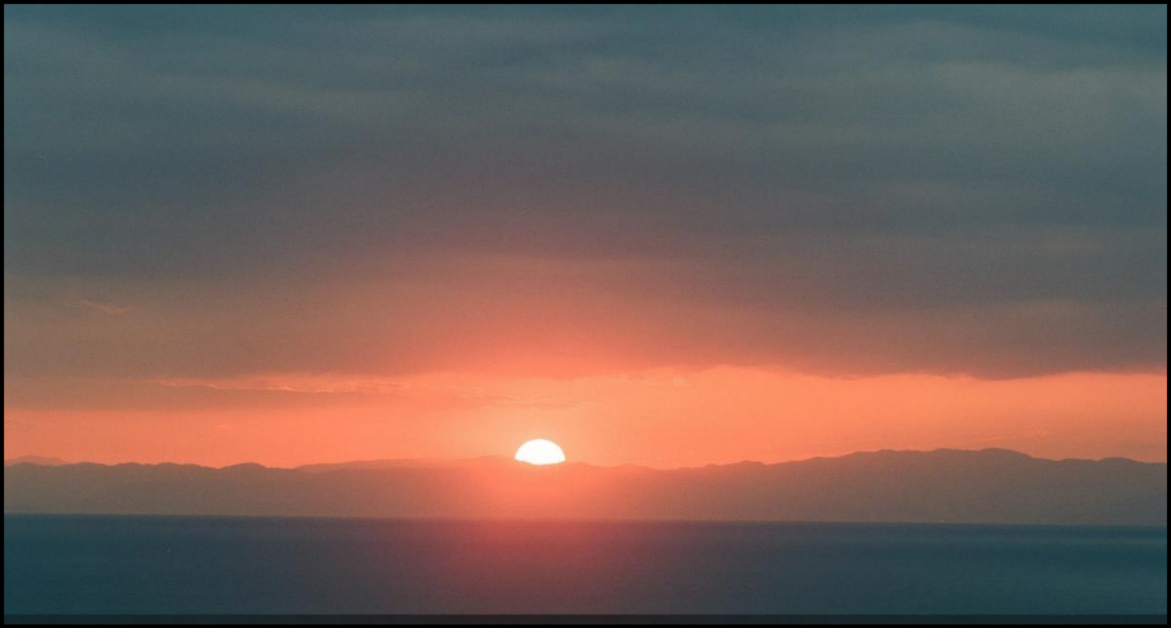
EM (γ) transitions from and to IAS and axial-vector and vector NMEs associated with DBDs



Hiro Ejiri
RCNP Osaka

Thanks the organizers for invitation to NME-23

Subjects to be discussed:

I. Experimental DBD rates and DBD NMEs

II. Charge exchange nuclear reactions and axial-vector NMEs associated with DBD NMEs

III. Electro-magnetic (EM γ) NMEs for IAS

M1 /E1 EM-γ NMEs for axial-vector /vector DBD NMEs

IV. Photo nuclear reactions to IASs to study DBD NMEs

Concluding remarks

I. Exp. rate for neutrino-less ββ decays

$$1/(T_{1/2}\ G^{0\nu}) = [M^{0\nu}\ m_\nu]^2$$

EXP

Atomic Physics

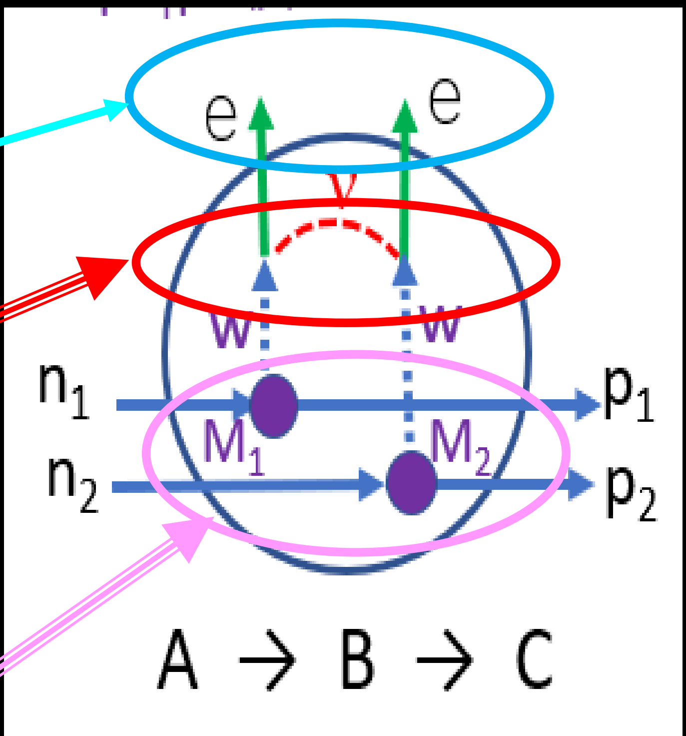
Phase space pe, Z

Particle physics

Majorana ν, m_ν CP, RHC

Nuclear phys.

g_A^{eff} isobar , τ σ correlation



$M=M^{0\nu} K_{\nu R}$ are keys for new physics in DBD

$$1/t_{1/2} = T^{0\nu} /\ln 2 = G^{0\nu} \; B(NP)$$

$$1/(t_{1/2}G^{0\nu}) = B(NP) \qquad B(NP)=|M|^2 \qquad M=M^{0\nu} K_{\nu R}$$

(Corresponds to 1/ft = B(GT/F) derived experimentally)

$G^{0\nu}$ = include $(g_A=1.27)^4$, $M^{0\nu}$ includes g_A^{eff} and g_V^{eff} .

$$K_{\nu R} =[\langle m_\nu\rangle^2 + C_\lambda \langle\lambda\rangle^2 + C_\eta \langle\eta\rangle^2 + \text{interference terms}]$$

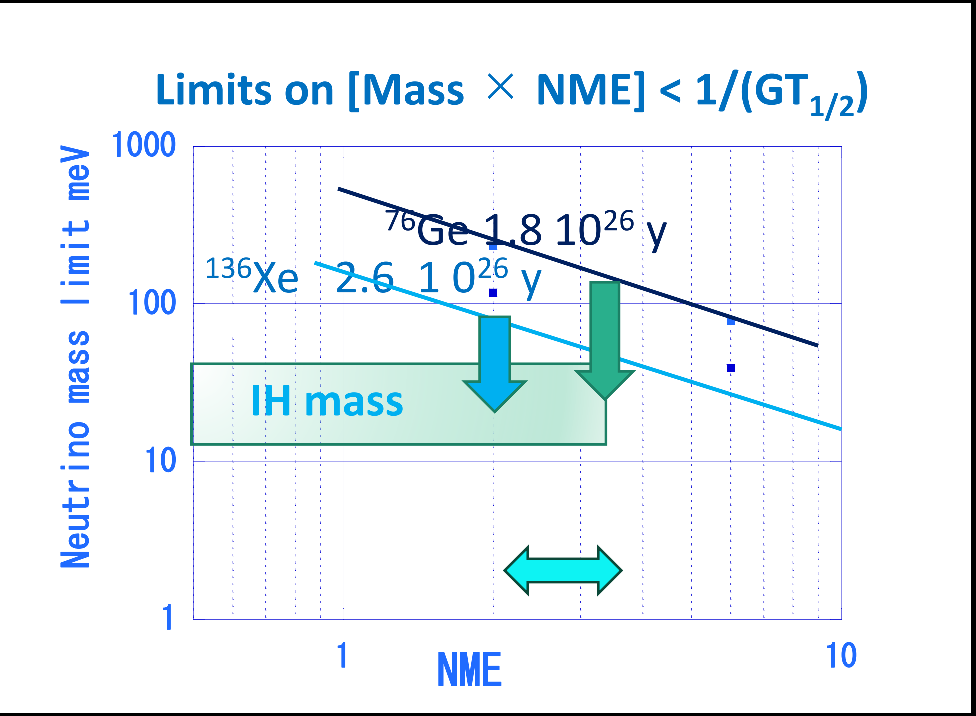
$$\langle m\rangle=|\Sigma m_j U_{ej}| \qquad \langle\lambda\rangle=(M_L/M_R)^2 |\Sigma U_{ej} V_{ej}| \qquad \langle\eta\rangle=\tan\theta_{LR} |\Sigma U_{ej} V_{ej}|$$

C_λ and C_η are phase spaces and NMEs in units of those for m_ν

$1/t_{1/2} = T^{0\nu} /\ln 2$ gives product of $M^{0\nu}$ and ν-mass/λ/η.

