

# Neutrino-nucleus interactions and the axial coupling

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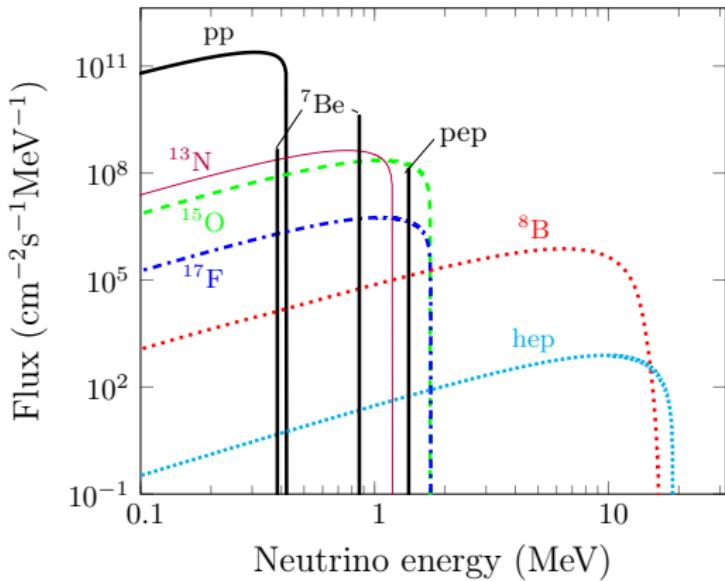
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## Contents:

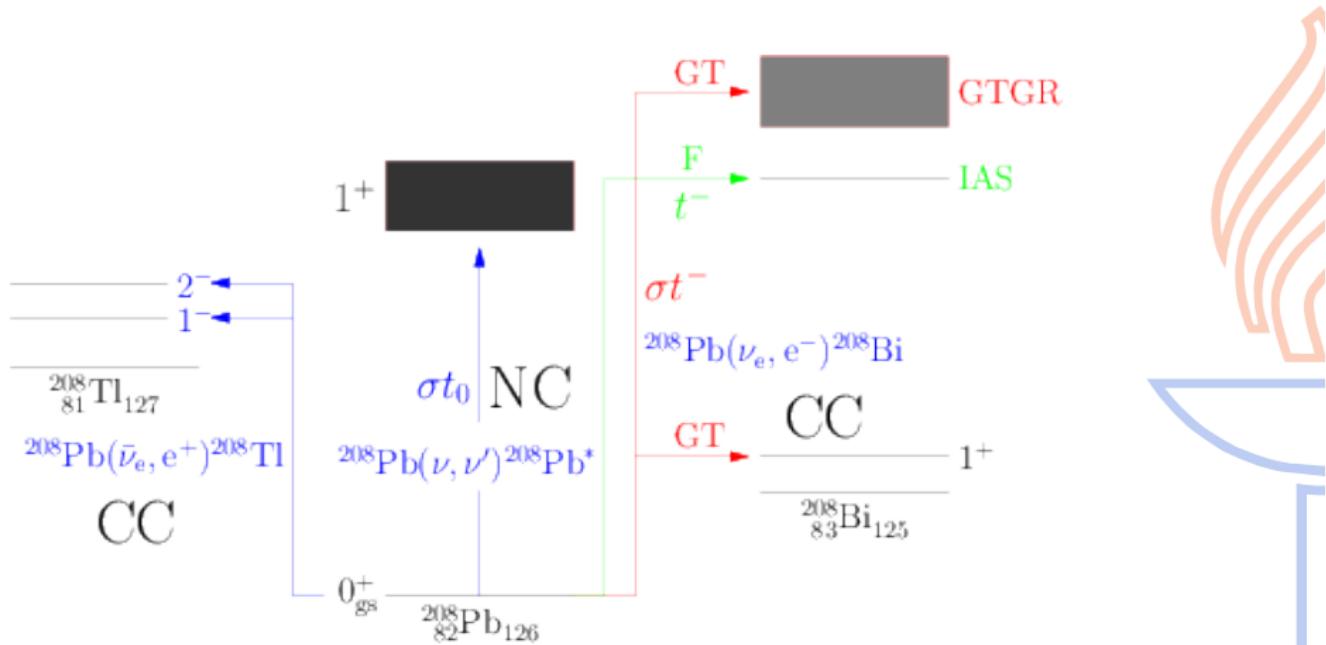
- INTRO: Nuclear-structure aspects of  $\nu$  scattering off nuclei
- Weak decays and the axial coupling
- Beta-electron spectral shapes
- Ordinary muon capture, a probe of  $g_A$  at momentum exchanges of  $\sim 100$  MeV/c

# Example: Solar-neutrino fluxes



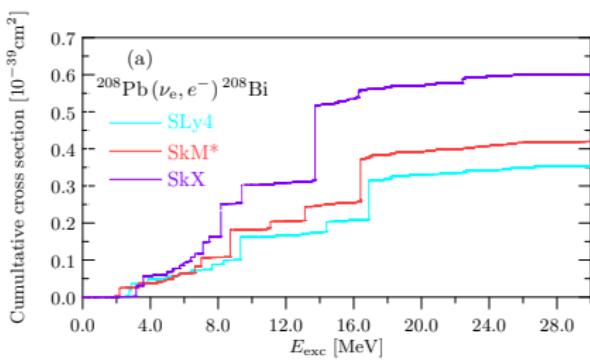
- Supernova-neutrino fluxes extend to several tens of MeV
- Accelerator-neutrino fluxes can go to hundreds of MeV and beyond

# Spin and isospin properties of nuclear excitations



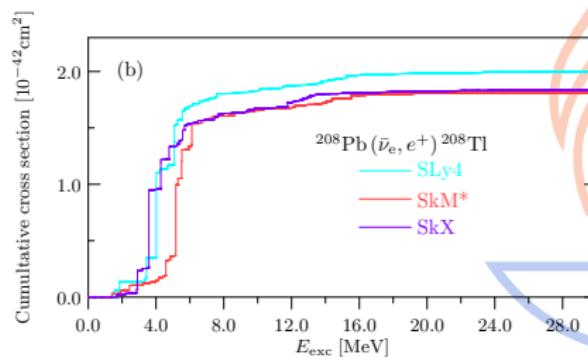
Traditionally (the "shell-model way"):  $g_A(\sigma\tau^-) \rightarrow g_A(q\sigma\tau^-)$ ,  $q$  = quenching factor.  
 Can also be interpreted as:  $g_A \rightarrow g_A^{\text{eff}} = q g_A$ .

# Nuclear-structure aspects: Cumulative sums of solar-neutrino folded CC cross sections for $^{208}\text{Pb}$



Neutrino scattering

Contributions also from the GTGR



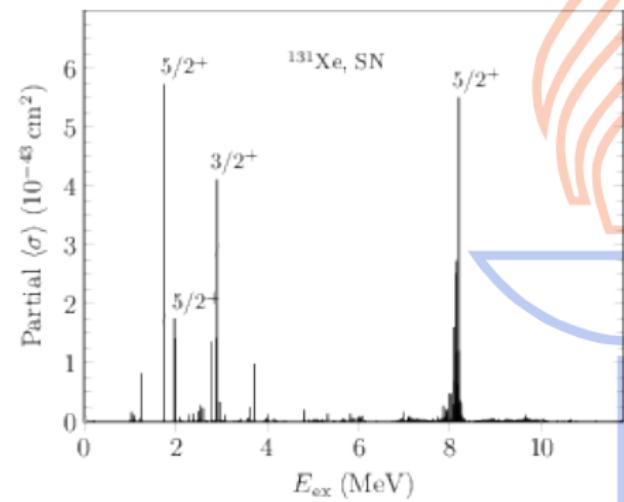
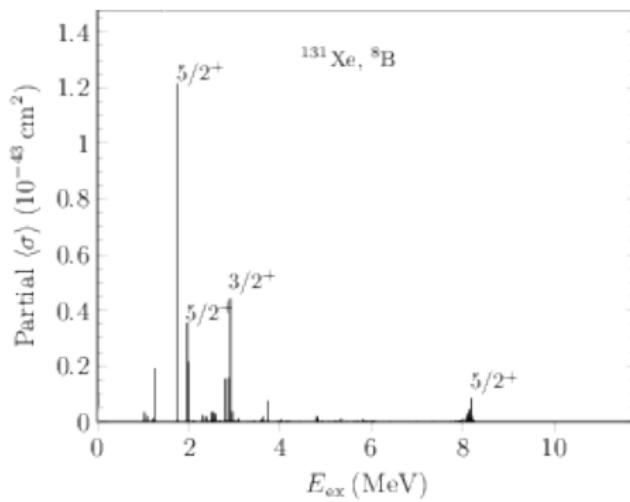
Antineutrino scattering

Contribution mainly from low energies

pnQRPA Calculations done with the SkX, SKM\*, SLy4 Skyrme interactions (W. Almosly *et al.*, Phys. Rev. C 94 (2016) 044614).

