Nuclear Theory Studies in Finland

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- Theoretical Nuclear-structure physics in Finland
- Some highlights

Theoretical nuclear-structure physics in Finland:

Theoretical nuclear-structure physics in Finland

$\Leftrightarrow$

Team 4 of the CoE of the Academy of Finland:

Nuclear and Accelerator Based Program at JYFL

Key players

Jouni Suhonen (JYFL)
Jacek Dobaczewski (University of Jyväskylä, Academy of Finland, FiDiPro)
Markus Kortelainen (Helsinki Institute of Physics)

Team 4: Frontier Applications of Nuclear Theory

Spherical and deformed nuclei

- Sophisticated EDFs
- New innovative many-body approaches

⇕

Weak-interaction processes

- Formalism for beta and double beta decays
- Neutrino-nucleus processes

⇔

Present and future applications

- Masses and spectroscopy of exotic nuclei (FiDiPro collaborates with Teams 1 and 2)
- Neutrinoless $\beta\beta$ decays (Collaboration of Team 4 with the NEMO and COBRA)
- Resonant neutrinoless ECEC decays (Collaboration of Team 4 with the DAMA, collaboration with the Penning trap group at JYFL)
- Extremely slow β decays (Collaboration of Team 4 with the Penning trap group at JYFL)
- Neutrino-nucleus scattering for supernova modelling (together with the FiDiPro team)
- Renormalization of the axial-vector coupling constant (Team 4 with La Plata, Osaka, COBRA)

Markus Kortelainen: 6-year HIP project started in 2014

A six-year project, 3 postdocs and 2 PhD students

Awarded to Markus Kortelainen by the HIP

- Cabibbo-kobayashi-Maskawa mixing matrix
- Double beta decays
- Beta-decay rates and electromagnetic responses of r-process nuclei
- Uncertainties in energy density functionals

Some highlights

Some highlights of the group lead by Jouni Suhonen

Case I: Low Q-value and highly-forbidden β decays

Search and theoretical investigations of low-Q-value transitions for neutrino-mass measurements and determination of the effective value of g_{A} in β-decay processes of varying forbiddeness

At present the JYFL theory group is practically the only one in the world being able to address these processes

Neutrino Mass Measurements with low Q values

The KArlsruhe TRItium Neutrino experiment = KATRIN

$Q_{\beta^-} = 18.6\,\text{keV}$, Allowed ${}^{3}\text{H}(1/2^+) \rightarrow {}^{3}\text{He}(1/2^+)\ \beta^-$ decay

$\Downarrow$

The Microcalorimetric Array for a Rhenium Experiment = MARE

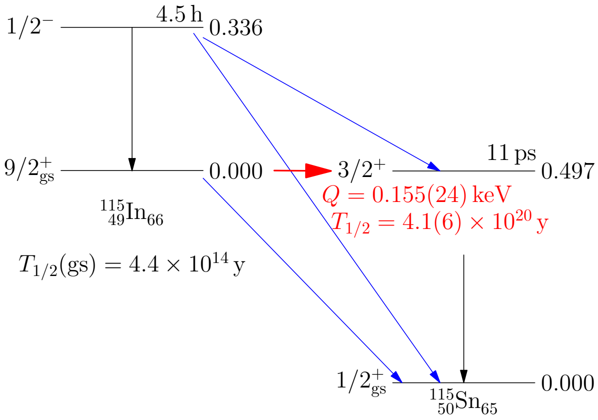
$Q_{\beta^-} = 2.469(4)\,\text{keV}$, First-forbidden unique ${}^{187}\text{Re}(5/2^+) \rightarrow {}^{187}\text{Os}(1/2^-)\ \beta^-$ decay

$\Downarrow$

?