Current limits

Current limits (GERDA PRL 125 252502, ,KamLAND PRL 130 051801)



DBD EXPs : $M^{0\nu}$ =5.2-0.023 A=2~3.5 ((Ejiri Jokiniemi, Suhonen PR C Lett. 2023) smooth function of A.

may reach IH mass, by a factor ~ 3 in ν-mass and $>10^2$ in NT/I

$$(t_{1/2})^{-1} = G_{01} M_m{}^2 m_\nu{}^2 + G_{02} M^2_\lambda \lambda^2 + G_{09} M_\eta{}^2 \eta^2 + \text{Cross terms}$$

Phase space $G_{01} : G_{02} : G_{09} = 1 : 5 : 0.5\ 10^5$ (recoil term)

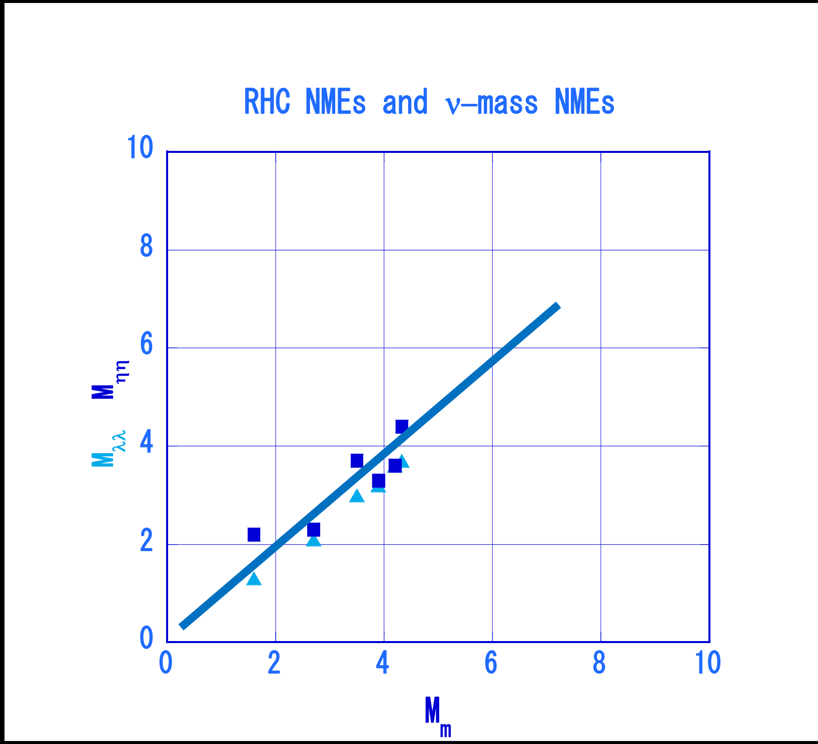
$M_m = M(GT)(1-F+T)M$

M_λ = Effective NME~ M(GT)

M_η = Effective NME~ M(GT)

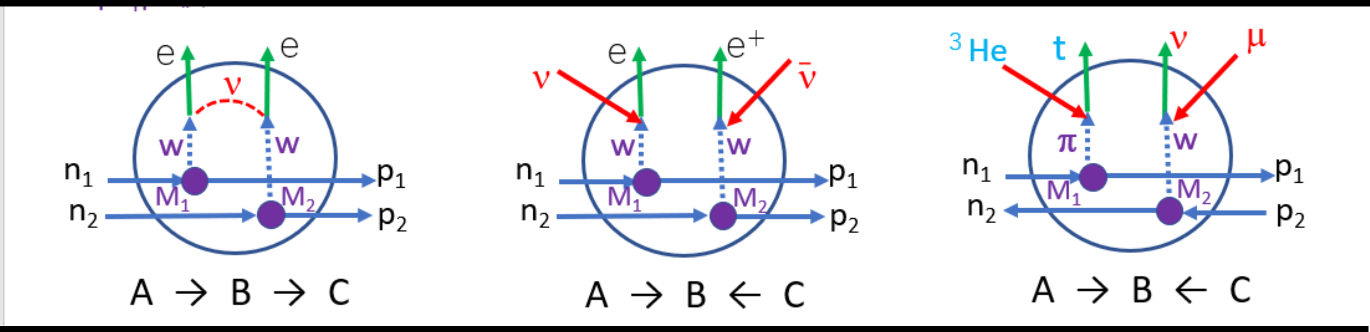
$M_\lambda \sim M_h \sim M_m$
in case of QRPA

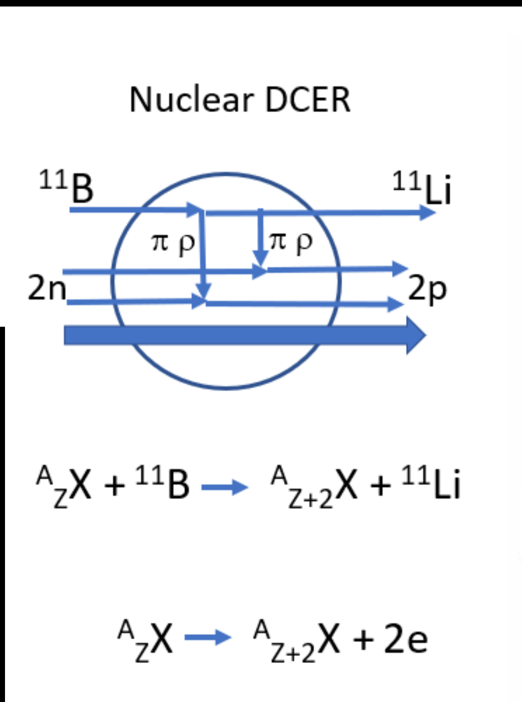
Thus the ν-mass sensitivity in units of m_e corresponds to the λ and η sensitivities smaller by the factors , SQRT of G_{02} and G_{09} = 2 and 200.



Muto et al., Z. Phys. A 334 187

Single and double CERs at RCNP



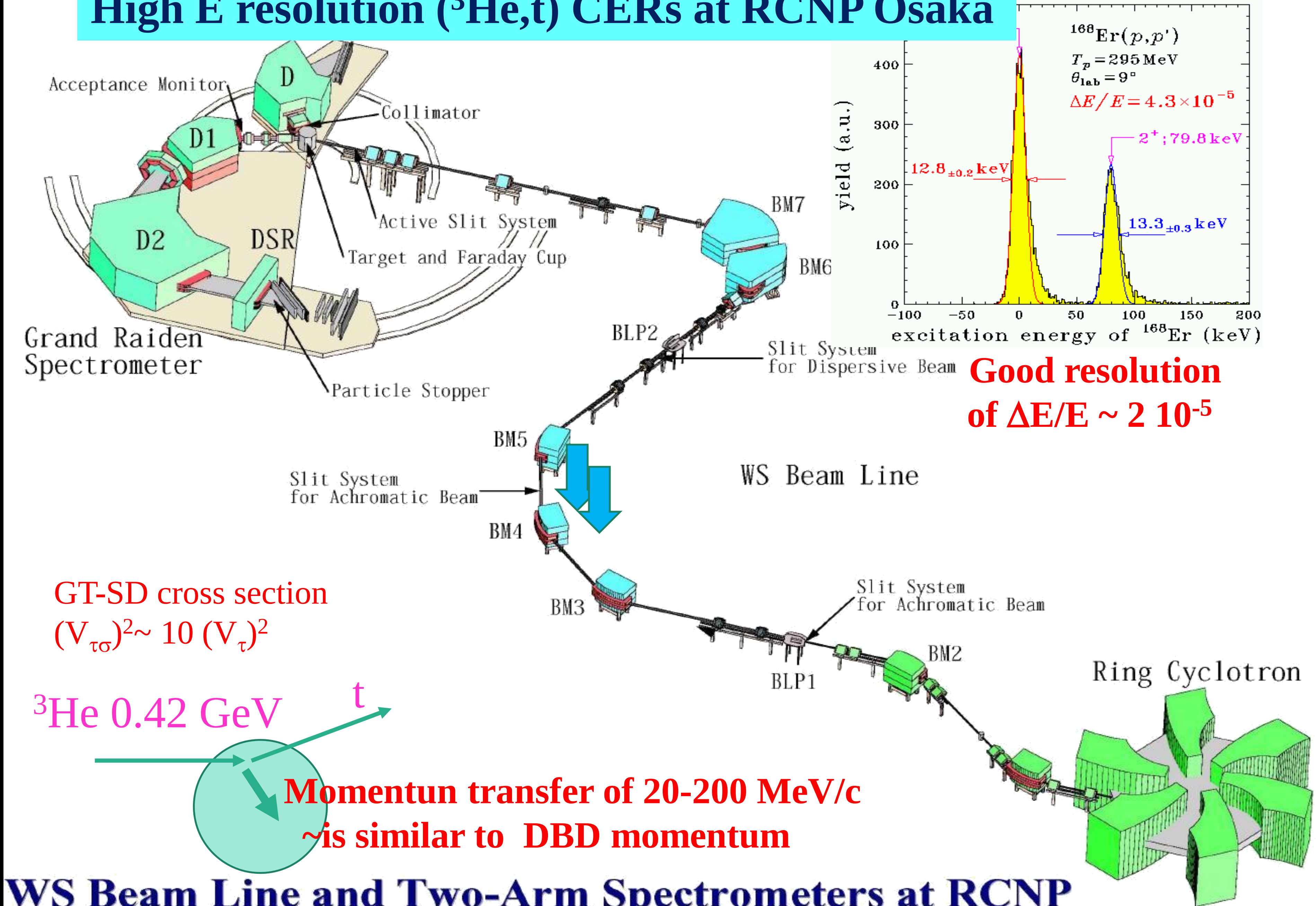


DBD M_1 , M_2 via neutrino potential by single β, ν, μ. CER NMEs

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

CERs: H. Ejiri, Universe 6, 225 (2020); Frontiers in Physics 9, 650421 (1921).