NC scattering of  $\nu_e$  off  $^{131}\text{Xe}$ :  $^8\text{Be}$  and supernova-neutrino folded cross sections

Folding affects the importance of nuclear excitations at different energy ranges: relative importance of the  $5/2^+$  spin-flip M1 giant resonance



Comparison of the most important contributions to the  $^8\text{B}$  solar and supernova (SN) electron-neutrino cross section for  $^{131}\text{Xe}$  (with  $3/2^+$  ground state).

## Relevance of the effective value of the weak axial coupling $g_A$

### Motivation:

Effective value of the weak coupling  $g_A$  is involved in all weak processes, and thus have impact on

- studies of  $\beta$  decays
- processes in neutrino physics ( $\beta\beta$  decay, low-energy (anti)neutrino-nucleus scattering, nuclear muon capture, ...)
- processes in astrophysics (allowed and forbidden  $\beta$  decays, (anti)neutrino-nucleus scattering cross sections, ...)

See the recent reviews:

H. Ejiri, J. S., K. Zuber: Neutrino-nuclear responses for astro-neutrinos, single beta decays and double beta decays, Physics Reports 797 (2019) 1–102

K. Blaum, S. Eliseev, F. A. Danevich, V. I. Tretyak, S. Kovalenko, M. I. Krivoruchenko, Yu. N. Novikov and J. S., Neutrinoless double-electron capture, Reviews of Modern Physics 92 (2020) 1–61.

# What we know about the effective value of $g_A$ :

At the quark level  $g_A^{\text{quark}} = 1$



At the free-nucleon level: Free-nucleon value of  $g_A$  (Particle Data Group 2016) from the decay of a free neutron:  $g_A^{\text{free}} = 1.2723(23)$



At the nuclear level: Nucleon weak current in a nucleus:

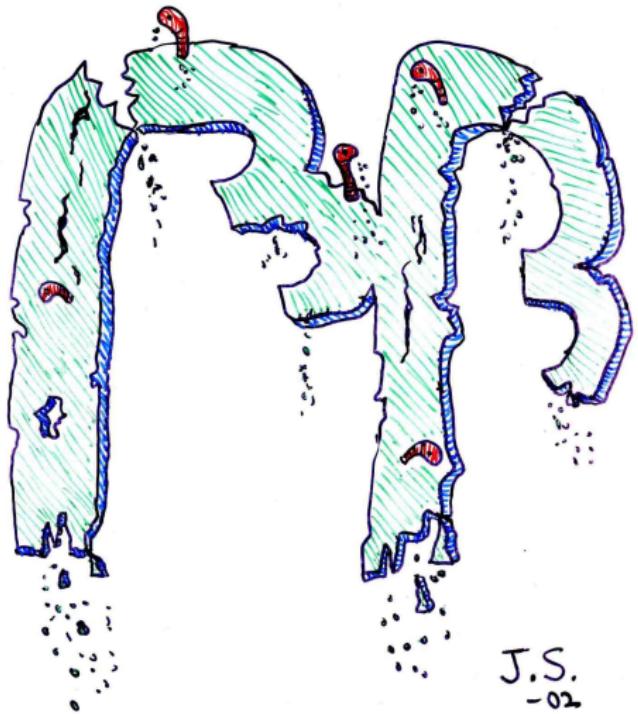
$$j_N^\mu = g_V \gamma^\mu - g_A^{\text{eff}} \gamma^\mu \gamma^5$$

The free-nucleon value of  $g_A$  is changed in nuclear-structure calculations by:

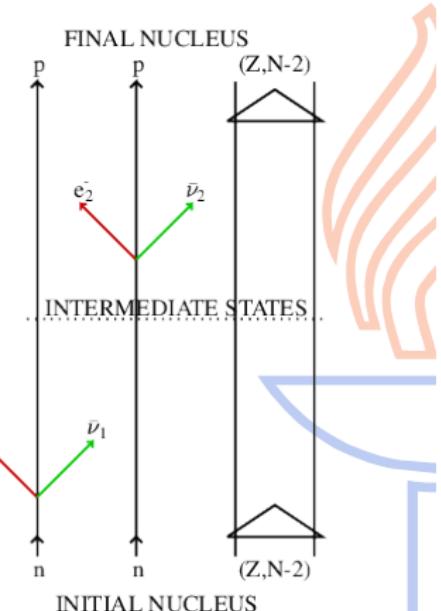
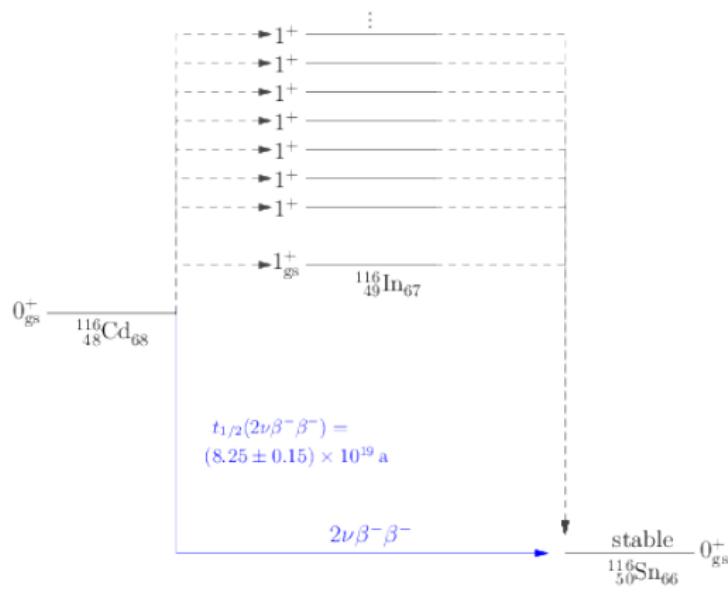
- Non-nucleonic degrees of freedom (e.g.  $\Delta$  resonances)
- Effects beyond the impulse approximation (e.g. two-body meson-exchange currents)
- Deficiencies in nuclear many-body approaches (e.g. restricted valence spaces, lacking many-body configurations, omission of three-body nuclear forces)

See also: "Value of the axial-vector coupling strength in  $\beta$  and  $\beta\beta$  decays: A review" Frontiers in Physics 5 (2017) 55.