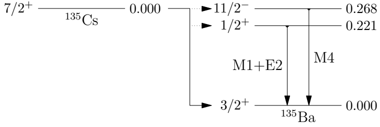
^{115}In: Beta decay with an ultra-low Q value

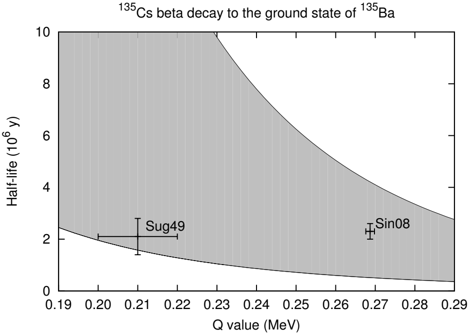
First discovered by Cattadori et al. (Nucl. Phys. A 748 (2005) 333)

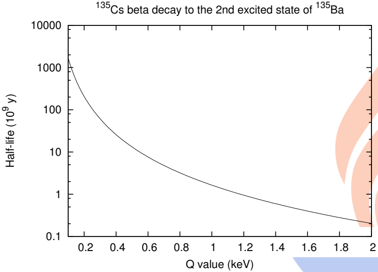


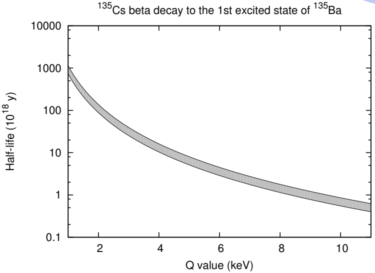
Suggested as a possible independent experiment to look for the neutrino mass

Decays of ^{135}Cs (1st and 2nd forbidden transitions)









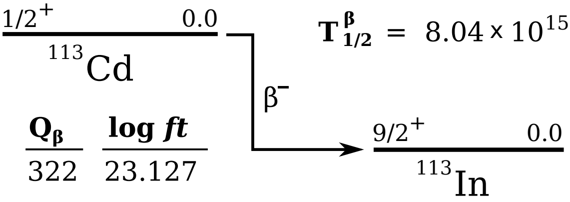
Important to revisit the *Q*-value msrmt!

M.T. Mustonen and J. Suhonen, PLB 703 (2011) 370

Other interesting cases

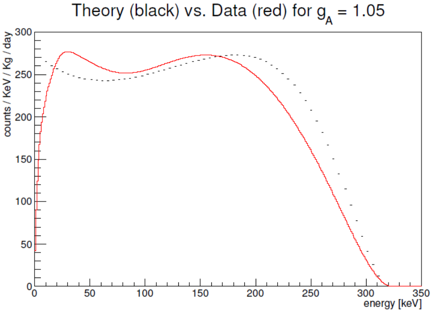
initial state	final state	E^* in keV	decay type	Q in keV
$^{77}\mathrm{As}(3/2^-)$	$^{77}\mathrm{Se}(5/2^+)$	680.1046(16)	1st non-unique β^-	2.8 ± 1.8
$^{111}\mathrm{In}(9/2^+)$	$^{111}\mathrm{Cd}(3/2^+)$	864.8(3)	2nd unique EC	-2.8 ± 5.0
	$^{111}\mathrm{Cd}(3/2^+)$	866.60(6)	2nd unique EC	-4.6 ± 5.0
$^{131}\mathrm{I}(7/2^+)$	$^{131}\mathrm{Xe}(9/2^+)$	971.22(13)	allowed β^-	-0.4 ± 0.7
$^{146}\mathrm{Pm}(3^-)$	$^{146}\mathrm{Nd}(2^+)$	1470.59(6)	1st non-unique EC	1.4 ± 4.0
$^{149}\mathrm{Gd}(7/2^-)$	$^{149}\mathrm{Eu}(5/2^+)$	1312(4)	1st non-unique EC	1 ± 6
$^{155}\mathrm{Eu}(5/2^+)$	$^{155}\mathrm{Gd}(9/2^-)$	251.7056(10)	1st unique β^-	1.0 ± 1.2
$^{159}\mathrm{Dy}(3/2^-)$	$^{159}\mathrm{Tb}(5/2^-)$	363.5449(14)	allowed EC	2.1 ± 1.2
$^{161}\mathrm{Ho}(7/2^-)$	$^{161}\mathrm{Dy}(7/2^-)$	857.502(7)	allowed EC	1.4 ± 2.7
	$^{161}\mathrm{Dy}(3/2^-)$	858.7919(18)	2nd non-unique EC	0.1 ± 2.7