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



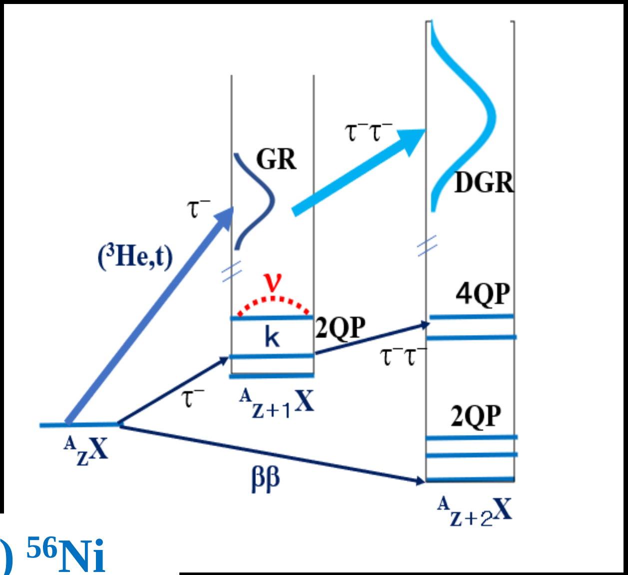
Good resolution of $\Delta E/E \sim 2\ 10^{-5}$

GT-SD cross section
$(V_{\tau\sigma})^2 \sim 10\ (V_\tau)^2$

Momentun transfer of 20-200 MeV/c
~is similar to DBD momentum

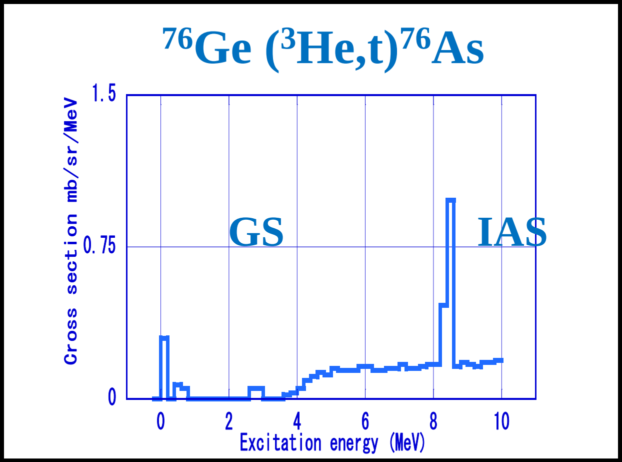
Double Charge Exchange Reaction

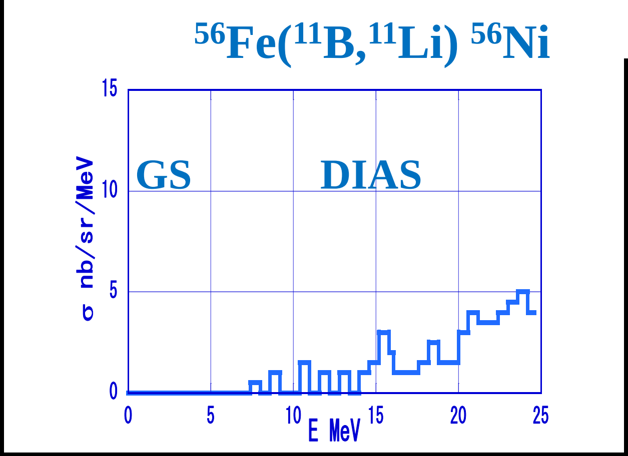
H. Ejiri Universe 2022, 8, 457, Takahisa



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

1. $(V_{\tau\sigma}/V_\tau)^2$ ~ 3.4 enhance τσ GT SD excitation
2. Q value = - 50 MeV. Thus p-transfer 100 MeV/c is same as DBD, and L=1 enhances SD





GT SD NMEs derived by referirng to IAS DIAS cross sections with known B(F)

SCER ^{76}Ge (^{3}He,t)^{76}As excites SD states with strength of 0.1 of QP strength. Then we get the quenching of sqrt of 0.1 = $k_{\tau\sigma}$ ~ 0.3 with respect to QP.

DCER ^{56}Fe(^{11}B,^{11}Li) ^{56}Ni excites very little low-QP GT-SD states with strength of 0.01 of QP strength. Then the quenching of sqrt of 0.01=$(k_{\tau\sigma})^2$~ 0.1

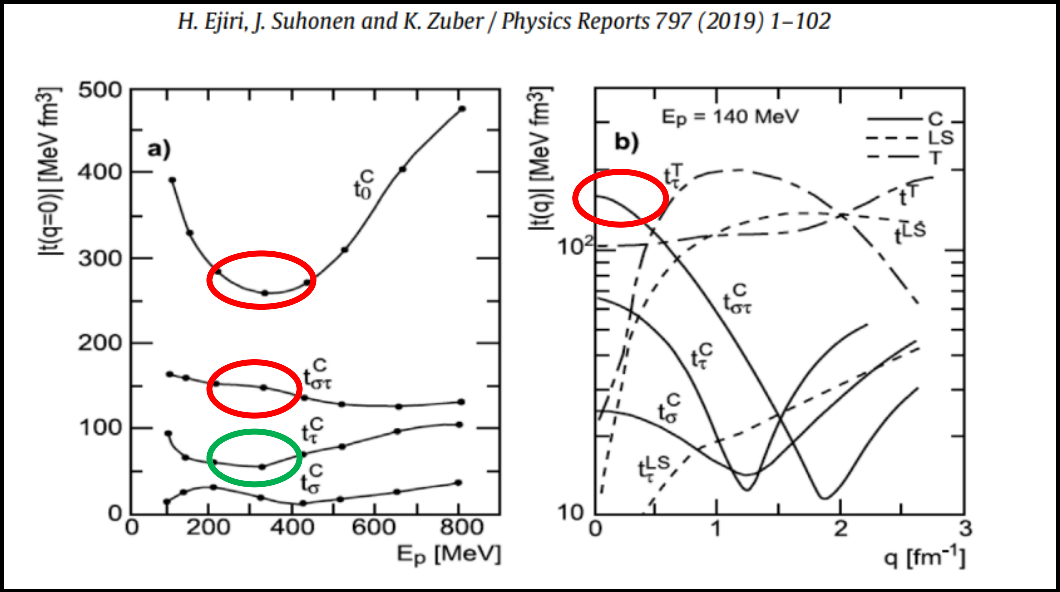
Limits of nuclear CERs

1. **Nuclear interactions :**
   Strong interactions, large cross sections , easy experiments.
   Complex/multi interaction operators, hard analyses of the data.
   Absolute NMEs are uncertain because of the absorptions and distortion, and complex interaction strength.

2. **Limited to relative $\tau\sigma$ (GT) NME.**
   E=200 MeV 0. deg. q~0

3. **Tensor operator**
   Mainly axial vector
   $$T(J=i+) = \tau\sigma + \delta\tau[\sigma x Y_2]_1$$

No vector NMEs



The Nucleon-Nucleon Interaction and Nucleon-Nucleus Scattering
WG Love, MA Franey, F Petrovich - Spin Excitations in Nuclei, 1984 - Springer

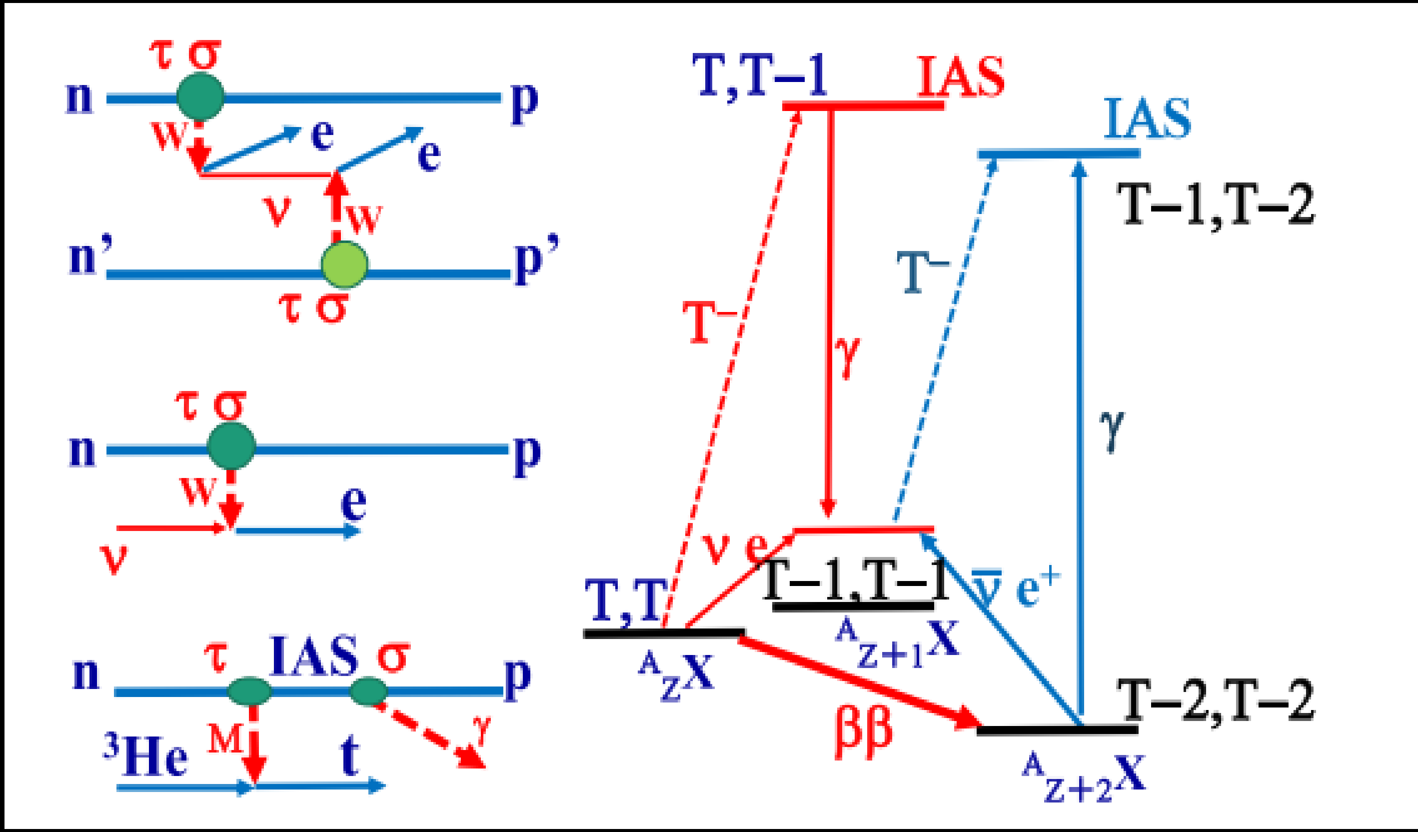
EM-IAS transition schemes and DBD

Axial-vector NMEs

DBD

Astro- ν

IAS γ



IAS-γ H. Ejiri, Phys. Rev. C. Lett, 108 L011302 (2023).