# Most striking examples: Rates of $\beta\beta$ decay

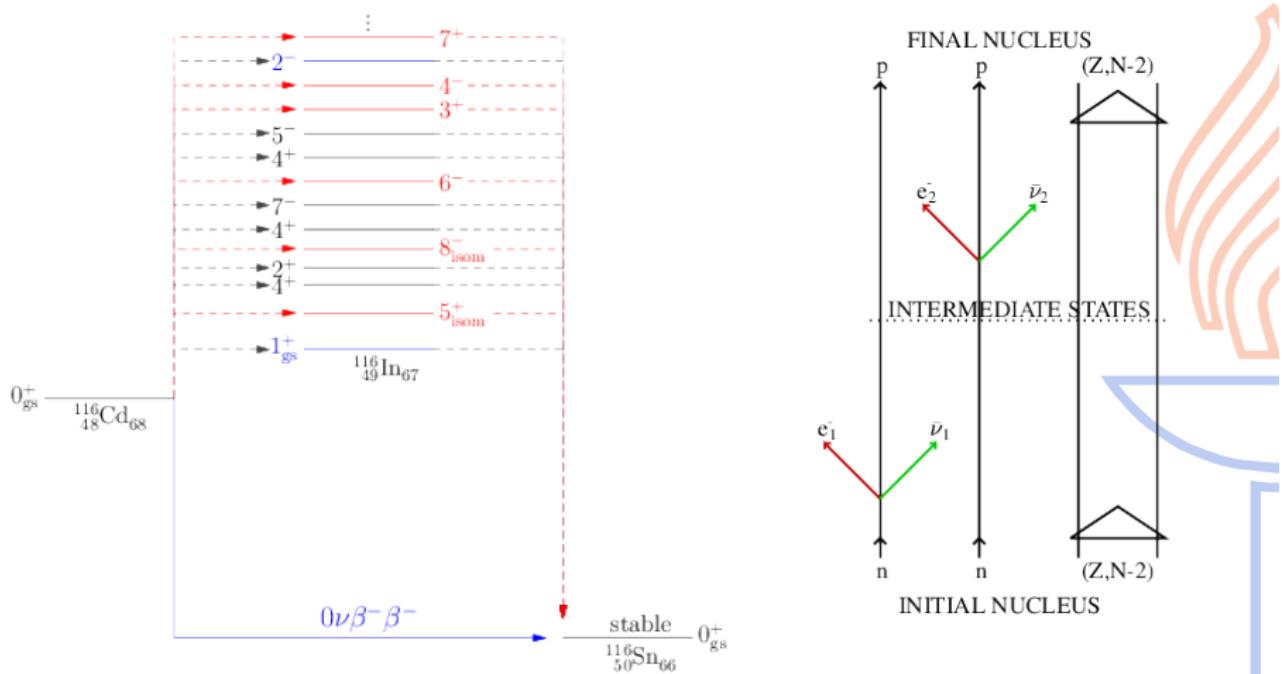


# Two-neutrino $\beta\beta$ decay of $^{116}\text{Cd}$



$$2\nu\beta\beta - \text{rate} \sim \left| M_{\text{GTGT}}^{(2\nu)} \right|^2 = (\varrho_A^{\text{eff}})^4 \left| \sum_{m,n} \frac{M_L(1_m^+) M_R(1_n^+)}{D_m} \right|^2$$

# Neutrinoless $\beta\beta$ decay of $^{116}\text{Cd}$ (mass mode)



$$0\nu\beta\beta - \text{rate} \sim \left| M_{\text{GTGT}}^{(0\nu)} \right|^2 = (g_{A,0\nu}^{\text{eff}})^4 \left| \sum_{J^\pi} (0_f^+ || \mathcal{O}_{\text{GTGT}}^{(0\nu)} (J^\pi) || 0_i^+) \right|^2$$

# Gamow-Teller $\beta$ and $2\nu\beta\beta$ decays

There are data on:

Gamow-Teller  $\beta$  transitions and  $2\nu\beta\beta$  transitions

For these we have the low-momentum-exchange limit of  $0\nu\beta\beta$  decay

$$g_{A,0\nu}(J^\pi) \xrightarrow{q \rightarrow 0} g_A(J^\pi),$$

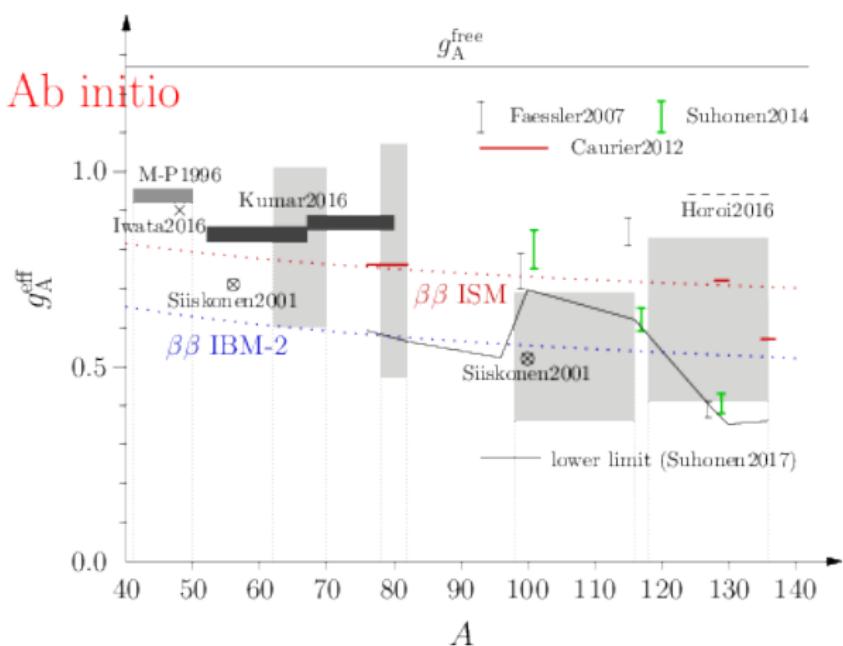
where the usual convention is  $g_A \equiv g_A(1^+)$

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Nuclear models:

ISM (Interacting Shell Model)  
pnQRPA (proton-neutron QRPA)  
IBM-2 (microscopic interacting boson model)

# Results extracted from the GT $\beta^\pm$ /EC and $2\nu\beta\beta$ calculations



**Ab initio:** P. Gysbers *et al.*, Nature Physics 15 (2019) 428

- Faessler2007: pnQRPA A. Faessler *et al.*, arXiv 0711.3996v1 [Nucl-th]
- Suhonen2014: pnQRPA J. Suhonen *et al.*, Nucl. Phys. A 924 (2014) 1
- Suhonen2017: pnQRPA J. Suhonen, Phys. Rev. C 96 (2017) 055501
- Caurier2012: ISM E. Caurier *et al.*, Phys. Lett. B 711 (2012) 62
- Horoi2016: ISM M. Horoi *et al.*, Phys. Rev. C 93 (2016) 024308
- M-P1996: ISM G. Martínez-Pinedo *et al.*, Phys. Rev. C 53 (1996) R2602
- Iwata2016: ISM Y. Iwata *et al.*, Phys. Rev. Lett. 116 (2016) 112502
- Kumar2016: ISM V. Kumar *et al.*, J. Phys. G 43 (2016) 105104 Phys. Lett. B 711 (2012) 62
- Siiskonen2001: ISM T. Siiskonen *et al.*, Phys. Rev. C 63 (2001) 055501
- $\beta\beta$  ISM and IBM-2: J. Barea *et al.*, Phys. Rev. C 87 (2013) 014315
- Light hatched regions: pnQRPA H. Ejiri *et al.*, J. Phys. G 42 (2015) 055201 ; P. Pirinen *et al.*, Phys. Rev. C 91 (2015) 054309 ; F. Deppisch *et al.*, Phys. Rev. C 94 (2016) 055501

# How do we extract information on the value of $g_A$ ?

These methods are now available:

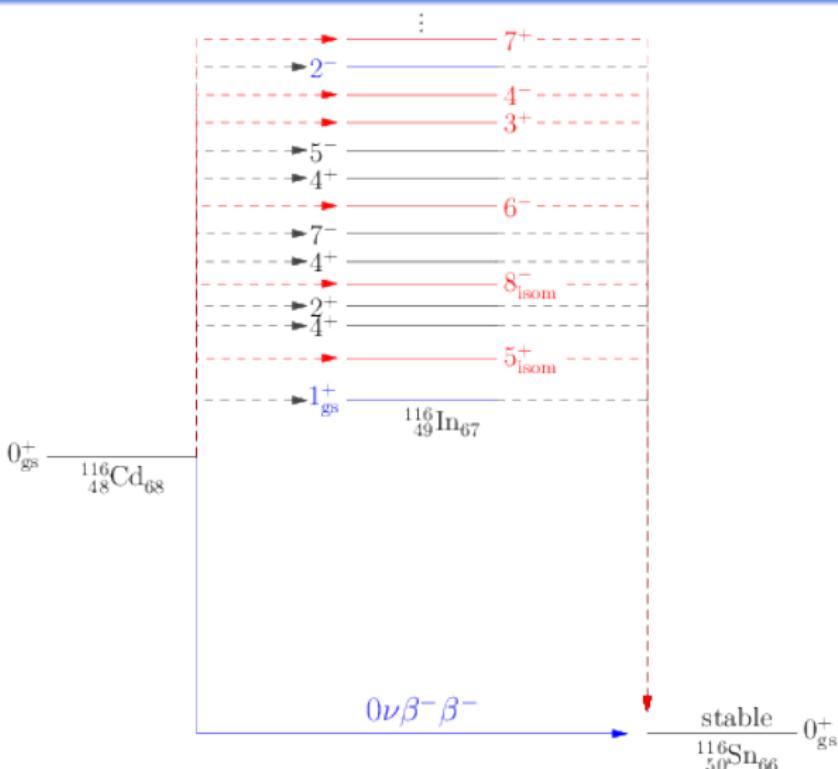
## For low momentum exchanges ( $g_A$ ):

- study half-lives of  $\beta$  decays ( $1^+$  and  $2^-$  states)
- study half-lives of  $2\nu\beta\beta$  decays ( $1^+$  states)
- Study electron spectral shapes of  $\beta$  decays ( $J^\pi$  states)

## For high momentum exchanges like $0\nu\beta\beta$ decay ( $g_{A,0\nu}$ ):

- Study nuclear muon capture ( $J^\pi$  states)

BUT:  $0\nu\beta\beta$  decay, as also the (anti)neutrino scattering, can go through states of higher angular momentum!