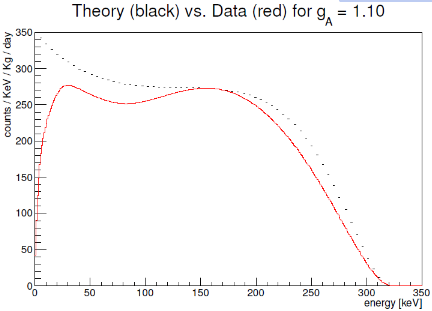
Beta spectrum shape: access the effective value of g_A



Q_β	log *ft*
322	23.127

$$T^{\beta}_{1/2} = 8.04 \times 10^{15}\ \text{yr}$$


Theory (black) vs. Data (red) for g_A = 1.05


Theory (black) vs. Data (red) for g_A = 1.10

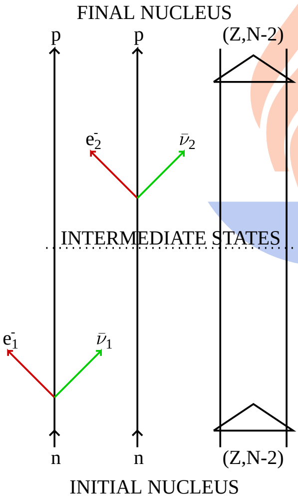
Case II: Neutrinoless double beta decay

Various modes of double beta decays

The JYFL theory group is and has been one of the key players in nuclear-structure physics related to these processes in the world scale (the “Jyväskylä School of Thought”)

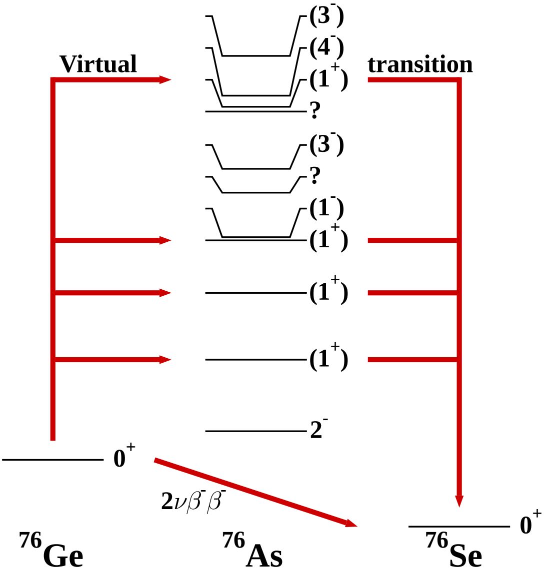
Two-neutrino double beta decay

Nucleus	half-life (years)	experiments
^{48}Ca	$4.2 \cdot 10^{19}$	laboratory
^{76}Ge	$1.4 \cdot 10^{21}$	laboratory
^{82}Se	$9 \cdot 10^{19}$	laboratory, geochemical
^{96}Zr	$2.1 \cdot 10^{19}$	laboratory, geochemical
^{100}Mo	$8.0 \cdot 10^{18}$	laboratory
^{116}Cd	$3.3 \cdot 10^{19}$	laboratory
^{128}Te	$2.5 \cdot 10^{24}$	geochemical
^{130}Te	$9 \cdot 10^{20}$	geochemical
^{136}Xe	$2.4 \cdot 10^{21}$	laboratory
^{150}Nd	$7.0 \cdot 10^{18}$	laboratory
^{238}U	$2.0 \cdot 10^{21}$	radio-chemical



10^{20} years =
10000000000 × age of the UNIVERSE

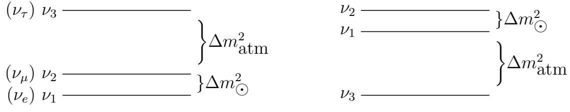
$2\nu\beta\beta$ decay from nuclear-structure point of view



Neutrinoless double β^- decay

$0\nu\beta\beta$ Decay is Able to:

- Reveal if the neutrino is a Majorana particle
- Probe the neutrino effective mass $\langle m_\nu \rangle = \sum_{j=\mathrm{light}} \lambda_j^{\mathrm{CP}} |U_{\mathrm{e}j}|^2 m_j$
- Probe the degenerate or inverted mass hierarchies (next-generation experiments!)
- Probe possibly the CP phases (nuclear matrix elements are critical!)