γ-IAS H. Ejiri, A. Titov, Phys. Rev. C 88 054010 (2013.)

EM-IAS studies : 4 merits

1. EM couplings of e and μ and the interaction operators are well defined compared with nuclear ones in nuclear CERs.
   No distortion effect. No tensor interaction. No multipole mixing.

2. IAS is a sharp strong τ-GR with small non-resonant effects.
   Very small (30 keV) width due to isospin-forbidden n decays.
   Then γ-branch versus n-decay gets as large as 10^{-4} or so.

3. BG free exp. is possible by γ-detection in coincidence with CER to IAS.

4. Experiments are feasible by using a γ-detector array and a high energy-resolution spectrometer,

DIAS γ Romeo, Menendez Pena PL B 827 136968 2022.

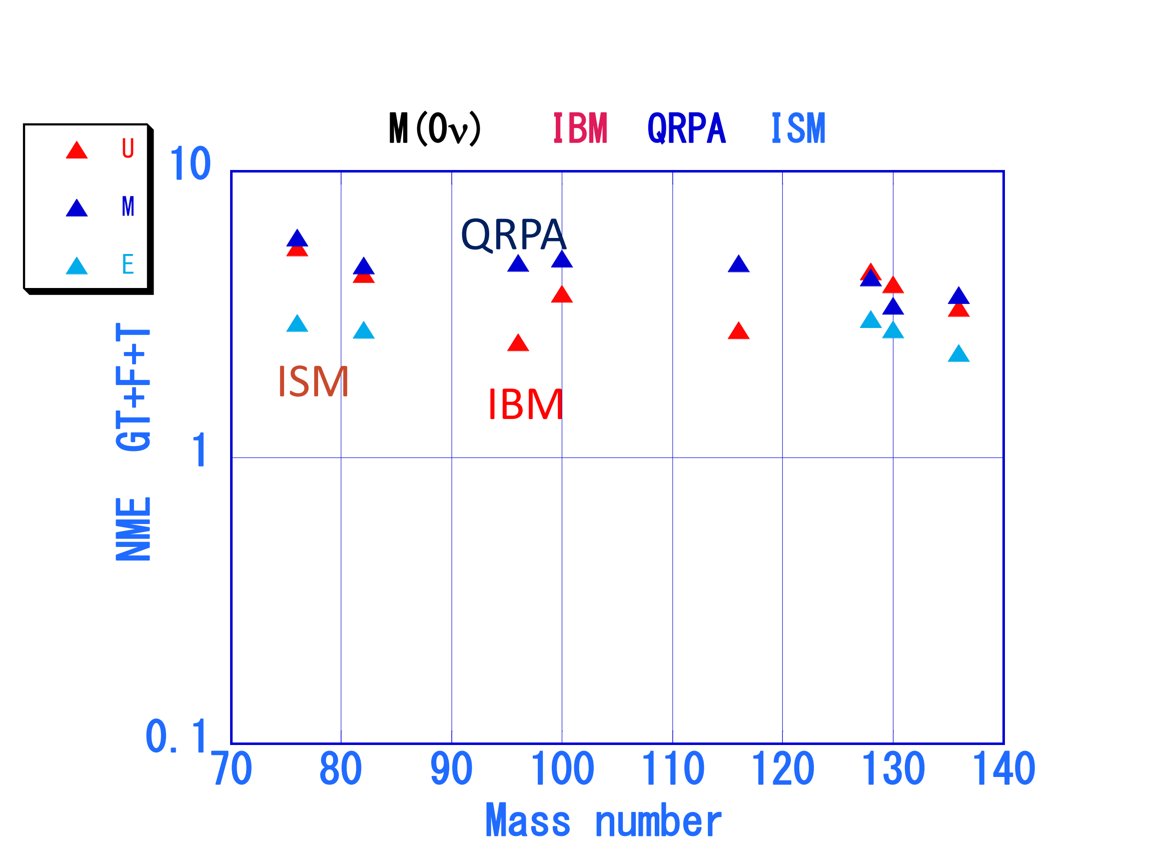
Comparison of NMEs pnQRPA, ISM, IBM2

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

QRPA P.R. C98 024608 2018 Jokiniemi, Ejiri Suhonen

ISM M. Horoi S. Stoica PR C 81 024302 2010 .

IBM J. Barea, . Kotila F. Iachello PR C 87 014315 2013



Axial-vector & vector NMEs depend much on the models used.

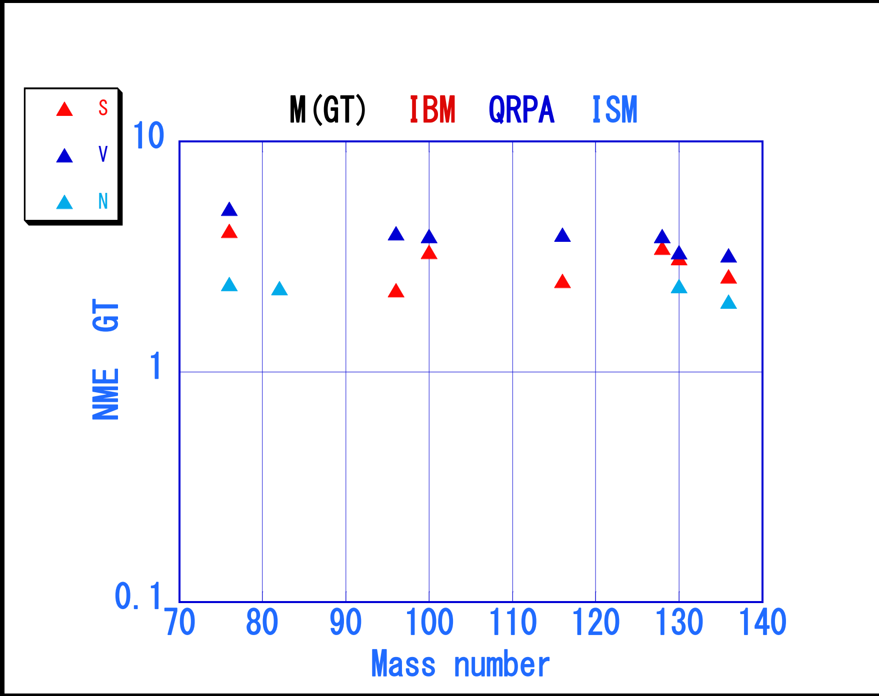
QRPA Large and smooth as A

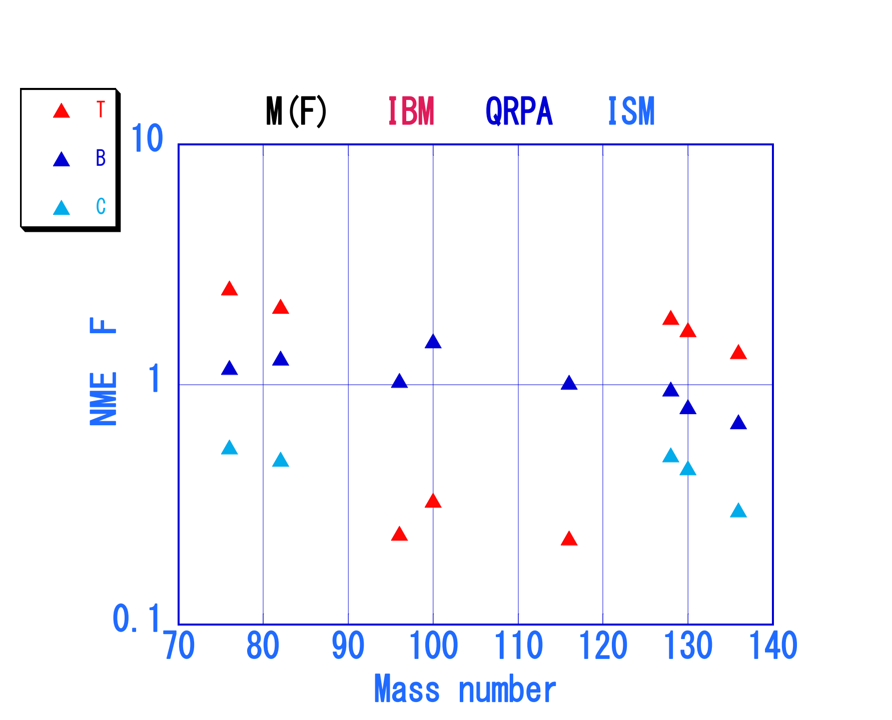
ISM Small and smooth as A.

IBM Fluctuate much as A

Axial vector NMEs depend on models.

Thus require model-dependent g_A^{eff} to incorporate the effects beyond models.





QRPA Large and smooth as A

ISM Small and smooth as A.