# Introducing the SSM: Spectrum-Shape Method

$$g_{A,0\nu}(J^\pi) \xrightarrow{q \rightarrow 0} g_A(J^\pi)$$

Higher-multipole transitions: Spectrum-Shape Method (SSM)\*:

Effective value of  $g_A(J^\pi)$

as derived from

electron spectra of

forbidden non-unique  $\beta$  decays

\*First introduced in: M. Haaranen, P. C. Srivastava and J. S., Forbidden nonunique  $\beta$  decays and effective values of weak coupling constants, Phys. Rev. C 93 (2016) 034308

# Spectral shape of higher-forbidden non-unique $\beta$ decays

Half-life:

$$t_{1/2} = \kappa/\tilde{C}.$$

Dimensionless integrated shape function:

$$\tilde{C} = \int_1^{w_0} C(w_e) p w_e (w_0 - w_e)^2 F_0(Z_f, w_e) dw_e .$$

Shape factor:

$$C(w_e) = \sum_{k_e, k_\nu, K} \lambda_{k_e} \left[ M_K(k_e, k_\nu)^2 + m_K(k_e, k_\nu)^2 - \frac{2\gamma_{k_e}}{k_e w_e} M_K(k_e, k_\nu) m_K(k_e, k_\nu) \right] ,$$

where

$$\lambda_{k_e} = \frac{F_{k_e-1}(Z, w_e)}{F_0(Z, w_e)} ; \quad \gamma_{k_e} = \sqrt{k_e^2 - (\alpha Z_f)^2} ,$$

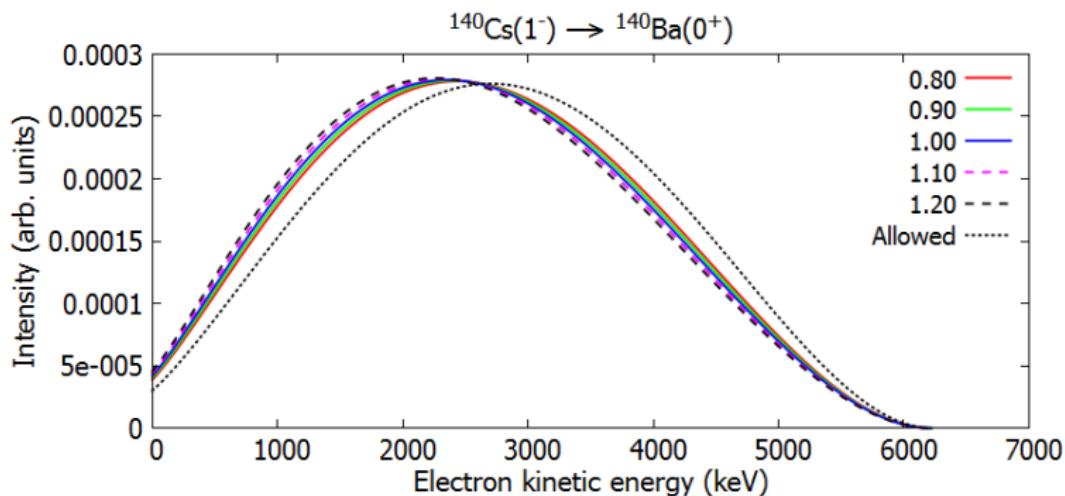
$F_{k-1}(Z, w_e)$  being the generalized Fermi function.

## Decomposition of the shape factor:

$$C(w_e) = g_V^2 C_V(w_e) + g_A^2 C_A(w_e) + g_V g_A C_{VA}(w_e).$$

EXAMPLE: 1st-forbidden nonunique decay of  $^{140}\text{Cs}$ 

First-forbidden nonunique  $\beta^-$  transition  $^{140}\text{Cs}(1^-) \rightarrow ^{140}\text{Ba}(0^+)$ : a high-yield fission product → **Contributes to the reactor-flux anomalies!**

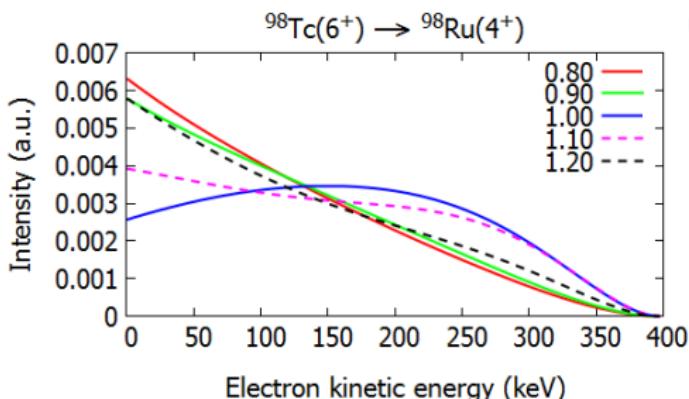
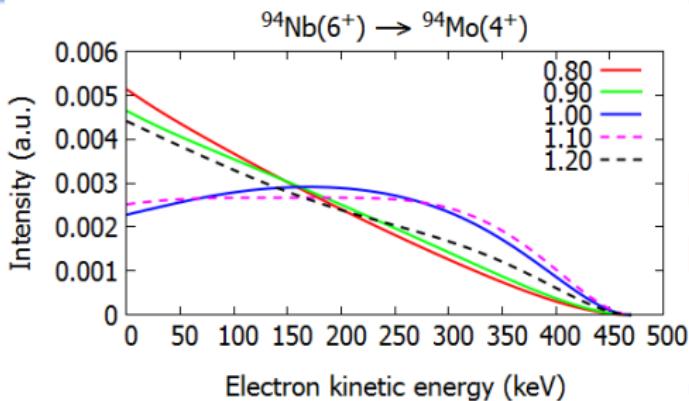


For the allowed approximation we have just a multiplicative factor and a universal spectral shape (independent of  $g_A$ ):  $C(w_e)_{\text{allowed}} = \frac{1}{2J_i+1} \left( g_A^2 M_{\text{GT}}^2 + g_V^2 M_{\text{F}}^2 \right) \neq$  function of  $w_e$

# ISM-computed $\beta^-$ spectra for different values of $g_A$

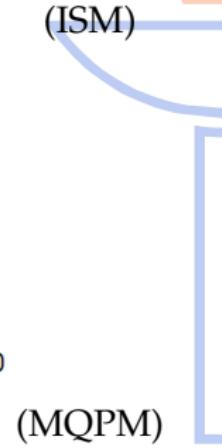
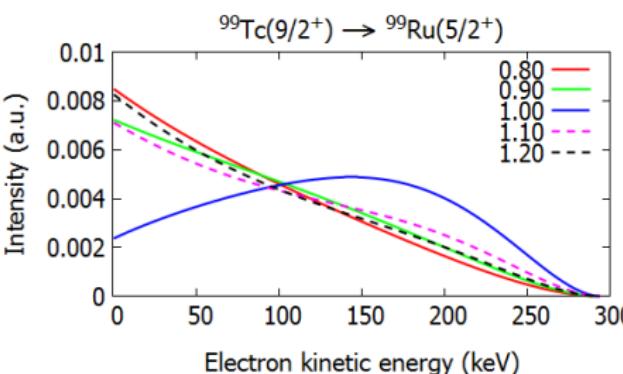
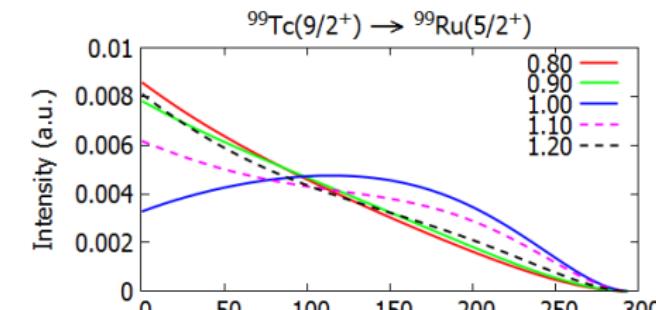
Normalized ISM-computed electron spectra for the **2nd-forbidden nonunique**  $\beta^-$  decays of  $^{94}\text{Nb}$  and  $^{98}\text{Tc}$  ( $g_V = 1.0$ ).

