# Experimental studies of neutrino nuclear responses for double beta decays

**Hiro Ejiri**
**RCNP Osaka**

**2015.12, Catania**

**Thank the organizers for the invitation.**

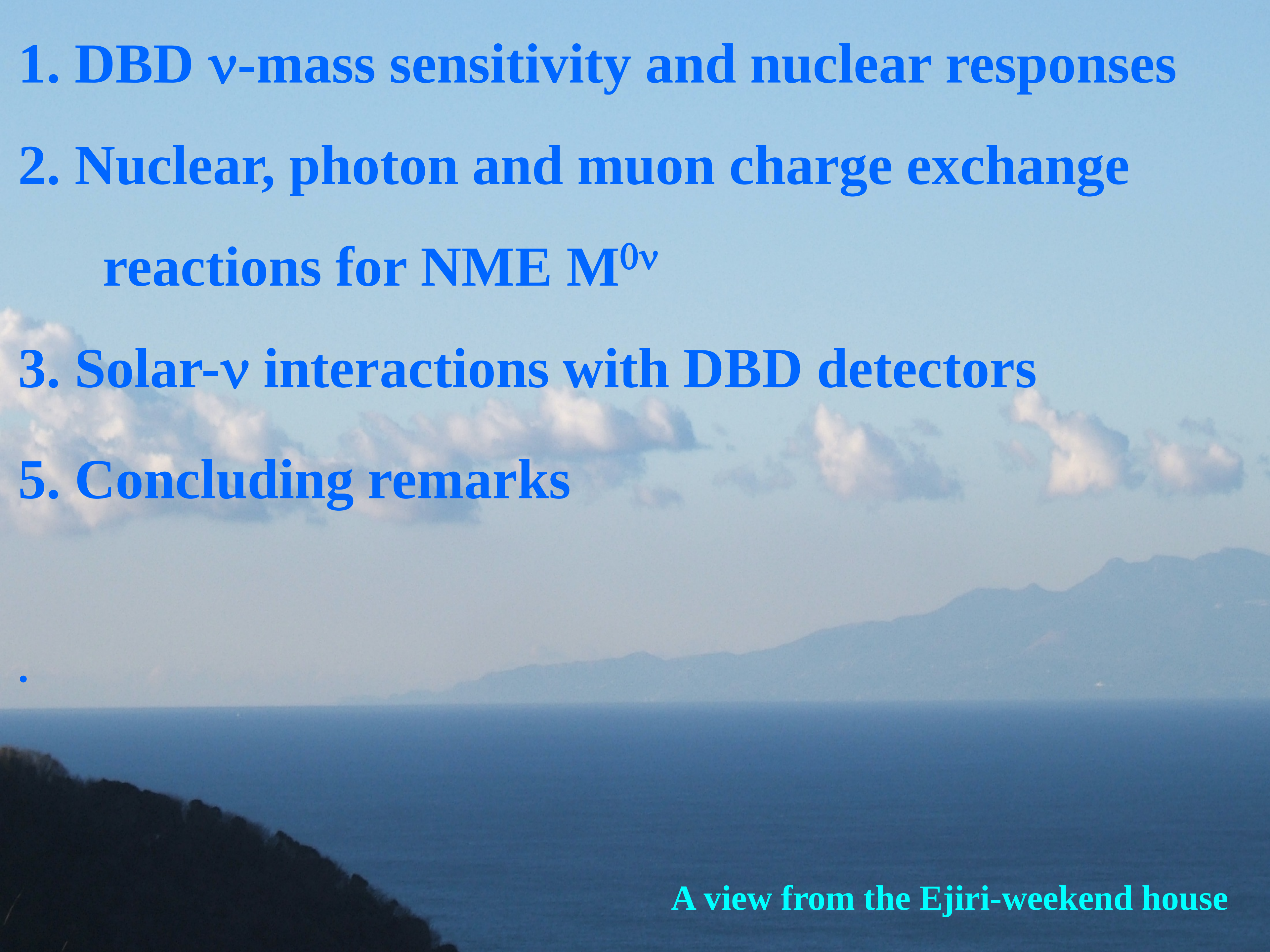
1. DBD ν-mass sensitivity and nuclear responses

2. Nuclear, photon and muon charge exchange reactions for NME $M^{0\nu}$

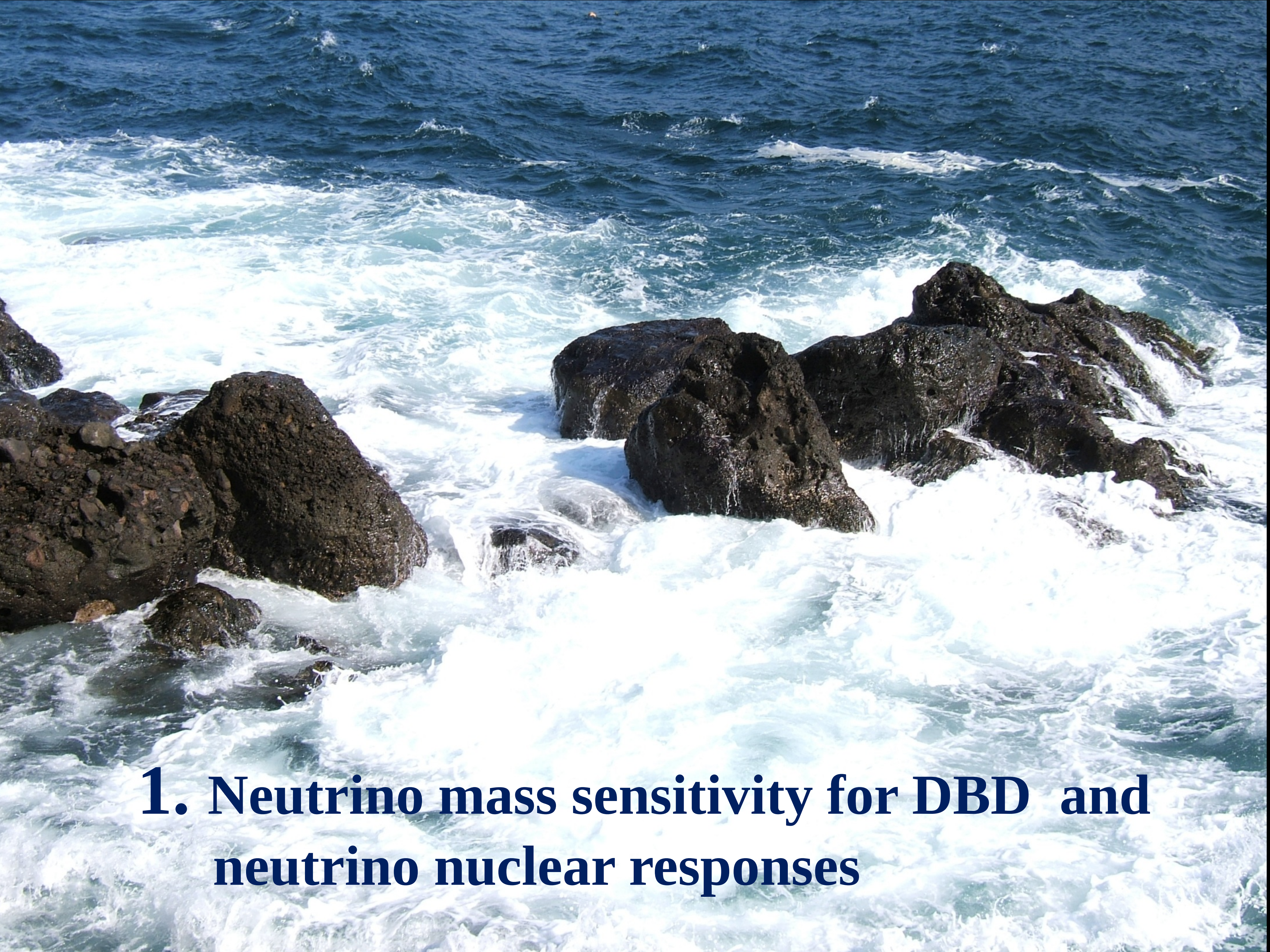
3. Solar-ν interactions with DBD detectors

5. Concluding remarks

.

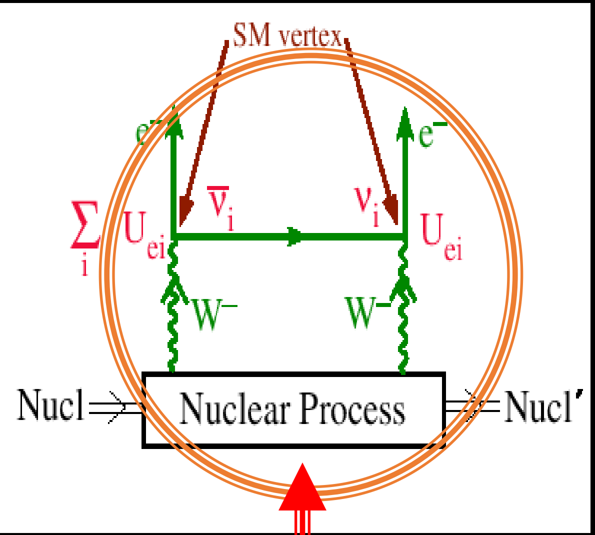


A view from the Ejiri-weekend house



# 1. Neutrino mass sensitivity for DBD and neutrino nuclear responses

# Majorana neutrinos and $0\nu\beta\beta$ decays




$0\nu\beta\beta$ $A = B + \beta + \beta$

Lepton number $\Delta L=2$ beyond SM.

•

Particle astro physics

Majorana $\nu$, $m_\nu$ CP

$$T^{0\nu} = G^{0\nu} [M^{0\nu} \; m_\nu]^2$$

EXP

NNR Nucl. phys.

$g_A$ nuclear medium

$\tau$ $\sigma$ correlation

FEMTO(fm)-HC.

to enhance $\nu$-exchange

Large luminosity

$10^{83}cm^{-2}$ /y ton of $\beta\beta$ nuclei

$\sigma\sim10^{-83}cm^2$ IH

J. Vergados, H. Ejiri, F. Simkovic ROPP 75 106301 2012.

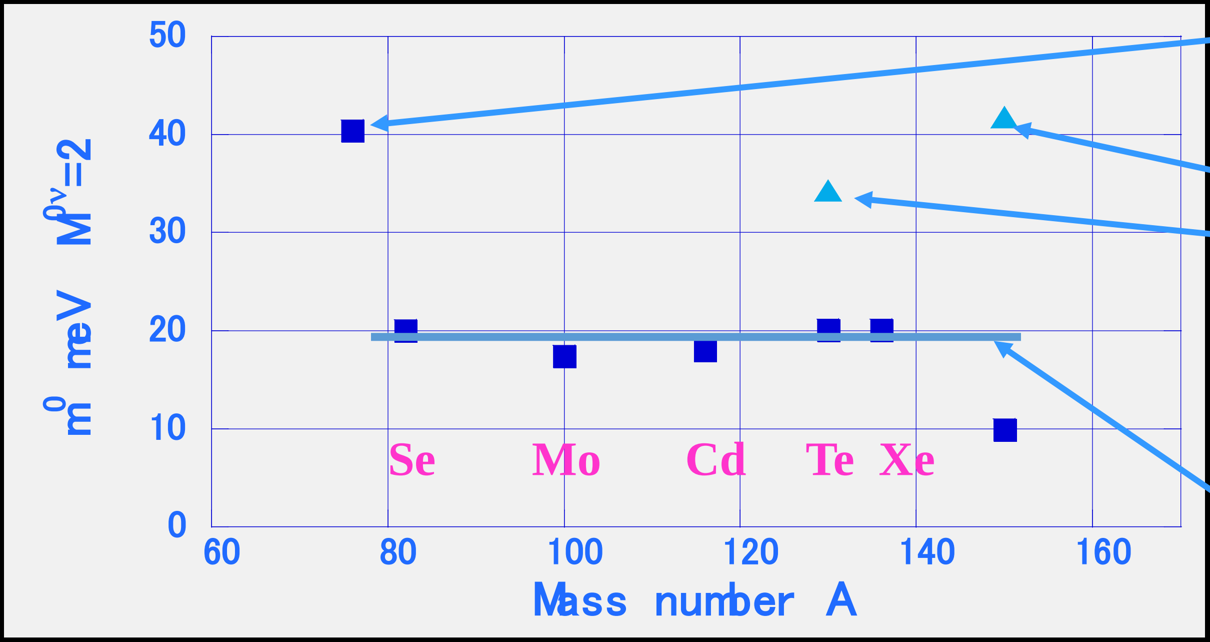
# 0νββ mass sensitivity and NME

$T = G\,[m_\nu M^{0\nu}]^2$  $S = T(NT) > (BG)^{1/2}$  $BG = B\,NT$

Mass sensitivity= ν-mass to be detected with 90% CL

$m_\nu = m^0\ 1.3\ \varepsilon^{-1/2}\,[B/(NT)]^{1/4} \sim 2\ m_0$  if B=1/t y  NT=1 t y

$m^0 = 39\ \text{meV}\ [2/M^{0\nu}]^{1} / G^{-1/2}$  $G = G/0.01A$




$^{76}$Ge :Small $G^{0\nu}$

$^{n}$Te $^{n}$Xe : $R^{-1/2}$

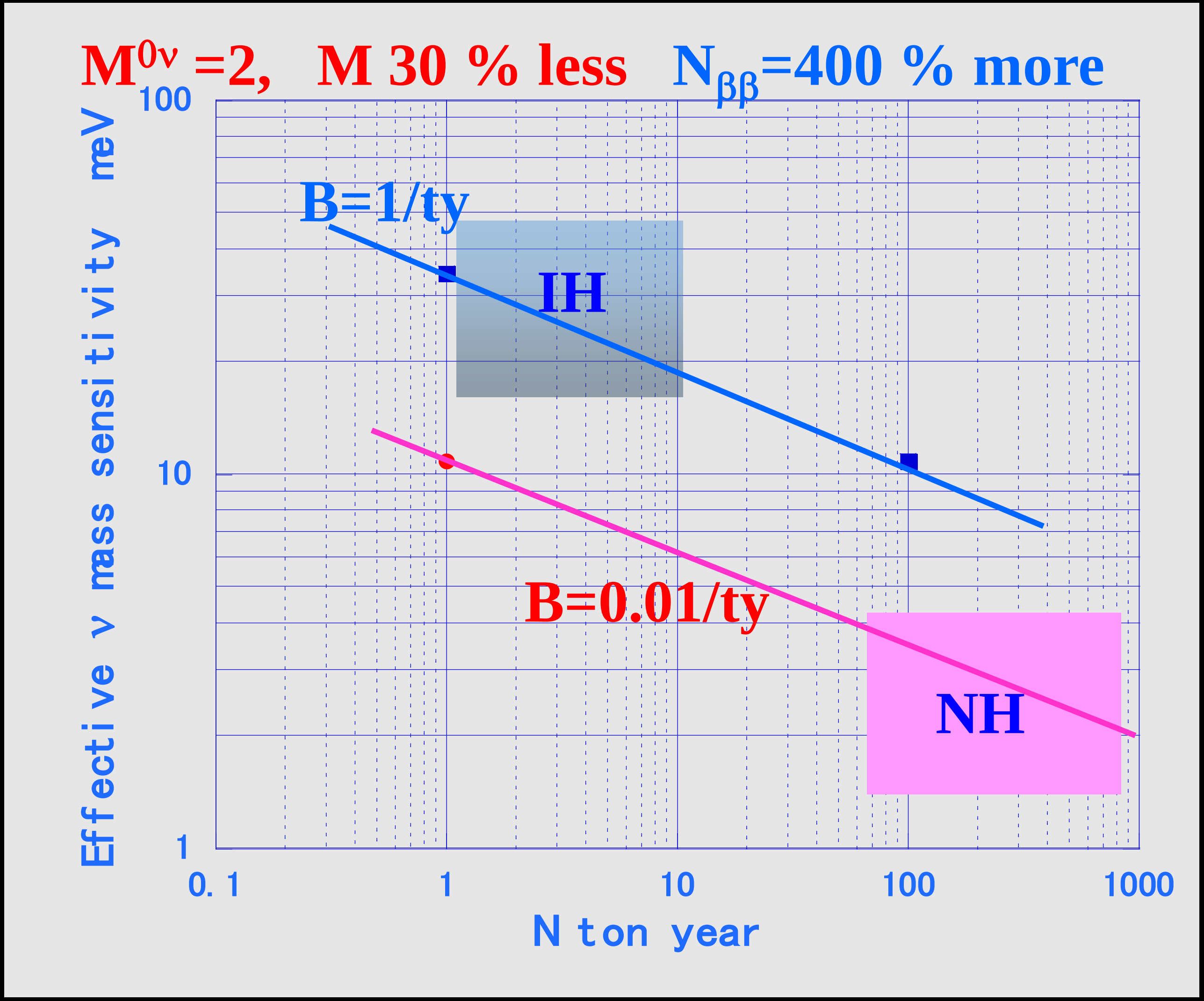
N ton of $^{n}$Te

B/ton of $^{n}$Te

$m^0$~20 meV IH

# Mass sensitivities $<m_\nu> = k\,[M^{0\nu}]^{-1}\,G^{-1/2}\,(NT)^{-1/4}\,(BG)^{1/4}$

## Keys: $M^{0\nu}\sim 2$, $G \sim 4$, $NT \sim 10$ ty, $BG \sim 1$/ty for IH



# Nuclear matrix element for 0νββ

**Momentum transfer 0νββ**

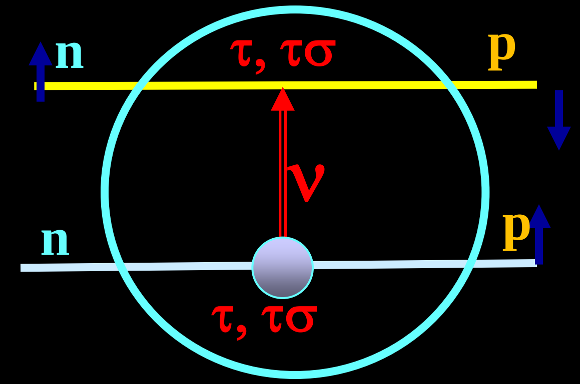
**ν exchange**

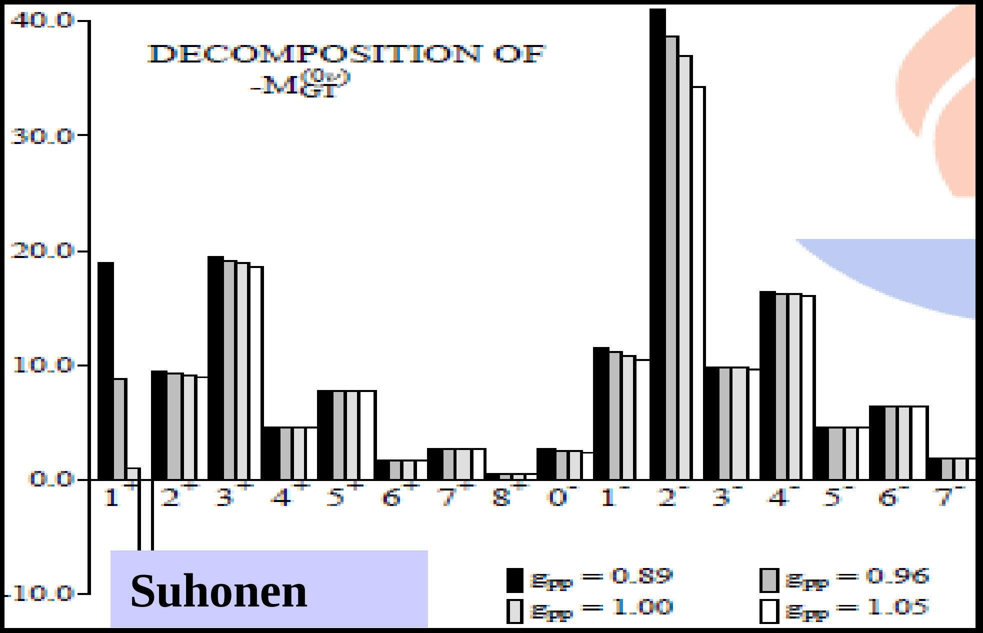
**$q \sim 1/\Delta r = 1\text{-}0.3\ \mathrm{fm}^{-1}$**

**$\Delta l = qR = 1\text{-}2$**

**$J^{\pi} = 2-, 2+, 3+$**

**$T(2^{-}) = g_A\, \tau\, [\sigma \times f(r)\, Y_1]_2$**



# Nuclear matrix element for $0^+ \Rightarrow 0^+$

$M^{\beta} =\langle\tau\sigma^{s}\rangle$, $M^{2\nu}=\langle\tau\sigma^{s}\tau\sigma^{s}\rangle$, $M^{0\nu}=\langle\tau\tau\sigma^{s}\sigma^{s}h(r)\rangle$ s=0, 1

1. Sensitive to $\tau$ $\sigma$ correlation and nuclear medium effects,
   $T^{\beta\beta} = [M_{\beta\beta}]^2 \sim M_{\beta}{}^4$ Detector mass = $N_{\beta\beta} \sim M_{\beta}{}^8$
   $g_F=1$, $g_A= 1.26 \Rightarrow 0.9$ : $T^{\beta\beta} \Rightarrow$ 1/4, $N_{\beta\beta}$ 1 $\Rightarrow$ 16 tons

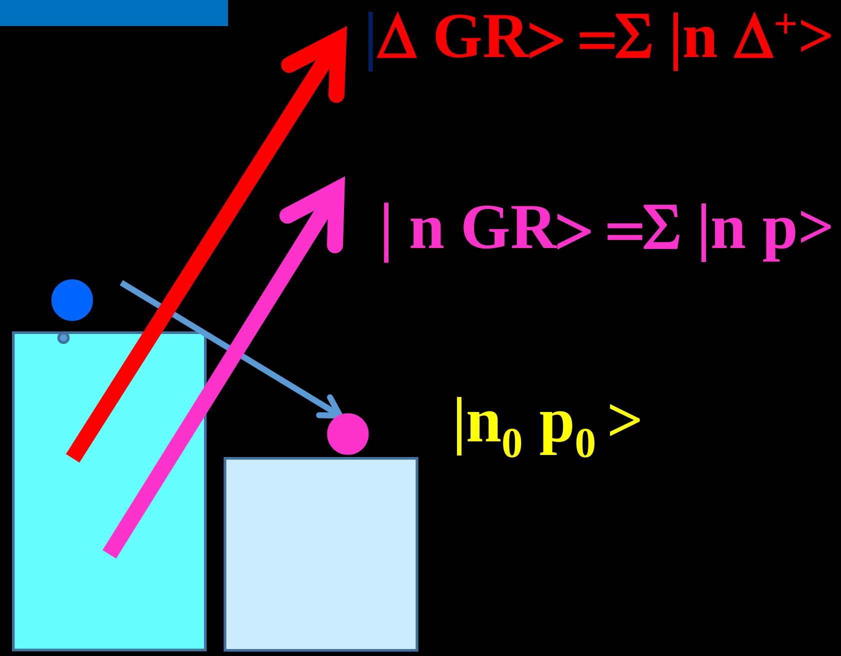
2. Extremely small,
   $M_{\beta}$ $10^{-1}$ $M_{\beta}$(SP) ~ 3 $10^{-2}M_{\beta}$(SUM)
   $M_{\beta}M_{\beta}$ $10^{-2}$ $M_{\beta\beta}$(SP) ~ 1 $10^{-3}M_{\beta\beta}$(SUM)

3. $M=k^{eff}$ M(SQP) $k^{eff} = k^{eff}(\tau\sigma)\, k^{eff}(\Delta)$
   $k^{eff}(\tau\sigma) \sim$ 0.4 from $\tau\sigma$ polarization
   $k^{eff}(\Delta) \sim$ 0.6 $g_A$ $\Delta$ $\tau\sigma$ polarization

CERs provide exp. data to help/confirm $M^{0\nu}$ evaluations

# Schematic view of ββ and GR

1. $n_0$ and $p_0$ are parts of
   the ground $0^+$ state
   on the Fermi surface




2. nτσGR : coherent sum of
   many (N~30) $\Sigma\ |n^{-1}p\rangle$

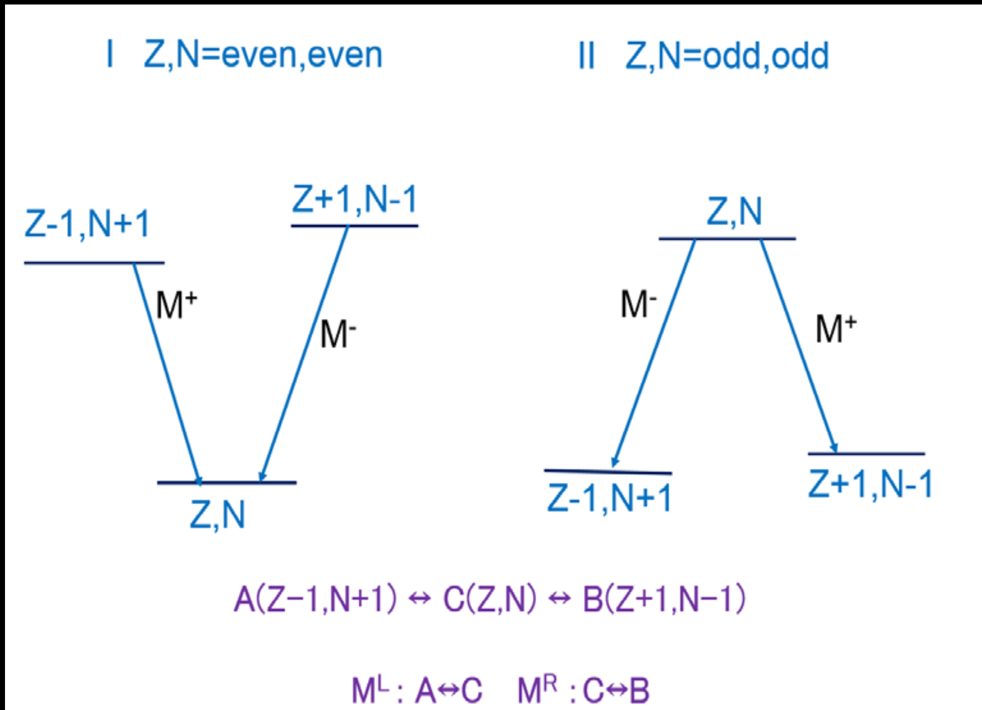
3. Δ GR: coherent sum of
   many (N=60) quark spin flip $\Sigma\ |n^{-1}\Delta^+\rangle$

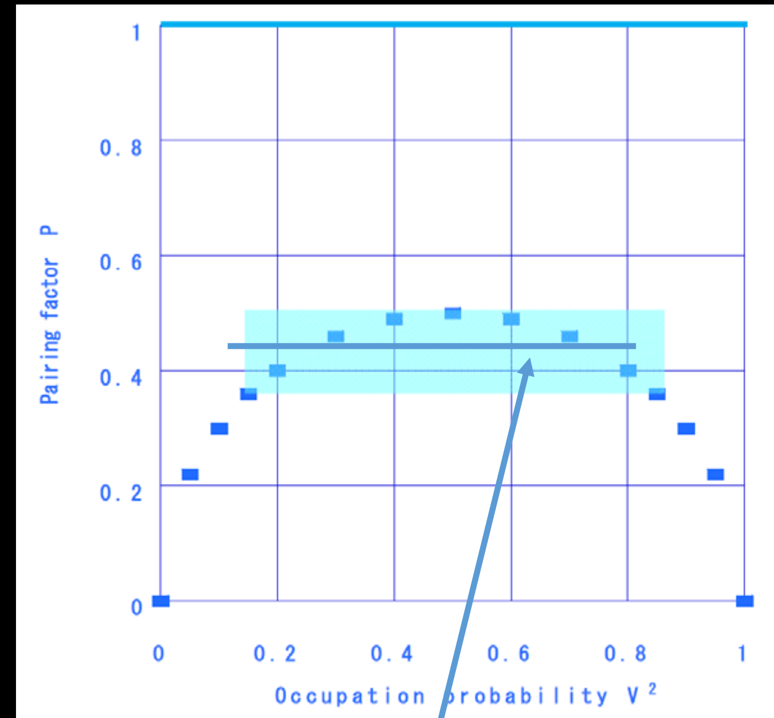
They mix destructively via repulsive interaction as

$$|np\rangle = |n_0\ p_0\rangle - \varepsilon\ |\ n\tau\sigma\ GR\rangle - \delta\ |\Delta\ GR\rangle$$

GR and other effects are uniform, and are given by
experimental renormalization of $k^{eff} = k^{eff}(\tau\sigma) \times k^{eff}(\Delta)$