Normal hierarchy

Inverted hierarchy

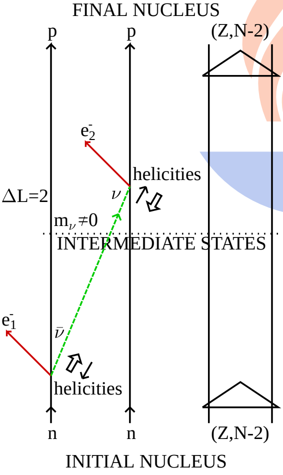
$$\Delta m^2_\odot = 7.67^{+0.16}_{-0.19} \times 10^{-5}\,\mathrm{eV}^2$$

$$\Delta m^2_{\mathrm{atm}} = 2.39^{+0.11}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$$

[Global 3ν oscillation analysis (2008)]

MASS MODE:

$$T^{-1}_{1/2} \propto \langle m_\nu \rangle^2$$



Nuclear Matrix Elements and the $0\nu\beta\beta$ Decay

Decay rate:

$$\frac{\ln 2}{T_{1/2}} = {g_{\rm A}}^4 G^{(0\nu)}(Q)[M^{(0\nu)}]^2 \langle m_\nu \rangle^2$$

- $G^{(0\nu)}(Q) \propto Q^5$ is the phase-space factor
- $M^{(0\nu)}$ = NUCLEAR MATRIX ELEMENT
- Effective neutrino mass:

$$\langle m_\nu \rangle = \sum_{j=\rm light} \lambda_j^{\rm CP} |U_{{\rm e}j}|^2 m_j$$

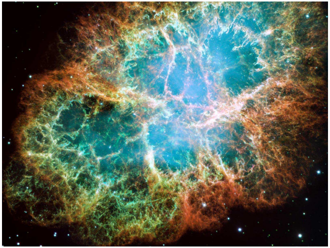
Presently computed by: QRPA (Jyväskylä, Chapel Hill, Tübingen-Bratislava-Caltec), ISM (Strasbourg-Madrid), IBA-2 (Yale), Gogny-based EDF+GCM (Darmstadt), Projected HFB (Indian-Mexican collaboration)

Case III: Neutrino-nucleus scattering at supernova energies

Neutrino-nucleus scattering and supernova neutrinos

The JYFL theory group has recently become one of the key players in nuclear-structure physics related to these processes in the world scale

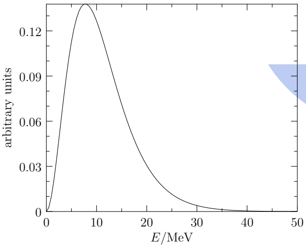
Supernova neutrinos

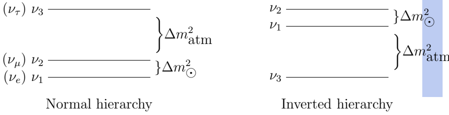


Important probes of:

