobar

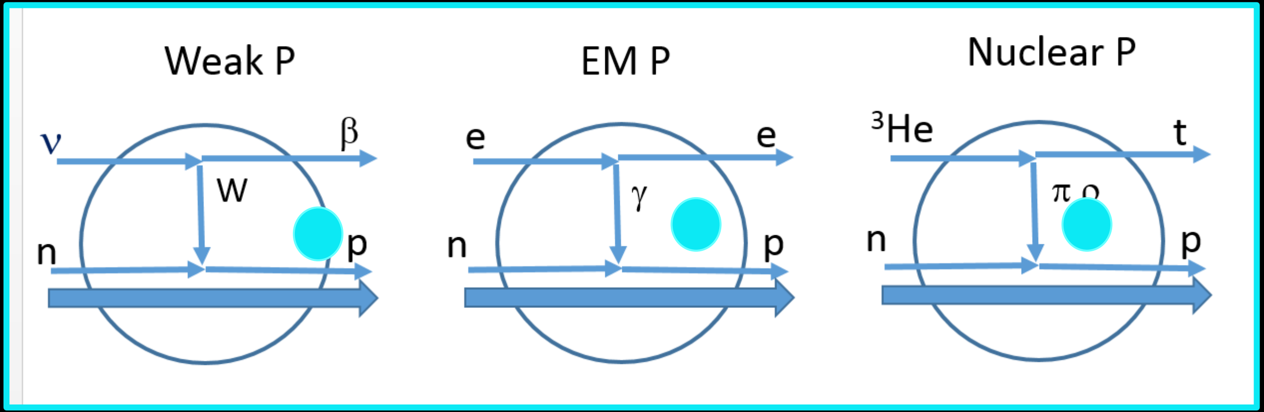
$|I\rangle = |NP\rangle - \varepsilon\,|GRn\rangle - \delta\,|GR\,\Delta\rangle$

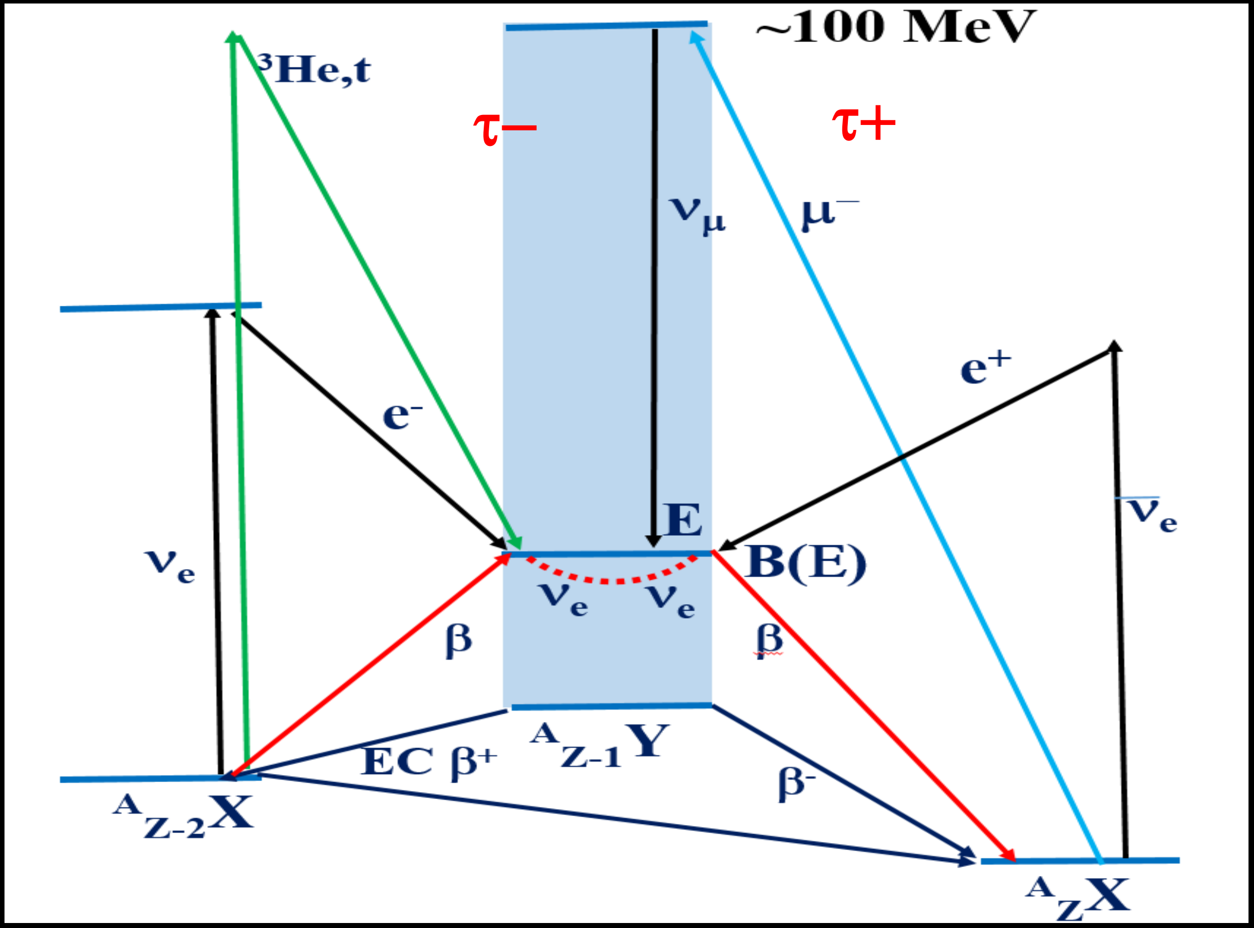
$M^{\beta} \sim k^{eff} M_0 \quad k^{eff}\ (\tau\sigma) \sim 1/(1+\chi_{\tau\sigma}) = 0.4$

$k^{eff}\ (\Delta) \sim 0.6$ $\quad \chi_{\tau\sigma}$: susceptibility

2. Experimental studies for ν nuclear responses for low and medium momentum transfers

Lepton & nuclear CERs : CC



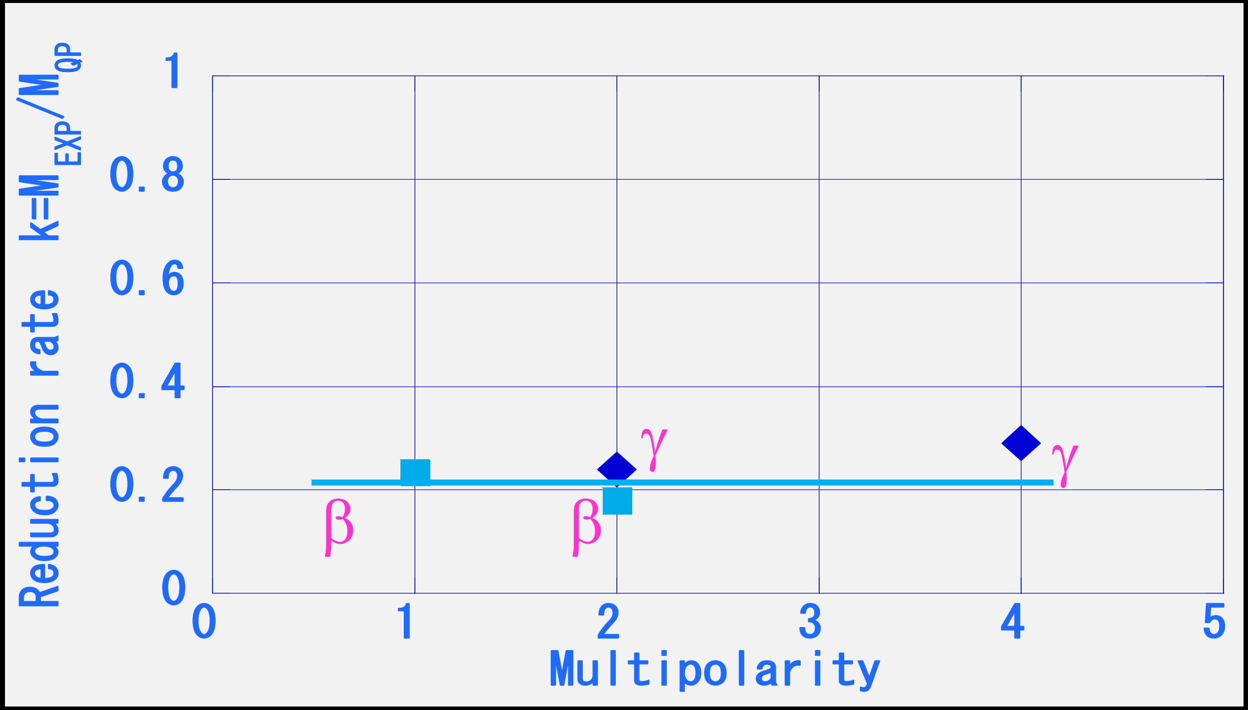


Neutrino response studies .
A: So far

1. Low energy low p (a few MeV/c) β decays ,
   mostly allowed decays F , GT L=0 s wave neutrino
   1960-1980 Ejiri Fujita PR 34 1978