# $M(GT) = \langle \tau^{\pm} (\sigma) \rangle$   $M(SD) = \langle \tau^{\pm} (\sigma Y_1) \rangle$   Ejiri Suhonen



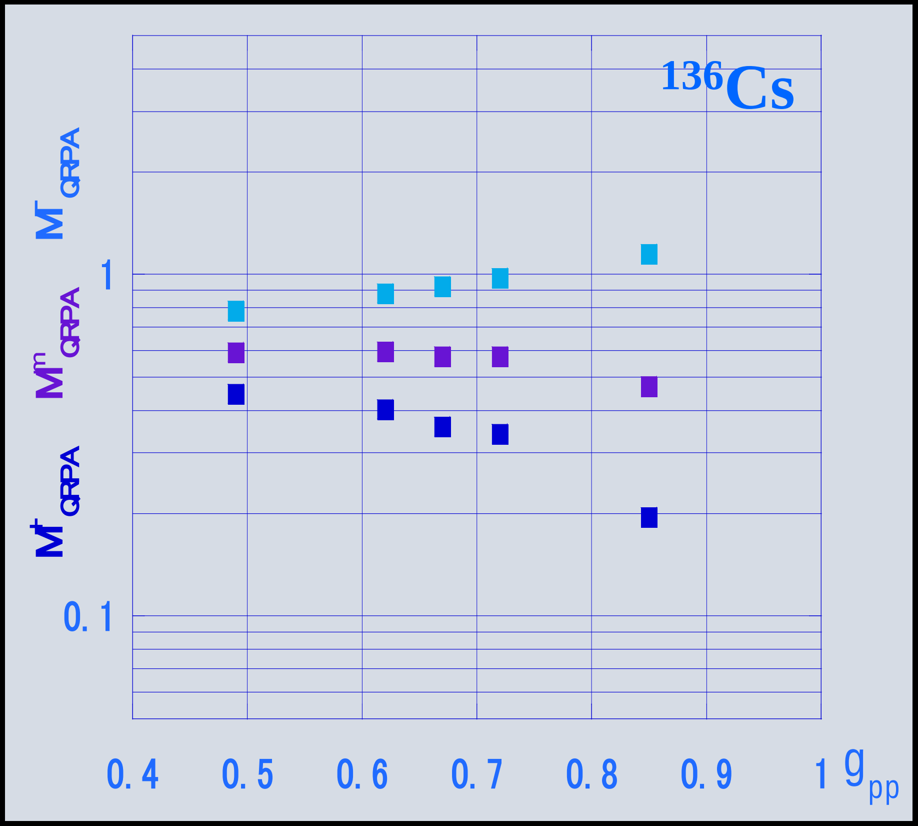



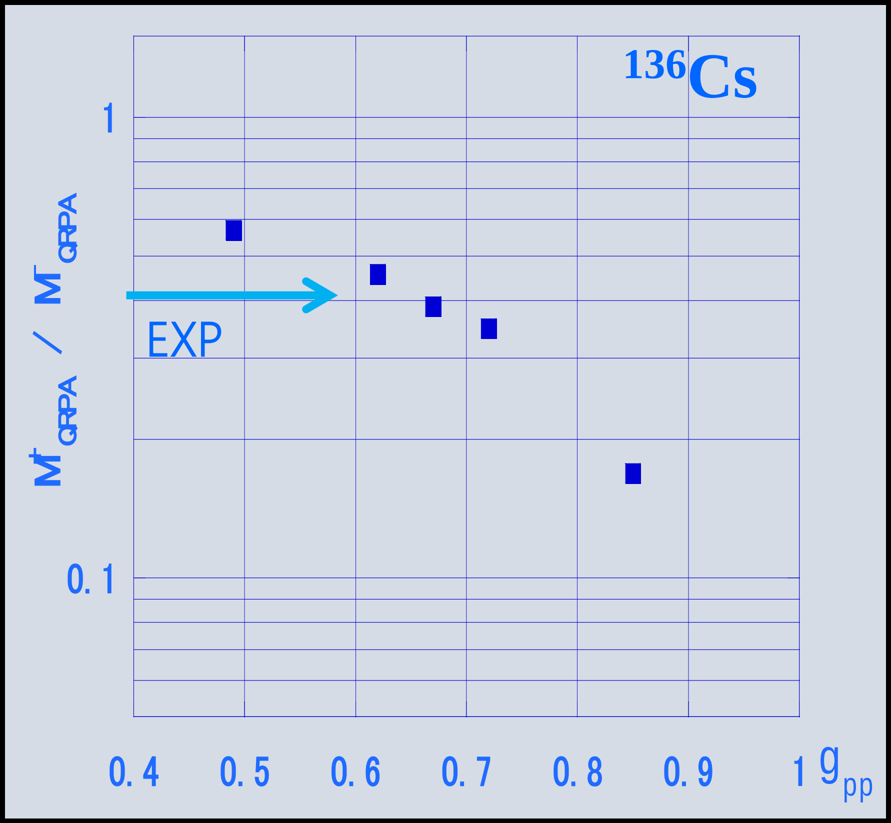

**Geometrical mean $M^m = (M^+ \times M^-)^{1/2}$**

**1. $M^m(QP) = M^m(SP)\,[U_p V_n\, U_n V_p]^{1/2} \sim 0.43\, M^m(SP)$**
**Insensitive to U &V nuclear surface effects and $g_{pp}$**

**2. NMEs in $\beta\beta$ are $(M^m)^2 = (M^+ \times M^-)$**

# QRPA M(GT) dependence on $g_{pp}$ p-p interaction




$M^m$ (violet) is independent of $g_{pp}$ since the effects on $M^+$ & $M^-$ cancel.

$M^+$ / $M^-$ is sensitive to $g_{pp}$. Exp. ratio gives $g_{pp}$ = 0.6-0.7

NMEs GT H. Ejiri J Suhonen J. Phys. G. 2015 42 055201

# GT $1^+$ τσ NN & nuclear medium $g_A$

$M^m_{exp}$ << $M^m_{QRPA}$ << $M_{qp}$

$M^m_{exp} = k\, M_{qp}$

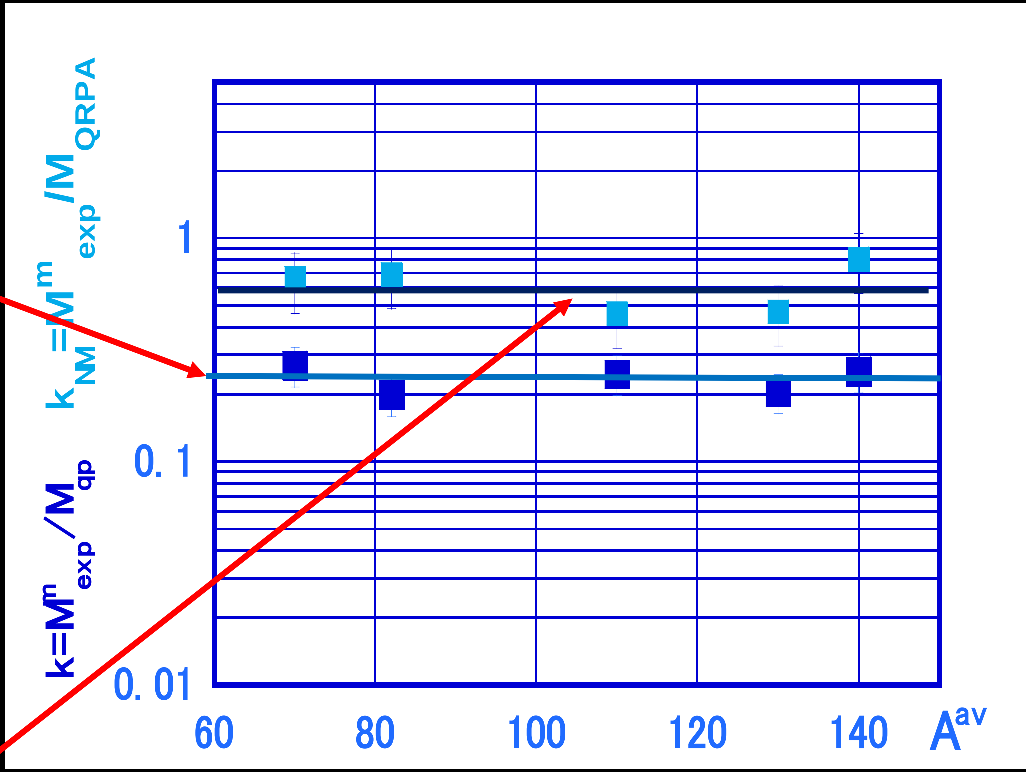
$k = k_{\tau\sigma}\, k_{NM} \sim 0.23$

$M^m_{QRPA} = k_{\tau\sigma}\, M_{QP}$

$k_{\tau\sigma} \sim 0.4$  NN τσ

$M^m_{exp} = k_{NM}\, M_{QRPA}$

$k_{NM} \sim 0.6 = g_A^{eff}$  NΔ




H, Ejiri J. Suhonen
J. Phys. G. 42 2015 055201

# SD $2^-$ $\tau\sigma$ correlation & nuclear medium $g_A$

$M(EXP) = k\,M(QP)$

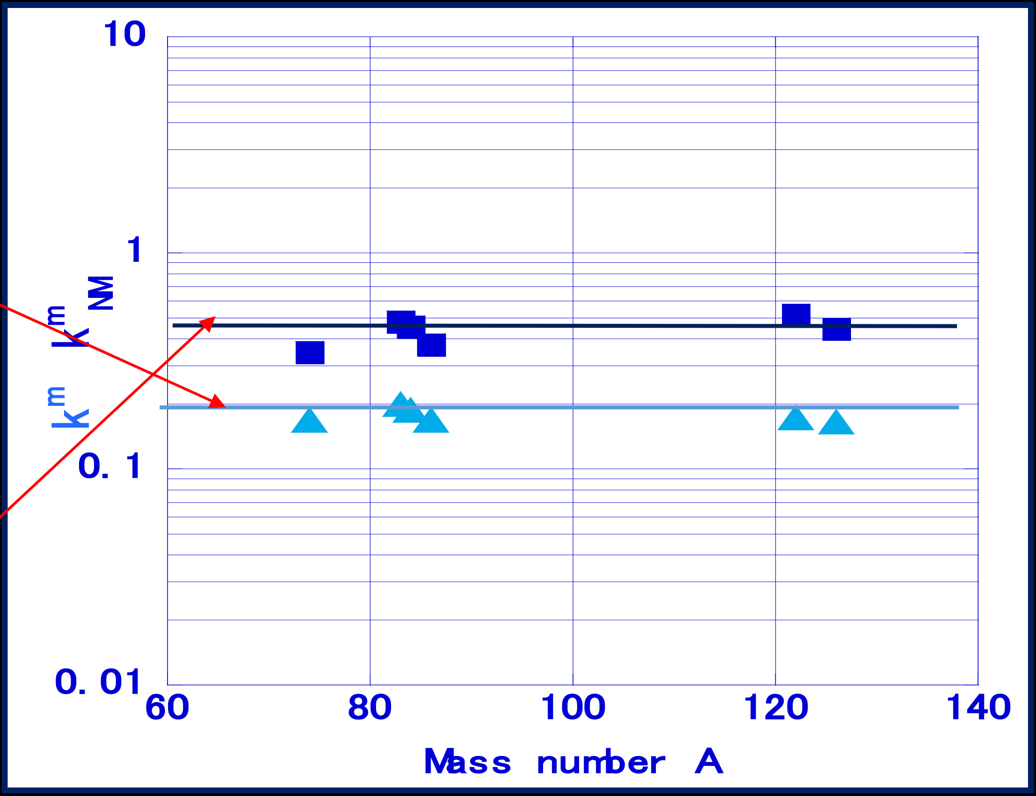
$k = k_{\tau\sigma}\, k_{NM} \sim 0.2$

$M(QRPA) = k_{\tau\sigma}\, M(QP)$

$k_{\tau\sigma} \sim 0.4$ $\tau\sigma$ correlation

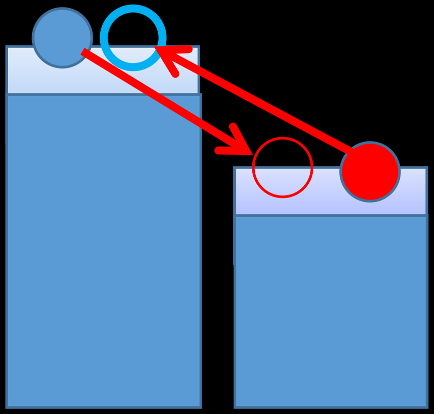
$M(EXP) = k_{NM} M(QRPA)$

$k_{NM} \sim 0.5 = g_A^{eff}$ n-medium




*H. Ejiri, N. Soukouti, and J. Suhonen, Phys. Lett. B 729 (2014)

# FSQP : Fermi Surface Quasi Particle



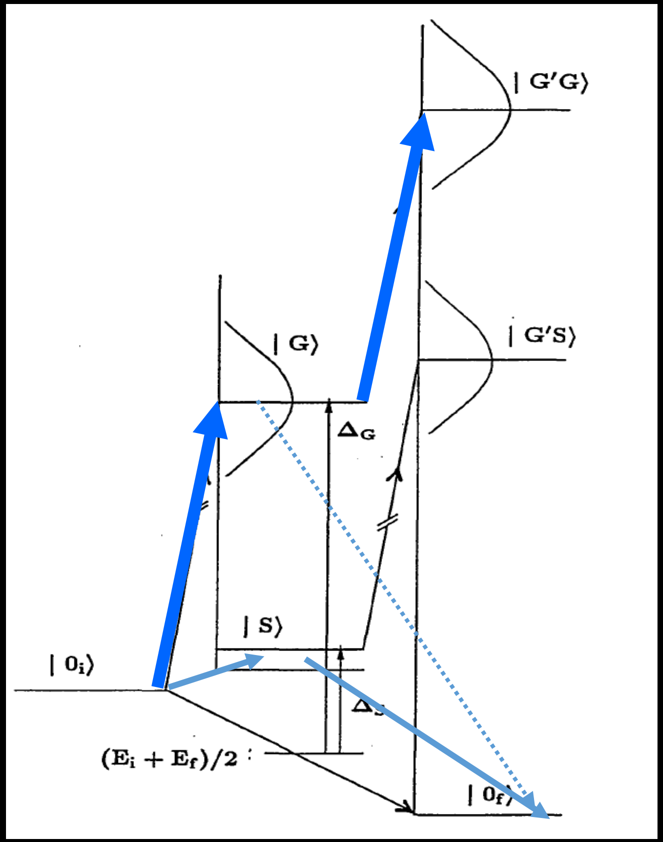
**Ground states $0^+$ — $0^+$QP vacuum**

**n p on the diffused Fermi surface**

$$M(\beta\beta) = M^- M^+ / E$$

$$M^- (n \rightarrow p \;\; V_n U_p) \; M^+ (p \rightarrow n \;\; V_p U_n)$$

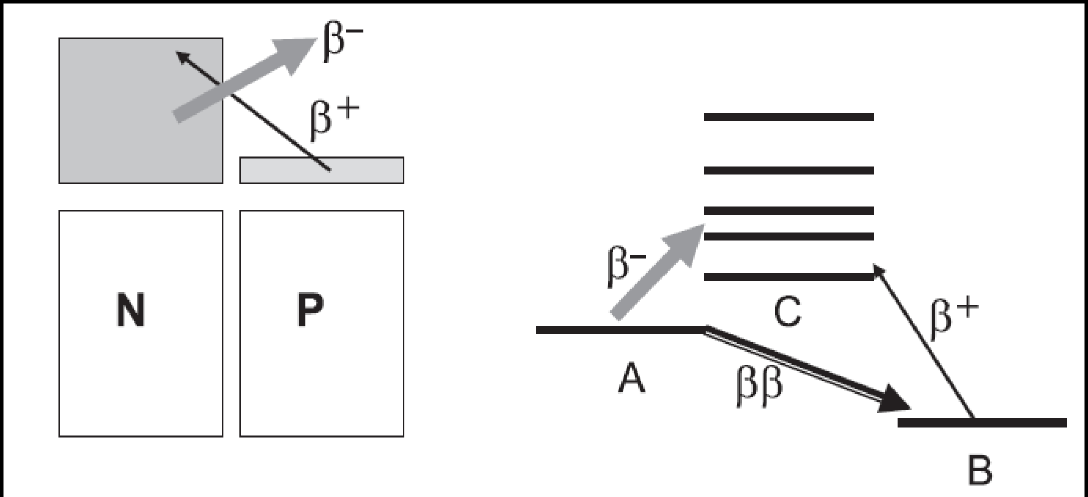
**Transitions are between partially filled partially vacant n and p states. in low FSQP states within $\Delta$ = 2 MeV**




**GT GR → D GT GR, and not |0> in 2νββ .**

H. Ejiri et al. J. Phys. Soc. J. Lett. 65 (1996) 

# FSQP: Fermi Surface Quasi Particle Model




Ground state ββ

Fermi surface QP

$0^+$ (nn) → $0^+$ (pp)

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

$$M^-_k = (k^{eff}_i)\ m_{ij} V_n U_p \quad M^+_k = (k^{eff}_f)\ m_{ij} U_n V_p$$

$M^-_k$ and $M^+_k$ are same sign

$k^{eff}_A$ : τσ & medium/isobar effects,

derived from exp. β, EC, CER,

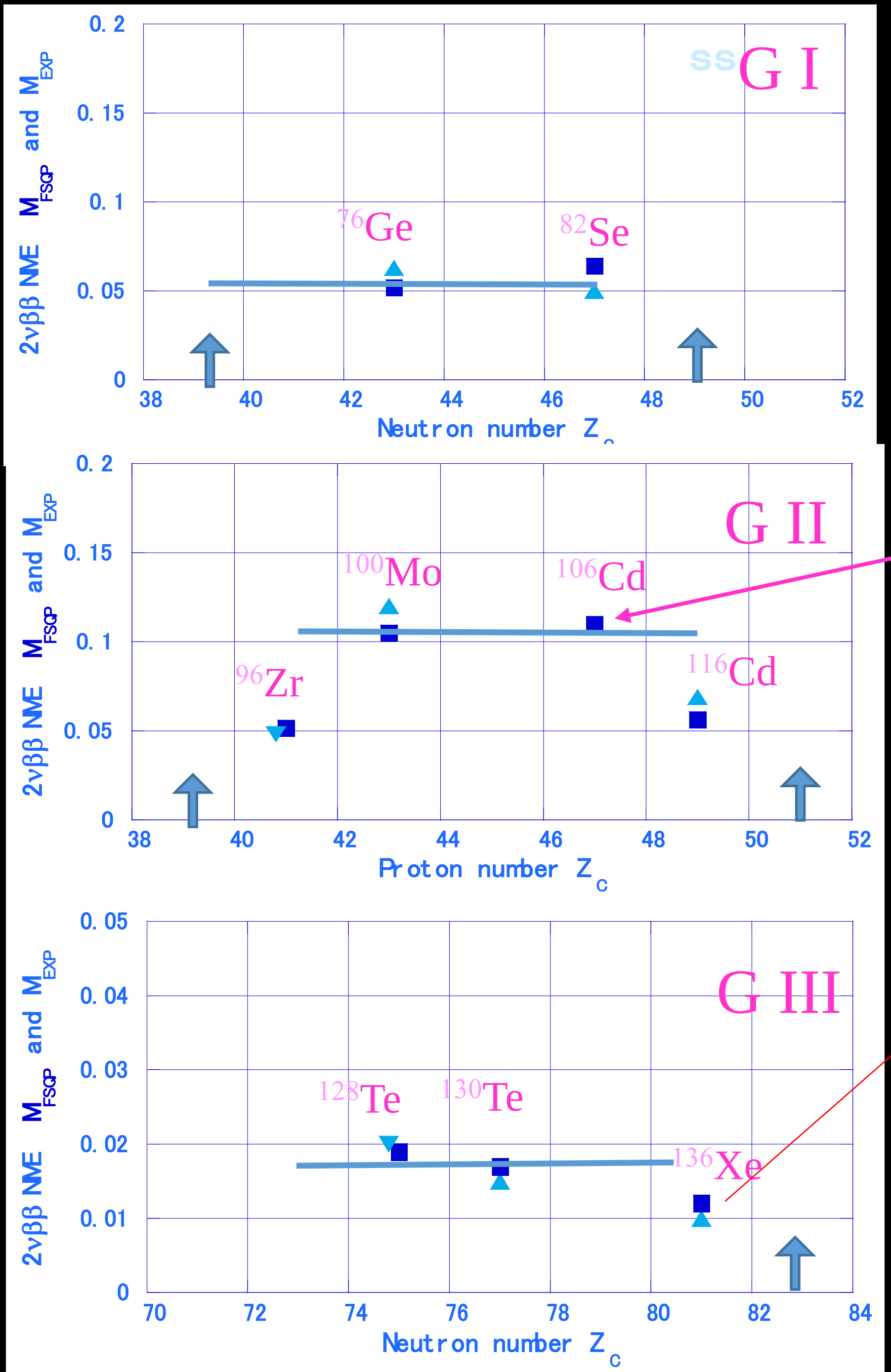
$(k^{eff}_A)^2 \sim (0.23)^2 = 0.05$

H. Ejiri et al. J. Phys. Soc. Japan Lett. 65 (1996) 7; JPSJ 78 (2009) No 7.

# 2νββ matrix element

**M(FSQP)**

**M(EXP)**




2p1/2-2p3/2

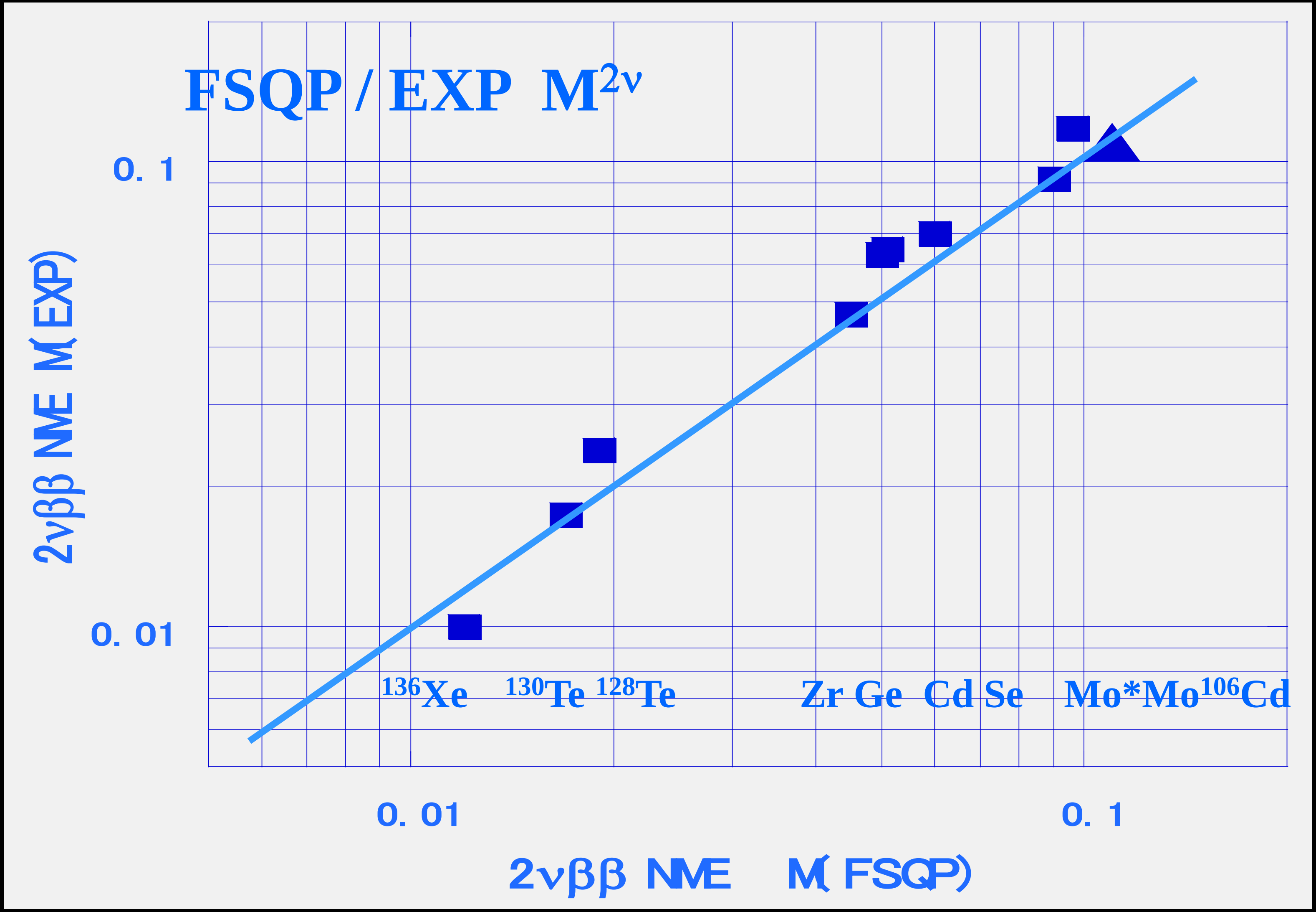
$^{106}$Cd predicted

$T_{1/2}$(ECEC)=5.2 $10^{22}$

1g7/2-1g9/2

N=82, p X n

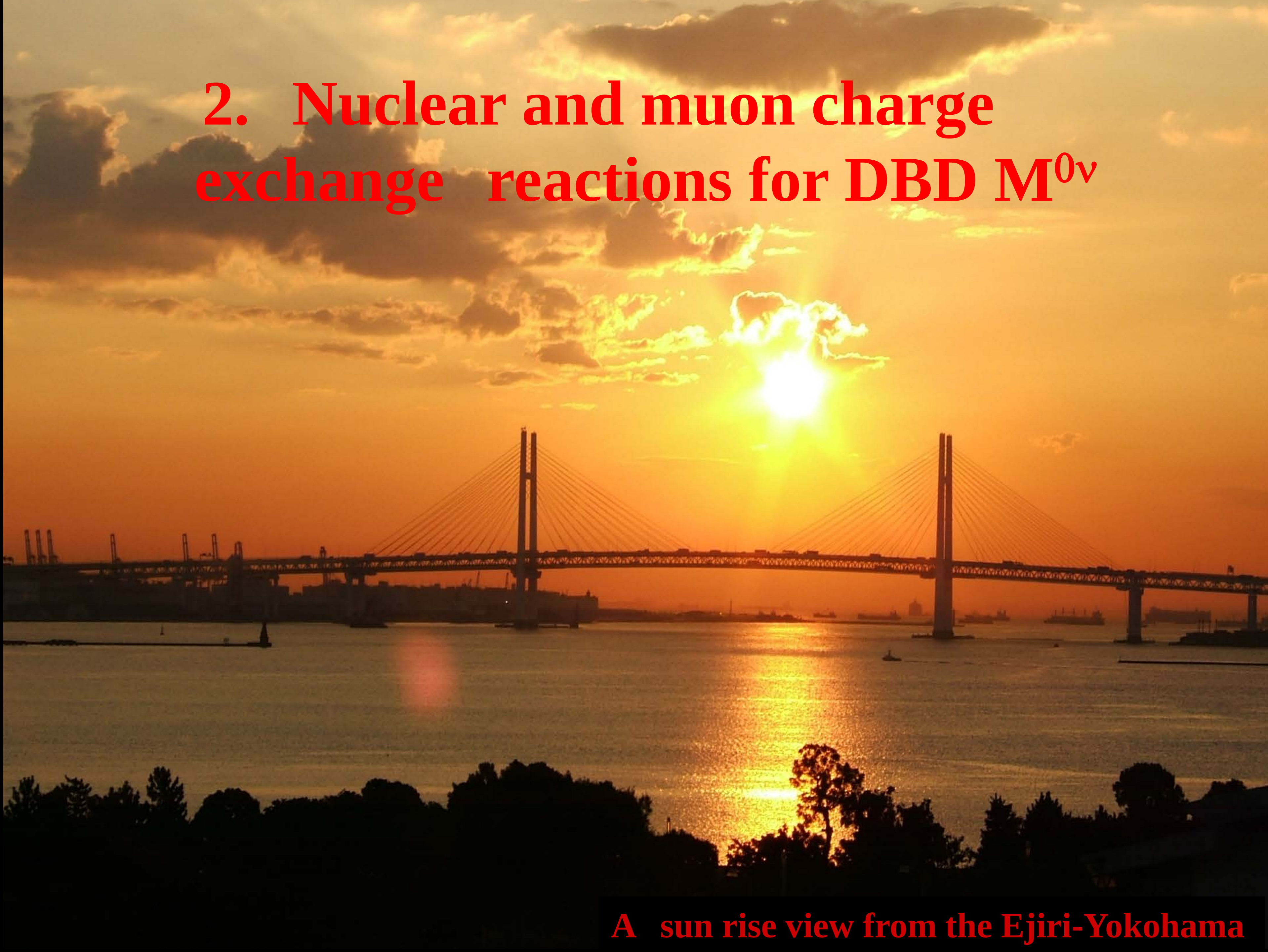
2d3/2-2d5/2




$M^{2\nu}$ : small by $(k^{eff})^2$ ~0.05, depend on VU, E($1^+$) , not by $g_{pp}$