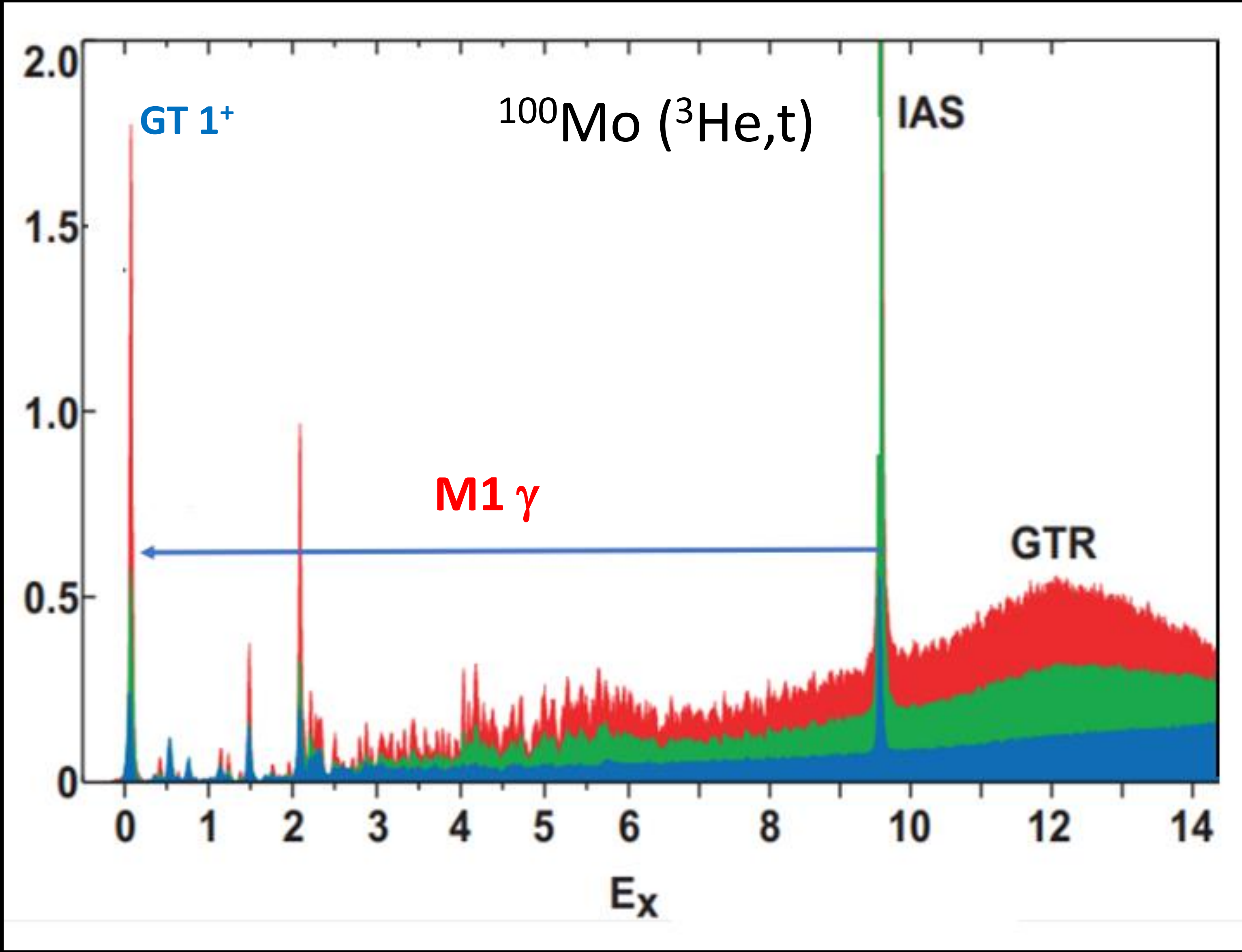
IBM Fluctuate very much as A

Vector NMEs do depend on models.

Thus require model-dependent g_V^{eff} to incorporate the effects beyond models.

CVC 0^+-0^+ IAS : constant, but not for non-IAS states.

In case of M1 γ from IAS of ^{100}Mo.



β NMEs with α=GT, V1 are given by γ NMEs with α'=M1,E1 γ from IAS (Ejiri et al, PRL 1968) as

$$M^{-}(\alpha) \approx \sqrt{2T}M^{\mathrm{IA}}(\alpha'),$$

IAS-γ cross section (1000-100 nb) is given by product of IAS cross section (10 mb) and γ branching ratio ($10^{-(4-5)}$) as

$$\frac{d\sigma^{\mathrm{IA}}(\alpha')}{d\Omega} = \frac{d\sigma^{\mathrm{IA}}}{d\Omega}\frac{\Gamma^{\mathrm{IA}}(\alpha')}{\Gamma(T)},$$

γ–width (1-0.1 eV) is given by product of $(E_\gamma)^3$= (10 MeV)^3 ~ 1000 and the reduced width B^{IA}

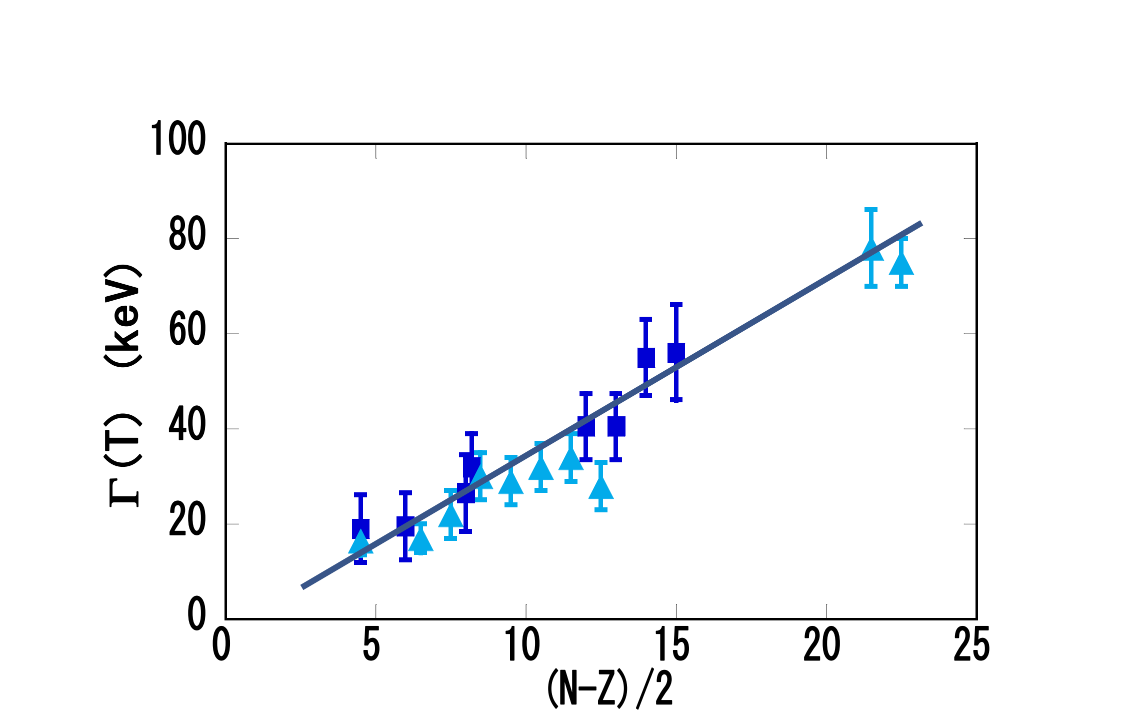
$$\Gamma^{\mathrm{IA}}(\alpha') = K_{\alpha'}E^3_{\alpha'}B^{\mathrm{IA}}(\alpha'),$$

The reduced width is given by the square of the IAS γ NME

$$B^{\mathrm{IA}}(\alpha') = g^2_{\alpha'}|M^{\mathrm{IA}}(\alpha')|^2 S^{-1},$$

g_e^{eff} derived from Exp M (E1) /QRPA M (E1) is used to get g_V^{eff}
g_m^{eff} derived from Exp M(M1) /QRPA M(M1) is used to get g_A^{eff}

IAS total widths are known experimentally as given below.



Dark blue ; CER Exp. Present work

Light blue H.L.Harney et al, RMP 58 607 1986

It is given as a function of the isospin z component as

$$\Gamma(T) \approx 3.5 T_z \,\mathrm{keV}, \quad T_z = (N-Z)/2.$$

It is a factor 30 smaller than a typical n-decay width because of the isospin forbidden for n decay.

Evaluated IAS γ widths and the cross-sections

TABLE I. M1γ widths and the IAS γ cross sections for DBD nuclei and ^{71}Ga for the solar νs. Shown are E(IA) in units of MeV, E(GT) in units of MeV, B(GT), B^{IA}(M1) in units of 10^{-2}, Γ^{IA}(M1) in units of 10^{-2} eV, and $\sigma^{IA}(M1)=d\sigma^{IA}(M1)/d\Omega$ in units of nb (10^{-9}b)/str.

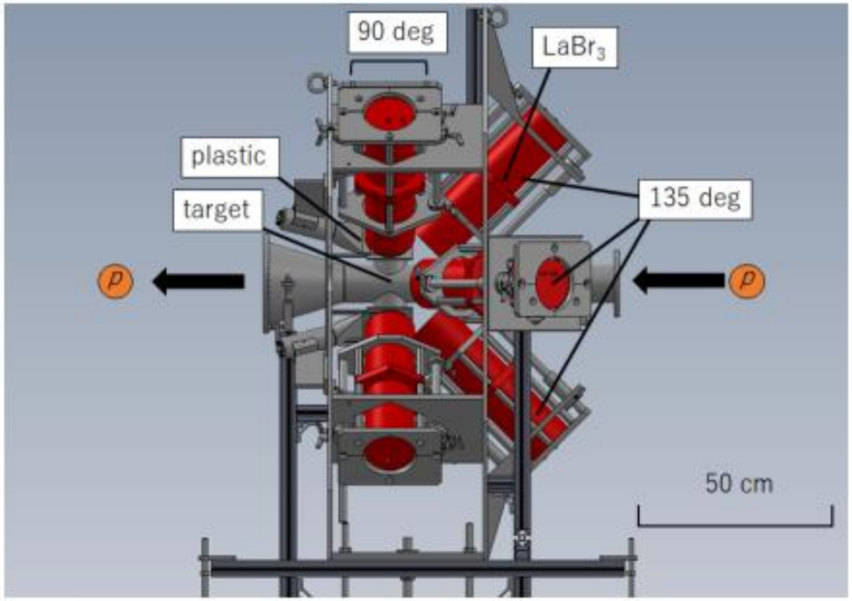
A	E(IA)	E(GT)	B(GT)	B^{IA}(M1)	Γ^{IA}(M1)	σ^{IA}(M1)
^{76}Ge	8.31	1.07	0.14	1.45	6.4	41
^{82}Se	9.58	0.075	0.34	3.0	30.0	150
^{96}Zr	10.9	0.69	0.16	1.25	15.3	76
^{100}Mo	11.1	0	0.35	2.7	43.4	170
^{116}Cd	12.1	0	0.14	0.88	18.0	51
^{128}Te	12.0	0	0.079	0.41	8.2	17
^{130}Te	12.7	0	0.072	0.35	8.2	17
^{136}Xe	13.4	0.59	0.23	1.03	25	45
^{150}Nd	14.4	0.11	0.13	0.54	18.0	35
^{71}Ga	8.91	0	0.085	1.2	9.8	51