From: J. Kostensalo and J. S.,  
 $g_A$ -driven shapes of electron spectra of forbidden  $\beta^-$  decays in the nuclear shell model, Phys. Rev. C 96 (2017) 024317



# Example: ISM- and MQPM-computed electron spectra

Normalized electron spectra for the **2nd-forbidden nonunique  $\beta^-$  decay** of  $^{99}\text{Tc}$  ( $g_V = 1.0$ ) using different values of  $g_A$ .

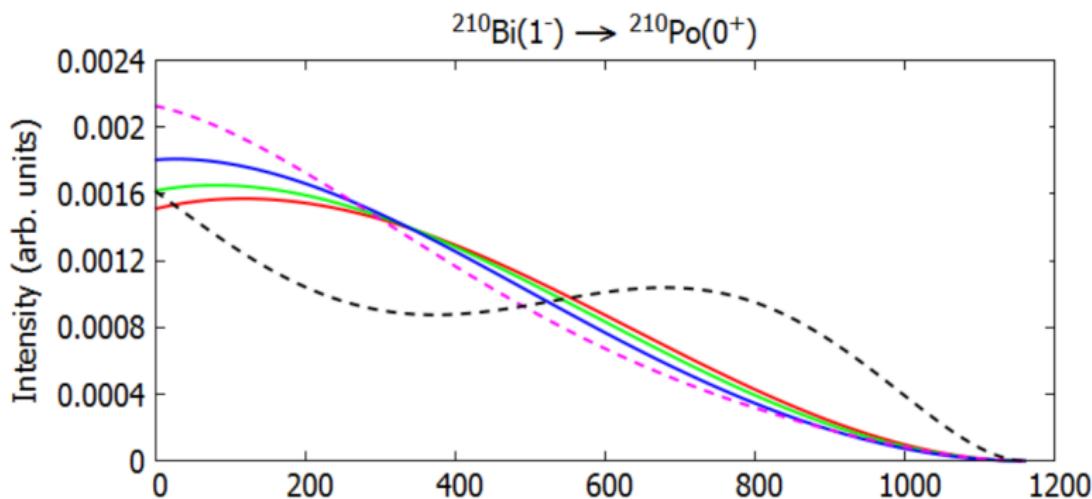


Going to be measured by the IBS-KNU-KRIS experimental group (South Korea) + calculations by the JYFL-LUKE (Finland) group: **gA EXPERiment and Theory collaboration = gA-EXPERT**

EXAMPLE: 1st-forbidden nonunique decay of  $^{210}\text{Bi}$ 

First-forbidden nonunique  $\beta^-$  transition  $^{210}\text{Bi}(1^-) \rightarrow ^{210}\text{Po}(0^+)$

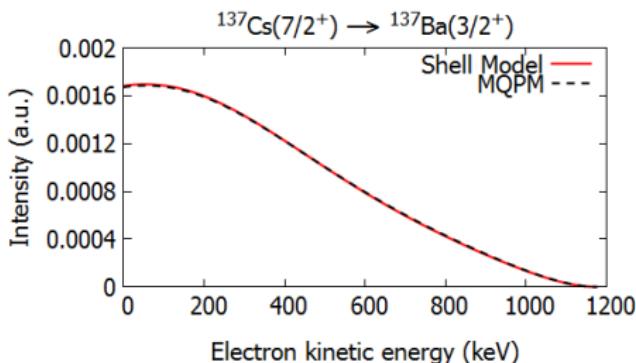
Spectral shapes for different values of  $g_A = 0.80$ (solid red), 0.90, 1.00, 1.10, 1.20(dashed black)



Measured and currently analyzed by the **gA-EXPERT**.

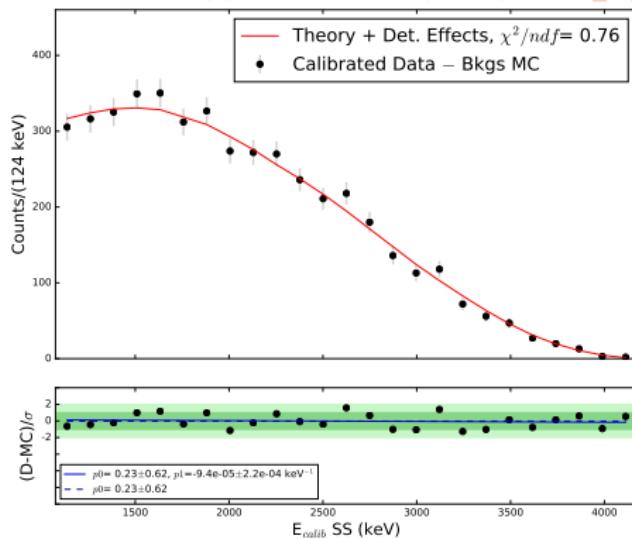
# $\beta$ spectral shapes without dependence on $g_A$

Normalized computed electron spectrum for the 2nd-forbidden nonunique  $\beta^-$  decay of  $^{137}\text{Cs}$



From: J. Kostensalo and J. S., Phys. Rev. C 96 (2017) 024317

First-forbidden nonunique  $\beta^-$  decay



From: S. Al Kharusi *et al.* (EXO-200 Collaboration), Phys. Rev. Lett. 124 (2020) 232502.

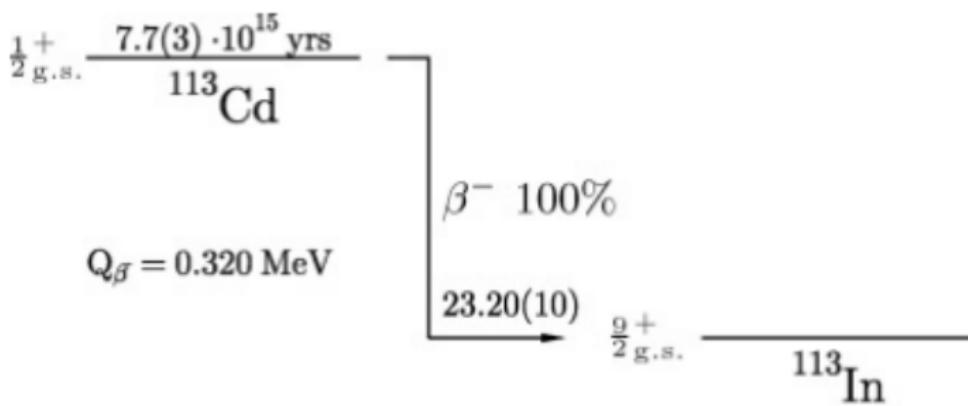
# Current list of $g_A$ -dependent $\beta$ -spectrum shapes