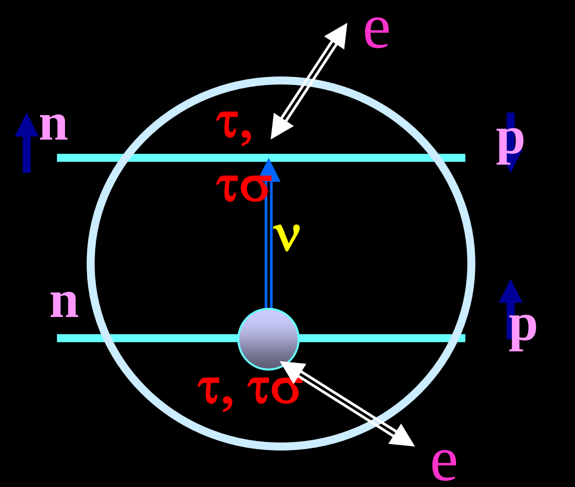
$M^{0\nu}$, likewise, small by $k^{eff}$ for $2^-$ etc, depend on V,U ( N=82)

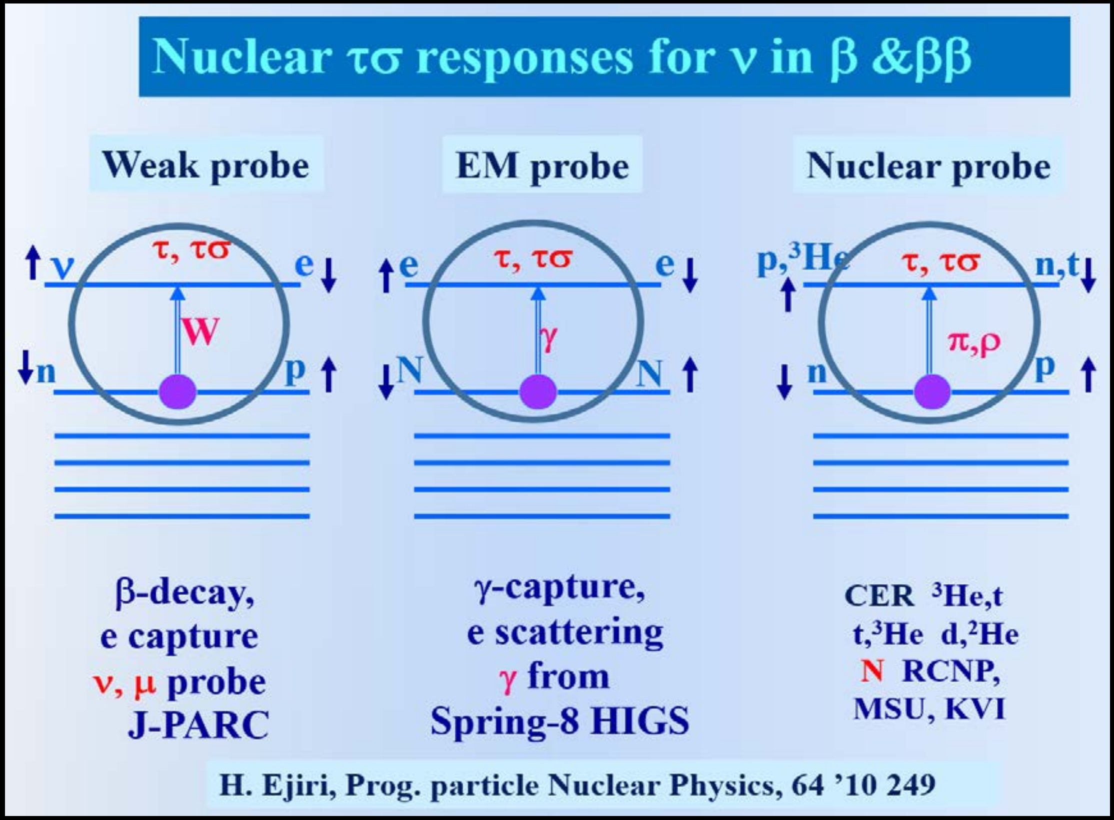
# 2. Nuclear and muon charge exchange reactions for DBD $M^{0\nu}$

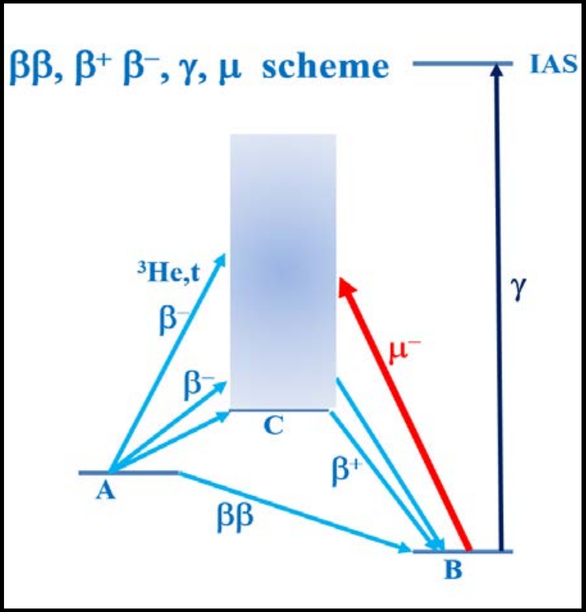


A sun rise view from the Ejiri-Yokohama

# CER. Probs for ν-responses



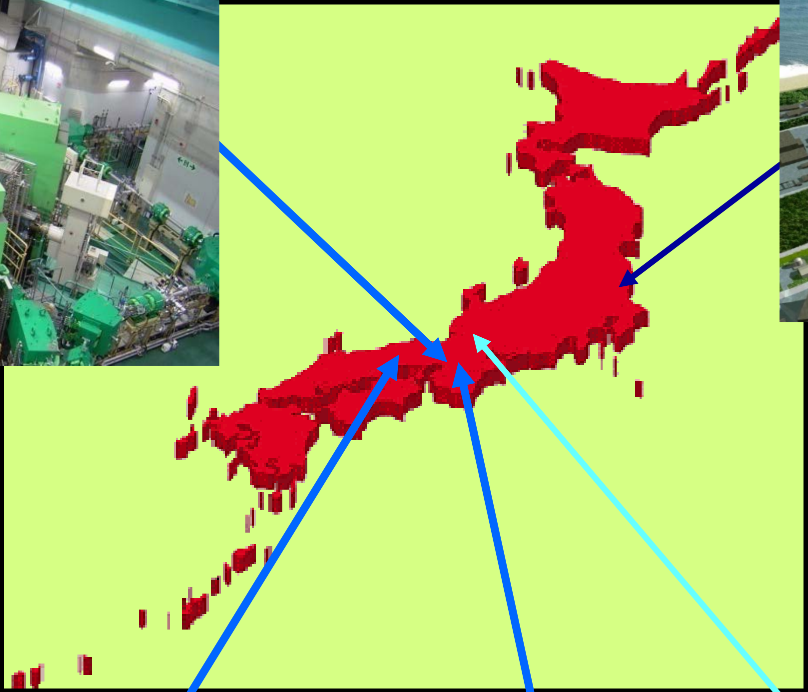




0νββ:two body operator, but single β NMEs are useful for 0νββ
H. Ejiri PR 338 265 2000.

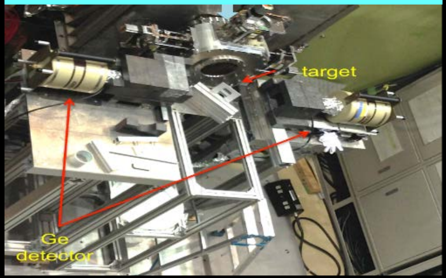
# Neutrino response studies by RCNP/Osaka

**RCNP Osaka p,He, HI, μ**

**J-PARC 3-50 GeV p, ν, μ**



**MLF D2 μ**



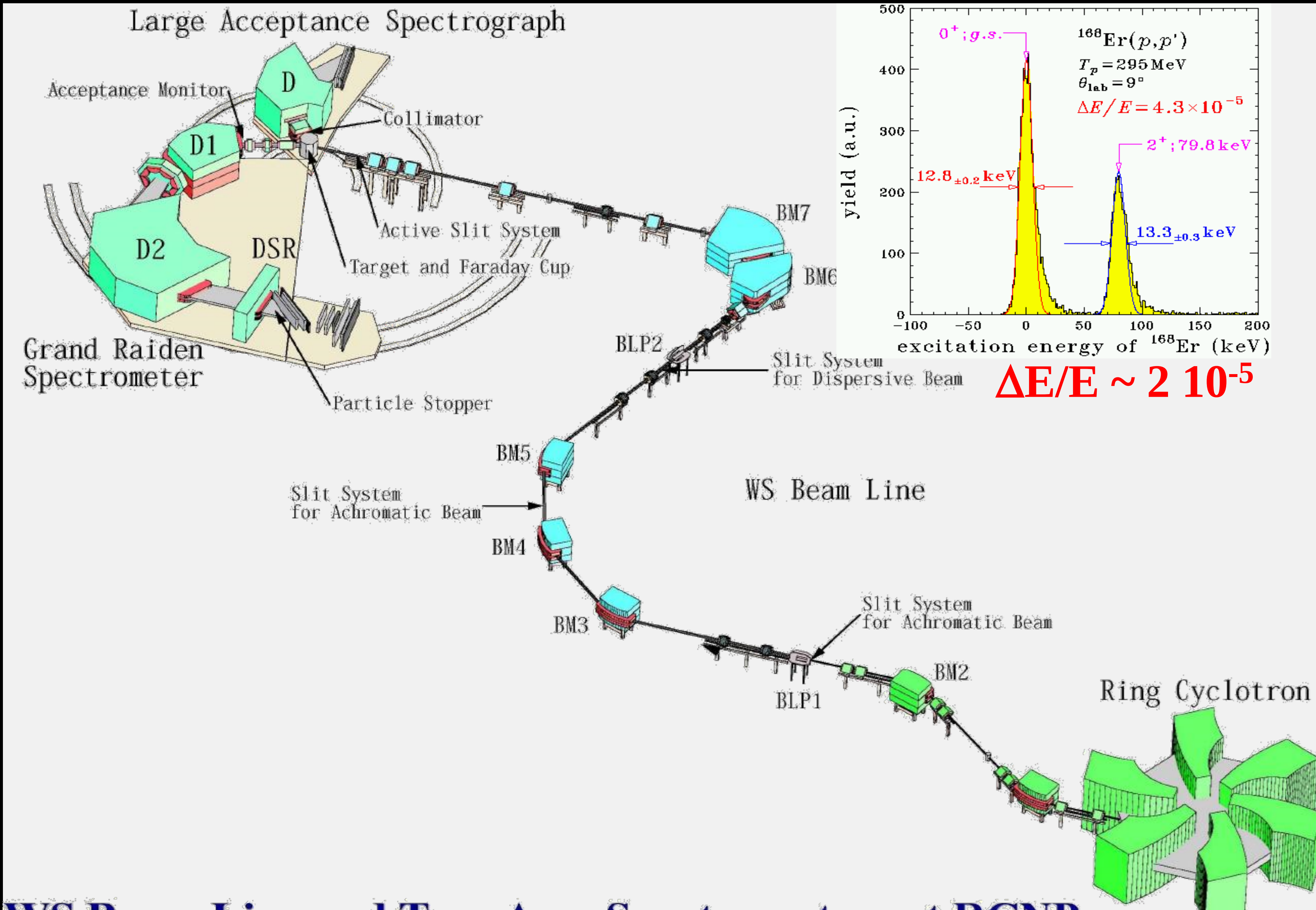

**MuSIC μ**

**Spring-8 GeV- MeV pol. γ**

**Oto under ground lab.**
**ββ–ν, DM in nuclei**

**SK/KamLAND**
**Underground lab.**
**ν-osc. T2K. ν / SN,**
**the sun and earth,**

# High E resolution ($^3$He,t) CERs at RCNP

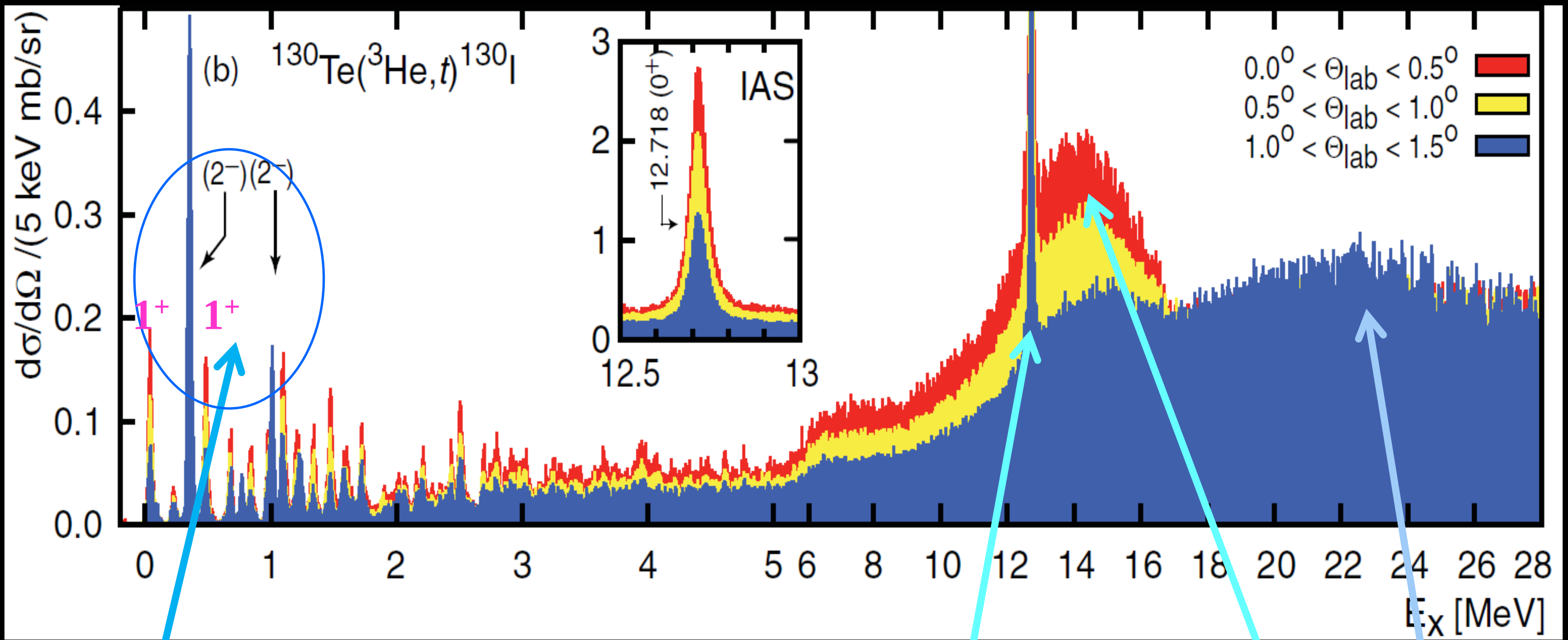



**ΔE/E ~ 2 $10^{-5}$**

**WS Beam Line and Two-Arm Spectrometers at RCNP**

## Single β (τσ) strengths on DBD Ge,Se, Zr,Mo,(Cd),Te,Xe

**Nucl CERs Konan, KVI, MSU, Munster, RCNP/Osaka, and others. Faessler et al**




**Tiny GT($1^+$), $2^-$ $3^+$at low E.**

**B(GT) ~ $10^{-3}$ B(SUM)**

**Strong IAS ($0^+$ ), GT( $1^+$), SD( $2^-$)**

**GR : B(GT) ~ 0.5 B(SUM)**

… H.E PR C 84 2011

**P.Puppe et al PRC86 044603**

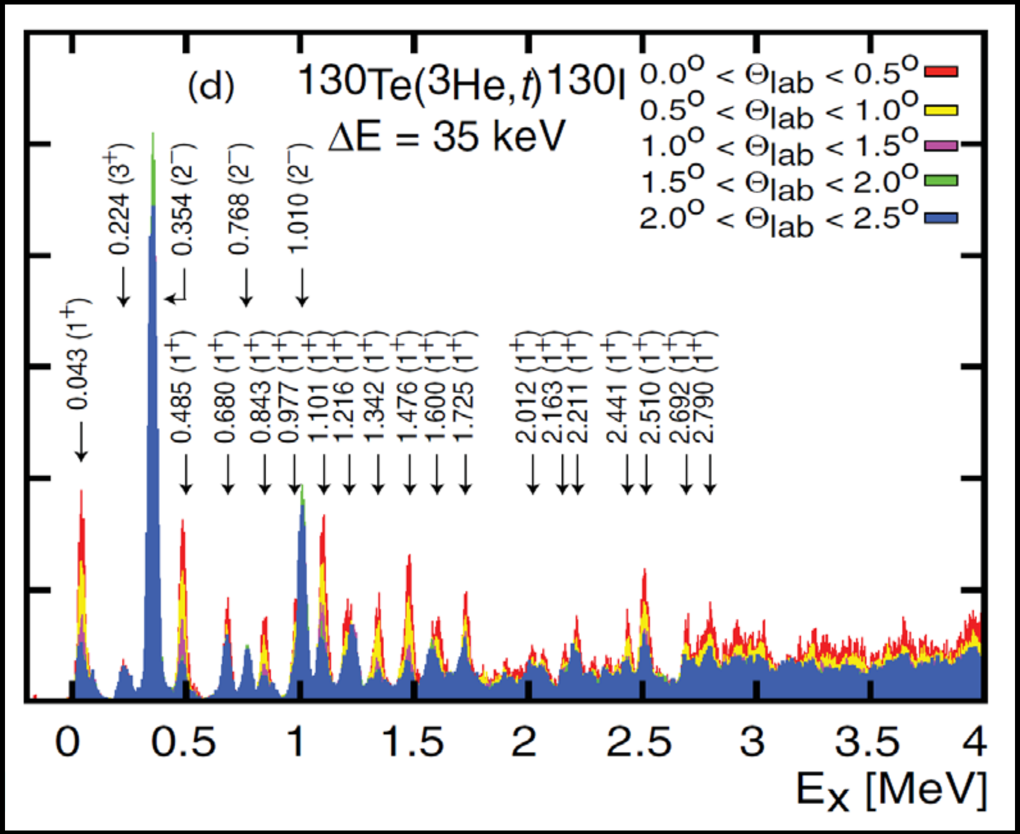
**D. Frekers in Dec.2nd .**

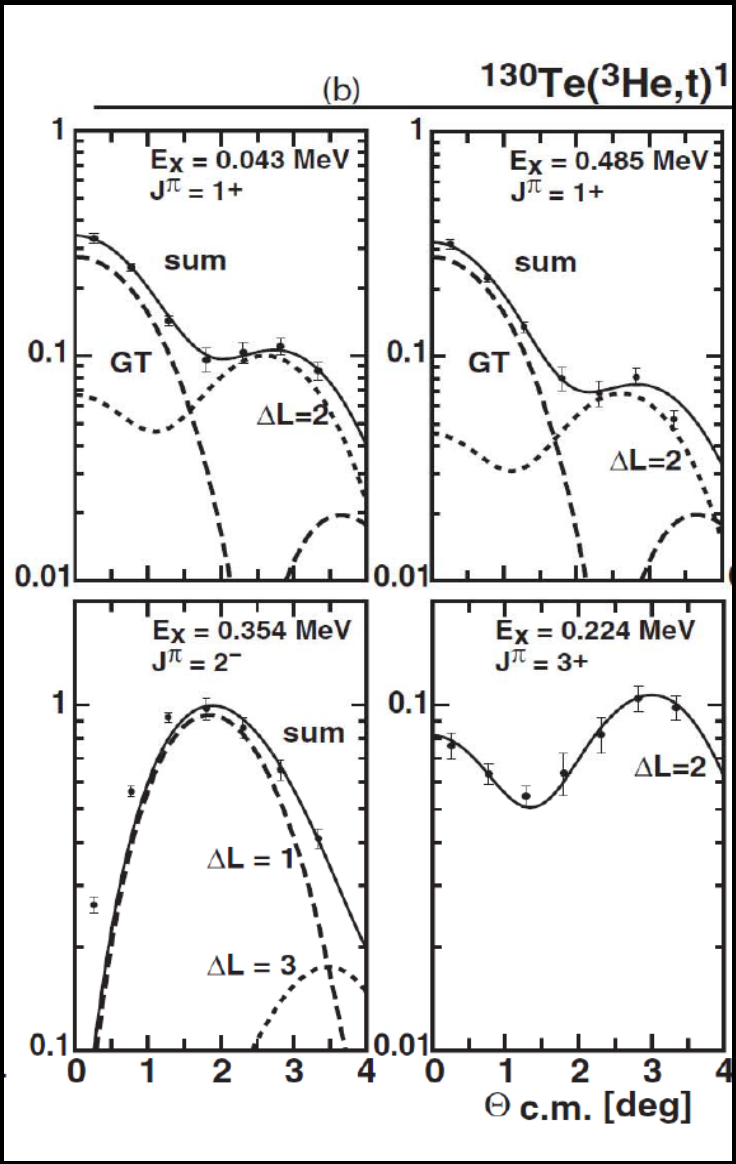
**H.Ejiri et al. PR 176 (1968) 1277**

**First $2^-$ GR based on reduced B(SD)**

$$\frac{d\sigma_\alpha(0^o)}{d\Omega}\frac{1}{K(E_i,0)N_\alpha^D} = |J_\alpha|^2 B(\alpha), \quad \alpha = \mathrm{F, GT}.$$

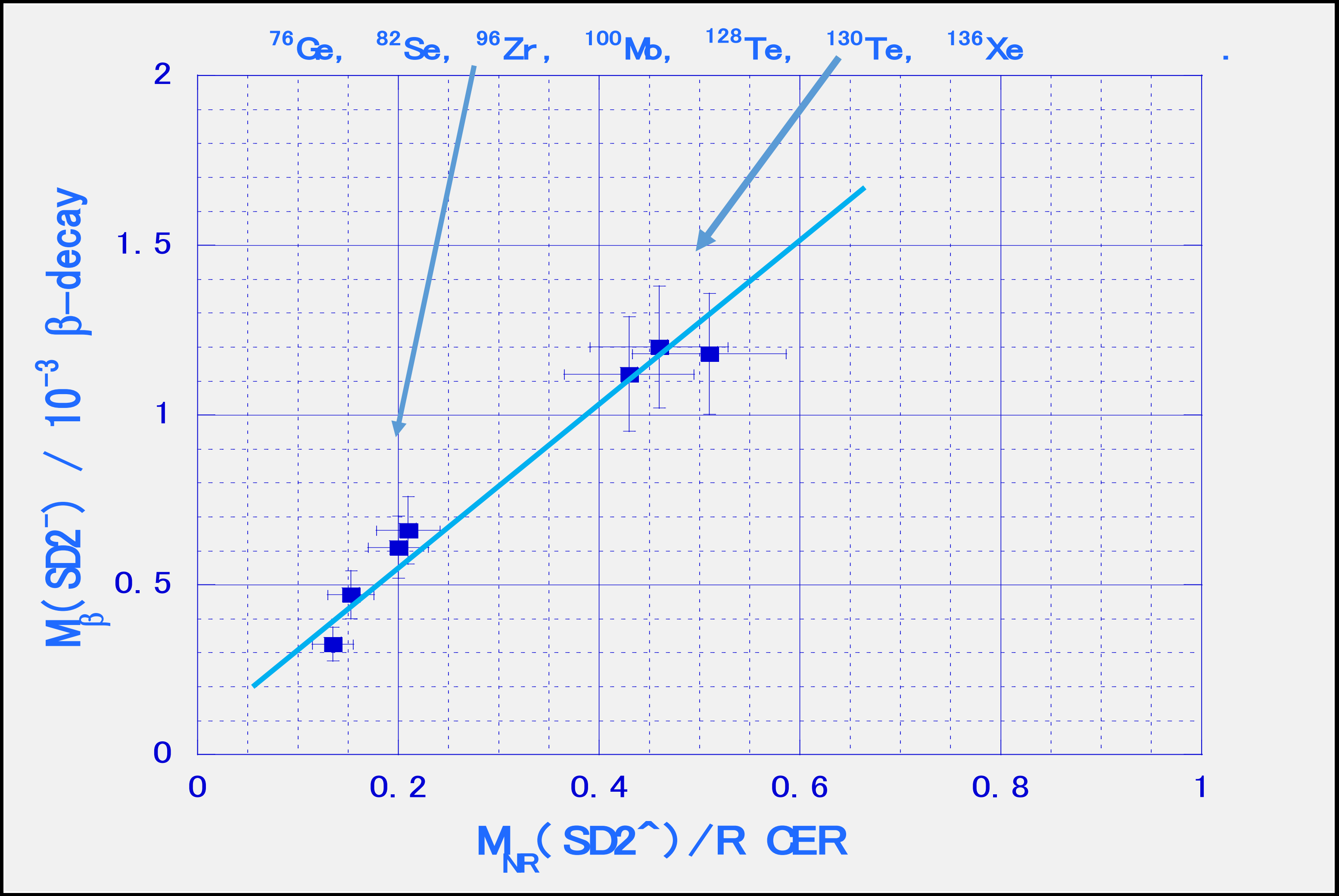
$$B(\alpha)=(2J+1)^{-1}M(\tau\sigma Y_l)^2$$




**Angular distributions give J=1+ (l=0), or J=2-(l=1), or J=3+(l=2).**

RCNP CER Puppe Ejiri Frekers et al PRC86 44603

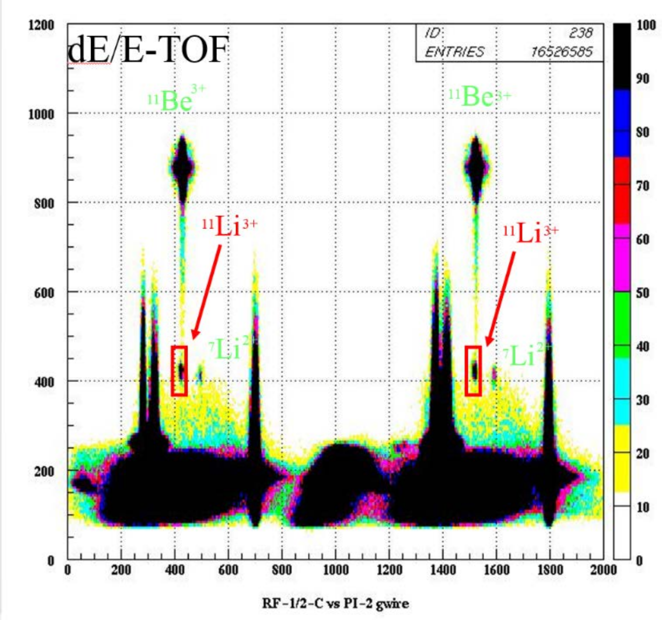


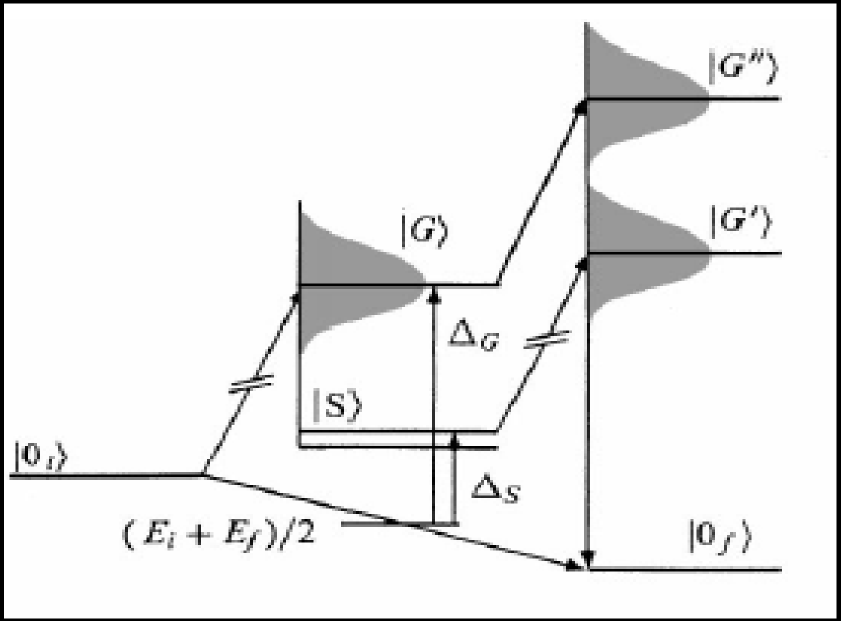

SD NMEs (Y axis) with $g_A$ from ft data in neighboring nuclei by H.E

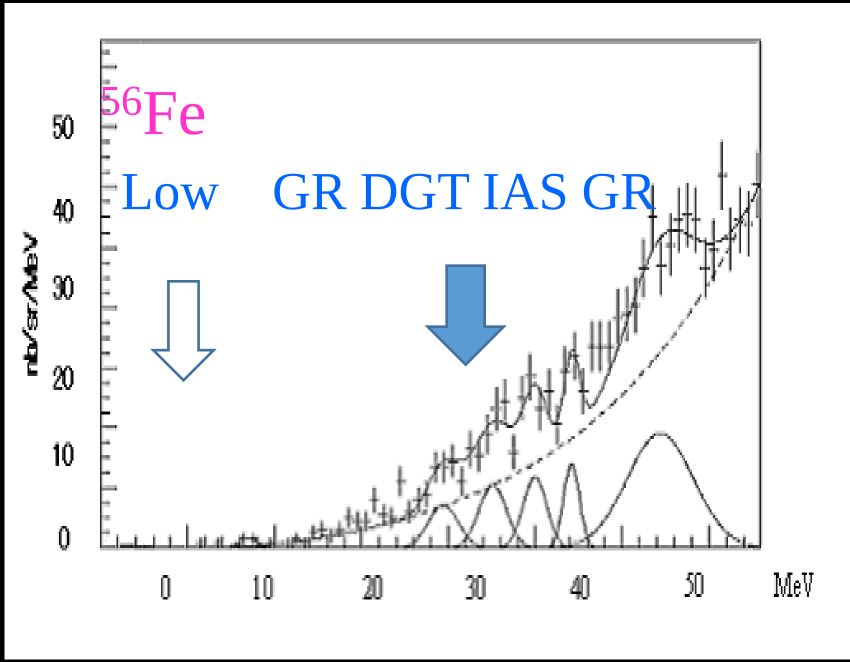
Exps planned on SD with Agodi, Akimune, Capuzzello, Frekers et al.