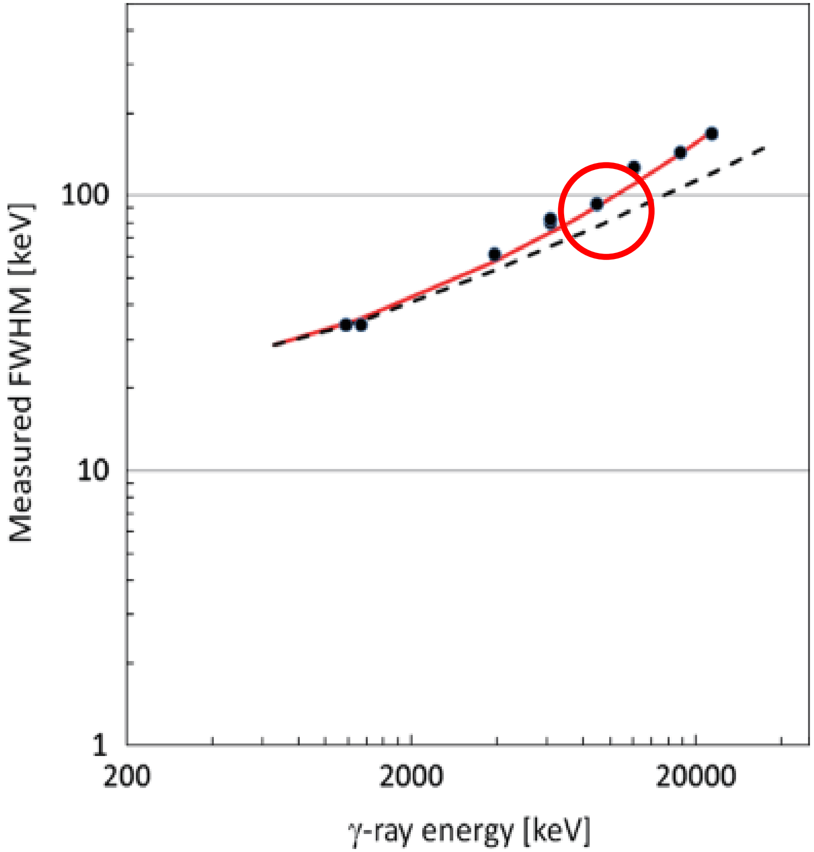
A	E(IAS)	E(V1)	B(V1)	B^{IA}(E1)	Γ(E1)	σ^{IA}(E1)
^{96}Zr	10.9	3	6.8	43	220	1080
^{100}Mo	11.1	3	7.5	47	260	1020
^{130}Te	12.7	3	1.0	3.8	36	75

The M1 and E1 widths are 10-50 10^{-2} eV and 30-300 10^{-2} eV
The M1 and E1 cross sections are 50-200 nb and 100-1000 nb.

Technical Information on the Scintillation Gamma-Ray Detector Array Coupled with the Grand Raiden Spectrometer

A. Tamii[a], N. Kobayashi[a]





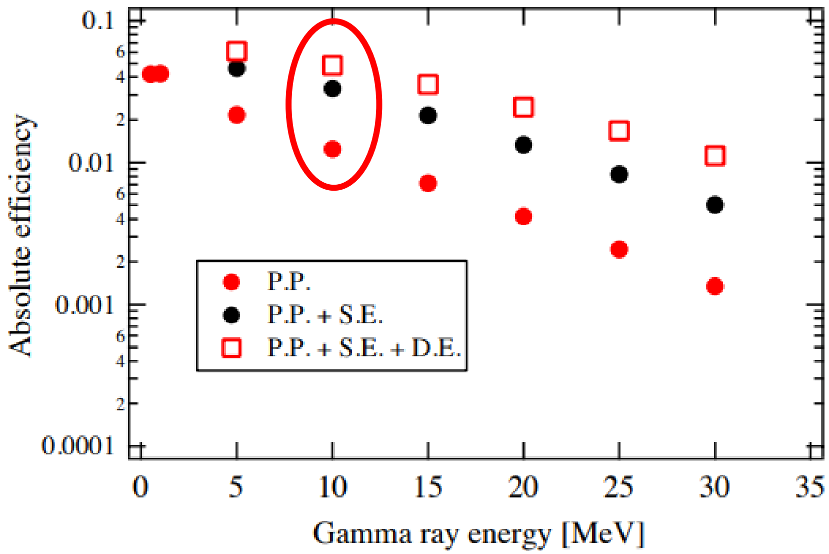
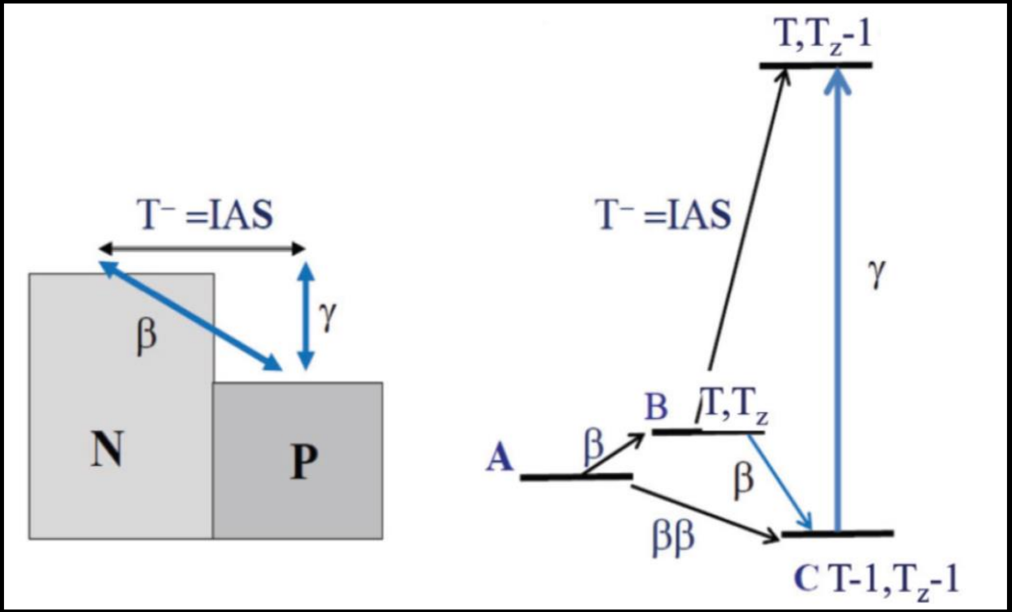
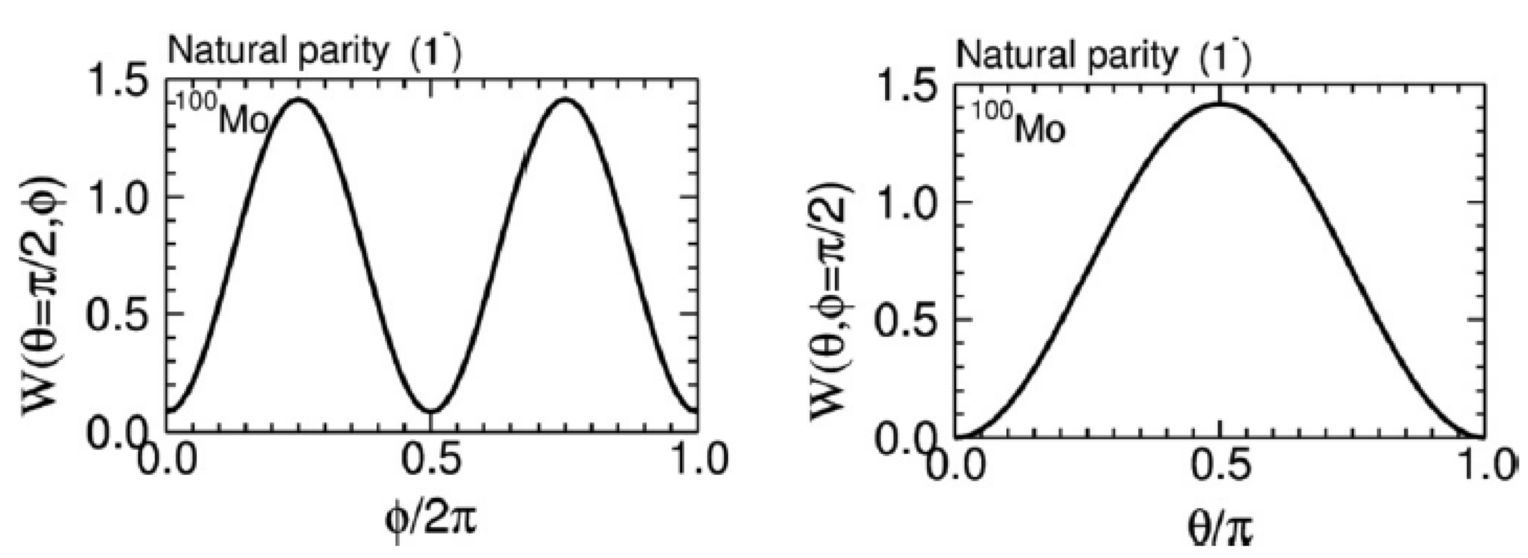


Photo nuclear reaction

Isovector component by IAS isospin T from Ground state with T-1





Ejiri H, et al. Phys. Rev. Lett. 2119 1968 373
Ejiri H, Titov. A, et al., Phys. Rev, C 88 2013 054610

$$\sigma(\gamma, n) = \frac{S(2J+1)\pi}{k_\gamma^2} \frac{\Gamma_\gamma \Gamma_n}{(E - E_R)^2 + \Gamma_t^2/4}, \qquad (10)$$

where Γ_γ, Γ_t, and Γ_n are the γ capture width, the total width, and the neutron decay width, S is the spin factor, and k_γ is the incident photon momentum.