2. CERs at forward angles.
   $p=p_i-p_f$ ~ a few MeV for θ= 0 deg. L=0 s-wave
   Fermi τ and GT τσ responses
   1980-2000 Ejiri PR 338 2000

Universal reductions of axial vector β & γ in low p



Ejiri Fujita
PR 34 85 1978

$k = k(\tau\sigma)\, k(NM) \sim 0.25$ with respect to QP

$k = k(\tau\sigma) \sim 0.5$: Nucleonic long range $\tau\sigma$ GR

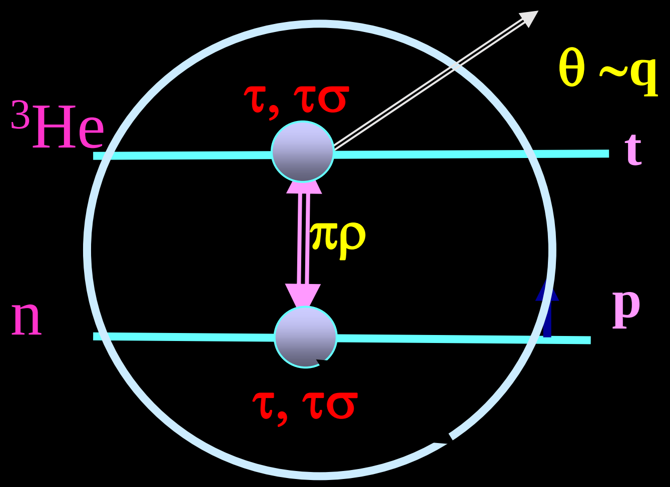
$k(NM) \sim g^{eff}_A / g_A \sim 0.6$: Short range nucl. medium $\Delta\ \pi$

H, Ejiri J. Suhonen J. Phys. G. 42 2015

H. Ejiri N. Soucouti, J. Suhonen PL B 729 2014 .

L. Jokiniemi J. Suhonen H. Ejiri AHEP2016 ID8417598

B Medium momentum (20-200 MV/c)
B1: Nuclear CER (present)

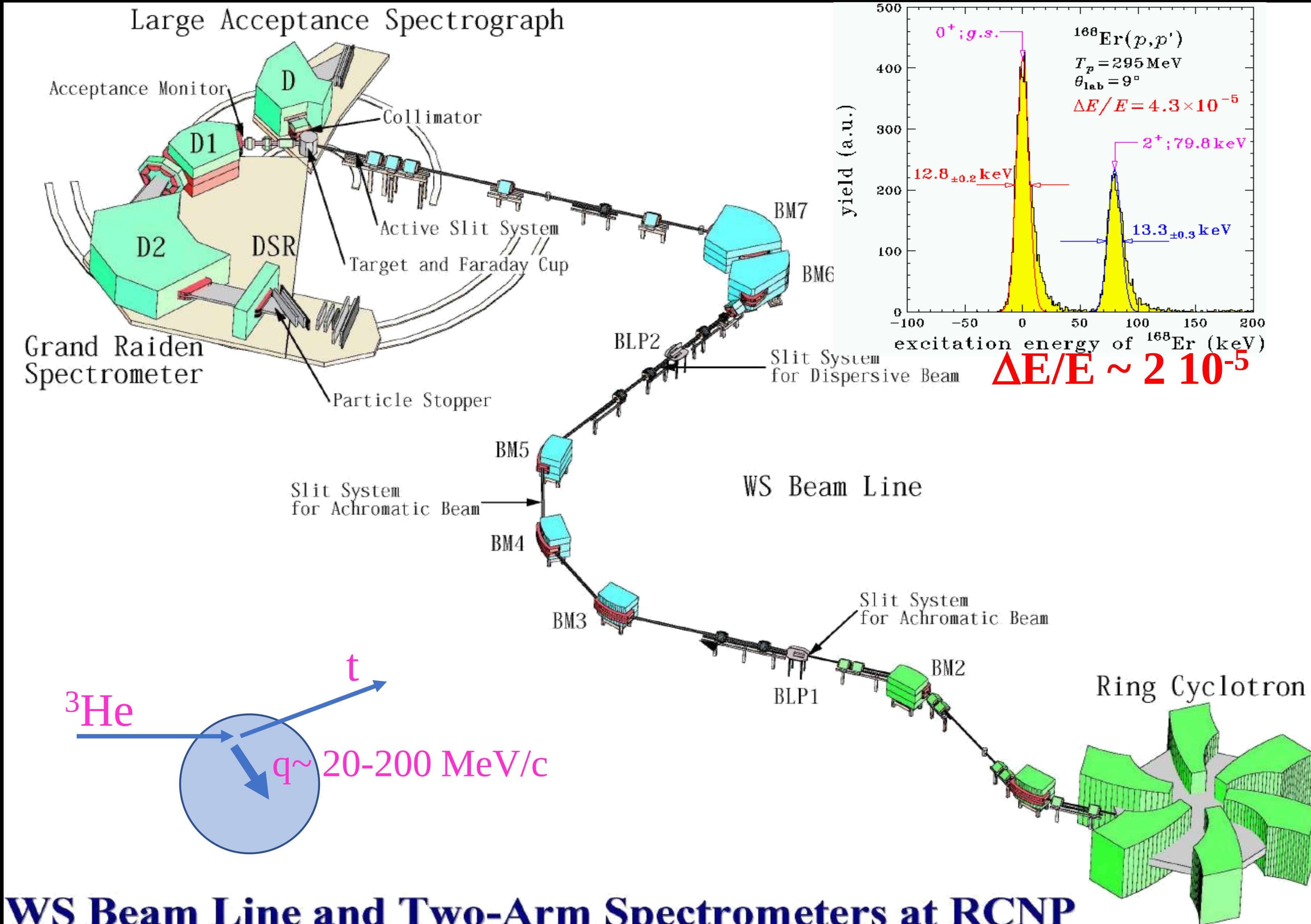


Momentum transfer

$p = p_i - p_f$ ~ 20 -200 MeV
for θ= 0-5 deg.
L=qr=0,1,2,3,4,

$T = G\,|M(q)|^2$
$G \sim K\,[2L+1)\,j_L(qr)]^2$

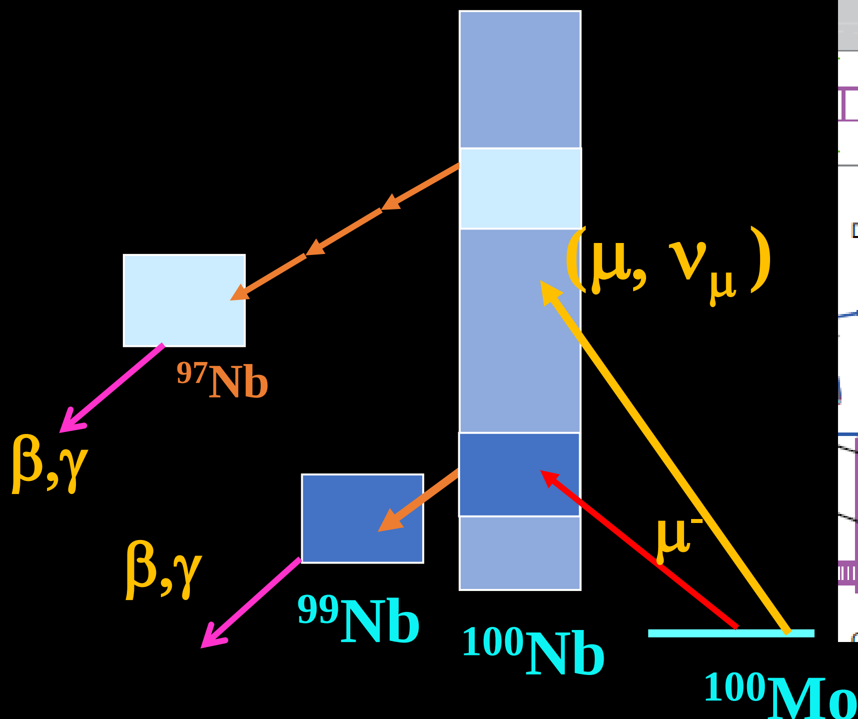
High E resolution (^{3}He,t) CERs at RCNP Osaka