# Double charge exchange reaction ∗

RCNP 0.76 GeV $^{11}B$, $^{11}Li$




$^{13}C$ strengths at low high states

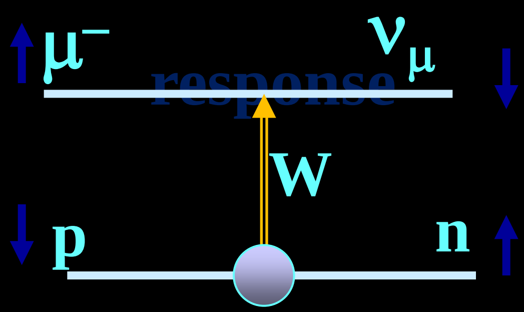
$^{56}Fe$ no low states, mostly GRs

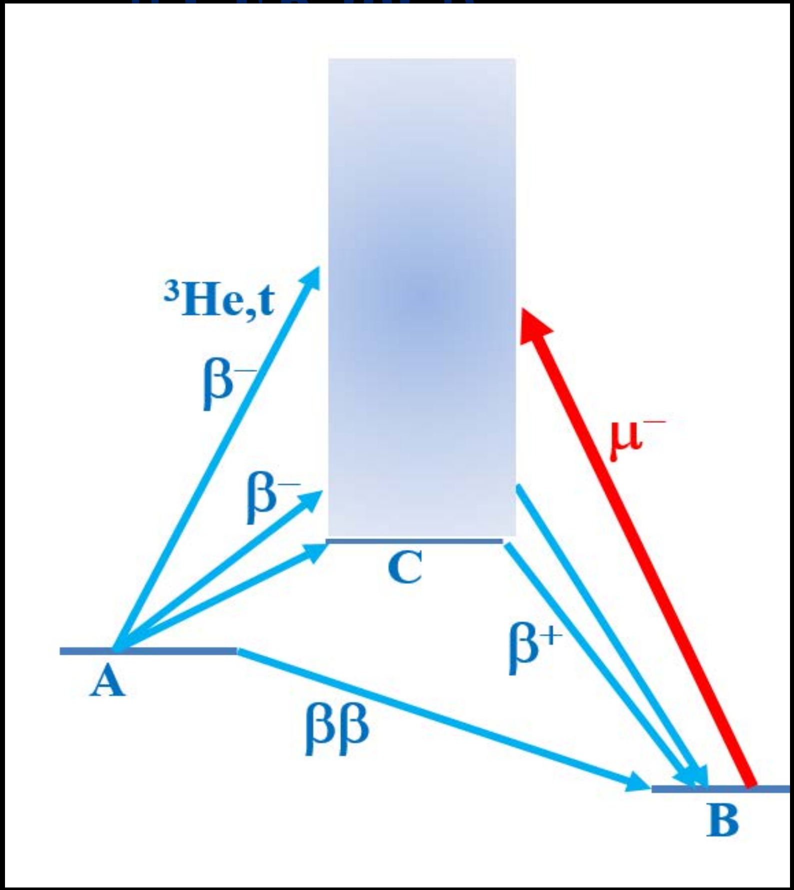
Dec.2nd Takai HI

NUMEN !!

Takahisa Ejiri et al 2010

# Muon charge exchange reactions




E ~ NME in 0-100 MeV

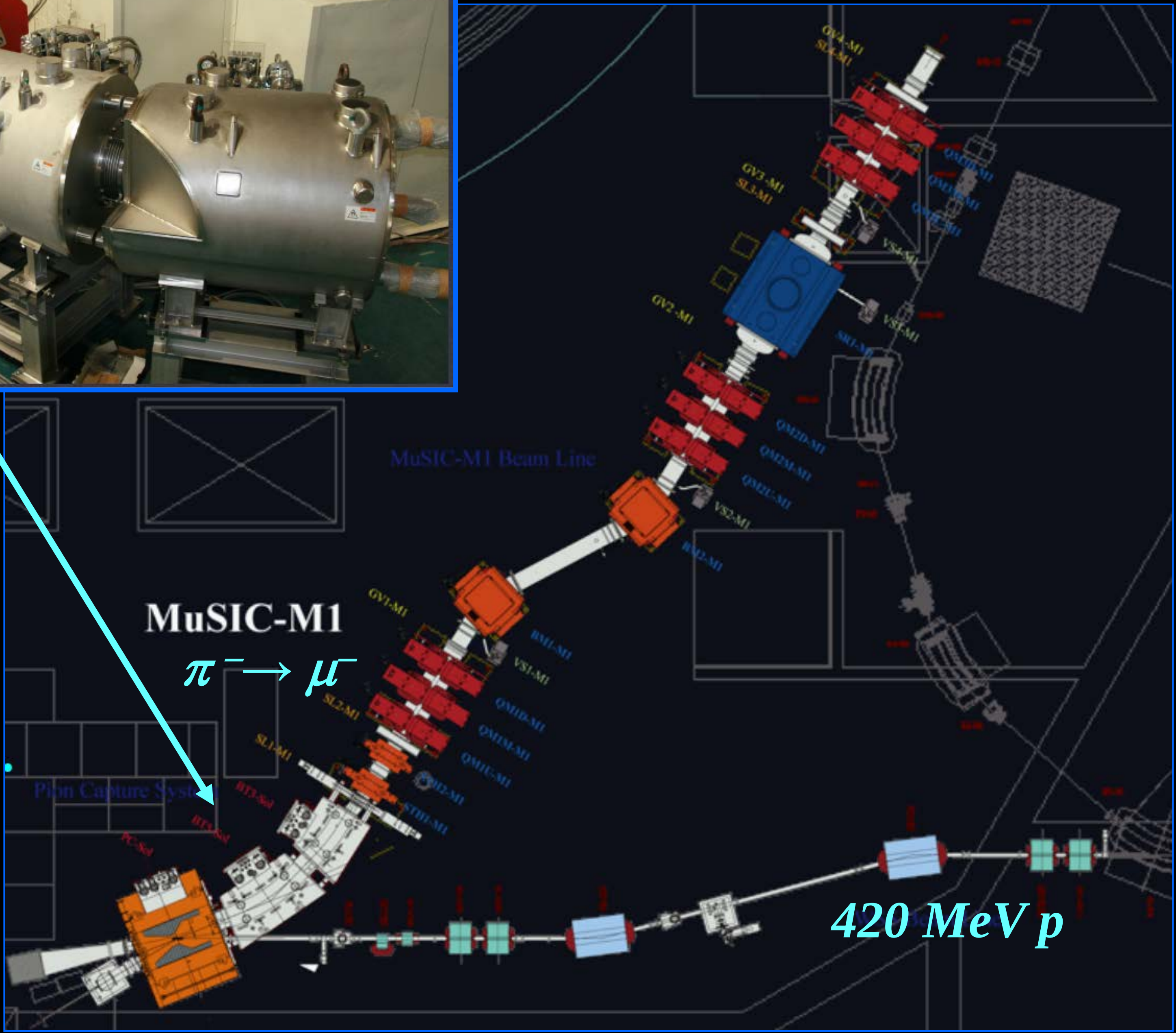
$\beta^+$ anti-ν response

for ββ–ν SN ν

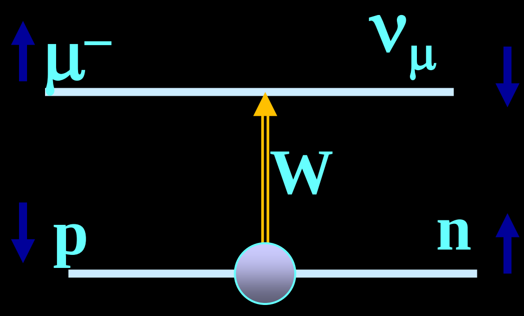
Large μ capture rate ~ 1

H. Ejiri Proc. EM interactions 1972. AIP Conf. MEDEX11 2011.
J. Suhonen, M. Kortelainen Czech. J. Phy. 56 2006 519, EXP 453.
V. Egorov (μ, γ , n γ, p γ) on $^{48}$Ti, $^{76}$Se 2004 γ D.R. Zinatalina et al. .

# *MUSIC RCNP Osaka*
# *DC $\mu$ beam*



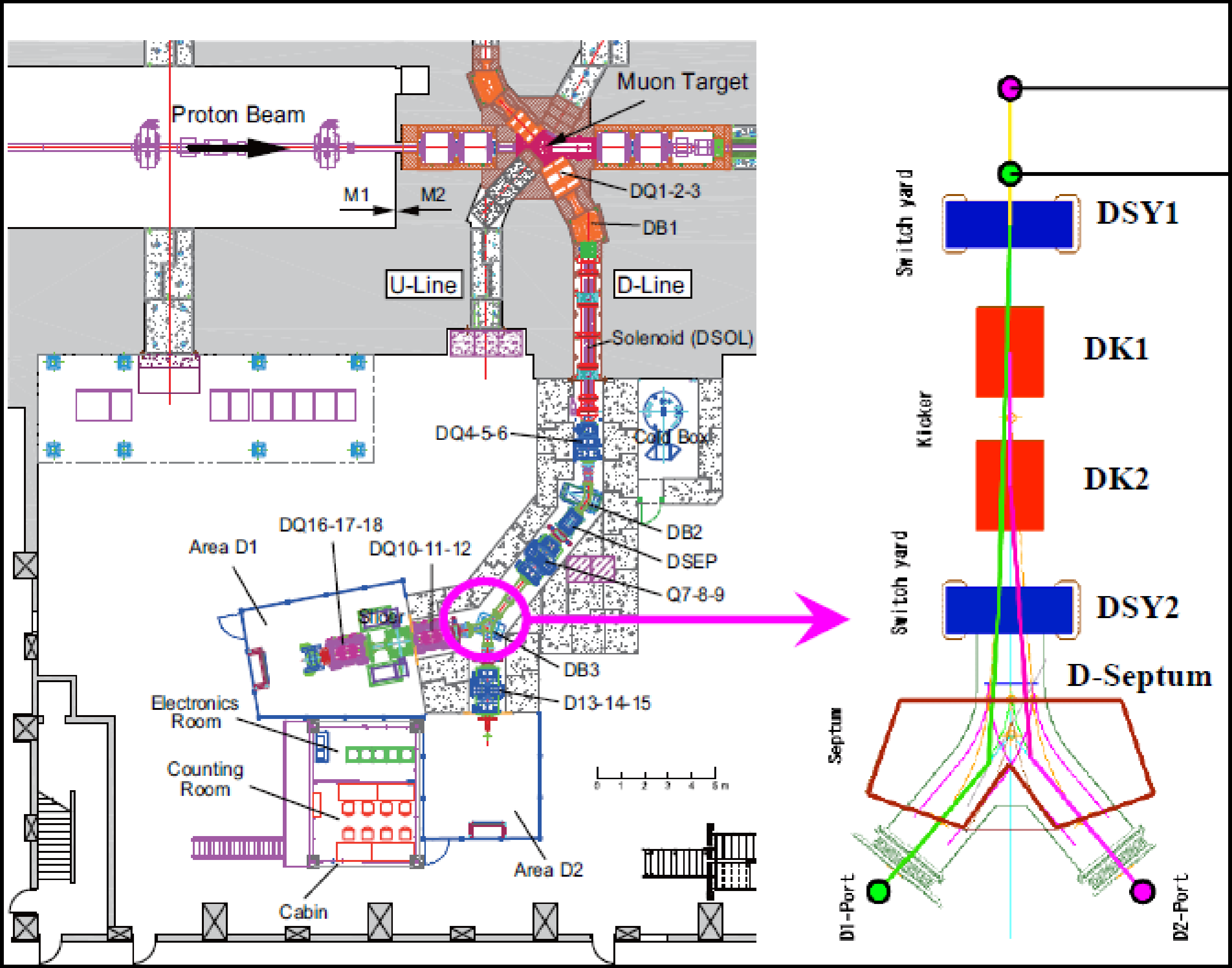
# MLF μ probe




MLF (pulsed)

Enriched

$^{100}Mo(\mu,\nu_{\mu}\ xn\ \beta\gamma)$



# Present CER $^{100}$Mo($\mu,\nu_\mu$, xn $\gamma$)$^{100-x}$Nb $\nu$–$\tau(\beta)$+ responses

$F(E_n) = E \exp(-E_n/kT)$

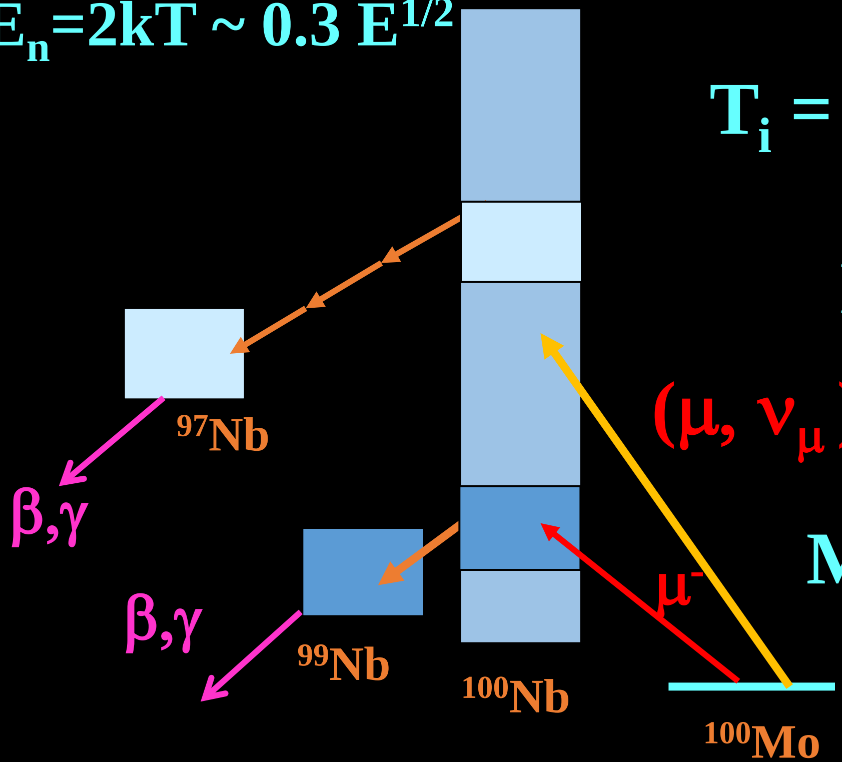
$E_n = 2kT \sim 0.3\, E^{1/2}$

$T = \Sigma\, T_i$ transition at i$^{th}$ excited state

$T_i = G_i M_i^2$ with

$G_i = k(Q-E_0)^2$ phase space

$M_i$ : NME




$M_i = g_A M_A + g_V M_V$ for i =0,1,2,..

Effective $g_A$ for i =0,1,2,..

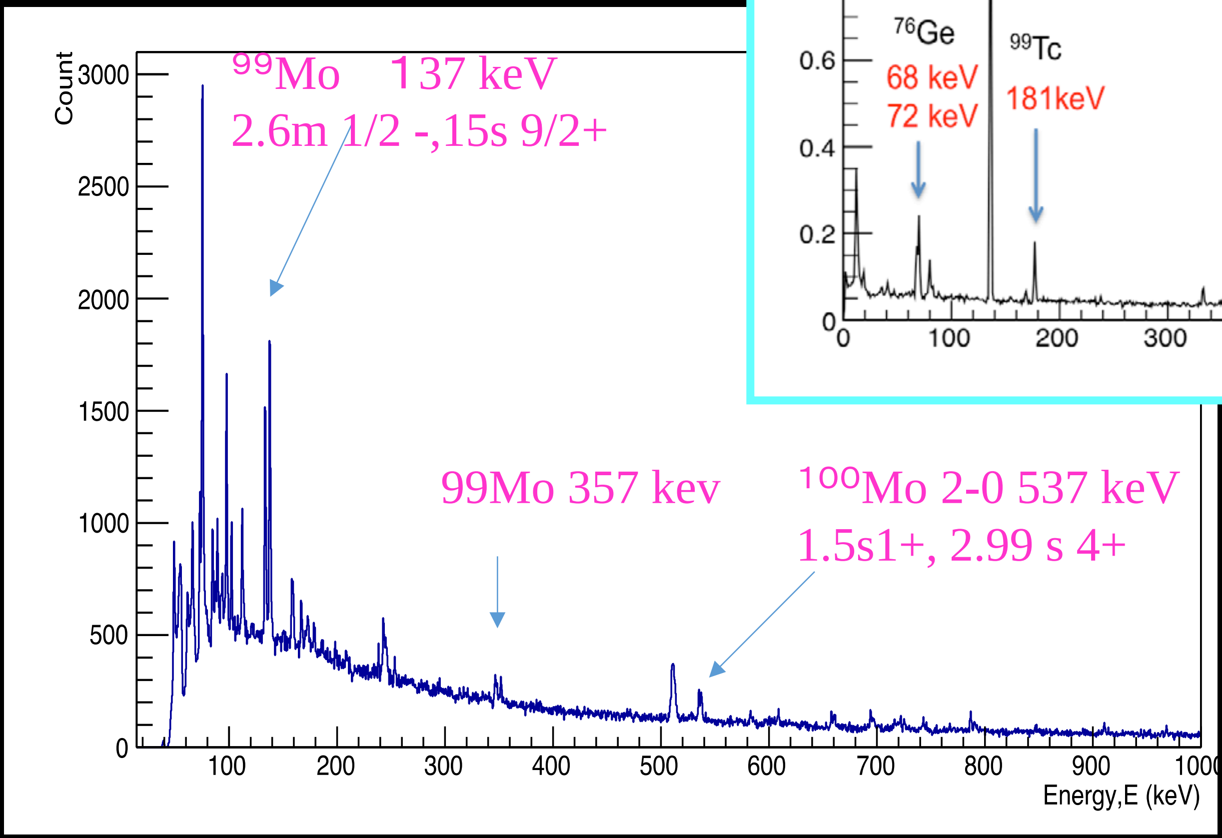
$\gamma_i$ from $^{100\text{-}i}$Nb gives the isotope i distribution, relative strength in the whole excitation region. Life time gives the absolute strength

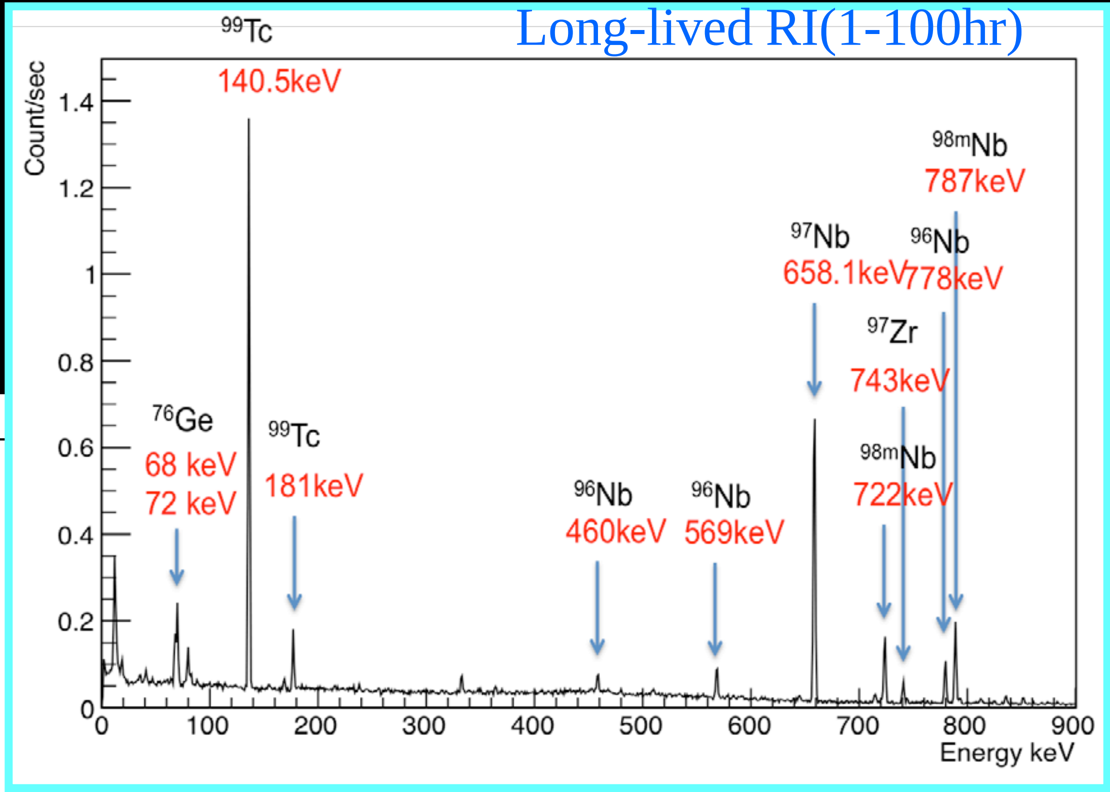
H. Ejiri Proc. e-$\gamma$ conference Sendai 1972

# MLF (pulsed)

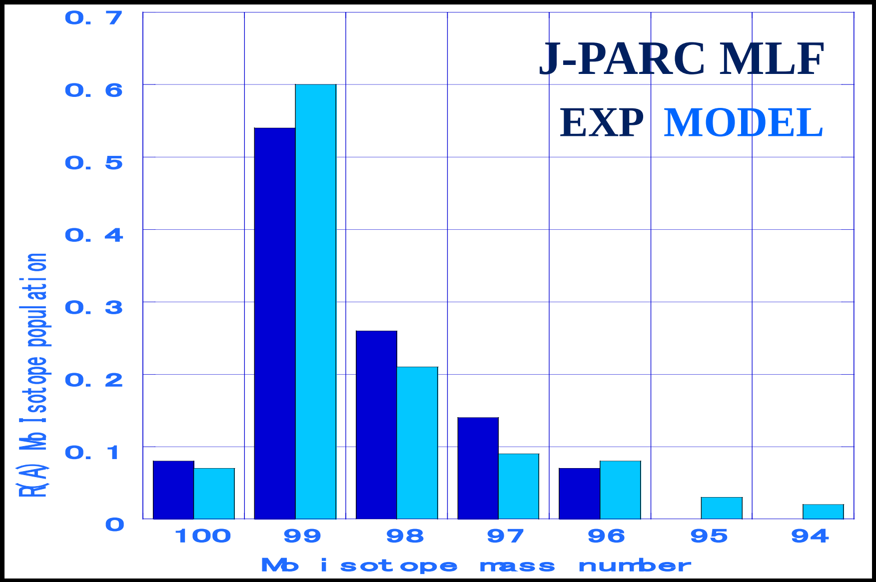
## $^{100}$Mo(μ,$ν_μ$ xn βγ)

## Short-lived RI(1-200s)



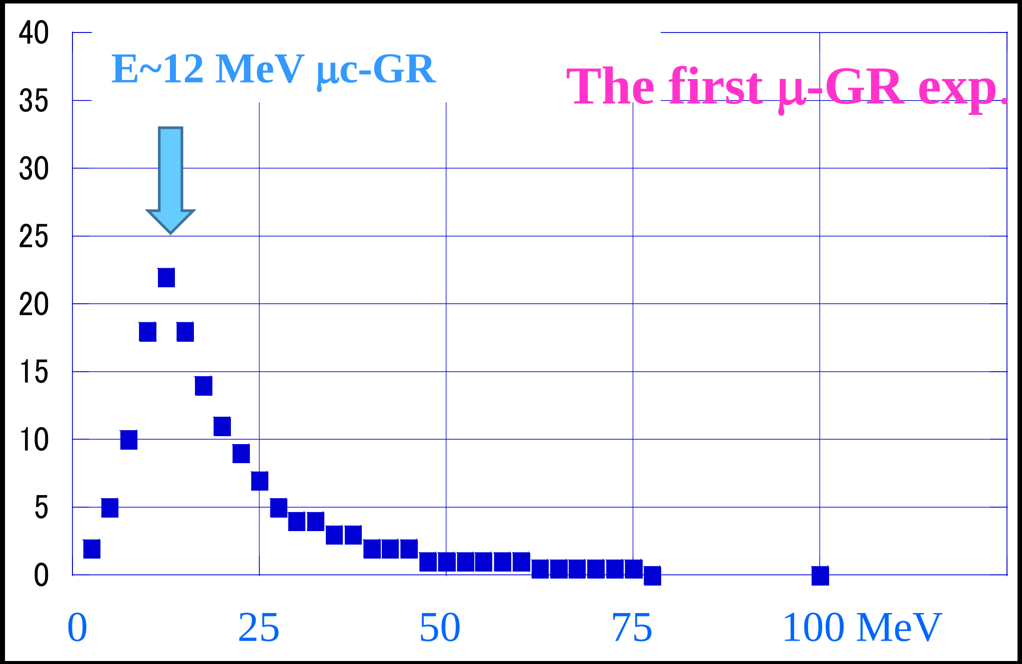

**Izyan Hashim PhD Thesis, NNR14 Proc.**

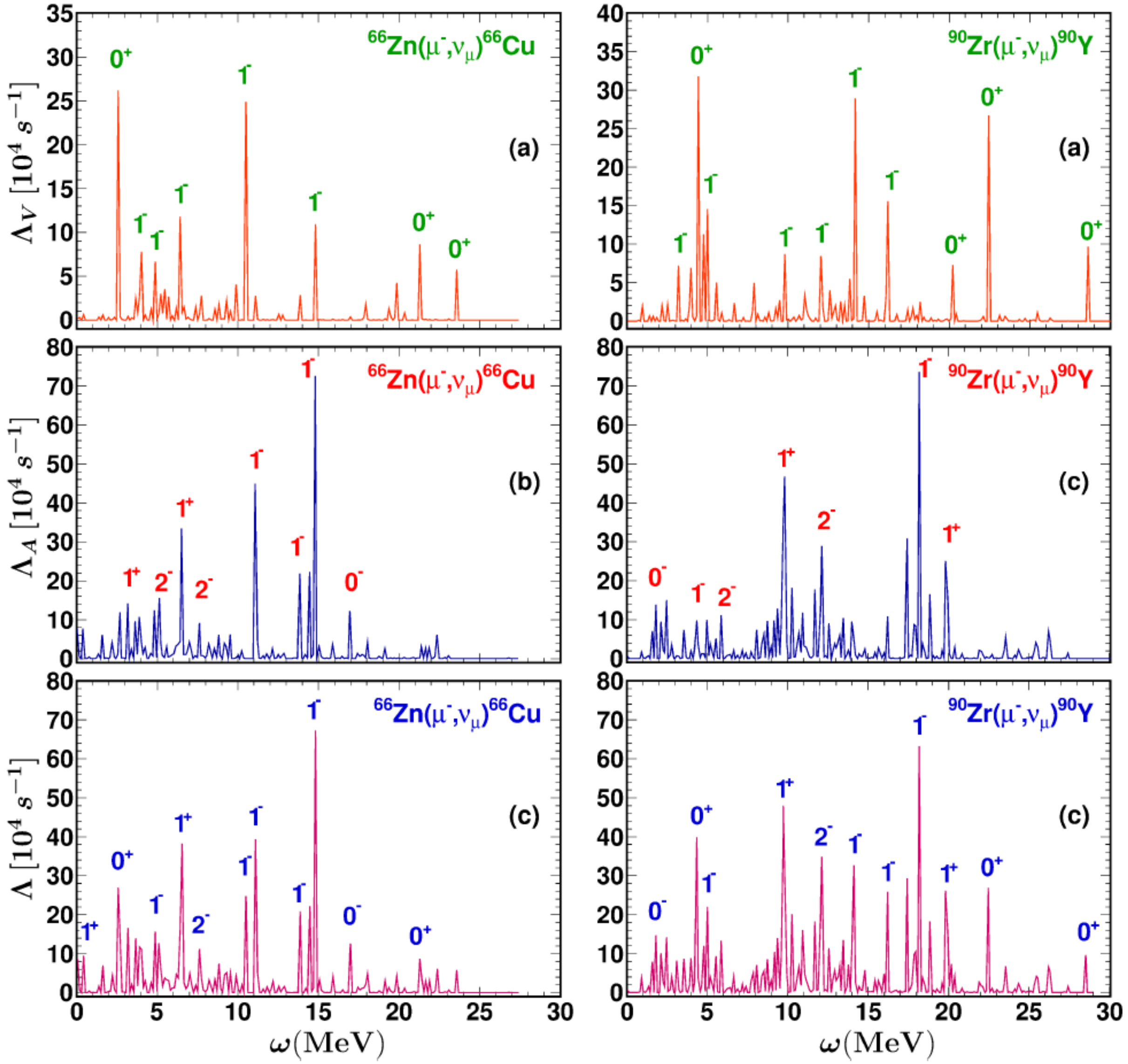



Observed isotope population agrees with calculation with μ- GR as given below.