The integrated photonuclear cross section is given by

$$\int \sigma(\gamma, n) dE = \frac{S(2J+1)2\pi^2}{k_\gamma^2} \frac{\Gamma_\gamma \Gamma_n}{\Gamma_t}. \qquad (11)$$

$\Gamma_t \approx \Gamma_n$, where Γ_n is the sum of the neutron decay widths

$$\int \sigma(\gamma, n) dE = \pi^2 k_\gamma^{-2} \Gamma_\gamma,$$

$$\int \sigma(\gamma, n) dE = 2.9 \times 10^{-3} \text{ MeV fm}^2 \quad (E1), \qquad (14)$$

$$\int \sigma(\gamma, n) dE = 2.7 \times 10^{-3} \text{ MeV fm}^2 \quad (M1). \qquad (15)$$

Then the counting rates with a typical target of 10 g/cm^2 are $Y(E1) = 1.7 \times 10^{-6} \epsilon N_\gamma/\text{s}$ and $Y(M1) = 1.6 \times 10^{-6} \epsilon N_\gamma/\text{s}$,

$N_\gamma \approx 10^{8\text{–}9}/(\text{MeV s})$.

4. Concluding remarks

1. DBD experiments give $1/(t_{1/2}G^{0\nu}) = B(NP)$, $B(NP)=|M^{0\nu} K_{\nu R}|^2$ with $K_{\nu R}$ = ν-mass, λ η in LR model. NMEs are crucial for them.

2. CE (^{3}He,t) and DCE (^{11}B,^{11}Li) reactions with E/A~0.1 GeV give axial-vector GT-SD. Cross section ratios to the IAS and DIAS are used. The tensor term interfere with the central ones.

3. E1 /M1 γ NMEs for IAS and photo-nuclear excitations of IAS provide absolute GT / V1 β NMEs since the EM couplings and transition operators are well known.

4. Small γ width of eV –sub-eV is overcome by using sharp IAS with small width around 30 keV to get some 10^{-4} γ branch.

5. Measurements of γ rays in coincidence with CER to IAS makes BG-free measurement. The event rates are around 50 per day, showing that the experiments are quite feasible .

Thank you for your attention

PHYSICAL REVIEW C **108**, L011302 (2023)

Letter

Electromagnetic transitions from isobaric analog states to study nuclear matrix elements for neutrinoless $\beta\beta$ decays and astro-neutrino inverse β decays

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(Received 26 February 2023; revised 7 April 2023; accepted 22 June 2023; published 10 July 2023)

Experimental studies of nuclear matrix elements (NMEs) for neutrinoless double-β decays (DBDs) and astro-neutrino (ν) inverse β decays (IBDs) are crucial for ν studies beyond the standard model and the astro-ν studies since accurate theoretical calculations of the NMEs are hard due to the high sensitivity of the NMEs to the nuclear models and the nuclear parameters used for the models. Some of the important NMEs of electromagnetic transition operators associated with DBD and IBD, including the effective weak couplings, are found to be experimentally obtained by measuring the corresponding electromagnetic gamma (EM:γ) transitions from the isobaric analog states (IASs) of the DBD and IBD nuclei. Then the experimental NMEs and the couplings are used for evaluating the DBD and IBD NMEs and for checking the model calculations. The EM-NMEs, the cross sections, and the event rates for the IAS-γ transitions are estimated for DBD and IBD nuclei to show the feasibility of the experiments.

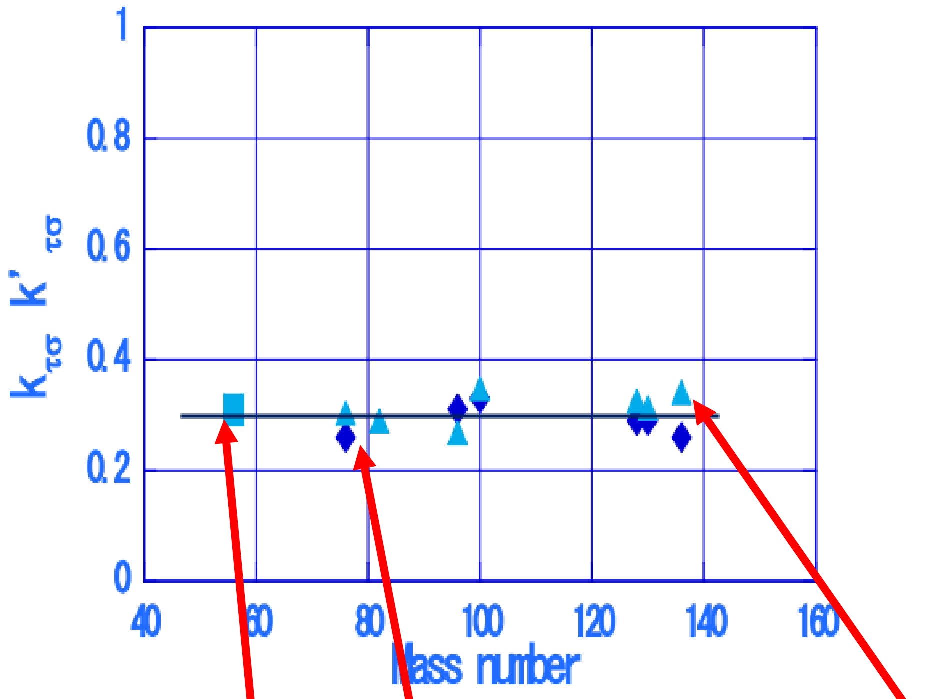


Figure 3. Reduction coefficients for axial-vector NMEs. Light blue triangles: $k_{\tau\sigma}$(SD,QP) for the QP SD states by SCERs on DBD nuclei. Blue diamonds: $k'_{\tau\sigma}$(SD,L) for low-ling SD states by SCERs on DBD nuclei. Light blue square: $(k_{\tau\sigma}(\text{GTSD,QP}))^{1/2}$ for the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

RCNP Ring cyclotron provided ^{11}B with E/A=0.08 GeV.

Grand RAIDEN high resolution spectrometer for ^{11}Li momentum analysis, and identification by TOF and energy loss.

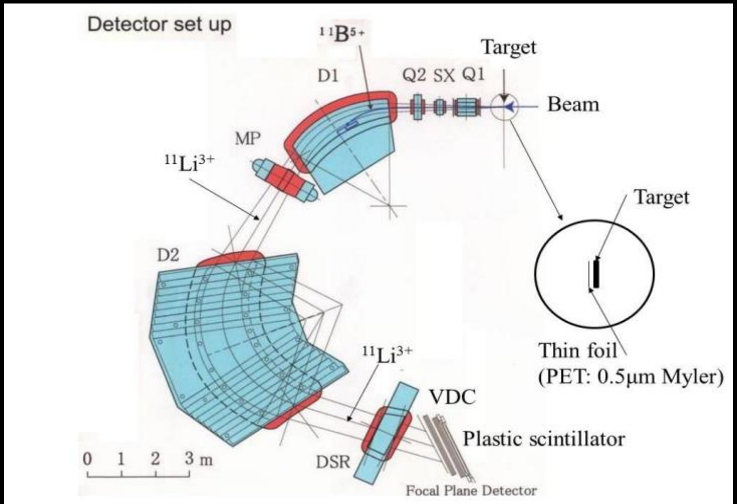


Figure 1. The Grand Raiden spectrometer. Q1, Q2: quadrupole D1: DSR: for DCER(^{11}B,^{11}Li)

$^{13}C(^{11}B,^{11}Li)^{13}O$ ground state is well identified.