Transition	$J_i^{\pi_i}$ (gs)	$J_f^{\pi_f}$ ( $n_f$ )	Branching	K	Sensitivity	Nuclear model
$^{59}\text{Fe} \rightarrow ^{59}\text{Co}$	$3/2^-$	$7/2^-$ (gs)	0.18%	2	Moderate	ISM
$^{60}\text{Fe} \rightarrow ^{60}\text{Co}$	$0^+$	$2^+$ (gs)	<b>100%</b>	2	Moderate	ISM
$^{87}\text{Rb} \rightarrow ^{87}\text{Sr}$	$3/2^-$	$9/2^+$ (gs)	<b>100%</b>	3	Moderate	MQPM, ISM
$^{94}\text{Nb} \rightarrow ^{94}\text{Mo}$	$6^+$	$4^+$ (2)	<b>100%</b>	2	<b>Strong</b>	ISM
$^{98}\text{Tc} \rightarrow ^{98}\text{Ru}$	$6^+$	$4^+$ (3)	<b>100%</b>	2	<b>Strong</b>	ISM
$^{99}\text{Tc} \rightarrow ^{99}\text{Ru}$	$9/2^+$	$5/2^+$ (gs)	<b>100%</b>	2	<b>Strong</b>	MQPM, ISM
$^{113}\text{Cd} \rightarrow ^{113}\text{In}$	$1/2^+$	$9/2^+$ (gs)	<b>100%</b>	4	<b>Strong</b>	MQPM, ISM, IBFM-2
$^{115}\text{In} \rightarrow ^{115}\text{Sn}$	$9/2^+$	$1/2^+$ (gs)	<b>100%</b>	4	<b>Strong</b>	MQPM, ISM, IBFM-2
$^{136}\text{Te} \rightarrow ^{136}\text{I}$	$0^+$	$(1^-)$ (gs)	<b>8.7%</b>	1	<b>Strong</b>	ISM
$^{137}\text{Xe} \rightarrow ^{137}\text{Cs}$	$7/2^-$	$5/2^+$ (1)	<b>30%</b>	1	<b>Strong</b>	ISM
$^{138}\text{Cs} \rightarrow ^{138}\text{Ba}$	$3^-$	$3^+$ (1)	<b>44%</b>	1	<b>Strong</b>	ISM
$^{210}\text{Bi} \rightarrow ^{210}\text{Po}$	$1^-$	$0^+$ (gs)	<b>100%</b>	1	<b>Strong</b>	ISM

- Electron spectra of  $^{113}\text{Cd}$  (L. Bodenstein-Dresler *et al.*, Phys. Lett. B 800 (2020) 135092) measured by the **COBRA collaboration**.
- Electron spectrum of  $^{115}\text{In}$  measured by using the LiInSe<sub>2</sub> bolometer (**Experimentalists-Jyväskylä collaboration**).

# EXAMPLE: 4th-forbidden nonunique decay of $^{113}\text{Cd}$

4th-forbidden nonunique  $\beta^-$  transition  $^{113}\text{Cd}(1/2^+) \rightarrow ^{113}\text{In}(9/2^+)$



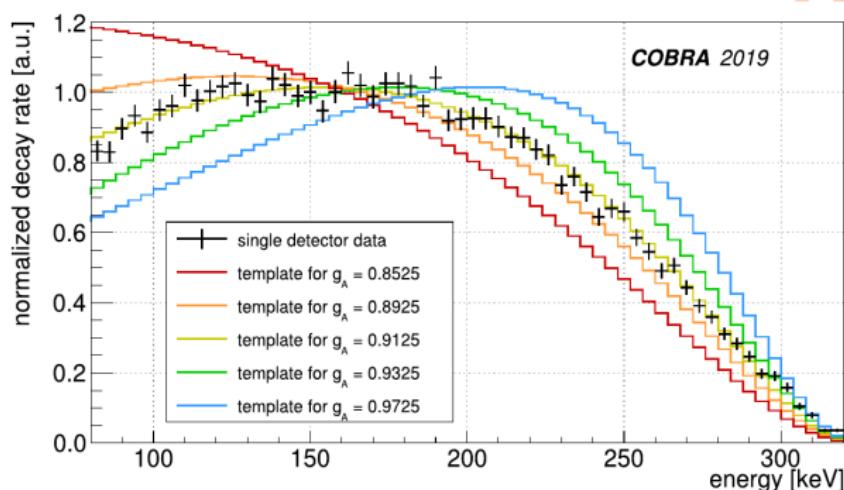
Calculated by using the **Interacting Shell Model (ISM)**, the **Microscopic Quasiparticle-Phonon Model (MQPM)** and the **microscopic Interacting Boson-Fermion Model (IBFM-2)**. NOTE: The  $^{113}\text{Cd}$  decay has recently been attacked by the **Spectral-Moments Method (SMM)** (J. Kostensalo, E. Lisi, A. Marrone and J.S., Study of  $^{113}\text{Cd}$   $\beta$ -decay spectrum and  $g_A$  quenching using spectral moments, submitted to Phys. Rev. C)

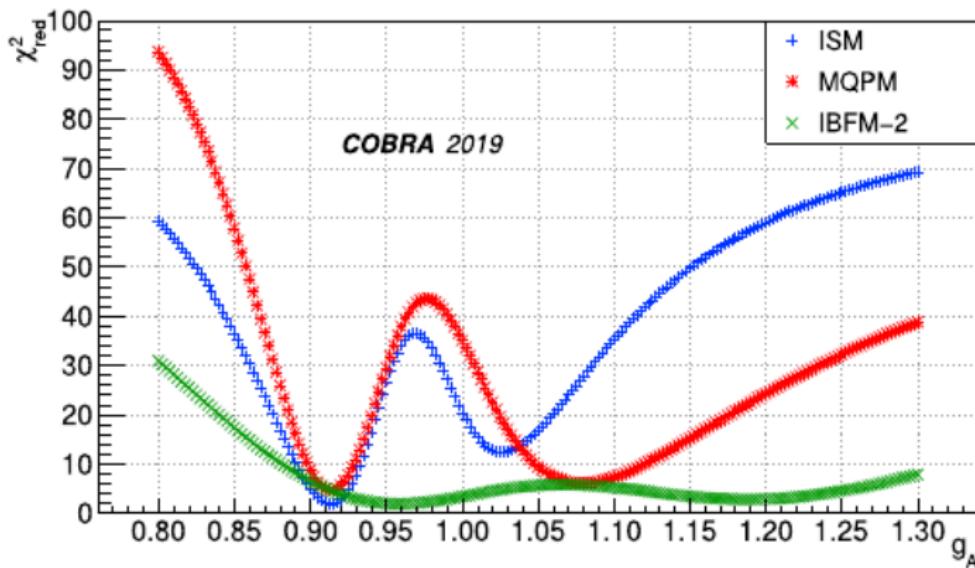
# Decay of $^{113}\text{Cd}$ – Comparison with data

Normalized electron spectra  
for the **4th-forbidden**  
**nonunique  $\beta^-$**  transition  
 $^{113}\text{Cd}(1/2^+) \rightarrow ^{113}\text{In}(9/2^+)$   
( $g_V = 1.0$ ).

Experimental data from  
The **COBRA** collaboration:  
**PLB2020:** L. Bodenstein-Dresler  
*et al.*, Phys. Lett. B 800 (2020)  
135092.

Measured spectrum by detector no. 54:

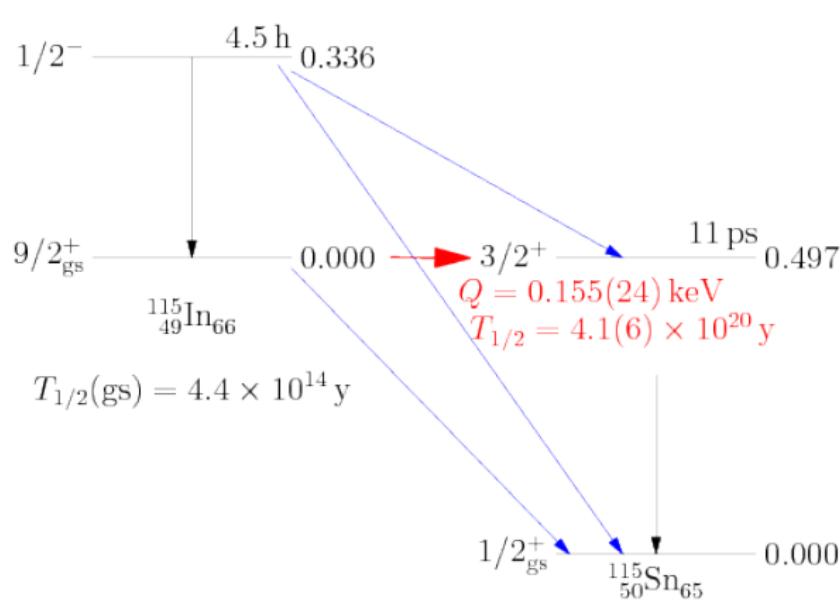


Decay of  $^{113}\text{Cd}$  – Comparison with data

PLB2020 :  $\bar{g}_A(\text{ISM}) = 0.914 \pm 0.008$ ; PLB2021 :=  $0.907 \pm 0.064$

PLB2020 :  $\bar{g}_A(\text{MQPM}) = 0.910 \pm 0.013$ ; PLB2021 :=  $0.993 \pm 0.063$

PLB2020 :  $\bar{g}_A(\text{IBFM-2}) = 0.955 \pm 0.035$ ; PLB2021 :=  $0.828 \pm 0.140$

EXAMPLE: 4th-forbidden nonunique transition  $^{115}\text{In}(9/2^+) \rightarrow ^{115}\text{Sn}(1/2^+)$ 

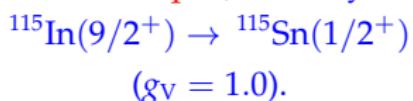
Interesting ultra-low  $Q$ -value transition: The 2nd-forbidden unique transition

$^{115}\text{In}(9/2^+) \rightarrow ^{115}\text{Sn}(3/2^+)$  has the smallest known  $Q$  value of a nuclear transition: J. S. E.