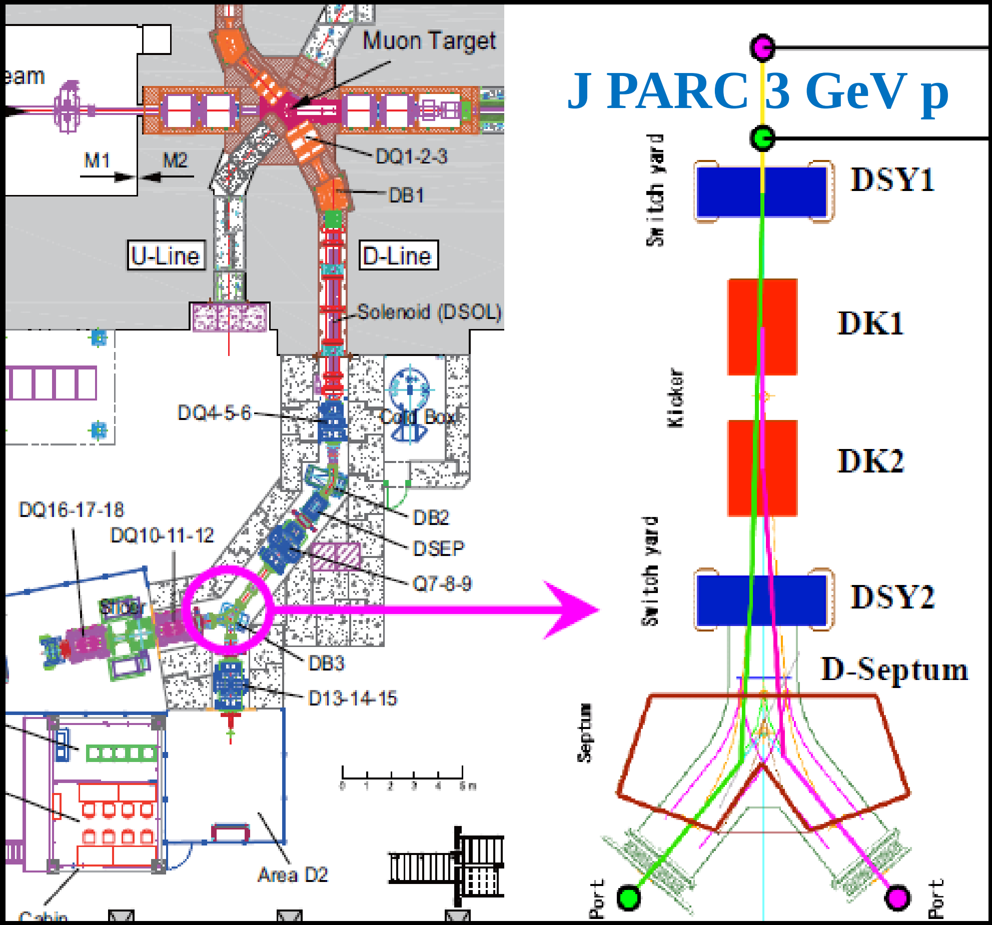


B2: Lepton CER

$(\mu, \nu_\mu, xn\ \gamma)$

β^+ ant-ν q~50-100 MeV/c





γ_i from $^{100-i}$Nb: relative strength   Life time : the absolute strength

H. Ejiri Proc. e-γ conference Sendai 1972, H. Ejiri et al., JPSJ 2014
NNR19:I. Hashim , Hashim H. Ejiri et al., PRC 97 (2018) 014617

3. Neutrino nuclear responses in medium momentum region

Letters

IOP Publishing — Journal of Physics G: Nuclear and Particle Physics

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Letter

Spin-dipole nuclear matrix element for the double beta decay of ^{76}Ge by the (^{3}He, *t*) charge-exchange reaction

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Abstract

Nuclear matrix elements (NMEs) for double beta decays (DBDs) are crucial for studying the neutrino mass and other neutrino properties beyond the standard electro-weak model by measuring neutrino-less DBDs. The spin-dipole (SD) $J^{\pi} = 2^{-}$ NME is one of the major components associated with the DBD NME. The SD NME for ^{76}Ge was derived for the first time by using the

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^{76}Ge DBD

High sensitivity by high energy resolution

Majorana 0.02 t

PR L 120 2018 132502

GERDA / LEGEND 0.2 t

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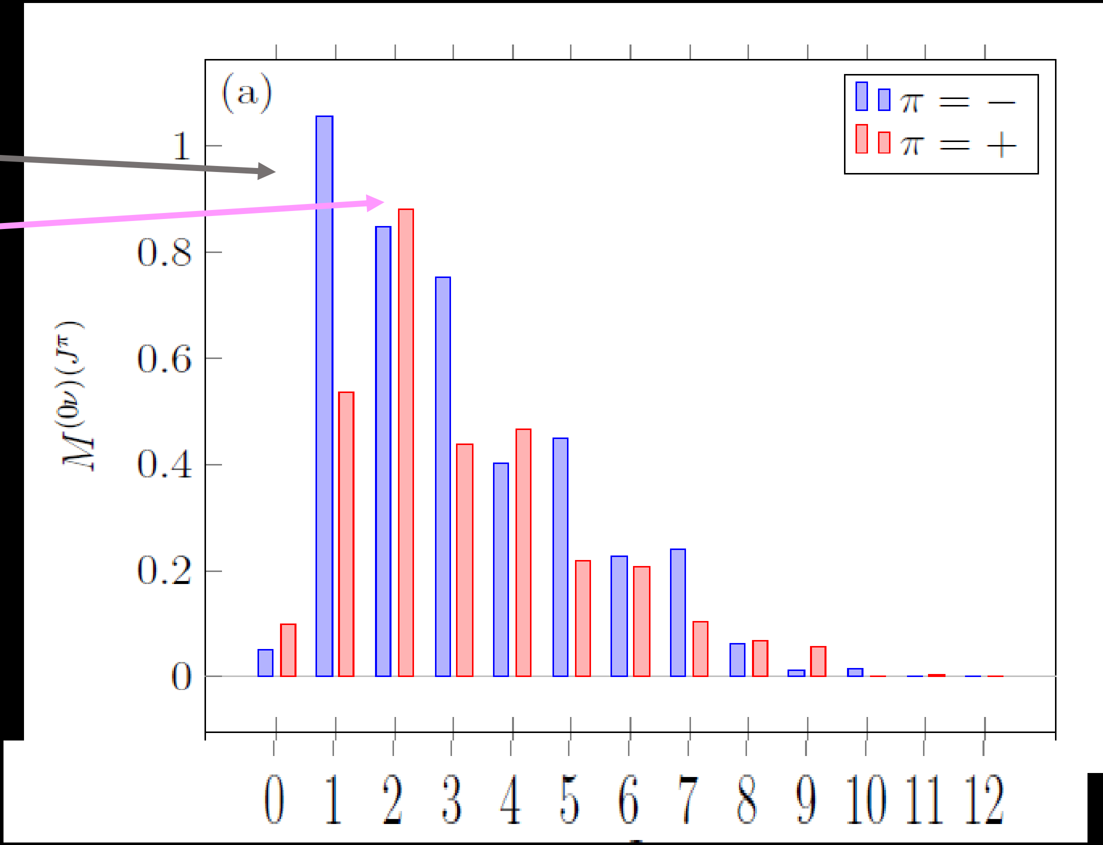
M Theory pnQRPA

Jokiniemi Ejiri Suhonen Frekers PR C 98 024608

L=1 p-wave 60 MeV/c

1^- (Y_1)

2^- SD (σ x Y_1) g_A=1)



M Experiment

So far GT (L=0)

SD ^{76}Ge—^{76}As – ^{76}Se

Present CER β-decay

Derive B(α) , NME M(α) with α=F, GT, SD in CERs

The CER cross section for the α mode excitation by the α mode interacti
in terms of the α mode nuclear response $B(\alpha)$ as [2, 3, 14, 15]

$$\frac{d\sigma(\alpha)}{d\Omega} = C_\alpha B(\alpha),$$

$$B(\alpha) = (2J_i + 1)^{-1}|M(\alpha)|^2,$$

$$C_\alpha = K(\alpha, \omega)F(\alpha, q, \omega)J(\alpha, \omega)^2,$$

where $K(\alpha, \omega)$ and $J(\alpha, \omega)$ are the kinematic factor and the volume integral

So far F =IAS; B(F)=N-Z & GT with q~0 .

1. **C(GT)=constant = proportional coefficient : No , Very crude**
2. **C(GT)= DWBA includes distortion, assuming J(GT) interaction.**

   Tensor interaction (L=2) effect ?

3. **C(GT): calibrate by B(GT) known from β decay , apply**

   it for neighboring nuclei with similar w.f and distortion.

Derive C(α) for α=SD , SQ with q~100 MeV/c & L=1,2 .

So far No experimental, No theoretical ways

Present SD L=1 q= 30~130 MeV/c

Check angular distribution by DWBA.

Calibrate C(SD) by known B(SD) from β decay in ^{74}Ge.