H. Ejiri et al. JPSJ 84 044202 2013

I. Hashim PhD Thesis 2015





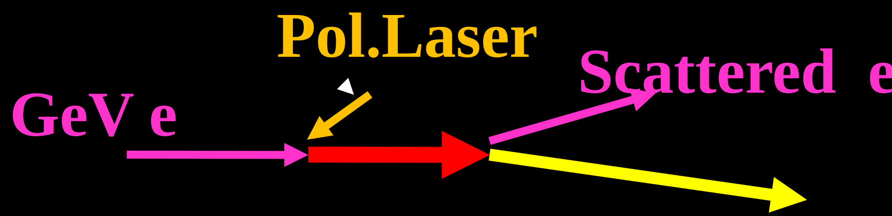

a Vector, b Axial vector c Total $^0Zr.$

**P.G. Giannaka T.S. Kosmas PR C 2015**

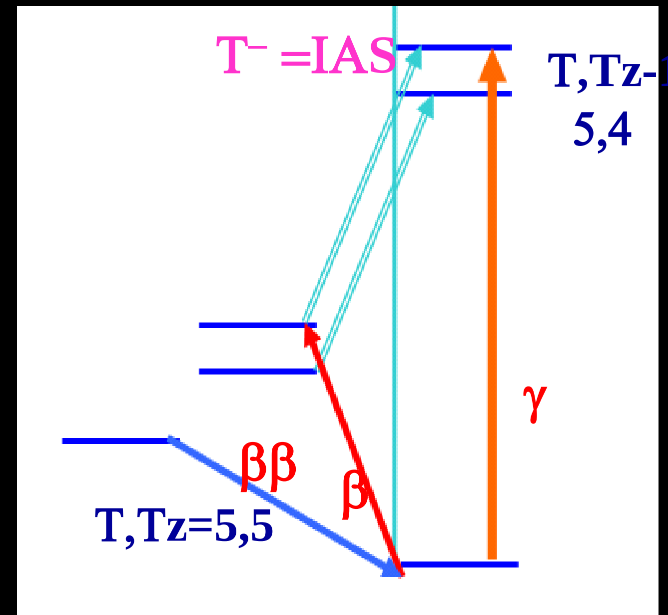
# LEPS Photon probe

H. Ejiri PRL 21 ’68, PR 38 ’78
H. Ejiri, A. Titov PR C 88 054610 2013

## Laser electron photon Sources

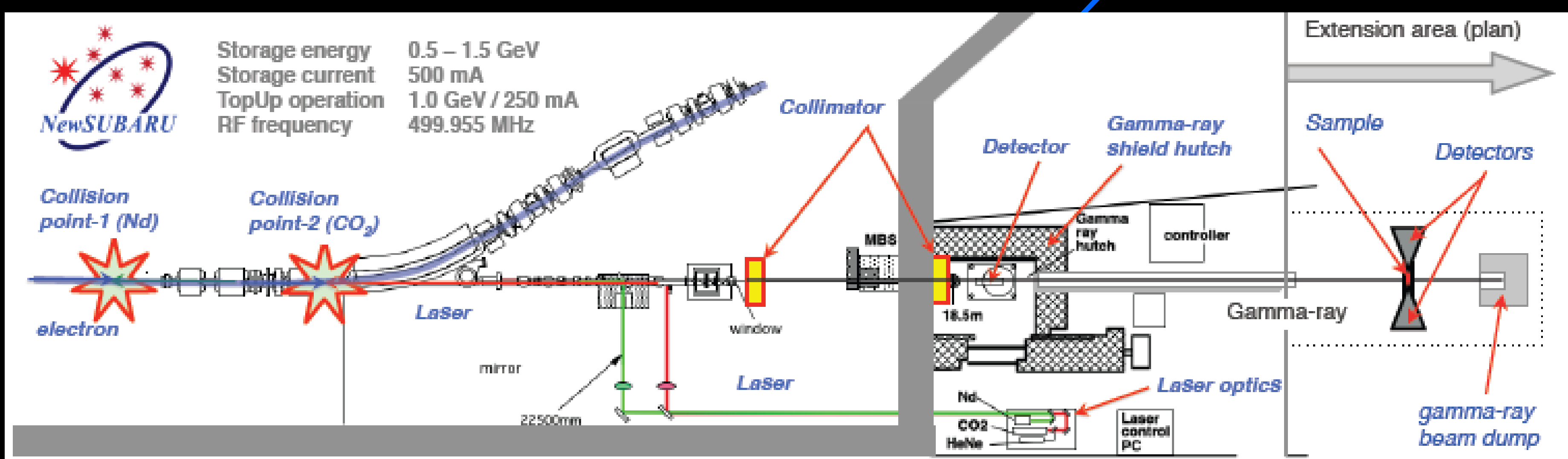



$E_\gamma \sim 4\,\gamma^2\, E_l = 2\,10^8\, E_l \sim 20$ MeV,




β+ responses via IAS γ

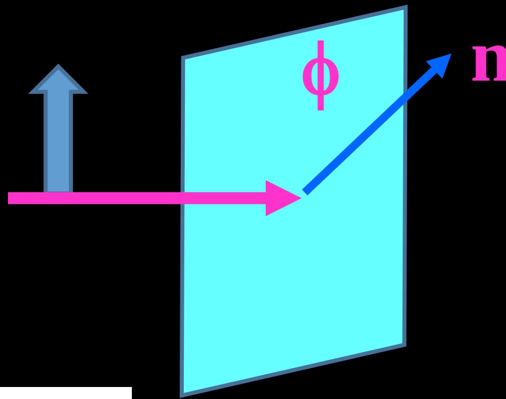
$<f\ |g\ M_\beta|\ i> = g/e\ (2T)^{1/2} <f\ |\ em_\gamma\ |\ I>$

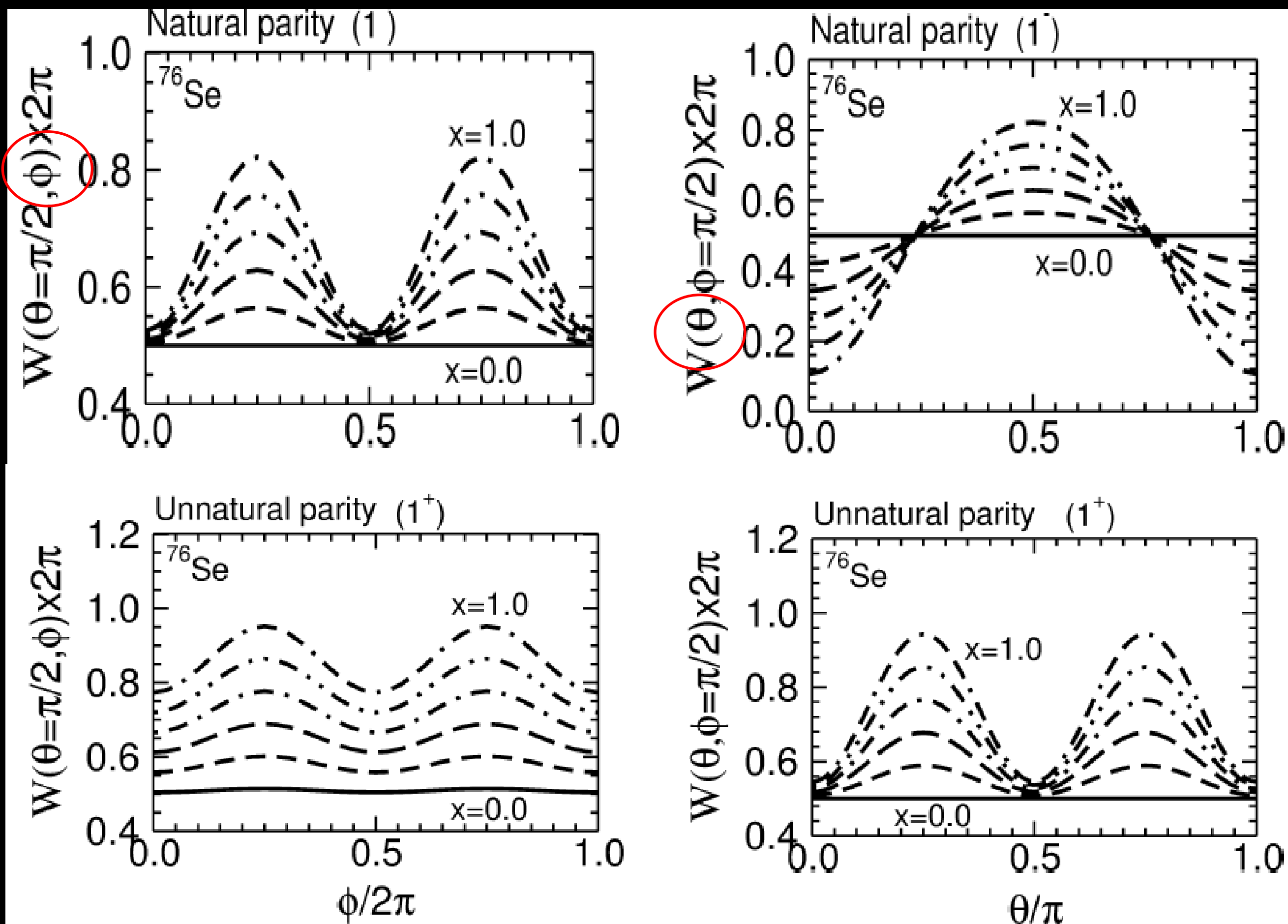


# Polarized photon

$$\int \sigma(\gamma, n)dE = 2.9 \times 10^{-3} MeV\,fm^2 \quad E1\ 0^+ \rightarrow 1^-,$$

$$\int \sigma(\gamma, n)dE = 2.7 \times 10^{-3} MeV\,fm^2 \quad M1\ 0^+ \rightarrow 1^+.$$




$\gamma + {}^{76}Se$ =IAS $J^\pi$

$n + {}^{75}Se\ \ 3/2^-$

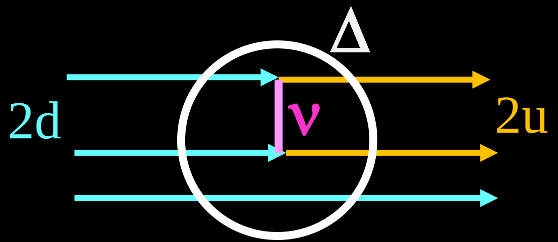
x=d/s, f/p fraction

V $\tau$ $1^-$ $2^+$

AV $\tau\sigma$ $1^+$ $2^-$

H. Ejiri, A. Titov
PR C 88 054610
2013

# Hadrons ( Δ, π) *

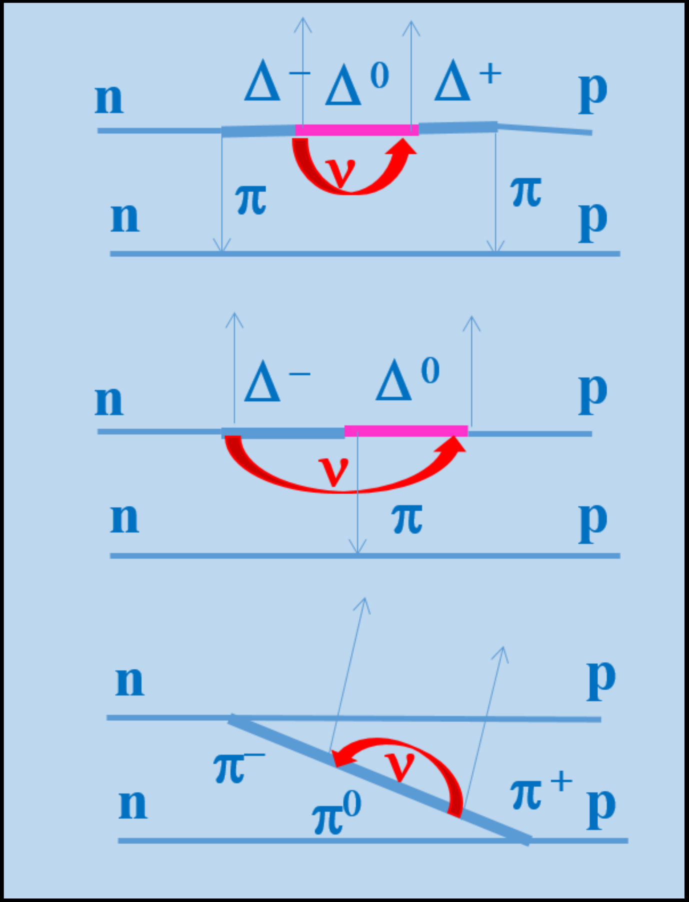



**N ⇒Δ quark τσ flip GR**
**0.3 GeV high excitation**
**0νββ in Δ,π enhanced**

**Effect on low ββ $0^+$ - $0^+$**
**$P(\Delta)^2 \sim (10^{-2})^2 \sim 10^{-4} \sim (k=0.2)^4$**

**|n Δ> interferes with |n p>**
**$|I\rangle = |n\,p\rangle - \varepsilon\,|n,\Delta^+\rangle$**
**$M^{\beta} \sim k^{eff} M_0$ $k^{eff}$ (Δ)~ 0.6**

**Exp by β deays and CER**




*Pontecorvo; Haxton, Stephenson, Kotani Doi .

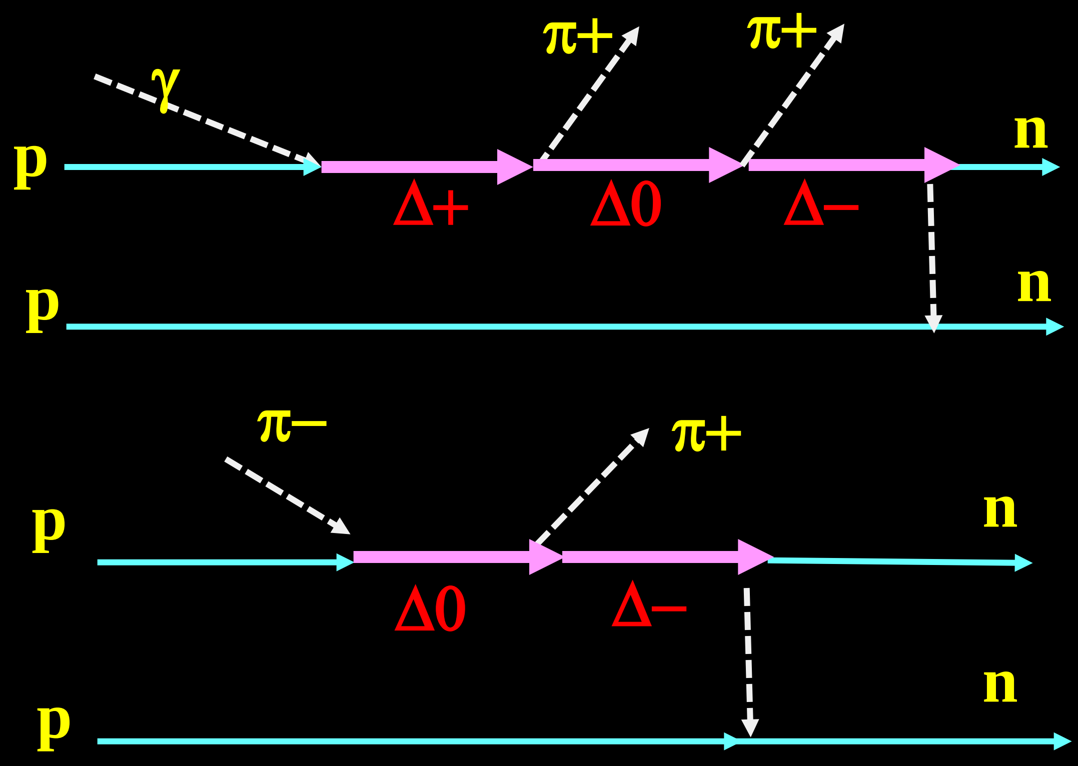
# DCE of hadrons

$\gamma + 2p = 2\pi^{+} + 2n$

$\Delta+\ \ \Delta-$ DCE

$\pi^{-} + 2n = \pi^{+} + 2p$

$\pi+\ \ \pi-$ DCE

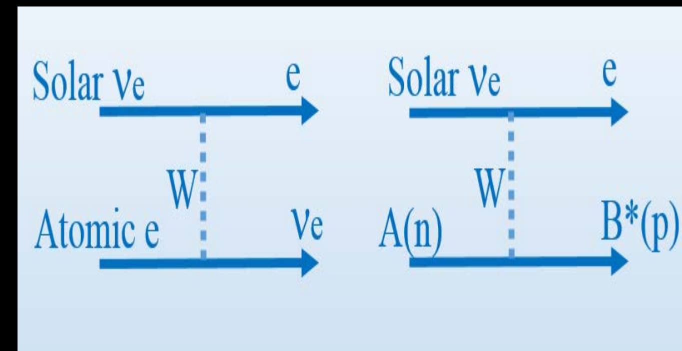


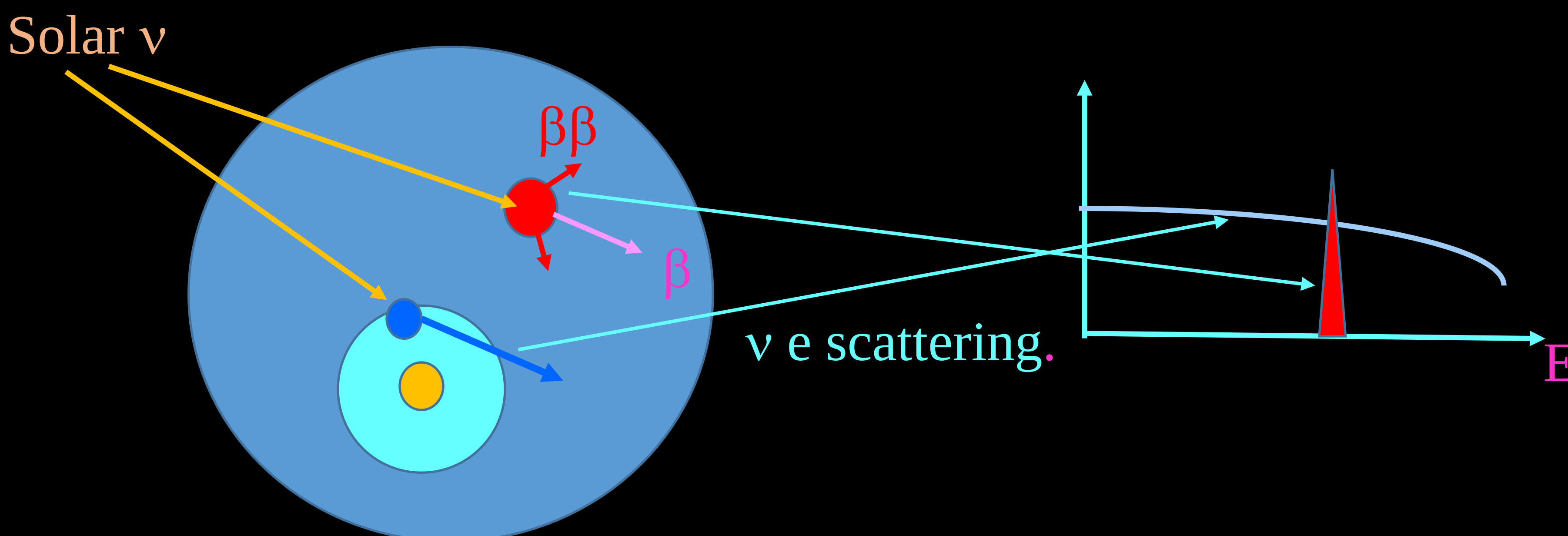

Hodron contributions

# 3. Solar-$\nu$ interactions with DBD detectors and BG contributions

# Solar-ν interactions with nuclei and atomic electrons in DBD detectors are serious BGs

- **Solar ν unavoidable.**
- **BG rate ~ or > or < ββ signal rate**
- **ν cross section on DBD nucleus,**
- **E-resolution, ratio of DBD nuclei to scintillation detector atoms**



# BG rate and solar-ν interaction by CER

Mass sensitivities $\langle m_\nu \rangle = (2\ m^0 \sim 40\ \text{meV})\ (NT)^{-1/4}\ (B)^{1/4}$

with M=2, ε=0.6 B=BG/t y NT=t y

BG /t y ≤ 1 NT/t y~4 y t to get IH 30 meV

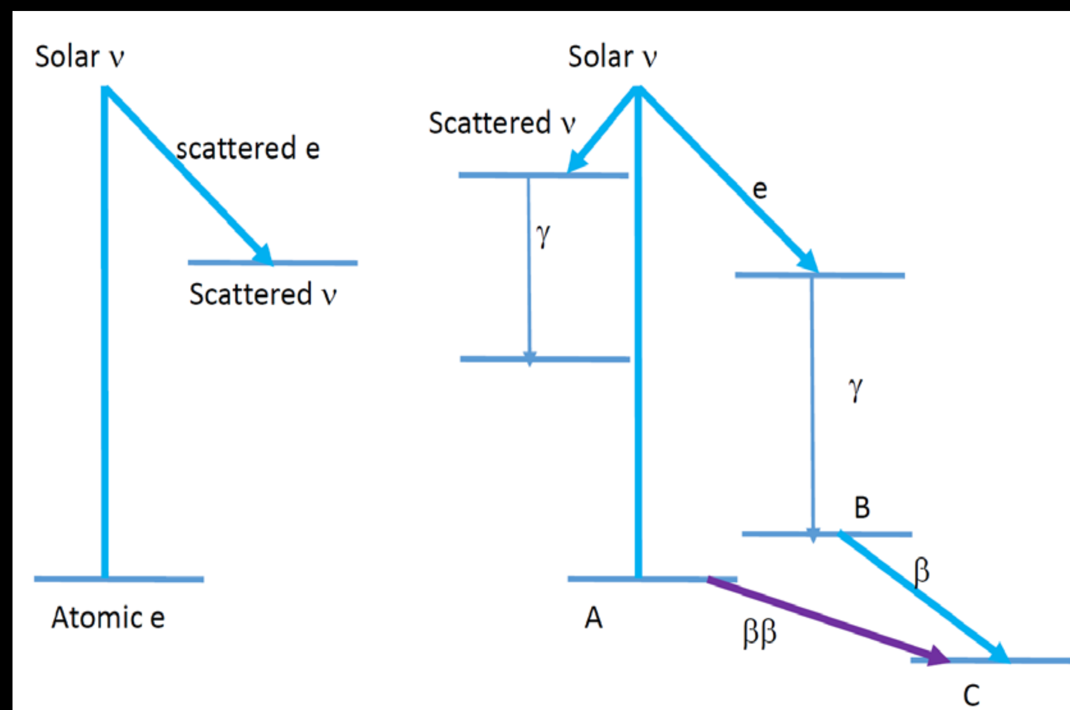
≤0.01/ty NT ~ 100 ty to get NH 3 meV

Solar ν interactions

i. DBD nuclei

ii. Other isotopes
if enrichment
<<100%

iii. Liquid scintillator
atoms and nuclei
if concentration << 1



# Solar-ν CC int.with DBD nuclei

| Isotope | pp | pep | $^{7}$Be | $^{8}$B | $^{13}$N | $^{15}$O | Total |
|---|---|---|---|---|---|---|---|
| $^{76}$Ge | 0 | 0.7 | 0 | 5.0 | 0.06 | 0.4 | 6.2 |
| $^{100}$Mo | 390 | 8.2 | 126 | 6.0 | 6.7 | 8.3 | 545 |
| $^{130}$Te | 0 | 3.0 | 23.2 | 6.1 | 1.3 | 2.4 | 35.9 |
| $^{136}$Xe | 0 | 6.0 | 50.9 | 9.8 | 2.3 | 4.7 | 73.4 |

H. Ejiri et al *
PR L 85 2000 2917

H. Ejiri S. Elliott
PR C 89 2014

Solar ν GT responses from the GT responses by CER ($^{3}$He,t)

1.Large pp-ν to $1^{+}$ ground state for pp-ν study * Ejiri Zuber

2. $^{130}$Te, B=1.3/ty at ε'=5 % (SNO+)

SSTC 12.4 hr and/or E-resolution of 0.2%

B=0.05 with ε'=0.2% (CUORE) << B(RI)= $10^{3}$/t y at 2014

3. $^{136}$Xe, B=1.5/ty at ε'=5 % Large $Q_{\beta}$~$Q_{\beta\beta}$ SSTC 13.2d. Tracking

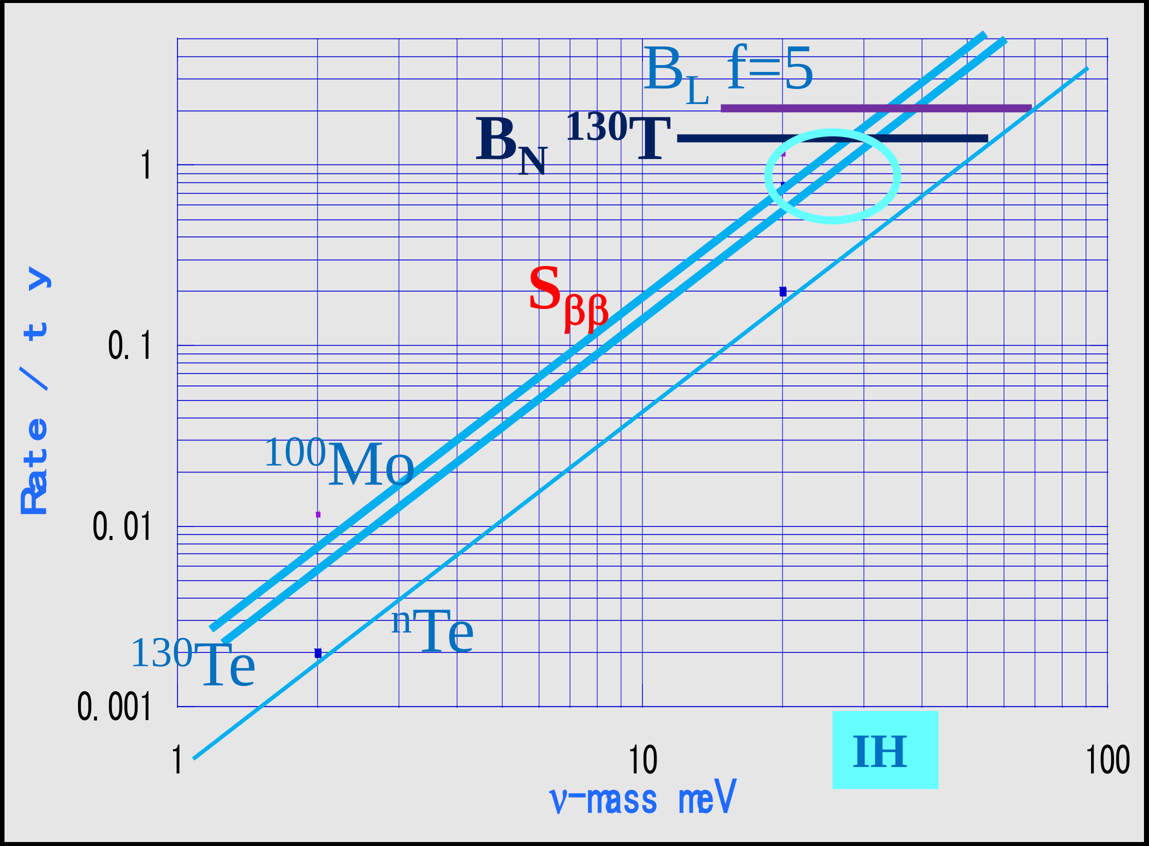
<< B~100/t y at 2012 EXO

# Solar-ν BG rates for liquid scintillator and ββ signal rate

Solar-ν $B_L = 0.4\ f$ with f= ε'(E-resolution) / R(concentration)

$S_{\beta\beta} = 0.7\ [M/2]^2\ [m_n/20\ \text{meV}]^2$


H. Ejiri
K. Zuber
2015

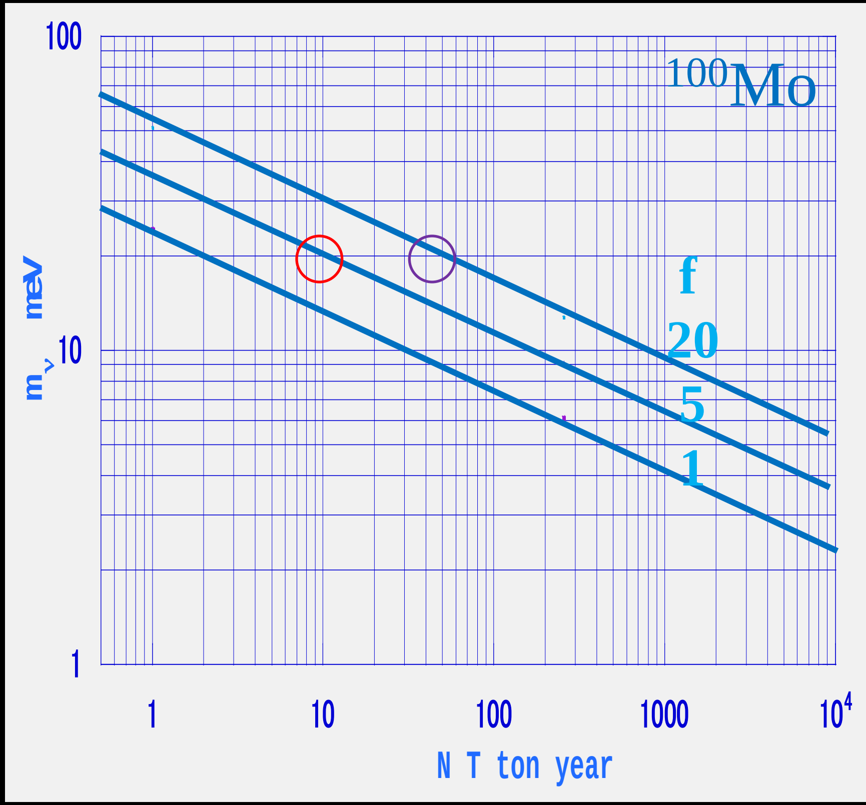

$^{130}$Te $B_L$=2.2 /ty, $^{136}$Xe $B_L$=3.0 /ty in case of f=5, ε'=5% R=1%

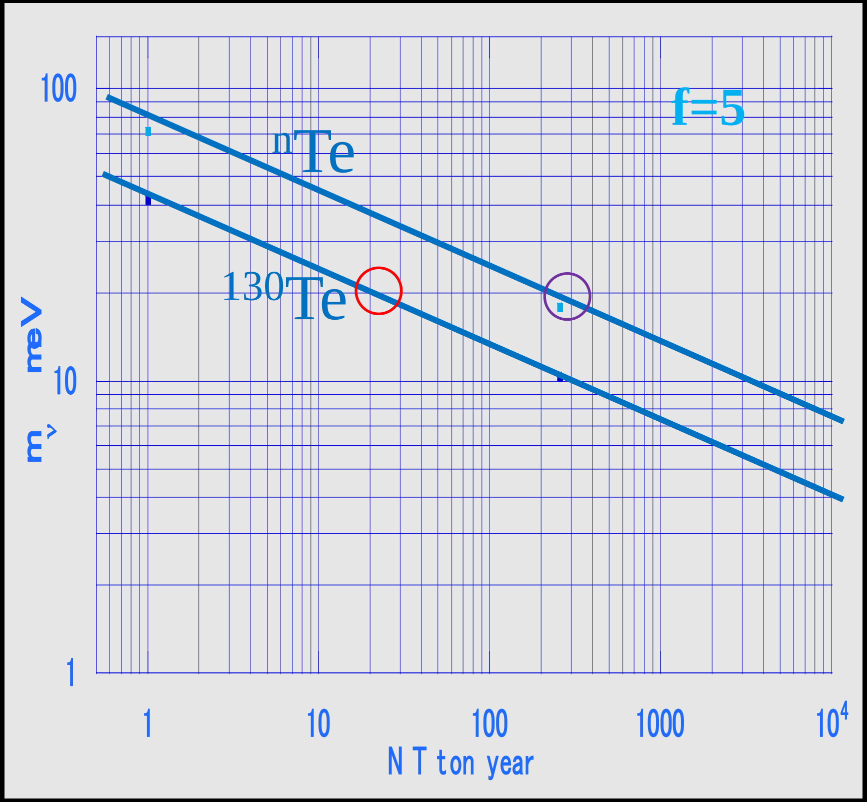
# Solar-ν in liquid scinti. with DBD isotope*

- H. Ejiri,
- K . Zuber 2015

B=Solar-ν e scat. in liq.scinti. $m = m^0 k [f^{1/4} / (NT)^{1/4}]$

f= ε'/R, ε'= Energy resolution R=N(ββ)/(/N(Liq.) Concentration




M=2, f=5 (ε'=5%, R=1%) 10 ty, f=20 (ε'=10%, R=0.5%) NT=40 t y for IH.