Wieslander *et al.*, Phys. Rev. Lett. 103 (2009) 122501; B. J. Mount *et al.*, Phys. Rev. Lett. 103 (2009) 122502.

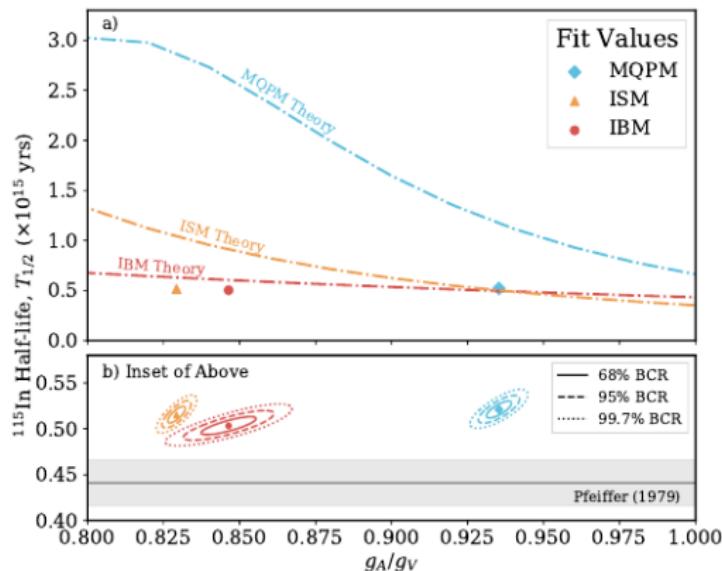
# Decay of $^{115}\text{In}$ – Comparison with data

Normalized electron spectra  
for the *4th-forbidden*  
*nonunique*  $\beta^-$  decay



Result from  
The CEA-CNRS-CSNSM-  
INR-JYFL-MIT-UCB  
collaboration: A. F. Leder *et*  
*al.*, Phys. Rev. Lett. 129 (2022)  
232502

Currently studied also by  
the ACCESS (Array of  
Cryogenic Calorimeters to  
Evaluate the Spectral Shape  
of forbidden beta decays)  
collaboration



$\bar{g}_A(\text{ISM}) = 0.830 \pm 0.002$
$\bar{g}_A(\text{IBFM-2}) = 0.845 \pm 0.006$
$\bar{g}_A(\text{MQPM}) = 0.936 \pm 0.003$

# Still extracting information on the value of $g_A$

These methods are now available:

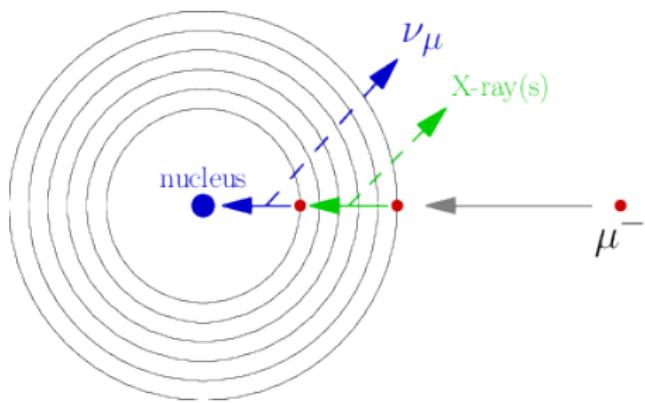
## For low momentum exchanges ( $g_A$ ):

- study half-lives of  $\beta$  decays ( $1^+$  and  $2^-$  states)
- study half-lives of  $2\nu\beta\beta$  decays ( $1^+$  states)
- Study electron spectral shapes of  $\beta$  decays ( $J^\pi$  states)

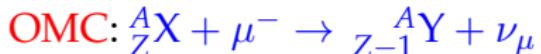
## For high momentum exchanges like $0\nu\beta\beta$ decay and accelerator neutrinos ( $g_{A,0\nu}$ ):

- Study nuclear muon capture ( $J^\pi$  states)

# Ordinary Muon Capture (OMC)



Nuclear muon capture:

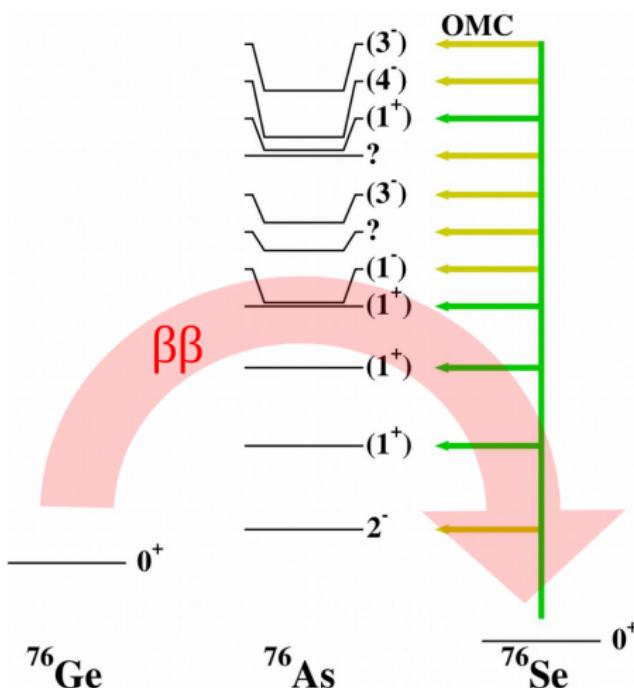
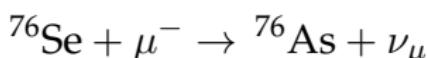


Also:

Muon decay:  $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$  ( $\tau = 2.2\mu\text{s}$ )

OMC probability  $\sim Z^4$   
(in Fe 91% are captured,  
breakeven at  $Z \sim 11$ )

# Ordinary muon capture (OMC) on $^{76}\text{Se}$



$$m_\mu c^2 \approx 105 \text{ MeV}$$

- OMC and  $0\nu\beta\beta$  operate in the  $q \approx 100 \text{ MeV}$  momentum-exchange region  $\Rightarrow g_{A,0\nu}(J^\pi)$
- Induced currents ( $g_P!$ ) are activated