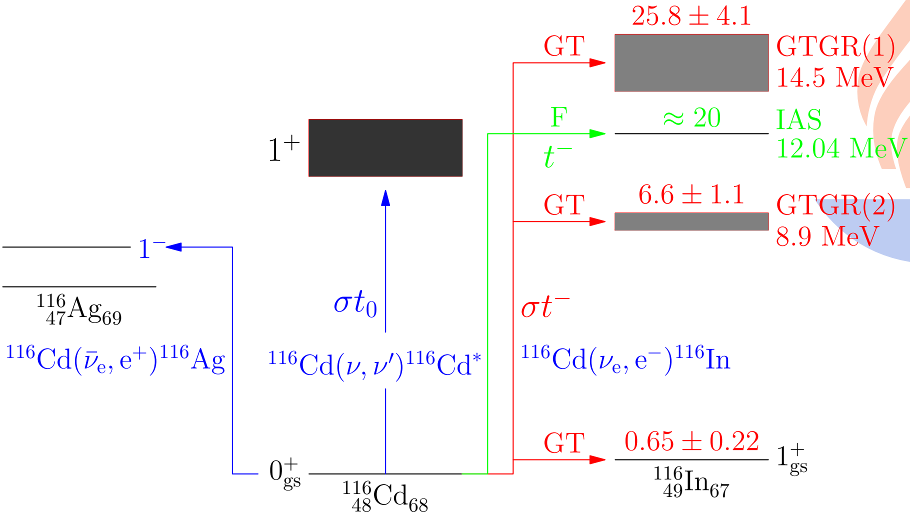
- Unknown supernova mechanisms, ν and $\bar{\nu}$ energy profiles
- Neutrino physics beyond the SM: ν oscillations in (dense) matter and the ν mass hierarchy
- Only observations so far from SN1987a

Neutrino-nucleus interactions are crucial in supernova explosions and for the nucleosynthesis of heavy elements





Example: spin, isospin and spin-isospin properties of NC and CC excitations of ^{116}Cd



25.8 ± 4.1

GT

GTGR(1)
14.5 MeV

F

≈ 20

IAS
12.04 MeV

t^-

1^+

GT

6.6 ± 1.1

GTGR(2)
8.9 MeV

1^-

$^{116}_{47}\mathrm{Ag}_{69}$

σt_0

σt^-

$^{116}\mathrm{Cd}(\bar{\nu}_\mathrm{e},\mathrm{e}^+)^{116}\mathrm{Ag}$

$^{116}\mathrm{Cd}(\nu,\nu')^{116}\mathrm{Cd}^*$

$^{116}\mathrm{Cd}(\nu_\mathrm{e},\mathrm{e}^-)^{116}\mathrm{In}$

GT

0.65 ± 0.22

0^+_gs

$^{116}_{48}\mathrm{Cd}_{68}$

$^{116}_{49}\mathrm{In}_{67}$

1^+_gs

Progress thus far and prospects

The Bonn-A interaction

- CC and NC scattering on ^{92,94,96,98,100}Mo studied by the QRPA
- CC and NC scattering on ^{95,97}Mo studied by the MQPM (Microscopic Quasiparticle-Phonon model)
- Important for the MOON (Mo Observatory Of Neutrinos) experiment

The Bonn-A interaction

- CC and NC scattering on ^{106,108,110,112,114,116}Cd studied by the QRPA
- CC and NC scattering on ^{111,113}Cd studied by the MQPM (Microscopic Quasiparticle-Phonon model)
- Interesting for the COBRA (cadmium-telluride experiment)

The Skyrme interactions

- CC scattering on ^{116}Cd recently studied by the HOSPHE (pnQRPA)
- CC scattering on ^{204,206,208}Pb studied by the HOSPHE (projected to start soon, important for the HALO experiment)

Neutrino-nucleus interactions in ^{116}Cd

Excitations in ^{116}Cd, ^{116}Ag and ^{116}In with Bonn-A force

QRPA and pnQRPA calculations

IOP Highlight article 2013 (caregory: Nuclear and Particle Astrophysics)

W. Almosly, E. Ydrefors and J. Suhonen, Neutral- and charged-current supernova-neutrino scattering off ^{116}Cd, J. Phys. G: Nucl. Part. Phys **40** (2013) 095201

Charge-changing excitations of ^{116}Cd

Isospin and spin-isospin excitations of ^{116}Cd with 10 different Skyrme forces

The pnQRPA code HOSPHE with full diagonalization in 15 harmonic-oscillator major shells

Publication:

W. Almosly, B.G. Carlsson, J. Dobaczewski, J. Suhonen, J. Toivanen, P. Vesely and E. Ydrefors, Charged-current neutrino and antineutrino scattering off ^{116}Cd described by Skyrme forces, Phys. Rev. C **89** (2014) 024308