Apply it for DBD ^{76}Ge

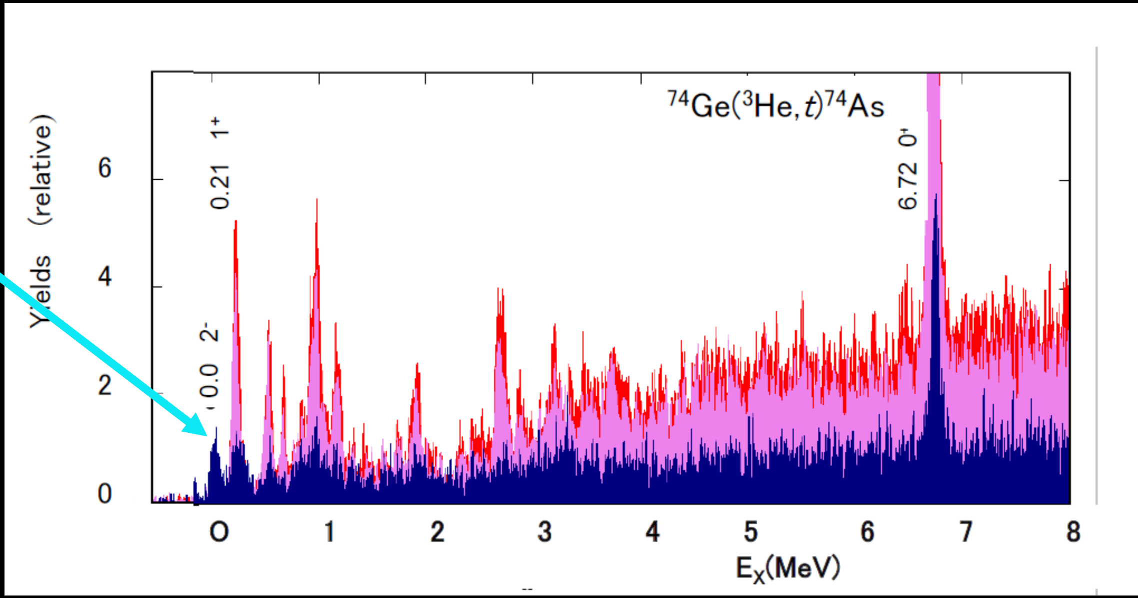
with similar distortion. & w.f 1g9/2 to 1f5/2

Use relative values with references of

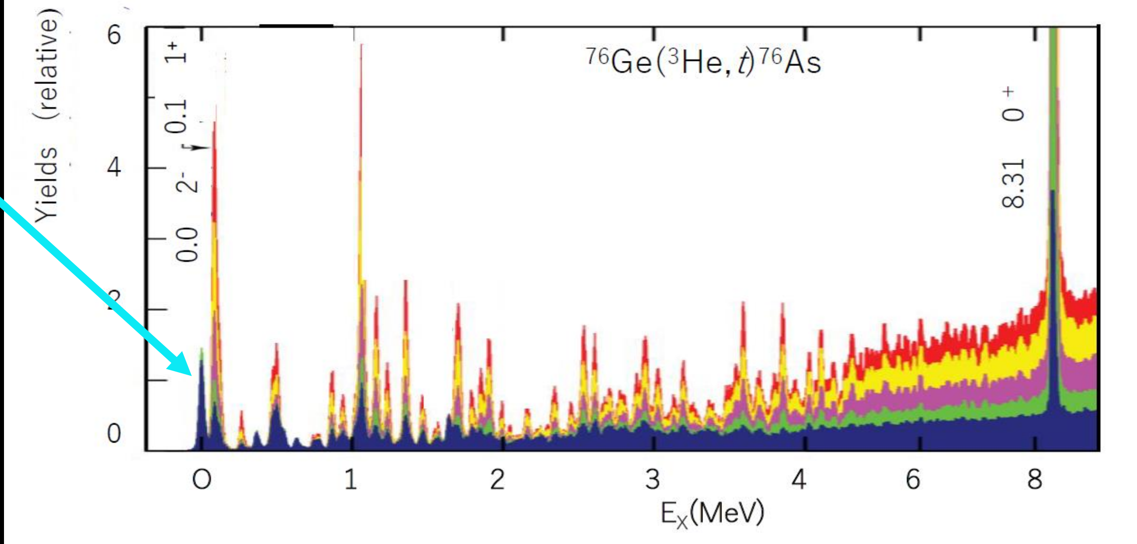
F=IAS with B(F)=N-Z

Energy spectra for CERs on ^{74,76}Ge

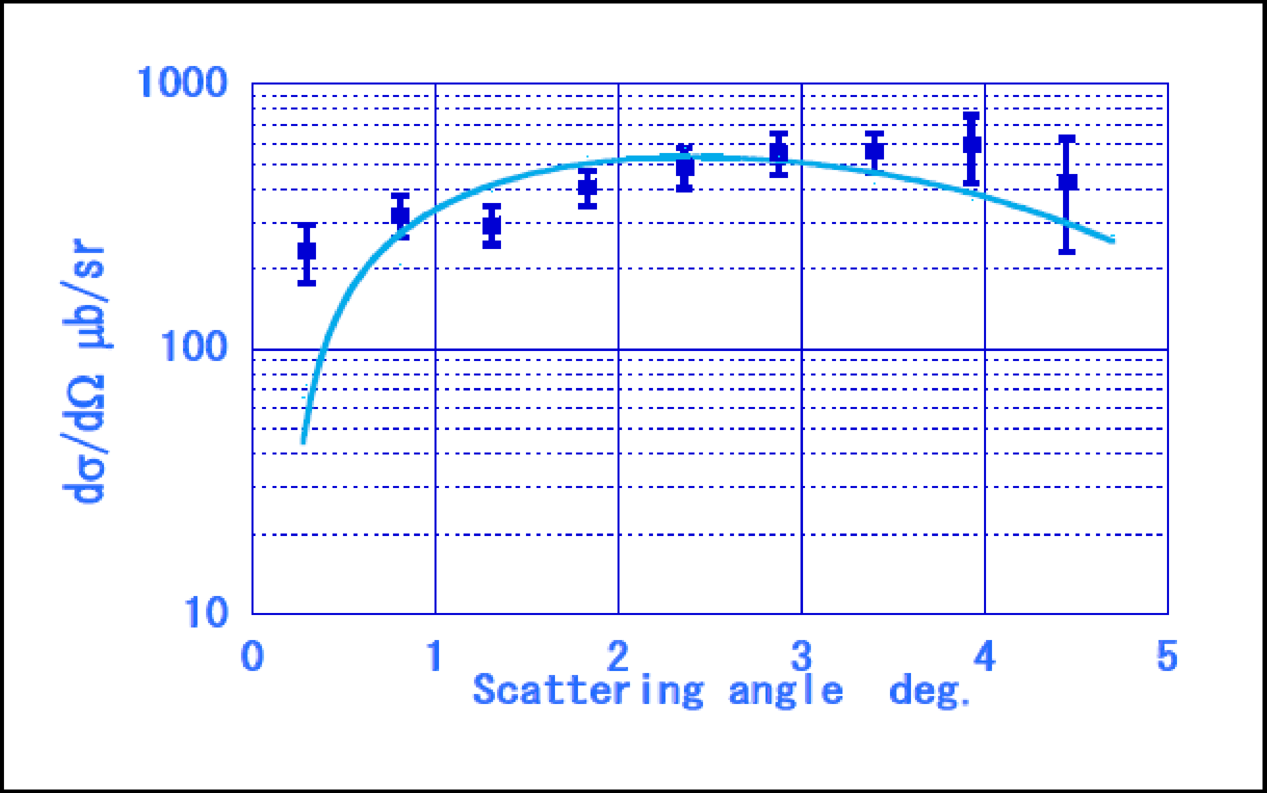
B(SD) known from β decay, used to get C(SD)



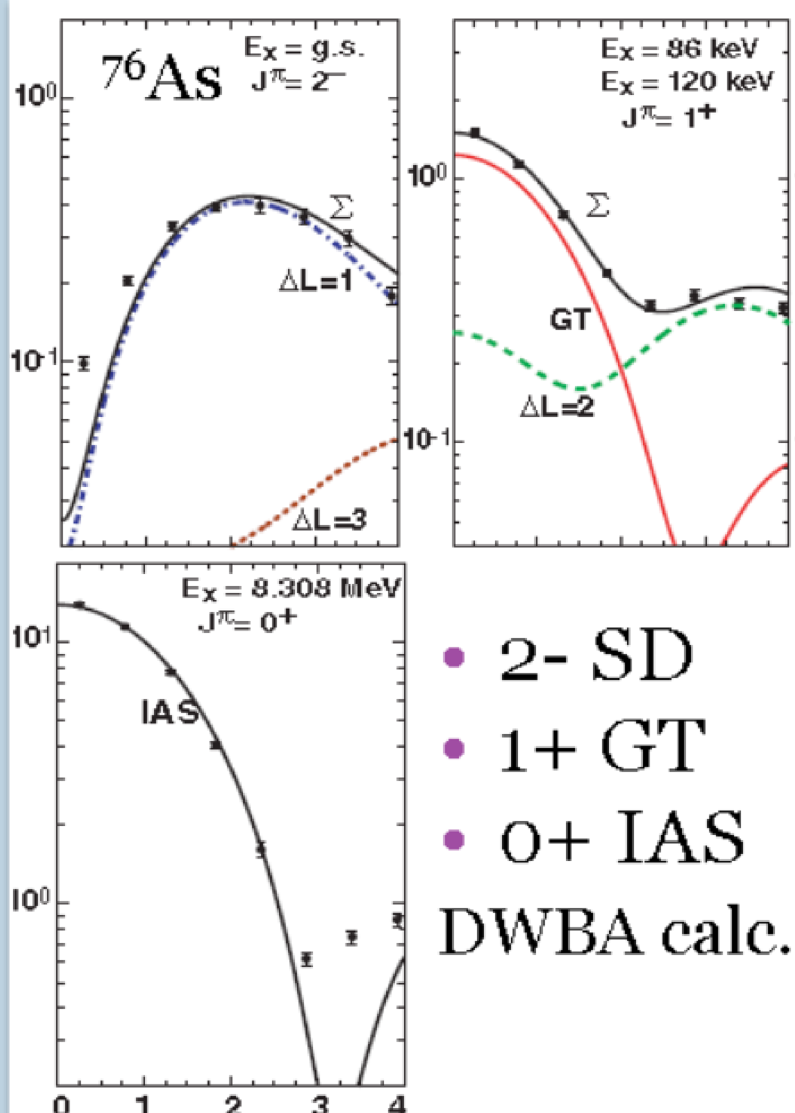
B(SD) to be derived from σ(SD) and C(SD) for ^{76}Ge



Angular (transferred momentum) distribution
Exp. and DWBA with L-1 and L=3.