○ M=2, f=5 (ε'=5%, R=1%), NT=20 t y for IH, 200 ty if $^{n}$Te.

# Summary

1.Single β NMEs with i=$1^+$, $2^-$, ( $3^+$) low-states and GRs by
high ΔE (He,t) CERs, and $\beta^+$ GR ($1^+$,$1^-$,$2^-$) by
μ CER ($\mu,\nu_\mu$xn βγ) help/confirm theories for $g_A{}^2 M_{\beta\beta}$.

2. Experimental $M^\beta$(1+, 2-, 3+) for low states by CERs
are used to evaluate $M^{\beta\beta}$ on the basis of FSQP

3. $M^\beta$(1+, 2-, 3+) are reduced from QP by $k^{eff}$~ 0.2,
$k_{\tau\sigma}$ ~ 0.4 due to nuclear τσ, and
$k_m$ ~ 0.5 due to medium isobar effects ($g_A$~0.65),
which are not included in pnQRPA

4. Solar ν CC & NC with DBD nuclei/atoms and atoms
in liquid scintillator with DBD are, if ε'~5 %
resolution, BG~a few/t y ~ S(ββ) , serious BG for IH exps.

# Remarks

It is timely to discuss realistic and coordinated studies of IH-DBD EXPs and DBD NMEs.

1. EXPs with N~tons >80%, B<1/t y, $\Delta$E<a few %

2. NMEs theories and CER experiments if $M^{0\nu}$~ > or <2, if $g_A$ ~ 0.9~0.6

3. The NUMEN workshop/project will contribute much to studies of DBD NMEs

# Thank you for your attention

**Ejiri-weekend house at Shounan**

**Group I**
**28<N<50**
**28<Z<50**

**Group II**
**50<N<82**
**28<Z<50**

**Group III**
**50<N<82**
**50<Z<82**

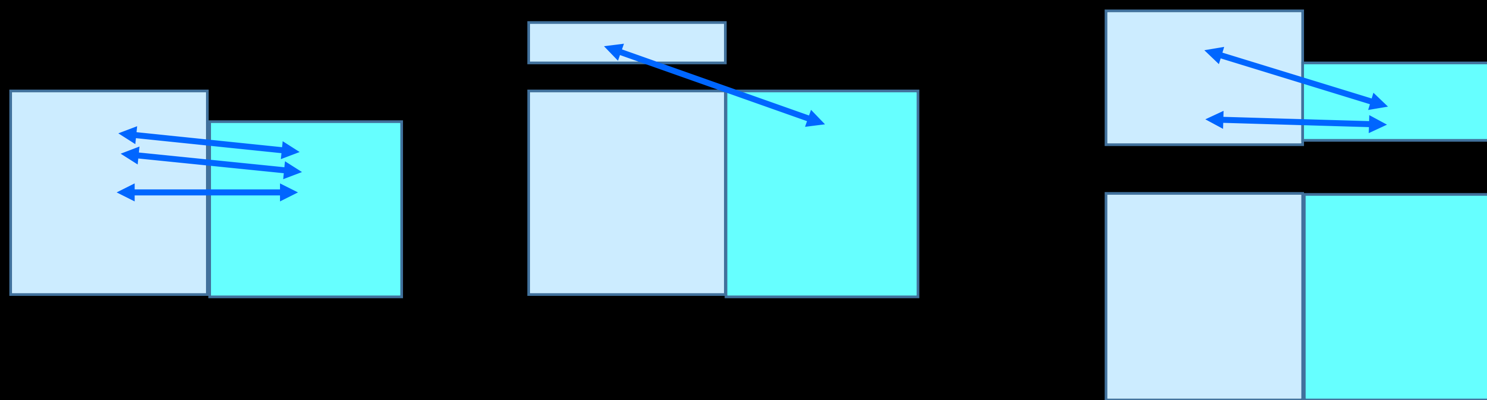
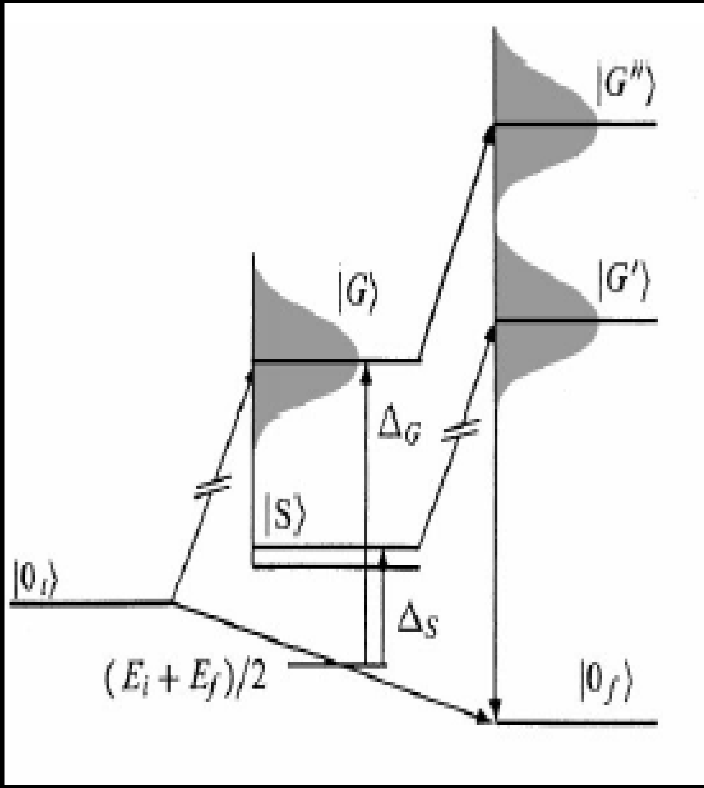


**Table 1.** FSQP shell configurations for DBD nuclei.

| Group | $Z, N$ | FSQP GT configuration | DBD nucleus |
|---|---|---|---|
| I | 28$\leq Z, N \leq$50 | $1g^p_{9/2}1g^n_{9/2}$, $1f^p_{5/2}1f^n_{5/2}$, $2p^p_{3/2}2p^n_{1/2}$ | $^{76}$Ge, $^{82}$Se |
| II | 40$\leq Z \leq$50, 50$\leq$N $\leq$70 | $1g^p_{9/2}1g^n_{7/2}$ | $^{96}$Zr $^{100}$Mo, $^{106}$Cd $^{116}$Cd$^{128}$ |
| III | 50$\leq Z, N \leq$82 | $2d^p_{5/2}2d^n_{3/2}$, $1h^p_{11/2}1h^n_{11/2}$ | $^{128}$Te, $^{130}$Te, and $^{136}$Xe |

# Double ββ symmetry and GR

$T^{2\nu}=\tau\tau\sigma\sigma/\Delta$, $T^{0\nu}=\tau\sigma\tau\sigma\ /|r_1-r_2|$,




$[H, T] \sim E_{GG}\, T$

T|i> Double (β-phonon) GR,

GR(ββ) absorbs most T(ββ) ,

Little for other; <f|T|i> ~0

2νββ T=τστσ,

T|i> = |DGT GR> , most strength

Little GT ββ to low states

$M^{2\nu}\sim 2\ 10^{-2}\ M^{2\nu}$(SUM) $B(GT^2)\sim 4\ 10^{-4}\ B(GT^2$ SUM)

although $M^{2\nu}$ to low states are favored by the E denominator

0νββ T=τστσH(r,r), T|i> = |ββ GR> ,

Little 0νββ strength left to low states as in 2νββ ??.

# Solar-ν interactions with DBD isotopes* and atoms**

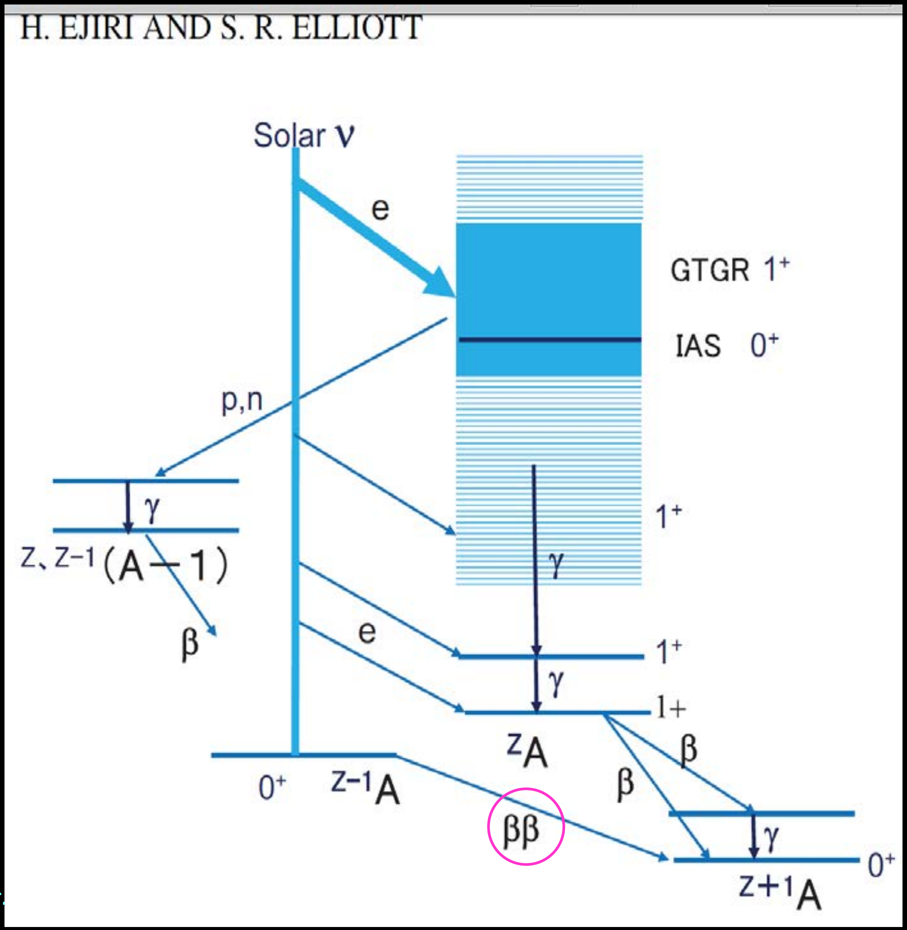
CC with nuclei : main

A.CC GT pp-ν, $^{7}$Be-ν β >ββ

B.GT GR by $^{8}$B-ν, γ(e)

C.CC ν-e

D. (ν,e p/n) γ(e) β




Since they are continuum spectra, good E resolution is effective.

- * H. Ejiri S. Elliott PRC 89 2014 055502, (DBD nuclei)
- ** N. deBorros K. Zuber, PRC 79 2012 6 (DB atomic electrons)

# 5. Concluding remarks

# Concluding remarks

It is crucial and timely to discuss
realistic and coordinated IH ν-mass DBD exps.

Key points are

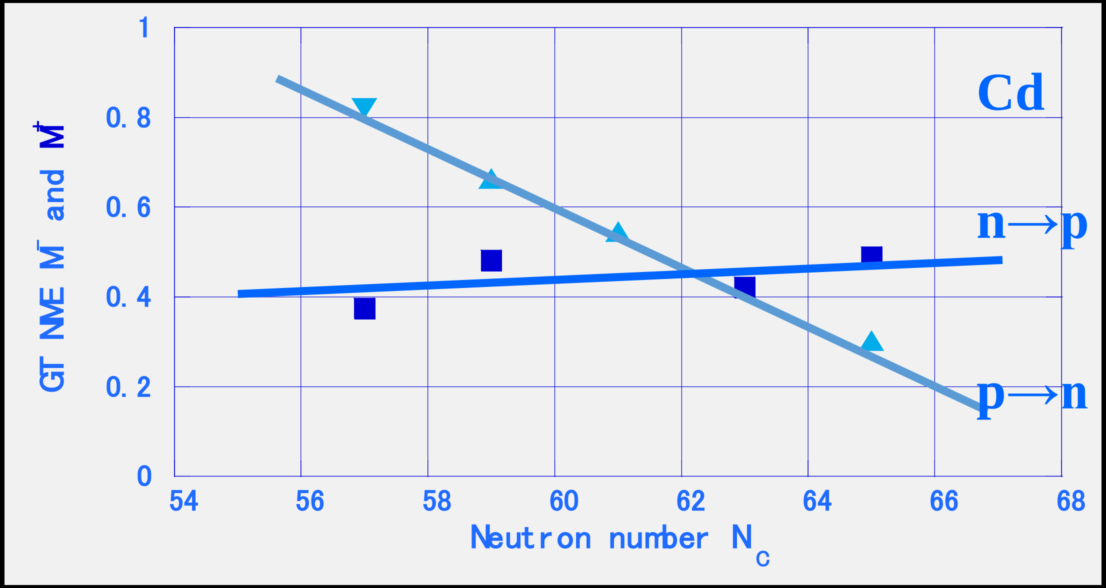
S(ββ) > 1-2/y for 25 meV
$M^{0\nu}(g_A)$ ~2 or ? ⇐ Present workshop
N~multi-ton ~80% enrichment,

BG~0.3/t y or less
ε=resolution < a few %,
R=N(DBD)/N'(others) > 0.1

$M(\beta\beta) = M^- M^+ / E$

$M^-$ $(n \rightarrow p \;\; V_n U_p)$ $M^+$ $(p \rightarrow n \;\; V_p U_n)$

$P = (P^- = V_n U_p)(P^+ = V_p U_n) \sim$ constant



# A. Muon capture nuclear γ at SIN

**Ordinary muon capture (OMC) studies for the matrix elements in ββ decay.**

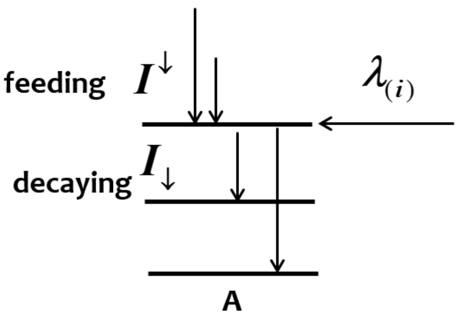
What do we gain from μ-capture for the ββ decay?

**Experiment: PSI, beamline μ-E4**

K.Ya. Gromov, **D.R. Zinatulina**, **D. Frekers**, C. Briançon, V. Egorov, R. Vasiliev, M. Shirchenko, I. Yutlandov, C. Petitjean, J. Deutsch.

14.06.2013
JINR DLNP

## Extraction of the partial rates




$$\lambda_{(i)} = \frac{\sum I_{\downarrow} - \sum I^{\downarrow}}{\varepsilon \sum I(nK)}$$

**detailed balance**

$$\lambda_{cap} = \lambda_{total} - Q\lambda_{decay} \quad Q \rightarrow \text{Huff-factor}$$

$$\lambda_{(i)}[\%] = \frac{\lambda_{(i)}}{\lambda_{cap}}$$

**($\mu$, $\nu_{\mu}$) low states,**

**No $\nu_{\mu}$ measurement, but many γ from and to the state**
**Very hard to get the strength**
**Limitted to low states.**

J. Suhonen, M. Kortelainen Czech. J. Phy. 56 2006 519, EXP 453.
V. Egorov (μ, γ , n γ, p γ) on $^{48}$Ti, $^{76}$Se 2004 γ –exp.

# SD 2$^-$ τσ NN & nuclear medium $g_A$

$M(EXP) = k\, M(QP)$

$k = k_{\tau\sigma}\, k_{NM} \sim 0.2$

$M(QRPA) = k_{\tau\sigma}\, M(QP)$

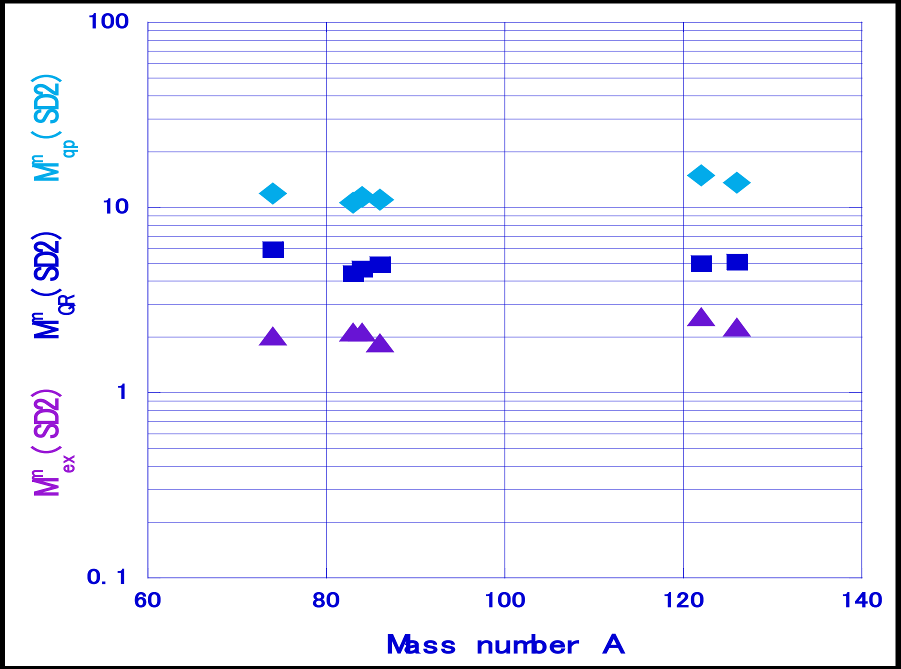
$k_{\tau\sigma} \sim 0.4$ τσ correlation

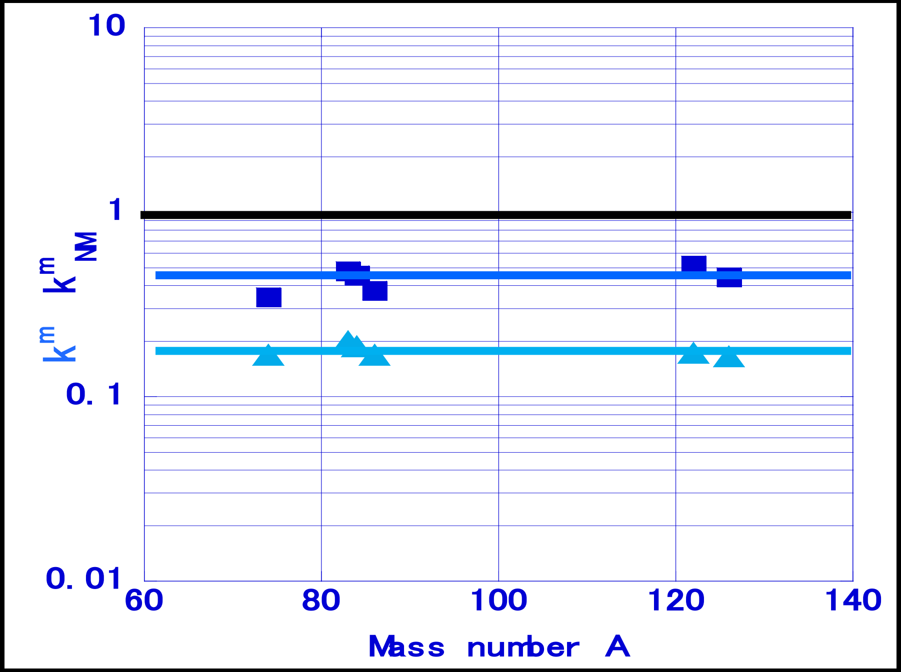
$M(EXP) = k_{NM} M(QRPA)$

$k_{NM} \sim 0.5 = g_A^{eff}$ n-medium

H. Ejiri, N Soucouti, J. Suhonen, PL B729, 27 2014 .

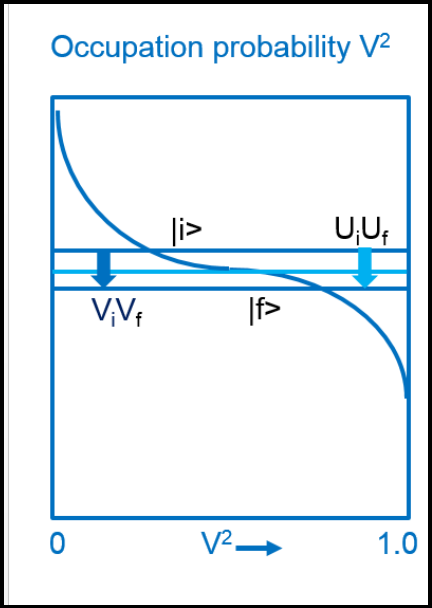
Similar $g_A$ in J. Suhonen O. Civitarese PLB 725 (2013) 153

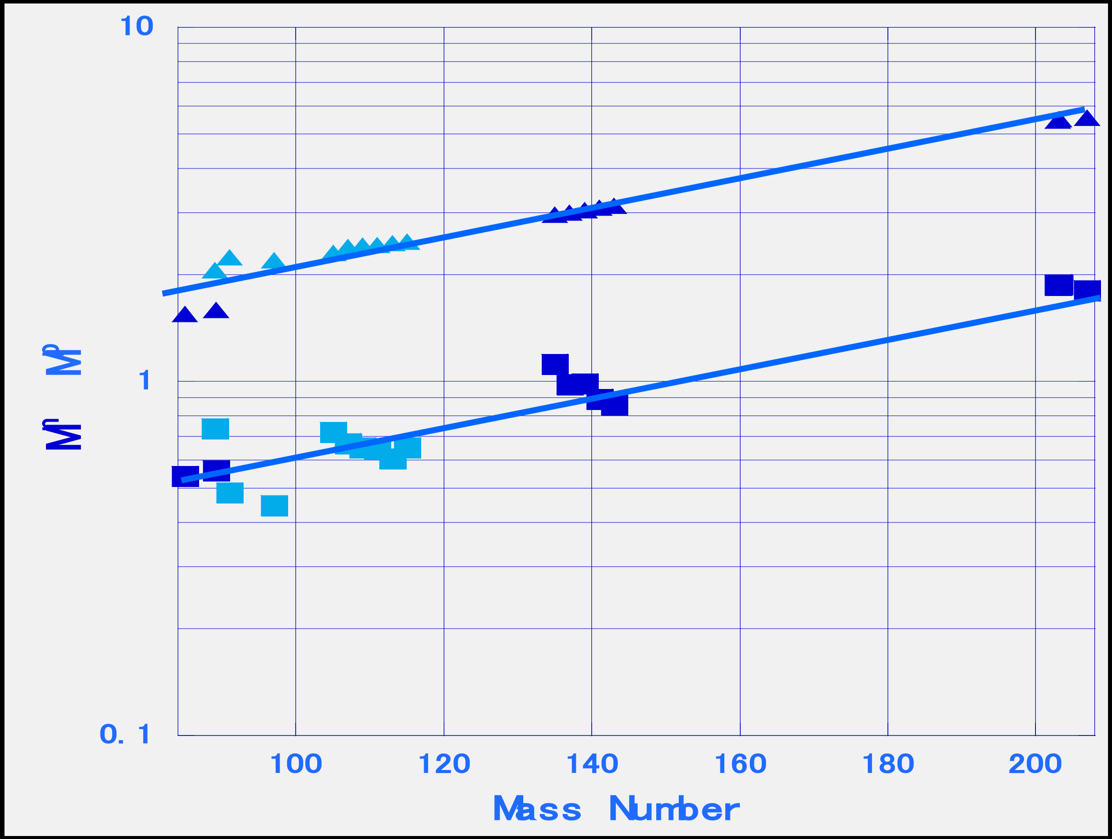


# SO (Spin Octupole) ν-responses =(NME(SO))$^2$

$$M(SO) = \langle \tau^{\pm} (\sigma \times r^3 Y_3 \rangle \sim M4\,\gamma$$



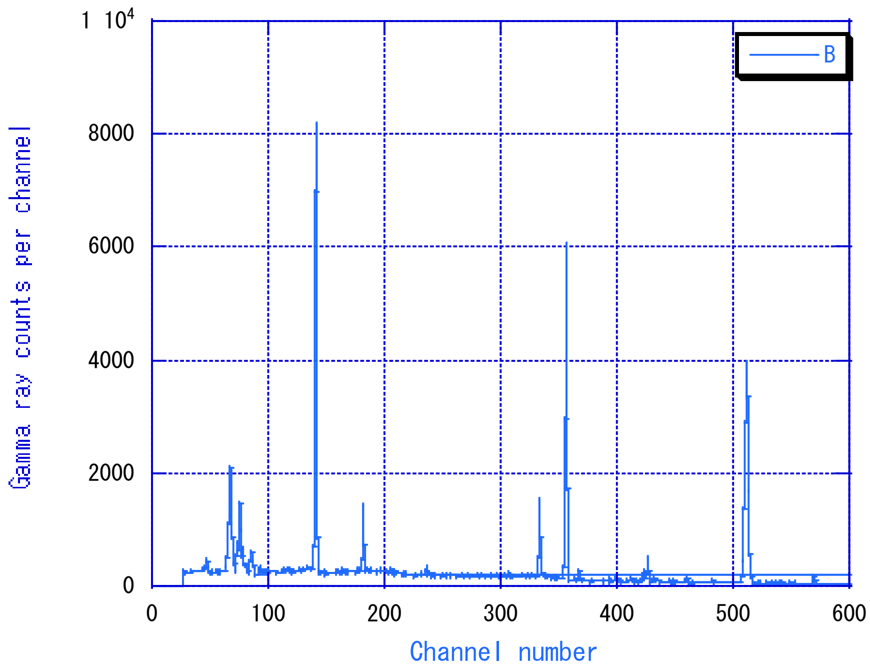

$M(M4) = M_{sp}\, P$

$P = V_i V_f + U_i U_f \sim 1$

M4 γ  M(EXP) =kM(QP) k~0.33 for proton and neutron

# Non distructive nuclear isotope detections

## RPID Mo Au (γ,n)



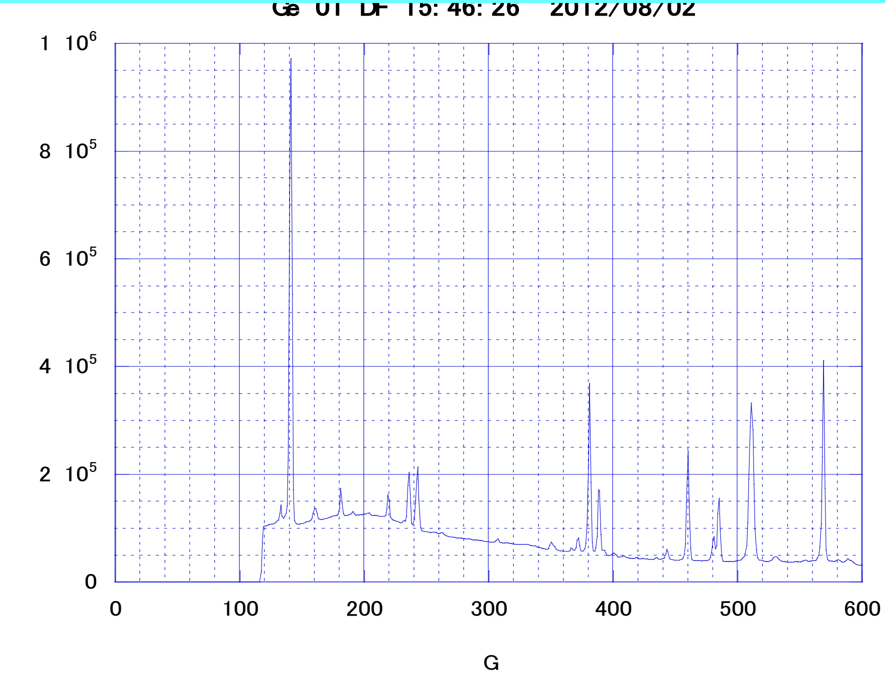

$^{197}$Au 7.3 % in Mo ⇒ 5 ppm ➡ppb

3 $10^{10}$ γ at NewSUBARU

$^{99}$Tc 140 kev γ for medical applications

H..Ejiri, T. Shima et al., JPSJ 80 (2011), Phy Rev ST 15 (2012)

## MCID Mo (μ,n)




$^{100}$Mo 9.6 % in Mo ⇒ 7 ppm ➡ppb

3 $10^{9}$ μ ( 0.7 hr I μA p)) at RCNP

MuSIC $^{99}$Tc 140 kev γ for medical

H.Ejiri, I.Hashim, Y.Kuno, K.Ninomiya, A. Sato, T.Shima, K.Takahisa, et al.. JPSJ 82 2013 044202 (2013).