## Experiments:

RCNP, Osaka ; J-PARC MLF, Japan ; PSI, Villigen, Switzerland

# OMC first suggested as an experimental probe for $0\nu\beta\beta$ matrix elements in:

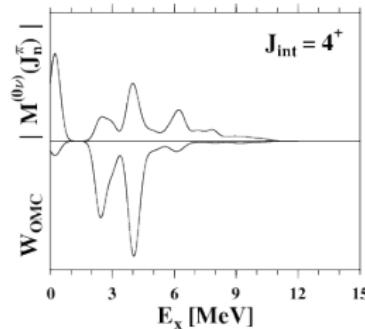
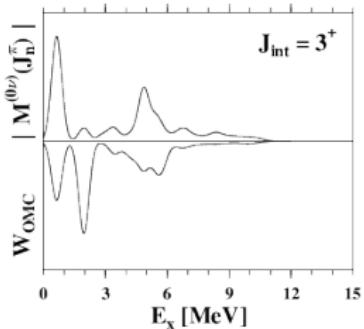
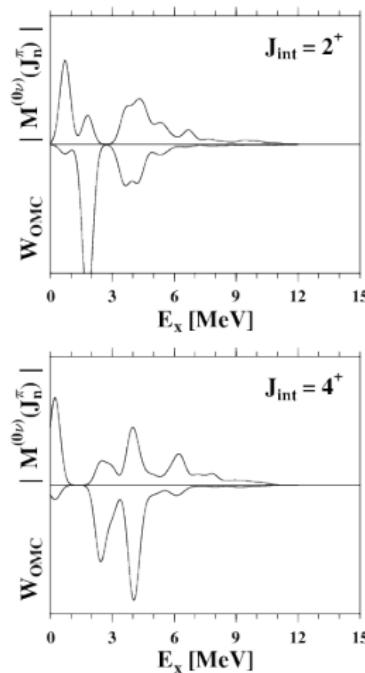
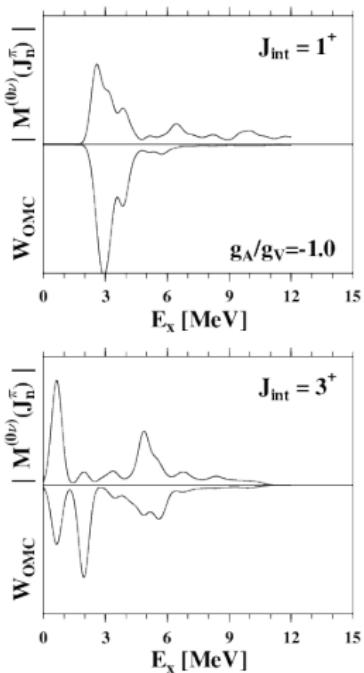
Pioneering works:

M. Kortelainen and J. S., Ordinary muon capture as a probe of virtual transitions of  $\beta\beta$  decay, *Europhysics Letters* **58** (2002) 666-672

M. Kortelainen and J. S., Microscopic study of muon-capture transitions in nuclei involved in double-beta-decay processes, *Nuclear Physics A* **713** (2003) 501-521

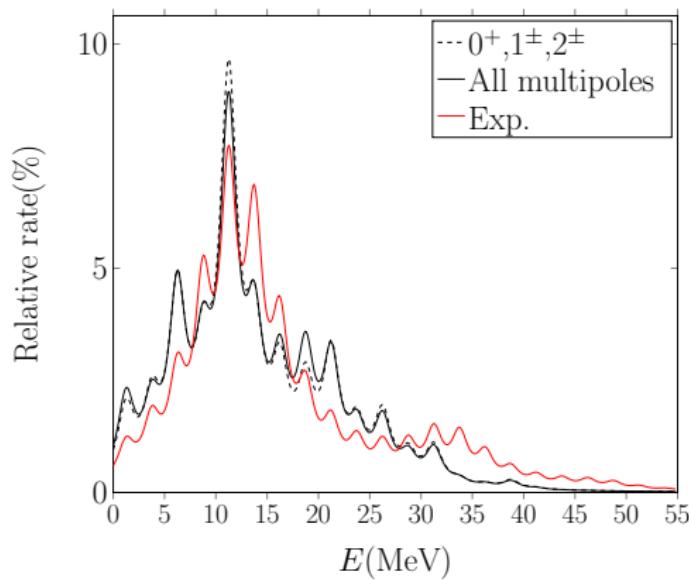
M. Kortelainen and J. S., Nuclear muon capture as a powerful probe of double-beta decays in light nuclei, *Journal of Physics G: Nucl. Part. Phys.* **30** (2004) 2003-2018

Original theory from: M. Morita and A. Fujii, Theory of allowed and forbidden transitions in muon capture reactions, *Phys. Rev.* **118** (1960) 606.

OMC as a tool to probe the  $0\nu\beta\beta$  decay (Case of  $^{48}\text{Ca}$ )

M. Kortelainen and J. S., J. Physics G: Nucl. Part. Phys. 30 (2004) 2003-2018: **ISM calculation**

# HIGHLIGHT: OMC on $^{100}\text{Mo}$ and the associated strength distribution



First evidence on OMC giant resonance:

L. Jokiniemi, J. S., H. Ejiri, I.H. Hashim, Pinning down the strength function for ordinary muon capture on  $^{100}\text{Mo}$ ,

Phys. Lett. B 794 (2019) 143.

Experiments: MuSIC beam channel at RCNP (Research Center for Nuclear Physics), Osaka, Japan

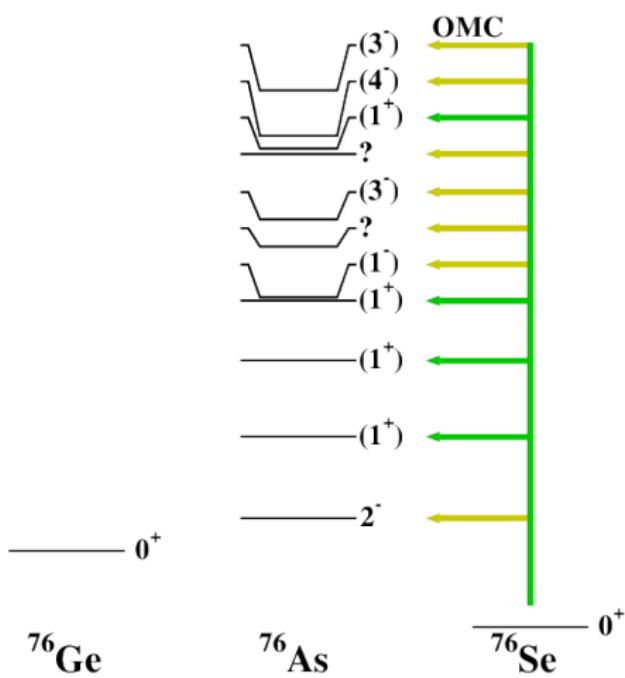
D2 beam channel in J-PARC (Japan Proton Accelerator Research Complex) MLF, Ibaraki, Japan

Ongoing work: experiments at the  $\mu\text{E4}$  beamline at PSI by The MONUMENT Collaboration



# OMC to individual $J^\pi$ states

OMC on  $^{76}\text{Se}$ :



OMC on  $^{76}\text{Se}$ : Rates to states  $J^\pi$  in  $^{76}\text{As}$   
below some 1 MeV: no-core

large-basis pnQRPA calculation

( $g_V(0) = 1.0$ ,  $g_A(0) = 0.8$ ,  $g_P(0) = 7.0$ )

$J^\pi$	Exp. (1/s)	Th. (1/s)
$0^+$	5120	414
$1^+$	218 240	236 595
$1^-$	31 360	28 991
$2^+$	120 960	114 016
$2^-$	145 920 + g.s.	177 802
$3^+$	60 160	55 355
$3^-$	53 120	34 836
$4^+$	-	2797
$4^-$	30 080	23 897

Data from: D. Zinatulina *et al.*, Phys. Rev. C 99 (2019) 024327

Calculation from: L. Jokiniemi and J.S.,  
Phys. Rev. C 100 (2019) 014619

# Conclusions and outlook

## Conclusions:

- The **effective value of  $g_A$**  is involved in all weak processes, and thus has impact on **studies of rare weak decays, neutrino physics and astrophysics**
- The large amount of calculations of Gamow-Teller  $\beta$  decays and  $2\nu\beta\beta$  decays are (surprisingly!) **consistent with each other** and clearly point to a  **$A$ -dependent quenched  $g_A$**
- The **spectrum-shape method (SSM)** for forbidden non-unique  $\beta$  decays is a **robust tool** to search for the **effective value of  $g_A$** . Recently: **spectral-moments method (SMM)**.
- The **OMC** can test the weak axial couplings ( $g_A$  and  $g_P$ ) at the **momentum-exchange region** relevant for the  **$0\nu\beta\beta$  decay** and neutrino-nucleus scattering at supernova/accelerator energies; it is also a sensitive probe of **nuclear wave functions**

## Outlook:

- Urge **measurements of the  $\beta$  spectra** for beta decays amenable to the SSM and SMM
- **Measurements of the OMC rates** for the  $0\nu\beta^-\beta^-$ -decay daughters will yield important information on the (induced) axial couplings relevant for  $0\nu\beta\beta$  decay and scattering of supernova/accelerator neutrinos off nuclei
- Ongoing experiments, like the **MONUMENT** will produce interesting new information on OMC strength functions and rates for transitions to individual states

## The (hopefully happy) end

**THANKS FOR PATIENCE!**