$^{74,76}Ge(^3He,t)^{74,76}As$



- 2- SD
- 1+ GT
- 0+ IAS

DWBA calc.

J.H. Thies, D. Frekers et.al PRC86 014304(2012)

^{74}Ge σ(SD/σ(F) =C(SD/C(F) B(SD)/B(F)

Exp. 0.16 β-decay B(SD) / B(F)= N –Z

^{76}Ge σ(SD/σ(F) =C(SD/C(F) B(SD)/B(F) B(F)=N-Z=12

Derive B(SD) and NME (SD)= 1.5 ± 0.15 10^{-3} nu.

Tensor interaction + sys. & statistical errors

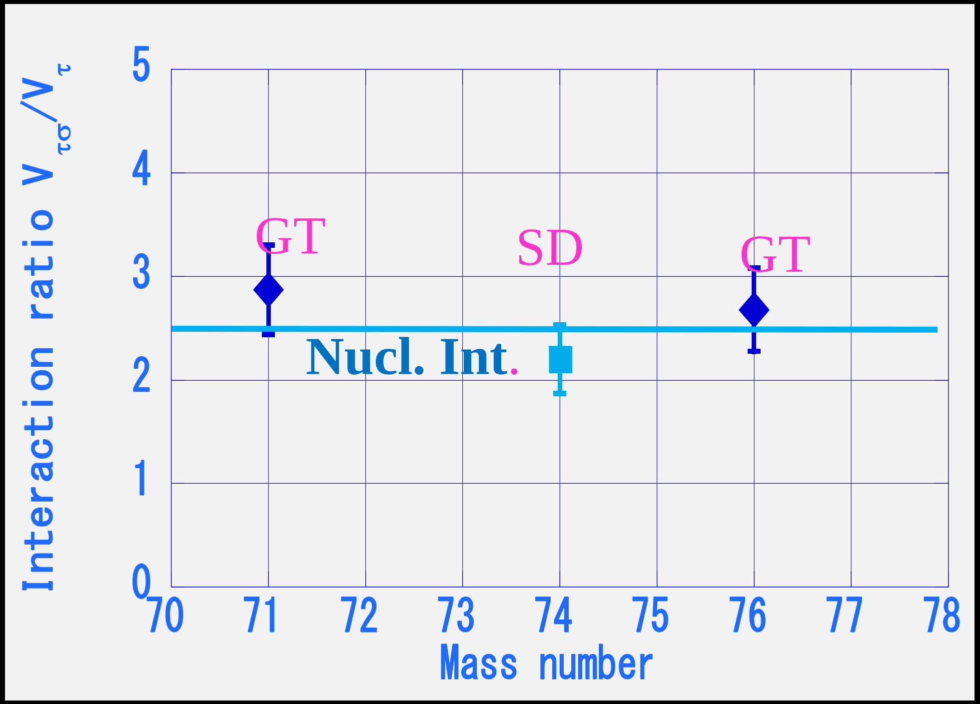
Similar to NME(SD)=1.7 for ^{74}Ge, and

Smaller than NME(QRPA) ~ 6,

suggesting quenched g_A=0.3.

Nuclear Spin Isospin Interactions

CER cross section to response B(α) from β-decay rate gives



Exp. C(GT, SD)/C(F)

$= k\,[V_{\tau\sigma}/V_{\tau}]^2$

agree with n-n

interaction ratio of

$V_{\tau\sigma}/V_{\tau} \sim 2.5$

Uncertainty include contributions from tensor interactions

SD NMEs M(EXP) , M(QP) and M(QRPA)

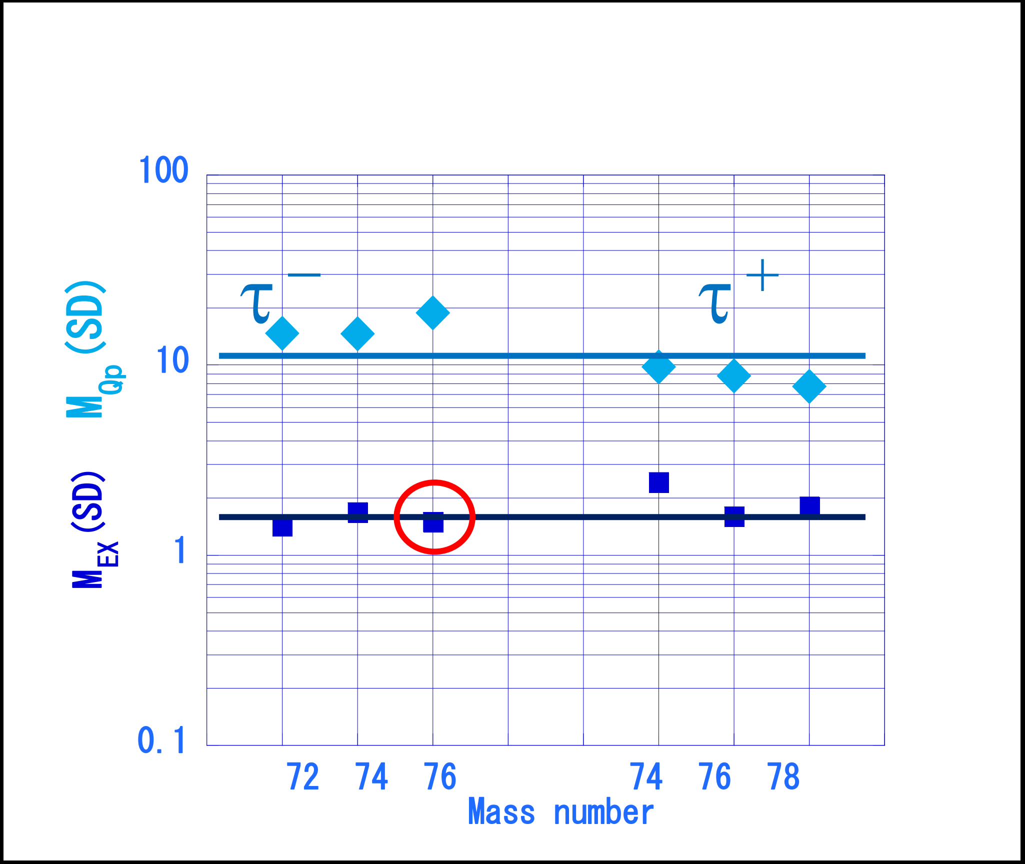
M(EX) ~ 1.9 ± 0.5

M(QP) with
pairing correlation
~ 10

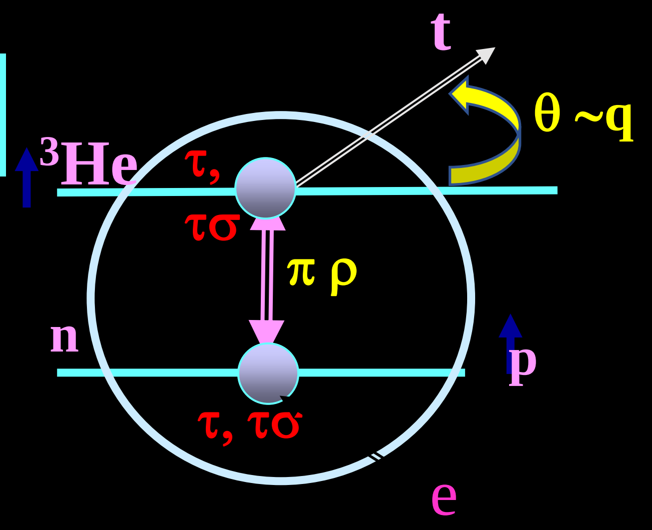
M(QRPA) with
nucleon correlation
~ 5-6

M(EXP) = g_A^{eff} M(QRPA)

g_A^{eff}/g_A^{free} ~ 0.3- 0.4 for
non-nucleonic correlations which are not in QRPA.