# GR / Medium Effect on single β/τσ responses

P-space ; Quasi-particle

$M(SQP) = k_A m_{sp} V_n U_p$

occupied n ⇒ vacant p

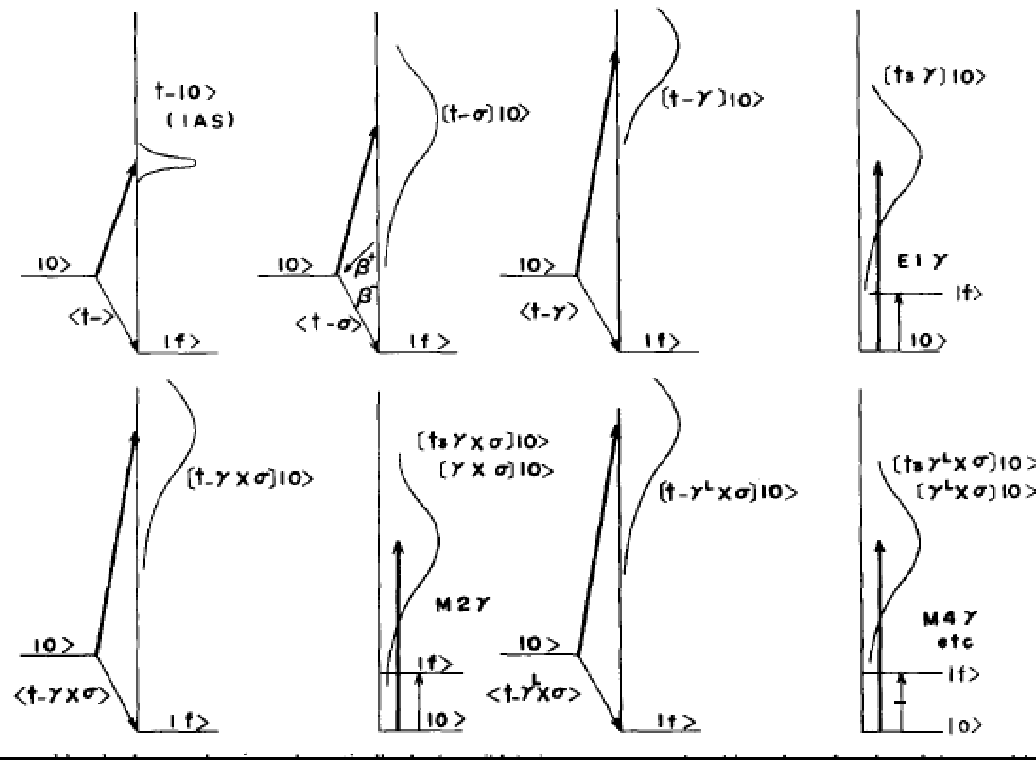
Q=1-P space  $M = k^{eff} M(SQP)$

$k^{eff} = k^{eff}(\tau\sigma)\, k^{eff}(\Delta)$

$k^{eff}(\tau\sigma) \sim 0.33$ from τσ polariz

$k^{eff}(\Delta) \sim 0.7$   Δ τσ polar

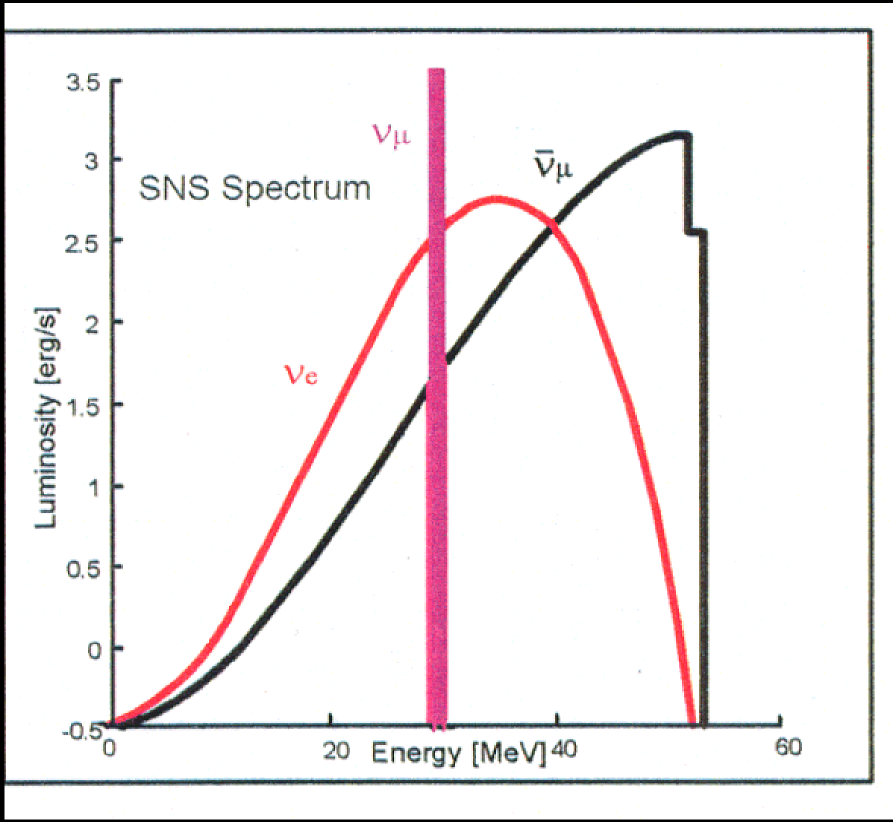
Δ effect on GT Bohr M




Small admixtures of GR and Δ/π , nuclear medium effects are hard to calculate.  $k^{eff}$ : uniform effect is given by exp.

# Low energy ν probes

$p + Hg \rightarrow n\ \pi^+$
$\pi^+ \rightarrow \mu^+ + \nu_\mu$
$\mu^+ \rightarrow e^+ + \nu_e + \text{anti-}\underline{\nu}_\mu$




H. Ejiri NIM. 503 (2003) 276 – 278.


$E(\nu_e)\ E(\nu_\mu) \sim$ 20-50 MeV

$\sim E(\nu$ SN), $E(\nu\ \beta\beta)$

$I(\nu) \sim 10^{14}$ / MW

$\sigma \sim 10^{-40}$ cm $^2$

Detectors ~ 1 ton

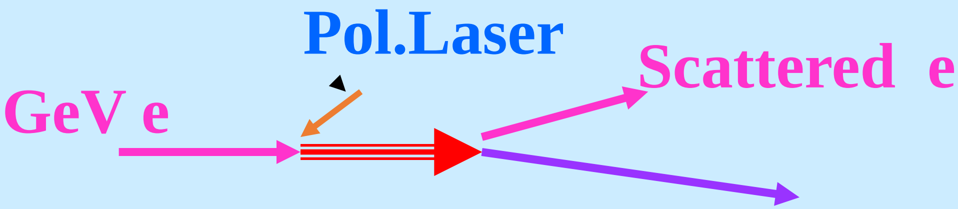
J-PARC 0.4 – 3 GeV,

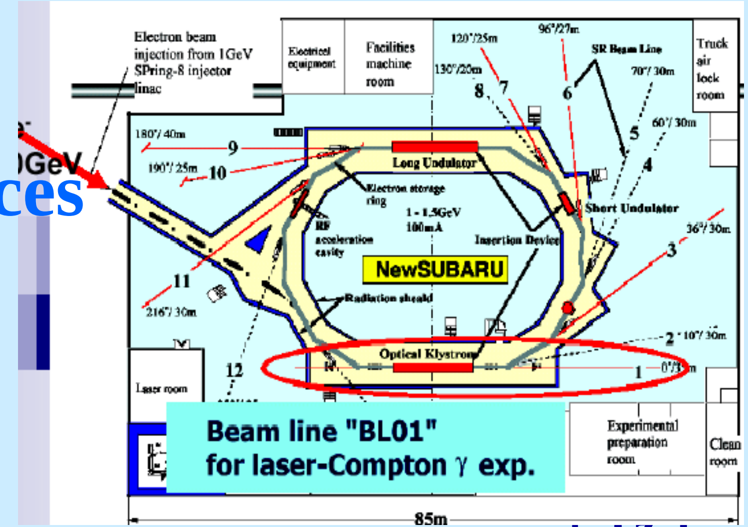
SNS 1GeV

RCNP 1MW under discussion

# Photon Probes

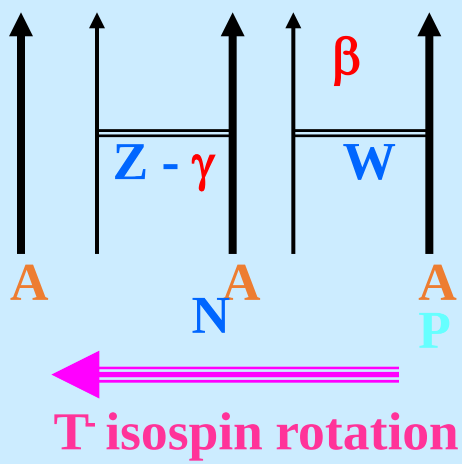
## LEPS Laser electron photon Sources

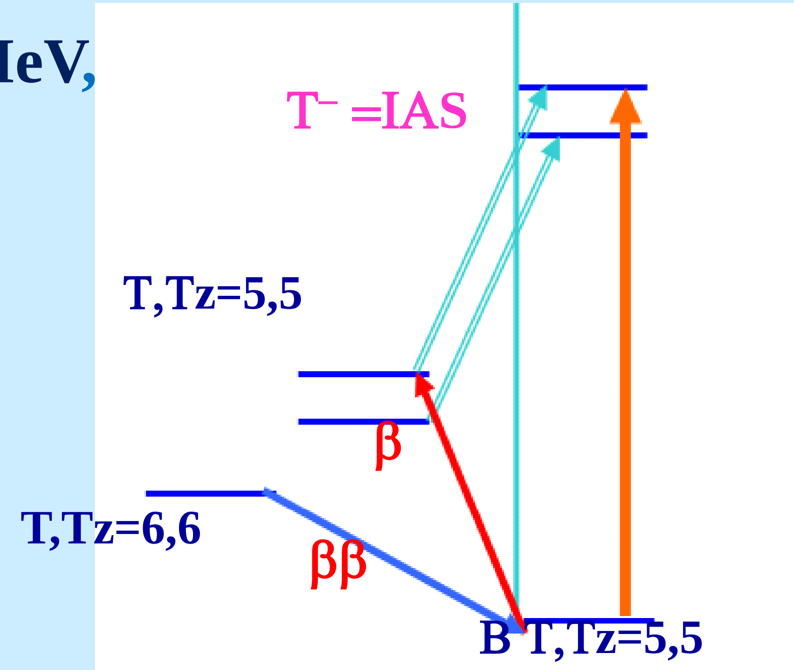



**Pol. Laser electron photon**

$E_\gamma \sim 4\,\gamma^2 E_l = 2\;10^8\, E_l \sim 20$ MeV,




**Responses via IAS**

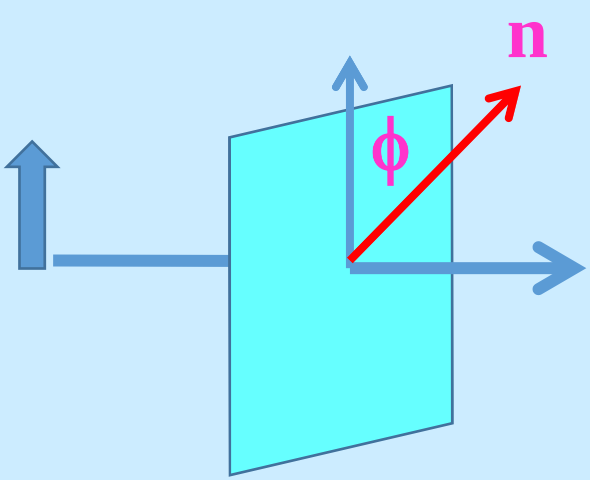
$\langle f\;|g\,M_\beta|\;i\rangle = g/e\,(2T)^{1/2}\,\langle f\;|\;em_\gamma\;|\;I\rangle$

H. Ejiri PRL 21 '68, PR 38 '78

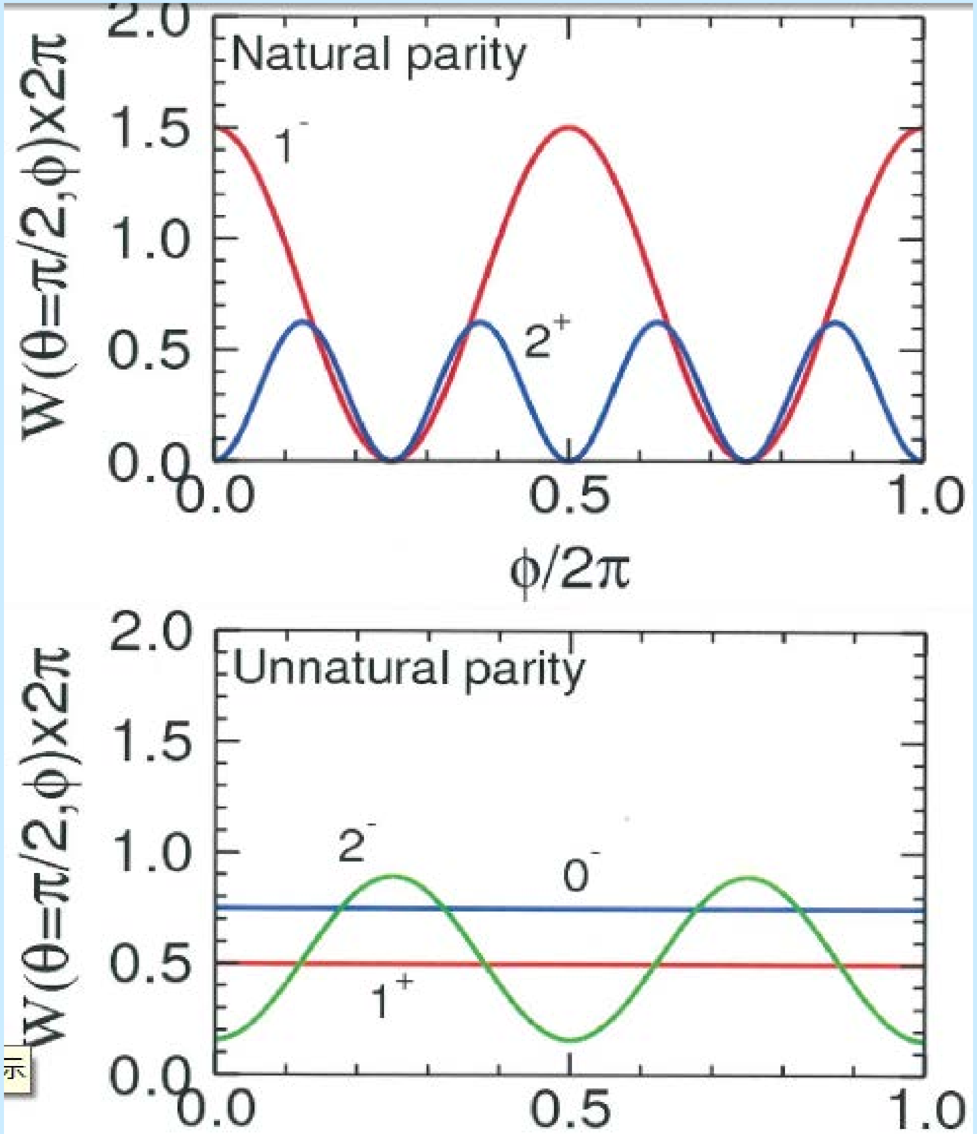
# Polarized photon

**Vector C** $\tau$ $1^-$

**Axial vector C** $\tau\sigma$ $1^+$ $2^-$




$\gamma + {}^{100}\mathrm{Mo} = n + {}^{99}\mathrm{Mo}$




**Ejiri Titov 2012**

# Single β τσ symmetry, τσ GR , τσ polarization

1. T= β transition/phonon operator

   $T= \tau Y_l, \tau\sigma\ Y_l$

2. $[H, T] \sim E_G T$

   T|i> ; T GR, most T strengths, and little <f|T|i> ~0

T=τ T|i> = IAS No τ Fermi strength

T=τσ, T|i> = GT GR , little (~ $10^{-2}$) GT strength to low states

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

Civitarese, Muto, T symmetry

3. T polarization

   $|f\rangle = |f\rangle_0 - \varepsilon|GR\rangle \quad M = M_0[1 - \varepsilon M_{GR}/M_0] = k^{eff} M_0$

$\varepsilon \sim 0.05$, $\varepsilon^2 \sim 0.003$ admixture of GR makes $k^{eff}$ =0.2 -0.1, as exps.

# Experiments for β/ββ responses/ ME

## To help evaluate/confirm $M^{2\nu}$, $M^{0\nu}$ theories.

1. Absolute/relative values for $M^{0\nu}$ , $g^{eff}_A$ $M^{0\nu}$ 20 %

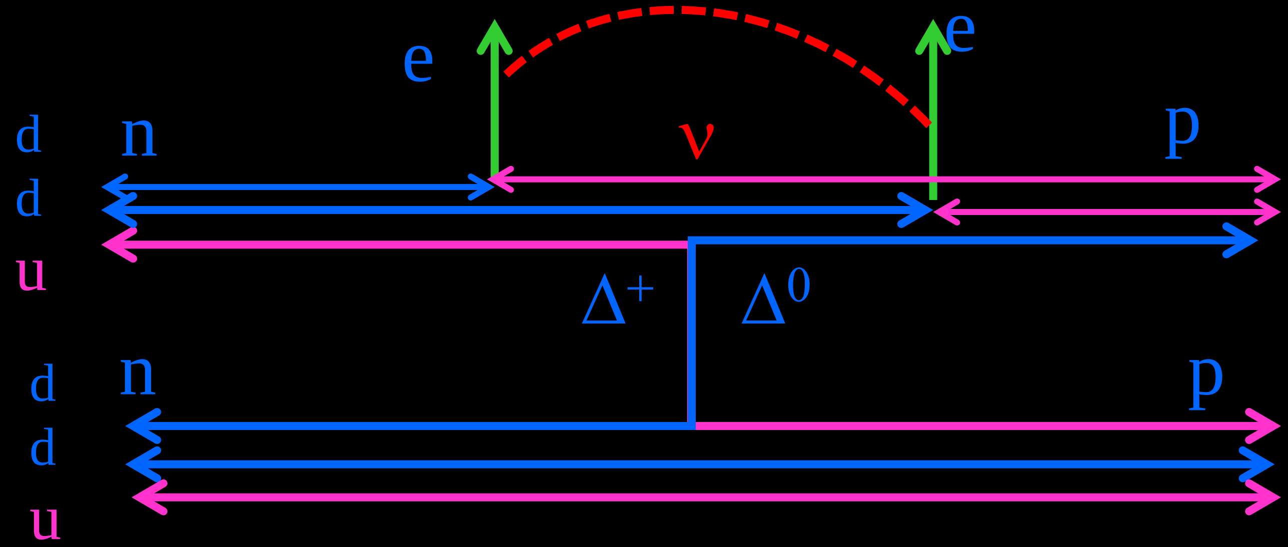
   Absolute values for [$m_\nu$, SUSY …] within 20%
   Hierarchy : m(IH)/m(NH) > 4, depending on α ,δ
   Mechanisms of light ν-mass /SUSY .

2. Experimental design
   Detector mass factor 4 more if $M^{0\nu}$ is 30 % less
   Choice of detector (ββ) nuclei and detector volume

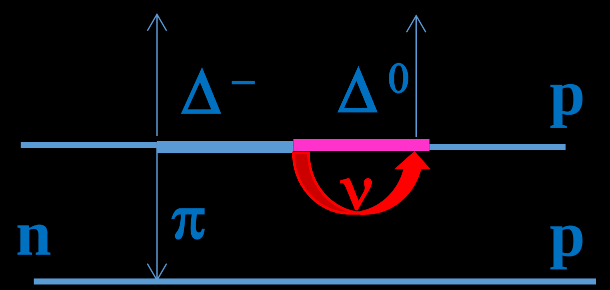
3. Experimental consistency if light ν-mass term.

**Non nucleonic degree Δ**

**ν-exchange in Δ ισ enhanced**

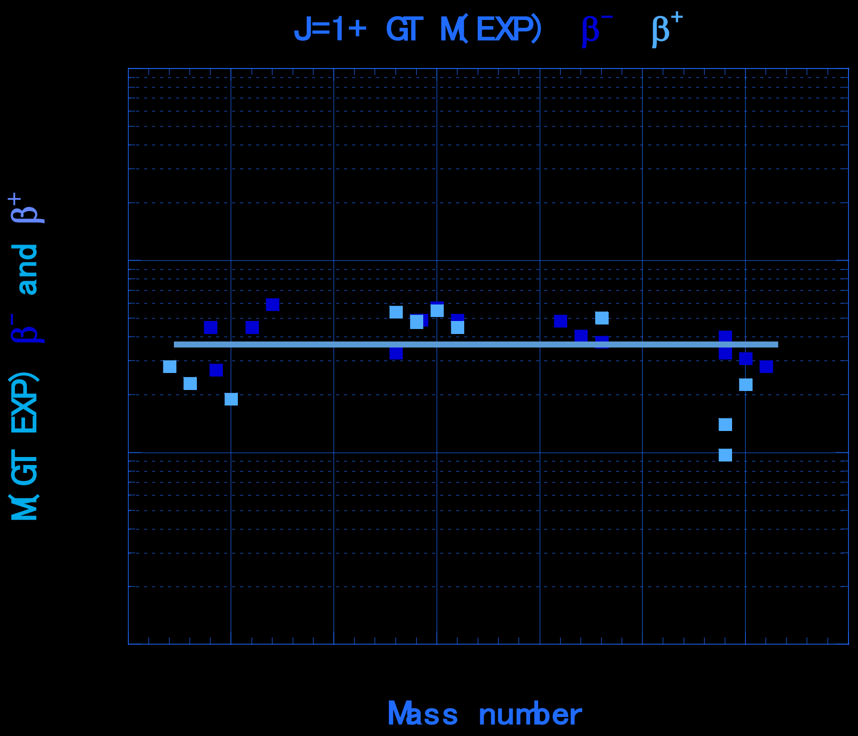


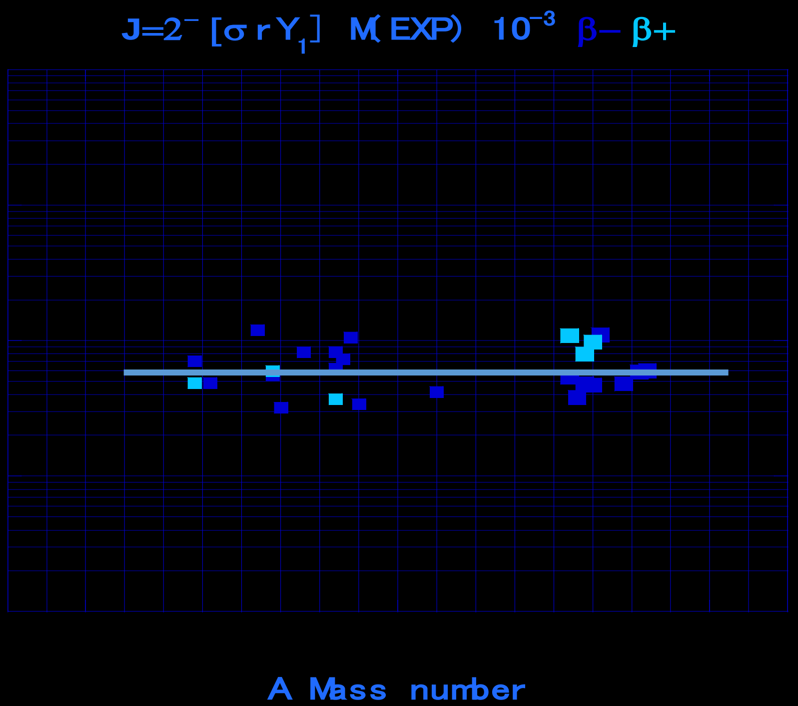

**Primacoff & Rosen process forbidden in 0+ - 0+ Doi, Kotani**




**Intermediate φ(pn)＋εφ (Δn) + εφ(Δp)** $M^{\beta} \sim k^{eff}(D) M^{\beta}{}_{0}$

# Nuclear Matrix elements from 0+ to $1^+$ and $2^-$




**M(1+) ~ 0.4**

**$k^{eff}$ =M(1+)/M(SQP) ~0.25**

**M($2^-$)~0.6 $10^{-3}$ n.u**

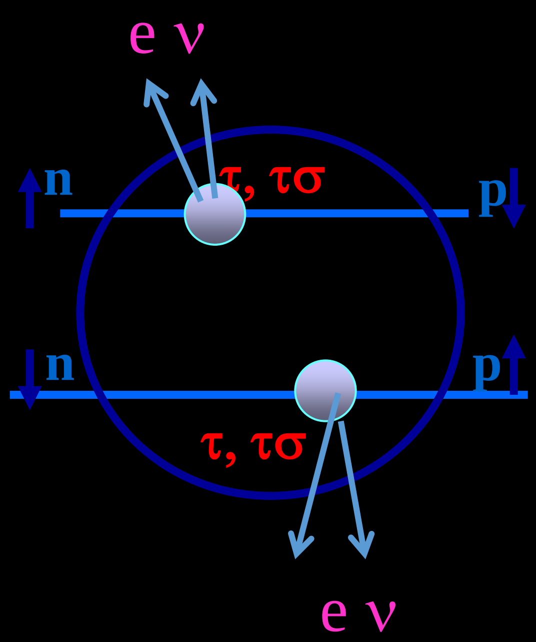
**$k^{eff}$ =(M($2^-$)/M(SQP) ~ 0.1**

| E keV | $T_{1/2}$ | 100Mo | 98 | 97 | 96 | 95 | 94 | 92 | RI |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | A RT |
| 140.5 | 66+6h | 1n | | | | | | | 99 Nb-Mo-Tc |
| 181 | 66h | 1n | | | | | | | 99 Nb Mo Tc |
| 658.1 | 72.1h | 3n | 1n | | | | | | 97 Nb Mo |
| 743.4 | 17h | 3n | 1n | | | | | | 97 Nb Mo |
| 459.9 | 23h | 4n | 2n | 1n | 0n | | | | 96 Nb Mo |
| 778.2 | 23h | 4n | 2n | 1n | 0n | | | | 96 Nb Mo |
| 849.9 | 23h | 4n | 2n | 1n | 0n | | | | 96 Nb Mo |
| 1200.2 | 23h | 4n | 2n | 1n | 0n | | | | 96 Nb Mo |
| 204.1 | 87h | 5n | 3n | 2n | 1n | | | | 95 Nb Mo |
| 934.5 | 10.2d | | 6n | 5n | 4n | 3n | 2n | | 92 Nb Zr |
| 141.2 | 14.6h | | | | 6n | 5n | 4n | 2n | 90 Nb Mo |
| 1129.2 | 14.6h | | | | 6n | 5n | 4n | 2n | 90 Nb Zr |
| 2319 | 14.6h | | | | 6n | 5n | 4n | 2n | 90 Nb Zr |
| 908.9 | 78h | | | | | 6n | 5n | 3n | 89 Nb Zr Y |
| 388.5 | 80h | | | | | 6n | 5n | 3n | 87 Nb Zr Y Sr |
| 484.8 | 80h | | | | | | 7n | 5n | 87 Nb Zr Y Sr |
| 380.8 | 13.4h | | | | | | 7n | 5n | 87 Nb Zr Y |
| 1076.7 | 4.7 | | | | | | 8n | 6n | 86 Nb Zr Y St |

# Nuclear waek/ν responses for ββ–ν

2νββ  A = B + 2β +2ν

$T^{2\nu} = G^{2\nu} [M^{2\nu}]^2$




$M^{2\nu} = (g_A)^2 <\tau\sigma\tau\sigma>$

GT isospin spin τσ 1*

F ττ is only to double |IAS>

H.Ejiri, Phys. Report 338 (2000) 265.