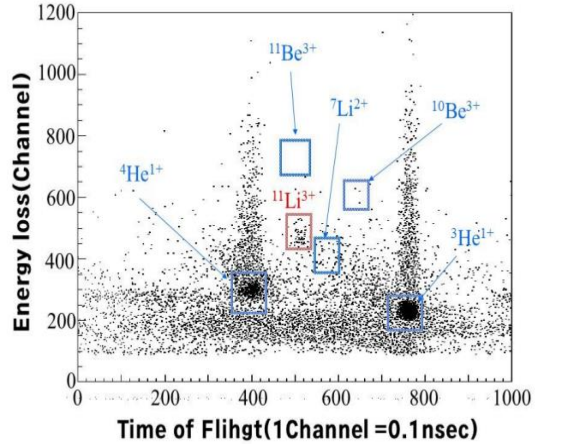
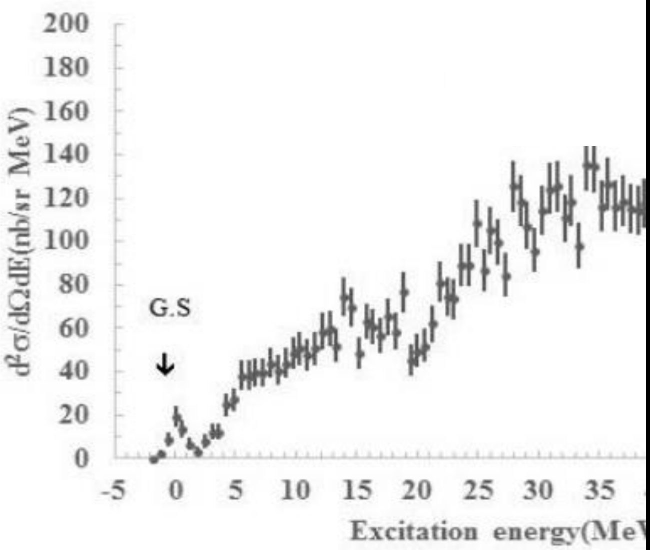


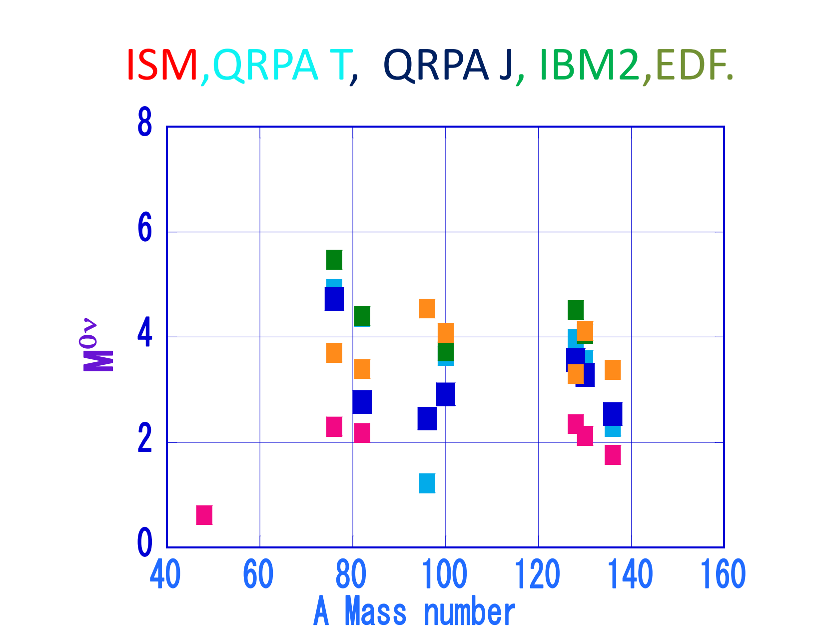
Figure 2. Particle identification of the scattered ^{11}Li particle by using TOF and the energy loss at plastic scintillator (thickness:3mm). The start signal of the TOF is RF signal from the Ring cyclotron.



Experimental inputs on DBD NMES to help Theories

1. They depend on the models the parameters (weak couplings etc) , H_{ij}, etc.
2. The region of NMEs do not mean the possible region of the NMEs
3. Adjusted g_A, g_{pp} etc for $2\nu\beta\beta$ do not guarantee the right 0ν NMEs.
4. Shell model interactions are not adjusted to fit to β–γ NMEs. ^{71}Ga,^{69}Ga,

   M(SM)/M(EXP)=g_A= 0.75 for 3/2-1/2, 6.1 for 3/2-5/2 .
5. $M^{0\nu}$, M(GT), M(F) in pnQRPA depends 30% on SP levels and g_A parameters. for given 2nbb NME (Ejiri Jokiniemi, Suhonen PR C Lett. 2023



ROPP 2014 Vergados Ejiri Simkovic Menendetz, Suhonen, and many

g^{eff} from $2\nu\beta\beta$

M(EXP)/M(Model)

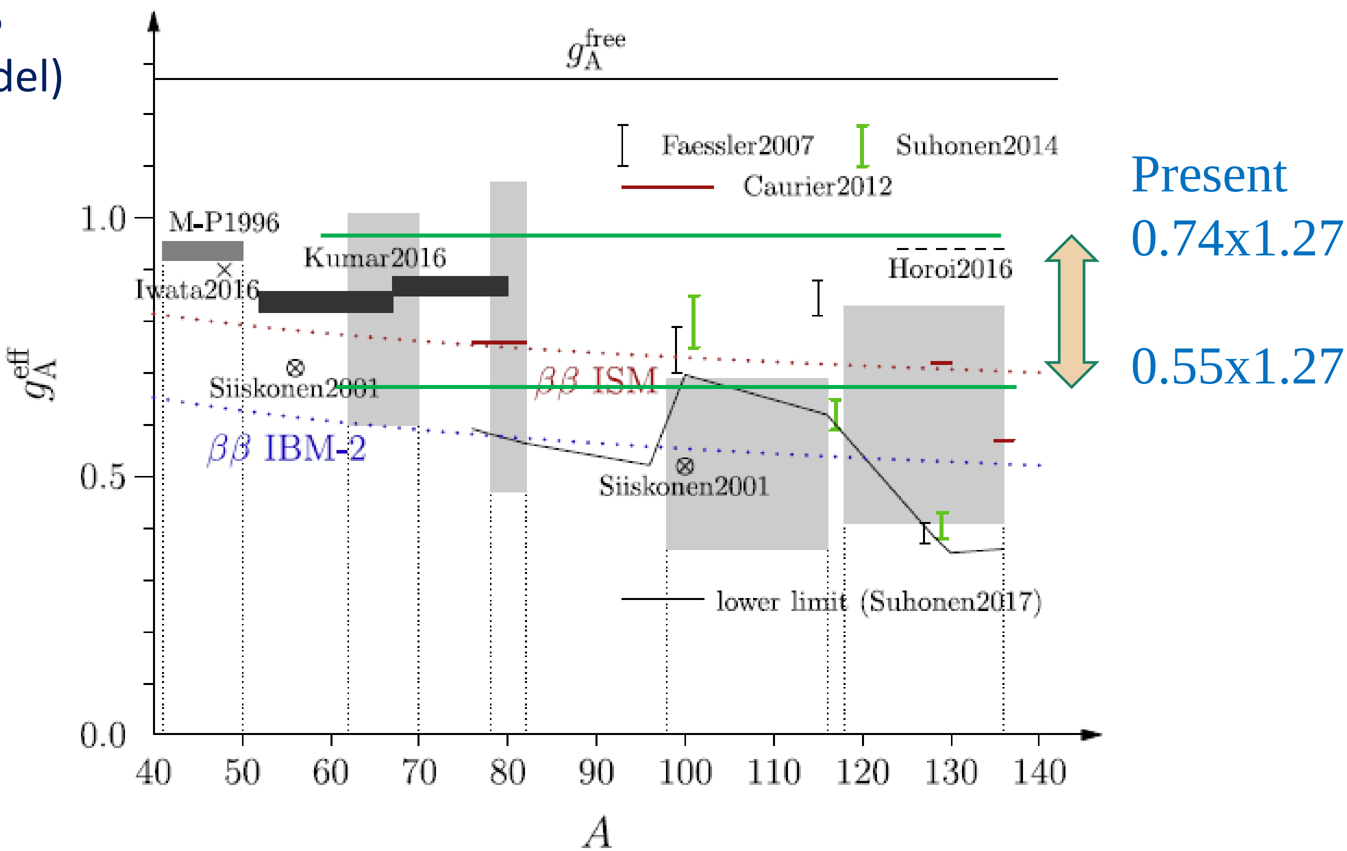


Fig. 29. Effective values of g_A in different theoretical β and $2\nu\beta\beta$ analyses for the nuclear mass range $A = 41 - 136$. The quoted references are *Suhonen2017* [216], *Caurier2012* [233], *Faessler2007* [242], *Suhonen2014* [243] and *Horoi2016* [235]. These studies are contrasted with the 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

Schematic diagrams of SCER, DCER, and DBD

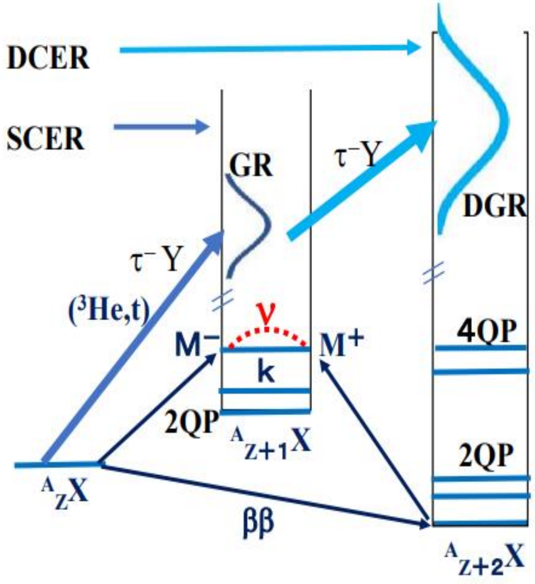


Figure 1. Schematic diagram for the $0\nu\beta\beta$ DBD transition of ${}^A_Z X \to {}^A_{Z+2}X$ with a neutrino exchange. SCER: ${}^A_Z X \to {}^A_{Z+1}X$. DCER: ${}^A_Z X \to {}^A_{Z+2}X$.. QP: Quasi particle-hole state. GR: Giant resonance. DGR: Double giant resonance. M^- (M^+): τ^- (τ^+) single-β response associate with DBD.

Axial-vector τσ NMEs for low-lying (Q) states are reduced by nucleonic and non-nucleonic τσ correlations, some of them are in model, others are incorporated by axial-vector coupling, (g_A^{eff}/g_A)

Double τσ τσ NMEs for low-lying (Q) states are doubly reduced by nucleonic and non-nucleonic τσ τσ correlations, some of them are in model, others are incorporated by axial-vector coupling, $(g_A^{eff}/g_A)^2$