CER. F, GT &SD q-dependence



$$d\sigma(q) = C\,|f_a(qr)|^2\, M_\alpha(q)^{\,2}$$

$f_a(qr) \sim$ DWBA $\sim j_a(qr)$: kinematical q dependence

$$M_\alpha(q) = k^{eff}(q)\, M_\alpha(QP)$$

j_0 for IAS, GT, j_1 for SD

$k^{eff}(q) = g_A^{eff}(q) \sim$ constant q=20 – 100 MeV/c

Ejiri H, 2019 J. Phys. G. Nucl. Part. Phys. 46 125202

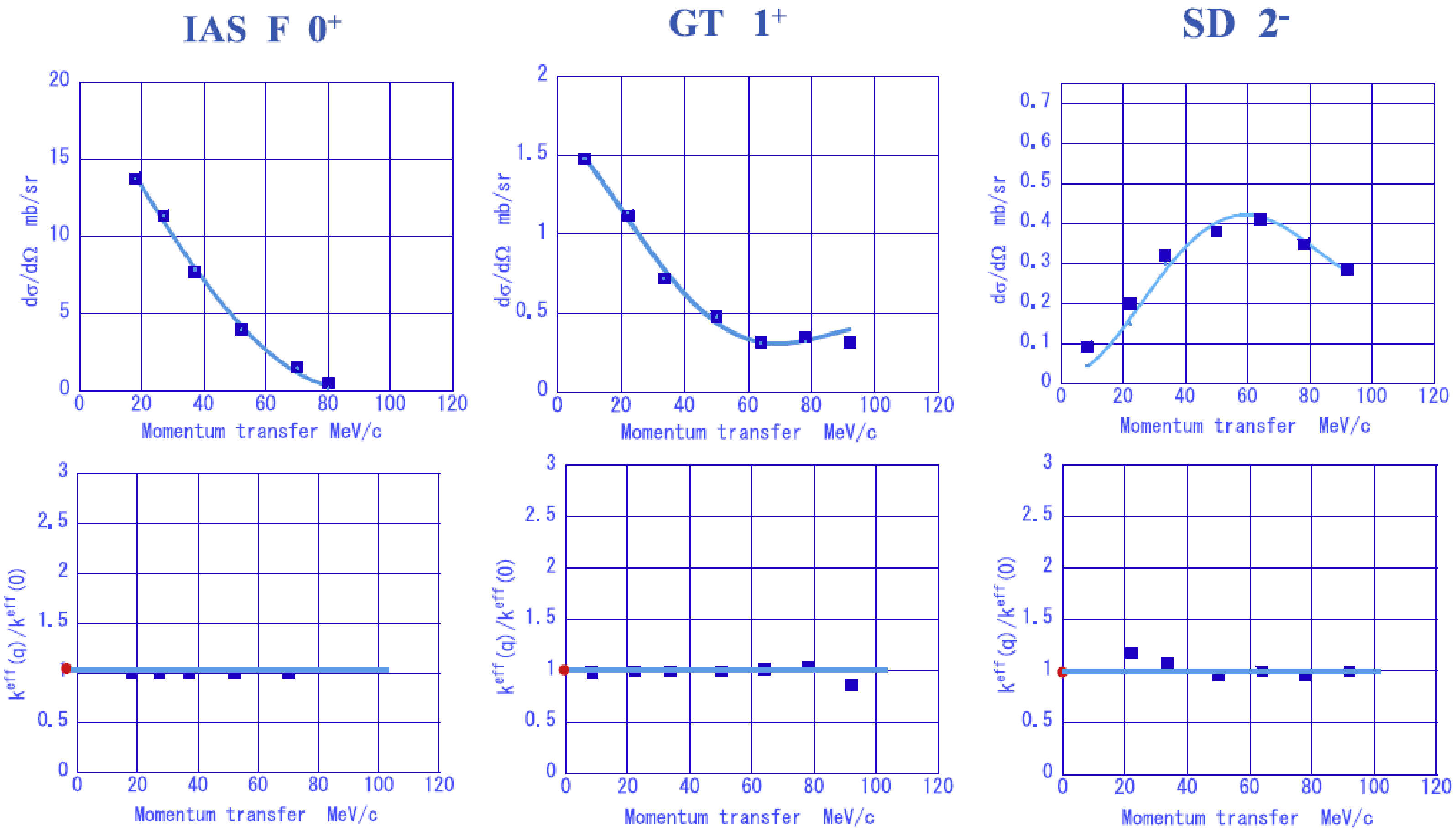


Fig. 15. Top: The ^{76}Ge(^{3}He,t) CER cross sections as functions of the momentum transfer q [95]. F 0^{+}: 8.31 MeV IAS, GT 1^{+}: the 0.12 MeV GT state, SD 2^{-} the ground SD state. The solid lines are the DWBA calculations. Bottom: The ratio $k^{\mathrm{eff}}(q)/k^{\mathrm{eff}}(q=0)$ for α = F (IAS), GT (1st GT state), and SD (groun states. The red point is the normalization point at $q = 0$. See [103].

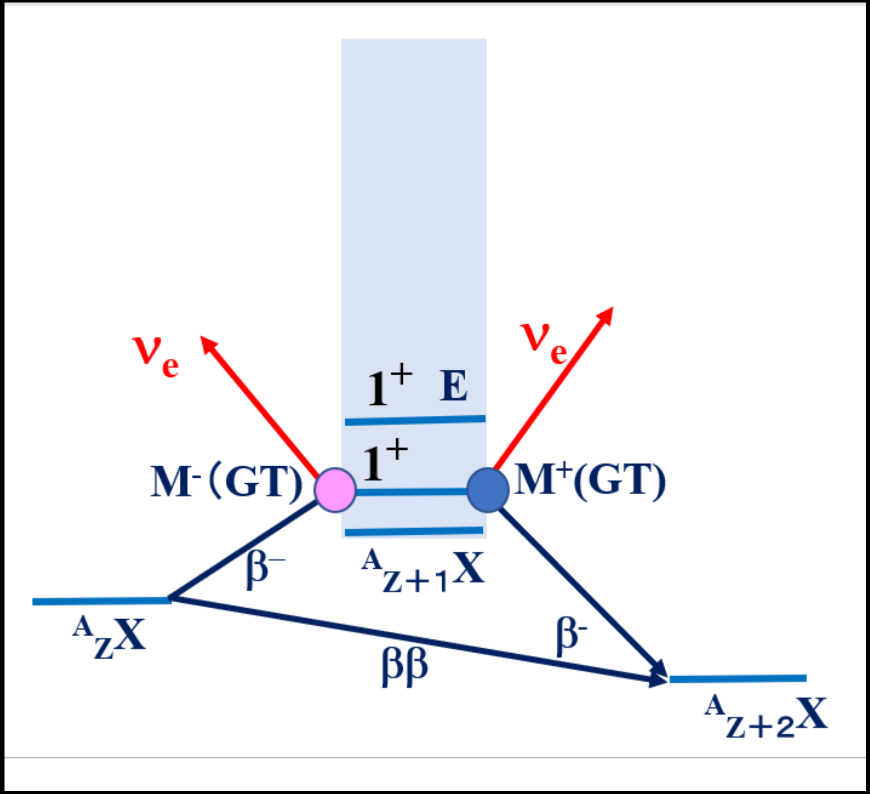
g_A^{eff}~const over q=0-100 MeV/c

Ejiri H, Suhonem J, Zuber K PR 797 1 2019

4. Impact on DEDs and neutrino nucleosynthesis.

DBD $2\nu\beta\beta$ NME by using single β NMEs

$$M^{2\nu} = \left(\frac{g_A^{\rm eff}}{g_A}\right)^2 \sum_i \left[\frac{M_i(\beta^-)M_i(\beta^+)}{\Delta_i}\right],$$



$M^-_k = (k^{\rm eff}_i)\, M^-_k$(GT QP)

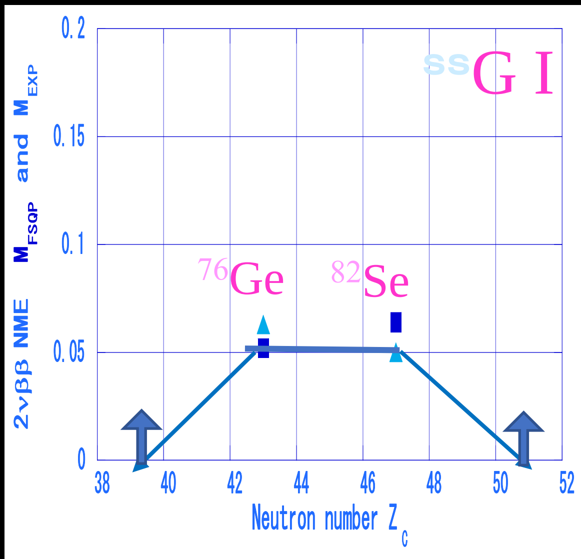
$k^{\rm eff} = g_A^{\rm eff} / g_A$

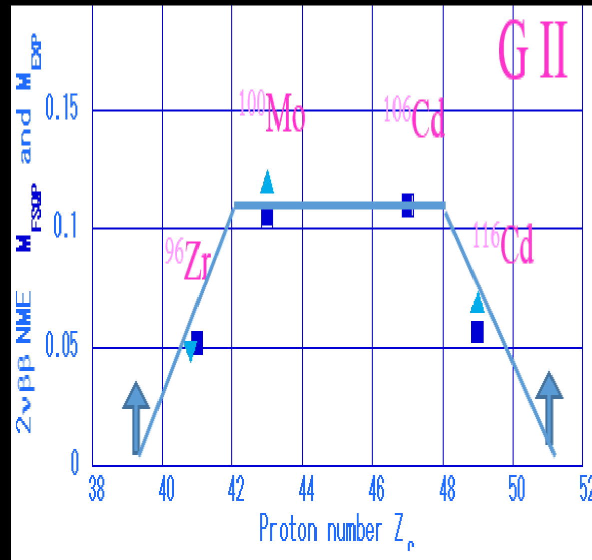
M^-_k and $(k^{\rm eff}_i)$ from Single β/CER exp.