# T(β, ββ) mode GR quenches β and ββ to low states,

$k^{eff}$ = 0.3 for β , $k^{eff} = 0.3^{2} \sim 0.1$ for ββ, but

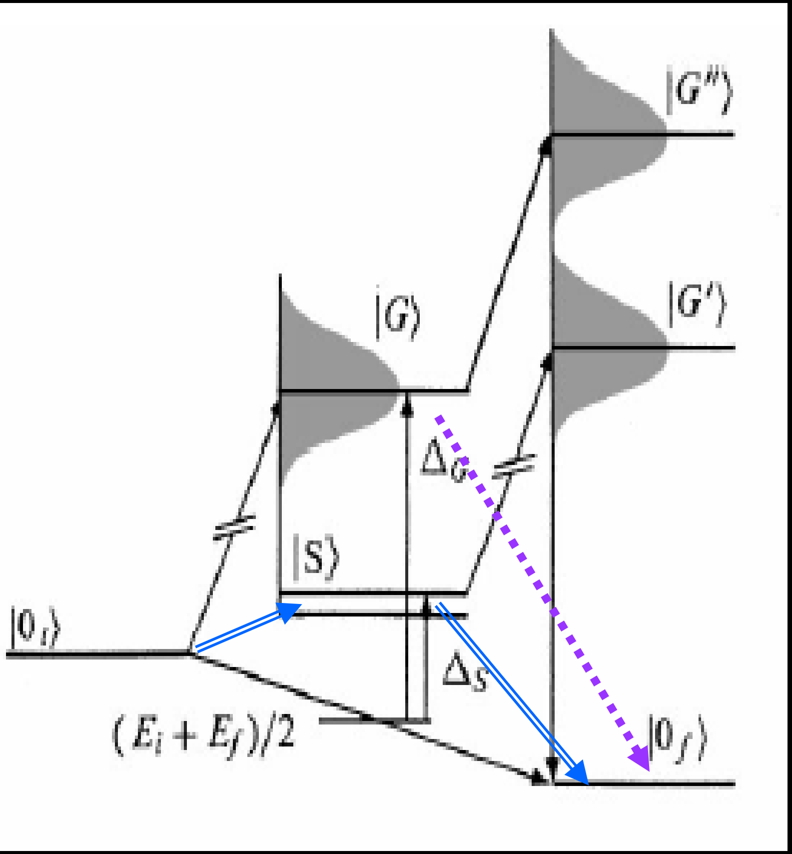
GR itself contributes little to ββ to low states

$$|S\rangle = Q_S|0_i\rangle, \qquad Q_S = Q_S^0 - \varepsilon Q_G^0 ,$$

$$|G\rangle = Q_G|0_i\rangle, \qquad Q_G = Q_G^0 + \varepsilon Q_S^0 ,$$

$$|0_f\rangle = Q_{S'}|S\rangle = Q_{S'}Q_S|0_i\rangle \quad \text{with } Q_{S'} = Q_{S'}^0 - \varepsilon' Q_{G'}^0$$

$$M^{2\nu}(GT) \simeq \frac{M_S^\nu M_{S'}^\nu}{\Delta_S} + \frac{\varepsilon M_S^\nu M_G^\nu}{\Delta_G}\left(1 - \frac{\varepsilon'}{\varepsilon}\right) .$$




$M^{0\nu} \sim M_s M_{s'} [1+\delta]$

$\delta = \varepsilon \; MG/Ms(1-\varepsilon/\varepsilon') \ll 1$

0.1 10 0.1

Ejiri Phys. Rep. 338 (2000)

Ejiri NP A577 (1994), JPSJ 65(199

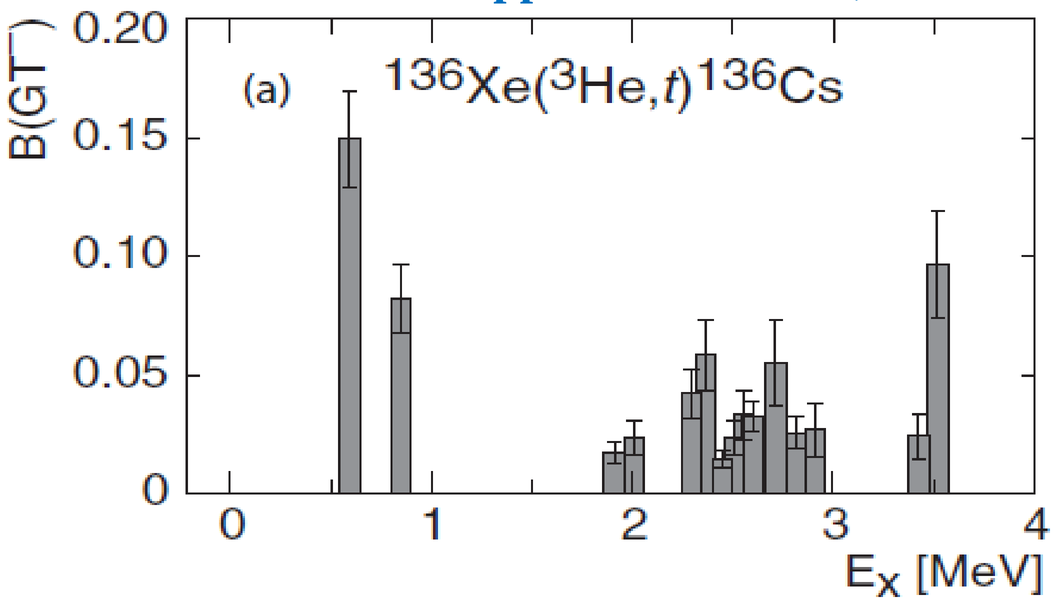
Ericson et al., PL B328 259 '94

Puppe frekers .. H.E, …PR C 84

## Spin strength

$B(GT) = |\sigma|^2$

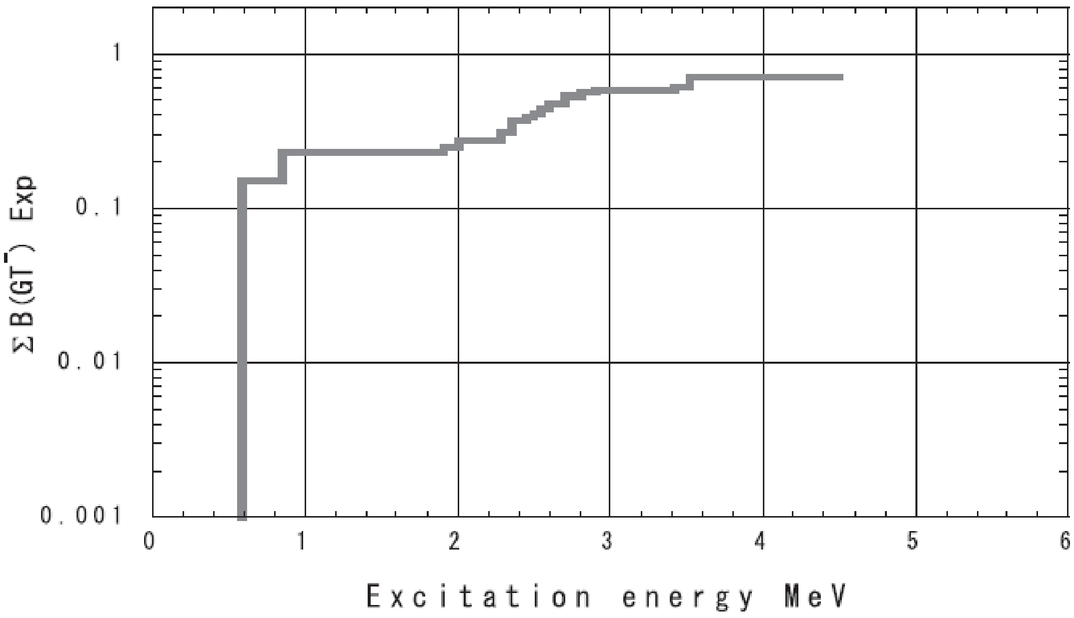
,




## Sum spin strength

$\Sigma B(GT) = \Sigma|\sigma|^2$

,



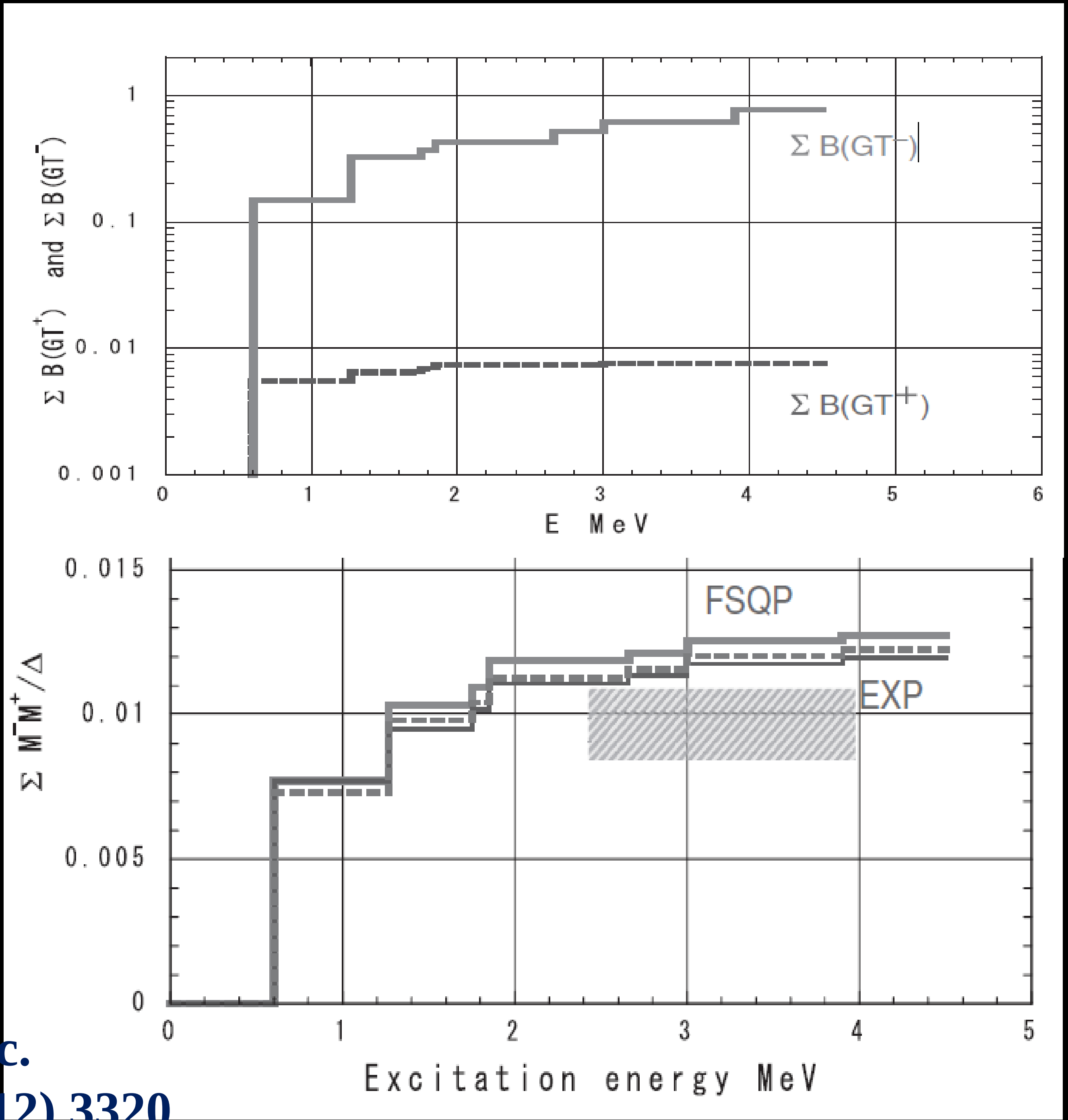
$\Sigma |M^{-}_{k}|^2$

$\Sigma |M^{+}_{k}|^2$

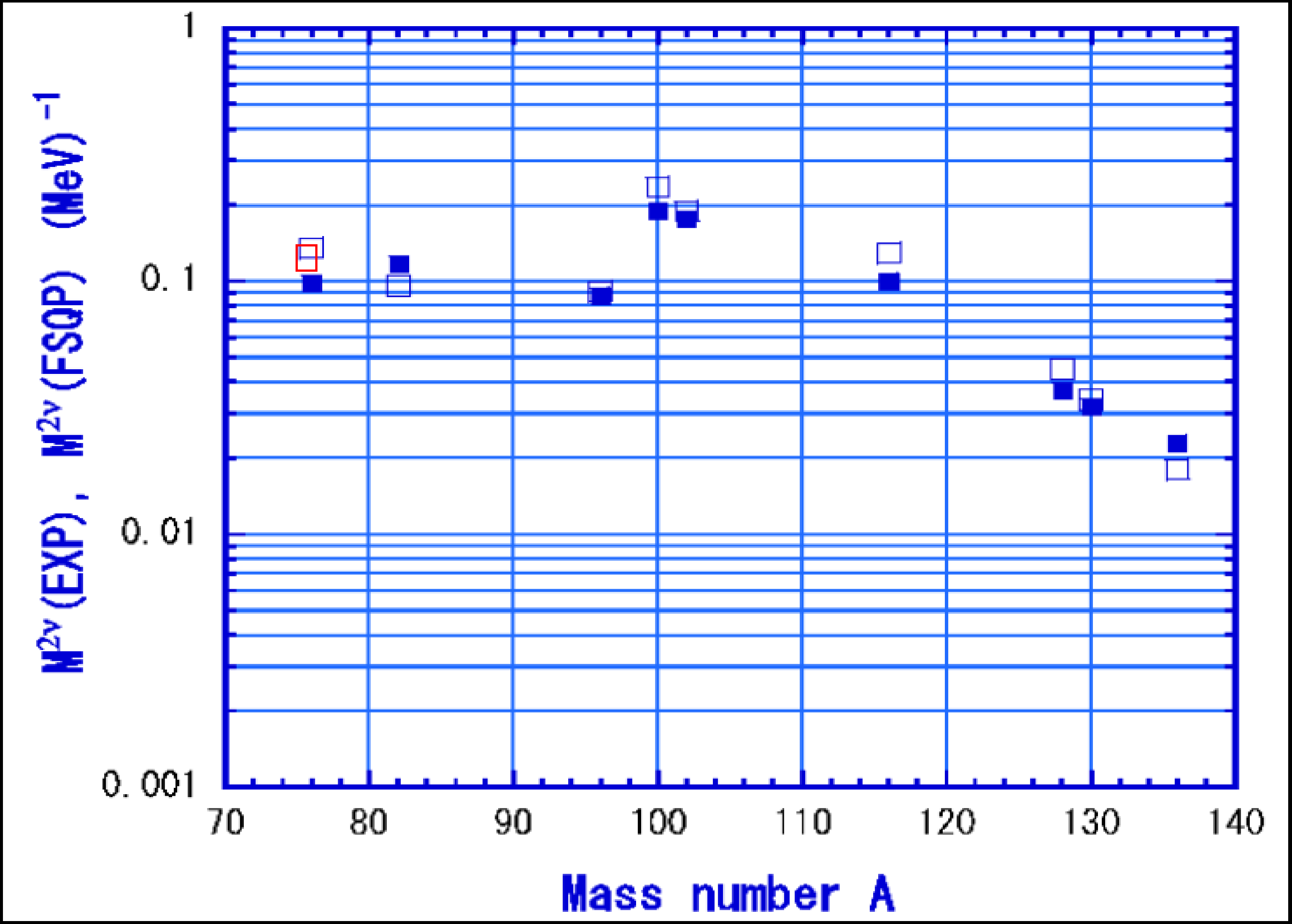
$M^{2\nu\beta\beta} =$

$\Sigma_k M^{-}_{k} M^{+}_{k} / \Delta_k$

**EXP: EXO KamLAND**




H. Ejiri J Phys. Soc. Japan Lett. 81 (2012) 3320

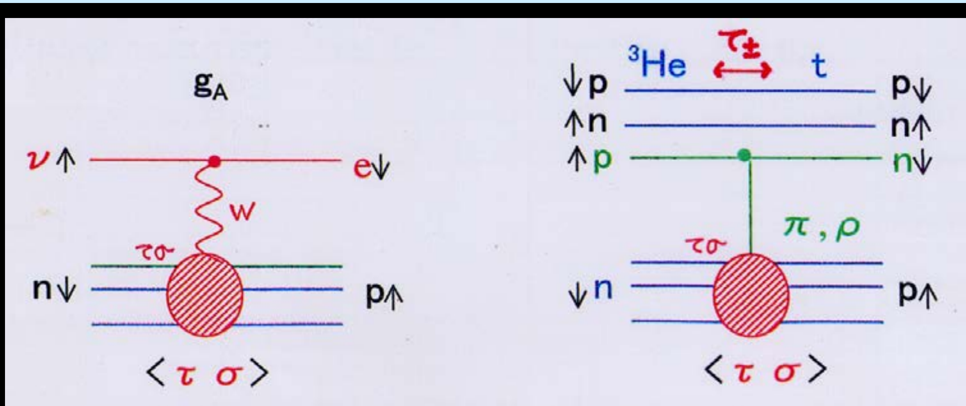



**All FSQP 1+ states contribute. In case of $^{96}$Zr, $^{100}$Mo, $^{116}$Cd, where n & p are in N=4 & 3 major shells, only 1 g7/2 g7/2 1+ state.**
**SSD The ground 1+ state ($^{100}$Mo, $^{128}$Te) dominate 2νββ.**

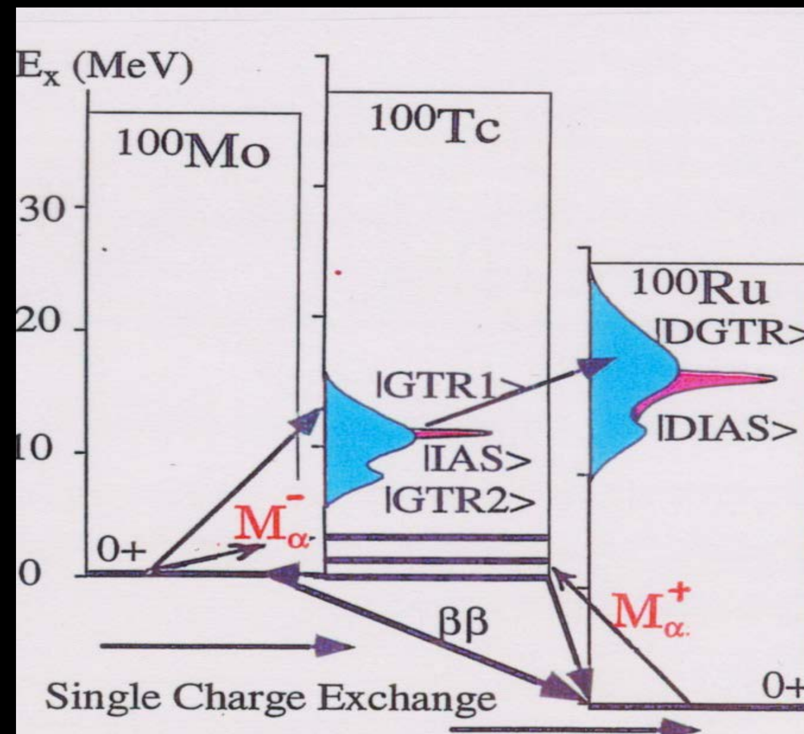
# CER:Charge exchange reactions for ν-responses

**RCNP ($^3$He,t) ($^7$Li, $^7$Be), MSU (t,$^3$He), KVI (d,$^2$He)**

**RCNP/Osaka, KVI, Munster, MSU Frekers**




$$\frac{d\sigma_\alpha(0^o)}{d\Omega}\frac{1}{K(E_i,0)N_\alpha^D} = |J_\alpha|^2 B(\alpha), \quad \alpha = \mathrm{F, GT.}$$




**($^3$He,t), ($^{11}$B, $^{11}$Li), (t,$^3$He)**

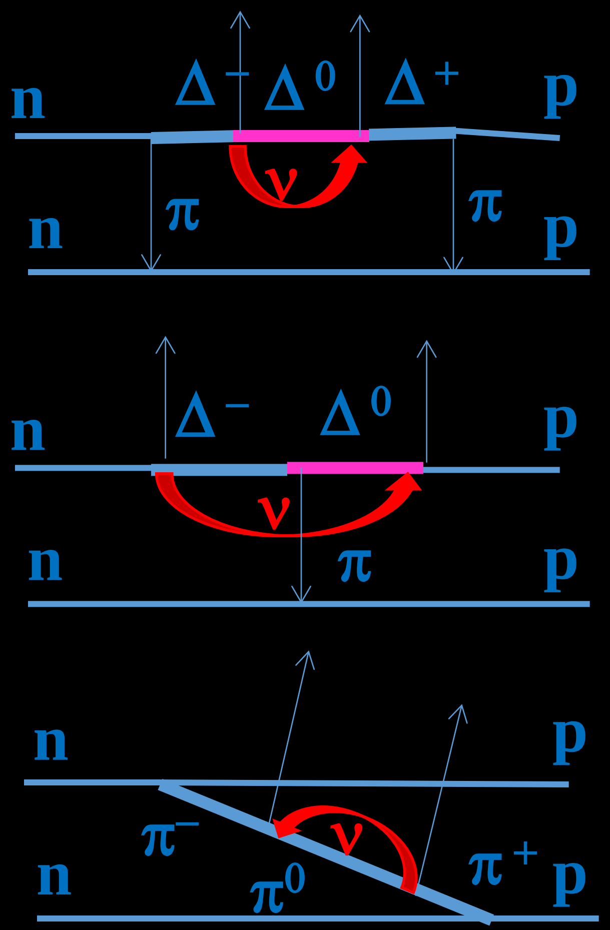
**β⁻ ββ β⁺**

**Non-central V**

**CER q-dependence and EC/β rates are used to get weak responses**

# Hadronic ( Δ, π) *

$N \Rightarrow \Delta$ quark $\tau\sigma$ flip GR
0.3 GeV high excitation
$0\nu\beta\beta$ in $\Delta,\pi$ enhanced




Effect on low $\beta\beta$ $0^+$ - $0^+$
$P(\Delta)^2 \sim (10^{-2})^2 \sim 10^{-4}$

|n Δ> interferes with |n p>
$|I\rangle = |n\,p\rangle - \varepsilon\,|n,\Delta^+\rangle$
$M^\beta \sim k^{eff} M_0$ $k^{eff}$ $(\Delta) \sim 0.7$

Exp by β deays and CER

*Pontecorvo; Haxton, Stephenson, Kotani Doi .

# Nuclear Matrix Elements for Two-Neutrino Double Beta Decays

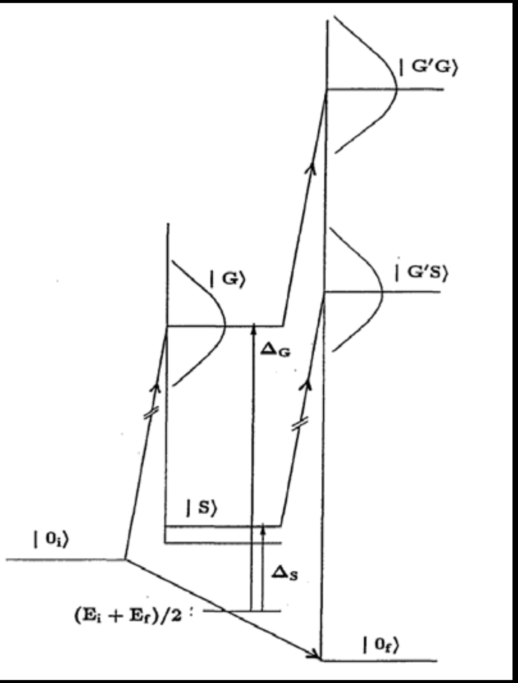
JPSJ Lett 65 '96 7

Hiroyasu EJIRI* and Hiroshi TOKI**

*Research Center for Nuclear Physics (RCNP), Osaka University, Mihogaoka, Ibaraki, Osaka 567*

(Received October 16, 1995)

Nuclear matrix elements $M^{2\nu}$ for two-neutrino double beta decays in medium-heavy even nuclei are found to be given by a product of matrix elements $M^{\nu}_{S} M^{\nu}_{S'}$ for successive single beta decays through low-lying single particle-hole $1^+$ states in intermediate nuclei. The empirical systematics is explained theoretically by coupling of single particle-hole $1^+$ states with GT (Gamow Teller) giant resonances.



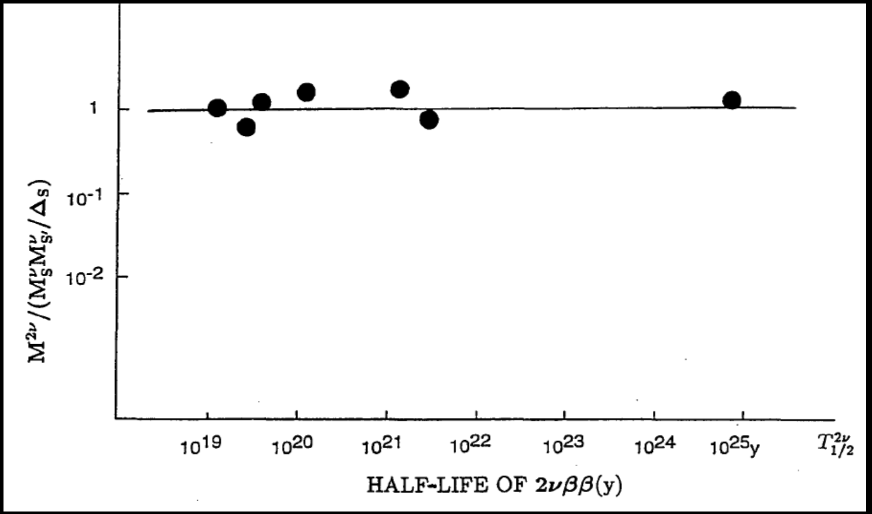

Now let us introduce the $\tau\sigma$-type interaction $H_I$ between $|S\rangle_0$ and $|G\rangle_0$. Then $|S\rangle$ and $|G\rangle$ are expressed as

$$|S\rangle = Q_S|0_i\rangle, \quad \text{with} \quad Q_S = Q^0_S - \varepsilon Q^0_G, \tag{11}$$

$$|G\rangle = Q_G|0_i\rangle, \quad \text{with} \quad Q_G = \varepsilon Q^0_S + Q^0_G. \tag{12}$$

$$M^{2\nu}(1^+) = \left(\frac{M^{\nu}_{S} M^{\nu}_{S'}}{\Delta_S}\right)(1+\delta),$$

$$\delta = \frac{\Delta_S}{\Delta_G} \cdot \frac{\varepsilon M^{\nu}_{G}}{M^{\nu}_{S'}} \left(1 - \frac{\varepsilon'}{\varepsilon}\right). \tag{25}$$




**Start CER to get low-lying GT 1+, SD 2- , ･･･ for 2νββ and 0νββ.**