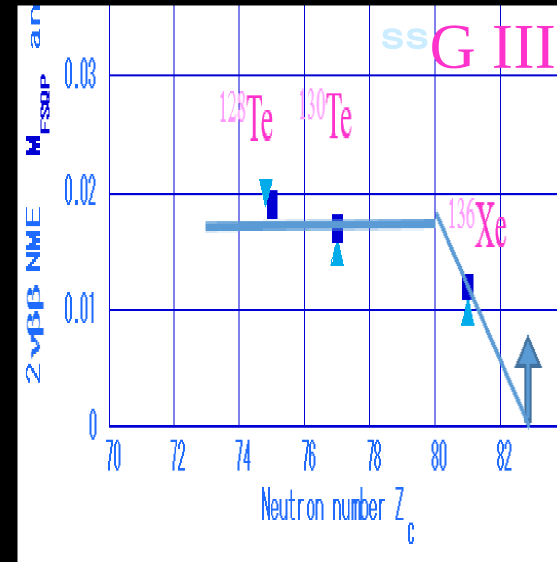
Ejiri H, J. Phys. 2017 44 115201 , JSPS 2009 78 074201

DBD 2νββ NME

QRPA 0νββ NMEs (Engel et al. PRC 89 (2014) 064308







Triangle =exp, Squares=FSQP(Ejiri) J. Phys. 2017

$$M^{2\nu\beta\beta} = \Sigma_k \, M^{-}_{k} M^{+}_{k} / \Delta_k$$

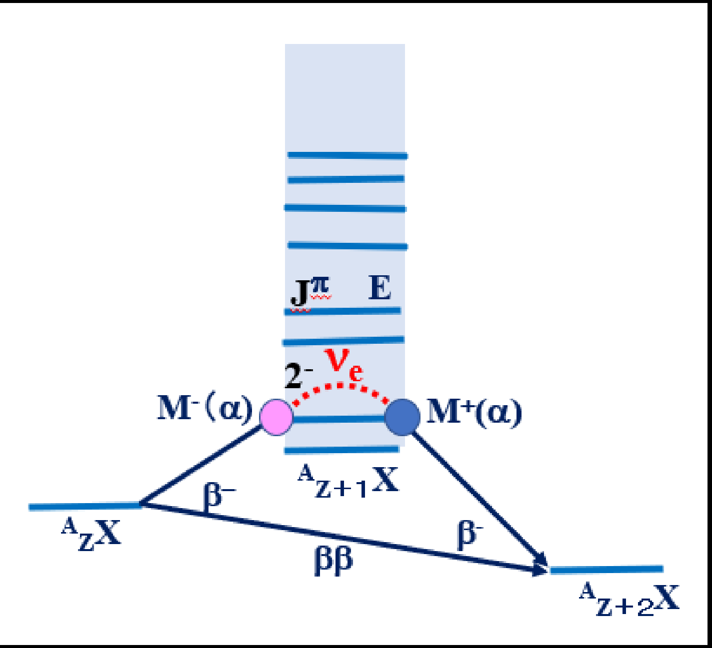
$$M^{-}_{k} = (k^{eff}_{i}) \; m_{ij} V_n U_p \,, \quad M^{+}_{k} = (k^{eff}_{f})$$

$$m_{ij} U_n V_p \,, \quad (k^{eff}_{A})^2 \sim (0.23)^2 = 0.05$$

Shell closure makes U or V small, and thus UV small .

DBD 0νββ NME

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



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

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

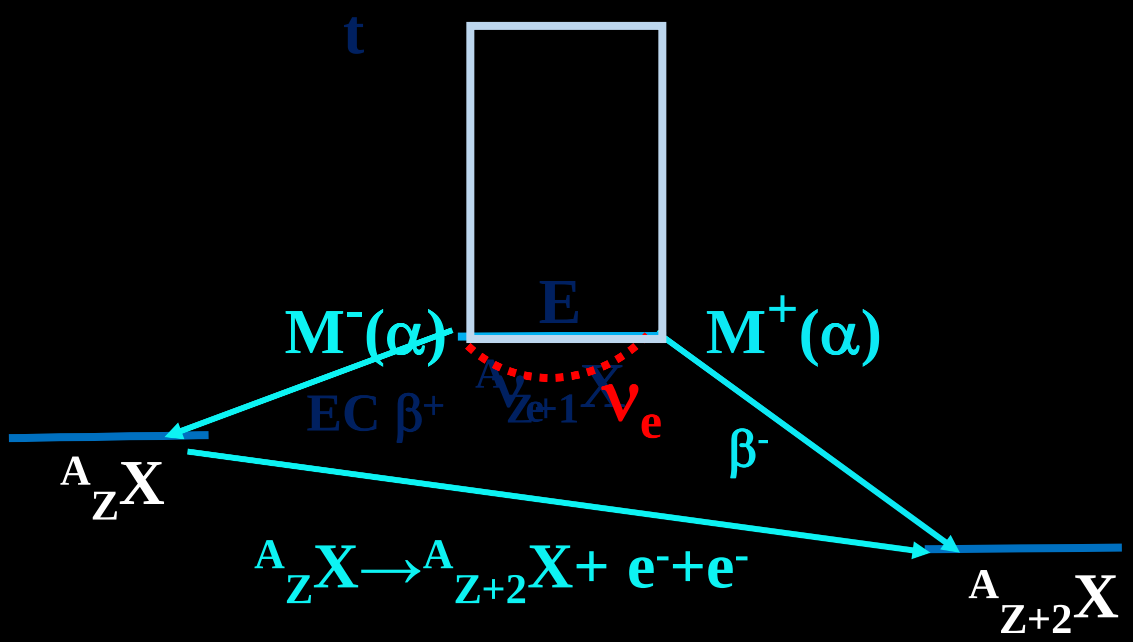
$$M_{\rm T}^{0\nu} = \sum_k \langle t_\pm h_{\rm T}(r_{12}, E_k) S_{12} t_\pm \rangle ,$$

$H(r_{12}) \sim 1/r_{12}$ neutrino potential for 2 n for ν-exchange .

$M^{0\nu} = \Sigma_J M(J)$ J= 1^+ GT, 2^- SD, 3^+ SQ multipole sum

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

DBD NME by referring to experimental single β NME



Select one main component, M(SD 60 MeV L=1)

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

$$M(SD\ \beta^{\pm}) = (g_A^{eff})^{\pm}\ M(QRPA\ SD\ \beta^{\pm})$$

$$(g_A^{eff})^2 = (g_A^{eff})^{-}\ (g_A^{eff})^{+} \sim (0.3)^2$$

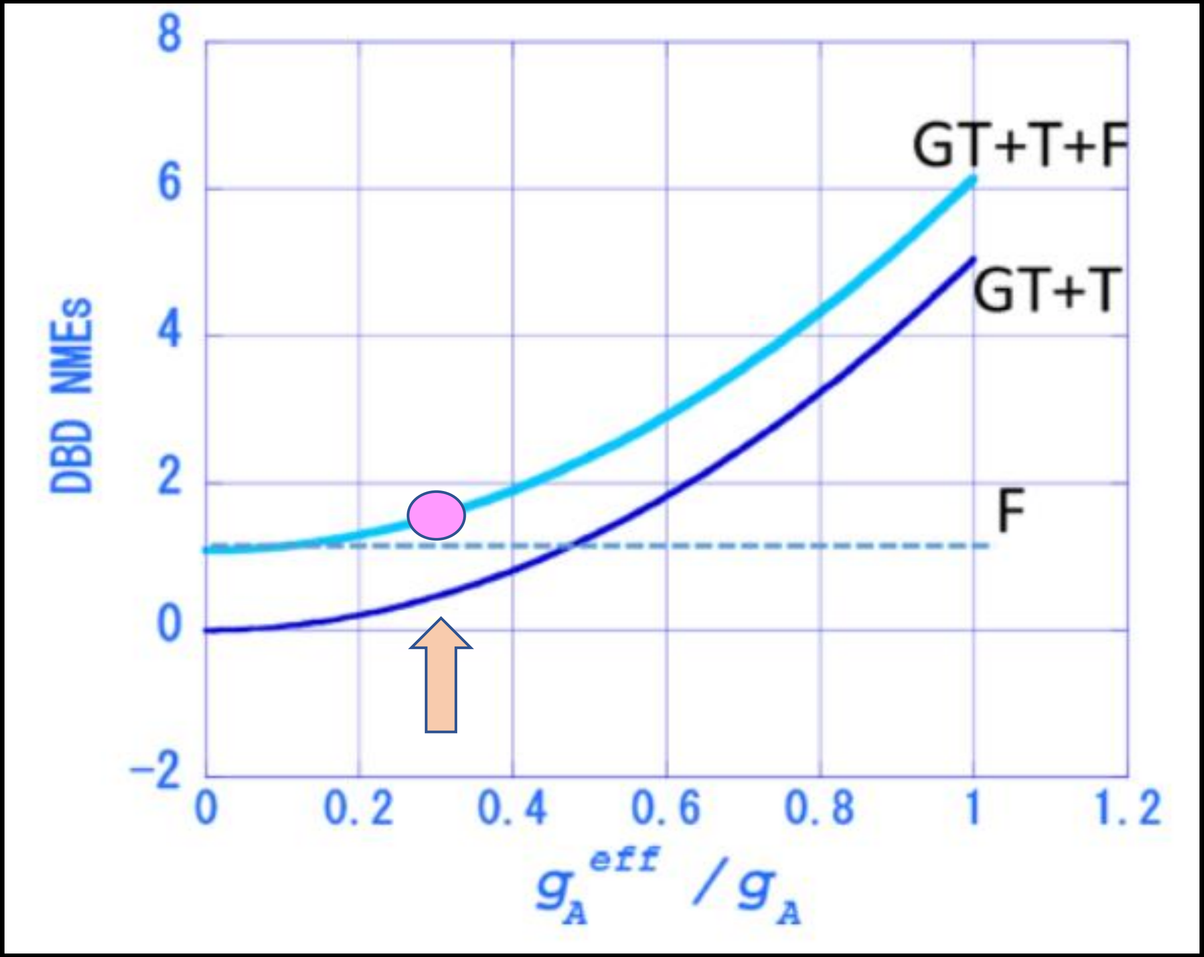
$$M^{0\nu} = [\frac{g_A^{eff}}{g_A}]^2[M_M^{0\nu}(GT) + M_M^{0\nu}(T)] + [\frac{g_V}{g_A}]^2 M_M^{0\nu}(F),$$

M(α) Model

pnQRPA

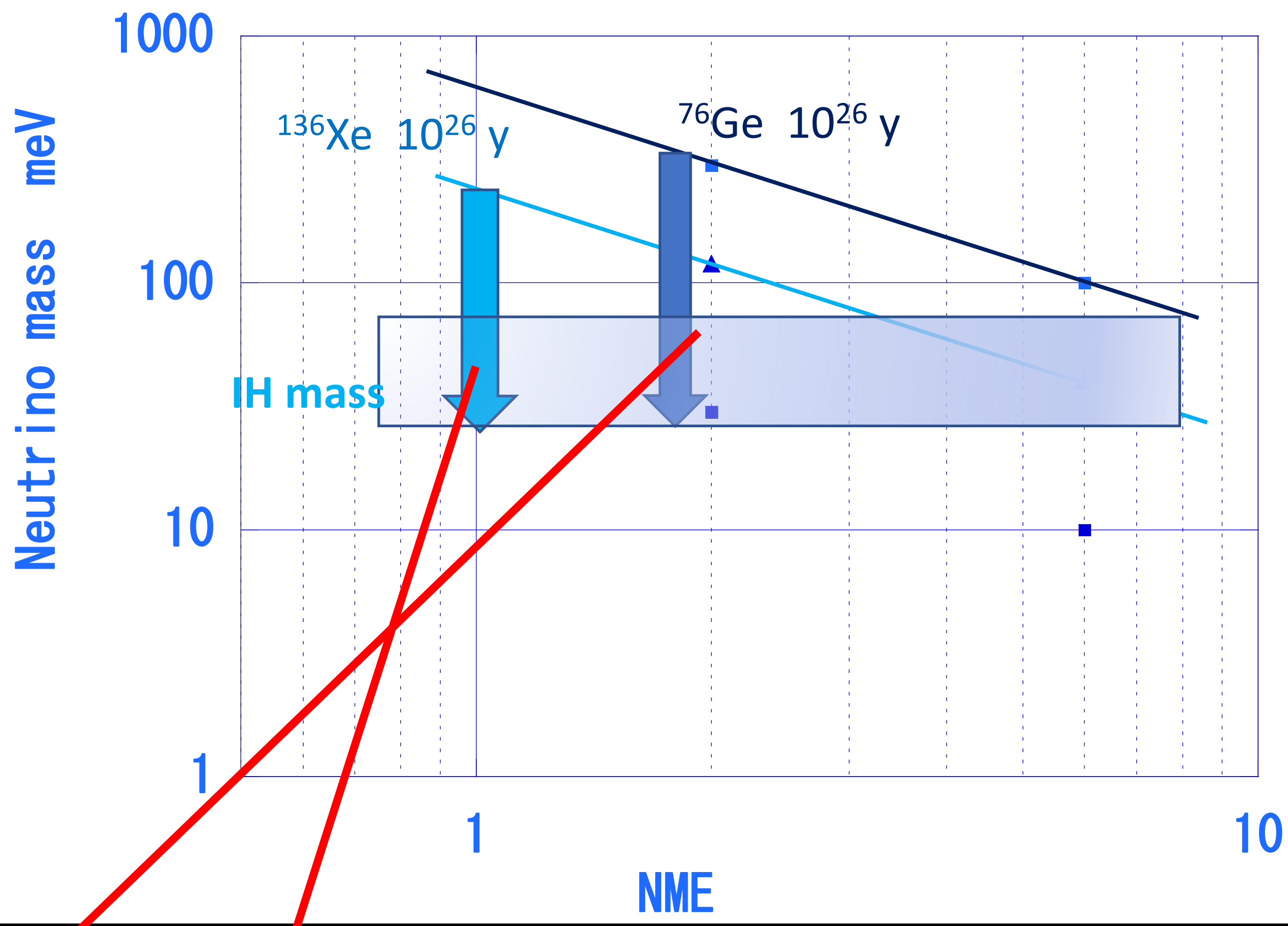
^{76}Ge

M(GT)=5.4,
M(T)=-0.36
M(F)=1.76
Jokiniemi, Ejir, Suhonen PR C 98 2018



g_A^{eff}/g_A= 0.3 leads to reductions 0.1 for M(GT), 0.3 for $M^{0\nu}$, 0.1 for DBD rate, ~ 100 for DBD detector mass

Limits on [Mass × NME] < k/T $_{1/2}$



To reach IH mass = 16 meV,

factor 20 and 12.5 in mass and 1.6 10^5 and 2.4 10^4 in NT/B

SN neutrino nuclear interaction

$$S(E_\nu) = cT_\nu^{-1} \frac{(E_\nu/T_\nu)^2}{\exp(E_\nu/T_\nu - a) + 1},$$

SN 10 kpc 3 10^{53} erg
In all 3 neutrinos

SN tempereture

at the neutrino surface

$E(\nu_{\mu\tau})$~ 10-20 MeV,

$E(\nu_{\mu\tau})$ ~20-50 MeV,

Large contribution from

ν_e to $\nu_{\mu\tau}$ oscilation CC & NC

$E(\nu)$ ~ E(e) + 15 = 40-50 MeV

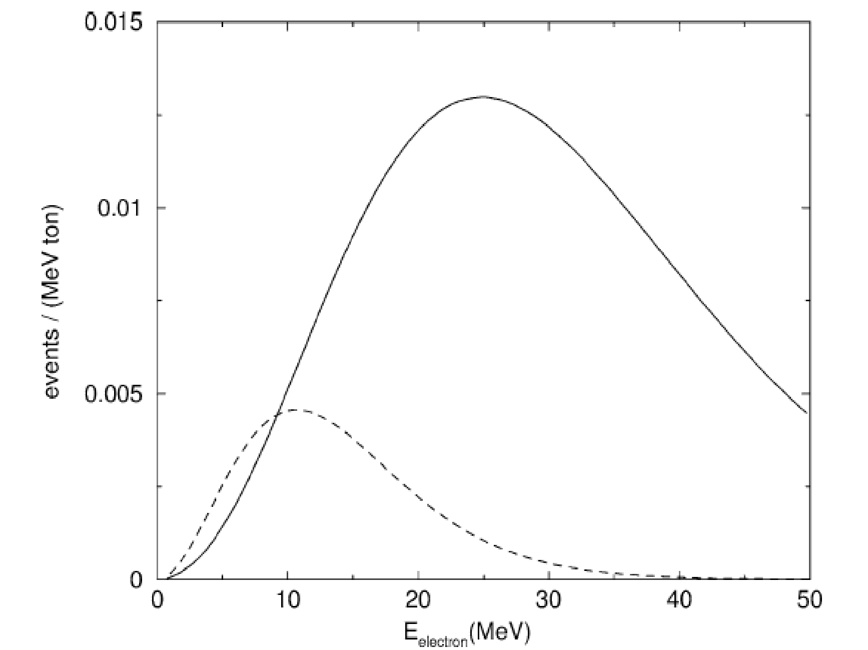


Fig. 2. The calculated energy spectra of electrons produced by charged-current interactions of both ν_e (dashed line) and ν_{ex} (solid line), assuming equipartition of SN energy among all flavors. The vertical axis is the number of electrons per MeV per ton of ^{100}Mo.

Ejiri H et al P L B 530 29 2002

5. Remarks

1. CER: (^{3}He,t) provides NMEs J= 0-2, p=5-100 MeV/c used for evaluating $\mu\tau-\nu$ astro and DBD ν responses. Complementary to CER (μ,ν_μ) J = 0-3, p=50-100 MeV/c used for astro and DBD anti-ν responses.

2. ^{76}Ge M(SD β^-)=1.5 $\pm$ 0.15 10^{-3} nu was obtained for the first time by CER. Combining it with M(SD β^+)=1.60, one gets g_A^{eff}/g_A=0.26 for ^{76}Ge. Using $g^{eff}{}_A$ (SD)~0.3 for Ge region, one get M($\beta\beta$)=1.5 and $g^{eff}{}_A$ (DBD)~0.25

3. M(SD) , M(DBD) for p-wave medium p at A~76 are re reduced with respect to QRPA MODEL by (g_A^{eff}/g_A).~0.3 .


Thanks for your attention   Greenary Nimph 翠の精